Karlsruhe Institute of Technology

BSM $\Phi \rightarrow \tau\tau$ search

23.09.2014, GK Workshop Bad Liebenzell
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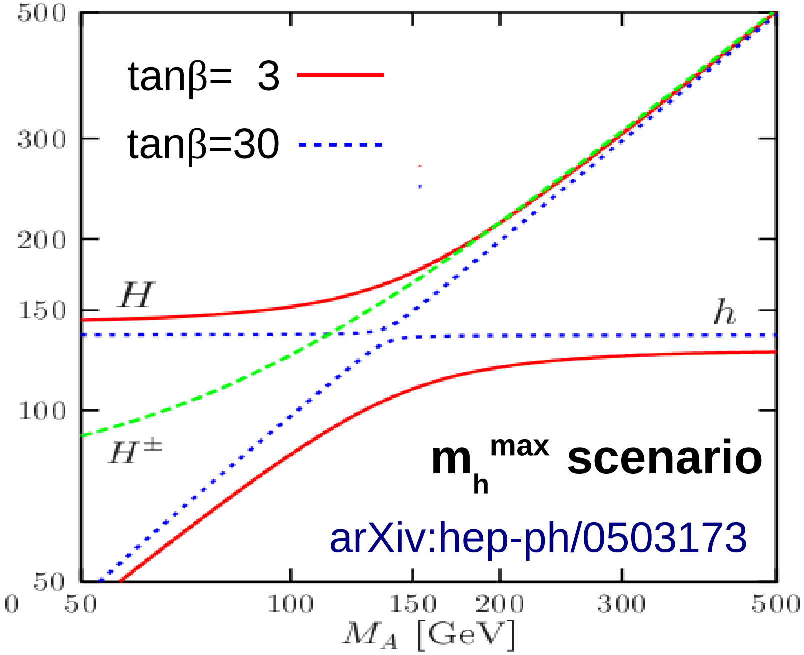
INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY

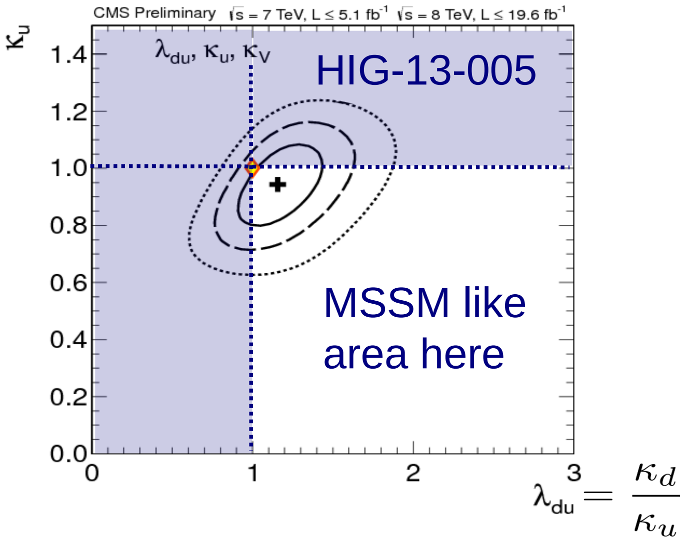
Higgs Bosons in the MSSM

- 2 Higgs doublets in MSSM
- 8 degrees of freedom
    - → 3 Gauge-Bosons W^+, W^-, Z
    - → 5 Higgs-Bosons
        - h, A, H, H^+, H^-
- On tree level Higgs masses defined by m_A and tanβ
    - m_A – mass of pseudoscalar A
    - tanβ – ratio of the vacuum expectation values of the Higgs doublets
- Couplings to down-type quarks usually enhanced
- Pseudoscalar A decays into fermions
    - Motivation for the considered MSSM Higgs production processes (ggΦ, bbΦ) and ττ decay channels



m_h^{max} scenario

arXiv:hep-ph/0503173



HIG-13-005

MSSM like area here

Analyzed channels and datasets

- eμ + eτ + μμ + μτ + ττ

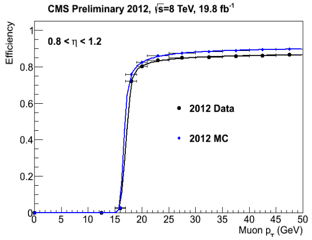
- 4.9 fb^{-1} at 7TeV and 19.8 fb^{-1} at 8TeV
  - ττ uses only 8TeV dataset (=18.3 fb^{-1})

- Shape analysis
  - Invariant di-τ mass used as final discriminator between signal and background

- Paper:
  - HIG-13-021

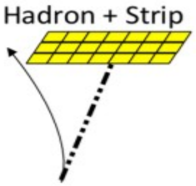
Analysis Flow

Trigger



→

Object selection



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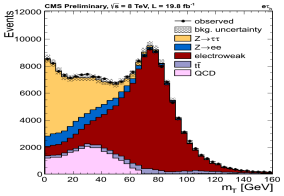
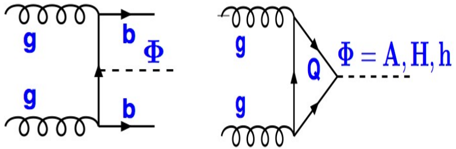
Background estimation



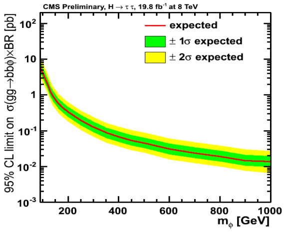
→

Categorization



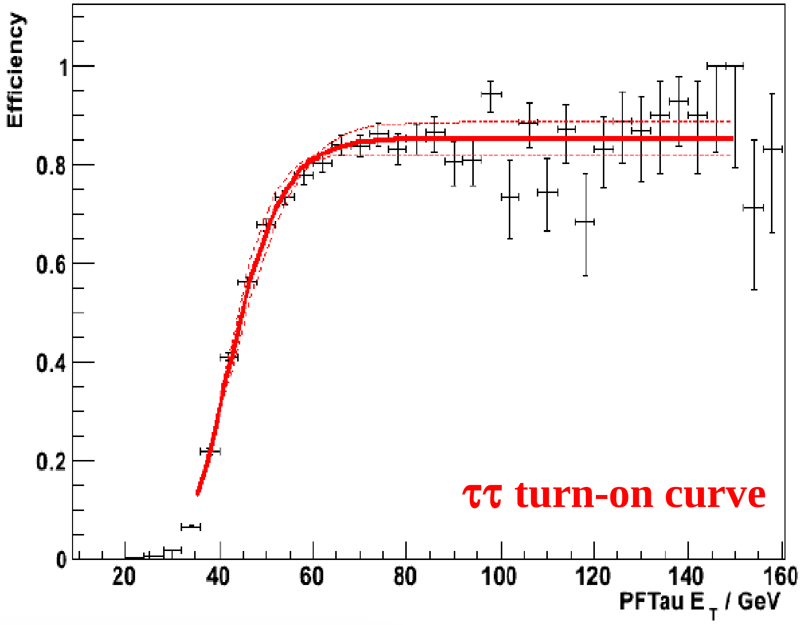
←

Interpretation



Triggers

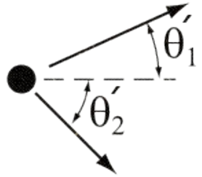
- Distinct triggers for each channel
  - μτ : μ > 17 GeV + isolated τ > 20 GeV
  - eτ : e > 22 GeV + isolated τ > 20 GeV
  - eμ : μ > 17(8) GeV + e > 8(17) GeV
  - μμ : μ > 17 GeV + μ > 8 GeV
  - ττ : 2 isolated τ > 35 GeV



Reconstruction of Di-τ System

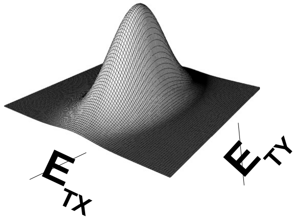
- Determine invariant mass of di-τ system with maximum likelihood method

L =



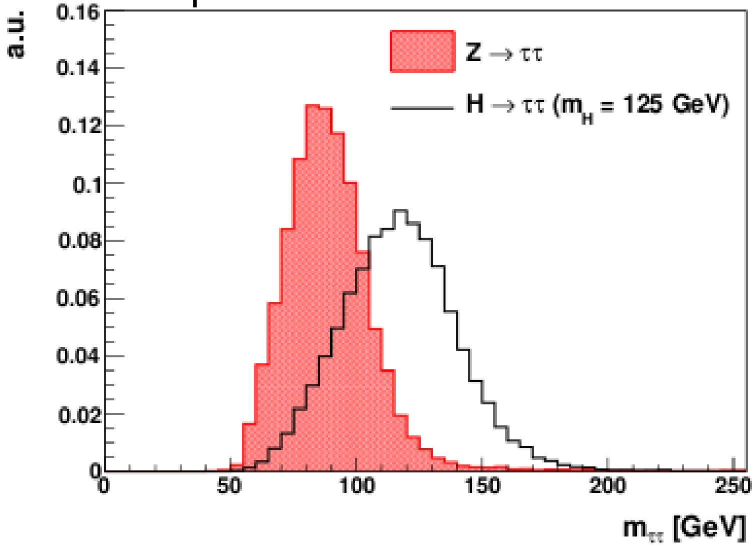
Phasespace of τ-decays

x



Expected $\not{E}_T$ Resolution

Separation of Z→ττ & H→ττ



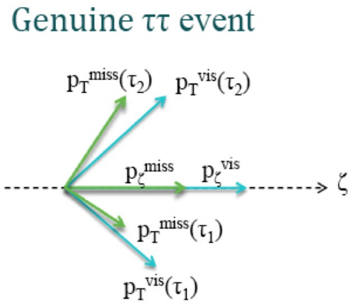
- Estimate of di-τ system, to be true for given value of $m_{\tau\tau}$
- Inputs: four-vector information of visible leptons, x- and y-component of $\not{E}_T$ on event basis.
- Free Parameters: φ, θ^*, $m_{\upsilon\upsilon}$ per τ (4-6 parameters)
- Full integration of kernel to determine maximum for given $m_{\tau\tau}$
  - Scan of $m_{\tau\tau}$ from m_τ up to 2TeV
- 10-20% resolution of the reconstructed $m_{\tau\tau}$ mass depending on decay mode

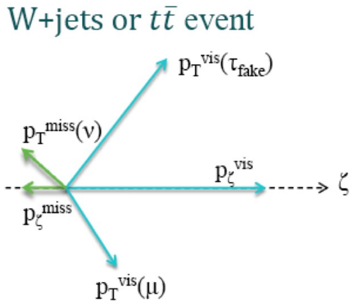
Event selection

- Two well reconstructed, isolated leptons of opposite sign:

channel	p_T	$\lvert\eta\rvert$	p_T	$\lvert\eta\rvert$
eμ	> 20 GeV (e/μ)	< 2.3 (e/μ)	> 10 GeV (μ/e)	< 2.3 (μ/e)
eτ	> 24 GeV (e)	< 2.1 (e)	> 20 GeV (t)	< 2.1 (τ)
μμ	> 20 GeV (μ)	< 2.1 (μ)	> 10 GeV (μ)	< 2.1 (μ)
μτ	> 20 GeV (μ)	< 2.1 (μ)	> 20 GeV (τ)	< 2.3 (τ)
ττ	> 45 GeV (τ)	< 2.1 (τ)	> 45 GeV (τ)	< 2.1 (τ)

- eμ: $D_\zeta = P_\zeta - 1.85 \cdot P_\zeta^{vis} > -20$ GeV


Genuine ττ event


W+jets or $t\bar{t}$ event

- eτ, μτ: $M_T < 30$ GeV

- μμ: Special BDT trained for rejection of $Z/\gamma^* \rightarrow \mu\mu$ events

Event categorization

- Make use of production signatures to maximize sensitivity

B-Tag:

≥ 1 b-tagged jets with p_T > 20 GeV

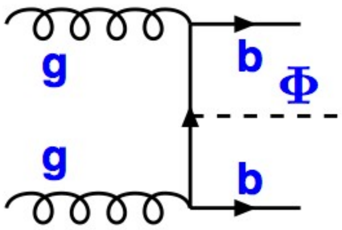
< 2 jets with p_T > 30 GeV

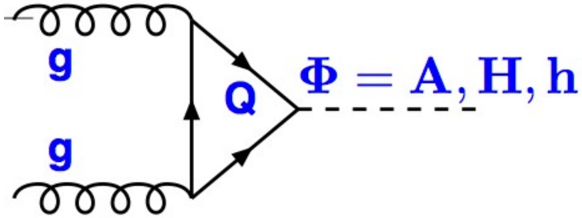
Sensitive to bbΦ

No-B-Tag (inclusive):

no b-tagged jets with p_T > 20 GeV

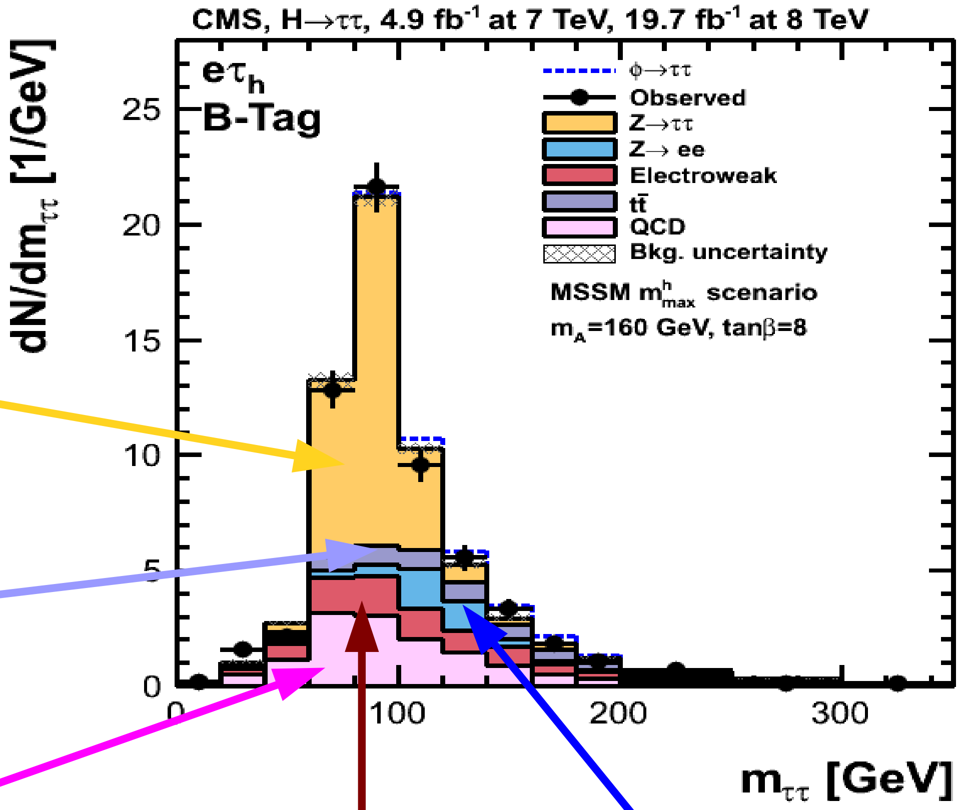
Contains rest of signal events.





- No further categorization to minimize model dependency

Discrimination of signal from backgrounds



Z/γ* → ττ:

- Embedding: in Z → μμ, replace μ by sim. τ decay
- Normalized to Z → μμ events

ttbar:

- Shape from simulation
- Normalization from sideband

QCD:

- Normalization and shape from SS/OS or fake-rate

Di-boson/W+jets:

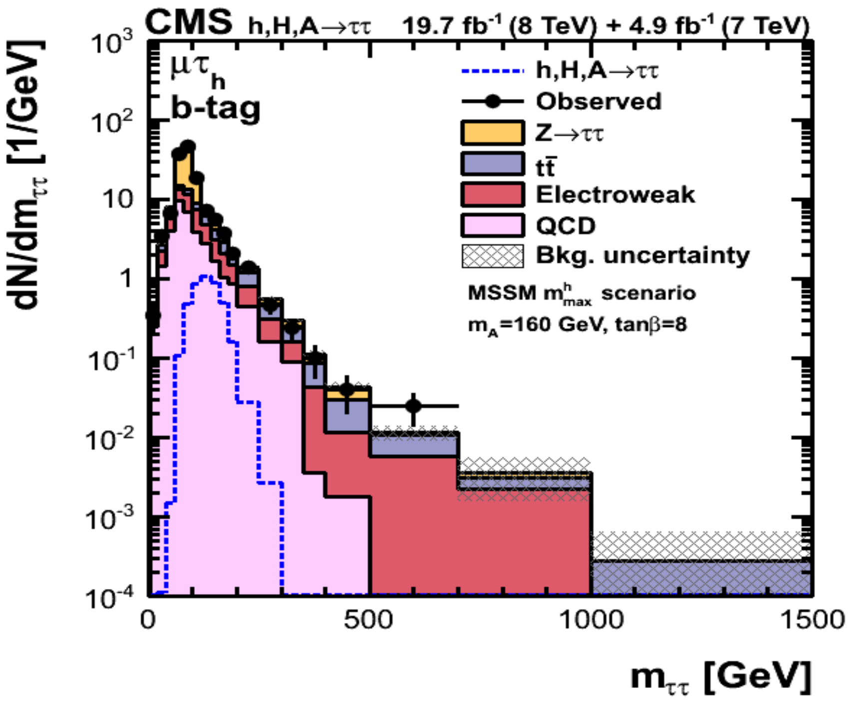
- Shape from simulation
- Normalization from sideband (W-jets) or from MC (Di-bosons)

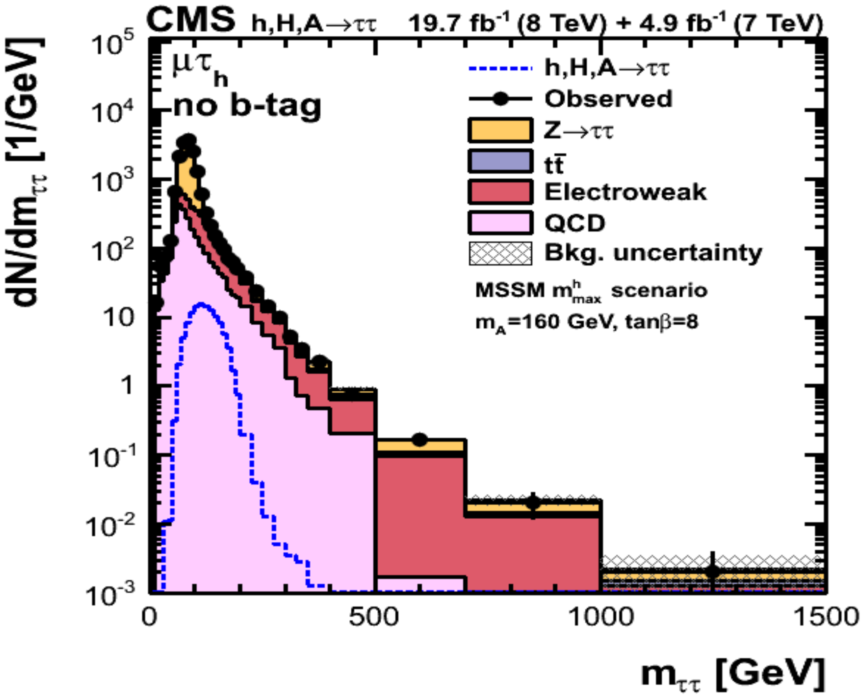
Z/γ* → ee (μμ):

- From data (μμ–channel) or simulation (all other channels)
- Corrected for jet → τ, e/μ → τ fake-rate

Invariant di-τ mass plots

- Plots show the di-τ mass distribution in the μτ channel for both categories after performing the global fit

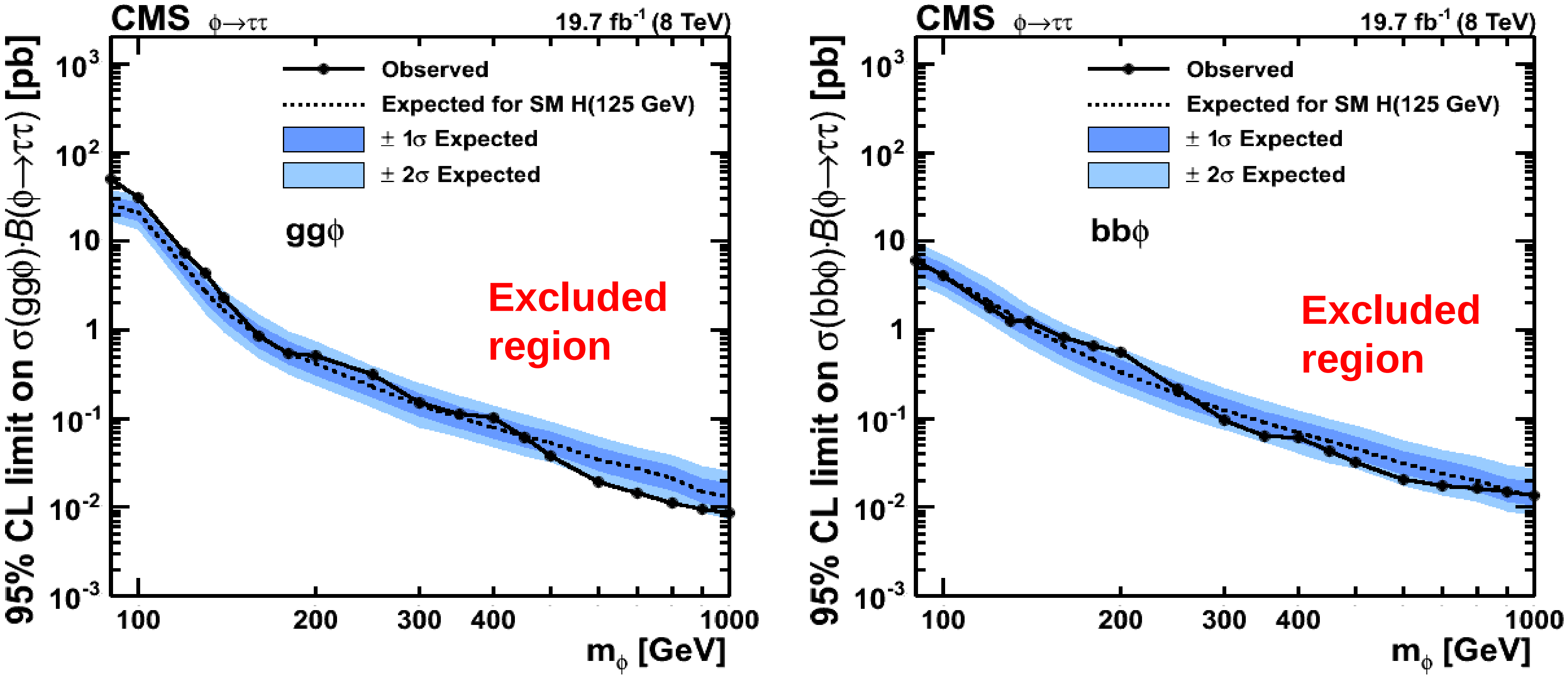




- Less events but better signal to background ratio
  - Here**: S/B ≈ 0.1**

- Overall more events but less signal to background ratio
  - Here**: S/B ≈ 0.01**

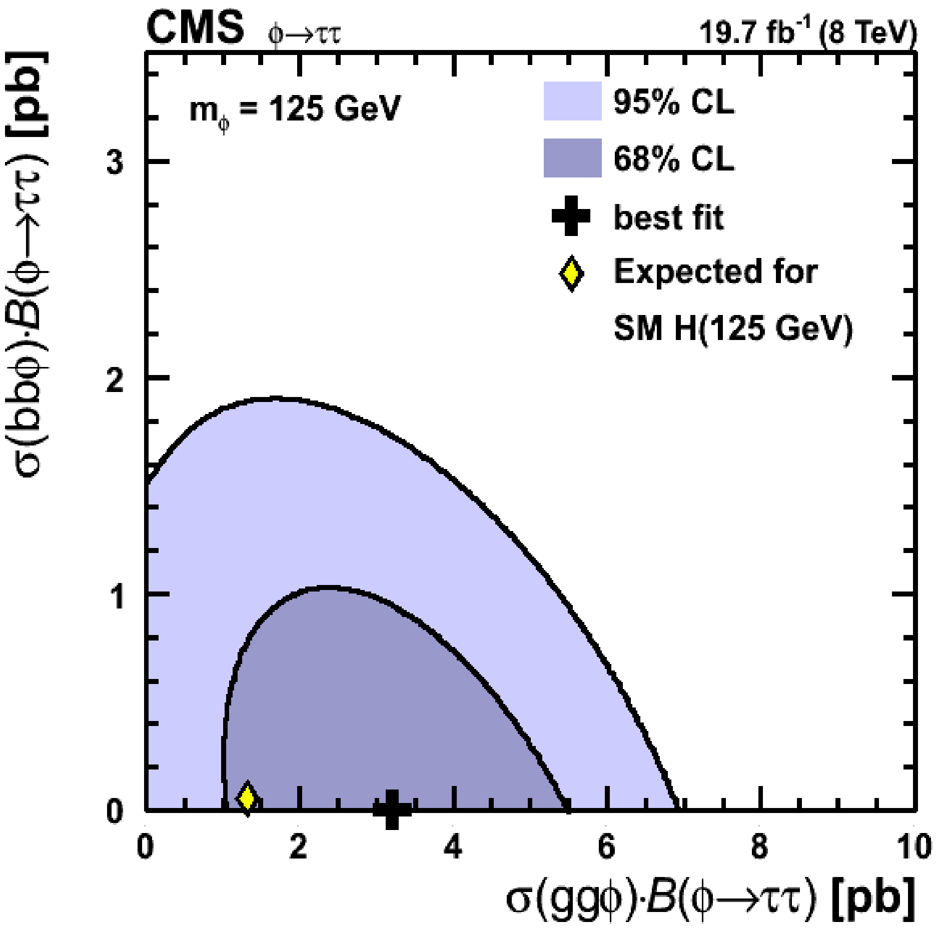
H → ττ : Cross section limits



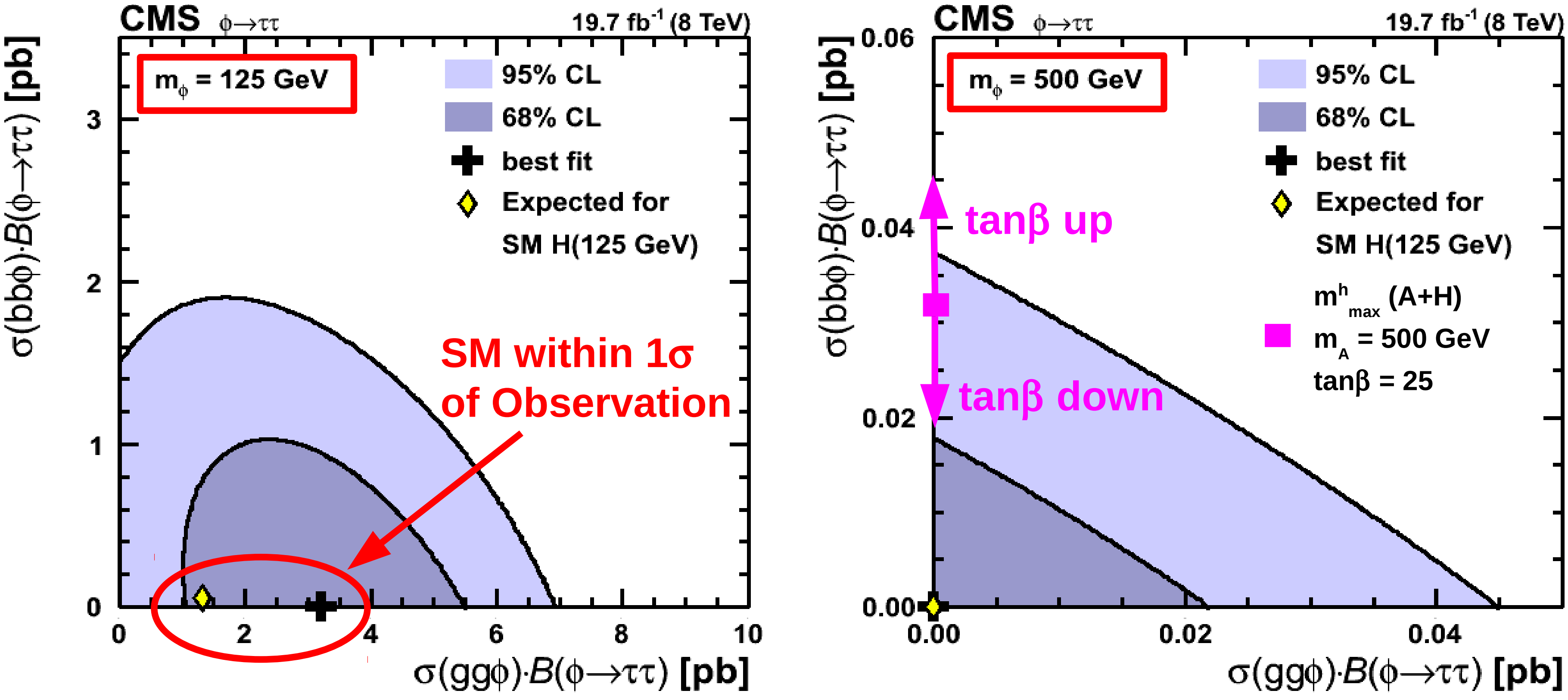
- Calculate σ*BR limit on one process while the other is left floating freely
- Expected limit is computed with a pseudo dataset including the SM Higgs boson at 125 GeV next to the nominal SM backgrounds

2D scan

- 2D scan performed in the ggΦ→ττ – bbΦ→ττ plane (40000 scan points at each mass)
- At each point compute:
  $\Delta(\chi^2) = \chi^2(\text{bestfit}) - \chi^2(\text{point})$
- Bestfit: $\Delta(\chi^2) = 0.00$
- 68% CL: $\Delta(\chi^2) = 2.30$
- 95% CL: $\Delta(\chi^2) = 5.99$



H → ττ : comparison with models



SM within 1σ of Observation

tanβ up

tanβ down

- Search for single narrow resonance
- Likelihood scan of ggΦ – bbΦ – m_ϕ space projected to ggΦ – bbΦ plane
  - m_Φ from 90-1000 GeV scanned
- Possibility to compare observation to model predictions

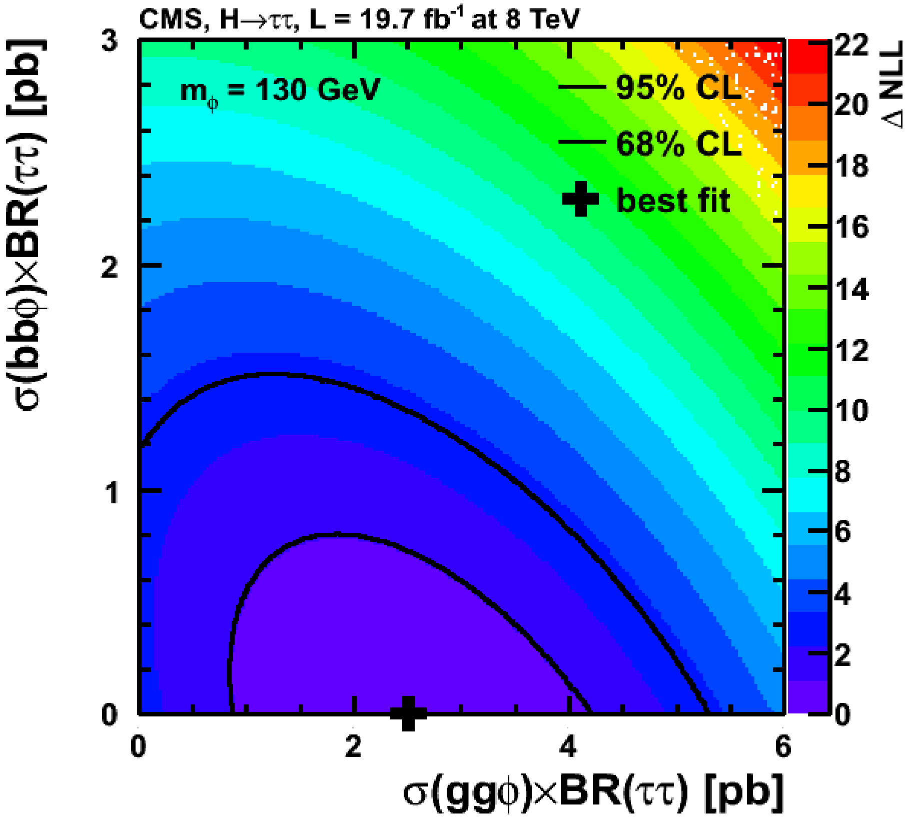
2D database

- All 40000 grid points for each mass are provided in a txt file
  - Four columns in txt file:

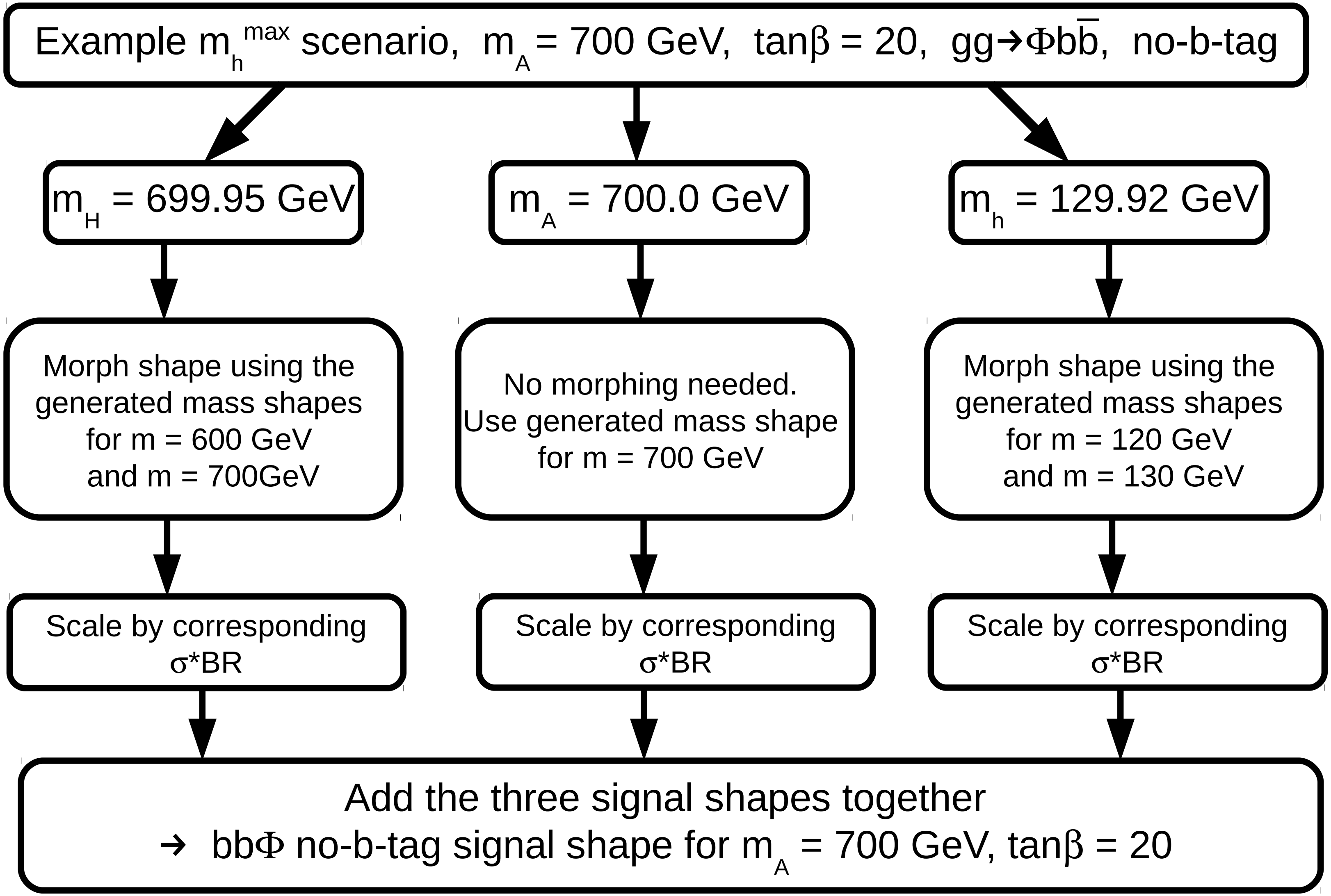
    m_Φ $gg\Phi\tau\tau$ $bb\Phi\tau\tau$ $\Delta(\chi^2)$
- Scans performed for different settings of the likelihoods

  observed
  - L (data | BG)
  - L (data | BG+h_{SM})

  expected
  - L ($asimov_b$ | BG)
  - L ($asimov_{b+SMHiggs}$ | BG+h_{SM})
- Masses:
  - 125 GeV
  - 90 – 250 GeV in 10 GeV
  - 250 – 500 GeV in 25 GeV
  - 500 – 1000 GeV in 50 GeV



From model independent to model dependent



Example m_h^{max} scenario, $m_A = 700$ GeV, $\tan\beta = 20$, $gg \rightarrow \Phi b\bar{b}$, no-b-tag

$m_H = 699.95$ GeV

$m_A = 700.0$ GeV

$m_h = 129.92$ GeV

Morph shape using the generated mass shapes for m = 600 GeV and m = 700GeV

No morphing needed. Use generated mass shape for m = 700 GeV

Morph shape using the generated mass shapes for m = 120 GeV and m = 130 GeV

Scale by corresponding σ*BR

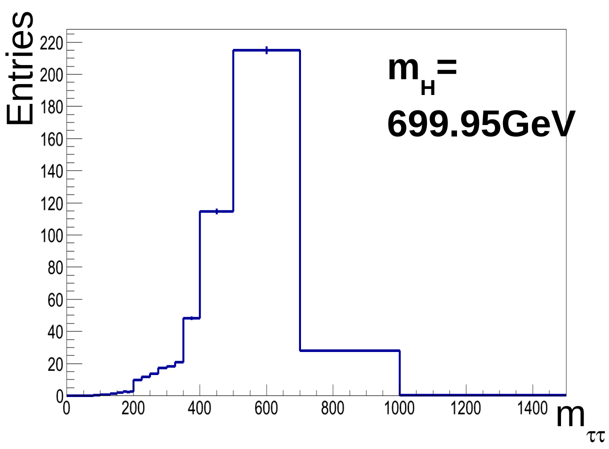
Scale by corresponding σ*BR

Scale by corresponding σ*BR

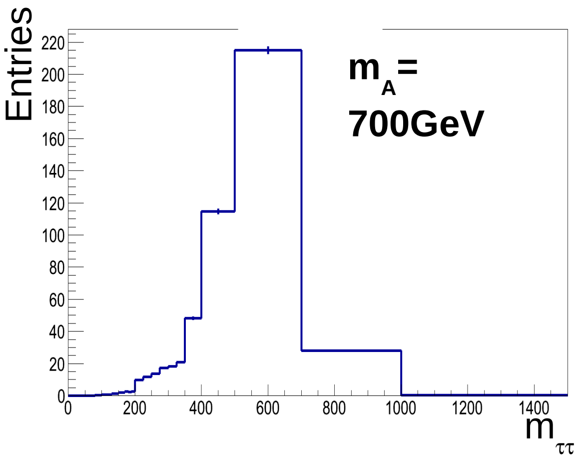
Add the three signal shapes together

→ $bb\Phi$ no-b-tag signal shape for $m_A = 700$ GeV, $\tan\beta = 20$

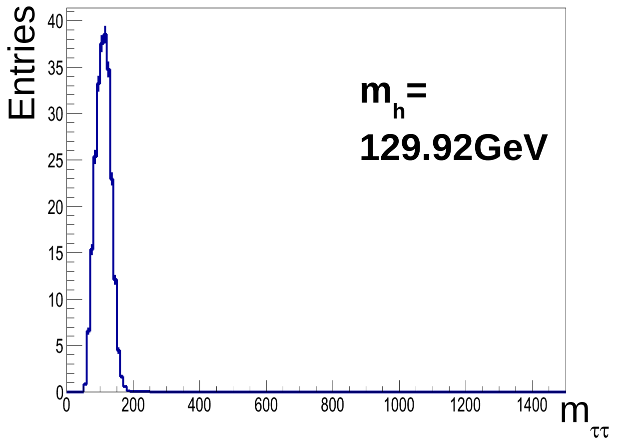
From model independent to model dependent



m_H= 699.95GeV



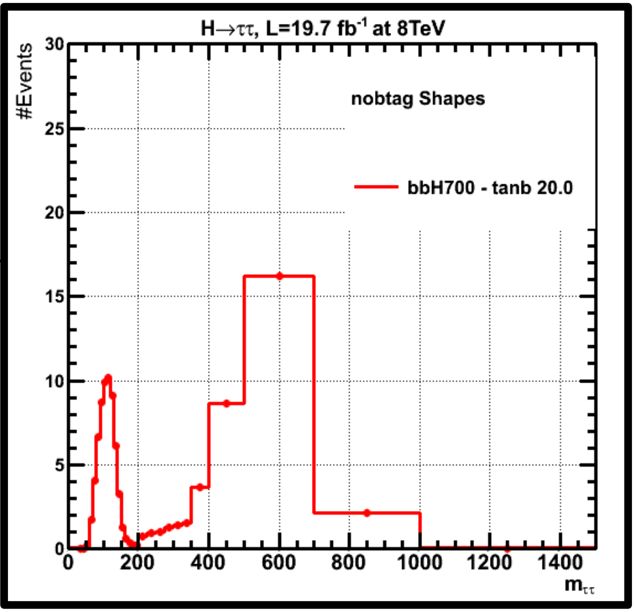
m_A= 700GeV



m_h= 129.92GeV

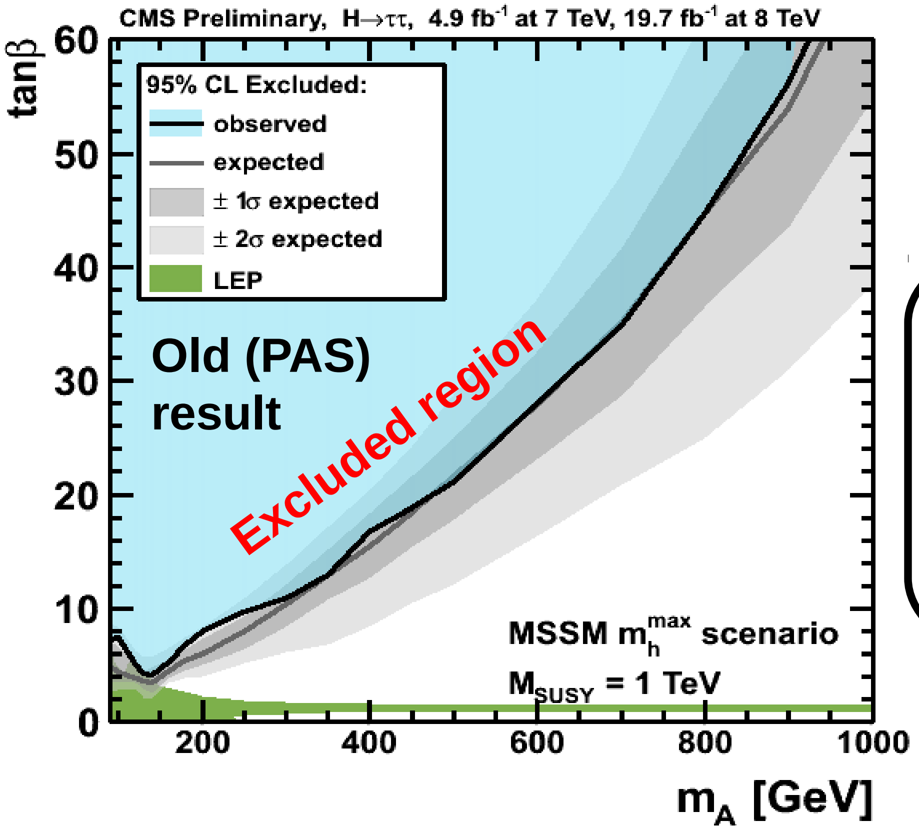
Shapes of A, H and h constructed using horizontal interpolation of generated masses

Scale each shape by corresponding σ*BR



Example: m_h^{max} scenario, m_A=700GeV, tanβ=20, bbΦ, no-b-tag, μτ

Model dependent interpretations: Different statistical approaches



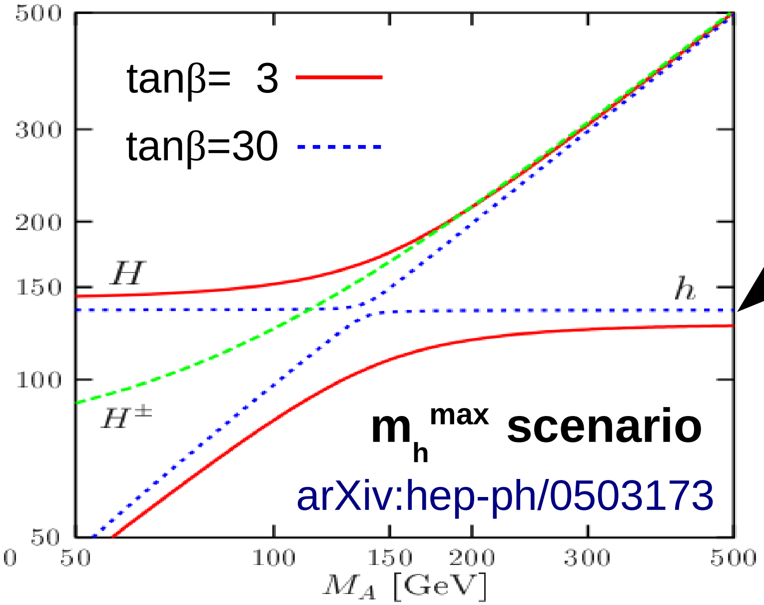
PAS approach:

- Testing MSSM vs background only
  - (h+H+A + BG) vs (BG)
- New discovered particle h_{SM} was not taken into account

Paper Approach:

- Take into account the discovered Higgs boson at 125 GeV
- Hypothesis test of MSSM vs SM → (h+H+A + BG) vs (h_{SM} + BG)

Limits on MSSM benchmarks



m_h^{max} scenario

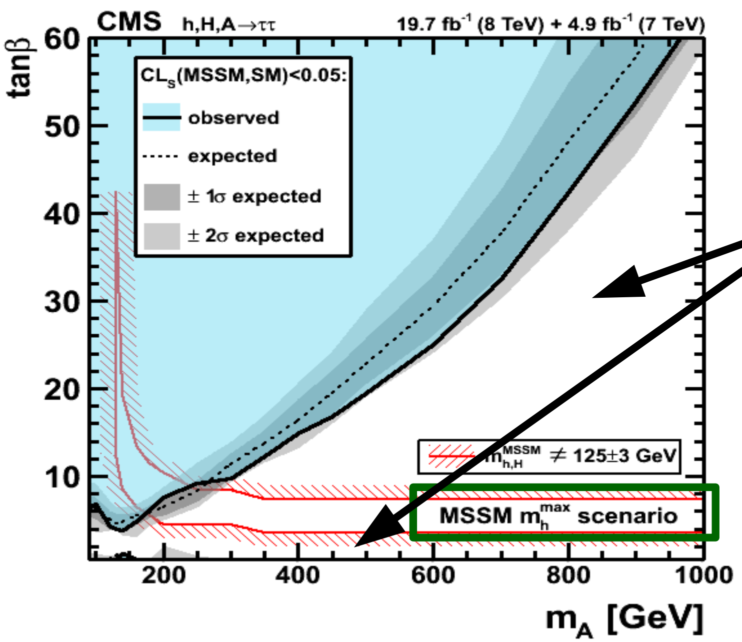
arXiv:hep-ph/0503173

In m_h^{max}: $m_h \approx 130$ GeV.

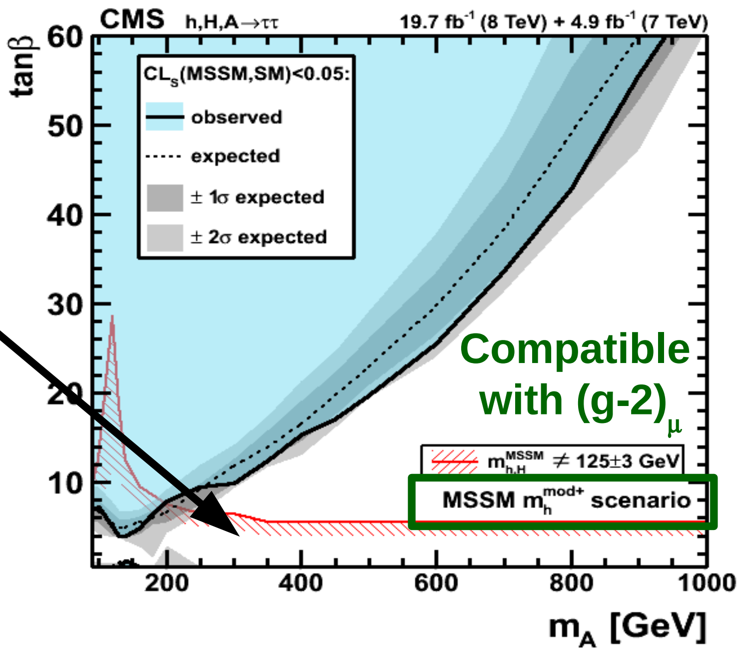
→ Move to new scenarios with **$m_h \approx 125$ GeV**.

- 6 new MSSM benchmark scenarios:

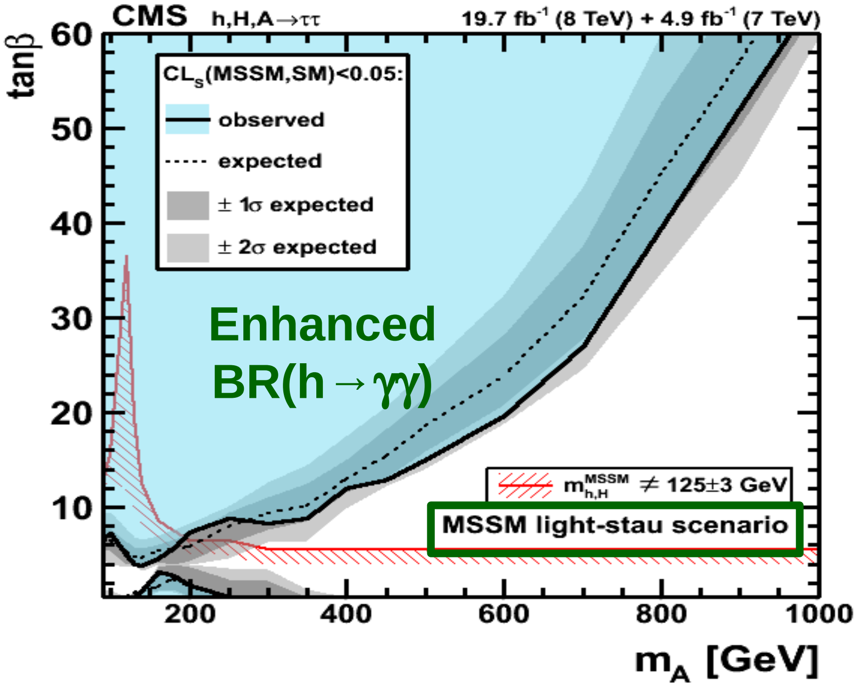
  Proposed by Carena et al., Eur.Phys.J.C73, 2552 (2013)
- Each addressing a certain **phenomenology**



Incompatible with 125±3 GeV mass constraint

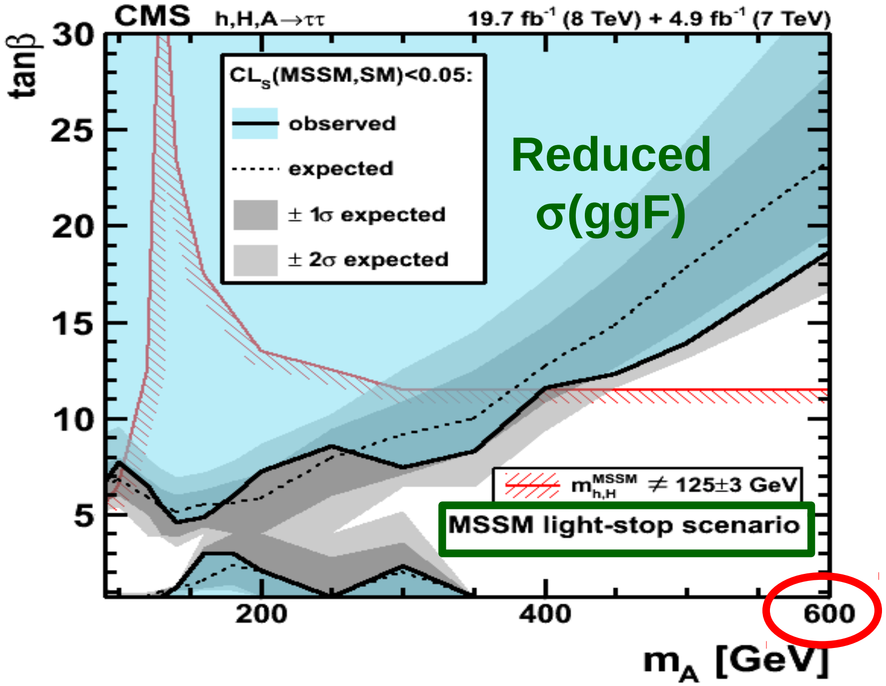


Compatible with $(g\text{-}2)_\mu$



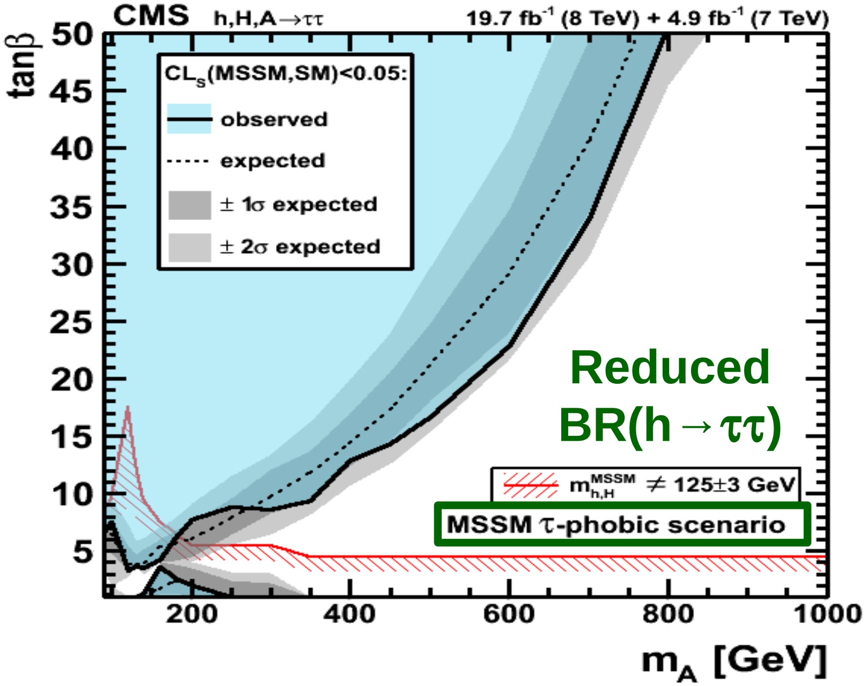
Enhanced BR(h → γγ)

MSSM light-stau scenario



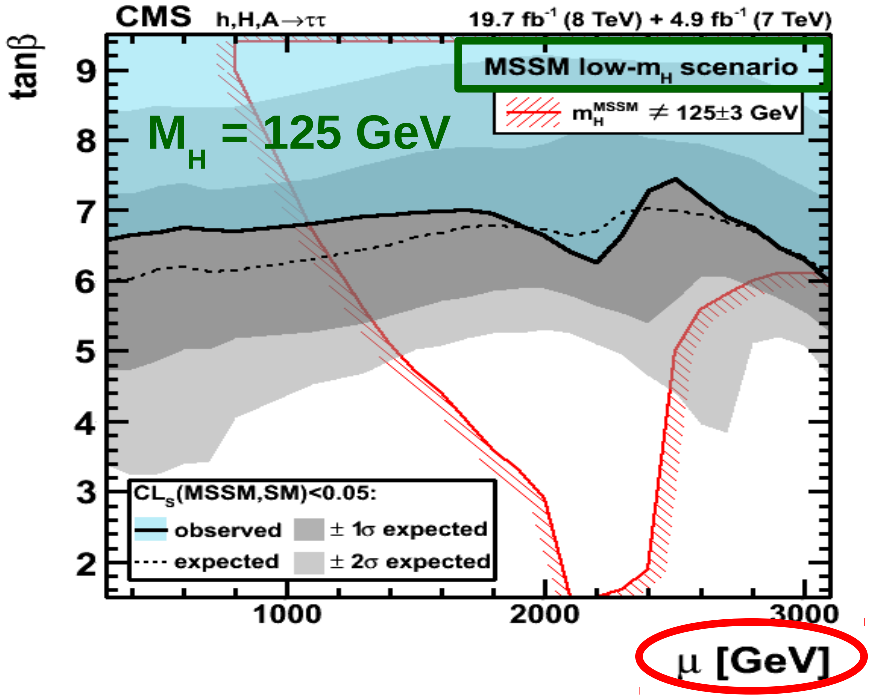
Reduced σ(ggF)

MSSM light-stop scenario



Reduced BR(h → ττ)

MSSM τ-phobic scenario

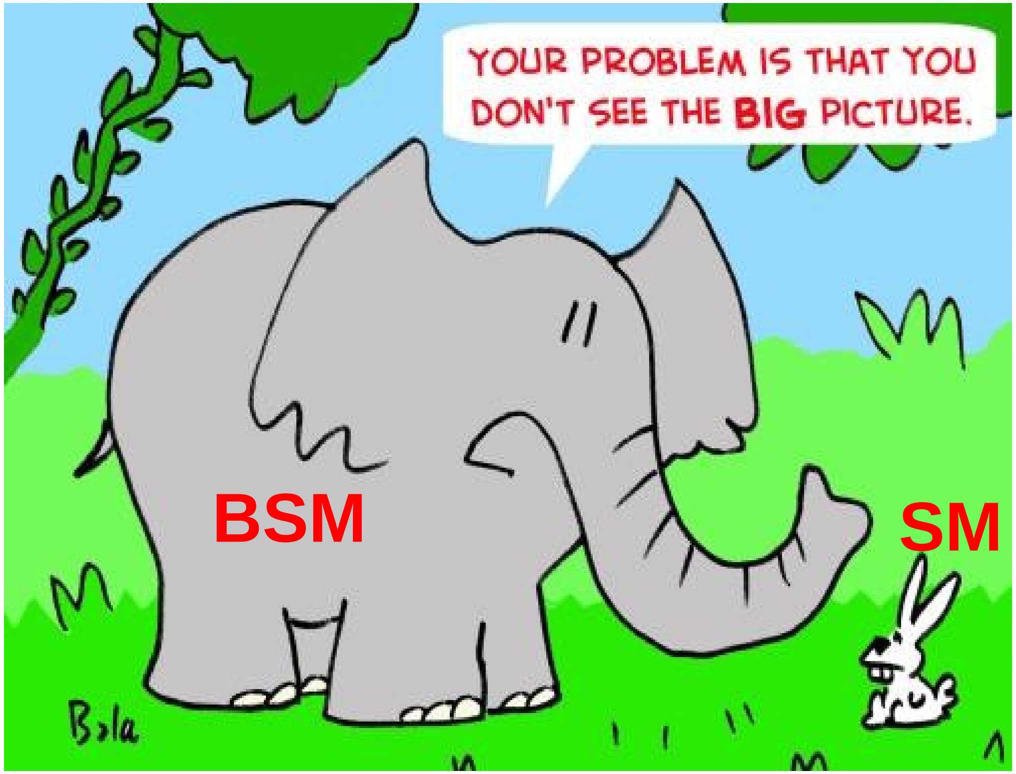


MSSM low-m_H scenario

M_H = 125 GeV

Summary

- H → ττ is a excellent channel to search for additional Higgs bosons
- Full dataset of 2011 and 2012 have been analyzed
- Results interpreted in model independent ways as well as in various MSSM models
- Awaiting BSM discovery in LHC RUN II



Backup

Trigger and Object Selection

Objects

- Muons and Electrons
  - Muons Require tight particle-flow (PF) muon identification criteria
  - Electrons Identified using a BDT discriminator
  - Cuts against electrons coming from photon conversions
  - $\text{Isolation}_{R<0.4} < 0.10 \cdot p_T(e/\mu)$ applying $\Delta\beta$ corrections to address pile-up
- Taus
  - Reconstructed using the Hadron plus Strips (HPS) algorithm
  - HPS Combined $\Delta\beta$ 3Hit algorithm used for isolation
  - Apply anti-muon and anti-electron discriminators
- PF Jets
  - B-Jets tagged by medium WP of “Combined Secondary Vertex” (CSV)
- MVA missing transverse energy E_T
  - Improves resolution by about 40% in typical 2012 pile-up conditions

