CMS Search for $H \to Z\gamma$ at $\sqrt{s} = 13$ TeV

Candidacy Exam

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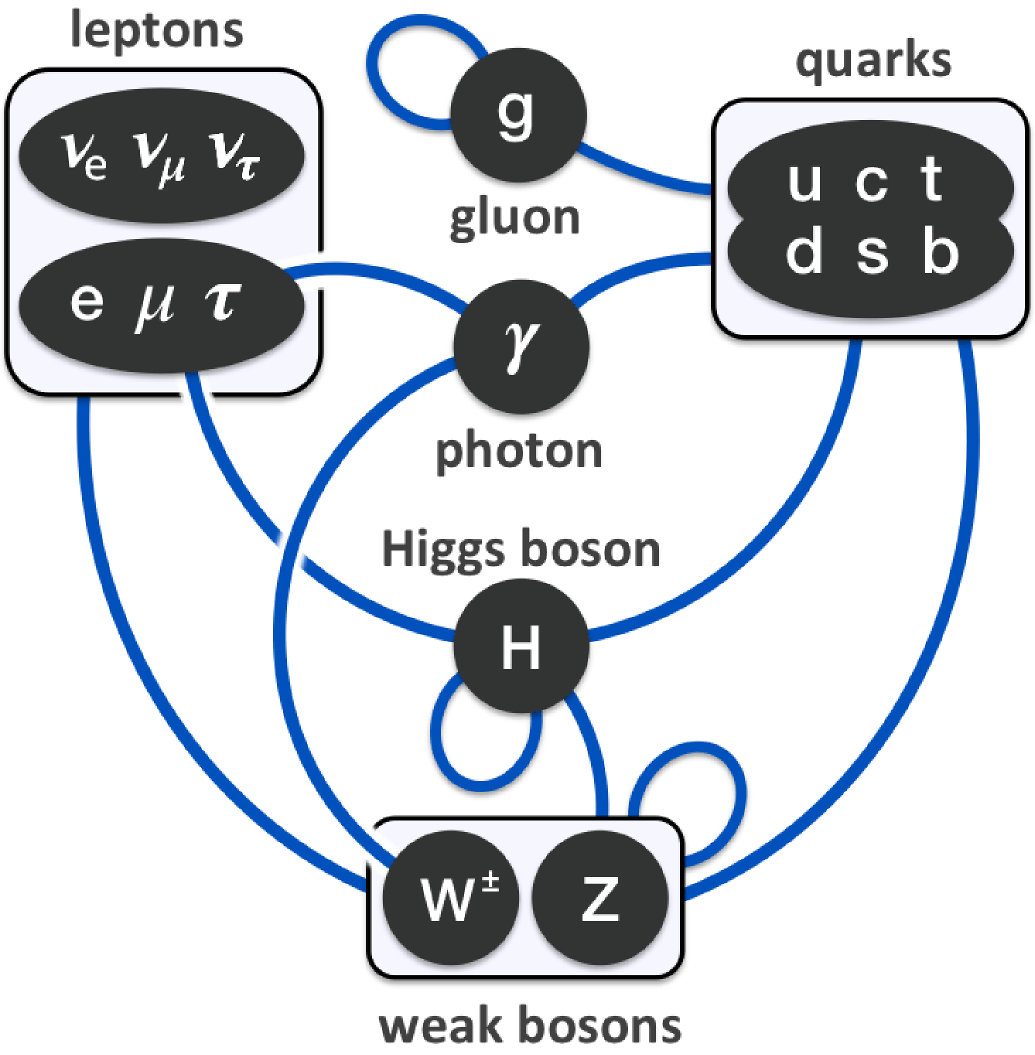
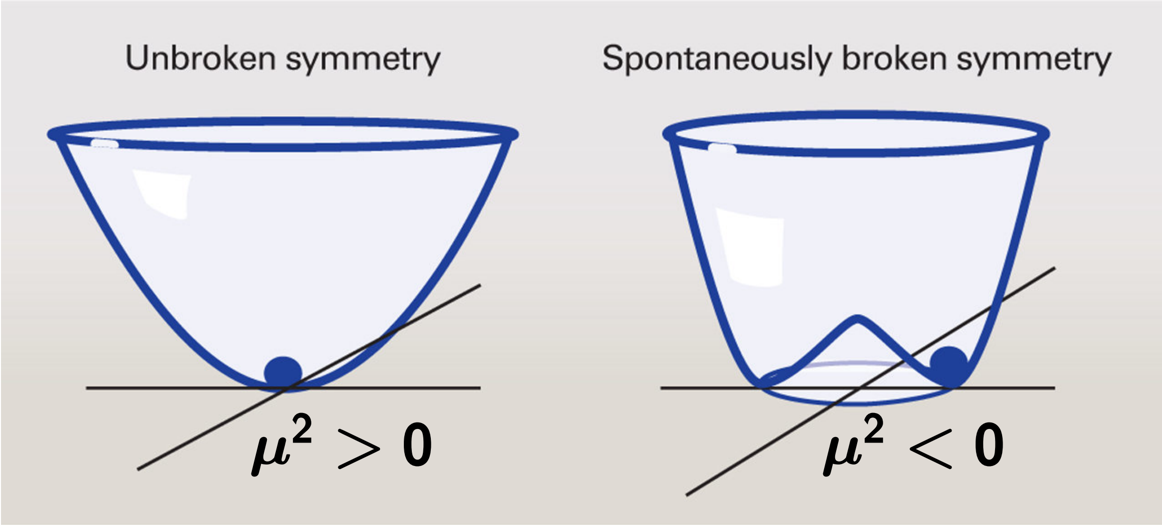
Overview

- introduction
- motivation for the $H \to Z\gamma$ search
- history and timeline of the analysis
- analysis strategy
  - physics object and event selection
  - multivariate analysis with boosted decision trees
  - kinematic constraints to improve mass resolution
  - photon p_T discrimination
  - signal and background modeling
  - uncertainties
  - expected upper limits for signal production
- projections for the full 13 TeV CMS dataset
- summary

The Standard Model



Higgs Mechanism



electroweak symmetry: SU(2)xU(1)

$$\mathcal{L} = (\mathrm{D}_\mu \Phi)^\dagger \mathrm{D}^\mu \Phi - \mathrm{V}(\Phi)$$

$$\mathrm{V}(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$

$$\mathrm{D}_\mu = \partial_\mu + \frac{\mathrm{ig}}{2}\sigma^{\mathrm{i}} \mathrm{W}^{\mathrm{i}}_\mu + \frac{\mathrm{ig}'\mathrm{Y}}{2}\mathrm{B}_\mu$$

$$< \Phi > = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v \end{bmatrix}$$

$\longrightarrow$

Physical Fields

$$\mathrm{W}^\pm = \frac{\mathrm{W}_1 \mp \mathrm{i}\mathrm{W}_2}{\sqrt{2}}$$

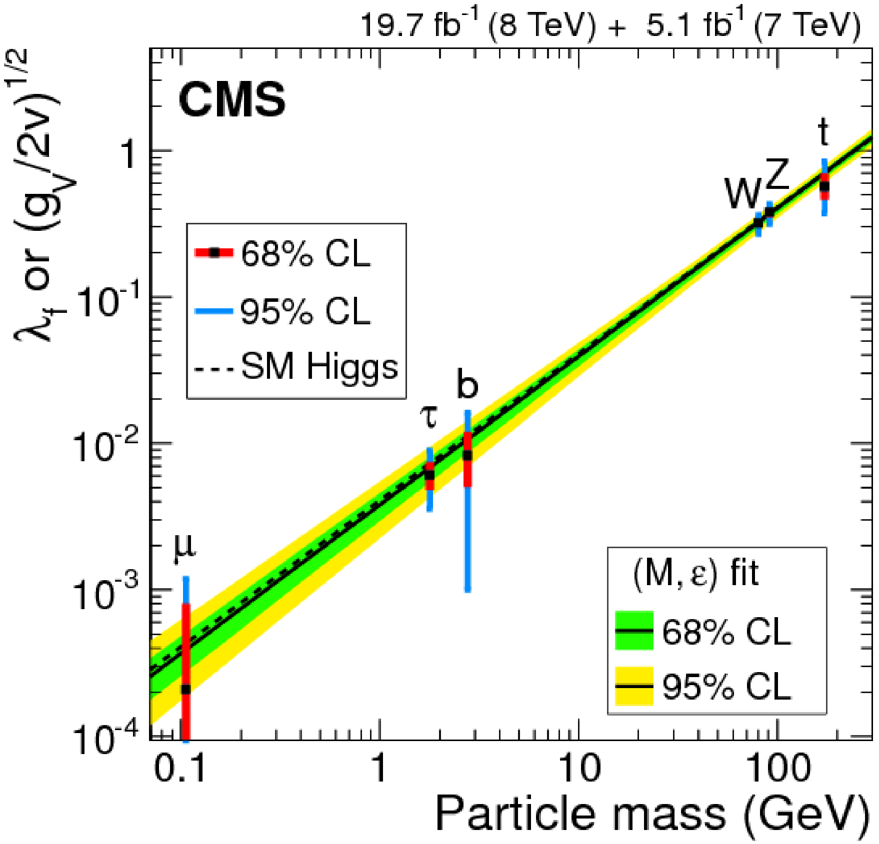
$$\mathrm{Z}_\mu = \frac{1}{\sqrt{\mathrm{g}^2 + \mathrm{g}'^2}}(\mathrm{g}\mathrm{W}^3_\mu - \mathrm{g}'\mathrm{B}_\mu)$$

$$\mathrm{A}_\mu = \frac{1}{\sqrt{\mathrm{g}^2 + \mathrm{g}'^2}}(\mathrm{g}'\mathrm{W}^3_\mu + \mathrm{g}\mathrm{B}_\mu)$$

Higgs field h

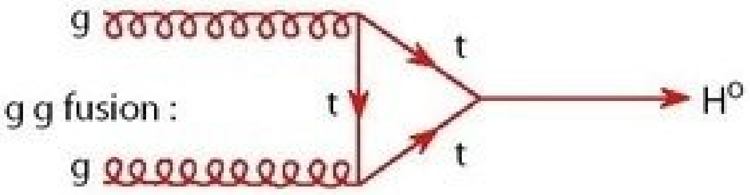
The SM Higgs Boson

- discovered at LHC by CMS and ATLAS in 2012
- by now, many production and decay modes have been observed and measured
- but some, like $H \to Z\gamma$, have eluded observation
- so far, the Higgs is SM-like
- but we know the SM is incomplete, and the measurement of rare Higgs processes provides a possible window into BSM physics

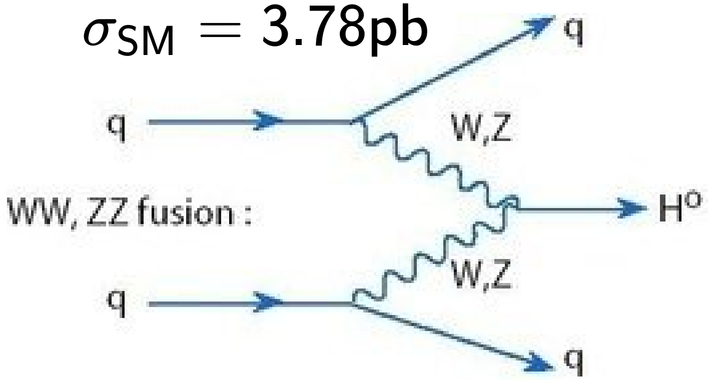


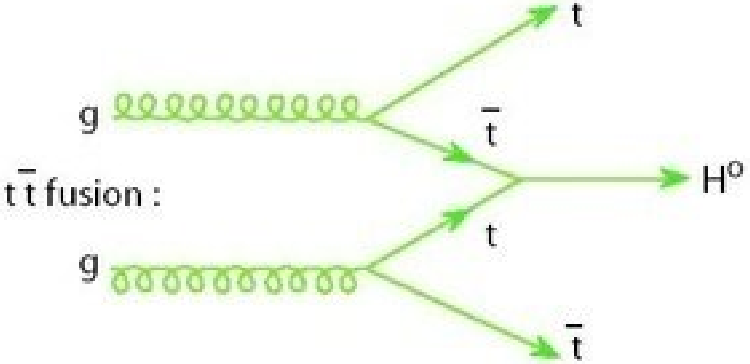
Higgs Production

$\sigma_{\text{SM}} = 48.58\text{pb}$



$\sigma_{\text{SM}} = 3.78\text{pb}$





$\sigma_{\text{SM}} = 0.507\text{pb}$

$\sigma_{\text{SM}} = 2.25\text{pb}$

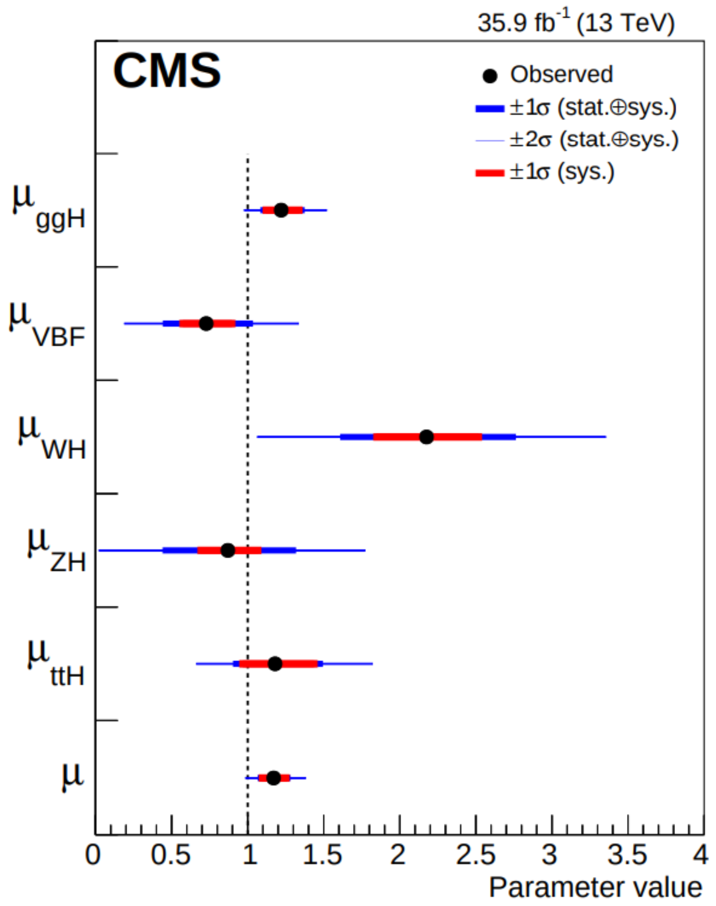
- from LHC Higgs cross section working group
- cross sections for $m_H = 125$ GeV and $\sqrt{s} = 13$ TeV

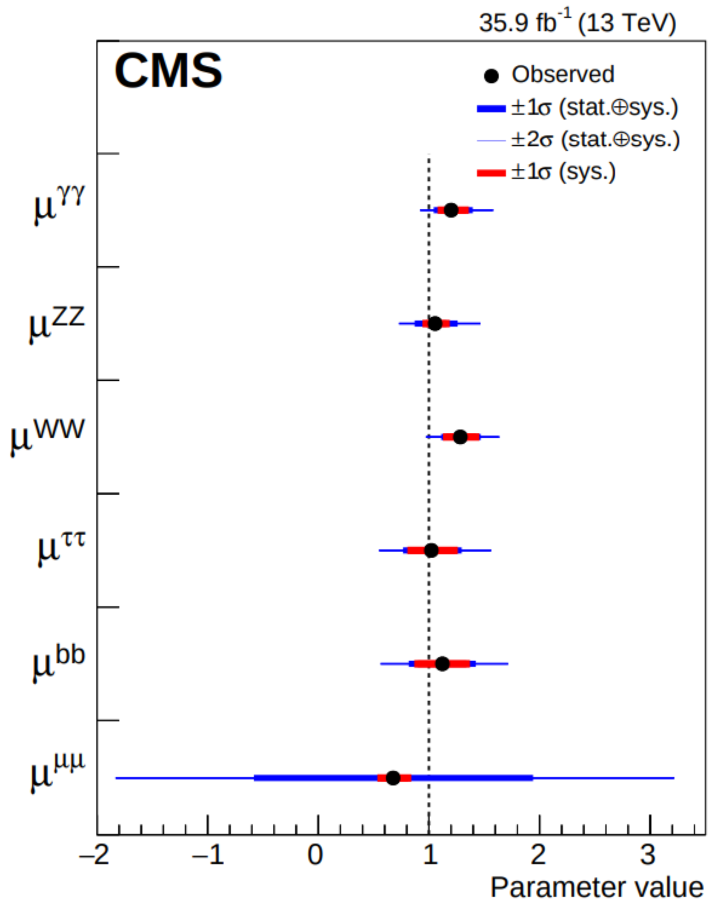
Higgs Decay

Decay Mode	Branching Fraction
$H \to b\bar{b}$	0.58
$H \to WW$	0.214
$H \to \tau\tau$	0.063
$H \to ZZ$	0.026
$H \to \gamma\gamma$	$2.27 * 10^{-3}$
$H \to Z\gamma$	$1.533 * 10^{-3}$

- from LHC Higgs cross section working group
- H $\to$ Zγ similar in rate to H $\to$ $\gamma\gamma$
  - but additional reduction from branching fraction for Z $\to$ $\ell\ell$ ~ 3.37%

