Search for high mass dilepton and diphoton resonances at the Large Hadron Collider (LHC).

LHCP2015

Otman Charaf

University of Alabama

September 1st 2015

Introduction

Theoretical motivation

- The Higgs boson discovery brought the last piece of the Standard Model (SM)
- But many extensions of the SM could manifest at higher energies $\rightarrow$ new resonances at the TeV scale $\rightarrow$ probe at the LHC

Models

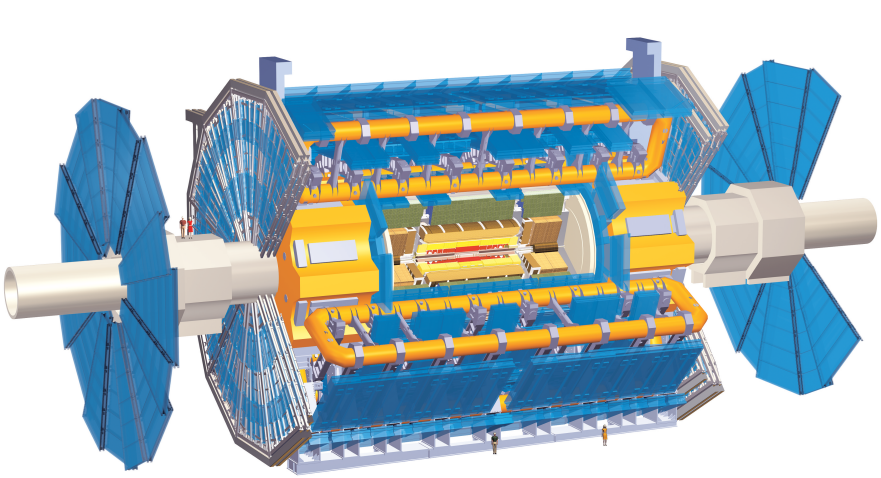
- A myriad of models probed by both ATLAS and CMS experiments, in almost every channel
- Extra dimensions: additional spatial dimensions of finite size to address the hierarchy mass problem $\rightarrow$ series of Kaluza-Klein excitations
  - Randall-Sundrum scenario: only one extra dimension with warped geometry $\rightarrow$ massive excitations of the graviton
  - Two parameters: the coupling $c = k/M_{Pl}$ and mass of the first excitation M
- Grand unification: new gauge bosons: Z'_{SSM} (benchmark model), Z'_{ψ}, Z'_{χ}, Z^*

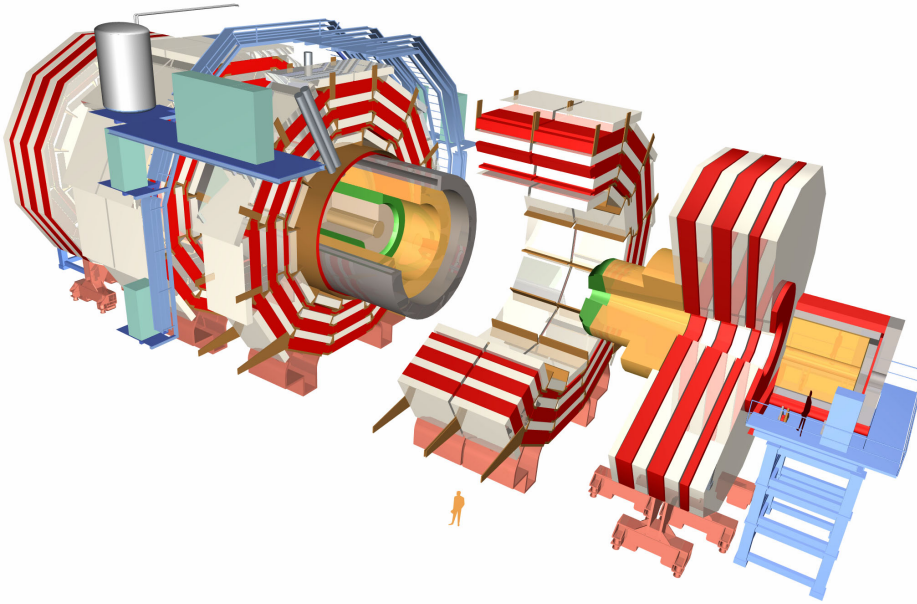
Introduction

Experimental searches

- Essentially looking for a peak over the background in the invariant mass distribution.
- Try to be as model independent as possible
- Diphoton channel very clean and good branching ratio for dilepton
- Mostly 8 TeV results

ATLAS and CMS

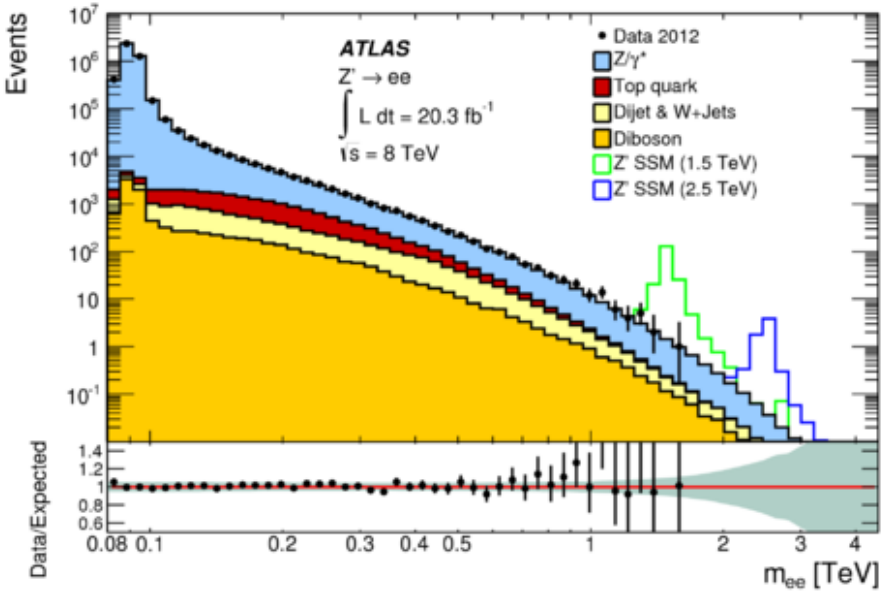


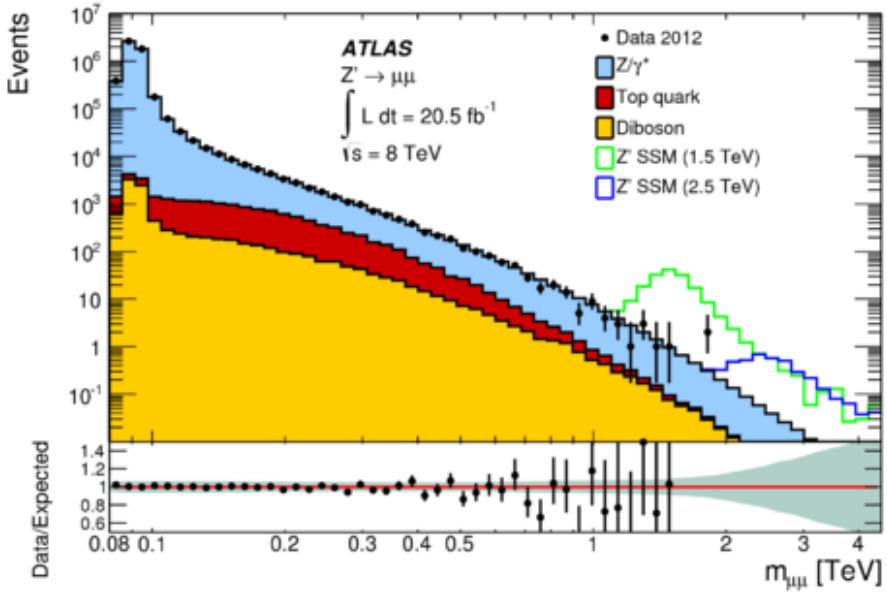


- Excellent energy resolution for both electromagnetic calorimeters
- ATLAS: longitudinal segmentation $\rightarrow$ e/π discrimination
- CMS: overall better tracking resolution

ATLAS Dilepton resonances ($X \to ll$) — arXiv

- Models: Randall-Sundrum, Sequential Standard Model, Z'_ψ, Z'_χ, Z^*
- Main backgrounds: irreducible Drell-Yan, $t\bar{t}$, QCD
- Lepton selection: shower shape + isolation
- Background estimation
  - Drell-Yan, $t\bar{t}$ and VV from Monte-Carlo
  - QCD multijets from fake rate method (matrix inversion)
  - Total background normalized to yields in 80-110 GeV region

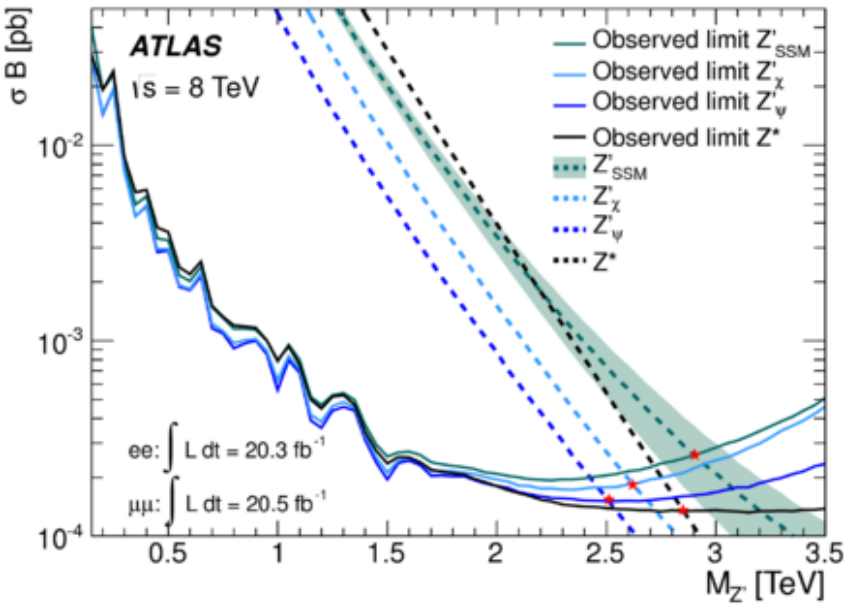


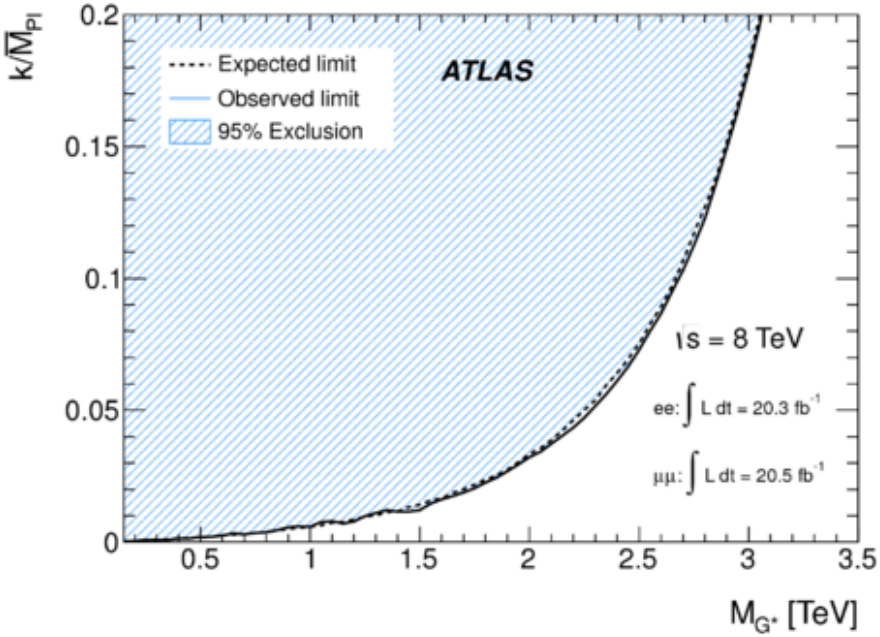


ATLAS Dilepton resonances ($X \to ll$) — arXiv

Statistical interpretation

- Binned likelihood ratio
- Parameter of interest: $\sigma \times B$ if no interference effects included, coupling strength otherwise.

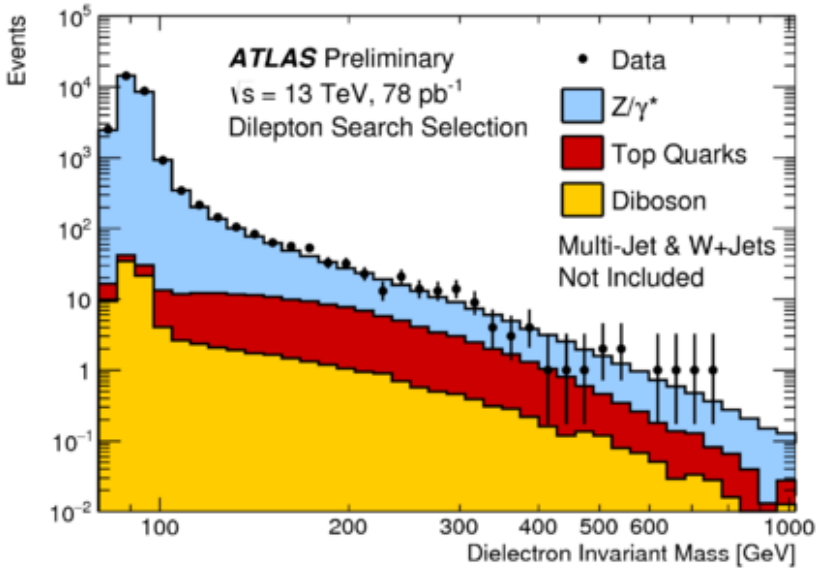


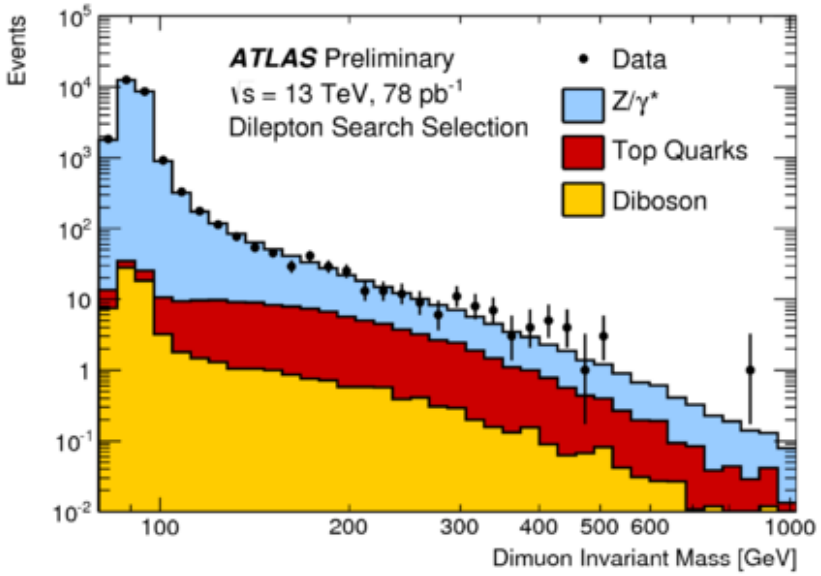


Model	Z'_{SSM}	Z'_{ψ}	Z'_{χ}	Z^*	$G(\tilde{k} = 0.2)$
Observed limits (TeV)	2.90	2.51	2.62	2.85	3.05
Expected limits (TeV)	2.87	2.46	2.60	2.82	3.05

