Tau Leptons: A tool for studying SM and BSM physics at CMS

Riccardo Manzoni
INFN & Università degli Studi Milano Bicocca
on behalf of the CMS collaboration

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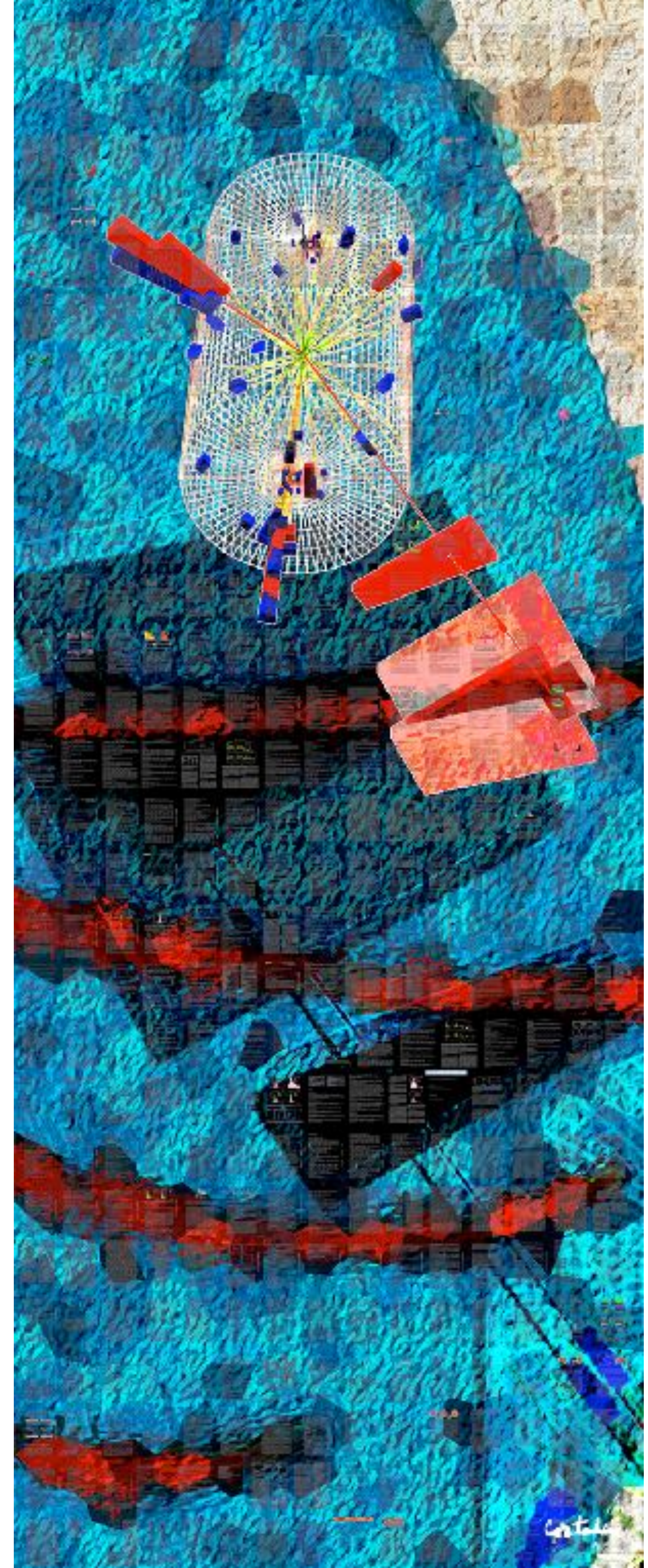


Why taus?

- **τ's are precious for SM Higgs measurements:**
  - Theoretical reasons:
    - Yukawa couplings are proportional to the mass of the interacting particle
    - **τ are massive → sizeable BR**
  - Experimental reasons:
    - **relatively clean experimental signature**,
      b-quarks couple more strongly to Higgs but are more difficult to identify

  → measure fermion couplings, and investigate possible deviations

- **τ's are precious for BSM searches:**
  - BSM physics manifests as **anomalous couplings**, e.g. Lepton Flavour Violation
  - a zoo of **new particles predicted to decay in channels with τ's**
    - often τ channels are enhanced, e.g. MSSM
    - τ's in final states of multiple decays involving H(125)

(some) τ analyses at a glance

- $h \to hh \to bb\tau\tau$
- LFV $H \to \mu\tau$
- SM $H \to \tau\tau$
- MSSM $\phi \to \tau\tau$
- $X \to hh \to bb\tau\tau$
- SM H CP meas.
- MSSM $H^{+} \to \tau\nu$
- EXO W’, Z’, N_{τ}

$h \to hh \to bb\tau\tau$

SM $H \to \tau\tau$

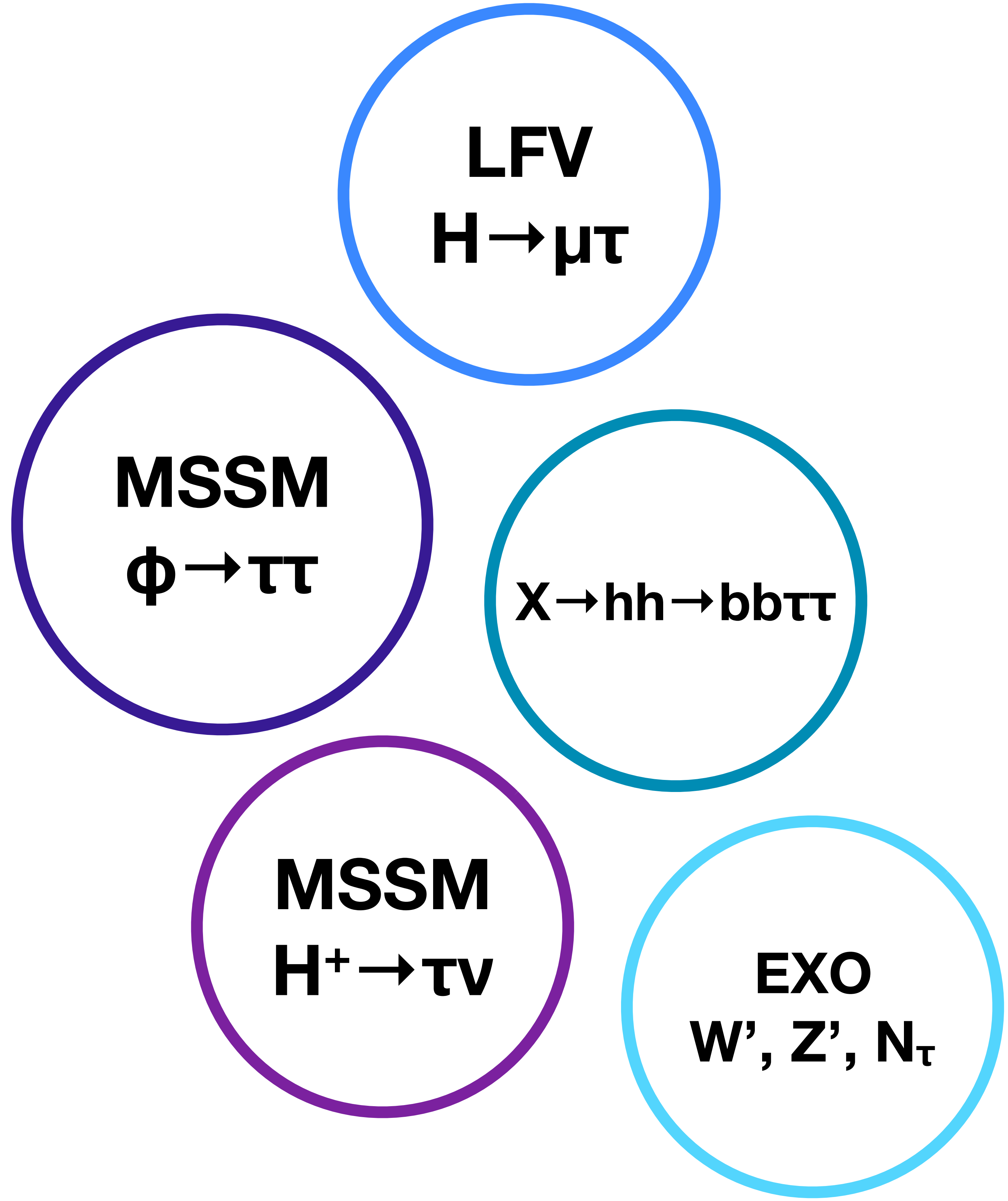
SM H
CP meas.

Study of the 125 GeV SM Higgs boson

- Higgs coupling measurement
- triple Higgs self coupling λ_{hhh} (for the future)
- measurement of Higgs CP (for the future)

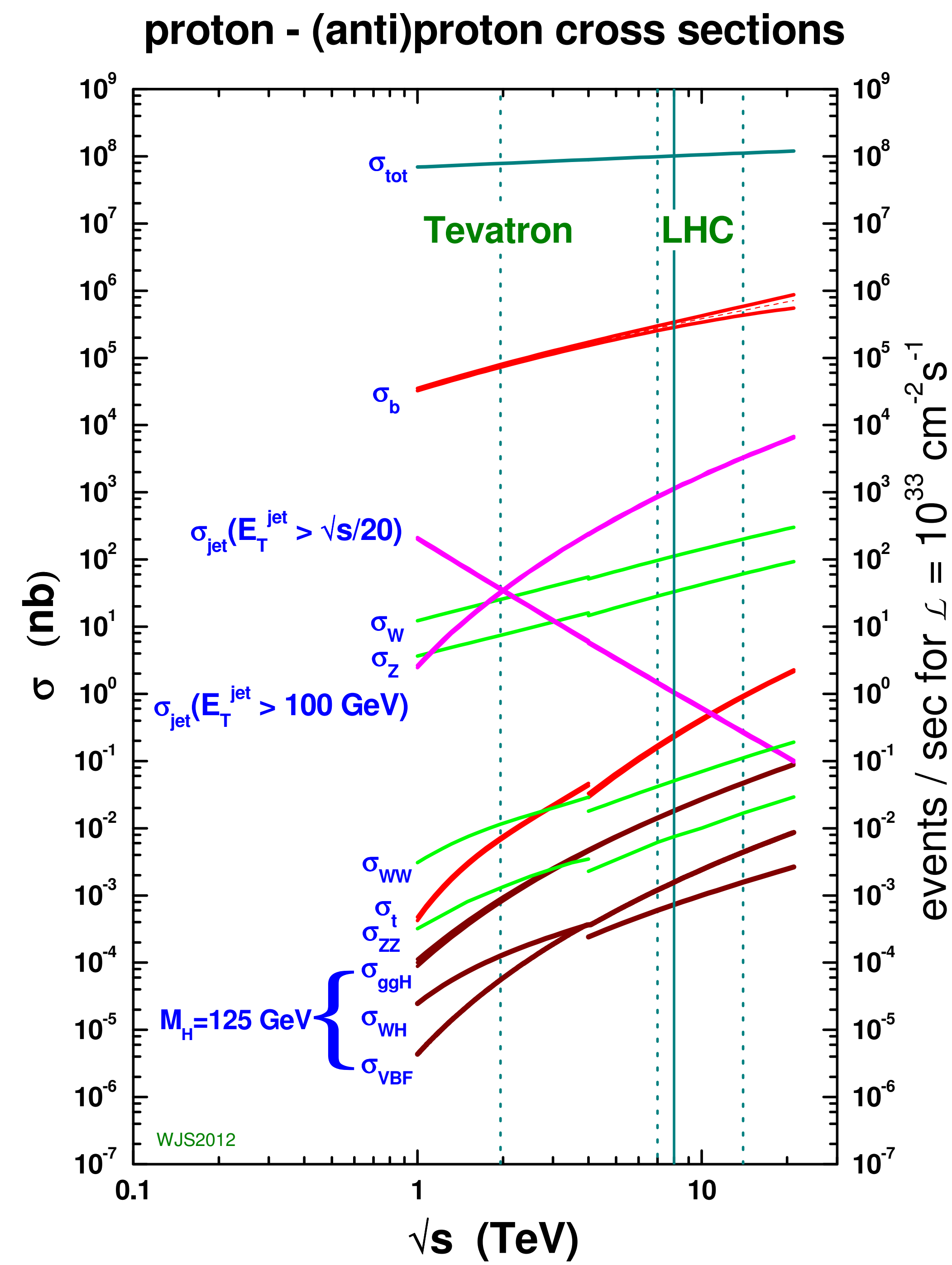
BSM searches

- τ analyses lead MSSM H sensitivity
- Lepton Flavour Violation in Higgs sector accessible only with τ's
- wealth of BSM resonances decaying in final states with τ's
- heavy resonance and boosted taus



Why τ's are challenging? - 1

- **overwhelming production of jets at hadronic colliders**
  - need to keep the jet→τ mis-identification probability as low as possible
  - → ***isolation*** is the main tool to reduce such contamination. It estimates of the activity around the tau: high for jets, low for taus
- **electrons and muons too can be erroneously identified as τ!**
- need to cope with diverse sources of contaminations



Why τ's are challenging? - 2

- **τ decays always involve neutrinos**
  - not detectable → E_T^{miss} → missing kinematic information
  - **impossible to directly reconstruct di-τ invariant masses**

    → need tools to estimate di-τ mass from visible products and E_T^{miss}

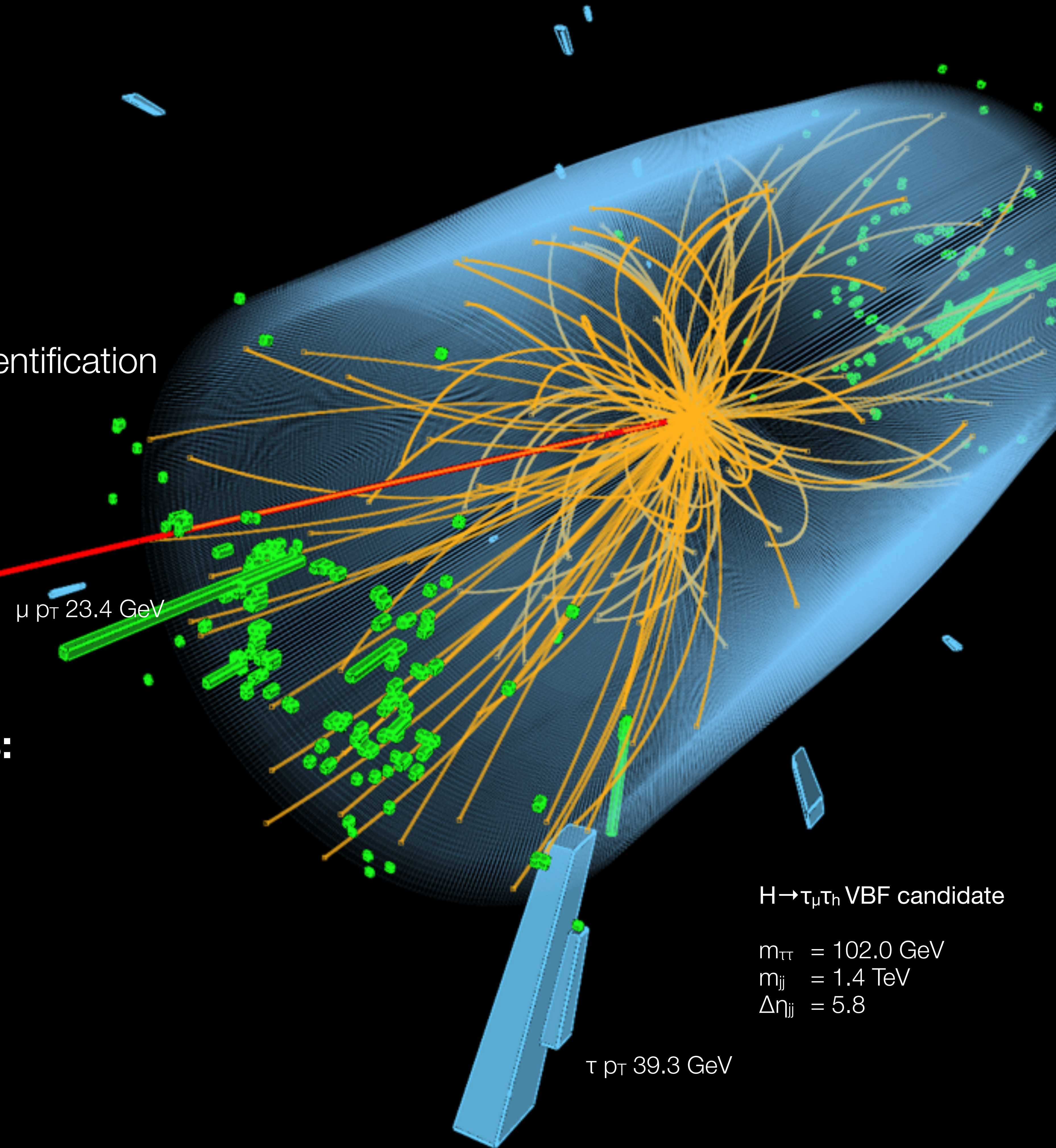
- **τ triggers need to efficiently select taus in such a busy environment**
  - **they need to fit into tight constraints of**
    - time spent analysing each event
    - number of events that can be saved per unit time
  - **avoid cutting phase space useful interesting physics**

    → often τ triggers are multi-object and analysis specific: $\ell\tau$, di-τ, τ+ E_T^{miss}

Outline

- **tau object in CMS**
  - reconstruction and identification
  - performance on data
  - tau triggers

- **tau in CMS analyses:**
  - Higgs: SM and BSM
  - Exotic searches



Tau object at CMS

https://cds.cern.ch/record/2196972

Tau reconstruction

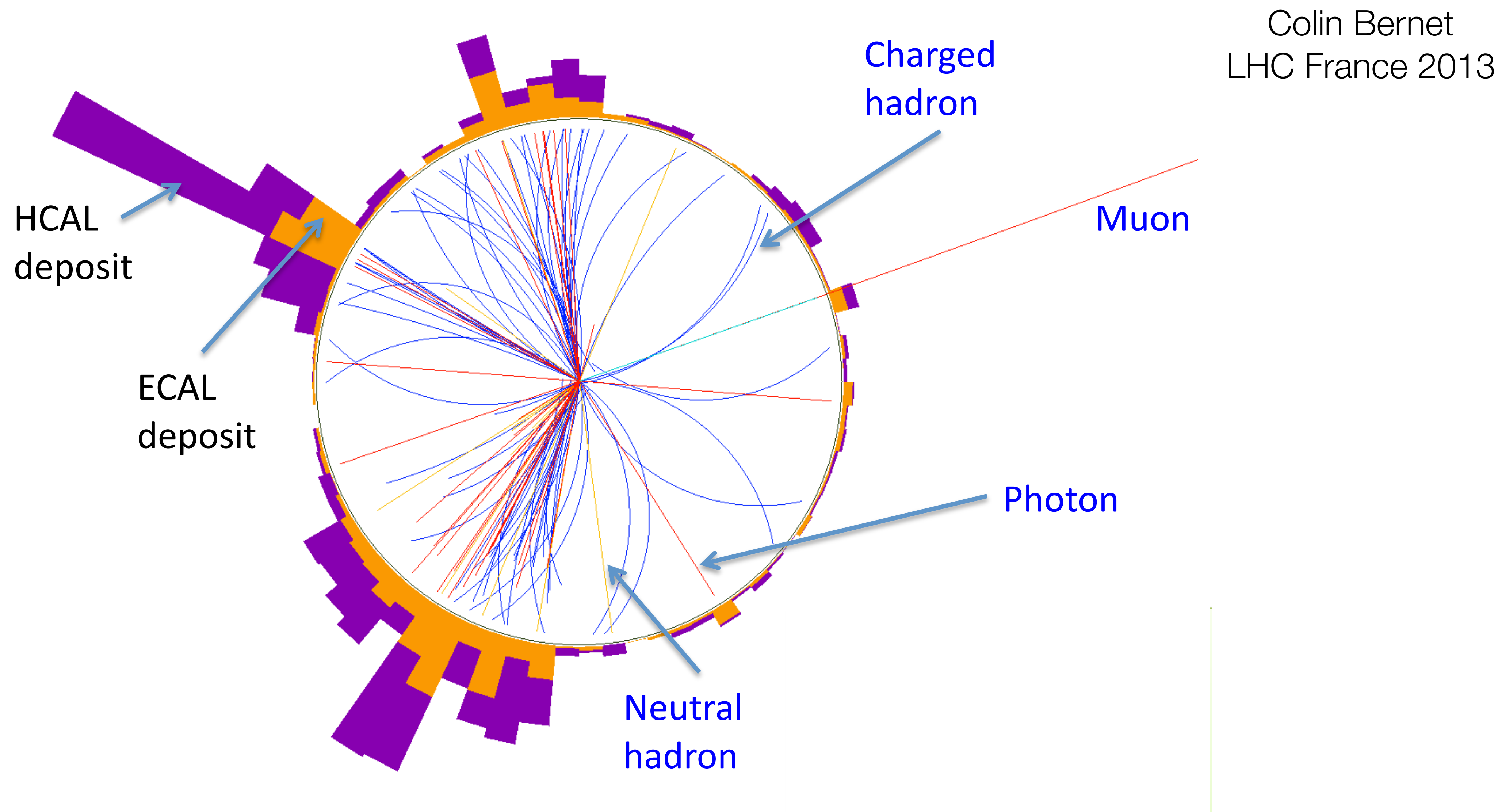
The τ lepton

- **τ is the only lepton heavy enough to decay into hadrons**
  m_τ = 1.777 GeV, lifetime 2.91E-13 s, cτ = 90 μm

- **out of the many possible hadronic tau decays (PDG),**
  we group them into three families or *decay modes*:
  - **1-prong**, **1-prong + nπ^0**, **3-prong**
    - *h* can be either *π* or *K*, but predominantly *π* and $m_\pi^{\pm}$ hypothesis is always assumed
  - π^0 are reconstructed from *e* and γ deposits in rectangular regions in ECal, called ***strips***

Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	10.8
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other modes with hadrons		1.8
All modes containing hadrons		64.8

Intermission - Particle Flow - 1

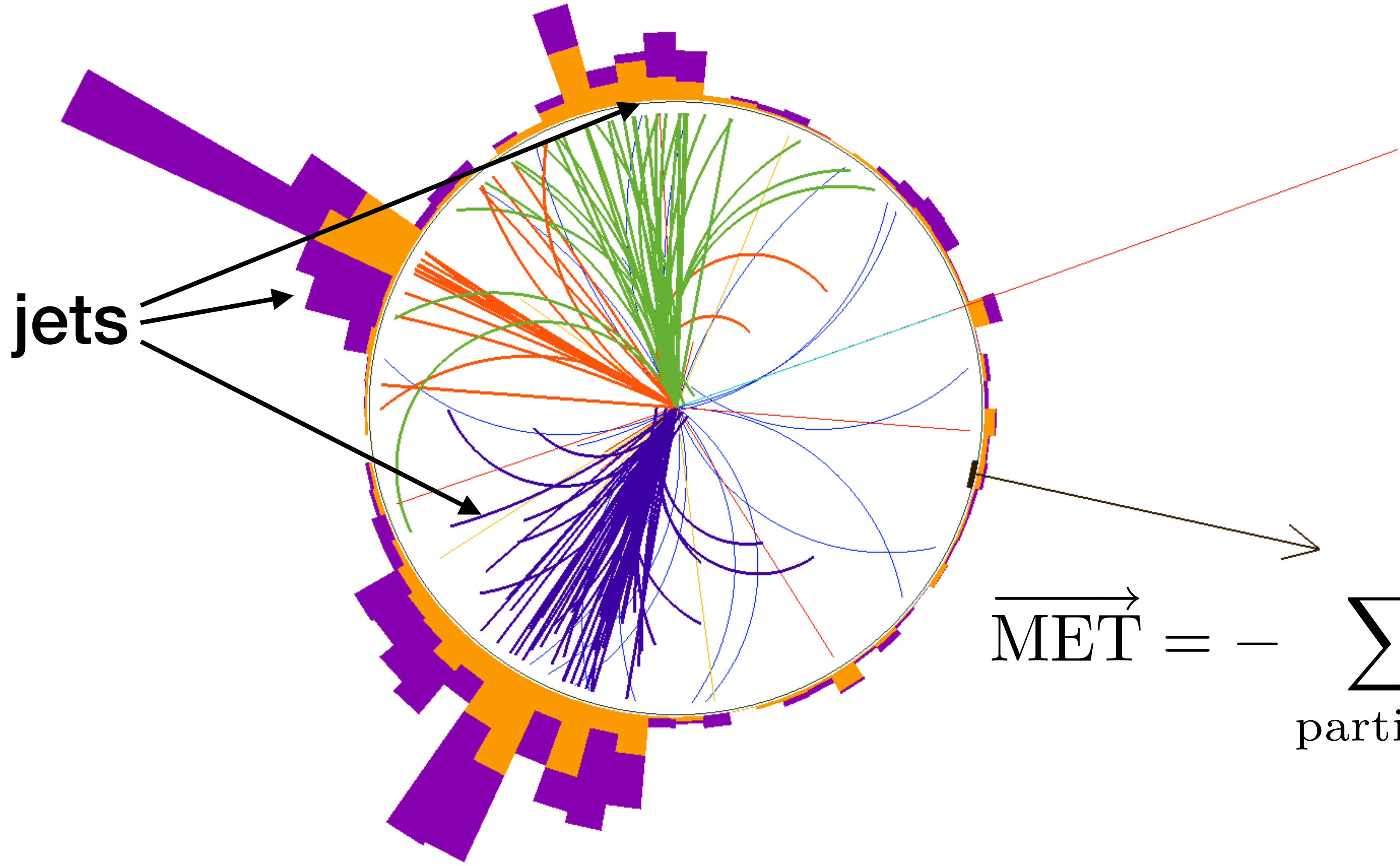


make use of all CMS sub detector: redundancy and inter-calibration

reconstruct all stable particles in the event: μ, e, γ, neutral/charged hadrons

Intermission - Particle Flow - 2

Colin Bernet
LHC France 2013

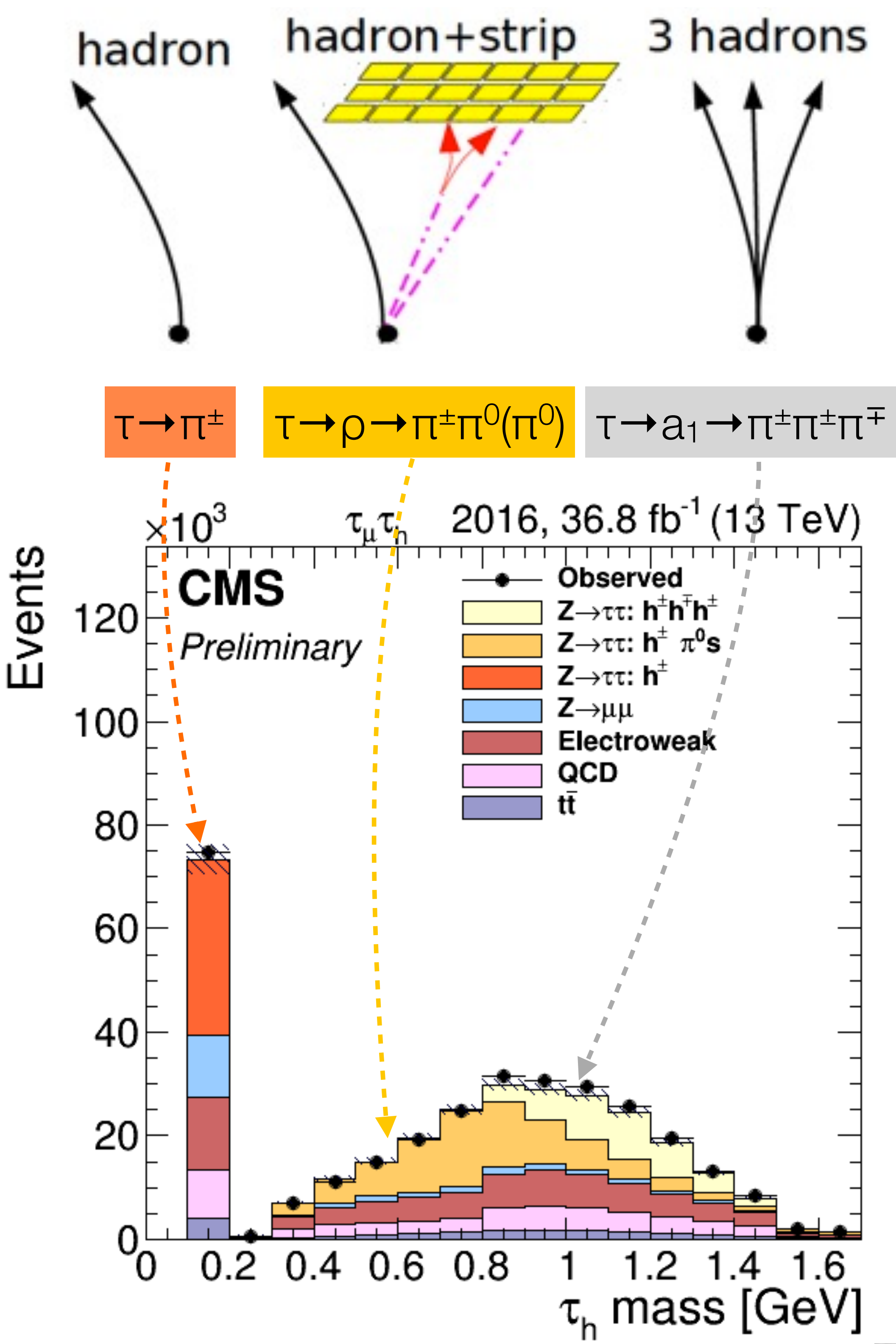


$$\overrightarrow{\mathrm{MET}} = - \sum_{\mathrm{particles}} \vec{p}_{\mathrm{T}}$$

PF particles are used to build high-level objects in a consistent way

global event description

τ_h reconstruction in CMS

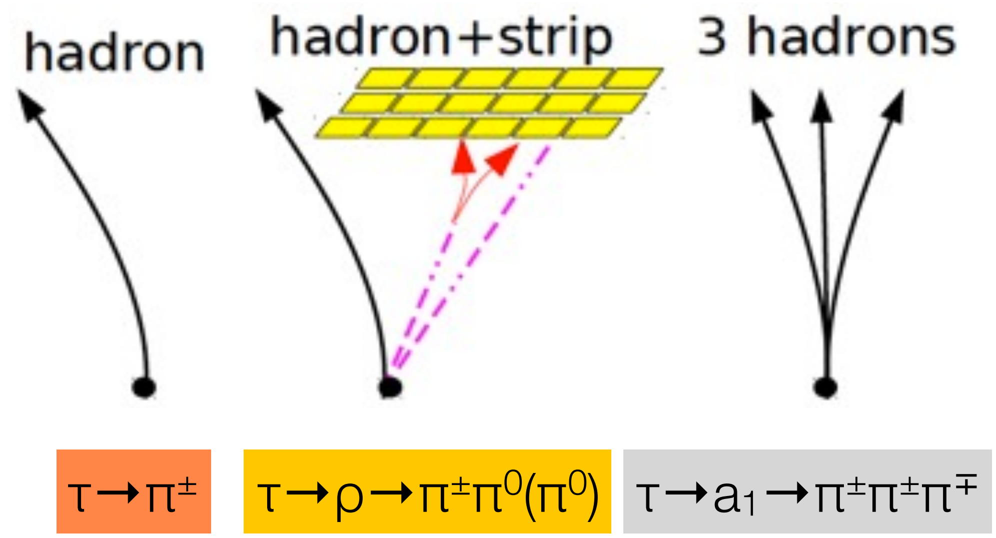


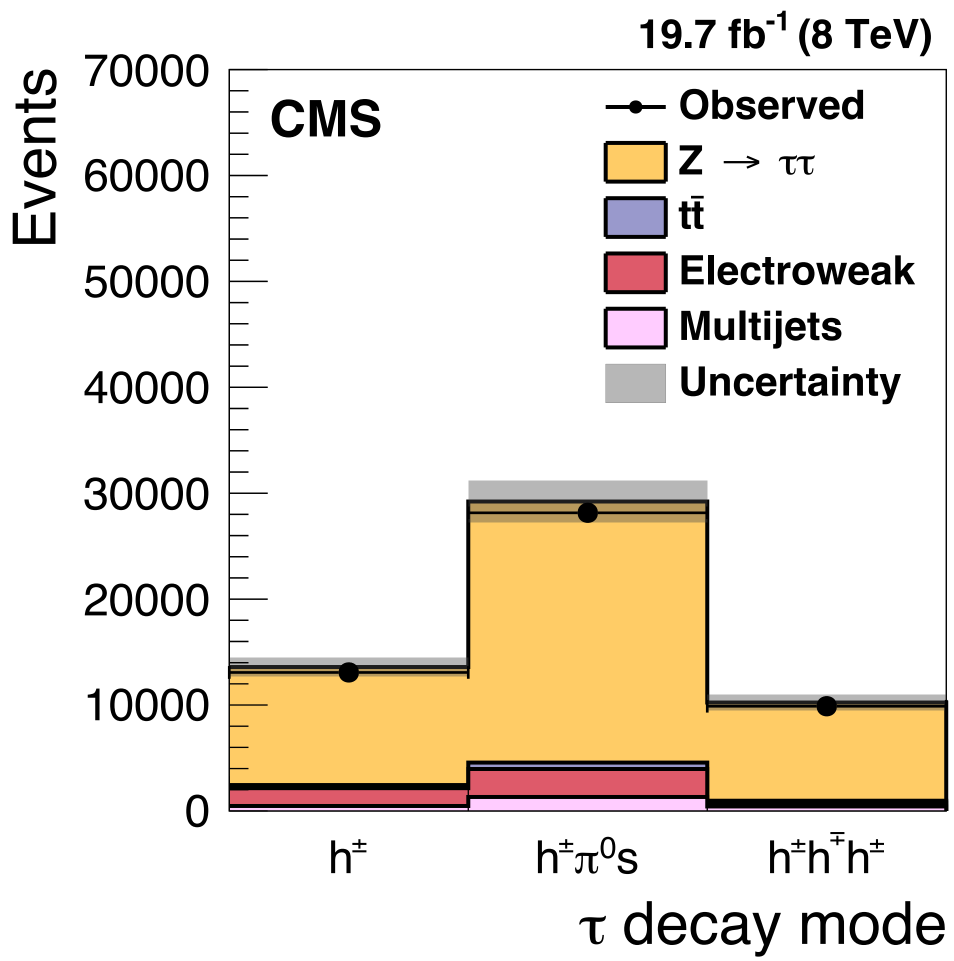
Hadron Plus Strip algorithm (HPS)

- **run on Particle Flow inputs:** jets and their charged and neutral constituents
- **can identify each τ_h decay mode**
- exploits the ρ(770) and a_1(1220) intermediate resonances through mass window requirements

Reconstructed	Generated		
	$\tau^- \to h^- \nu_\tau$	$\tau^- \to h^- \geq 1\pi^0 \nu_\tau$	$\tau^- \to h^- h^+ h^- \nu_\tau$
$\tau^- \to h^- \nu_\tau$	**0.89**	0.16	0.01
$\tau^- \to h^- \geq 1\pi^0 \nu_\tau$	0.11	**0.83**	0.02
$\tau^- \to h^- h^+ h^- \nu_\tau$	0.00	0.01	**0.97**

