Z boson production in association with at least two b jets in pp collisions at 13 TeV: signal versus background

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Overview

- Motivation
- Signal vs. Background
- Data-Driven Background Estimation
- Analysis Results
- Summary

Motivation (I)

- Z boson produced in associated with bottom quark jets (b-jets) provide important tests of perturbative quantum chromodynamics (pQCD) calculations

- The processes form major background for a variety of physics analyses
  - Higgs production in association with a Z boson, ZH(H→bb/cc)
  - Beyond Standard Model (BSM) search for new generations of heavy quarks (b',t') decaying to Z boson and a b quark (Z+b jet)

- Measurements of various event kinematic properties are important to tune Monte Carlo (MC) simulations of Z + jets production

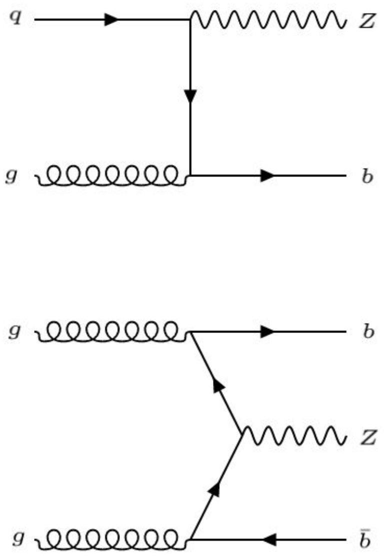


Fig 1. Feynman diagrams of tree-level contributions for Z + ≥ 1 b-jet (top) and Z + ≥ 2 b-jets (bottom) processes

Motivation (II)

- Z boson produced in association with ≥ 2 b-jets
  - Z boson decays into lepton (e^+e^-, $\mu^+\mu^-$) pair
  - Expect at least 2-jets, tagged by DeepCSV as b-jets

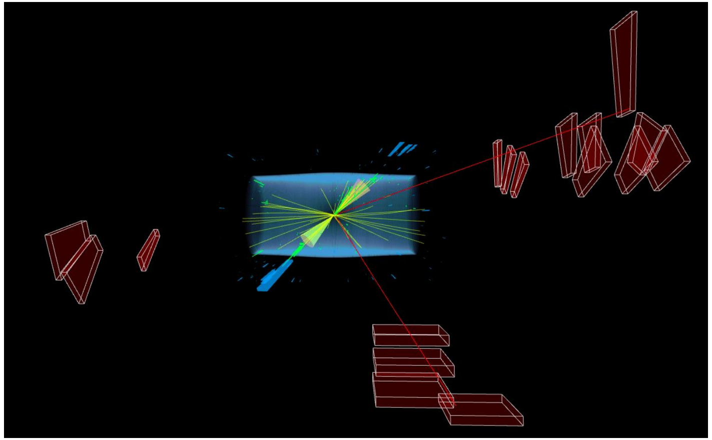


Fig 2. Event candidate for Z + two b-jets, Z decay into $\mu^+\mu^-$ pair

- Part of first on-going CMS analysis of Z+b-jets done at $\sqrt{s}$ = 13 TeV using full Run II data, 137 fb^{-1}
- Previous Z + heavy-flavor (HF) jets done at $\sqrt{s}$ = 8 TeV, Run I data*

Eur. Phys. J. C **77** (2017) 751, arXiv:1611.06507v2 [hep-ex].

Event Selection Criteria (I)

- Full Run II data with integrated luminosity of 137.1 fb^{-1} (2016, 2017, 2018)
- Trigger: SingleElectron, SingleMuon Trigger

- Leptons: isolated with leading (sub-leading) lepton p_T > 35 (25) GeV | η | < 2.4
- Z boson: pair of oppositely charged leading and sub-leading leptons within the mass window

  $71 \text{ GeV} < M_{\ell\ell} < 111 \text{ GeV}$

- Jet: jets reconstructed with anti-k_T algorithm with distance parameter of 0.4

  p_T > 30 GeV, | η | < 2.4, lepton overlap removal, tight jet ID

  jets from pileup events are excluded

Event Selection Criteria (II)