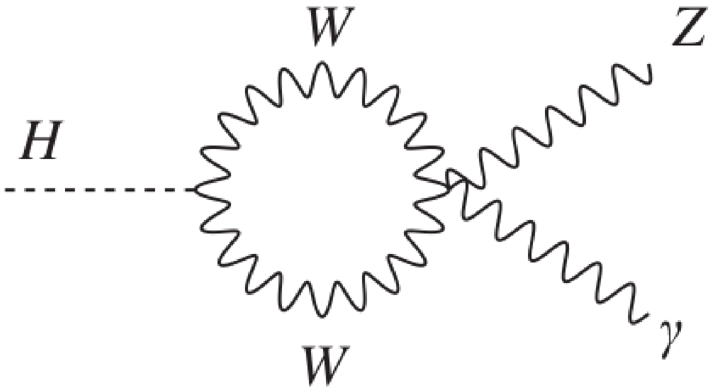
CMS 13 TeV Measurements

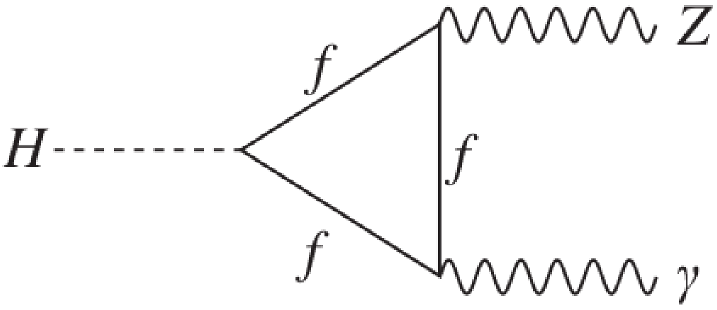


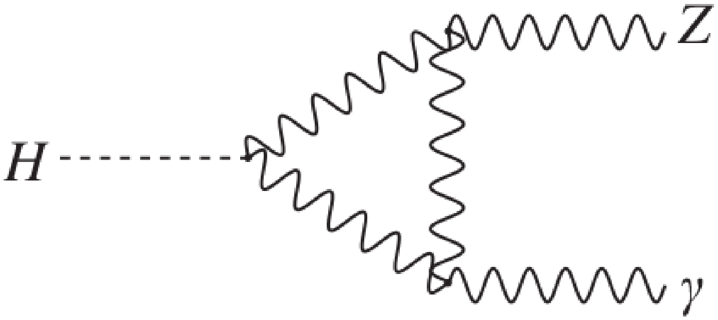


$H \to Z\gamma$ conspicuously absent

H $\rightarrow$ Zγ Decay



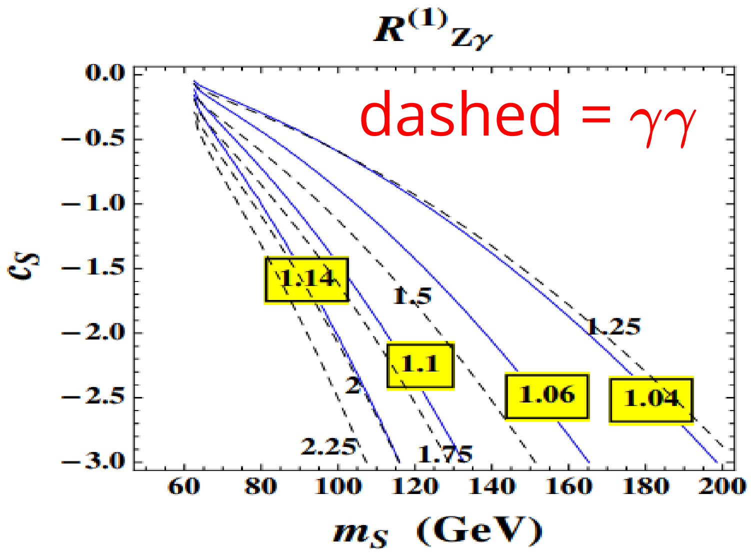


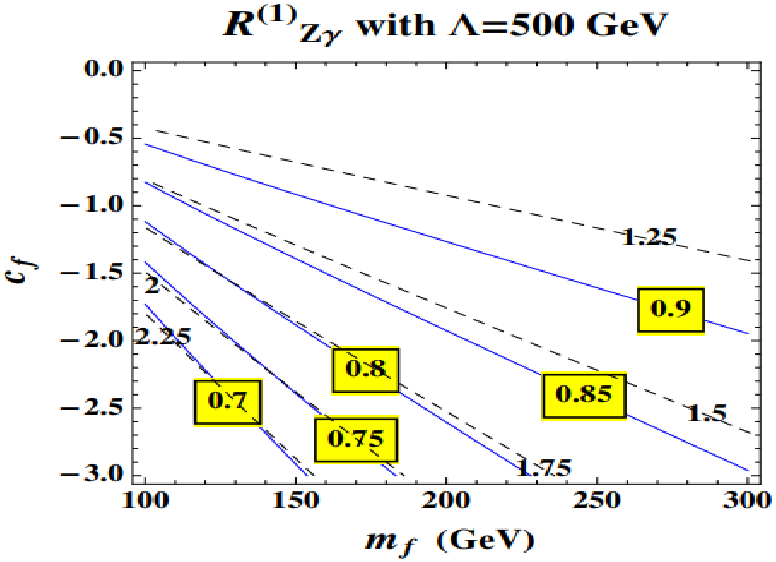


- loop-suppressed process
- never experimentally observed
- potentially sensitive to BSM physics

BSM Scenarios

- additional charged scalars
- additional charged fermions
  - correlated with H $\to \gamma\gamma$
  - so far, $\gamma\gamma$ somewhat enhanced, but still consistent with SM
- extended Higgs sector
- composite Higgs





https://arxiv.org/pdf/1206.1082.pdf

Analysis Considerations

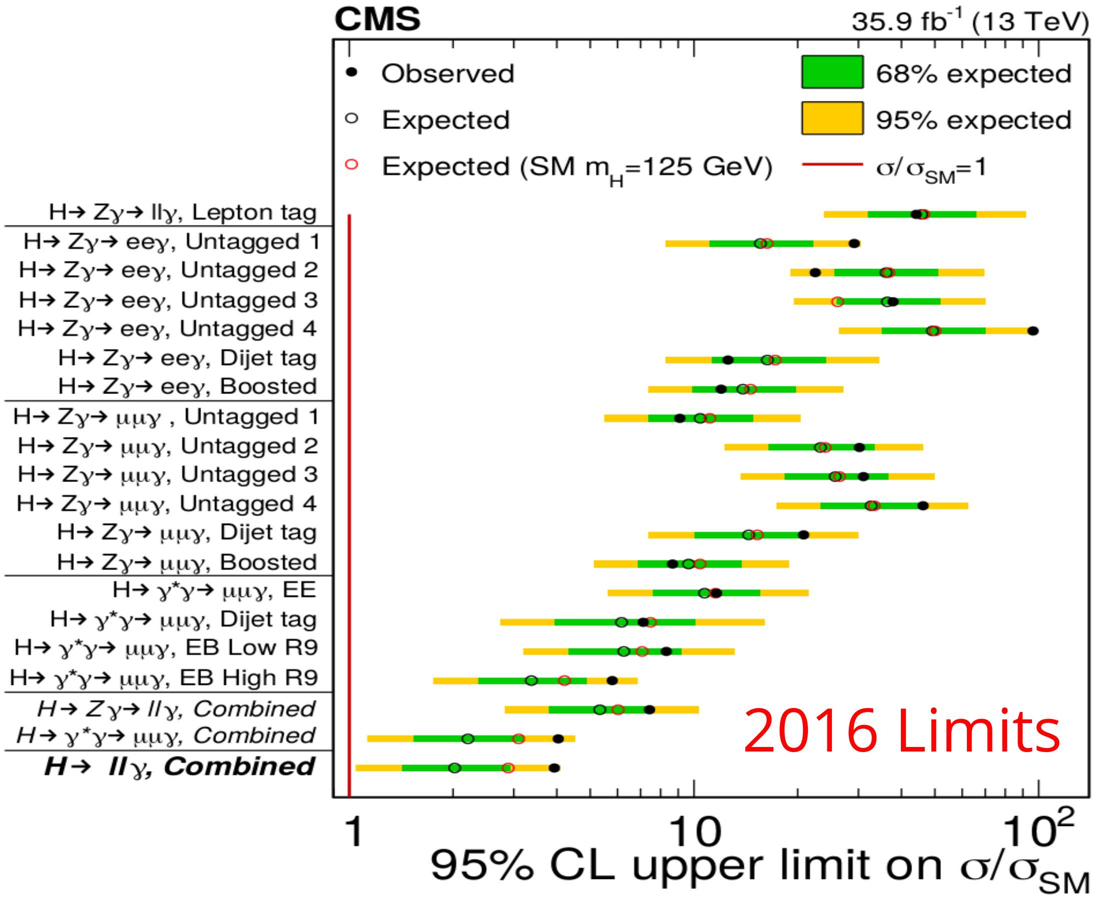
Signal

- $\ell\ell\gamma$ final state
  - same final state for rare decays involving quarkonia, like $\mathrm{H} \rightarrow \mathrm{J}/\psi(\Upsilon) + \gamma$
  - these related searches are also interesting, for example, in probing $\mathrm{H}c\bar{c}$
  - complication: same final state for Dalitz ($\mathrm{H} \rightarrow \gamma^*\gamma$ decay) handled by cutting at $m_{\ell\ell} > 50$ GeV; really have interference between the two channels
- VBF production: two additional forward jets
- $jj\gamma$ final state (hadronically decaying Z)
  - **not considered here**, but may be considered in the future
  - advantage is larger branching fraction of Z to hadrons
  - disadvantages: difficult to trigger on, poorer mass resolution

Backgrounds

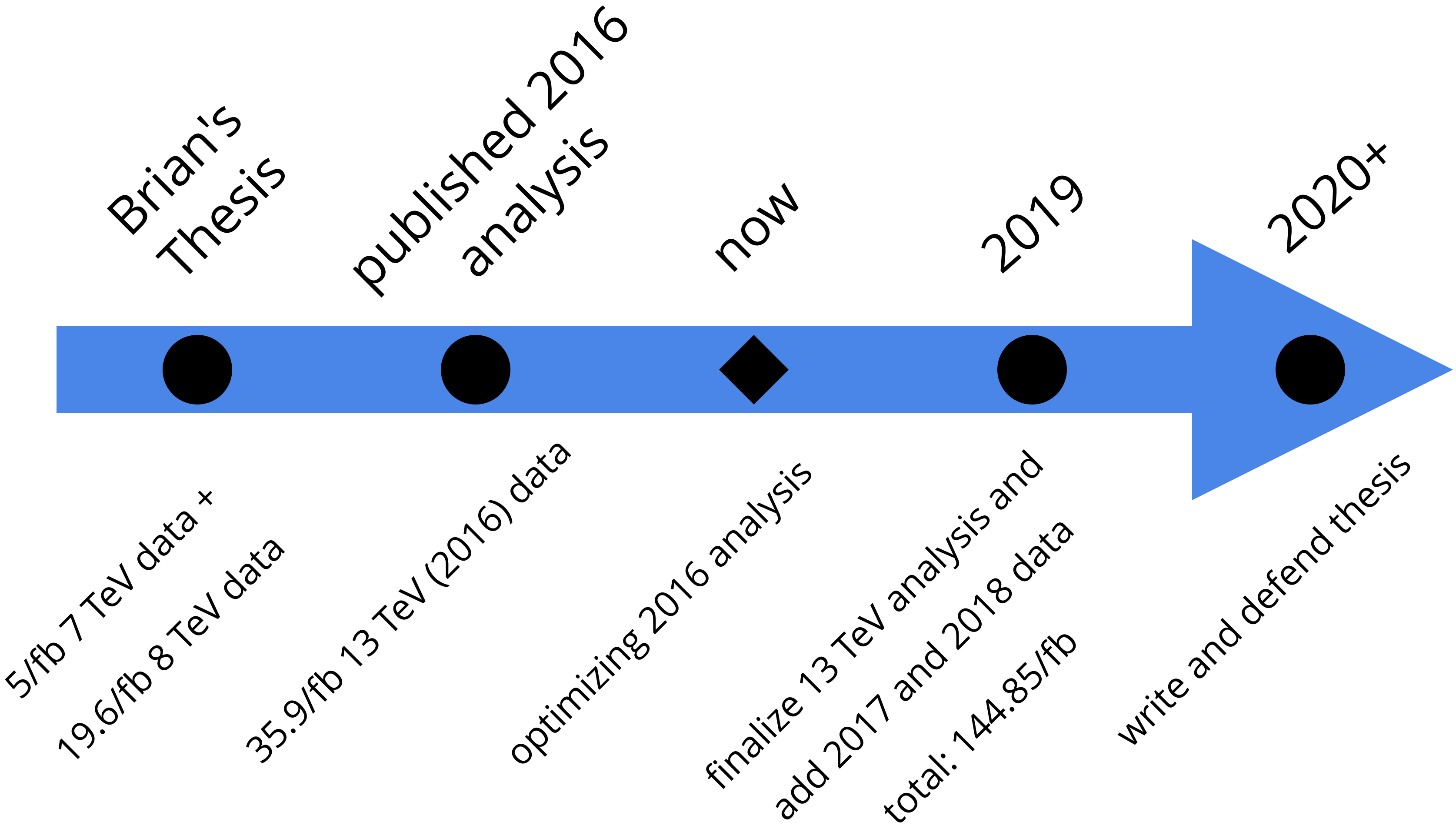
- irreducible contribution from SM $Z + \gamma$ production
- FSR in Z decays
- Z+jets with misreconstruction of jets as photons

History of H $\rightarrow Z\gamma$

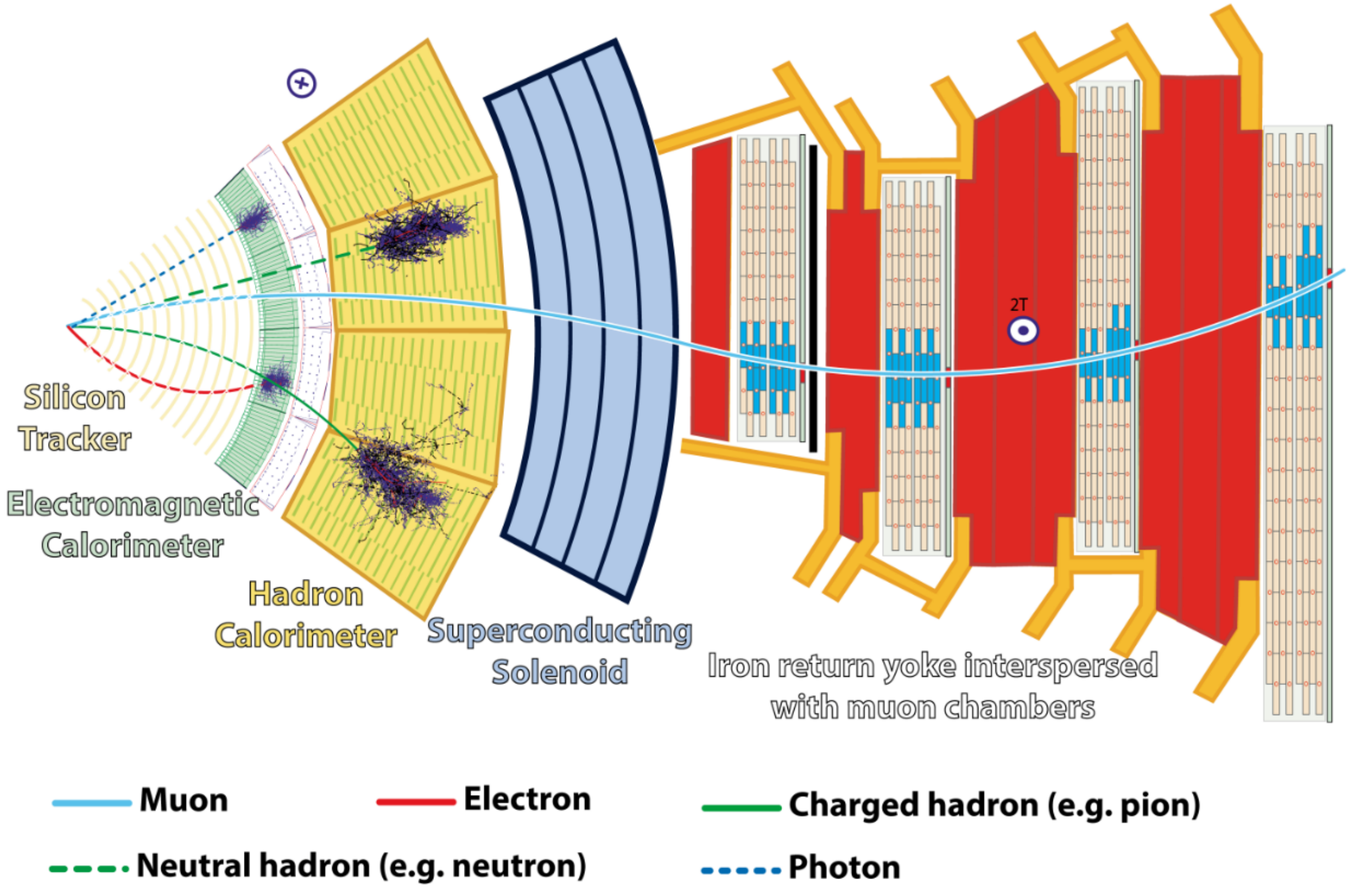


- collaboration between NU and NCU (Taiwan) groups
- published Run I analysis (B. Pollack's thesis)
- published Run II analysis (2016 data only)

Timeline


Brian's Thesis
published 2016 analysis
now
2019
2020+
5/fb 7 TeV data +
19.6/fb 8 TeV data
35.9/fb 13 TeV (2016) data
optimizing 2016 analysis
finalize 13 TeV analysis and
add 2017 and 2018 data
total: 144.85/fb
write and defend thesis

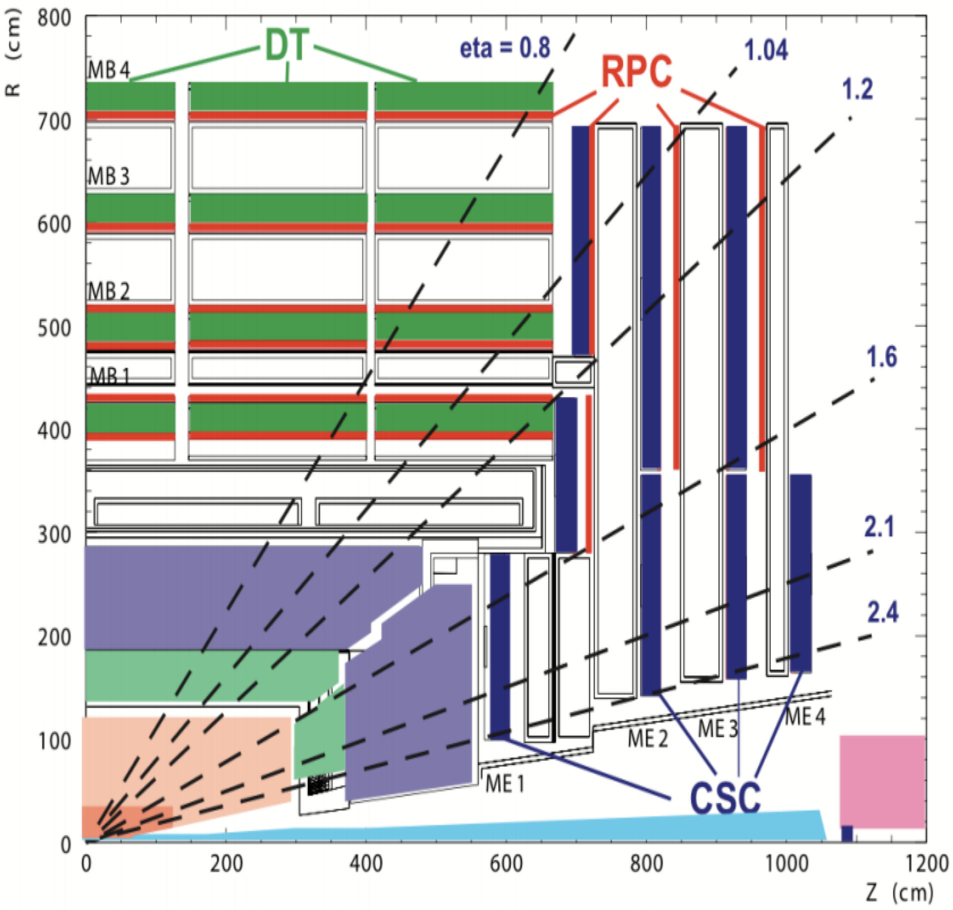
Experimental Signature



- **signal**
  - resonant $\ell\ell\gamma$ final state (at m_H)
  - VBF production: two additional jets
  - VH production: additional lepton
- **background**
  - irreducible nonresonant $Z\gamma$
  - Drell-Yan with misreconstructed jets