τ_h reconstruction in CMS





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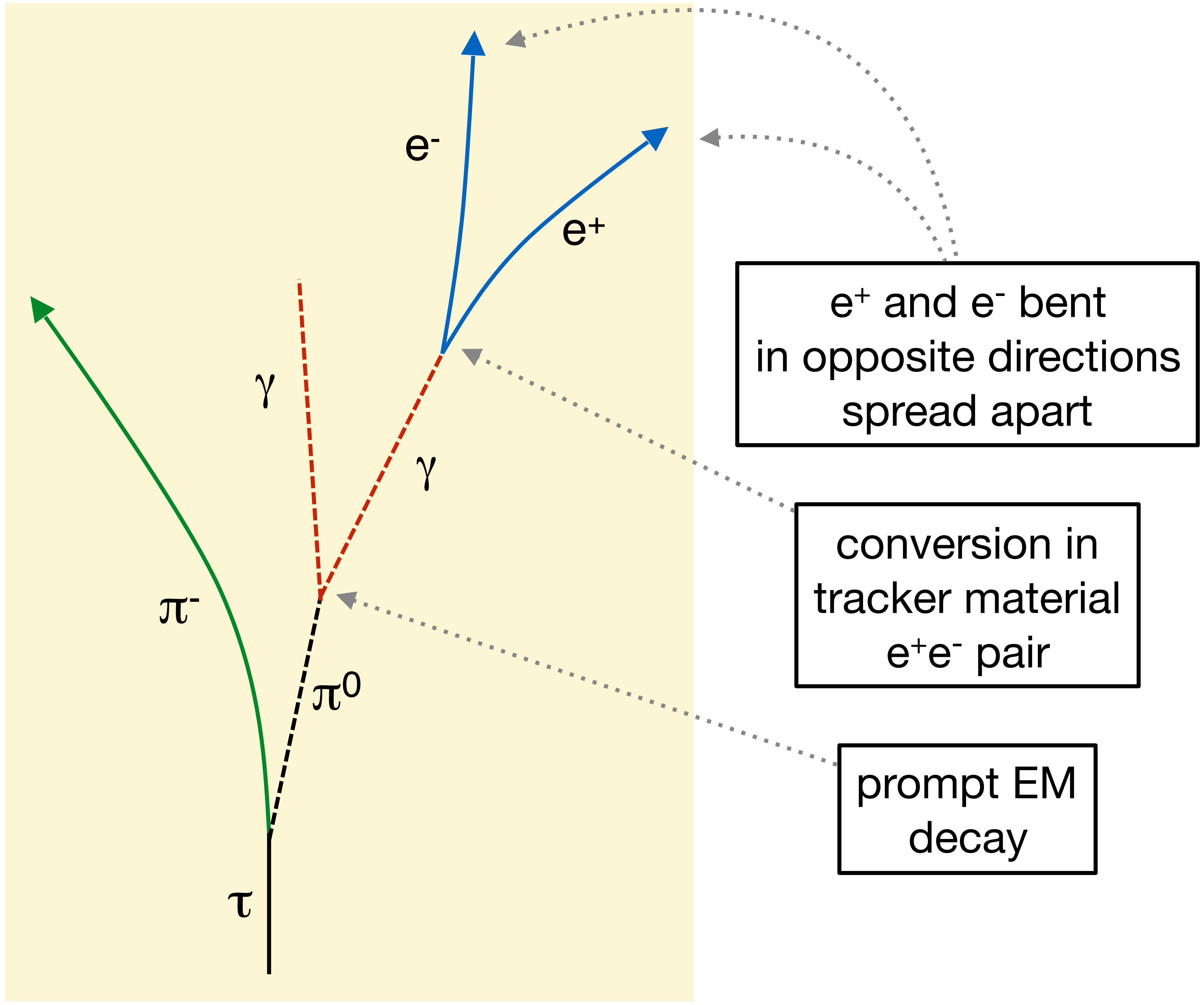
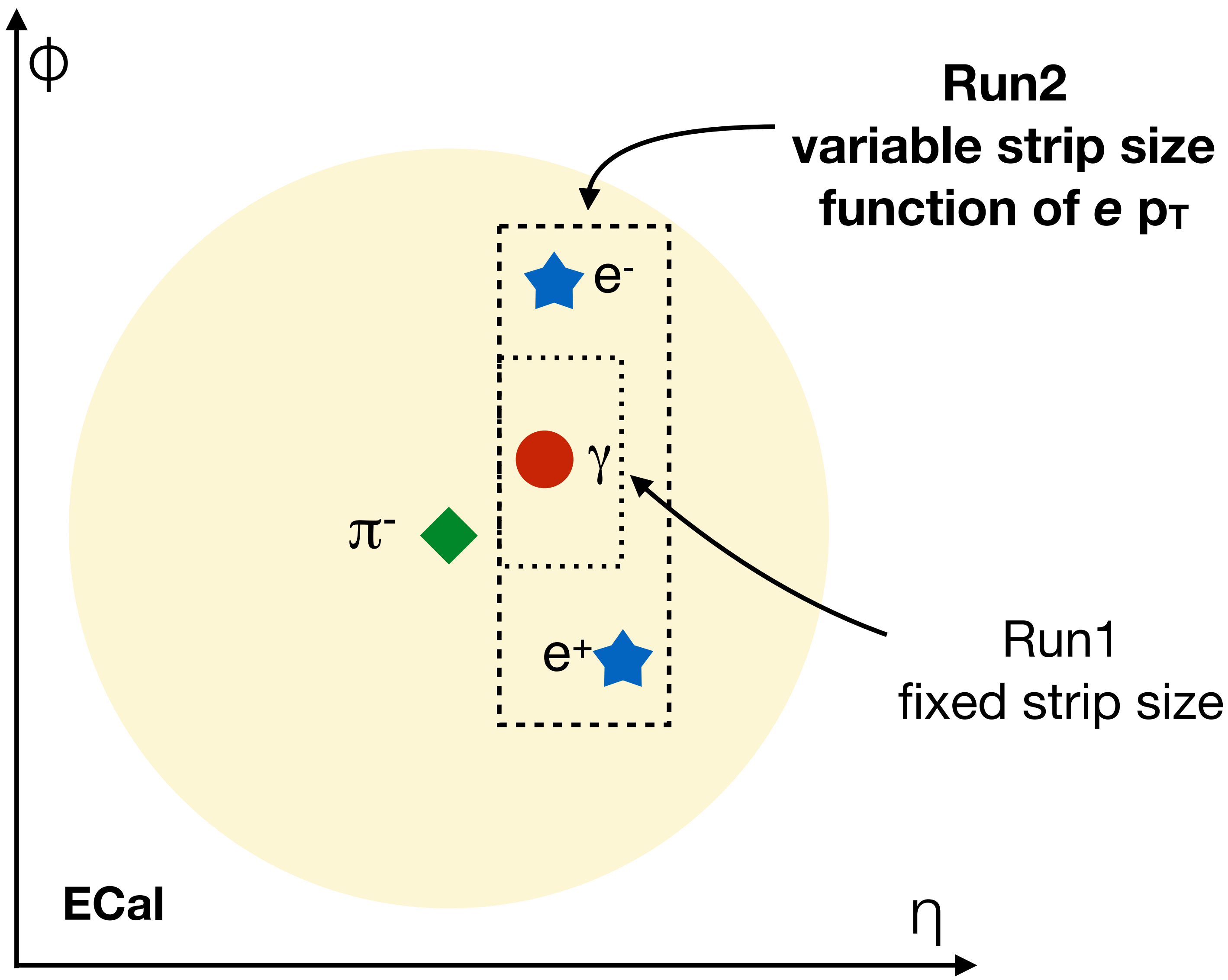
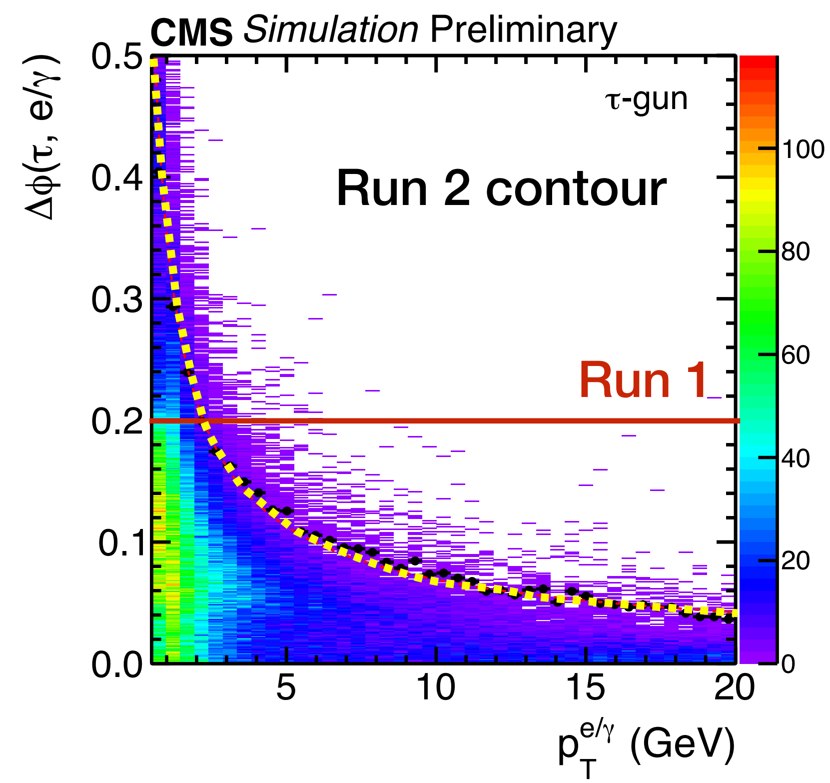
Dynamic strip reconstruction

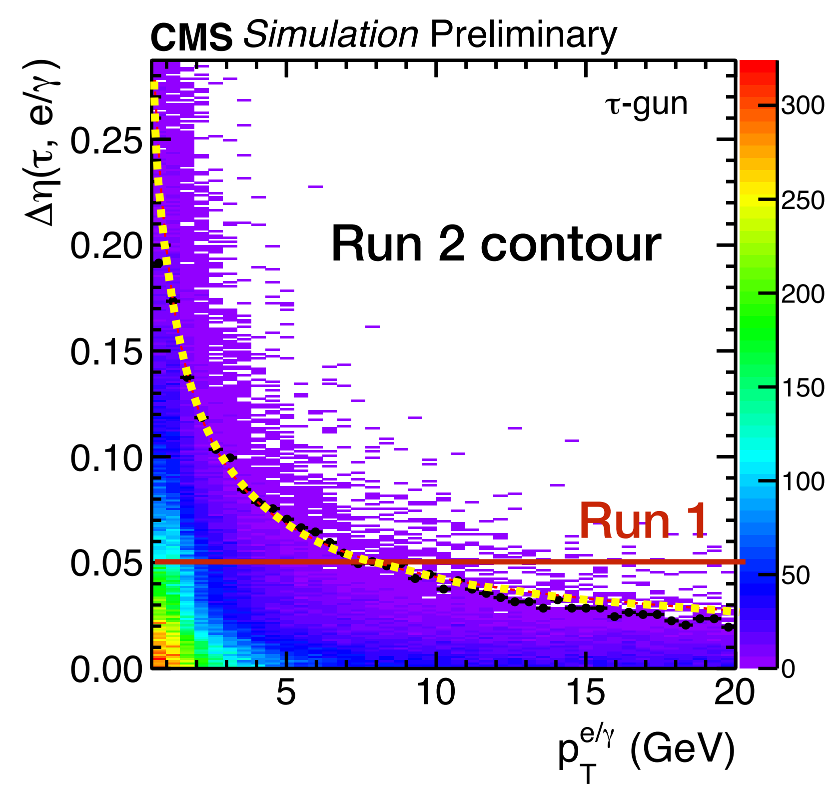
$\tau \to \pi^{\pm} + \pi^0(\pi^0) + \nu_\tau$
57% of all had
decaying τ's



Dynamic strip reconstruction





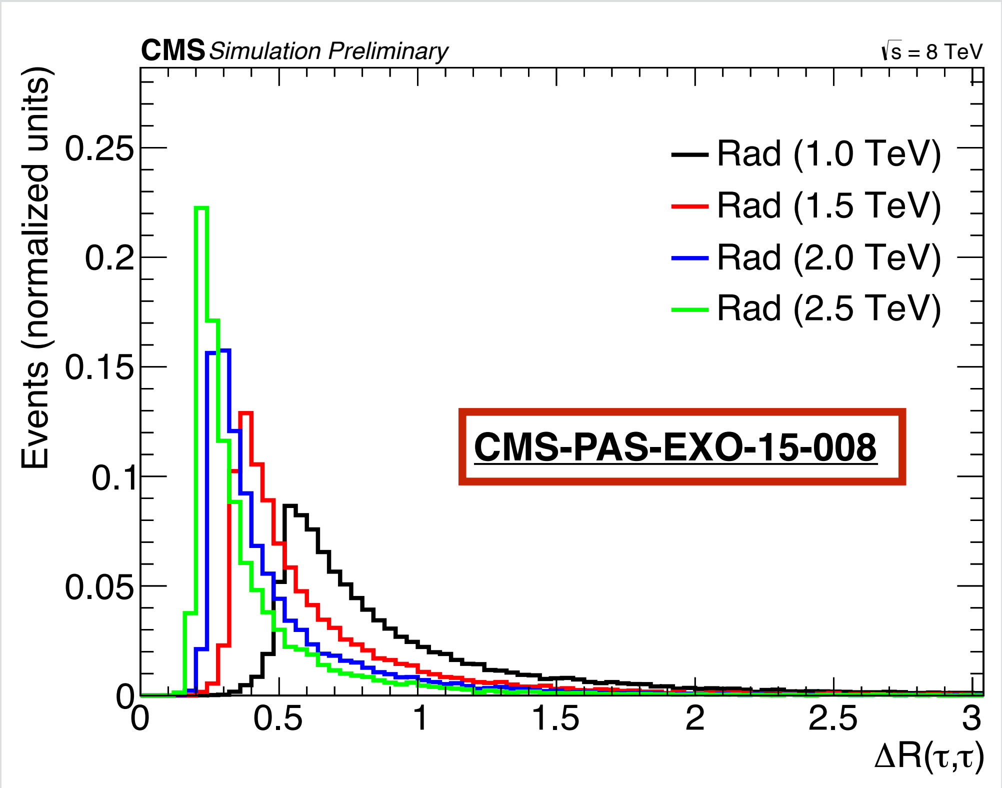


- **better acceptance for genuine taus**
- **lower probability that a tau product is accounted as isolation candidate**
- **signal cone shrinks at hight p_T, better fake rejection**
- **exploited further as part of isolation**

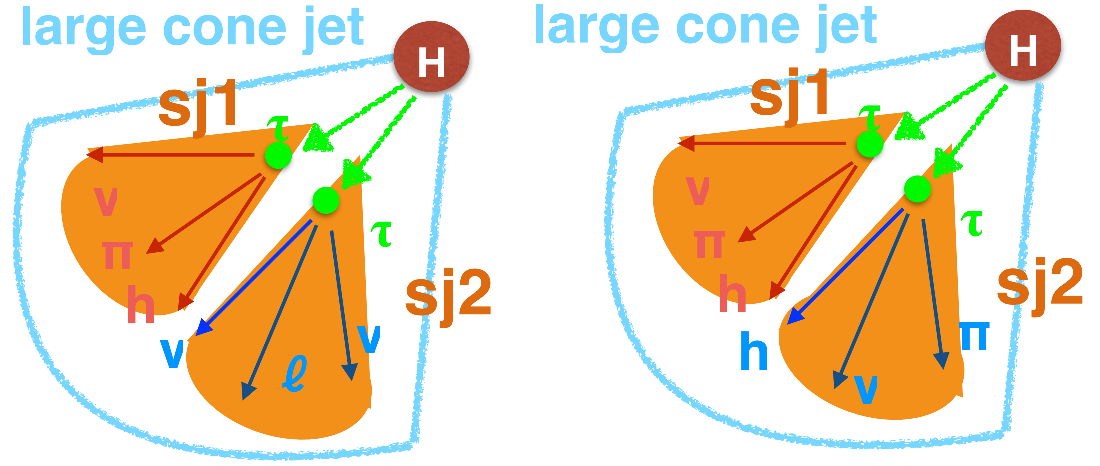
Boosted Taus

dedicated τ reconstruction for the high-p_T regime

- e.g. heavy X→hh→bbττ, where h's are highly boosted and their decay product overlap

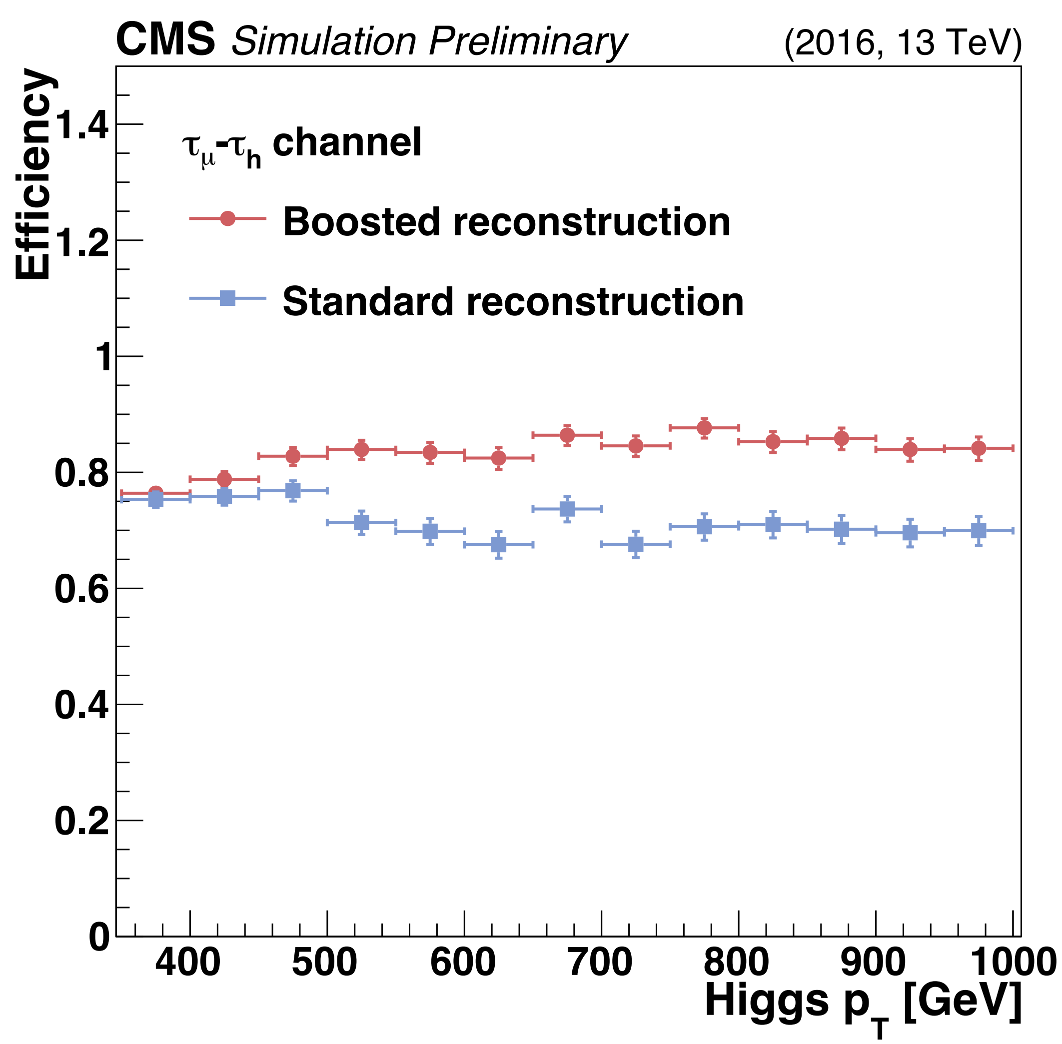


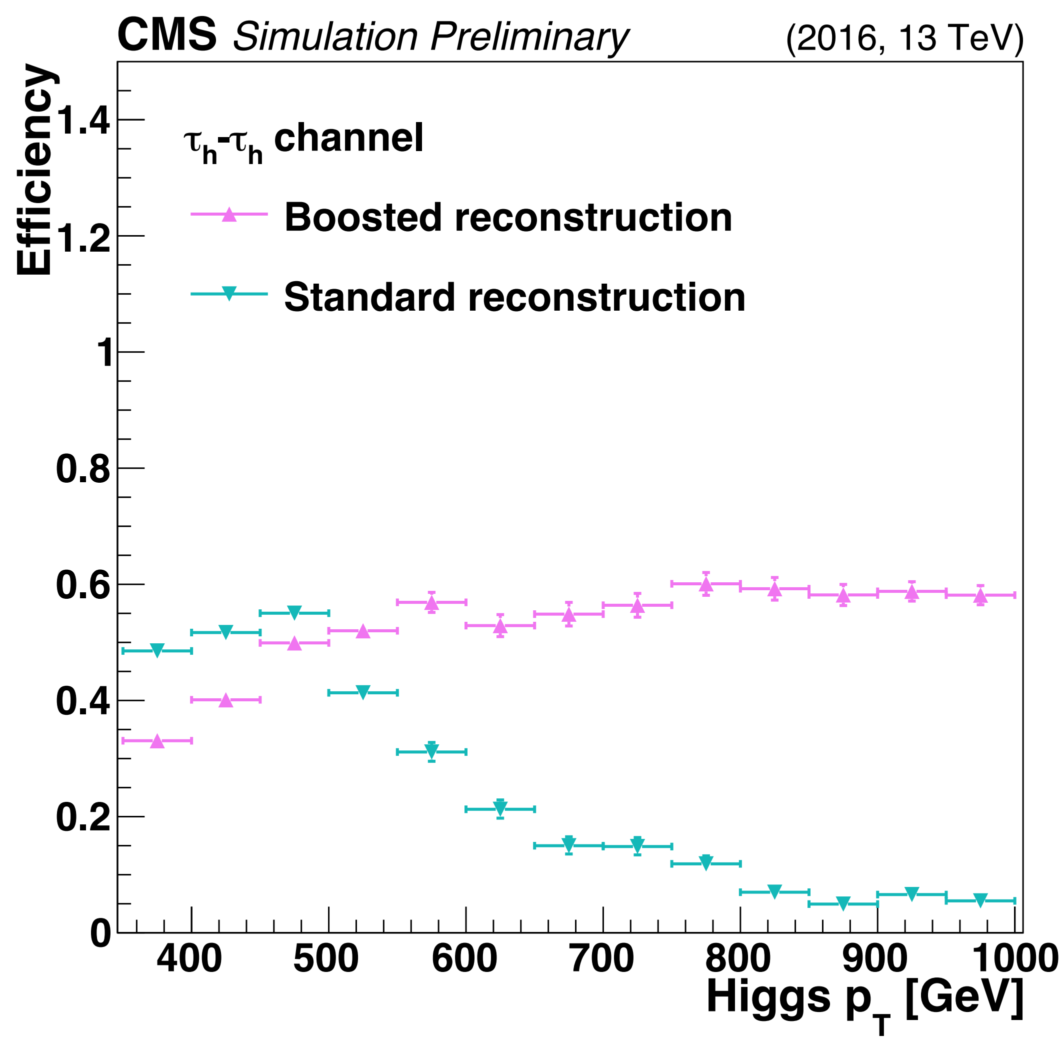
Semileptonic **Fully hadronic**



- **unified approach for both ℓτ and ττ**
- **start from a fat jet (cone R=0.8)**
- **identify subjets** (p_T>10 GeV)
  - ℓ are considered as subjets too
- **run standard τ reconstruction on subjets**
  - isolation computed within the subjet radius to avoid overlaps

Boosted taus - Performance

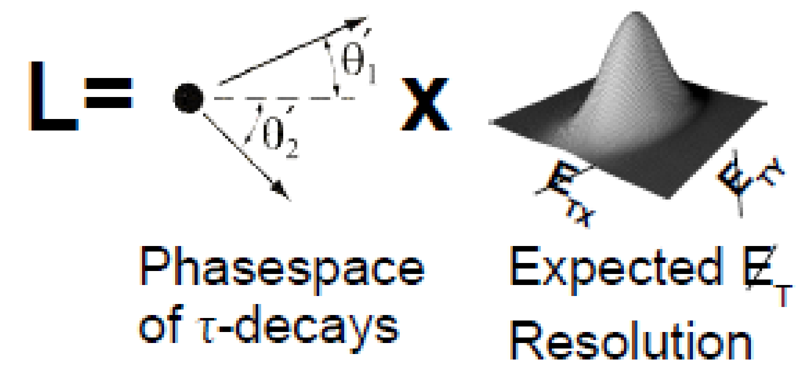




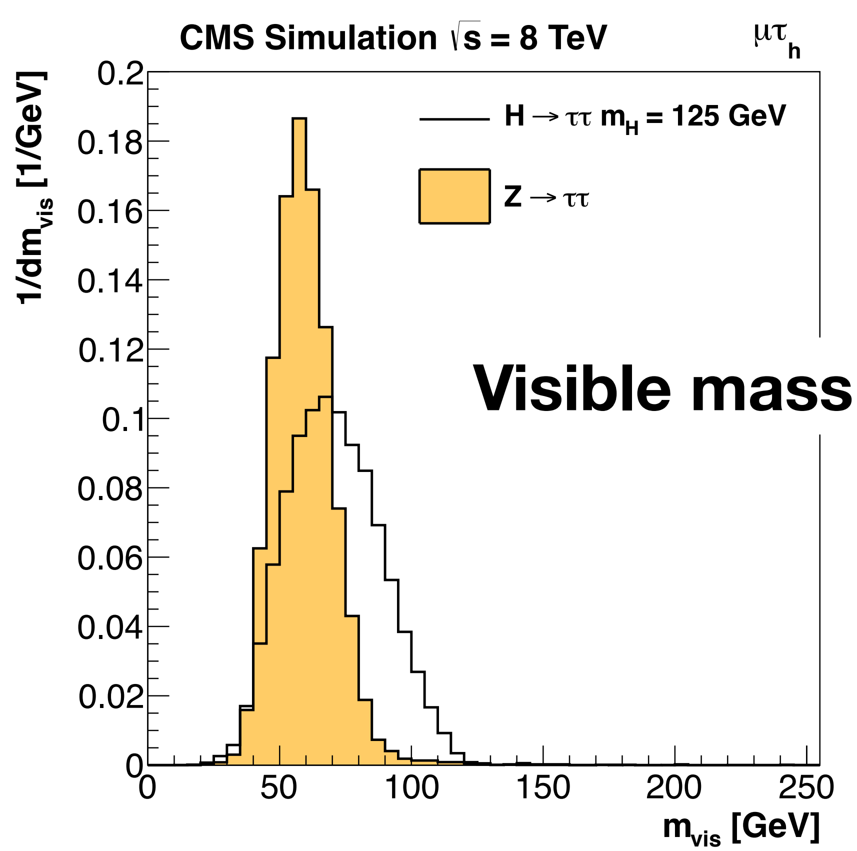
- **the boosted tau reconstruction significantly improves signal acceptance for high p_T^H > 500 GeV, especially for $\tau_h\tau_h$**

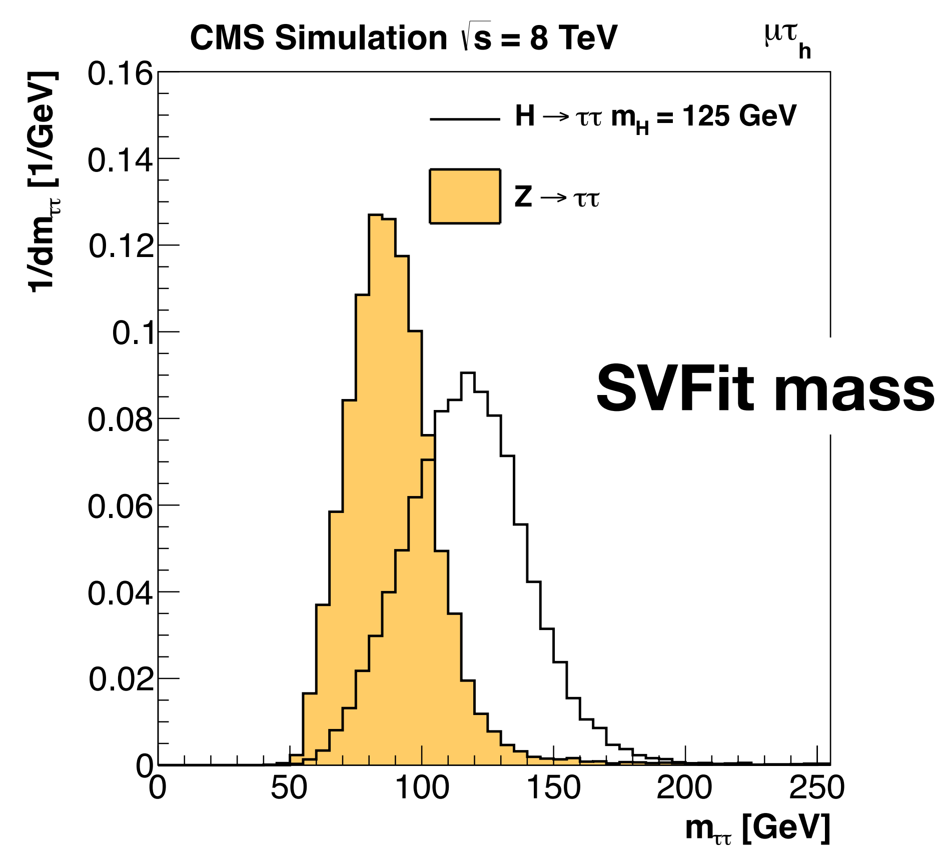
di-τ mass reconstruction: SVFit algorithm

- **SVFit: Maximum likelihood estimator of the di-τ system mass**



- Estimated event-by-event using four-momenta of visible decay products, E_x^{miss}, E_y^{miss}, and expected E_T^{miss} resolution, E_T^{miss} is assumed to be coming only from taus



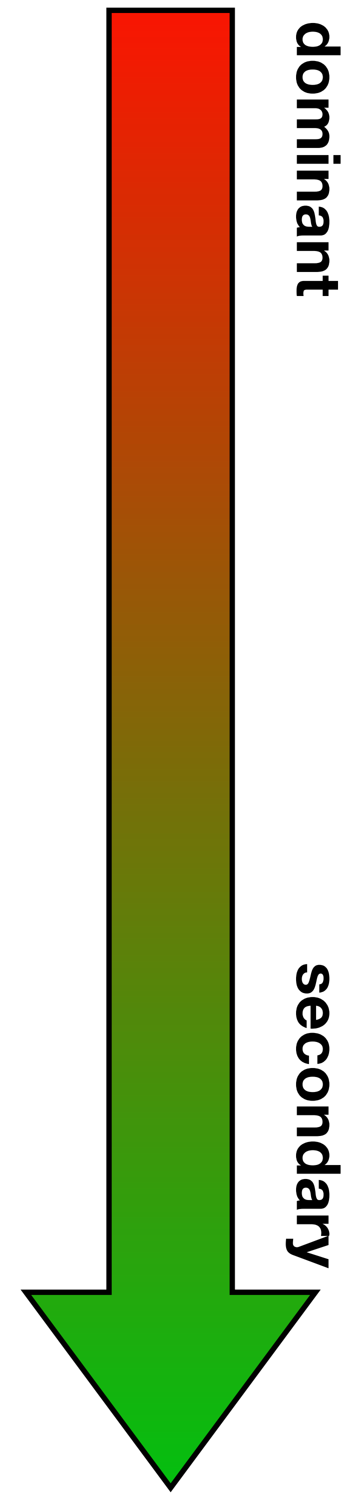


Z/H(125) separation largely improved, m_H resolution ~15%
essential tool for H→ττ analyses

Tau identification

Sources of misidentified τ's

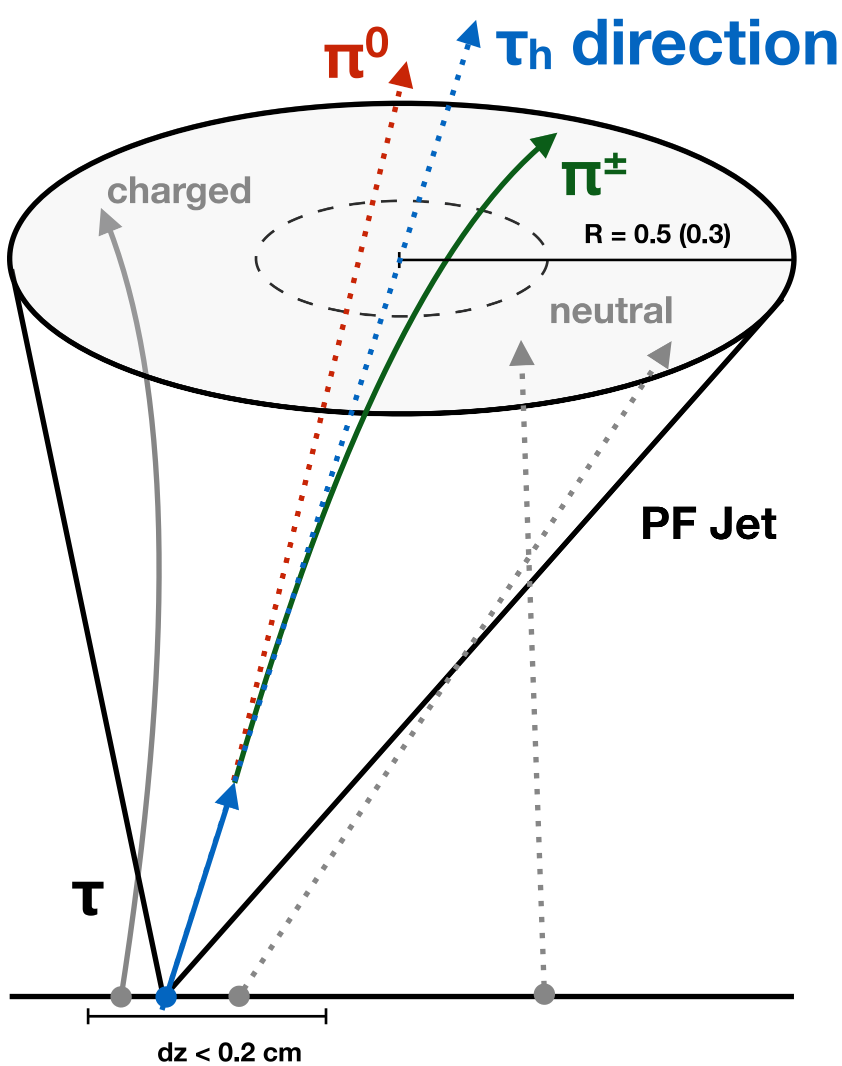
- **quark/gluon initiated jets**
    - cut- and MVA-based isolation discriminators
- **electrons can be misidentified as 1-prong or 1-prong + (n)π^0 τ_h**
    - both electrons and $\pi^\pm$ are associated to a track and calorimetric deposits
    - they can emit bremsstrahlung and the emerging γ (possibly converting back to e^+e^-) could be identified as π^0
    - multivariate discriminant
- **muons can be misidentified as 1-prong taus**
    - veto discriminants based on the presence of segments in the outer muon detectors
    - efficiency > 95% up to the TeV scale, $\mu \to \tau$ rate < 10^{-4}



Cut-based isolation

$$I_\tau = \sum p_T^{\text{charged}}(d_Z < 0.2\,\text{cm}) + \max\left(0, \sum p_T^{\gamma} - \Delta\beta \sum p_T^{\text{charged}}(d_Z > 0.2\,\text{cm})\right)$$

$$p_T^{\text{strip, outer}} = \sum p_T^{e/\gamma}(\Delta R > R_{\text{sig}}) < 0.10 \cdot p_T^{\tau}$$



charged isolation

- tracks compatible with τ's vertex
- pile-up robust

neutral isolation

- pile-up corrected γ's
- neutral pile-up subtraction proportional to charged pile-up through the empirical Δβ factor

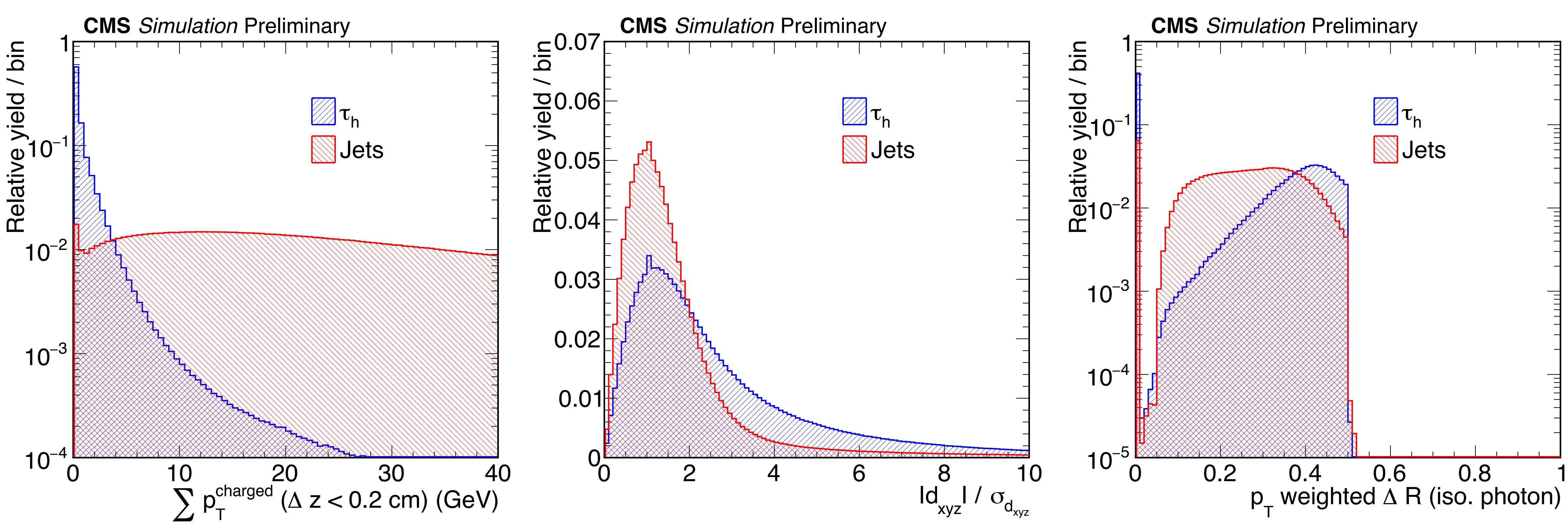
strip specific requirement

- on Σp_T of the strips far from the signal cone
- R_{sig} is defined as $0.05 < 3.0/p_T^{\tau} < 0.1$

MVA-based isolation

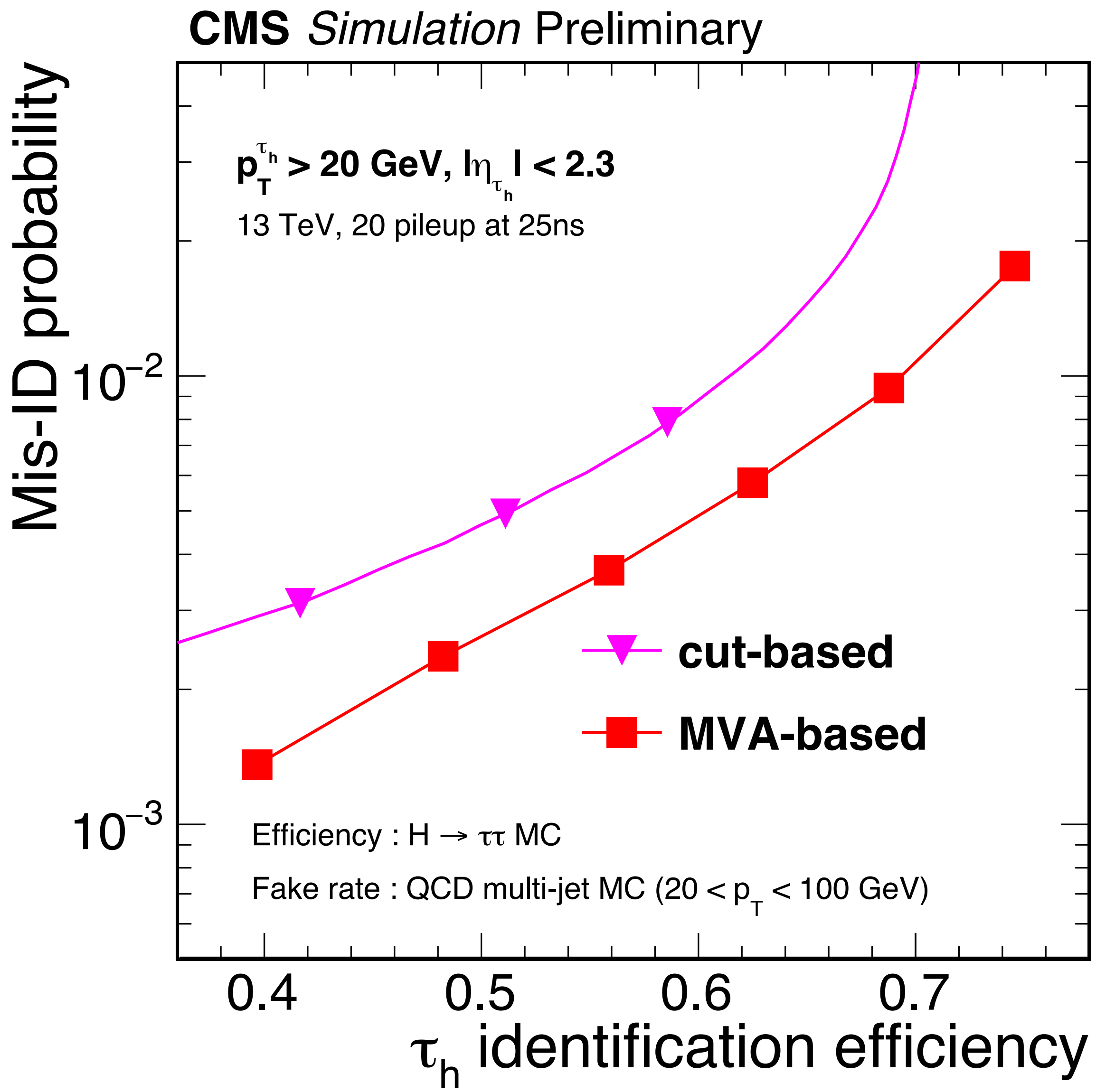
Boosted Decision Tree discriminator

- training includes all observables used in cut-based isolation plus:
  - **τ lifetime variables** impact parameter (transverse and 3D for 3-prong) and its significance
  - **shape variables** weighed ΔR, Δϕ and Δη between the e/γ in strip and the τ_h direction
  - **e/γ multiplicities** in signal and isolation cones
- training done on a mix of **genuine taus from DY, H, Z' and W'** and **fake taus from QCD and W+Jets** processes