- b-jets: jets tagged with DeepCSV tagger

  tight tagging operating point is required to reduce Drell-Yan (DY) + jets background: DY+bX, DY+XX, where X = c- or light jets

  loose, medium, tight operating points correspond to approximately 80%, 60%, 50% b quark tagging efficiency and 10%, 1%, and 0.1% misidentification rate for light jets

- Missing Transverse Energy (MET), MET < 50 GeV → reduces tt background

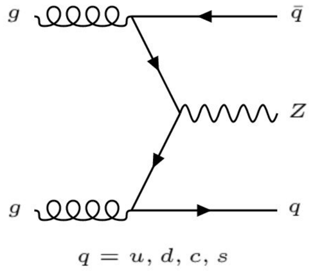


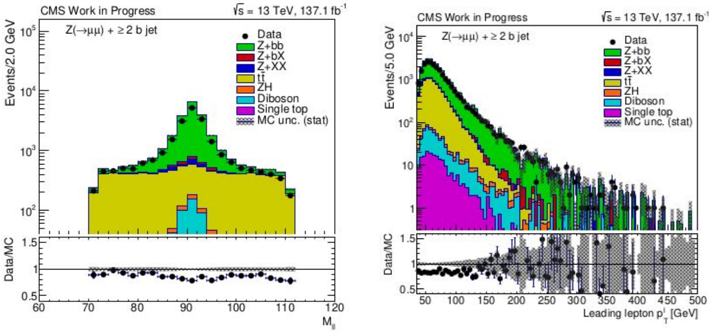
Fig 3. Background process for Z + ≥ 2 b-jets where c- or light (u,d,s) jets are produced in association

Events after Z + ≥ 2 b-jets Selection

- Numerous backgrounds in signal (DY+bb) region
- tt background is not negligible, accounts for ~⅓ of total events
- tt accounts for ~85% of overall background events

Table 12: Number of events after Z + $\geq$ 2 b jets selection

	2016		2017		2018	
	Electron	Muon	Electron	Muon	Electron	Muon
DY+bb	1976	4206	2241	4557	4361	8934
DY+bX	38	89	29	81	72	190
DY+XX	10	89	2	55	43	237
tt	784	1748	1102	2362	1825	3865
single t	18	40	22	59	48	99
VV	44	97	65	136	98	218
ZH	11	22	13	27	23	45
MC	2880	6291	3473	7278	6470	13589
Data	2549	5503	3070	6554	5070	10757
Data/MC	0.89	0.87	0.88	0.90	0.78	0.79



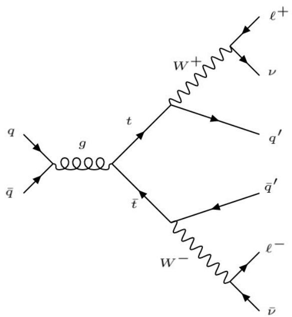


Fig 4. (Left to right, top to bottom) Dilepton invariant mass and leading lepton p_T distributions for muon channel (combined Run II data), Feynman diagram for tt production process

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Signal vs. Background

- MET in tt and signal events are very different

$$t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell^+\ell^-\nu\bar{\nu}b\bar{b}$$
$$Zb\bar{b} \rightarrow \ell^+\ell^-b\bar{b}$$

- Determine optimal MET cut to optimize event selection
- 50 GeV cut → 90% signal and 30% background events are kept
- Keep events where MET < 50 GeV

