Charged lepton flavour violation/lepton number violation searches and studies with the CMS experiment

Sören Erdweg[1]
on behalf of the
CMS Collaboration

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Physics Institute III A

RWTH AACHEN UNIVERSITY

Overview

Motivation

- Observation of lepton flavour violation in neutrino sector:
  - Search for lepton flavour violation in the charged leptons
  - Highly suppressed in the Standard Model
  - $\rightarrow$ Striking signature for new physics
- New beyond the Standard Model (BSM) particles might decay lepton flavour violating
  - Little standard model background

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Approach

- Search for resonances decaying with lepton flavour violation
  - Z boson ($\rightarrow e\mu$) — 91 GeV
  - H boson ($\rightarrow e\tau$ or $\mu\tau$) — 125 GeV
  - BSM particles ($\rightarrow e\mu$) — few 100 GeV - multi TeV

Disclaimer

Presented analysis

- Medium and heavy mass resonances decaying with lepton flavour violation
- Personal selection of presented analysis

Some other CMS LFV analyses

- Search for lepton flavour violating decays of the Higgs boson to $e\tau$ and $e\mu$ in proton?proton collisions at $\sqrt{s} = 8$ TeV PLB 763C (2016) 472
- Search for heavy Majorana neutrinos in $e^{\pm}e^{\pm}$ plus jets and $e^{\pm}\mu^{\pm}$ plus jets events in proton-proton collisions at $\sqrt{s} = 8$ TeV 1603.02248
- Search for displaced leptons in the $e - \mu$ channel EXO-16-022
- Search for R-parity violating supersymmetry with displaced vertices 1610.05133
- Search for R-parity violating supersymmetry in dilepton channels SUS-14-018

Outline

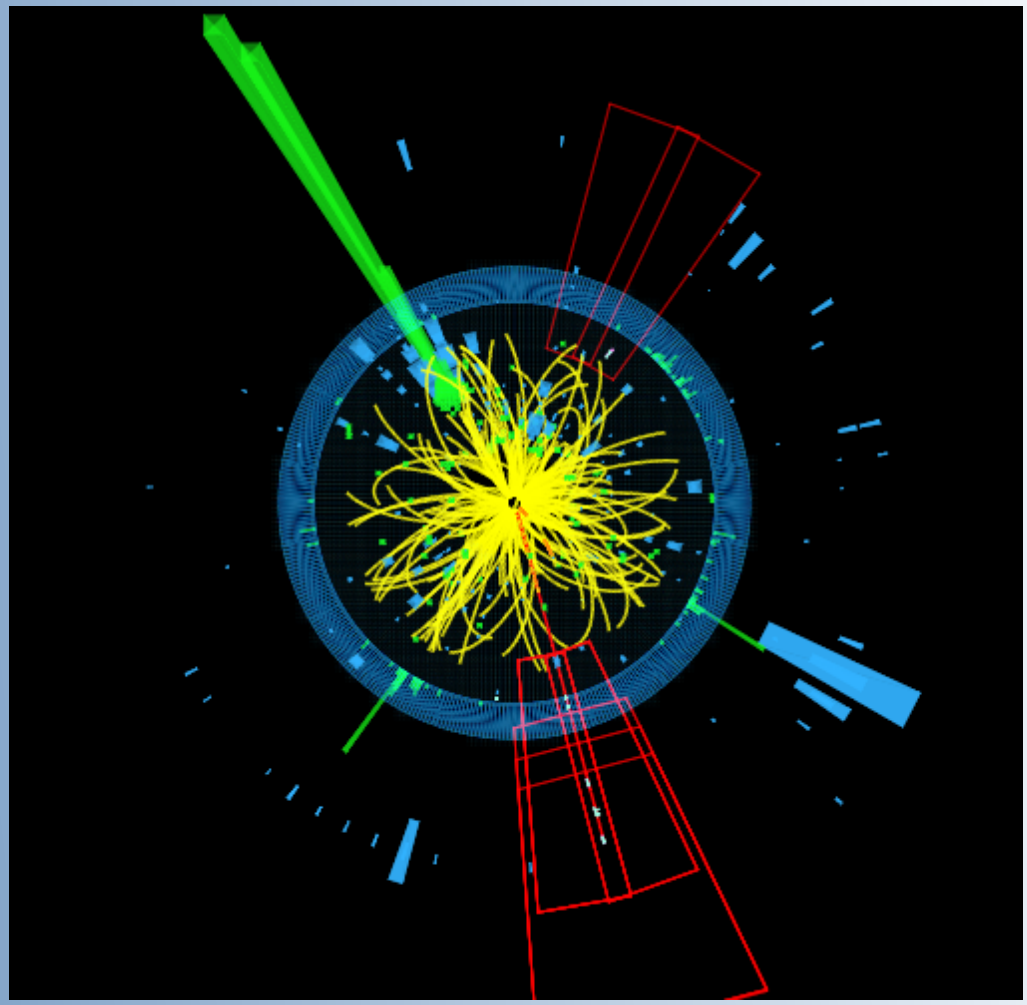
1 Introduction
- Overview
- LHC & CMS

2 Z-Boson

3 Higgs-Boson

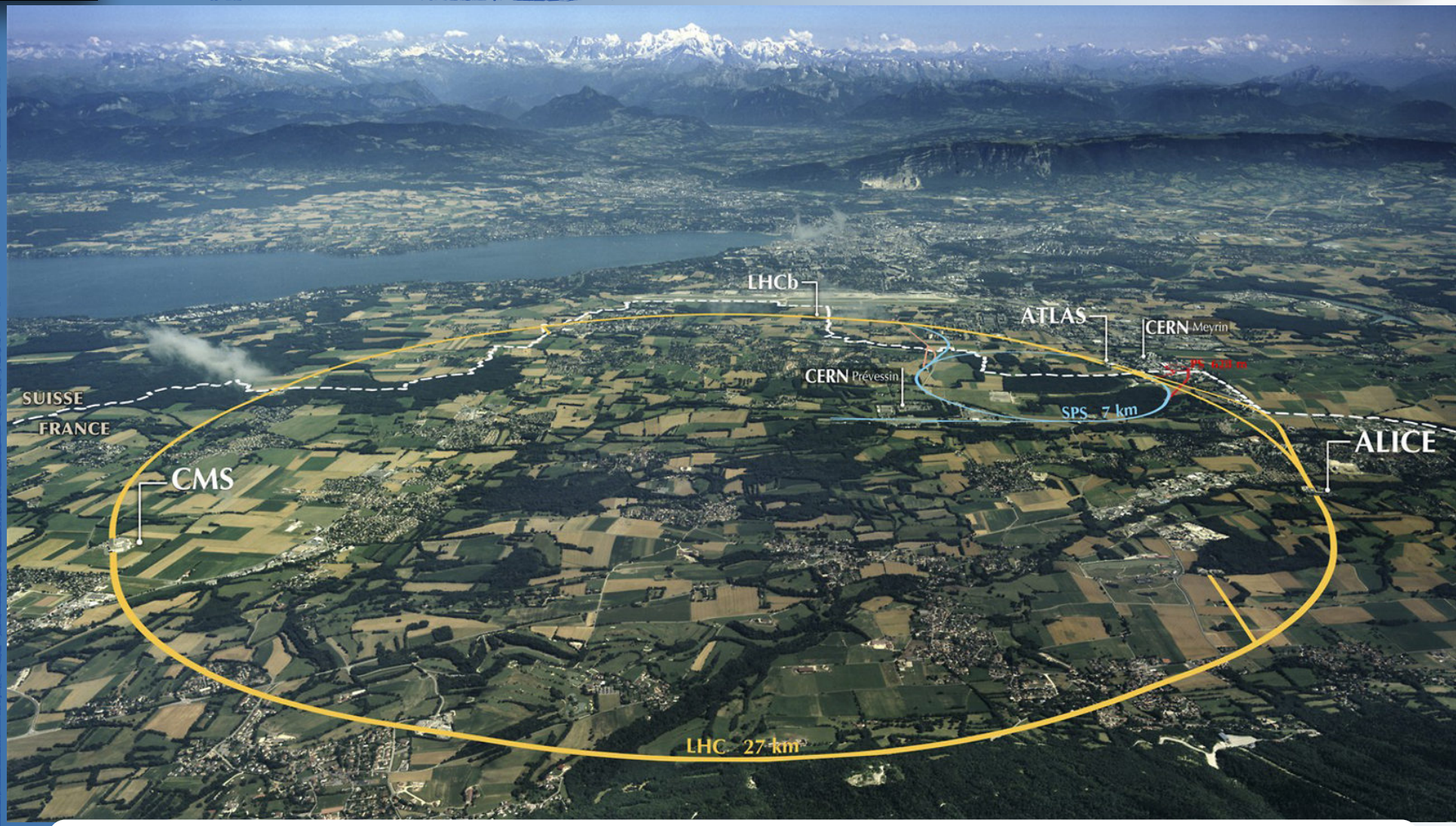
4 BSM particle

5 Summary



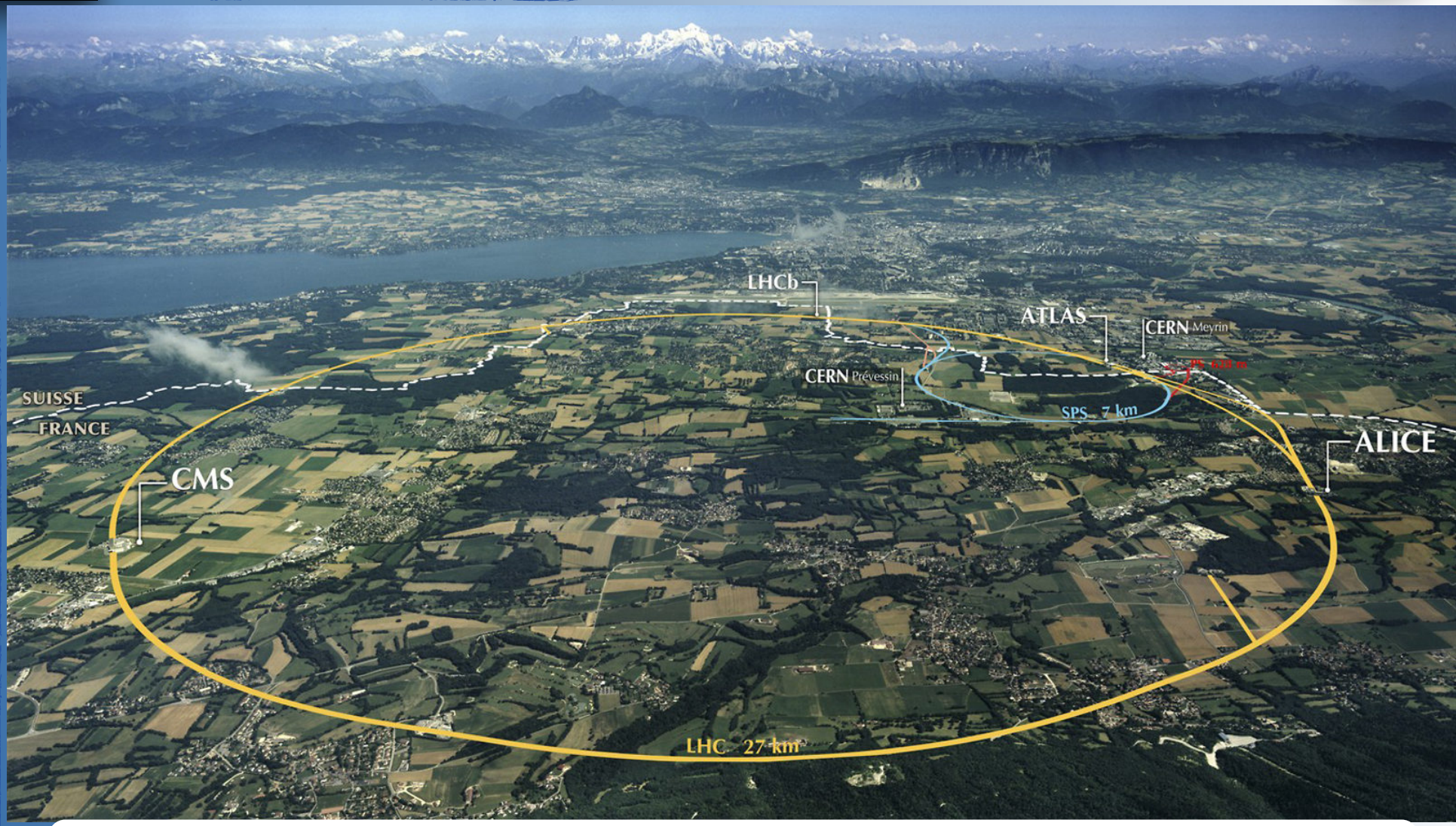
$M = 1.9\,\mathrm{TeV}$

LHC



Key figures

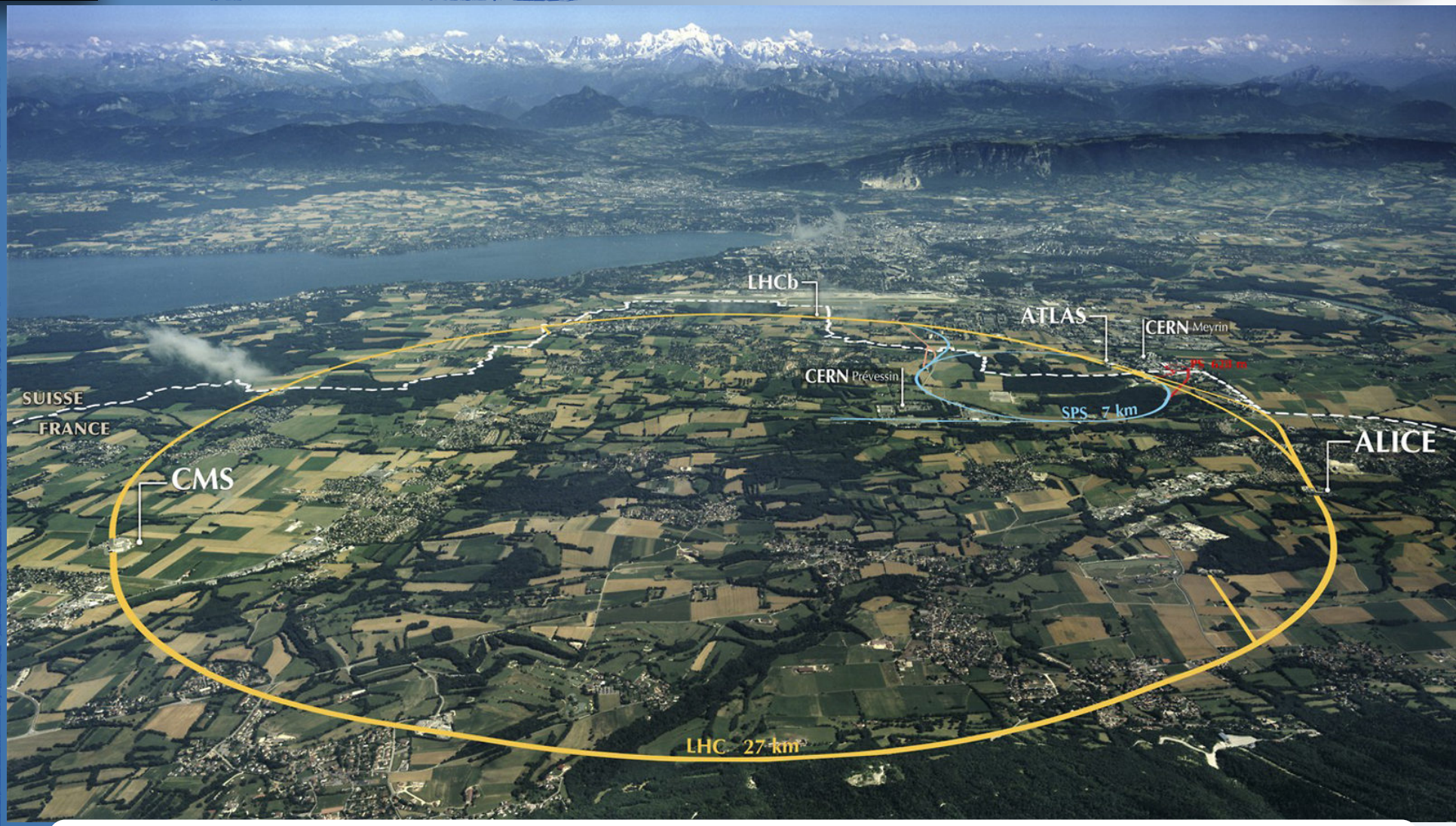
LHC



Key figures

- $\sqrt{s} = 13\,\text{TeV}$

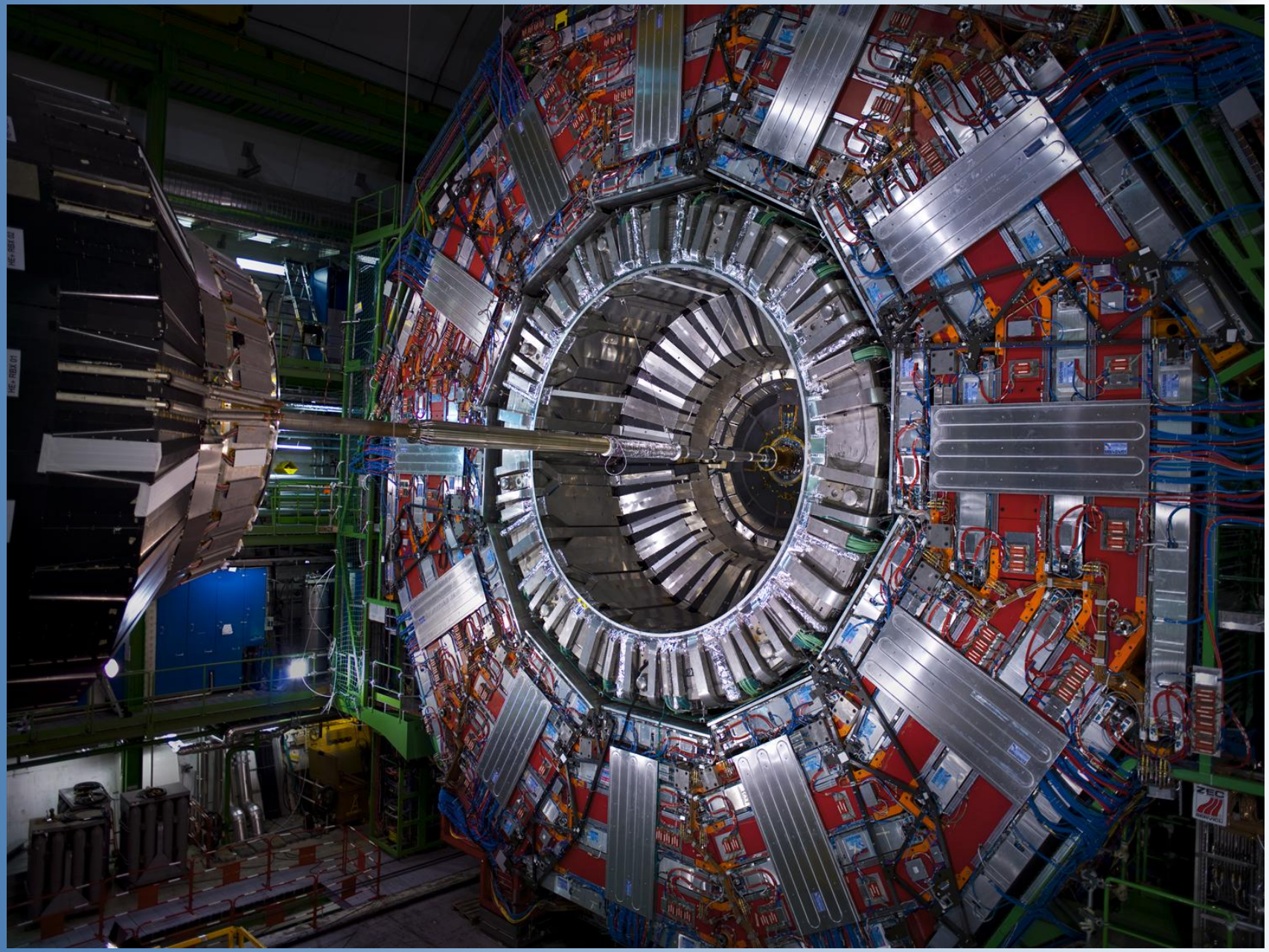
LHC



Key figures

- $\sqrt{s} = 13\,\text{TeV}$
- $\mathcal{L} = 1.53 \cdot 10^{34}\,\text{s}^{-1}\text{cm}^{-2}$

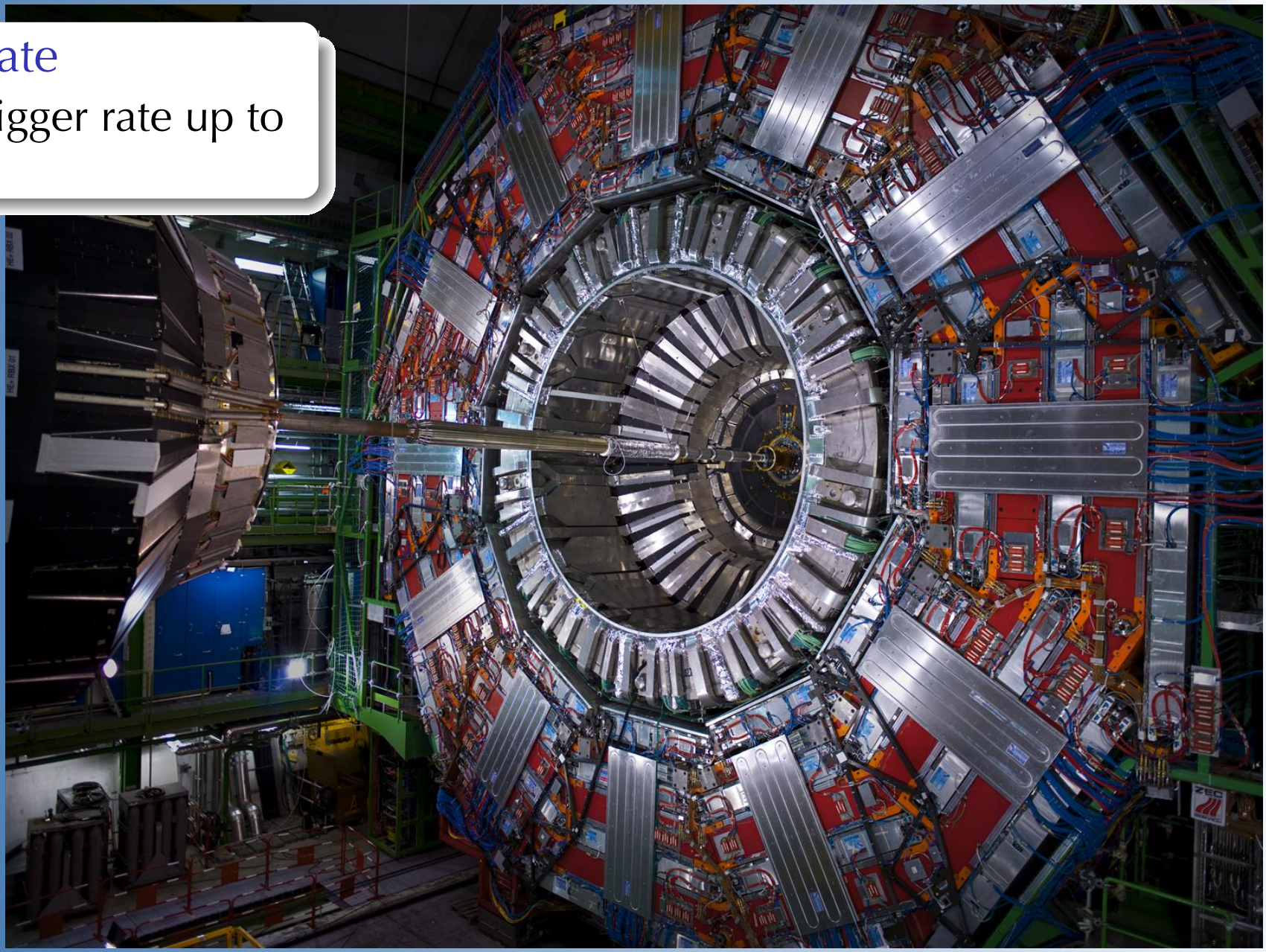
CMS



CMS

High rate

(HL) Trigger rate up to 1 kHz



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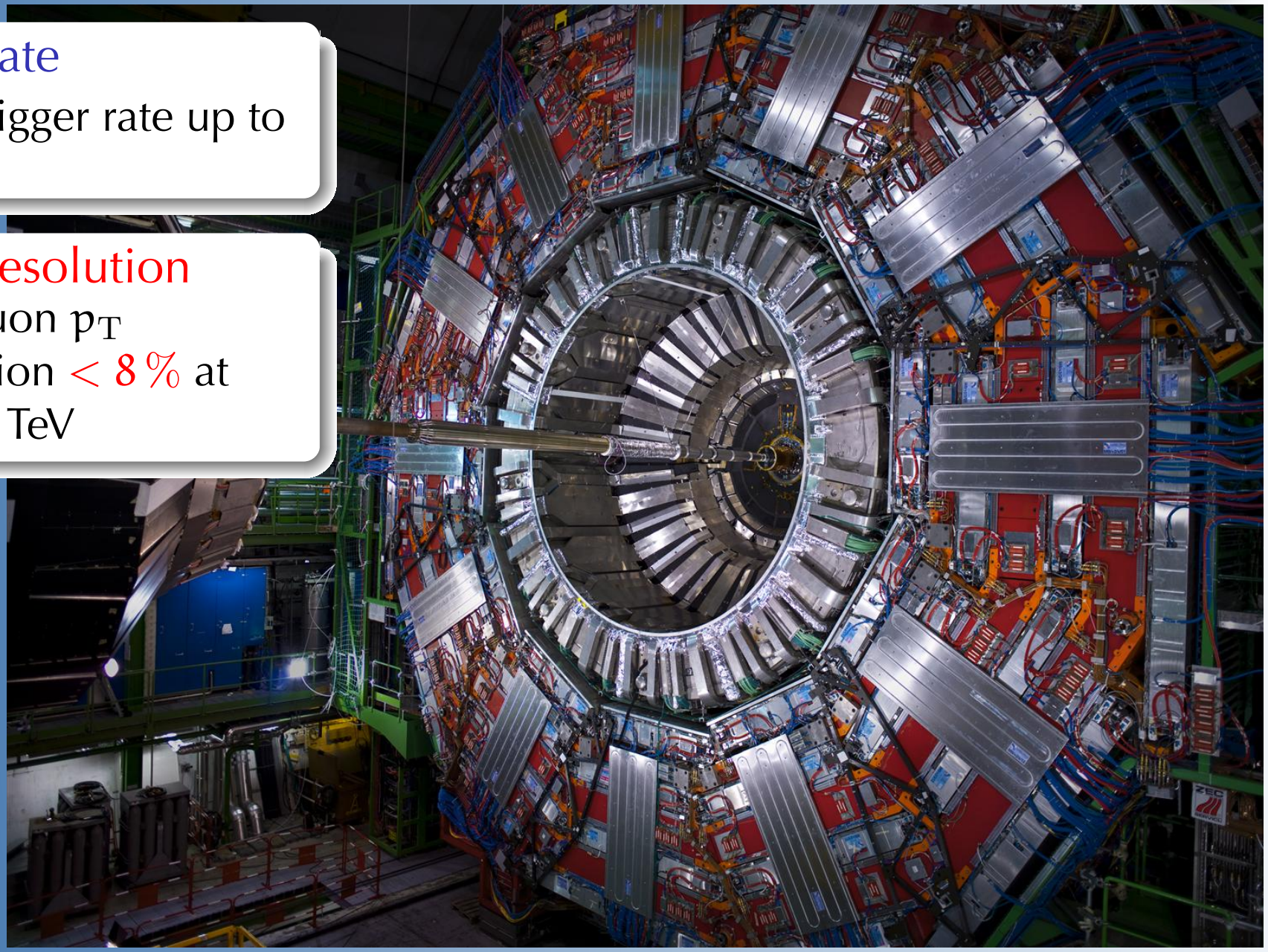
High resolution

e.g. muon p_T resolution $< 8\,\%$ at $p_T = 1\,\mathrm{TeV}$



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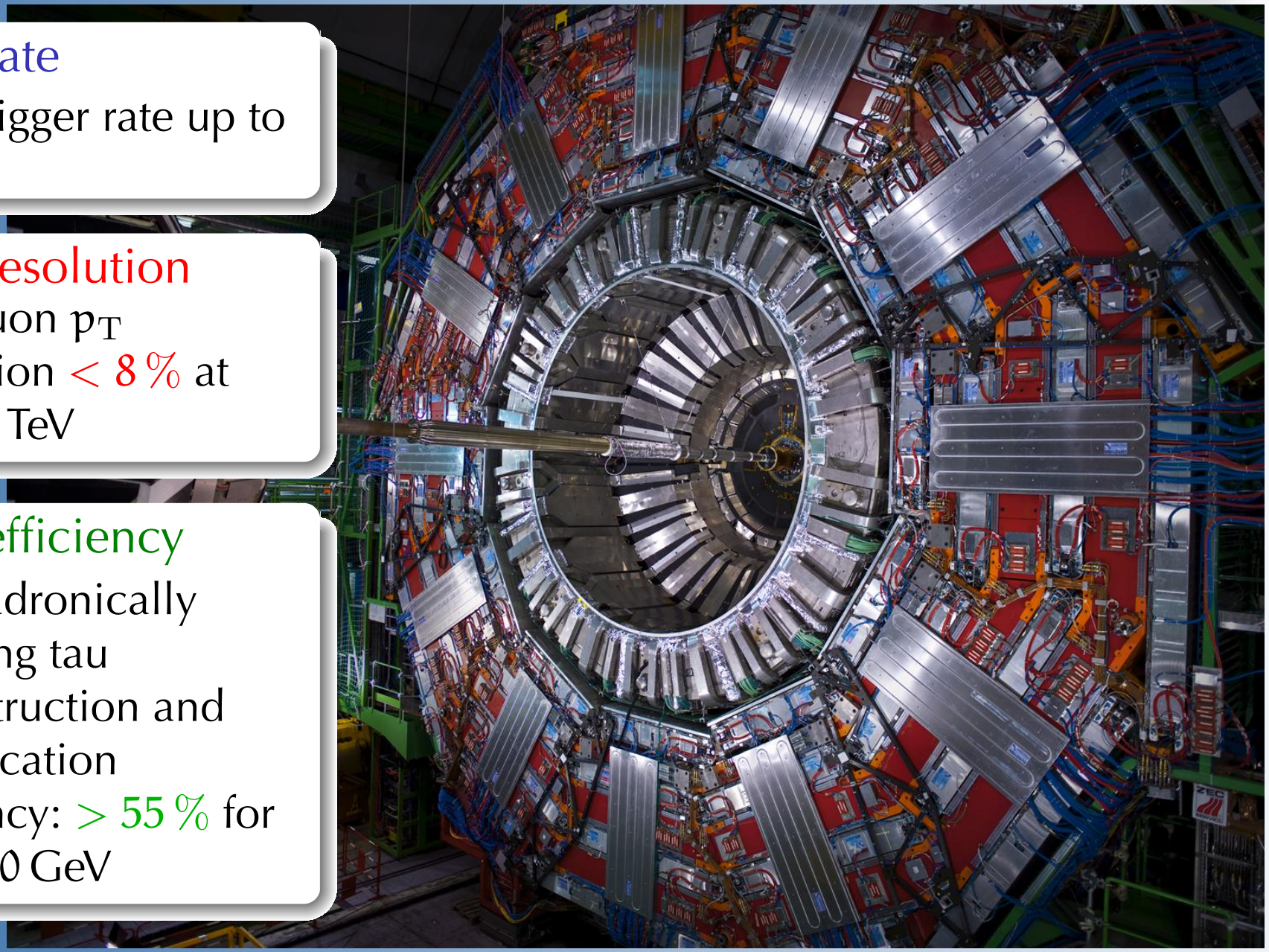
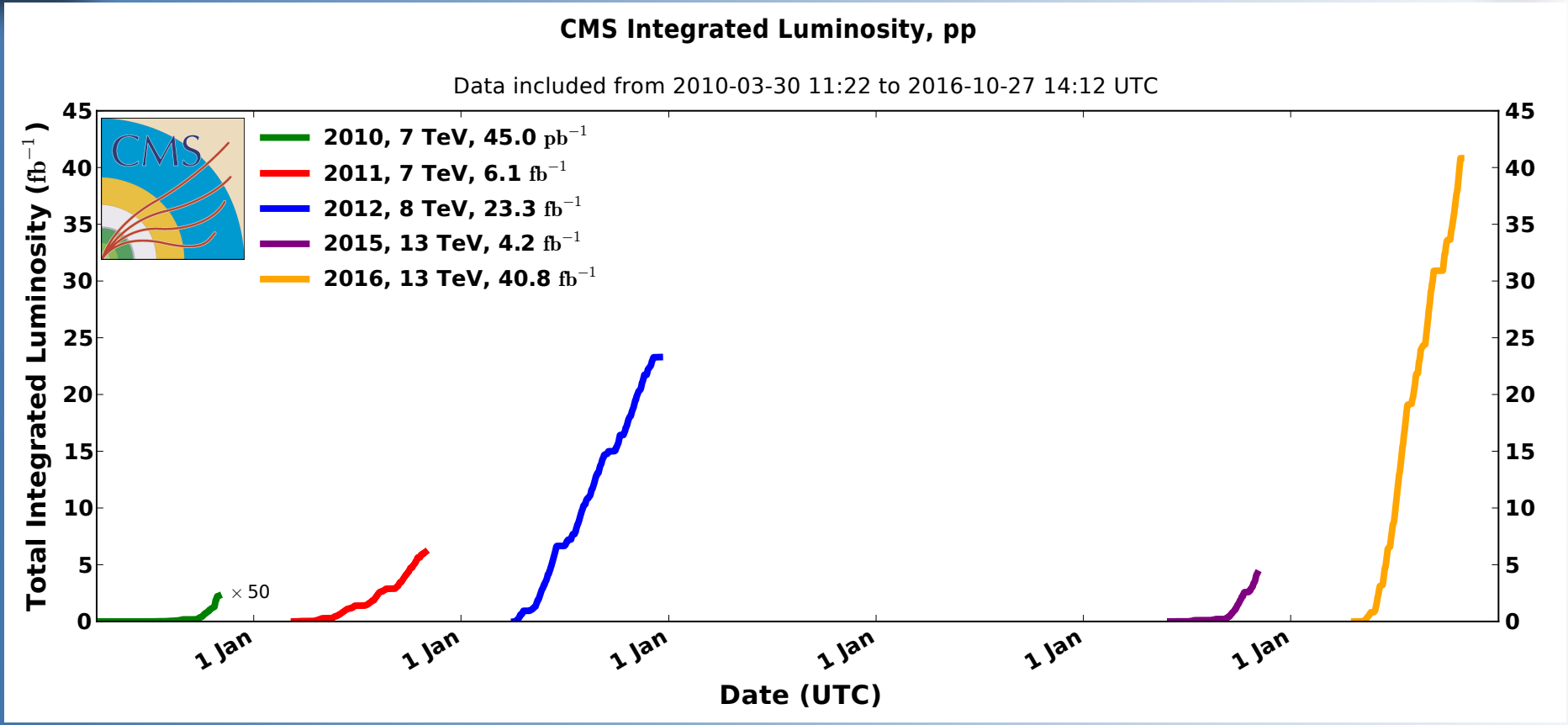
High efficiency

e.g. Hadronically decaying tau reconstruction and identification efficiency: $> 55\,\%$ for $p_T > 30\,\mathrm{GeV}$



Dataset(s)



- Very successful data taking over many years
  - LFV Z decays: 2012, 8 TeV
  - LFV BSM particle decays: 2015, 13 TeV
  - LFV H decays: 2016, 13 TeV