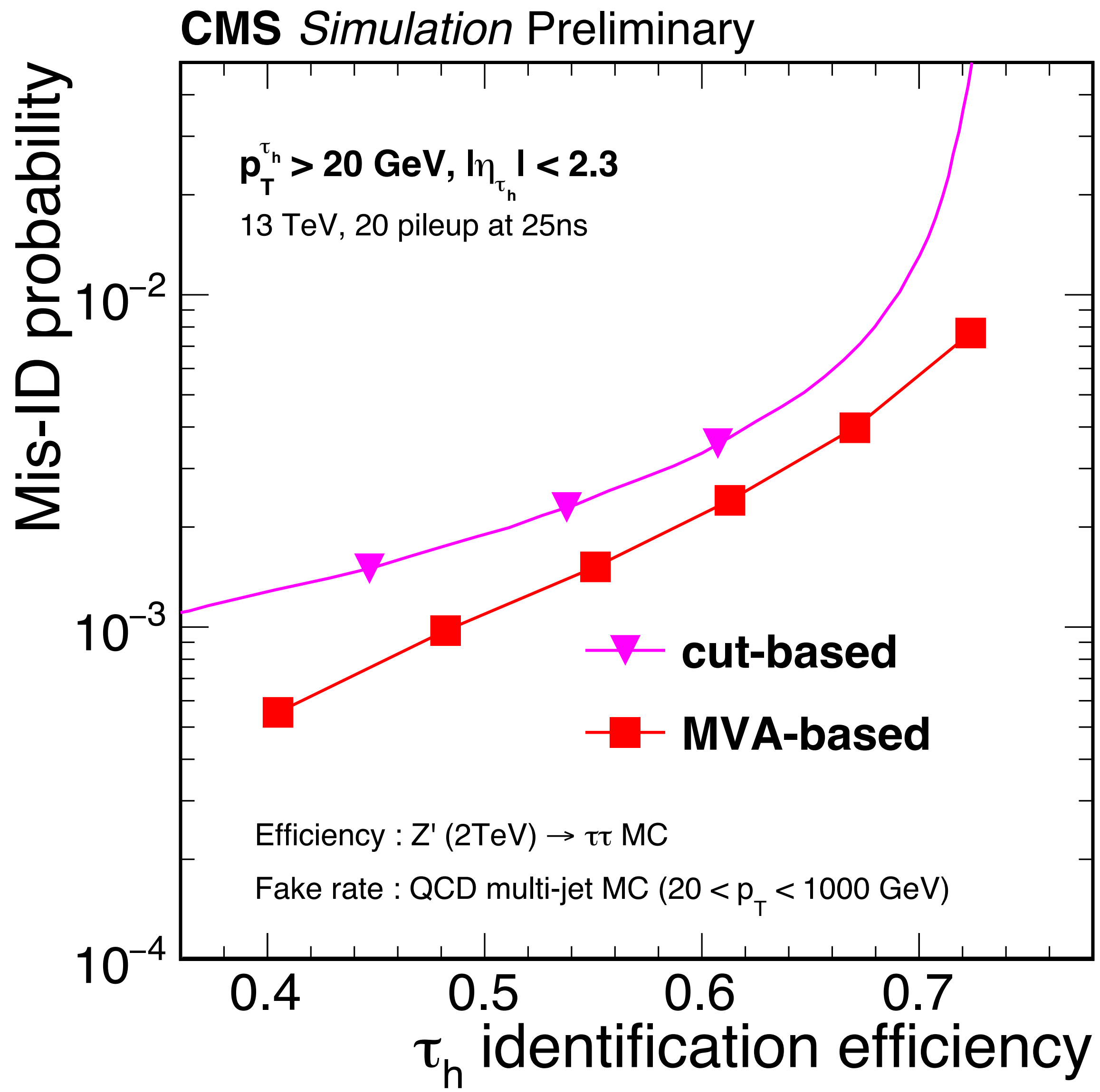


MVA-based isolation expected performance - 1

H→ττ

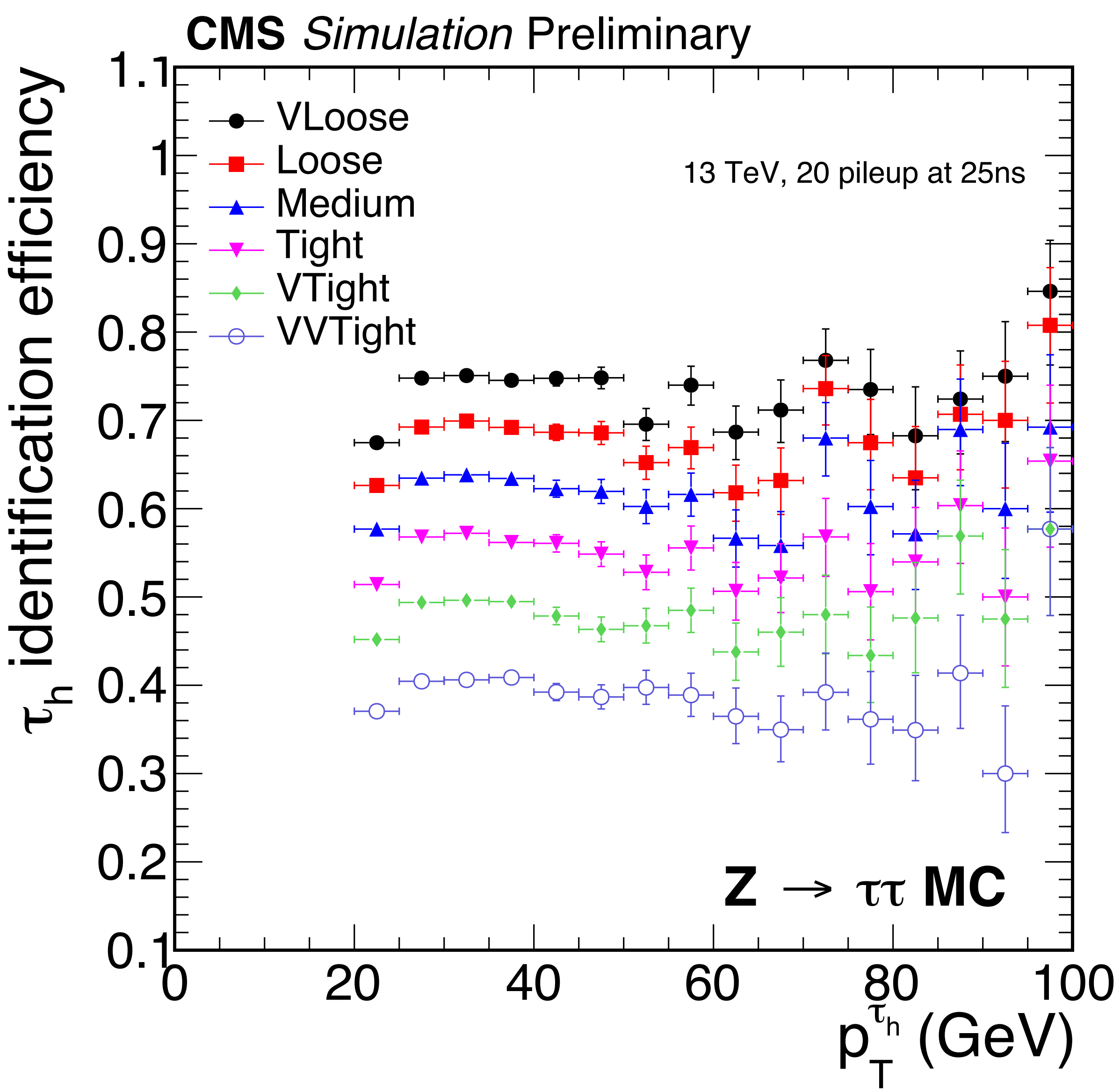


Z'(2TeV)→ττ

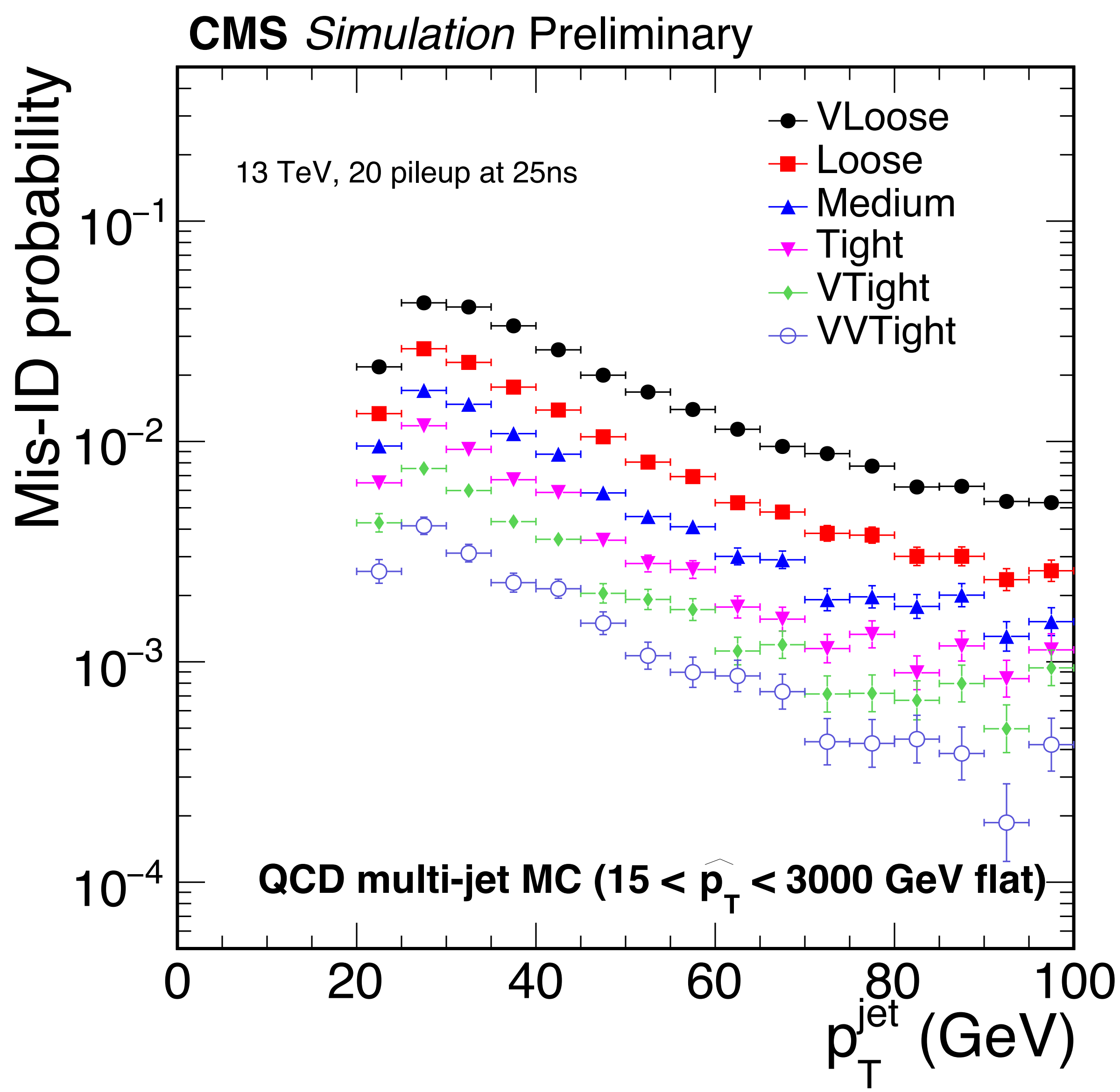


fakes are reduced by ~2x at equal efficiency

MVA-based isolation expected performance - 2

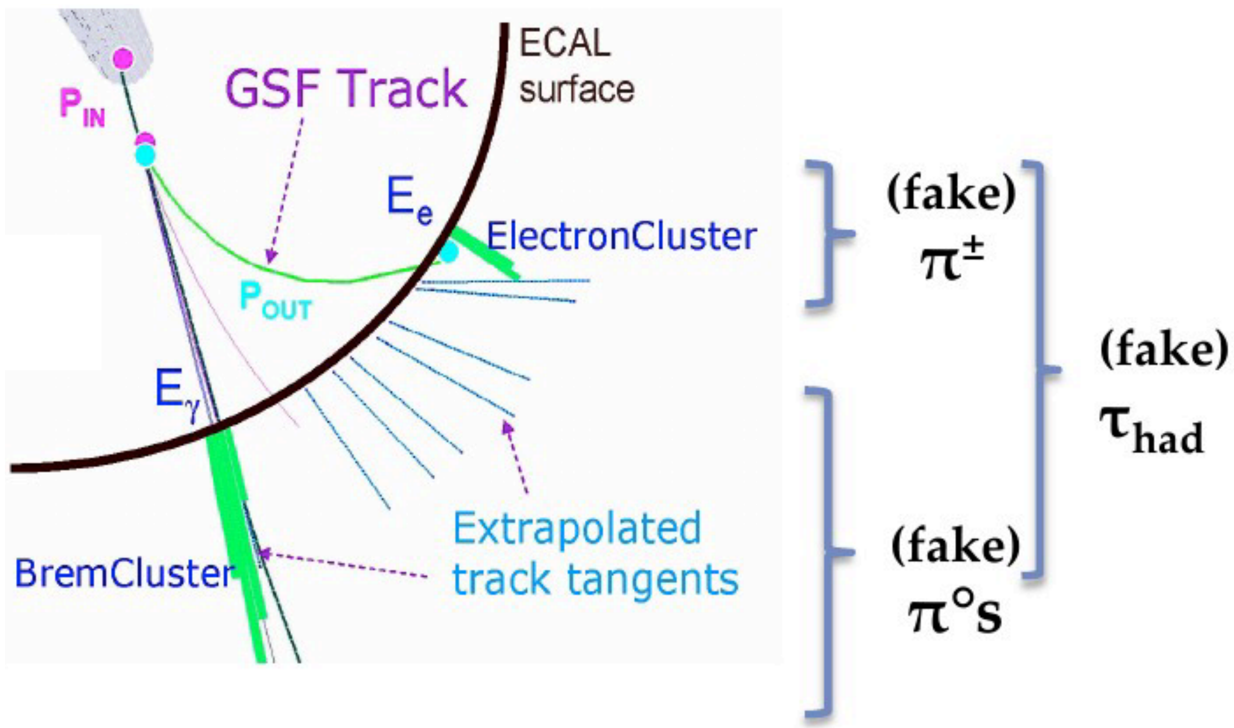


efficiency



fake rate

Anti-electron discriminator

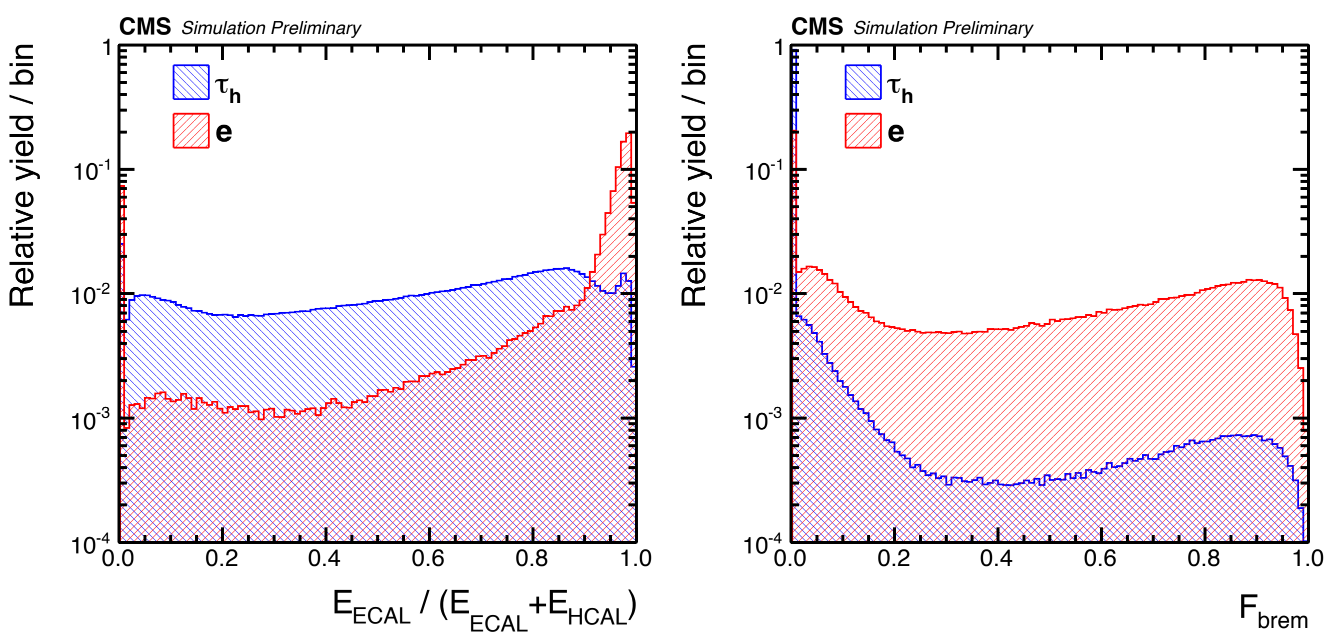


Electrons can easily mimic 1-prong τ's

If they emit bremsstrahlung can also be misidentified as 1-prong + (n)π^0 τ's

anti-electron
Boosted Decision Tree discriminator

- based on shape variables, HCal/ECal deposits, bremsstrahlung quantities and e/γ multiplicities
- training done on genuine taus from $Z/\gamma^* \rightarrow \tau\tau$ and fake taus from $Z/\gamma^* \rightarrow ee$
- medium WP: eff 80%, FR 3E-3

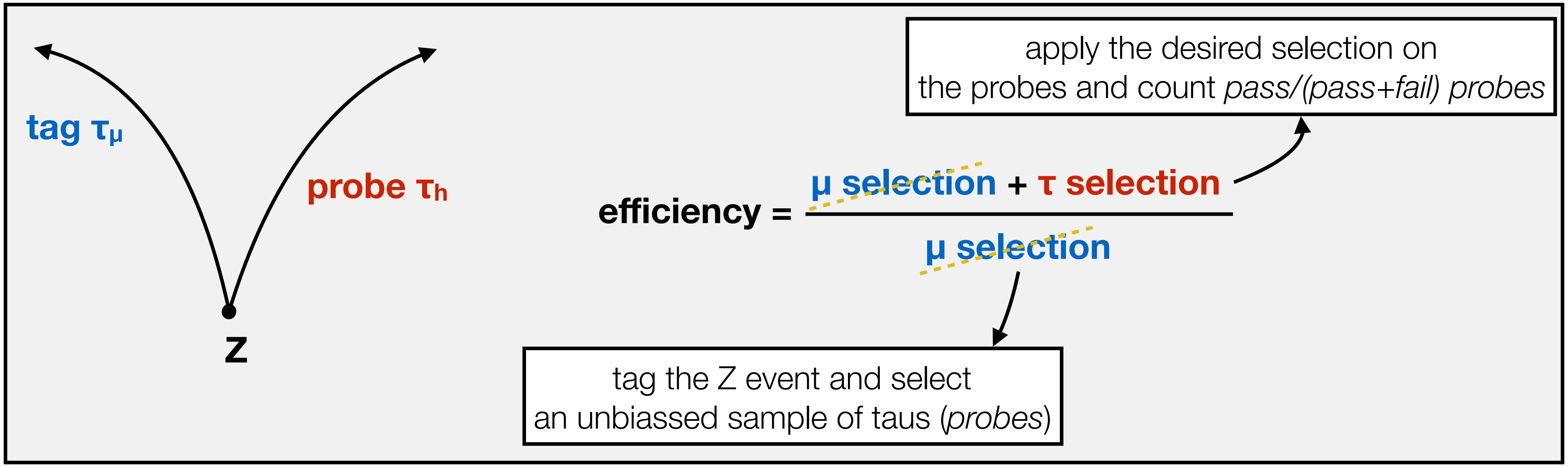


Tau identification performance on data

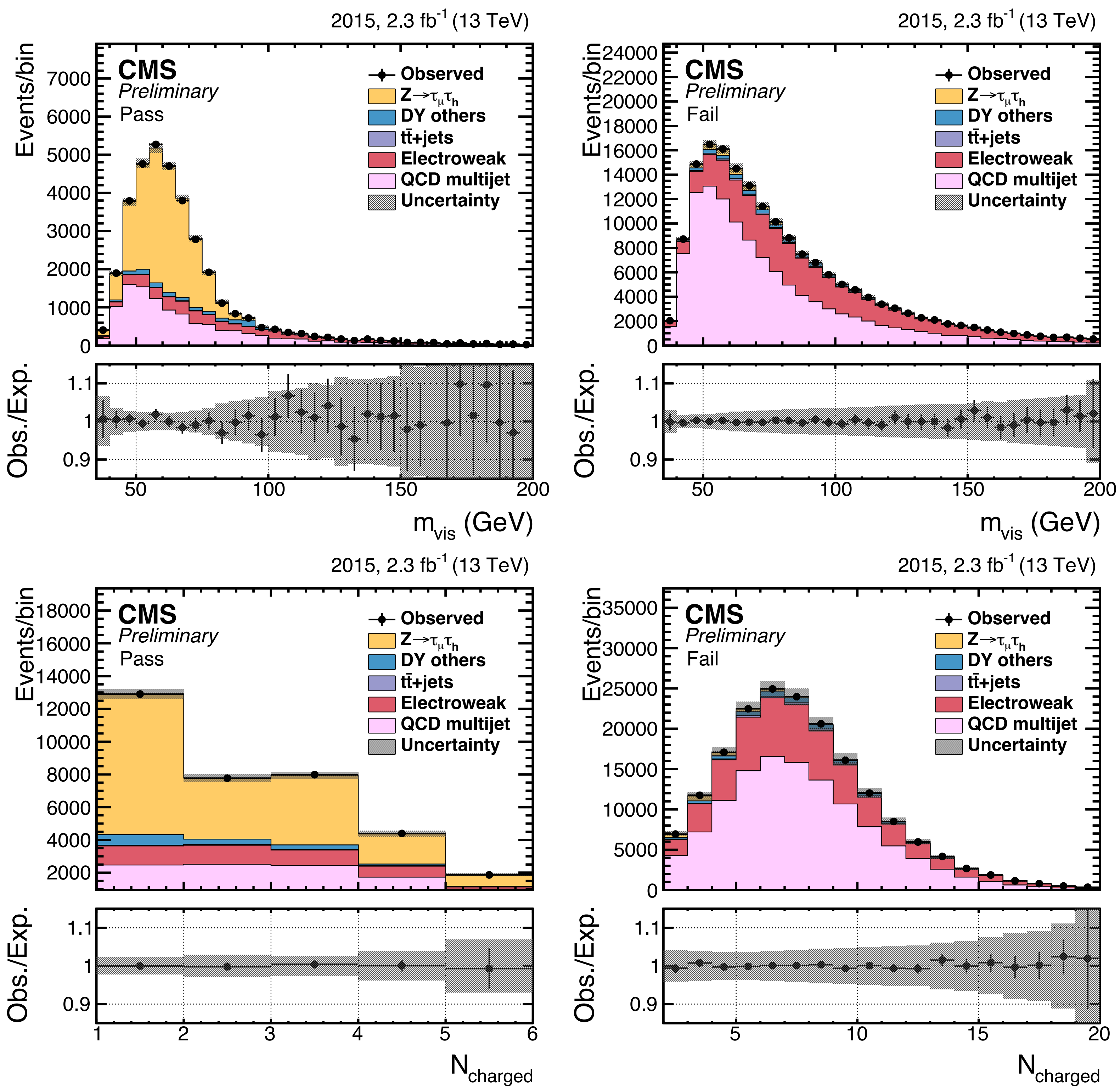
L = 2.3 fb^{-1} @ 13 TeV, 2015

Tau measurement techniques using data

- **$Z \to \tau\tau$ process is *the* standard candle for τ measurements in data**
- **different techniques are used**
  - $Z \to \tau_\mu \tau_h$ Tag&Probe — main method, workhorse
  - $Z \to \mu\mu$ / $Z \to \tau\tau$ — orthogonal method, different systematics
  - $W^* \to \tau\nu$ — to cover high p_T taus phase space



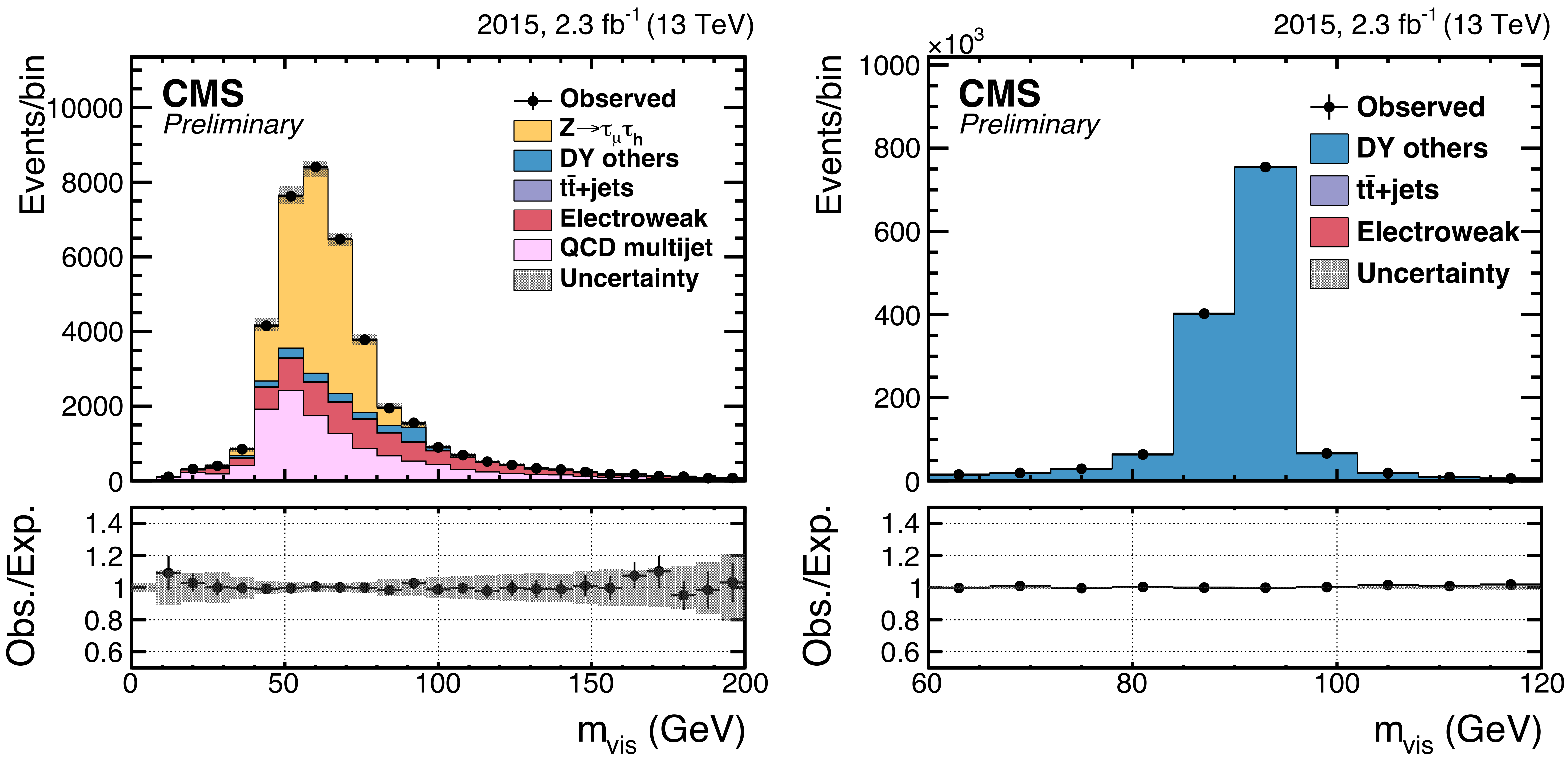
TauID efficiency measurement via T&P



T&P on $Z \to \mu\tau_h$ events

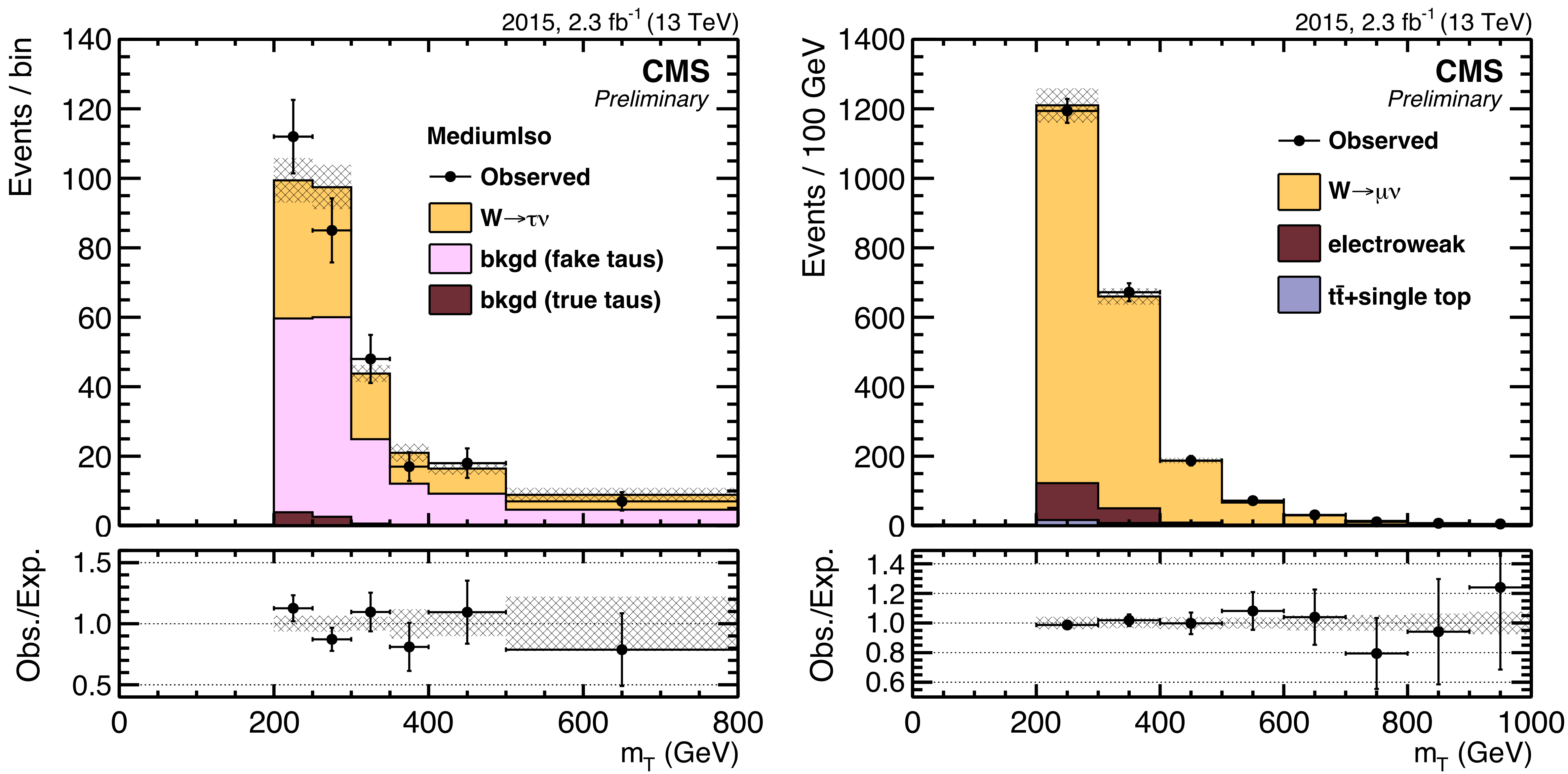
- τ_h isolation passing and failing probes
- two complementary observables:
  - visible $\tau_\mu\tau_h$ mass
  - track multiplicity in τ_h
- SFs compatible with 1. within 6% uncertainty

TauID efficiency measurement via $Z\rightarrow\tau_\mu\tau_h/Z\rightarrow\mu\mu$



- **similar selections to Zμμ and Zττ to improve Phase Space overlap. Cancellation of common systematic uncertainties: complementary to T&P**
- resulting SFs compatible with those obtained via T&P

TauID efficiency measurement at high p_T via $W^* \to \tau\nu$



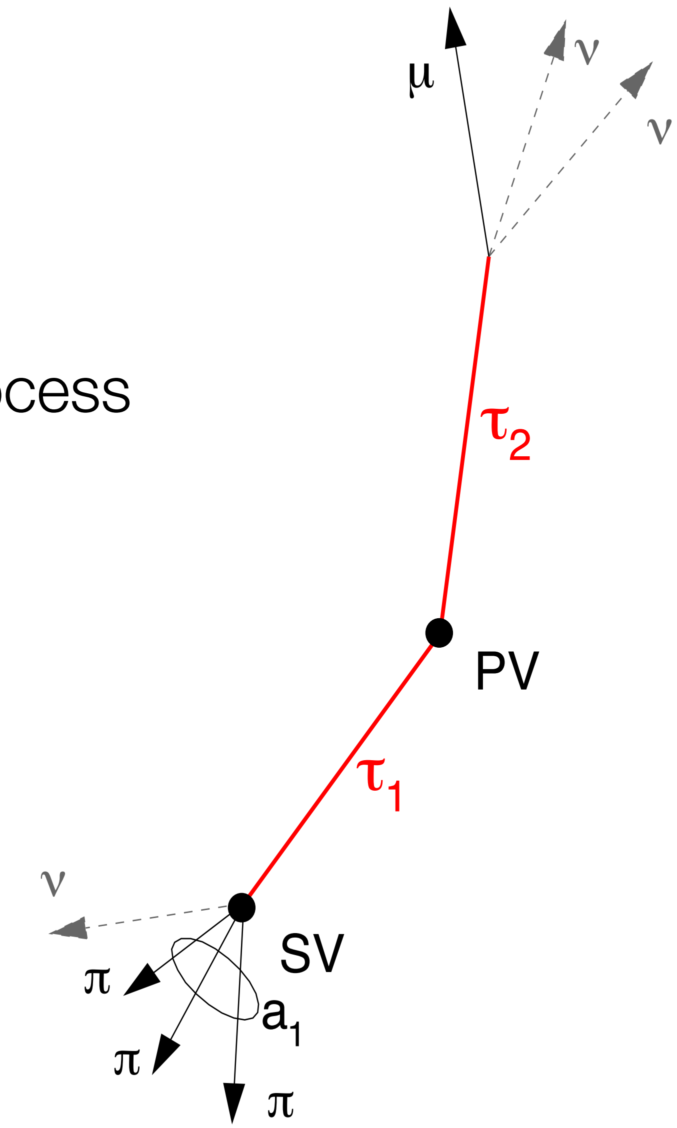
- **select highly virtual W boson (m_T > 200 GeV) to enrich the sample in high p_T taus**
- **similarly to the previous slide, use both $W^* \to \mu\nu$ and $W^* \to \tau\nu$**
- resulting SFs ~0.95 with 15% uncertainty

