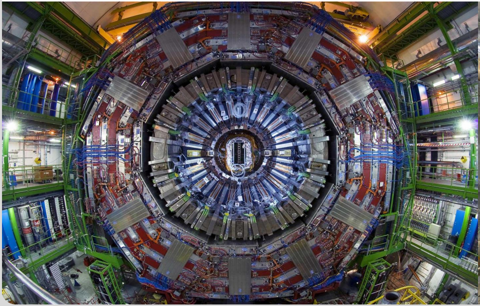
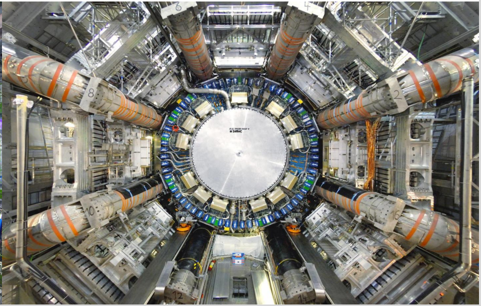
SM and BSM $H \rightarrow \tau\tau$ analyses with ATLAS and CMS

Artur Gottmann | April 10, 2018

INSTITUT FÜR EXPERIMENTELLE TEILCHENPHYSIK (ETP)

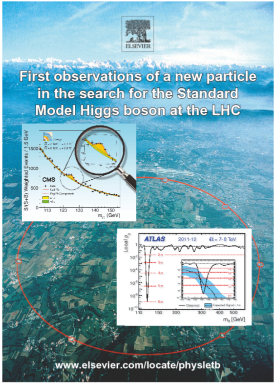




Introduction

- July 4, 2012: Higgs boson discovered as last missing piece of SM
- Following measurements of
  - Spin, parity
  - couplings to fermions and bosons
  - differential cross-sections
  - decay width constraints

so far compatible with SM expectations



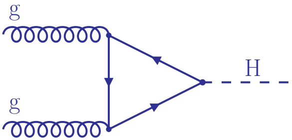
LHC Run II data-taking at $\sqrt{s} = 13$ TeV

In total $\approx 100\ \mathrm{fb}^{-1}$ delivered from 2015 to 2017

Relevant production modes

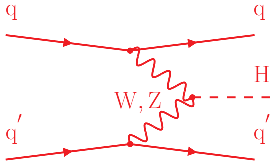
Dominant production mode despite of being loop suppressed, due to large number of gluons in a proton

gluon fusion
(SM Higgs: $\sigma = 48.52$ pb @ 13 TeV)



More than a factor 10 smaller, but clear signature
$\rightarrow$ helps to enrich signal in appropriate event categories

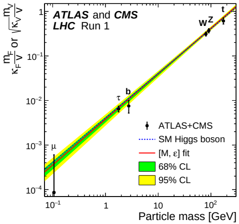
vector boson fusion
(SM Higgs: $\sigma = 3.779$ pb @ 13 TeV)



Cross-section values from CERN Yellow Report 4 of the LHCHXSWG for $m_H = 125.09$ GeV

Higgs boson decays

- Rich Higgs boson decay phenomenology for $m_H = 125$ GeV:
  - Decays to massive bosons W and Z
  - Decays to photons via loops
  - Fermions couple to the Higgs boson via Yukawa interactions
- Decays to fermions:
  - $H \to b\bar{b}$ (see Adinda's talk tomorrow at 16:00):
    - Highest branching ratio of 58 %
    - But also high QCD background
    - Requires advanced algorithms for b-jets identification
  - $H \to \tau\tau$:
    - Smaller branching ratio of 6 %
    - But main background also smaller
    - Muons & electrons in di-τ final state $\to$ Good tags for selection



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Branching ratio values from CERN Yellow Report 4 of the LHCHXSWG for SM Higgs boson with $m_H = 125.09$ GeV