Triggers

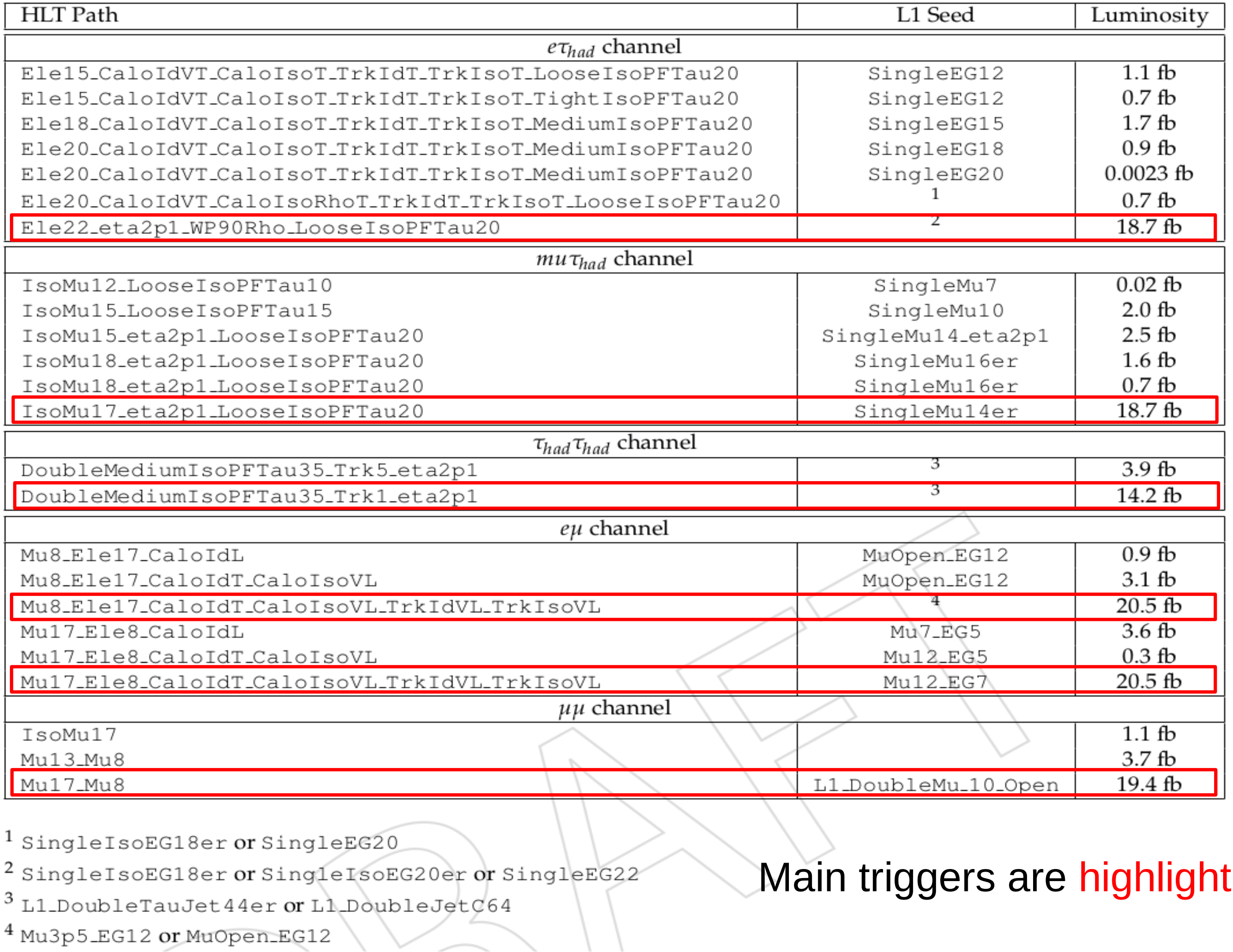
eτ

μτ

ττ

eμ

μμ



HLT Path	L1 Seed	Luminosity
$e\tau_{had}$ channel		
Ele15_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_LooseIsoPFTau20	SingleEG12	1.1 fb
Ele15_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_TightIsoPFTau20	SingleEG12	0.7 fb
Ele18_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_MediumIsoPFTau20	SingleEG15	1.7 fb
Ele20_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_MediumIsoPFTau20	SingleEG18	0.9 fb
Ele20_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_MediumIsoPFTau20	SingleEG20	0.0023 fb
Ele20_CaloIdVT_CaloIsoRhoT_TrkIdT_TrkIsoT_LooseIsoPFTau20	[1]	0.7 fb
Ele22_eta2p1_WP90Rho_LooseIsoPFTau20	[2]	18.7 fb
$mu\tau_{had}$ channel		
IsoMu12_LooseIsoPFTau10	SingleMu7	0.02 fb
IsoMu15_LooseIsoPFTau15	SingleMu10	2.0 fb
IsoMu15_eta2p1_LooseIsoPFTau20	SingleMu14_eta2p1	2.5 fb
IsoMu18_eta2p1_LooseIsoPFTau20	SingleMu16er	1.6 fb
IsoMu18_eta2p1_LooseIsoPFTau20	SingleMu16er	0.7 fb
IsoMu17_eta2p1_LooseIsoPFTau20	SingleMu14er	18.7 fb
$\tau_{had}\tau_{had}$ channel		
DoubleMediumIsoPFTau35_Trk5_eta2p1	[3]	3.9 fb
DoubleMediumIsoPFTau35_Trk1_eta2p1	[3]	14.2 fb
$e\mu$ channel		
Mu8_Ele17_CaloIdL	MuOpen_EG12	0.9 fb
Mu8_Ele17_CaloIdT_CaloIsoVL	MuOpen_EG12	3.1 fb
Mu8_Ele17_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL	[4]	20.5 fb
Mu17_Ele8_CaloIdL	Mu7_EG5	3.6 fb
Mu17_Ele8_CaloIdT_CaloIsoVL	Mu12_EG5	0.3 fb
Mu17_Ele8_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL	Mu12_EG7	20.5 fb
$\mu\mu$ channel		
IsoMu17		1.1 fb
Mu13_Mu8		3.7 fb
Mu17_Mu8	L1_DoubleMu_10_Open	19.4 fb

[1] SingleIsoEG18er or SingleEG20

[2] SingleIsoEG18er or SingleIsoEG20er or SingleEG22

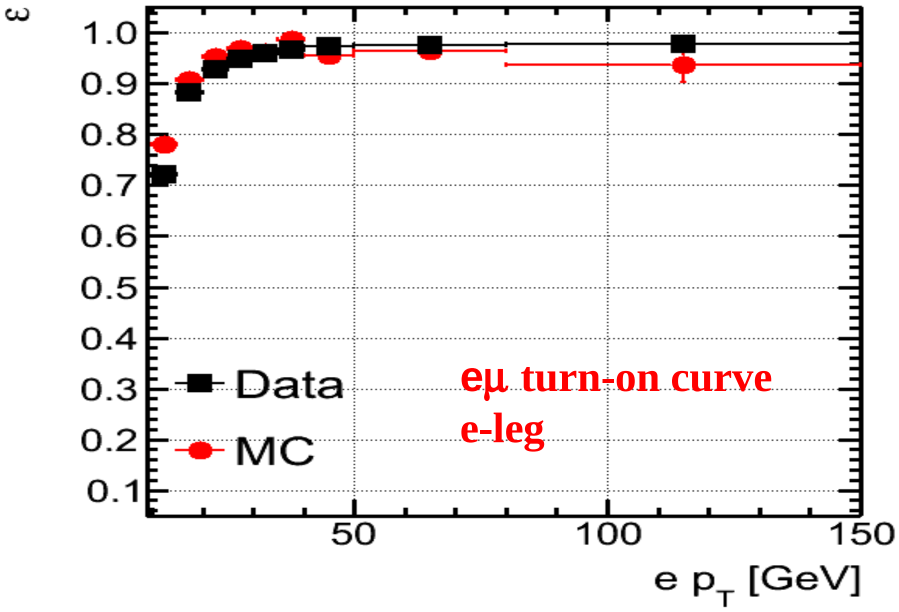
[3] L1_DoubleTauJet44er or L1_DoubleJetC64

[4] Mu3p5_EG12 or MuOpen_EG12

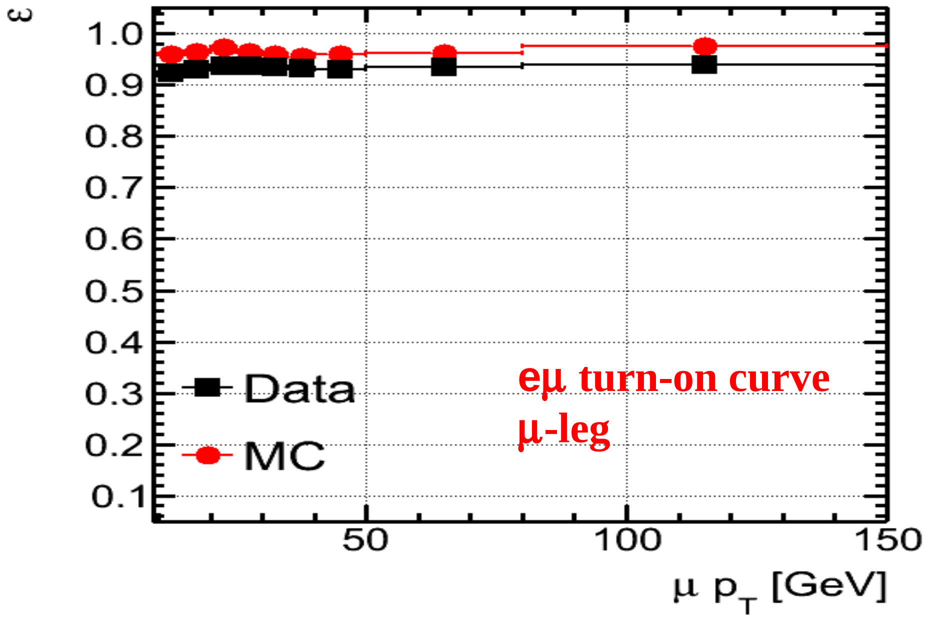
DRAFT

Main triggers are highlighted

Trigger control plots



eμ turn-on curve
e-leg



eμ turn-on curve
μ-leg

Electrons and Muons

- Muons (POG recommended)
  - Require tight particle-flow (PF) muon identification criteria

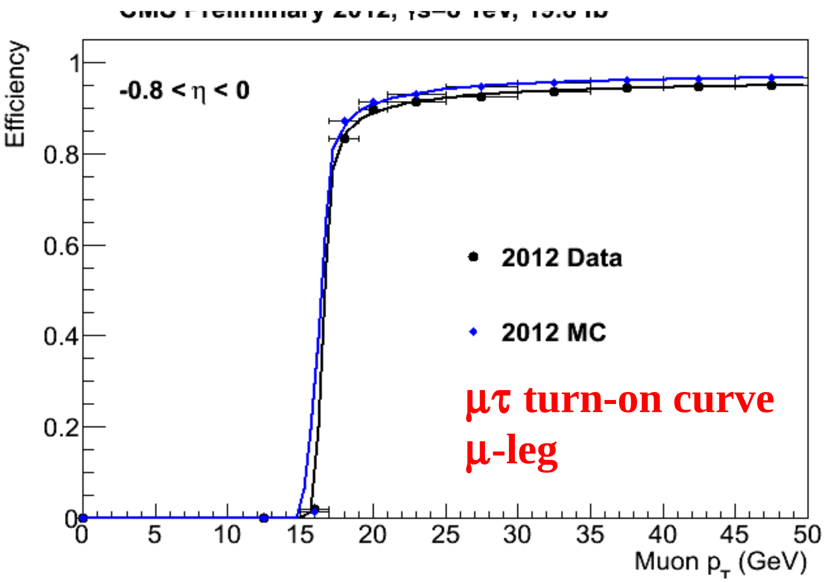
- Electrons (POG recommended)
  - Identified using a BDT discriminator
  - Cuts against electrons coming from photon conversions

- Isolation$_{R<0.4}$ < 0.10·p_T(e/μ) (POG recommended definition)

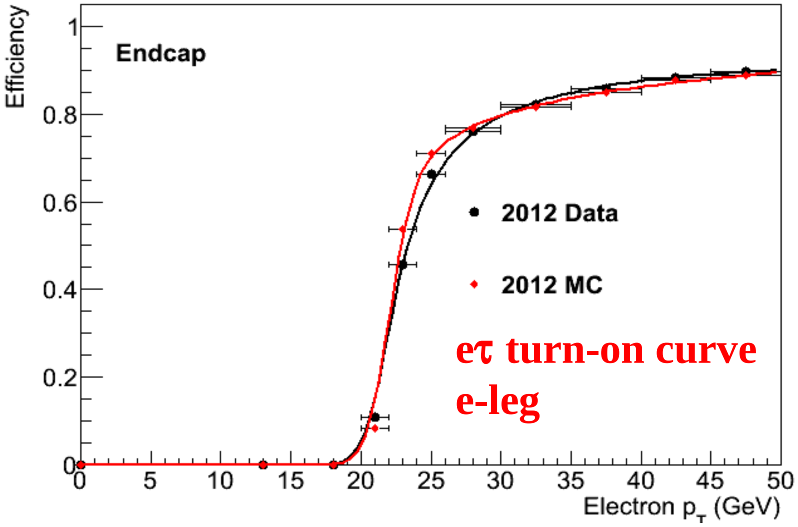
  (except in eμ channel: Iso$_{R<0.4}$ < 0.15·p_T(e/μ) in η < 1.479)
  - Applying Δβ corrections to address pile-up

$$Isolation_{R<0.4} = \Sigma\, p_T^{charged}\left(\Delta z < 2\mathrm{mm}\right) + max\left(p_T^{h0} + p_T^{\gamma} - \Delta\beta\,, 0\right)$$

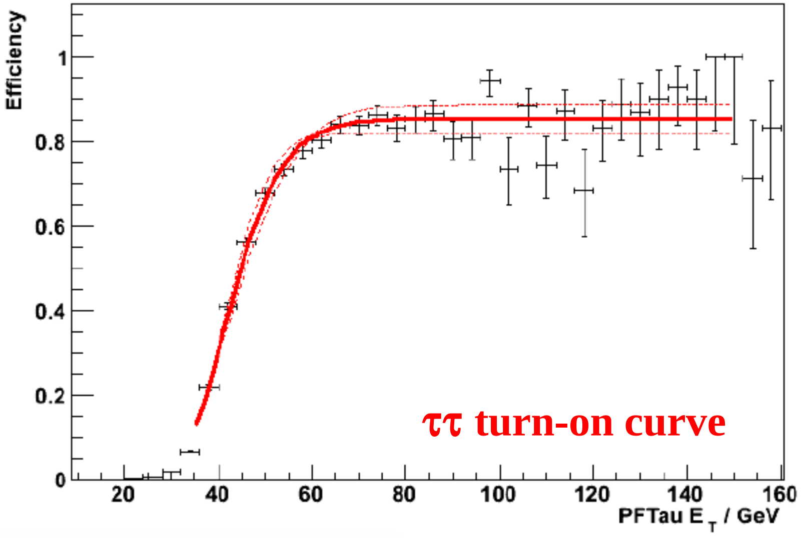
Trigger control plots



μτ turn-on curve
μ-leg

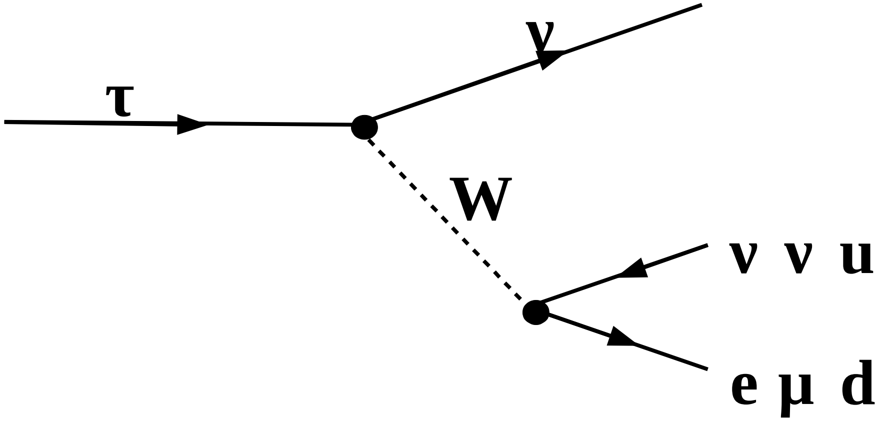


eτ turn-on curve
e-leg



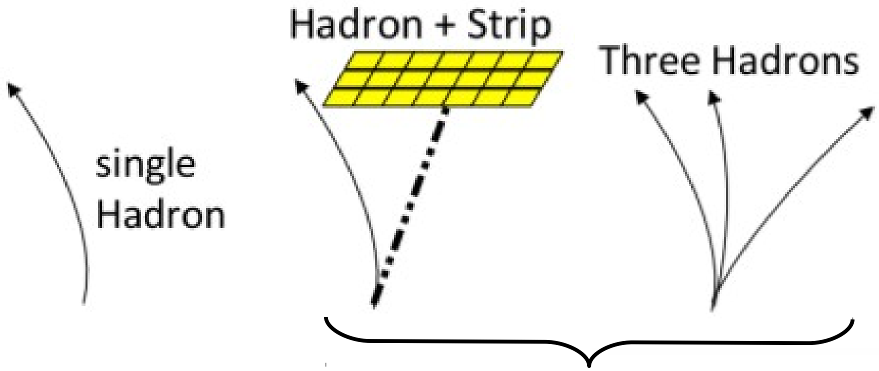
ττ turn-on curve

Reconstruction of τ's with CMS



Decay Mode	BR
$\tau \to e\nu\nu$	17%
$\tau \to \mu\nu\nu$	18%
$\tau \to h\nu$	12%
$\tau \to hh^0\nu$	37%
$\tau \to hhh\nu$	15%

Reco of hadronic decay modes:

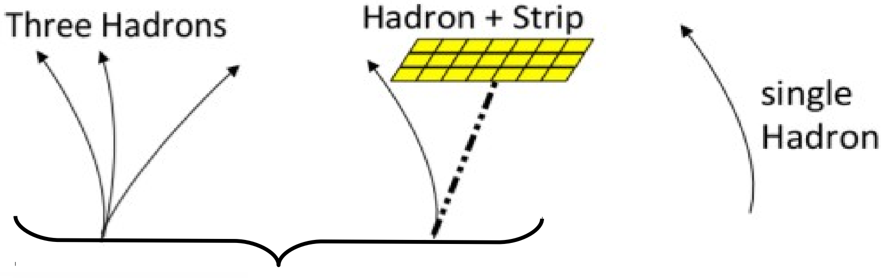


compatible with τ-mass

- Isolation (based on energy deposits in rings of ΔR≤0.5)
- Discrimination against e's (based on shower shape info and E/p)
- Discrimination against μ's

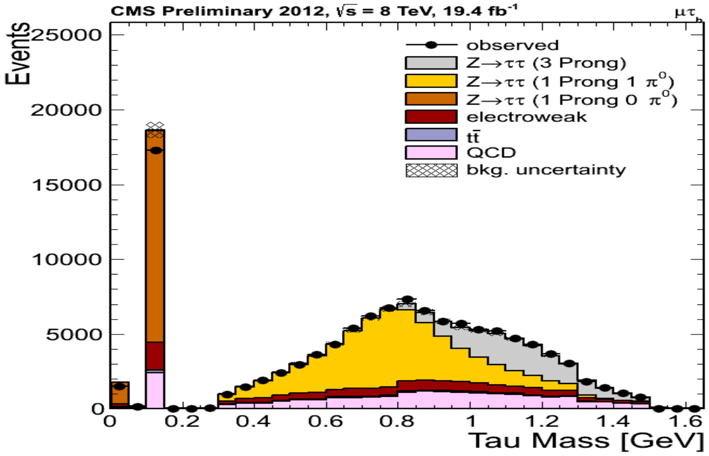
Hadronic decaying Taus

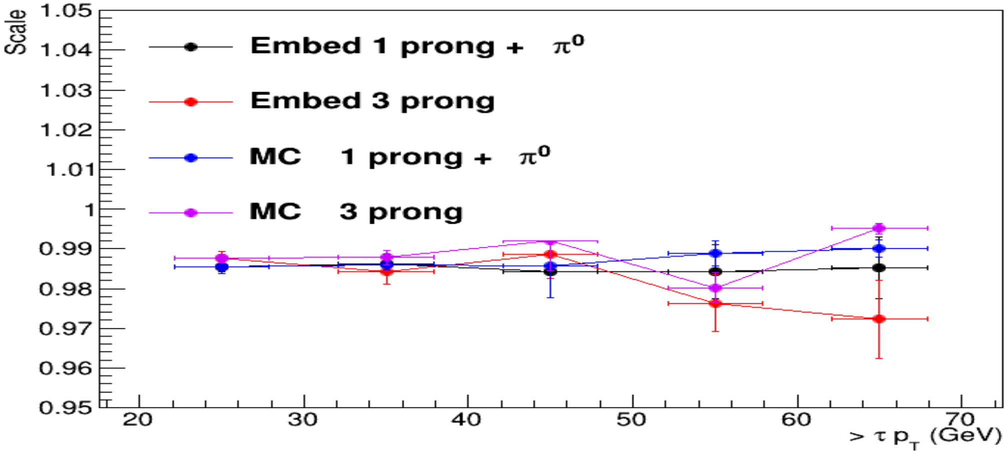
- Reconstructed using the Hadron plus Strips (HPS) algorithm
  - $\tau^{\pm} \rightarrow \pi^{\pm}\, \pi^{\mp}\, \pi^{\pm}\, \nu_T$
  - $\tau^{\pm} \rightarrow \pi^{\pm}\, \pi^{0}\, \pi^{0}\, \nu_T$
  - $\tau^{\pm} \rightarrow \pi^{\pm}\, \pi^{0}\, \nu_T$
  - $\tau^{\pm} \rightarrow \pi^{\pm}\, \nu_T$



compatible with a_1/ρ

- Correct tau energy scale with the tau mass
  - Fitting MC to data → a shift in respect to data would indicate a incorrect tau energy scale



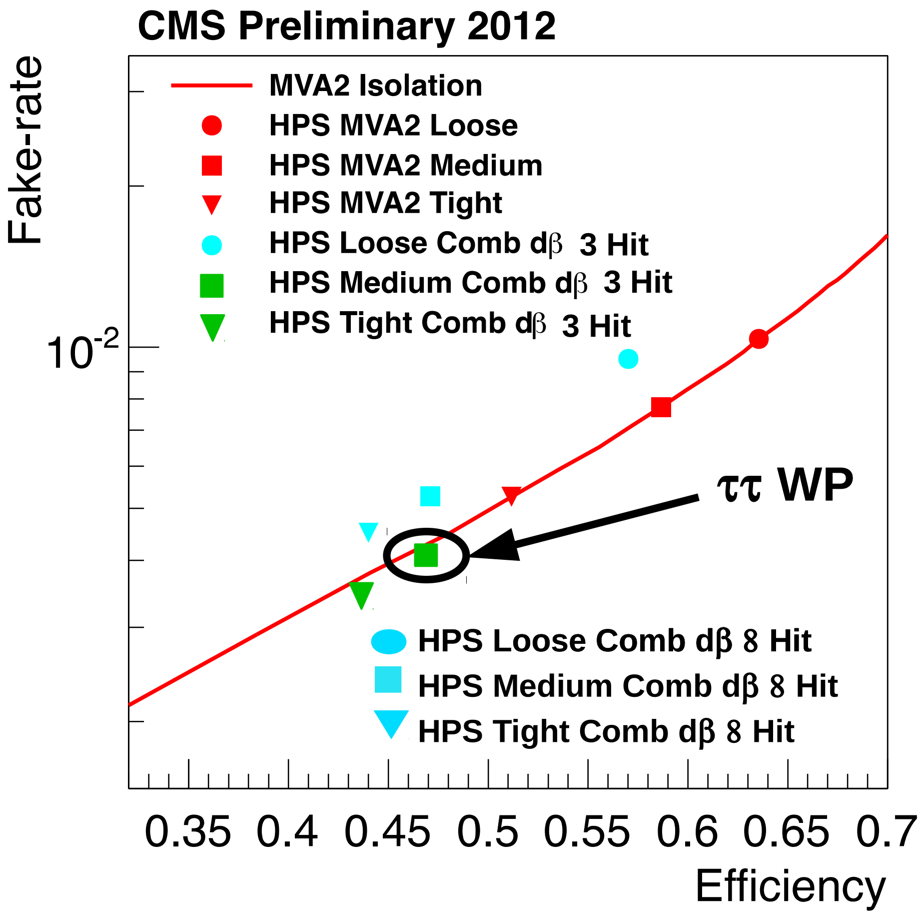


Hadronic tau Isolation

- Isolation defined as: $Isolation_{R<0.5} = \Sigma\, p_T^{charged}(\Delta z < 2\mathrm{mm}) + max(p_T^{\gamma} - \Delta\beta, 0)$

- Moved from MVA (=HCP 2012) approach to more simple HPS Combined Δβ 3Hit algorithm
  - Slightly better than MVA mainly due to loosened 'number of Hit requirement'

- After optimization in each channel:
  - $\mathrm{Isolation}_{R<0.5}$ < 1.5 GeV (for eτ, μτ),
  - $\mathrm{Isolation}_{R<0.5}$ < 1.0 GeV (for ττ)

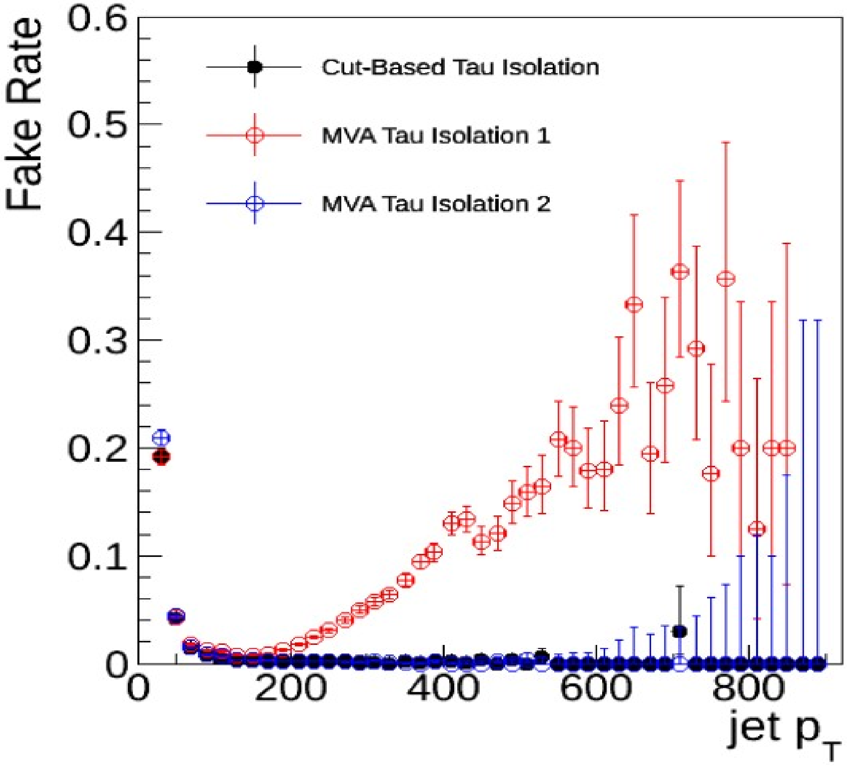


Hadronic tau isolation

- Isolation defined as:

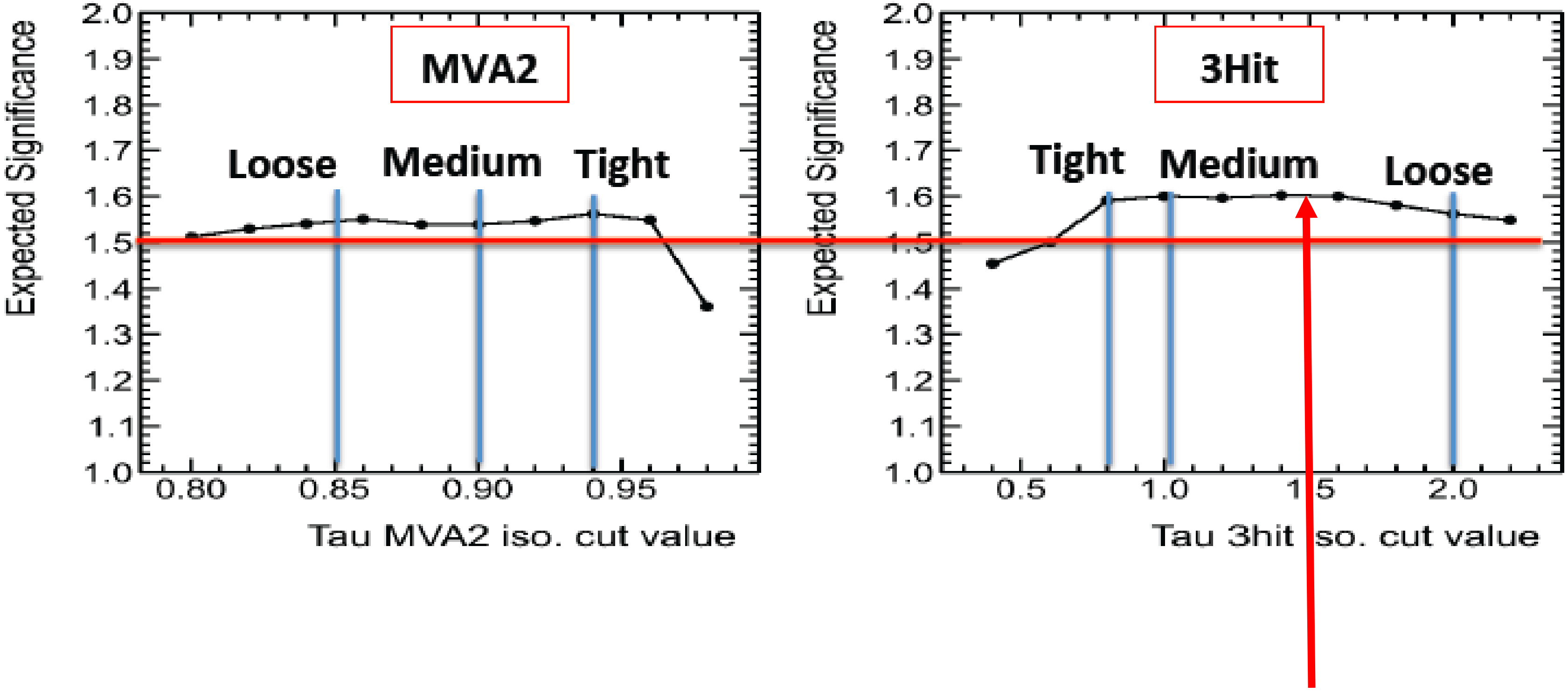
$$Isolation_{R<0.5} = \Sigma\, p_T^{charged}(\Delta z < 2\mathrm{mm}) + max(p_T^{\gamma} - \Delta\beta, 0)$$

  - Applying Δβ corrections to address pile up
  - Comparison of MVA1 with new trained MVA2 (new since HCP2012)



Hadronic tau Isolation

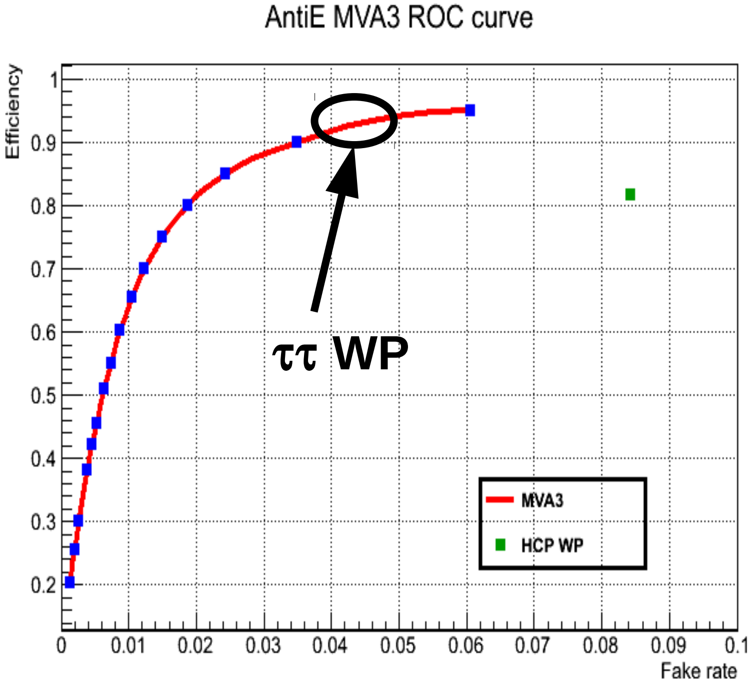
- Optimization (here in eτ SM analysis)



New working point

Tau discriminator from leptons faking tauons

- Anti-muon discriminator
  - Working-points defined by different τ identification efficiencies and μ→τ fake rates
    - Different channels chose different WPs (optimizing sensitivity)
- Anti-electron discriminator
  - In HCP2012 a combination of two MVA discriminators has been used
    - New training with single MVA: MVA3 gives better e→tau fake rejection
  - Working-points defined by output of multivariate discriminator trained to remove e→τ fakes
    - Different channels chose different WPs (optimizing sensitivity)



Muons

- Muon candidates require to pass the tight particle-flow (PF) muon identification criteria
  - Global and PF muon
  - > 0 pixel hits
  - > 5 tracker layer hits
  - > 0 hits in muon system
  - > 1 matches segments
  - χ^2 / N_{DoF} < 10.0 for global track fit
  - Transverse impact parameter of track reconstructed in pixel and strip silicon detectors d_{IP} < 2 mm with respect to the primary vertex

- Isolation$_{R<0.4}$ < 0.10·$p_T(\mu)$ (expect in eμ channel: Iso$_{R<0.4}$ < 0.15·$p_T(\mu)$ in η < 1.479)
  - Applying Δβ corrections to address pile up

$$Isolation_{R<0.4} = \Sigma\, p_T^{charged}(\Delta z < 2\mathrm{mm}) + max(p_T^{h0} + p_T^{\gamma} - \Delta\beta, 0)$$

Electrons

- Identified using a multivariate discriminator based on a BDT
  - Trained to separate electrons from jets faking electrons
  - Loose ($e\mu$) and Tight ($e\tau$) working points are defined

- Electron track associated to a hit in each layer of the Pixel detector which is crossed by the track
  - Removes electron candidates coming from photon conversions

- Reject electron candidate if track with opposite sign near and if both could be fitted to same vertex
  - Removes electron candidates coming from photon conversions

