Cross section measurement of the Higgs boson decaying in tau-lepton pair with the ATLAS detector

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on the behalf of the ATLAS collaboration

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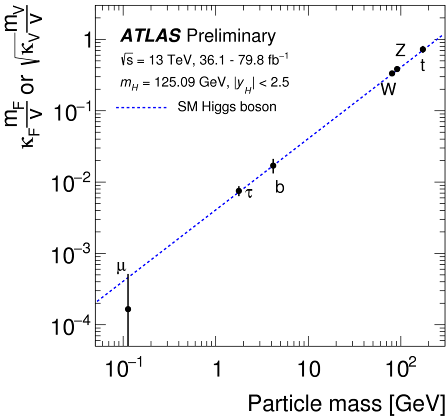
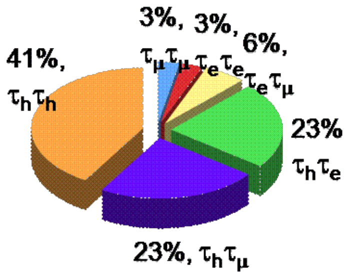
$H \to \tau\tau$ search motivation

- In the SM, $H \to \tau\tau$ is currently the only accessible decay at the LHC to establish Higgs-Yukawa coupling to leptons



Higgs couplings

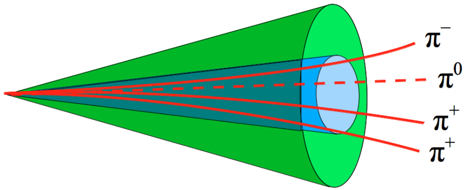


$H \to \tau\tau$ decay modes

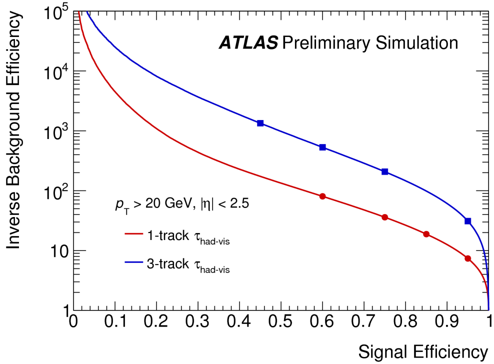
τ Decay Mode	BR [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	17.4
$\tau^- \to h^- \nu_\tau$	11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$	4.8
Others	3.2

Tau Reconstruction and Identification

- Tau candidates are seeded by anti-k_t jets with a distance parameter R = 0.4
- Track association to select tracks in the *core* ($0 < \Delta R < 0.2$) and *isolation* ($0.2 < \Delta R < 0.4$) regions around the tau candidate
- Identification algorithm based on *Boosted Decision Tree* (BDT) to reject background from q/g jets
  - use information from shower shape and track based variables



Scheme of a hadronic tau decay



Eur.Phys.JC76(5),1-26(2016)

Run 2 coupling measurement

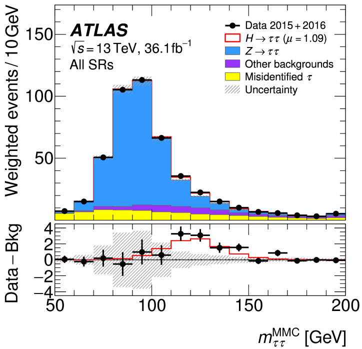
- Cut-based (CBA) analysis using 36.1 fb^{-1} of data collected at $\sqrt{s}$= 13 TeV during 2015+2016 (`https://arxiv.org/abs/1811.08856`)
- Targeting Vector Boson Fusion (*VBF*) and Gluon Fusion (*ggF*) Higgs boson production modes
- Harmonisation across different di-tau decay channels to use similar signal regions and similar object definitions