Run II H $\rightarrow \tau\tau$ analyses

Overview

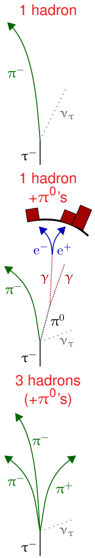
Run II H $\rightarrow \tau\tau$ analyses recently published & discussed during this talk

- SM H $\rightarrow \tau\tau$ with CMS:
  published in PLB 779 (2018) 283
- BSM H $\rightarrow \tau\tau$ with ATLAS:
  published in JHEP 01 (2018) 055
- BSM H $\rightarrow \tau\tau$ with CMS:
  submitted to JHEP (preprint: arXiv:1803.06553)

SM H $\rightarrow \tau\tau$ as part of $t\bar{t}$H analyses, e.g. with ATLAS:
submitted to Phys.Rev.D (preprint: arXiv:1712.08891)
$\rightarrow$ Details presented by Thomas tomorrow at 16:30

Hadronic τ-lepton (τ_h) reconstruction

- 4 di-τ final states considered as signal regions:
  $\tau_h\tau_h$ | $e\tau_h$ | $\mu\tau_h$ | $e\mu$ $\rightarrow \approx 90$ % with at least one τ_h
- **Motivates** to have a good τ_h reconstruction
- E.g. as discussed for the case of CMS:
  - Start with a jet reconstructed by the anti-k_T algorithm
  - Find its reconstructed charged hadron constituents
  - Reconstruct nearby neutral pion candidates:
    - $\pi^0 \rightarrow \gamma\gamma$ at almost 100 %
    - $\gamma \rightarrow e^+e^-$: high conversion probability
    - Combine electrons and photons in a $\eta - \phi$ window
  - Build ($\pi^{\pm}$,π^0) combinations to determine the best-matching decay-mode
  - Discriminate against gluon- & quark-jets, electrons and muons



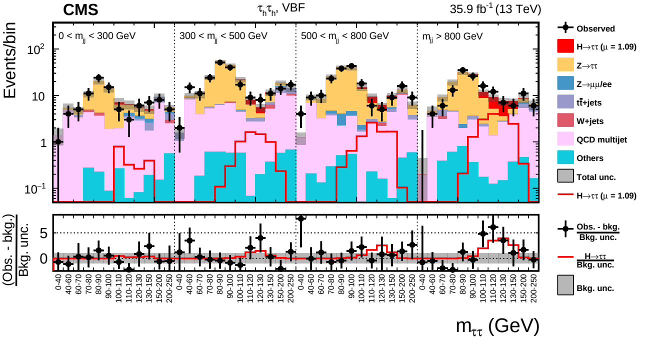
SM H $\rightarrow$ $\tau\tau$ with CMS: strategy

- Used decay channels: $\tau_h\tau_h$ $e\tau_h$ $\mu\tau_h$ $e\mu$
  - Identify well-isolated electrons, muons & τ_h-leptons
  - Construct di-τ pair
- Main categories:
  - 0-jet: to target gluon fusion production
  - 2-jet VBF: targeting VBF production
  - Boosted: defined to collect events failing the first two categories
- Choice of final discriminators depends on channel & category
  $\rightarrow$ Both 1D and 2D discriminators used for the likelihood fit

	0-jet	2-jet VBF	Boosted
$\tau_h\tau_h$	$m_{\tau\tau}$	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$
$\mu\tau_h$	m_{vis} vs τ_h DM	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$
$e\tau_h$	m_{vis} vs τ_h DM	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$
$e\mu$	m_{vis} vs p_T^{μ}	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$

m_{vis}: visible di-τ mass
$m_{\tau\tau}$: full di-τ mass
m_{jj}: invariant di-jet mass
$p_T^{\tau\tau}$: full di-τ p_T
p_T^{μ}: muon p_T
τ_h DM: decay mode