Tau helicity

https://cds.cern.ch/record/2216986

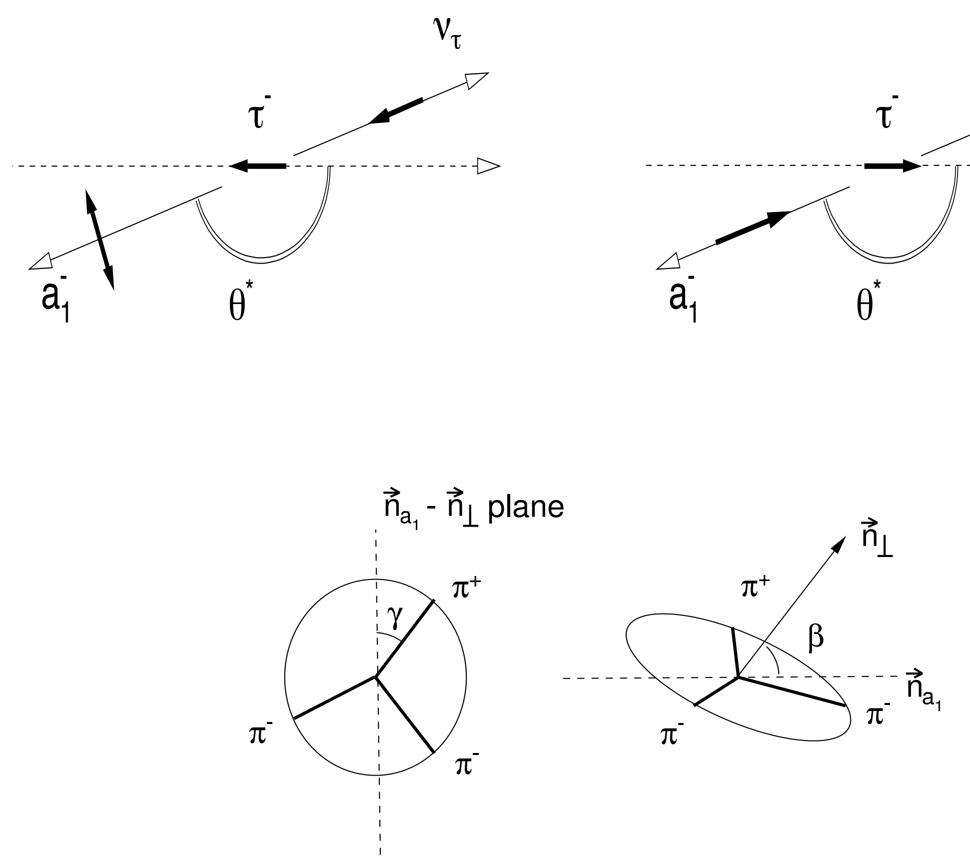
τ helicity measurement

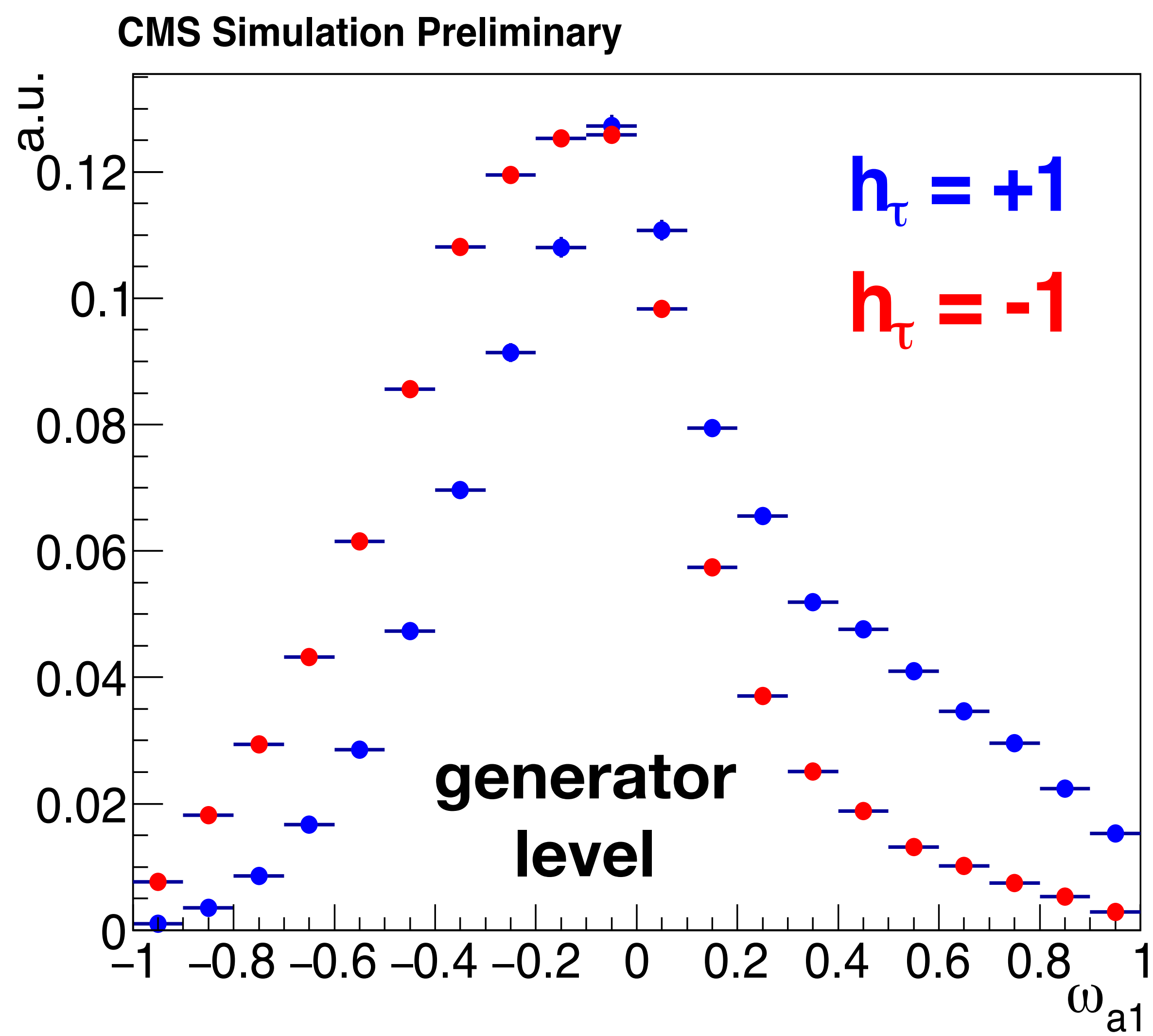
- **the τ polarisation is an interesting observable**
    - $\sin^2\theta_W \propto A_\tau = (N^+ - N^-)/(N^+ + N^-)$ where $N^\pm$ is the number of τ leptons with helicity ± 1 coming from the $Z \to \tau\tau$ process
    - Higgs CP properties can be measured through measuring the helicity of τ's from the $H \to \tau\tau$ process



- **tau spin can can be accessed through different polarisation-sensitive observables:**
    - **angular distributions of the τ decay products in $\tau^\pm \to a_1^\pm \nu_\tau \to \pi^\pm \pi^\pm \pi^\mp \nu_\tau$**
    - **energy asymmetry $E(\pi^\pm) - E(\pi^0)$ / $E(\pi^\pm) + E(\pi^0)$ in $\tau^\pm \to \rho^\pm \nu_\tau \to \pi^\pm \pi^0 \nu_\tau$**

τ helicity measurement - $\tau^{\pm}\to a_1^{\pm}\nu_\tau\to\pi^{\pm}\pi^{\pm}\pi^{\mp}\nu_\tau$

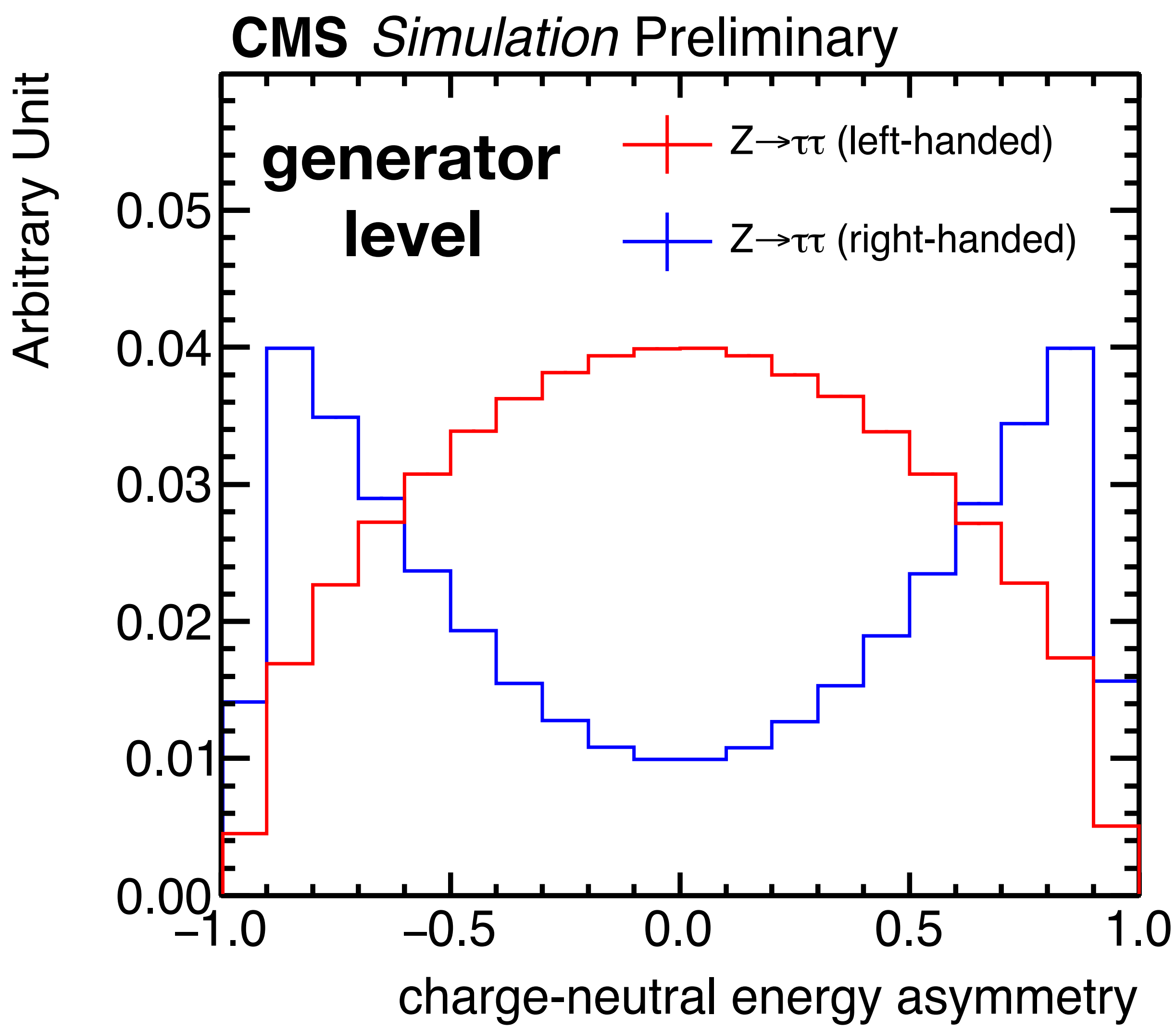


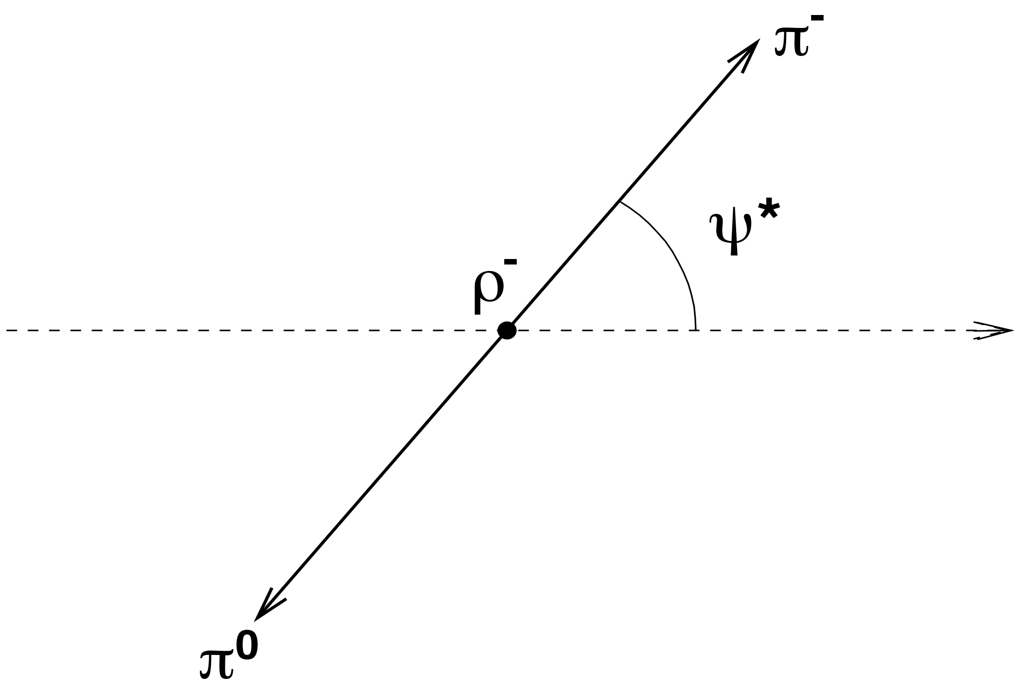


$$\omega_{a_1} = \frac{|M_+(\theta^*,\beta,\gamma)|^2 - |M_-(\theta^*,\beta,\gamma)|^2}{|M_+(\theta^*,\beta,\gamma)|^2 + |M_-(\theta^*,\beta,\gamma)|^2}$$

optimal 1D observable ∝ A_τ

τ helicity measurement - $\tau^{\pm} \to \rho^{\pm}\nu_{\tau} \to \pi^{\pm}\pi^{0}\nu_{\tau}$



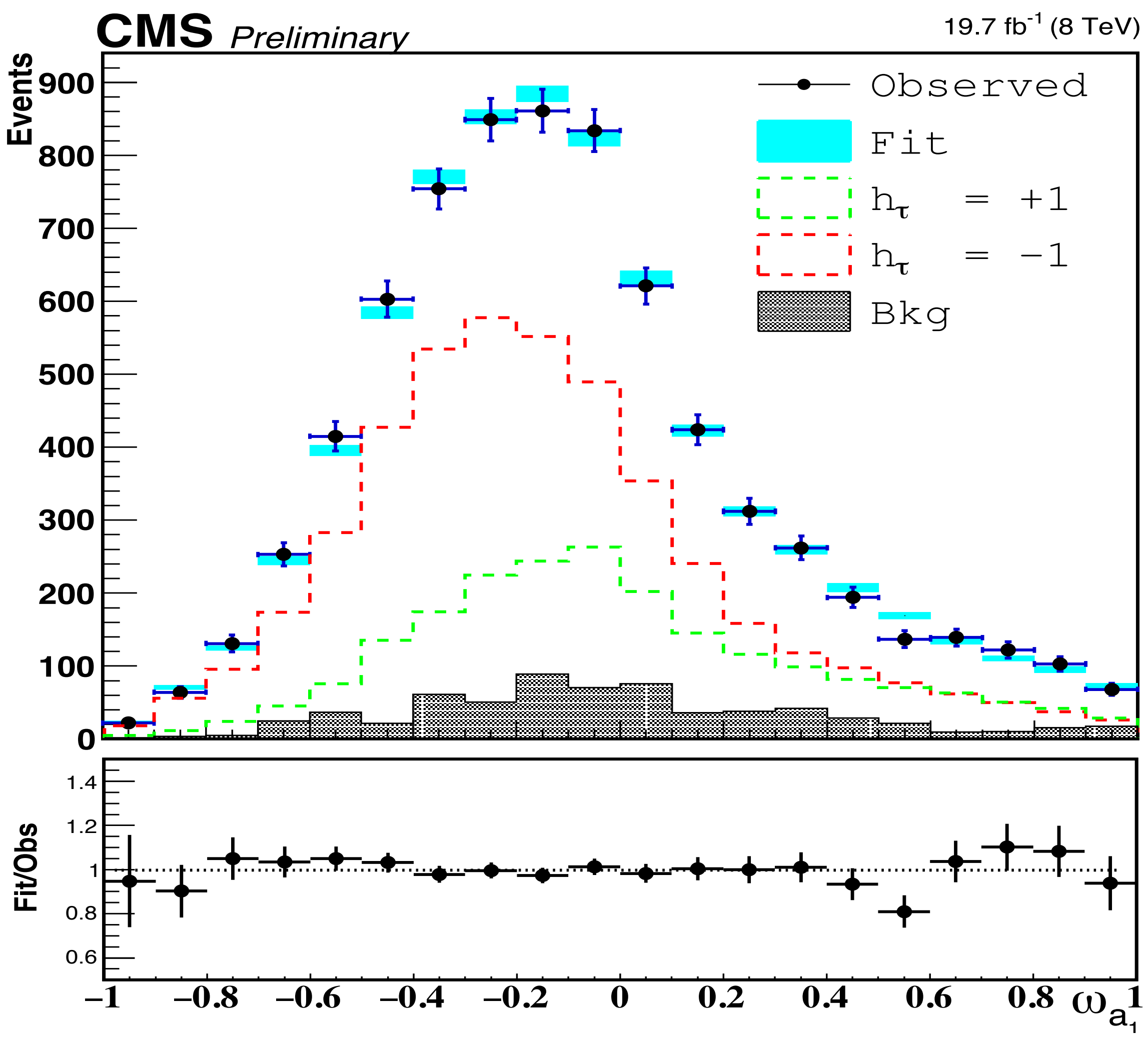


$$\cos\psi^* = \frac{m_\rho}{\sqrt{m_\rho^2 - 4m_\pi^2}} \frac{E_{\pi^-} - E_{\pi^0}}{|\vec{P}_{\pi^-} + \vec{P}_{\pi^0}|}$$

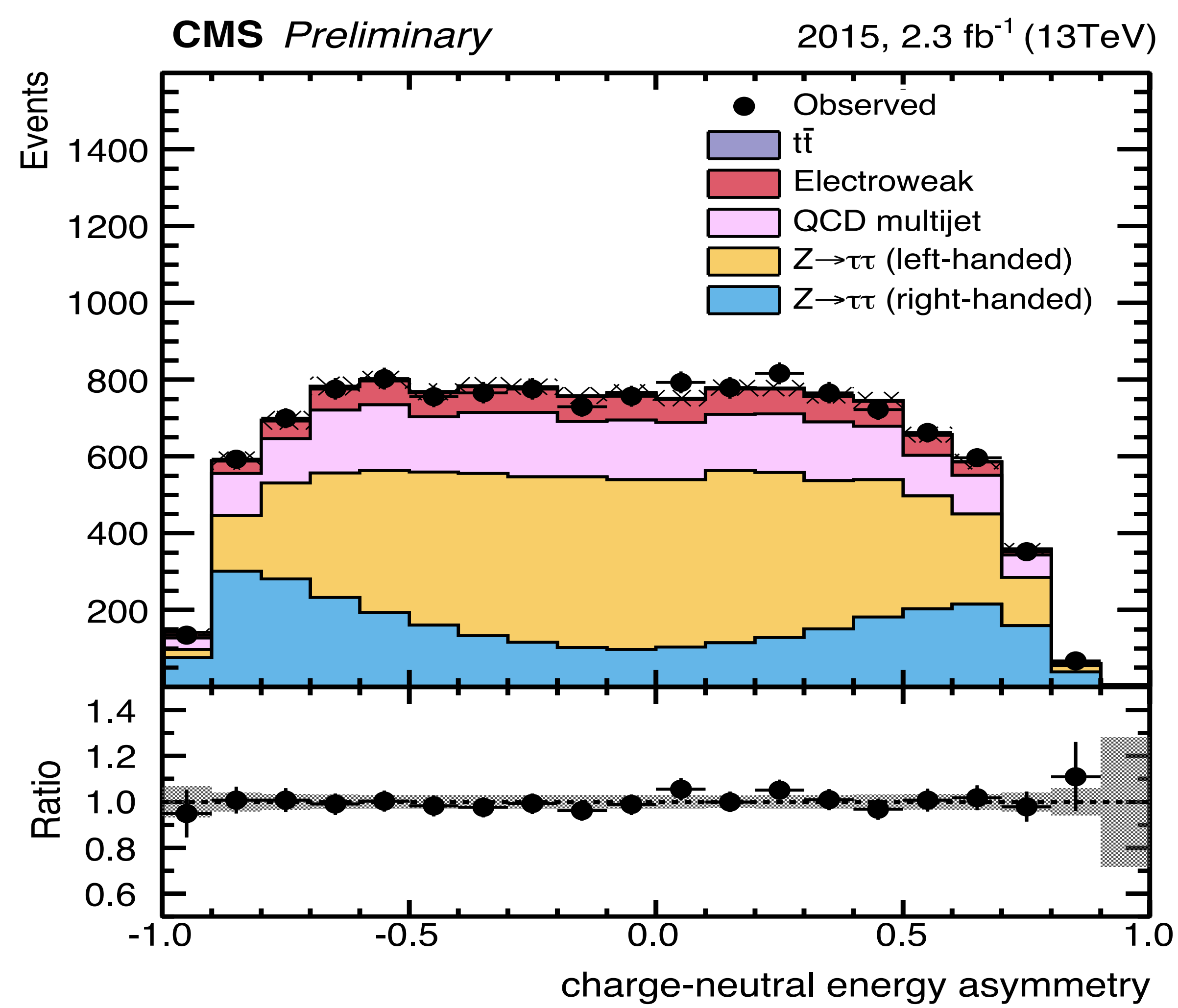
- **E_{ch}-E_n asymmetry ∝ cosψ* and polarisation-sensitive**
- detector effects (i.e. lower efficiency for soft π^0) only marginally smear the distribution shown here for the generator level

τ helicity measurement - validation on data

$\tau^{\pm} \to a_1^{\pm} \nu_{\tau} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}\nu_{\tau}$



$\tau^{\pm} \to \rho^{\pm}\nu_{\tau} \to \pi^{\pm}\pi^{0}\nu_{\tau}$



- **in both measurements the measured polarisation values are well compatible with MC prediction**
  - indication of **robustness of PF-based τ reconstruction algorithm**

Tau triggers

τ triggers

- **the CMS trigger system comprises two distinct subsystems:**
  - **Level-1:** hardware based, fast but coarse, 40 MHz → 100 kHz
  - **High Level Trigger:** software based, sophisticated but slower, 100 kHz → 1 kHz
  - **the goal is to maximise the signal efficiency at minimum cost in terms of rate and CPU time**

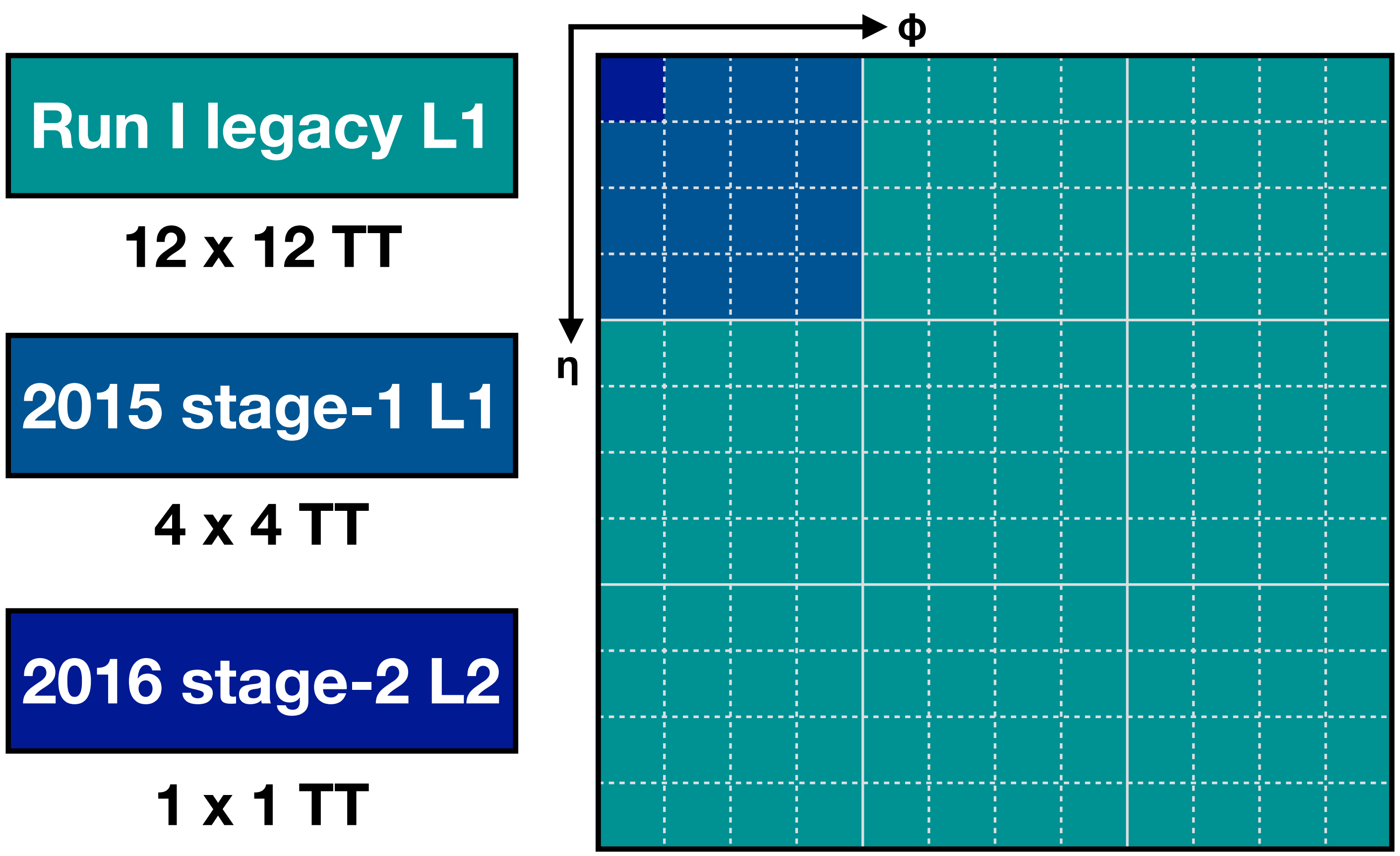
- **taus are reconstructed at both levels and a variety of triggers are used by the analyses, often as multi object triggers**

Tau triggers in 2016

Channel	typical trigger selection	used by
μτ	iso μ 19 GeV, iso τ 20 GeV	SM & MSSM H→ττ, hh→bbττ, Z'
eτ	iso e 22 GeV, iso τ 29 GeV	SM & MSSM H→ττ, hh→bbττ, Z'
ττ	double iso τ 35 GeV	SM & MSSM H→ττ, hh→bbττ, Z'
$\tau+E_T^{miss}$	iso τ 50 GeV, E_T^{miss} 100 GeV	$H^{\pm}\to\tau\nu$, W'
τ	iso τ 140 GeV	$H^{\pm}\to\tau\nu$, W'

Upgraded CMS Level 1 trigger

- **in 2016 the upgrade of CMS L1 trigger system has been completed**
- **the calorimetric system can now read out at much finer granularity**
    - L1 taus are purely calorimetric objects and vastly profit from the upgraded system



the minimal grain is a Trigger Tower (TT) 0.087η x 0.087ϕ, comprises 1 HCal unit and 5x5 ECal crystals

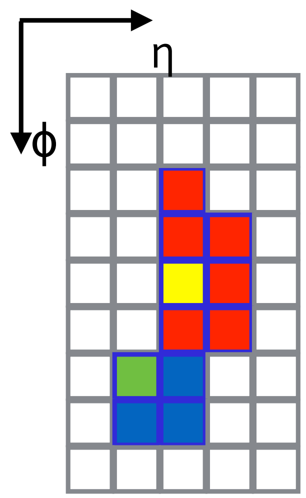
~ offline τ cone size

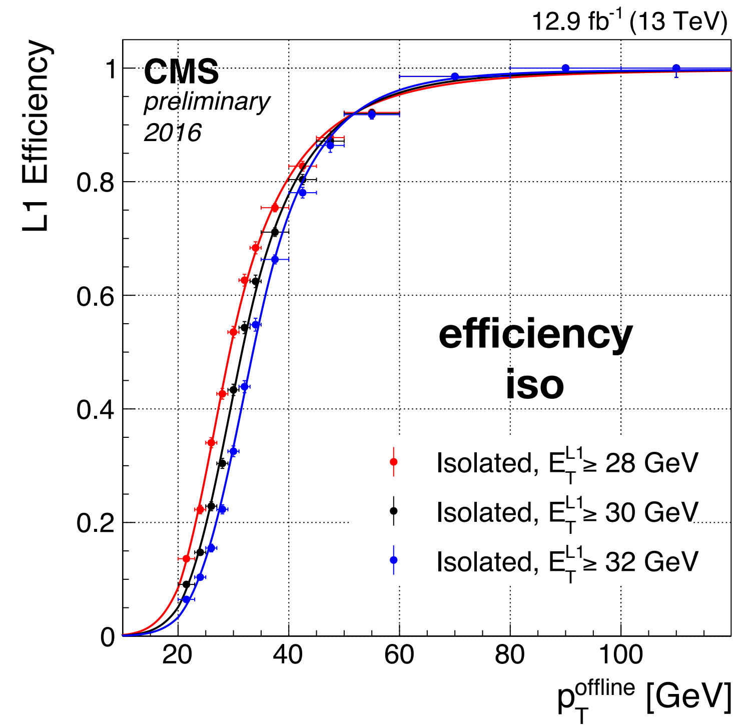
in 2016, CMS L1 can *'see'* each TT

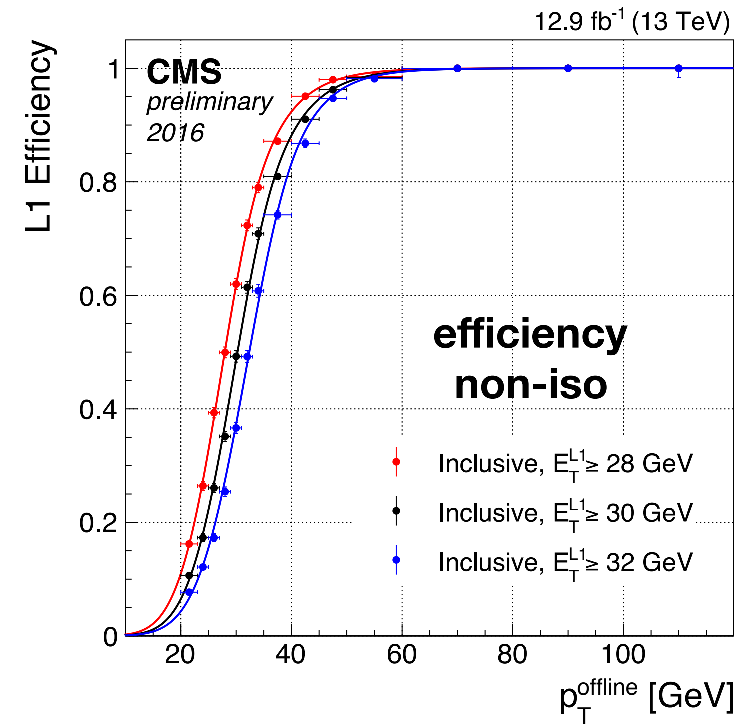
τ's at Level-1

τ identification

- build clusters around local maxima
- template shapes
- contiguous clusters can be merged
  - gather all the $\pi^{0/\pm}$ from τ decay





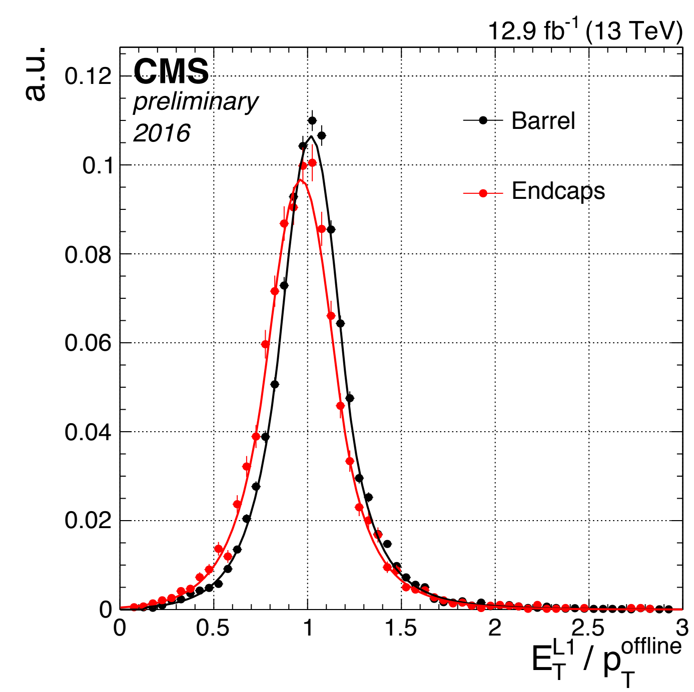


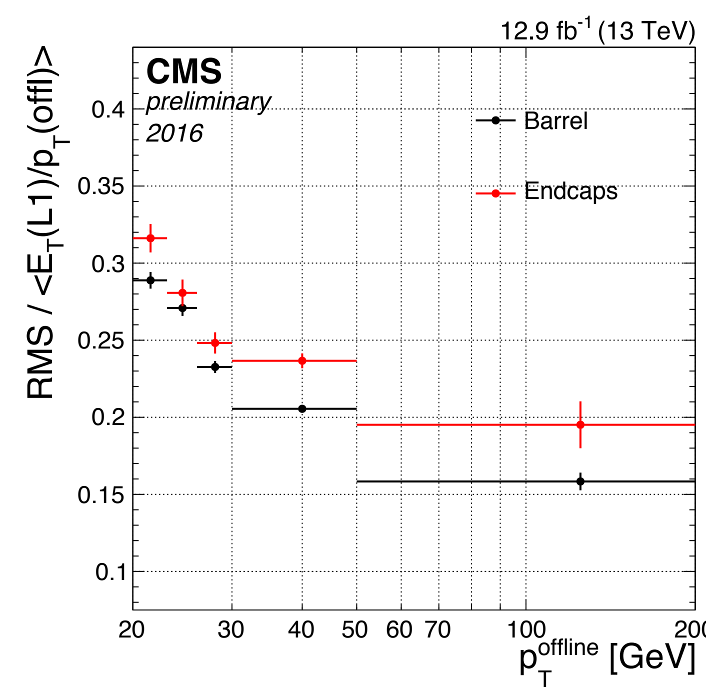
τ isolation

- compute energy in a 6x9 ηϕ region

pile-up subtraction

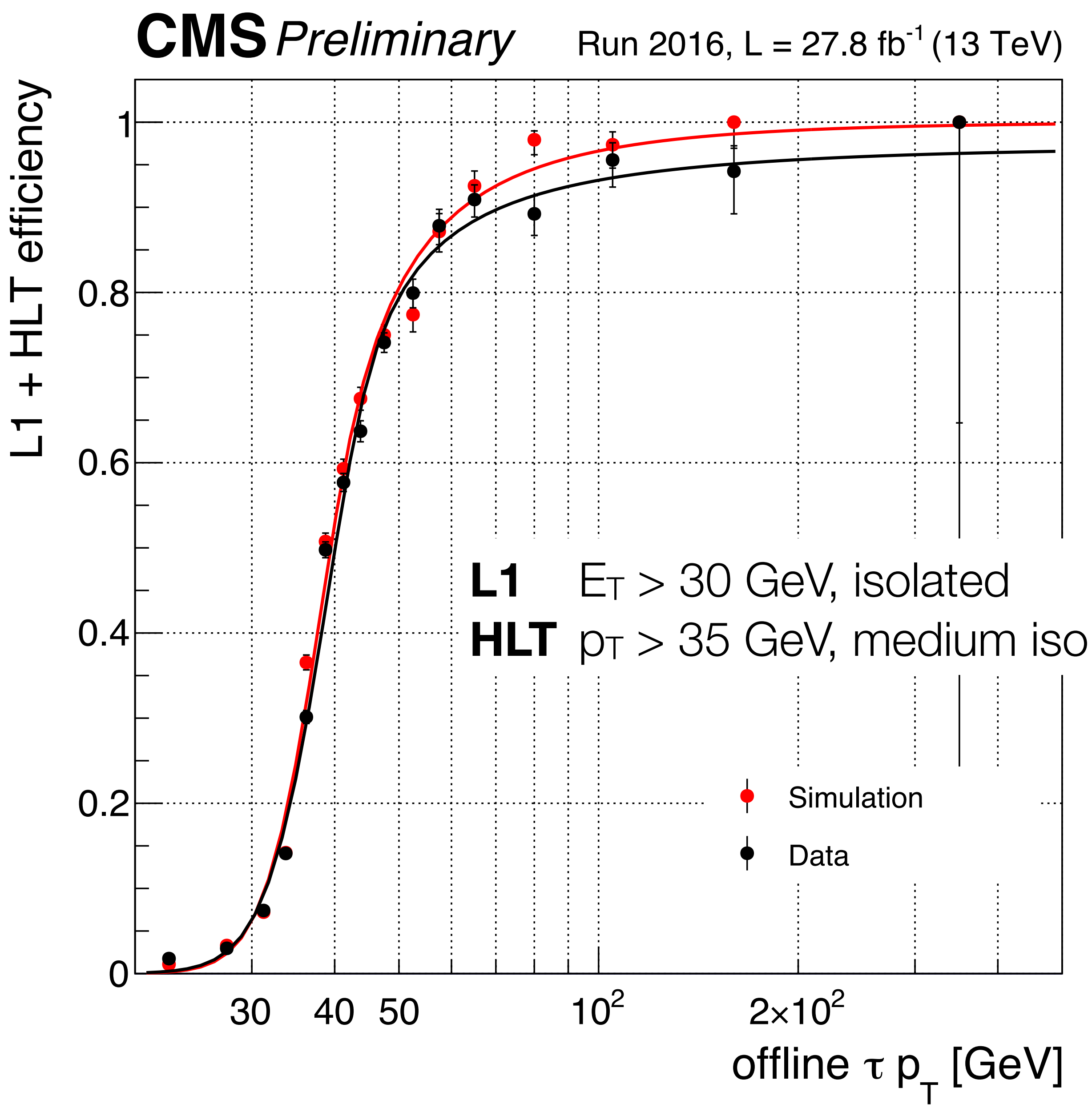
- estimate average PU by counting # of trigger towers with $E_T > 0$ GeV





τ's at HLT

- **based on ParticleFlow@HLT** (simplified tracking)
- **streamlined reconstruction:**
  - $\pi^{\pm}$ and $\pi^0 \to \gamma\gamma$ are built as in offline, but decay modes not explicitly enforced
  - main goal is to minimise CPU consumption preserving efficiency
  - cut-based isolation



Tau in CMS analyses

CMS analyses using taus

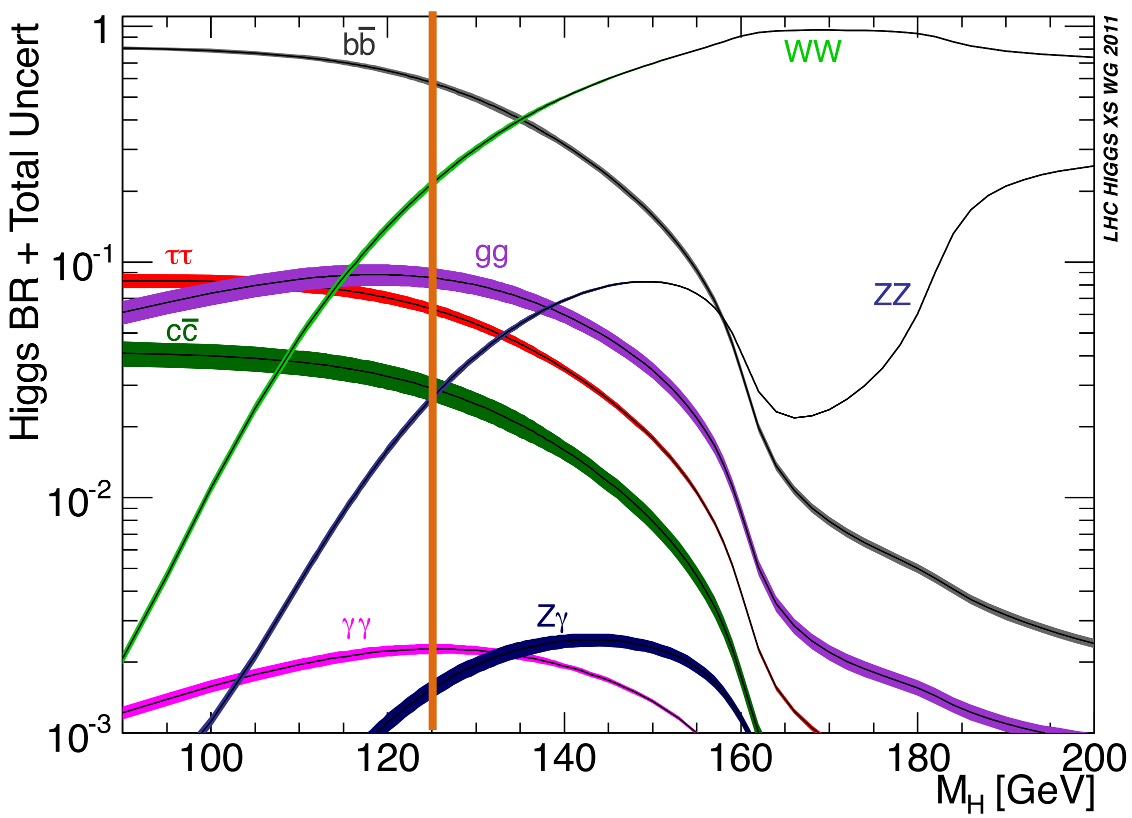
- **τ_h are used in several realms, both in SM and BSM scenarios**
  - couplings and search of new resonances
- **I will discuss only a subset of representative analyses**
  - SM $H\rightarrow\tau\tau$: couplings and properties
  - MSSM $\phi\rightarrow\tau\tau$ @13 TeV
  - $H^{\pm}\rightarrow\tau\nu$ @13 TeV
  - $X\rightarrow h_{125}h_{125}\rightarrow\tau\tau$ bb @13 TeV
  - LFV $H\rightarrow\mu\tau_{(e,h)}$
- all CMS public results are collected here
- many of the analyses presented in the following are being updated for coming Moriond17… stay tuned!