- $\mathrm{Isolation}_{R<0.4} < 0.10 \cdot p_T(e)$ (expect in $e\mu$ channel: $\mathrm{Iso}_{R<0.4} < 0.15 \cdot p_T(e)$ in $\eta < 1.479$)
  - Applying $\Delta\beta$ corrections to address pile up

$$Isolation_{R<0.4} = \Sigma\, p_T^{charged}(\Delta z < 2\mathrm{mm}) + max(p_T^{h0} + p_T^{\gamma} - \Delta\beta, 0)$$

Other Objects

- MVA missing transverse energy $\not{E}_T$
  - Improves resolution by about 40% in typical 2012 pile-up conditions

- Transverse mass M_T (for $e\tau$, $\mu\tau$) and D_ζ variable (for $e\mu$)
  - used to suppress various sources of backgrounds mainly W+jets

- PF Jets
  - $p_T > 30$ GeV, $|\eta| < 4.7$
  - Require loose identification criteria to reject fakes
  - Loose working-point of “full ID” MVA discriminators against pile-up jets
  - Jets with $p_T > 20$ GeV and “Combined Secondary Vertex” (CSV) discriminator of $d > 0.679$ are considered b-tagged (medium WP)

Missing transverse energy $\not{E}_T$

- MVA $\not{E}_T$ algorithm is used
  - Utilizes the fact that pile-up predominately produces unclustered energy and low p_T jets while leptons and high p_T jets originate from hard-scatter interactions
  - Reduces the sensitivity to pile-up significantly
  - Improves resolution by about 40% in typical 2012 pile-up conditions
  - Used for reducing backgrounds (with $\not{E}_T$ based variables M_T and D_ζ)

- Z-recoil corrections are applied
  - correct for residual differences in $\not{E}_T$ response and resolution between data and MC
  - Applied to $Z/\gamma^* \rightarrow ll$ (e, μ, τ), W+jets and signal samples

Transverse mass M_T and P_ζ variable

- M_T is computed using the transverse mass of the electron (muon) plus the missing transverse energy of the event

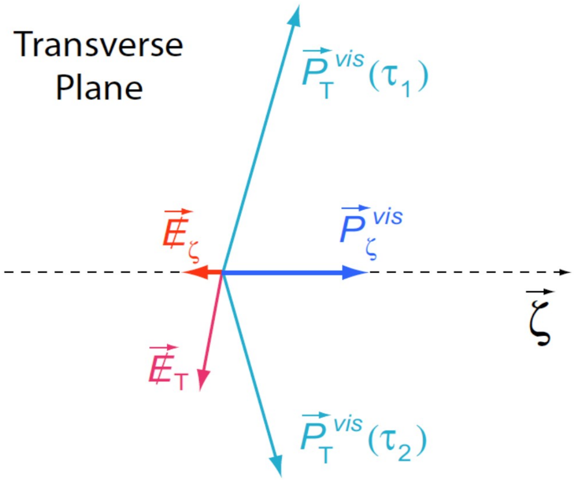
$$M_T = \sqrt{(P_T^\ell + \not{E}_\mathrm{T})^2 - \left((P_x^\ell + \not{E}_x)^2 + \left(P_y^\ell + \not{E}_y\right)^2\right)}$$

- The quantity $D_\zeta = P_\zeta - 1.85 \cdot P_\zeta^{vis}$ utilizes the fact that the angle between the neutrinos and the visible tau decay products is typically small

$$P_\zeta = P_T^{vis_1} + P_T^{vis_2} + \not{E}_\mathrm{T}$$

$$P_\zeta^{vis} = \vec{P}_T^{vis_1} + \vec{P}_T^{vis_2}$$

- Both used to suppress various sources of backgrounds mainly W+jets



Jets

- Particle-flow jets, $|\eta| < 4.7$
- Anti-k_T algorithm with distance parameter R=0.5
- Require jet candidates to pass a set of loose jet identification criteria
  - Rejection of fake jets
- Loose working-point of the “full ID” MVA-based jet identification discriminator
  - Suppress jets originating from pile-up
- Fastjet-ρ-based jet energy corrections applied in order to compensate pile-up effects

- Jets with $p_T > 20$ GeV and “Combined Secondary Vertex” (CSV) discriminator of $d > 0.679$ are considered b-tagged (medium WP)

- Jets and b-tagged Jets are used for final event categorization

Event Selection

Event selection in eμ

- Pass any eμ trigger
- Two opposite sign leptons
- Electron:
  - Pass loose MVA based electron identification
  - $p_T > 10$ GeV, $|\eta| < 2.3$,
    $\mathrm{Iso}_{R<0.4} < 0.10 \cdot p_T$ for $|\eta| > 1.479$, $\mathrm{Iso}_{R<0.4} < 0.15 \cdot p_T$ for $|\eta| < 1.479$
- Muon
  - Passing tight PF muon identification
  - $p_T > 10$ GeV, $|\eta| < 2.1$,
    $\mathrm{Iso}_{R<0.4} < 0.10 \cdot p_T$ for $|\eta| > 1.479$, $\mathrm{Iso}_{R<0.4} < 0.15 \cdot p_T$ for $|\eta| < 1.479$
- One of the lepton is required to have $p_T > 20$ GeV with respect to the used trigger
- If >2 leptons in event → chose the leptons with the highest sum $p_T(e) + p_T(\mu)$
- $P_\zeta - 1.85 \cdot P_\zeta^{vis} > -20$ GeV

Event selection in eτ

- Pass any eτ trigger
- Two opposite sign leptons
- Electron
  - Tight MVA based electron identification
  - $p_T > 24$ GeV, $|\eta| < 2.1$, $\mathrm{Iso}_{R<0.4} < 0.10 \cdot p_T$
  - No second electron with loosened requirements
- Tau
  - $p_T > 20$ GeV, $|\eta| < 2.3$, $\mathrm{Iso}_{R<0.5} < 1.5$ GeV
  - Medium working-point of MVA3 anti-e discriminator
  - Loose working-point of anti-μ discriminator
- If >2 leptons in event → chose the leptons with the highest sum $p_T(e) + p_T(\tau)$
- $M_T < 30$ GeV

Event selection in μμ

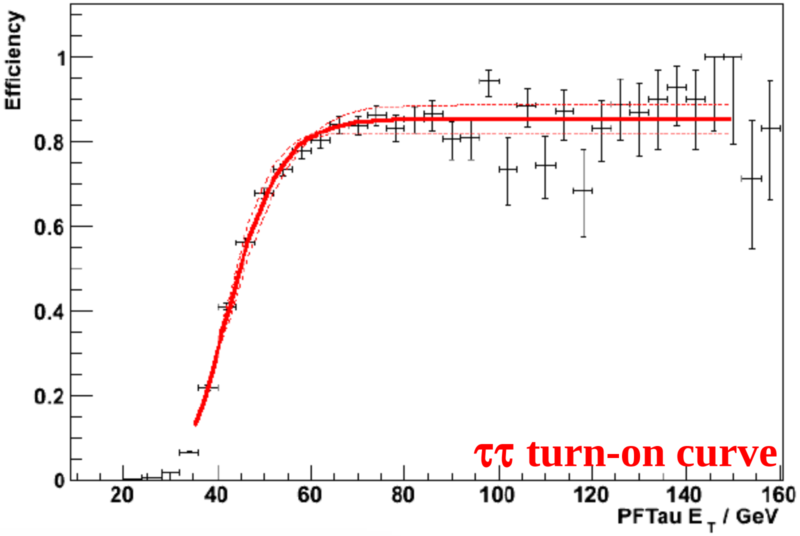
- Pass any μμ trigger
- Two opposite leptons
- Muon
  - Pass tight PF muon identification
  - $p_T(\mu_1) > 20$ GeV, $p_T(\mu_2) > 10$ GeV, $|\eta| < 2.1$ (2.4 depending on used trigger), $Iso_{R<0.4} < 0.10 \cdot p_T$ if $p_T > 10$ GeV, $Iso_{R<0.4} > 0.15 \cdot p_T$ if $p_T > 20$ GeV)
- A BDT is trained to reject Z/γ* → μμ events, $BDT_{\tau\tau} > -0.35$ for B-tag and > -0.5 for no-B-tag category

Event selection in $\mu\tau$

- Pass any $\mu\tau$ trigger
- Two opposite sign leptons
- Muon
  - Tight PF muon identification
  - $p_T > 20$ GeV, $|\eta| < 2.1$, $\mathrm{Iso}_{R<0.4} < 0.10 \cdot p_T$
  - No second muon with loosened requirements
- Tau
  - $p_T > 20$ GeV, $|\eta| < 2.3$, $\mathrm{Iso}_{R<0.5} < 1.5$ GeV
  - Loose working-point of the cut-based anti-e discriminator
  - Tight working-point of anti-μ discriminator
- If >2 leptons in event → chose the leptons with the highest sum $p_T(\mu) + p_T(\tau)$
- $M_T < 30$ GeV

Event selection in ττ

- Pass ττ trigger
  - Parked datasets (di-tau trigger is used)
    - No jet is needed to trigger events
- Two opposite sign taus
- Tau
  - Pass medium working-point of HPS combined isolation 3-hits discriminator
  - $p_T > 45$ GeV, $|\eta| < 2.3$
  - Loose working-point of MVA3 anti-e discriminator
- If >2 taus in event
  → chose taus with the lowest sum
  $\mathrm{Iso}_{R<0.5}(\tau_1) + \mathrm{Iso}_{R<0.5}(\tau_2)$



Background Estimation

$Z/\gamma^* \rightarrow \tau\tau$ backgrounds estimations

- Embedding technique
  - Select $Z/\gamma^* \rightarrow \mu\mu$ events in data
    - Replace muons by simulated tau decays
  - Normalized to $Z/\gamma^* \rightarrow \mu\mu$ measured in control region
  - Use scale-factor method to obtain yield in $Z/\gamma^* \rightarrow \tau\tau$ after event selection by using MC for $Z/\gamma^* \rightarrow \tau\tau$ in control region and $Z/\gamma^* \rightarrow \mu\mu$ after event selection

- Small additional background fraction arises from events in which one tau escapes detection and the reconstructed e, μ, τ is due to a fake
  - Taken from MC $Z/\gamma^* \rightarrow \tau\tau$

QCD background estimation

- General idea in all channels:
  - Find QCD dominated control region and correct it by subtracting other backgrounds
  - Extrapolate to QCD signal region
- ττ:
  - Measure fake rate scale factors in SS as ratio of anti-isolated/isolated
  - Apply factors to anti-isolated OS region to obtain OS isolated region (=signal region)
- eμ:
  - Using the fake-rate technique
  - Probability e_{fake} for loose electron candidates to pass electron ID and ISO is measured in QCD dominated control region
  - Categorization cuts and e_{fake} is applied to obtain the QCD background in b-tag and no-b-tag separately
- eτ, μμ, μτ:
  - Define OS and SS anti-isolated (invert isolation in e or μ) regions and SS isolated region
  - Measure ratio of OS/SS in anti-isolated region
  - Apply ratio to SS isolated region to obtain OS isolated region (=signal region)

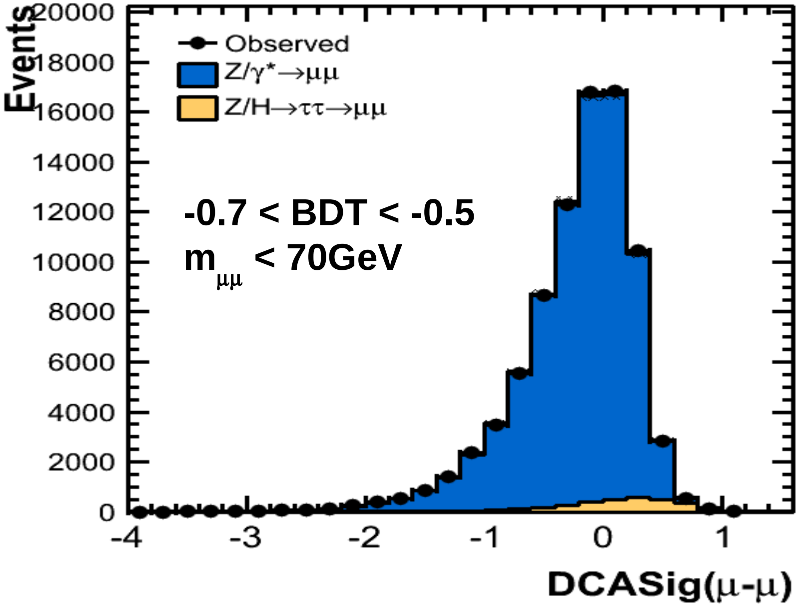
W+jets background estimation

- Important background for $e\tau$ and $\mu\tau$
- Shape from MC; Normalization from data
- High M_T sideband is build in each category by inverting the M_T < 30 GeV cut to M_T > 70 GeV
- The extrapolation factor of the ratio sideband/signalband is obtained by using MC W+jets

Z/γ* → ee and Z/γ* → μμ background estimation

- μμ:
  - Largest background for μμ
  - Perform fit of DCA: Z/H → ττ and Z → μμ to data
  - Derive (BDT_{red}, $m_{\mu\mu}$)–dependent scale-factors for Z → μμ MC
  - Before the fit is performed QCD, W+jets, $t\bar{t}$, single top and di-boson backgrounds are subtracted from data

- eμ, eτ, μτ and ττ:
  - Modeled using MC
  - In eτ corrected for e → τ fakes



BDT based MVA selection

- Following preselection and event categorization, BDT based MVA selection is applied
- Variables used as an input to BDT
  - Inter-muon DCA significance
  - Dimuon pt to the scalar sum of muons' pt ratio
  - Dimuon eta
  - Azimuthal angle between missing pt and mu+ pt
  - Decay angle of mu+ in the rest frame of dimuon system (Z candidate)
  - Angle between by mu+ pt and dimuon production plane in the rest frame of the dimuon system
  - Validity of collinear approximation (binary variable)
- Event is accepted in the final sample if it passes cut on BDT discriminant
  - Optimized separately for each event category (b-tag & no-b-tag) and data period (7TeV & 8TeV)

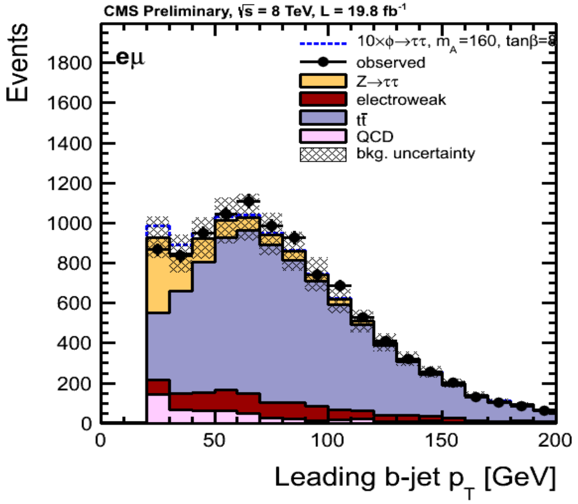
Other background estimation

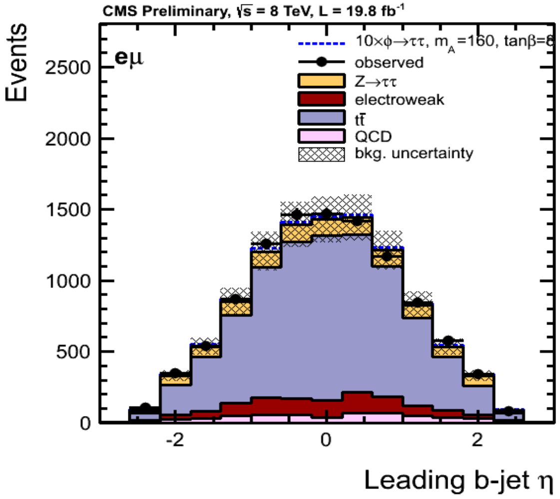
- $t\bar{t}$
  - Shape from MC; Normalization from data
  - Derive MC correction factors in eμ $t\bar{t}$ control region
    - Correction factors applied to $t\bar{t}$ MC in all channels
  - 7TeV MC is normalized to measured inclusive cross-section from CMS
  - 8TeV MC is normalized to NNLO

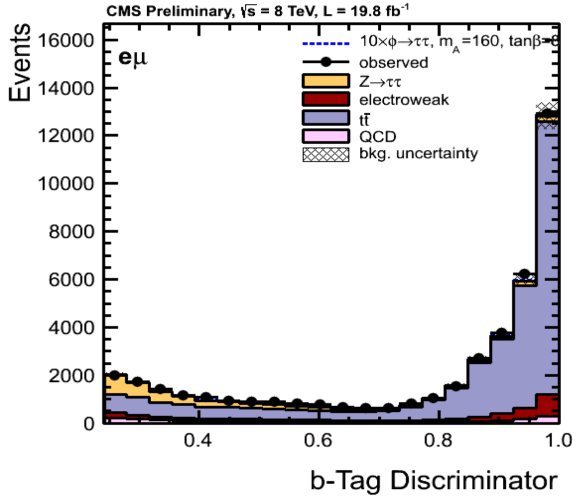
- Single top and di-boson
  - Contributions are small
    - 3% in μτ 8TeV b-tag

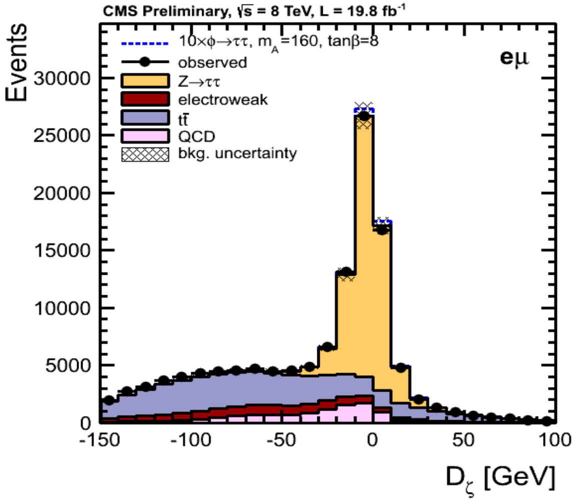
  - Fully rely on MC

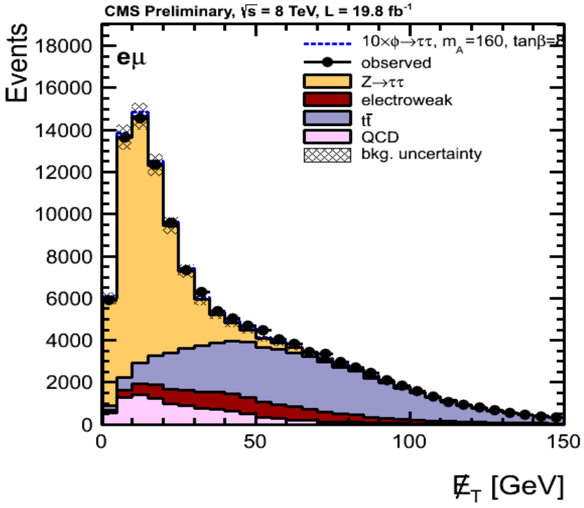
Control plots for eμ (postfit)

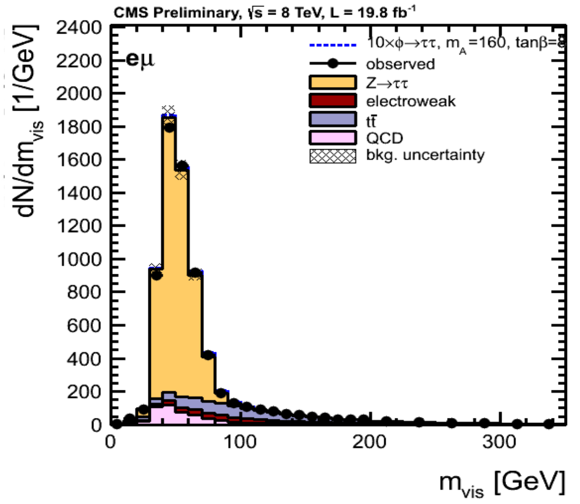




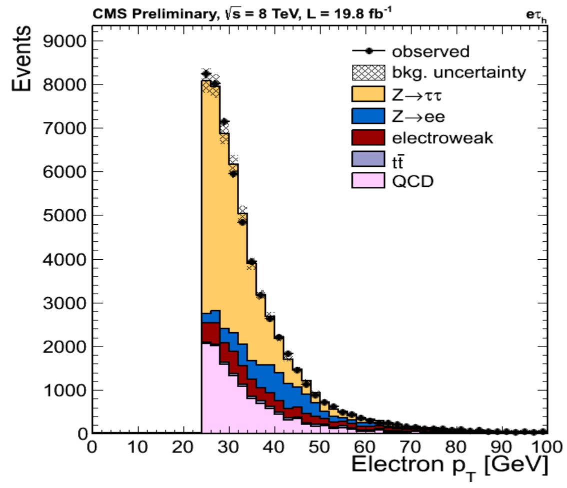


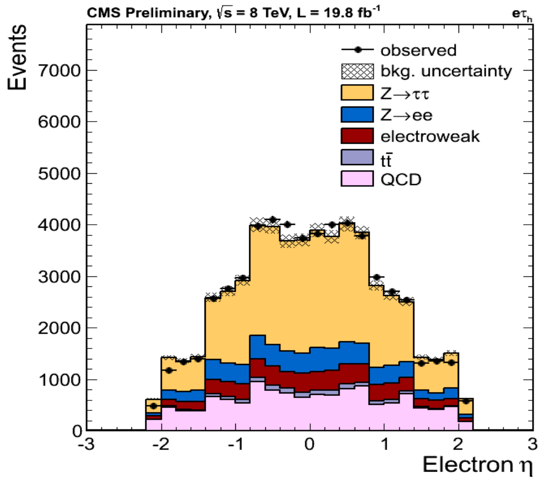


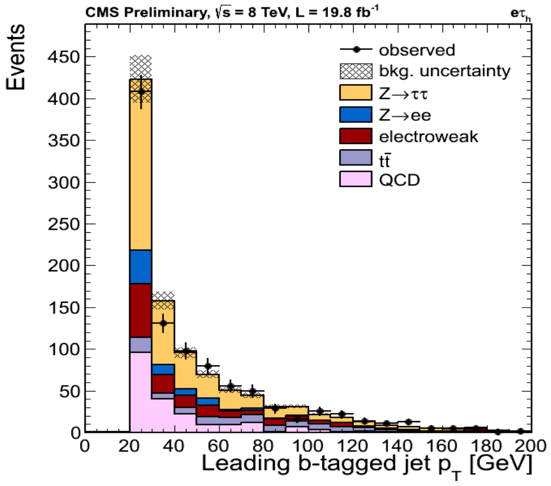


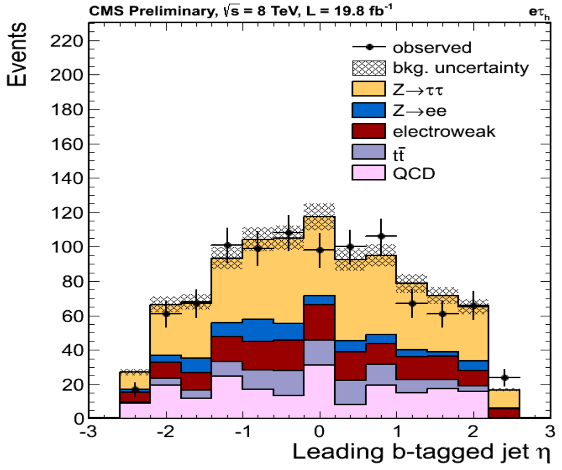


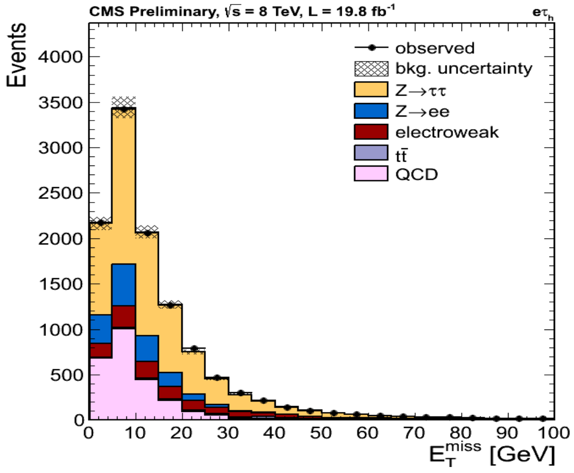
Control plots for eτ (postfit)

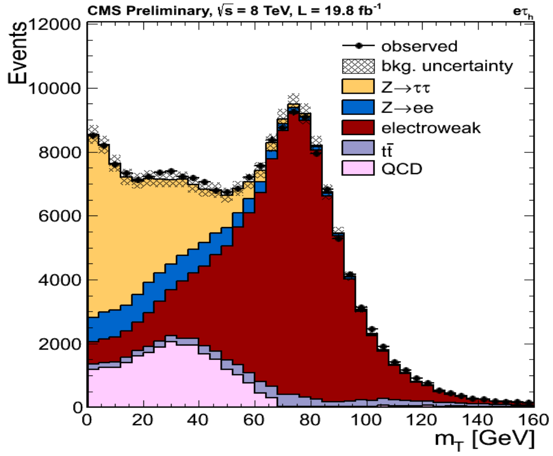




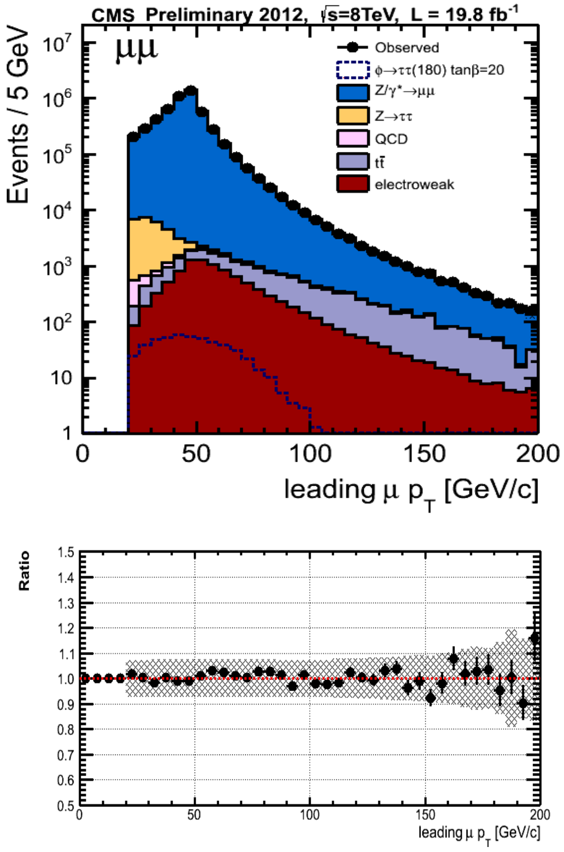


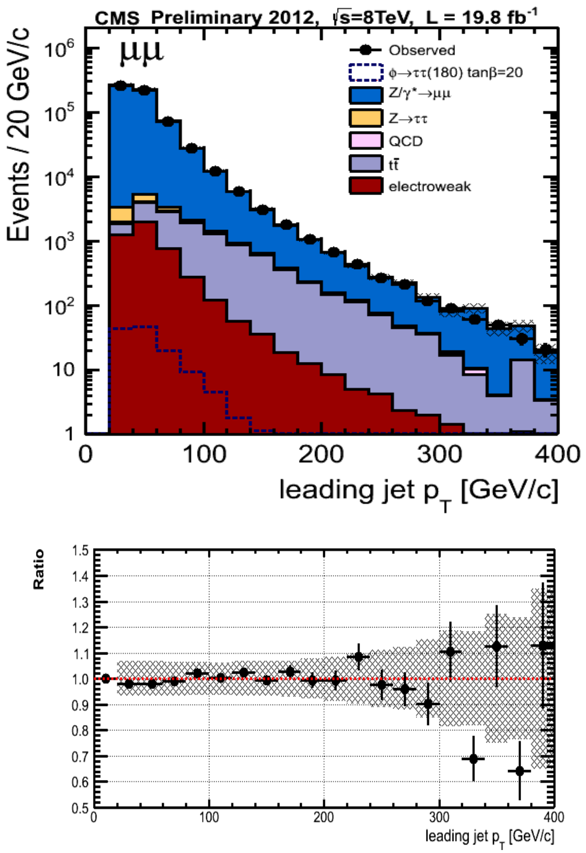


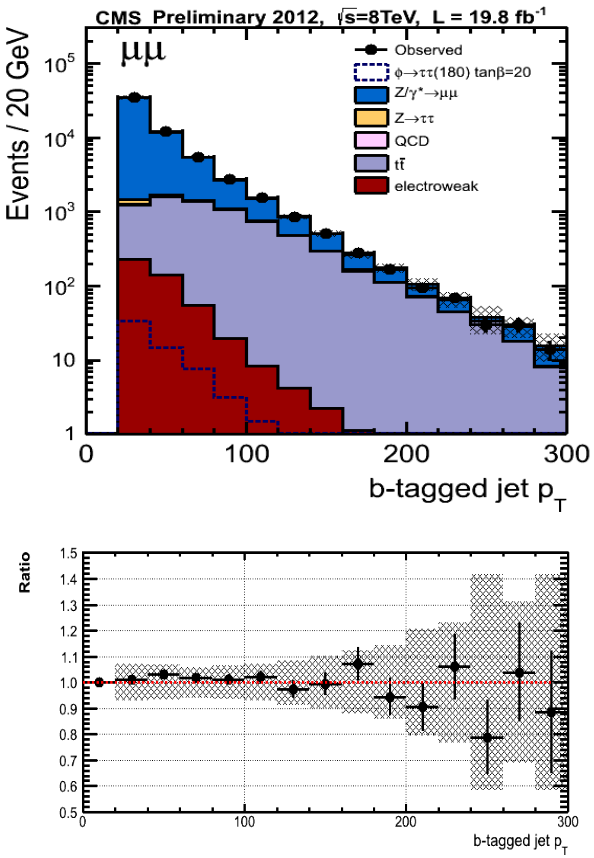




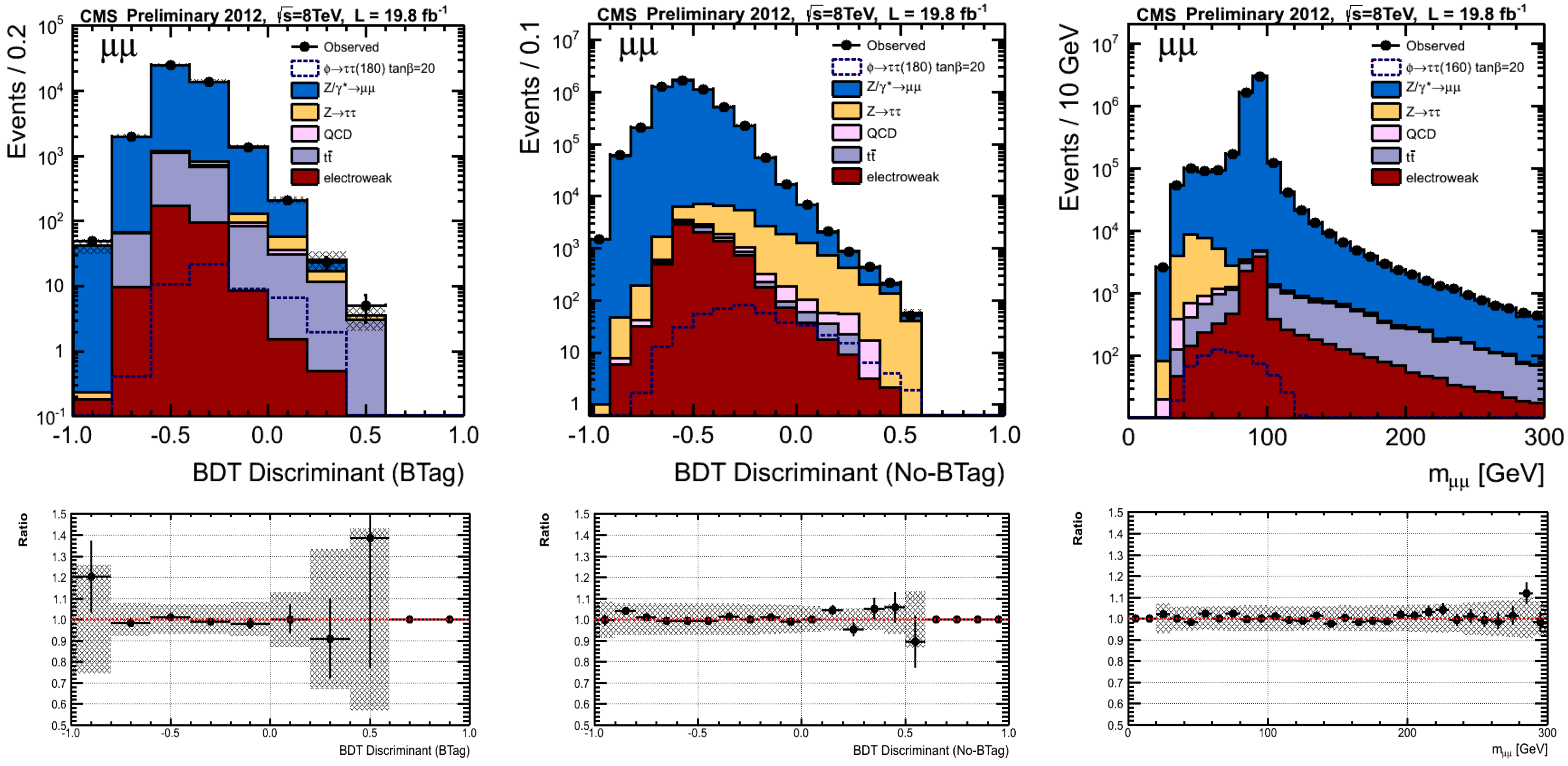
Control plots for μμ (postfit)