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- Introduction
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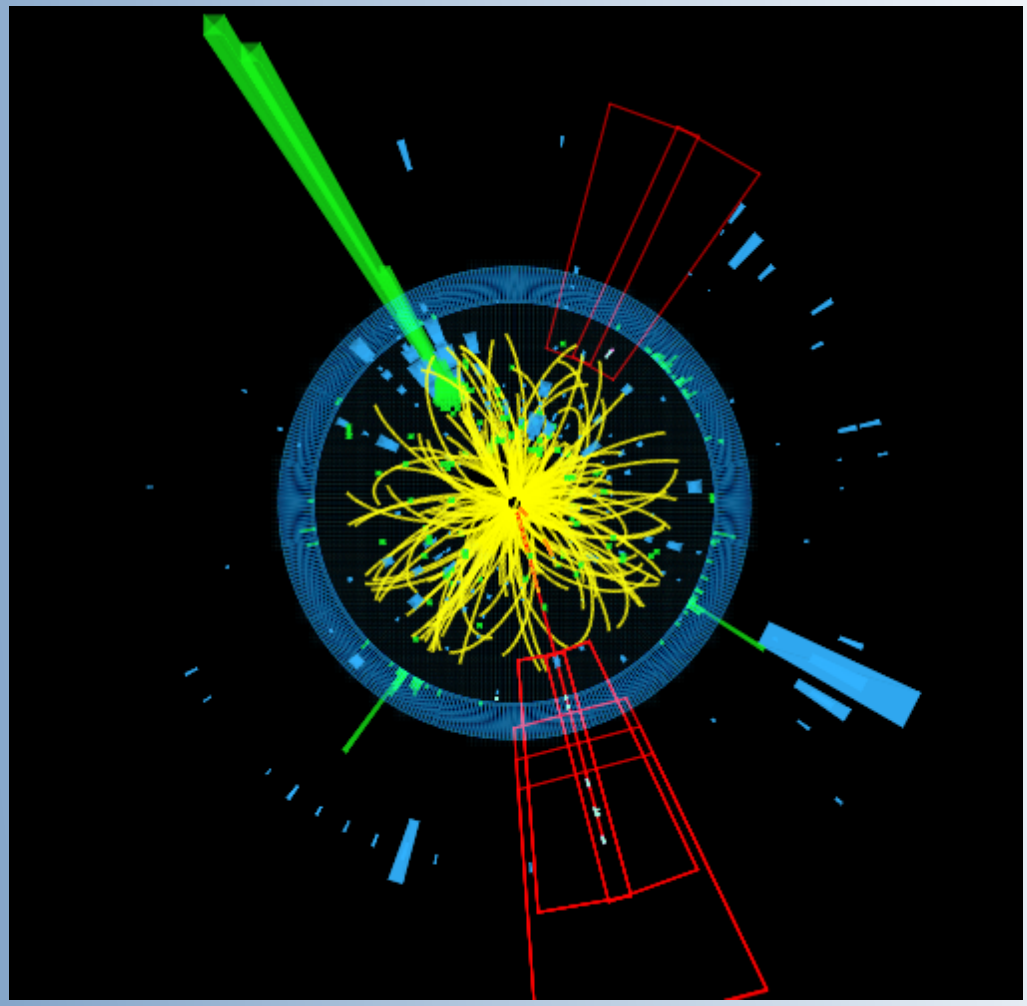

$M_{e\mu} = 1.9\,\text{TeV}$

Introduction

CMS PAS-EXO-13-005 [1]

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Motivation

- $Z \to e\mu$ suppressed in the SM ($BR < 4 \cdot 10^{-60}$)
- Clear signature for new physics (μ^+e^- or μ^-e^+)

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Analysis key points

- 2012 data set of up to $19.7\,\mathrm{fb}^{-1}$ of proton-proton data at $\sqrt{s} = 8\,\mathrm{TeV}$
- Search for Z mass resonance

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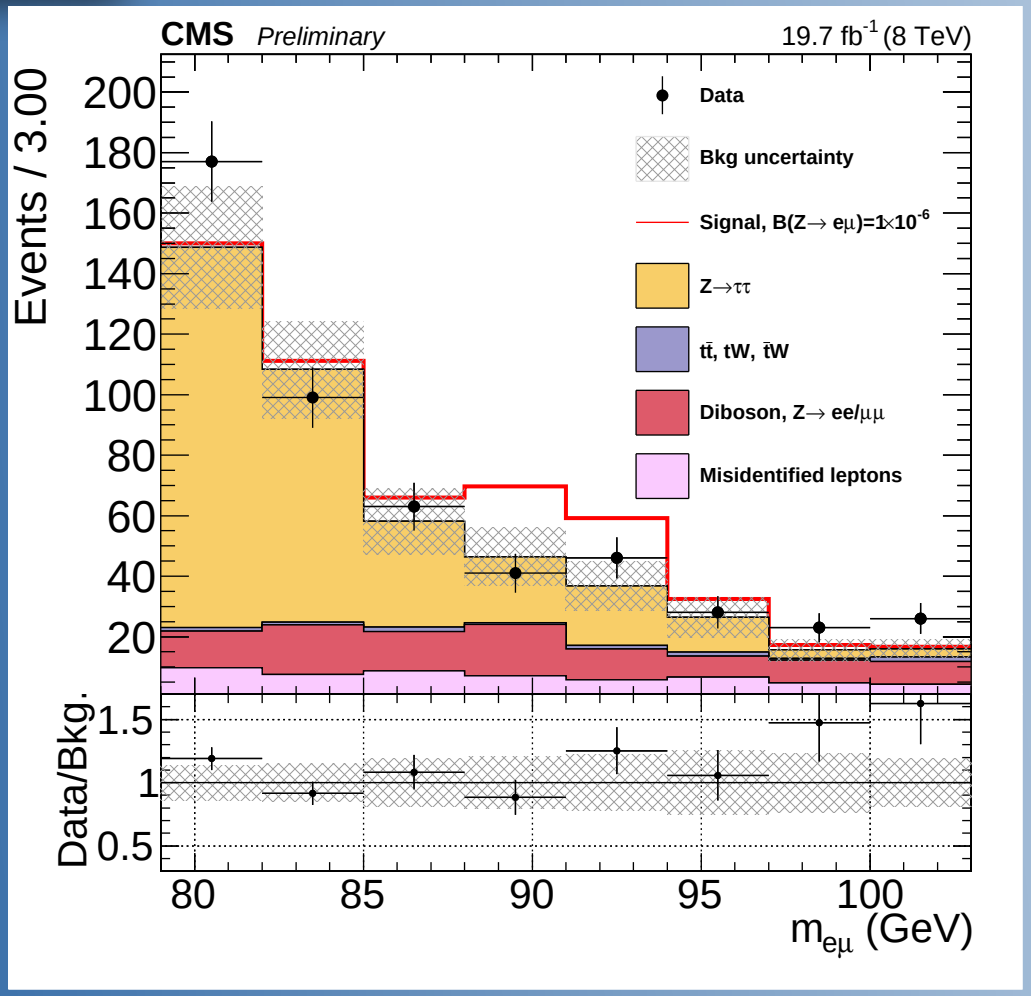
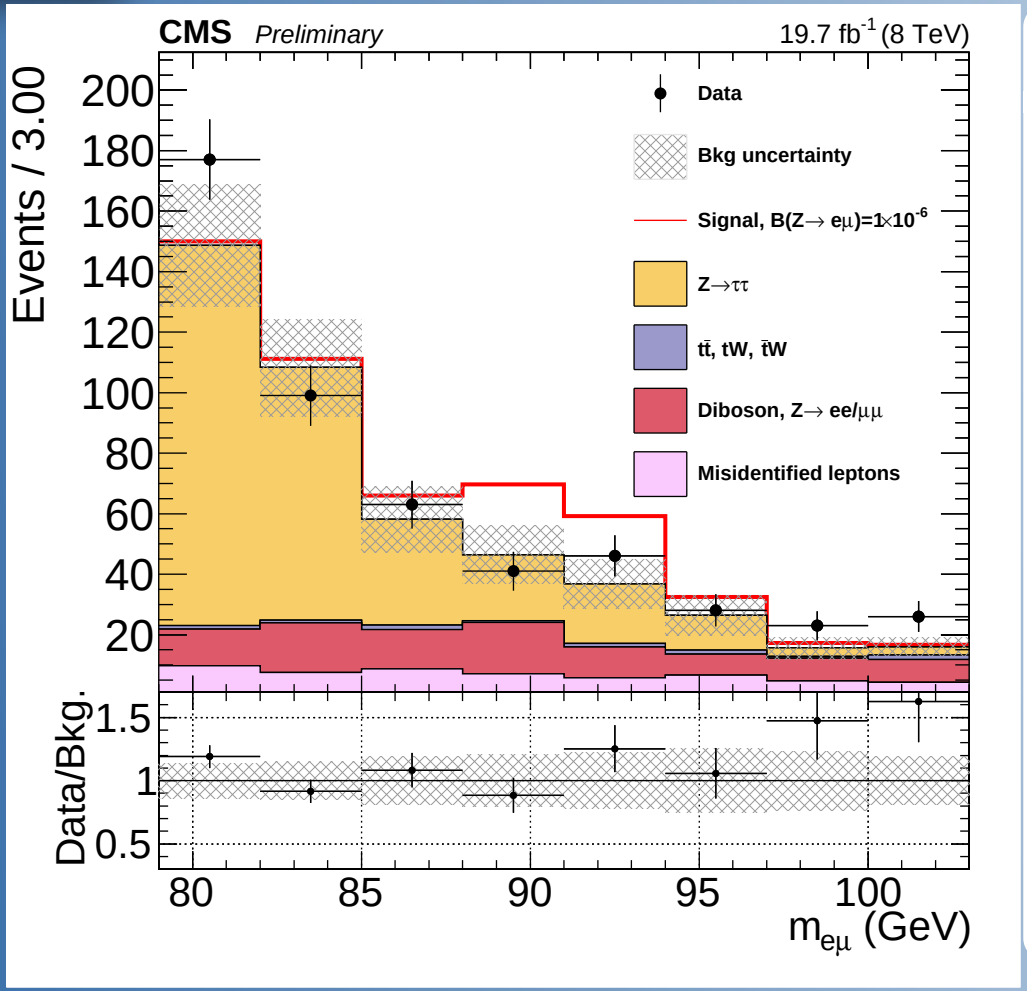
Event selection

- Trigger: electron + muon ($E_T > 17\,\mathrm{GeV}$ and $E_T > 8\,\mathrm{GeV}$)
- Particle flow identification/isolation criteria for electron / muon
- Veto other leptons, high p_T Jets, $m_T(\mu, E_T^{miss}) < 60\,\mathrm{GeV}$, $p_T^{e\mu} < 10\,\mathrm{GeV}$
- Selection efficiency: 6.6%

Result


CMS Preliminary
19.7 fb^{-1} (8 TeV)
Events / 3.00
Data
Bkg uncertainty
Signal, B(Z→ eμ)=1×10^{-6}
Z→ττ
tt̄, tW, t̄W
Diboson, Z→ ee/μμ
Misidentified leptons
Data/Bkg.
$m_{e\mu}$ (GeV)

Result



Systematic uncertainties

Effect on background (signal) > 1%

- Luminosity: 2.6%
- Pileup: 3.3% (0.8%)
- μ p_T scale: 2.9% (0.2%)
- e E_T scale: 3.1% (1.1%)
- E_T^{miss}: 0.6% (2.2%)
- $e\mu$ p_T: 0.4% (1.1%)
- PDF: 1.0% (1.0%)
- N(MC events): 10.6% (1.2%)
- Normalisation: 6.8% (3.3%)

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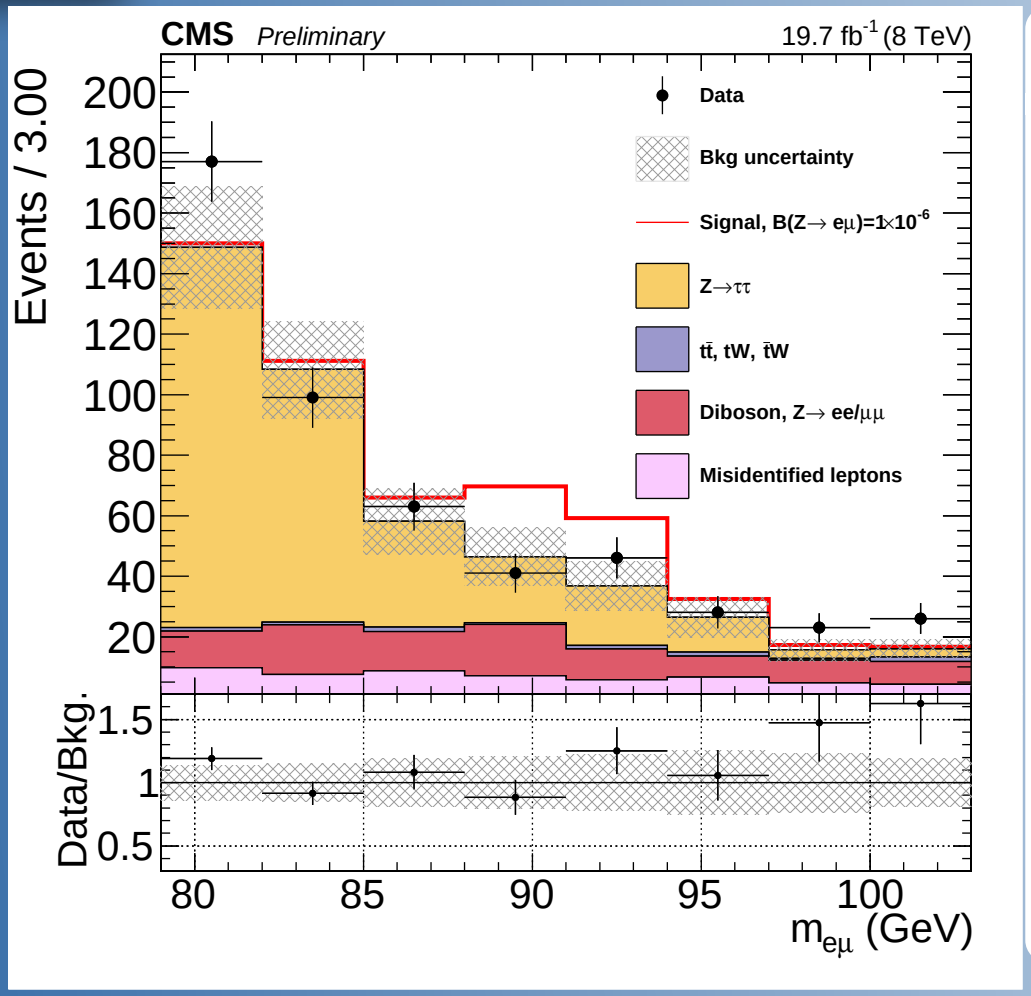

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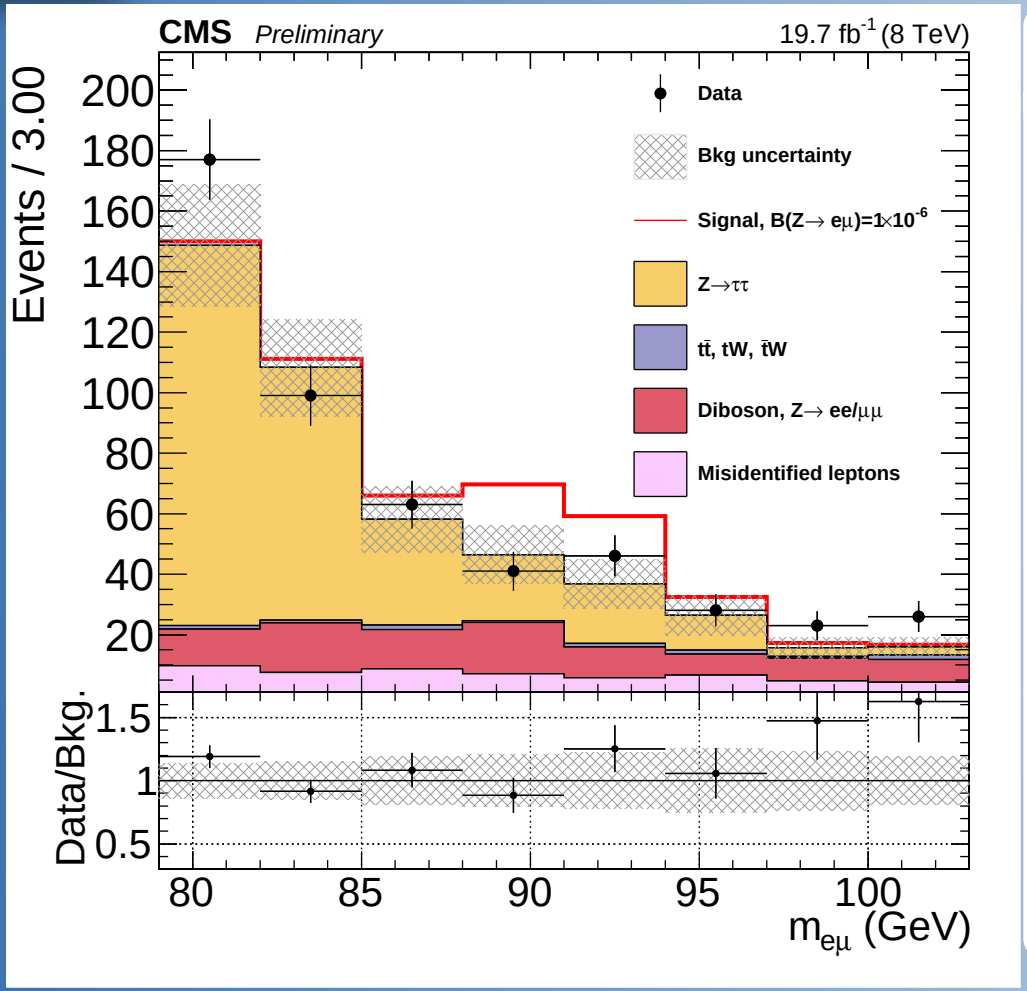

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87 (obs.), 83 ± 9 (SM exp.) events in signal region (88 – 94 GeV)

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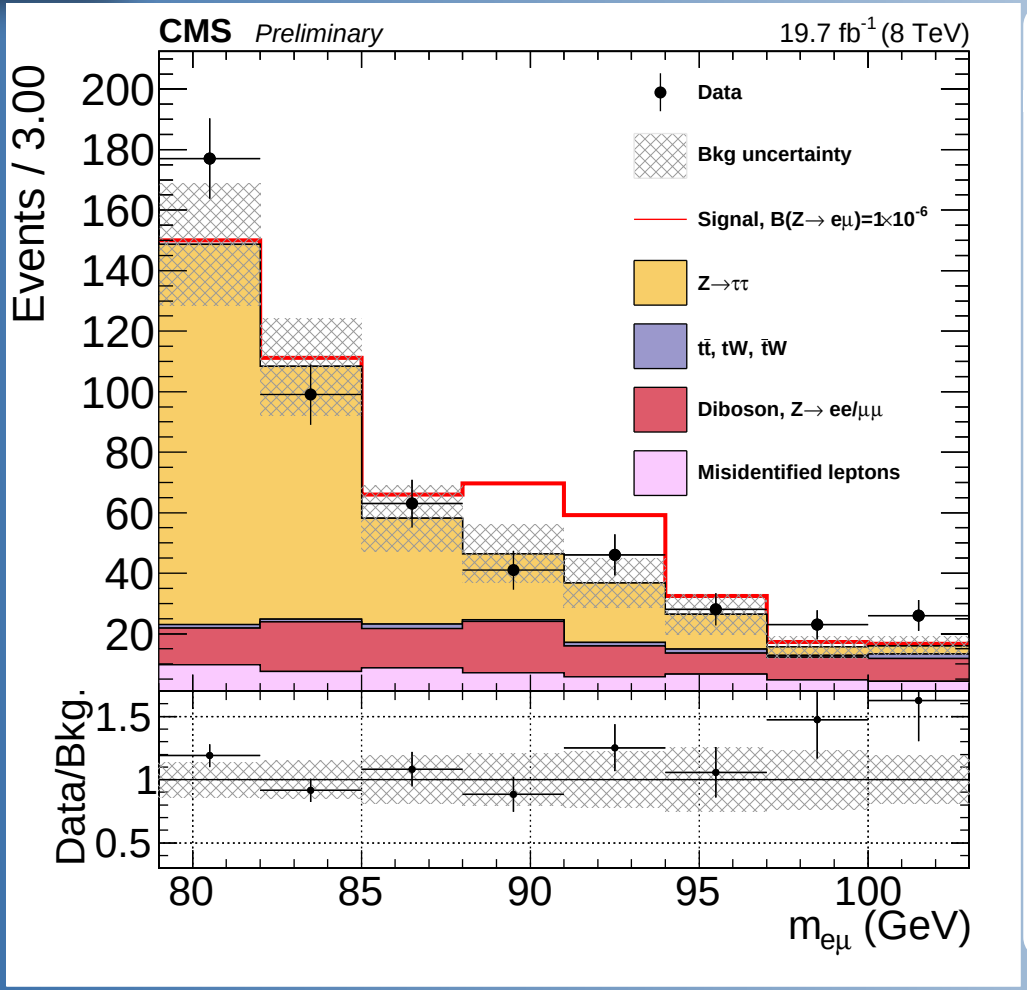

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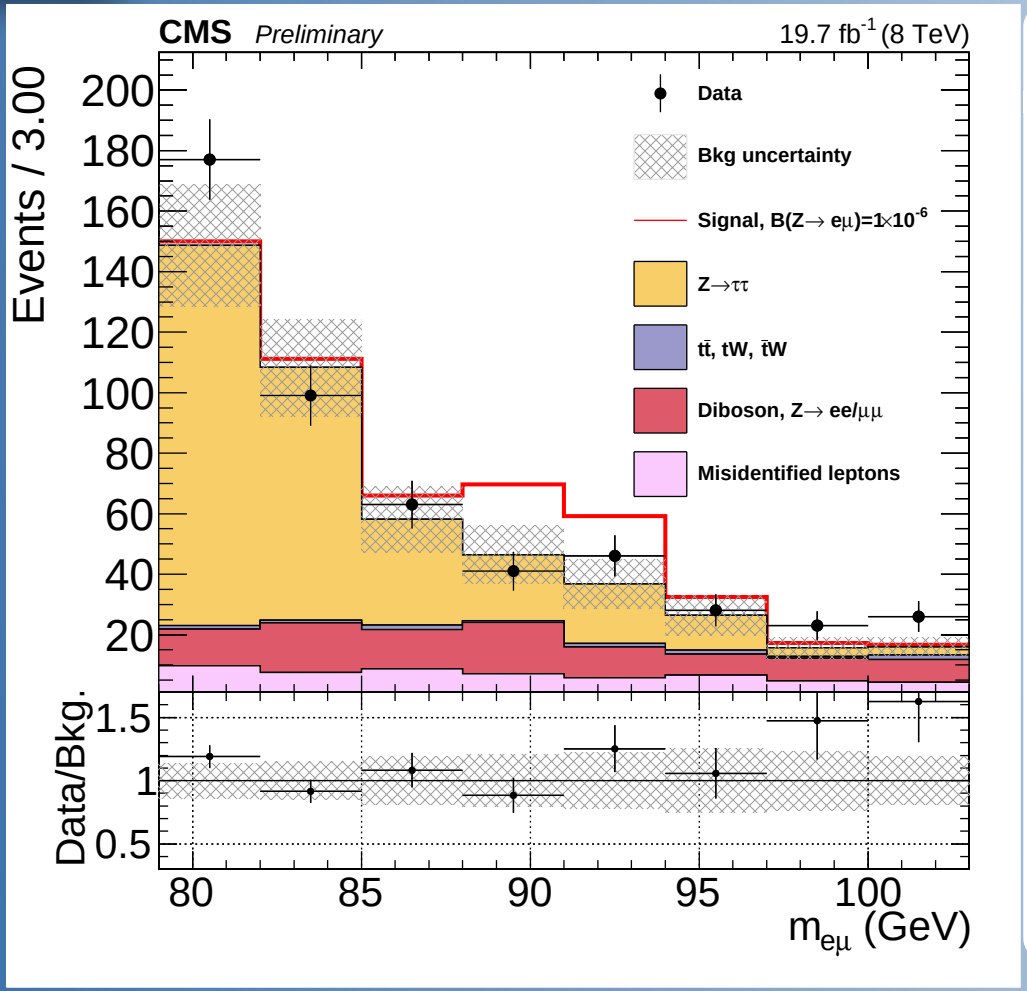

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Observed limit

$$\mathcal{B}(Z \to e\mu) < 7.3 \cdot 10^{-7}$$

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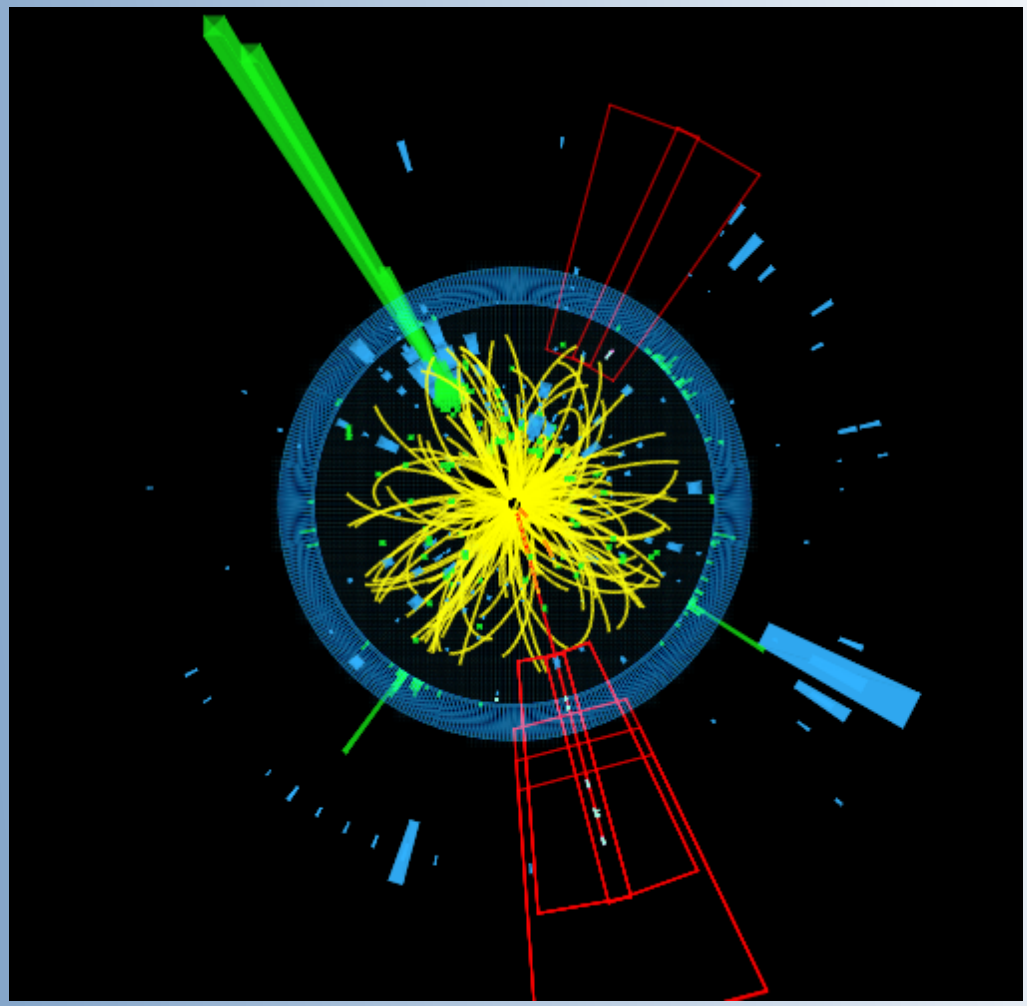

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Introduction

CMS PAS-HIG-17-001 [2]

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Basic idea

- Lepton flavour violating Higgs decay
- Two studied decays ($H \to e\tau$ / $H \to \mu\tau$)
- Four final states ($\mu\tau_h$, $\mu\tau_e$, $e\tau_h$ and $e\tau_\mu$)

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Analysis key points

- 2016 data set of $35.9\,\mathrm{fb}^{-1}$ of proton-proton data at $\sqrt{s} = 13\,\mathrm{TeV}$
- Two analysis methods: boosted decision tree (BDT) and cut based (as cross check)
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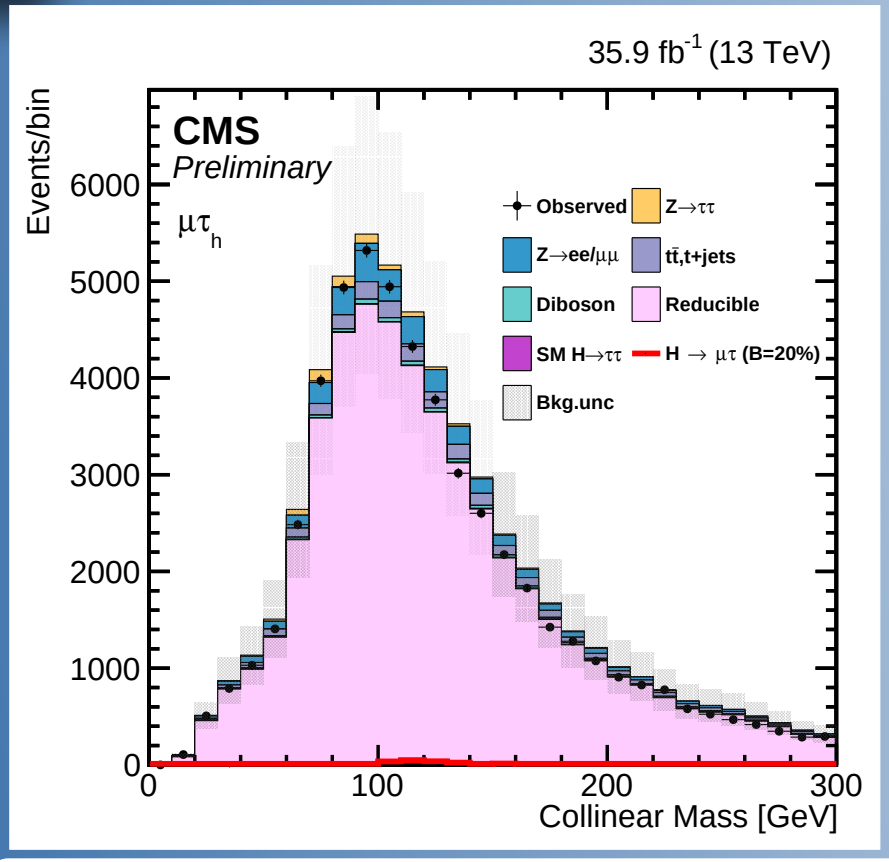
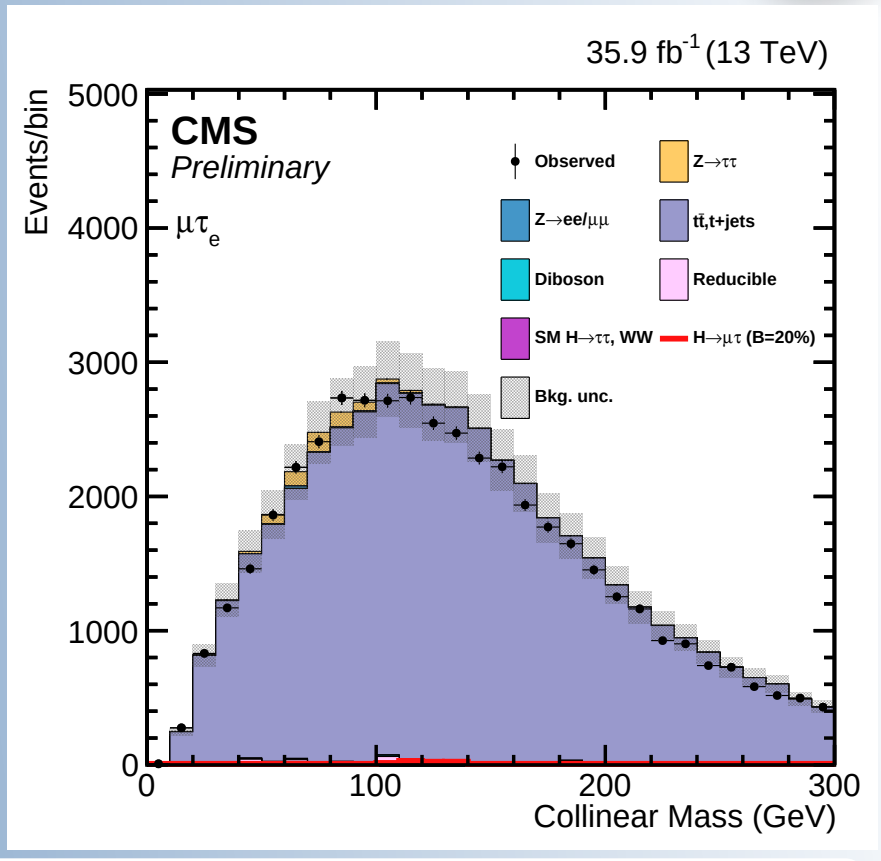
Event selection

- Isolated lepton triggers (e or μ)
- Split analysis in production channels (n_{Jet} and/or M_{jj})

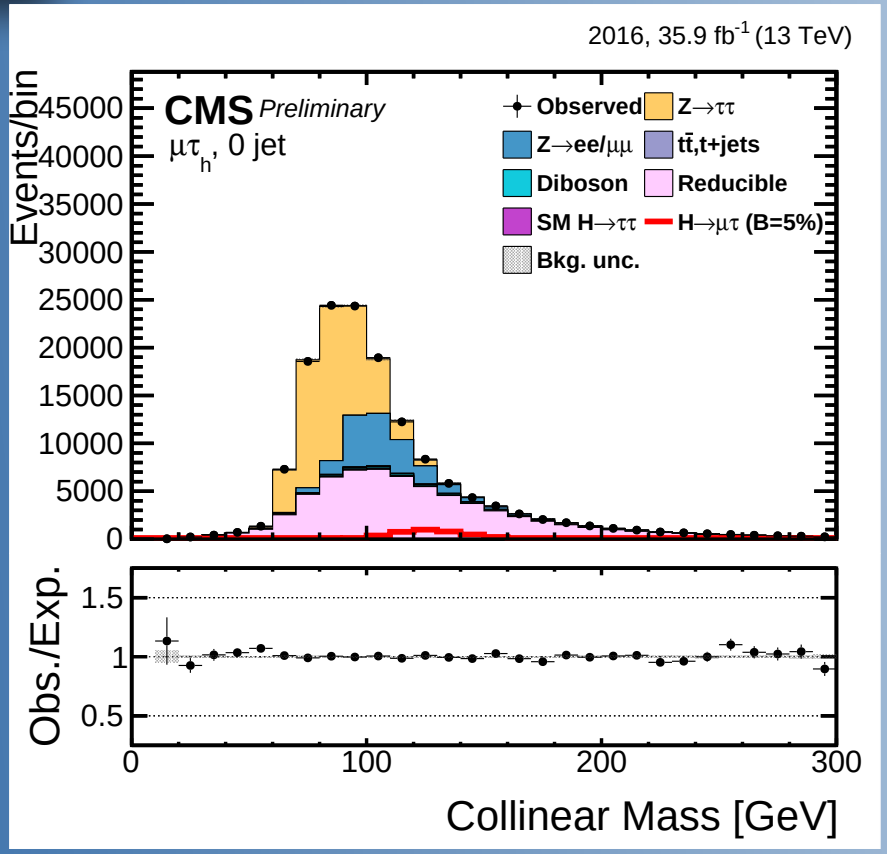
Background description





- Processes with prompt leptons (e.g. $t\bar{t}$, Diboson and $H \to \tau\tau$)
  - Estimated from Monte Carlo simulation
  - Corrected for known mis-modelling effects
- Contribution from misidentified leptons
  - Estimated from collision data with inverted isolation

Result for $\mu\tau$



Cut based analysis

- $p_T^{\mu} > 26\,\text{GeV}$ and $|\eta^{\mu}| < 2.4$
- $p_T^{\tau_h} > 30\,\text{GeV}$ and $|\eta^{\tau_h}| < 2.3$
- Cut on $M_T\,(\tau_h)$

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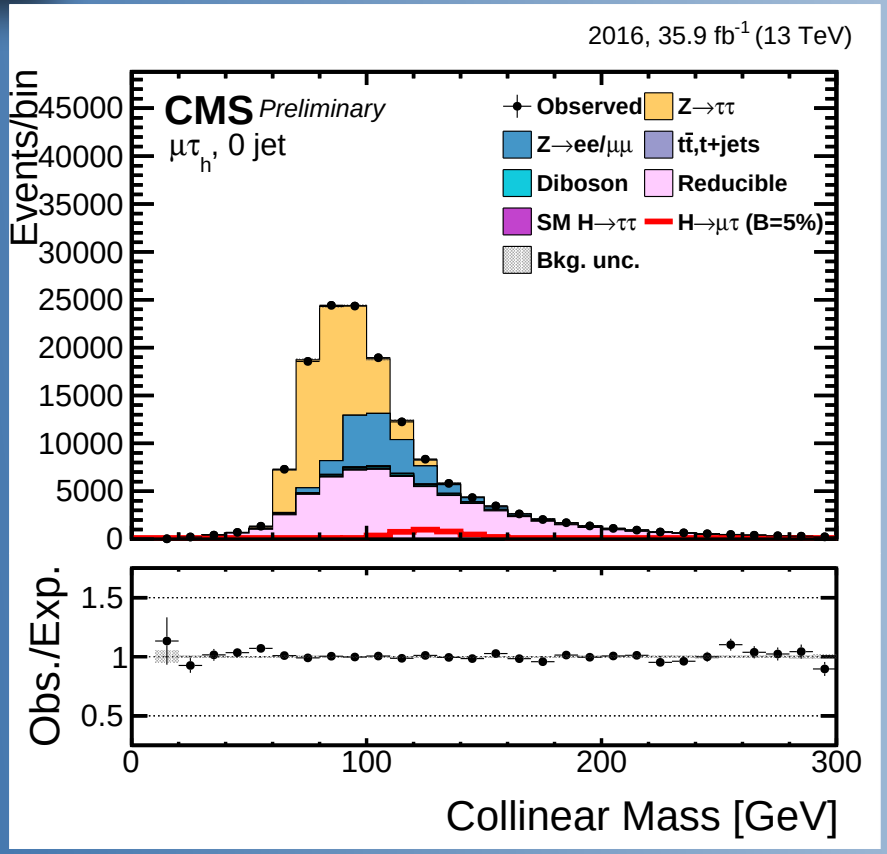