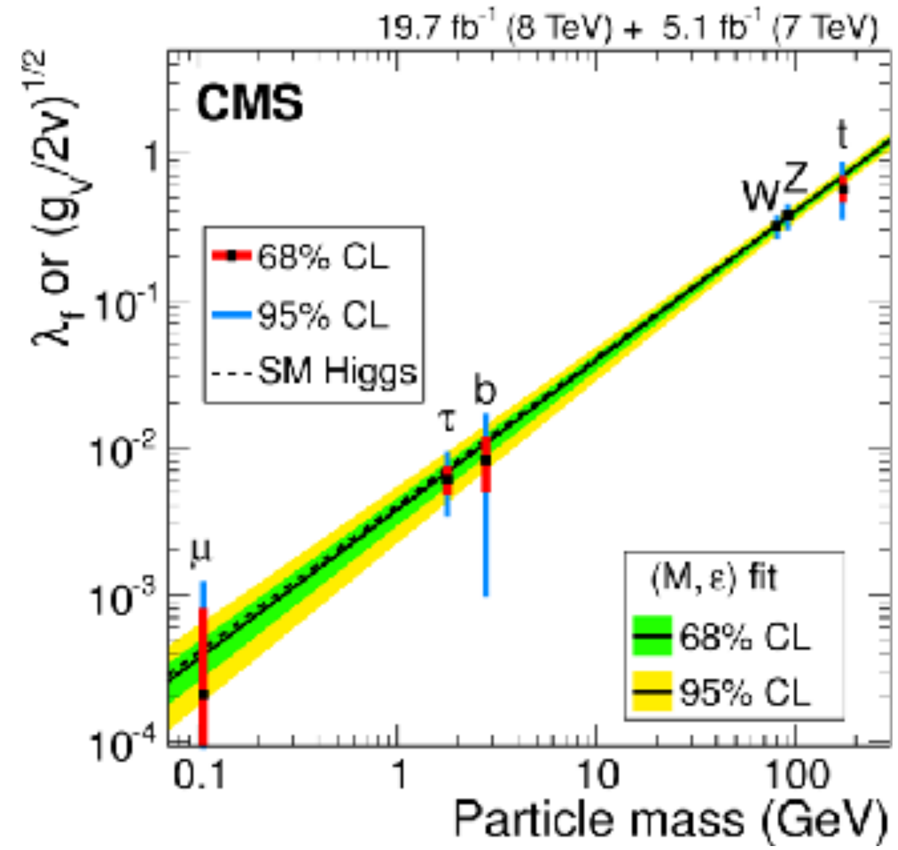
SM H→ττ

H→ττ analysis motivations

Boson with mass 125 GeV discovered by ATLAS & CMS

is this the SM Higgs boson? ⇒ measure the couplings



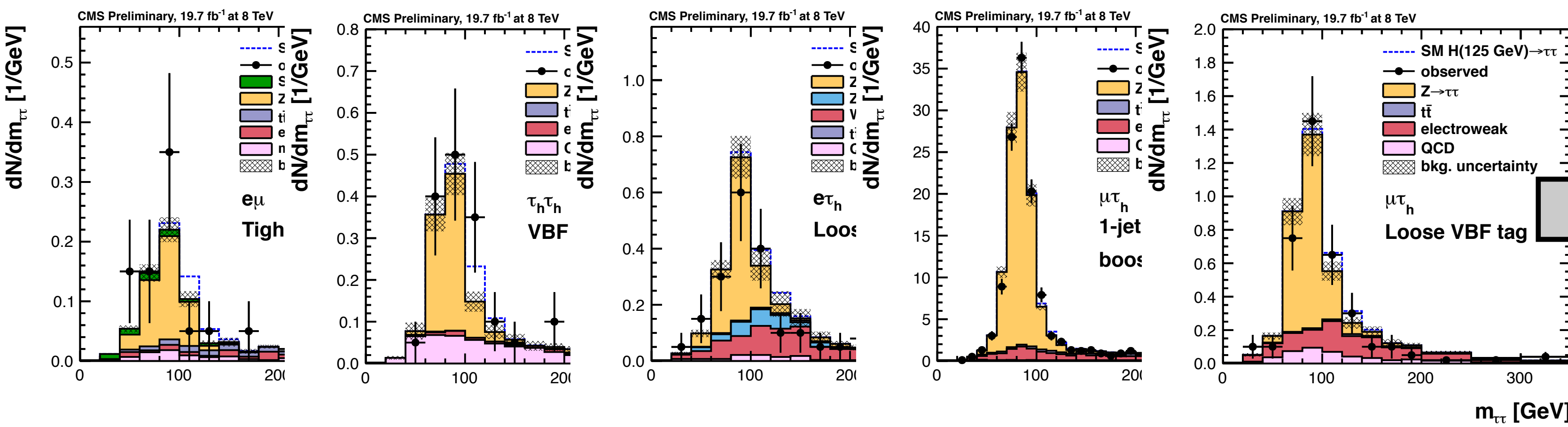


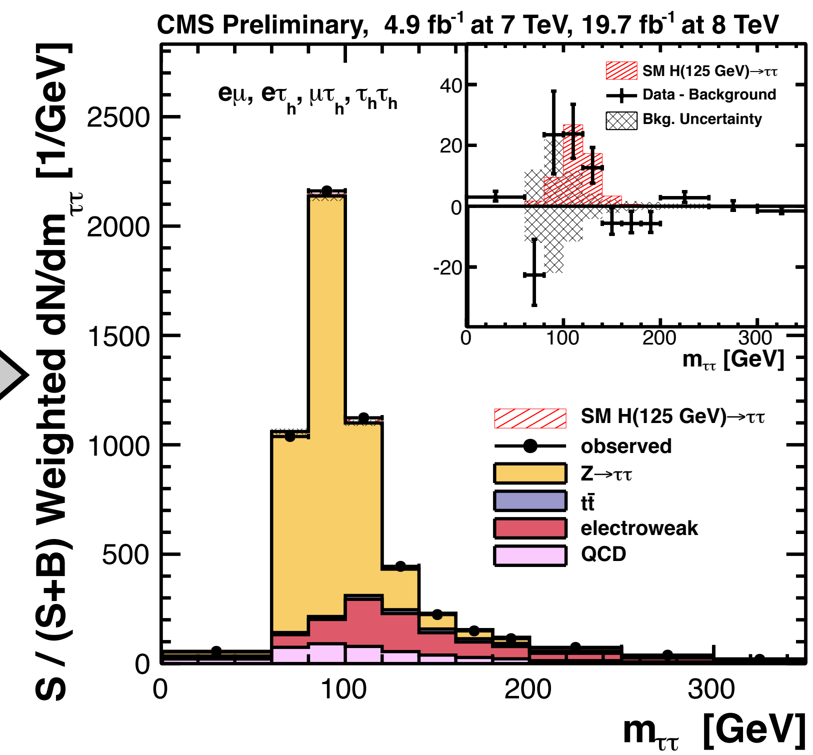
- **H→ττ main probe to test Higgs Yukawa coupling to fermions**
- **τ is heavy:** sizeable BR(H→ττ) = 6.3% at m_H = 125 GeV
- **cleaner experimental signature than H→bb**

SM H→ττ analysis

J. High Energy Phys. 05 (2014) 104

- **complex analysis:**
    - (6 di-τ final states) x (VBF, VH, ggF) x (categories)

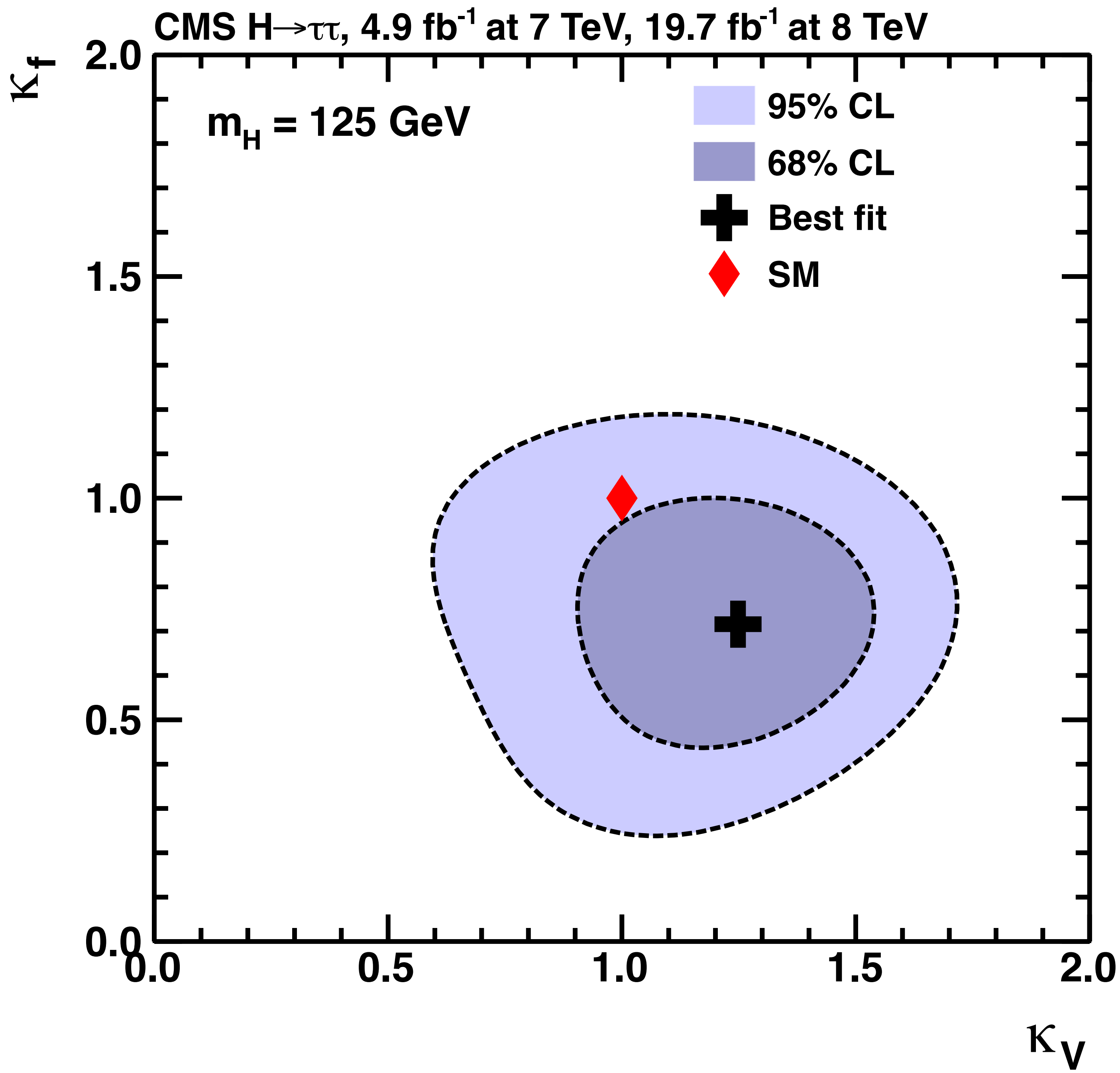


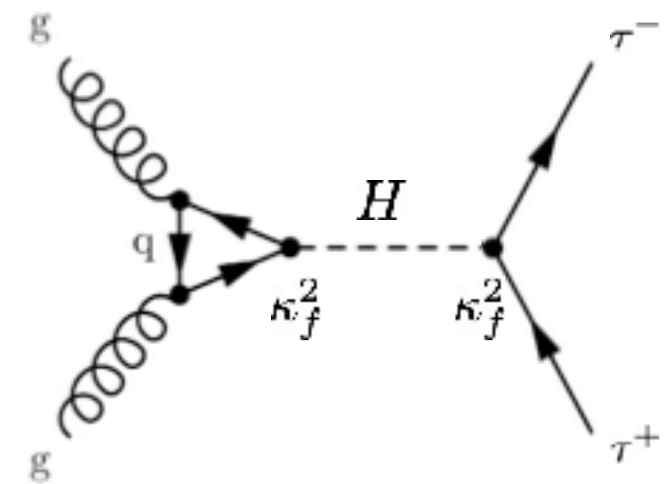


- **relies on reconstructing $m_{\tau\tau}$ using SVfit**
- Run2 analysis will be published soon:
    - Run1 sensitivity surpassed only with the full 2016 statistics
    - 8 → 13 TeV made BSM searches more interesting with the first data

H→ττ as a probe to fermion couplings

[J. High Energy Phys. 05 (2014) 104](#)





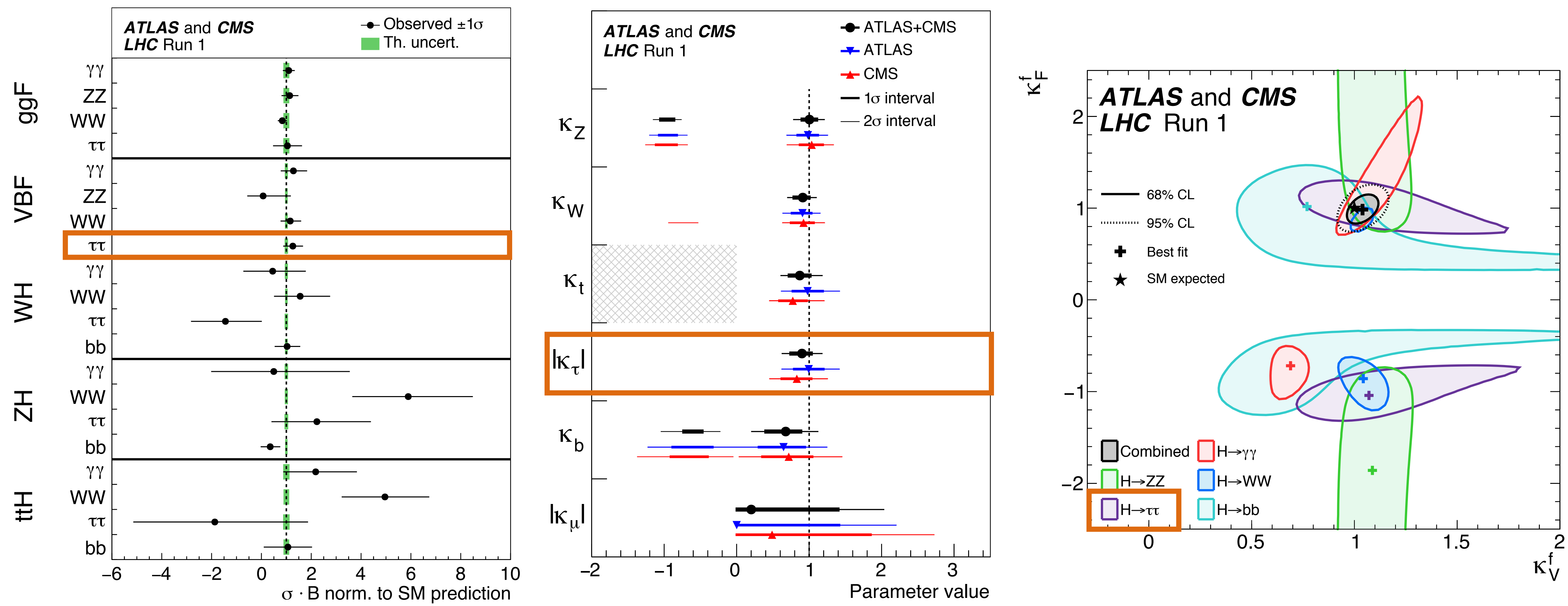
H →ττ very sensitive channel to kf

kf measured with 30% precision

sensitivity to kV from VBF and VH

H→ττ in the big Higgs picture

J. High Energy Phys. 08 (2016) 045



- **ATLAS + CMS: 5σ H→ττ observation!**
- **provides strong constraints on:**
  - fermion coupling modifier κ_F
  - VBF H cross section

serves both as measurement and as search through deviations

MSSM A/H and $H^{\pm}$

H/A→ττ and $H^{\pm}$→τν as a probe for MSSM

the Minimal Supersymmetric Standard Model is the simplest extension to the SM including SUSY partners of the SM particles

- **5 Higgs bosons**
  - **2 charged $H^{\pm}$**
  - **3 neutral** (collectively labelled as ϕ)
    - 1 light **h** (SM-like)
    - 2 heavy **A/H** (CP-odd/even)

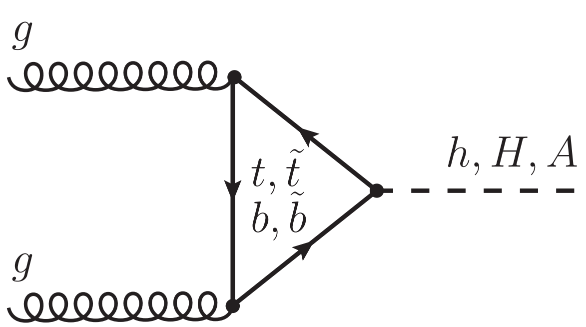
- **two parameters describe the model at the tree level**
  - m_A mass of the heavy CP-odd Higgs
  - **tanβ** related to ratio of the couplings to up/down-type fermions

for moderate-to-large values of tanβ, the couplings to τ's are greatly enhanced

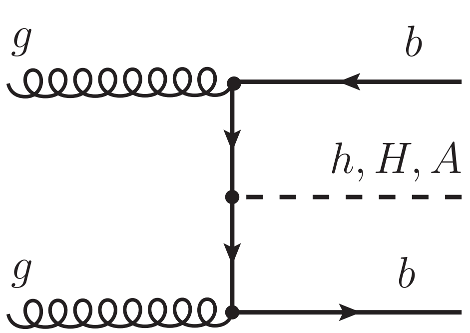
MSSM H/A→ττ - strategy

https://cds.cern.ch/record/2231507

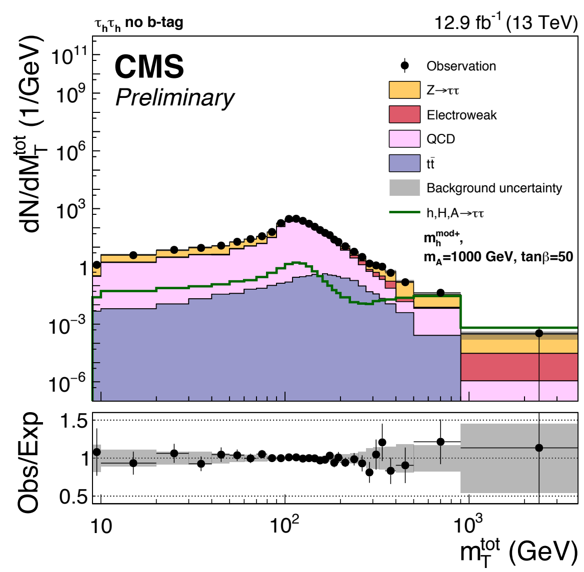
- four final states considered **μτ, eτ, ττ** and **eμ**
- **two categories based on the presence of b-jets** to address the two dominant production modes

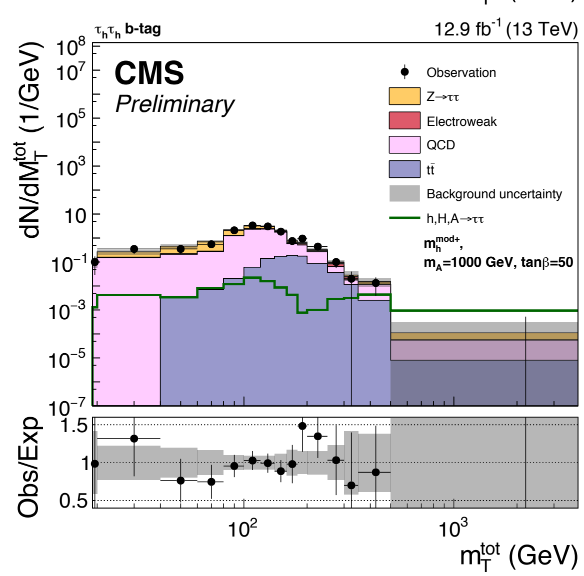


no b-tag



b-tag

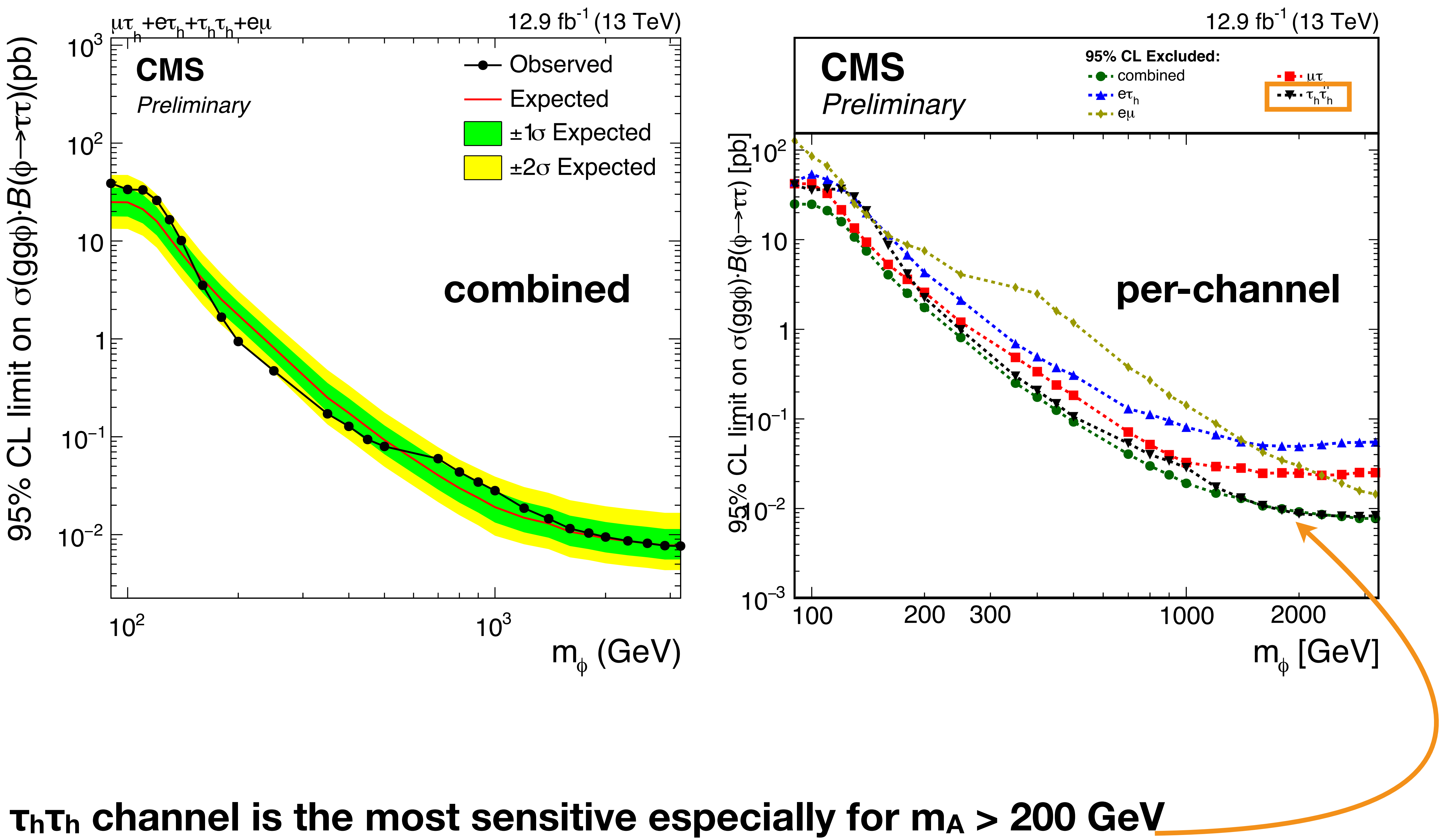




- **fit to the total transverse mass distribution m_T^{tot}**

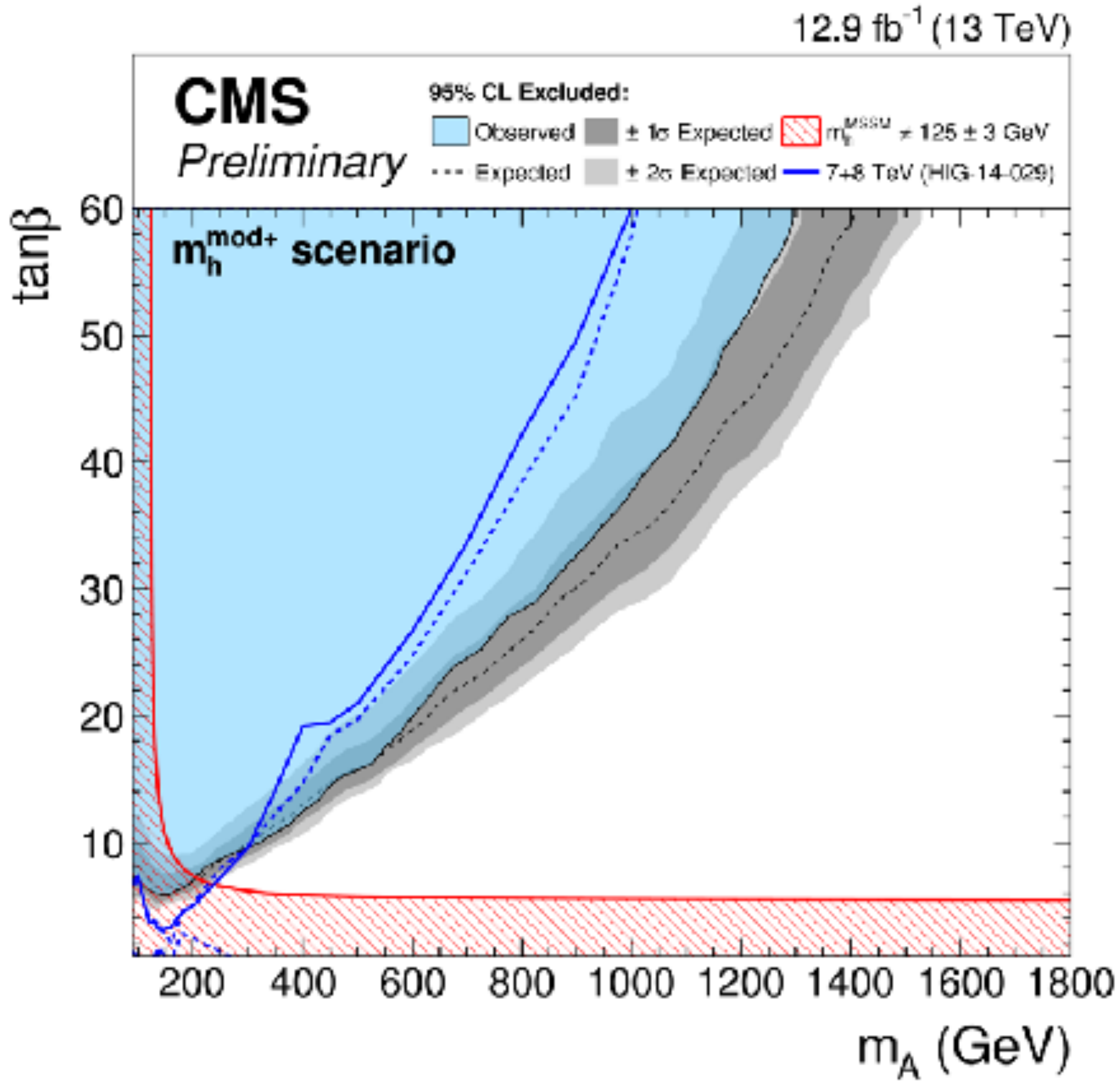
$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_1^{\mathrm{vis}})^2 + m_{\mathrm{T}}(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_2^{\mathrm{vis}})^2 + m_{\mathrm{T}}(\tau_1^{\mathrm{vis}}, \tau_2^{\mathrm{vis}})^2}$$

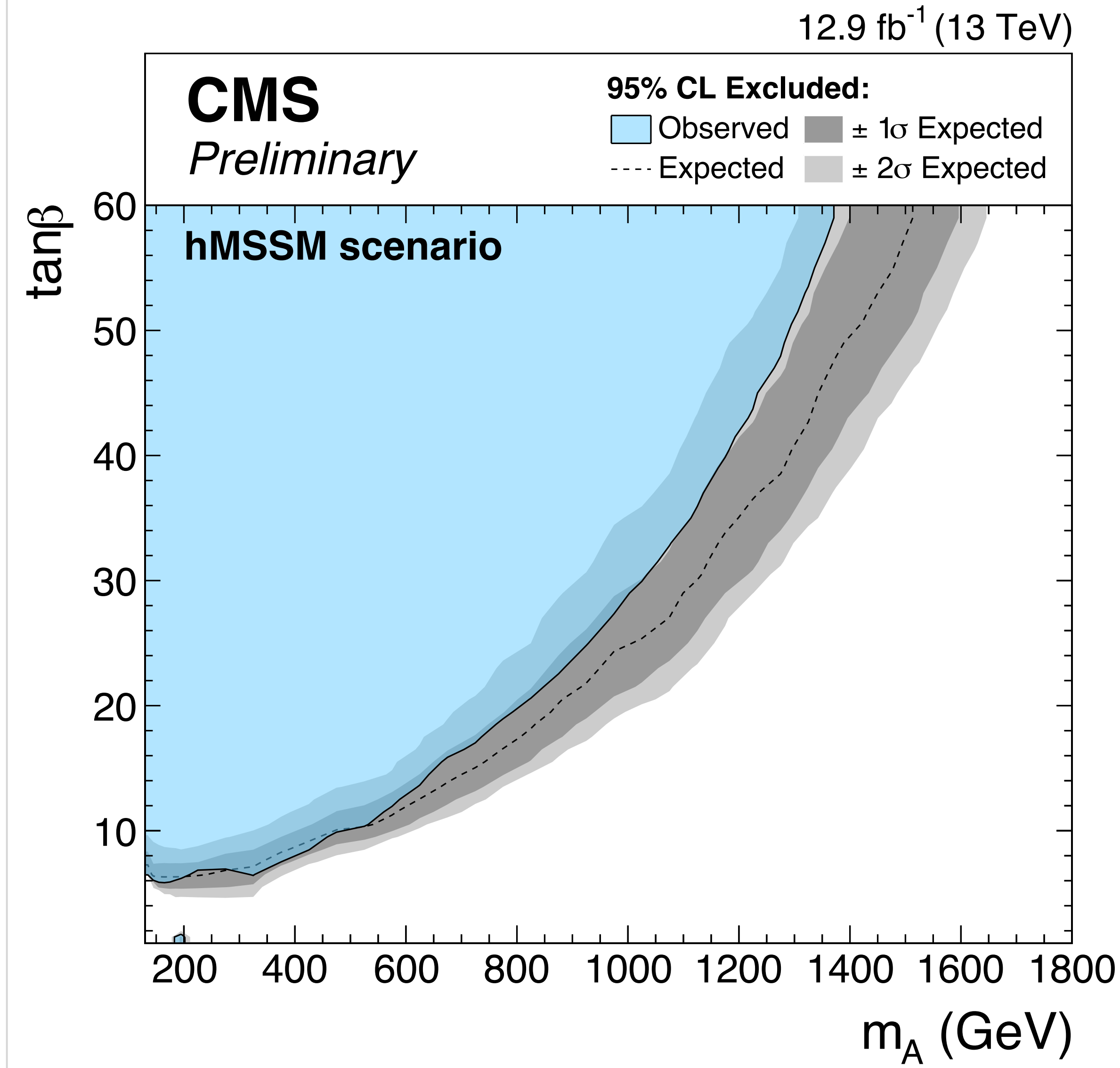
MSSM H/A→ττ - model independent results



- **$\tau_h\tau_h$ channel is the most sensitive especially for m_A > 200 GeV every improvement on τ reconstruction/ID impacts here directly**

MSSM H/A→ττ - model dependent results





- **exclusion contour in the MSSM vs SM hypothesis test**
- **already surpassed Run-1 performance at high mass thanks to 8→13 TeV and both analysis and τ_h improvements**

$H^{\pm}\rightarrow\tau\nu$ - strategy

https://cds.cern.ch/record/2223865

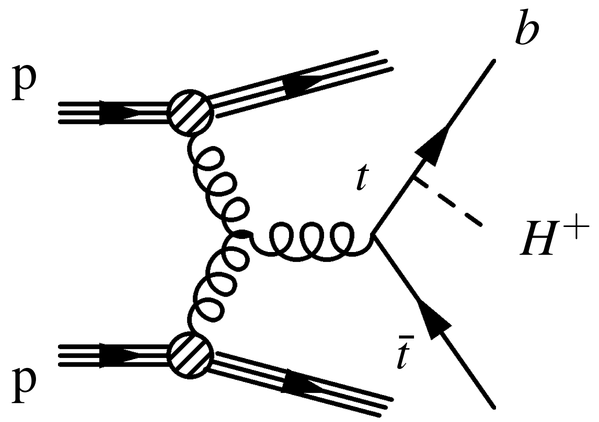
- **two different scenarios:**

heavy charged Higgs:	$m_{H\pm} > m_t - m_b$
light charged Higgs:	$m_{H\pm} < m_t - m_b$

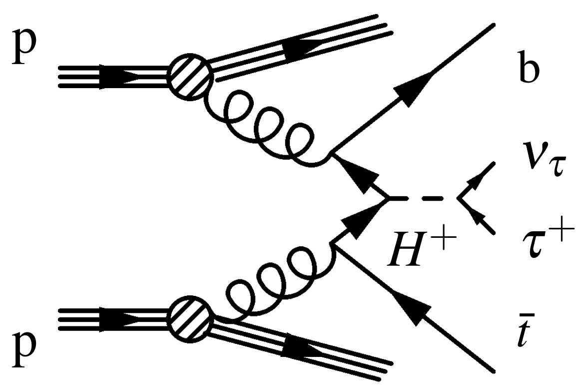
sensitivity dominated by $H^{\pm}\rightarrow tb$