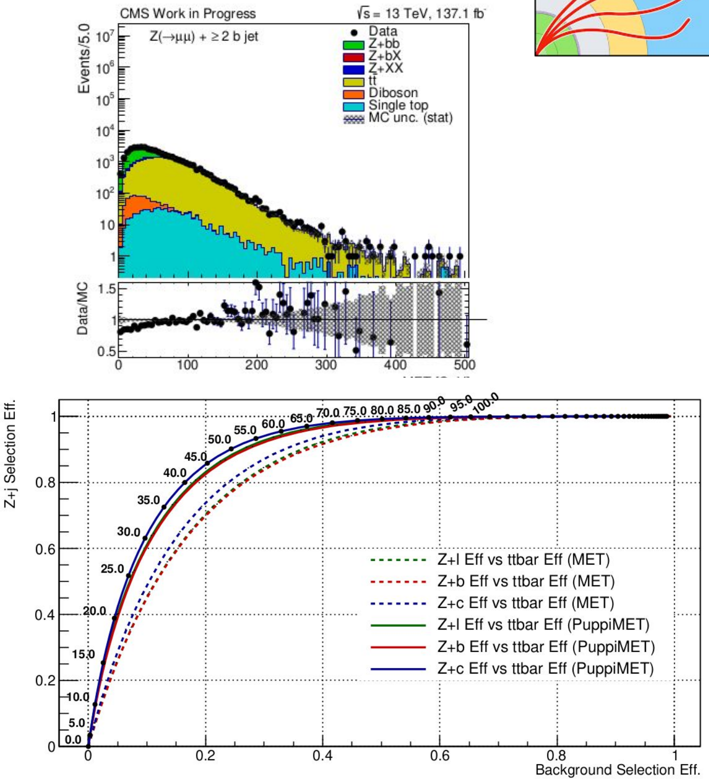

Fig 5. MET distribution (top) and Receiving operating characteristic (ROC) curve (bottom) for Z+jet and tt selection efficiency as a function of MET

Data-Driven Background Estimation (I)

- Backgrounds can be estimated using MC simulations
- tt can be more precisely estimated with data-driven methods
- Technique applied in earlier analyses at CDF (Tevatron)*, CMS**
- Outside Z signal region, events are mostly composed of background events
- Estimate background rate using sideband region

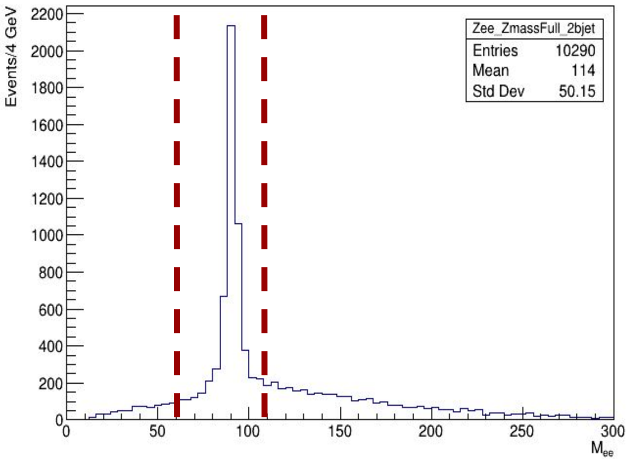

Fig 6. e^+e^- invariant mass distribution for 2018 data; the region within the dashed lines indicates the signal region

* *Phys. Rev. D* **79** (Mar, 2009) 052008, doi:10.1103/PhysRevD.79.052008.

***Eur. Phys. J. C* **77** (2017) 751, arXiv:1611.06507v2 [hep-ex].

Data-Driven Background Estimation (II)

- Use same trigger, event selection criteria as analysis
- Sideband regions $40 < M_{\ell\ell} < 66$ GeV $M_{\ell\ell} > 116$ GeV
- Enrich tt sample (suppress Z+jet events) by using events where MET > 80 GeV
- Match sideband regions (ee,μμ) with eμ events
- Fit dilepton data distribution to pull normalization constant between dilepton and eμ distributions
- Expect $c_t = 0.5$ due to combinatorics of final state particles

$$N_{\ell\ell} = c_t \cdot N_{e\mu} \qquad \ell\ell = ee,\ \mu\mu$$

$$c_t \sim \tfrac{1}{2}$$

Results (I)

- Scale eμ sample by extracted coefficient
- Scaled sample matches sideband regions and tt MC simulation within uncertainty