ATLAS Dilepton resonances ($X \to ll$) — EXOT

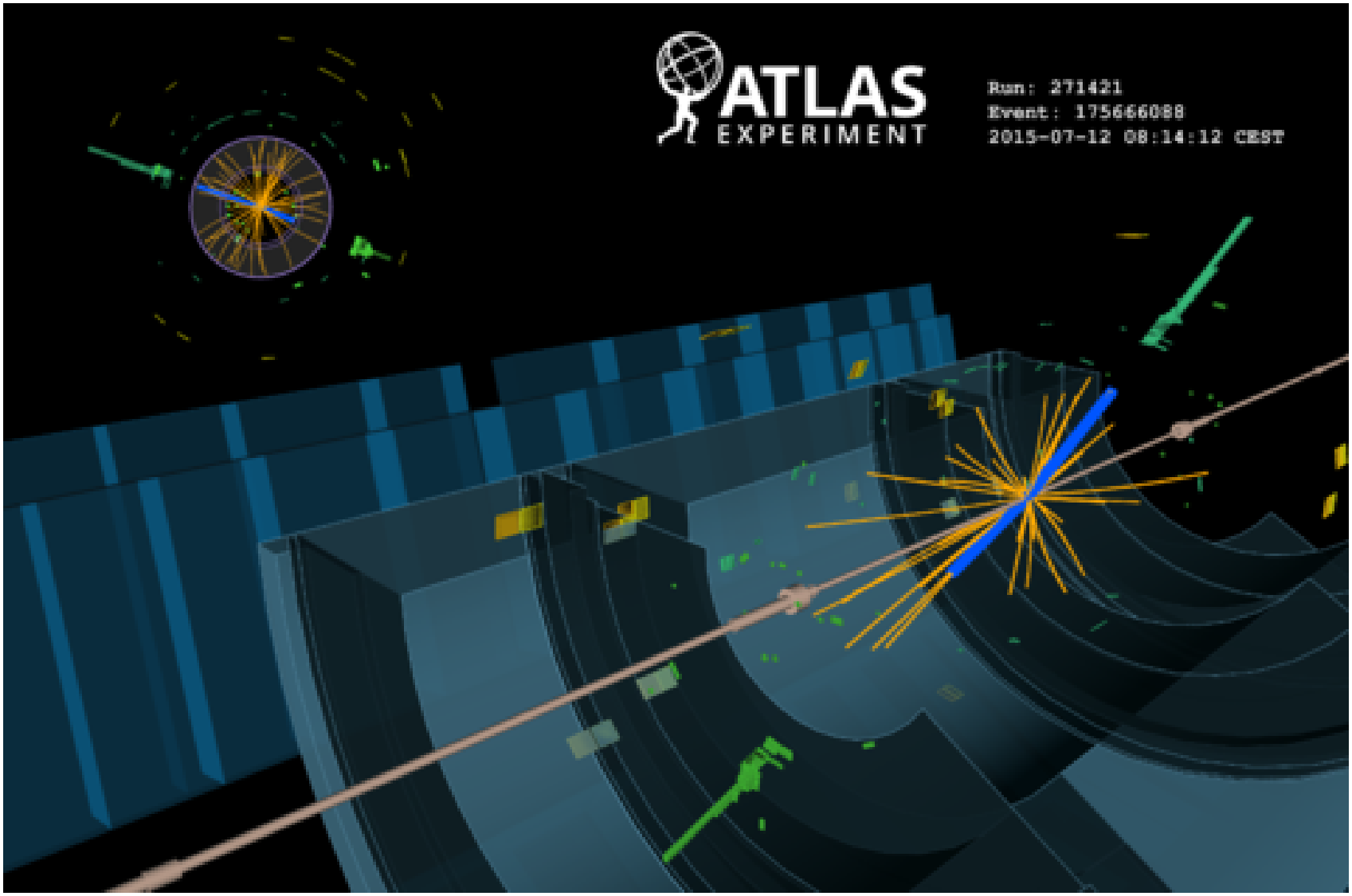
- 13 TeV invariant mass distributions
- 78 pb^{-1} of integrated luminosity
- Good agreement between data and total background expectations in whole mass range





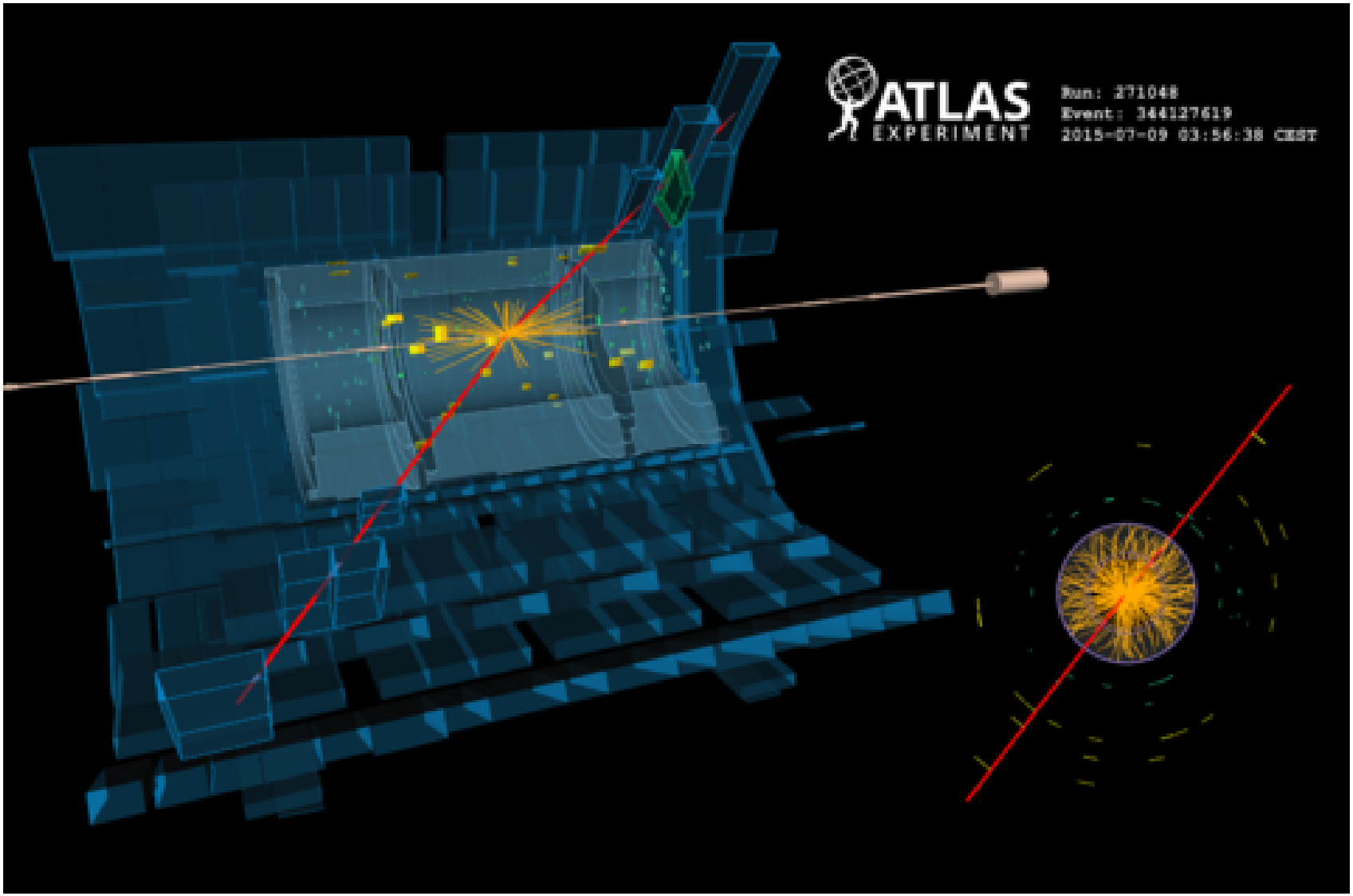
ATLAS Dilepton resonances ($X \to ll$) — EXOT

- 13 TeV ATLAS highest ee mass event: $M_{ee} = 739$ GeV
- $(E_{T,1}, \eta_1) = (189$ GeV, 1.08), $(E_{T,2}, \eta_2) = (177$ GeV, -1.58)



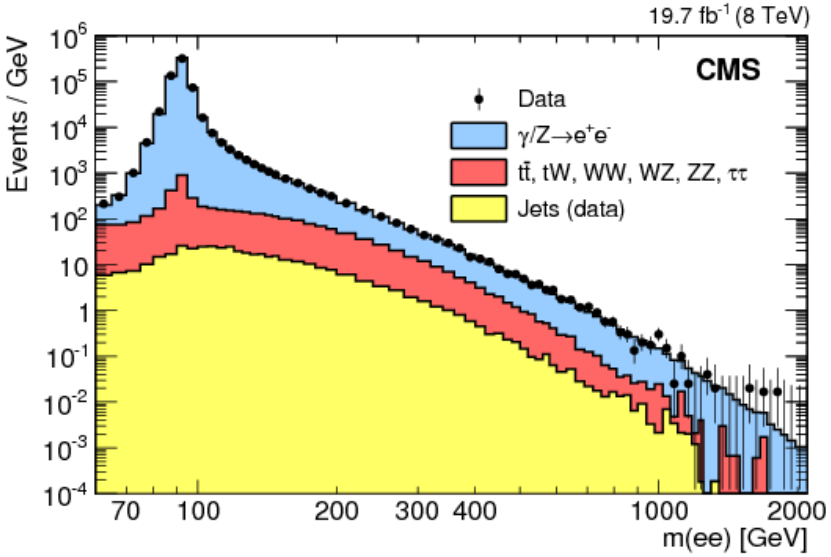
ATLAS Dilepton resonances ($X \to ll$) — EXOT

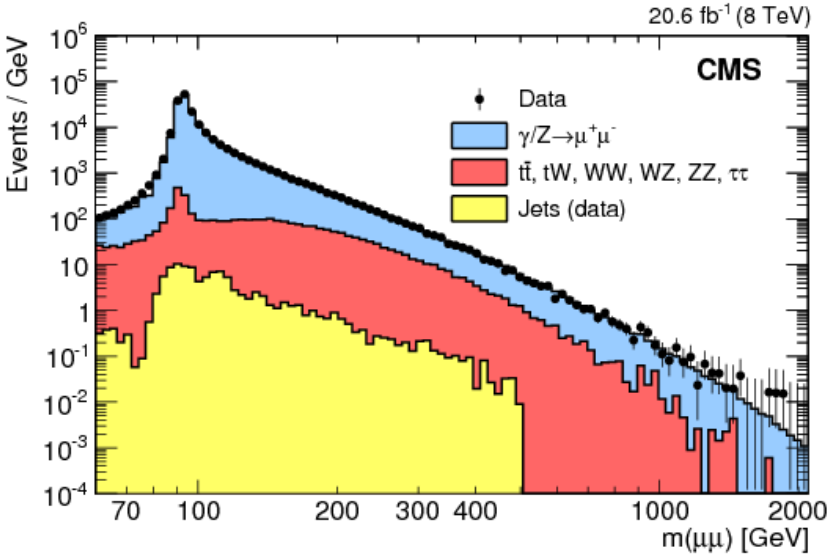
- 13 TeV ATLAS highest $\mu\mu$ mass event: $M_{\mu\mu} = 881$ GeV
- $(p_{T,1}, \eta_1) = (305$ GeV, -1.03), $(p_{T,2}, \eta_2) = (300$ GeV, 0.82)



CMS Dilepton resonances ($X \to ll$) — arXiv

- Models: Randall-Sundrum, Sequential Standard Model, Z'_ψ
- Main backgrounds: irreducible Drell-Yan, $t\bar{t}$, QCD
- Lepton selection: shower shape + isolation
- Background estimation
  - Drell-Yan estimated from Monte-Carlo
  - QCD multijets from double-differential fake rate method (E_t, η)
  - $t\bar{t}$, tW, VV extracted from Monte-Carlo but cross-checked with $e\mu$ method.
  - Total normalized to 60-110 GeV region $\to$ cancel some uncertainties

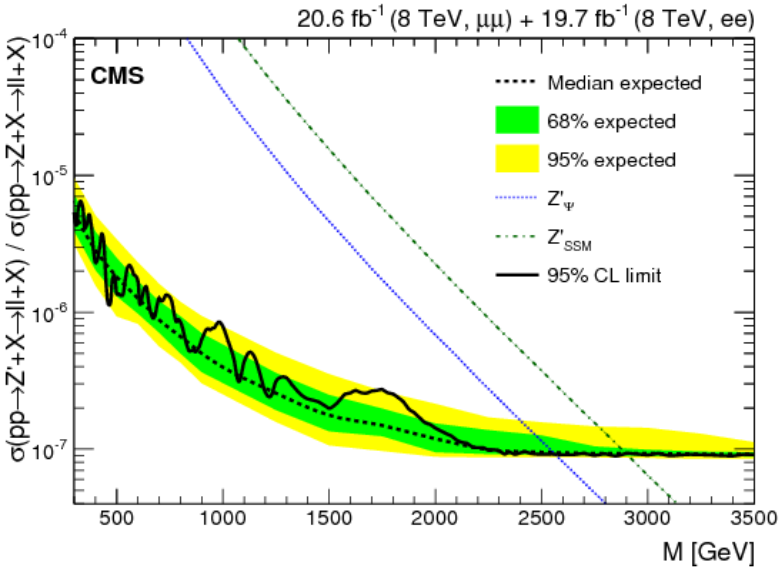


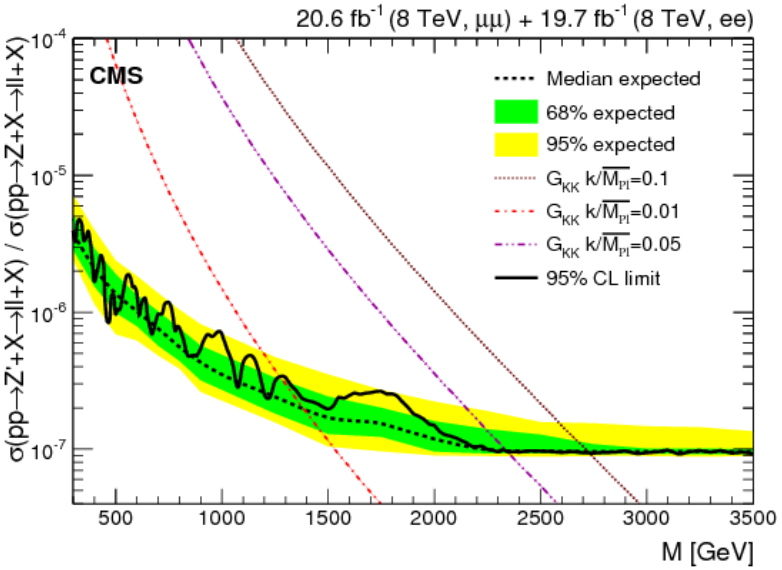


CMS Dilepton resonances ($X \to ll$) — arXiv

Statistical interpretation

- unbinned likelihood ratio (Bayesian interpretation)
- Parameter of interest: cross section ratio $R_\sigma = \sigma'_Z/\sigma_Z$.
- Limits set on narrow resonance, can be reinterpreted in any model predicting a resonant structure.