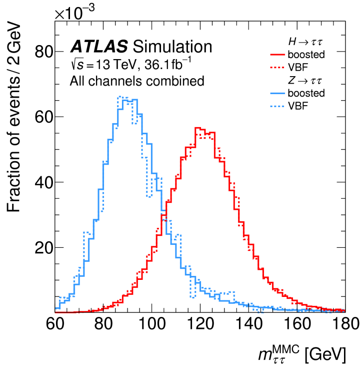
<table>
<tr><th colspan="2">Signal Region</th><th>Inclusive</th><th>$\tau_{\text{lep}}\tau_{\text{lep}}$</th><th>$\tau_{\text{lep}}\tau_{\text{had}}$</th><th>$\tau_{\text{had}}\tau_{\text{had}}$</th></tr>
<tr><td rowspan="3">VBF</td><td>High-$p_{\text{T}}^{\tau\tau}$</td><td rowspan="3">$p_{\text{T}}^{j_2} > 30$ GeV
$|\Delta\eta_{jj}| > 3$
$m_{jj} > 400$ GeV
$\eta_{j_1} \cdot \eta_{j_2} < 0$
Central leptons</td><td colspan="2">—</td><td>$p_{\text{T}}^{\tau\tau} > 140$ GeV
$\Delta R_{\tau\tau} < 1.5$</td></tr>
<tr><td>Tight</td><td>$m_{jj} > 800$ GeV</td><td>$m_{jj} > 500$ GeV
$p_{\text{T}}^{\tau\tau} > 100$ GeV</td><td>Not VBF high-p_{T}
$m_{jj} > (1550 - 250 \cdot \Delta\eta_{jj})$ GeV</td></tr>
<tr><td>Loose</td><td colspan="3">Otherwise</td></tr>
<tr><td rowspan="2">Boosted</td><td>High-$p_{\text{T}}^{\tau\tau}$</td><td rowspan="2">Not VBF
$p_{\text{T}}^{\tau\tau} > 100$ GeV</td><td colspan="3">$p_{\text{T}}^{\tau\tau} > 140$ GeV
$\Delta R_{\tau\tau} < 1.5$</td></tr>
<tr><td>Low-$p_{\text{T}}^{\tau\tau}$</td><td colspan="3">Otherwise</td></tr>
</table>

- Combined fit on the di-tau mass based on Maximum Likelihood Estimation to determine the cross section
  - di-tau mass estimated using the *Missing Mass Calculator*

The *Missing Mass Calculator*

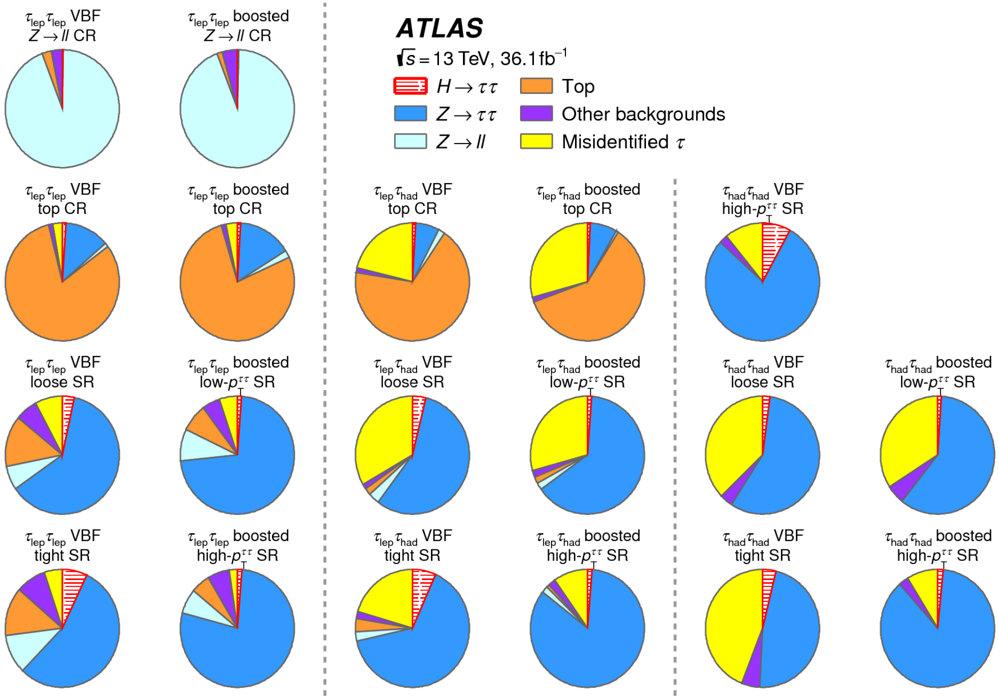
- Reconstruction of the mass of a resonance decaying into a pair of tau leptons is difficult because of the neutrinos in final state
- Missing Mass Calculator $^{(*)}$:
  - the orientations of the neutrinos and other decay products must be consistent with the mass and decay kinematics
  - result is achieved by minimising a likelihood in the allowed phase space region
- Successfully used in Run1, re-tuned in Run2 due to ATLAS detector upgrades
- Good separation power between $Z \to \tau\tau$ (main irreducible background) and Signal