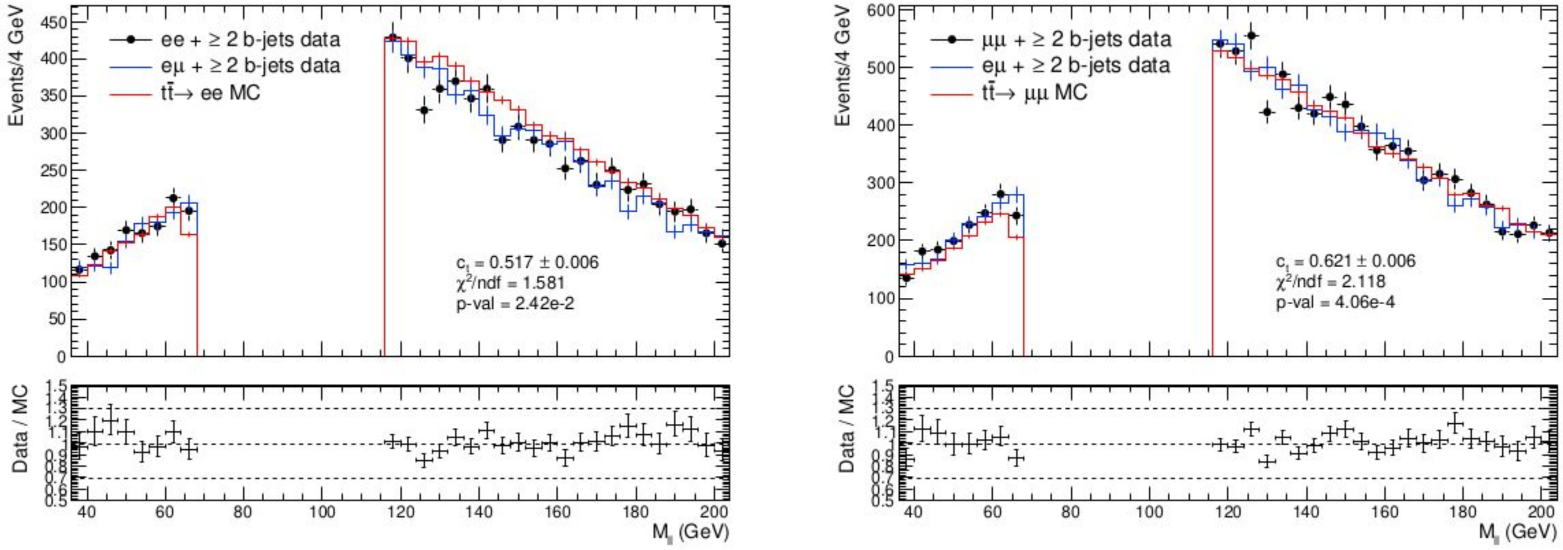

FIG 7. Z + ≥ 2 b-jets dilepton invariant mass sideband region fitted for electron (left) and muon (right) channels, 2018 data

Results (II)

- Subtract eμ events from the dilepton invariant mass distribution to isolate the signal
- Scaled eμ sample matches tt MC over entire region within 10%