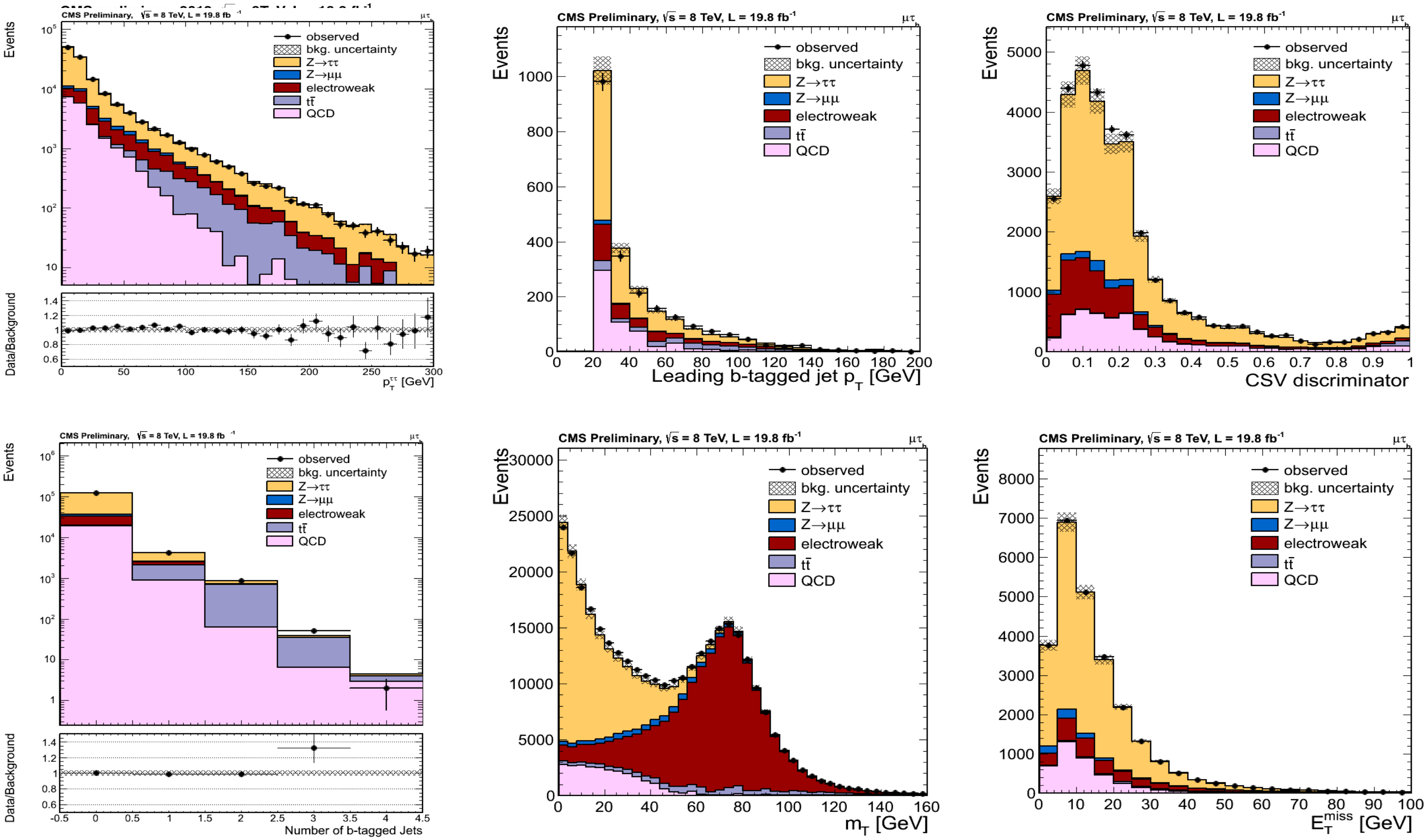




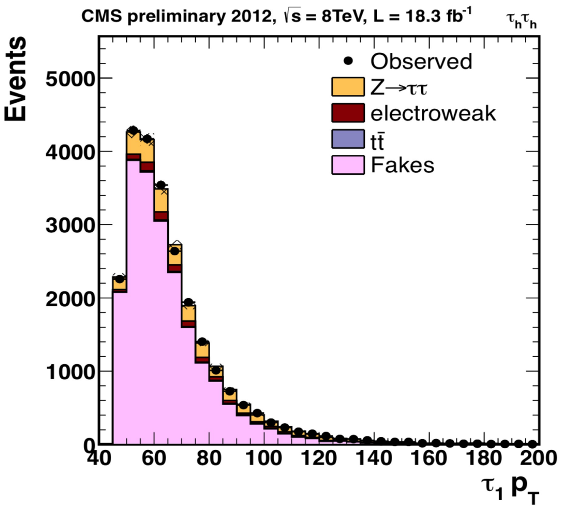
Control plots for μμ (postfit)

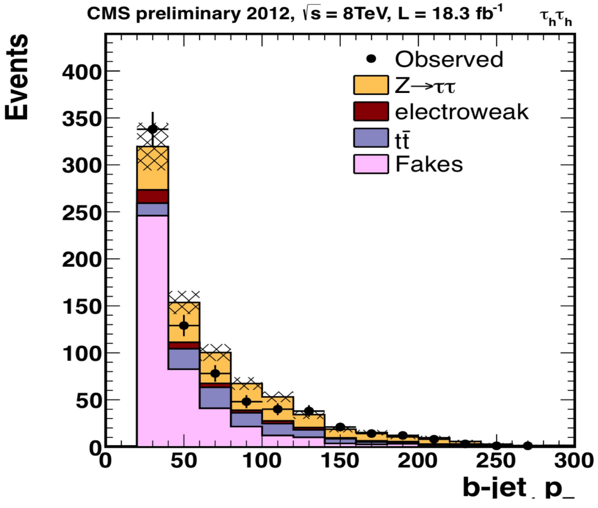


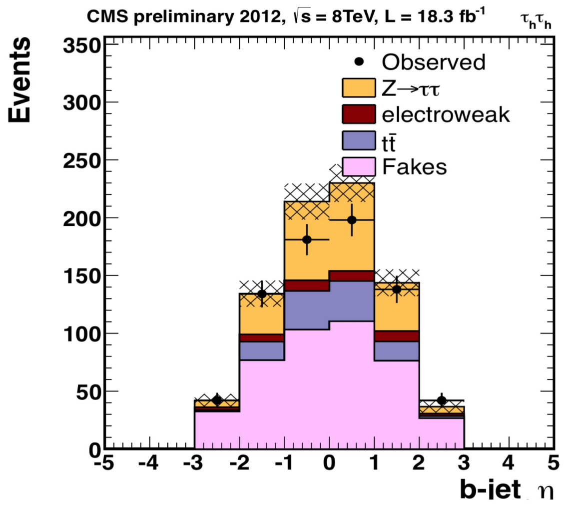
Control plots for μτ (postfit)

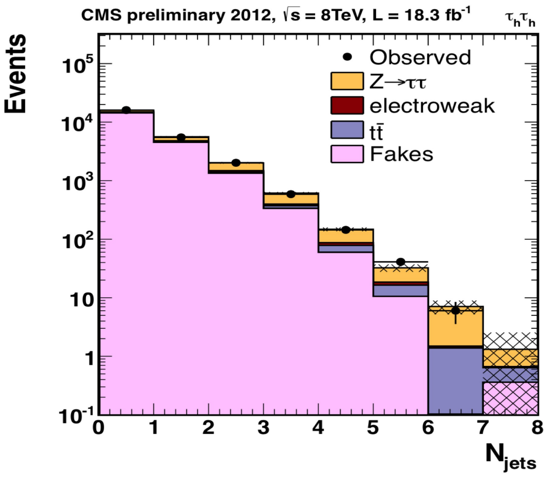


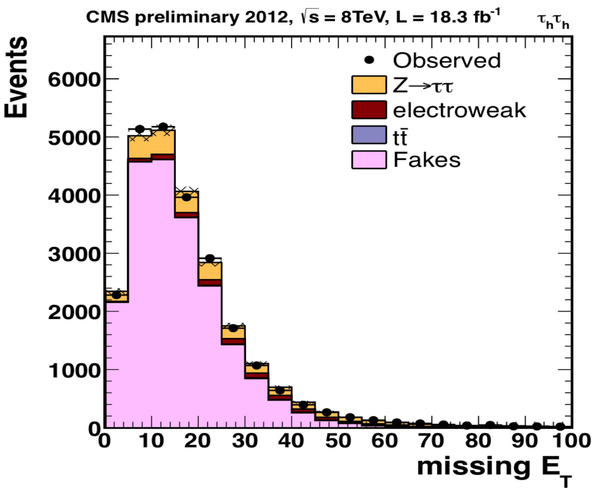
Control plots for ττ (postfit)

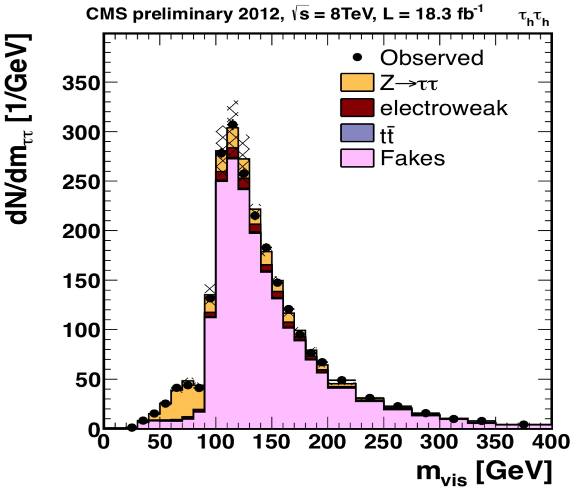






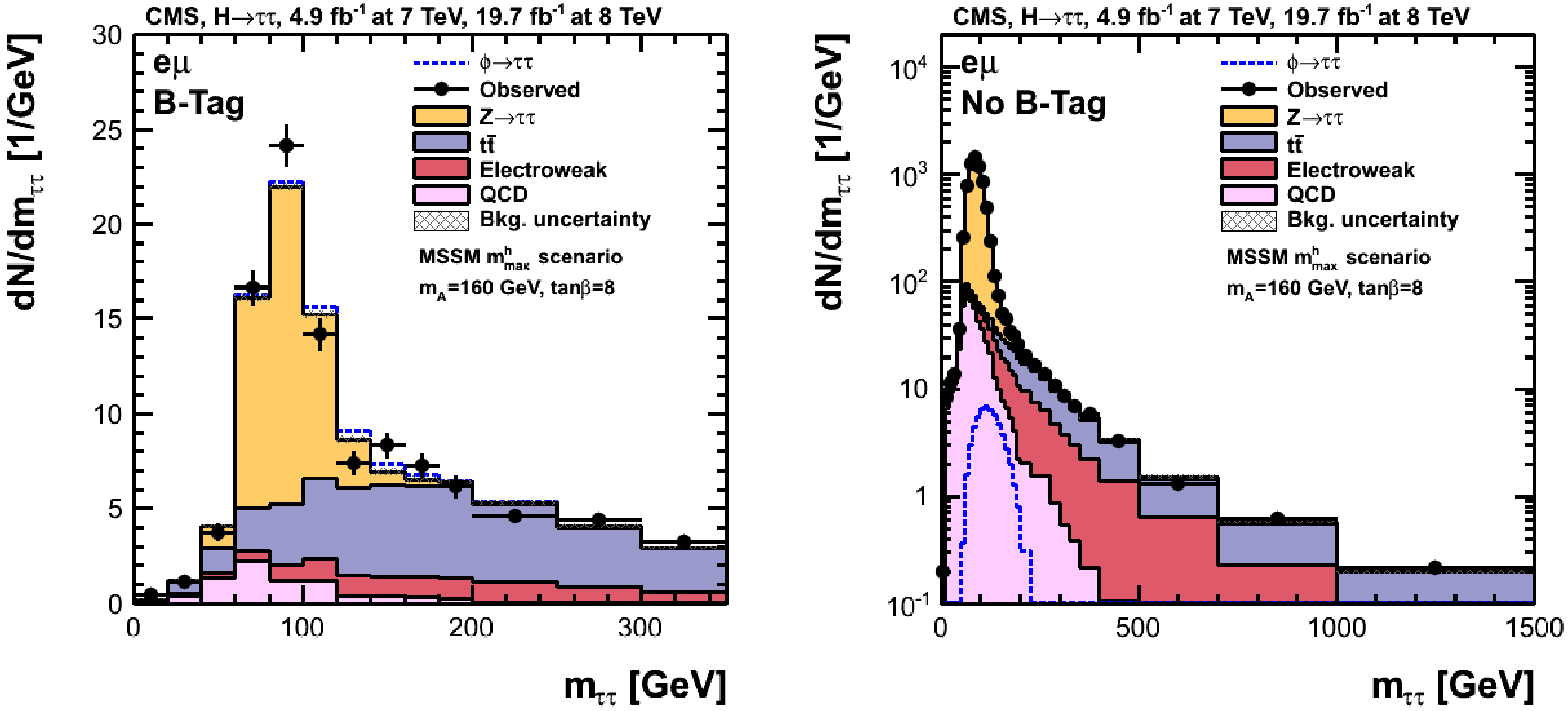




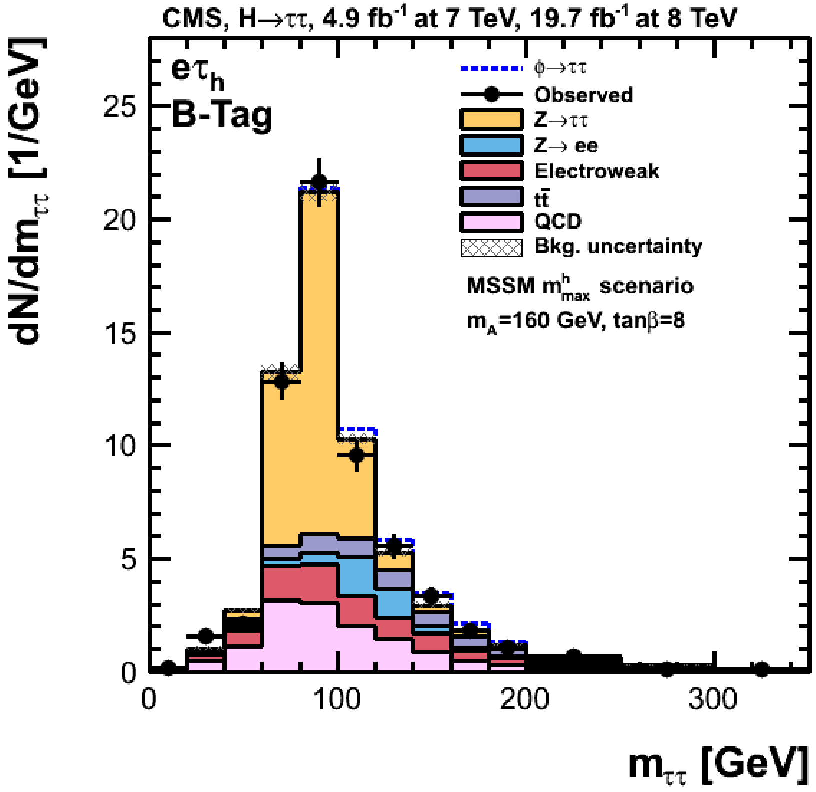


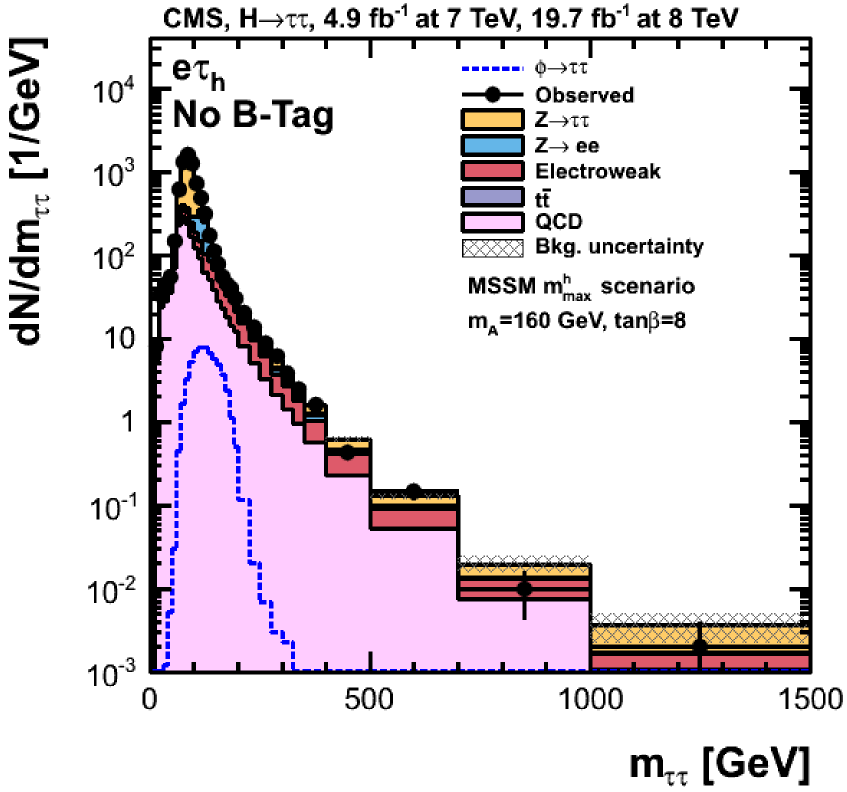
Invariant Mass Plots

Invariant mass plots – eμ

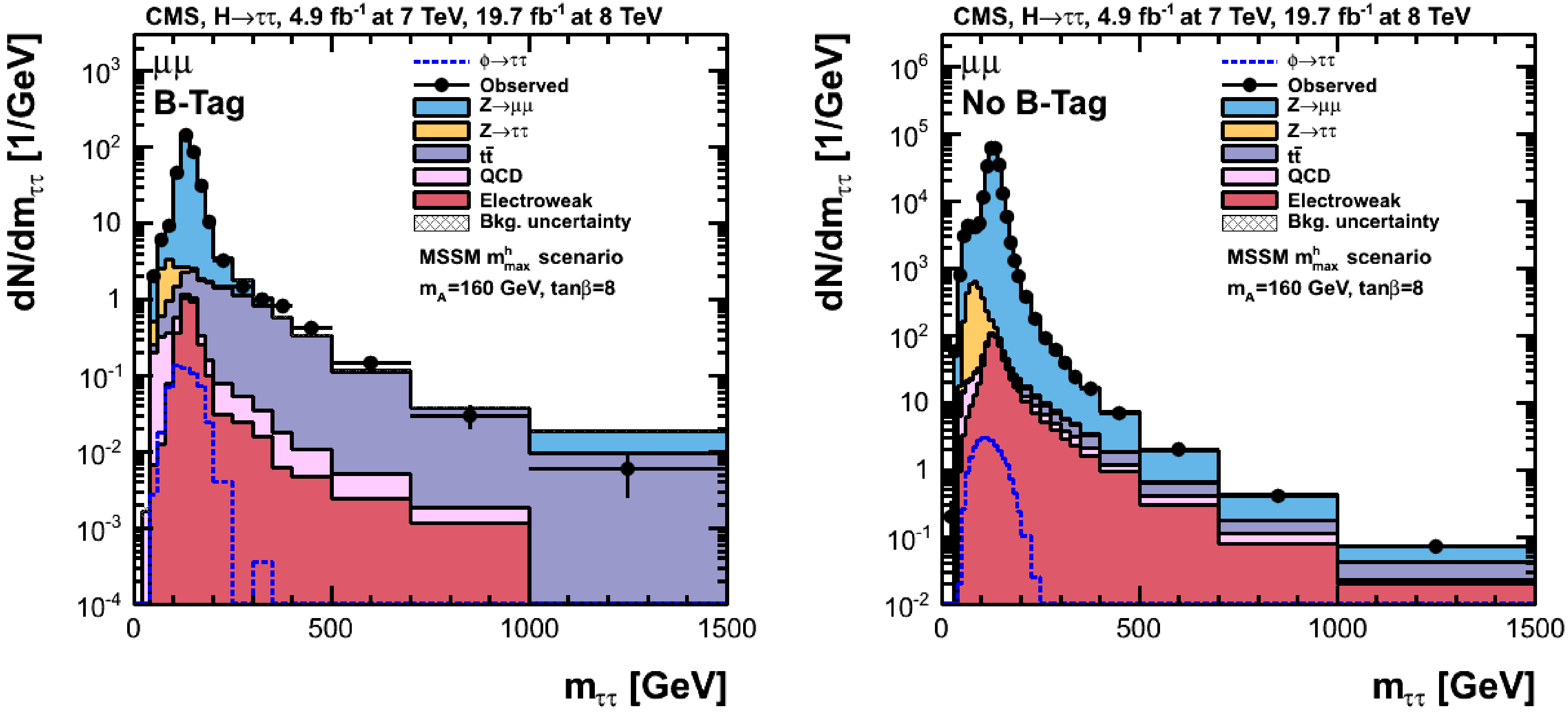


Invariant mass plots – eτ

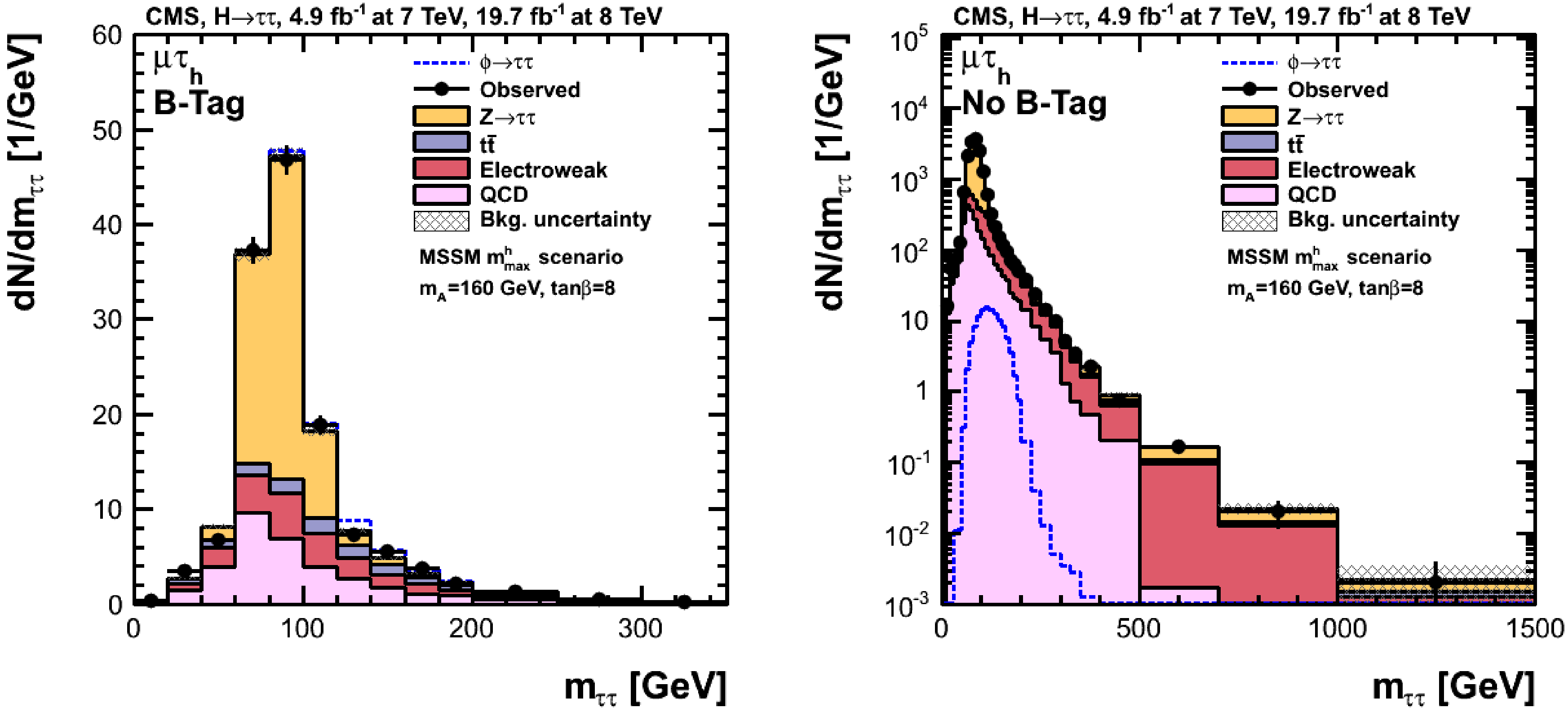




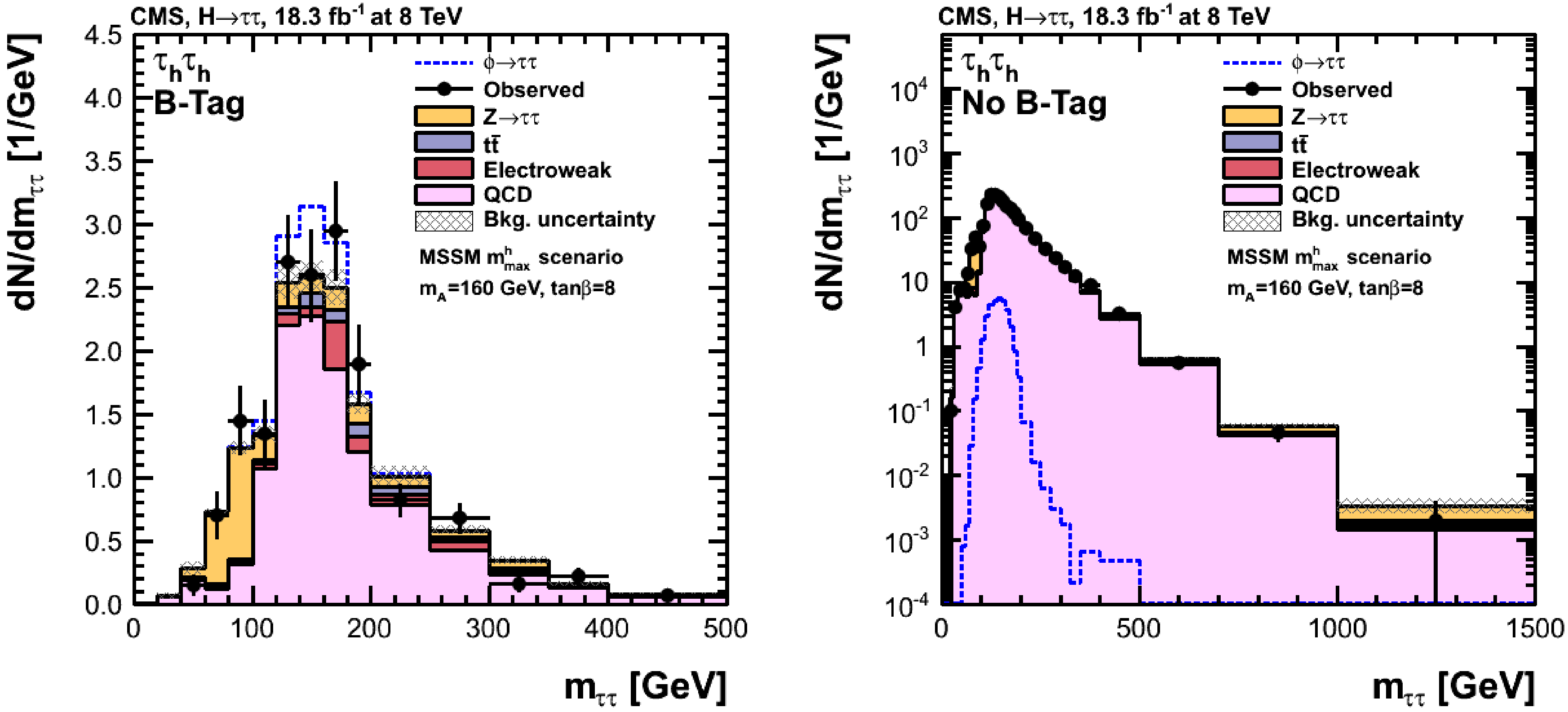
Invariant mass plots – μμ



Invariant mass plots – μτ



Invariant mass plots – ττ



Uncertainties

No changes with respect to
PAS **HIG-13-021**

Yield uncertainties

- trigger, identification, isolation efficiency
  - 2% for electrons
  - 2% for muons
  - 6% for taus (identification efficiency)
  - 3% (4.5% per leg) for the hadronic tau leg in $e\tau$ and $\mu\tau$ ($\tau\tau$) trigger
- $e \rightarrow \tau$ and $\mu \rightarrow \tau$ fake rates
  - 30% for both coming from scale-factor measurements ($e\rightarrow\tau$) and Tau POG recommendations ($\mu\rightarrow\tau$)
- Jet energy scale
  - Provided as function of p_T and η by JetMET POG
- B-tag scale-factors
  - Provided by the BTV POG
- Luminosity
  - 4.4%