SM H $\rightarrow \tau\tau$ with CMS: $\tau_h\tau_h$ 2-jet VBF



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	0-jet	2-jet VBF	Boosted
$\tau_h\tau_h$	$m_{\tau\tau}$	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$
$\mu\tau_h$	m_{vis} vs τ_h DM	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$
$e\tau_h$	m_{vis} vs τ_h DM	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$
$e\mu$	m_{vis} vs p_T^{μ}	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$

- Most sensitive category
- Unrolled 2D distribution after the global fit
- Largest signal excess in the $m_{jj} > 800$ GeV bin

SM H $\to \tau\tau$ with CMS: $\mu\tau_h$ 0-jet

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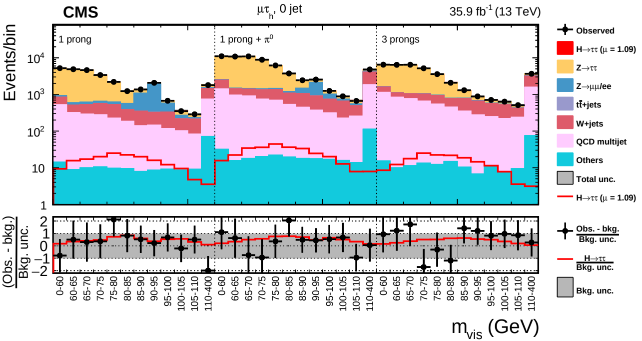

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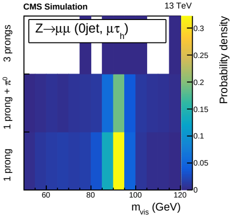
- mostly used to constrain uncertainties
- Unrolled 2D distribution after the global fit



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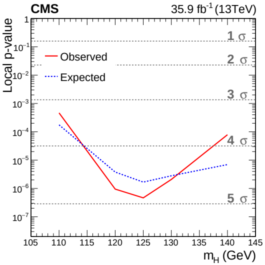
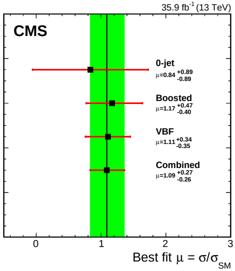
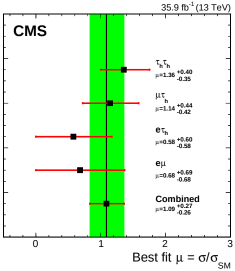
	0-jet	2-jet VBF	Boosted
$\tau_h\tau_h$	$m_{\tau\tau}$	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$
$\mu\tau_h$	m_{vis} vs τ_h DM	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$
$e\tau_h$	m_{vis} vs τ_h DM	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$
$e\mu$	m_{vis} vs p_T^{μ}	$m_{\tau\tau}$ vs. m_{jj}	$m_{\tau\tau}$ vs. $p_T^{\tau\tau}$

SM H $\to \tau\tau$ with CMS: results

- Fitted signal strength: $\mu = 1.09^{+0.27}_{-0.26}$
- Most sensitive category: VBF, most sensitive channel: $\tau_h\tau_h$







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Discovery from single channel, single experiment

@ 125 GeV: observed significance of 4.9σ, combined with Run I: 5.9σ

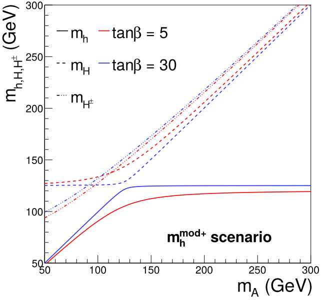
Higgs sector in SM extensions

- Observed Higgs boson could also be part of an extended Higgs sector, e.g. in MSSM
- Additional expected Higgs bosons in this case: scalars h & H, pseudoscalar A, charged $H^{\pm}$
- At LO in MSSM only 2 free parameters: m_A and $\tan\beta = \frac{v_d}{v_u}$
- Additional parameters entering at HO fixed to define MSSM benchmark scenarios, e.g. m_h^{mod+} and hMSSM
- Couplings of H, A to down-type fermions enchanced at high $\tan\beta$