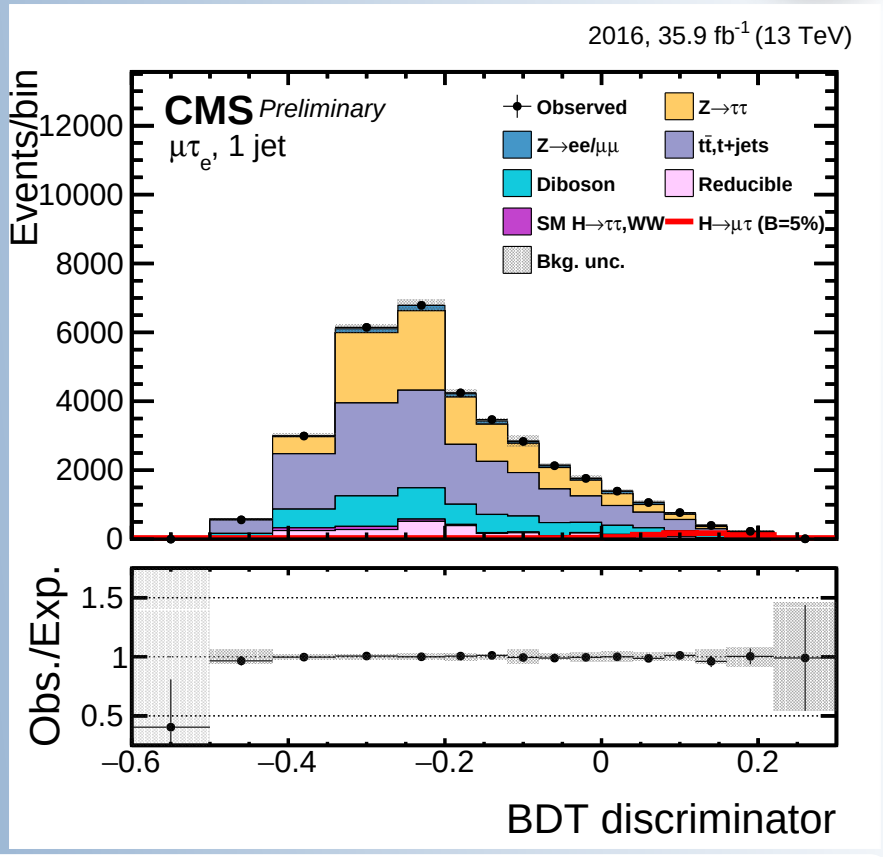

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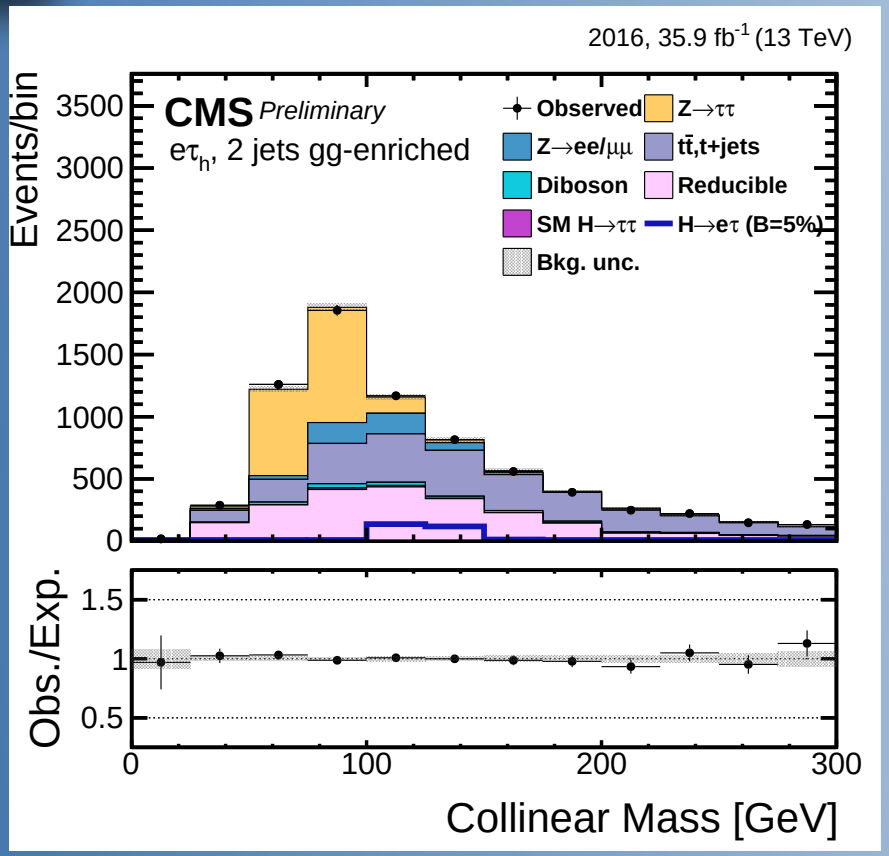
- Cut on $M_T(\tau_h)$

BDT analysis

- Input variables:

p_T^{μ}, $p_T^{\tau_e}$, M_{Col}, E_T^{miss}, $M_T(\tau_e)$, $\Delta\eta(\mu, \tau_e)$, $\Delta\phi(p_T^{\mu}, p_T^{\tau_e})$ and $\Delta\phi(p_T^{\tau_e}, E_T^{miss})$

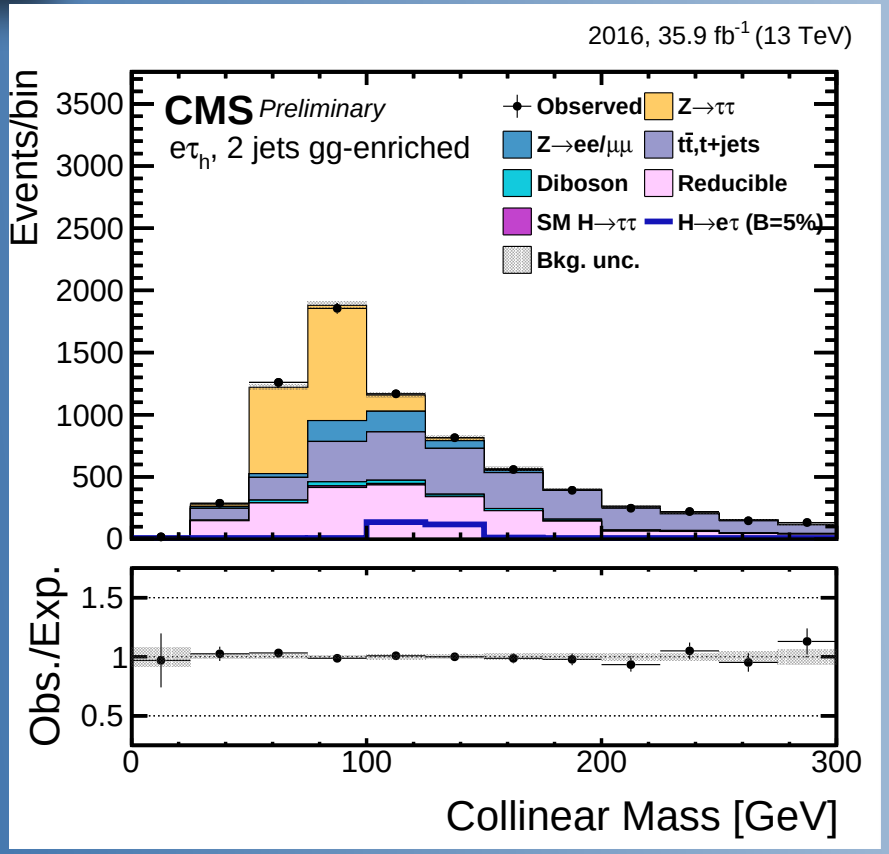
Result for $e\tau$

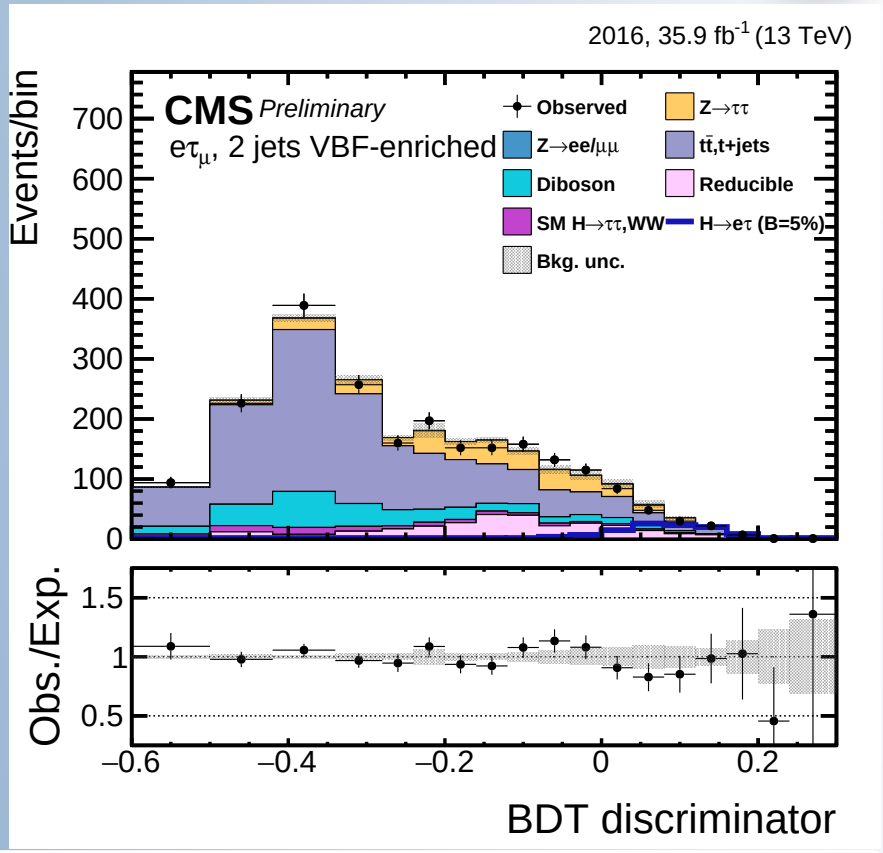


Cut based analysis

- $p_T^e > 26\,\text{GeV}$ and $|\eta^e| < 2.1$
- $p_T^{\tau_h} > 30\,\text{GeV}$ and $|\eta^{\tau_h}| < 2.3$
- Cut on $M_T(\tau_h) < 60\,\text{GeV}$

Result for $e\tau$





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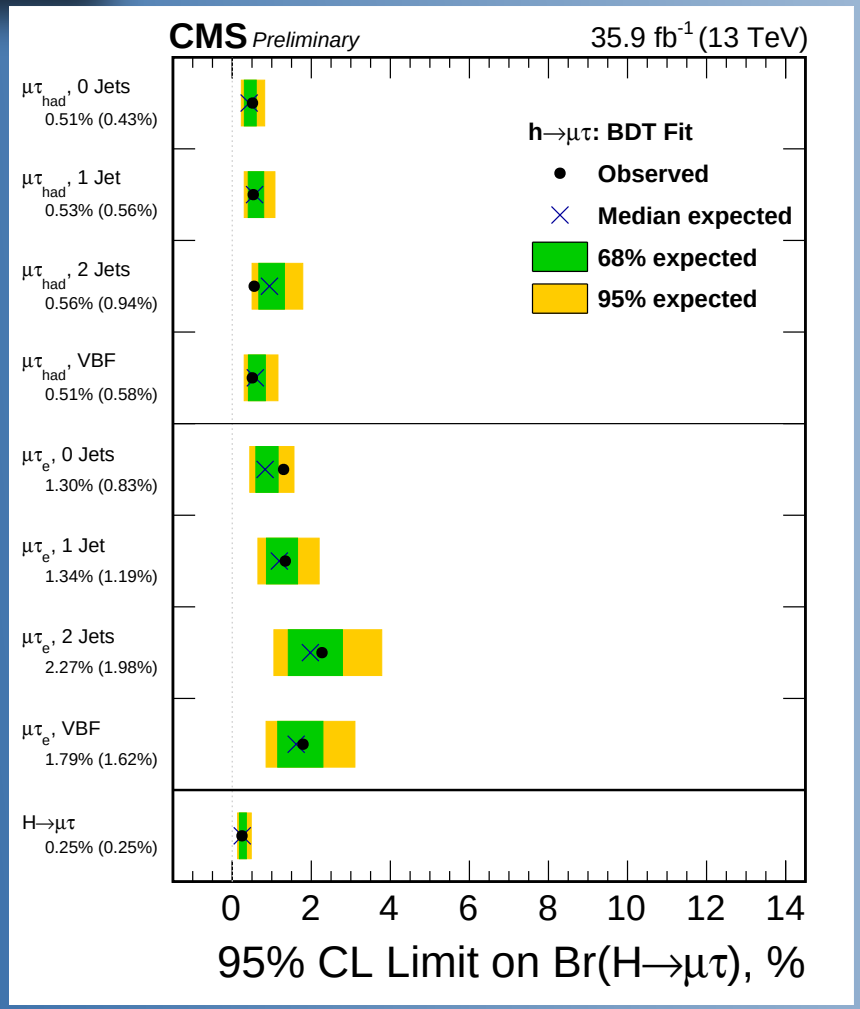
BDT analysis

- Input variables:

p_T^e, $p_T^{\tau_\mu}$, M_{Col}, E_T^{miss}, $M_T(\tau_\mu)$, $\Delta\eta(e, \tau_\mu)$, $\Delta\phi(p_T^e, p_T^{\tau_\mu})$, M_{vis} and $\Delta\phi(p_T^{\tau_\mu}, E_T^{miss})$

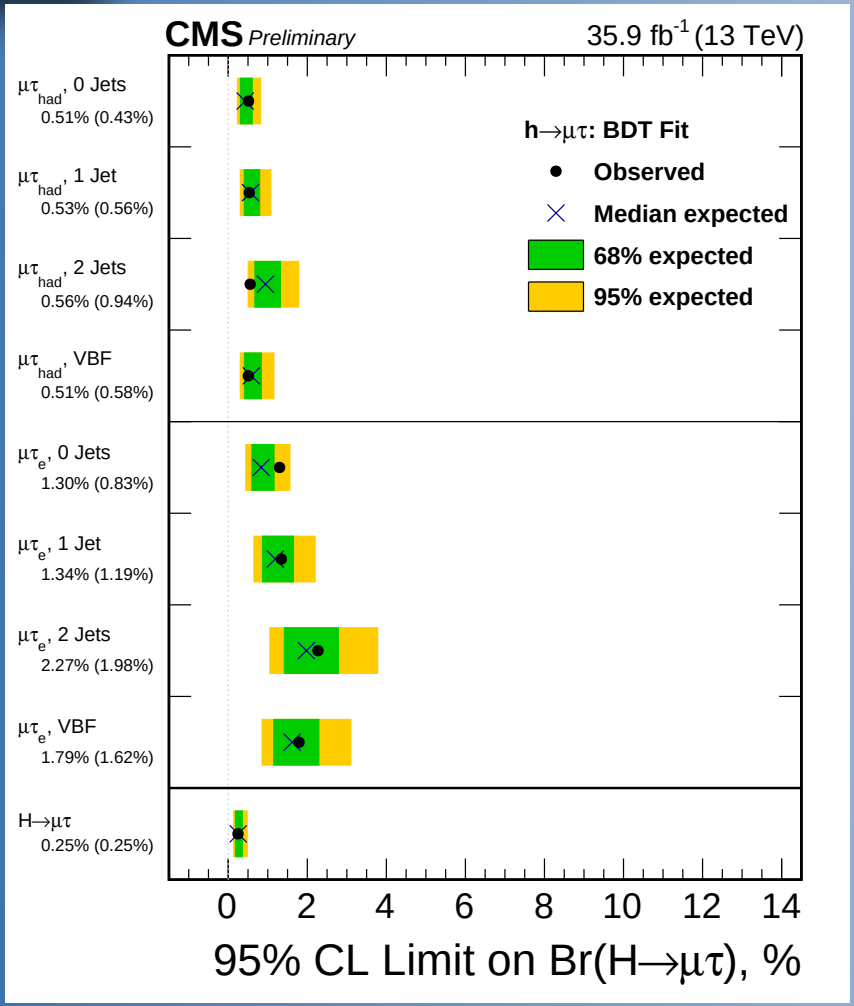
Interpretation for $\mu\tau$



Limits

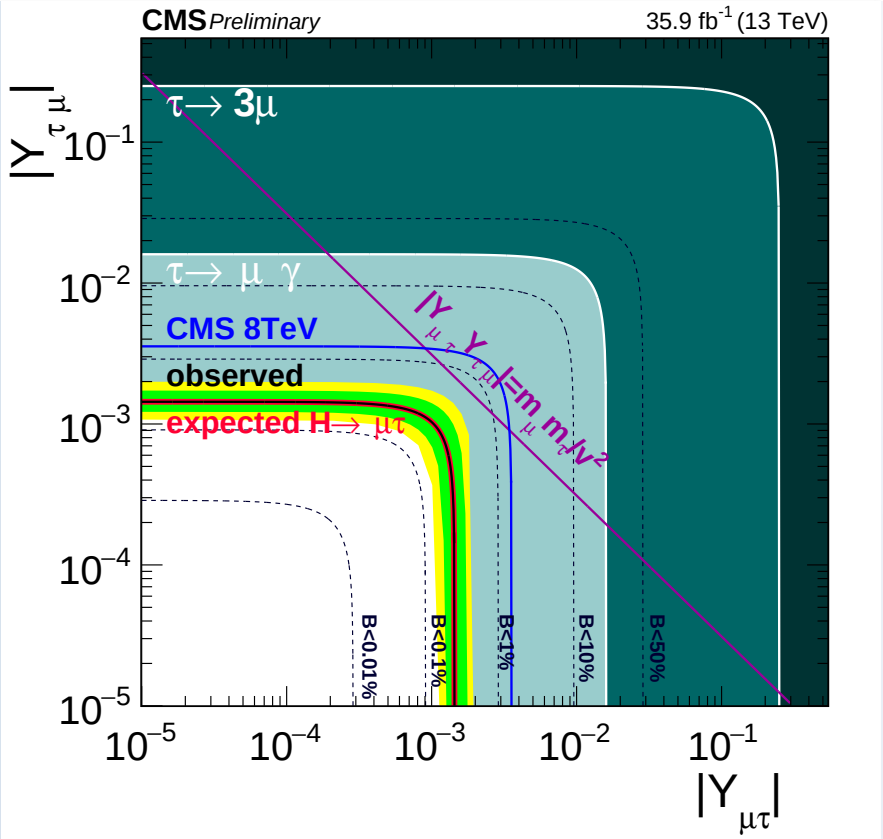
- Observed and expected limit on $\mathcal{B}(H \to \mu\tau)$

Interpretation for μτ



Reinterpretation

- Treat as LFV Yukawa coupling $Y_{\mu\tau}$
- Limit: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \cdot 10^{-3}$



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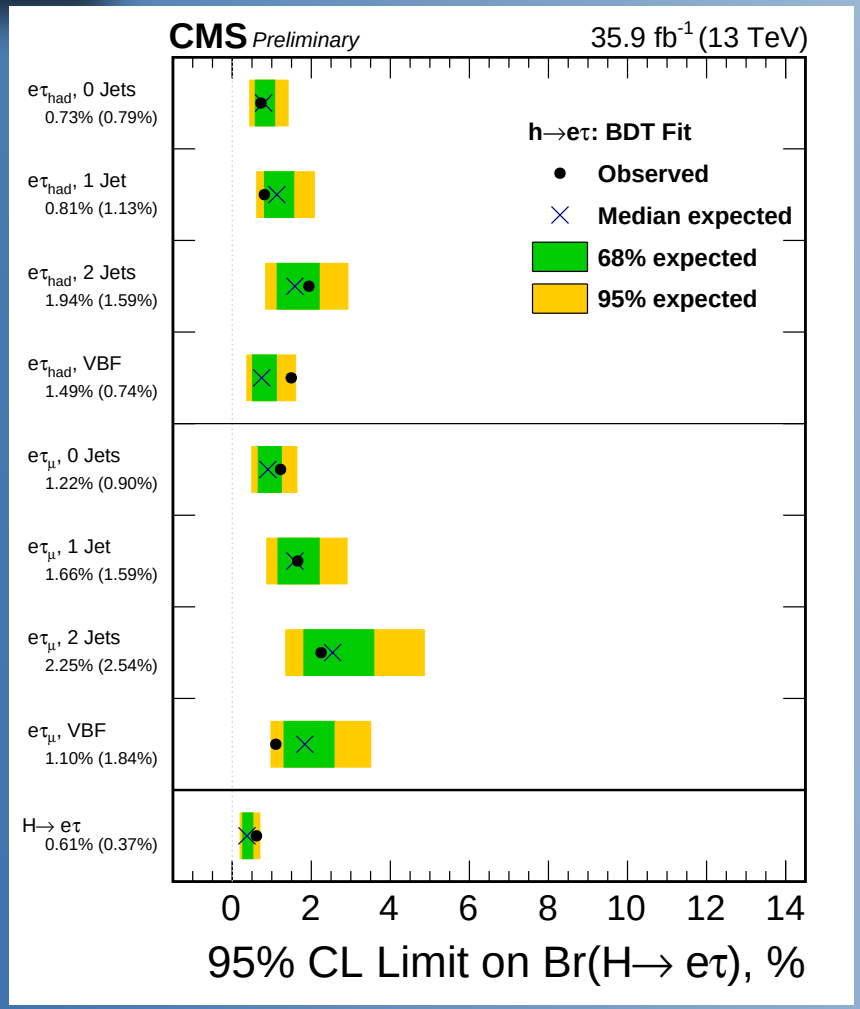
Interpretation for $e\tau$



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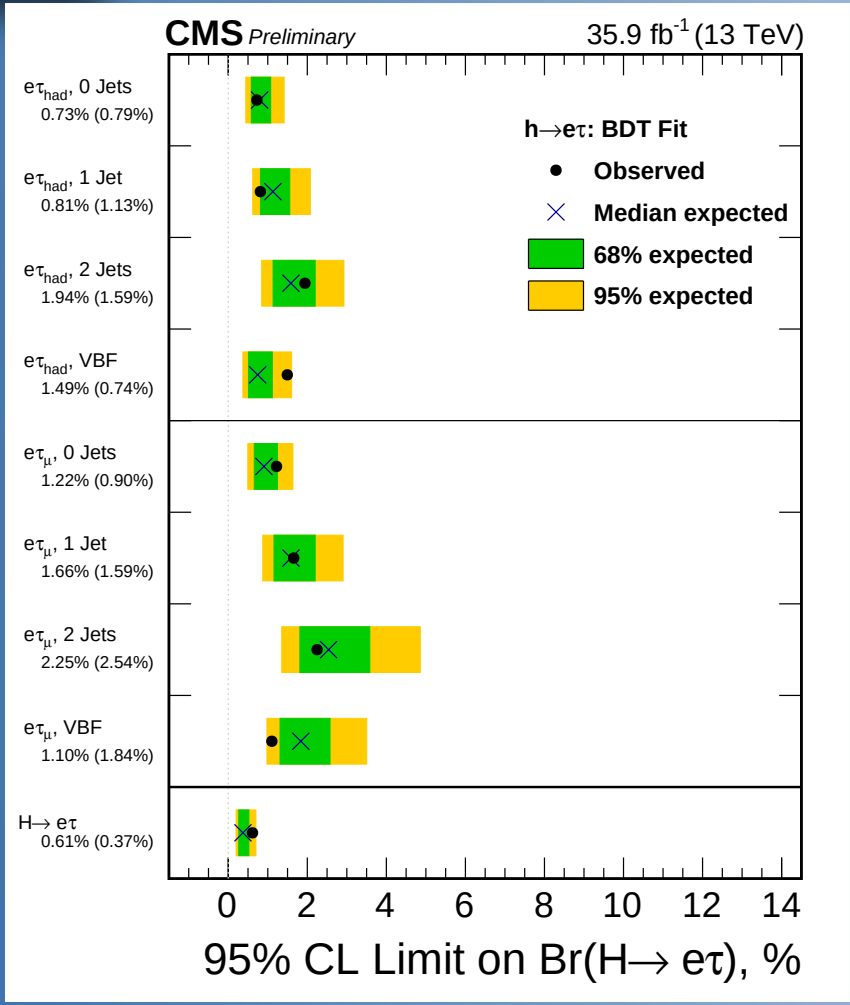
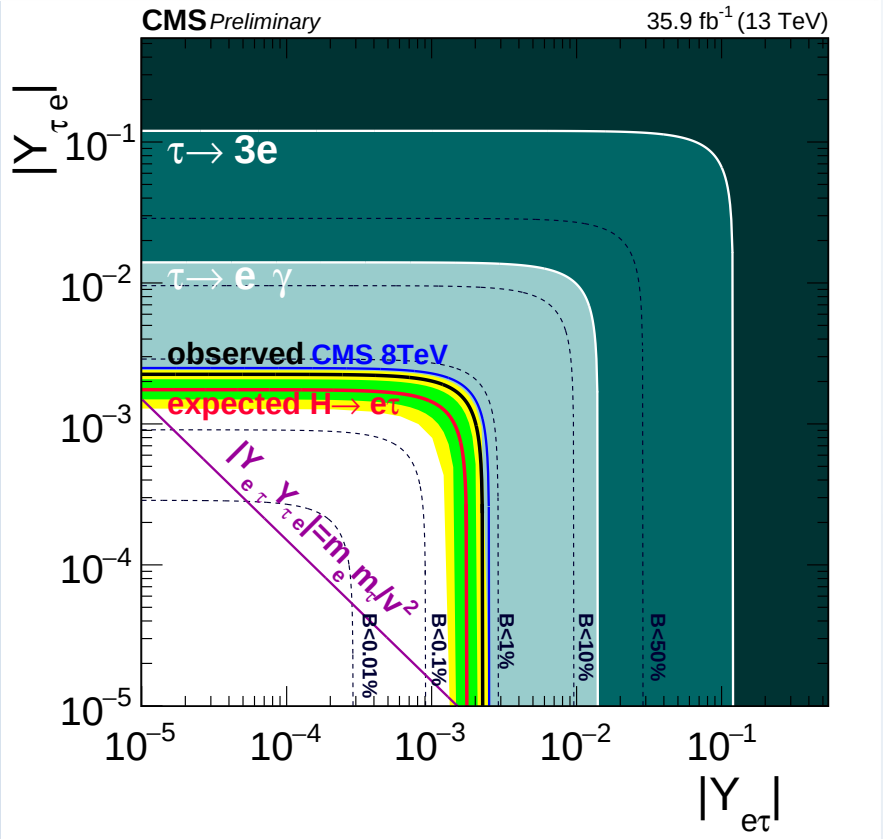


Reinterpretation

- Treat as LFV Yukawa coupling $Y_{e\tau}$
- Limit: $\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26 \cdot 10^{-3}$



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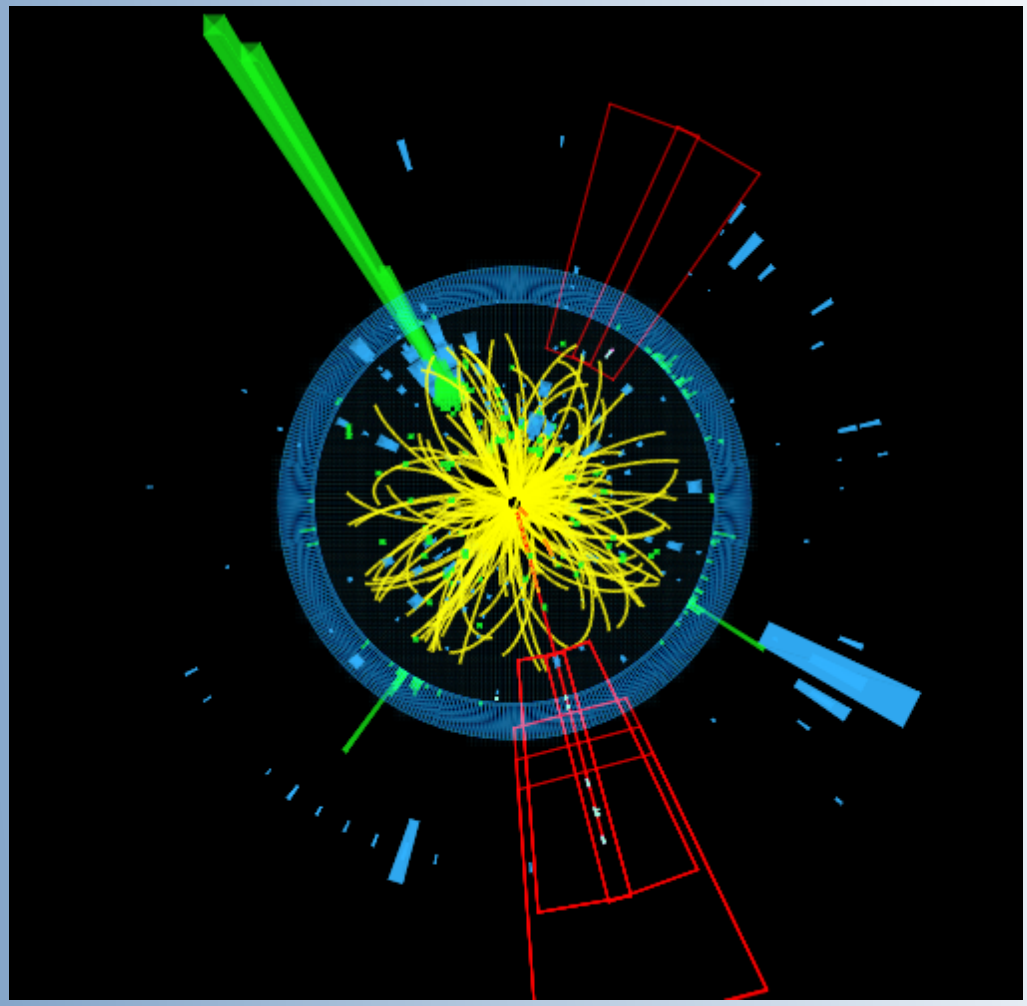

$M_{e\mu} = 1.9\,\text{TeV}$

Introduction

CMS PAS-EXO-16-001 [3]

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Motivation

- R-parity violating SUSY model (RPV $\tilde{\nu}_\tau$)
- Quantum black holes (QBH)
- Decay to high mass $e\mu$ pairs

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Analysis key points

- 2015 data set of $2.7\,\mathrm{fb}^{-1}$ of proton-proton data at $\sqrt{s} = 13\,\mathrm{TeV}$
- Search for high mass resonances

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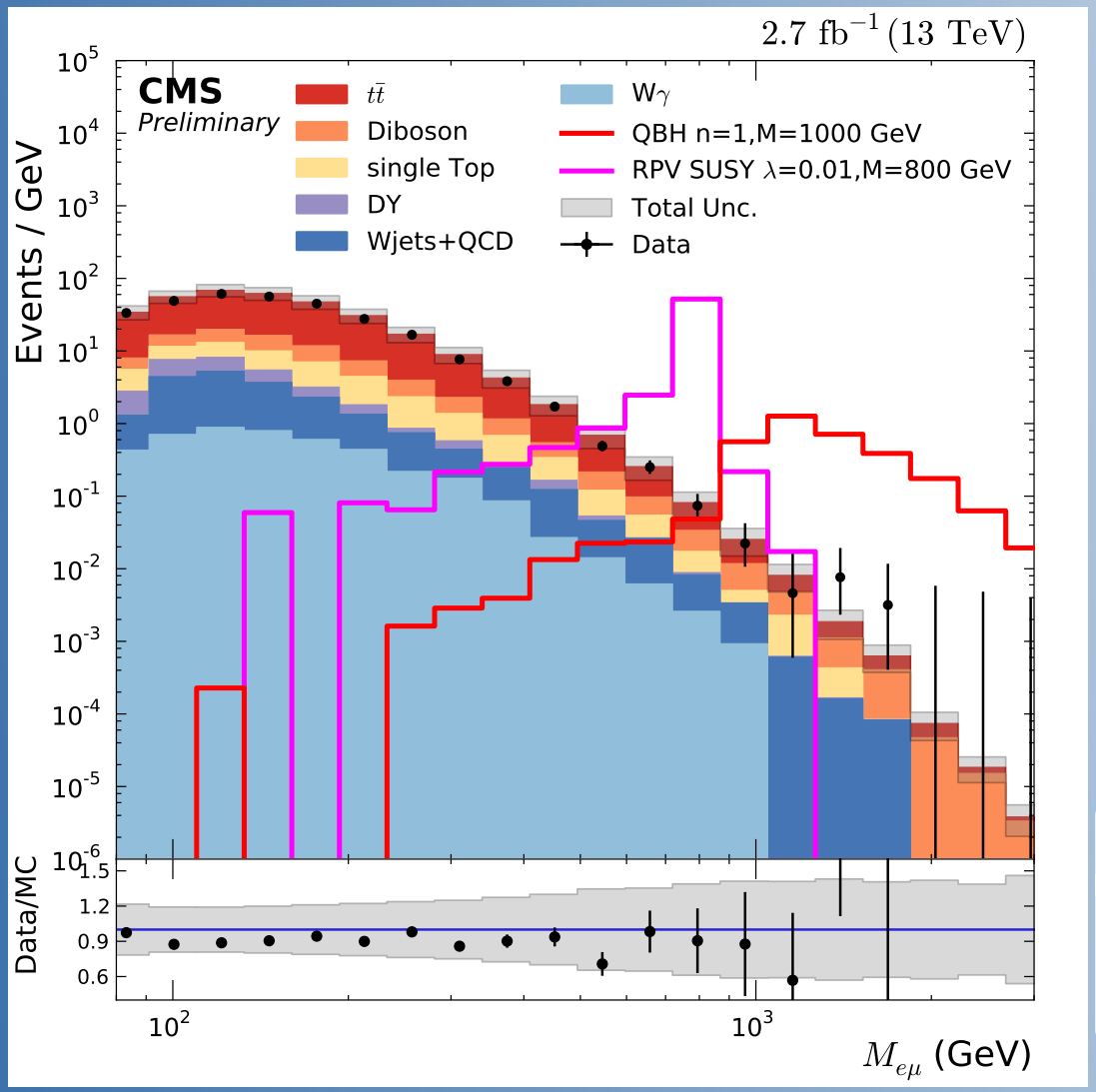
Event selection

- Dedicated high E_T/p_T identification criteria for electrons/muons
- Final selection efficiency at $M_{\tilde{\nu}_\tau} = 1\,\mathrm{TeV}$: $\sim 65\%$ (similar for QBH)