Muon Reconstruction

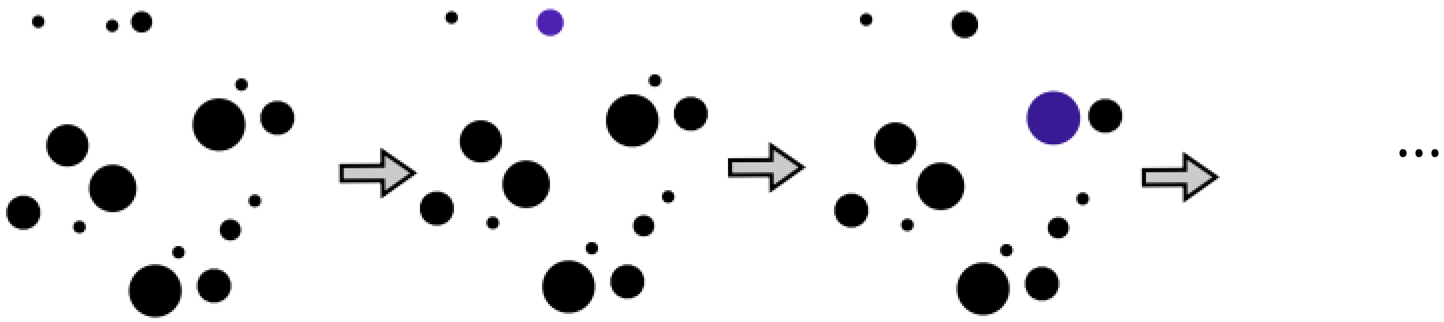
- three types of detectors in the muon system: drift tubes, resistive plate chambers, cathode strip chambers
- all based on gas ionization and measurement of induced charge
- muon trajectories also measured in the tracker
- match muon system hits and segments with tracker hits
    - inside-out and outside-in approaches both used



e/γ Reconstruction

- for both e, γ: ECAL hits $\rightarrow$ clusters $\rightarrow$ superclusters
- electron also associated with tracking information (trajectory)
- photons vetoed if linked to charged particle track, unless that track is consistent with a γ conversion

Jet Reconstruction



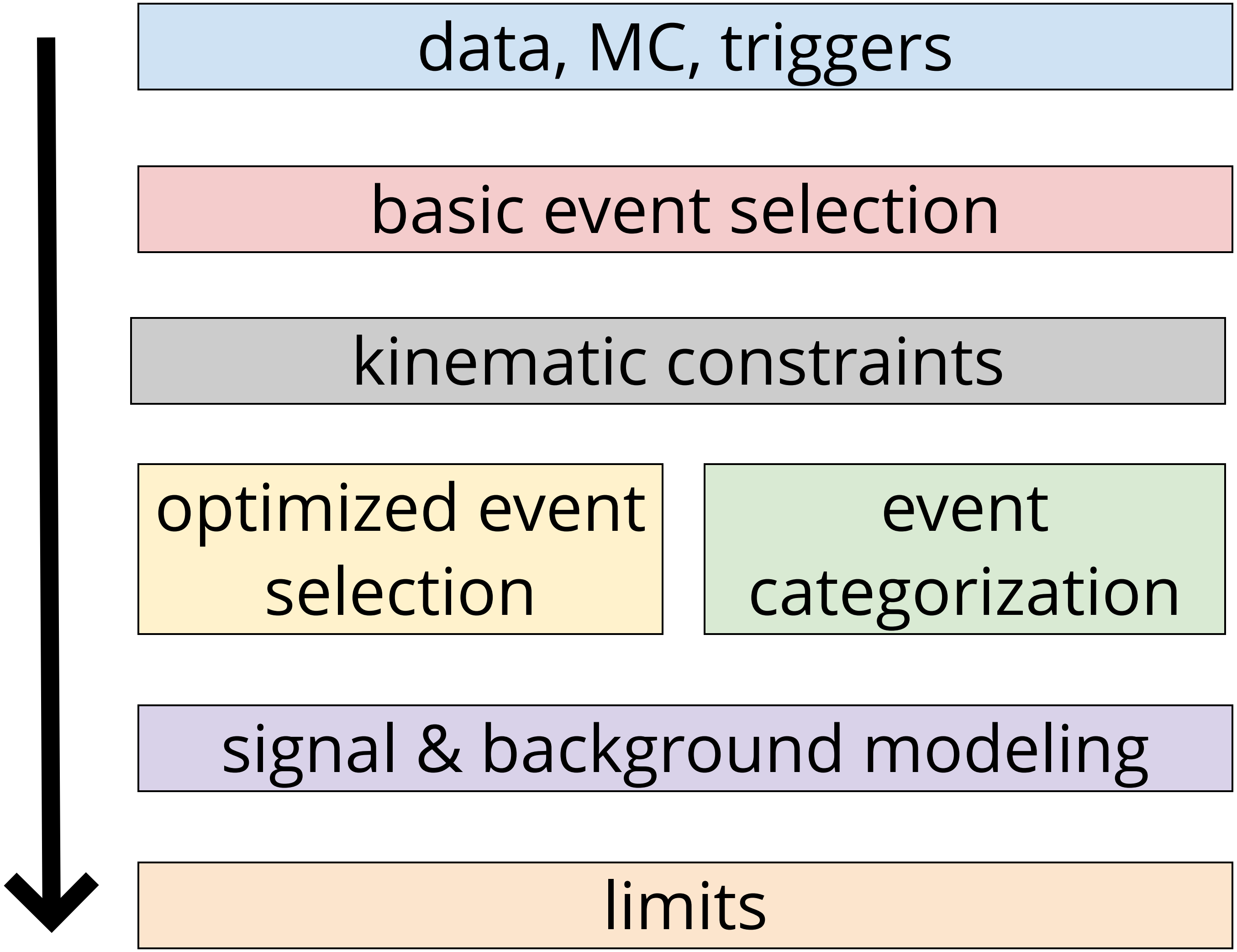
$$\mathsf{d_{ij}} = \mathsf{min}(\mathsf{p_{ti}}^{-2}, \mathsf{p_{tj}}^{-2})\Delta \mathsf{R_{ij}^2}/\mathsf{R}^2$$

$$d_{iB} = p_{ti}^{-2}$$

- anti-kT algorithm
- start with calorimeter clusters
- merge by smallest $\mathsf{d_{ij}}$
- stop when $\mathsf{d_{ij}} > \mathsf{d_{iB}}$

distance parameter (0.4)

Analysis Strategy



Data and Triggers

$\mu^+\mu^-\gamma$ Final State

- $\mathcal{L} = 35.9\ \mathrm{fb}^{-1}$ data at $\sqrt{s} = 13$ TeV (2016)
- double muon trigger
- leading trigger leg: $p_T^{\mu} > 17$ GeV
- trailing trigger leg: $p_T^{\mu} > 8$ GeV

$e^+e^-\gamma$ Final State

- $\mathcal{L} = 35.9\ \mathrm{fb}^{-1}$ data at $\sqrt{s} = 13$ TeV (2016)
- double electron trigger
- leading trigger leg: $p_T^{e} > 23$ GeV
- trailing trigger leg: $p_T^{e} > 12$ GeV

Monte Carlo Simulation

- ggF $H \to Z\gamma$ ($m_H = 125$ GeV)
- VBF $H \to Z\gamma$ ($m_H = 125$ GeV)
- ZH $H \to Z\gamma$ ($m_H = 125$ GeV)
- W(+/-) $H \to Z\gamma$ ($m_H = 125$ GeV)
- ttH $H \to Z\gamma$ ($m_H = 125$ GeV)

- inclusive Z+jets ($m_{\ell\ell} > 50$ GeV)
- dedicated SM $Z\gamma \to \ell\ell\gamma$
- overlapping events are removed from Z+jets sample
- used for data/MC validation and MVA training but **not** for background modeling

Event Selection

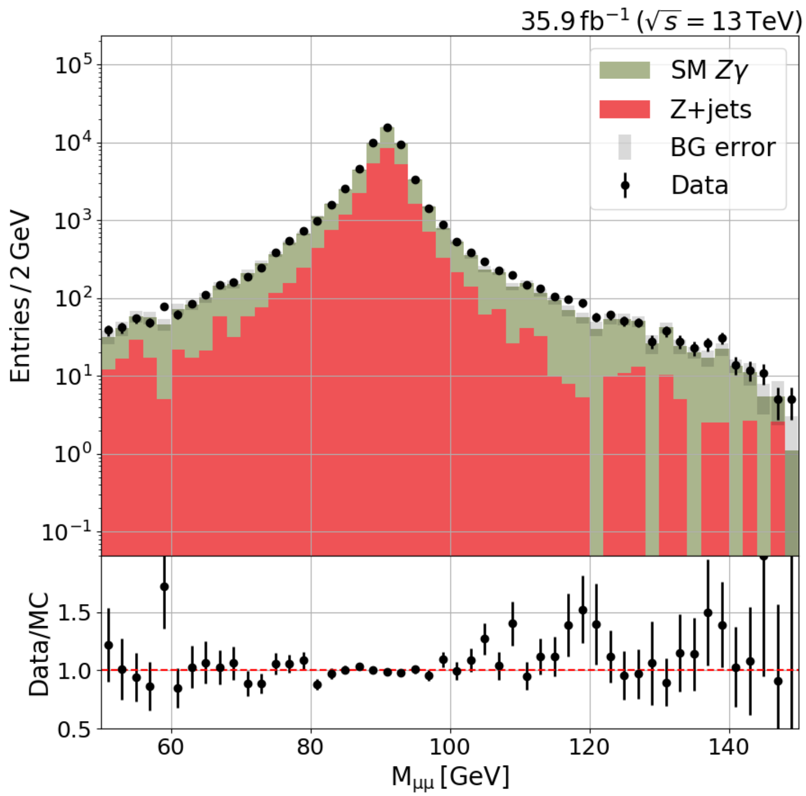
Dilepton Pair Selection

- leading $p_T^{\mu\,(e)} > 20\ (25)$ GeV
- trailing $p_T^{\mu\,(e)} > 10\ (15)$ GeV
- opposite signed
- $m_{\ell\ell} > 50$ GeV
- choose pair with invariant mass closest to Z

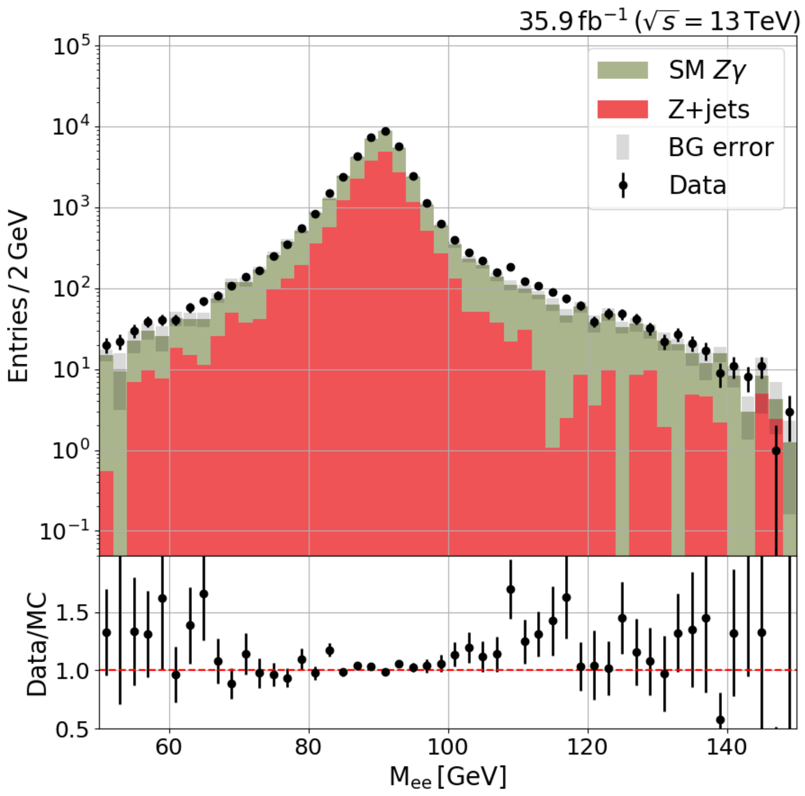
Three Body Selection

- $p_T^{\gamma} > 15$ GeV
- $\Delta R(\gamma, \ell) > 0.4$
- $E_T^{\gamma}/m_{\ell\ell\gamma} > 15/110$
- $m_{\ell\ell\gamma} \in (100, 180)$ GeV
- $m_{\ell\ell\gamma} + m_{\ell\ell} > 185$ GeV