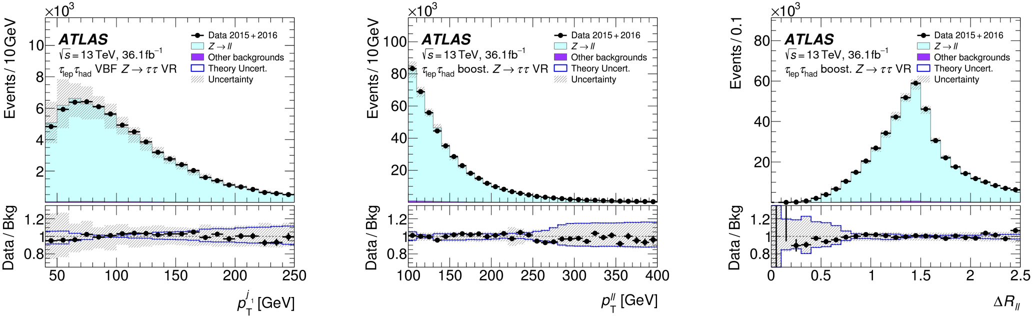


$^{(*)}$ https://arxiv.org/pdf/1012.4686.pdf

Signal/Control regions composition

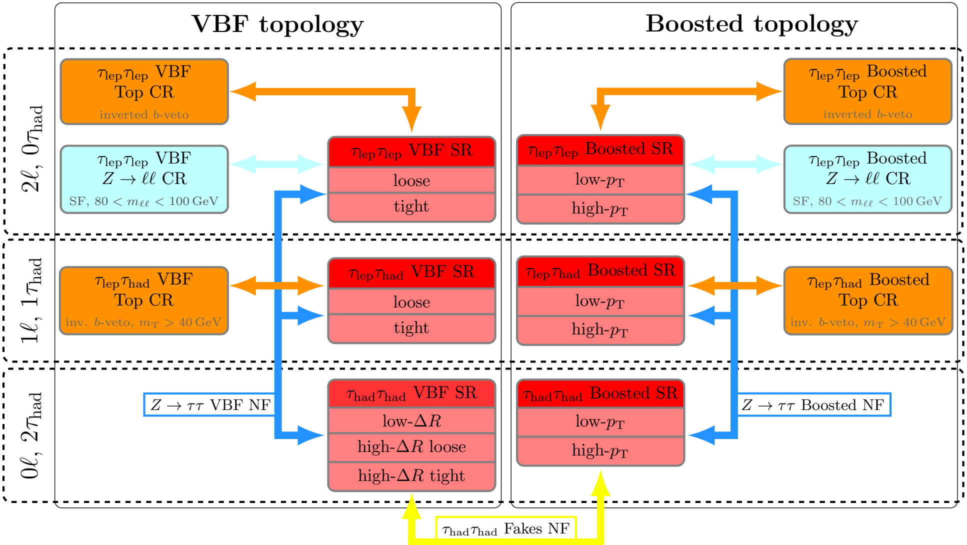


$Z \to \tau\tau$ MC validation

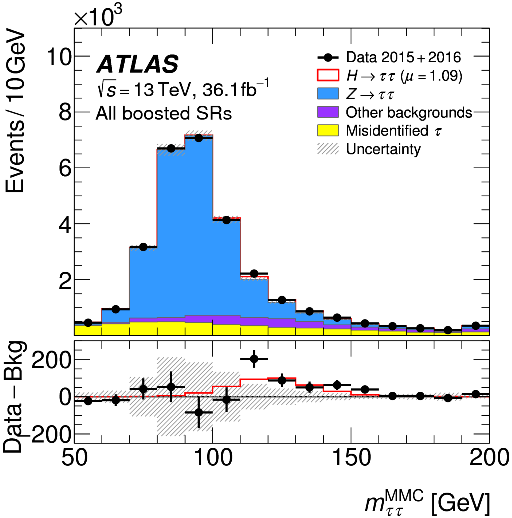


- Validate the MC simulation of the main kinematic variables used to define Boosted and VBF region
- Using $Z \to ll$ events as proxy of $Z \to \tau\tau$ due to high purity selection

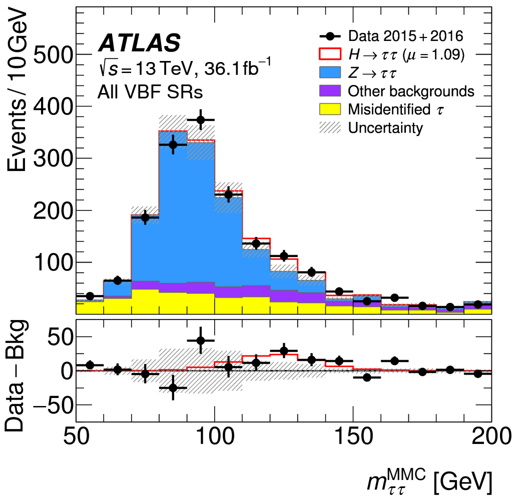
Fit Model



- 13 signal regions + 6 control regions to constrain $Z \to ll$ and $t\bar{t}$ normalisation
- $Z \to \tau\tau$ free floating in fit and correlated across the different
- *Fake* background estimated through data-driven techniques