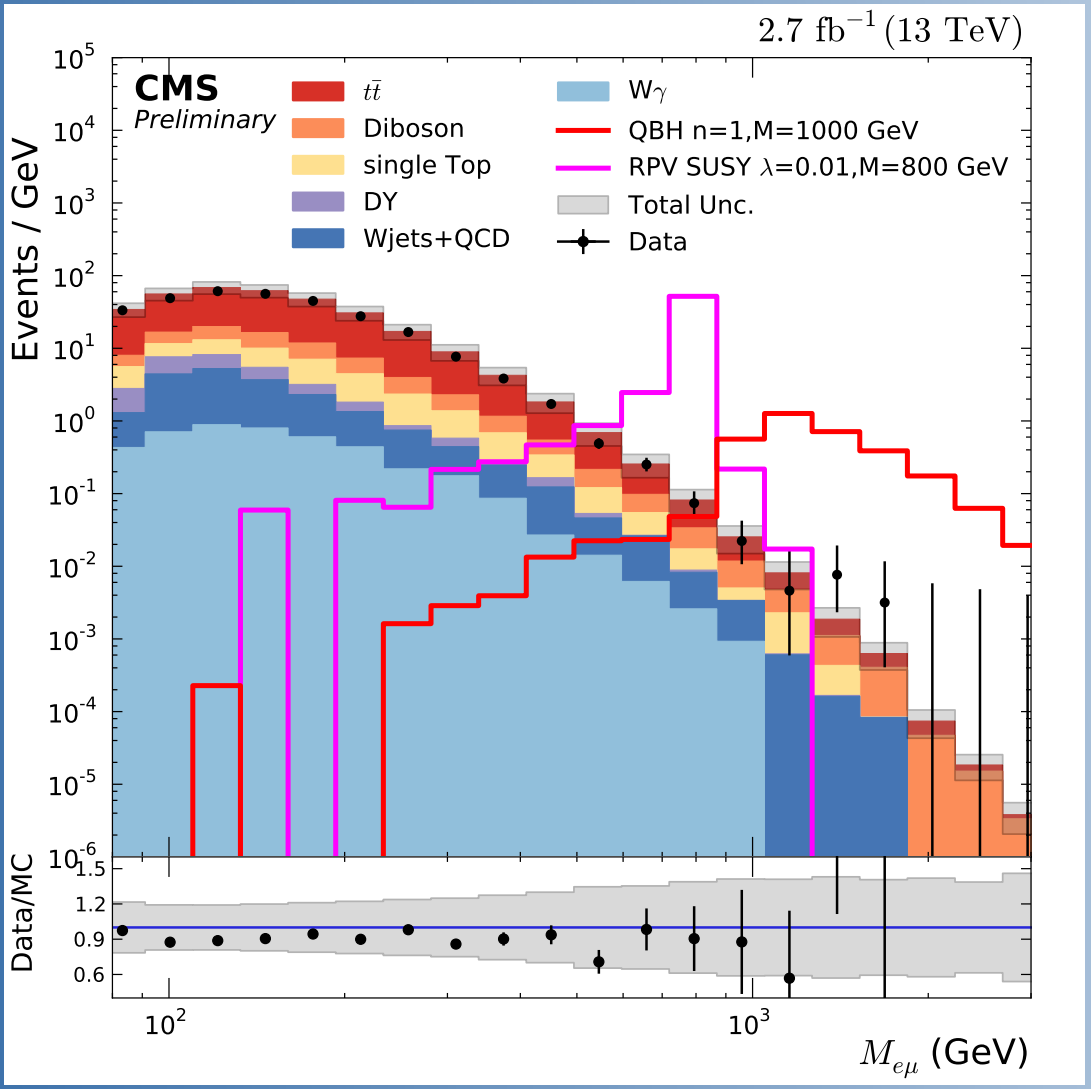
Mass distribution



Number of events

- Expected: 10379 ± 1557
- Observed: 9608

Mass distribution



Systematic uncertainties

- Luminosity: 2.7%
- Normalisation: 5%
- μ p_T scale: ~ 10%
- Top background shape: ~ 20%
- Total uncertainty:
  - 15% at 200 GeV
  - 31% at 2 TeV

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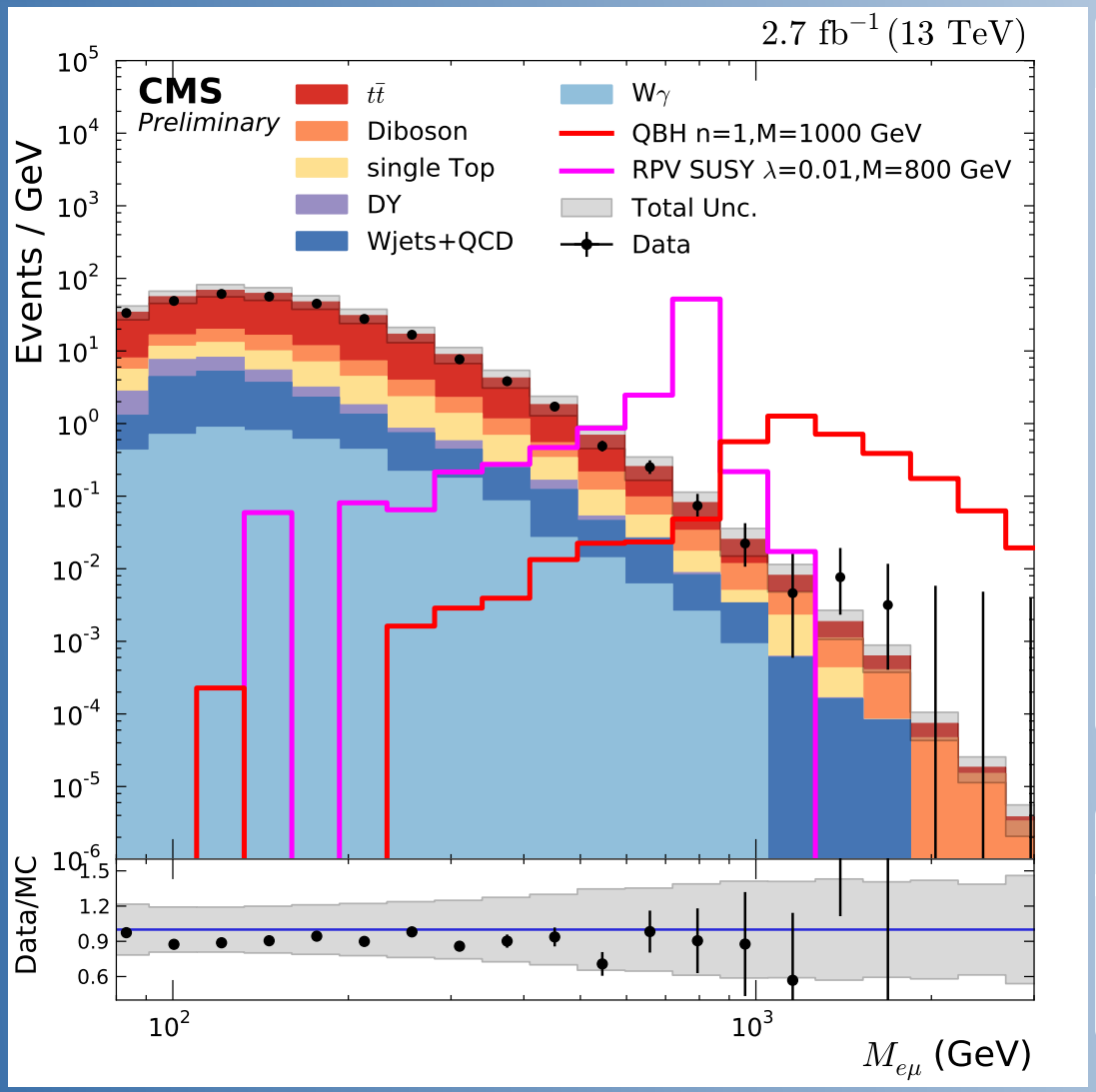

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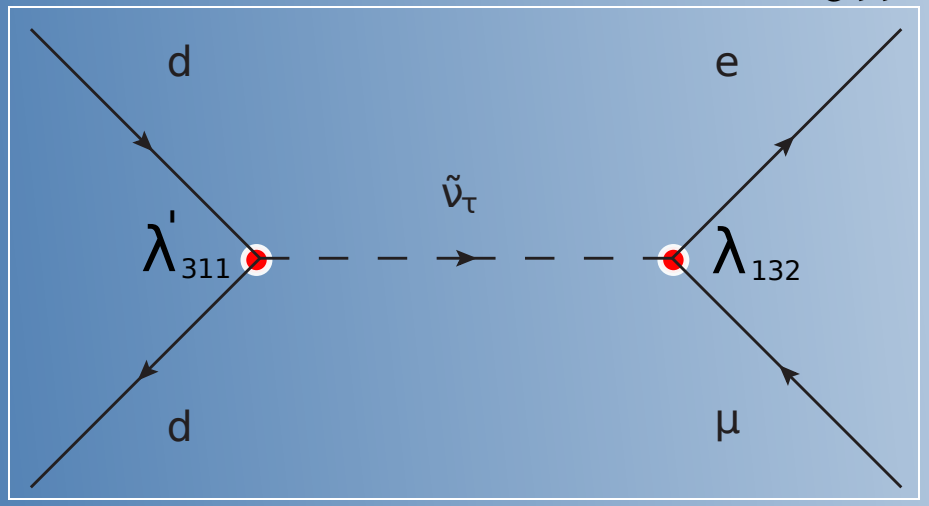
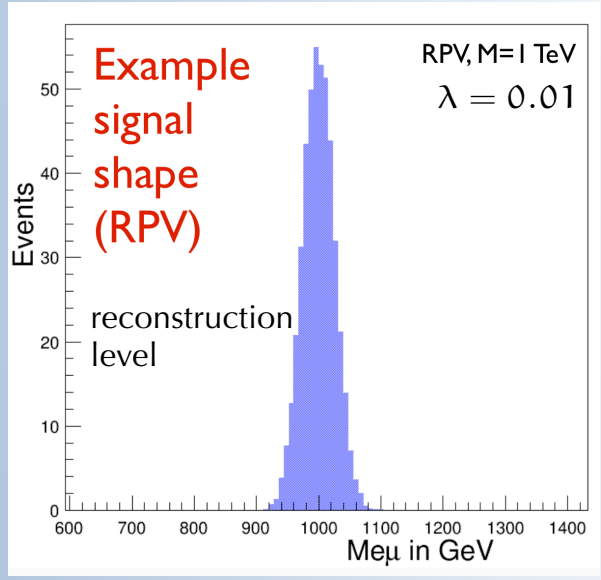
Introduction RPV

- R-parity violating supersymmetry (RPV SUSY) model
- Resonant sparticle production is allowed
  - Assume $\tilde{\nu}_\tau$ to be the LSP
  - Assume two dominant couplings λ'_{311} (production) and λ_{132} (decay)



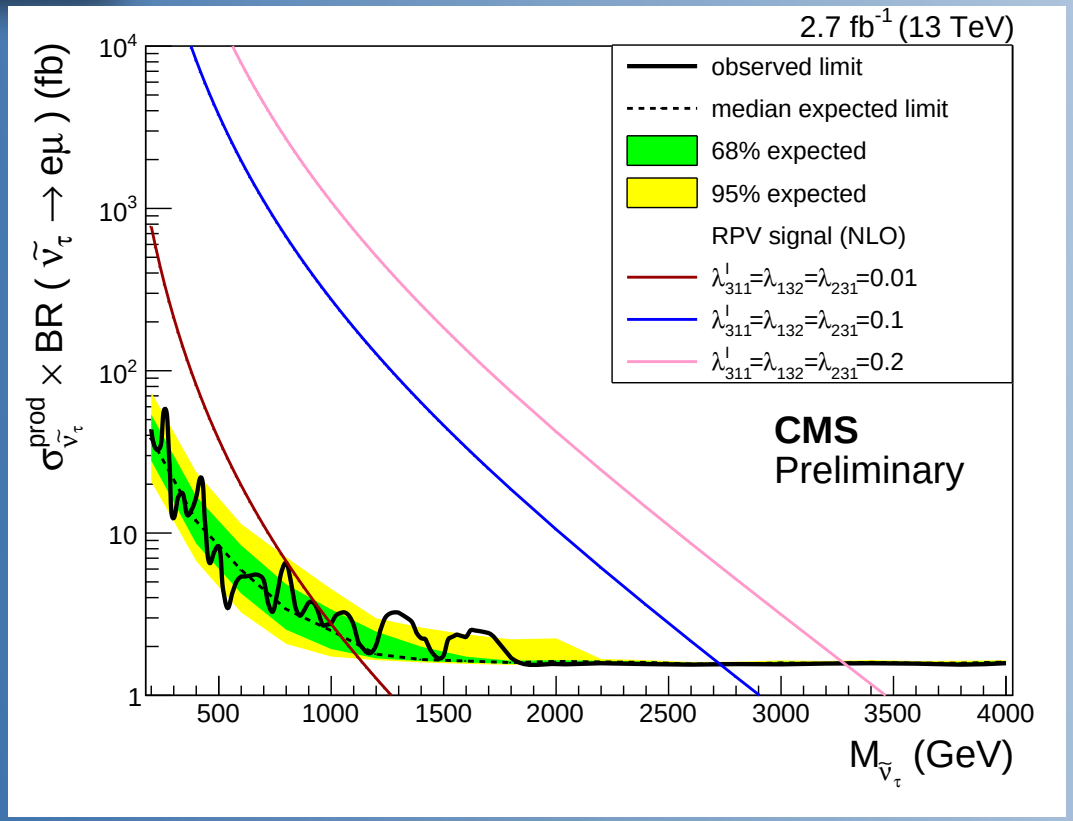


  - eμ resonance with narrow width

$$\Gamma_{tot} = \left(3\lambda'^2_{311} + 2\lambda^2_{132}\right) M(\tilde{\nu}_\tau)/16\pi$$

- Three model parameters: λ'_{311}, λ_{132} and $M_{\tilde{\nu}_\tau}$

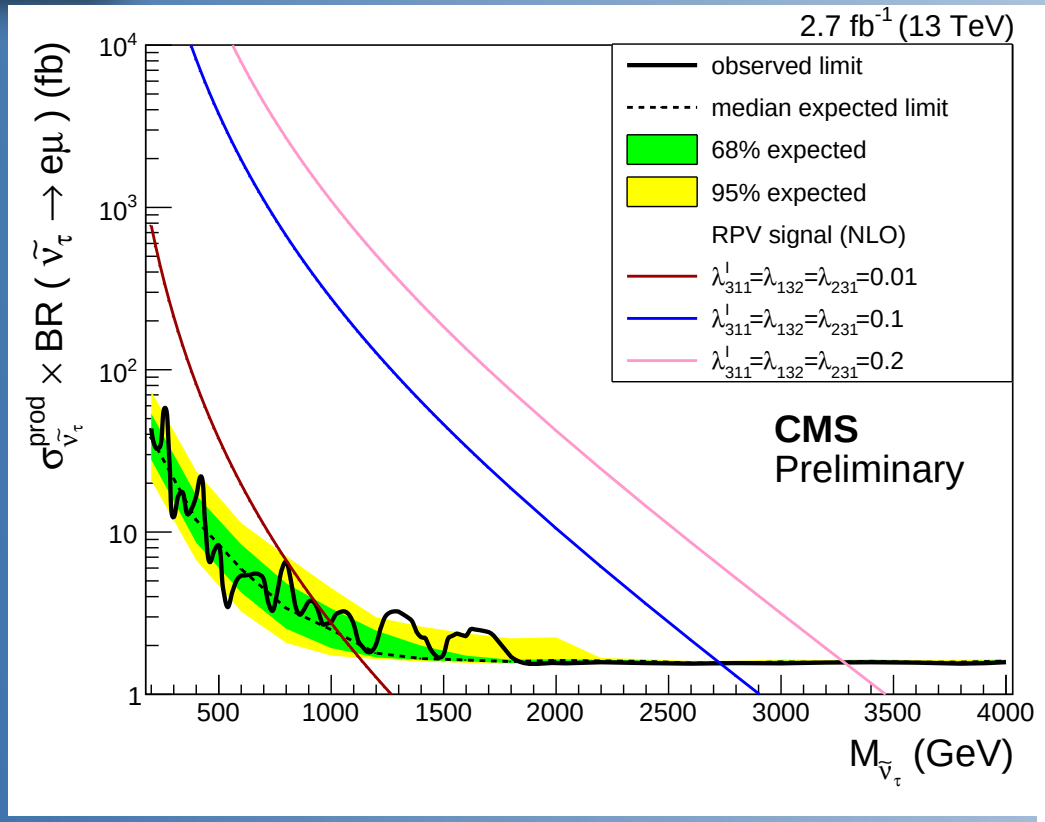
RPV Result

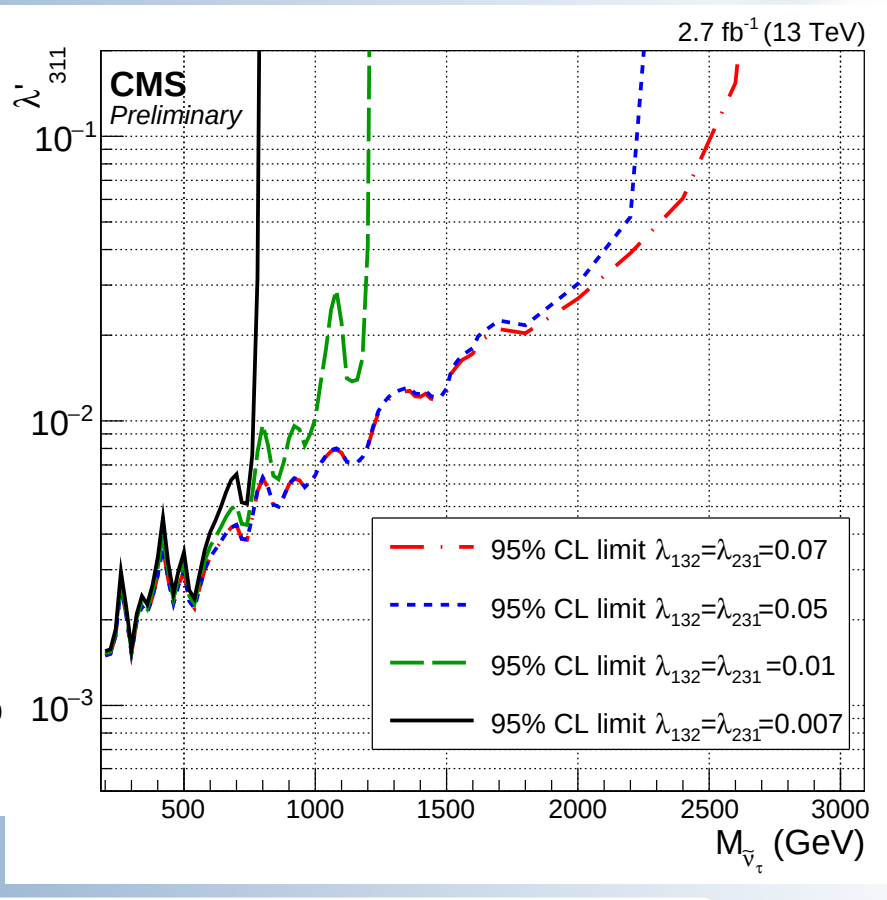


Exclusion limits

- Excluded cross section $\times$ BR
- Mass limit for $\lambda = 0.01$ of 1.0 TeV

RPV Result





Exclusion limits

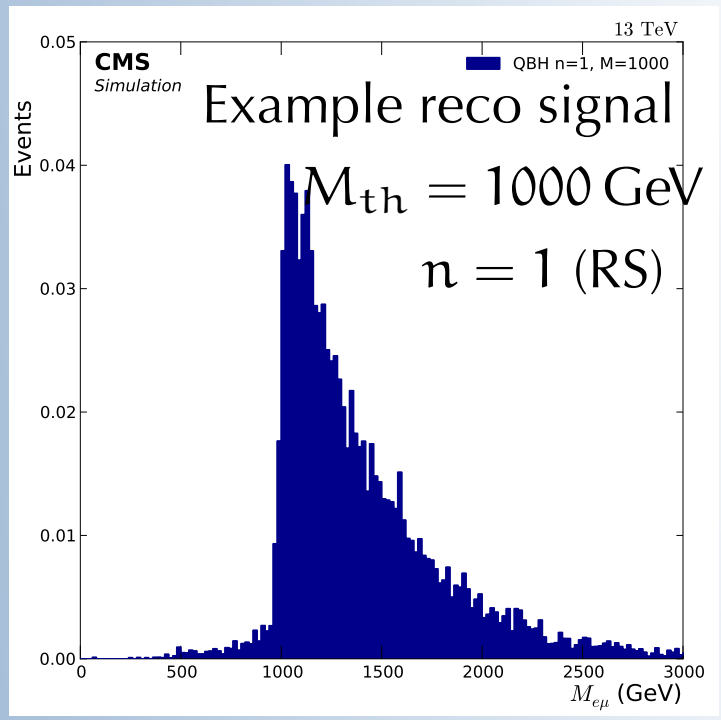
- Excluded cross section $\times$ BR
- Mass limit for $\lambda = 0.01$ of 1.0 TeV
- Limit also in the $M_{\tilde{\nu}_\tau} - \lambda_{311}$-plane

Introduction QBH

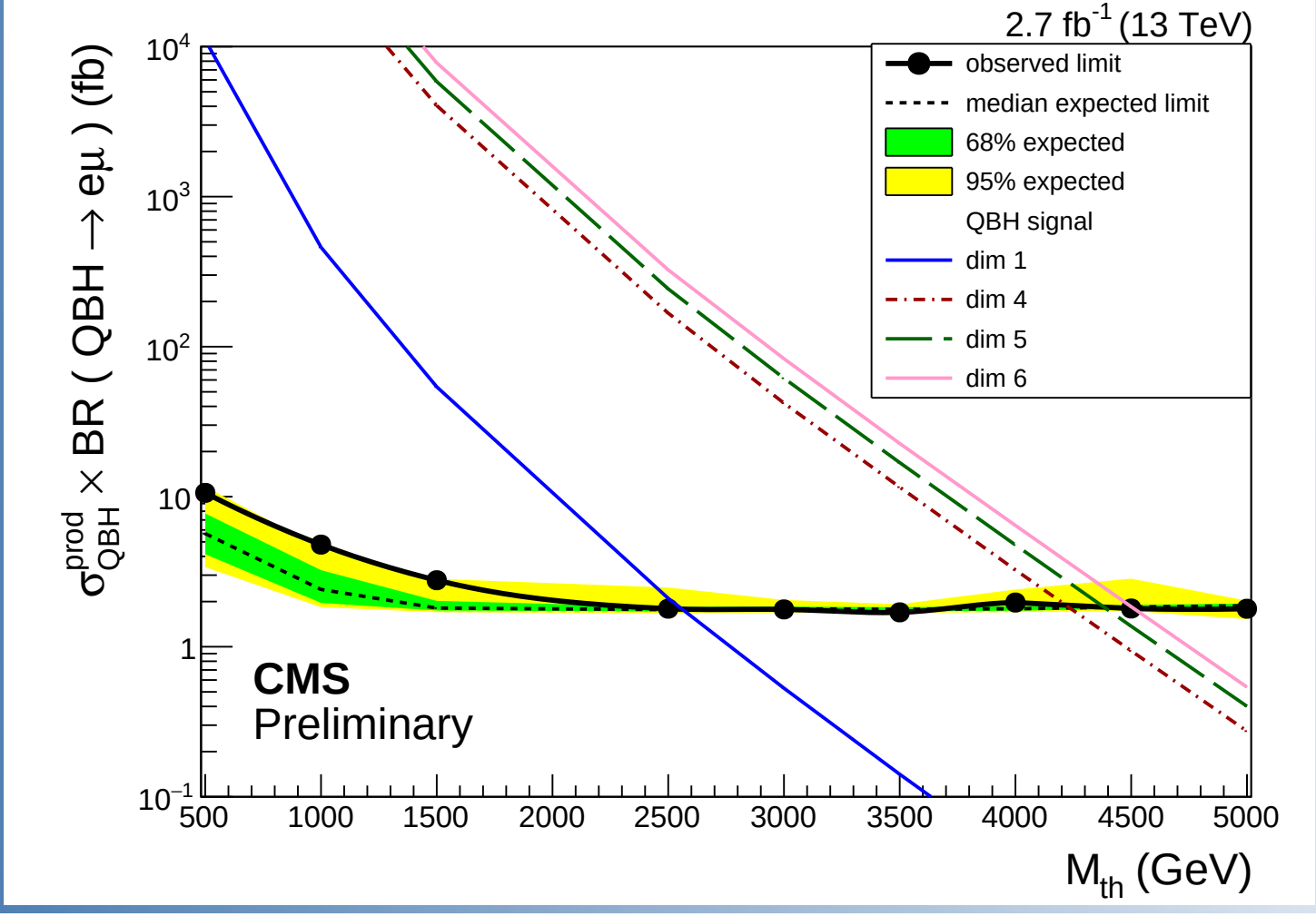
Quantum black holes (QBH):

- Can be produced in low scale gravity scenarios at the LHC
- Planck scale smaller than a few TeV
- No Hawking radiation (many particle final state)
- Decay into $e + \mu$

- Spin-0, colorless, neutral QBH
- Model parameters:
  - Threshold mass: M_{th}
  - Number of extra dimensions: n
  - Extra dimension model: Randall-Sundrum (RS) or Arkani-Hamed-Dimopoulos-Dvali (ADD)
- Signal shape:
  - Threshold of QBH production
  - Signal falls for high mass due to PDFs



QBH Result



Exclusion limits

- Excluded cross section $\times$ BR
- Mass threshold limit for $n = 1$ ($n = 6$) of 2.5 TeV (4.5 TeV)

Outline

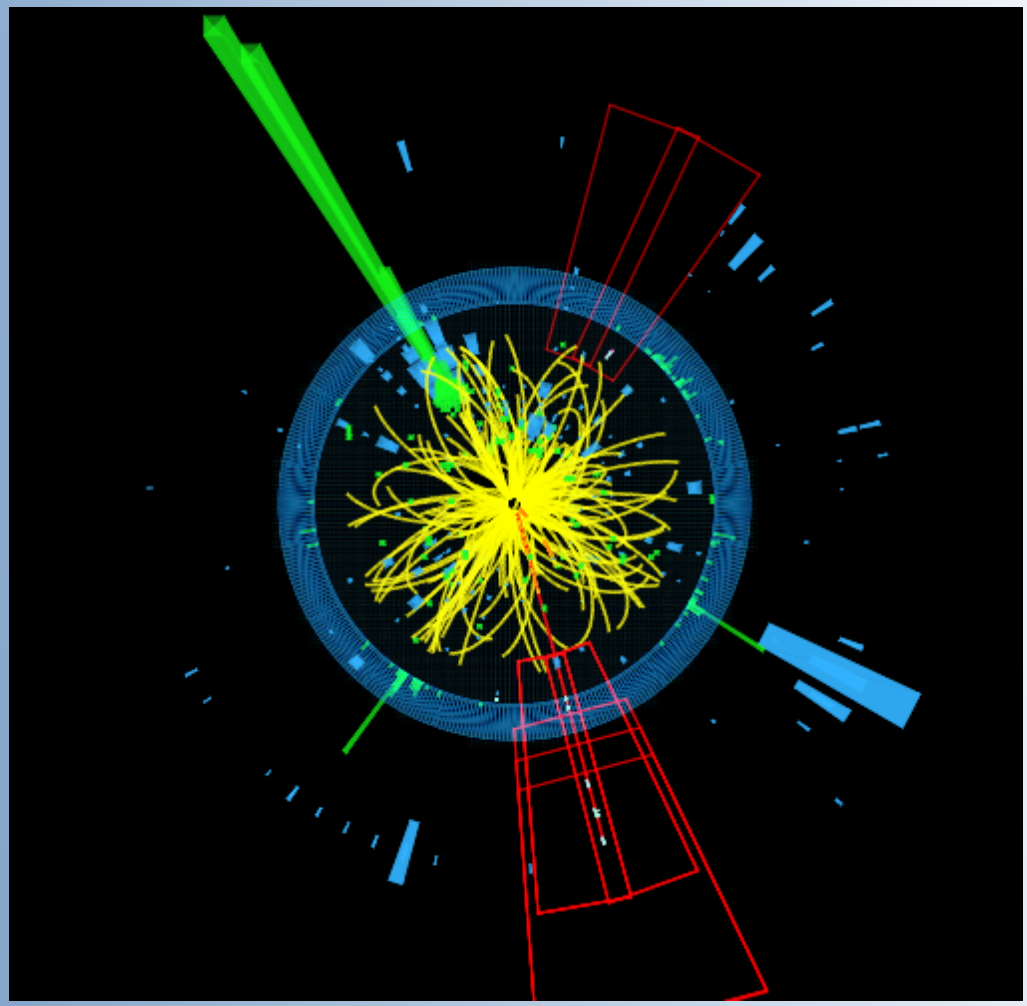
1 Introduction

2 Z-Boson

3 Higgs-Boson

4 BSM particle

5 Summary



$M_{e\mu} = 1.9\,\text{TeV}$

Summary

Z Boson (CMS PAS-EXO-13-005)

- Search for $Z \to e\mu$ decays
- Limit on the branching ratio $\mathcal{B}(Z \to e\mu) < 7.3 \cdot 10^{-7}$

H Boson (CMS PAS-HIG-17-001)

- Search for $H \to e\tau$ and $H \to \mu\tau$ decays
- Limit on $\mathcal{B}(H \to e\tau/\mu\tau)$ of $< 0.61\,\%$ / $< 0.25\,\%$
- Limit on LFV Yukawa coupling
  - $\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26 \cdot 10^{-3}$
  - $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \cdot 10^{-3}$

BSM particles (CMS PAS-EXO-16-001)

- Search for new high mass particles decaying to $e\mu$
- Limit on RPV: $M_{\tilde{\nu}_\tau} > 1.0\,\text{TeV}$ for $\lambda = 0.01$
- Limit on QBH: $M_{th} > 4.5\,\text{TeV}$ for $n = 6$

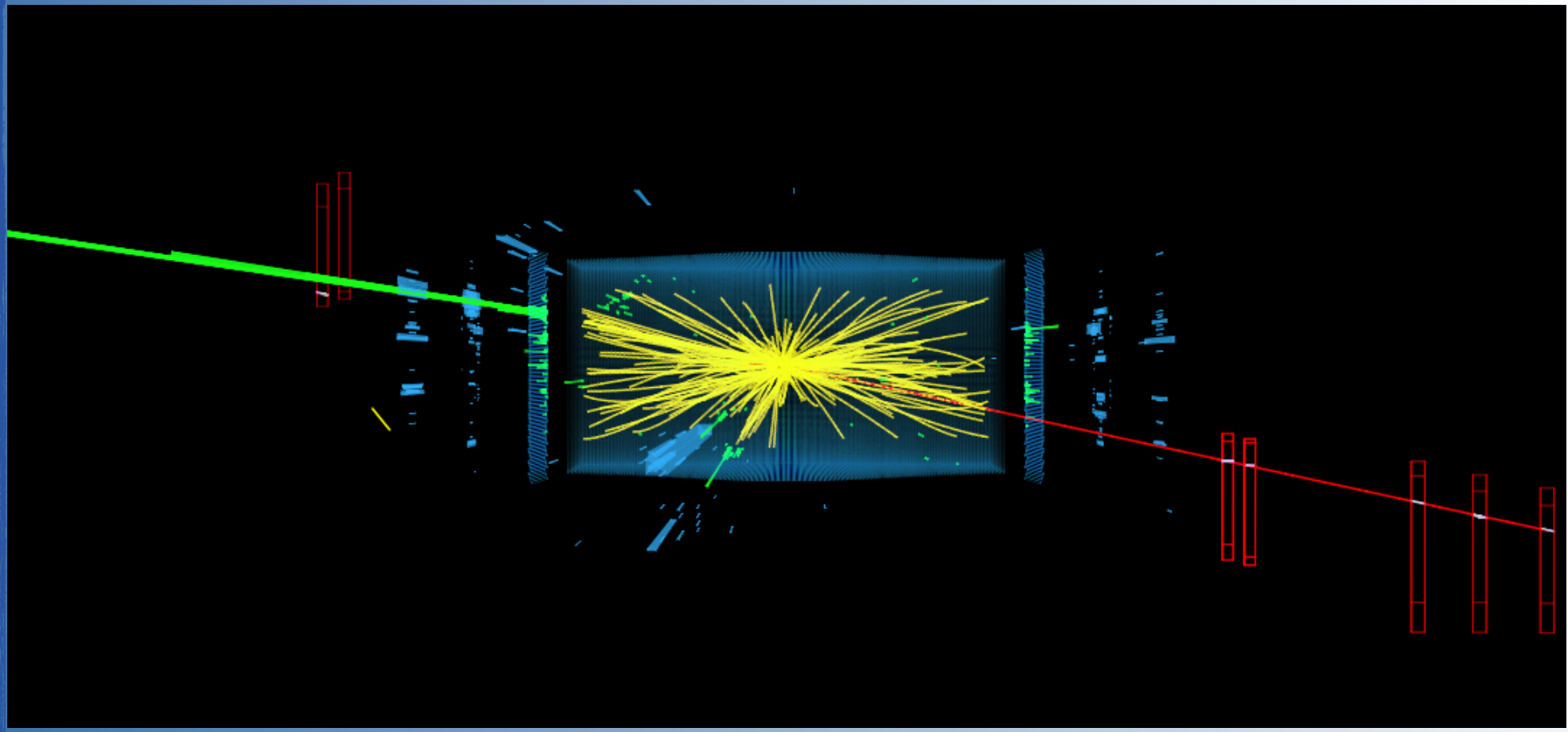
All CMS physics results can be found at ▸ link

Backup

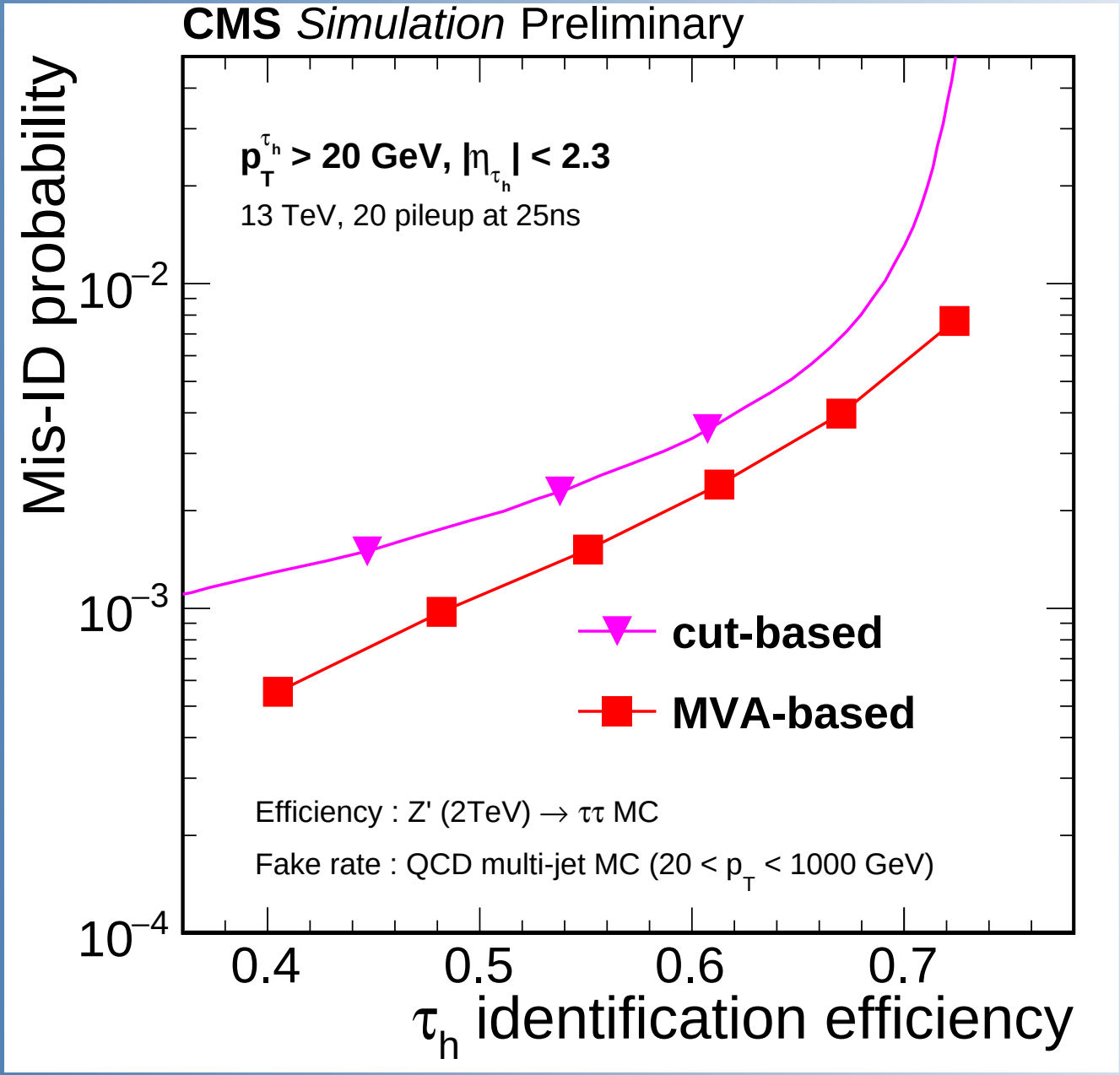
References

- Search for Lepton Flavor Violation in Z decays in pp collisions at sqrt(s)=8 TeV.
  Technical Report CMS-PAS-EXO-13-005, CERN, Geneva, 2015.
- Search for lepton flavour violating decays of the Higgs boson to $\mu\tau$ and $e\tau$ in proton-proton collisions at $\sqrt{s} = 13$ TeV.
  Technical Report CMS-PAS-HIG-17-001, CERN, Geneva, 2017.
- Search for high-mass resonances and quantum black holes in the $e\mu$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV.
  Technical Report CMS-PAS-EXO-16-001, CERN, Geneva, 2016.