$m_{\ell\ell}$



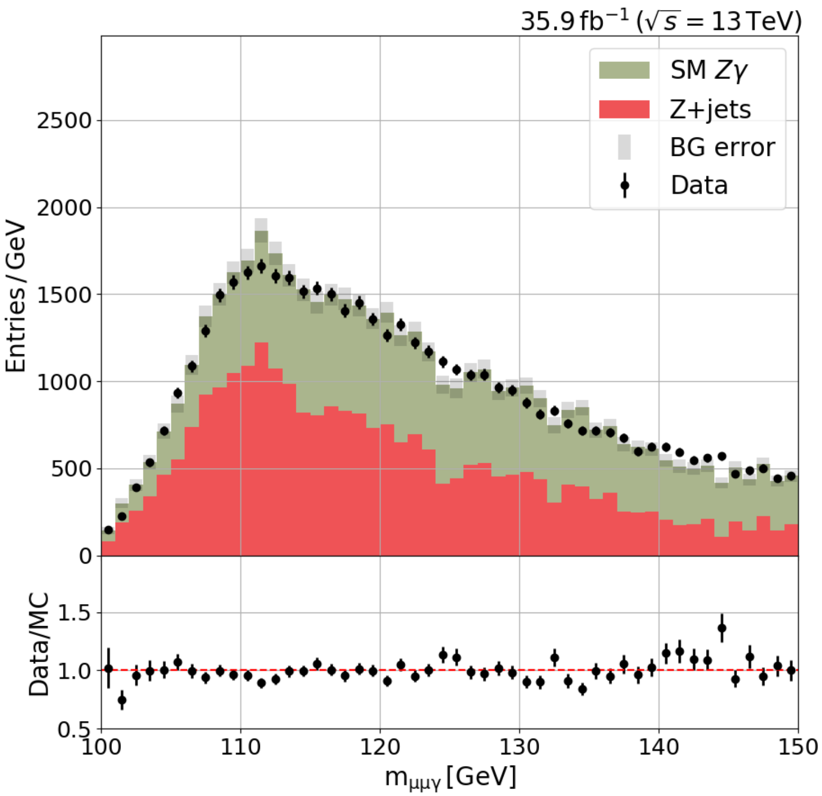
muon channel



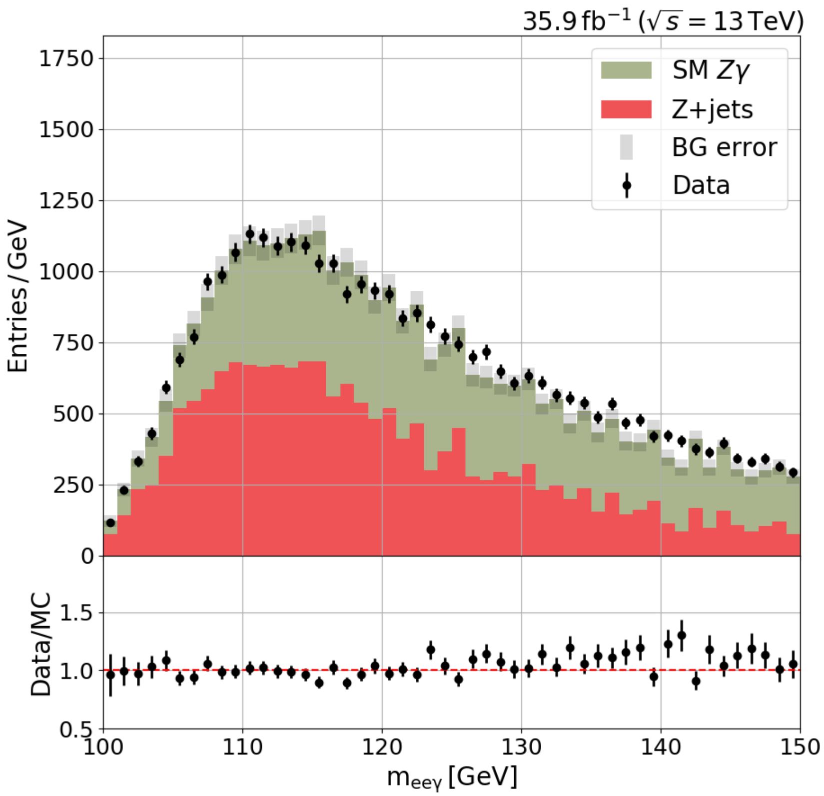
electron channel

https://drive.google.com/drive/u/1/folders/1t4OloVVAk8wsSlBlaGV13lowkUdu24PD

$m_{\ell\ell\gamma}$



muon channel



electron channel

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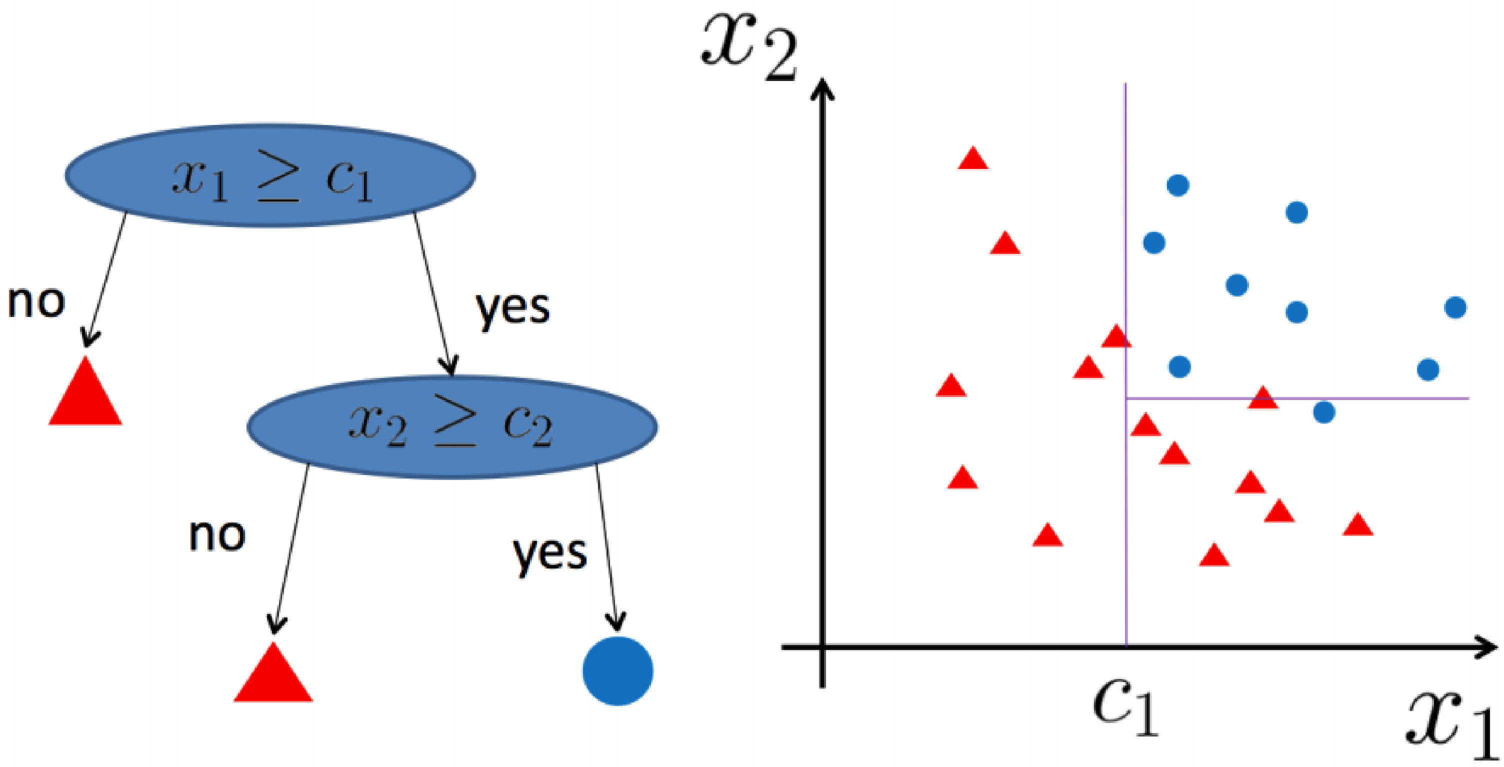
Boosted Decision Trees



- train a binary classifier (signal/background)
- output is a series of cuts in the feature space for optimal separation
- **boosting**: prioritize misclassified examples

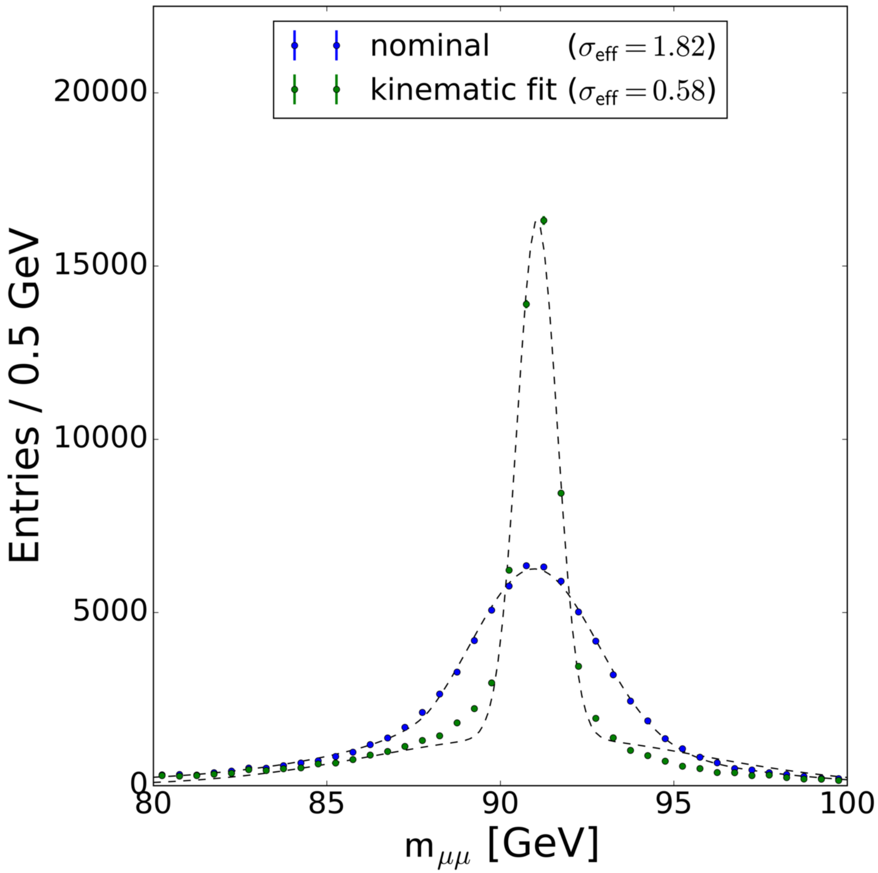
Kinematic Fits

- in general: use physics knowledge to constrain and correct object kinematics and improve resolution
- for $\mathsf{Z} \to \ell\ell$ decays, know Z mass PDF
  - $\rho_Z(m) = \frac{1}{(m^2 - m_Z^2)^2 + m^4 \Gamma_Z^2 / m_Z^2}$
  - assume PDG values for m_Z and Γ_Z
- account for the lepton energy resolution
  - $\rho_1(E_1)$ and $\rho_2(E_2)$
  - resolution functions are well-modeled by double crystal ball PDF, but parameter values depend on the detector response
  - for each lepton, obtain resolution parameters from MC via semi-parametric MVA training
- kinematic fit: maximize $\rho_1(E_1)\rho_2(E_2)\rho_Z(m) \to$ obtain corrected energies and assign to new four-momenta

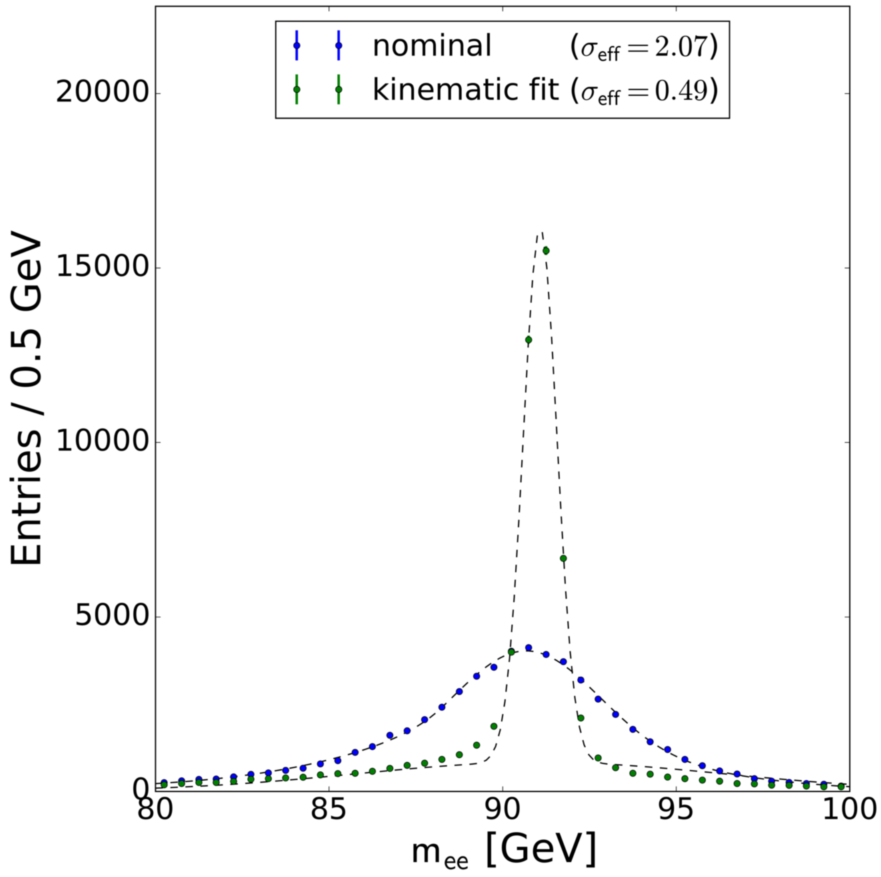
Training Procedure

- train on Z+jets MC sample
  - double lepton triggers
  - $80 < m_{\ell\ell} < 100$
  - matched to generator-level leptons from Z
- semi-parametric BDT training
  - input is a set of detector features for leptons
  - objective is a double CB fit to energy resolution in chunks of events
  - result is a mapping from detector features to the set of regressed double CB parameters

$m_{\ell\ell}$ Improvement



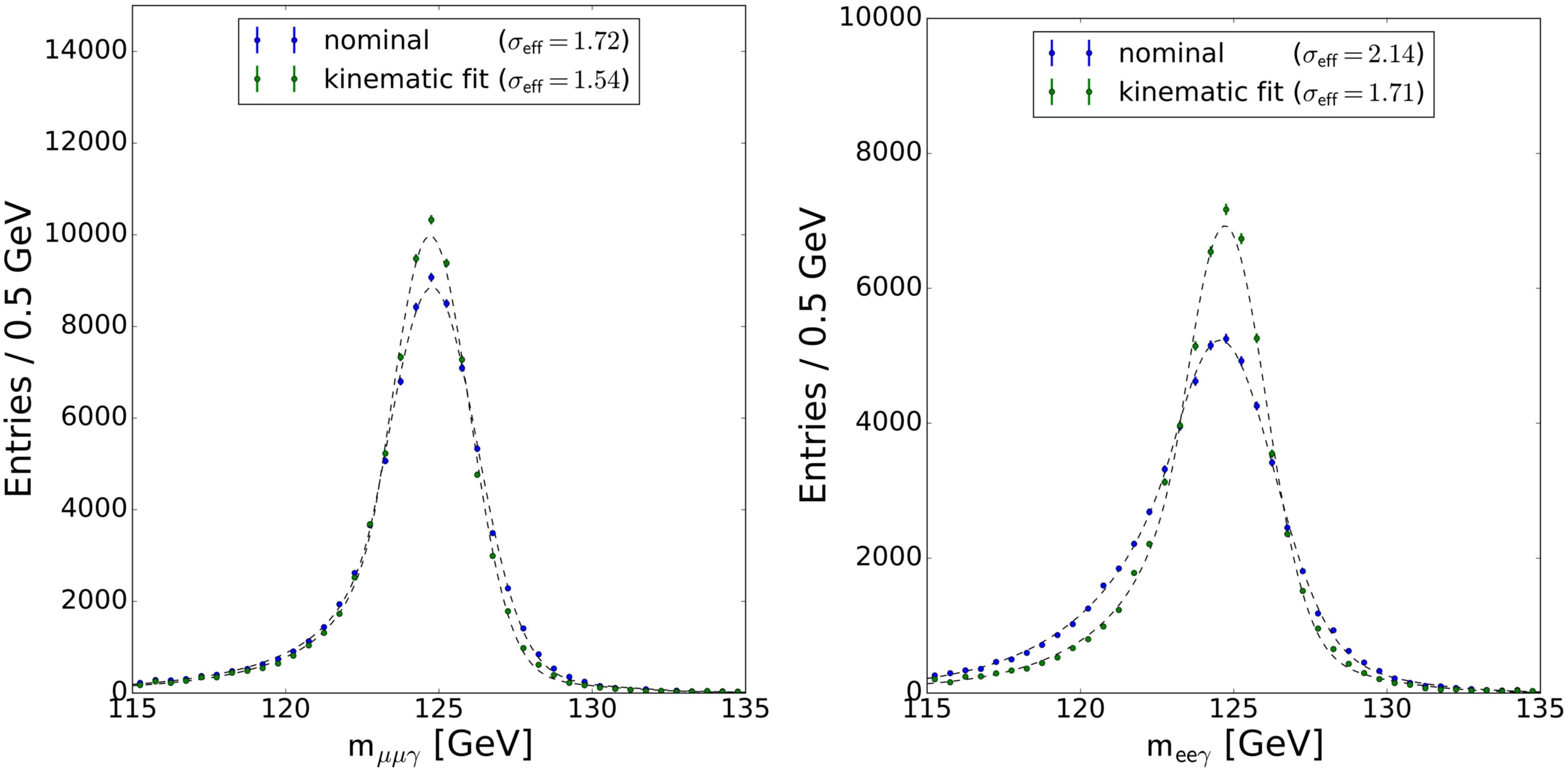
muon channel



electron channel

plots show signal events

$m_{\ell\ell\gamma}$ Improvement



muon channel

electron channel

plots show signal events

Alternative Method

- assume resolution function is Gaussian
- use Gaussian uncertainties on the measured lepton momenta
- advantages: simpler, no MVA training required, easier to assess uncertainties
- possible disadvantages: may not fully model the resolution function, may offer less power
- need to compare the two methods in more detail

$$\mathsf{L}(\mathsf{p}_\mathsf{T}^1, \mathsf{p}_\mathsf{T}^2 | \mathsf{p}_\mathsf{T}^{\mathsf{reco1}}, \sigma^1, \mathsf{p}_\mathsf{T}^{\mathsf{reco2}}, \sigma^2) = \mathcal{N}(\mathsf{p}_\mathsf{T}^{\mathsf{reco1}}; \mathsf{pT}^1, \sigma^1 \mathsf{p}_\mathsf{T}^1)\mathcal{N}(\mathsf{p}_\mathsf{T}^{\mathsf{reco2}}; \mathsf{pT}^2, \sigma^2 \mathsf{p}_\mathsf{T}^2)\mathsf{L}(\mathsf{m}_\mathsf{Z}^{\mathsf{reco}} | \mathsf{m}_\mathsf{Z})$$

Old 2016 Categorization

events

lepton tag:
additional lepton with $p_T^{e(\mu)} > 7(5)$ GeV

dijet:
two jets
$p_T^j > 30$ GeV
$m_{jj} > 500$ GeV
|zepp| < 2.5
$\Delta\phi(jj, \ell\ell\gamma) > 2.4$

boosted:
$p_T^{\ell\ell\gamma} > 60$ GeV

untagged 1:
$|\eta_\gamma| < 1.4442$
$R9_\gamma > 0.94$
$|\eta^1_{\mu(e)}| < 2.1(1.4442)$
$|\eta^2_{\mu(e)}| < 0.9(1.4442)$

untagged 2:
$|\eta_\gamma| < 1.4442$
$R9_\gamma < 0.94$
$|\eta^1_{\mu(e)}| < 2.1(1.4442)$
$|\eta^2_{\mu(e)}| < 0.9(1.4442)$

untagged 3:
$|\eta_\gamma| < 1.4442$

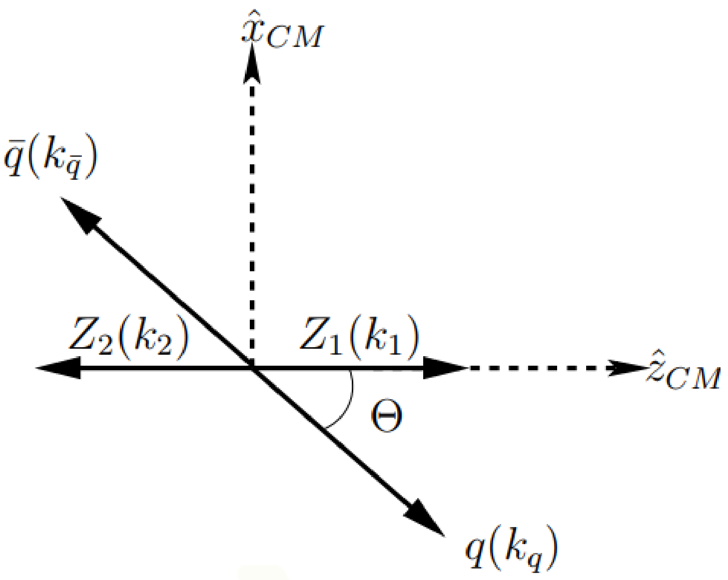
- electron: one lepton with $|\eta| > 1.4442$
- muon: both leptons $|\eta| > 0.9$ or one lepton $|\eta| > 2.1$

untagged 4:
$|\eta_\gamma| > 1.566$

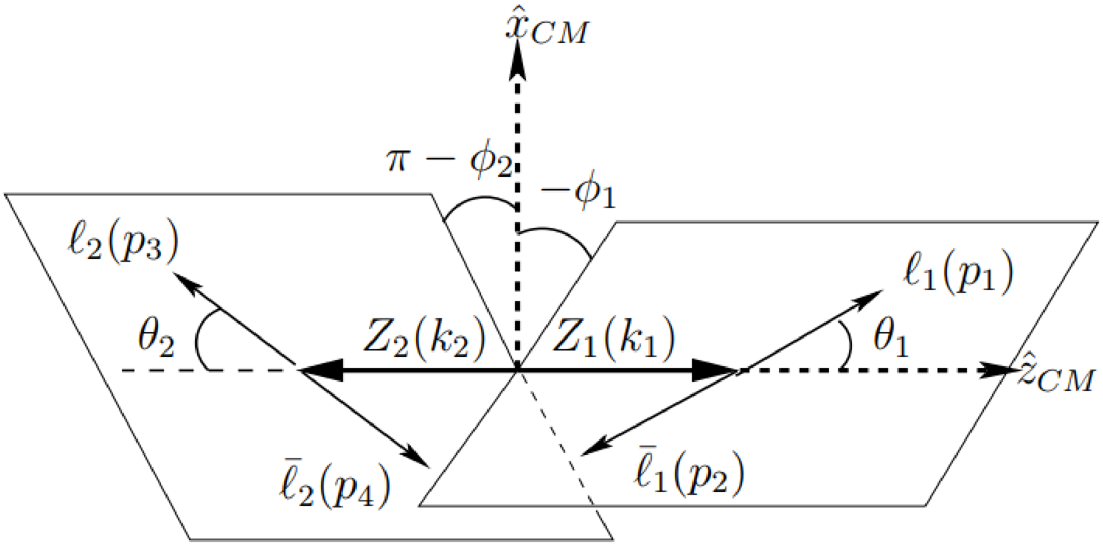
MVA Strategy

- train two discriminators
  - one kinematic discriminator for signal vs. background
  - additional discriminator for VBF vs. non-VBF production
- VBF MVA $\rightarrow$ optimized VBF categories
- kinematic MVA $\rightarrow$ optimized cuts to improve sensitivity and replace untagged categories with optimized kinematic categories