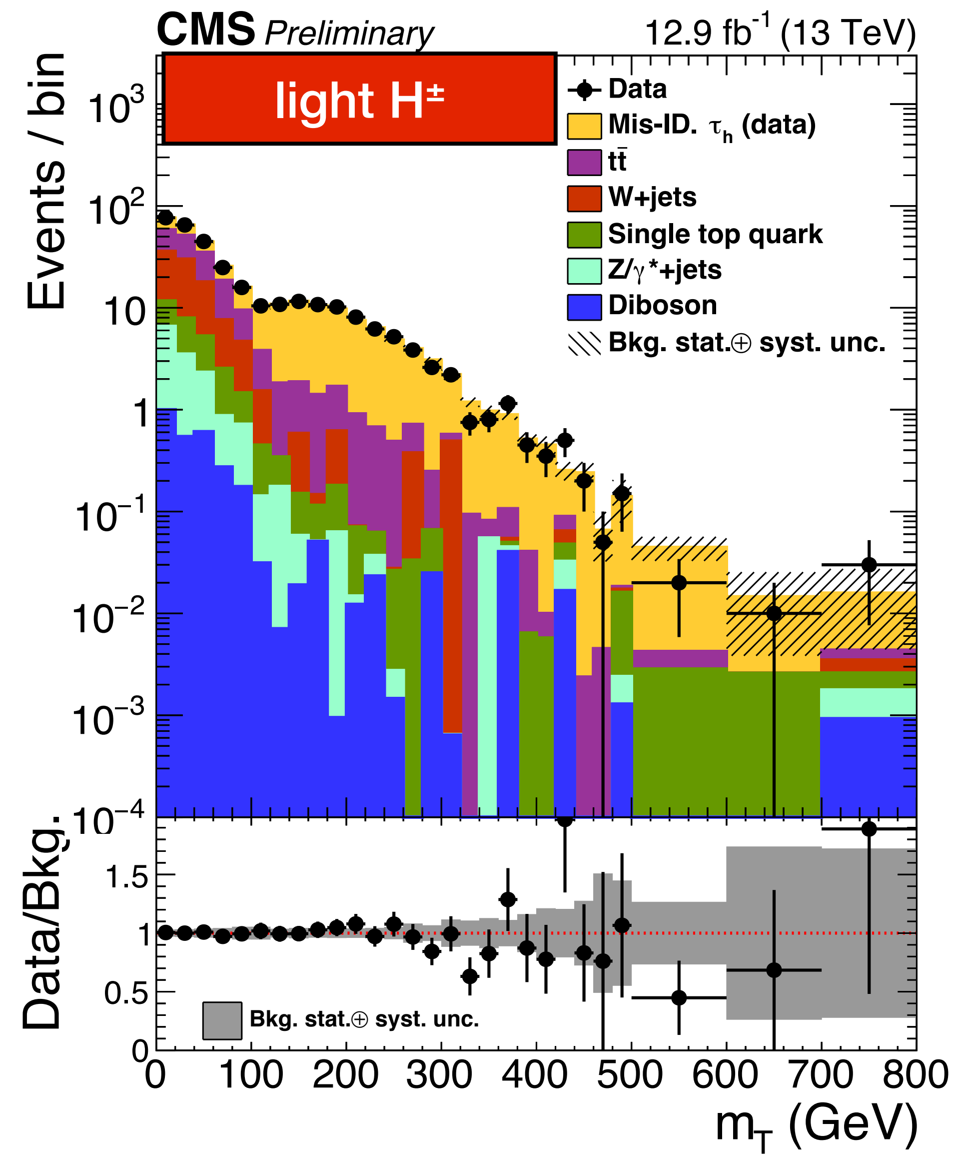
sensitivity dominated by $H^{\pm}\rightarrow\tau\nu$

light H±



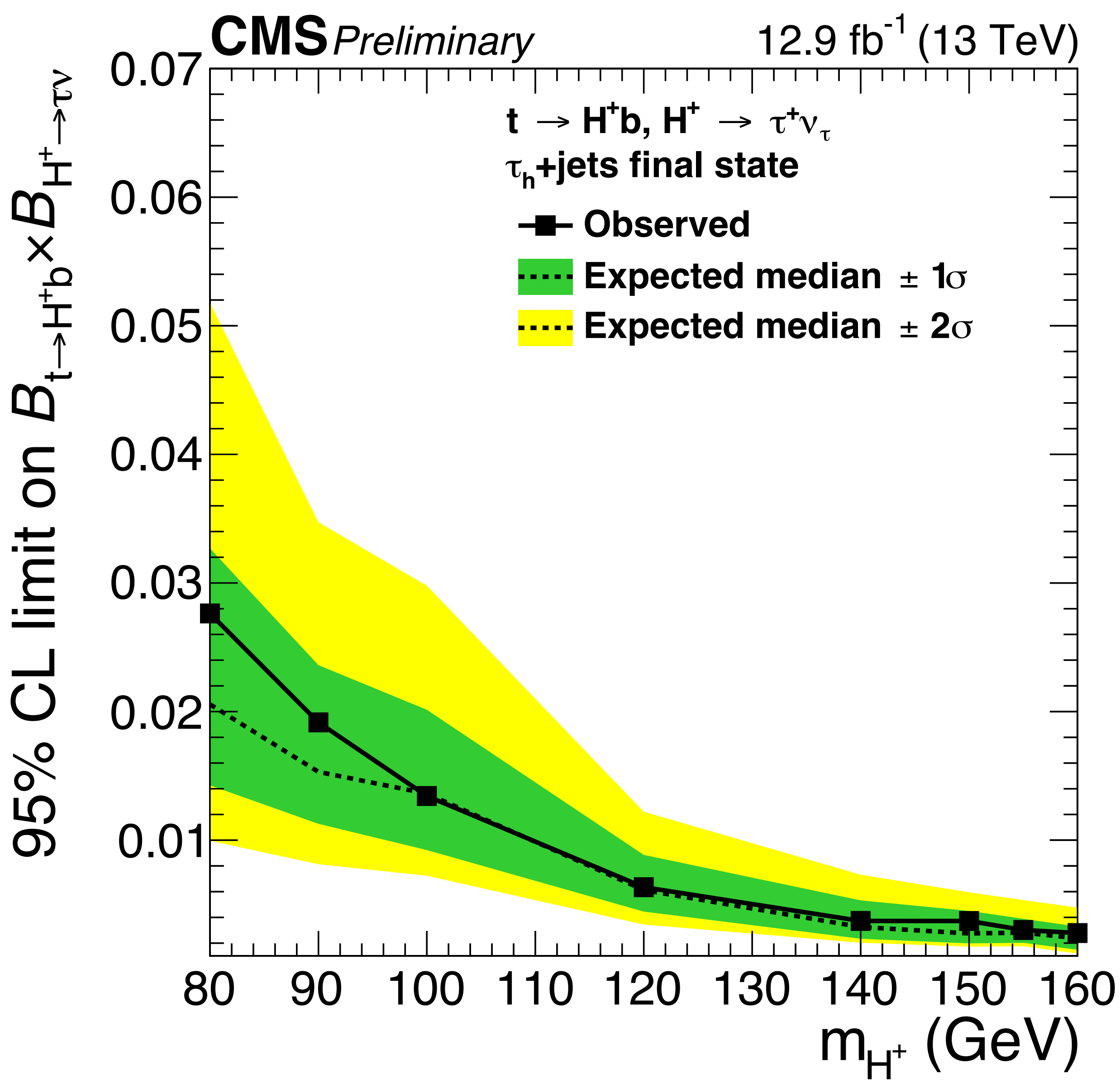
heavy H±

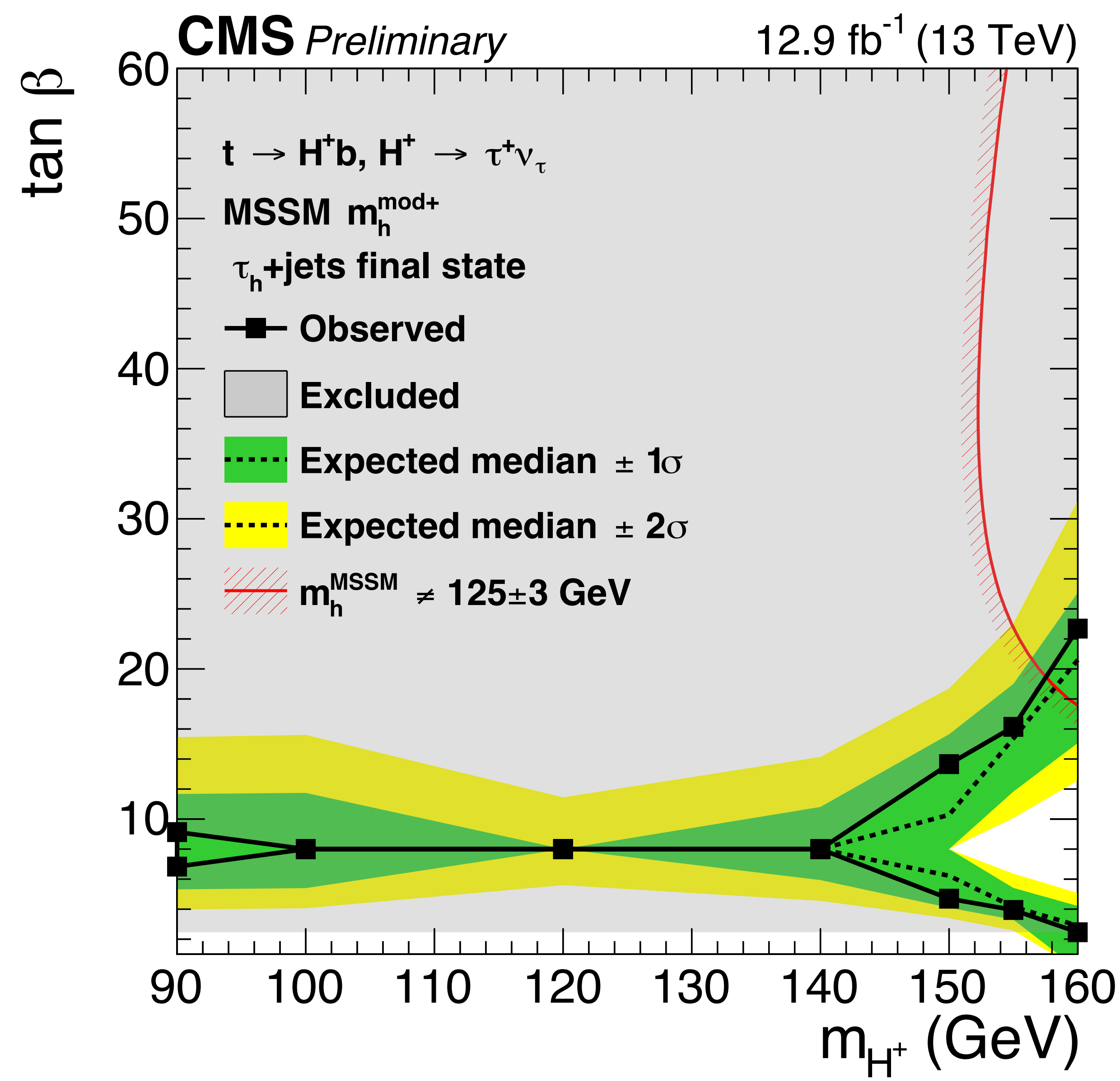




- **signature:** 1 τ_h, ≥ 3 jets, ≥ 1 b-jets, E_T^{miss} and 0ℓ
- different kinematic selections for the two scenarios
- **topological selections:** $\Delta\phi(\tau_h, E_T^{miss})$ vs $\Delta\phi(\text{jet}, E_T^{miss})$
- **signal extraction through a fit to m_T distribution**

H± → τν - results

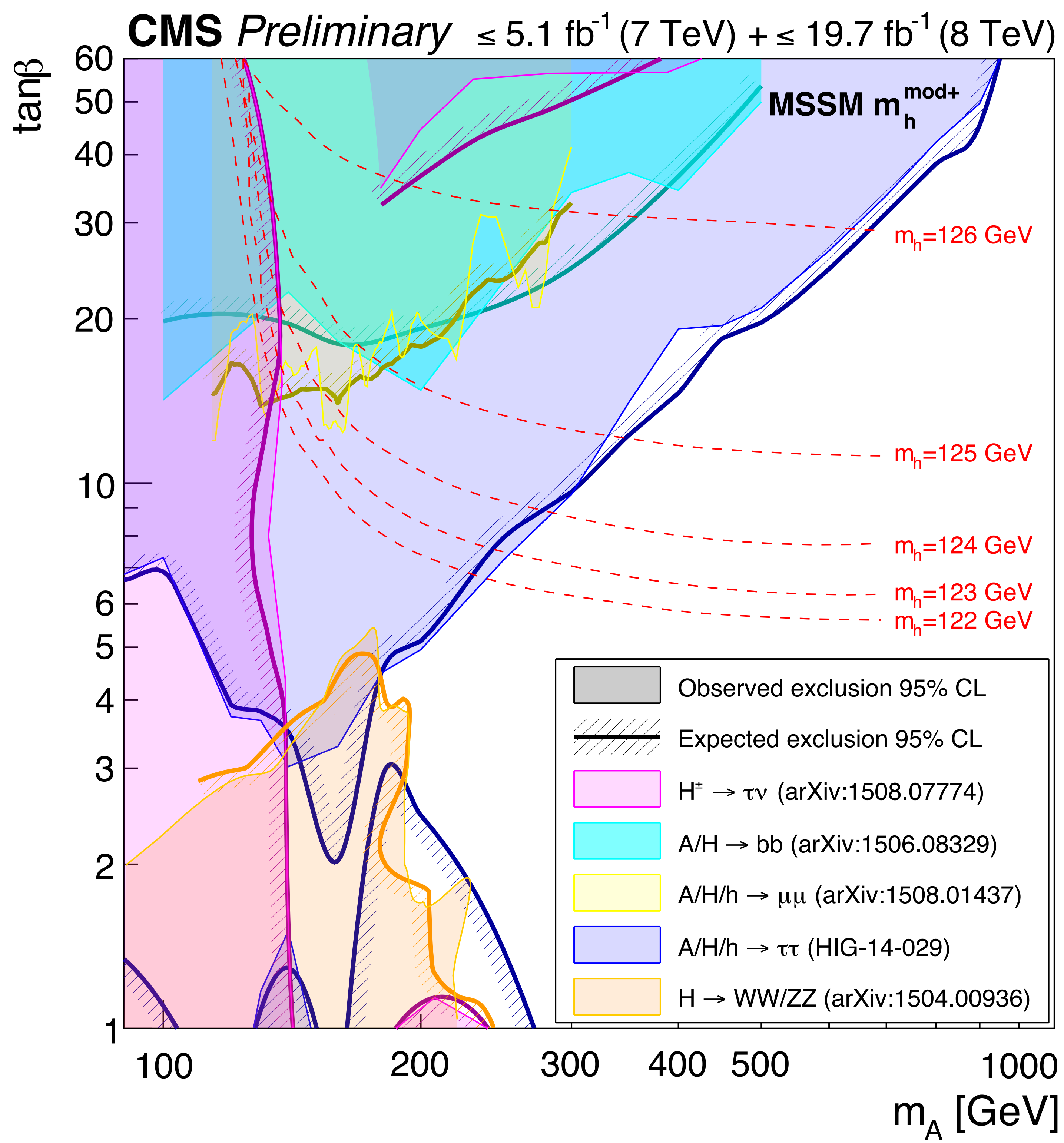




- **light H± almost ruled out in MSSM m_h^{mod+}** (and most of other) **scenario**(s)

Summary of MSSM analyses - 8 TeV

https://cds.cern.ch/record/2142432



H→ττ dominates the exclusion in the large tanβ region

H±→τν rules out the low mass region

τ analyses driving force of MSSM H bosons searches

Lepton Flavour Violation

Search for Lepton Flavour Violating $H\rightarrow\mu\tau_{(e,h)}$

- **LFV Higgs decays are prohibited in the SM, but can arise in a vast number of BSM models**
    - 2HDM, SUSY, composite Higgs, Randall-Sudrum, …

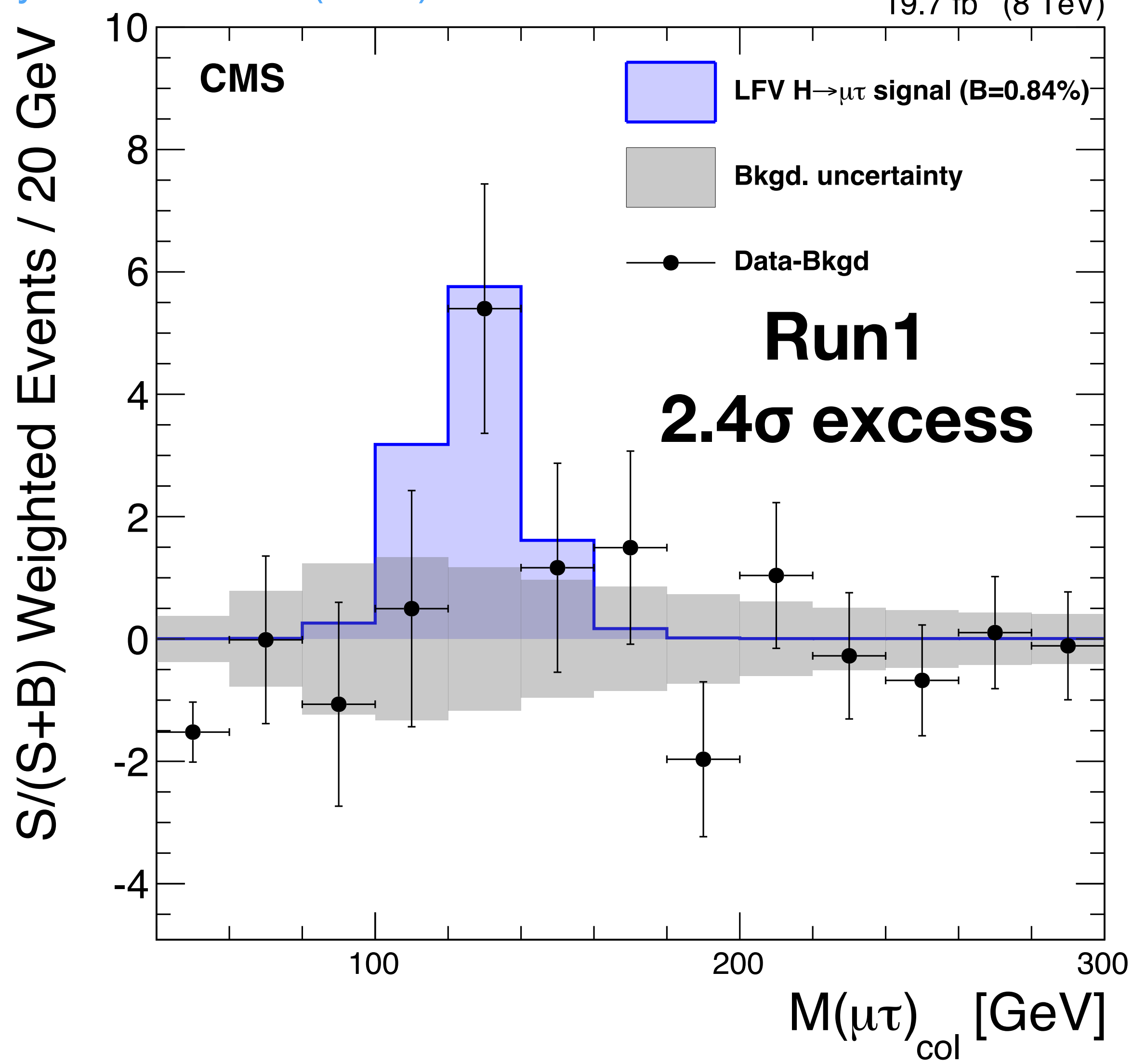
- **why taus?**
  taus are the heaviest leptons and couple favourably to the Higgs

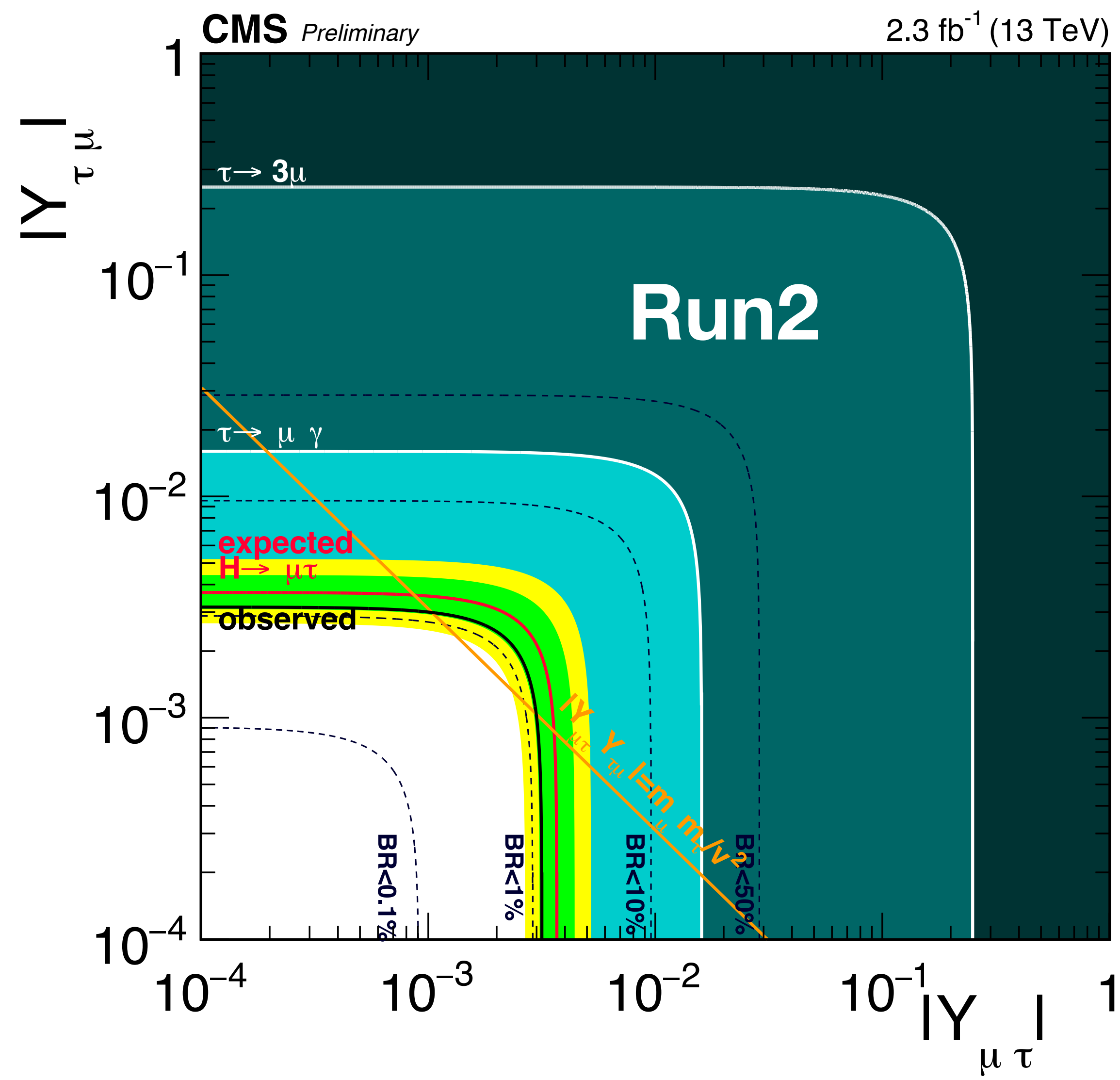
- **analysis strategy:**
    - **similar to SM $H\rightarrow\tau\tau$, but μ has higher p_T being prompt**
    - events are sorted in categories based on the number of jets
    - signal is extracted through a ML fit to the **collinear mass** distribution
    - M_{coll} is bult assuming that neutrino(s) arising from the τ decay are highly boosted and their direction can be approximated to that of the visible products of the τ

Search for Lepton Flavour Violating $H \to \mu\tau_{(e,h)}$

Phys. Lett. B 749 (2015) 337

https://cds.cern.ch/record/2159682



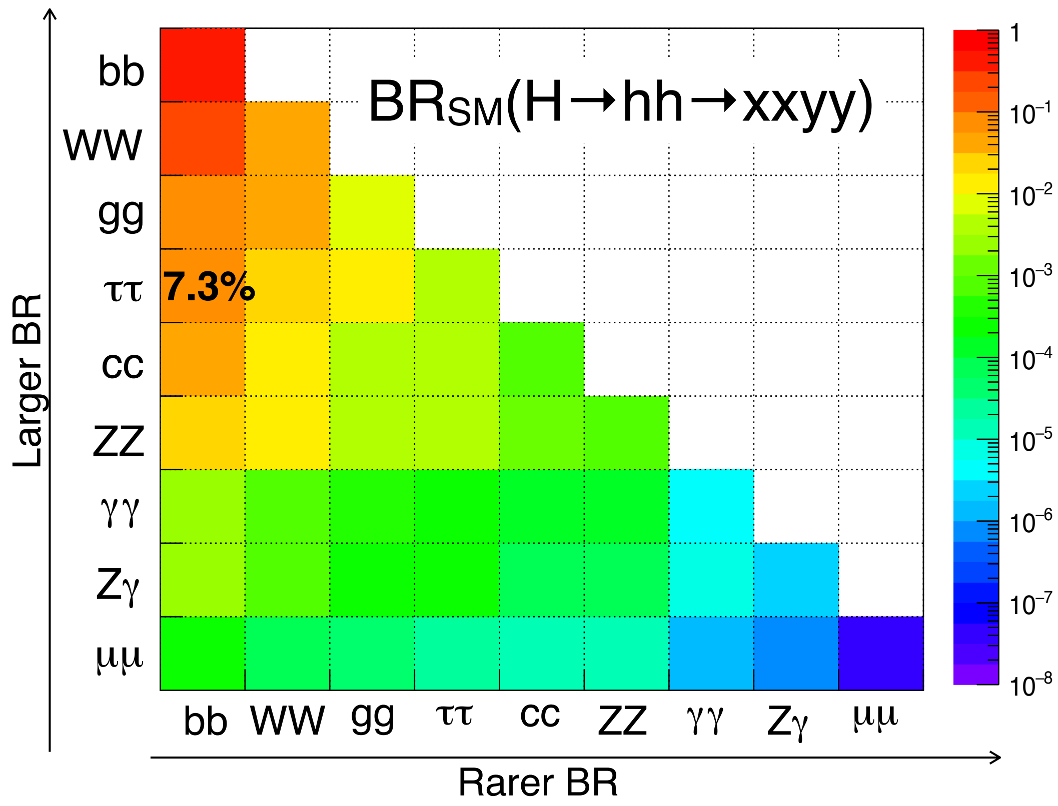


- **observed $B(H \to \mu\tau) < 1.2\%$: most stringent limit on LFV Yukawa coupling**
    - 13 TeV analysis **does not confirm the 2.4σ excess** observed in the 8 TeV analysis, but the Run2 analysis not as sensitive as Run1 yet

Resonant (and non-resonant) $X(h) \to hh \to bb\tau\tau$

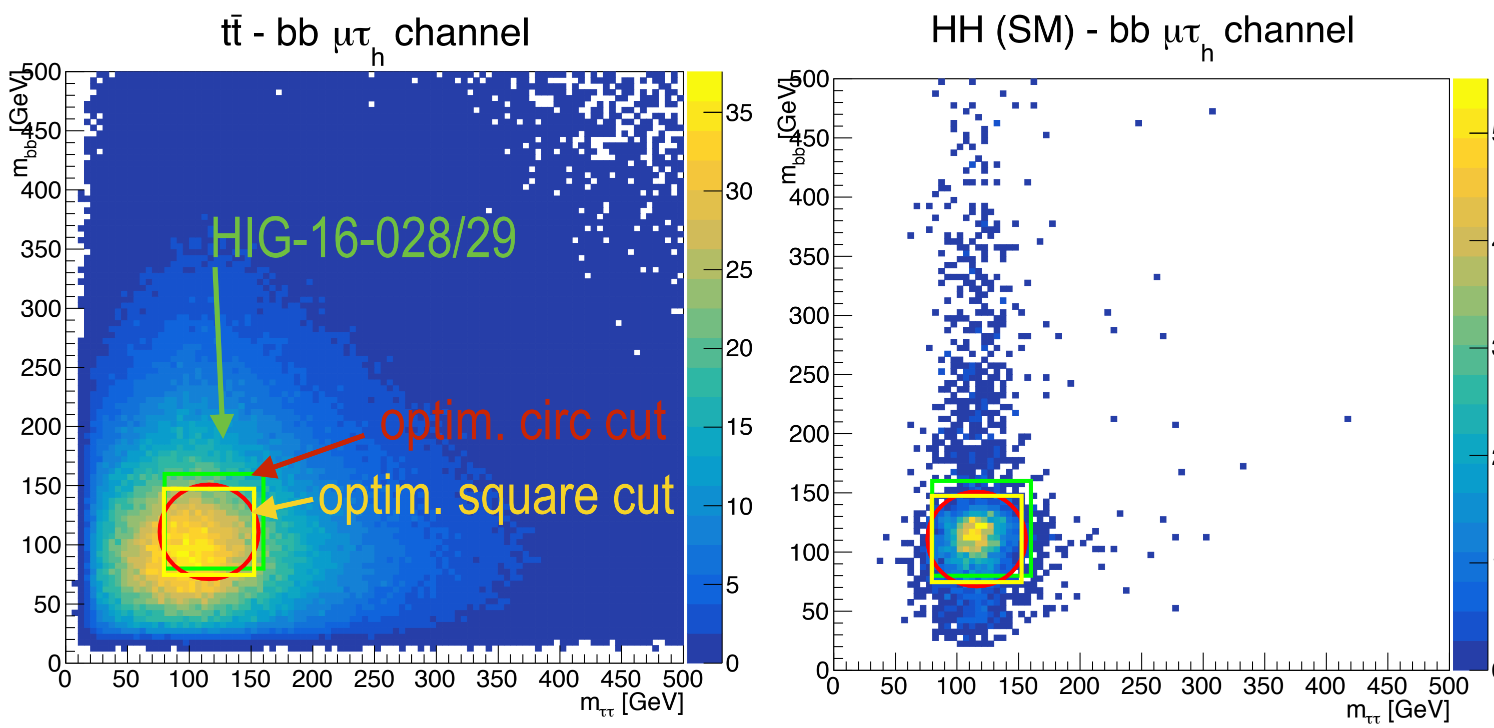
Motivations for X/h→hh→bbττ

- **non resonant:**
  - predicted SM process, access to Higgs trilinear self coupling λ_{hhh} (Higgs potential) (beyond reach in Run2, need HL-LHC)
  - BSM contributions can modify the coupling: $\kappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM}$
- **resonant:**
  - in several models, heavy particles can decay in hh, e.g.: Radion, Graviton, MSSM H
- **the bbττ final state is chosen because it has good BR 7.3% and sufficiently clean experimental signature**
  - μτ, eτ, ττ channels considered



X/h→hh→bbττ - strategy

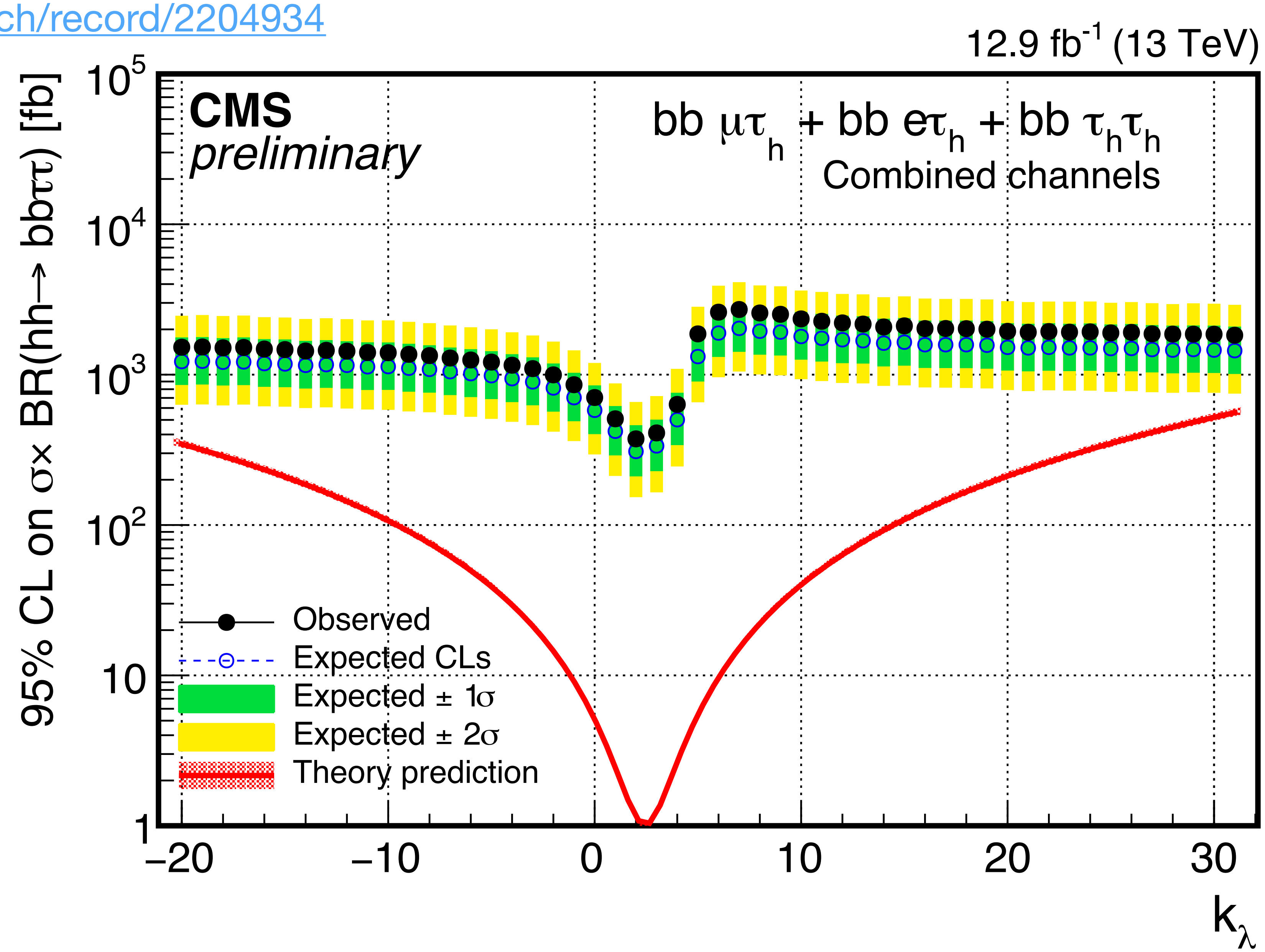
- **strategy largely common for the two analyses**
  - events with a good di-τ pair and a good b-jet pair
  - $m_{\tau\tau}$ and m_{bb} mass windows around 125 GeV
  - BDT discriminator to reduce ttbar (angular variables, NR only)
  - categorisation:
    - 2 b-jet resolved
    - 1 b-jet resolved + 1 jet
    - boosted b-jets (relevant for m_X > 600 GeV)



- **signal extraction through a fit to the 4-body $m_{\tau\tau bb}$ invariant mass**
  - 4-body mass computed using a kinematic fit imposing $m_{bb} = m_{\tau\tau}$ = 125 GeV

Non-resonant h→hh→bbττ - results

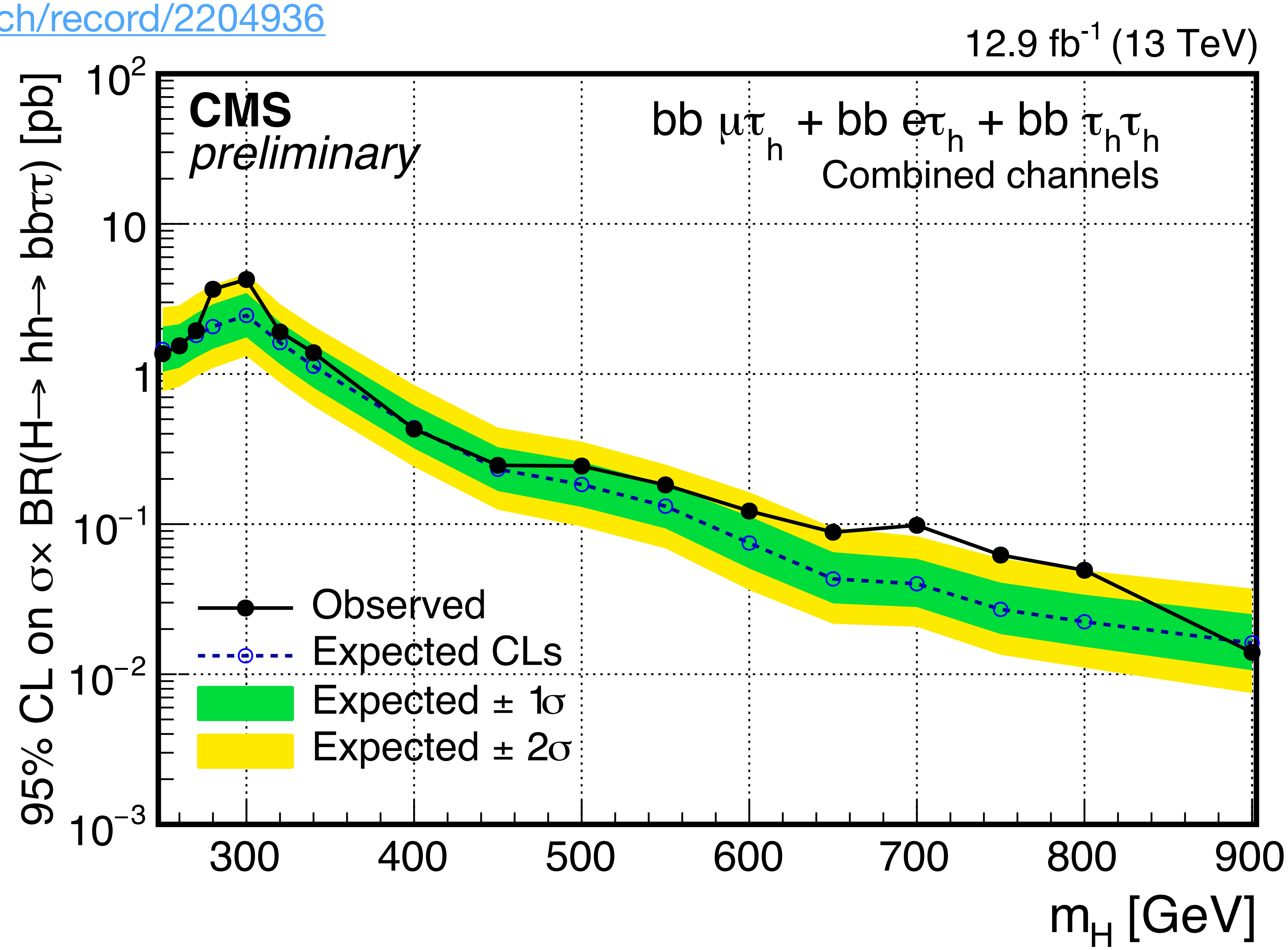
https://cds.cern.ch/record/2204934



- **exclusion limit on σ x BR as a function of the coupling modifier kλ**

Resonant X→hh→bbττ - results

https://cds.cern.ch/record/2204936

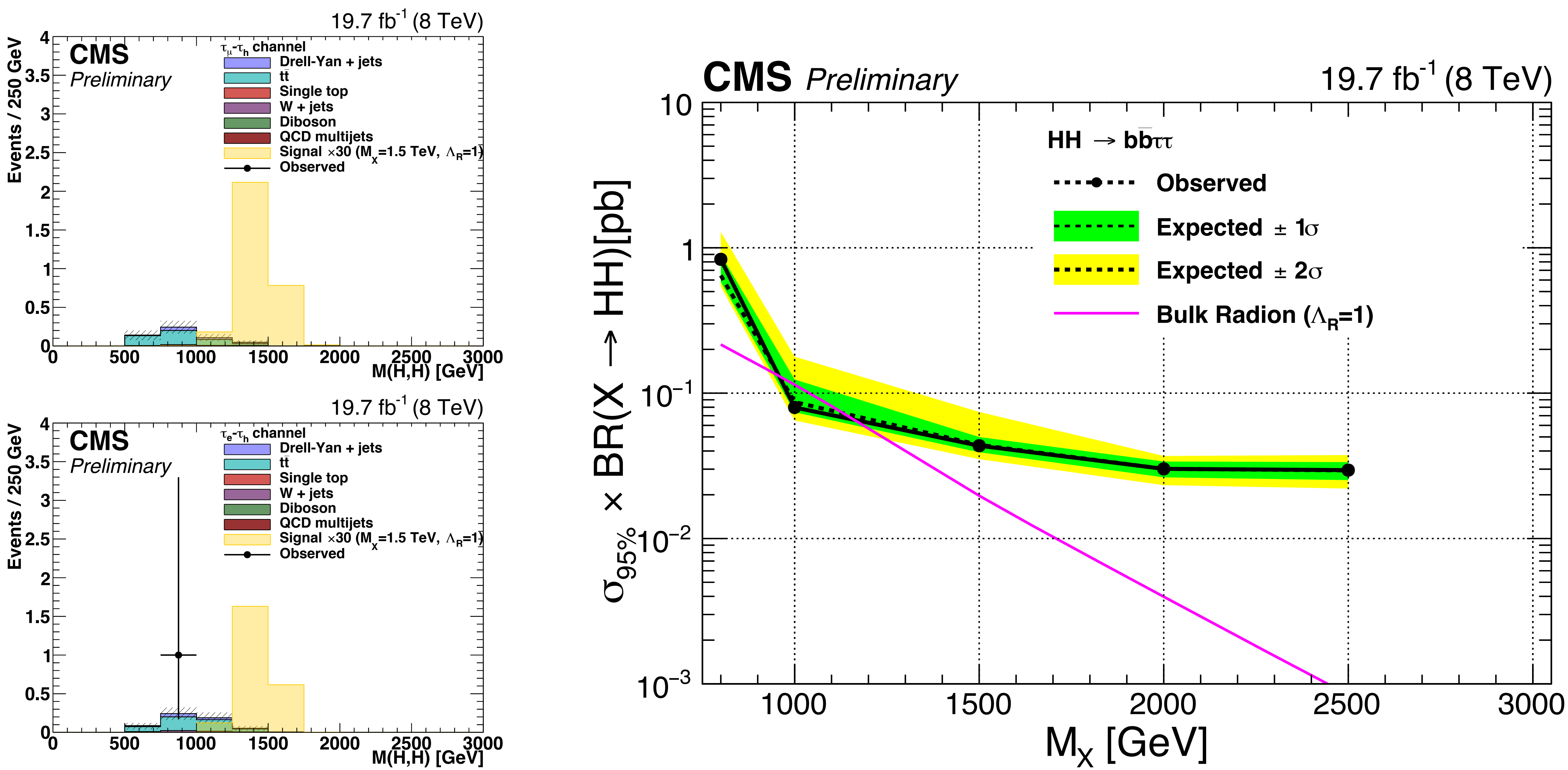


- **exclusion limit on σ x BR as a function of the mass of the resonance**

High mass X→hh→bbττ with boosted taus

https://cds.cern.ch/record/2125293

- **extend the search to masses up to 2.5 TeV**
- the two h125 from the heavy resonance are boosted and their decay products very close to each other → boosted b's and τ's