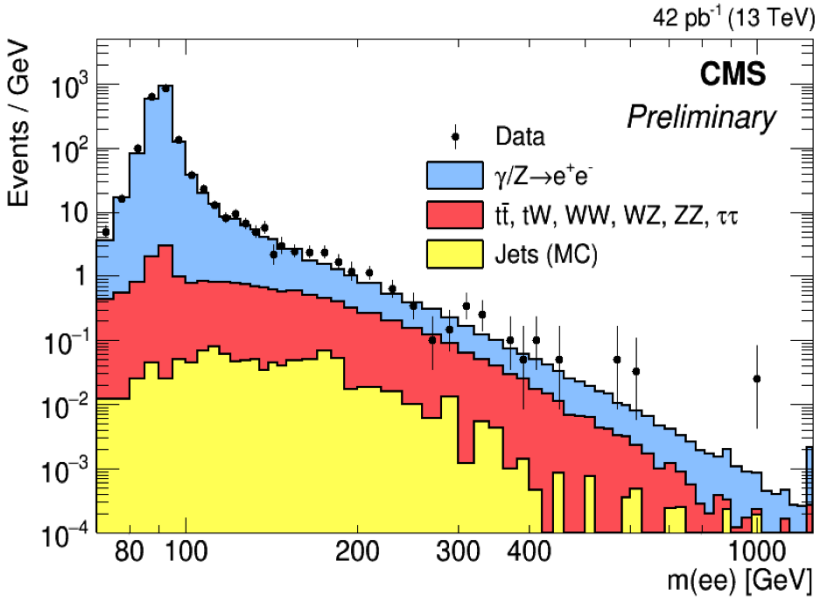


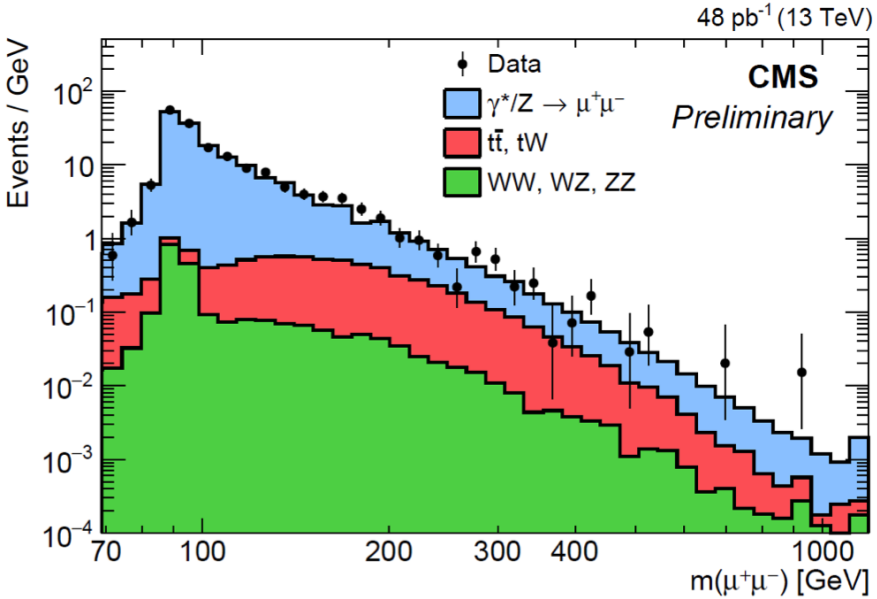


- Observed limits (TeV): Z'_{SSM} (2.90), Z'_ψ (2.57), G (2.73) for $\tilde{k} = 0.1$

CMS Dilepton resonances ($X \to ll$) — 13 TeV

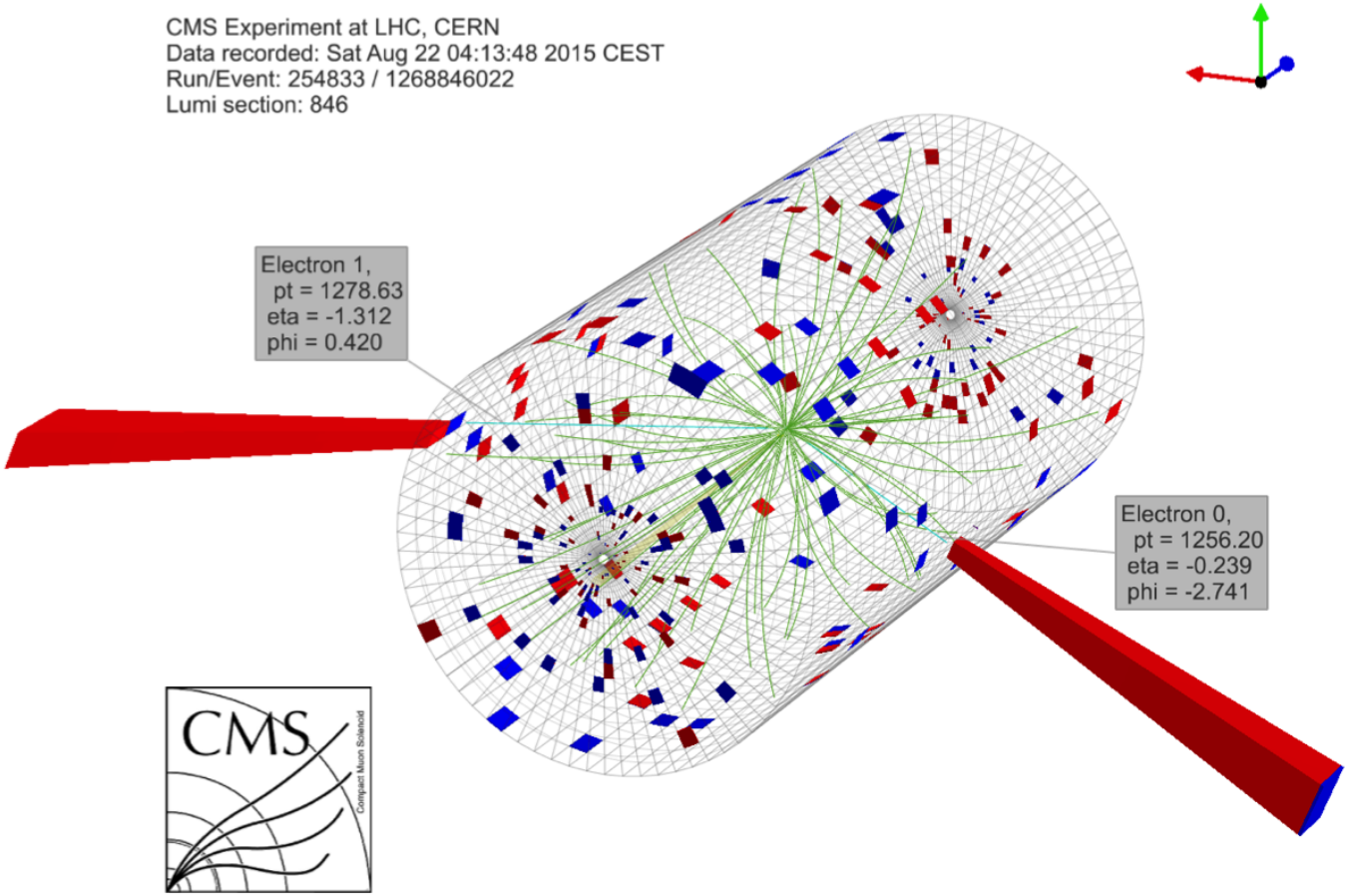
- $\mu\mu$: Contributions from multijet and W+jets events not shown (negligible)
- $\mu\mu$: Preliminary alignment of tracker-muon system





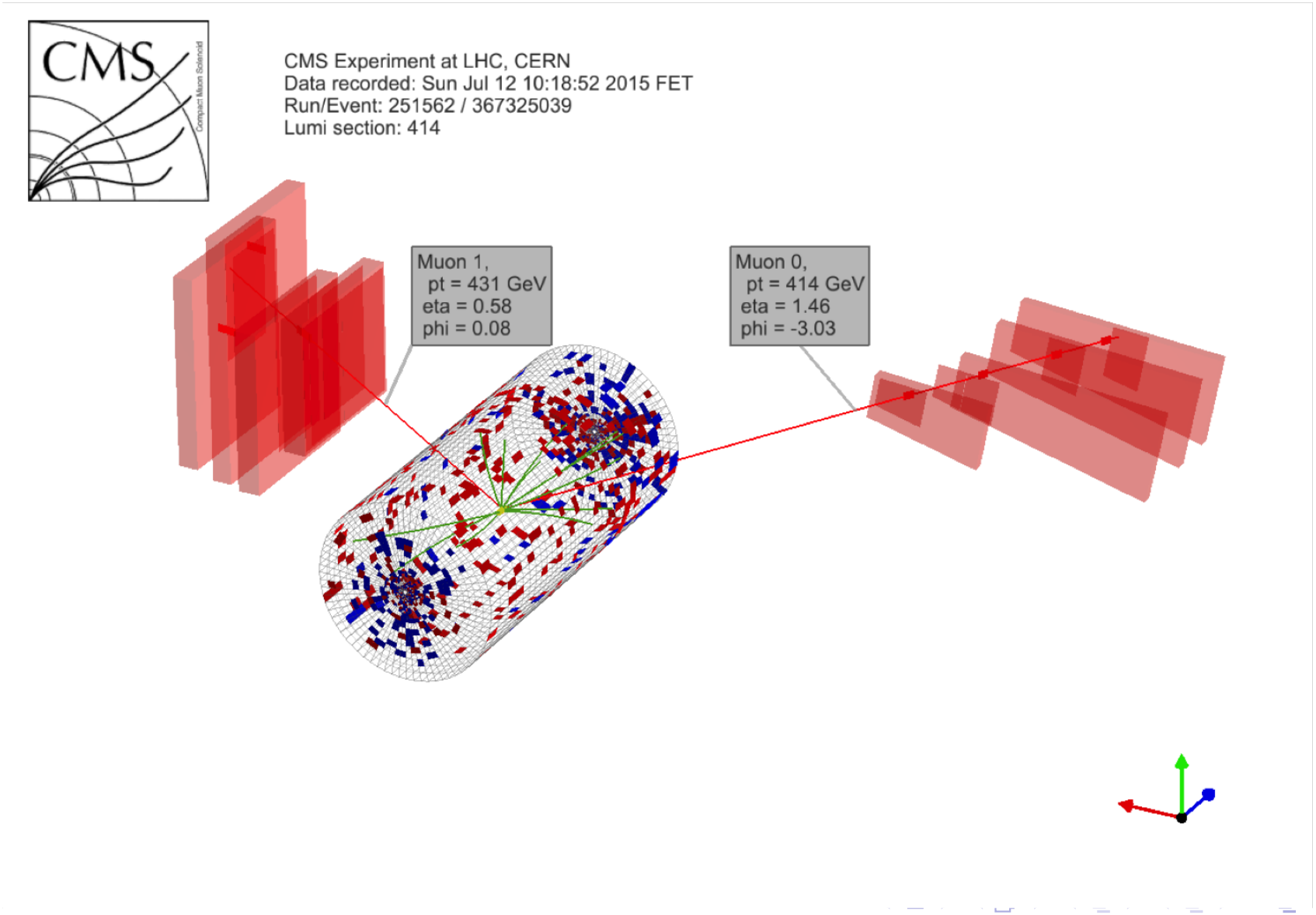
CMS Dilepton resonances ($X \to ll$) — 13 TeV

- 13 TeV CMS highest ee mass event: $M_{ee} = 2.9$ TeV



CMS Dilepton resonances ($X \to ll$) — 13 TeV

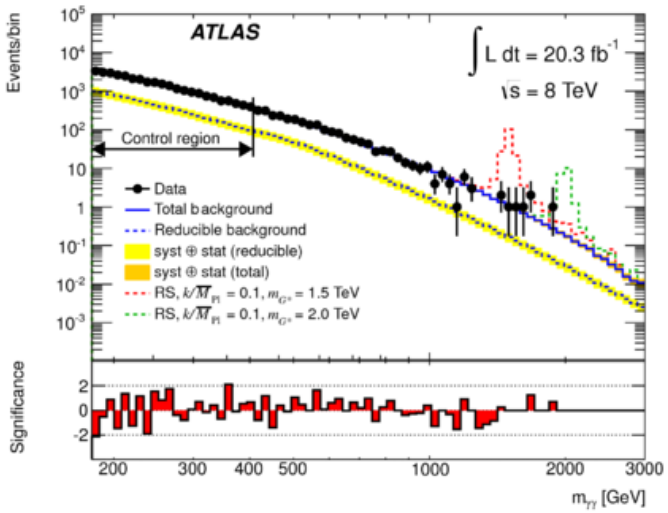
- 13 TeV CMS highest $\mu\mu$ mass event: $M_{\mu\mu} = 920$ GeV

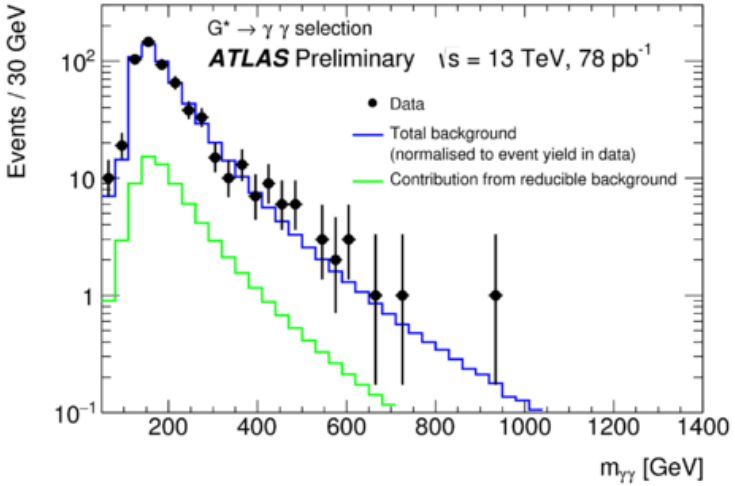


ATLAS diphoton resonances ($X \to \gamma\gamma$) — arXiv, EXOT

- Models: Randall-Sundrum graviton
- Irreducible background: SM $\gamma\gamma$ background (Born, Box processes) evaluated from Monte Carlo
- Reducible background: QCD dijet and γ+jet estimated using control region templates and extrapolated to signal region using a smooth function.
- Total background normalized to control region (179-409 GeV)

Main systematics from shape of irreducible background contribution (dominated by PDF uncertainties)