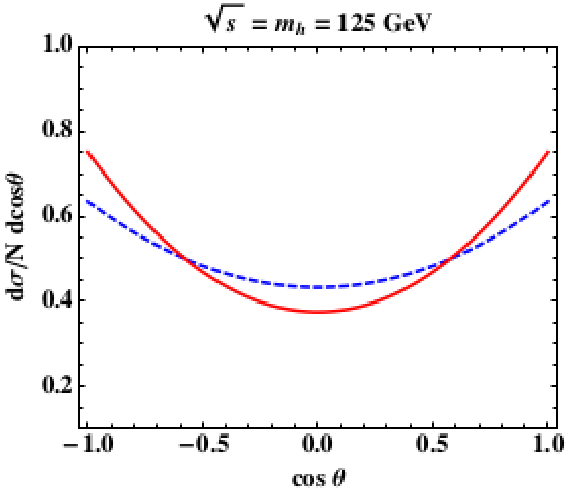
Angles



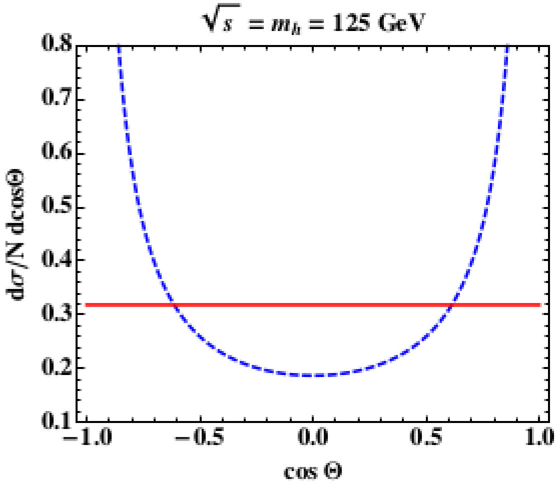
$\hat{x}_{CM}$
$\bar{q}(k_{\bar{q}})$
$Z_2(k_2)$
$Z_1(k_1)$
$\hat{z}_{CM}$
Θ
$q(k_q)$



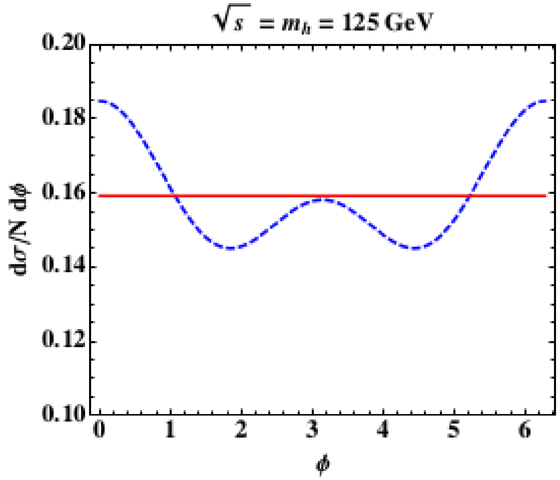
$\hat{x}_{CM}$
$\pi - \phi_2$
$-\phi_1$
$\ell_2(p_3)$
$\ell_1(p_1)$
θ_2
$Z_2(k_2)$
$Z_1(k_1)$
θ_1
$\hat{z}_{CM}$
$\bar{\ell}_2(p_4)$
$\bar{\ell}_1(p_2)$



$\sqrt{s} = m_h = 125$ GeV
$d\sigma/N\ d\cos\theta$
$\cos\theta$

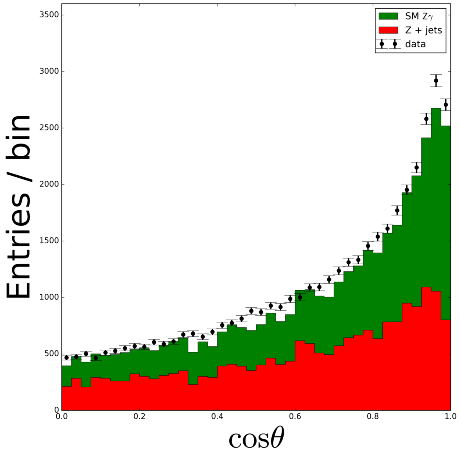


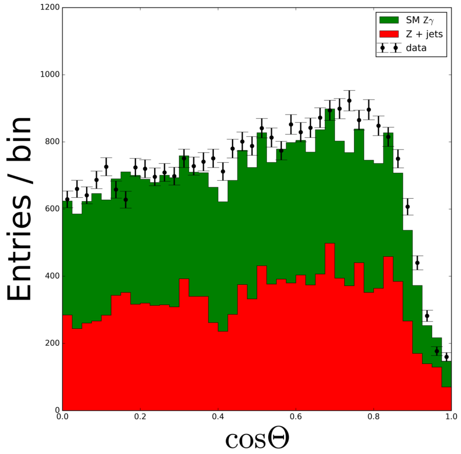
$\sqrt{s} = m_h = 125$ GeV
$d\sigma/N\ d\cos\Theta$
$\cos\Theta$

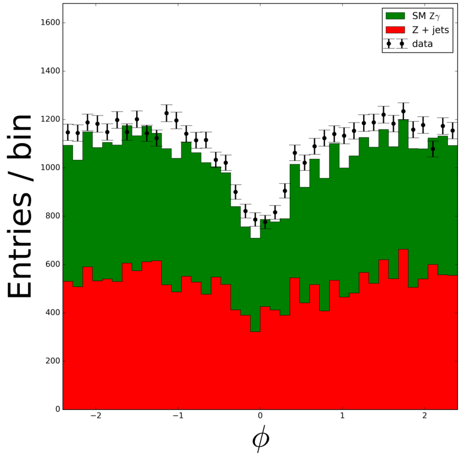


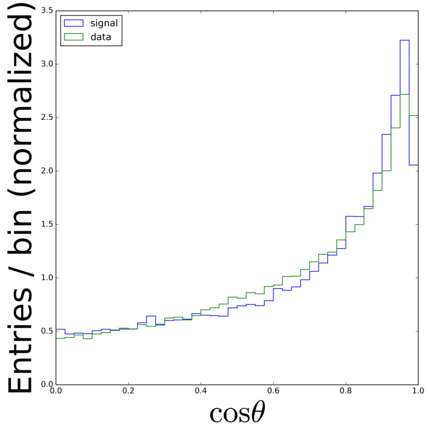
$\sqrt{s} = m_h = 125$ GeV
$d\sigma/N\ d\phi$
ϕ