→ Enchancement of H/A → $\tau\tau$ decay
→ Enchancement of production in association with b-quarks

b-tagging to identify b-jets

And use the number of b-jets for categorisation



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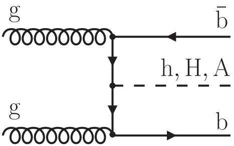

BSM H $\rightarrow\tau\tau$ with ATLAS: strategy

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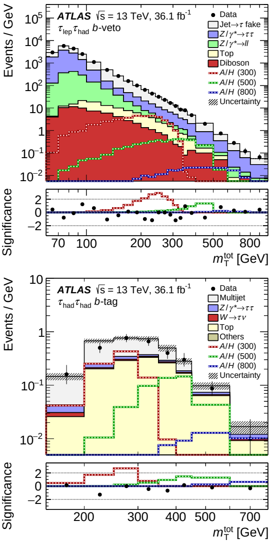
- To avoid biases in signal modelling: simple categorisation
  - 2 signal regions: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$ = $e\tau_h$ + $\mu\tau_h$
  - Construct di-τ pairs from well-identified & isolated electrons, muons and hadronic τ-leptons
  - 2 categories defined by the number of b-tagged jets:
    - b-tag: at least 1 b-jet
    - b-veto: no b-jets
- Focus on heavy resonances H and A
  $\rightarrow$ total transverse mass m_T^{tot} as final discriminator

$$m_T^{tot} = \sqrt{m_T^2(p_T^{\tau_1}, p_T^{miss}) + m_T^2(p_T^{\tau_2}, p_T^{miss}) + m_T^2(p_T^{\tau_1}, p_T^{\tau_2})},$$

$$m_T = \sqrt{2 p_T p_T' \left[1 - \cos(\Delta\phi)\right]}$$

BSM H $\rightarrow \tau\tau$ with ATLAS: m_T^{tot}

- m_T^{tot} shown for 2 categories: $\tau_{lep}\tau_{had}$ b-veto, $\tau_{had}\tau_{had}$ b-tag
- Major background contribution estimated from data: Jets reconstructed as τ_h's
- Other expected backgrounds (from MC):
  - Important in b-veto: $Z \rightarrow \tau\tau$
  - Important in b-tag: $t\bar{t}$
  - Minor contributions: $Z \rightarrow ll$, Electroweak
- Combined H/A $\rightarrow \tau\tau$ signals for $\tan\beta = 10$ and $m_{H/A}$ = 300, 600, 800 GeV (hMSSM) shown
- Signals peaking at higher m_T^{tot} values compared to backgrounds



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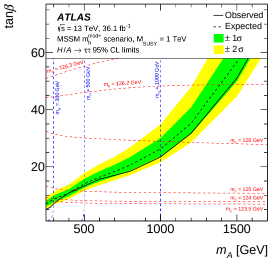
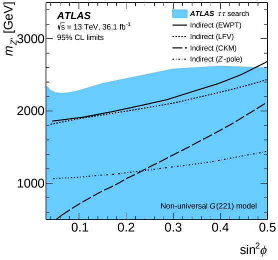
BSM H $\rightarrow \tau\tau$ with ATLAS: results

Interpretations in BSM benchmark scenarios

- Signal model:
  degenerate heavy H/A resonance
- Limits set on MSSM m_h^{mod+} (shown) and hMSSM
- Tested parameter space extended compared to Run I
- Higgs p_T @ NLO QCD precision
  $\rightarrow$ assuming SM couplings in loops of gluon fusion production
- Additional study:
  exclusion limits on Z' models