Boosted region



VBF region

- Sum over the respective channel signal regions
- Clear evidence of signal on top of the $Z \to \tau\tau$ mass tail distribution

Significance results

- Run 1 [(*)] (BDT) + Run 2 (CBA) combination results (in σ unit):

	Run 1	Run 2	Combination
Observed	4.5	4.3	6.4
Expected	3.4	4.1	5.4

- Nuisance parameters uncorrelated between the two LHC runs
- Different $Z \to \tau\tau$ background estimation between the two runs:
  - data driven estimation in Run 1 (embedding technique)
  - MC based estimation in Run 2

- Combination with Run 1 beyond 5 σ threshold:

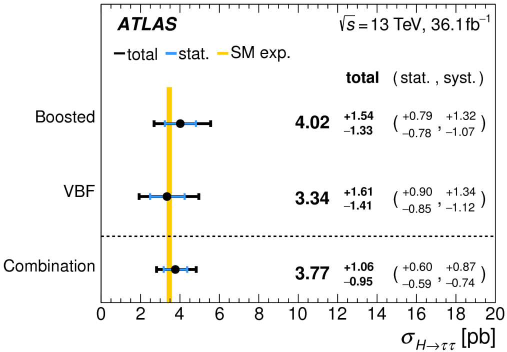
Observation of the $H \to \tau\tau$ decay with the ATLAS experiment