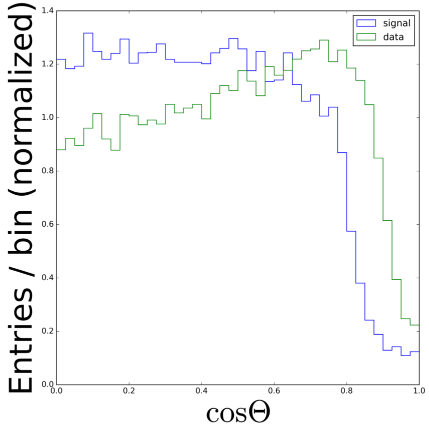
Reconstructed Angles

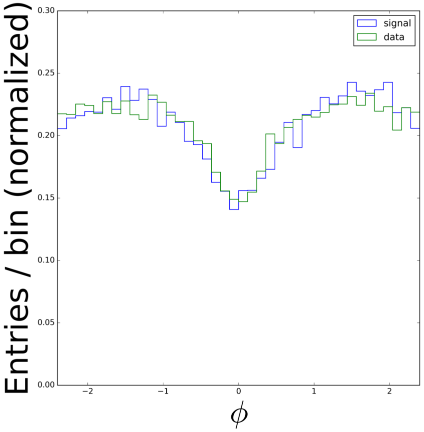




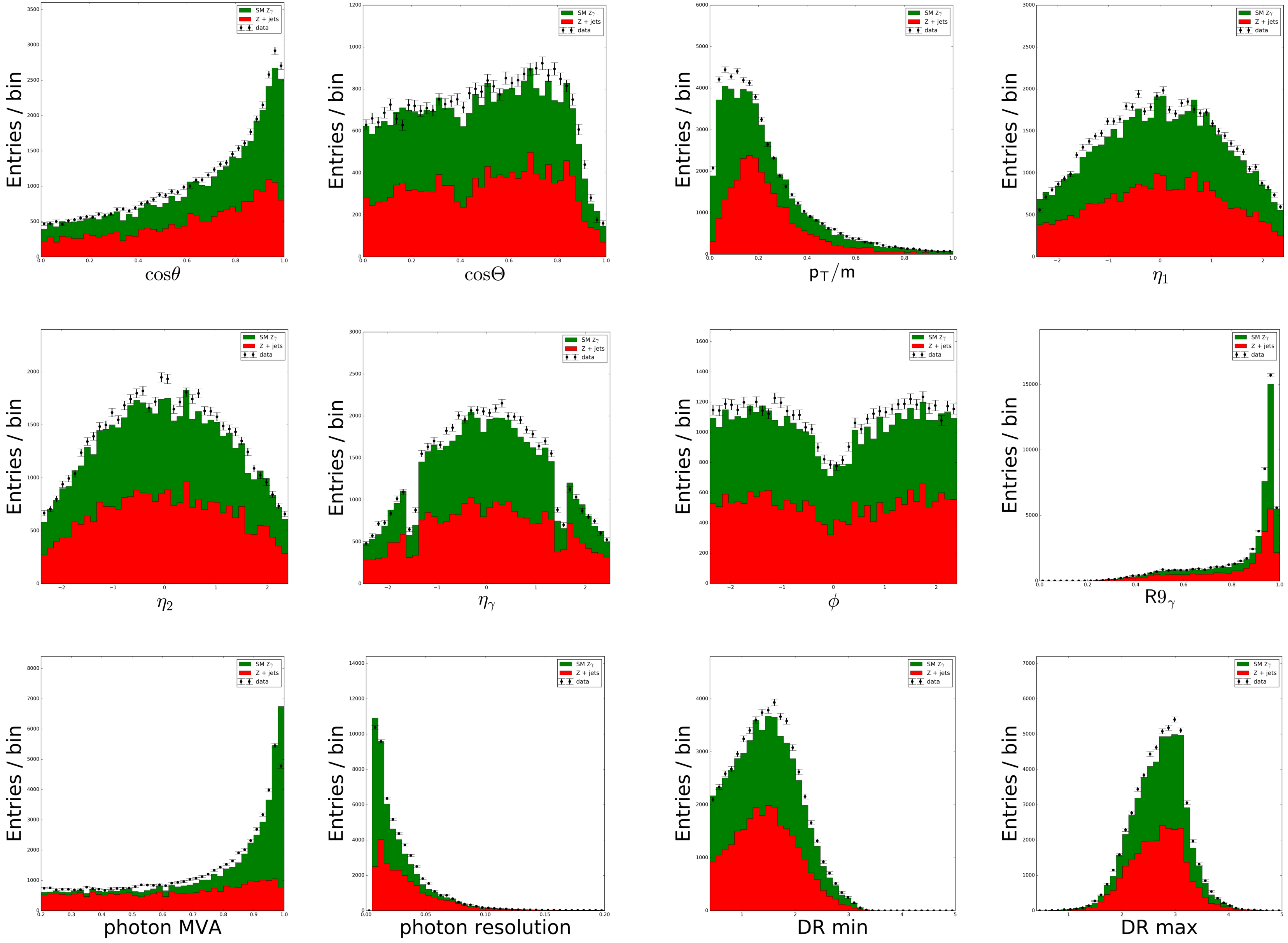




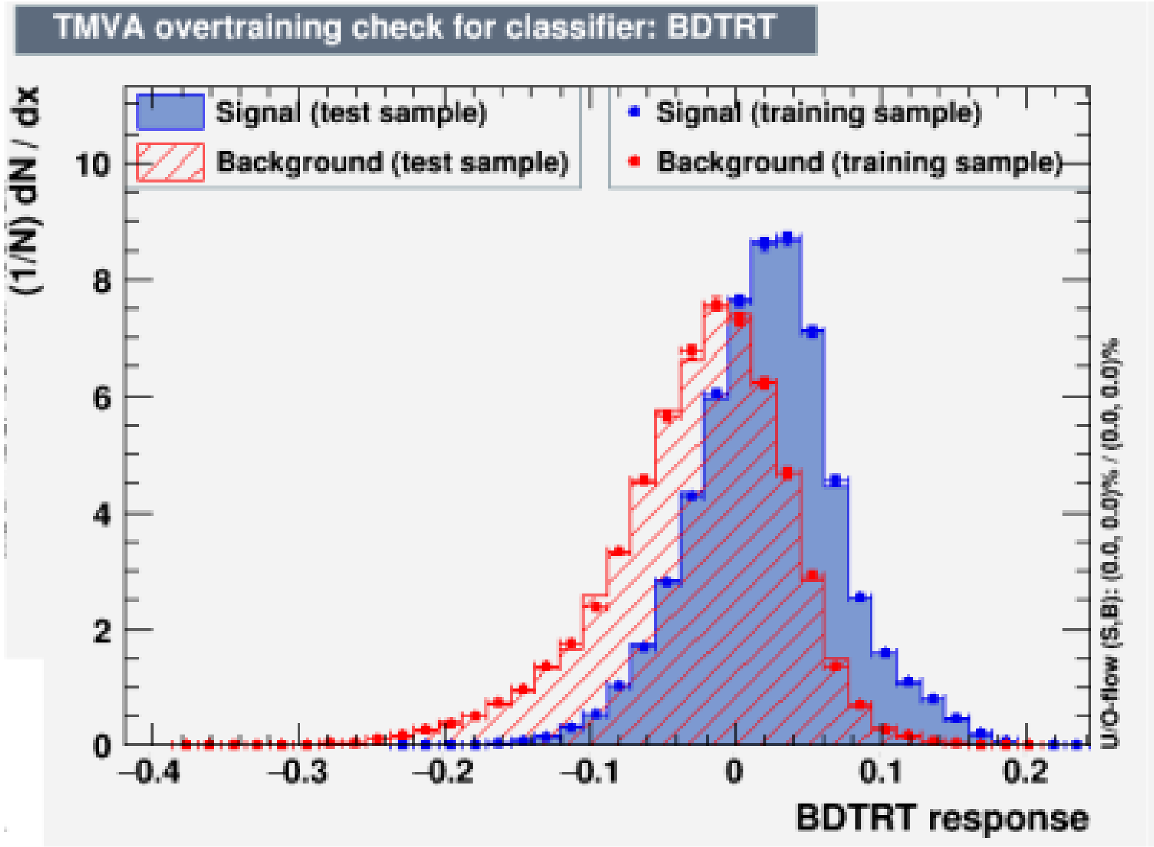




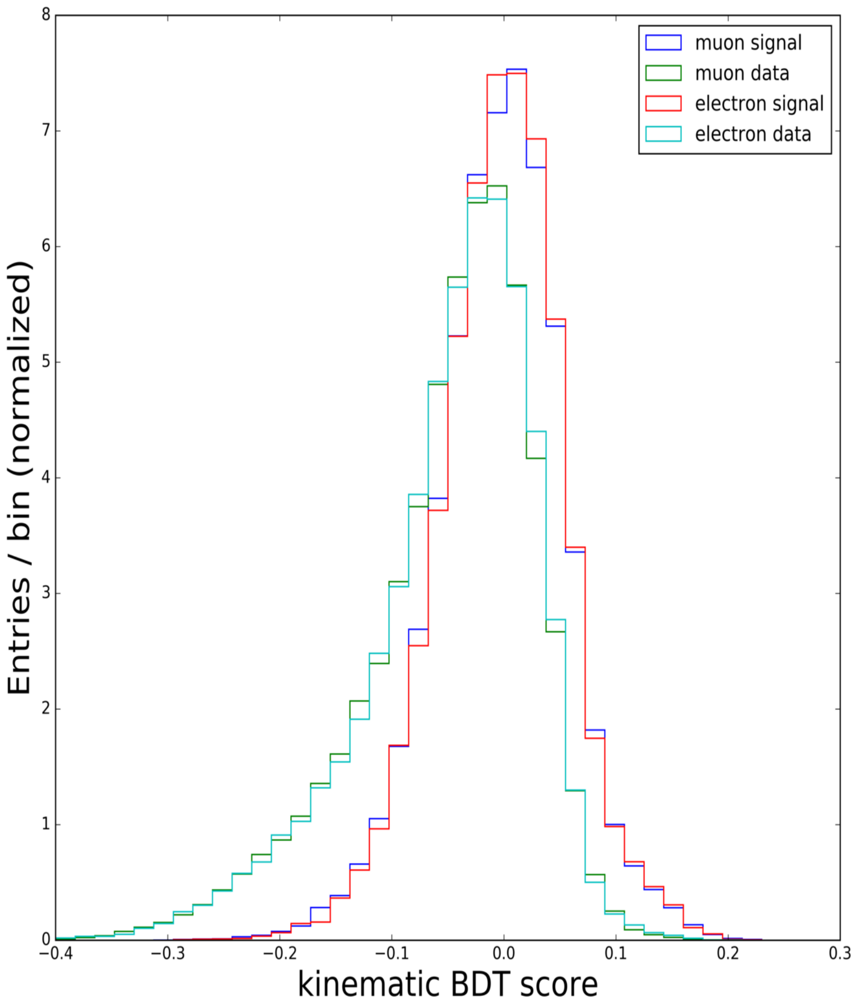
Kinematic BDT Inputs

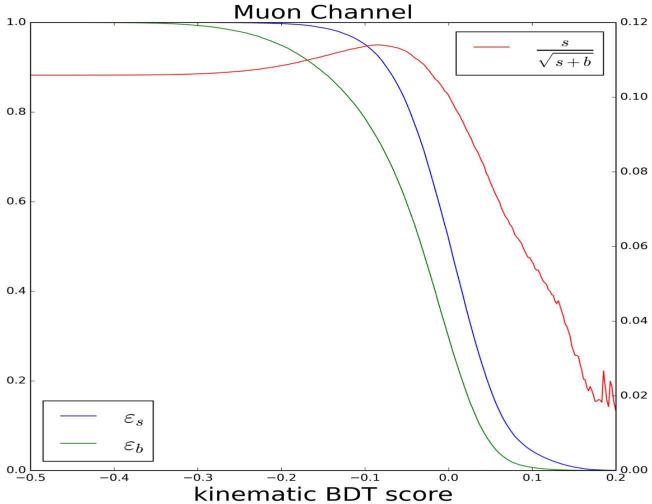


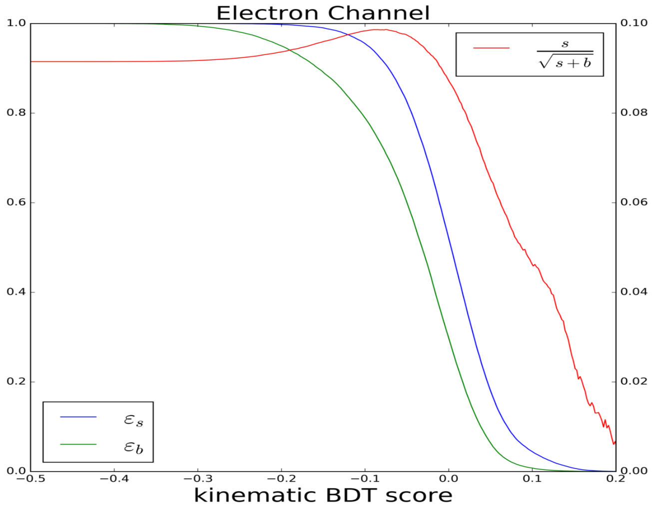
Kinematic BDT Training



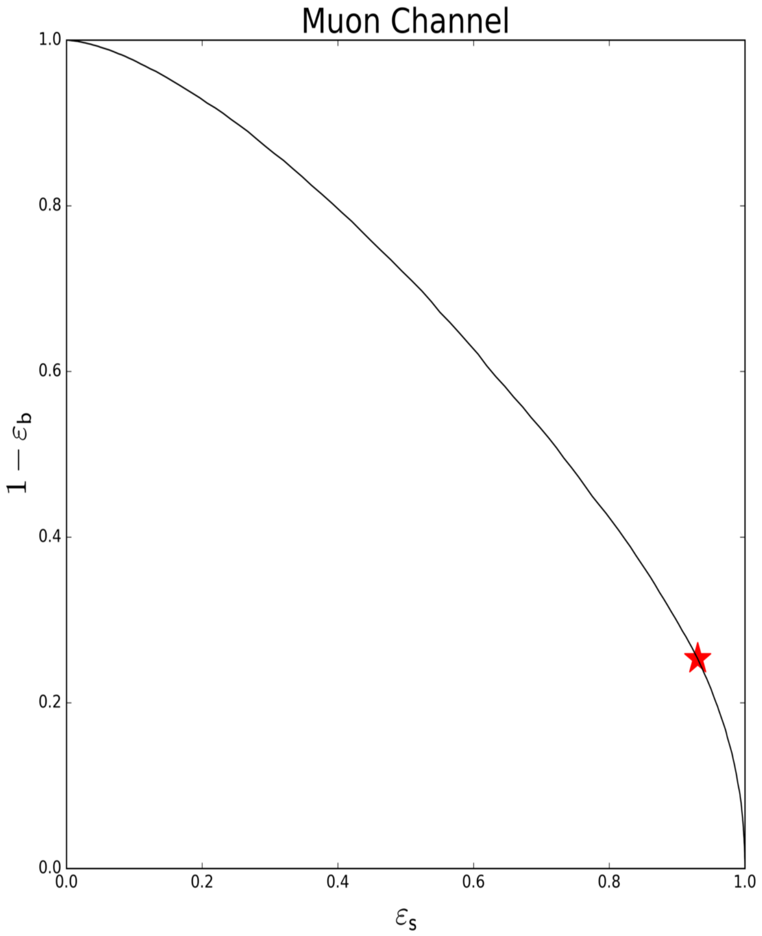
Kinematic BDT Output

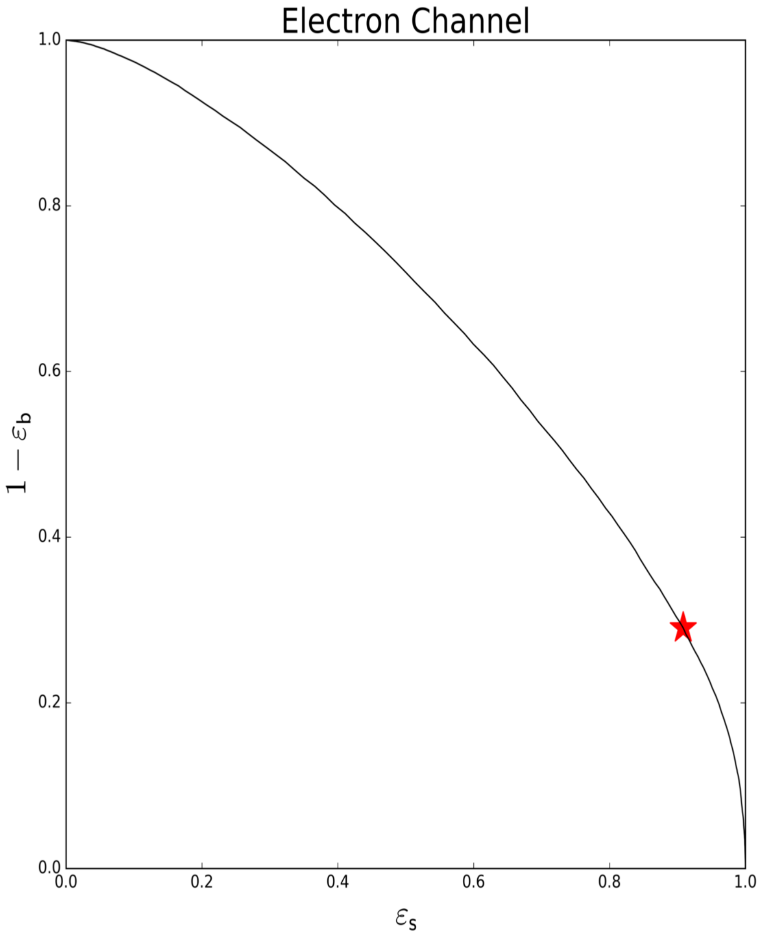




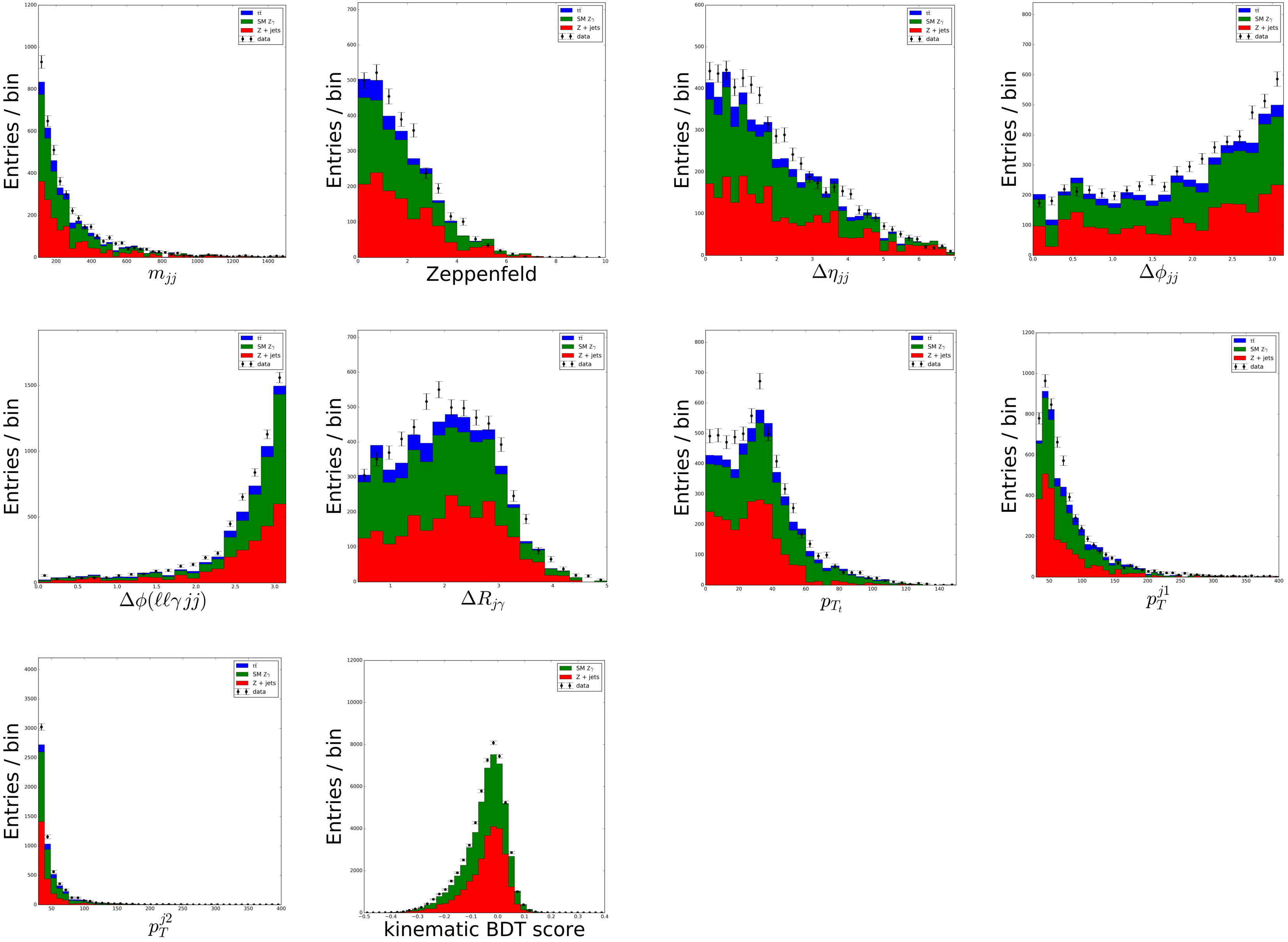


Kinematic BDT Power

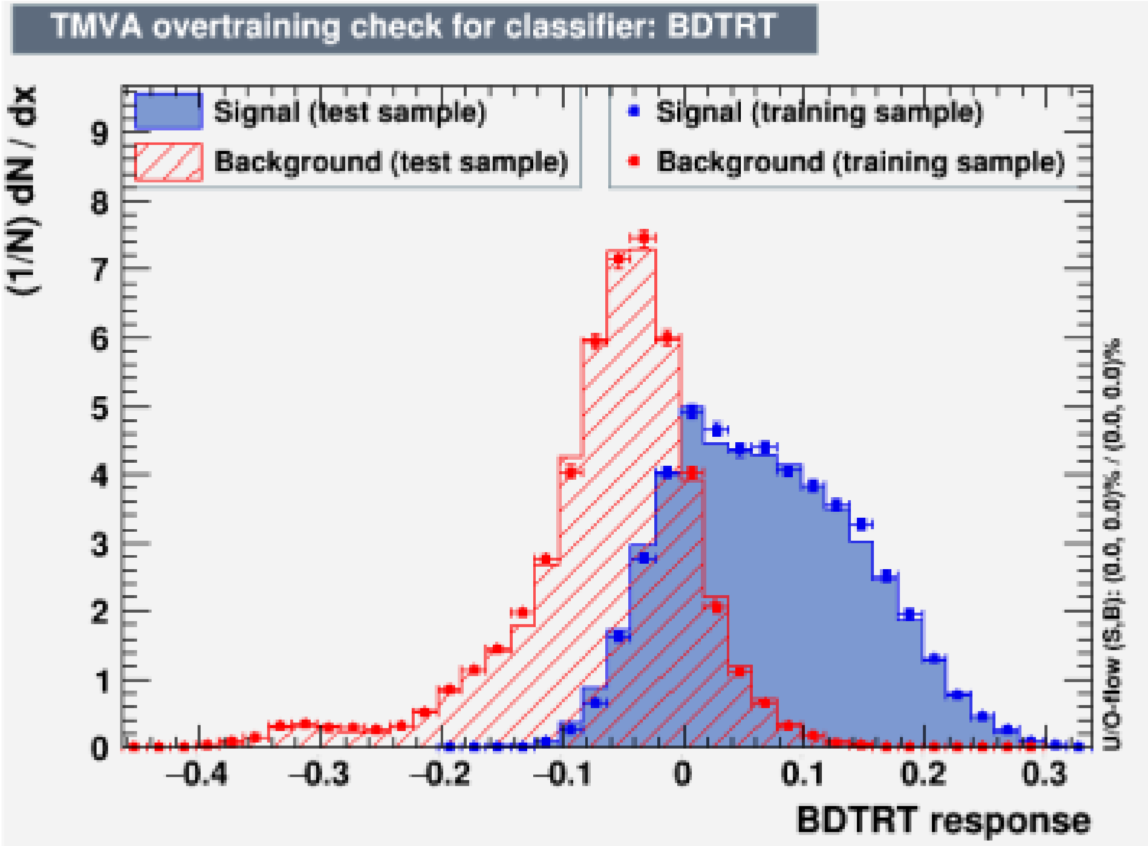




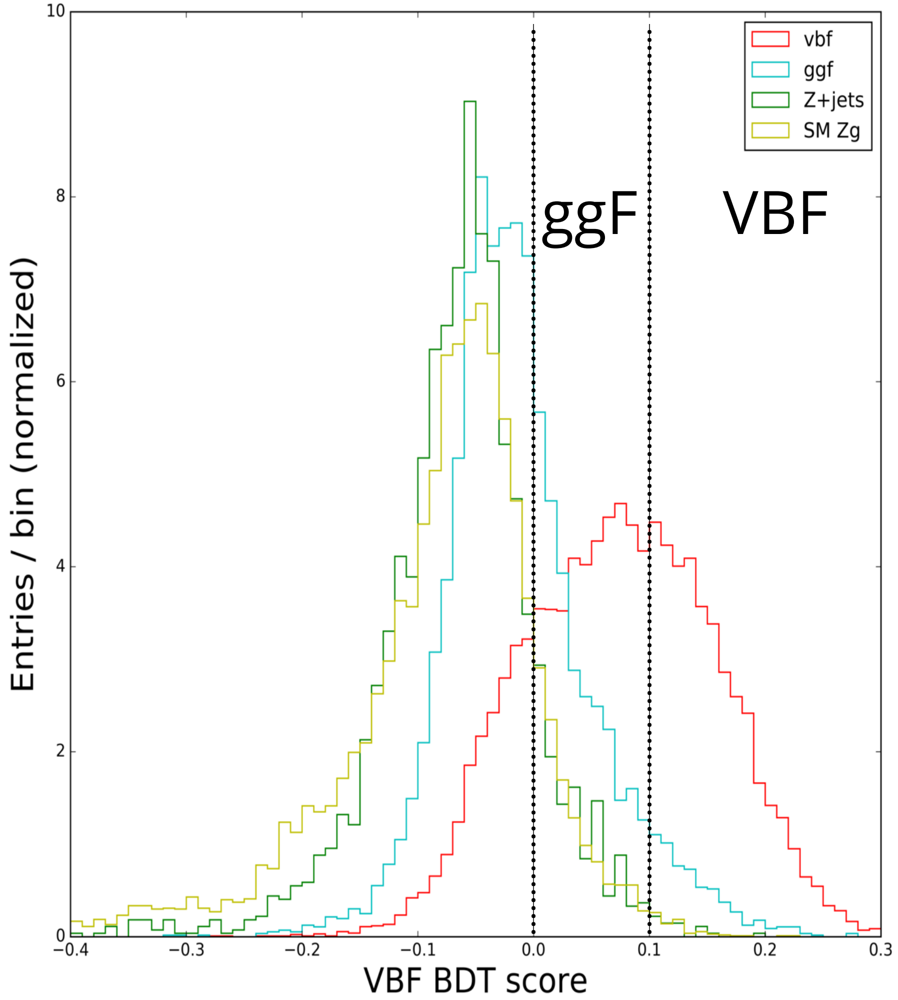
VBF BDT Inputs



VBF BDT Training

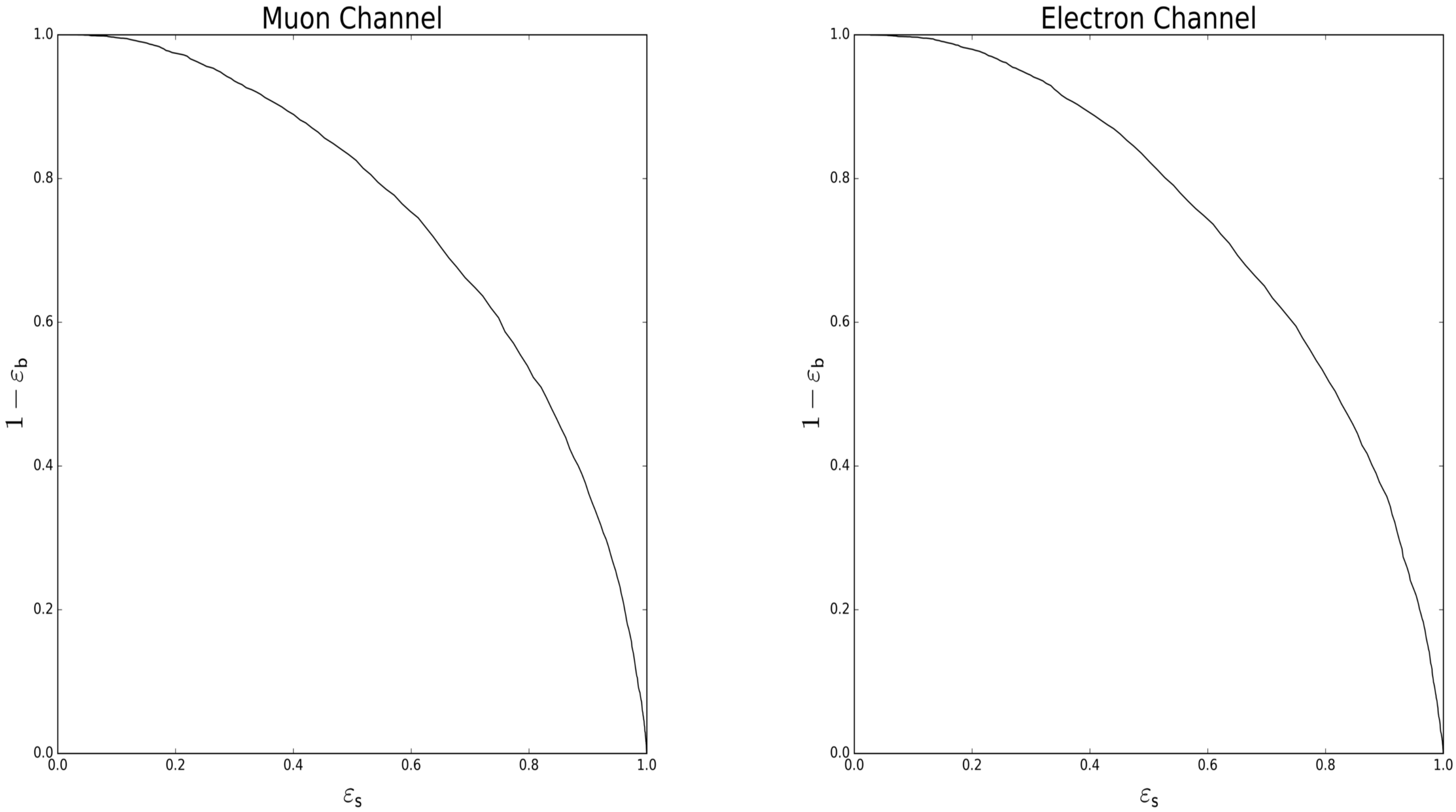


VBF BDT Output



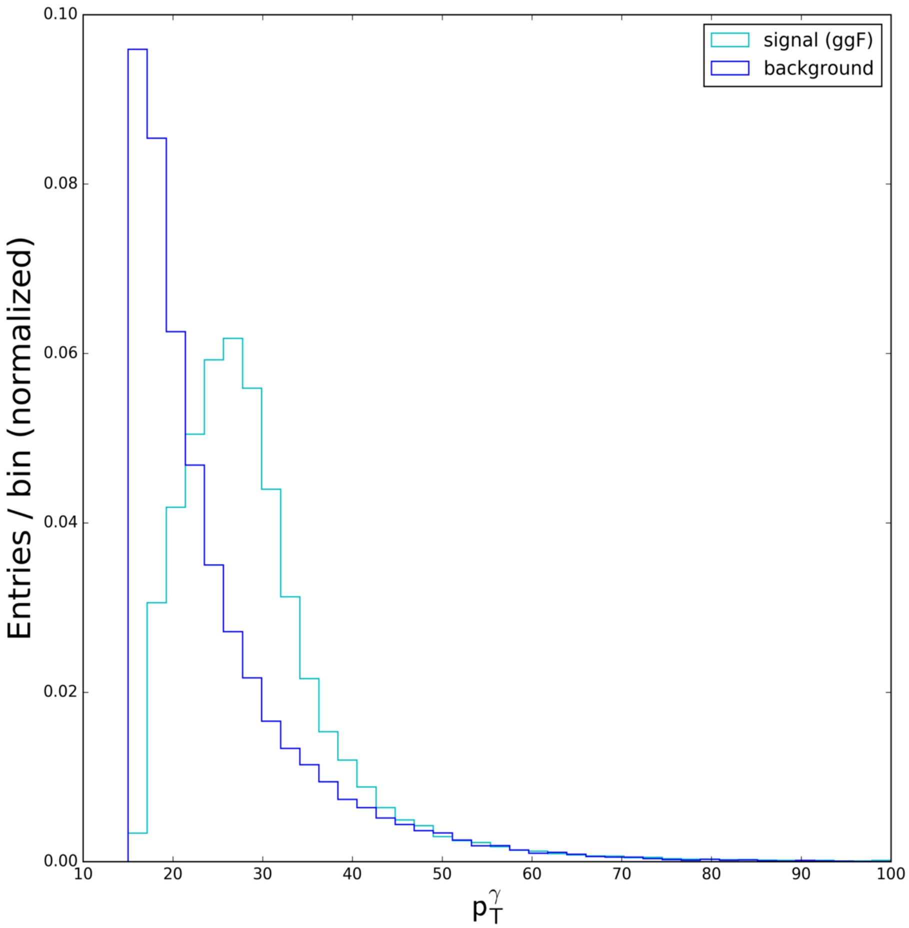
- based on the output, define two regions:
  - VBF-enriched region
  - ggF-enriched region
- VBF: score > 0.1
- ggF: -0.01 < score < 0.1

VBF BDT Power



Photon p_T Discrimination

- plotted after kinematic BDT cuts
- can we leverage this discrimination?
- baseline approach: split untagged categories 1 and 2
  - $p_T^\gamma > 25$ GeV sub-category
  - $p_T^\gamma < 25$ GeV sub-category
- makes minimal use of shape information
  - ie: we can do better



2D Fit Idea

$$\mathcal{L}_{\mathsf{2D}}(\mathsf{m}_{\ell\ell\gamma},\, \mathsf{p}_{\mathsf{T}}^{\gamma}) = \mathcal{L}(\mathsf{m}_{\ell\ell\gamma})\mathcal{L}(\mathsf{p}_{\mathsf{T}}^{\gamma}|\mathsf{m}_{\ell\ell\gamma})$$

mass PDF

histogram template

- use a conditional PDF
  - 2D histogram template
  - templates are taken from signal and background MC
  - solves the problem of correlation
  - each mass bin normalized to 1
- no need to change the mass modeling!
- still implementing; work in progress

New Categorization

- lepton tag category unchanged
- loosen dijet preselection and split into two categories
  - VBF-enriched
  - ggF-enriched
- remaining events:
  - cut on kinematic BDT score first
    - electron: Kin BDT > -0.075
    - muon: Kin BDT > -0.085
  - define four categories based on signal efficiency
    - 95%, 70%, 40%, else

New Categorization

events

lepton tag:
additional lepton with $p_T^{e(\mu)} > 7(5)$ GeV

dijet:
two jets
$p_T^j > 30$ GeV
$\Delta R(j, \ell/\gamma) > 0.4$

dijet 1:
VBF BDT > 0.1

dijet 2:
-0.01 < VBF BDT < 0.1

untagged 1:
electron: Kin BDT $\in$ (-0.075, -0.06)
muon: Kin BDT $\in$ (-0.085, -0.0665)

untagged 2:
electron: Kin BDT $\in$ (-0.06, 0.016)
muon: Kin BDT $\in$ (-0.0665, -0.02)

untagged 3:
electron: Kin BDT $\in$ (0.016, 0.022)
muon: Kin BDT $\in$ (-0.02, 0.019)

untagged 4:
electron: Kin BDT > 0.022
muon: Kin BDT > 0.019

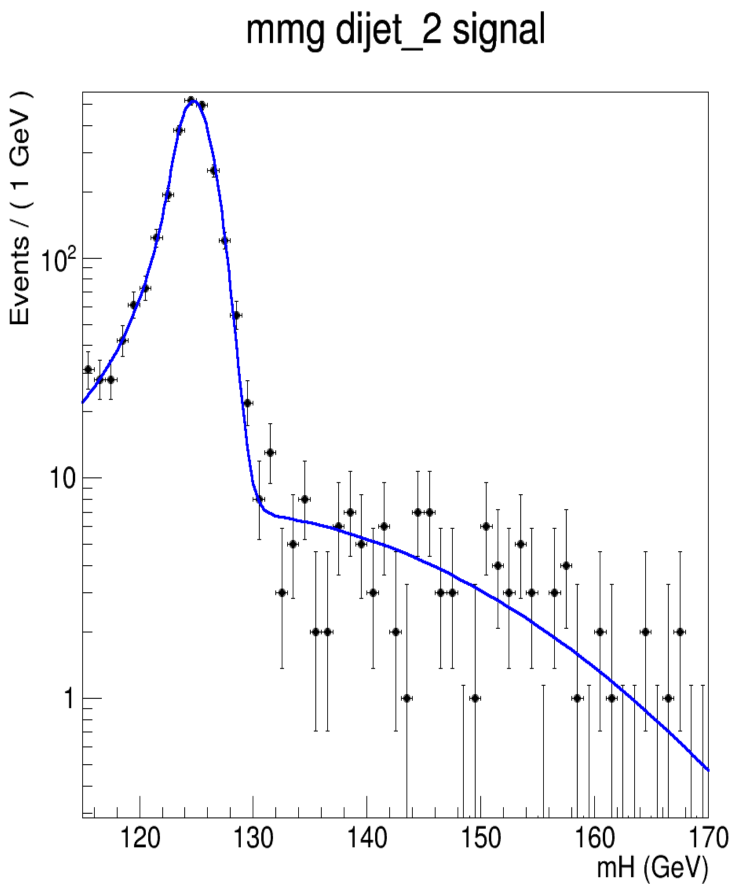
Signal Modeling

signal mass: crystal ball + gaussian mixture

Crystal Ball PDF

$$f_1(m;\mu,\sigma,\alpha,n) = N \begin{cases} \exp\left(-\frac{(m-\mu)^2}{2\sigma^2}\right) & \frac{m-\mu}{\sigma} > -\alpha \\ A\left(B - \frac{m-\mu}{\sigma}\right)^{-n} & \frac{m-\mu}{\sigma} \leq -\alpha \end{cases}$$