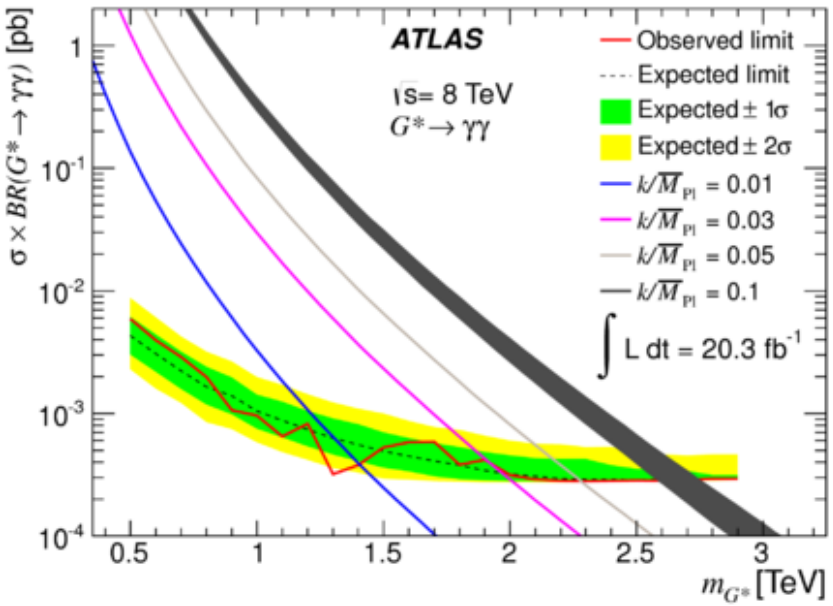


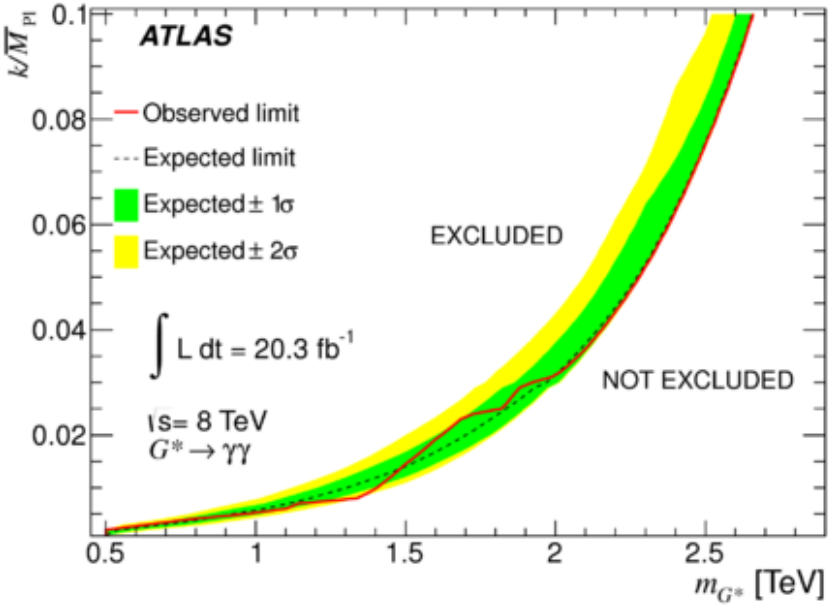


ATLAS diphoton resonances ($X \to \gamma\gamma$) — arXiv

Statistical interpretation

- Bayesian formalism (binned likelihood)
- Signal K factor: 1.6 to 1.9

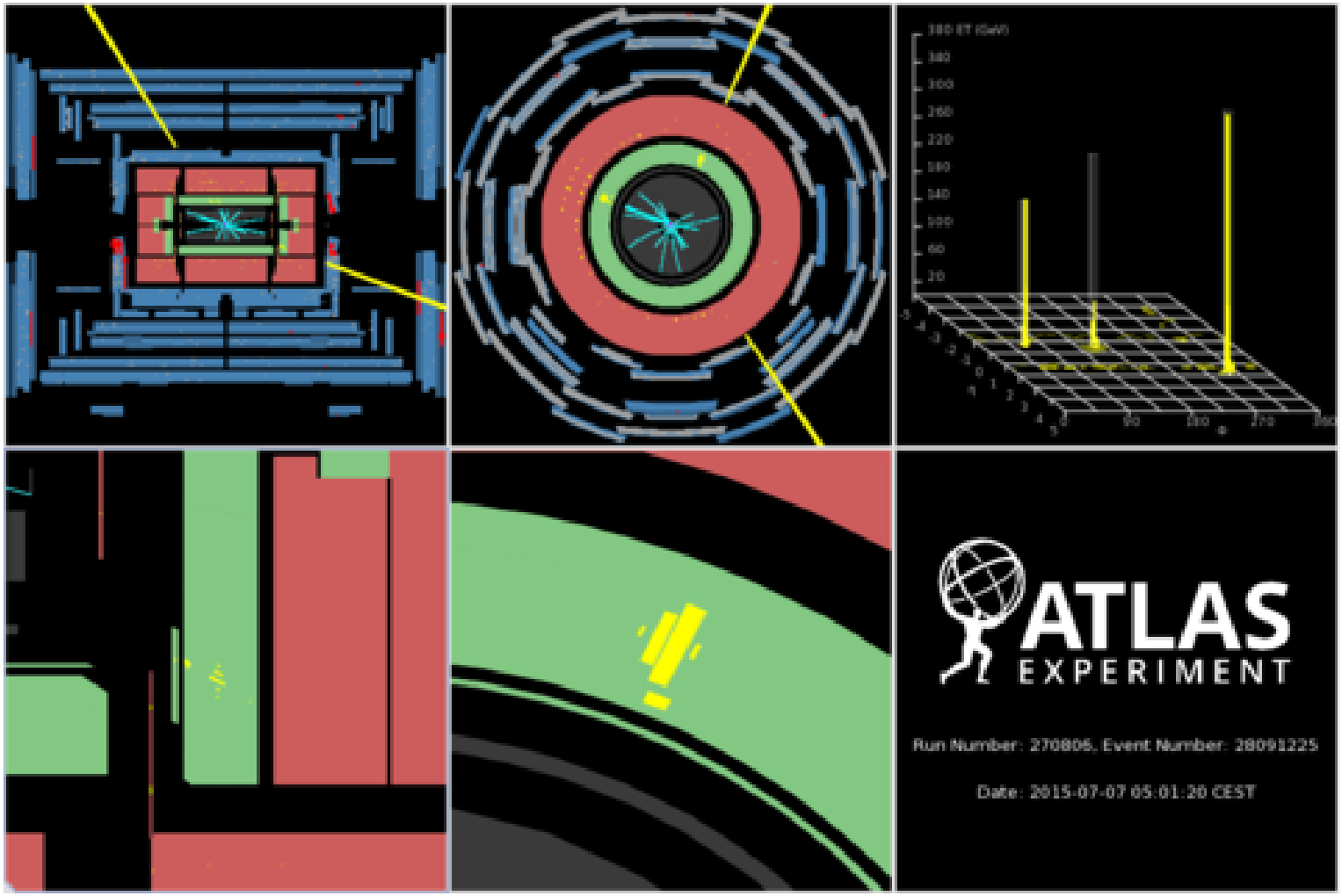




- Observed limits: 2.66 and 1.41 for $\tilde{k} = 0.1$ and 0.01 respectively.

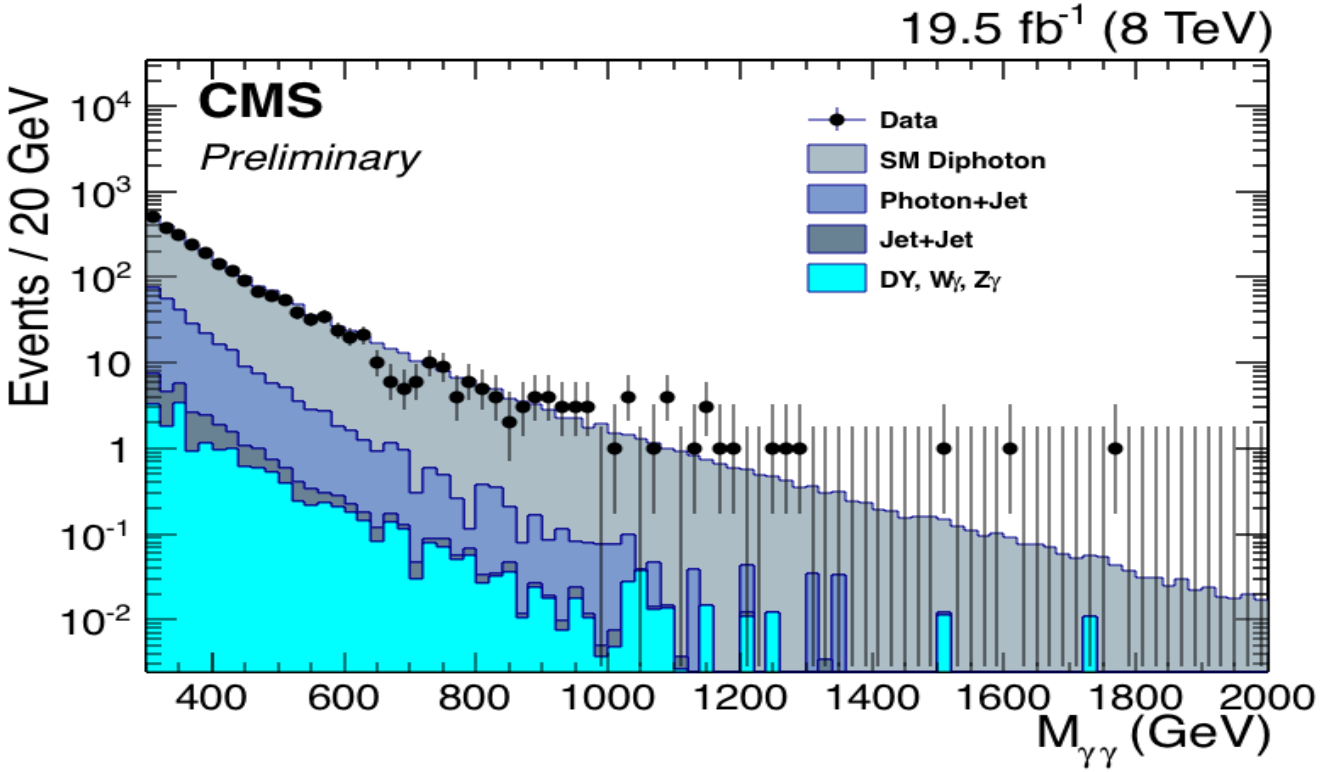
ATLAS diphoton resonances ($X \to \gamma\gamma$) — EXOT

- 13 TeV ATLAS highest $\gamma\gamma$ mass event: $M_{\gamma\gamma} = 940$ GeV
- $(E_{T,1}, \eta_1) = (374$ GeV, 1.71), $(E_{T,2}, \eta_2) = (212$ GeV, -0.60)



CMS diphoton resonances ($X \to \gamma\gamma$) — CDS

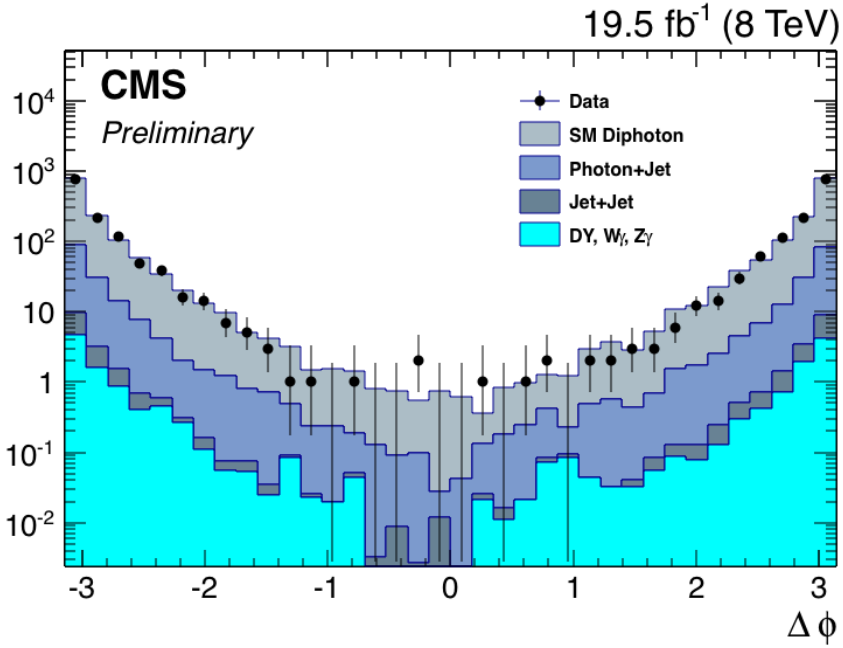
- Models: Randall-Sundrum graviton
- Irreducible background: SM $\gamma\gamma$ Born and Box processes evaluated from MC using a NNLO K factor calculated using 2γNNLO.
- Reducible background: QCD dijet and γ+jet estimated using data-driven fake rate approach
- No normalization to control region here $\to$ strict data/background comparison

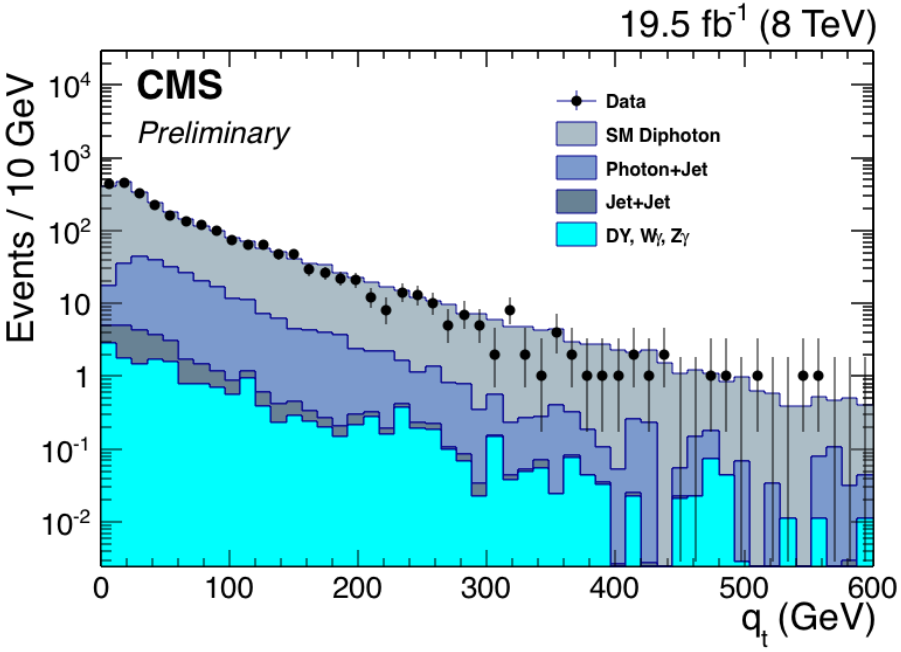


CMS diphoton resonances ($X \to \gamma\gamma$) — CDS

Azimuthal angle separation ($\Delta\phi$) and transverse momentum of the diphoton pair (q_t)

- Generally difficult to bring to agreement in all regions.
- Very good agreement observed.