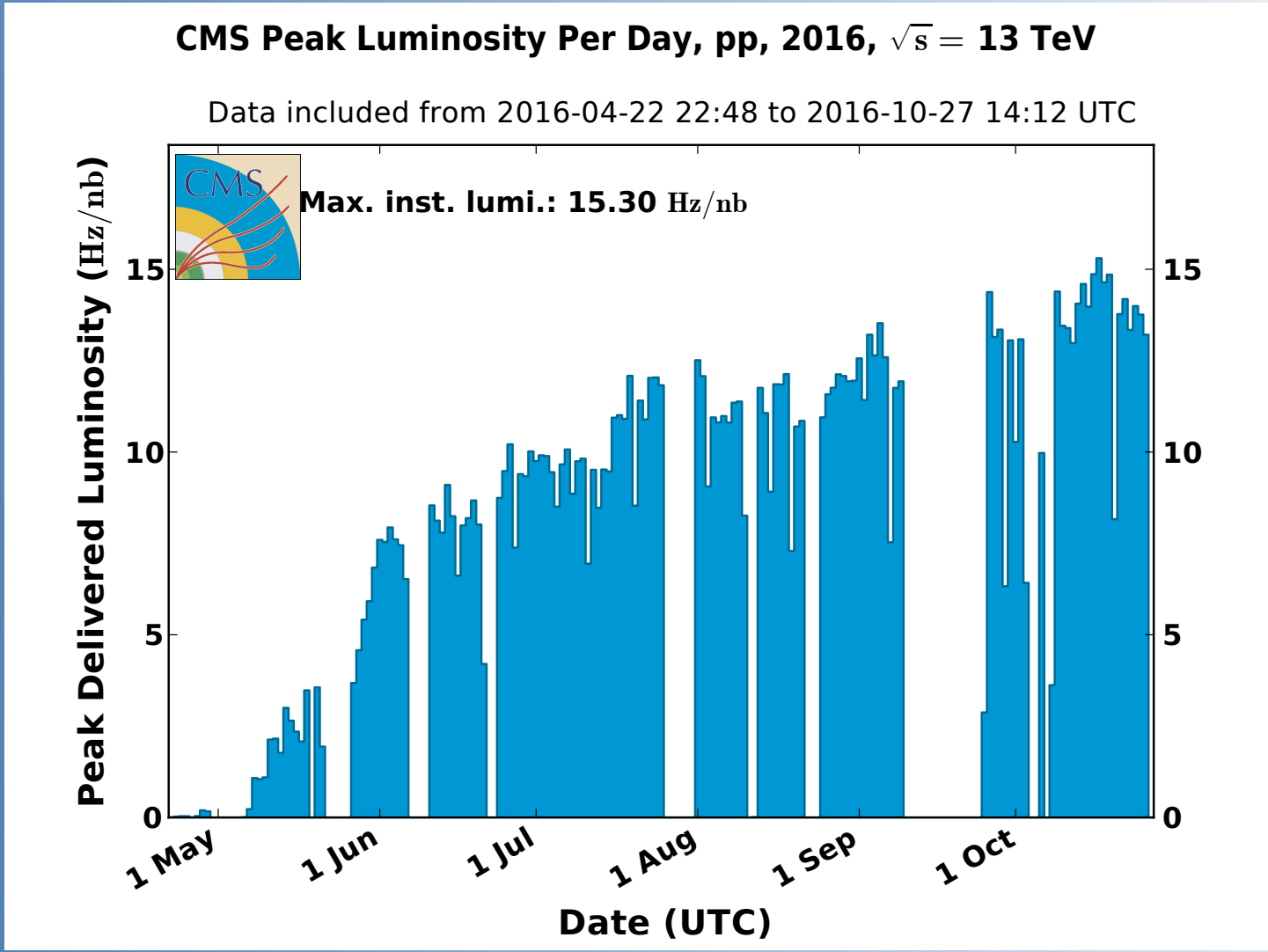
Eventdisplay $r - z$ view



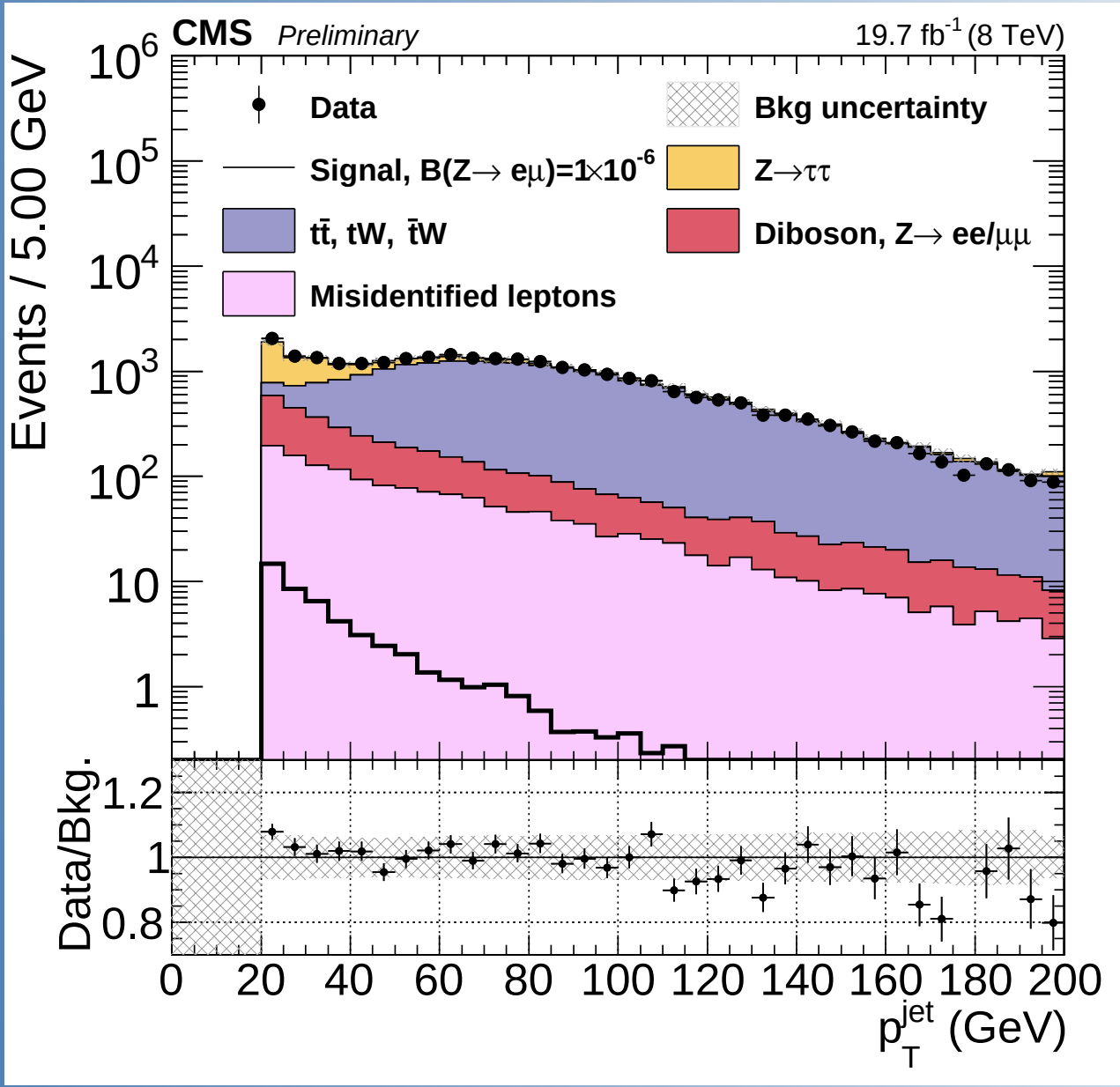
Tau ID performance



Peak luminosity (2016)



$Z \to e\mu$ jet p_T



Datadriven background estimate

Define regions: Signal (I), background enriched (III) and control (II and IV)

Region I	**Region II**
$\ell_1^{\pm}$ (isolated)	$\ell_1^{\pm}$ (isolated)
$\ell_2^{\mp}$ (isolated)	$\ell_2^{\pm}$ (isolated)
Region III	**Region IV**
$\ell_1^{\pm}$ (isolated)	$\ell_1^{\pm}$ (isolated)
$\ell_2^{\mp}$ (non-isolated)	$\ell_2^{\pm}$ (non-isolated)

Misidentification rate defined as (with $i = e, \mu, \tau$):

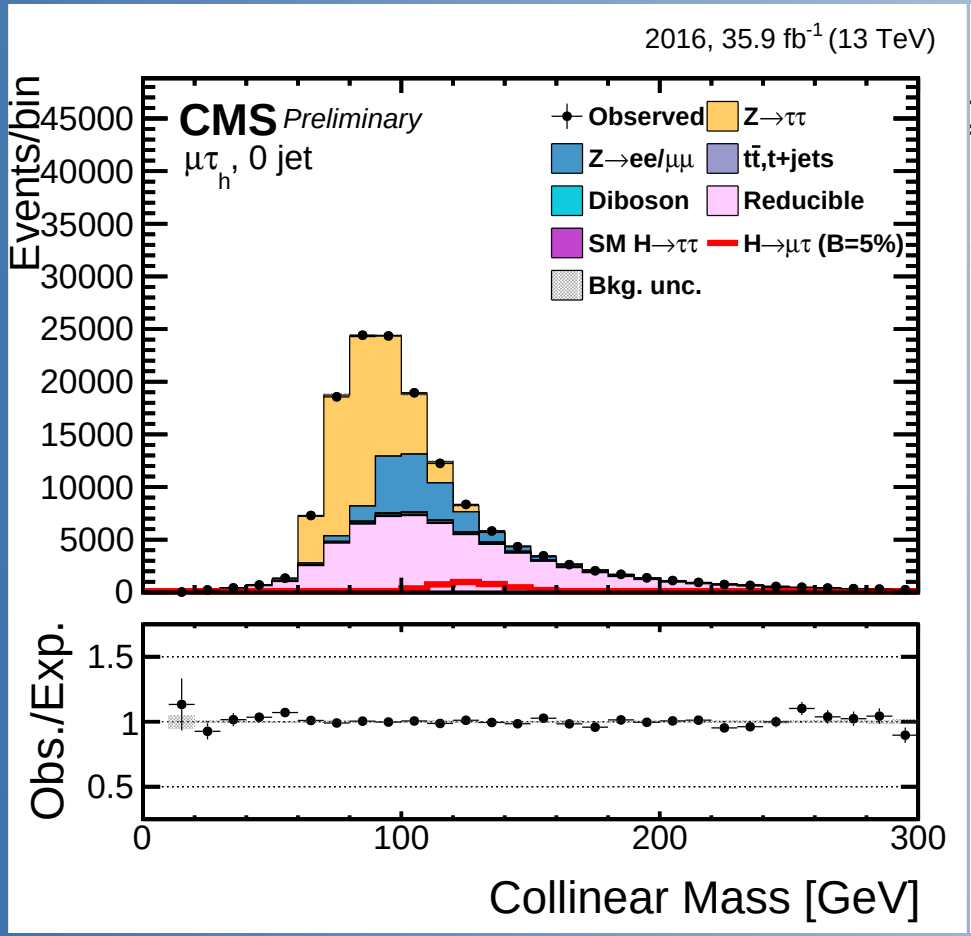
$$f_i = \frac{N_i\,(\text{region I})}{N_i\,(\text{region III}) + N_i\,(\text{region I})}$$

Number of misidentified events in the signal region:

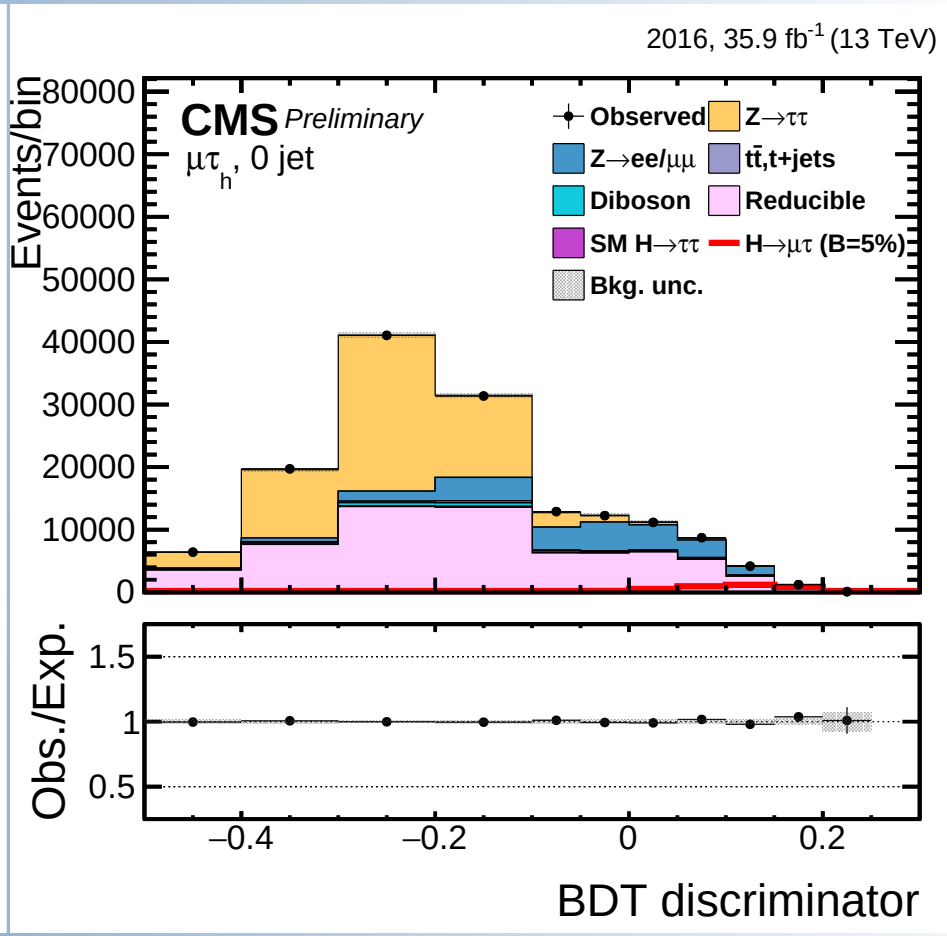
$$N_i\,(\text{misidentified}) = \frac{f_i}{1-f_i} N_i\,(\text{region III})$$

$\mu\tau_h$ channel, 0 Jets

Cut based analysis

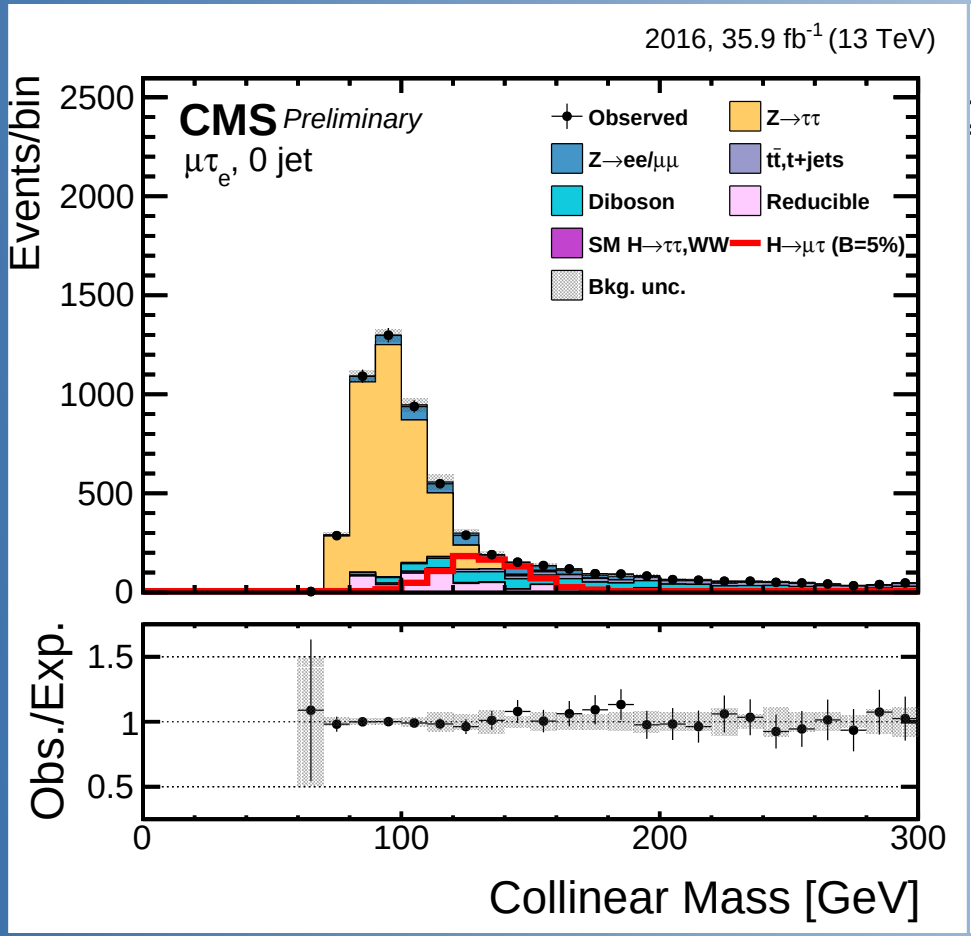


BDT analysis



$\mu\tau_e$ channel, 0 Jets

Cut based analysis



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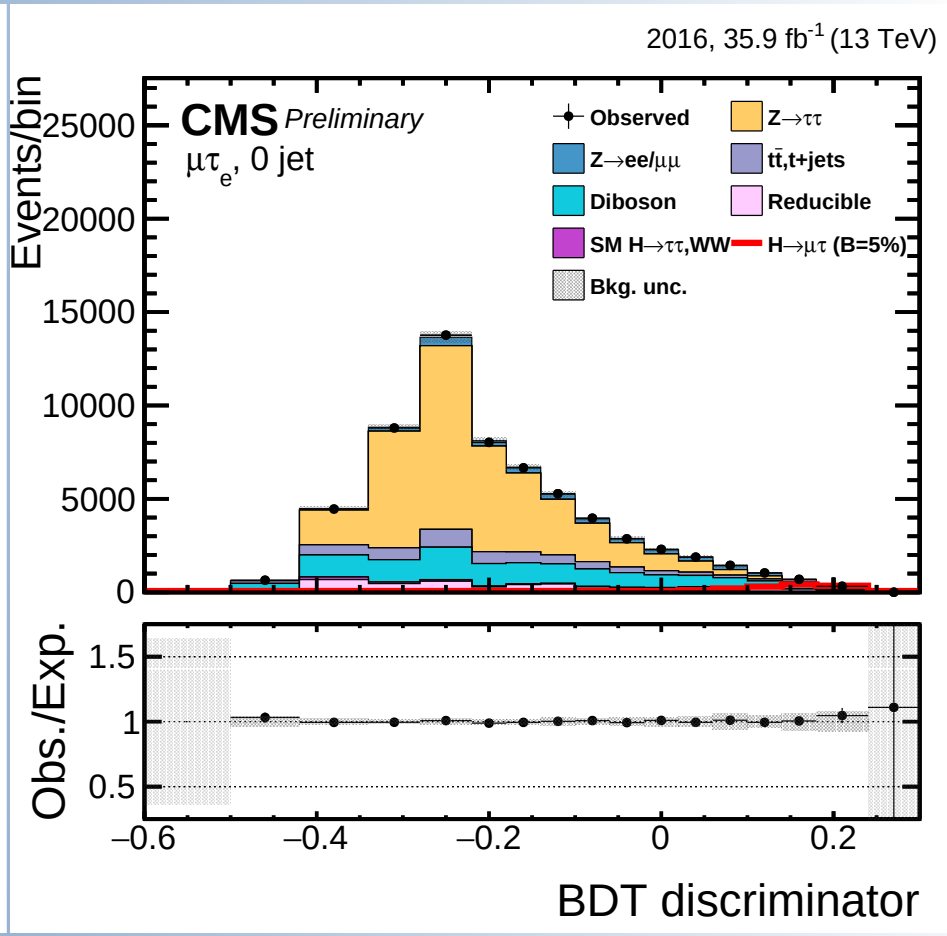
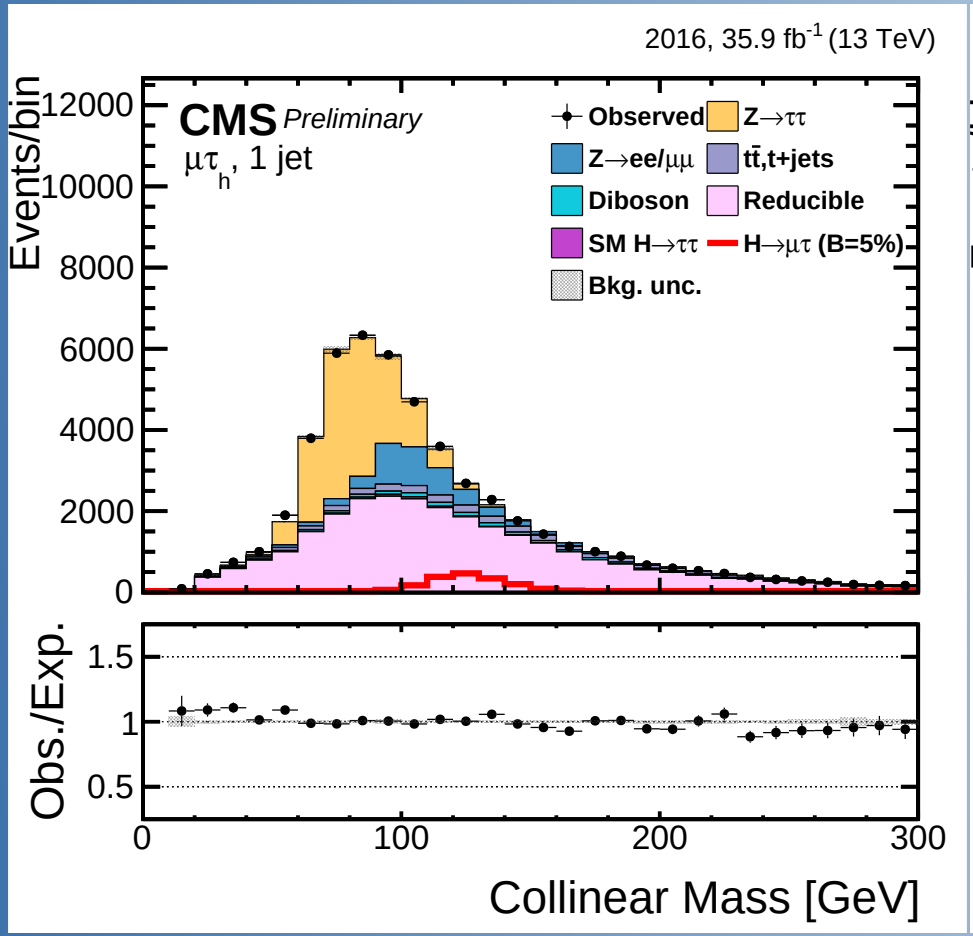


$\mu\tau_h$ channel, 1 Jets

Cut based analysis



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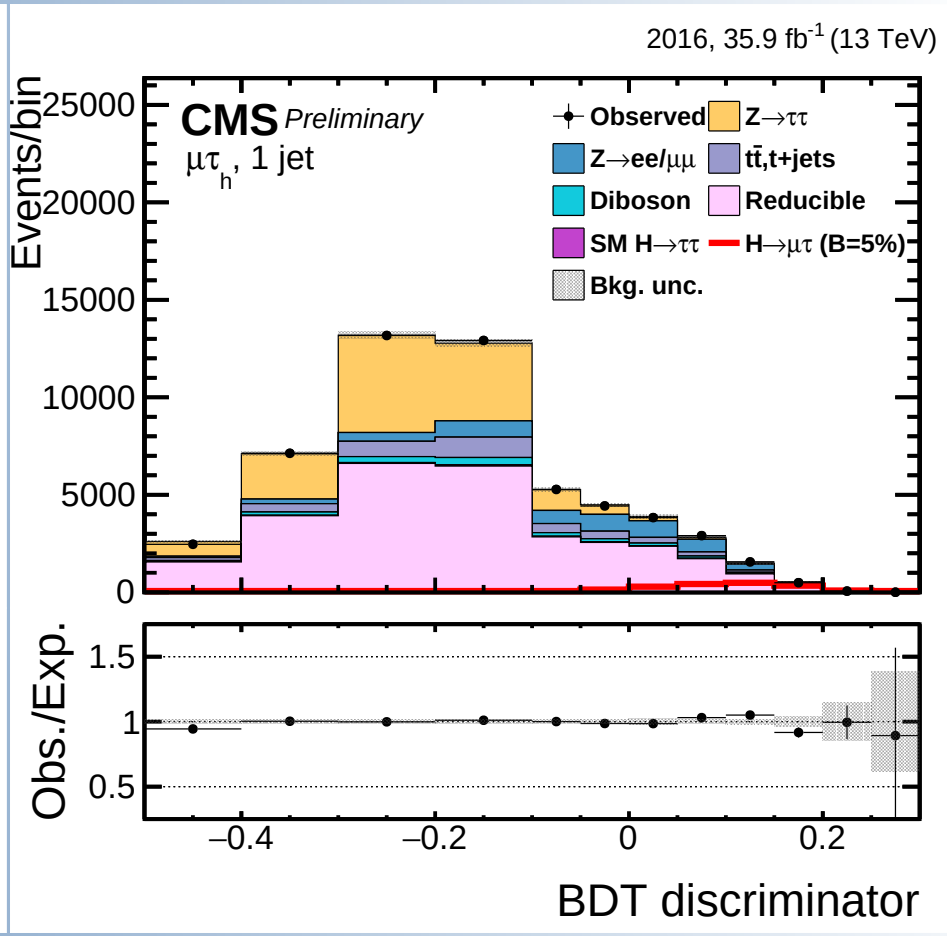

$\mu\tau_e$ channel, 1 Jets

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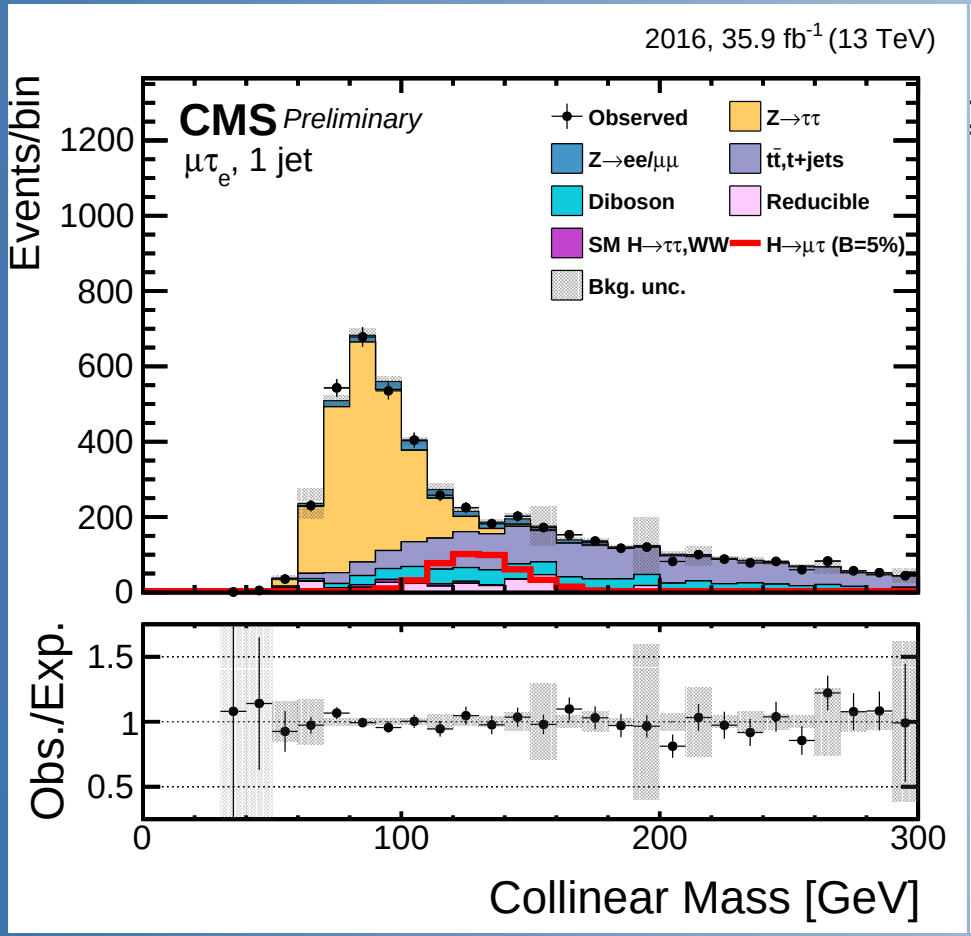

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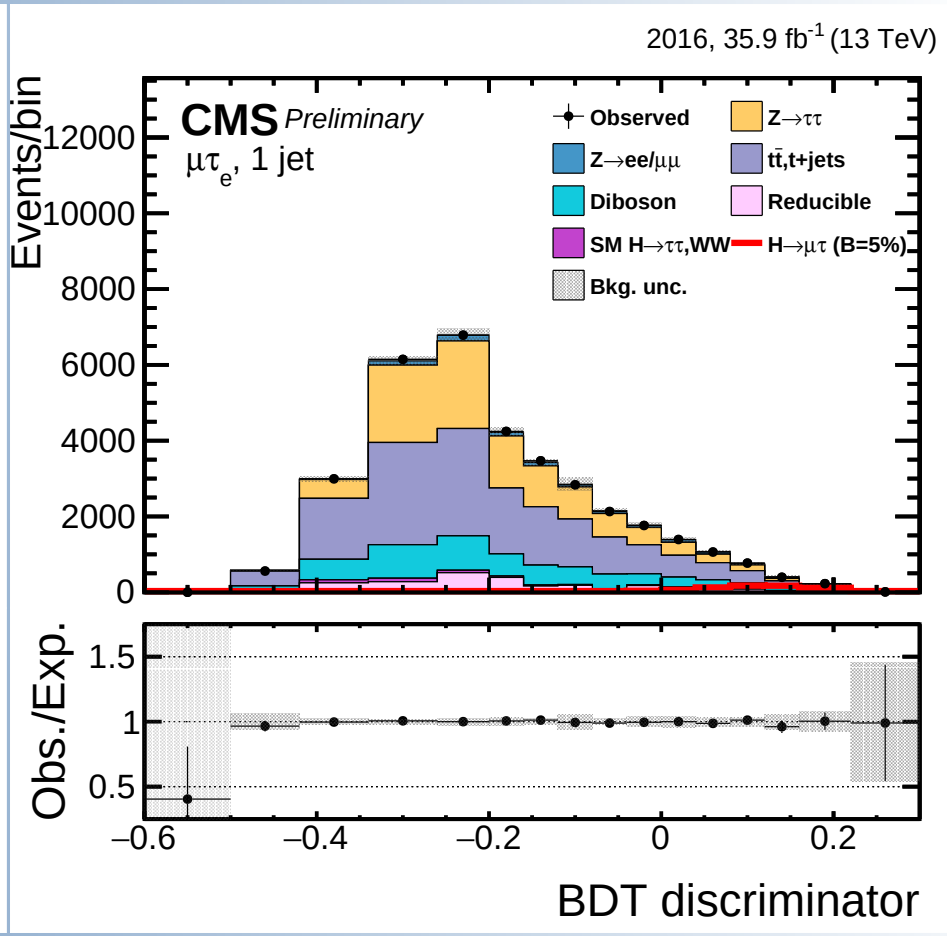
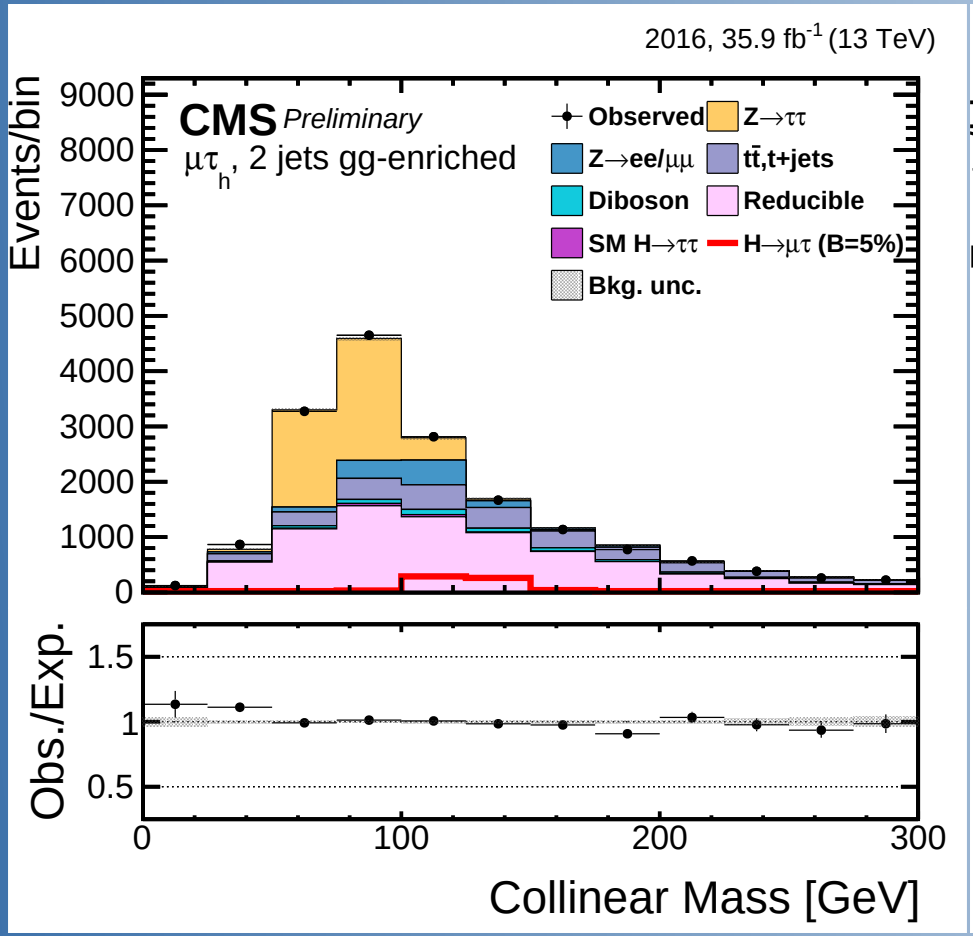


$\mu\tau_h$ channel, 2 Jets (gg)

Cut based analysis



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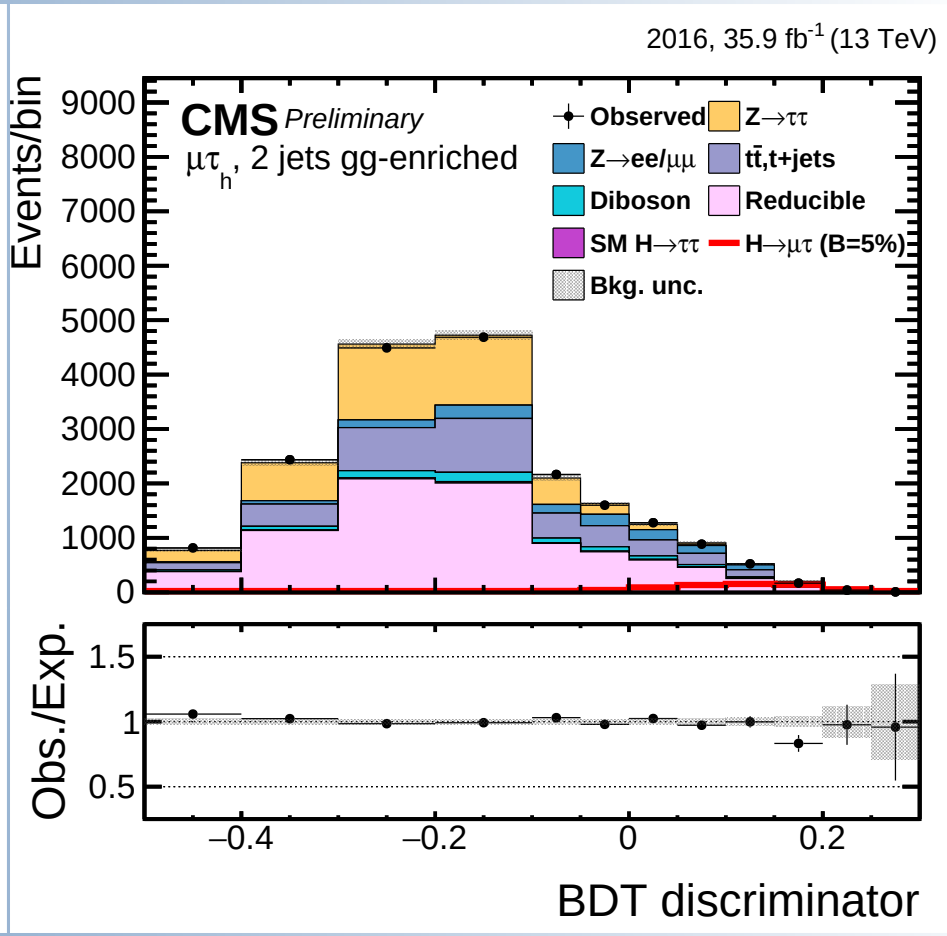