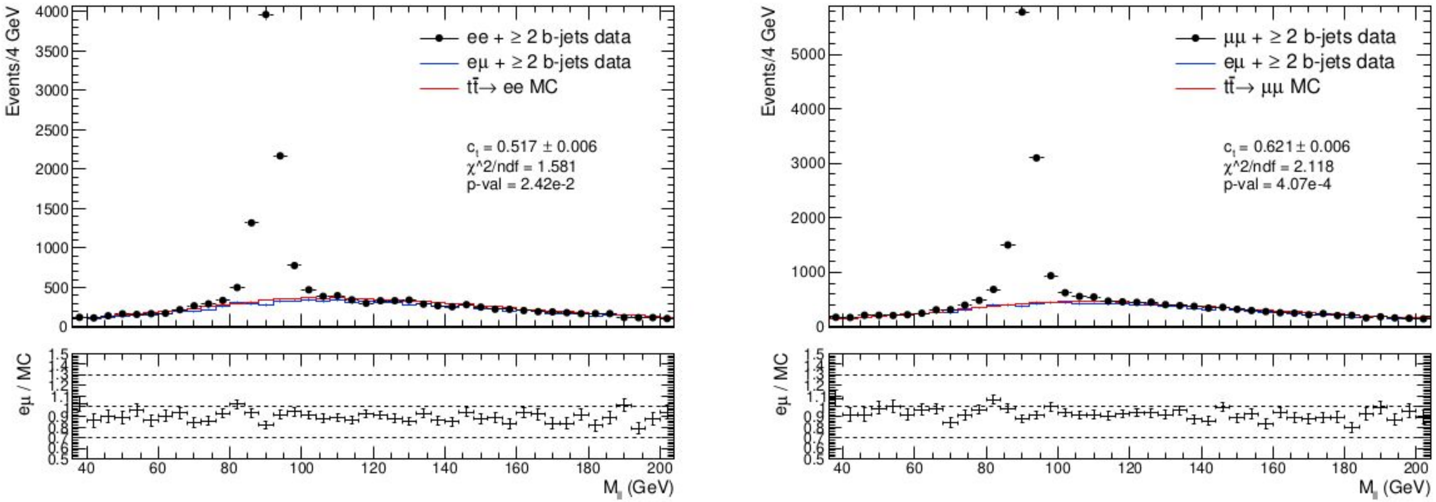

FIG 8. Z + ≥ 2 b-jets dilepton invariant mass fit between eμ data and ttbar MC samples for electron (left) and muon (right) channels, 2018 data

Results (III)

- Same process can be applied to MET, MET Significance distributions
- Various fits match within a maximum variation of 7%

$$S = \frac{E_T^{\text{miss}}}{\sigma}$$

Sample	Z Mass	MET	MET Significance
2016 Electron Channel	0.526 ± 0.008	0.528 ± 0.006	0.524 ± 0.007
2017 Electron Channel	0.530 ± 0.007	0.559 ± 0.005	0.544 ± 0.007
2018 Electron Channel	0.517 ± 0.006	0.537 ± 0.004	0.519 ± 0.005

Sample	Z Mass	MET	MET Significance
2016 Muon Channel	0.627 ± 0.009	0.643 ± 0.006	0.632 ± 0.007
2017 Muon Channel	0.620 ± 0.007	0.669 ± 0.005	0.640 ± 0.007
2018 Muon Channel	0.621 ± 0.006	0.656 ± 0.004	0.641 ± 0.005

Cross Section Results

- After Z + ≥ 2 b-jet selection and data-driven background estimation,

CHANNEL	MEASURED (pb)	MG5_aMC (LO) (pb)
Electron	0.66 ± 0.05 (stat) ± 0.08 (syst) ± 0.02 (theo)	0.677 ± 0.04 ± 0.01
Muon	0.65 ± 0.04 (stat) ± 0.07 (syst) ± 0.02 (theo)	0.677 ± 0.04 ± 0.01
Combined	0.65 ± 0.03 (stat) ± 0.07 (syst) ± 0.01 (theo)	0.677 ± 0.04 ± 0.01

- Measurements and predictions agree with each other

Summary

- Z+HF production provides important tests of pQCD calculations. It is an important background for numerous processes such as associated Higgs boson production ZH(H→bb/cc) and searches for New Physics

- In Z + 2 b-jets production, the background is dominated by tt events which can be reduced by MET requirements.

- Background rate can be estimated more accurately with data-driven method.

- Overall results show agreement between MC and data.

Thank you for listening.