Yield uncertainties

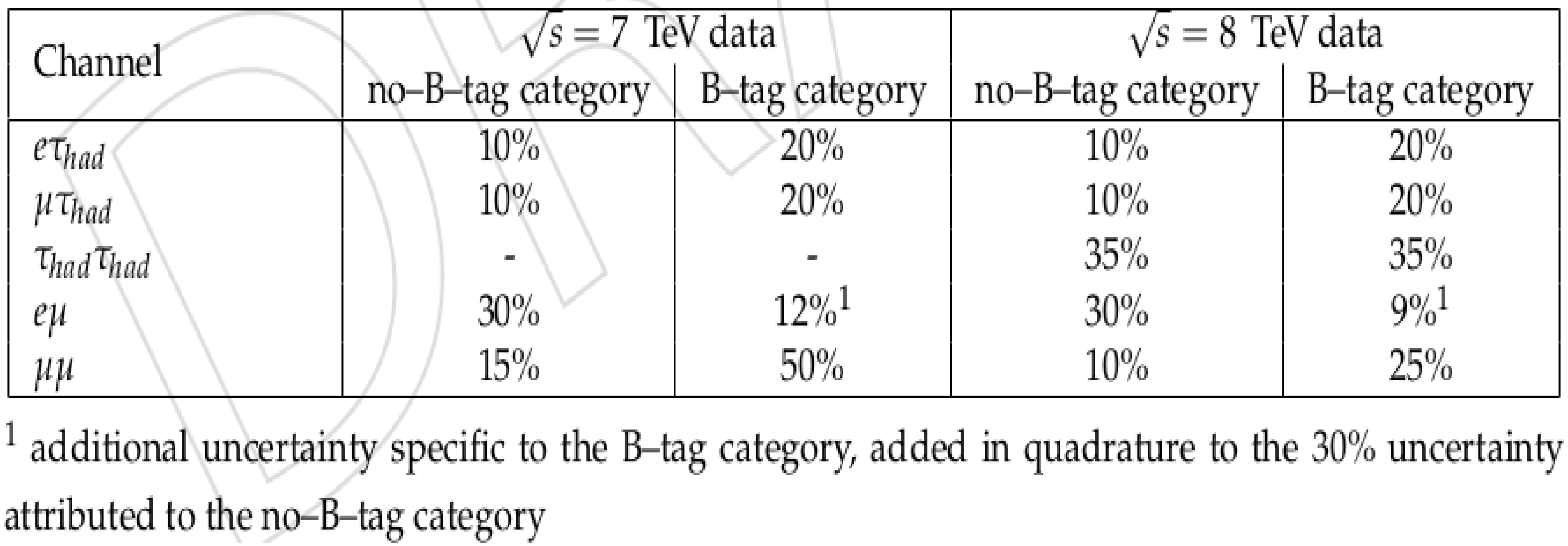
- $Z/\gamma^* \rightarrow ll$
  - $e\mu$, $e\tau$, $\mu\tau$, $\tau\tau$: 5%
  - $\mu\mu$: Obtained by varying the DCASig(2μ) shape templates within uncertainties
- $Z/\gamma^* \rightarrow \tau\tau$
  - 5% for no-b-tag category
  - 15% for b-tag category
- tt, single top, di-boson
  - 15% from cross-section uncertainty
- W+jets
  - Normalization uncertainty: Obtained from data using the high M_T sideband method
  - Extrapolation uncertainty: Obtained by using the 'Ersatz' method

Yield uncertainties

- QCD
  - Normalization uncertainty:

$$\delta_{norm} = \sqrt{\delta_{stat}^2 + \delta_{extra}^2}$$

    - δ_{stat}: Statistical uncertainty of yield of the QCD dominated region
    - δ_{extra}: Uncertainty of the extrapolation factors



Channel	$\sqrt{s} = 7$ TeV data		$\sqrt{s} = 8$ TeV data	
	no–B–tag category	B–tag category	no–B–tag category	B–tag category
$e\tau_{had}$	10%	20%	10%	20%
$\mu\tau_{had}$	10%	20%	10%	20%
$\tau_{had}\tau_{had}$	-	-	35%	35%
$e\mu$	30%	12%[1]	30%	9%[1]
$\mu\mu$	15%	50%	10%	25%

[1] additional uncertainty specific to the B–tag category, added in quadrature to the 30% uncertainty attributed to the no–B–tag category

Shape uncertainties

- e, μ, τ energy scale
  - 1% (2.5%) for electrons in the barrel (endcap)
  - 1% for muons in the mm channel (in all others negligible)
  - 3% for taus
- Z-recoil correction
  - Uncertainties on $\not{E}_T$ resolution and response are accounted for by varying the Z-recoil corrections parameters within the uncertainties determined within the method

Statistical Treatment

No changes with respect to PAS **HIG-13-021**

Bin-by-bin (bbb) uncertainties

- Allowed bbb for all backgrounds in all channels

- Add bbb uncertainty if

  the bin-error/bin-content > 5%
  - 2003 added

- Drop bbb uncertainty if

  pulls of bin-by-bin uncertainties • size of the prefit uncertainty < 10% of bin-content
  - 1696 dropped

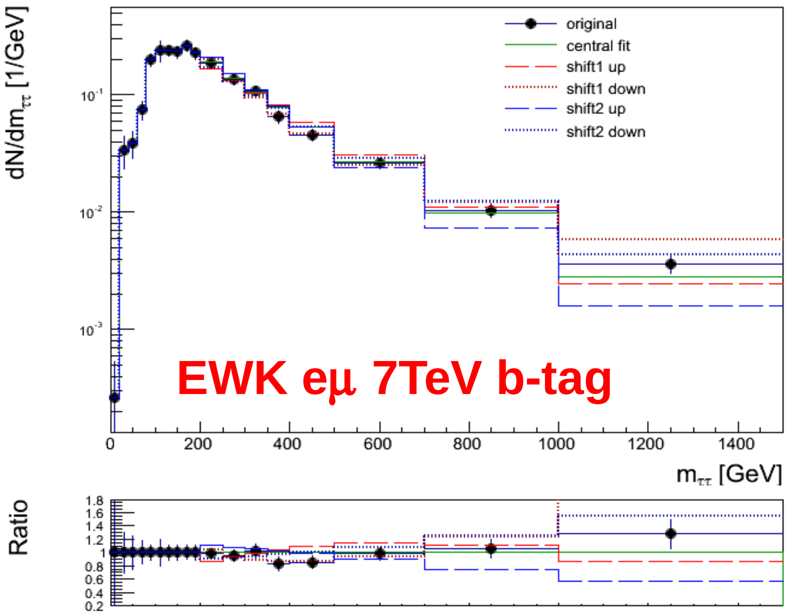
Tail-fitting

- For the high mass tails (typically $M_{\tau\tau} > 150$ GeV) of several backgrounds an analytic fit is performed

$$f=\exp[-m_{\tau\tau}/(c_0+c_1 m_{\tau\tau})]$$

- Used to estimate background in bins where MC-statistic is limited
- Uncertainties on the shape of the fit function are accounted by adding two shape nuisance parameters (corresponding to the two free parameters in the fit)
- Corrects for possible systematic miss modeling of the high mass tails

	no-btag	btag
e-mu (7TeV)	EWK,ttbar,Fakes	EWK,ttbar
e-mu (8TeV)	EWK,ttbar,Fakes	EWK,ttbar
e-tau (7TeV)	QCD,W	-
e-tau (8TeV)	QCD,TT,W	QCD,TT,W
mu-tau (7TeV)	QCD,W	QCD
mu-tau (8TeV)	QCD,TT,W	TT,W
tau-tau (8TeV)	QCD	QCD



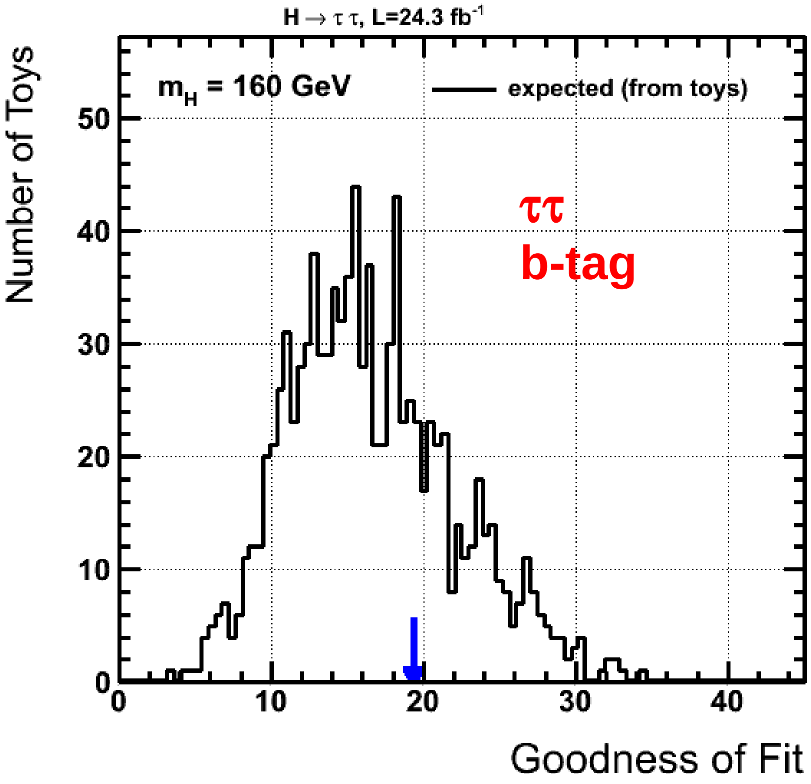
EWK eμ 7TeV b-tag

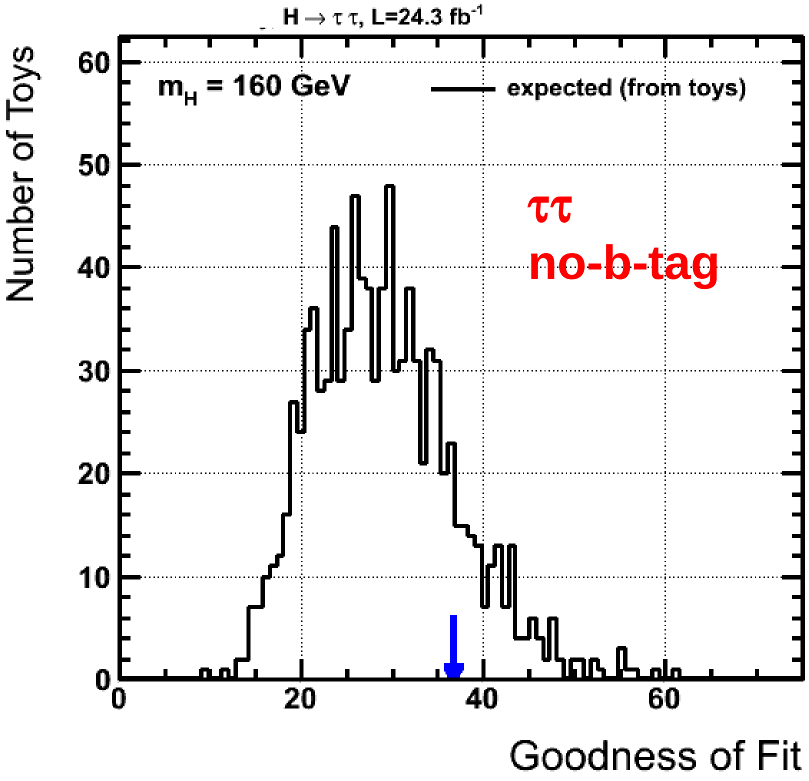
Goodness of Fit

No changes with respect to PAS **HIG-13-021**

Goodness-of-fit test

- The Goodness-of-fit test checks how well our statistical model describes the observation (blue arrow)
  - In a simple assumption it could be compared to a χ^2 test





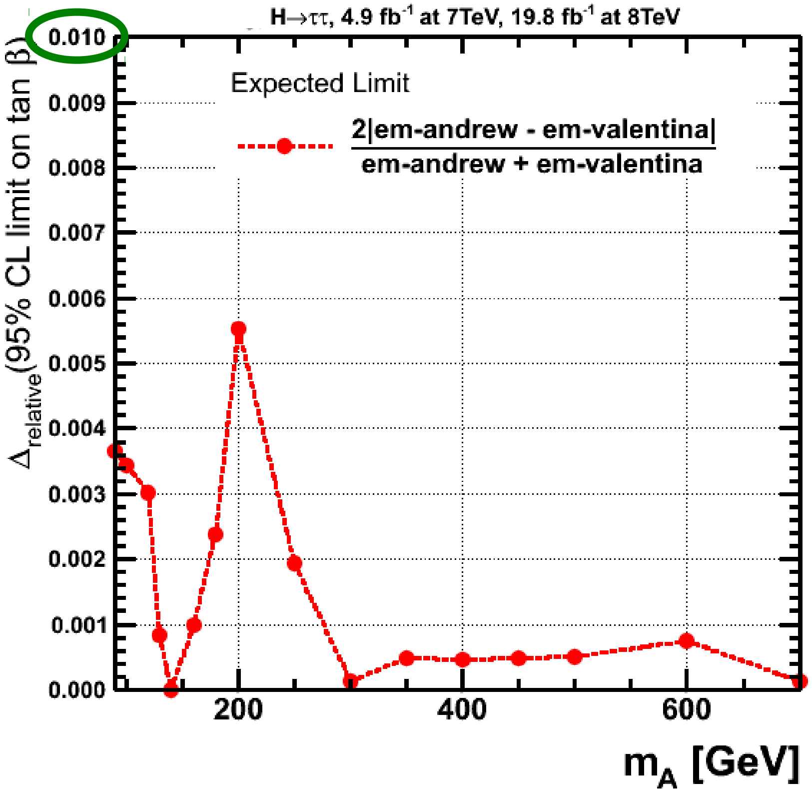
Synchronization

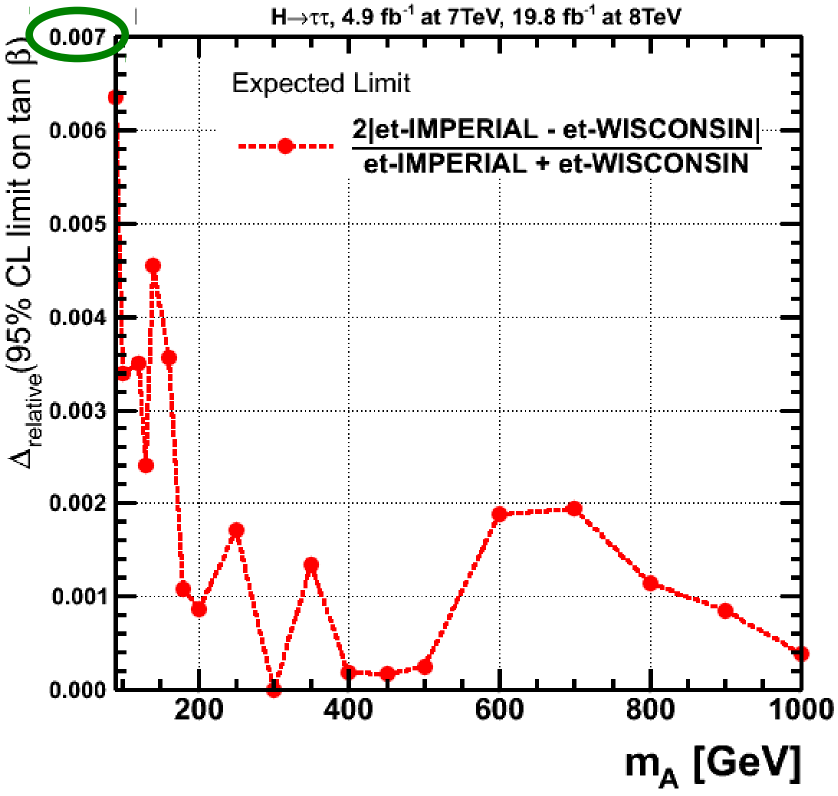
No changes with respect to PAS **HIG-13-021**

Synchronization

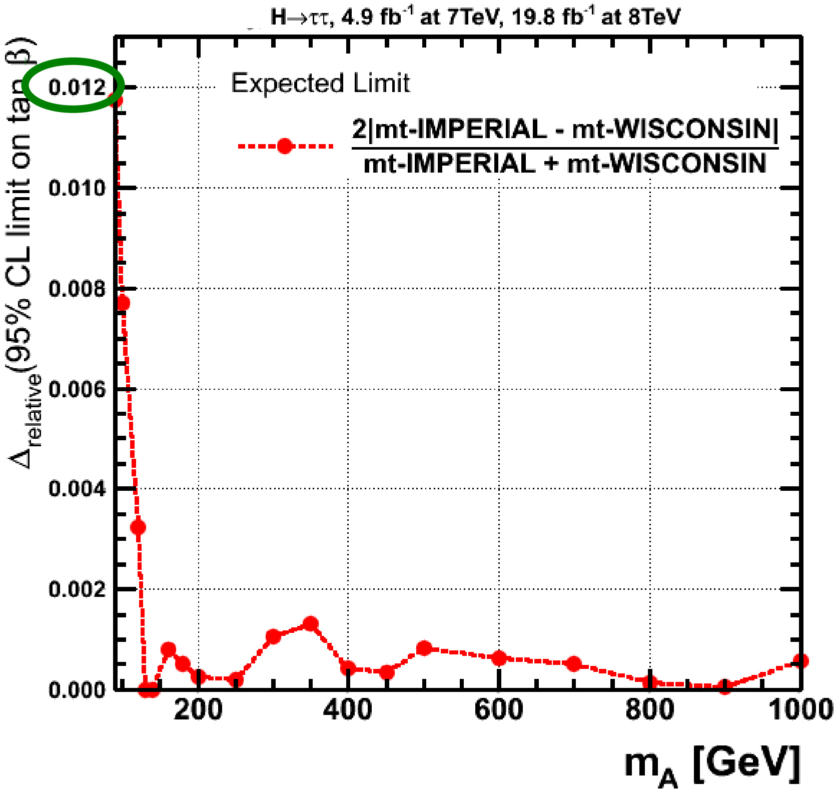
- Idea is to have at least two independent groups looking at each channel
  - Both groups do the complete analyses till delivering datacards
  - Used as independent cross checks
  - Used to debug

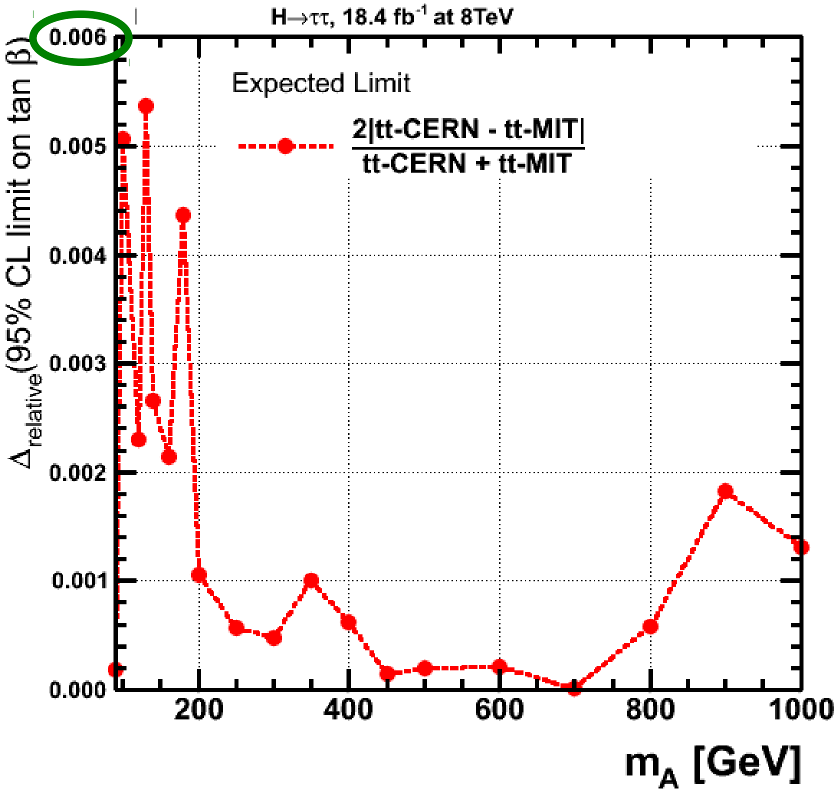
Synchronization of the expected Limit in the m_A-tanβ plane



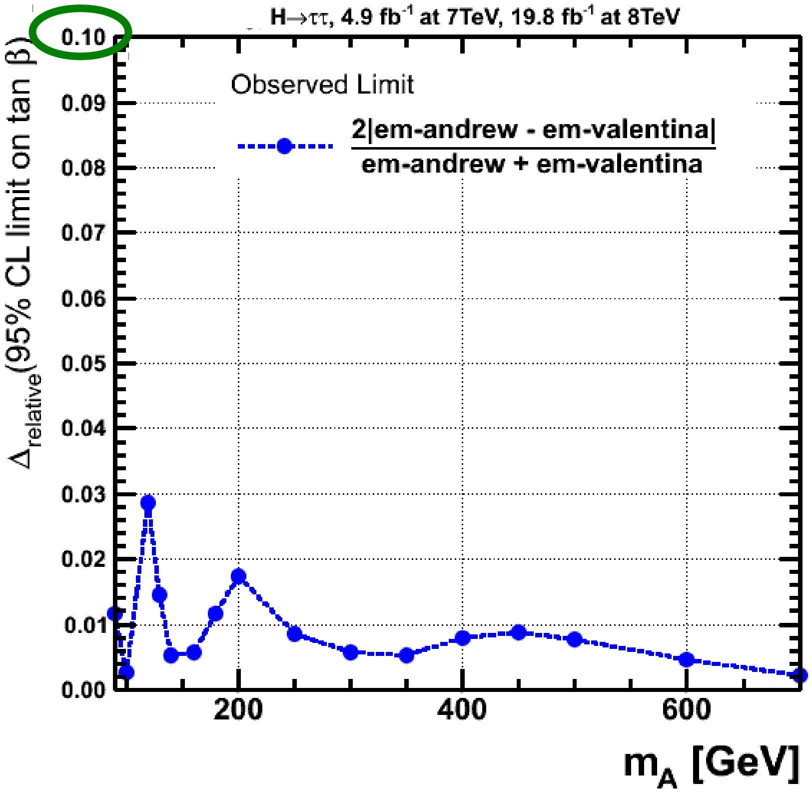


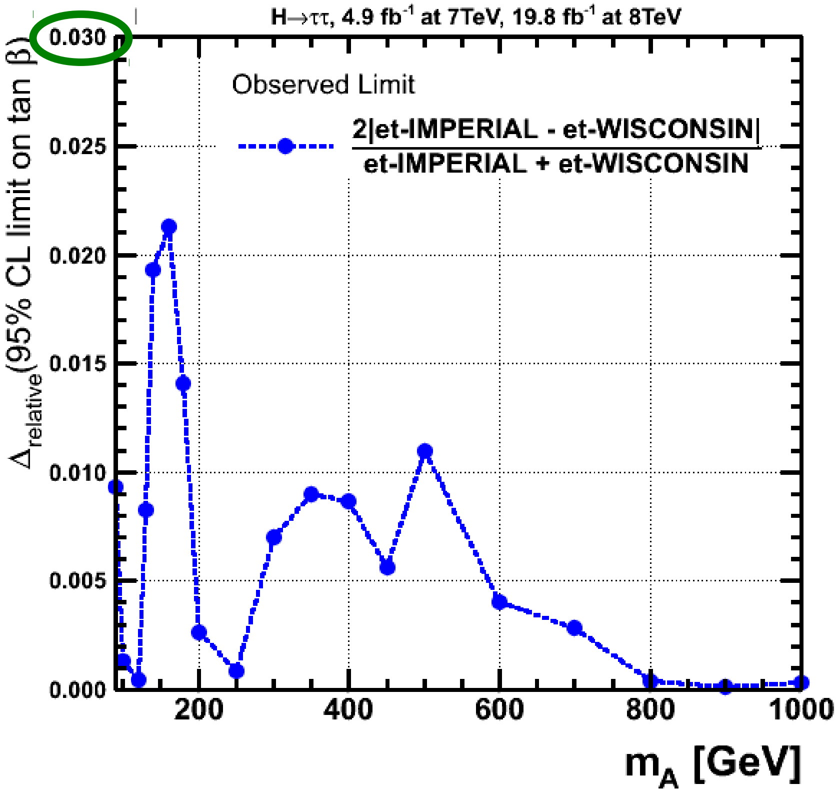
Synchronization of the expected Limit in the m_A-tanβ plane



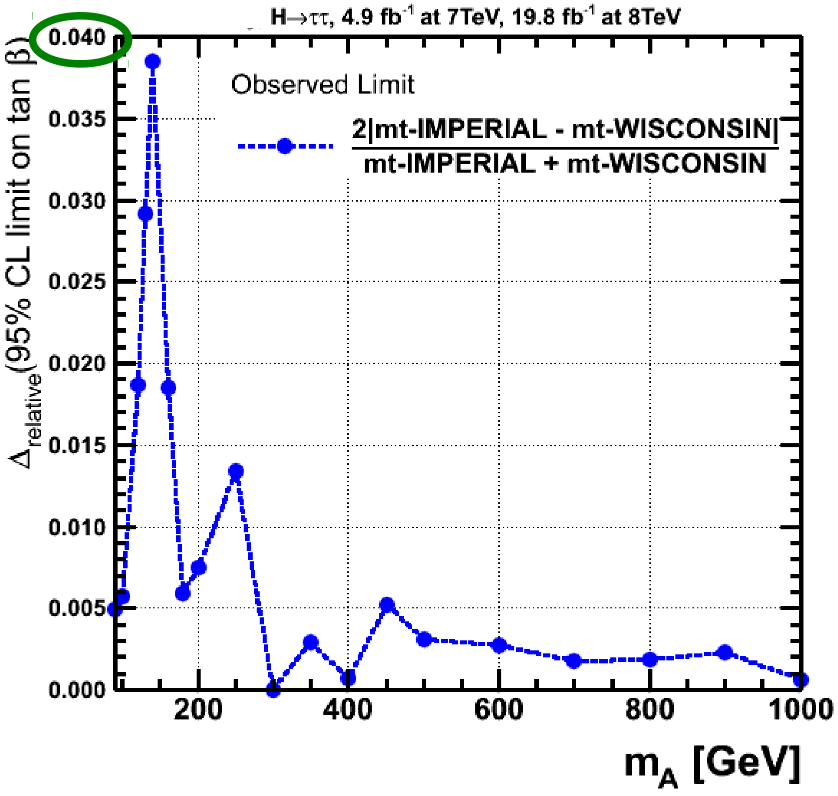


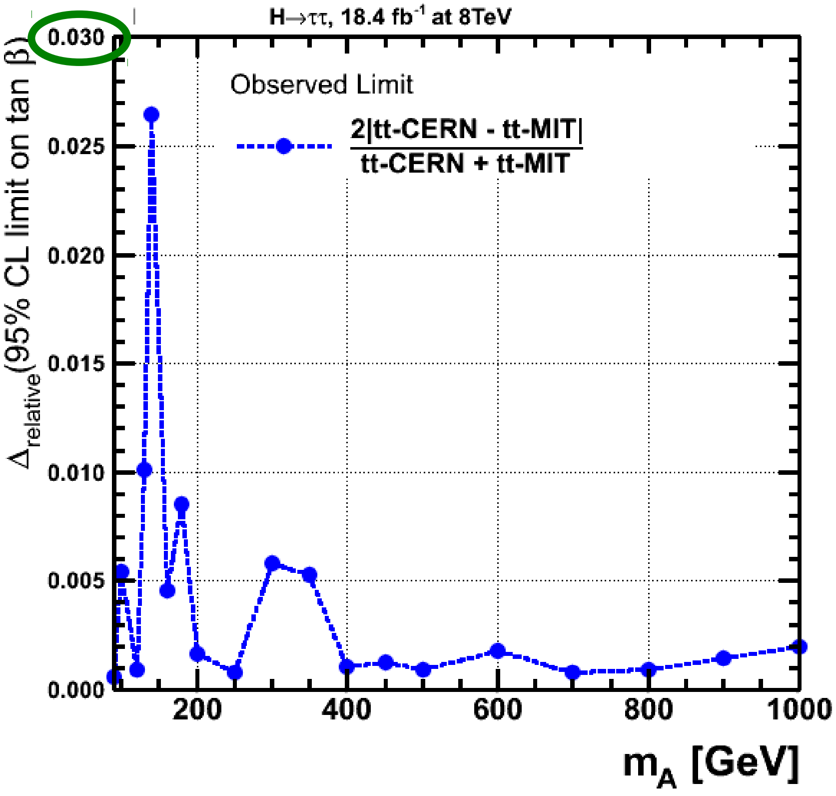
Synchronization of the observed Limit in the m_A-tanβ plane





Synchronization of the observed Limit in the m_A-tanβ plane



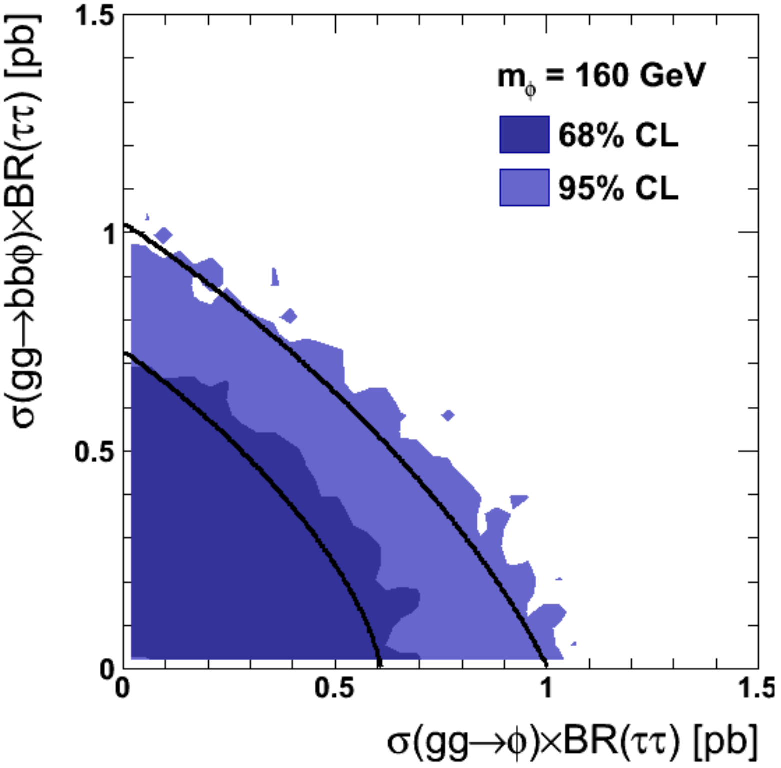


Results

2D crosscheck with Feldman-Cousins

- Black lines are taken from 68% and 95% contours of the likelihood scan
- Dark and light blue is 68% and 95% contours of Feldman-Cousins
- Same grid has been used (200*200 points)
    - For each gridpoint FC toys have to be thrown
- Took >20h to run FC with low number of toys (O(50))

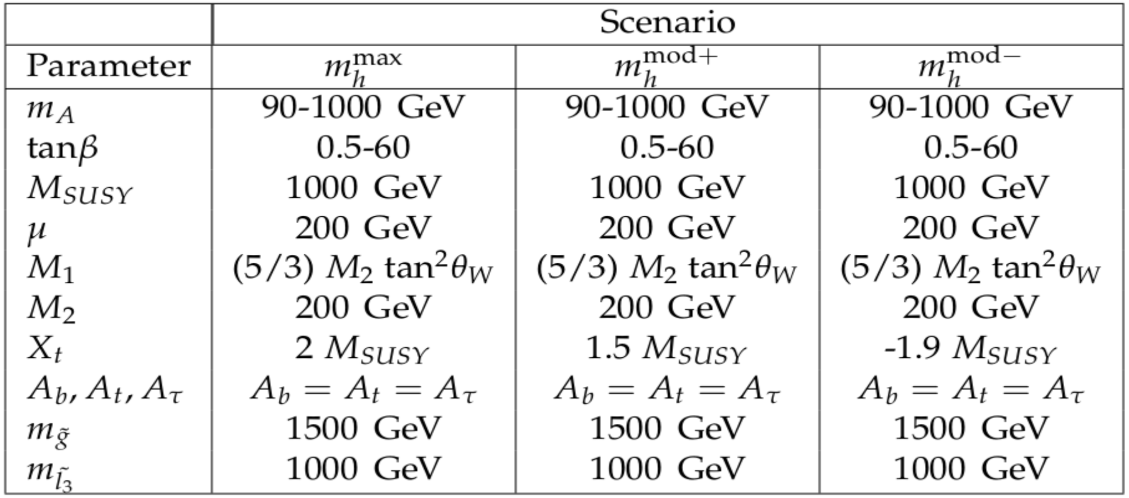
- Agreement with likelihood scan is good



MSSM benchmark scenarios

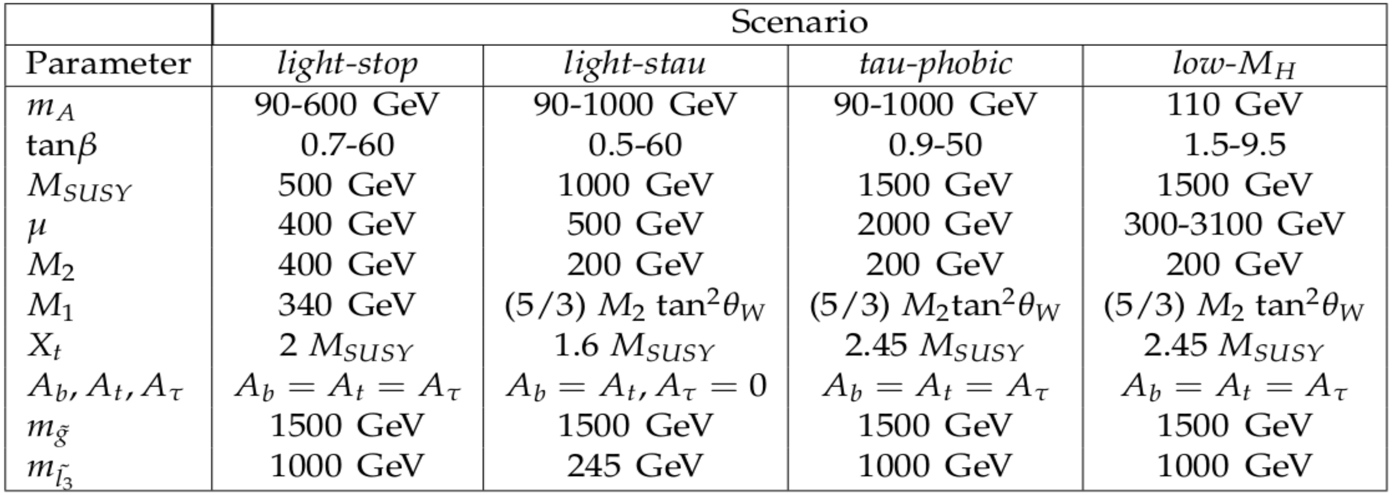
- Following a paper by M. Carena et al.: “MSSM Higgs boson searches at the LHC: benchmark scenarios after the discovery of a Higgs-like particle” - arXiv:1302.7033
- Seven (CP conserveing) scenarios are proposed which incorporate can incorporate a Higgs at 125 GeV while maintaining consistency with experimental results
  - **m_h^{mod+}** and **m_h^{mod-}**: allowed paramter space is maximized
    - **m_h^{mod+}**: better agreement with $(g\text{-}2)_\mu$ measurement
    - **m_h^{mod-}**-: better agreement with BR(b → sγ) measurement
  - **light-stau**: enhances the h ➔ γγ rate due to suppression of h ➔ bb/ττ rate
    - Motivated by excess in ATLAS measurement
  - **light-stop**: suppression of the ggΦ rate due to the presence of light stop
  - **tauphobic**: light scalar Higgs boson with suppressed couplings to down-type fermions
  - **low-m_H**: heavy Higgs boson at 125GeV. Light scalar below LEP due to reduced couplings to vector bosons.