[(*)] JHEP04(2015)117

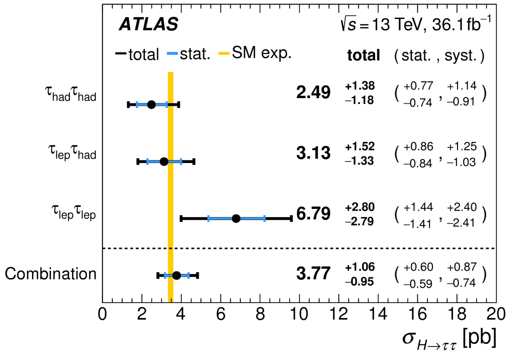
Cross section results

- Total cross section times branching ratio in agreement with SM expectation:

	Value (pb)	Expected value (pb)
$\sigma_{H\tau\tau}$	$3.77\ ^{+0.60}_{-0.59}\ (stat)\ ^{+0.87}_{-0.74}\ (syst)$	3.46 ± 0.13



Results per category

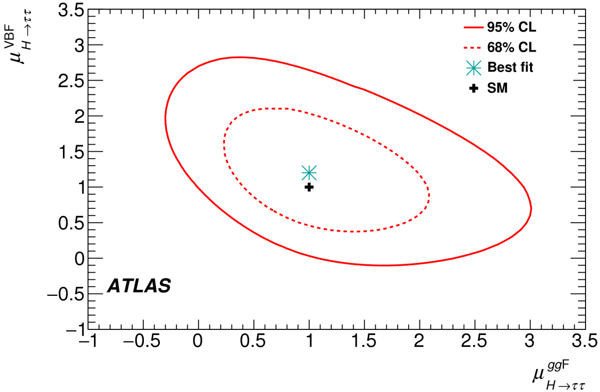


Results per final state

- Similar performance in *Boosted* and *VBF* regions
- Sensitivity driven by $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ final states

VBF vs ggF cross section

- 2 POI fit with free floating ggF and VBF normalisations
  - other production modes fixed to SM predictions
- Results in agreement with SM expectations



	Value (pb)	Expected value (pb)
$\sigma_{H\tau\tau}(\mathrm{VBF})$	0.28 ± 0.09 (*stat*) $^{+0.11}_{-0.09}$ (*syst*)	0.237 ± 0.006
$\sigma_{H\tau\tau}(\mathrm{ggF})$	3.0 ± 1.0 (*stat*) $^{+1.6}_{-1.3}$ (*syst*)	3.05 ± 0.13

Uncertainty breakdown

Source of uncertainty	Impact $\Delta\sigma/\sigma_{H\to\tau\tau}$ [%] Observed	Expected
Theoretical uncert. in signal	$+13.4$ / -8.7	$+12.0$ / -7.8
Background statistics	$+10.8$ / -9.9	$+10.1$ / -9.7
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	$+11.2$ / -9.1	$+10.4$ / -8.4
Background normalization	$+6.3$ / -4.4	$+6.3$ / -4.4
Misidentified τ	$+4.5$ / -4.2	$+3.4$ / -3.2
Theoretical uncert. in background	$+4.6$ / -3.6	$+5.0$ / -4.0
Hadronic τ decays	$+4.4$ / -2.9	$+5.5$ / -4.0
Flavor tagging	$+3.4$ / -3.4	$+3.0$ / -2.3
Luminosity	$+3.3$ / -2.4	$+3.1$ / -2.2
Electrons and muons	$+1.2$ / -0.9	$+1.1$ / -0.8
Total systematic uncert.	$+23$ / -20	$+22$ / -19
Data statistics	±16	±15
Total	$+28$ / -25	$+27$ / -24

- Systematic uncertainty greater than statistical uncertainty
- Largest impact from Theory uncertainties on the signal and Jets/E_T^{miss} related systematics
- MC statistical uncertainty has also sizable impact