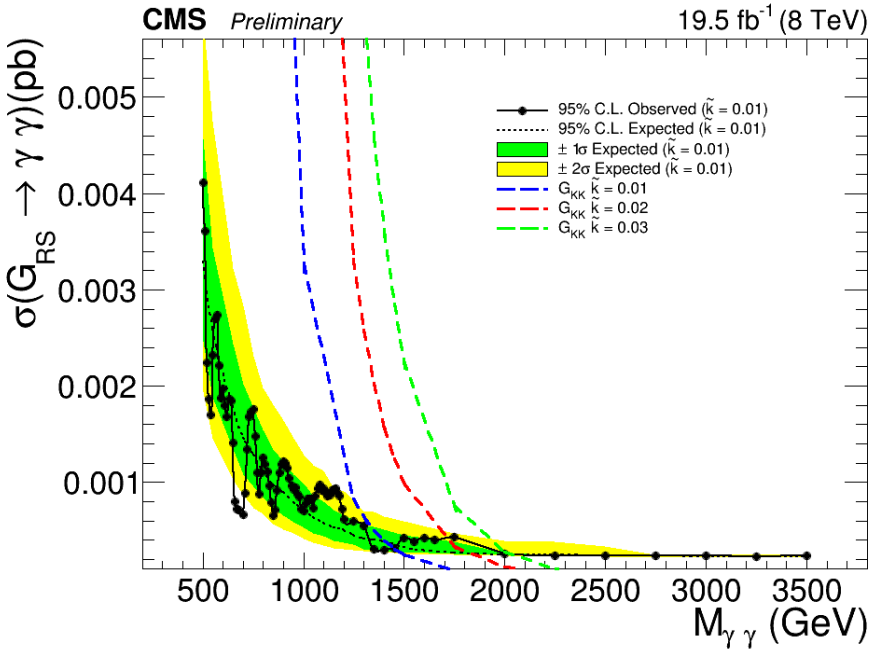


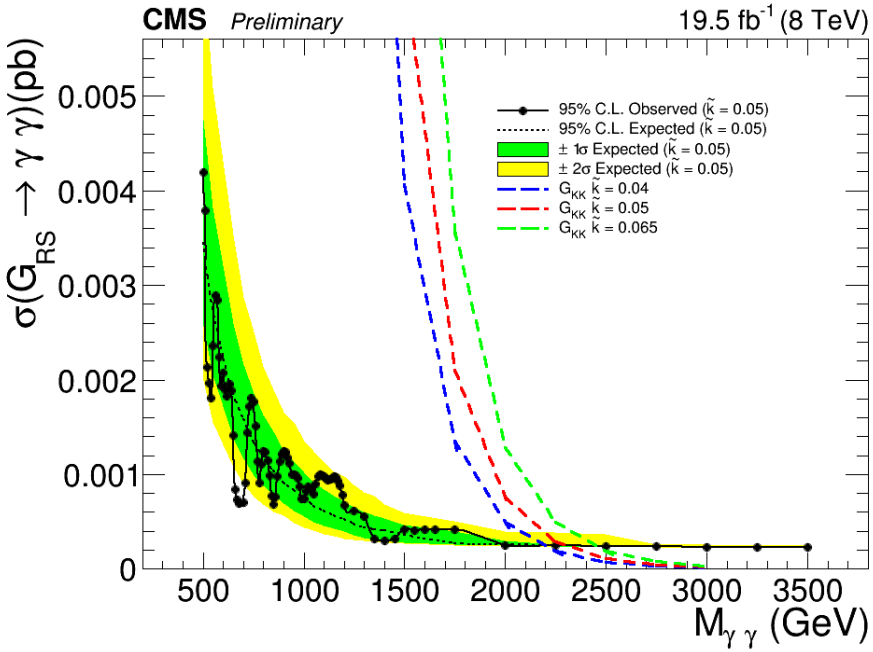


CMS diphoton resonances ($X \to \gamma\gamma$) — CDS

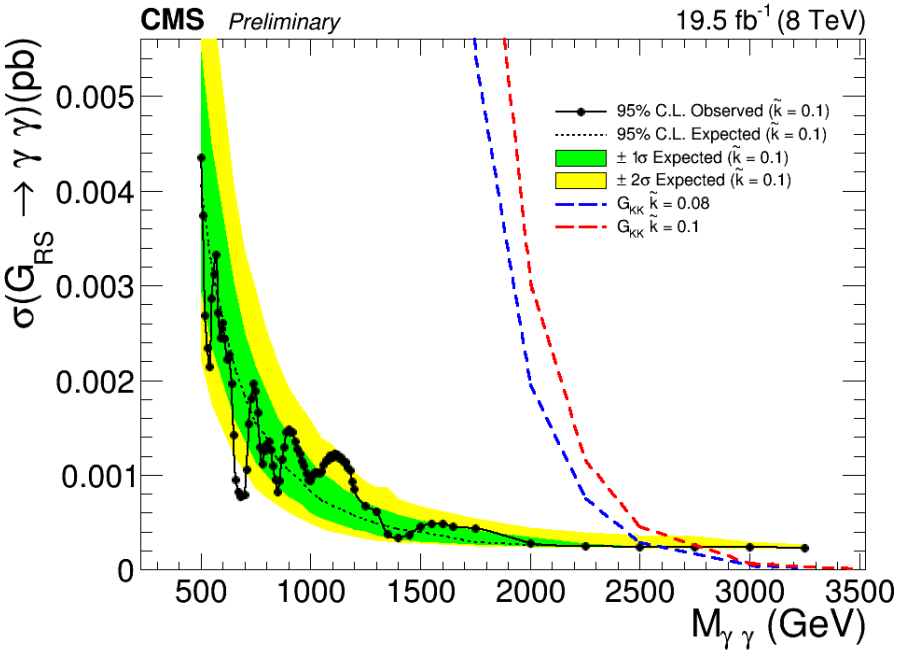
Statistical interpretation

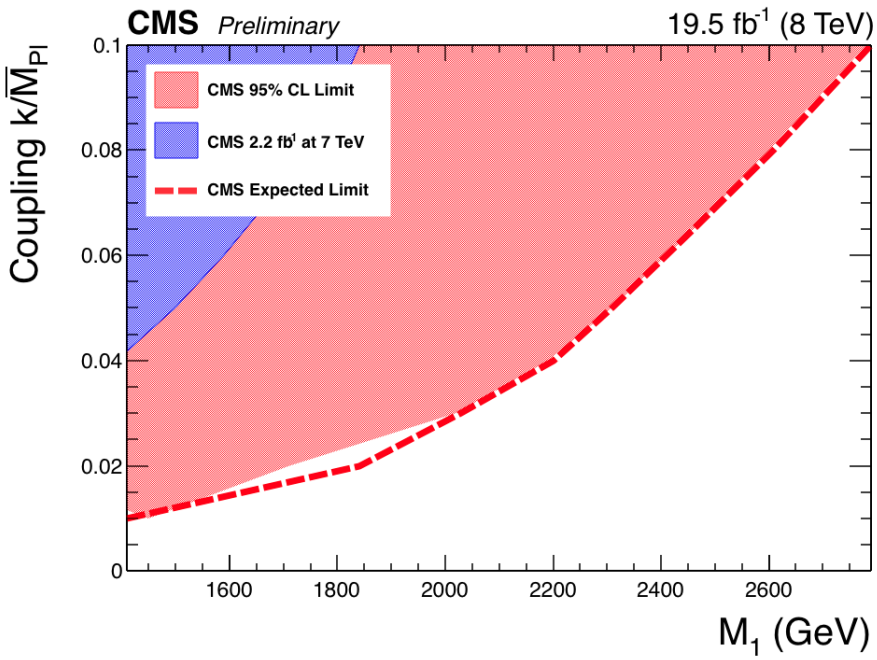
- Bayesian formalism (unbinned likelihood)
- Signal K factor: between 1.5 and 1.7





CMS diphoton resonances ($X \to \gamma\gamma$) — CDS

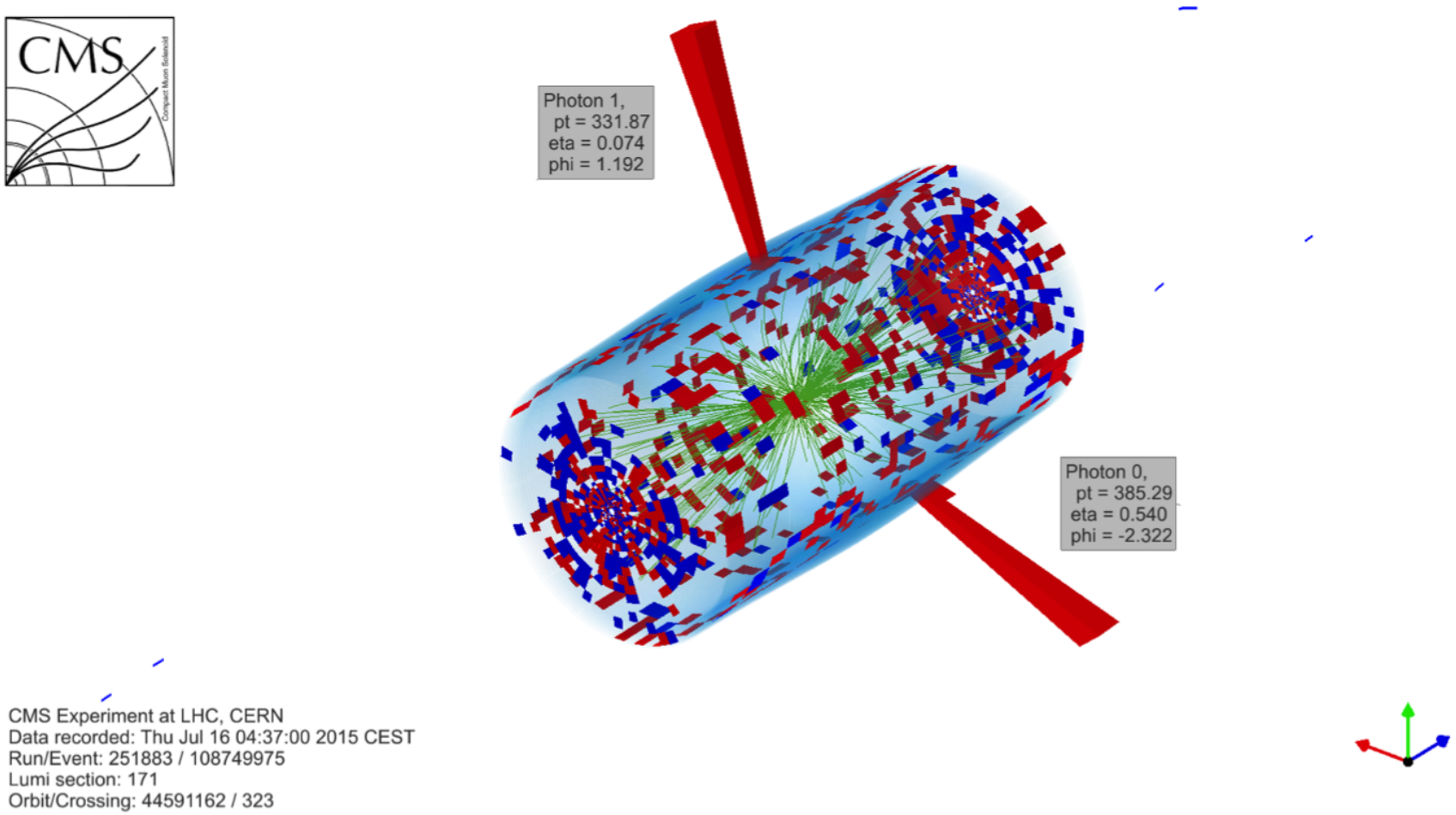




- Observed limits (TeV): 1.45, 2.31 and 2.78 for $\tilde{k} = 0.01$, 0.05 and 0.1

CMS diphoton resonances ($X \to \gamma\gamma$) — 13 TeV

- 13 TeV CMS highest $\gamma\gamma$ mass event: $M_{\gamma\gamma} = 733$ GeV



ATLAS $\tau\tau$ resonances ($X \to \tau\tau$) — JHEP

- Models: Z'_{SSM}, Z'_L, Z'_R, Z'_{NU}

Key features of the selection:

- lepton-hadron ($\tau_{lep}\tau_{had}$) and hadron-hadron ($\tau_{had}\tau_{had}$) channels
- Hadronic τ decays: BDT (shower shape and tracking) $\to$ false identification rate of q/g jets below 1%
- Leptons: isolation + shower shape (e) + muon quality criteria
- $\not{E}_t = |\sum \vec{p_{T,high}} + \sum \vec{p_{T,remain}}|$
- Opposite sign and back to back ($|\Delta\phi| < 2.7$ rad)

Background estimates

- $Z/\gamma^* \to \tau\tau$ from MC for both channels
- QCD multijet (high mass) from fake factors measured in multijet control region for $\tau_{had}\tau_{had}$ channel
- Events with q/g jet faking hadronic τ (W+jets) from fake factors measured in W+jets control region for $\tau_{lep}\tau_{had}$ channel

Systematic uncertainties

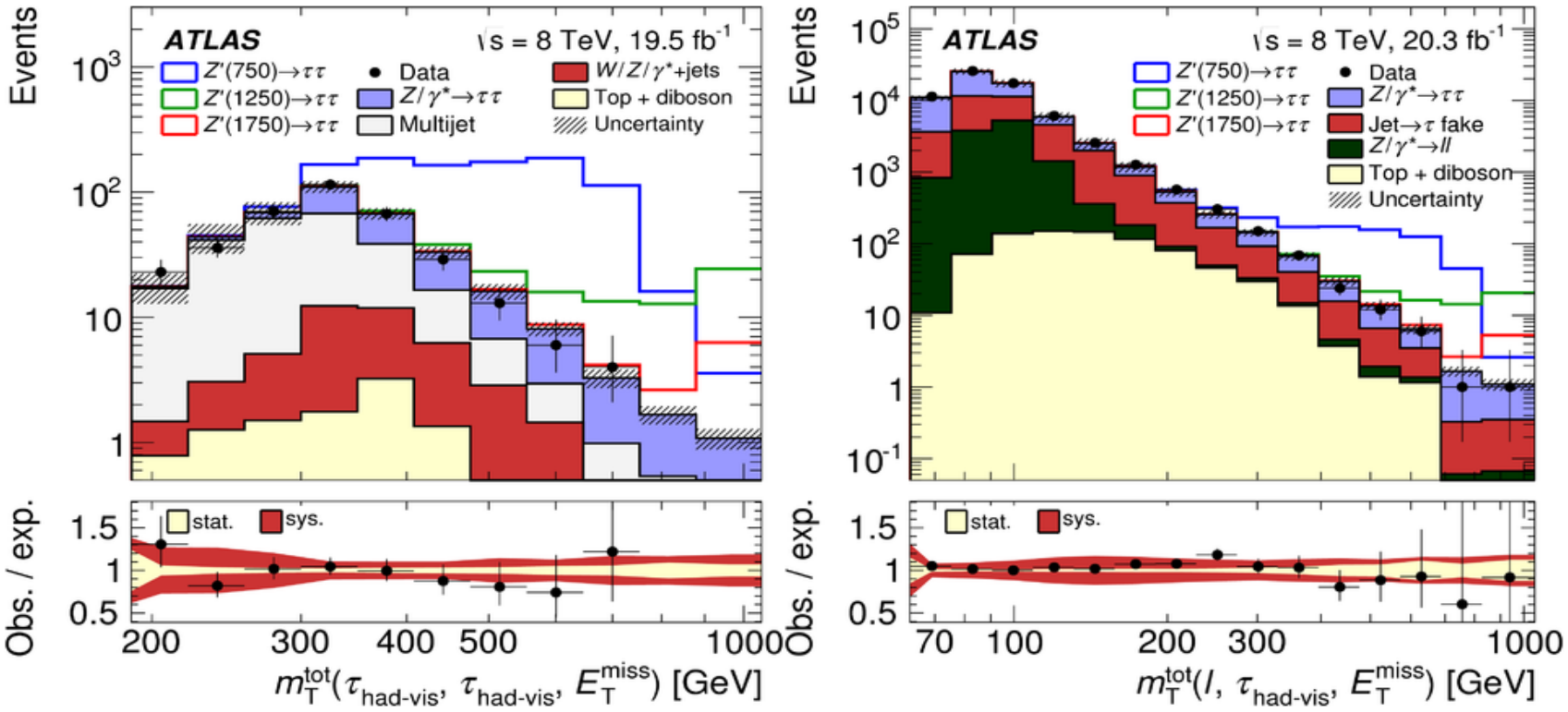
- $\tau_{had}\tau_{had}$: τ ID efficiency and energy scale
- $\tau_{lep}\tau_{had}$: statistical uncertainty on background (fake factor)

ATLAS $\tau\tau$ resonances ($X \to \tau\tau$) — JHEP

Define transverse mass: $m_T(p^A, p^B) = \sqrt{2p_T^A p_T^B (1 - \cos\Delta\phi(p^A, p^B))}$

Define total transvse mass:

$m_T^{tot}(\tau_1, \tau_2, \not{E}_t) = \sqrt{m_T^2(\tau_1, \tau_2) + m_T^2(\tau_1, \not{E}_t) + m_T^2(\tau_2, \not{E}_t)}$