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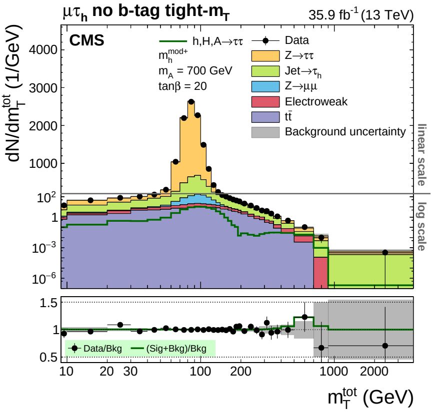
BSM H $\rightarrow \tau\tau$ with CMS: strategy

Similar strategy as with ATLAS:

- Decay channels:
  $\tau_h\tau_h$ $e\tau_h$ $\mu\tau_h$ $e\mu$
- Similar main categories:
  no b-tag & b-tag,
  subdivided further to increase sensitivity at high mass
- Same final discriminator m_T^{tot}
- Main backgrounds:
  Jet $\rightarrow \tau_h$ & $Z \rightarrow \tau\tau$



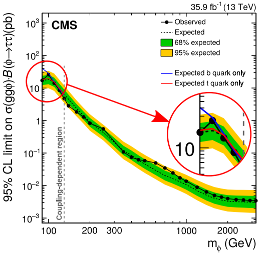
arXiv:1803.06553

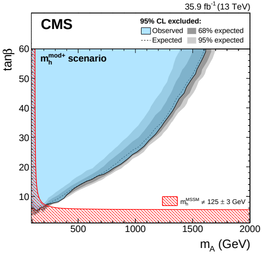
BSM H $\rightarrow \tau\tau$ with CMS: results

- Higgs p_T @ NLO QCD precision
- Model-independent limits in gluon fusion:
  - Assuming SM couplings
  - Checking coupling dependence with t-only & b-only limits $\rightarrow$ relevant only for low m_ϕ
- Model-dependent signal modelling:
  - combined signal template for h, H & A
  - $\tan\beta$ dependence in gluon fusion Higgs p_T taken into account by a reweighting method

Similar results from both experiments

Significant constraints on BSM models





arXiv:1803.06553

Conclusions

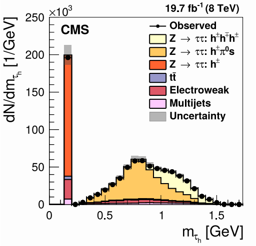
- SM H $\rightarrow \tau\tau$ established in single channel, single experiment analysis
- Next: explore channel to measure properties of the discovered Higgs boson
- Significantly extended parameter space to search for extensions of the Higgs sector
- Various improvements in categorisation, background & signal modelling

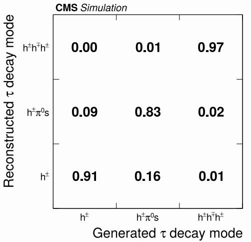
H $\rightarrow \tau\tau$: journey goes on

Intermediate results on the way to analyse the full LHC Run II dataset

Backup

τ_h reconstruction performance





τ_h reconstruction in decay modes, as introduced for Run I. Decay modes are reconstructed correctly at 83 % or higher

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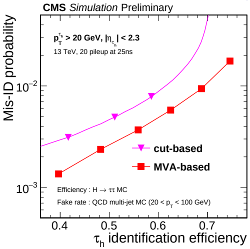
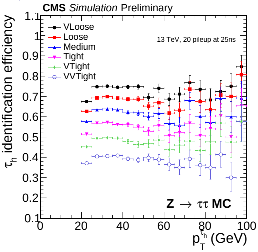
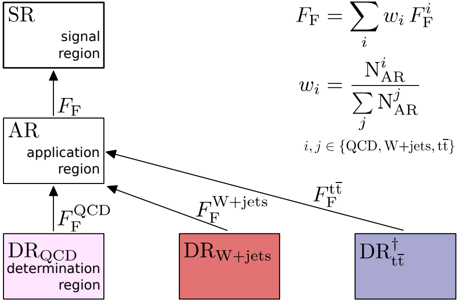




τ_h identification performance in Run II. MVA based-algorithm shows a better performance than the cut-based approach. Different efficiency working points are defined.