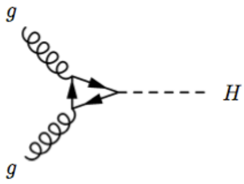
Summary

- $H \to \tau\tau$ measurement has been performed using 2015+2016 dataset (36.1 fb^{-1})
- $H \to \tau\tau$ observed combining Run 1 and Run 2 analyses with an observed (expected) significance of 6.4 (5.4) σ
- Measured cross sections times branching ration for VBF and ggF production modes are in agreement with SM expectations

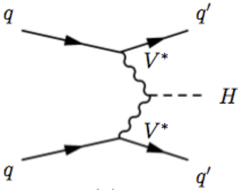
Thanks For Your Attention

Backup

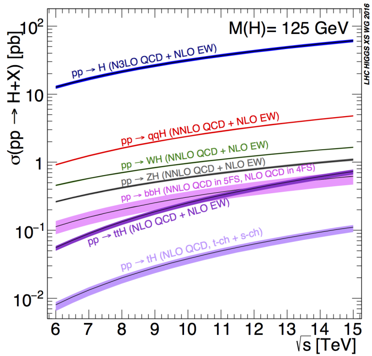
Higgs boson production modes



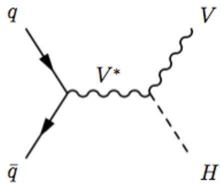
gluon fusion



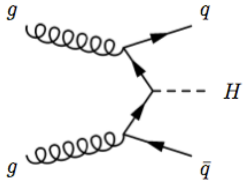
vector boson fusion



Higgs production cross section



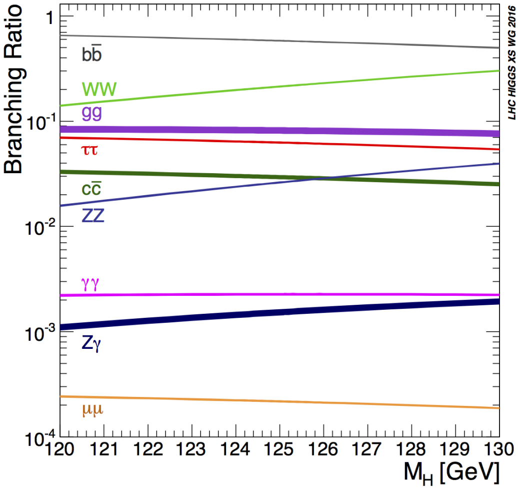
associated production with a gauge boson



associated production with a $t\bar{t}$ pair

- Largest cross section for gluon fusion (*ggF*) and vector boson fusion (*VBF*) production modes

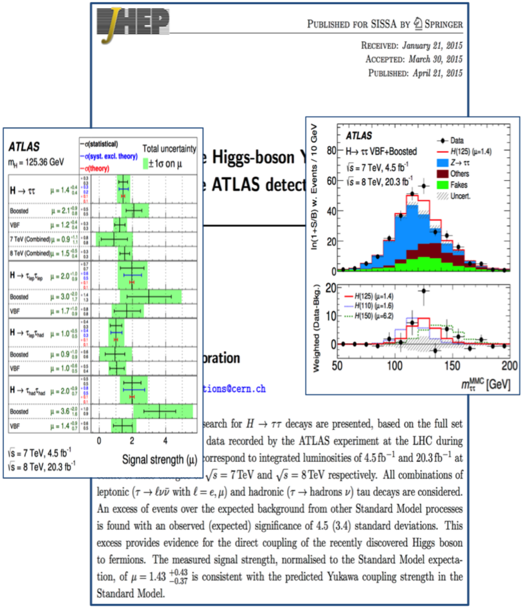
Higgs boson decay branching ratios



Higgs decay branching ratios

- Largest branching ratio (BR) for $H \to b\bar{b}$ and $H \to WW^*$, however poor mass resolution and large background contamination
- $H \to \tau\tau$ decay in only 6 % of the cases; mass resolution dominated by E_T^{miss} resolution
- $H \to \gamma\gamma$ and $H \to ZZ^*$ have low BR, but really good mass resolution and no neutrinos in the final state