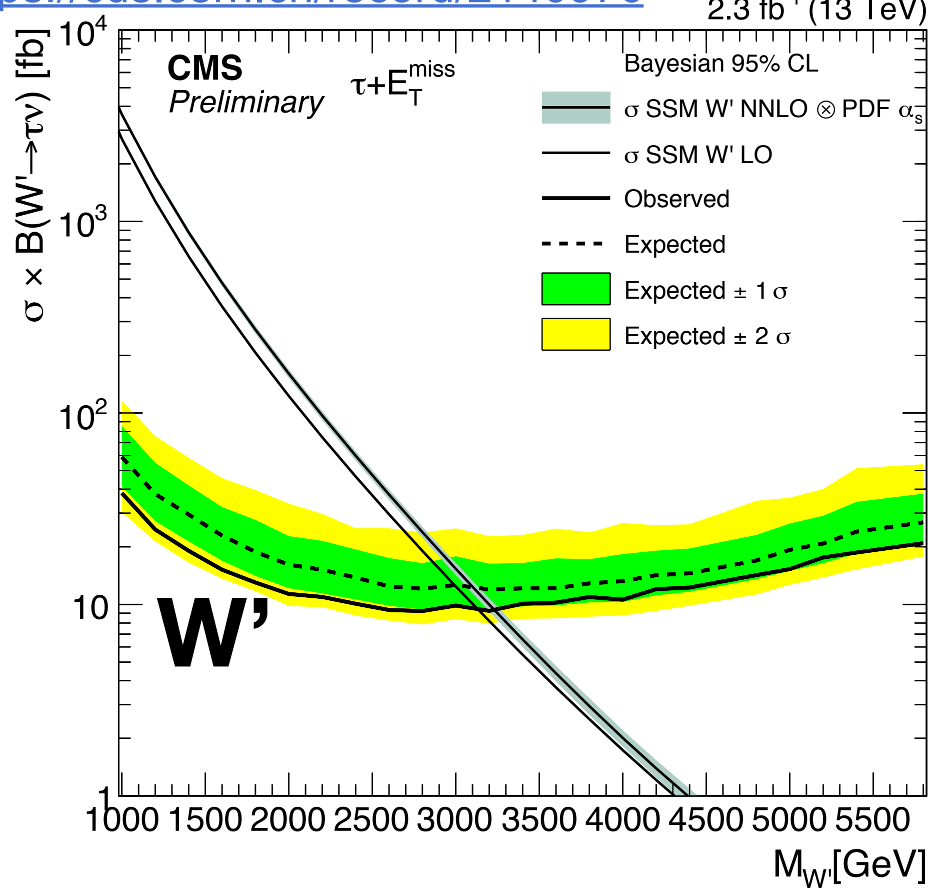


Exotic searches

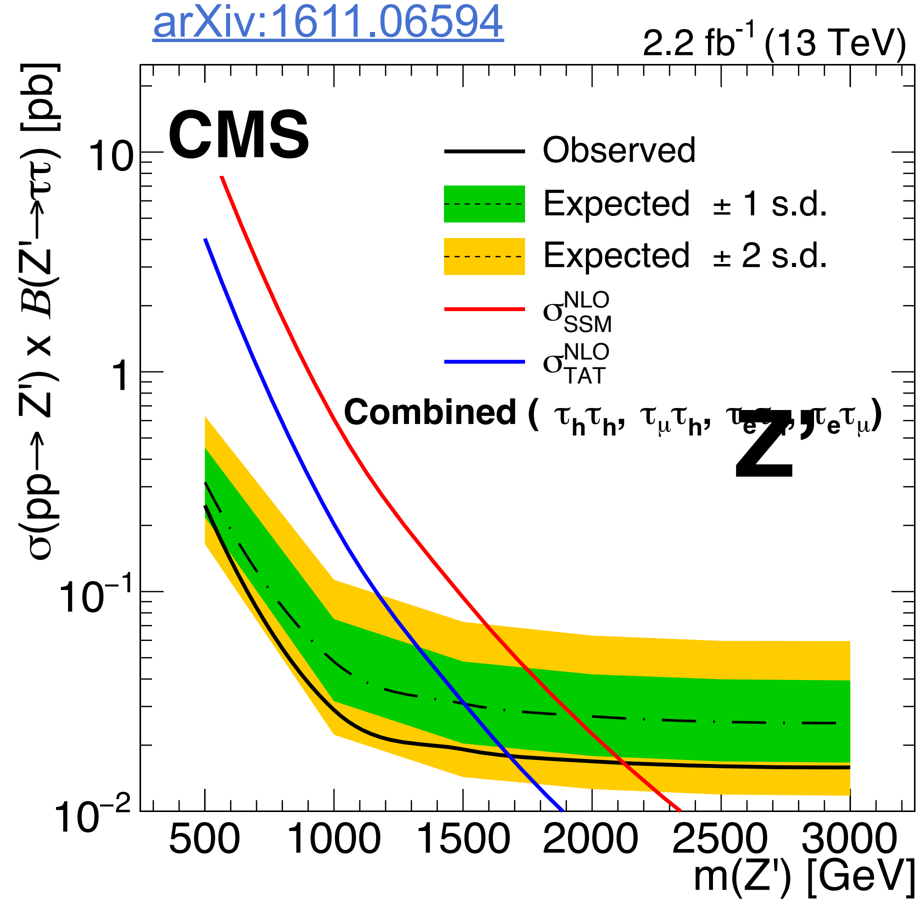
W'→τν and Z'→ττ searches

- **heavy gauge bosons are foreseen in several BSM models, e.g. Sequential Standard Model (SSM)**
- similar signature and properties to SM W & Z

https://cds.cern.ch/record/2140976



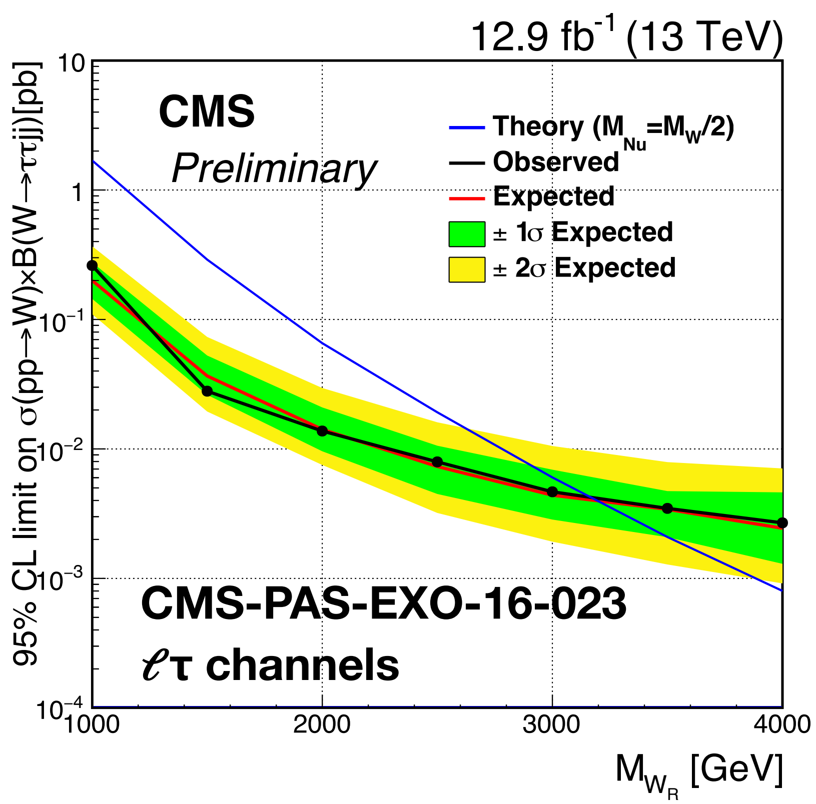
arXiv:1611.06594

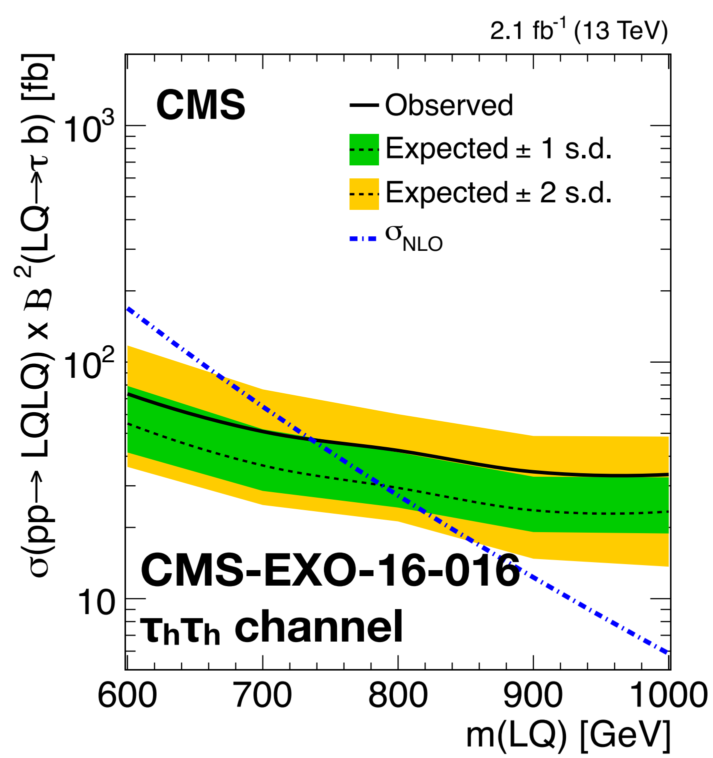


- **model dependent limits exclude**
  $M_{W'}$ < 3 TeV, $M_{Z'}$ < 2.1 TeV (SSM), $M_{Z'}$ < 1.7 TeV (TAT)

Heavy neutrinos and 3rd generation leptoquark

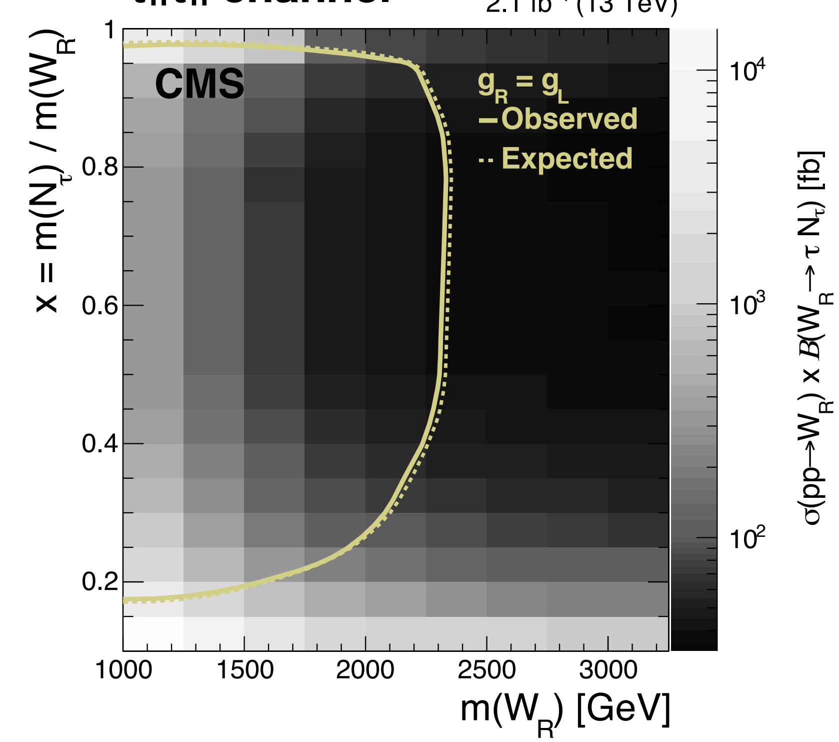
- **neutrino oscillations → $m_\nu > 0$ → seesaw mechanism → right-handed neutrinos**
- can be accommodated in **Left Right Symmetric Extensions (LRSE)** of the SM, which predict the existence of **heavy gauge bosons $W^{\pm}_R$** and Z’
- typical process in **$W^{\pm}_R \rightarrow \tau N_\tau \rightarrow \tau \tau \nu_\tau$** , where N_τ is the heavy neutrino
- Lepto-Quark (LQ) models also foresee signatures with two τ’s





CMS-EXO-16-016

τhτh channel



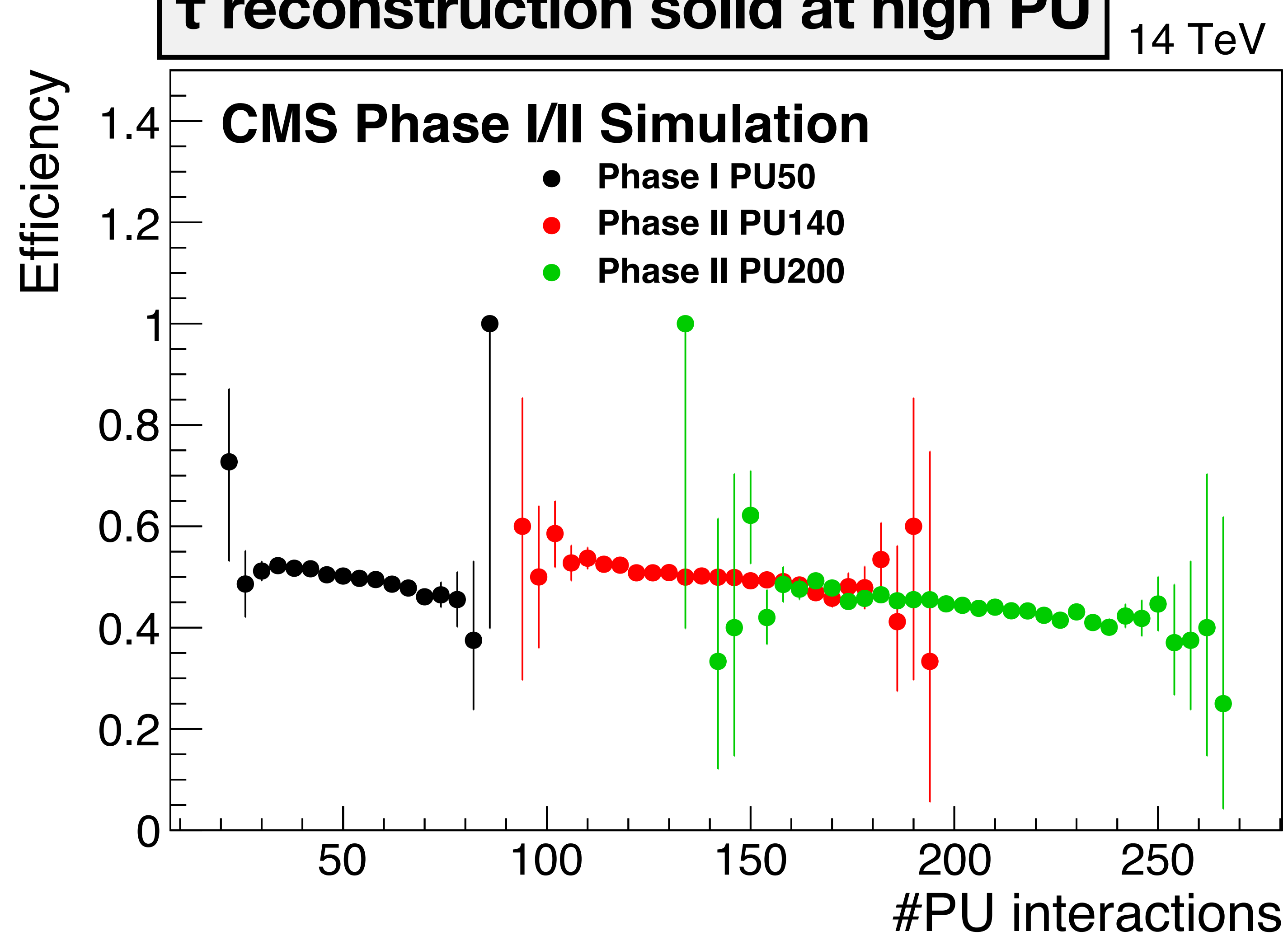
- **under model dependent assumptions, limits are set on m_{W_R}, m_{LQ} and m_{N_τ}**

Outlook to CMS upgrades impact on taus

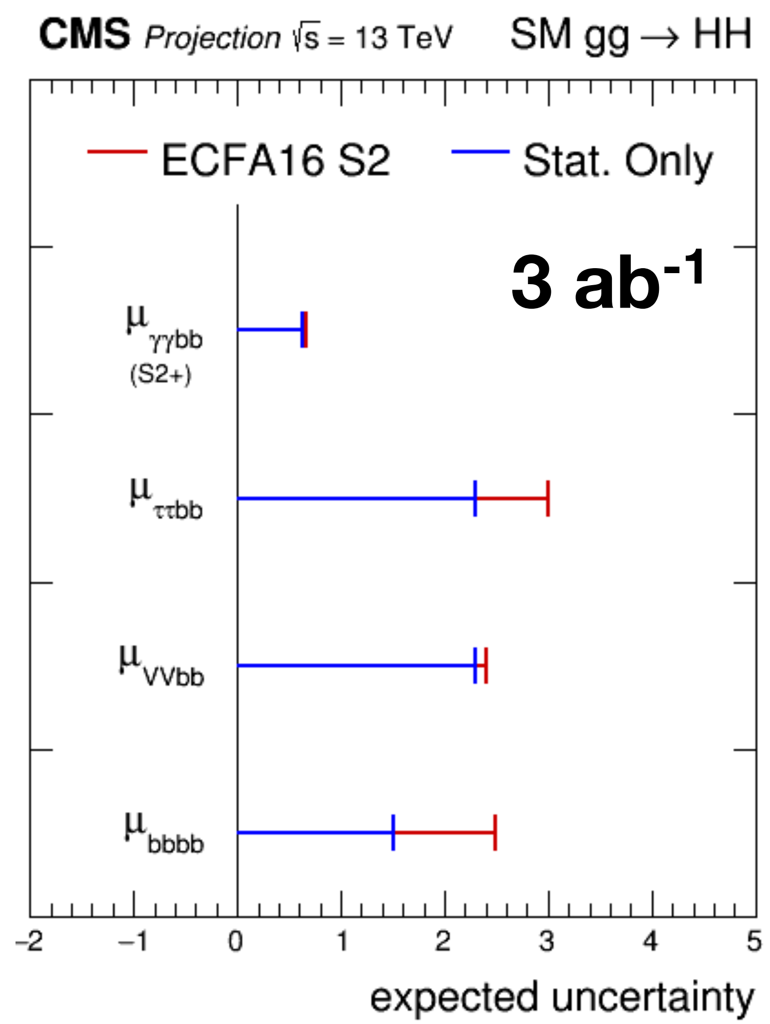
CMS detector upgrades towards HL-LHC

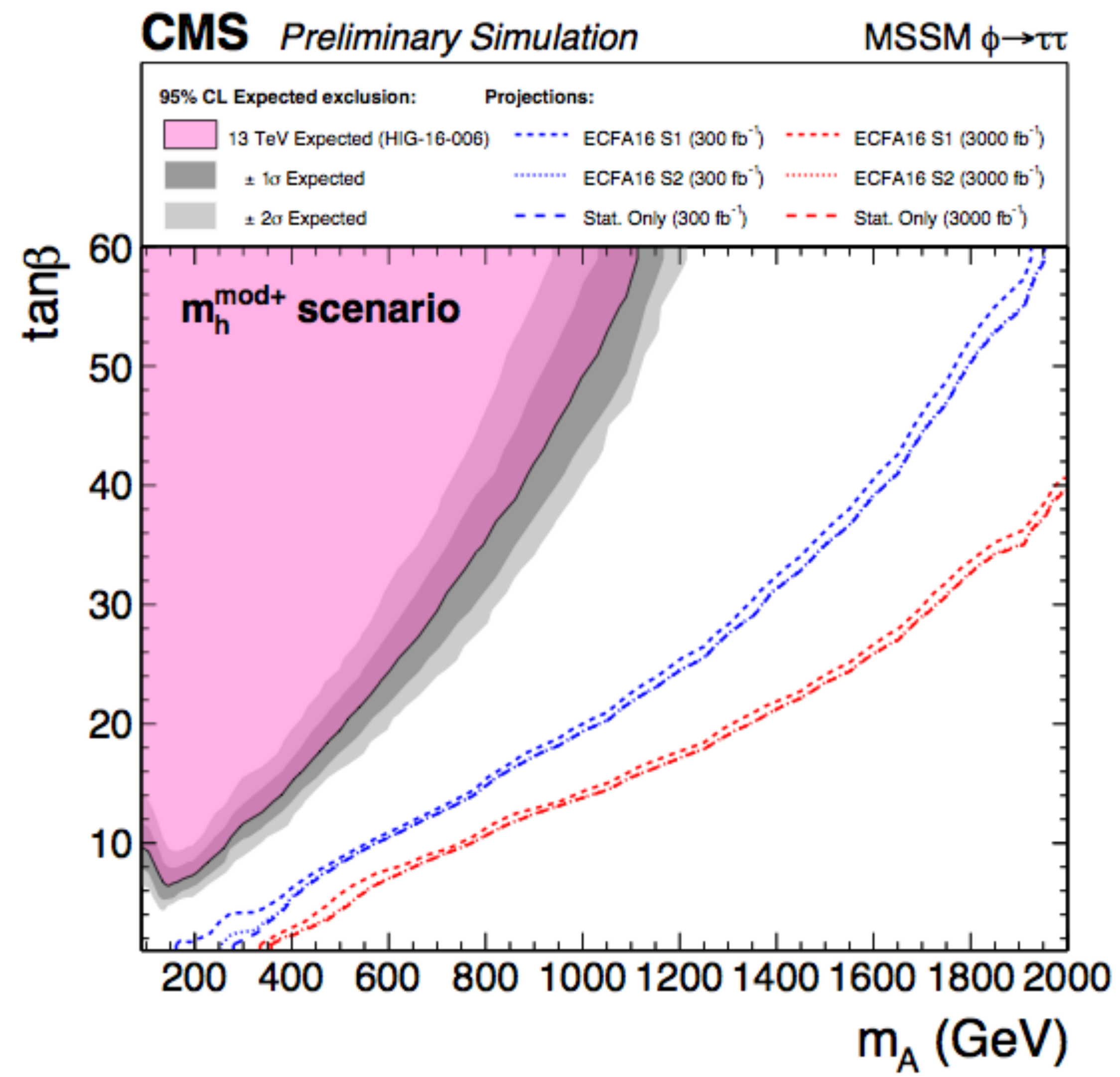
- **the name of the game: higher luminosity ⟷ higher PU (up to 200!)**
- **2017 phase-1: 4th pixel barrel layer and 3rd endcap disk**
  - better track/vertex resolution
  - improvement in tau reconstruction and performance, e.g. lifetime variables
- **HL-LHC phase-2:**
  - 4x tracker granularity
  - High Granularity Calorimeter
  - tracking at L1 trigger
  - more L1 bandwidth
  - muon system up to |η|~3

τ reconstruction solid at high PU



Projections to HL-LHC, 300-3000 fb^{-1}





- precision measurement of the SM Higgs couplings
- **at HL-LHC will reach sensitivity to SM h→hh**
- **push the exclusion limits in the MSSM scenario**

https://cds.cern.ch/record/2221747/

Conclusions

τ_h is a fundamental tool for a broad physics programme

look for new results at Moriond17 with full Run2 stats

τ_h reconstruction vastly improved in Run2

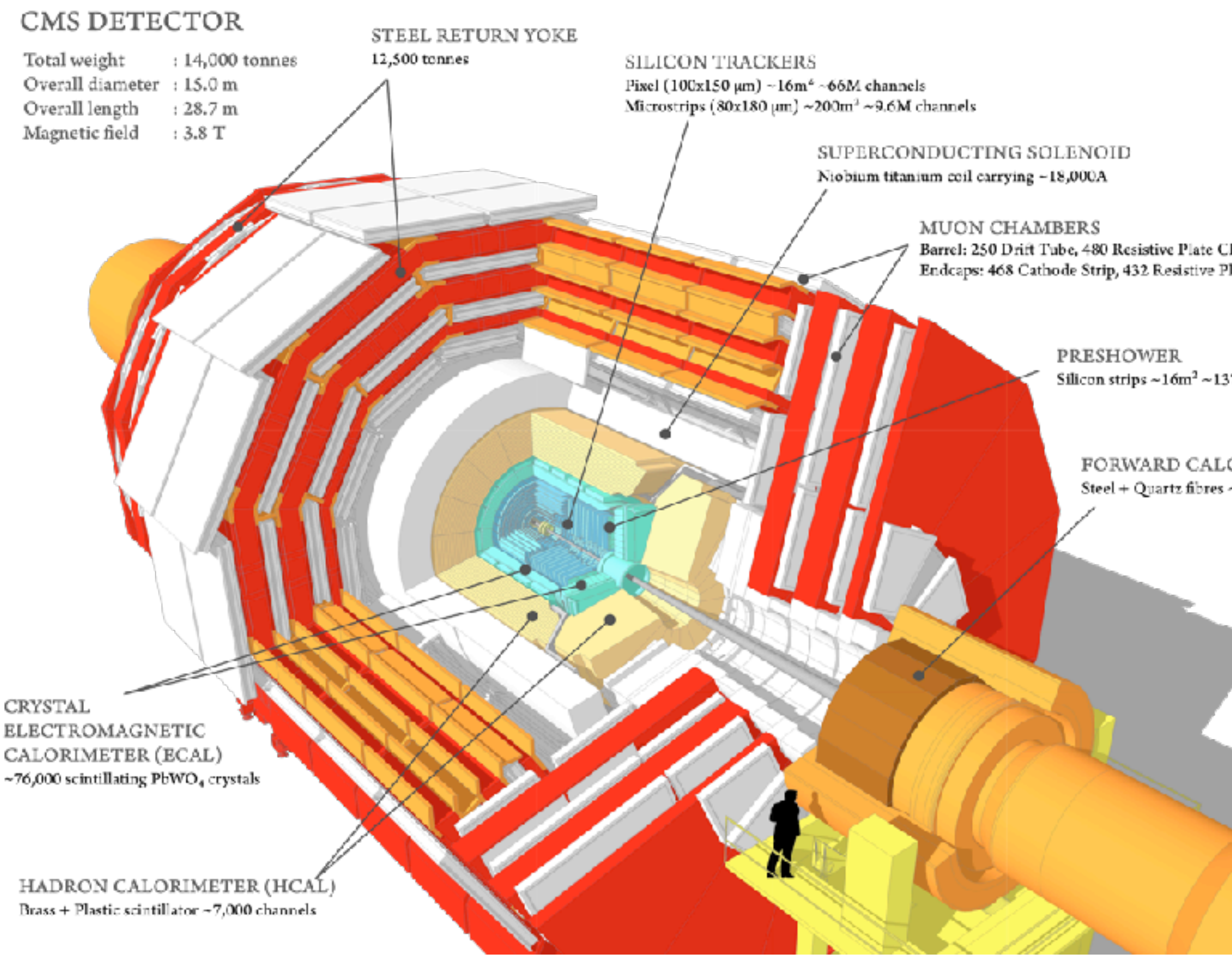
established algorithms, triggers, performance