ADDITIONAL SLIDES

Additional Fits

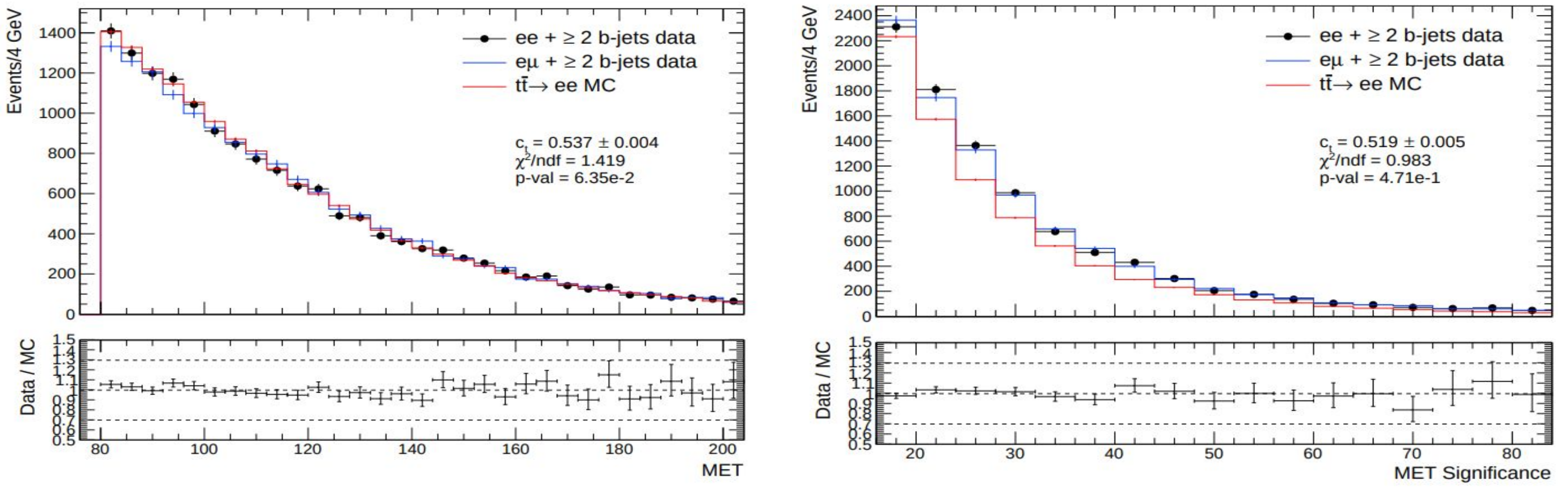

FIG 9. Z + ≥ 2 b-jets MET distribution (left) and MET significance distribution (right) fit between eμ data and ttbar MC samples for electron channel, 2018 data

tt Production

- Top quark decays into W boson and quark
- W boson decays into charged lepton and neutrino
- σ(tt→ℓℓ + MET + ≥ 2 jets) ~ 170 pb

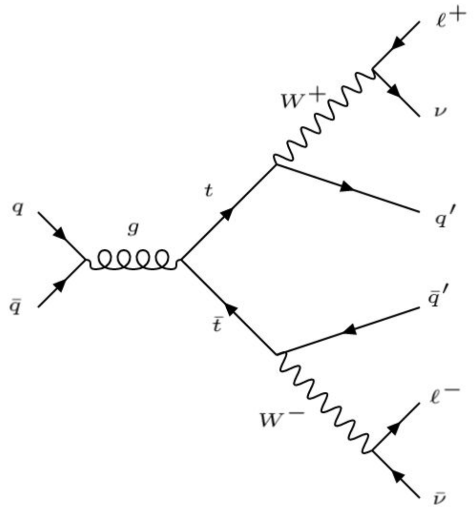

FIG 10. Feynman diagram for ttbar production

Missing Transverse Energy

- In ideal case,

$$\sum_{i=0}^{N} E_{T,i} = 0$$

- Neutrinos are not detected by CMS detector, leaving an imbalance in transverse energy
- Random noise in system, errors in detectors can lead to some level of imbalance
- Very few events will truly have MET = 0 GeV

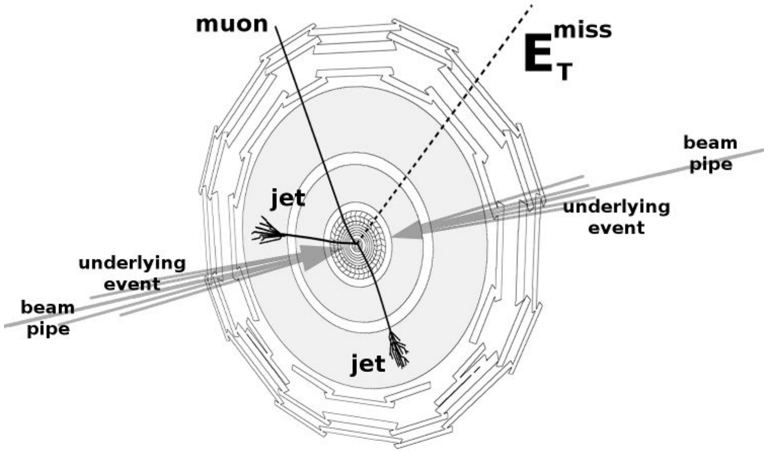

FIG 10. A sample cross section demonstration of missing transverse energy