MSSM benchmark scenarios



	Scenario		
Parameter	m_h^{max}	$m_h^{\text{mod}+}$	$m_h^{\text{mod}-}$
m_A	90-1000 GeV	90-1000 GeV	90-1000 GeV
$\tan\beta$	0.5-60	0.5-60	0.5-60
M_{SUSY}	1000 GeV	1000 GeV	1000 GeV
μ	200 GeV	200 GeV	200 GeV
M_1	$(5/3)\ M_2 \tan^2\theta_W$	$(5/3)\ M_2 \tan^2\theta_W$	$(5/3)\ M_2 \tan^2\theta_W$
M_2	200 GeV	200 GeV	200 GeV
X_t	$2\ M_{SUSY}$	$1.5\ M_{SUSY}$	$-1.9\ M_{SUSY}$
A_b, A_t, A_τ	$A_b = A_t = A_\tau$	$A_b = A_t = A_\tau$	$A_b = A_t = A_\tau$
$m_{\tilde{g}}$	1500 GeV	1500 GeV	1500 GeV
$m_{\tilde{l}_3}$	1000 GeV	1000 GeV	1000 GeV

*light-stop and m_h^{max} differ slightly from those proposed in original paper on previous slide



	Scenario			
Parameter	*light-stop*	*light-stau*	*tau-phobic*	*low-M_H*
m_A	90-600 GeV	90-1000 GeV	90-1000 GeV	110 GeV
$\tan\beta$	0.7-60	0.5-60	0.9-50	1.5-9.5
M_{SUSY}	500 GeV	1000 GeV	1500 GeV	1500 GeV
μ	400 GeV	500 GeV	2000 GeV	300-3100 GeV
M_2	400 GeV	200 GeV	200 GeV	200 GeV
M_1	340 GeV	$(5/3)\ M_2 \tan^2\theta_W$	$(5/3)\ M_2\tan^2\theta_W$	$(5/3)\ M_2 \tan^2\theta_W$
X_t	$2\ M_{SUSY}$	$1.6\ M_{SUSY}$	$2.45\ M_{SUSY}$	$2.45\ M_{SUSY}$
A_b, A_t, A_τ	$A_b = A_t = A_\tau$	$A_b = A_t, A_\tau = 0$	$A_b = A_t = A_\tau$	$A_b = A_t = A_\tau$
$m_{\tilde{g}}$	1500 GeV	1500 GeV	1500 GeV	1500 GeV
$m_{\tilde{l}_3}$	1000 GeV	245 GeV	1000 GeV	1000 GeV

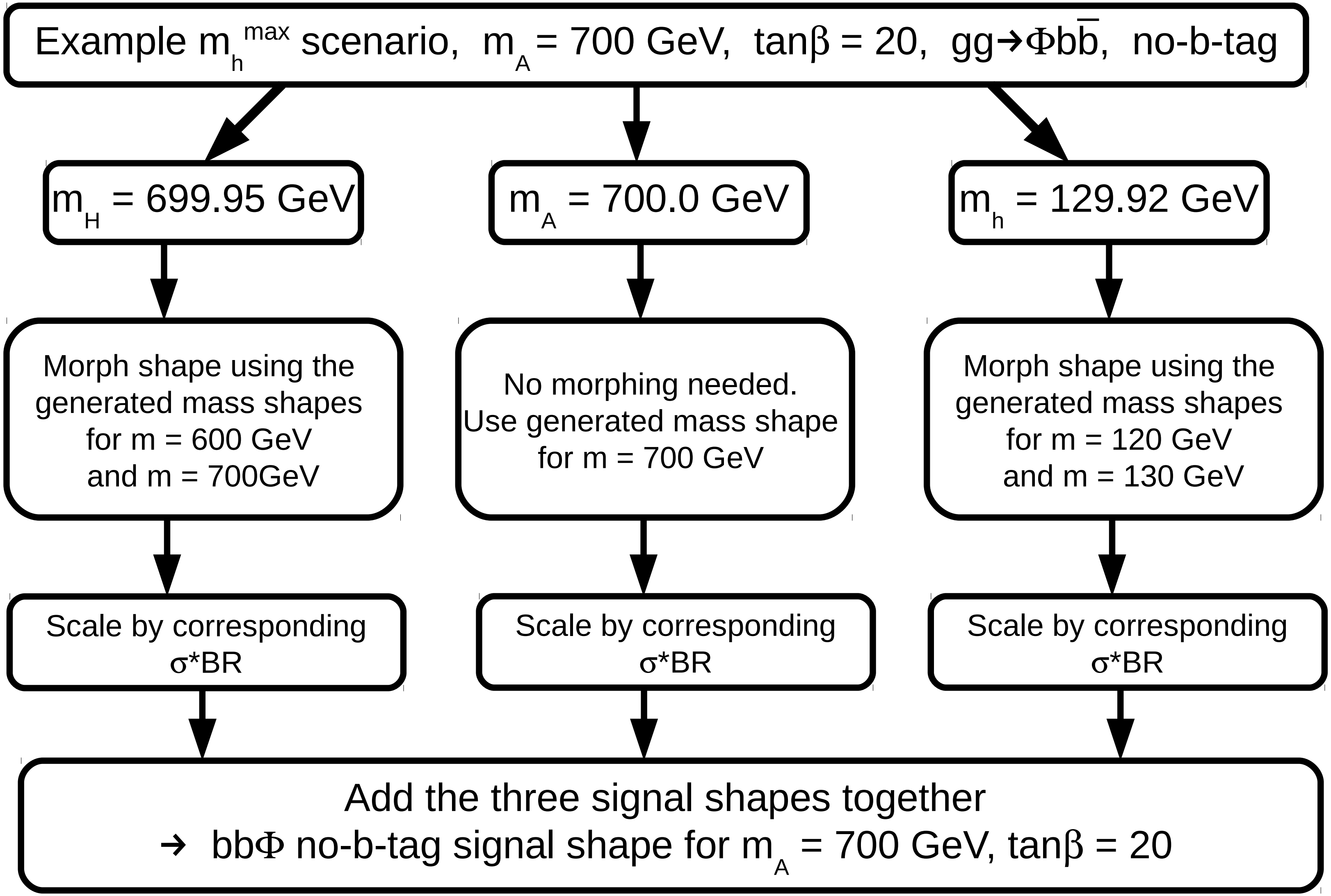
m_A-tanβ Limits – technical

- Chose a certain MSSM Higgs Sector model (here mhmax)
  - σ, BR and mass for each (neutral) Higgs-Boson is then defined

- At each m_A/tanβ point the signal constitutes of the contribution of the three neutral Higgs-Bosons

- The final shape template for a certain m_A/tanβ point is obtained by summing the individual templates up over all Higgs-Bosons weighting them by σ*BR/tanβ
  - The deviation by tanβ has purely technical reason to obtain limits on tanβ
  - Individual templates are obtained by using horizontal template morphing
  - MC signal samples range from 90 to 1000 GeV

From model independent to model dependent



Example m_h^{max} scenario, m_A = 700 GeV, $\tan\beta$ = 20, $gg\rightarrow\Phi b\bar{b}$, no-b-tag

m_H = 699.95 GeV

m_A = 700.0 GeV

m_h = 129.92 GeV

Morph shape using the generated mass shapes for m = 600 GeV and m = 700GeV

No morphing needed. Use generated mass shape for m = 700 GeV

Morph shape using the generated mass shapes for m = 120 GeV and m = 130 GeV

Scale by corresponding σ*BR

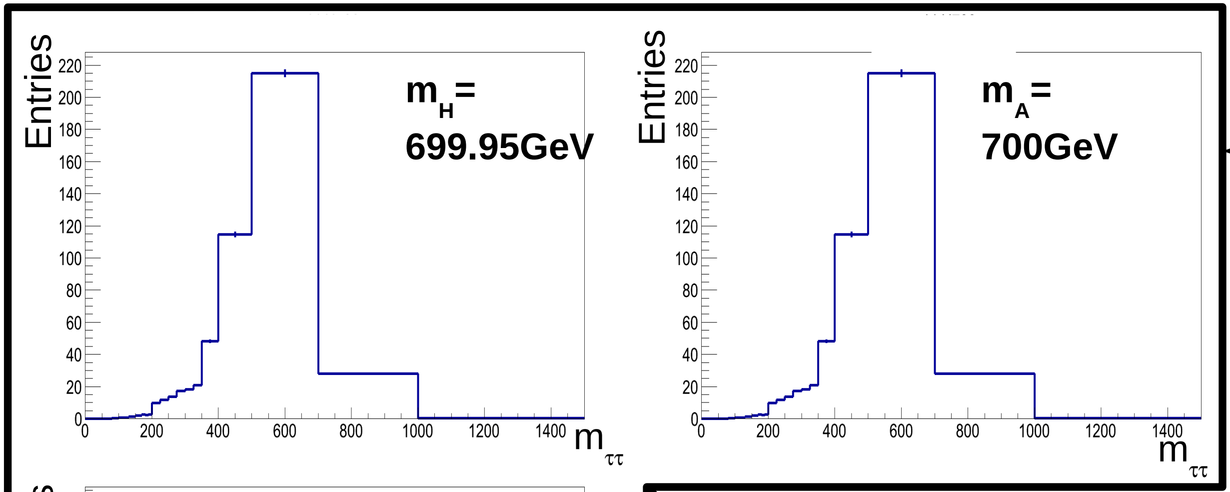
Scale by corresponding σ*BR

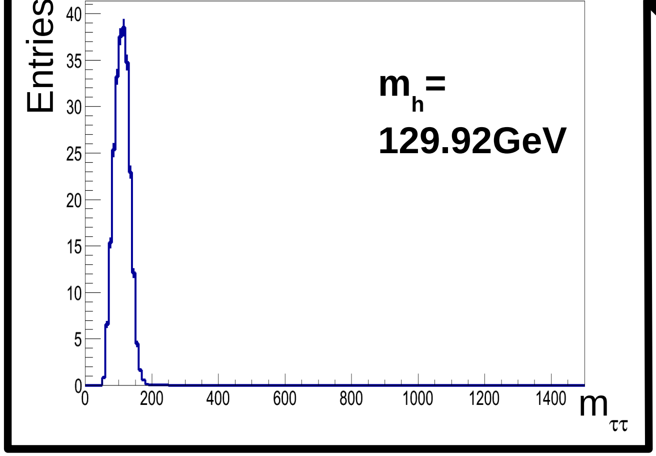
Scale by corresponding σ*BR

Add the three signal shapes together

→ $bb\Phi$ no-b-tag signal shape for m_A = 700 GeV, $\tan\beta$ = 20

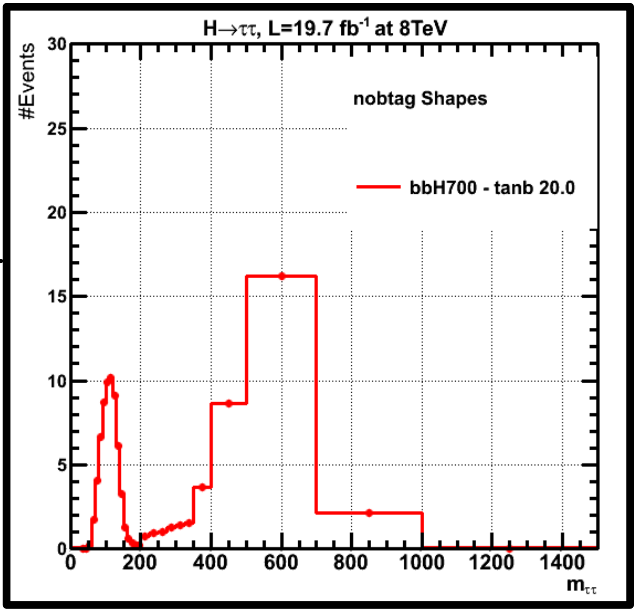
From model independent to model dependent





Shapes of A, H and h constructed using horizontal interpolation of generated masses

Scale each shape by corresponding σ*BR



Example: m_h^{max} scenario, m_A=700GeV, tanβ=20, bbΦ, no-b-tag, $\mu\tau$

MSSMvsBG

- In the past a MSSM signal in addition to non Higgs SM background was tested against the non Higgs SM background
  - Presence of a SM like Higgs boson at 125 GeV was not taken into account

$$q_{MSSMvsBG} = -2\ln\frac{L\left[data|\mu\cdot s+BG\right]}{L\left[data|\hat{\mu}\cdot s+\hat{BG}\right]}$$

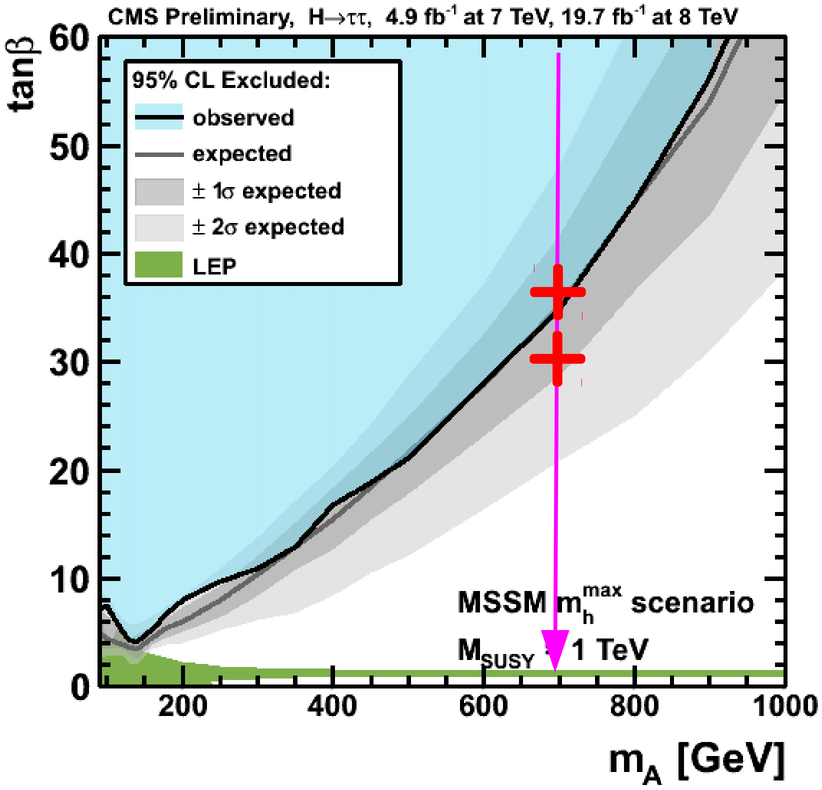
The quantity "$q_{MSSMvsBG}$" is called Profile Likelihood

  - s = h+H+A (fully determined MSSM parameter space point)
  - BG = Standard Model backgrounds, but not the SM Higgs boson.
    - Examples: ZTT, ttbar, VV, QCD, ZLL, W
  - The denominator is maximized for all μ>0
  - The nominator is maximized for a specific μ (we only test μ=1)

- Used statistical methods:
  - Asymptotic CL_s (Profile likelihood as test-statistic)

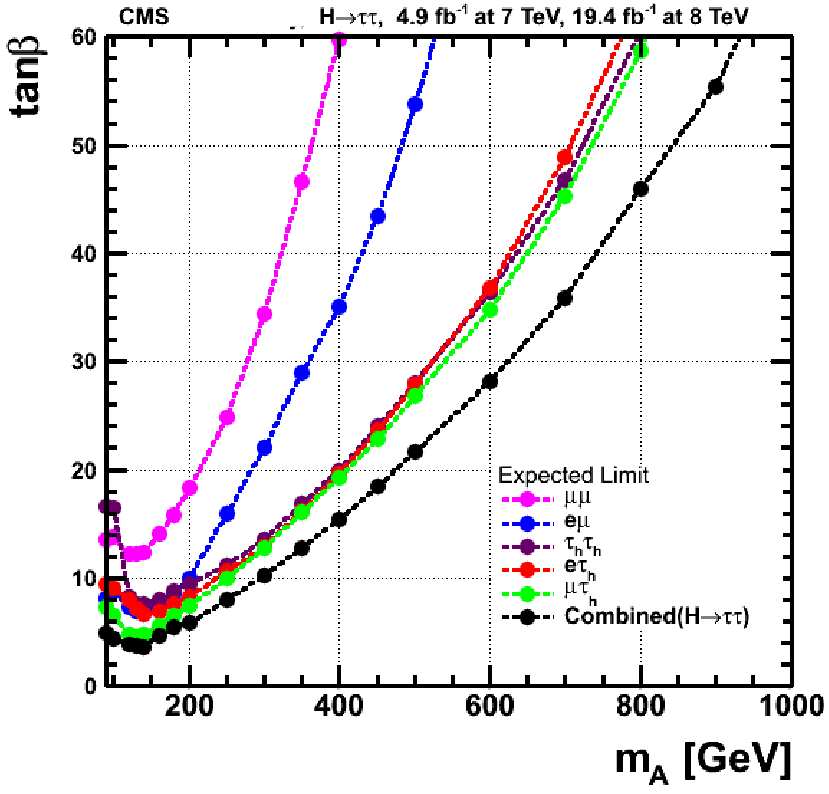
Calculating the limit

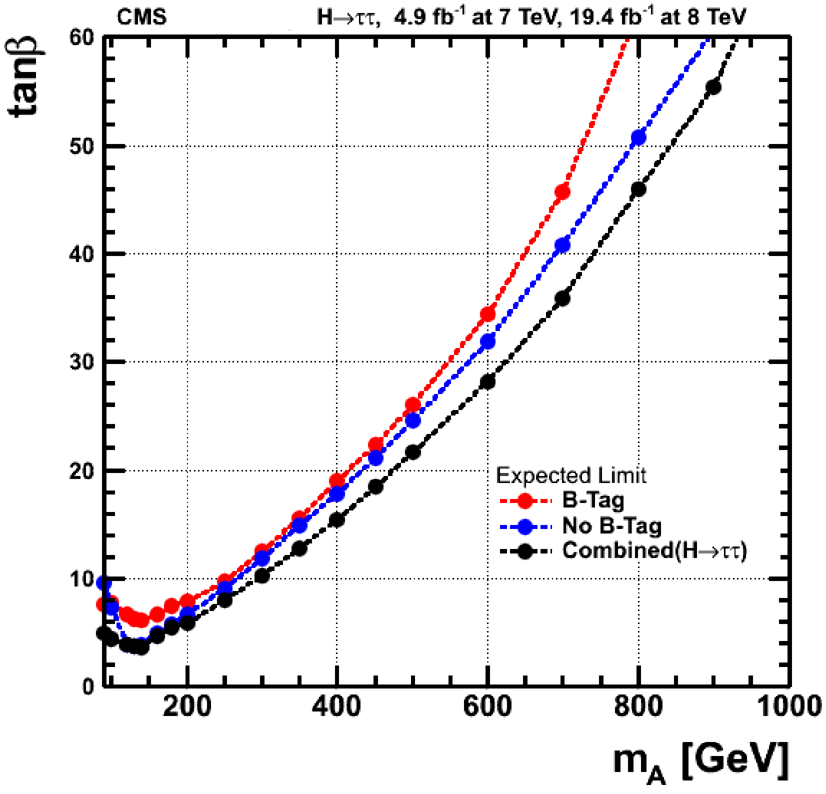
- Calculate at each (m_A/tanβ) point the asymptotic CL_s; scanning for each m_A from high tanβ to low tanβ
  (illustrated for m_A=700GeV)
  - $CL_s > 0.05$ → not excluded
  - $CL_s < 0.05$ → excluded
  - Separately for -2σ, -1σ, exp, +1σ, +2σ, obs exclusion curves
- Use interpolation for points inbetween
  (illustrated for tanβ = 30 to 35; observed limit)



Limits in tanβ-m_A plane

comparison of expected Limits

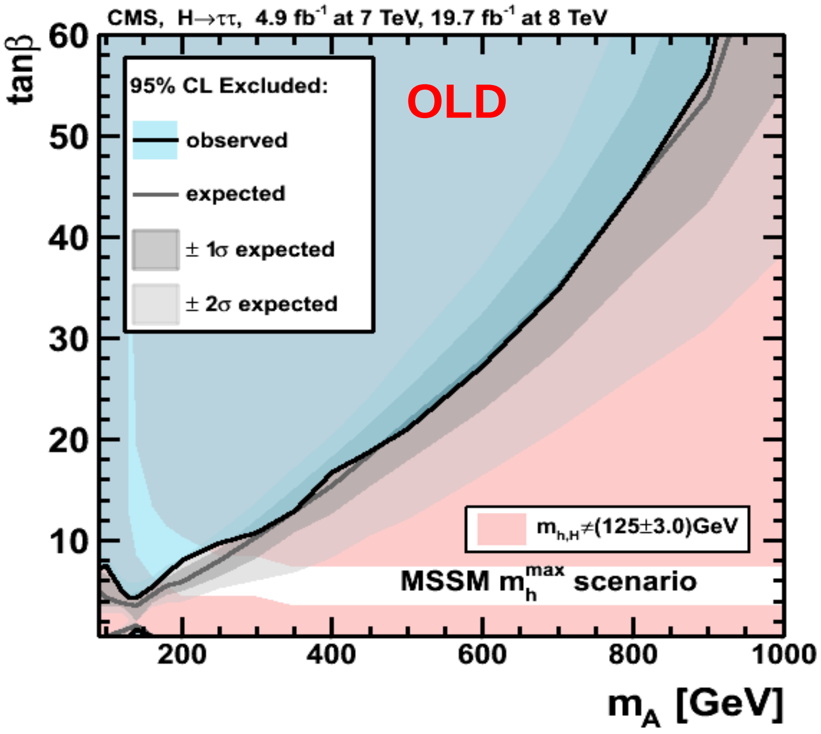


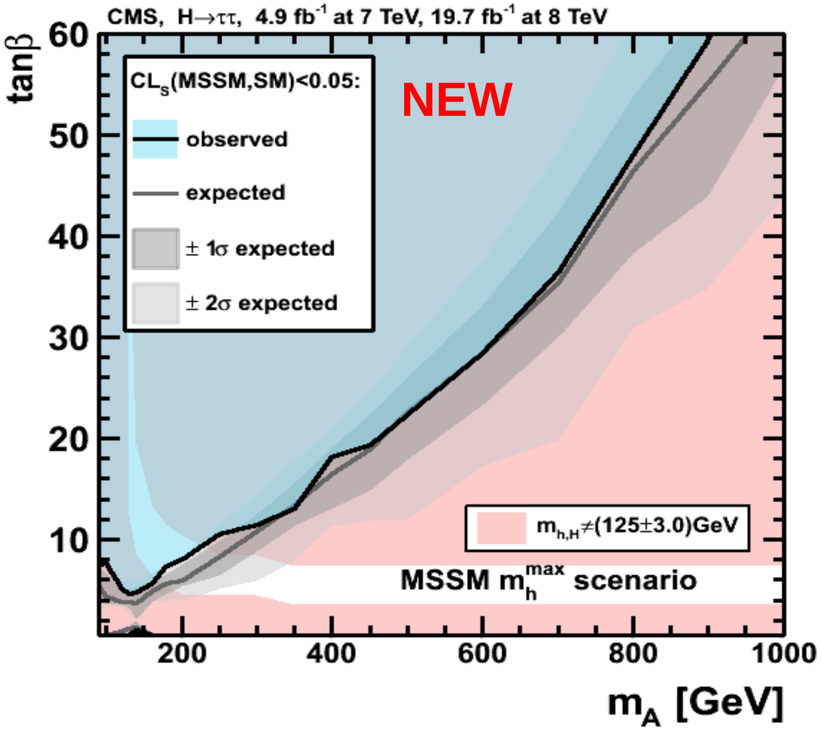


MSSM m_h^{max} scenario

Cross check with same hypotheses

- Tested is the agreement between the old and the new statistical approach using the same alternative (h+A+H + BG) and the same null hypothesis (BG)





Good agreement - already with low number O(5000) of toys for full CL_s!

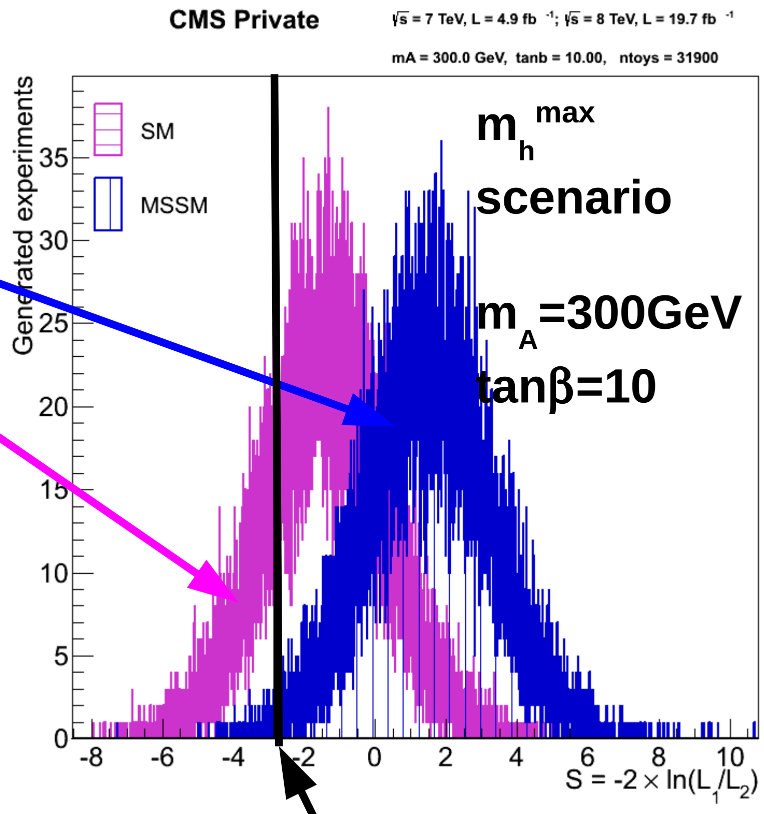
(More toys are used for the published plots)

Construction of the CL_s-like limit

- Throw O(60000) toys to build the probability density functions:

$$F\left(q_{MSSMvsSM} \mid h + H + A + BG\right)$$

$$F\left(q_{MSSMvsSM} \mid h_{SM} + BG\right)$$



Observed value of $q_{MSSMvsSM}$

- Build CL_s at each m_A-tanβ point

Example: Observed Limit:

  - Calculate

$$A = \int_{-\infty}^{q^{obs}_{MSSMvsSM}} (SM)$$

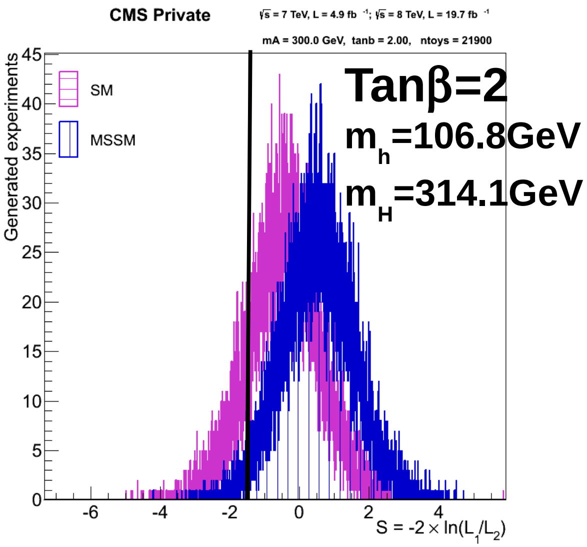
$$B = \int_{-\infty}^{q^{obs}_{MSSMvsSM}} (MSSM)$$

  - Discriminator

$$CL_s = \frac{B}{A}$$

  - $CL_s < 0.05$ → excluded at 95% CL

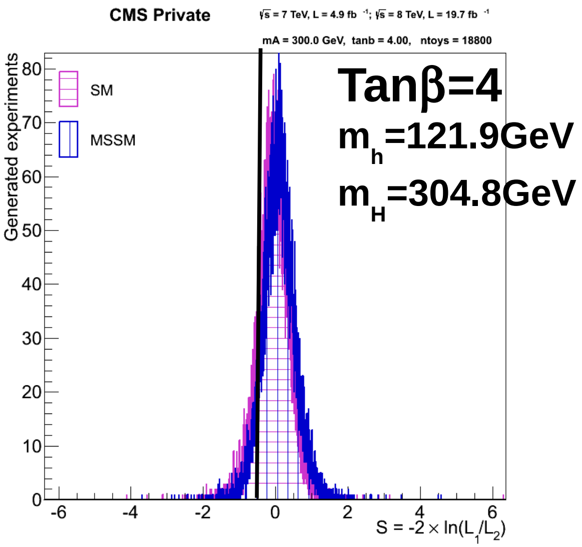
Example: m_A = 300 GeV , m_h^{max} scenario



