BMBF-Forschungsschwerpunkt
ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC

FSP 103
ATLAS

Measurements of Higgs-boson decays to leptons with the ATLAS detector

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on behalf of the ATLAS Collaboration

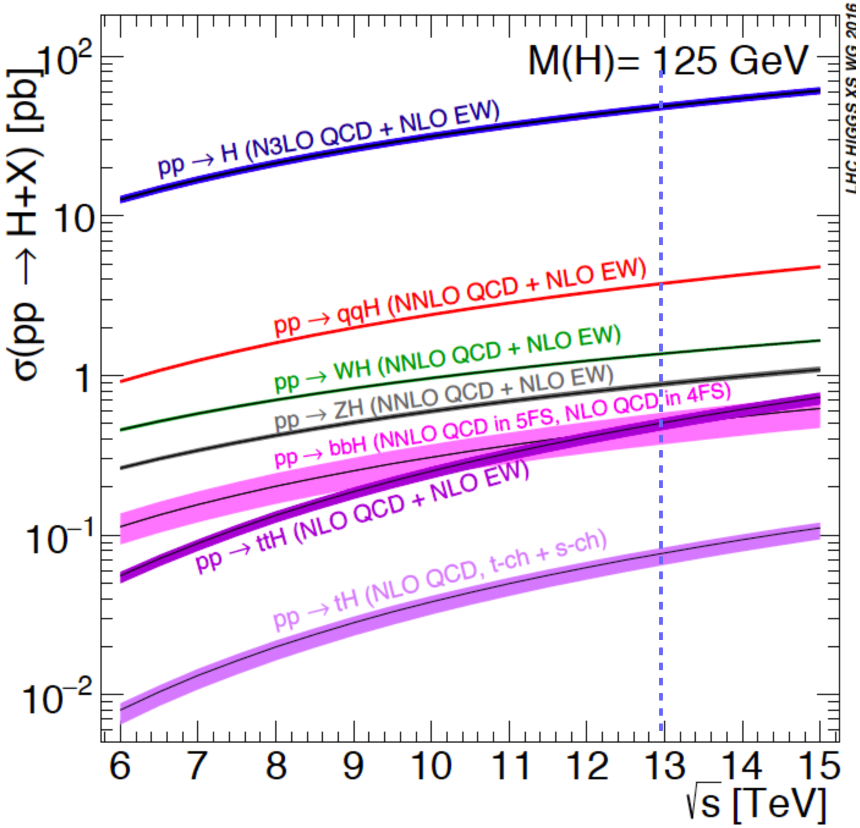
ATLAS EXPERIMENT

TAU 2018
Amsterdam
25th September 2018

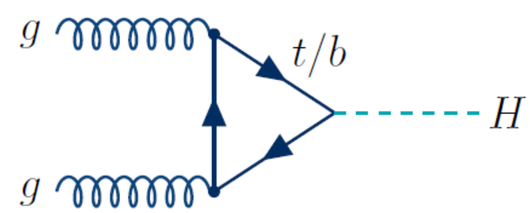
UNIVERSITÄT BONN

Higgs Production Processes

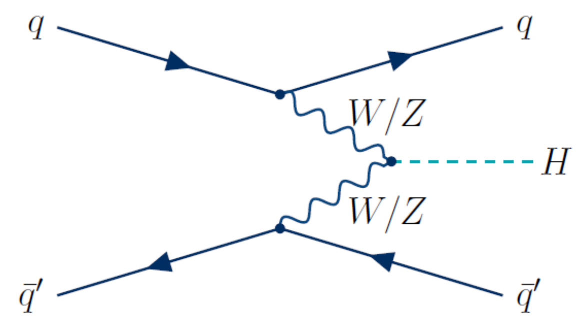
Run 2 @ 13 TeV



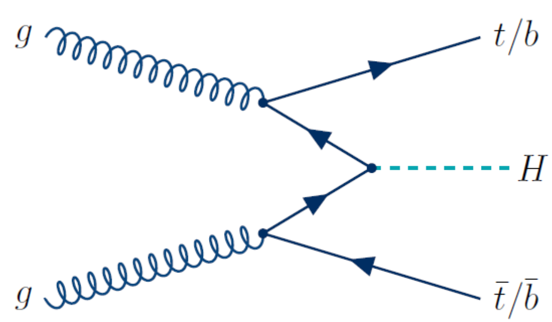
gluon-gluon fusion (ggF)



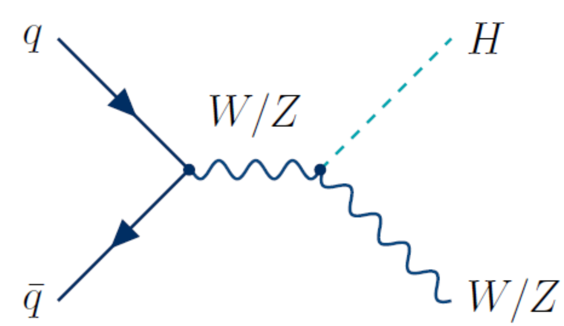
vector-boson fusion (VBF)



ttH/bbH production



VH production



- ggF: has highest production cross section but comes with large backgrounds
- VBF: large backgrounds from DY can be reduced efficiently by requiring two VBF-like jets

Higgs Decay Channels

SM Higgs Yukawa couplings to fermions:

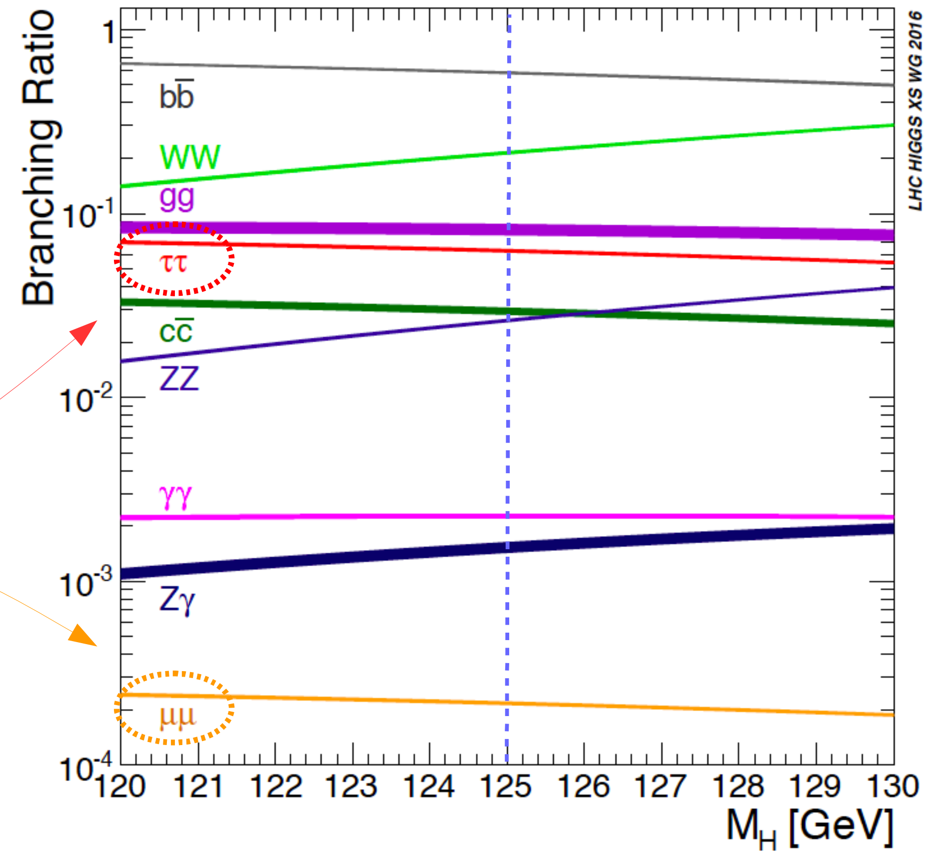
$$\mathcal{L}_{\text{Yukawa}} = \underbrace{-g_f v \bar{\psi}_f \psi_f}_{\text{mass term}} \underbrace{- g_f h \bar{\psi}_f \psi_f}_{\text{Higgs coupling}}$$

Standard Model branching ratios (m_H = 125 GeV)

leptonic Higgs decays:

$\mathcal{B}(H\rightarrow\tau\tau)_{SM} \approx 6.3\%$

$\mathcal{B}(H\rightarrow\mu\mu)_{SM} \approx 0.02\%$

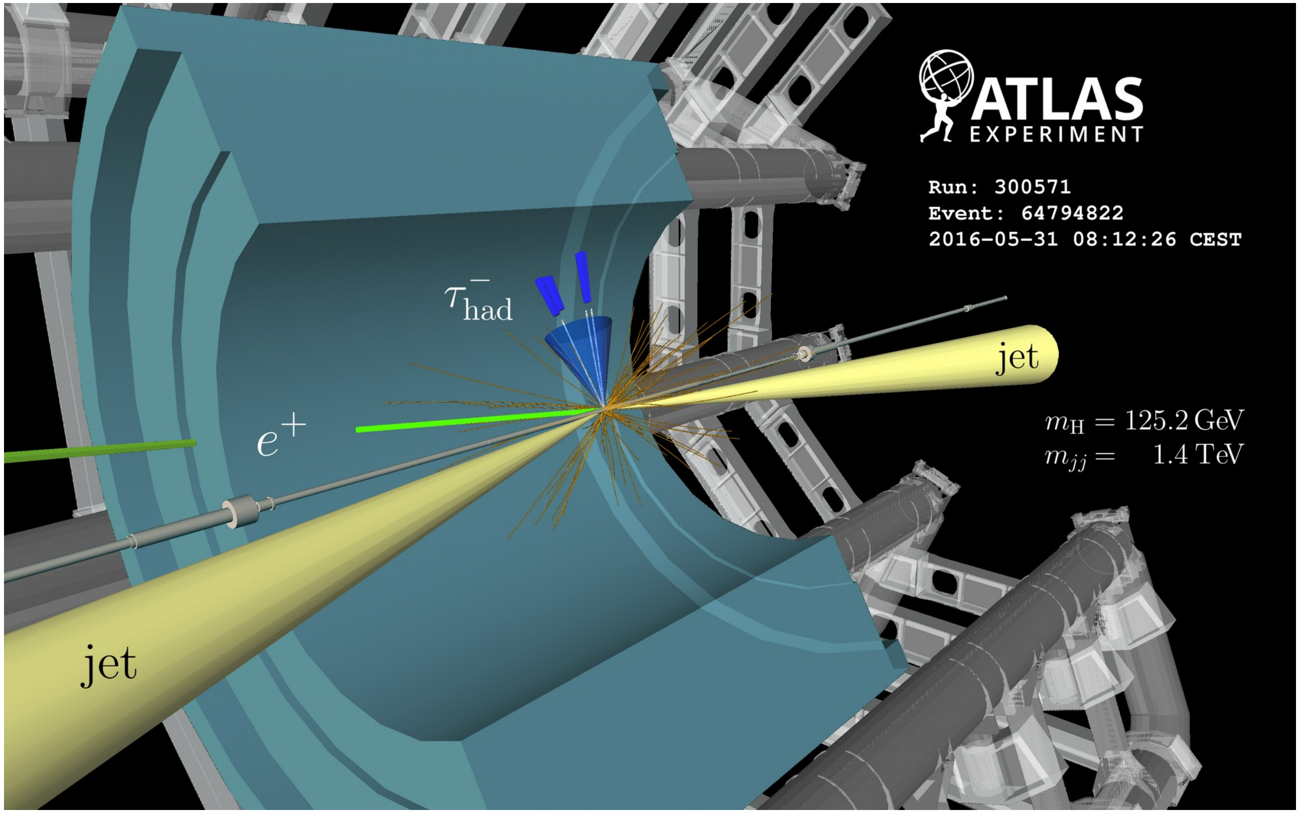


Precise measurements of the Higgs Yukawa couplings are powerful probe of the SM

Leptonic Higgs decay channels covered in this talk:

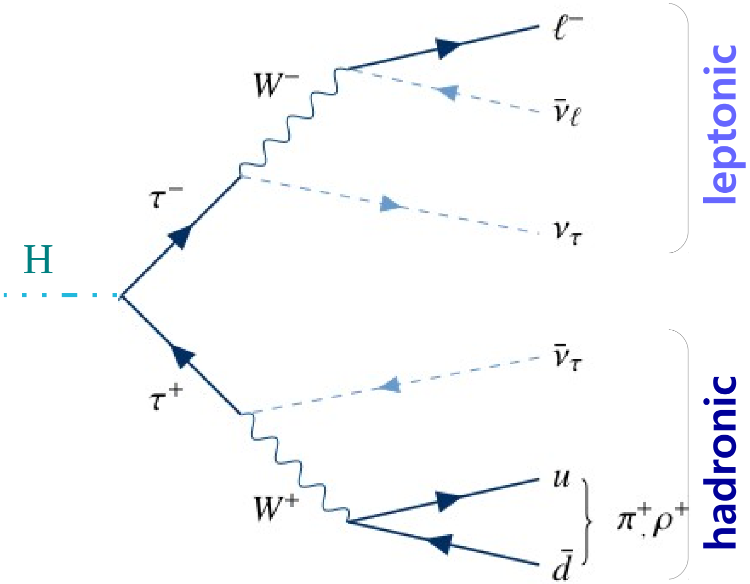
- measurement of $H \rightarrow \tau\tau$ cross section – ATLAS-CONF-2018-021, 36.1 fb^{-1}
- search for $H \rightarrow \mu\mu$ – ATLAS-CONF-2018-026, 79.8 fb^{-1}
- search for lepton-flavour-violating Higgs decays – Eur. Phys. J. C (2017)77:70, 20.3 fb^{-1}

H → τ τ Cross-Section Measurement



ATLAS-CONF-2018-021

ATLAS 2015+2016 data: 36.1 fb^{-1}



- cut-based analysis with likelihood fit to di-tau mass $m_{\tau\tau}$
- requires advanced techniques for di-tau mass reconstruction (challenging due to neutrinos in final state)
- exploit all tau decay modes (leptonic and hadronic), **channels**: lep-lep, lep-had, had-had
- split signal regions according to Higgs production process, **categories**: boosted ggF, VBF

Event Selection

Preselection

- exactly 2 opposite charge leptons (= τ,μ,e)
- missing transverse energy > 20 GeV (higher in lep-lep)
- veto on b-tagged jets (not in had-had)

VBF Higgs Signal Regions

- at least 2 jets
- large invariant mass of di-jet system

tight region
- high di-jet mass
- high Higgs p_T in lep-had

loose region
- lower di-jet mass

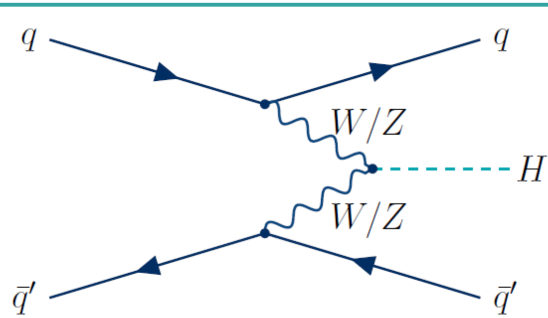
Boosted (ggF) Higgs Signal Regions

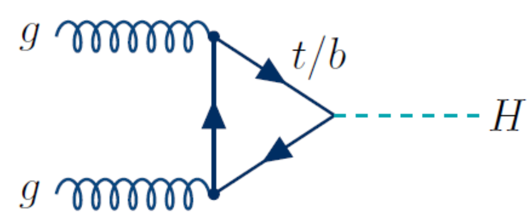
- high-p_T recoil jet → boost of the Higgs
- large Higgs transverse momentum