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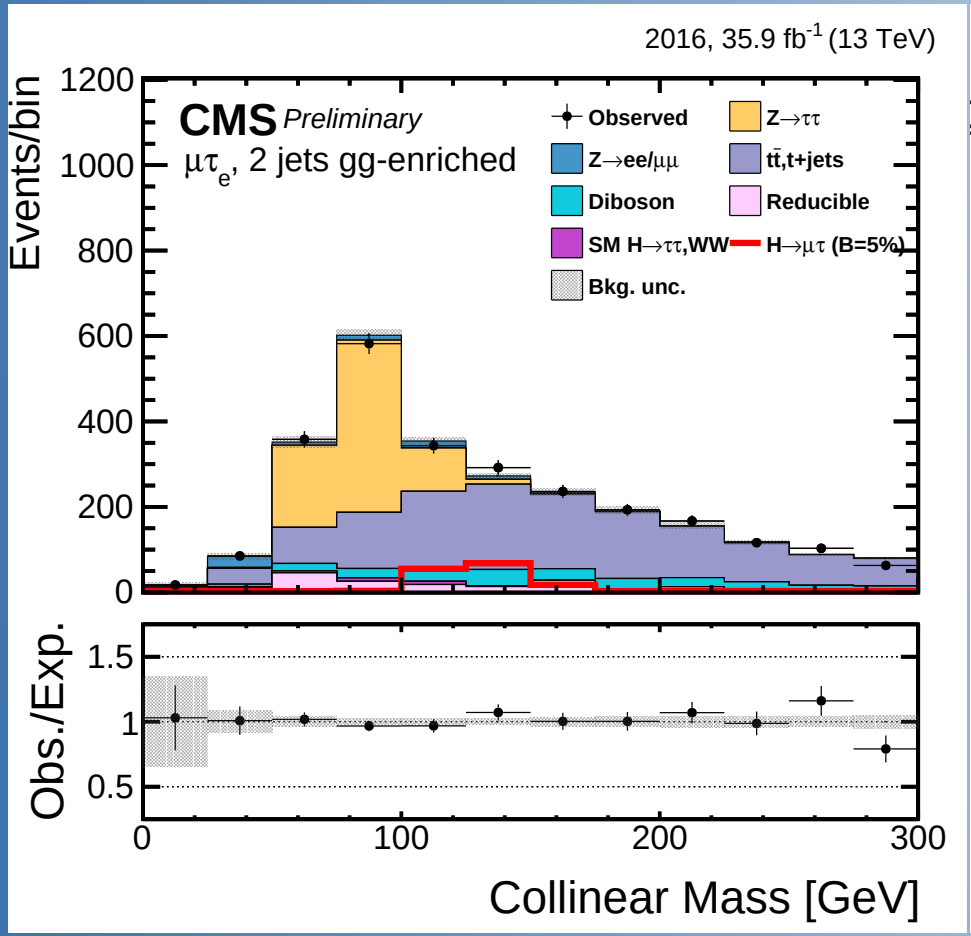

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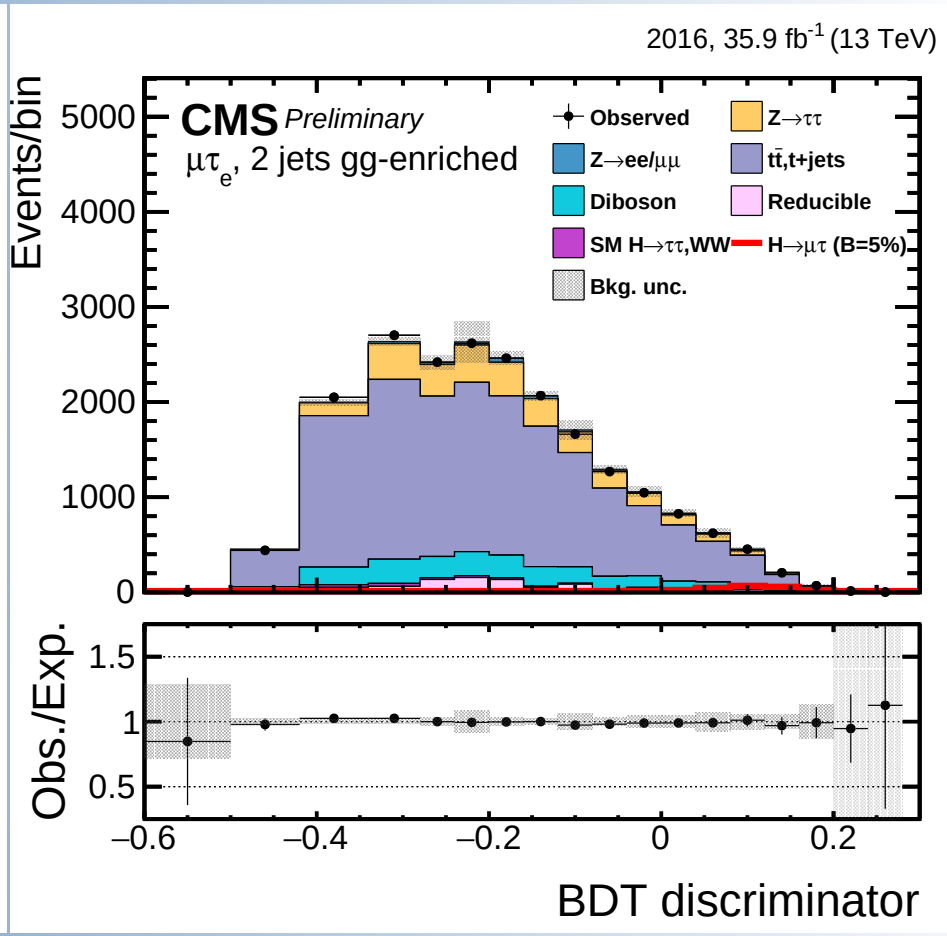
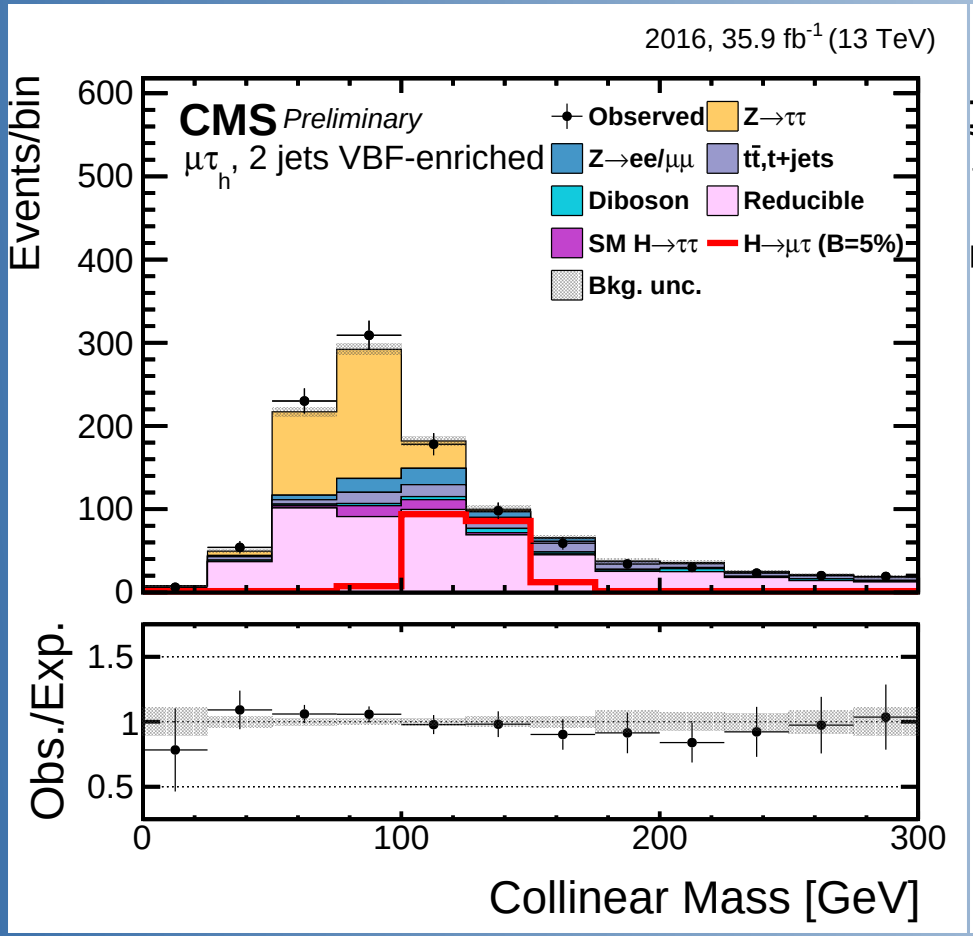


$\mu\tau_h$ channel, 2 Jets (VBF)

Cut based analysis



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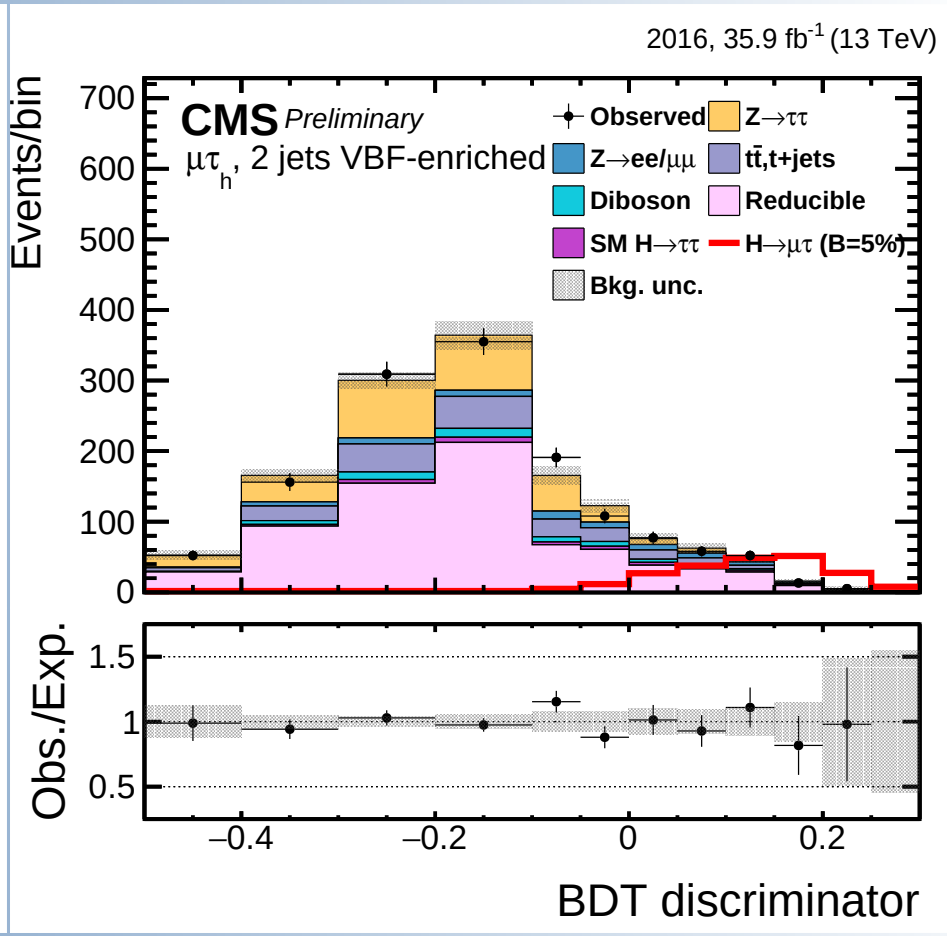
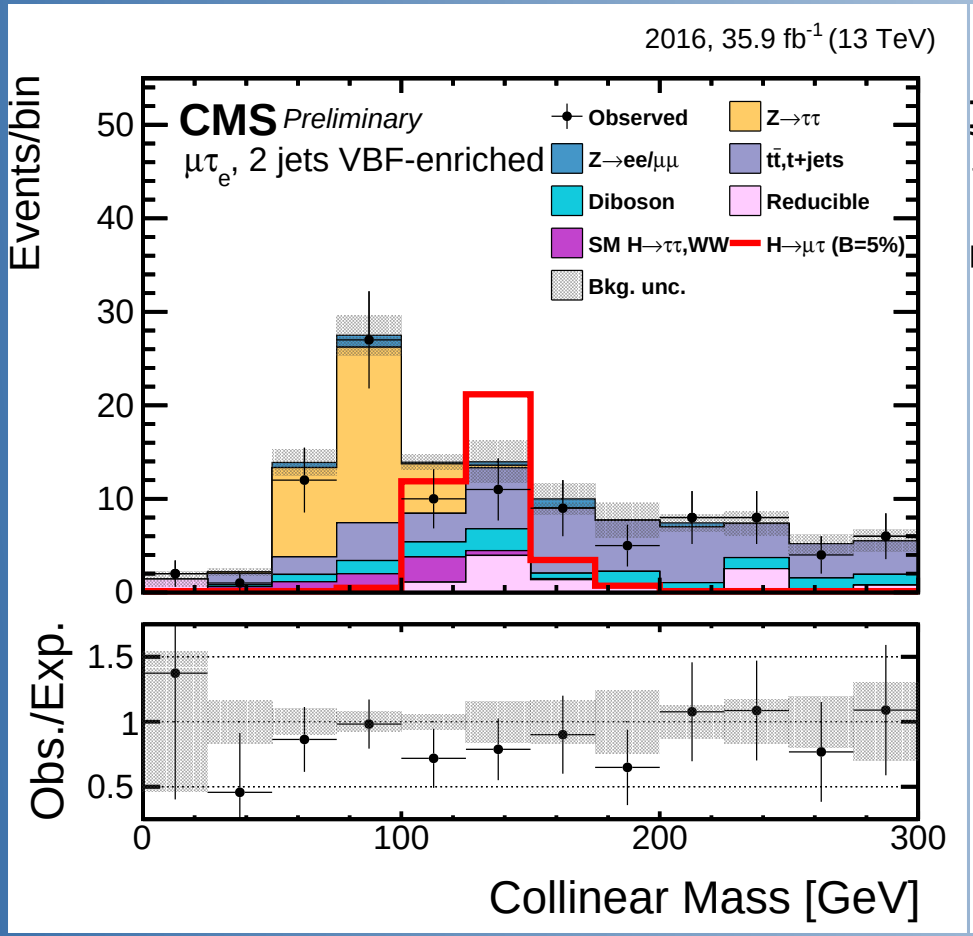


$\mu\tau_e$ channel, 2 Jets (VBF)

Cut based analysis



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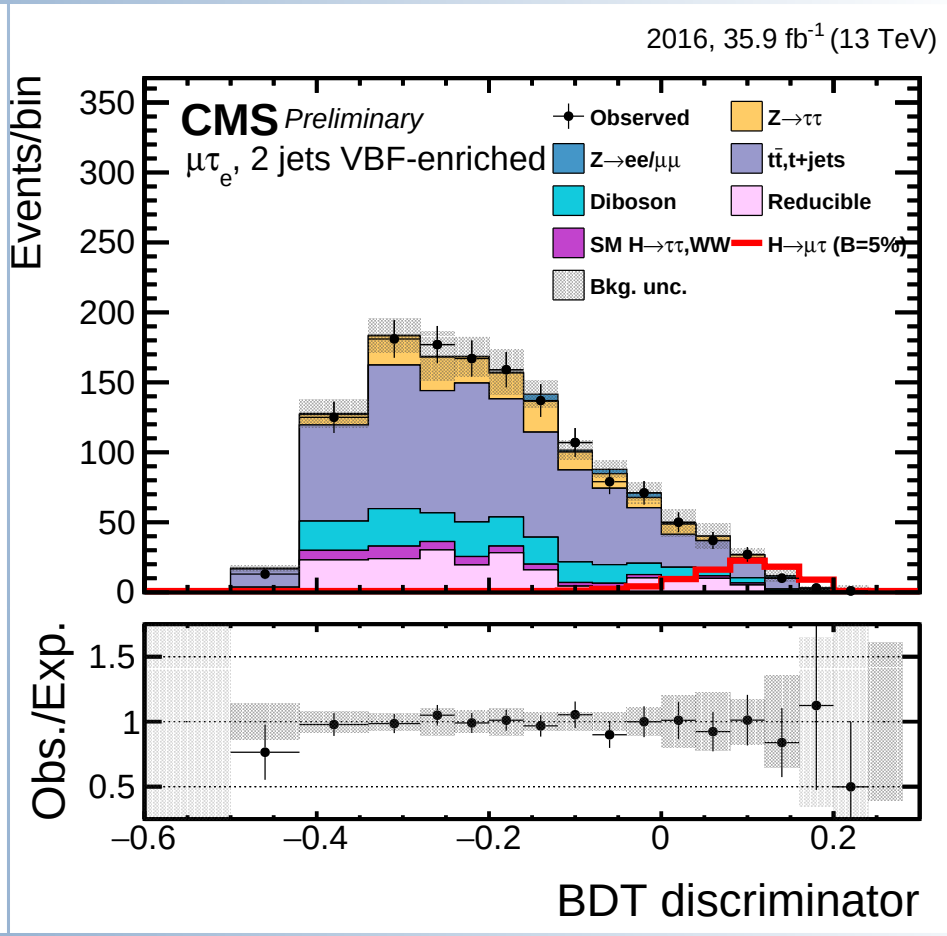
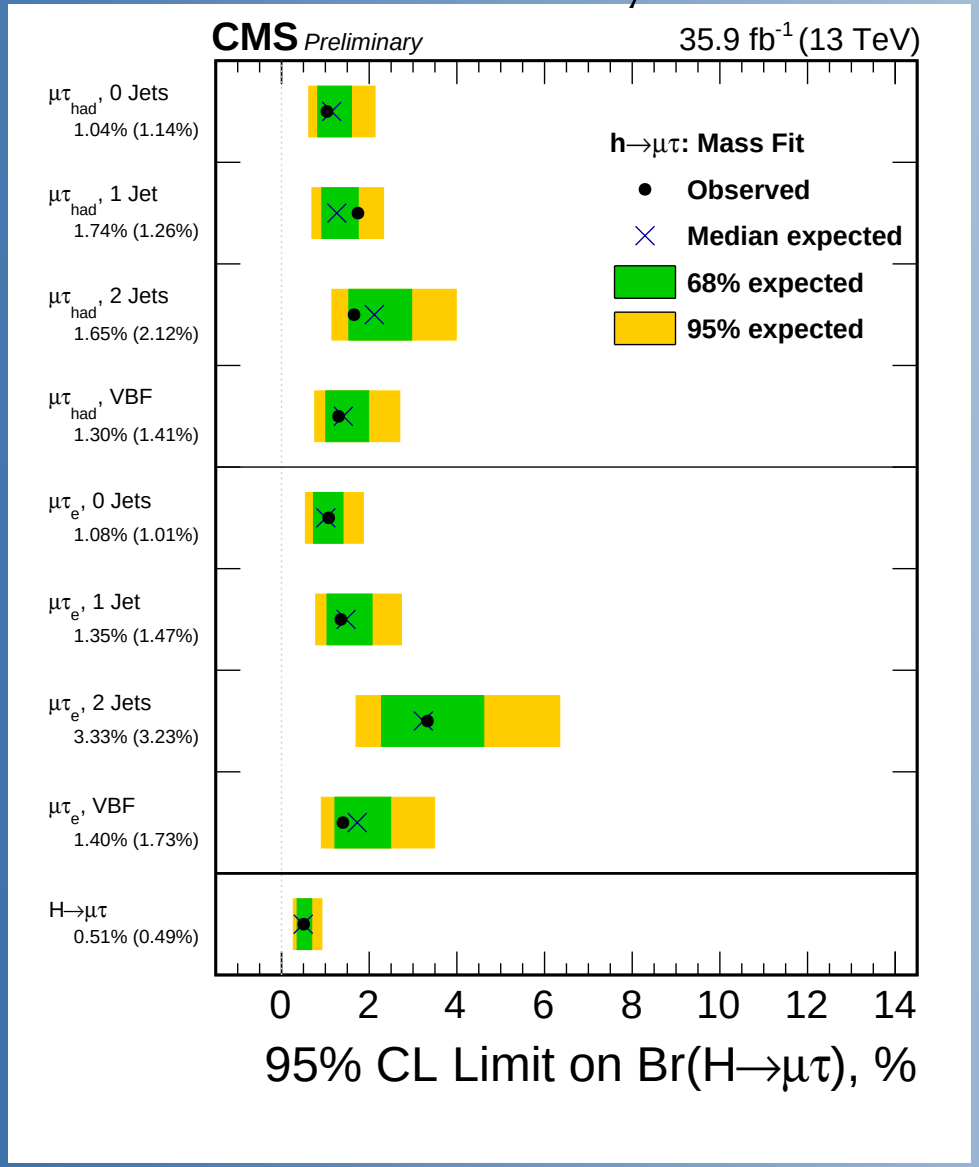


μτ results

Cut based analysis



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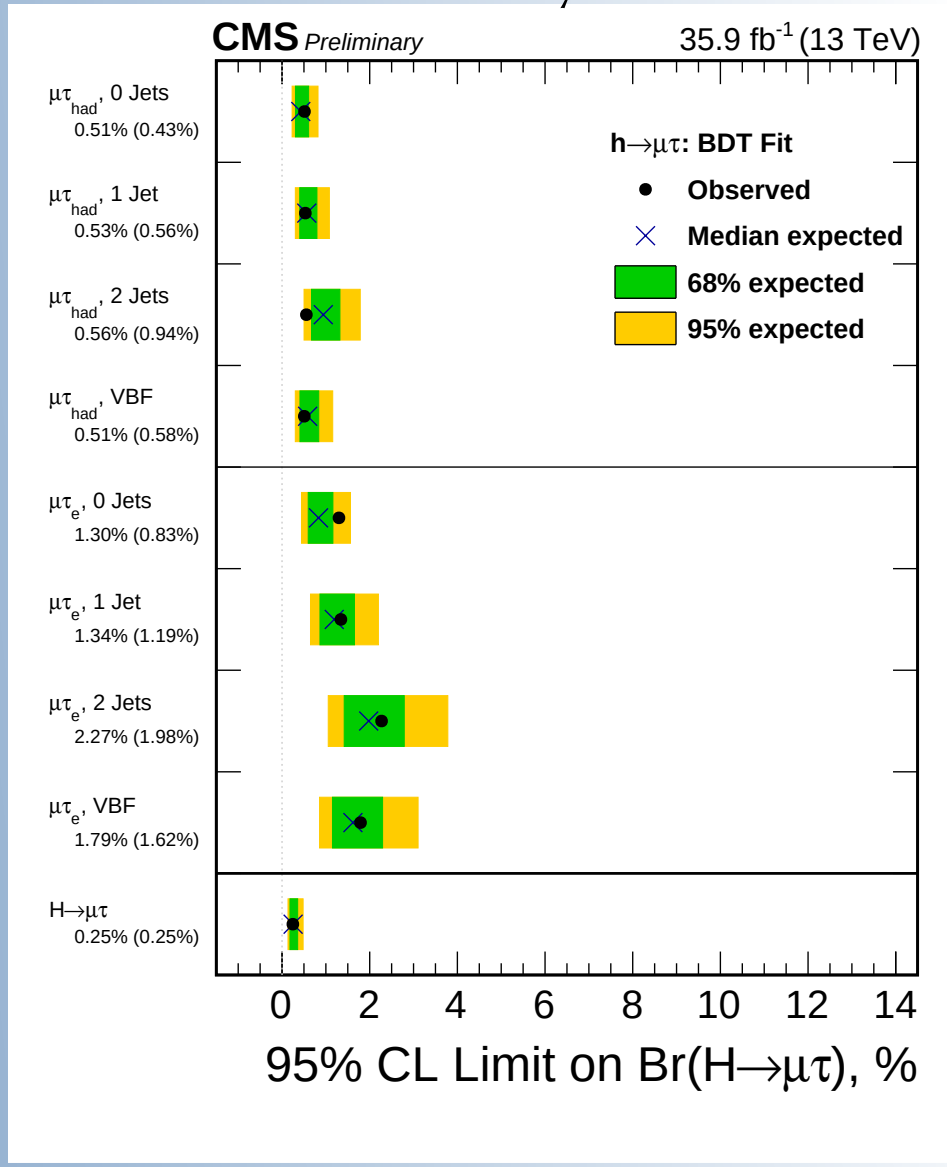
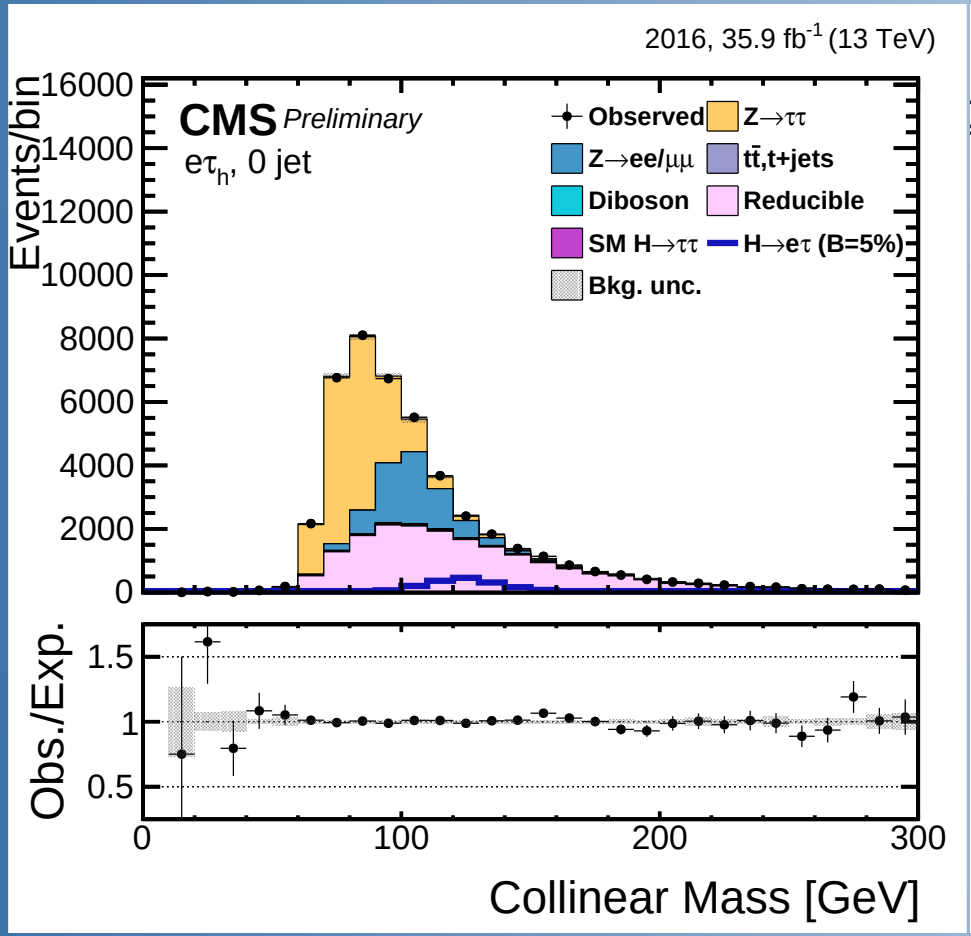


$e\tau_h$ channel, 0 Jets

Cut based analysis



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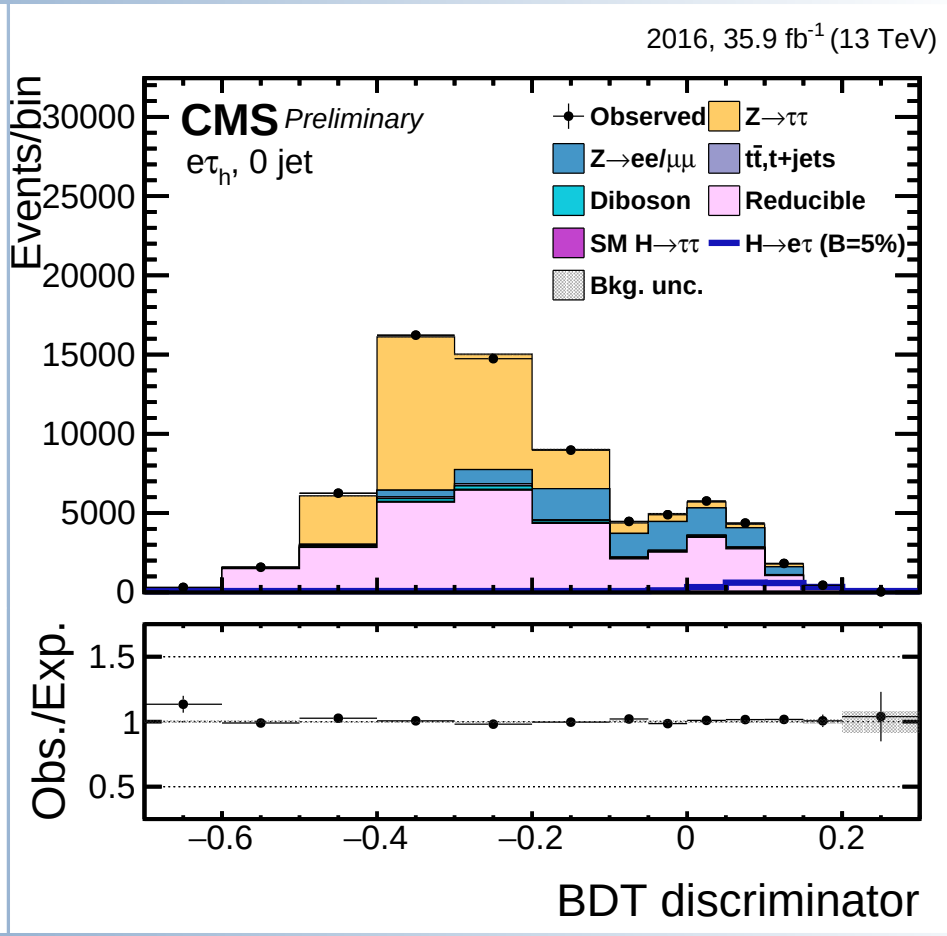
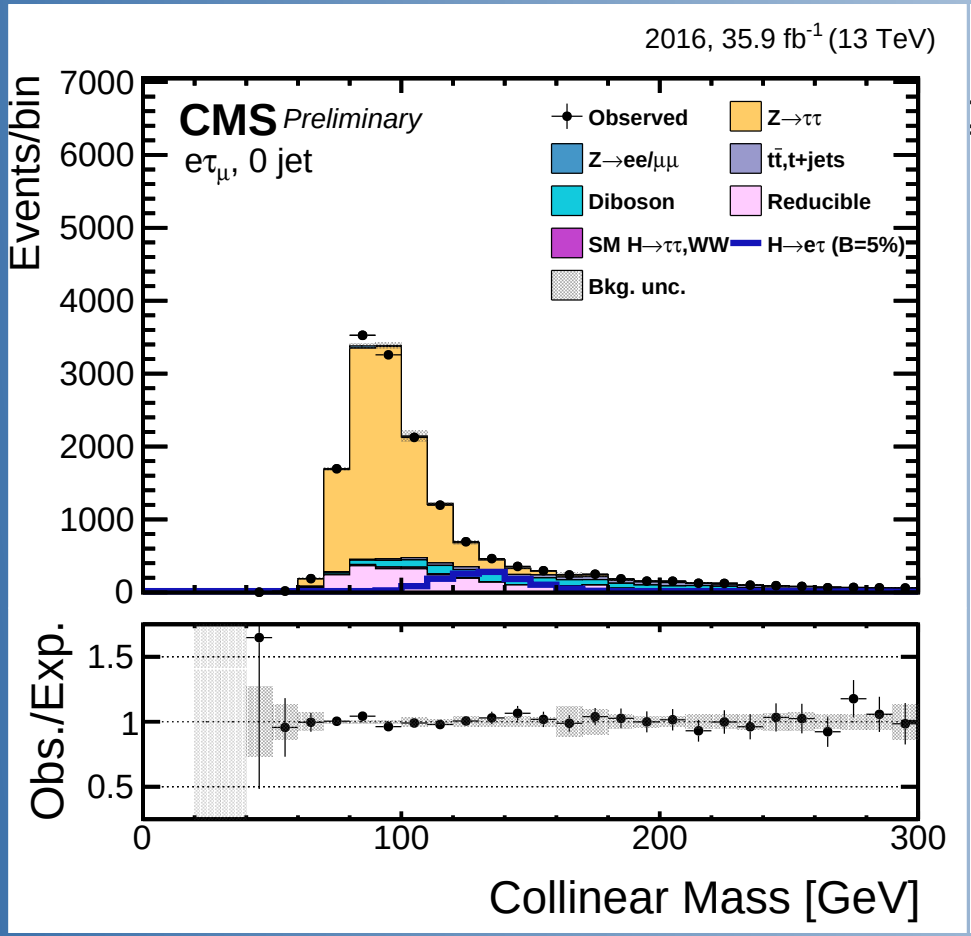


$e\tau_\mu$ channel, 0 Jets

Cut based analysis



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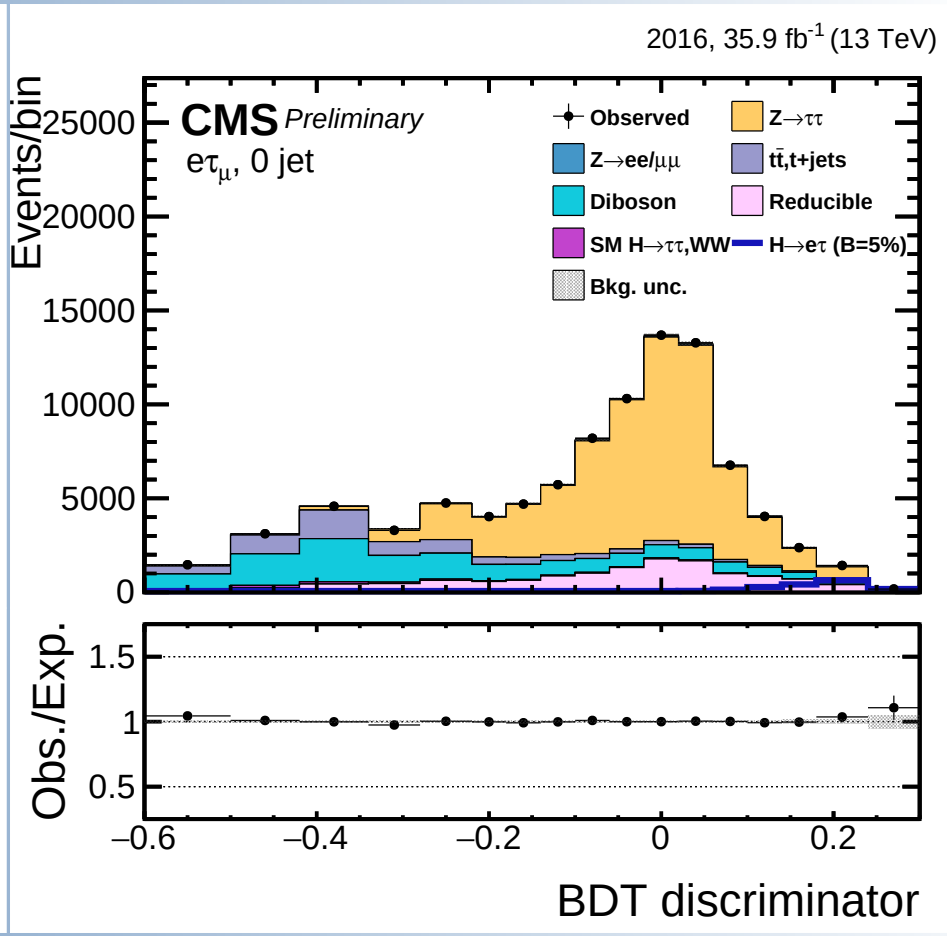
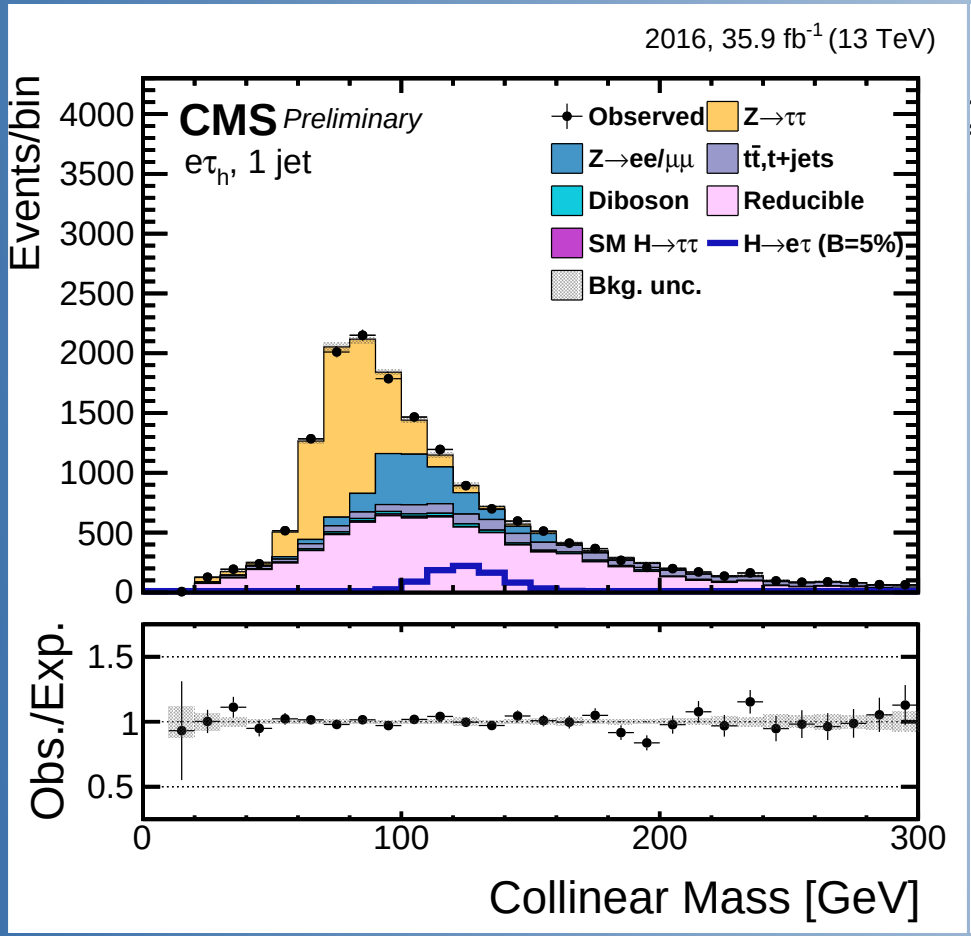