Tanβ=2

m_h=106.8GeV

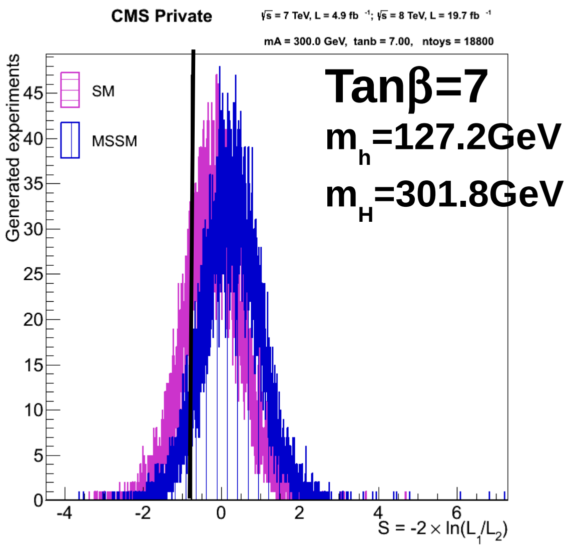
m_H=314.1GeV



Tanβ=4

m_h=121.9GeV

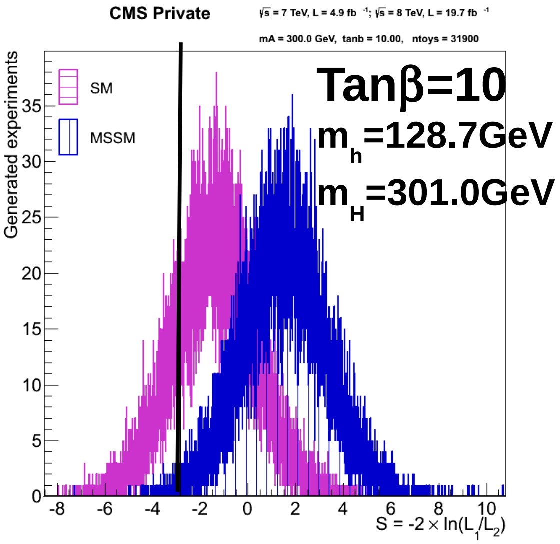
m_H=304.8GeV



Tanβ=7

m_h=127.2GeV

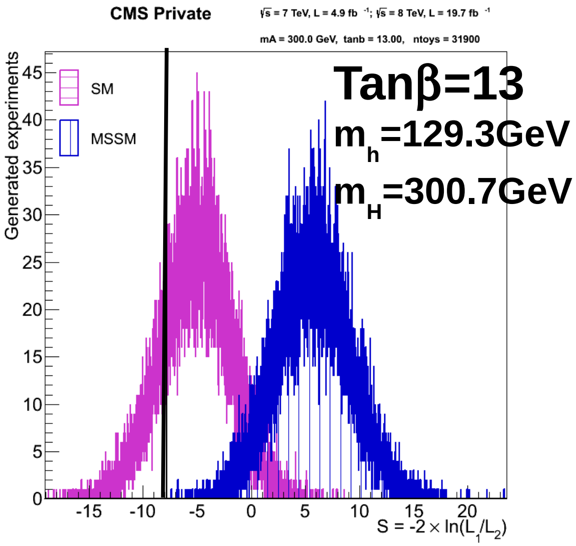
m_H=301.8GeV



Tanβ=10

m_h=128.7GeV

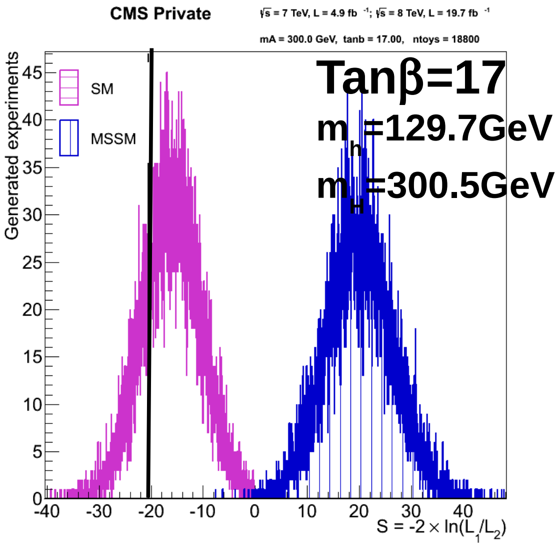
m_H=301.0GeV



Tanβ=13

m_h=129.3GeV

m_H=300.7GeV



Tanβ=17

m_h=129.7GeV

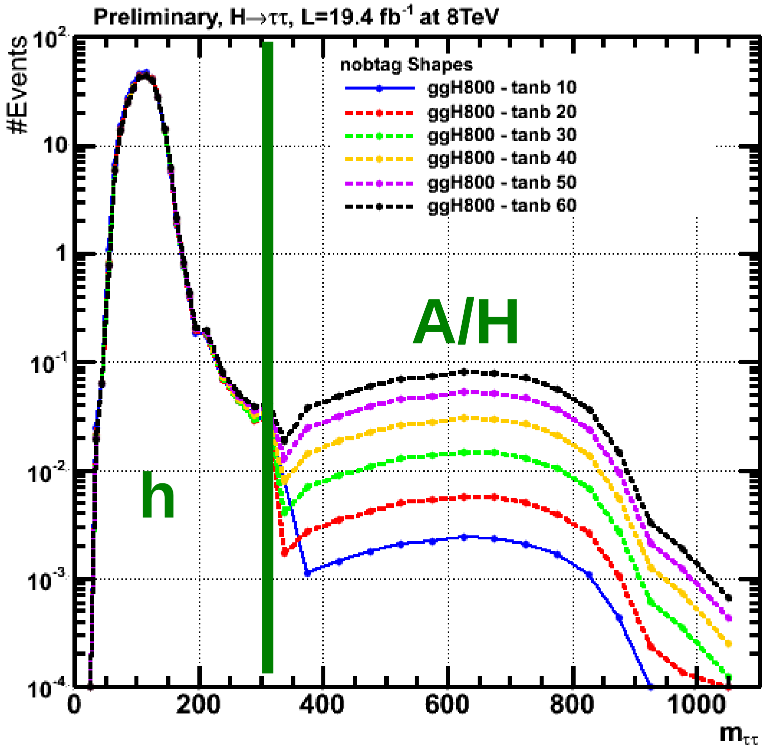
m_H=300.5GeV

Why MSSMvsSM?

- In any case BG only is the wrong null hypothesis, since there is a Higgs boson at 125 GeV (>3σ in H ➔ $\tau\tau$ alone).
- Question here: is it the SM or a MSSM Higgs boson (→ test of different hypotheses)?
  - E.g. single Higgs boson (like in SM) versus three Higgs bosons (like in MSSM).
- Using the old approach, MSSMvsBG, the presence of a single Higgs boson at 125 GeV can favor the MSSM hypothesis over the BG only hypothesis for a large parameter space.
  - Results cannot be interpreted any more.

- This is explicitly shown in an extreme example on slide 123.
  - Used pseudo-dataset with h_{SM}+BG.
  - Scaled 8TeV lumi to 500fb^{-1} to make effect plain clear.

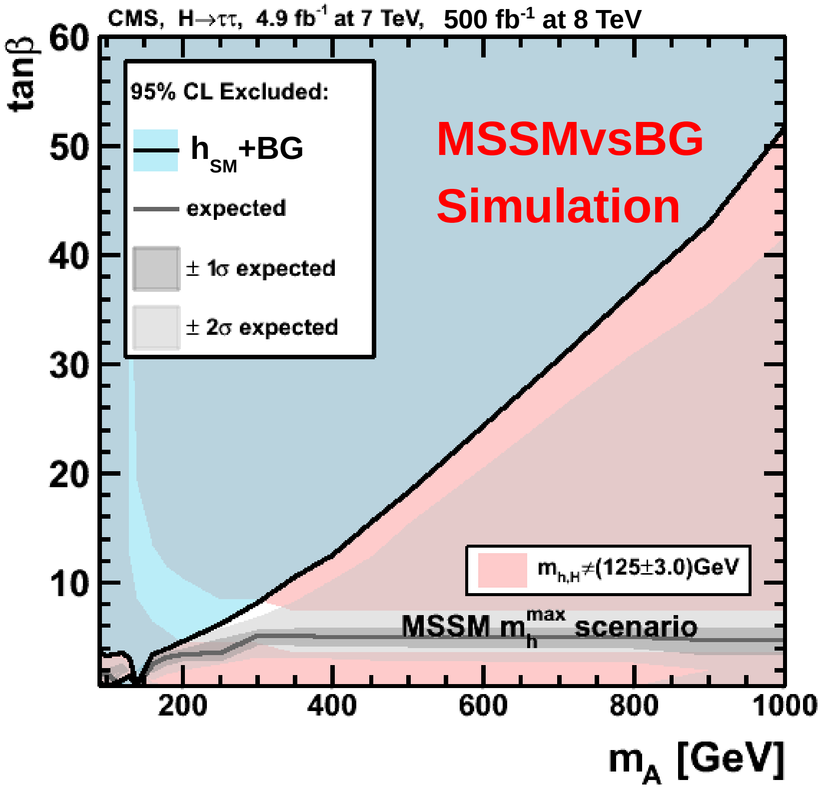
Signal templates (m_A=800GeV) for different tanβ

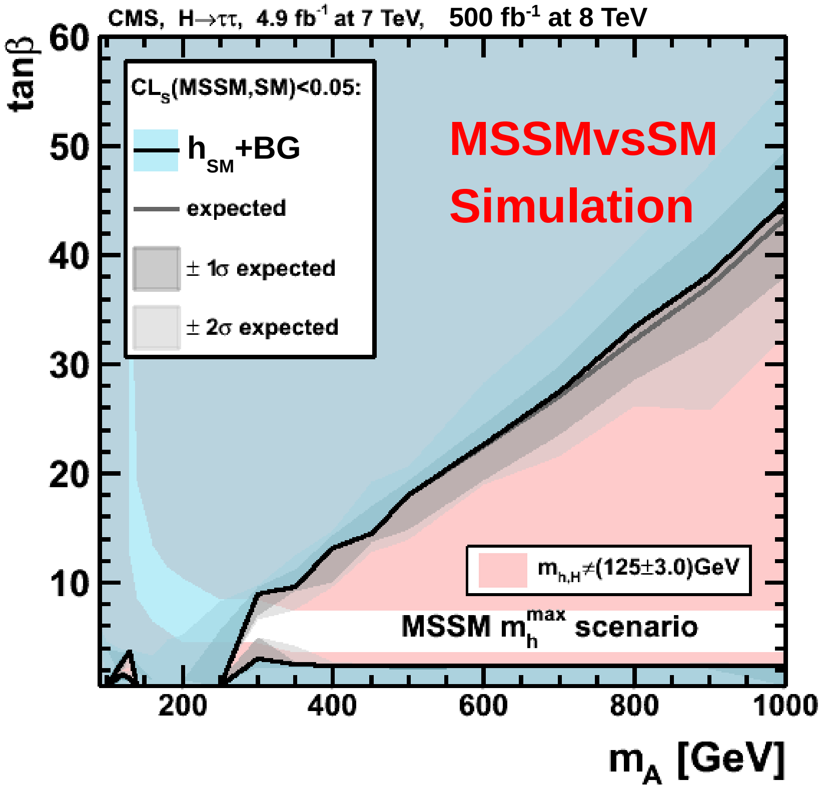


- μτ no-b-tag 8 TeV
- Shown is the ggH yield as a combination of all the neutral MSSM Higgs Bosons **Φ=h+A+H**
- Events in $m_{\tau\tau}$ < 300 GeV mainly originate from h
- Events in $m_{\tau\tau}$ > 300 GeV mainly originate from A and H
- Masses:
  - H and A ~ 800 GeV
  - h ~ 130 GeV

- At high m_A and low tanβ the gg➔h contributes the most to the exclusion.
  - For small A/H peaks the shape looks similar to a 125 GeV Higgs boson one
- If sensitivity for the h is reached, the BG only expected limit will exclude the MSSM plane down to low tanβ, since h is independent from tanβ.

MSSMvsSM and MSSMvsBG scaled to 500fb^{-1}

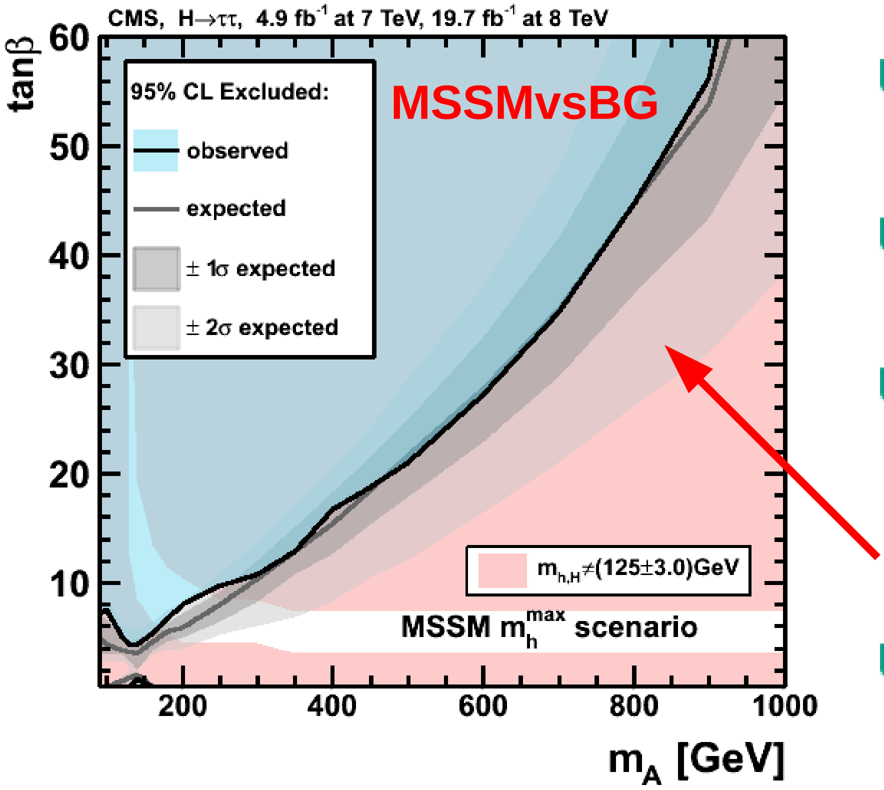




The expected limit is BG only. For low tanβ and high m_A it's driven by the little h which σ*BR is pretty constant.
A and H have negligible σ in this regions.

The expected limit includes additional to the BG a SM Higgs boson at 125 GeV.

Is this only a future issue (with more lumi)?



- Answer is clearly **NO!**
- In high m_A the -2σ already reaches sensitivity to the h peak.
- Here σ*BR(A+H) << σ*BR(h) therefore h_{SM} can fake MSSM since A+H peak is negligible small.
- Effect visible as a broad -2 sigma band.

Why MSSMvsSM: Conclusion

- For high m_A and medium to low tanβ the little Higgs h of the gluon-gluon fusion process dominates the contribution to the exclusion limit.
- In this region the A/H peak is small.
- So for testing BG against MSSM+BG a SM Higgs signal will be assigned to the MSSM+BG hypothesis rather than to the BG only hypothesis and therefore we see a “fake” discovery.
  - We are testing two (possible) false hypothesis against each other. (MSSM not yet discovered, and BG only no longer true)
- In contrast: For testing SM+BG against MSSM+BG a SM Higgs signal will NOT be assigned to the MSSM+BG hypothesis but to the SM+BG hypothesis

Why is the MSSMvsBG in some regions more sensitive than the MSSMvsSM and vice versa?

- Quantity CL_s for expected limit (simplified):
  - $CL_s(\text{MSSMvsBG}) = L(\text{ asimov}_{BG} \mid h+A+H + BG\ ) \quad / L(\text{ asimov}_{BG} \mid BG\ )$
    $\approx L(\text{ asimov}_{BG} \mid h+A+H + BG\ )$
  - $CL_s(\text{MSSMvsSM}) = L(\text{ asimov}_{BG+hSM} \mid h+A+H + BG\ ) / L(\text{ asimov}_{BG+hSM} \mid h_{SM} + BG\ )$
    $\approx L(\text{ asimov}_{BG+hSM} \mid h+A+H + BG\ )$

Why is the MSSMvsBG in some regions more sensitive than the MSSMvsSM and vice versa?

- m_A = 90 GeV / $\tan\beta$ = 1:
  - m_h = 74.3 GeV, m_H = 178.3 GeV

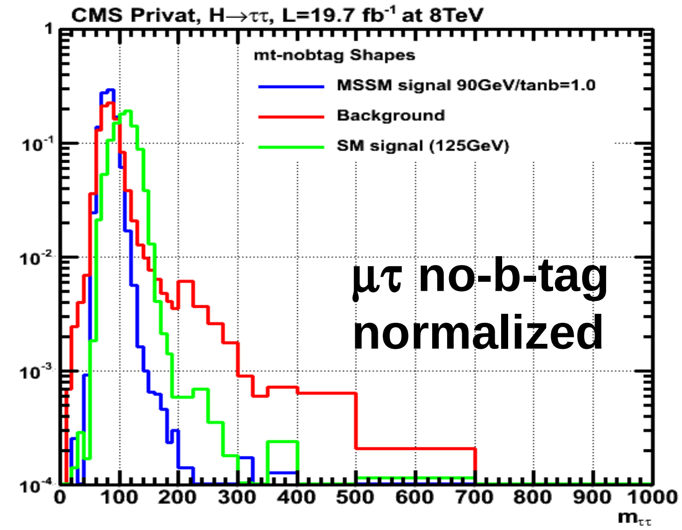
- h_{SM} and h+A+H shape look different:

L(asimov_{BG} | h+A+H + BG) > L(asimov_{BG+hSM} | h+A+H + BG)

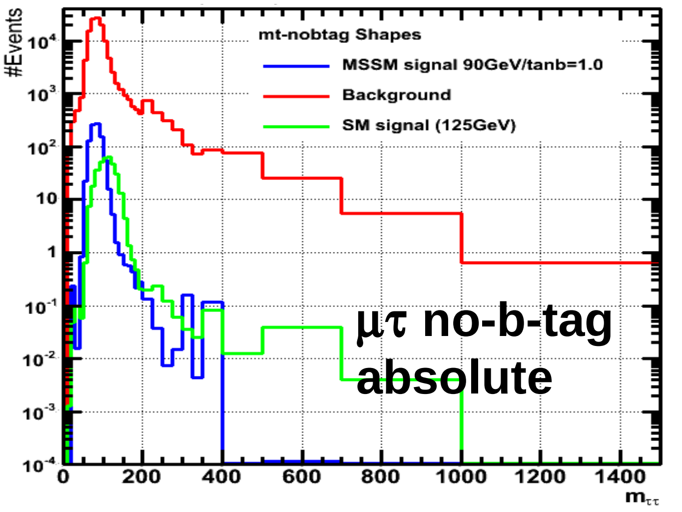
CL_s(MSSMvsBG) > CL_s(MSSMvsSM)

➜ **MSSMvsSM has lower CL_s therefore is more sensitive!**

This is true for regions with
Shape of h, A or H ≠ shape of h_{SM}



μτ no-b-tag normalized



μτ no-b-tag absolute

Why is the MSSMvsBG in some regions more sensitive than the MSSMvsSM and vice versa?

- $m_A = 140$ GeV / $\tan\beta = 1$:
  - $m_h = 85.2$ GeV, $m_H = 203.8$ GeV

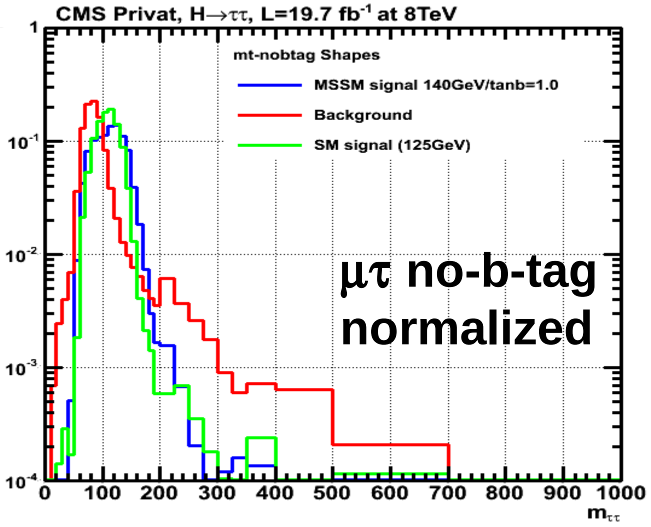
- h_{SM} and h+A+H shape look similar:

L(asimov_{BG} | h+A+H + BG) < L(asimov_{BG+hSM} | h+A+H + BG)

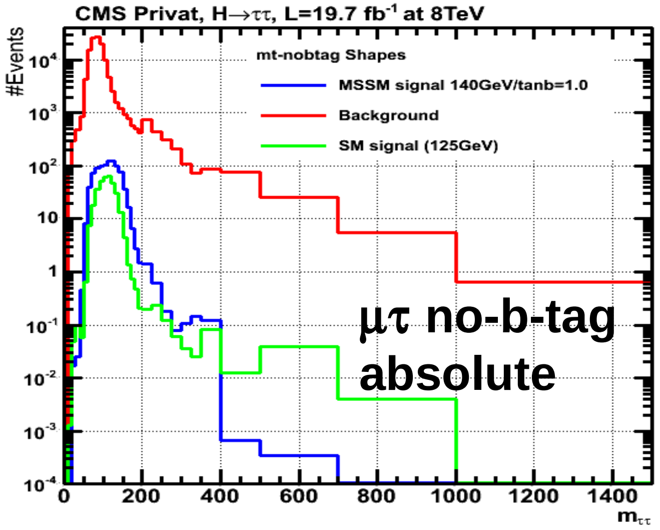
CL_s(MSSMvsBG) < CL_s(MSSMvsSM)

➜ **MSSMvsBG has lower CL_s therefore is more sensitive!**

This is true for regions with
Shape of h, A or H ≈ Shape of h_{SM}



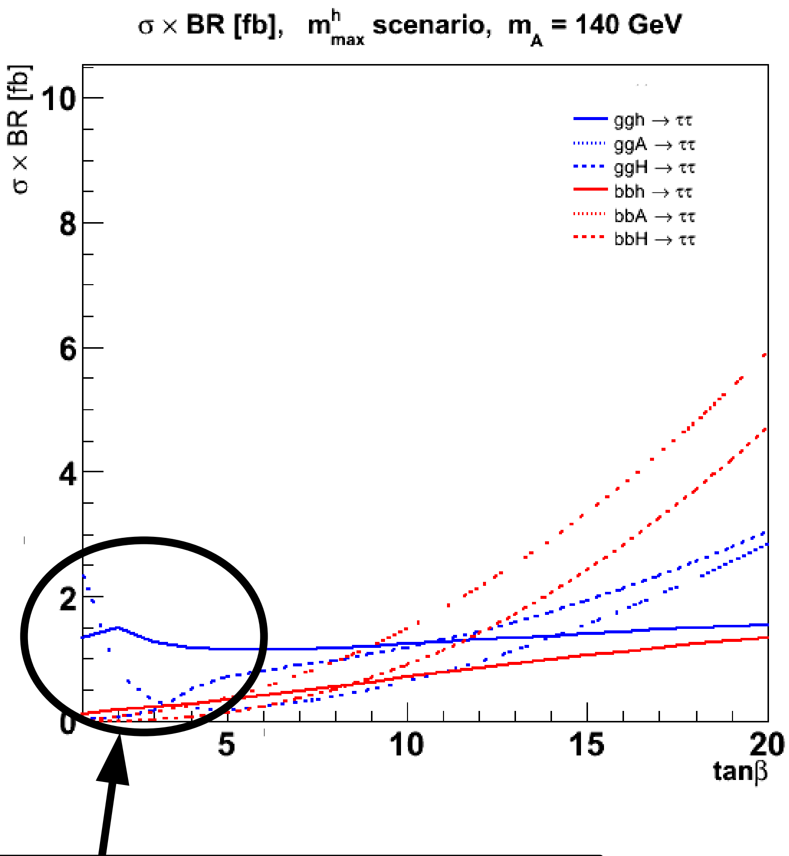
μτ no-b-tag normalized



μτ no-b-tag absolute

Why are we senstive to low tanβ regions?

- For low m_A the σ*BR has at around tanβ=4 (exact value depends on m_A). Here we have destructive interference in the gluon-gluon fusion loop. For lower and higher tanβ the σ*BR rises.
- On the right an example is shown for the MSSM m_h^{max} scenario at m_A = 140 GeV

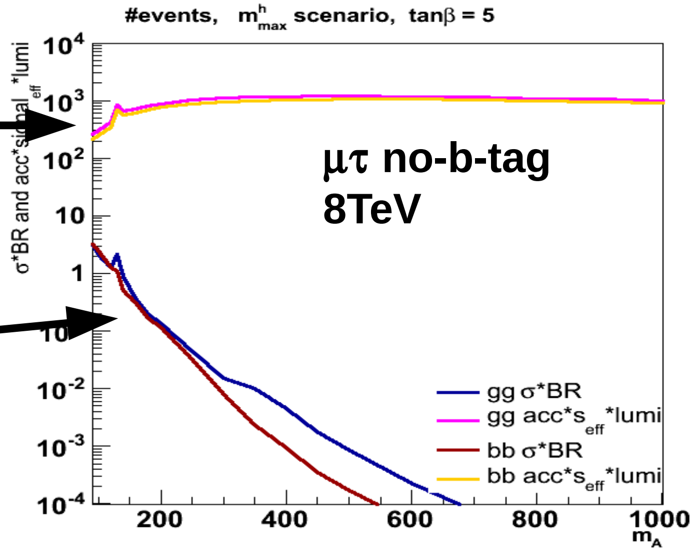


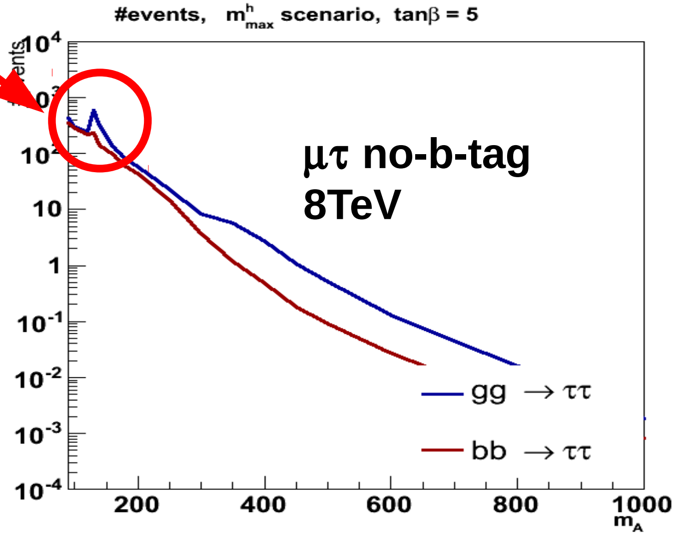
σ*BR rises again for ggh and ggA

Why do we reach maximum sensitivity at ~140GeV?

- The acceptance*signal$_{eff}$ is increasing for increasing m$_A$ and fixed tanβ
- The σ*BR is falling for increasing m$_A$ and fixed tanβ
- The product of both leads to a maximum at around 140 GeV

- Used degenerated mass mode
  - m$_A$>130GeV → take A+H
  - m$_A$=130GeV → take h+A+H
  - m$_A$<130GeV → take h+A

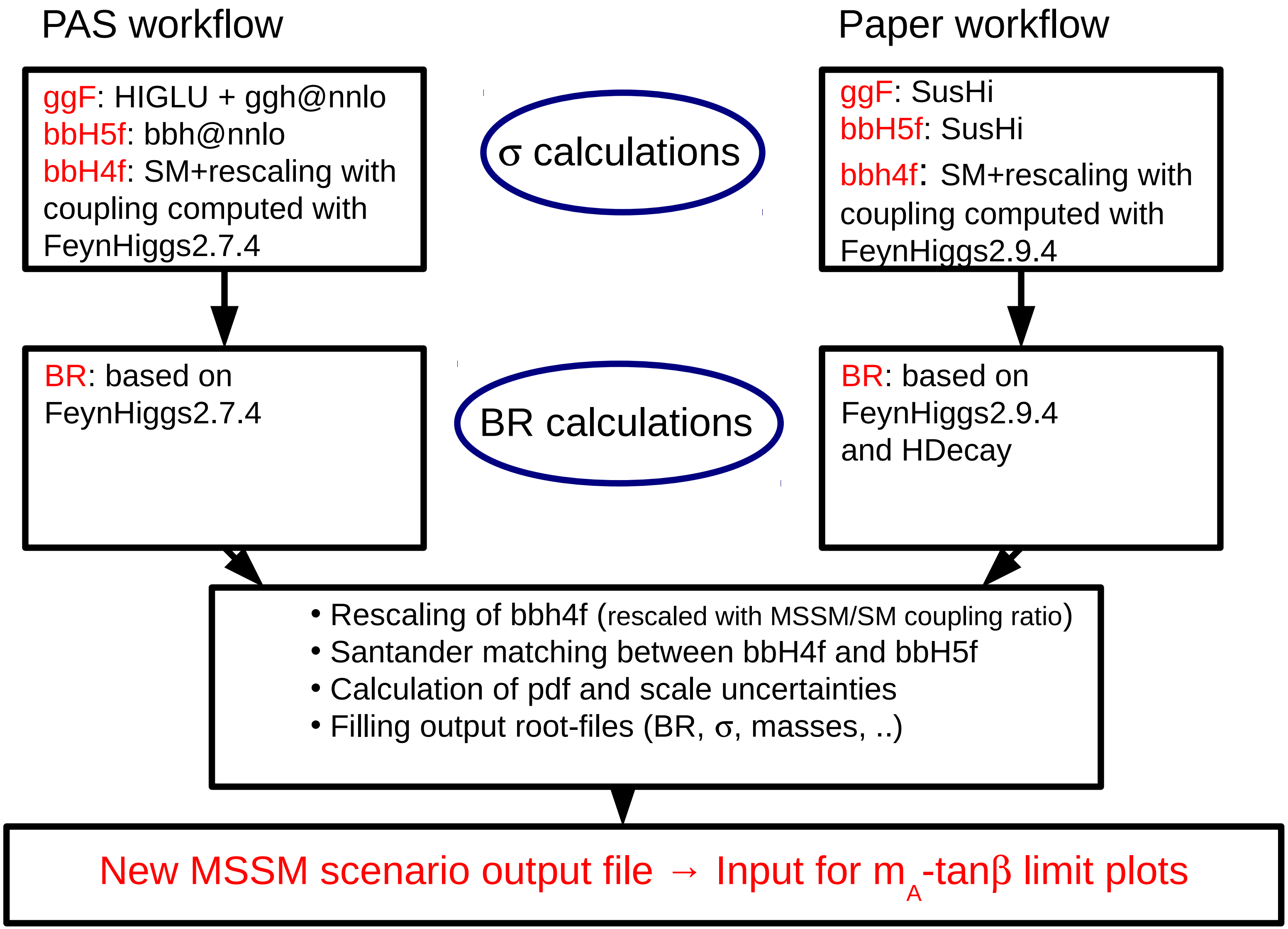




Theory Tools

- HIGLU
  - http://arxiv.org/abs/hep-ph/9510347
- ggh@ nnlo
  - http://arxiv.org/abs/hep-ph/0201206, http://arxiv.org/abs/hep-ph/0208096
- bbh@ nnlo (bbh 5flavour)
  - http://arxiv.org/abs/hep-ph/0304035
- bbh 4flavour
  - http://arxiv.org/abs/hep-ph/0309204
- SusHi
  - http://arxiv.org/abs/1212.3249
- FeynHiggs
  - http://arxiv.org/abs/hep-ph/9812320, http://arxiv.org/abs/hep-ph/0611326, http://arxiv.org/abs/hep-ph/0212020, http://arxiv.org/abs/hep-ph/9812472
- HDecay
  - http://arxiv.org/abs/hep-ph/9704448
- Santander matching
  - http://arxiv.org/abs/1112.3478

Workflow for creation of MSSM scenario files



PAS workflow

ggF: HIGLU + ggh@nnlo
bbH5f: bbh@nnlo
bbH4f: SM+rescaling with coupling computed with FeynHiggs2.7.4

BR: based on FeynHiggs2.7.4

σ calculations

BR calculations

Paper workflow

ggF: SusHi
bbH5f: SusHi
bbh4f: SM+rescaling with coupling computed with FeynHiggs2.9.4

BR: based on FeynHiggs2.9.4 and HDecay

- Rescaling of bbh4f (rescaled with MSSM/SM coupling ratio)
- Santander matching between bbH4f and bbH5f
- Calculation of pdf and scale uncertainties
- Filling output root-files (BR, σ, masses, ..)

New MSSM scenario output file → Input for m_A-tanβ limit plots