boosted high-p_T region
- higher Higgs p_T
- small angular distance between taus

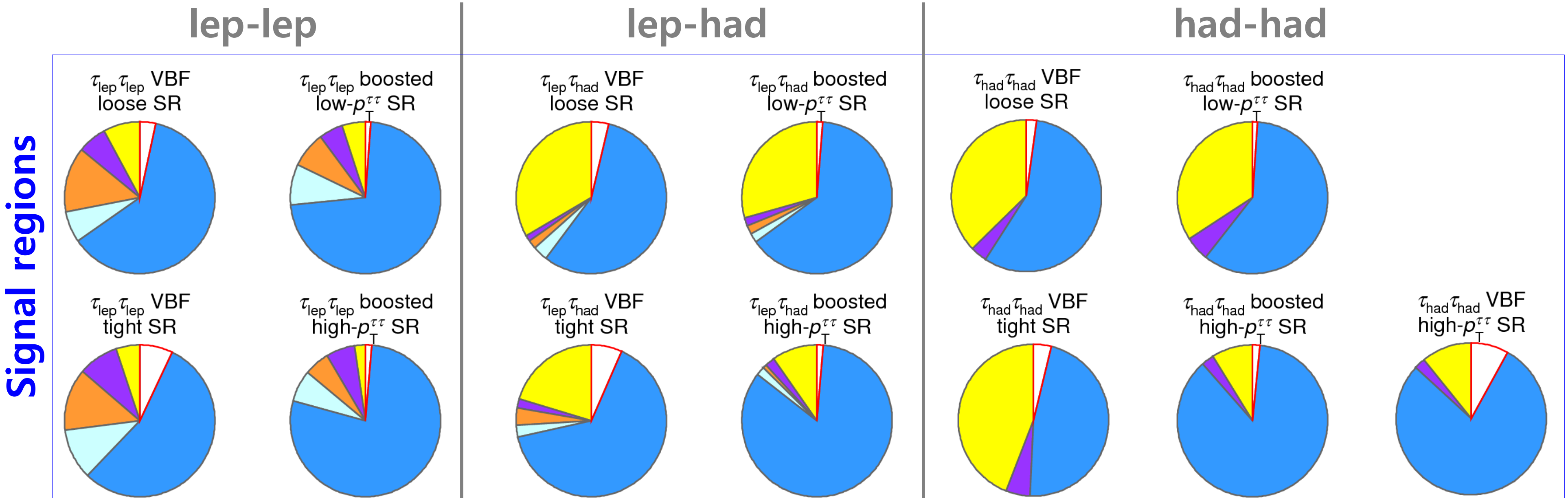
boosted low-p_T region

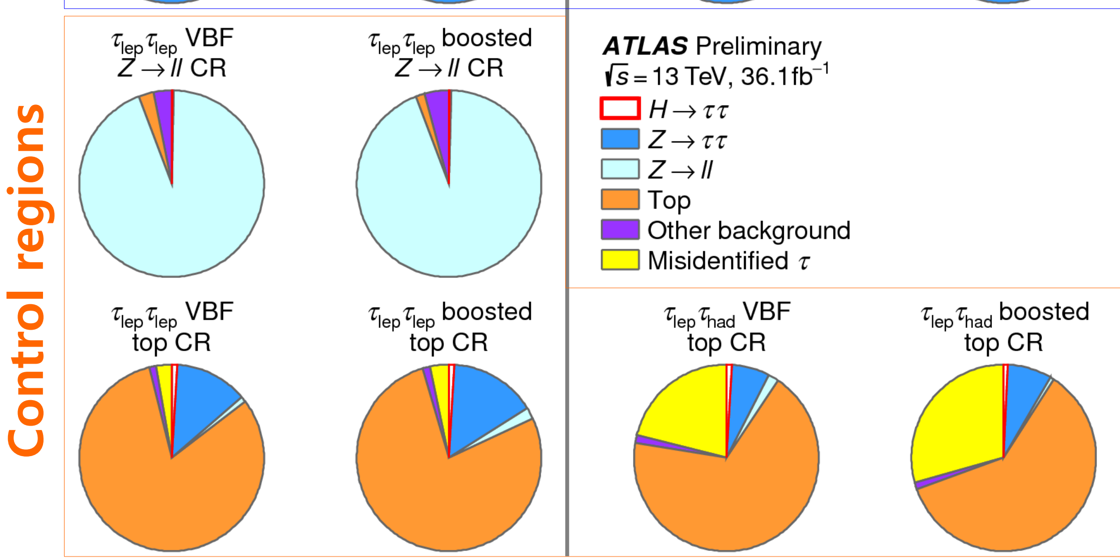
Signal Regions





Background Estimation





dominant background:
real taus from Z→ττ

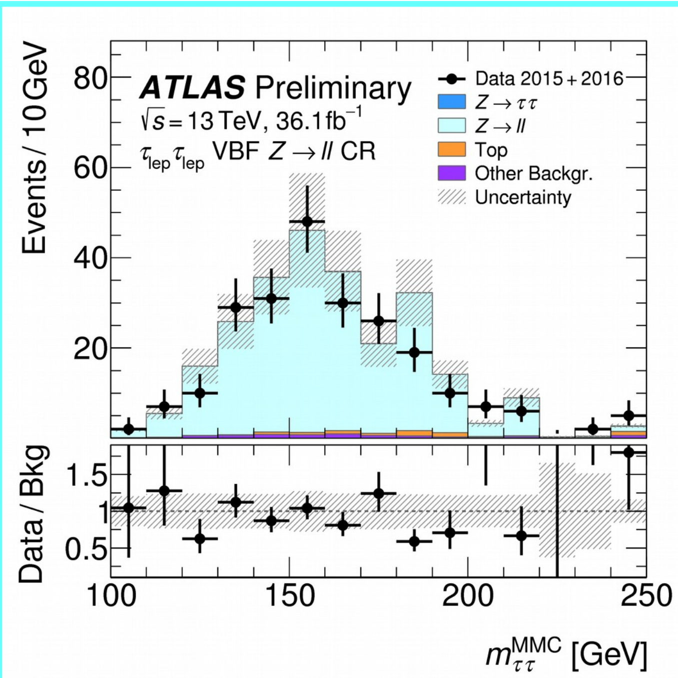
jets faking taus
(W+jets and multijets)

Z→ll events

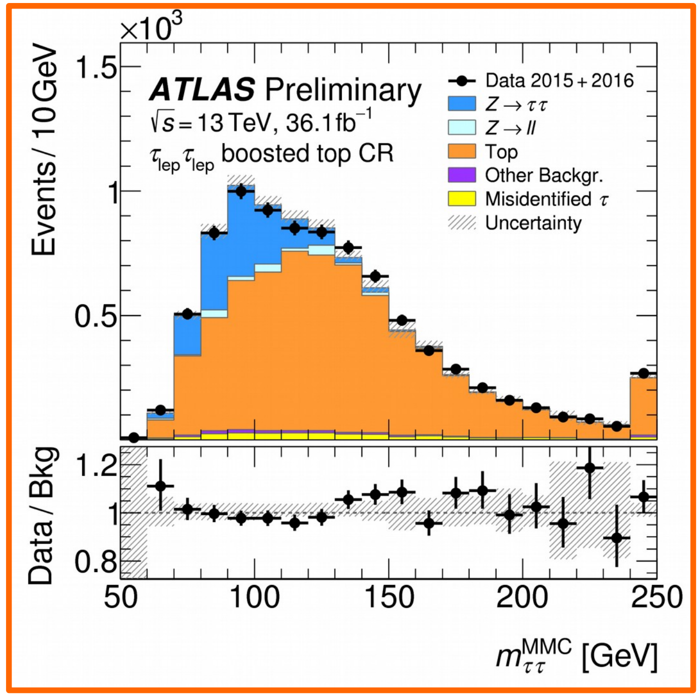
$t\bar{t}$ and single-top events

Challenge: fake-tau rejection → hadronic tau reconstruction **(talk by A.-C. Le Bihan)**

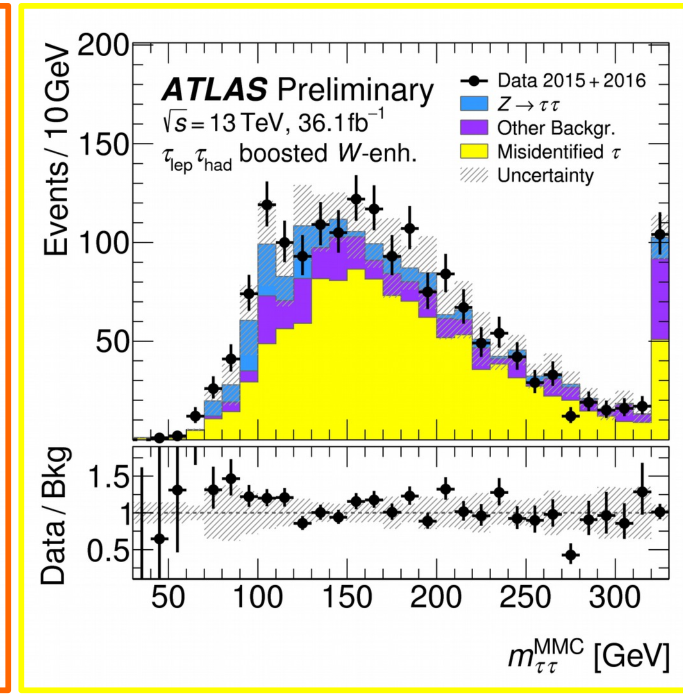
$H \rightarrow \tau\tau$ Background Estimation



Z→ll control region
(80GeV < m_{ll} < 100GeV)



Top control region
(inverted b-jet veto)



W-enhanced region
(q-jet dominated)

- Z→ll and top background normalizations constrained by event yields in respective CRs
- Z→ττ, Z→ll, top background estimated from simulation
- data-driven estimate for background from misidentified taus,
  fake-factor method in lep-had channel

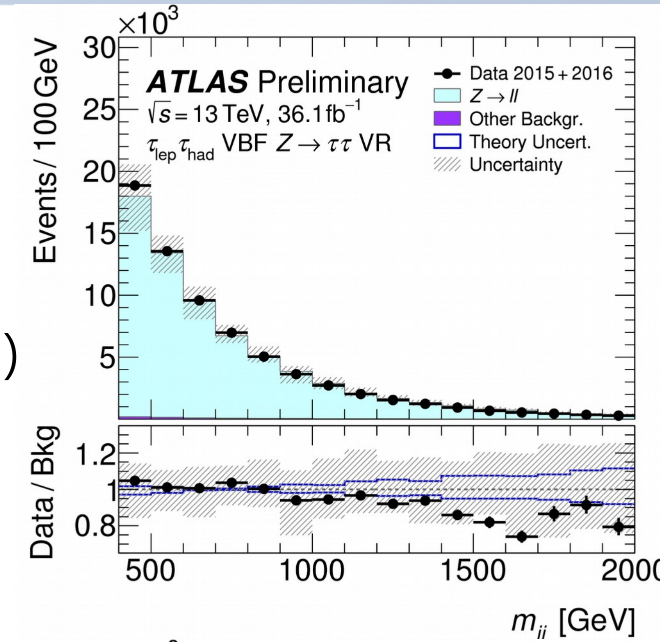
each CR modeled by single Poisson distribution
→ total expected event count in global fit

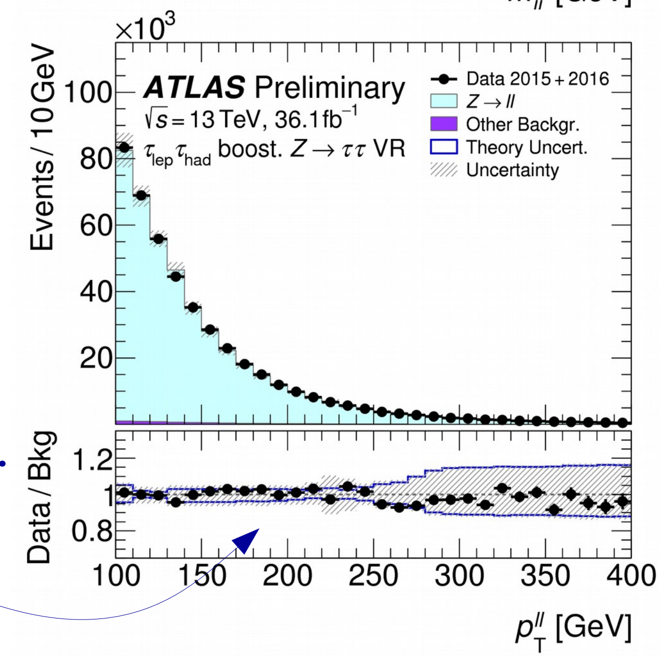
Background Estimation

Z→ττ validation regions

- Drell-Yan process is dominant irreducible background in all analysis categories (~50-90% of total background)
- Z→ττ modeling (Sherpa NLO) validated in regions with high purity in Z→ll events
- Z→ll in validation regions with similar kinematics to Z→ττ kinematics in SRs
- VR: Z→ll with low MET, SR: Z→ll with high MET
- predictions normalized to event yield in data
- very good agreement of simulation and data in the validation regions