$e\tau_h$ channel, 1 Jets

Cut based analysis



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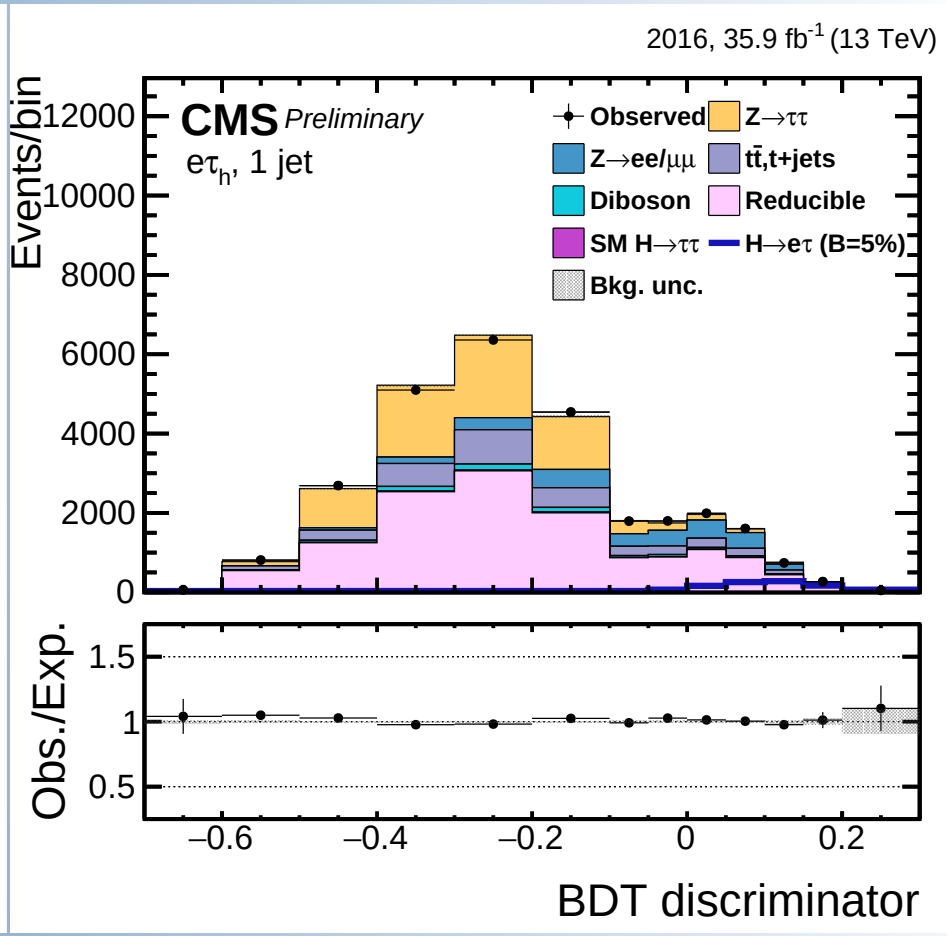
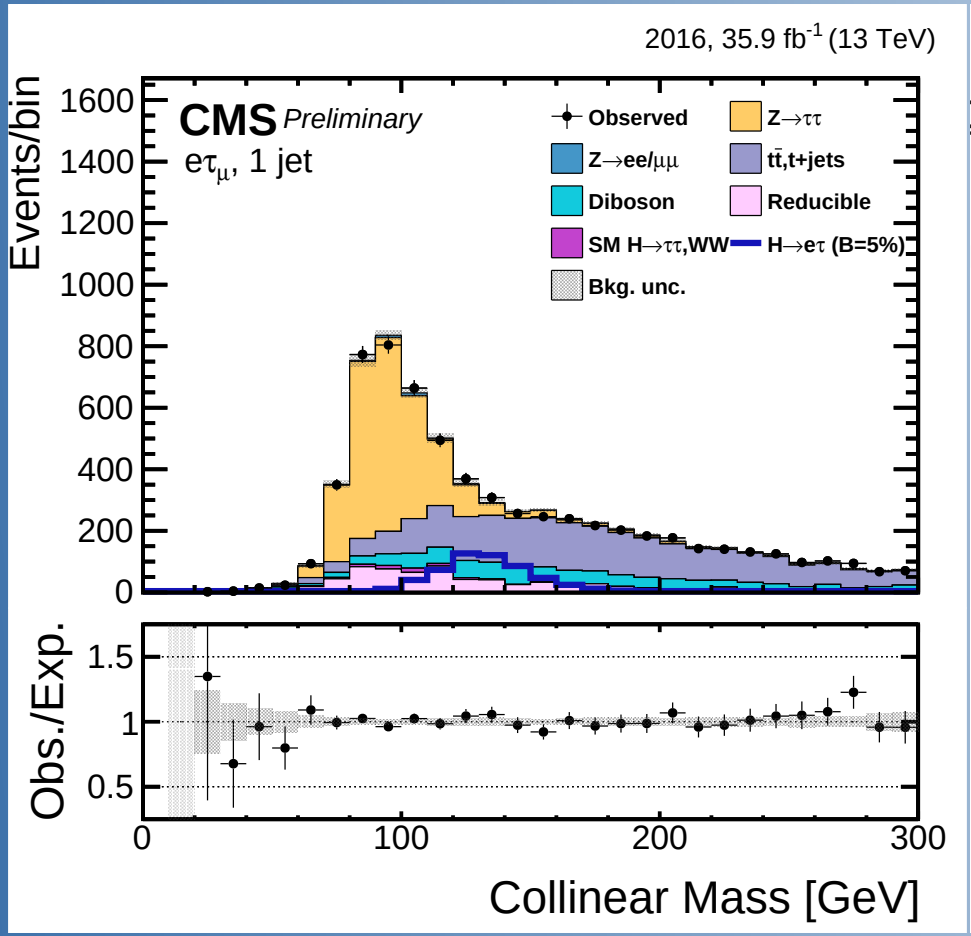


$e\tau_\mu$ channel, 1 Jets

Cut based analysis



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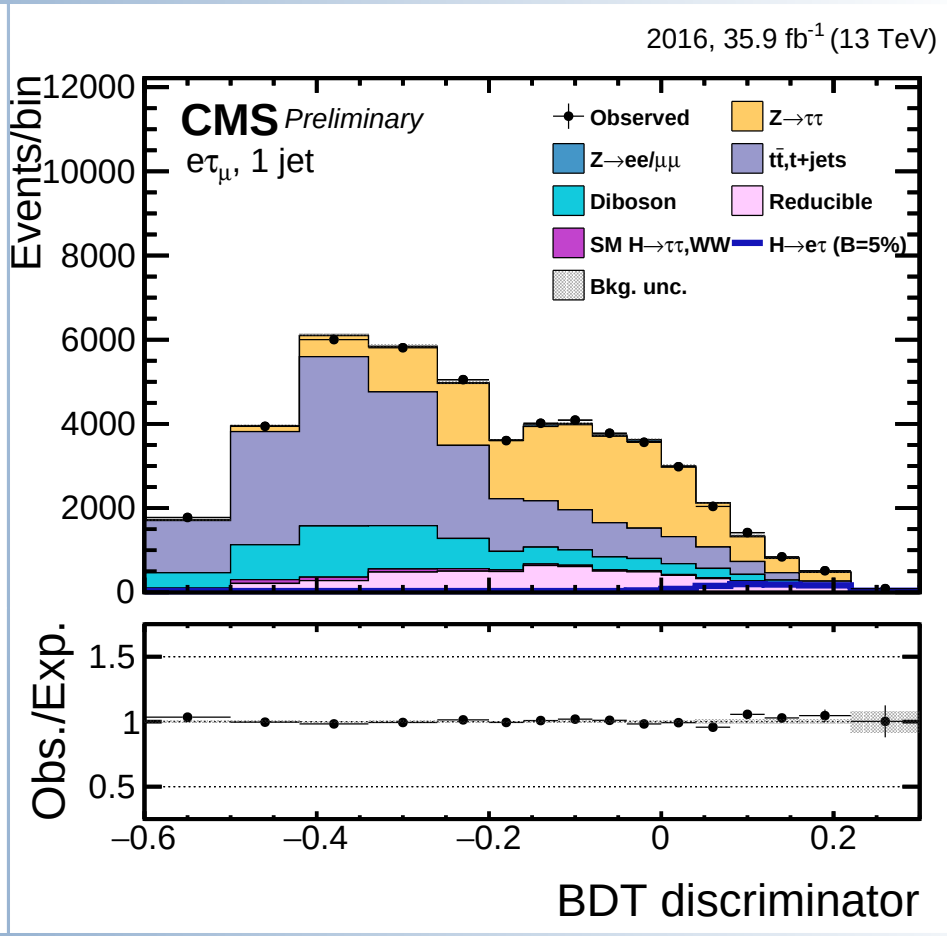
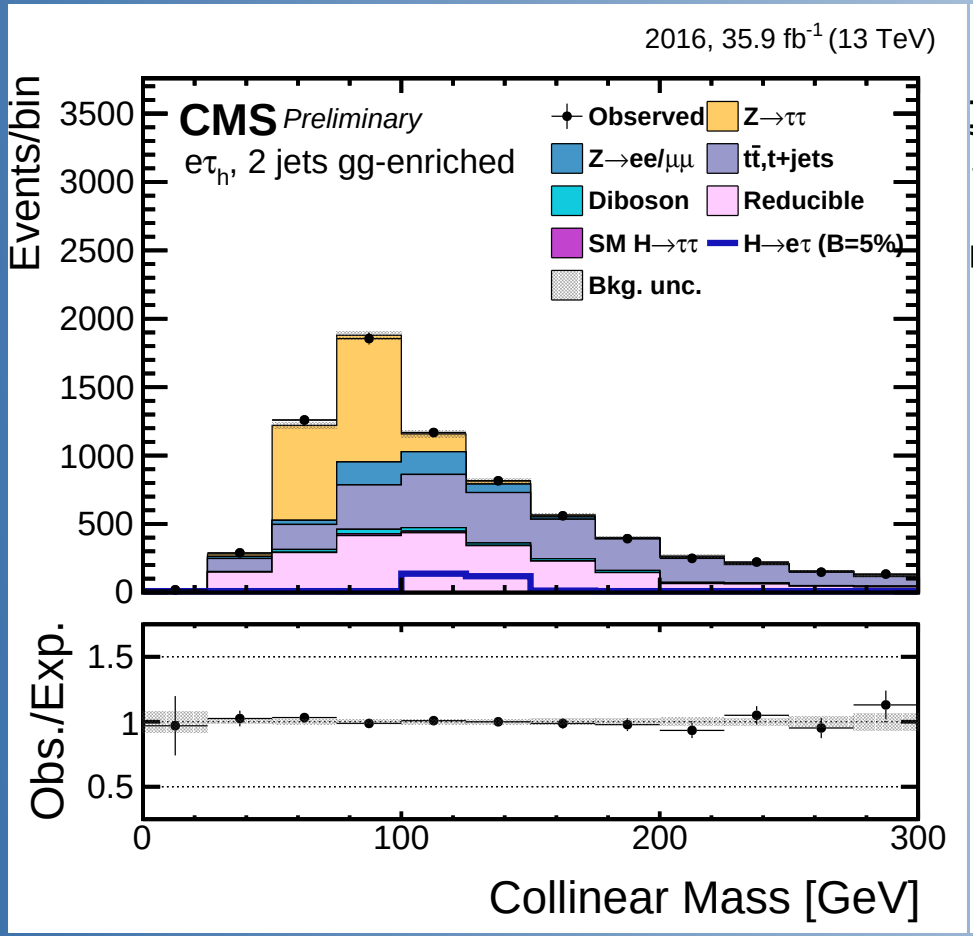


$e\tau_h$ channel, 2 Jets (gg)

Cut based analysis



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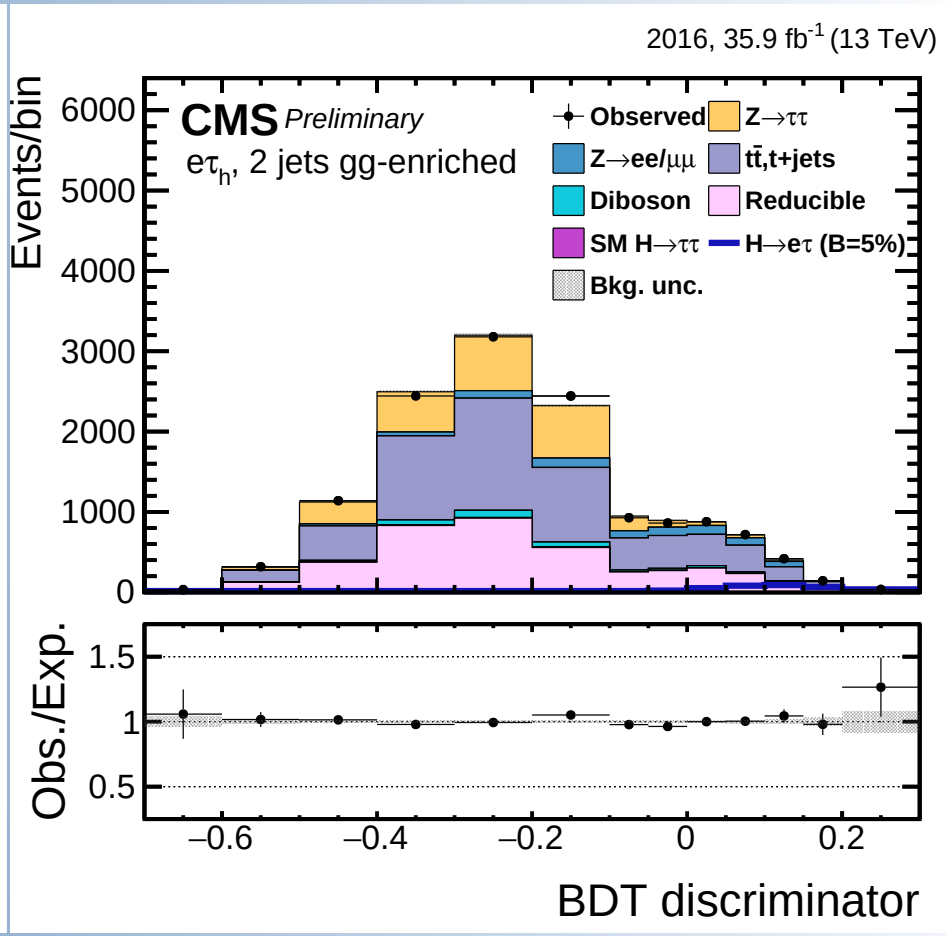
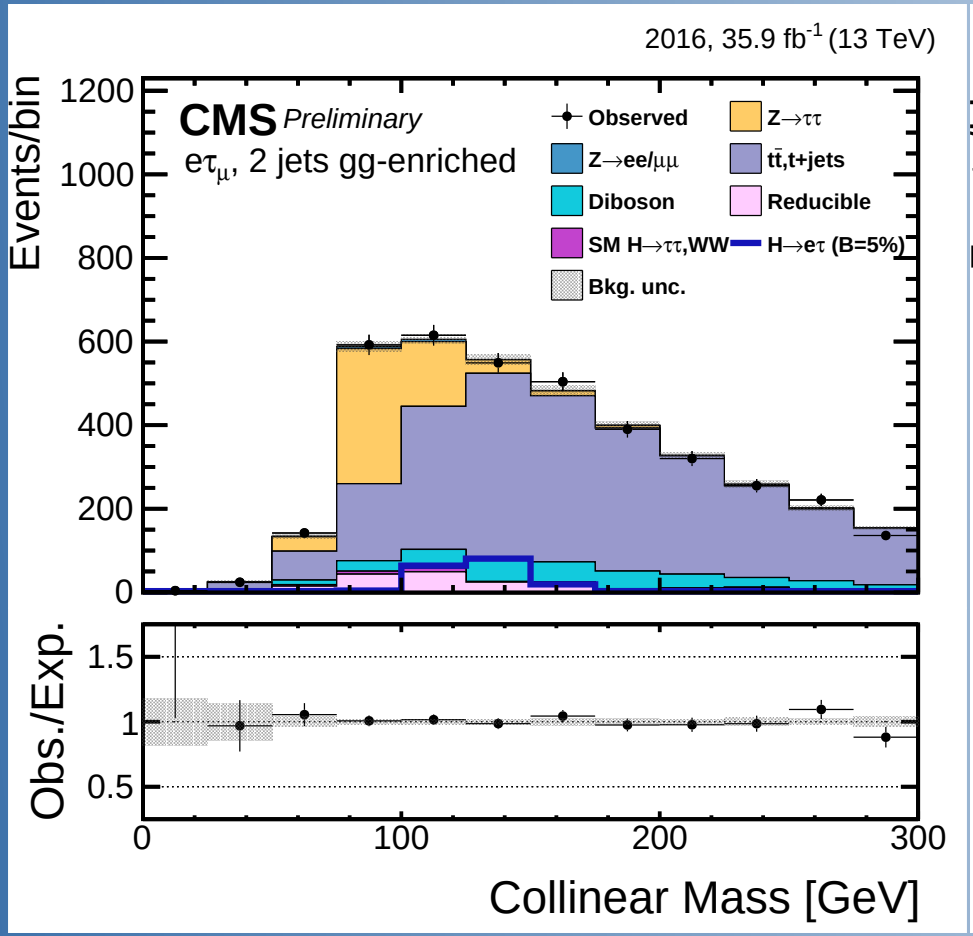
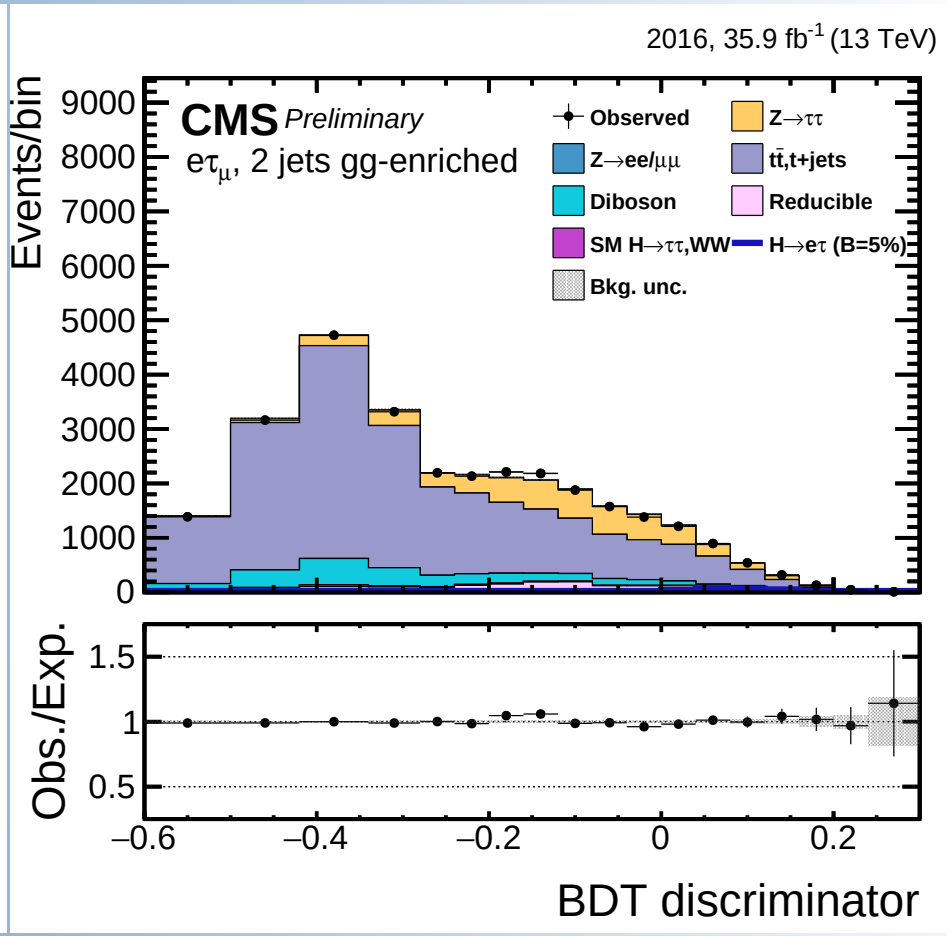


$e\tau_\mu$ channel, 2 Jets (gg)

Cut based analysis

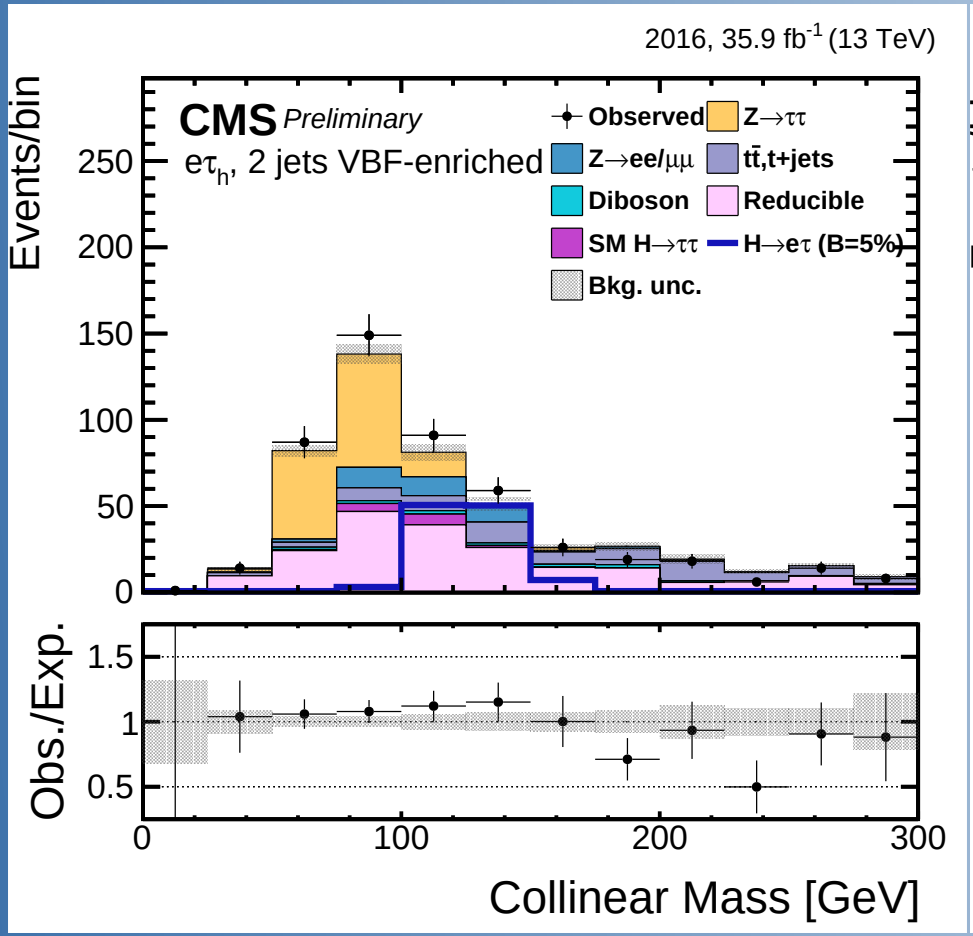


BDT analysis

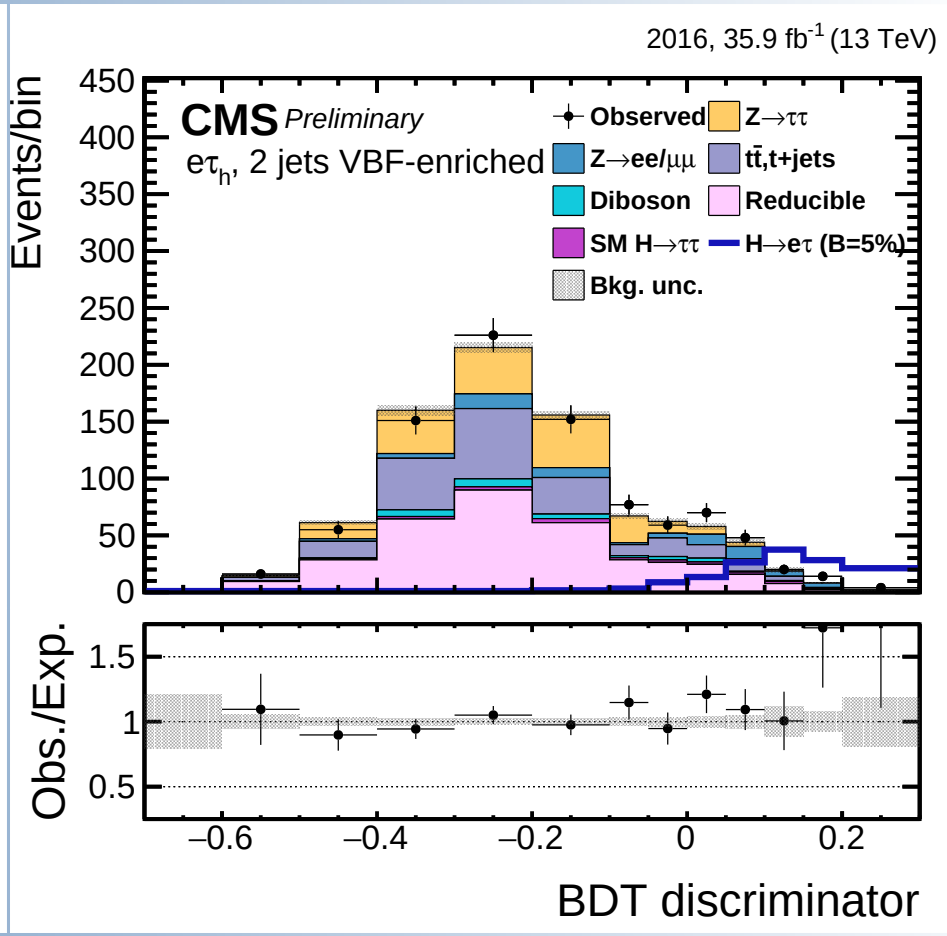


$e\tau_h$ channel, 2 Jets (VBF)

Cut based analysis

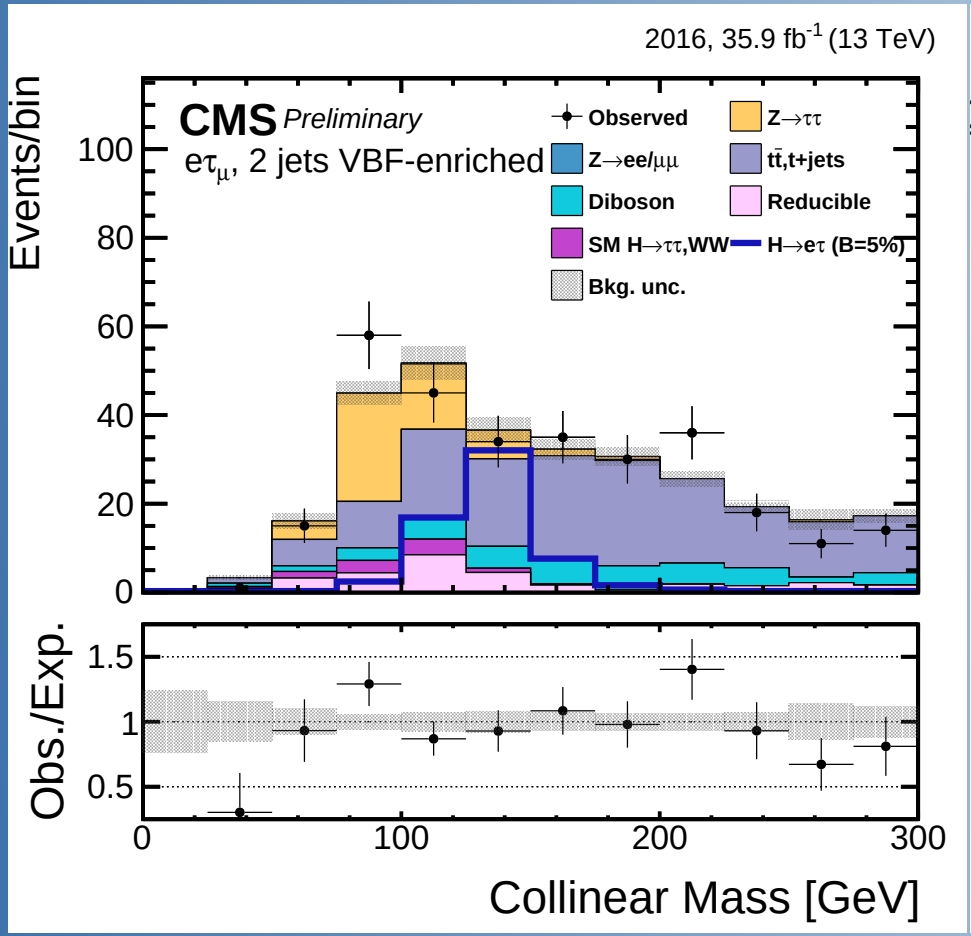


BDT analysis

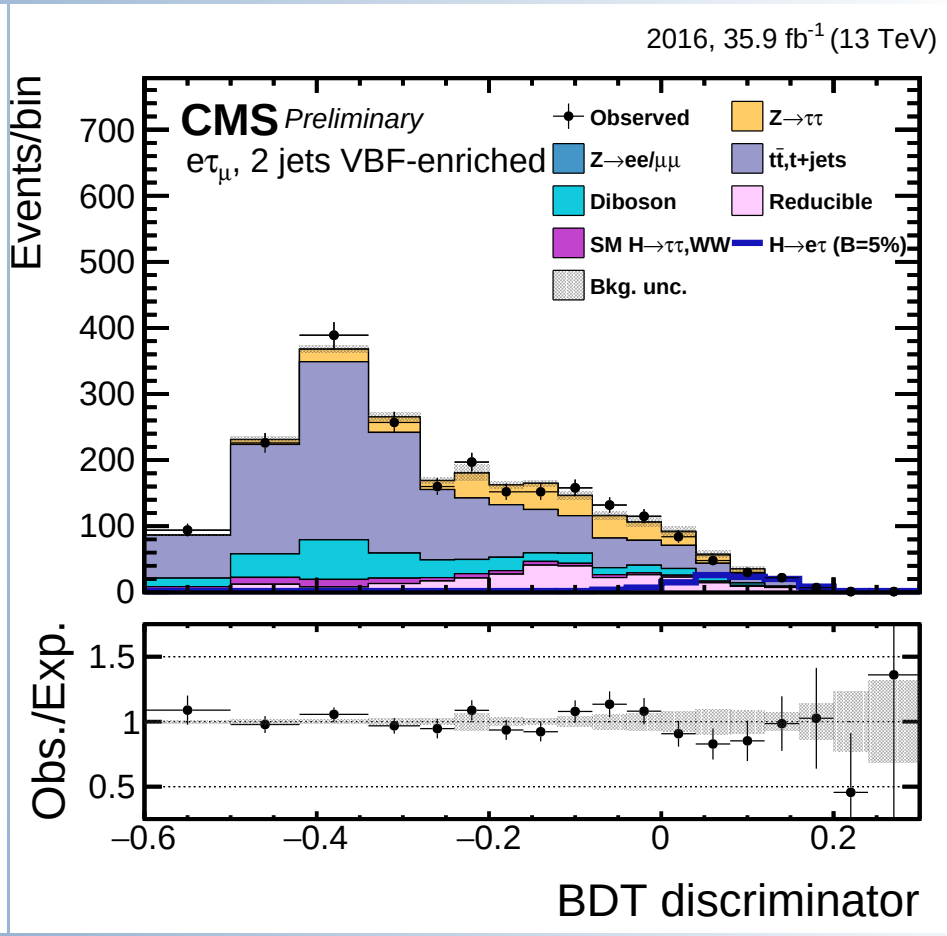


$e\tau_\mu$ channel, 2 Jets (VBF)