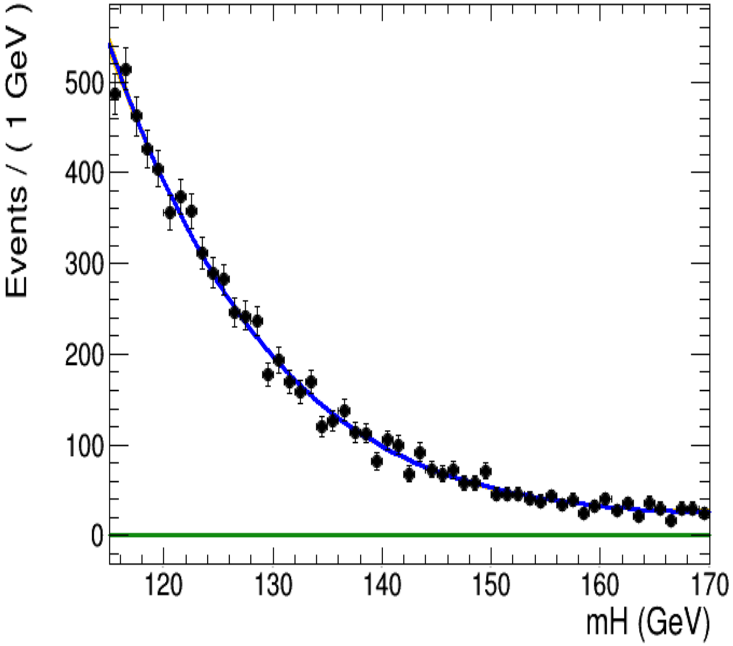
$$A = \left(\frac{n}{|\alpha|}\right)^n \exp\left(-\frac{|\alpha|^2}{2}\right)$$
$$B = \frac{n}{|\alpha|} - |\alpha|$$
$$N = \frac{1}{\sigma(C+D)}$$
$$C = \frac{n}{|\alpha|}\frac{1}{n-1}\exp\left(-\frac{|\alpha|^2}{2}\right)$$
$$D = \sqrt{\frac{\pi}{2}}\left(1 + erf\left(\frac{|\alpha|^2}{2}\right)\right)$$



example fit to signal MC

Background Modeling

- use data to model the background shape
- fit functions:
  - lepton and dijet categories: order 1 power law
  - untagged categories: order 4 Bernstein polynomial
- published 2016 analysis carried out F-tests and bias studies
  - this will need to be repeated for updated selection and categorization



example fit

Uncertainties

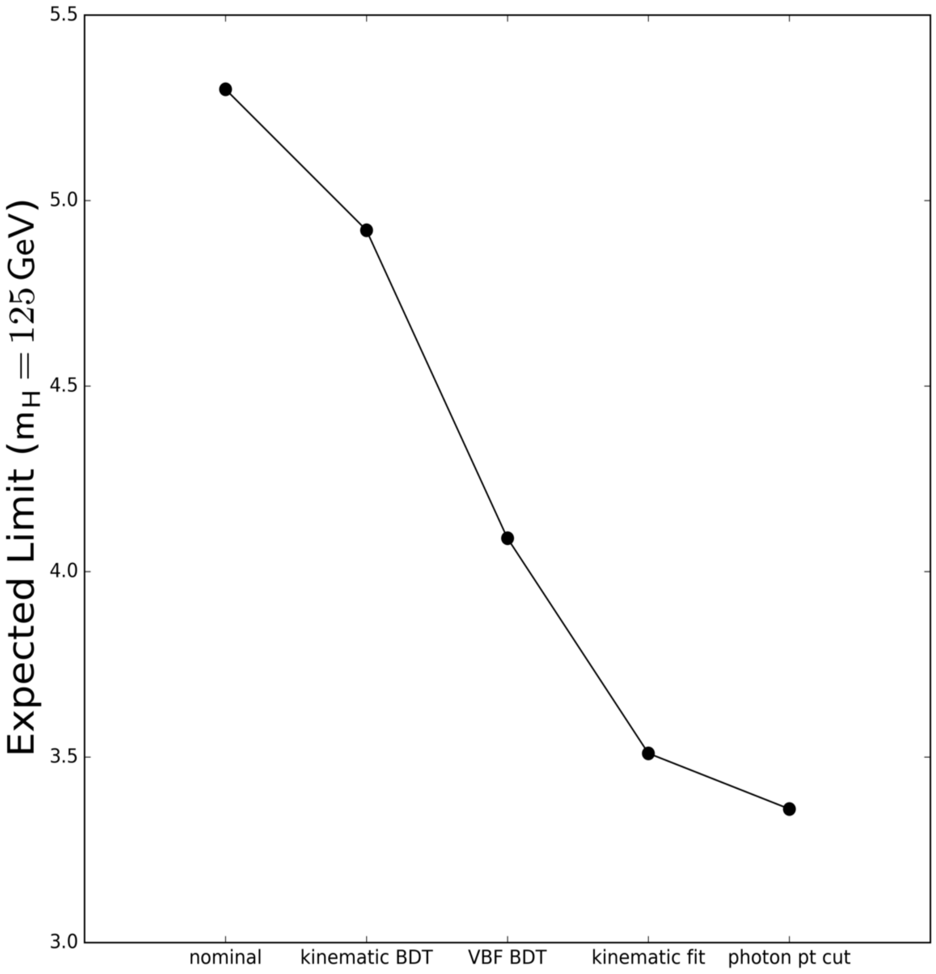
- main sources of systematic uncertainty:
  - theory (scale and PDF)
  - luminosity
  - MC corrections and scale factors
- evaluated in detail for each category in the published 2016 analysis
- need to be rederived for the new analysis scheme
  - **this is one of the major remaining pieces of work**
- systematic uncertainties not accurately accounted for in today's results

Source	Systematics
Theory	
- Gluon-gluon fusion cross section (scale)	$\pm$3.9%
- Gluon-gluon fusion cross section (PDF)	$\pm$3.2%
- Vector boson fusion cross section (scale)	+0.4% -0.3%
- Vector boson fusion cross section (PDF)	$\pm$2.1%
- W associate production (scale)	+0.5% -0.7%
- W associate production (PDF)	$\pm$1.9%
- Z associate production (scale)	+3.8% -3.1%
- Z associate production (PDF)	$\pm$1.6%
- Top pair associate production (scale)	+5.8% -9.2%
- Top pair associate production (PDF)	$\pm$3.6%
Branching fraction	$\pm$5.71%
Luminosity	2.5%
Lepton identification (ID) and isolation:	
- Muon channel	$\sim$ 0.6%
- Electron channel	$\sim$ 1.2%
Photon ID and isolation:	
- Muon channel	$\sim$ 2.3%
- Electron channel	$\sim$ 2.2%
PU reweighting:	
- Muon channel	0.6%
- Electron channel	0.9%
R9 reweighting:	
- Muon channel	6.5%
- Electron channel	6.8%
Trigger	
- Muon	1.3%
- Electron	$\sim$ 1%
Signal	
- Signal mean in muon channel	0.04%
- Signal resolution in muon channel	4%
- Signal mean in electron channel	0.15%
- Signal resolution in electron channel	4%
JEC	
- Muon	2.5%
- Electron	2.7%
JER	
- Muon	0.3%
- Electron	0.3%
Underline Event/Parton Shower	
- Muon	3%
- Electron	3%

Combined Fit Method

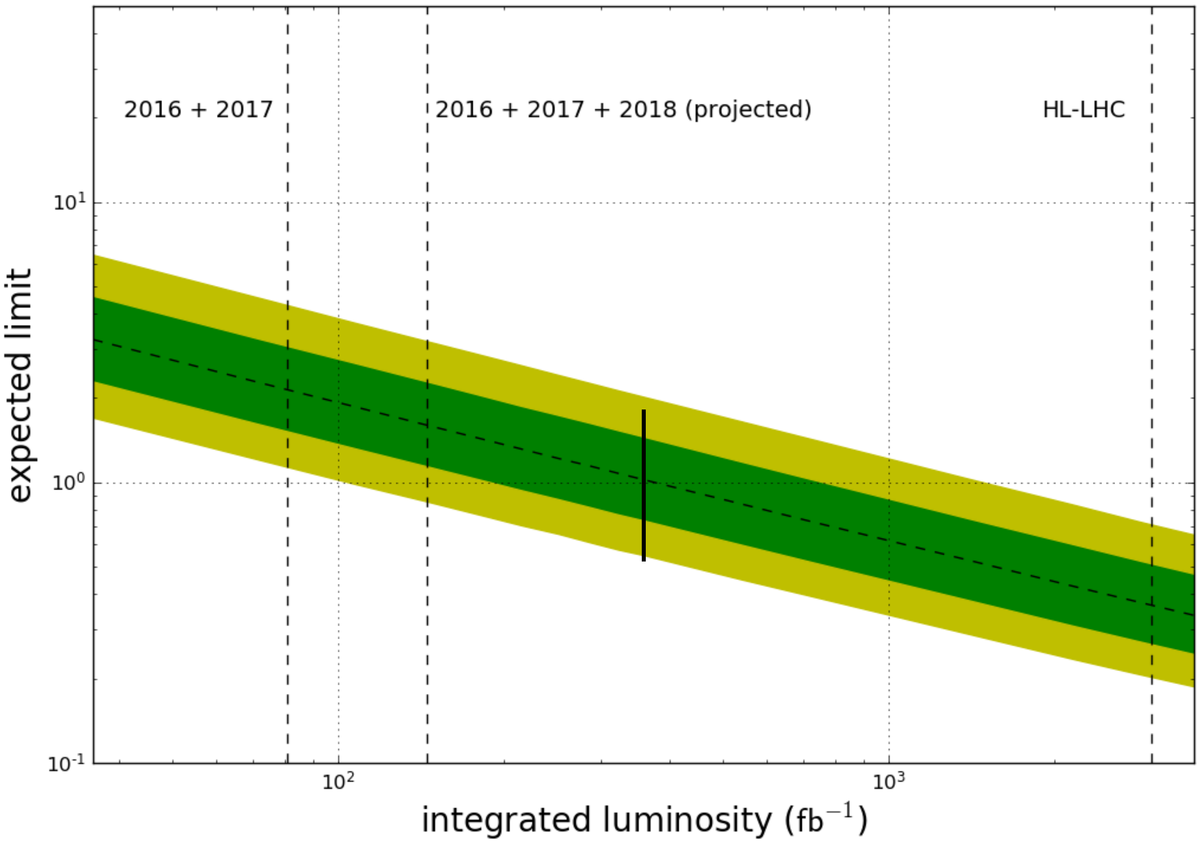
- obtain signal yields and signal shape for each category
- simultaneous fit to the data in all categories
  - parameter of interest: H $\rightarrow$ Zγ production rate μ
  - $\mu = 1$: SM expectation
  - shape parameters and uncertainties are nuisance parameters in the fit
- evaluate limits using asymptotic formulas for a profile likelihood upper limit test statistic