→ good modeling of Z→ττ background





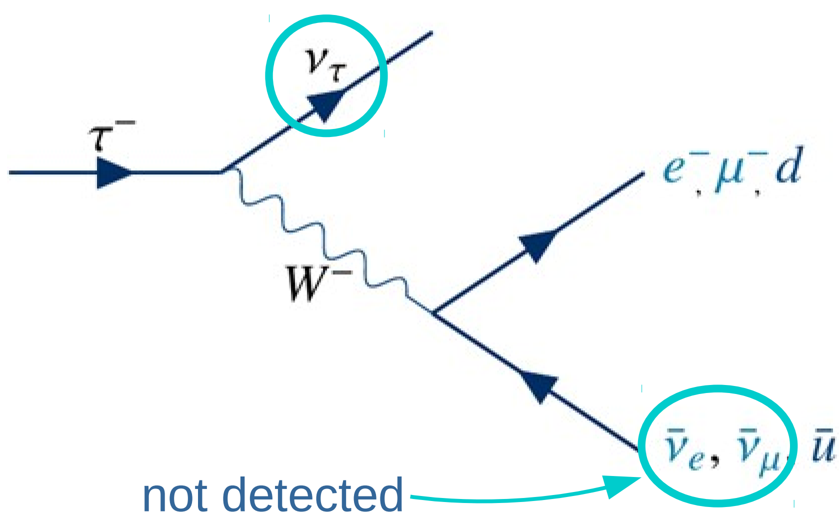
theory uncert. dominant

Observable Di-Tau Mass

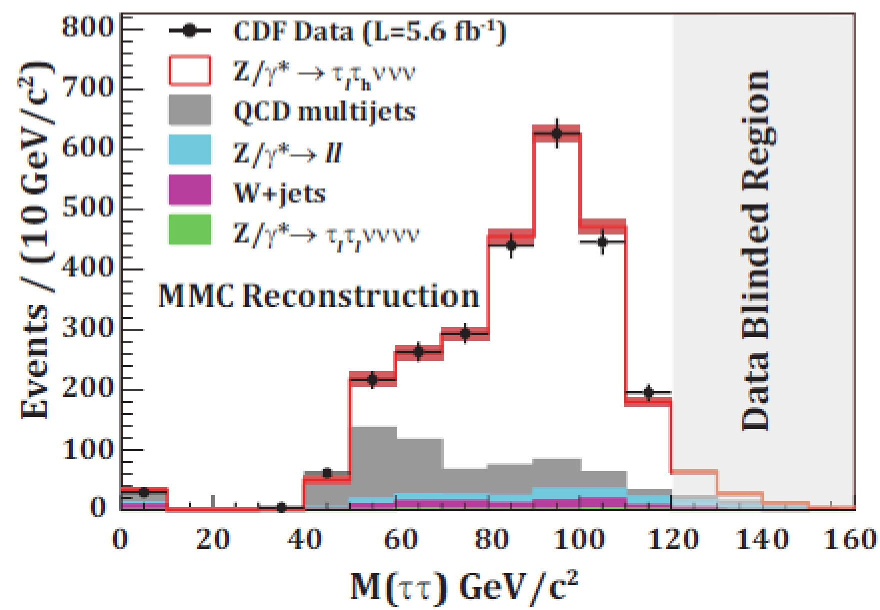
Challenge: Mass resolution of di-tau resonance
→ difficult because multiple neutrinos originate from tau decay

Missing Mass Calculator

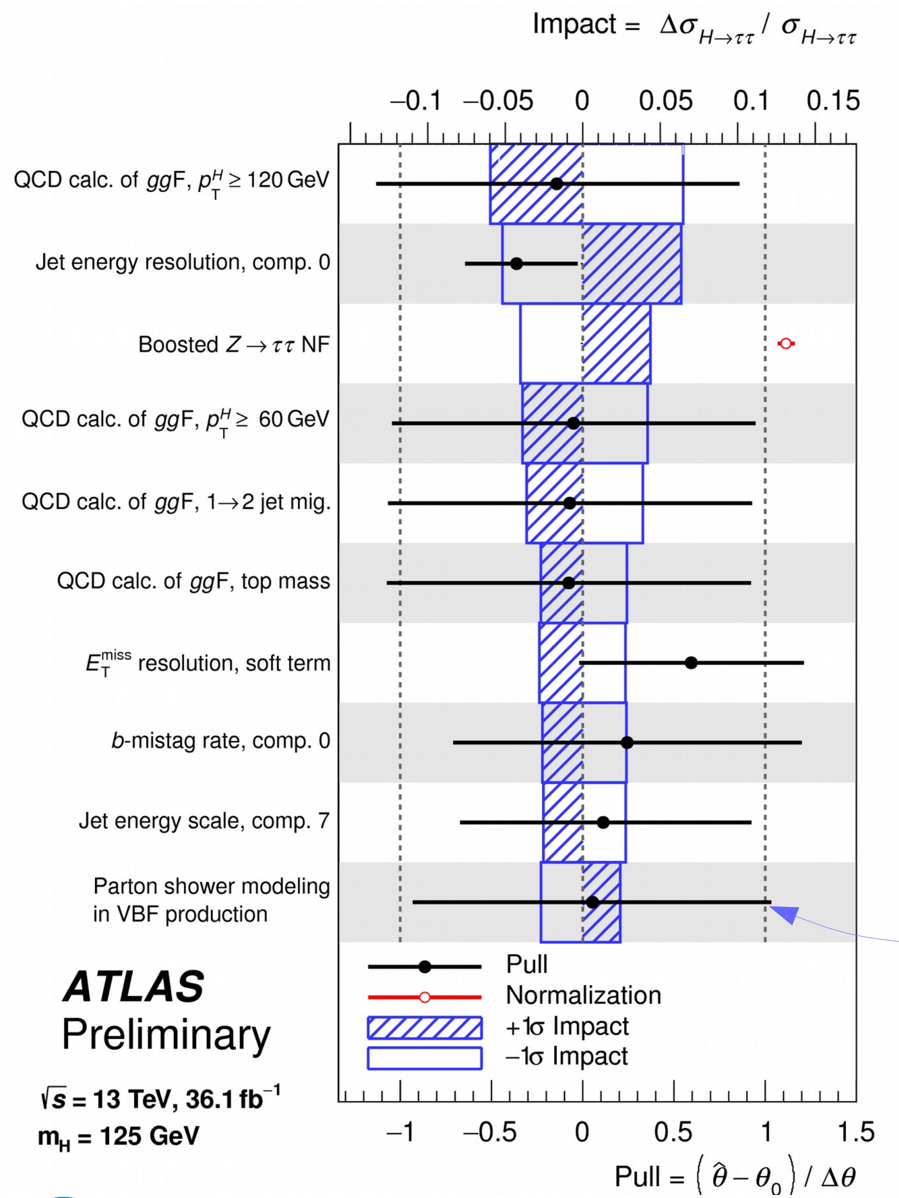
- takes into account the mass and decay kinematics of the tau leptons
- minimizes a likelihood function defined in kinematically allowed phase space



https://arxiv.org/pdf/1012.4686.pdf



Systematic Uncertainties



Sources:

- theoretical uncertainties in signal (predominantly in ggF)
- theoretical uncertainties in background
- experimental uncertainties

Dominant systematic uncertainties:

- missing higher-order QCD corrections
- jet energy resolution
- tau ID
- normalization of Z→ττ background

post-fit uncertainties of the nuisance parameters

- in most cases fitted parameters are in good agreement with nominal values

Results / Observation

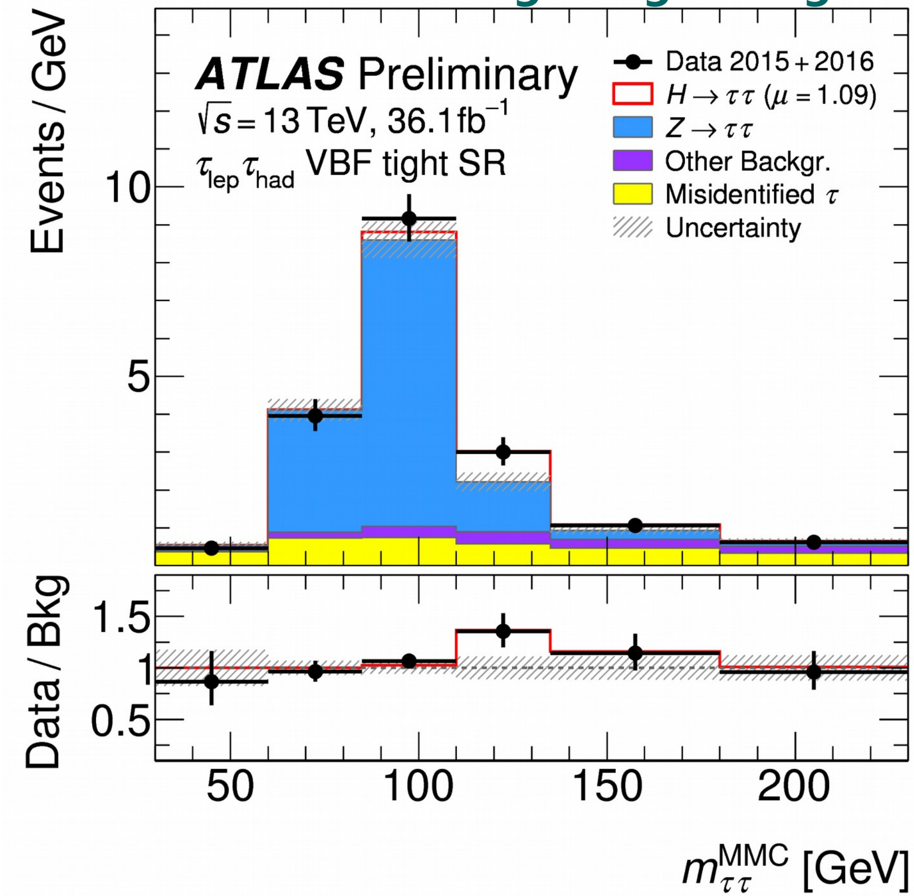
signal strength: ratio of measured signal yield to the SM expectation

$$\mu_{H\rightarrow\tau\tau} = 1.09^{+0.18}_{-0.17}(\text{stat.})^{+0.27}_{-0.22}(\text{syst.})^{+0.16}_{-0.11}(\text{theory syst.})$$

observed (expected) significances
@ $\sqrt{s}$ = 13 TeV:
4.4 (4.1) *σ*
combined with Run1 result
@ $\sqrt{s}$ = 7 TeV and 8 TeV:
6.4 (5.4) *σ*