CMS-PAS-TAU-16-002

Jet $\rightarrow \tau_h$ estimation



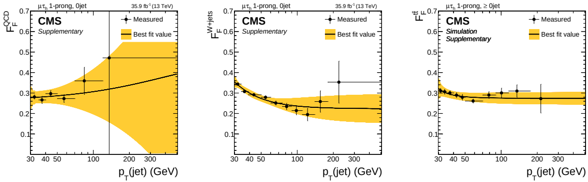
$$F_F = \sum_i w_i \, F_F^i$$

$$w_i = \frac{N^i_{AR}}{\sum_j N^j_{AR}}$$

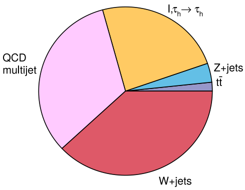
$i, j \in \{QCD, W{+}jets, t\bar{t}\}$

†Taken from simulation

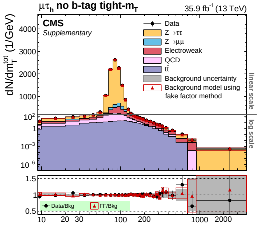
$$F_F^i = \frac{N^i(\text{isolated } \tau_h)}{N^i(\text{only loosely isolated } \tau_h)}$$



Composition of AR



MC driven cross-check



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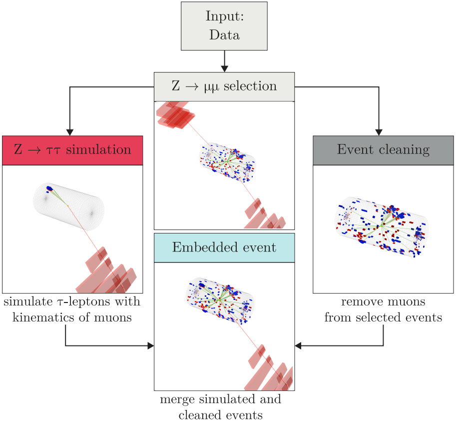
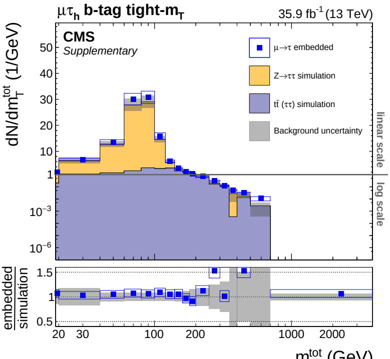
τ-Embedding for Z → ττ background



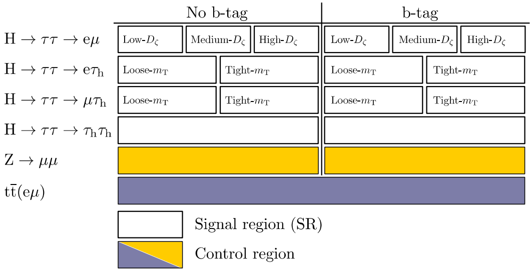
- $t\bar{t} \to \mu\mu$ contamination in Z → μμ selection ≈ 1 %
- Avoid double-counting by taking $t\bar{t} \to \tau\tau$ from τ-embedded samples



arXiv:1803.06553

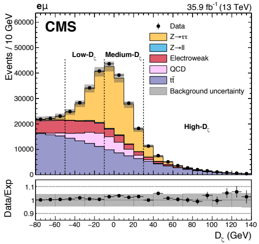
- Better description of pile-up, underlying event & jets
- Scales with recorded data

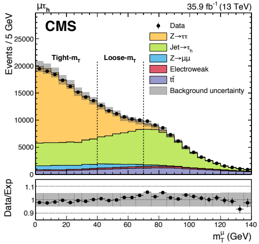
Categorisation in BSM $H \rightarrow \tau\tau$ with CMS



arXiv:1803.06553

- b-tag: at least one b-tagged jet (enriched with signal from b-associated production)
- No b-tag: no b-tagged jets (targeting mainly gluon fusion)