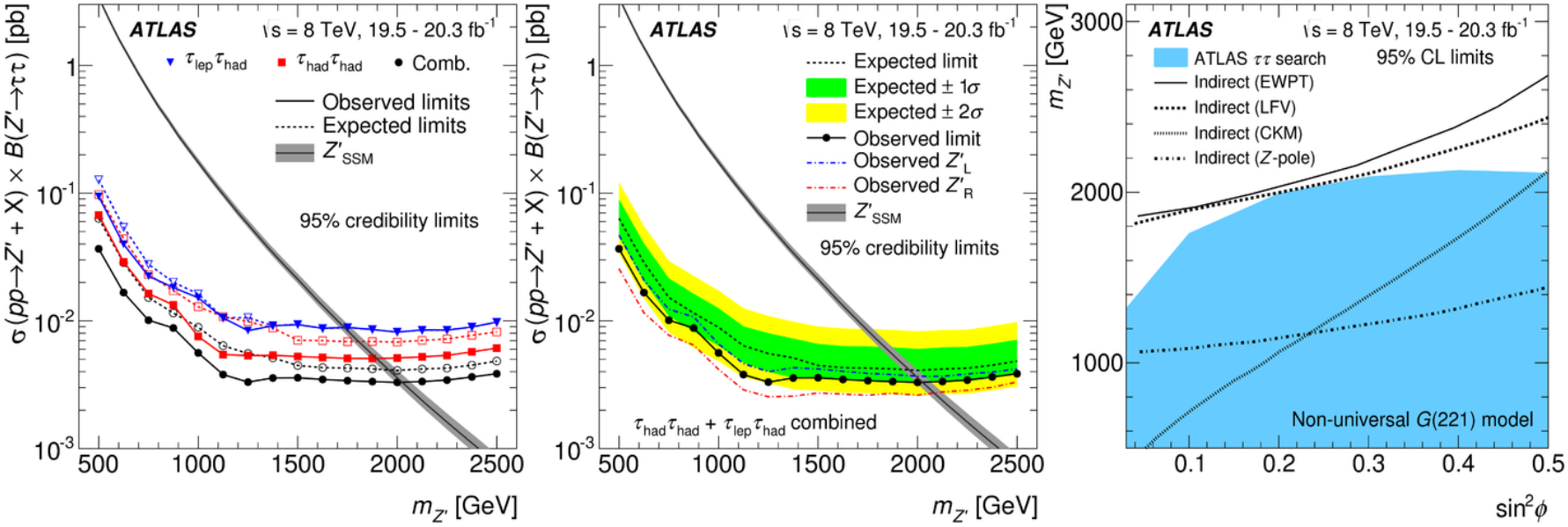


Good agreement between data and total background in both channels

ATLAS $\tau\tau$ resonances ($X \to \tau\tau$) — JHEP

Statistical interpretation

- Bayesian interpretation: likelihood from product of Poisson distributions in each channel
- m_T^{tot} optimized for best expected limits
- Z'/(Z/γ^*) interference effects neglected



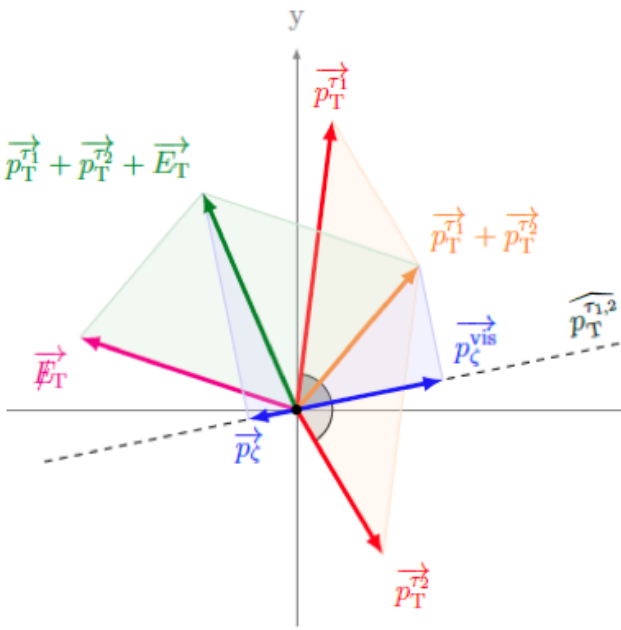
- Observed limits: 2.02 TeV for the Z'_{SSM}

CMS $\tau\tau$ resonances ($X \to \tau\tau \to e\mu\nu\nu$) — CDS

- Models: Z'_{SSM}, Z'_{ψ}

Key features of the selection:

- Back to back, isolated and well identified electron and muon of opposite charge and well separated.
- $\not{E}_t > 20$ GeV and $\not{E}_t$ direction consistent with originating from τ decays (ζ variable) to suppress contributions containing W bosons.
- No b-jets.



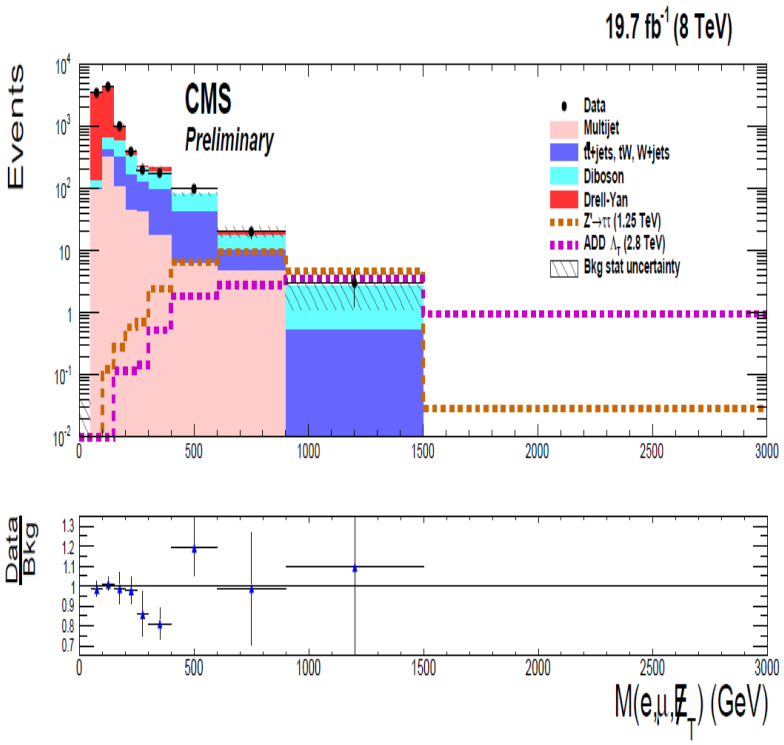
Background estimates

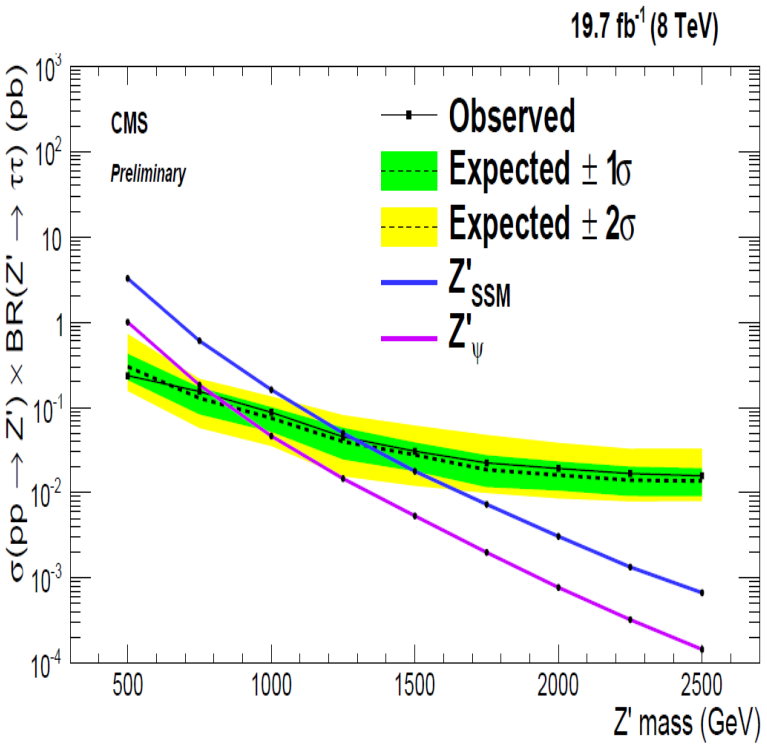
- $t\bar{t}$ contribution extracted from control regions
- QCD multijet contribution from like-sign method in high purity multijet sample
- Drell-Yan extracted from MC but compared to data in low mass region (M(μ,e,$\not{E}_t$) < 200 GeV).
- Similar approach for WW and W+jets.

CMS $\tau\tau$ resonances ($X \to \tau\tau \to e\mu\nu\nu$) — CDS

Statistical analysis

- Bayesian formalism
- Mass dependent signal K factors





- Observed limits (TeV): 1300 GeV (Z'_{SSM}) and 810 GeV (Z'_{ψ})

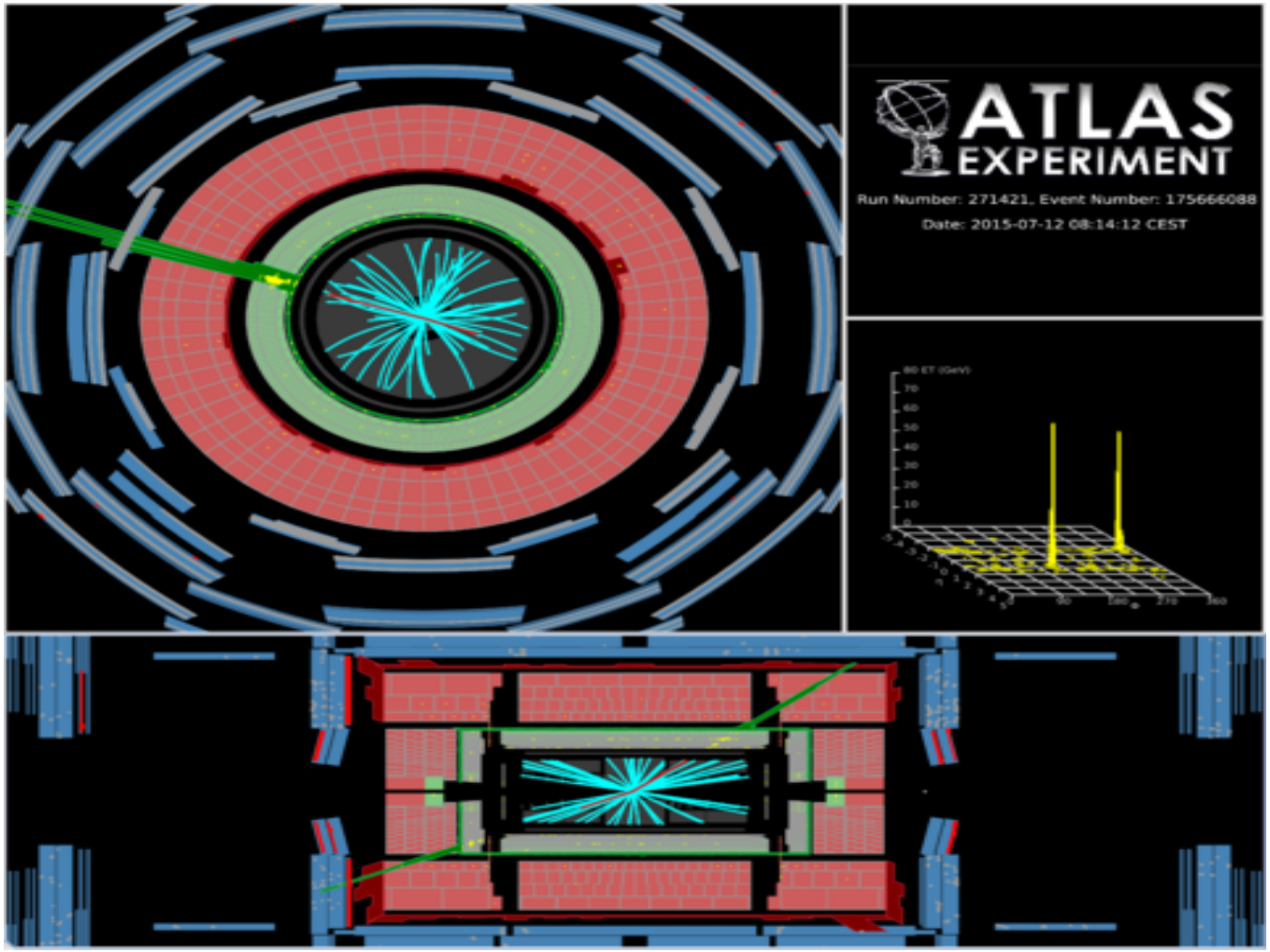
Conclusions

- Searches for high mass resonances performed in ATLAS and CMS collaborations
- Sringent limits published by both experiments
- Dedicated isolation techniques for searches involving leptons from boosted objects
- Not all searches covered here $\rightarrow$ ATLASExotica, CMSExotica, CMSB2G
- No sign of new physics so far
- 3 fb^{-1} expected for 2015 $\rightarrow$ supersede results of most analyses presented.
- Thanks to all LHC people
- Many thanks to the LHCP organizers.

ADDITIONAL MATERIAL

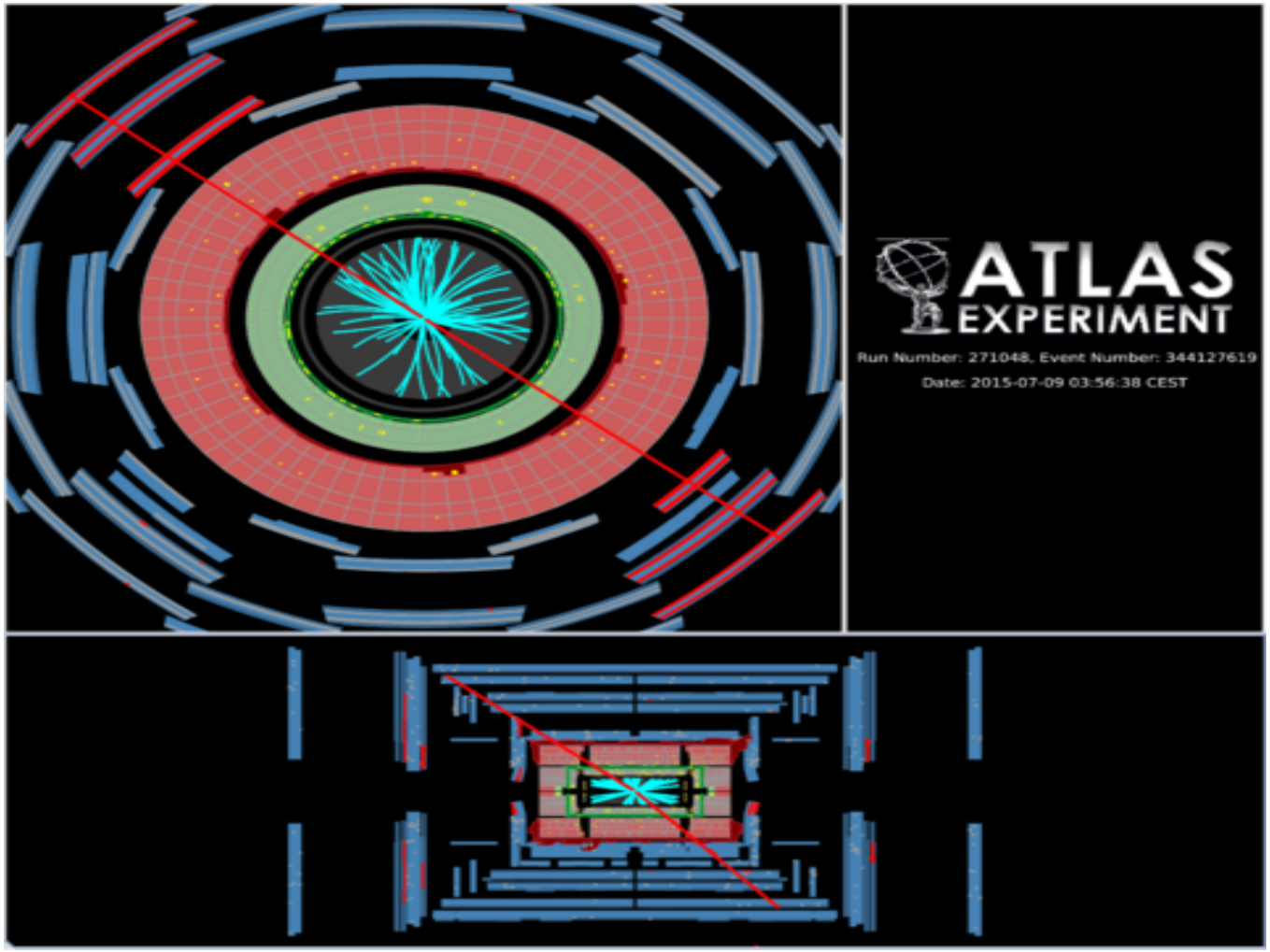
ATLAS Dilepton resonances ($X \to ll$) — EXOT