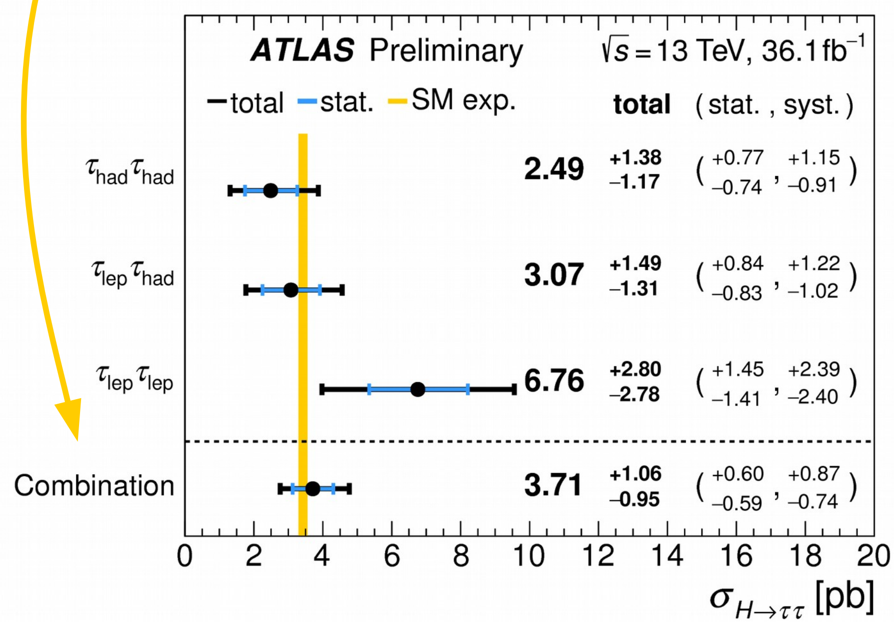
→ Observation!

VBF tight signal region

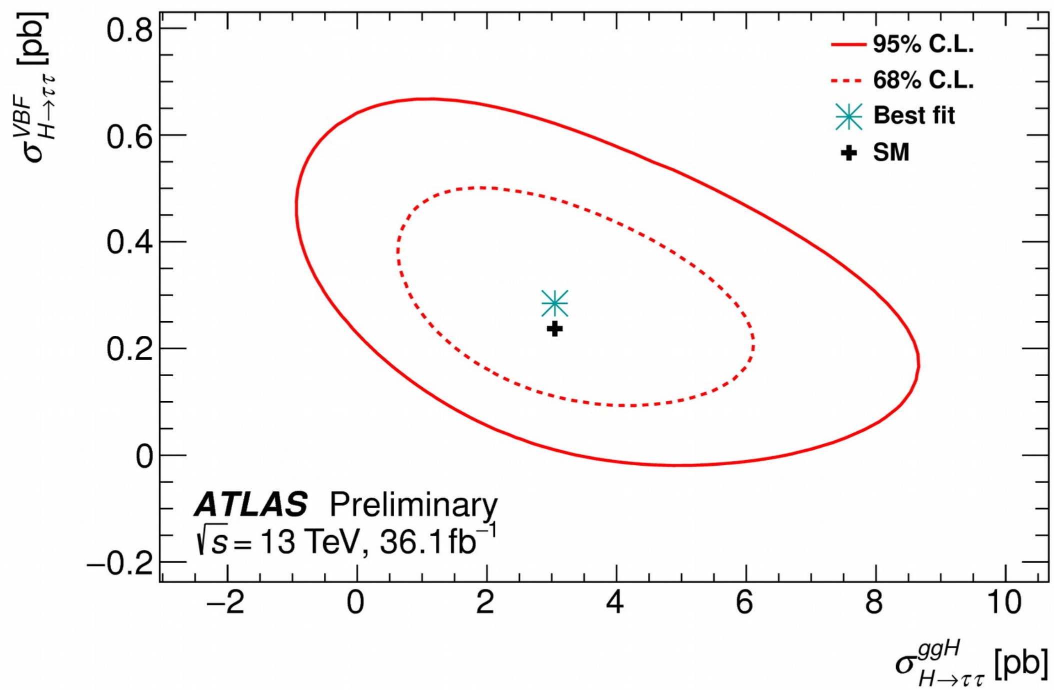


Results

measurement of total Higgs production cross section in H→ττ channel with single-parameter fit



two-parameter cross-section fit separating the ggF and VBF production processes



pp → H → ττ total cross section:

$$\sigma_{H\to\tau\tau} \equiv \sigma_H \cdot B(H\to\tau\tau)$$

$$\sigma_{H\to\tau\tau} = 3.71^{+0.60}_{-0.59}(\text{stat.})^{+0.87}_{-0.74}(\text{syst.})\,\text{pb}$$

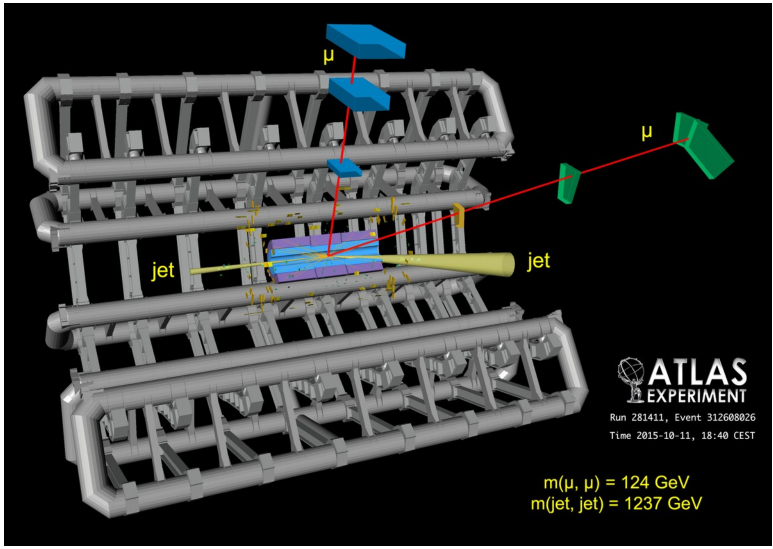
$$\sigma^{\text{ggH}}_{H\to\tau\tau} = 3.0 \pm 1.0(\text{stat.})^{+1.6}_{-1.2}(\text{syst.})\,\text{pb}$$

$$\sigma^{\text{VBF}}_{H\to\tau\tau} = 0.28 \pm 0.09(\text{stat.})^{+0.11}_{-0.09}(\text{syst.})\,\text{pb}$$

Search for H → μ μ

ATLAS-CONF-2018-026 ATLAS data @ $\sqrt{s}$ = 13 TeV, 79.8 fb^{-1}

- high $m_{\mu\mu}$ resolution with **two isolated opposite-sign μ**
- events are classified into **ggF- and VBF-enriched** regions
- **multivariate analysis (BDT)** is used to define VBF regions
- signal & background described by **analytic functions**



$$P_S(m_{\mu\mu}) = f_{CB} \times CB(m_{\mu\mu}, m_{CB}, \sigma_{CB}, \alpha, n) + (1 - f_{CB}) \times GS\left(m_{\mu\mu}, m_{GS}, \sigma_{GS}^{S}\right)$$

Crystal Ball function (CB) Gaussian function (GS)

$$P_B(m_{\mu\mu}) = f \times [BW(m_{BW}, \Gamma_{BW}) \otimes GS(\sigma_{GS}^{B})](m_{\mu\mu}) + (1 - f) \times e^{A \cdot m_{\mu\mu}} / m_{\mu\mu}^{3}$$

Breit Wigner (BW)
Gaussian function (GS)
exponential
cubic function

- **fit** of analytic functions to data, search for bump in mass window around Higgs mass (110 GeV < $m_{\mu\mu}$ < 160 GeV)