Cut based analysis

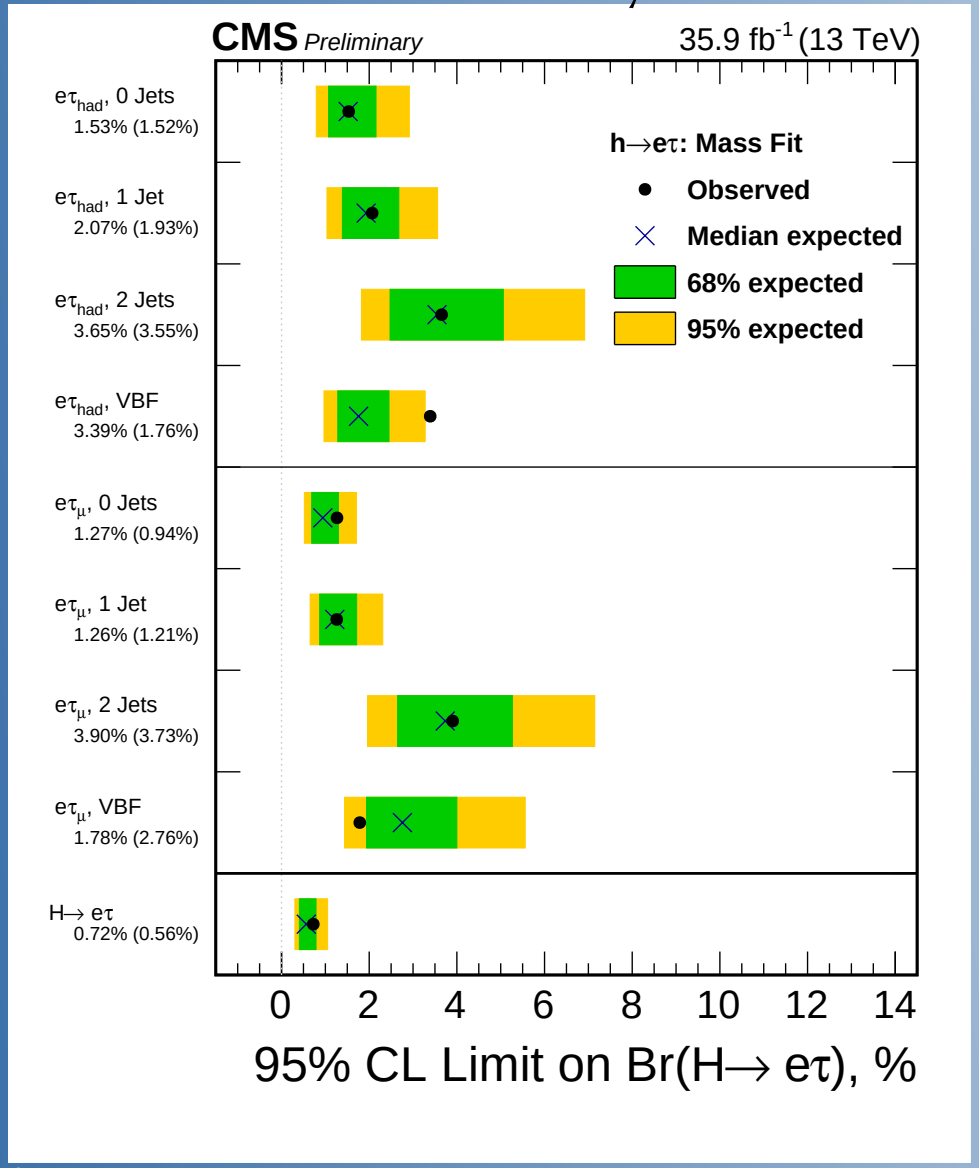


BDT analysis

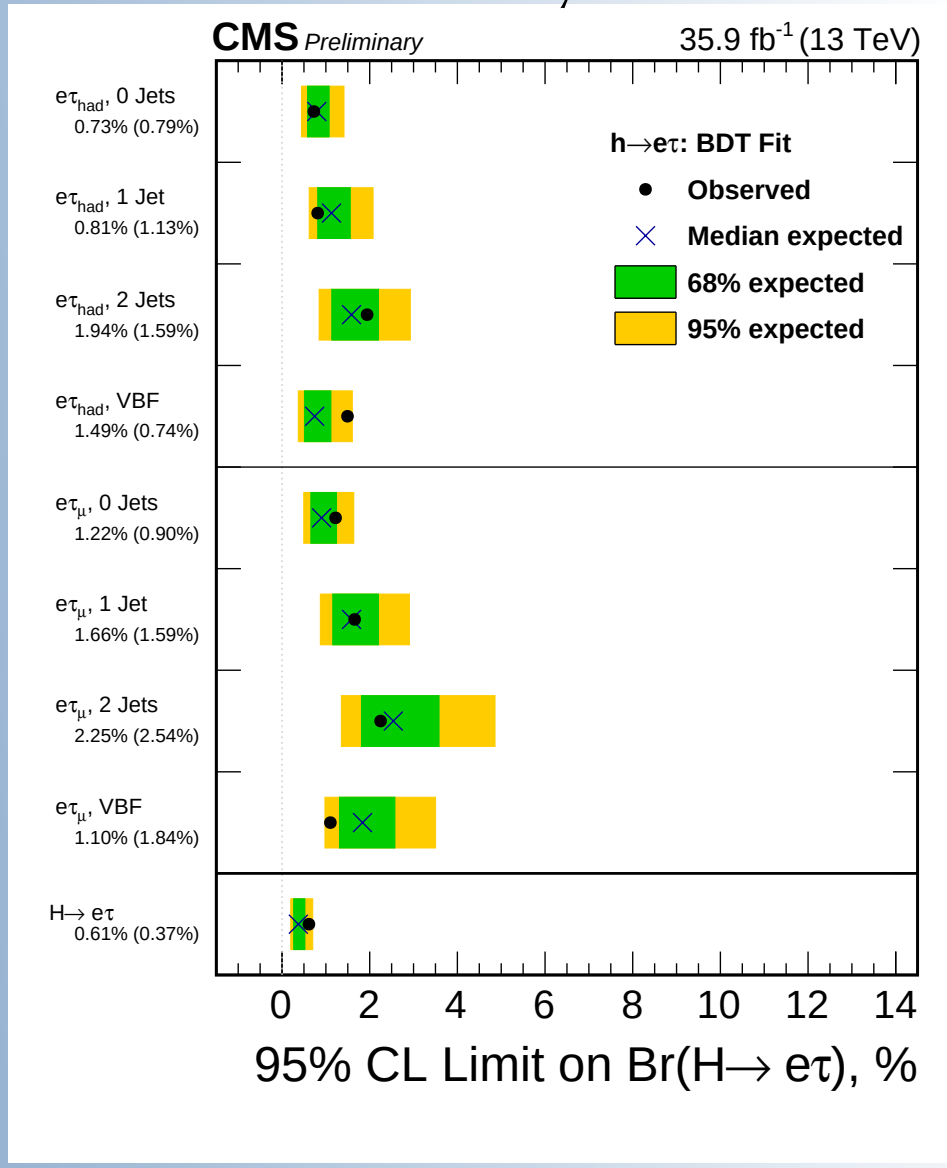


eτ results

Cut based analysis



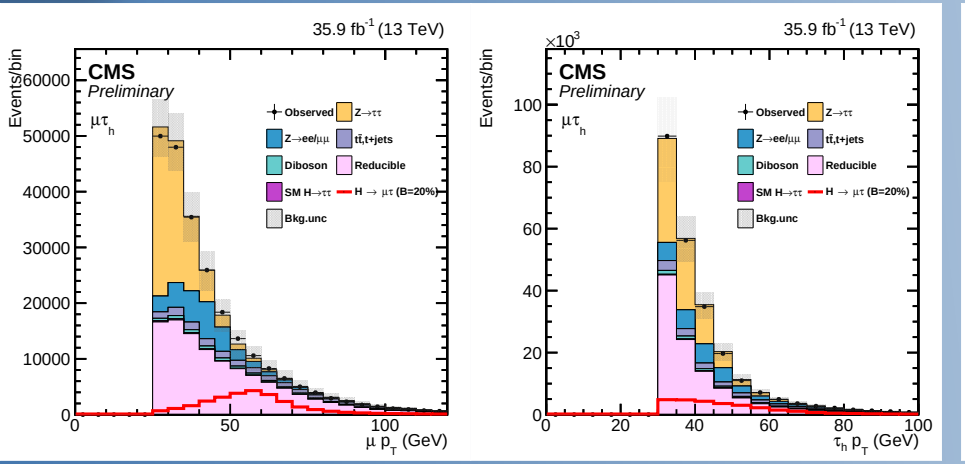
BDT analysis



Systematic uncertainties

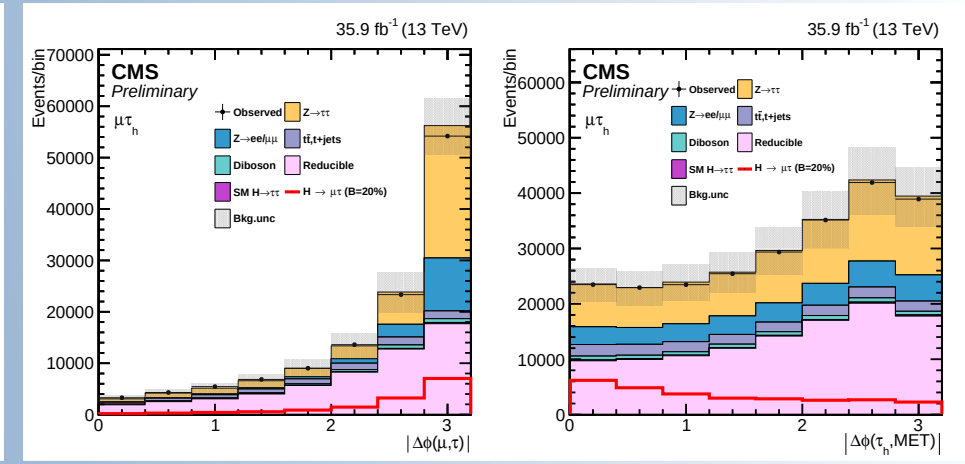
Systematic uncertainty	$H \to \mu\tau_e$	$H \to \mu\tau_h$	$H \to e\tau_\mu$	$H \to e\tau_h$
Muon trigger/ID/isolation	2%	2%	2%	-
Electron trigger/ID/isolation	2%	-	2%	2%
Hadronic τ efficiency	-	5%	-	5%
b-tagging veto	2.0–4.5%	2.0–4.5%	2.0–4.5%	-
$Z \to \mu\mu/ee$ +jets background	10%⊕5%	-	10%⊕5%	-
$Z \to \tau\tau$ +jets background	10%⊕5%	10%⊕5%	10%⊕5%	10%⊕5%
W + jets background	10%	-	10%	-
QCD multijet background	30%	-	30%	-
WW, ZZ background	5%⊕5%	5%⊕5%	5%⊕5%	5%⊕5%
$t\bar{t}$ background	10%⊕5%	10%⊕5%	10%⊕5%	10%⊕5%
$W + \gamma$ background	10%⊕5%	-	10%⊕5%	-
Single top production background	5%⊕5%	5%⊕5%	5%⊕5%	5%⊕5%
$\mu \to \tau_h$ background	-	25%	-	-
$e \to \tau_h$ background	-	-	-	12%
jet $\to \tau_h, \mu, e$ background	-	30%⊕10%	-	30%⊕10%
Jet energy scale	3–20%	3–20%	3-20%	3–20%
Hadronic τ energy scale	-	1.2%	-	1.2%
$e \to \tau_h$ energy scale	-	1.5%	-	3%
Electron energy scale	$\pm\sigma$	-	$\pm\sigma$	$\pm\sigma$
Muon energy scale	0.2%	0.2%	-	$\pm\sigma$
Unclustered energy scale	$\pm\sigma$	$\pm\sigma$	$\pm\sigma$	$\pm\sigma$
acceptance scale (GF H)	-3.0 – 2.0%	-3.0 – 2.0%	-3.0 – 2.0%	-3.0 – 2.0%
acceptance scale (VBF H)	-0.3 – 1.0%	-0.3 – 1.0%	-0.3 – 1.0%	-0.3 – 1.0%
QCD scale YR4 (GF H)	3.2%	3.2%	3.2%	3.2%
QCD scale YR4 (VBF H)	2.1%	2.1%	2.1%	2.1%
acceptance PDF (GF H)	-1.5 – 0.5%	-1.5 – 0.5%	-1.5 – 0.5%	-1.5 – 0.5%
acceptance PDF (VBF H)	-1.5 – 1.0%	-1.5 – 1.0%	-1.5 – 1.0%	-1.5 – 1.0%
PDF YR4 (GF H)	3.9%	3.9%	3.9%	3.9%
PDF YR4 (VBF H)	0.4%	0.4%	0.4%	0.4%
Bin-by-bin	Shape	Shape	Shape	Shape
Luminosity	2.5%	2.5%	2.5%	2.5%
Pile-up	Shape	Shape	Shape	Shape

BDT input for $H \to \mu\tau_h$

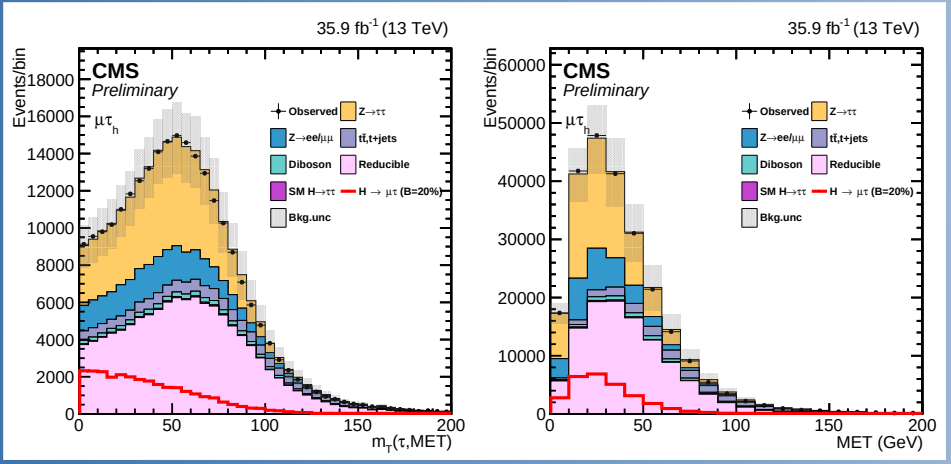


(a) μ p_T

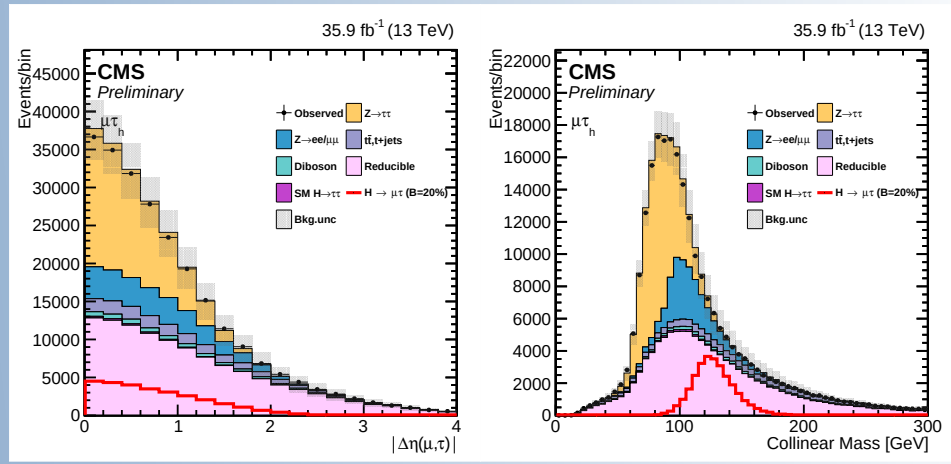
(b) τ p_T



(a) $\Delta\phi(\mu,\tau)$ (b) $\Delta\phi(\tau, E_T^{miss})$

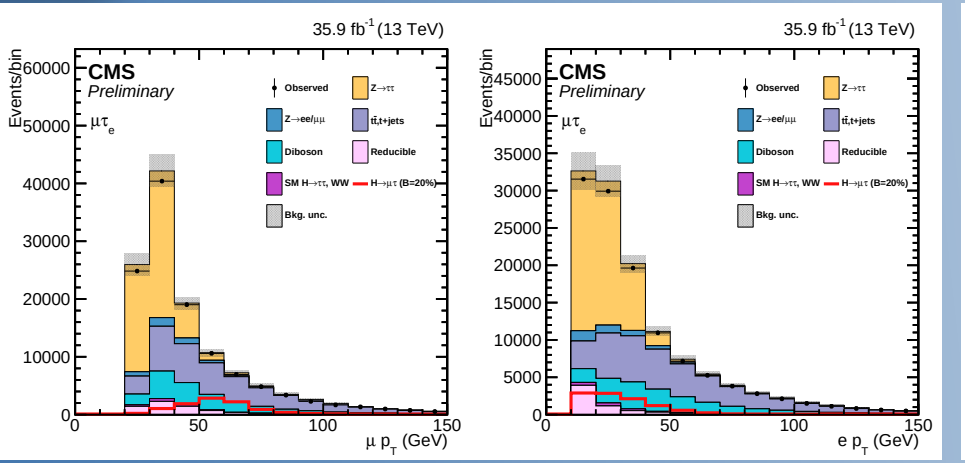


(c) M_T (τ, E_T^{miss}) (d) E_T^{miss}

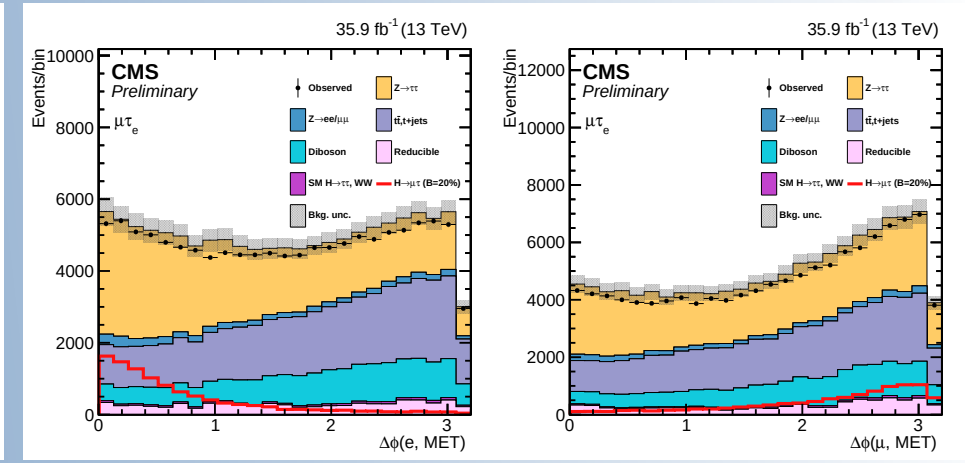


(c) $\Delta\eta(\mu,\tau)$ (d)

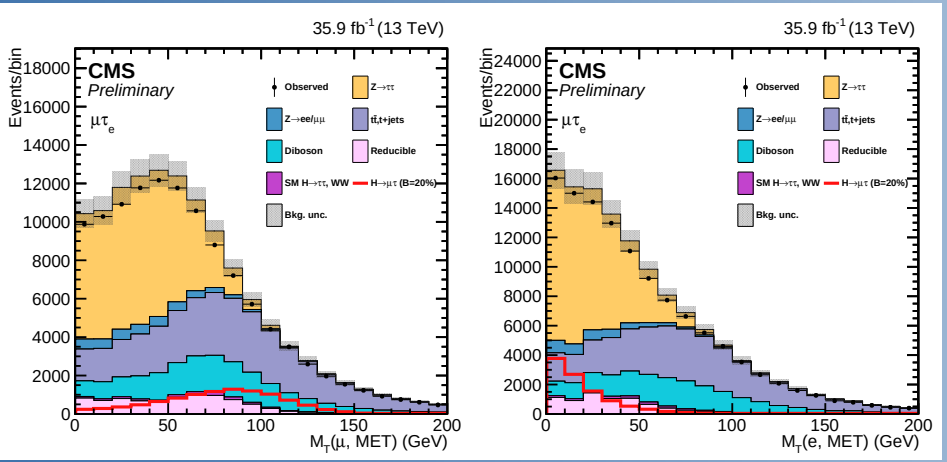
BDT input for $H \to \mu\tau_e$



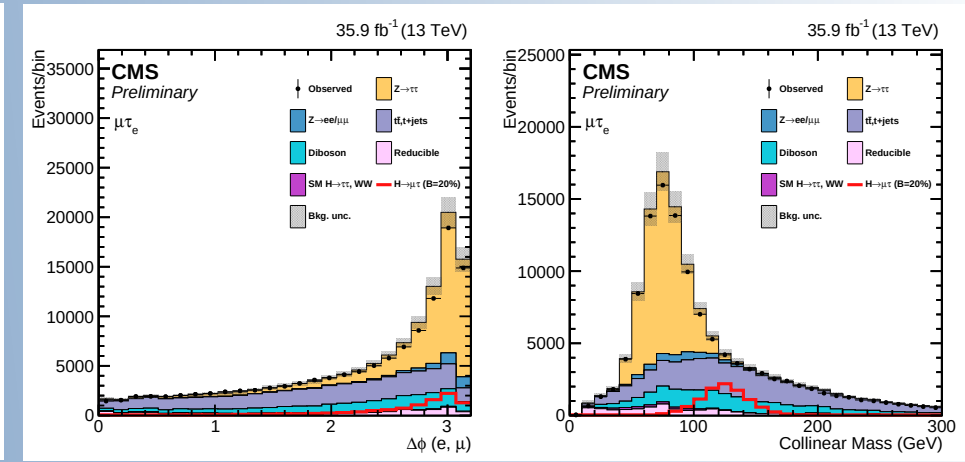
(a) μ p_T (b) e p_T



(a) $\Delta\phi(\mathrm{e}, E_T^{miss})$ (b) $\Delta\phi(\mu, E_T^{miss})$

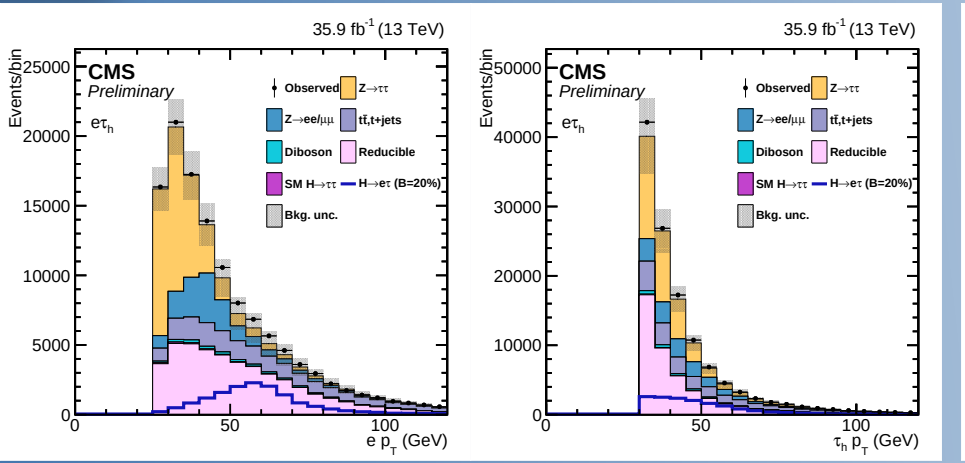


(c) M_T (μ,E_T^{miss}) (d) M_T (e,E_T^{miss})

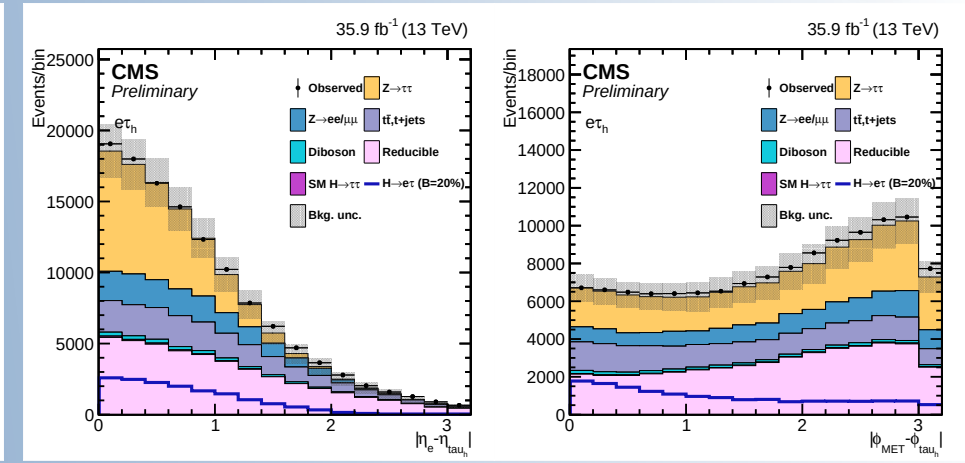


(c) $\Delta\phi(\mathrm{e}, \mu)$ (d)

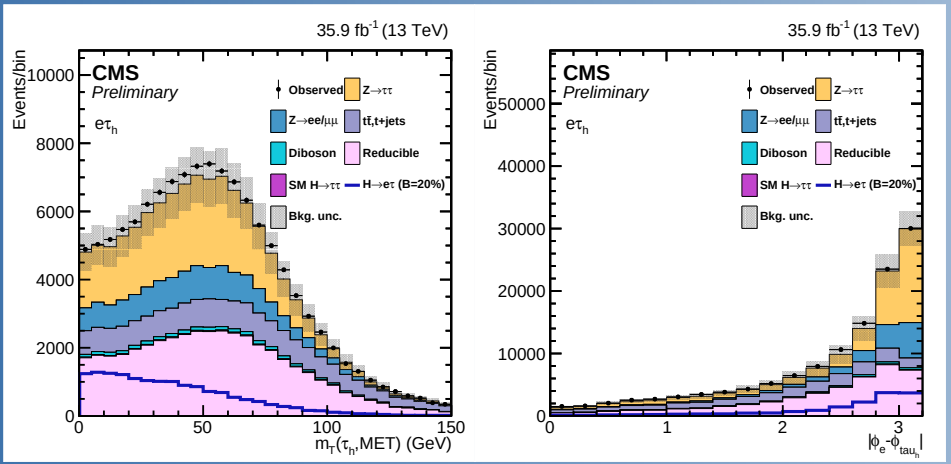
BDT input for $H \to e\tau_h$



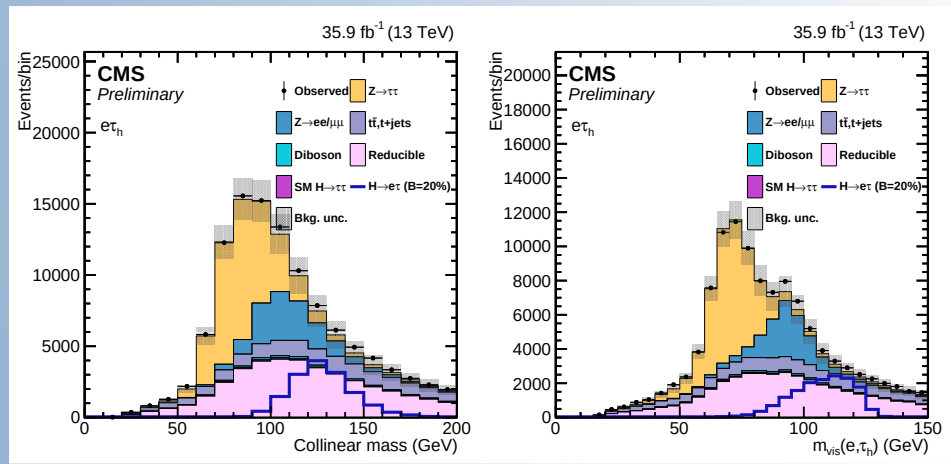
(a) e p_T (b) τ p_T



(a) $\Delta\eta(e,\tau)$ (b) $\Delta\phi(\tau, E_T^{miss})$

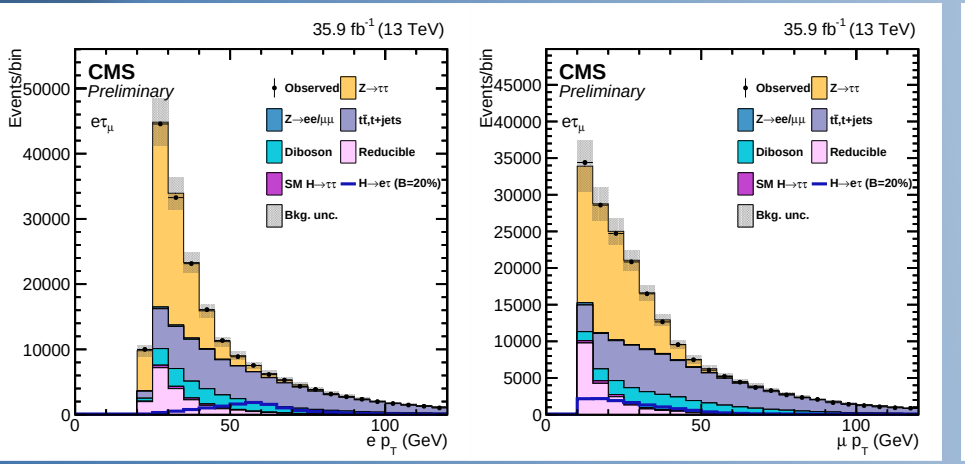


(c) M_T (μ,E_T^{miss}) (d) $\Delta\phi(e,\tau)$

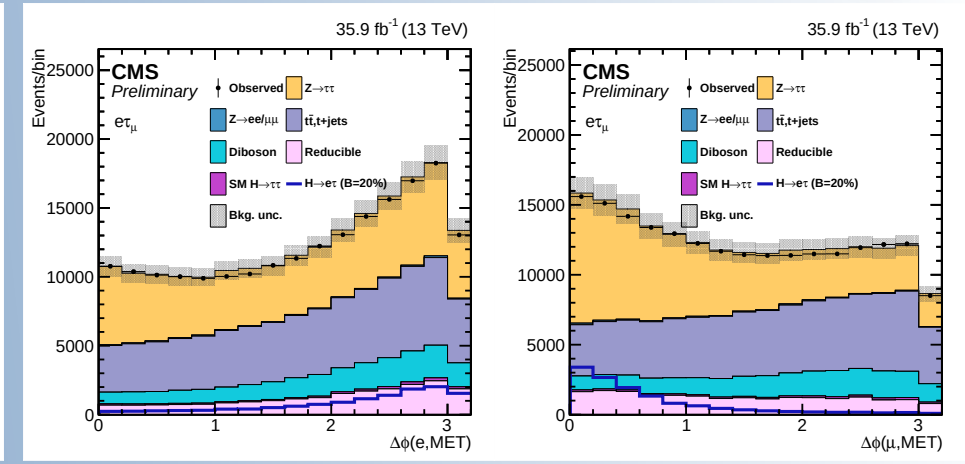


(c) (d)

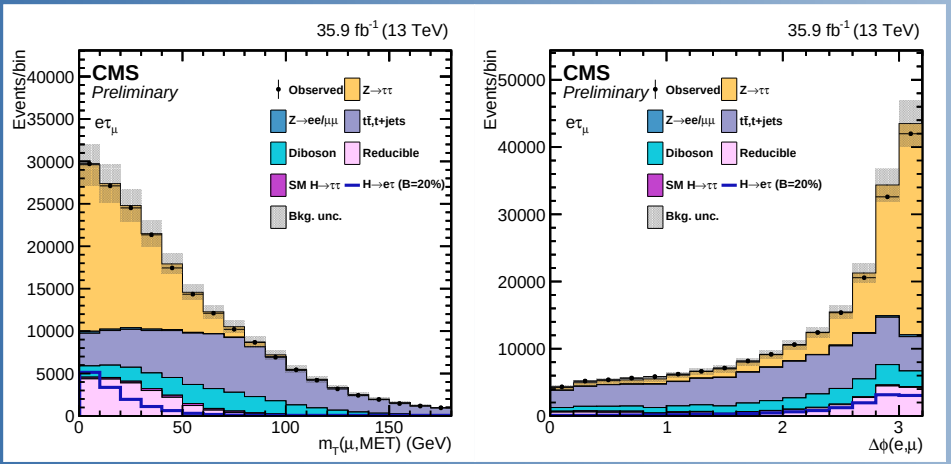
BDT input for $H \to e\tau_\mu$



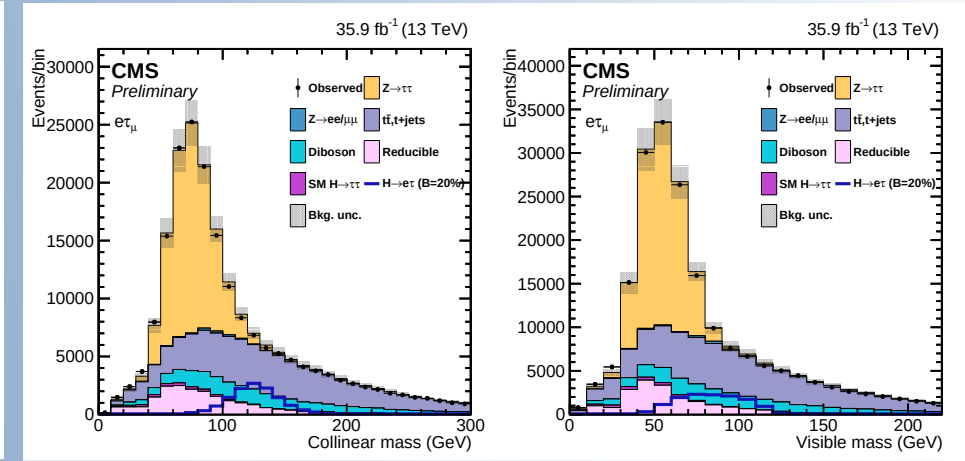
(a) e p_T (b) μ p_T

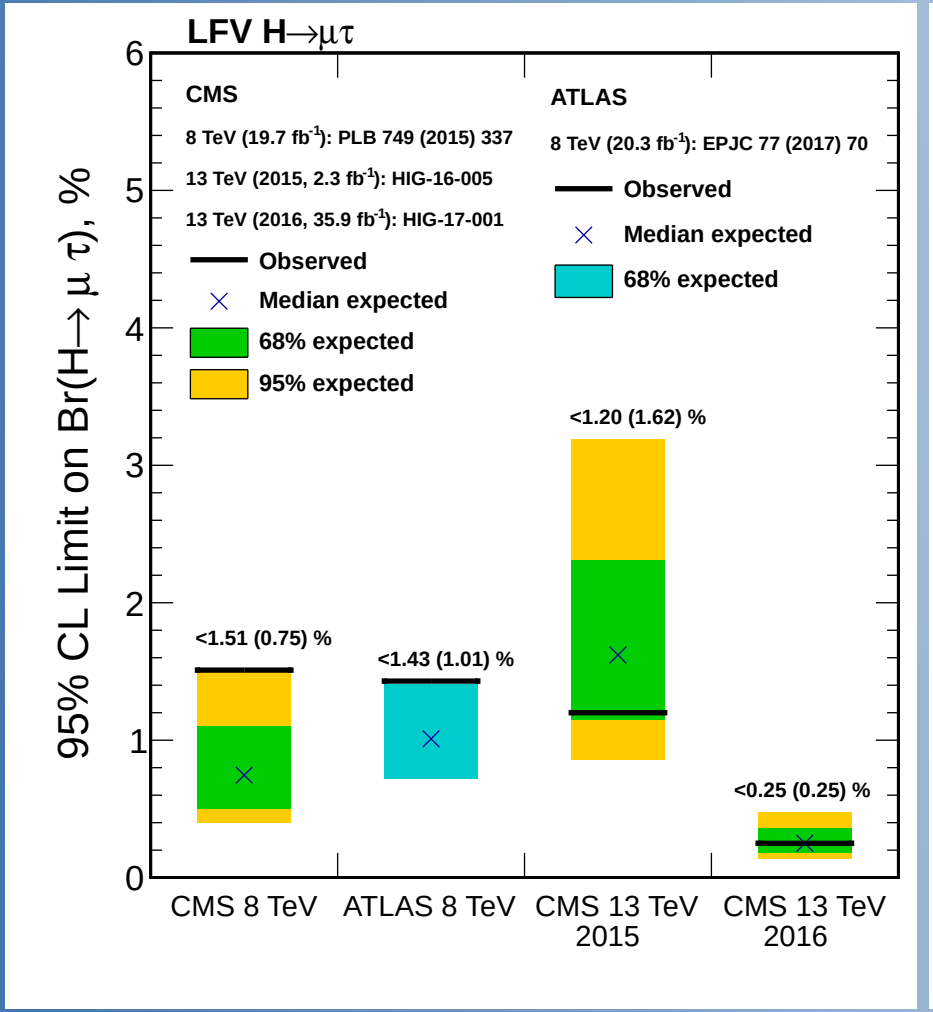
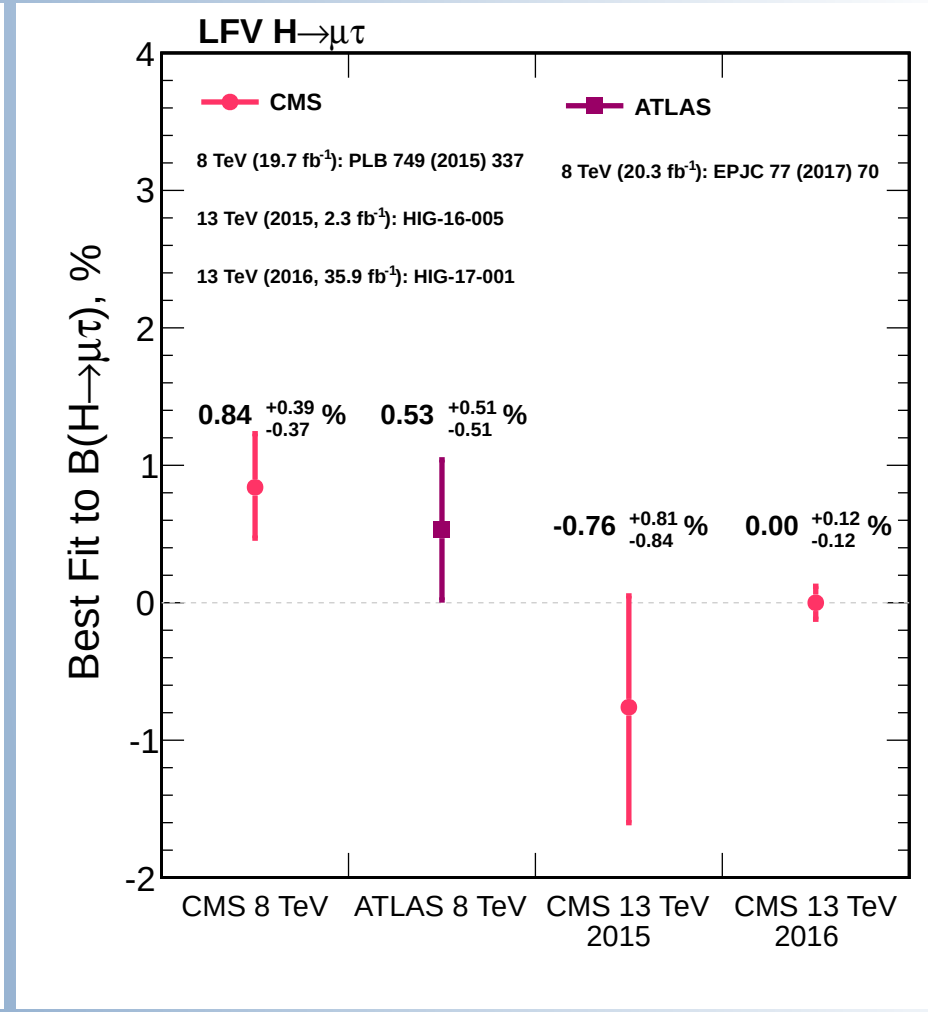


(a) $\Delta\phi(\mathrm{e}, E_T^{miss})$ (b) $\Delta\phi(\mu, E_T^{miss})$



(c) M_T (μ,E_T^{miss}) (d) $\Delta\phi(\mathrm{e}, \mu)$



(c) (d)

Comparison to other analysis