- Split in VBF and Boosted categories to enrich VBF and ggF topologies, respectively
- Analysis used both BDT and cut-based approach
- Focus on BDT result due to better performance
  - Observed (Expected) significance: 4.5 (3.4) σ



MC generators

Process	Monte Carlo generator	PDF	UEPS	Cross-section order
ggF	Powheg-Box v2	PDF4LHC15 NNLO	Pythia 8.212	N^{3}LO QCD + NLO EW
VBF	Powheg-Box v2	PDF4LHC15 NLO	Pythia 8.212	~NNLO QCD + NLO EW
VH	Powheg-Box v2	PDF4LHC15 NLO	Pythia 8.212	NNLO QCD + NLO EW
$t\bar{t}H$	MG5_aMC@NLO v2.2.2	NNPDF30LO	Pythia 8.212	NLO QCD + NLO EW
$W/Z+$jets	Sherpa 2.2.1	NNPDF30NNLO	Sherpa 2.2.1	NNLO
$VV/V\gamma^*$	Sherpa 2.2.1	NNPDF30NNLO	Sherpa 2.2.1	NLO
$t\bar{t}$	Powheg-Box v2	CT10	Pythia 6.428	NNLO+NNLL
Wt	Powheg-Box v1	CT10F4	Pythia 6.428	NLO

- Contribution from light lepton/jet mis-identified as τ is estimated thorugh data-driven technicques

Likelihood Construction

- Parametrised probability density function constructed using binned template histograms

$$\mathcal{P}(n_c, x_e, a_p \mid \phi_p, \alpha_p, \gamma_b) = \prod_{c \in \text{channels}} \left[\text{Pois}(n_c|\nu_c) \prod_{e=1}^{n_c} f_c(x_e|\boldsymbol{\alpha}) \right] \cdot G(L_0|\lambda, \Delta_L) \cdot \prod_{p \in \mathbb{S}+\boldsymbol{\Gamma}} f_p(a_p|\alpha_p)$$

Poisson probability of obtaining n events when μS+B are expected

Probability density function in channel *c* with *n* events bins contents x_e

Gaussian constraint term with luminosity parameter λ and nominal value L_0

Constraint term describing an auxiliary measurement a_p that constrains the nuisance parameter α_p

- The full likelihood is simply a *joint likelihood of a physics measurement and a calibration measurement* where both terms are treated on equal footing

P-value and significance

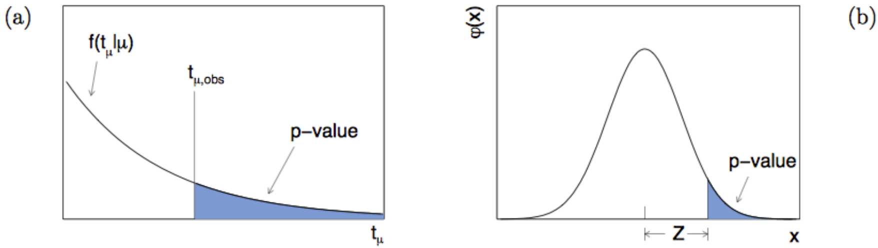


Figure 1: (a) Illustration of the relation between the p-value obtained from an observed value of the test statistic t_μ. (b) The standard normal distribution $\varphi(x) = (1/\sqrt{2\pi})\exp(-x^2/2)$ showing the relation between the significance Z and the p-value.

- *p-value* : probability, under the assumption of H, of finding data of equal or greater incompatibility with the predictions of H
  - exclude null hypothesis if its p-value is observed below a specified threshold
- conversion p-value/σ: $\sigma = \Phi^{-1}(1-p)$, where Φ^{-1} is the quantile of the standard Gaussian
- p-value $= 2.87 \times 10^{-7} \simeq 5\ \sigma \rightarrow$ particle discovery/process observation