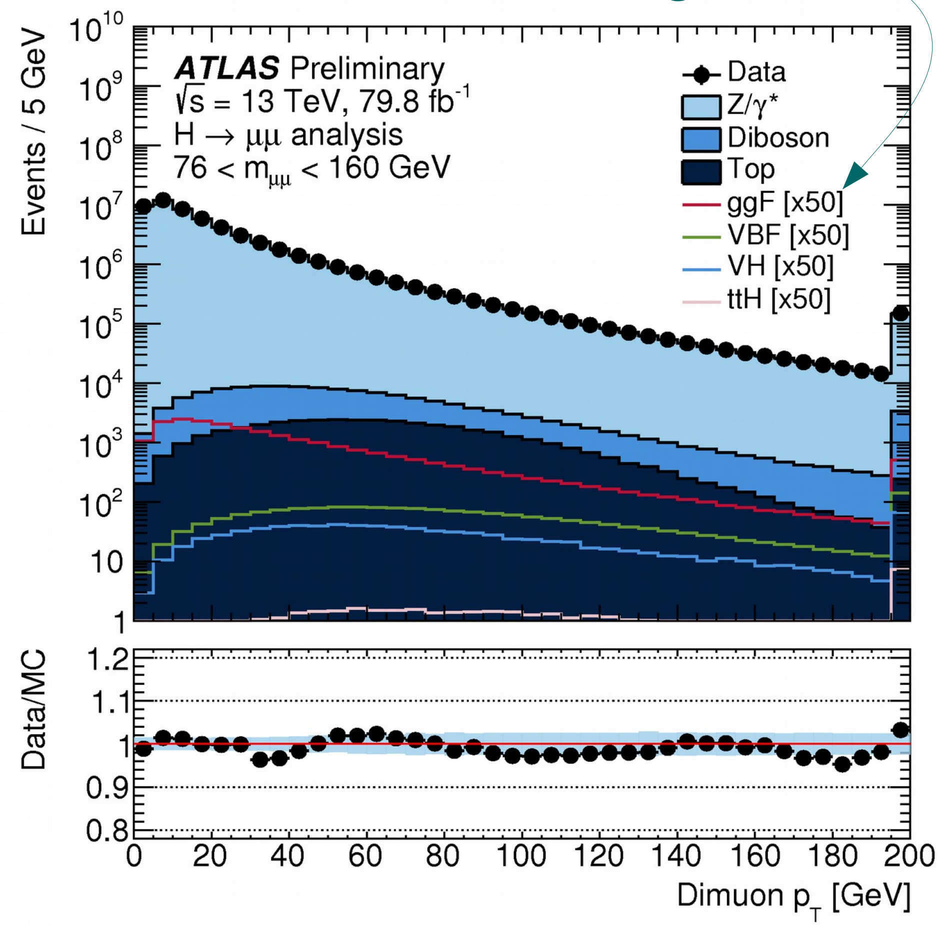
Background Modeling

Background Estimation

- dominant background from Drell-Yan process $Z/\gamma^* \rightarrow \mu\mu$
- MC simulation:
  - optimize the event selection
  - model the signal processes
  - develop **analytic functions** to model mass distributions for total background
- reweighting to improve modeling of $Z/\gamma^* \rightarrow ll$ p_T spectrum

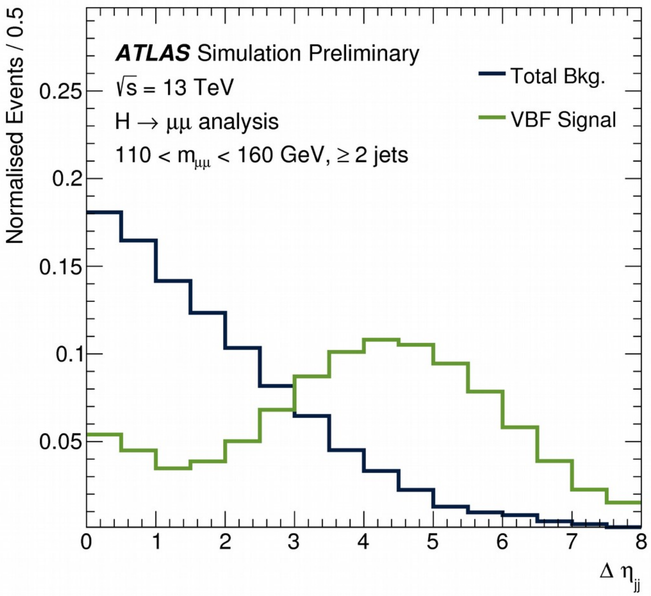
→ general agreement of data and simulation

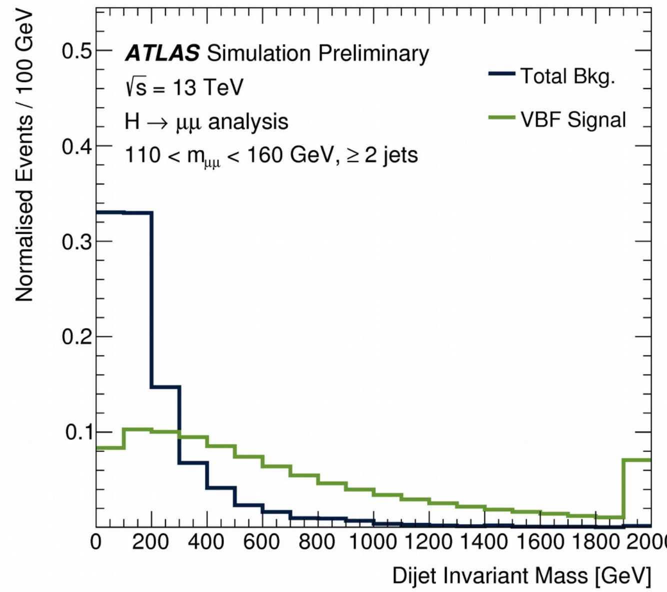
signal x50

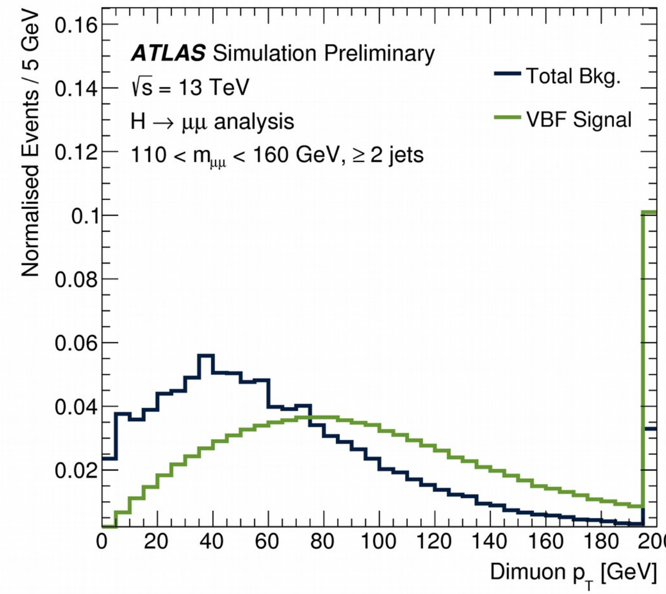


Dimuon transverse momentum p_T

$H \rightarrow \mu\mu$ Signal & Background Separation







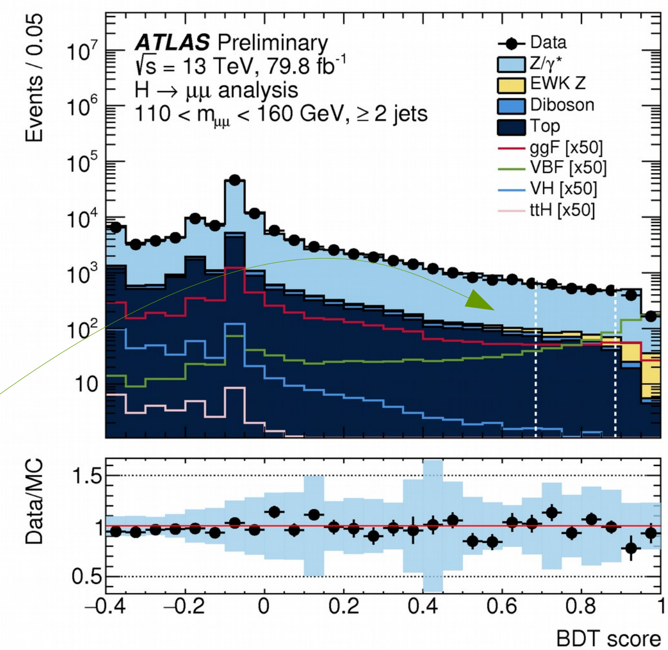
most sensitive BDT input variables

Boosted Decision Tree (BDT)

- maximize separation between VBF signal and total background
- BDT to select events in two VBF categories
- all other events categorised in 6 ggF categories based on dimuon p_T and $|\Delta\eta|$