- 13 TeV ATLAS highest ee mass event: $M_{ee} = 739$ GeV
- $(E_{T,1}, \eta_1) = (189$ GeV, 1.08), $(E_{T,2}, \eta_2) = (177$ GeV, -1.58)



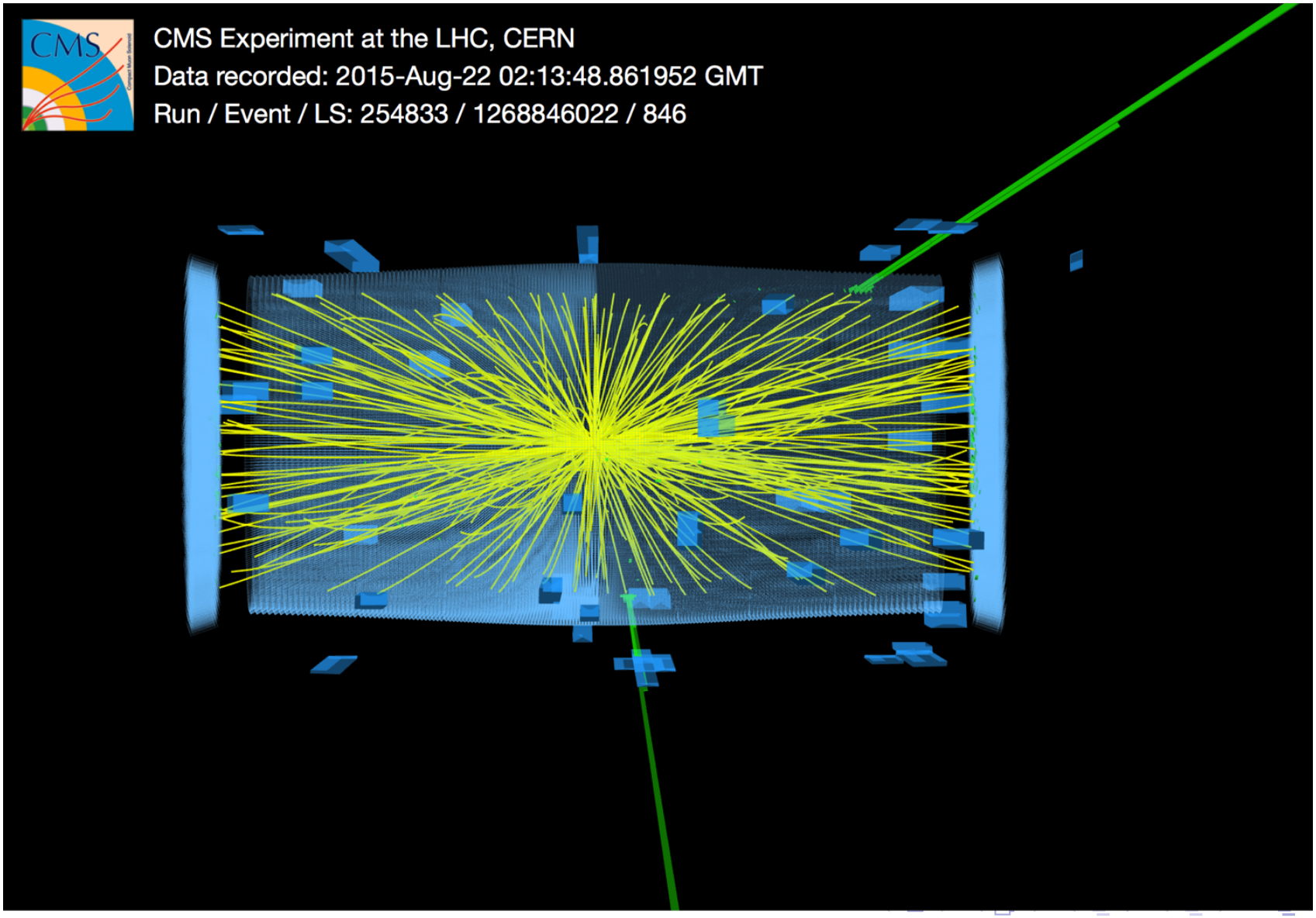
ATLAS Dilepton resonances ($X \to ll$) — EXOT

- 13 TeV ATLAS highest $\mu\mu$ mass event: $M_{\mu\mu} = 881$ GeV
- $(p_{T,1}, \eta_1) = (305$ GeV, -1.03), $(p_{T,2}, \eta_2) = (300$ GeV, 0.82)



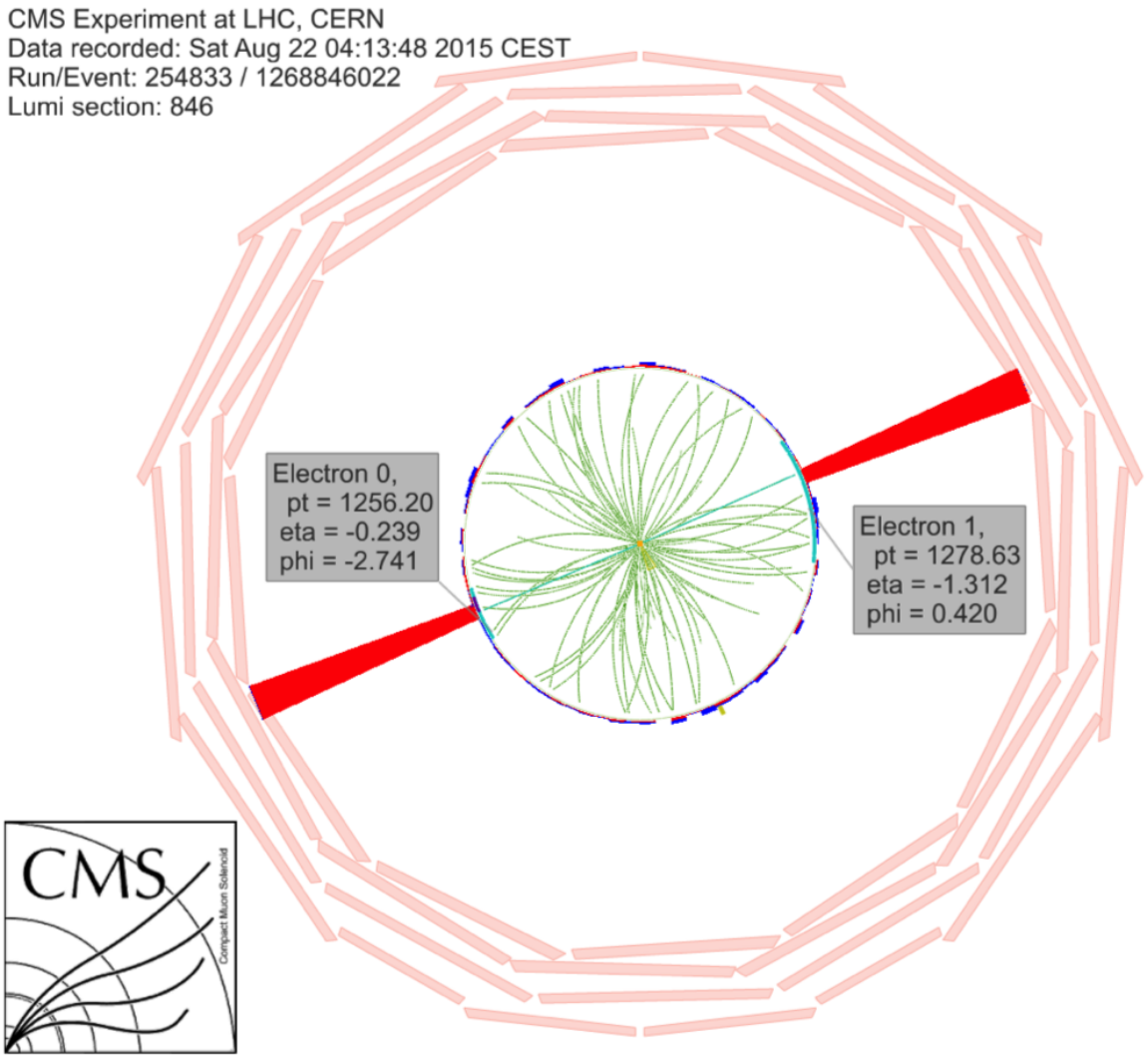
CMS Dilepton resonances ($X \to ll$) — 13 TeV

- 13 TeV CMS highest ee mass event: $M_{ee} = 2.9$ TeV



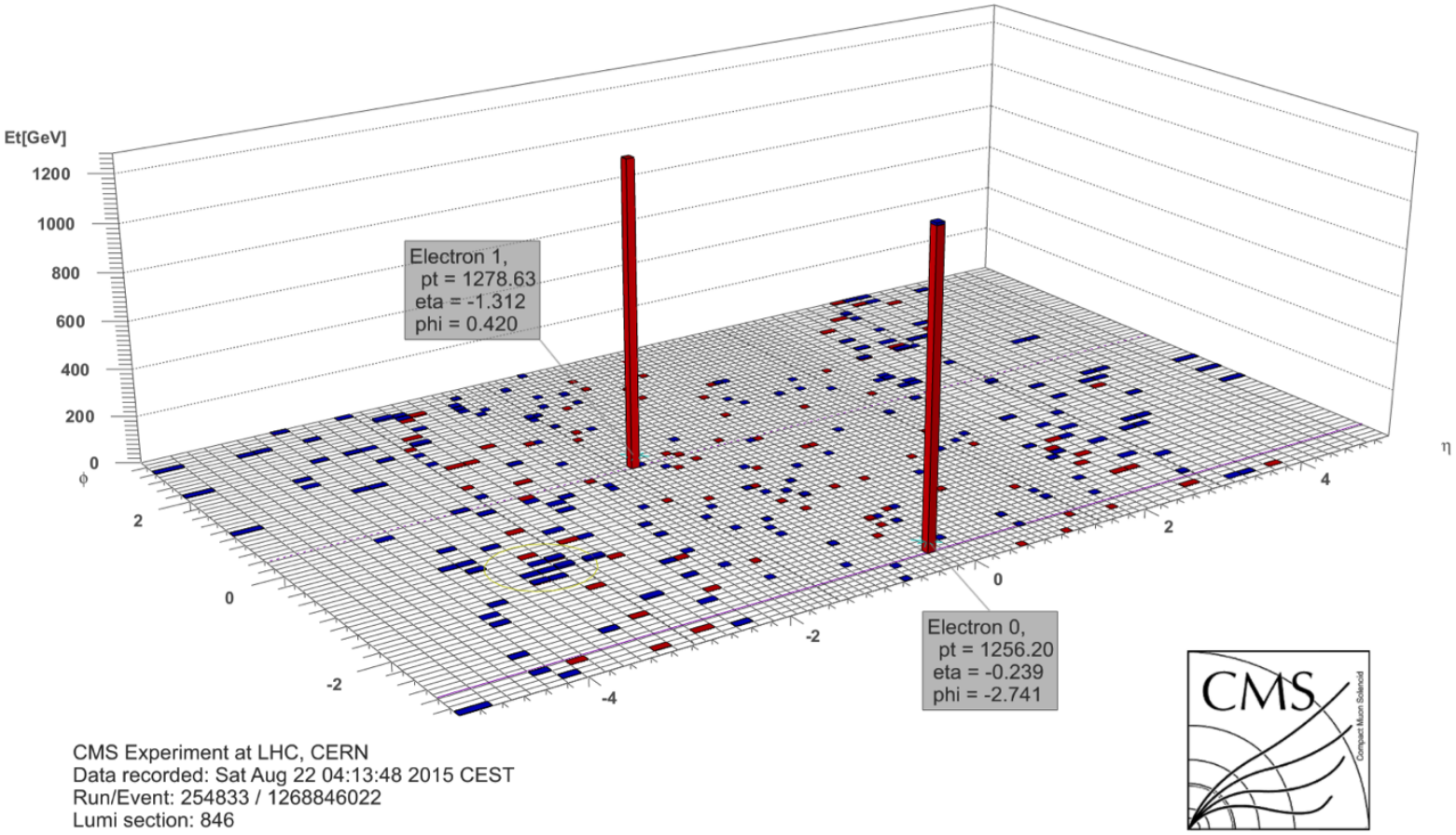
CMS Dilepton resonances ($X \to ll$) — 13 TeV

- 13 TeV CMS highest ee mass event: $M_{ee} = 2.9$ TeV



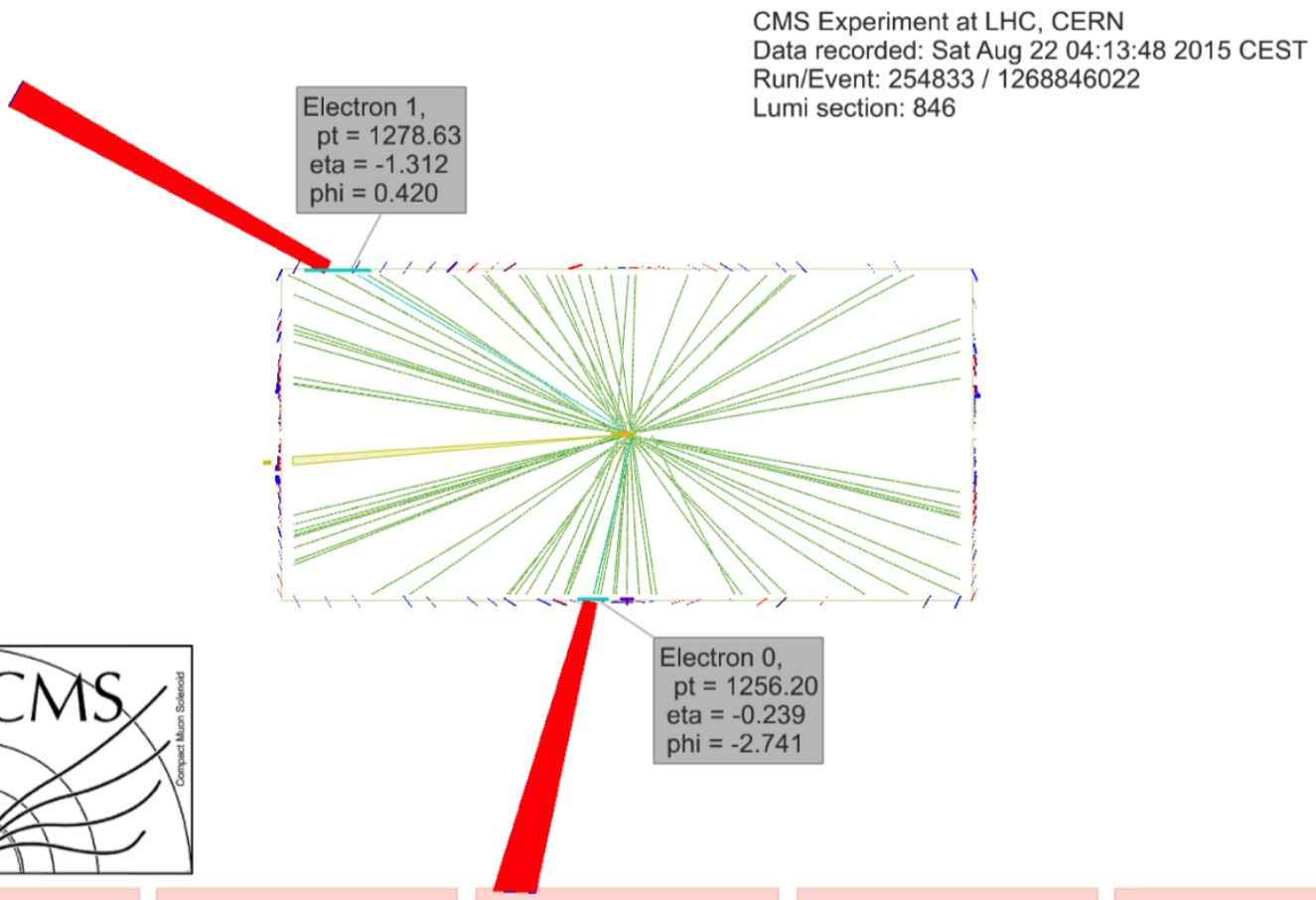
CMS Dilepton resonances ($X \to ll$) — 13 TeV