Results and Improvement



- kinematic BDT: 7%
- VBF BDT + cats: 17%
- kinematic fit: 14%
- photon cut: 4%
- **net: 37%**

Projected Limits



- as we approach 1, should also look at discovery sensitivity σ for a discovery test statistic
- to be added in future projections

Summary

- status of CMS $H \to Z\gamma$ search
- significant optimizations with respect to previous analysis methods
- currently project discovery-level sensitivity in Run III of the LHC, but CMS+ATLAS combination may be able to make a statement with Run II data alone
- my thesis will be the complete, optimized analysis at 13 TeV for the full Run II CMS data (~150/fb)

Backup

Variable Definitions

- photon r9: ratio of the energy of the most energetic 3x3 ECAL crystal array to the supercluster energy
- Zeppenfeld: $\eta_{\ell\ell\gamma} - (\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})/2$
- $\mathrm{p}_\mathrm{T}^\mathrm{t}$: $2|\mathrm{p}_\mathrm{Z}^\mathrm{x}\mathrm{p}_\gamma^\mathrm{y} - \mathrm{p}_\gamma^\mathrm{x}\mathrm{p}_\mathrm{Z}^\mathrm{y}|/\mathrm{P}_\mathrm{T}^\mathrm{h}$

Datasets and Triggers

Data

- 2016 February 3 re-miniaod
- $\mathcal{L} = 35.9\ fb^{-1}$
- DoubleMuon datastream
  - double muon trigger (17, 8) with DZ filter
- DoubleEG datastream
  - double electron trigger (23, 12) with DZ filter

Simulation

- DYJets M-50 amc@nlo
- $Z\gamma \rightarrow \ell\ell\gamma$ amc@nlo
- ggf $H \rightarrow Z\gamma$
- vbf $H \rightarrow Z\gamma$

Object Selection

Muons

- $H \to ZZ$ ID
  - $|d_{xy}| < 0.5$ cm; $|d_z| < 1.0$ cm
  - $SIP_{3D} < 4$
- relative PF isolation < 0.35
- L1EMTF fix
  - remove events having muons in same endcap region with $\Delta\phi < 70^\circ$
- $|\eta| < 2.4$
- $p_T > 5$ GeV

Electrons

- $H \to ZZ$ MVA ID (90% WP)
  - relative PF isolation < 0.35
- $|d_{xy}| < 0.5$ cm; $|d_z| < 1.0$ cm
- $SIP_{3D} < 4$
- $|\eta| < 2.5$
- $p_T > 5$ GeV

Photons

MVA ID (90% WP)

conversion-safe electron veto

$|\eta| < 1.4442 \cup 1.566 < |\eta| < 2.5$

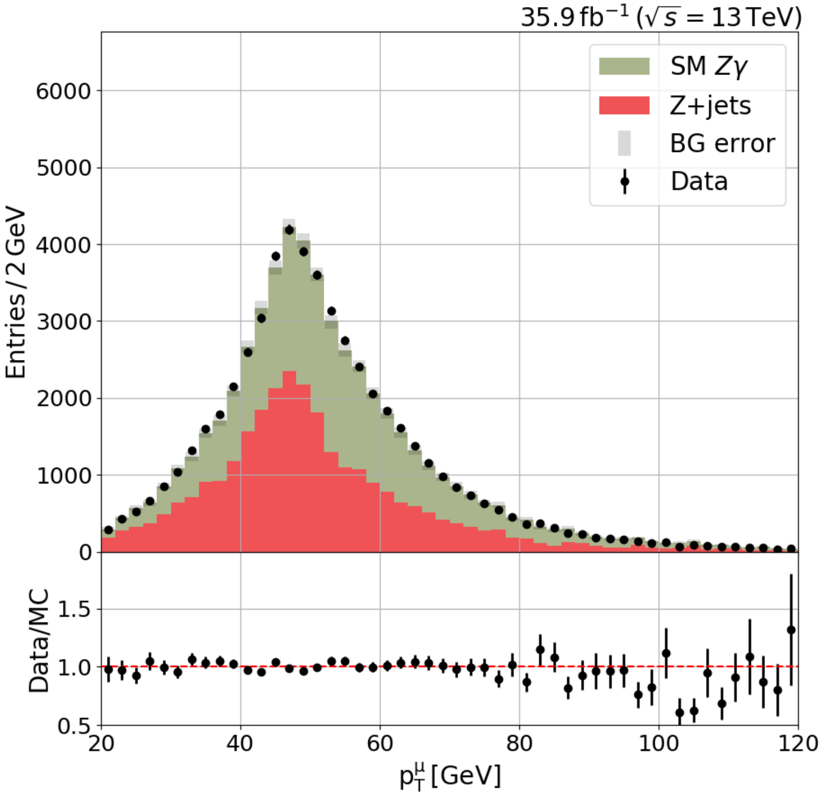
$p_T > 15$ GeV

Event Yields

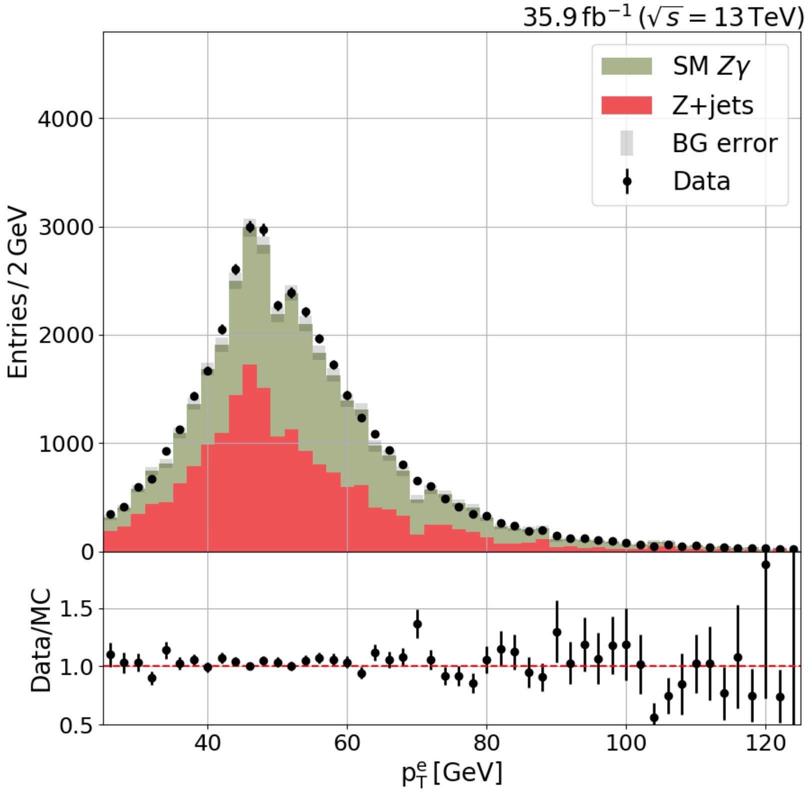
	muon	**electron**
ggF signal	28.02	20.50
VBF signal	2.18	1.60
WH signal	0.72	0.54
ZH signal	0.61	0.45
ttH signal	0.39	0.29
data	55,408	39,649
background	52,311.4	36,967.7

Kinematic Distributions

Leading Lepton



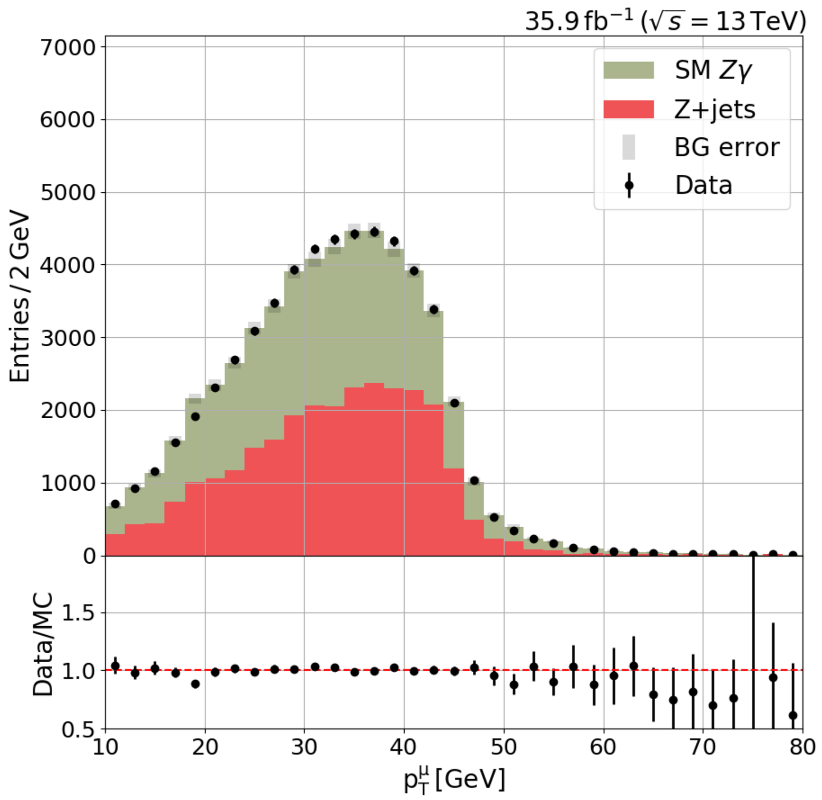
muon channel



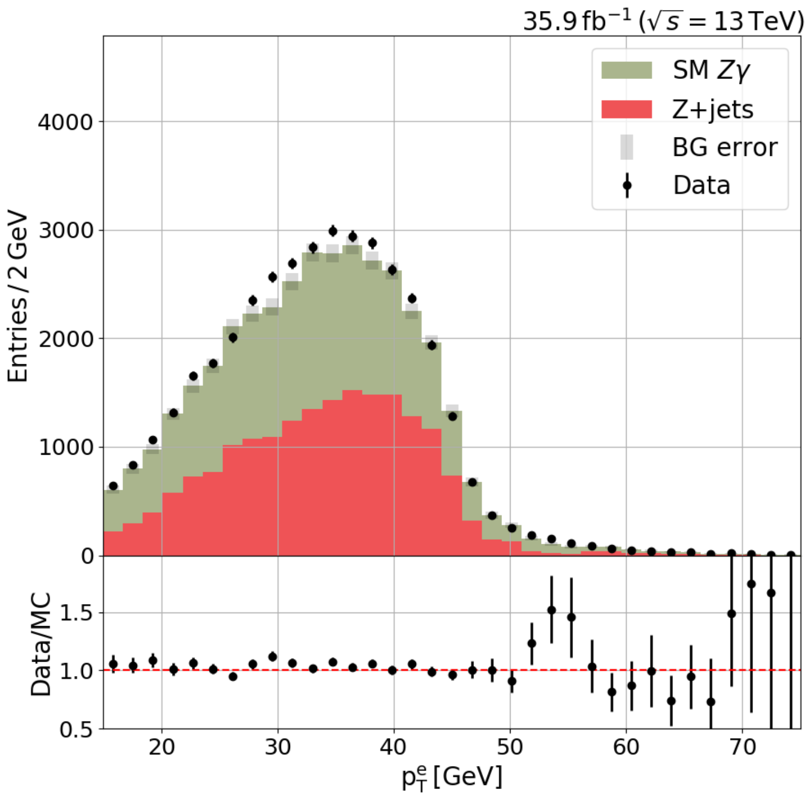
electron channel

https://drive.google.com/drive/u/1/folders/1t4OloVVAk8wsSlBlaGV13lowkUdu24PD

Trailing Lepton



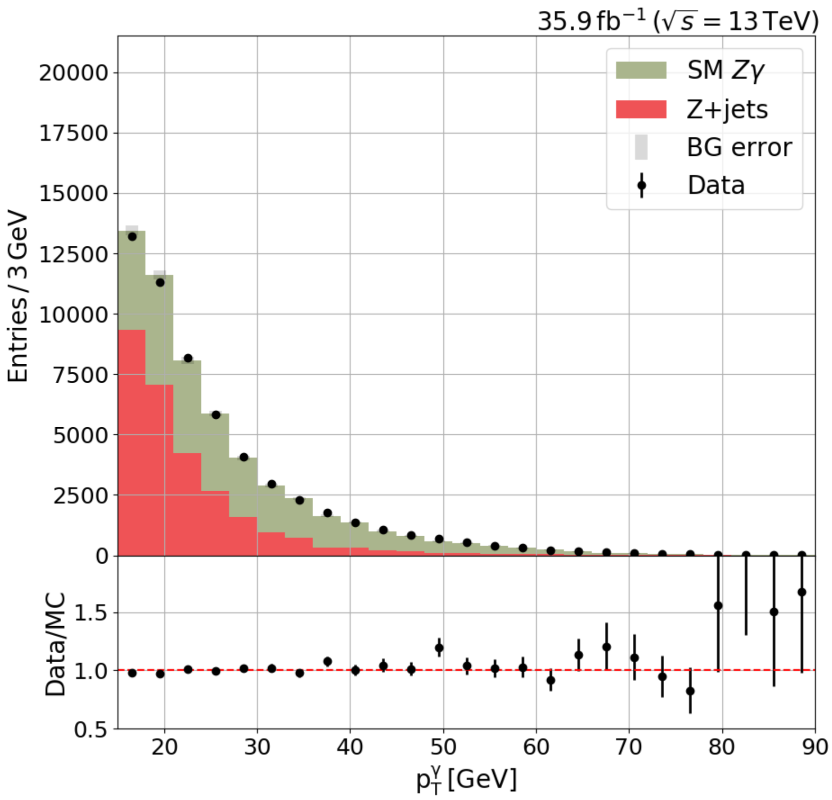
muon channel



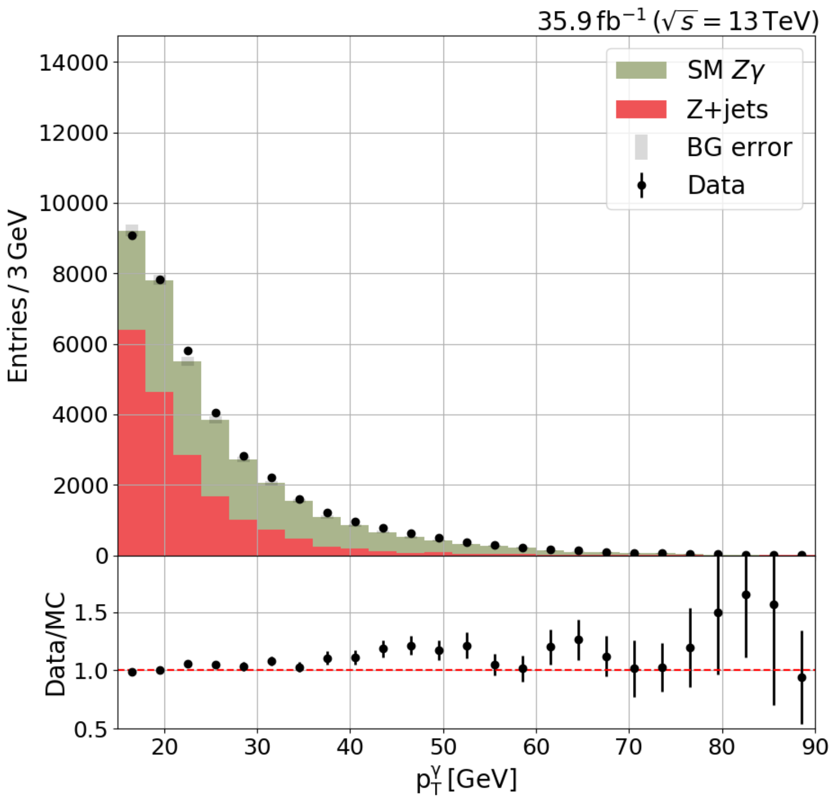
electron channel

https://drive.google.com/drive/u/1/folders/1t4OloVVAk8wsSlBlaGV13lowkUdu24PD

Photon



muon channel



electron channel

https://drive.google.com/drive/u/1/folders/1t4OloVVAk8wsSlBlaGV13lowkUdu24PD

Kinematic Fit Training

Muon Training

MVA Inputs

1. rho
2. energy
3. eta
4. χ^2
5. number of valid track layers
6. number of valid pixel hits
7. number of matched stations
8. charged hadron PF iso
9. neutral hadron PF iso
10. photon PF iso
11. pileup PF iso

- energy resolution model: double CB
- MVA target is a function fit to the training data in chunks
- only training on leading lepton
- power parameters taken to infinity

regressed parameters:

1. μ
2. σ
3. α_{L}
4. α_{R}

Electron Training

MVA Inputs

1. rho
2. energy
3. SC eta
4. SC phi
5. r9
6. E1x5/E
7. E2x5/E
8. E5x5/E
9. Brem fraction
10. H/E
11. SIEIE
12. charged hadron PF iso
13. neutral hadron PF iso
14. photon PF iso
15. pileup PF iso

- energy resolution model: double CB
- MVA target is a function fit to the training data in chunks
- only training on leading lepton

regressed parameters:

1. μ
2. σ
3. α_{L}
4. α_{R}
5. $\mathbf{n}_{\mathrm{L}}$
6. $\mathbf{n}_{\mathrm{R}}$