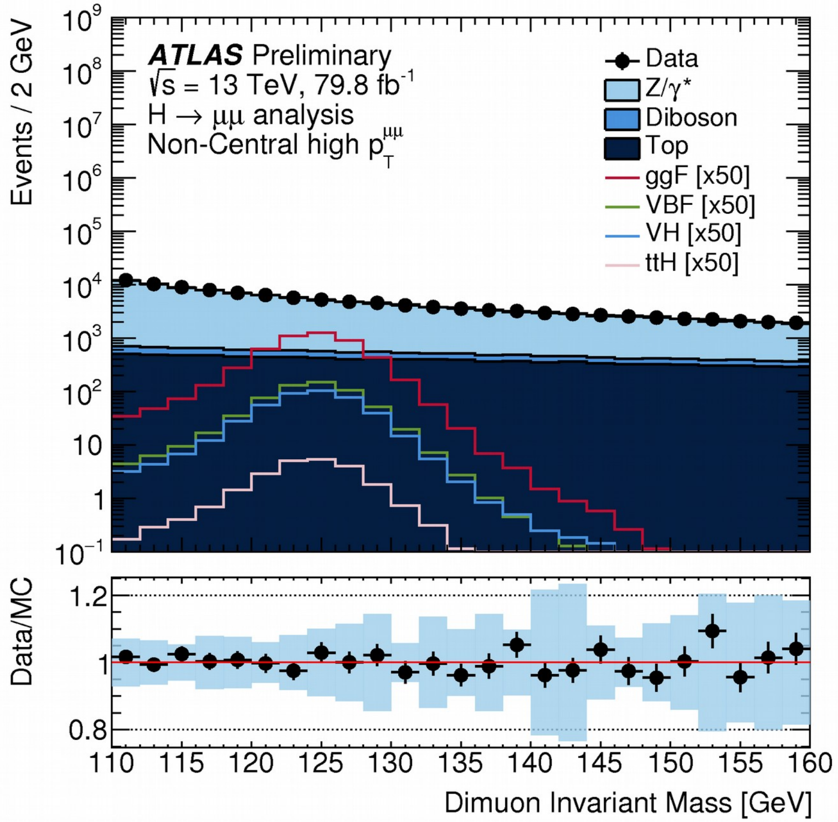
BDT score

VBF signal peaks at 1

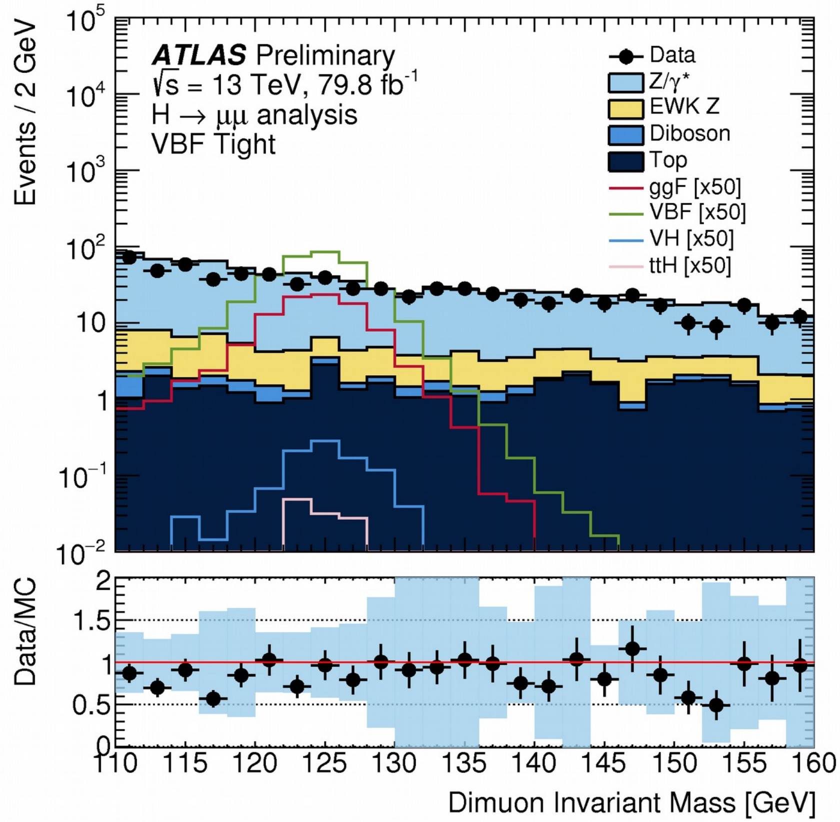


Signal Regions

dimuon mass $m_{\mu\mu}$ distributions for the two most sensitive categories:



Non-central high-p_T region



VBF tight region

Fit

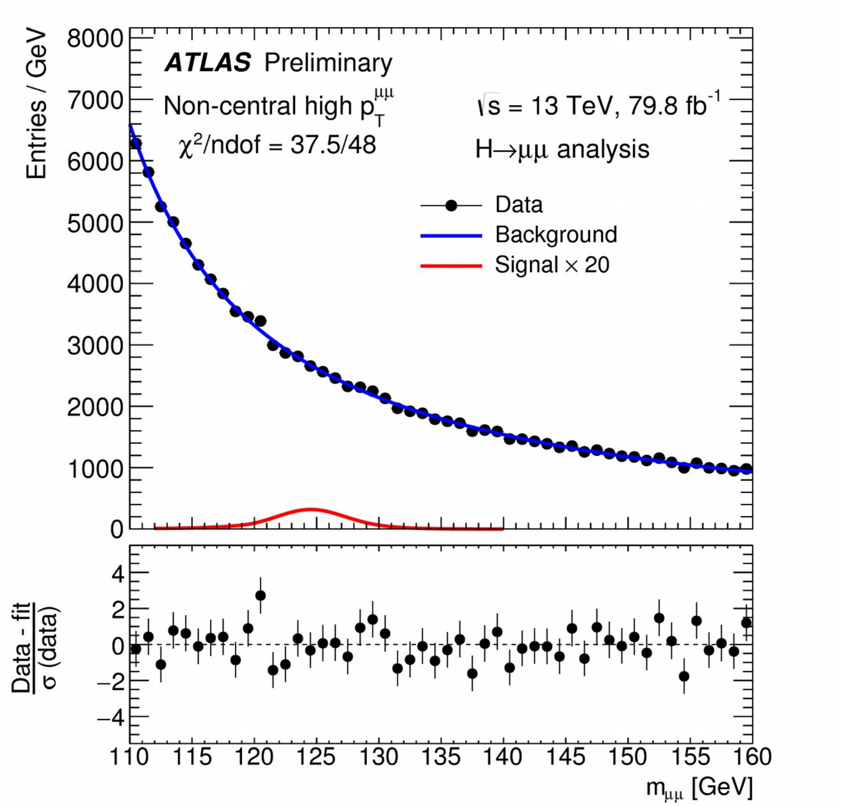
- signal+background fit to dimuon mass distribution in all signal regions

Results / Limits

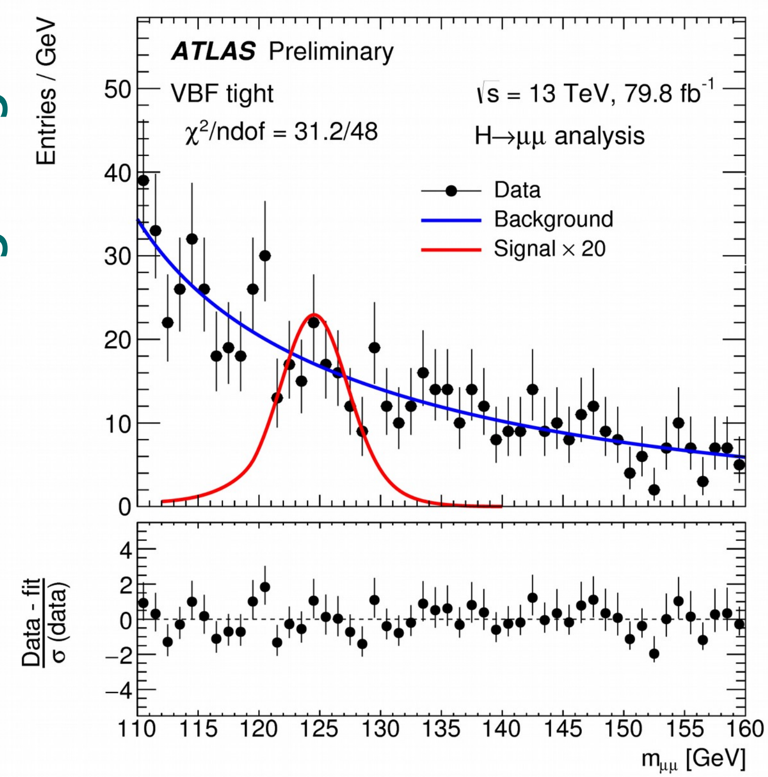
Results

- measured overall signal strength $\mu = 0.1^{+1.0}_{-1.1}$
- obs. (exp.) upper limit on signal strength μ < 2.1 (2.0) at 95% CL
- improvement of ~35% compared to previous ATLAS result

Non-central high p_T region



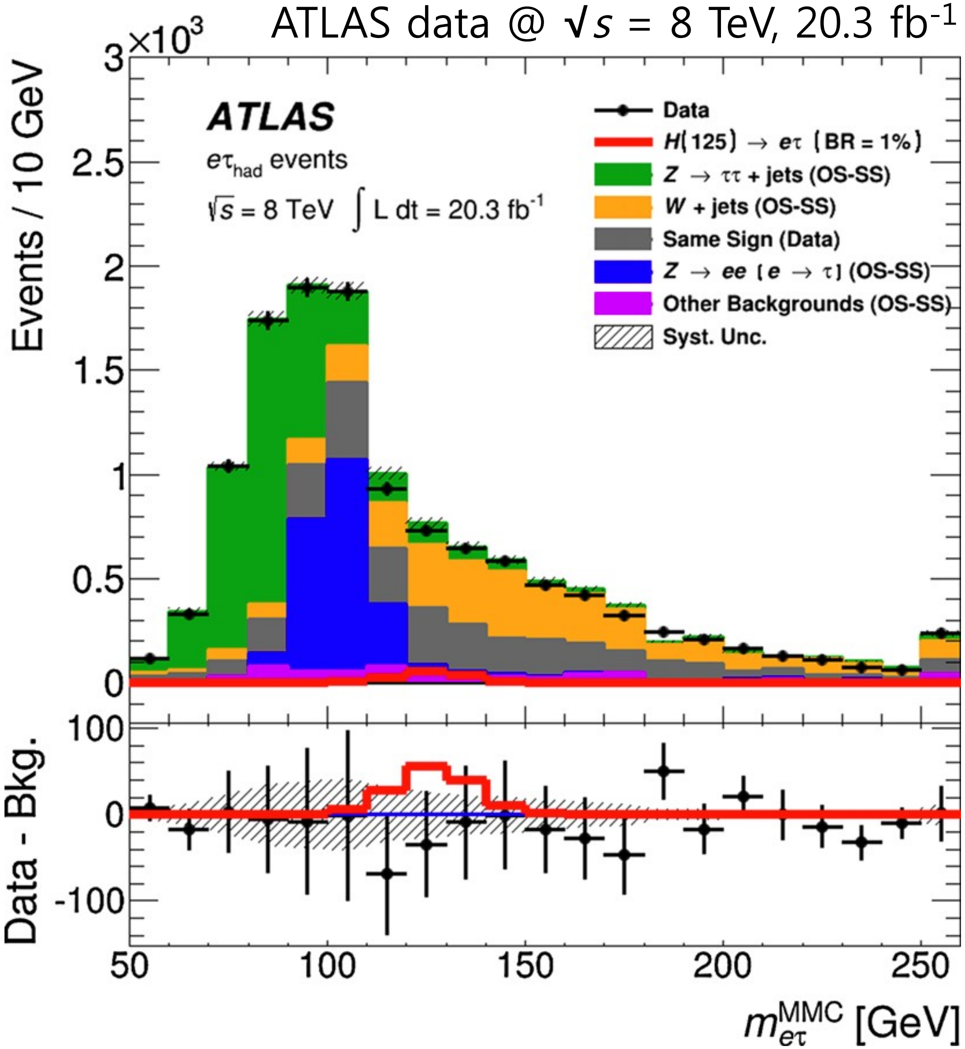
VBF tight region



Search for LFV Higgs decays

Eur. Phys. J. C (2017) 77:70

ATLAS data @ $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}



lepton-flavour-violating (LFV) Higgs decays (talk by B. Le @16:35)