- 13 TeV CMS highest ee mass event: $M_{ee} = 2.9$ TeV



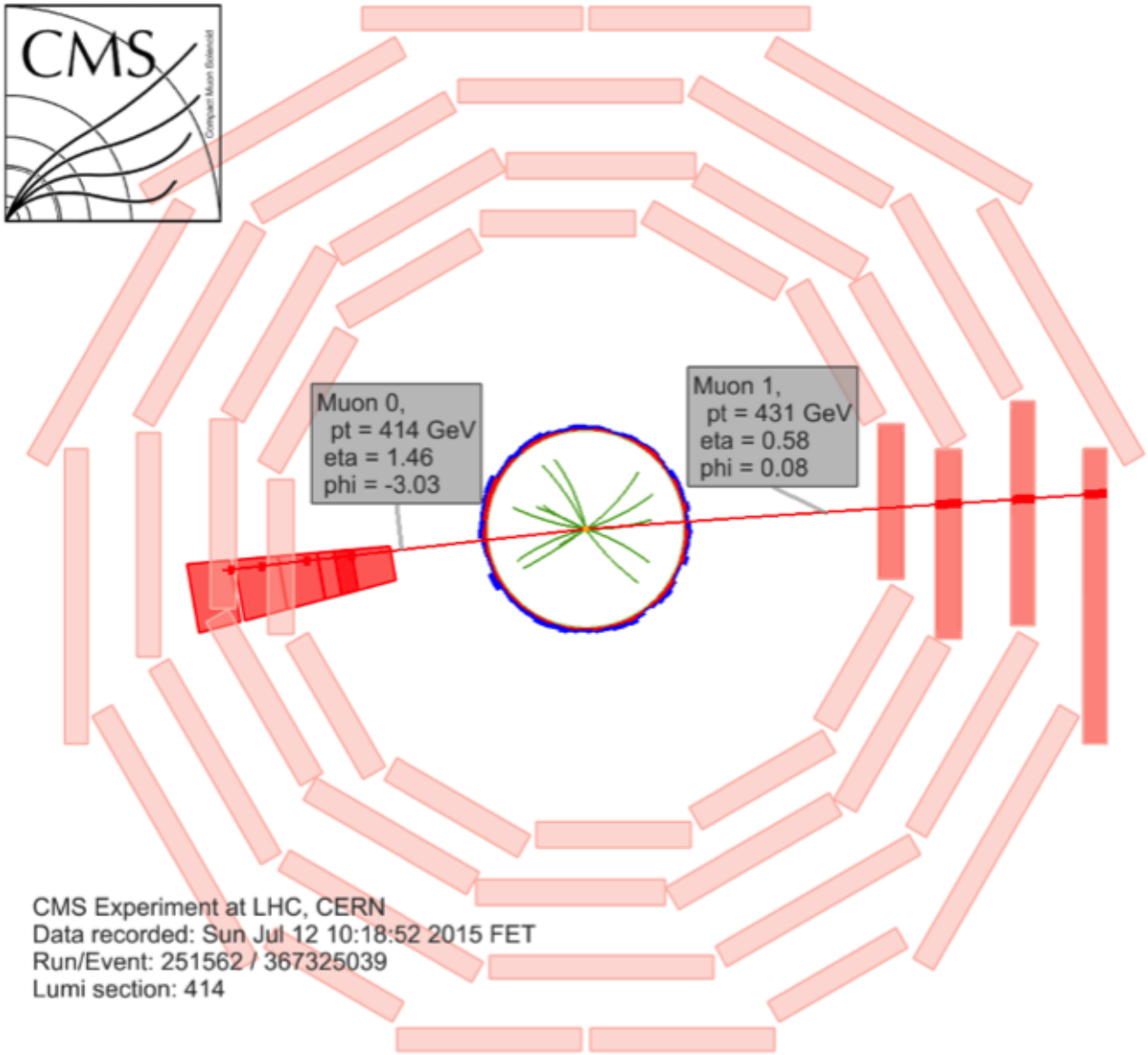
CMS Dilepton resonances ($X \to ll$) — 13 TeV

- 13 TeV CMS highest ee mass event: $M_{ee} = 2.9$ TeV



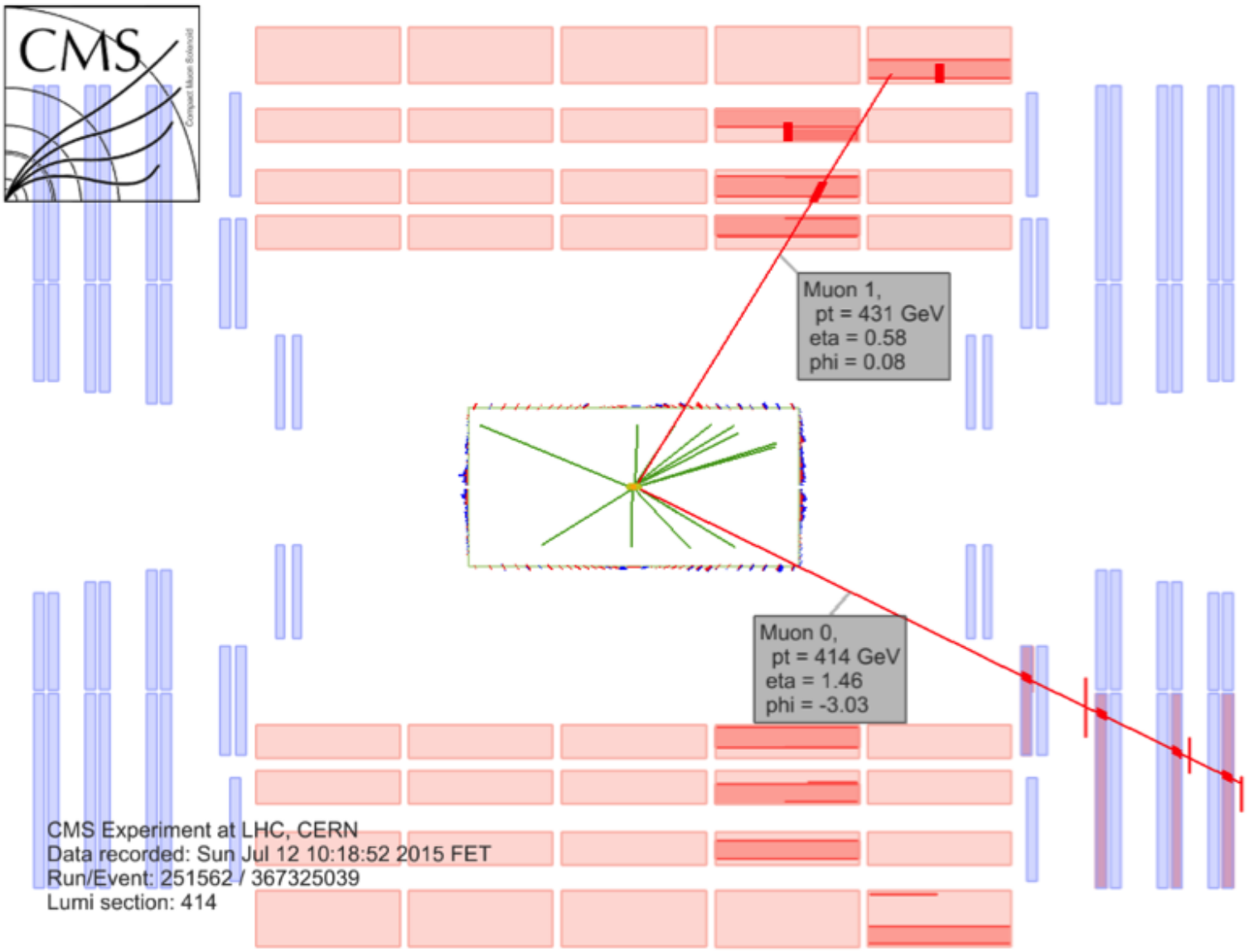
CMS Dilepton resonances ($X \to ll$) — 13 TeV

- 13 TeV CMS highest $\mu\mu$ mass event: $M_{\mu\mu} = 920$ GeV



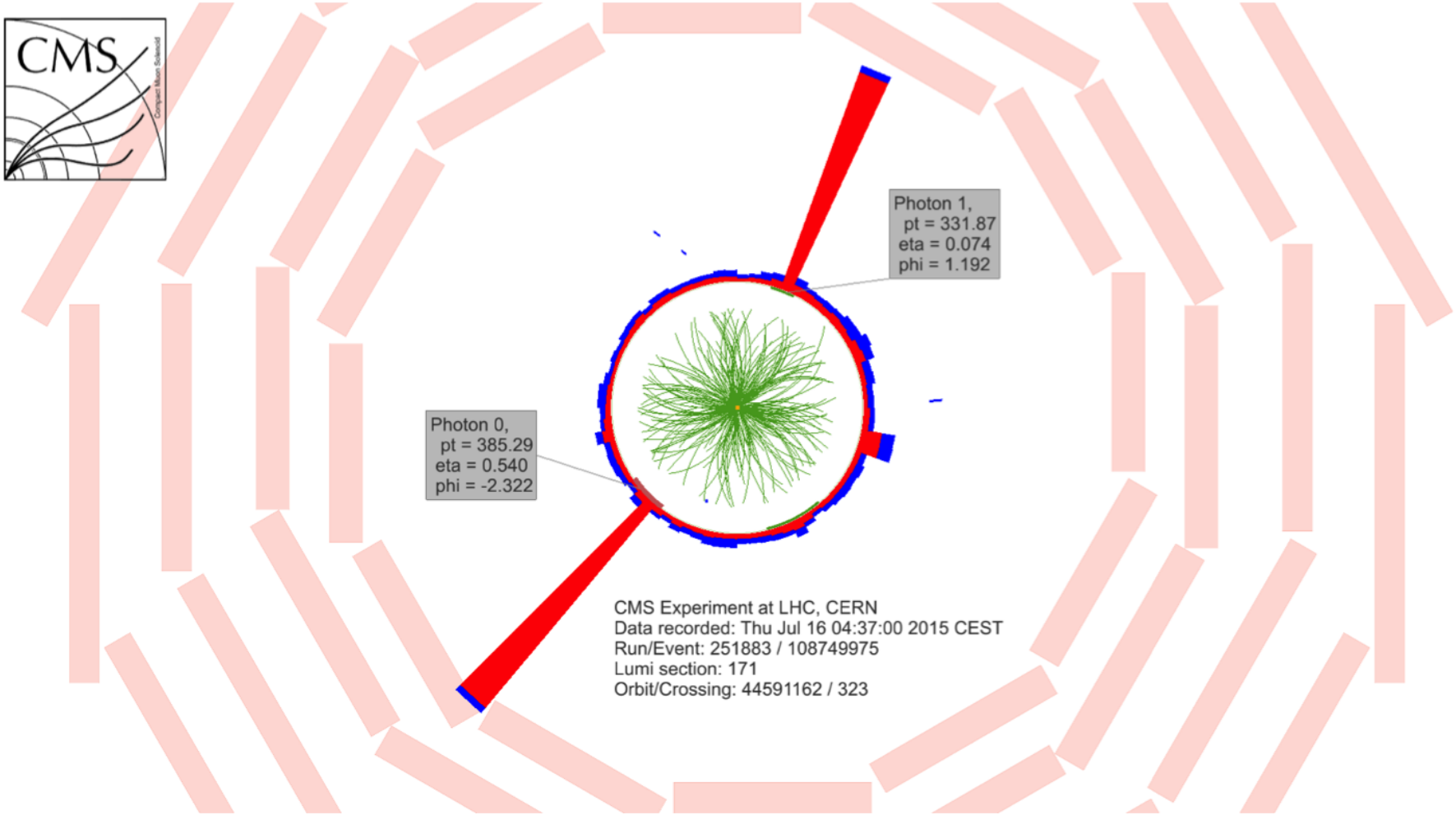
CMS Dilepton resonances ($X \to ll$) — 13 TeV

- 13 TeV CMS highest $\mu\mu$ mass event: $M_{\mu\mu} = 920$ GeV



CMS diphoton resonances ($X \to \gamma\gamma$) — 13 TeV

- 13 TeV CMS highest $\gamma\gamma$ mass event: $M_{\gamma\gamma} = 733$ GeV



Z' Interference effects at the LHC — arXiv

- Interference effects in case of Z'_{SSM}

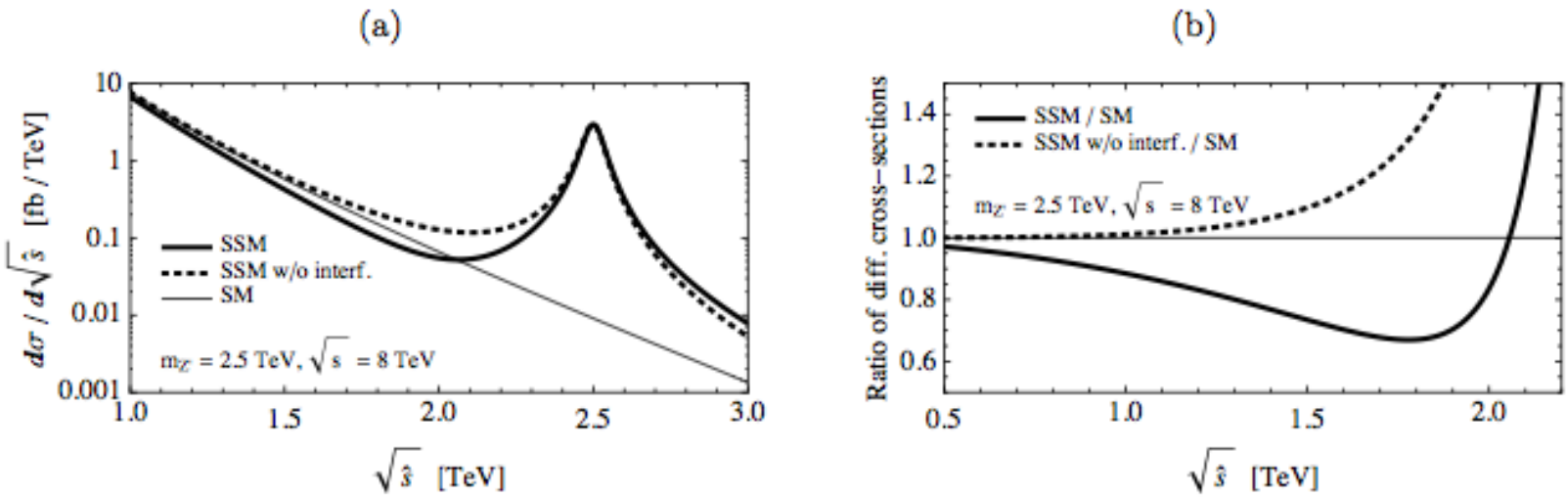


Figure 1. (a) Invariant mass distribution in the presence of a SSM Z' resonance, computed with and without interference between the Z' and the SM. (b) Ratio of these two predictions to the pure SM Drell-Yan result. LHC@8TeV with $M_{Z'}$=2.5 TeV is considered. No kinematical cuts are applied and the CT10 NLO best fit PDF set is used.