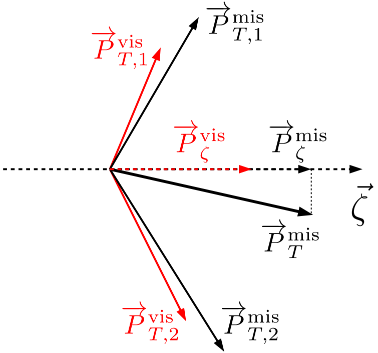
arXiv:1803.06553

Reconstruction of D_ζ

$$D_\zeta = P_\zeta - 1.85 \cdot P_\zeta^{vis}$$

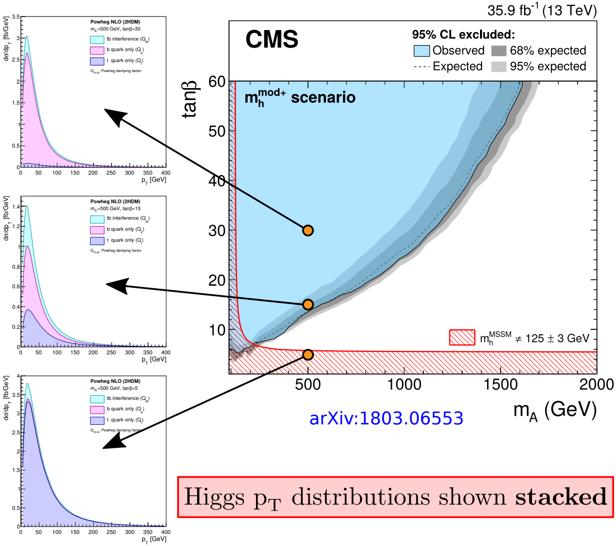
$$P_\zeta = (\vec{P}_{T,1}^{vis} + \vec{P}_{T,2}^{vis} + \vec{P}_{T}^{mis})\frac{\vec{\zeta}}{|\vec{\zeta}|}$$

$$P_\zeta^{vis} = (\vec{P}_{T,1}^{vis} + \vec{P}_{T,2}^{vis})\frac{\vec{\zeta}}{|\vec{\zeta}|}$$



Scanning through the m_A-tanβ grid

- Fractions of t-only, b-only & tb-interference change with tanβ
- Usual scan: O(2000) m_A-tanβ points
- Full simulation of all points **not feasible!**



Gluon Fusion Reweighting

Main idea

Reduce the problem to **one dimension** (m_A) by taking advantage of the $\tan\beta$-dependent Yukawa coupling modifiers Y_i. Transformation:

$$\hat{\sigma} = \left(\frac{\hat{Y}_t}{Y_t}\right)^2 \sigma_t(Q_t) + \left(\frac{\hat{Y}_b}{Y_b}\right)^2 \sigma_b(Q_t) + \left(\frac{\hat{Y}_t\hat{Y}_b}{Y_tY_b}\right) \left(\sigma_{t+b}(Q_{tb}) - \sigma_t(Q_{tb}) - \sigma_b(Q_{tb})\right)$$

- t-only, b-only & tb-interference computed for a reference $\tan\beta$ $\rightarrow$ In POWHEG: 5 samples for each mass m_ϕ
- **Reference** Y_t & Y_b remove reference $\tan\beta$ dependence
- **Target** $\hat{Y}_t$ & $\hat{Y}_b$ inject desired $\tan\beta$ dependence

Considered MSSM benchmark scenarios

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m_h^{mod+} (arXiv:1302.7033):

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 1.5\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= 1.6\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$

hMSSM (arXiv:1502.05653):

All parameters (under some assumptions) of HO MSSM are constrained by the mass of the light scalar, h: $\approx$ 125 GeV