$H \to e\tau$, $H \to \mu\tau$

motivation:

- beyond-SM physics models predict LFV Higgs decays
- $\tau \to 3\mu$ decay via Higgs boson

- final state like in $H \to \tau\tau$ analysis, but prompt lepton
- leptonic and hadronic tau decays considered

no significant excess observed
upper limits on LFV branching ratios:
$\mathcal{B}(H \to e\tau) < 1.04\%$
$\mathcal{B}(H \to \mu\tau) < 1.43\%$

Summary & Outlook

LFV

Search for lepton-flavour-violating Higgs decays

no significant excess observed

set new upper limits on LFV branching ratios:

$\mathcal{B}(H \rightarrow e\tau) < 1.04\%$, $\mathcal{B}(H \rightarrow \mu\tau) < 1.43\%$

$H \rightarrow \mu\mu$

Search for the decay of Higgs boson to dimuons

no significant excess observed

set more stringent upper limits on signal strength:

$\mu < 2.1$ (2.0) at 95% CL

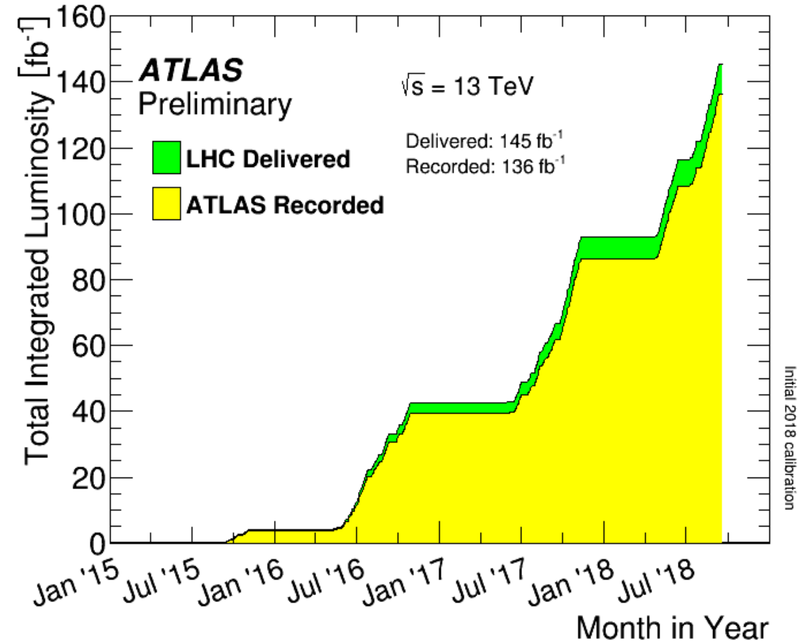
$H \rightarrow \tau\tau$

Cross-section measurement of $H \rightarrow \tau\tau$

Observation of $H \rightarrow \tau\tau$

significance **6.4** (5.4) ***σ***

Yukawa term in SM as expected ($pp \rightarrow ttH$, $H \rightarrow bb$)



ttH production: Phys. Lett. B 784 (2018) 173

$H \rightarrow bb$ decay: arXiv:1808.08238

- next goal: differential cross-section measurements
  - sensitive to new physics (e.g. composite Higgs models)

Looking forward to perform further precision measurements!


Van Gogh Museum, Amsterdam (Vincent van Gogh Foundation)

B O N U S

Event Selection

Preselection Cuts

<table>
<tr><th colspan="2">$\tau_{\text{lep}}\tau_{\text{lep}}$</th><th rowspan="2">$\tau_{\text{lep}}\tau_{\text{had}}$</th><th rowspan="2">$\tau_{\text{had}}\tau_{\text{had}}$</th></tr>
<tr><th>$ee/\mu\mu$</th><th>$e\mu$</th></tr>
<tr><td colspan="2">$N^{\text{loose}}_{e/\mu} = 2,\ N^{\text{loose}}_{\tau_{\text{had-vis}}} = 0$</td><td>$N^{\text{loose}}_{e/\mu} = 1,\ N^{\text{loose}}_{\tau_{\text{had-vis}}} = 1$</td><td>$N^{\text{loose}}_{e/\mu} = 0,\ N^{\text{loose}}_{\tau_{\text{had-vis}}} = 2$</td></tr>
<tr><td colspan="2">e/μ : Medium, gradient iso.</td><td>e/μ : Medium, gradient iso.</td><td></td></tr>
<tr><td colspan="2"></td><td>$\tau_{\text{had-vis}}$: Medium</td><td>$\tau_{\text{had-vis}}$: Tight</td></tr>
<tr><td colspan="2">Opposite charge</td><td>Opposite charge</td><td>Opposite charge</td></tr>
<tr><td colspan="2">$m^{\text{coll}}_{\tau\tau} > m_Z - 25$ GeV</td><td>$m_{\text{T}} < 70$ GeV</td><td></td></tr>
<tr><td>$30 < m_{\ell\ell} < 75$ GeV</td><td>$30 < m_{\ell\ell} < 100$ GeV</td><td></td><td></td></tr>
<tr><td>$E^{\text{miss}}_{\text{T}} > 55$ GeV</td><td>$E^{\text{miss}}_{\text{T}} > 20$ GeV</td><td>$E^{\text{miss}}_{\text{T}} > 20$ GeV</td><td>$E^{\text{miss}}_{\text{T}} > 20$ GeV</td></tr>
<tr><td>$E^{\text{miss, hard}}_{\text{T}} > 55$ GeV</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">$\Delta R_{\tau\tau} < 2.0$</td><td>$\Delta R_{\tau\tau} < 2.5$</td><td>$0.8 < \Delta R_{\tau\tau} < 2.5$</td></tr>
<tr><td colspan="2">$|\Delta\eta_{\tau\tau}| < 1.5$</td><td>$|\Delta\eta_{\tau\tau}| < 1.5$</td><td>$|\Delta\eta_{\tau\tau}| < 1.5$</td></tr>
<tr><td colspan="2">$0.1 < x_1 < 1.0$</td><td>$0.1 < x_1 < 1.4$</td><td>$0.1 < x_1 < 1.4$</td></tr>
<tr><td colspan="2">$0.1 < x_2 < 1.0$</td><td>$0.1 < x_2 < 1.2$</td><td>$0.1 < x_2 < 1.4$</td></tr>
<tr><td colspan="2">$p^{j_1}_{\text{T}} > 40$ GeV</td><td>$p^{j_1}_{\text{T}} > 40$ GeV</td><td>$p^{j_1}_{\text{T}} > 70$ GeV, $|\eta_{j_1}| < 3.2$</td></tr>
<tr><td colspan="2">$N_{b\text{-jets}} = 0$</td><td>$N_{b\text{-jets}} = 0$</td><td></td></tr>
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Event Selection

Signal Regions

Signal Region		Inclusive	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
VBF	High-$p_T^{\tau\tau}$	$p_T^{j_2} > 30$ GeV $\lvert\Delta\eta_{jj}\rvert > 3$ $m_{jj} > 400$ GeV $\eta_{j_1} \cdot \eta_{j_2} < 0$ Central leptons	—		$p_T^{\tau\tau} > 140$ GeV $\Delta R_{\tau\tau} < 1.5$
	Tight		$m_{jj} > 800$ GeV	$m_{jj} > 500$ GeV $p_T^{\tau\tau} > 100$ GeV	Not VBF high-$p_T^{\tau\tau}$ $m_{jj} > (1550 - 250 \cdot \lvert\Delta\eta_{jj}\rvert)$ GeV
	Loose		Not VBF tight		Not VBF high-$p_T^{\tau\tau}$ and not VBF tight
Boosted	High-$p_T^{\tau\tau}$	Not VBF $p_T^{\tau\tau} > 100$ GeV	$p_T^{\tau\tau} > 140$ GeV $\Delta R_{\tau\tau} < 1.5$		
	Low-$p_T^{\tau\tau}$		Not boosted high-$p_T^{\tau\tau}$		

$H \rightarrow \mu\mu$ Signal and Background Modeling

Higgs boson peak

- resolution effects
- final-state photon radiation

$$P_{\mathrm{S}}(m_{\mu\mu}) = f_{CB} \times CB(m_{\mu\mu}, m_{CB}, \sigma_{CB}, \alpha, n) + (1 - f_{CB}) \times \mathrm{GS}\left(m_{\mu\mu}, m_{\mathrm{GS}}, \sigma^{\mathrm{S}}_{\mathrm{GS}}\right)$$

Crystal Ball function (CB) Gaussian function (GS)

Background

- falling dimuon distributions dominated by Drell-Yan process
- flexibility to absorb potential differences between data and MC simulation
- allow variations in different categories
- additional contributions from minor background processes

$$P_{\mathrm{B}}(m_{\mu\mu}) = f \times [\mathrm{BW}(m_{\mathrm{BW}}, \Gamma_{\mathrm{BW}}) \otimes \mathrm{GS}(\sigma^{\mathrm{B}}_{\mathrm{GS}})](m_{\mu\mu}) + (1 - f) \times \mathrm{e}^{A \cdot m_{\mu\mu}} / m^{3}_{\mu\mu}$$

Breit Wigner (BW)

Gaussian function (GS)

exponential

cubic function