CMS upgrades will ensure this programme to continue

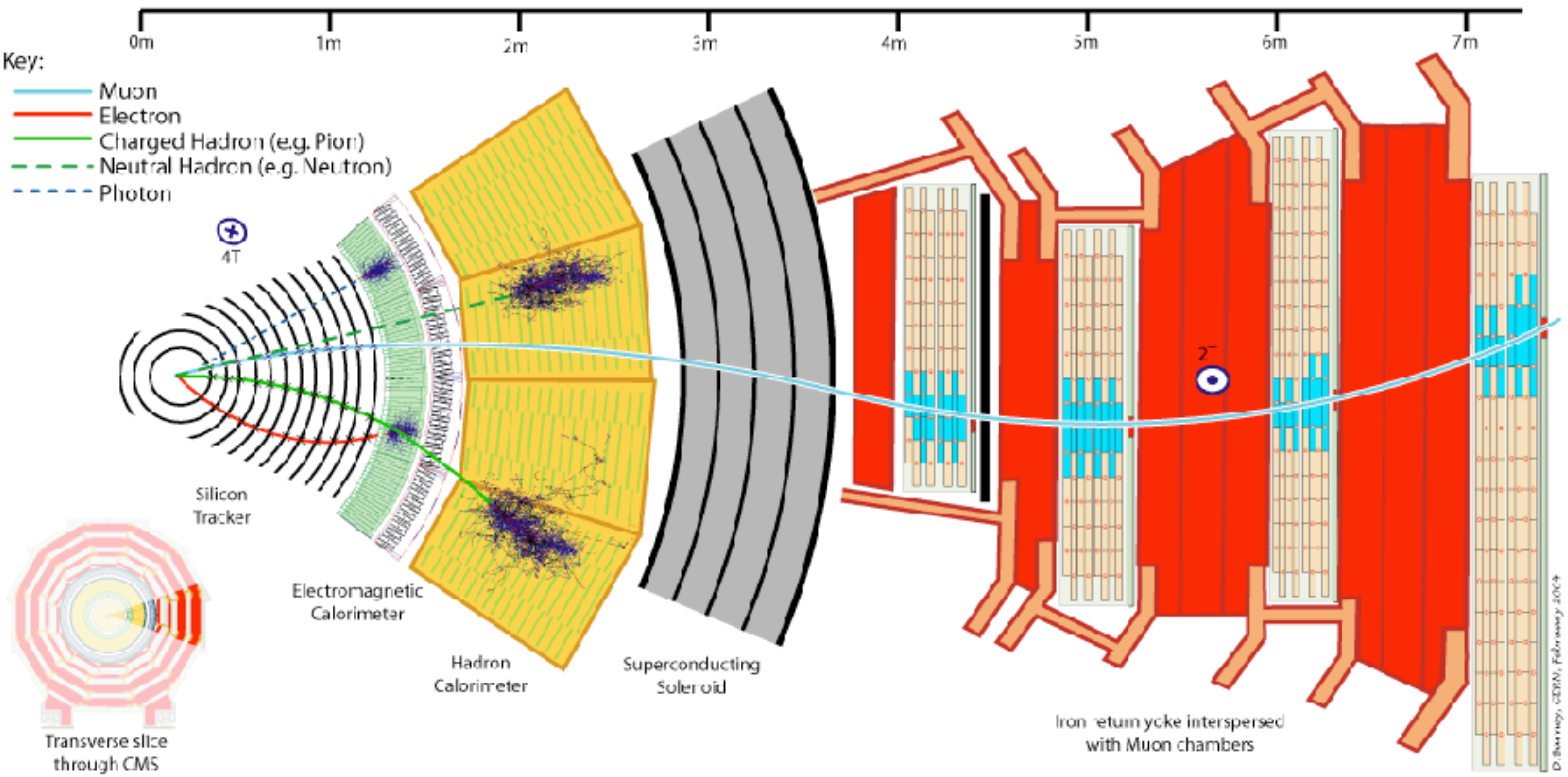
even in extremely harsh PU conditions

Backup

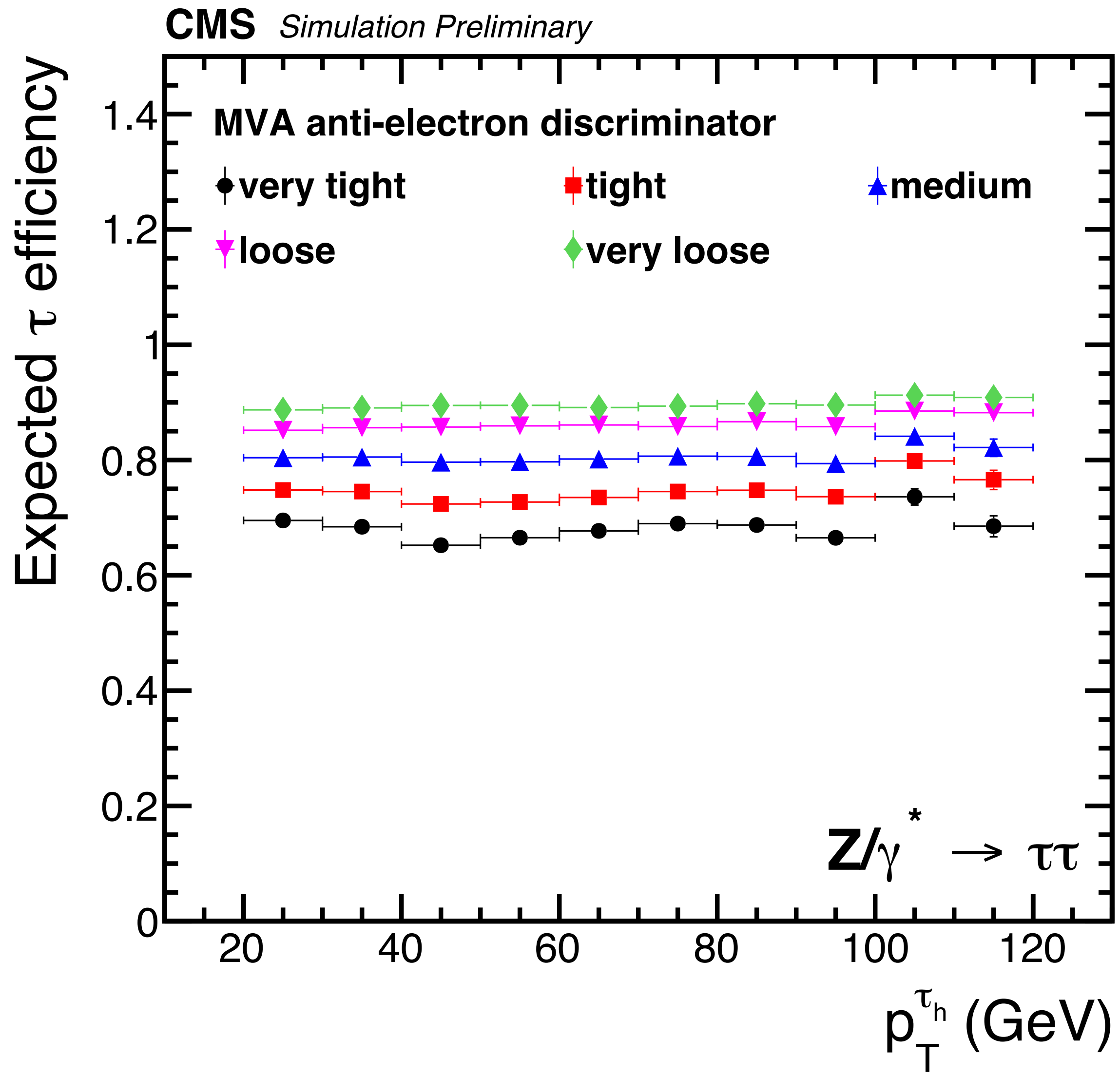
The Compact Muon Solenoid detector



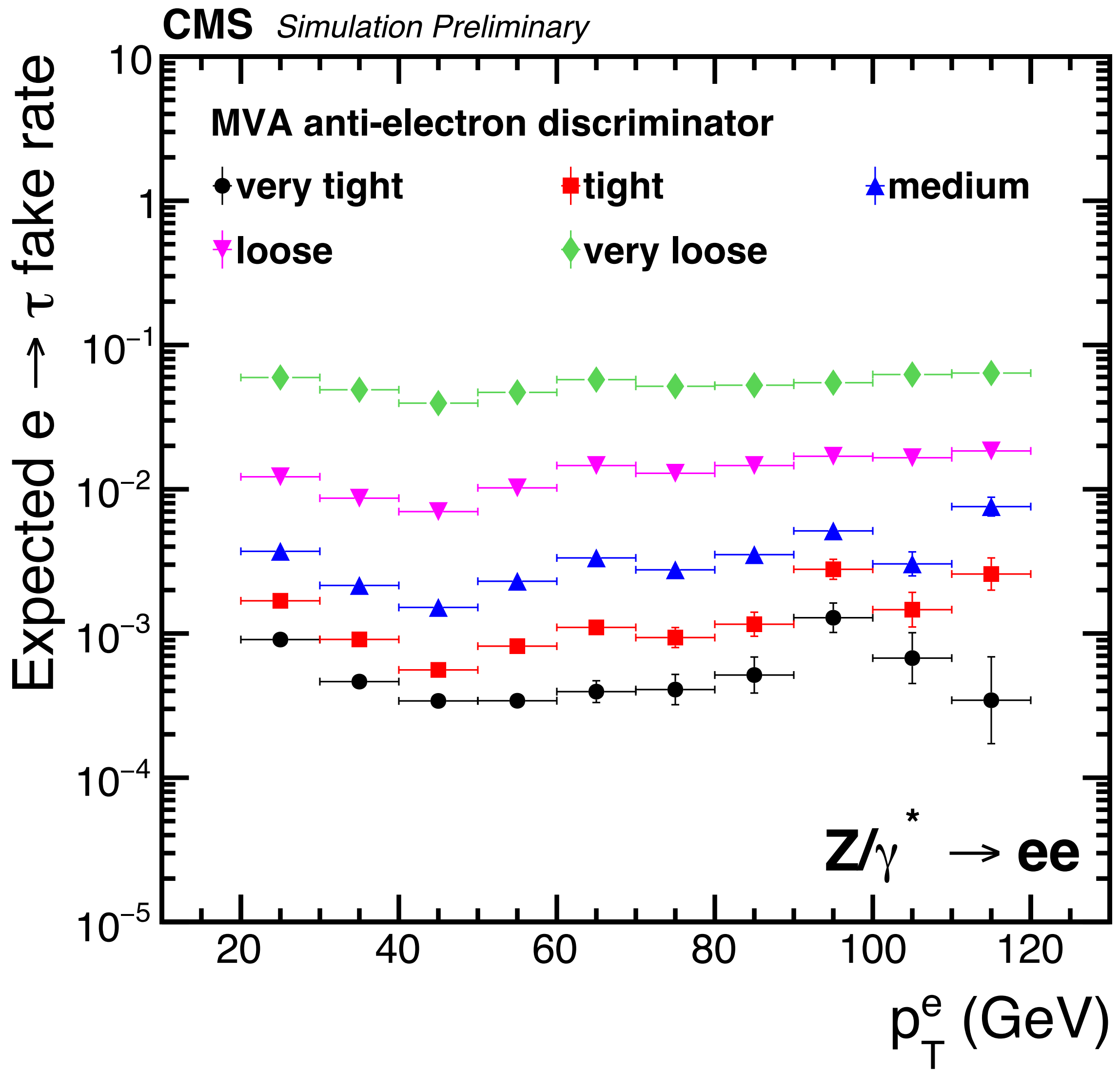
Particle signatures in CMS



Anti-electron discriminator expected performance



efficiency



fake rate

jet→τ_h rate measurement

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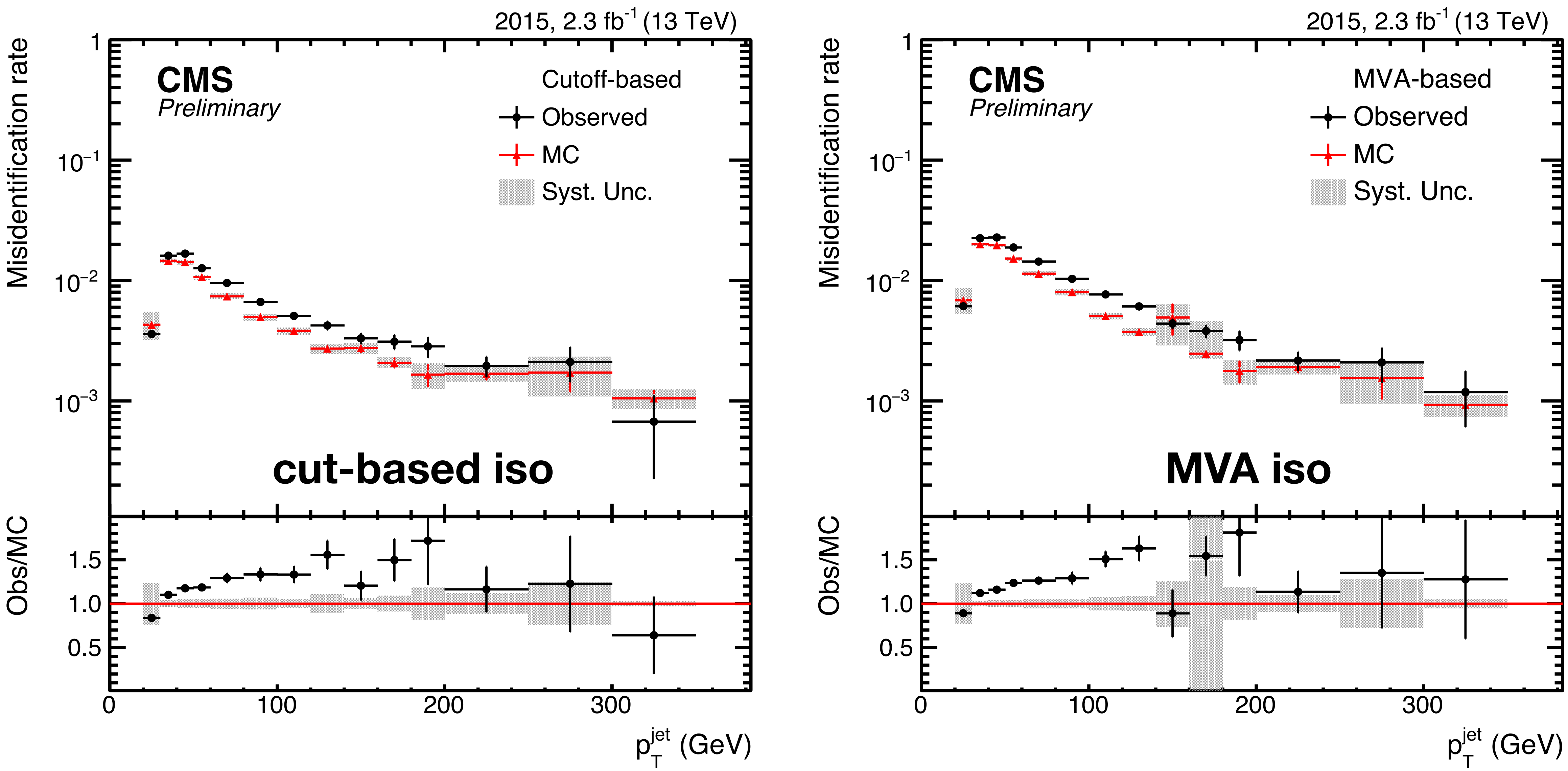
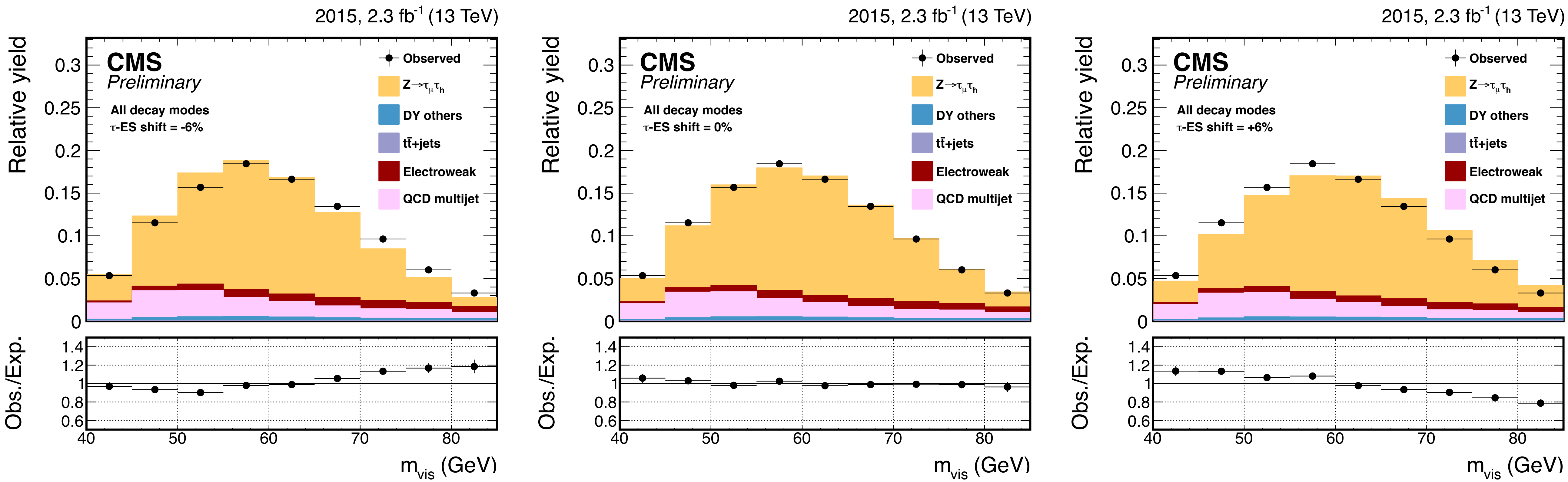


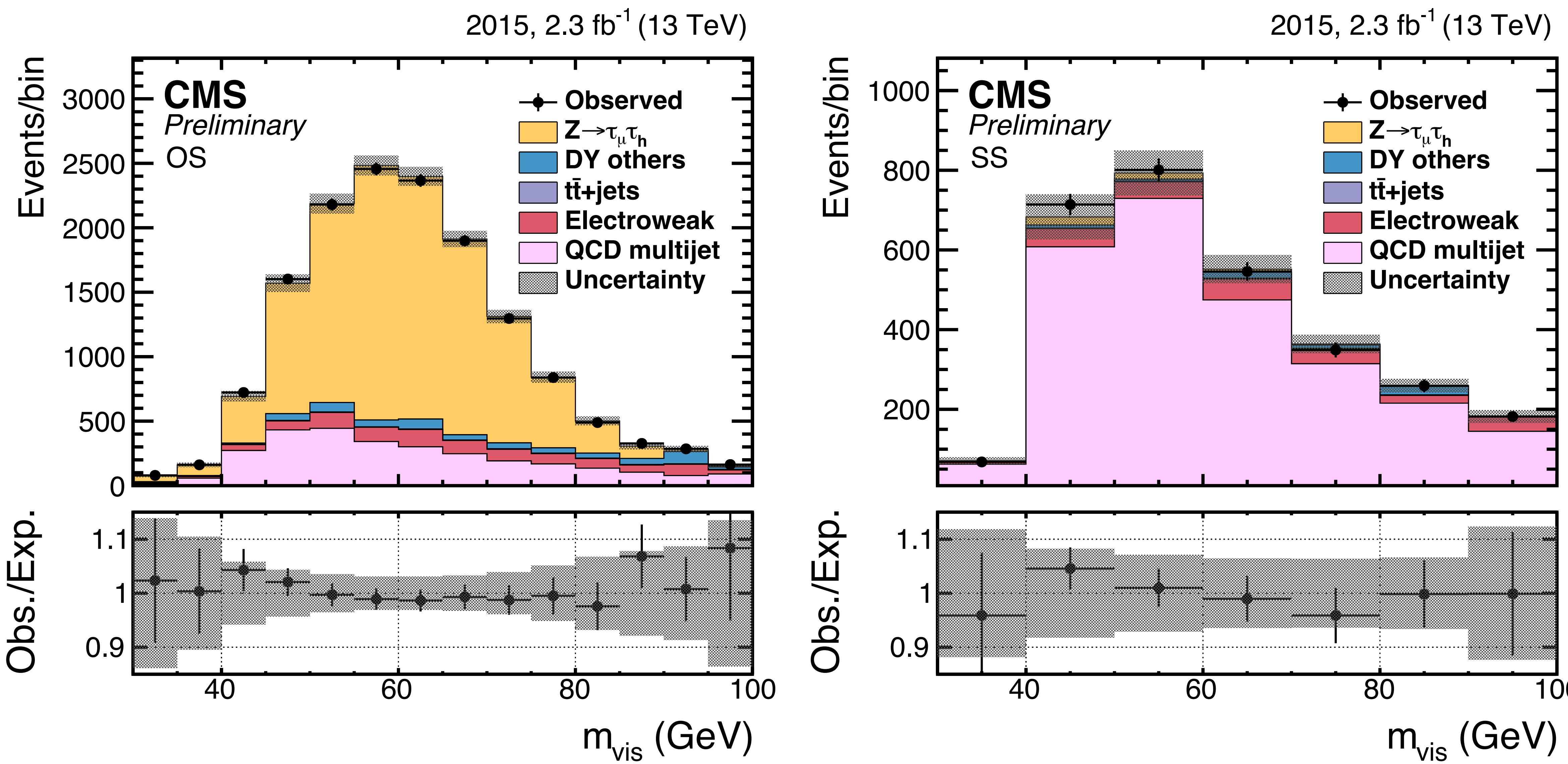
- **data/MC comparison shown form in W→μν + Jets enriched regions**
- **mis-ID probability strongly depends on parton flavour and on jet-τ_h charge mismatch**
    - measurements in other regions are performed too
- the data/MC disagreement is understood to be due ultimately to the MC hadronisation tune

Tau energy scale measurement



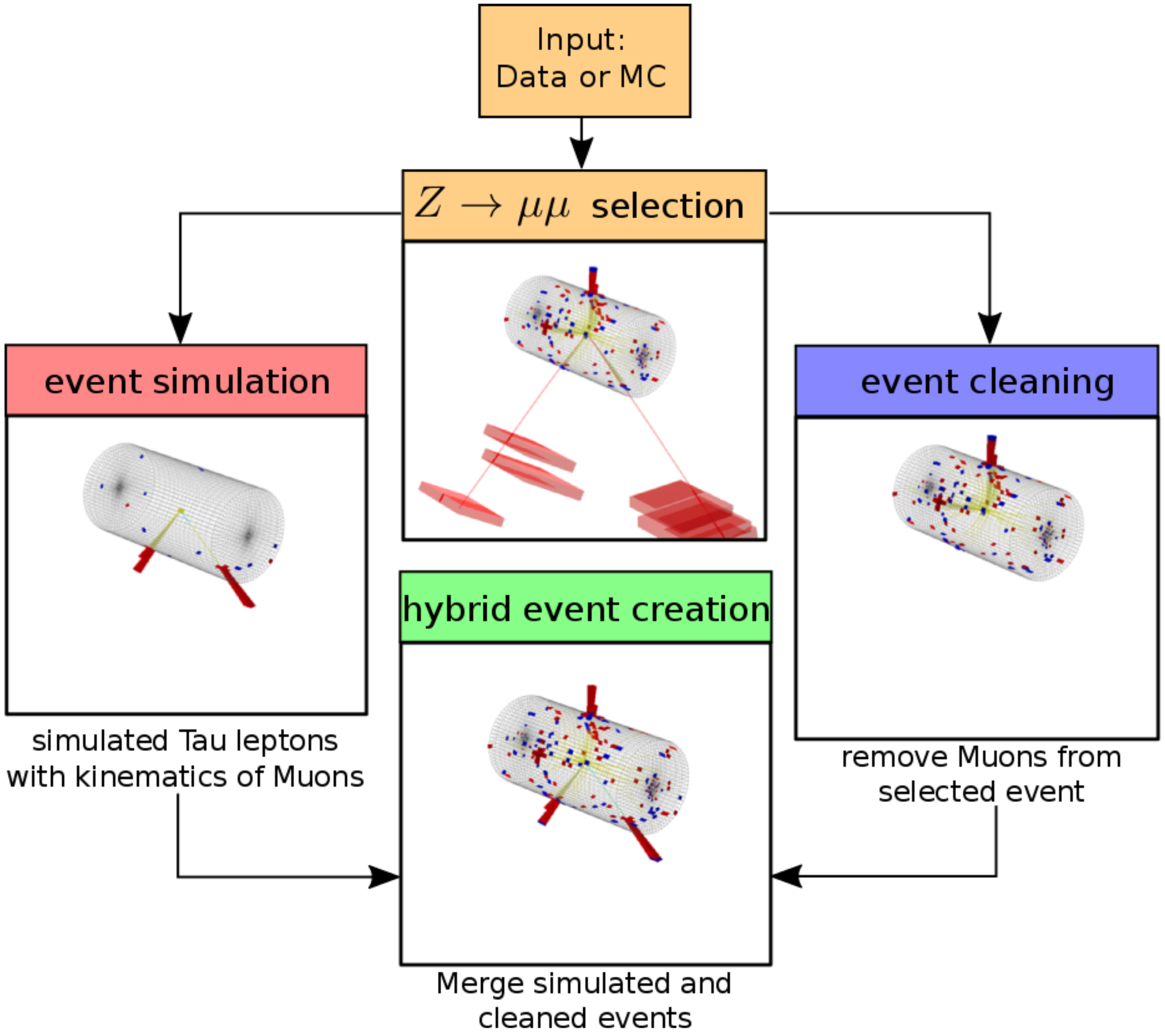
- **$m_{vis}(\mu\tau)$ and τ_h mass** (not shown here) **distributions are sensitive to τ_{ES}**
- produce $Z \rightarrow \tau_\mu \tau_h$ **templates in the -6% +6% energy scale range**
- **maximum likelihood fit to data with τ_{ES} (per decay mode) as POI**
- results range from -1.5% to +1.5% depending on the decay mode

τ charge misidentification measurement



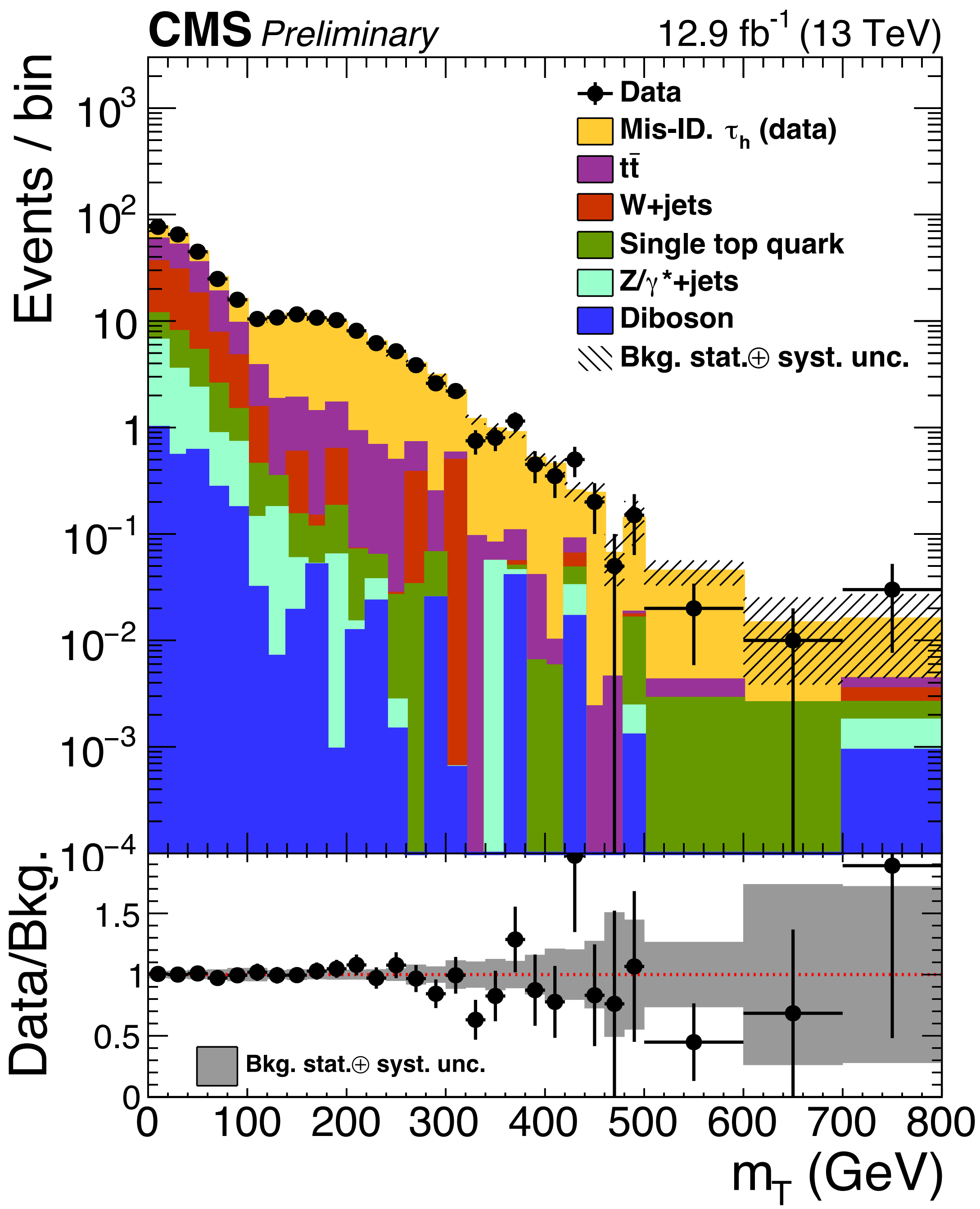
- selection of $Z\tau_\mu\tau_h$ enriched OS events and the corresponding SS sideband
- simultaneous ML fit to extract the charge misID probability
- upper limit PCF = 0.22%

Embedded sample

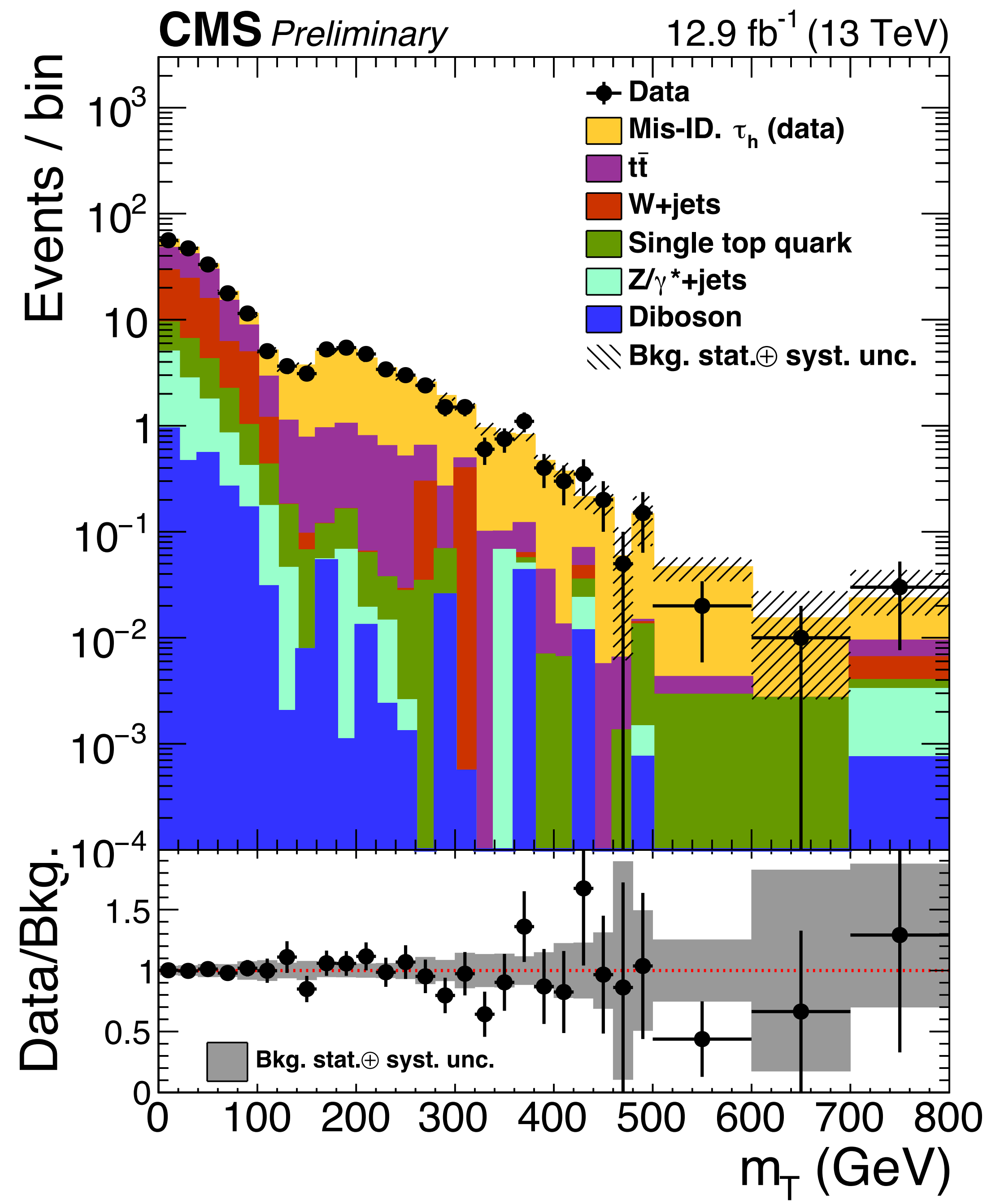


- **hybrid data + MC events**
- **Z kinematics, Jets, E_T^{miss} underlying event from data**
  - better modelling and small (if not absent) uncertainties
- only tau decay is left to the simulation

H±→τν - final distributions

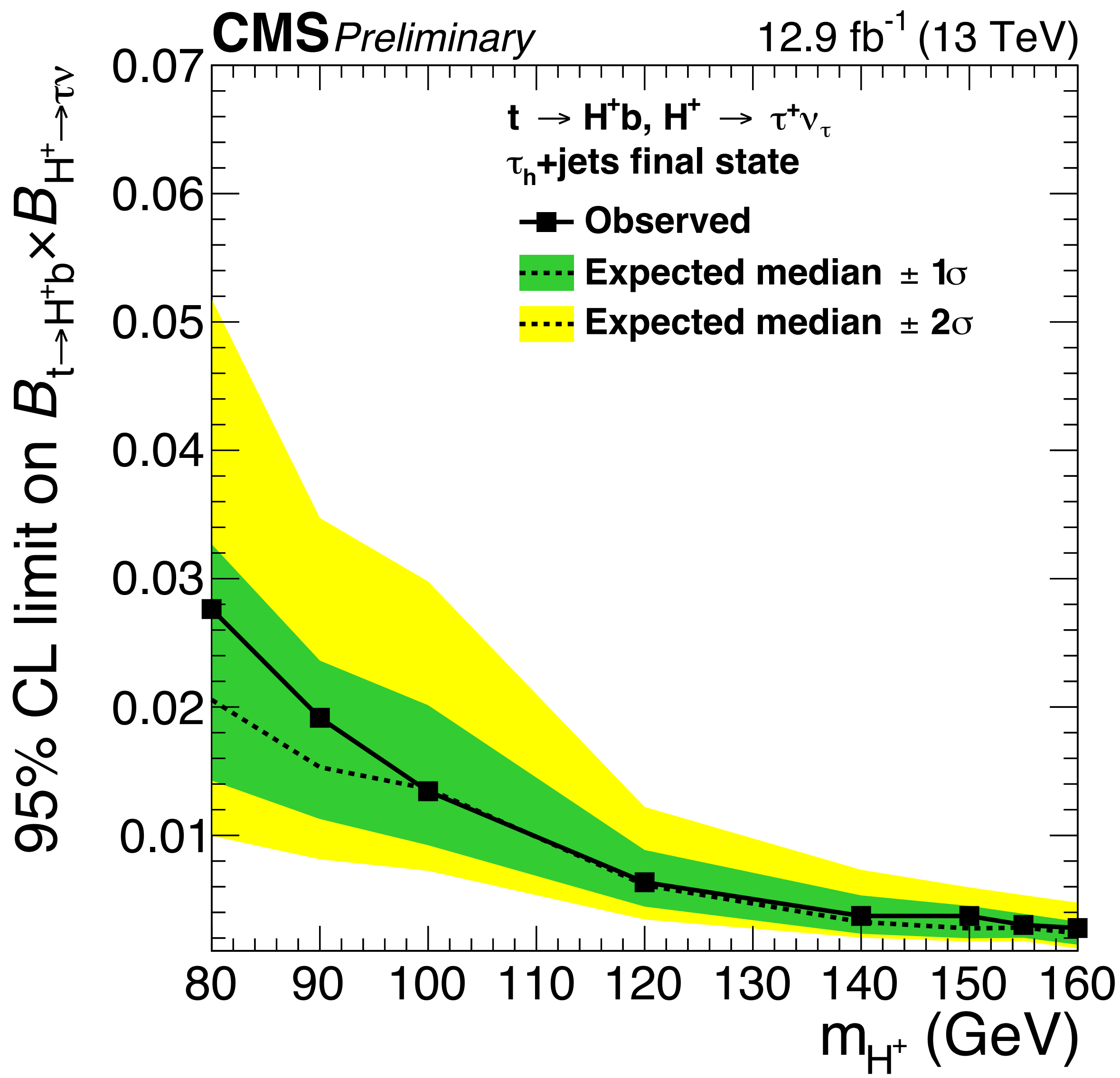


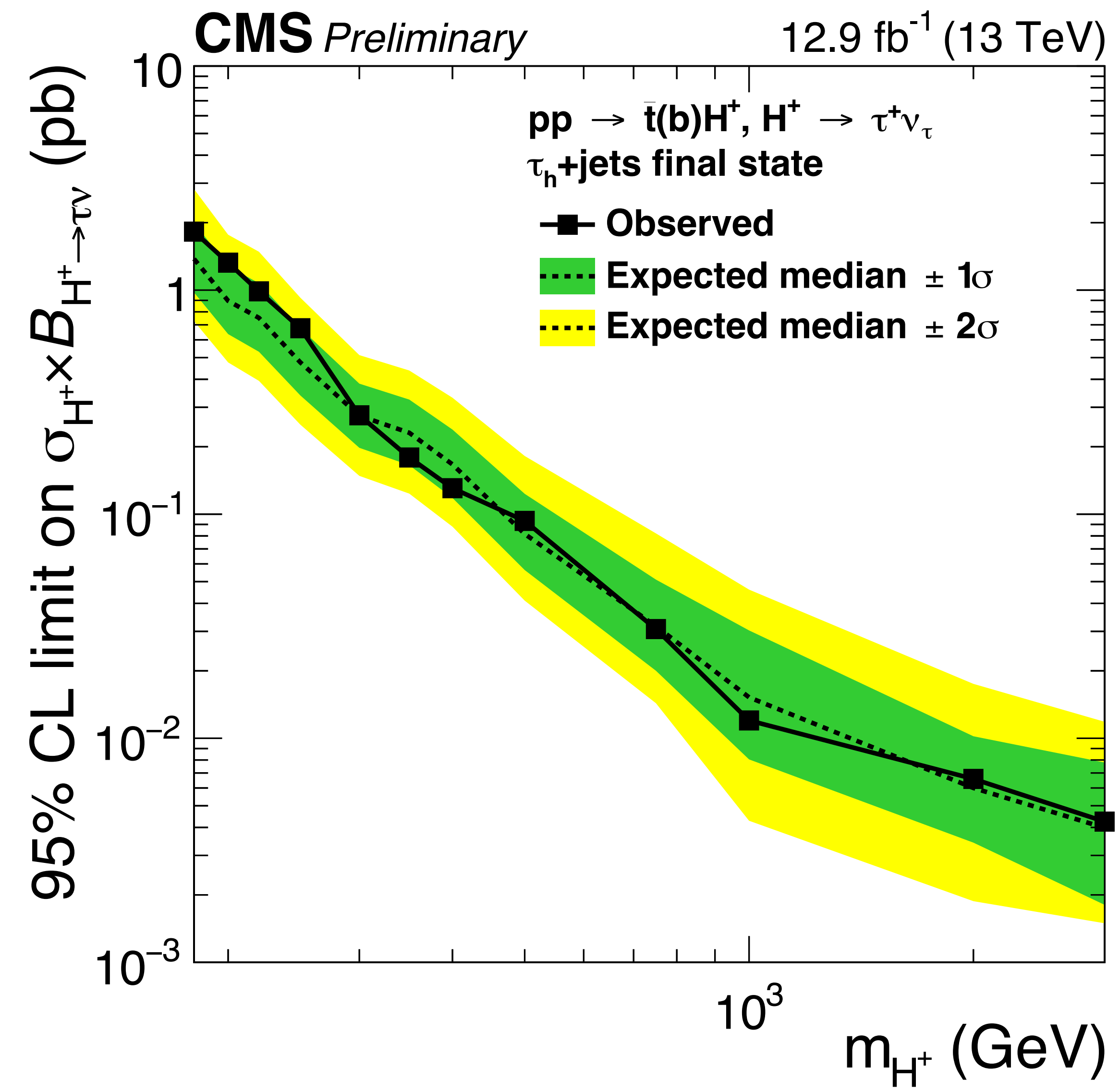
light H±



heavy H±

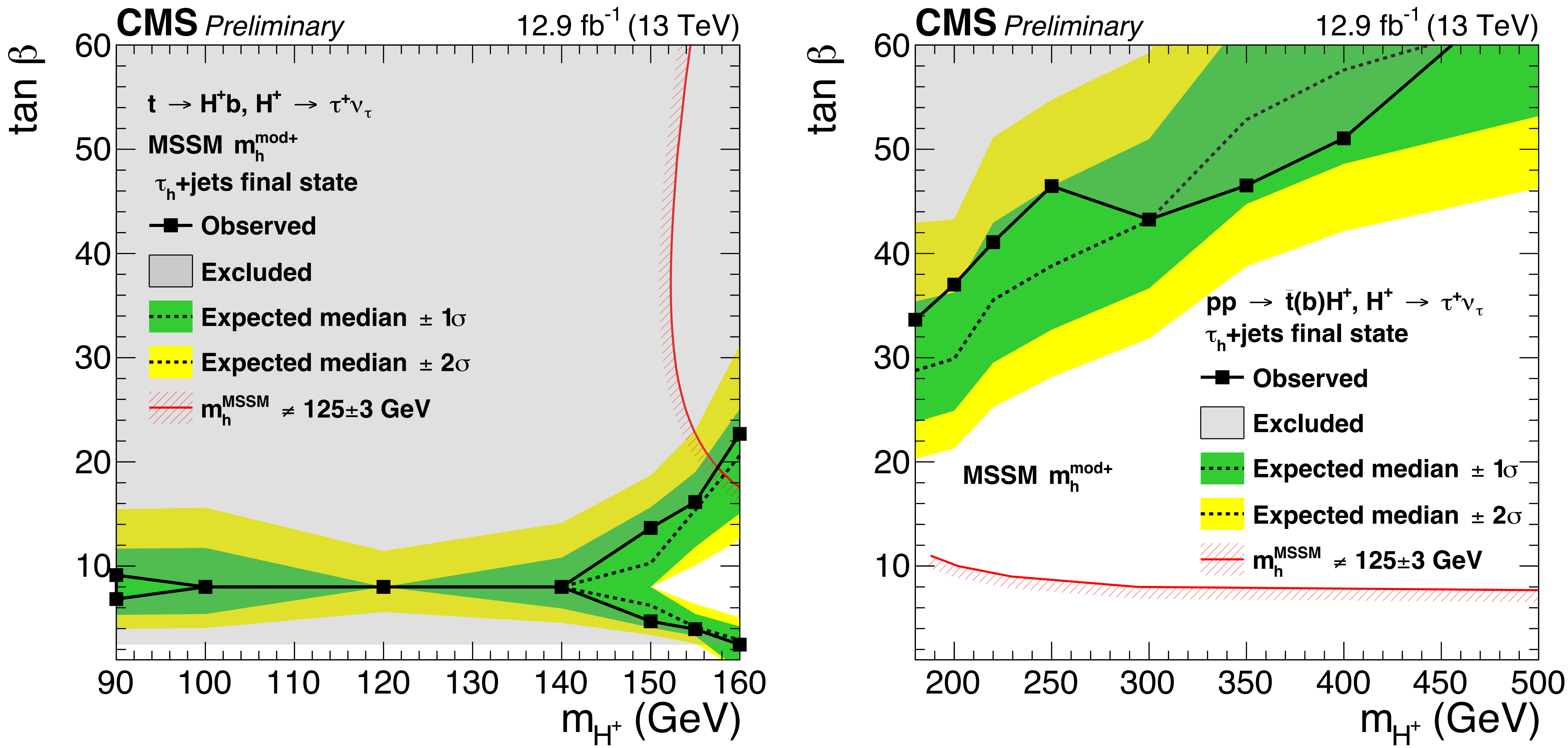
$H^{\pm} \to \tau\nu$ - model independent results





- Low Mass: model is the BR $\mathcal{B}(\mathrm{t} \to \mathrm{bH}^{\pm}) \times \mathcal{B}(\mathrm{H}^{\pm} \to \tau\nu)$
- High mass: $\sigma(\mathrm{pp} \to \mathrm{H}^{\pm}\mathrm{W}^{\mp}\mathrm{b\bar{b}}) \times \mathcal{B}(\mathrm{H}^{\pm} \to \tau\nu)$

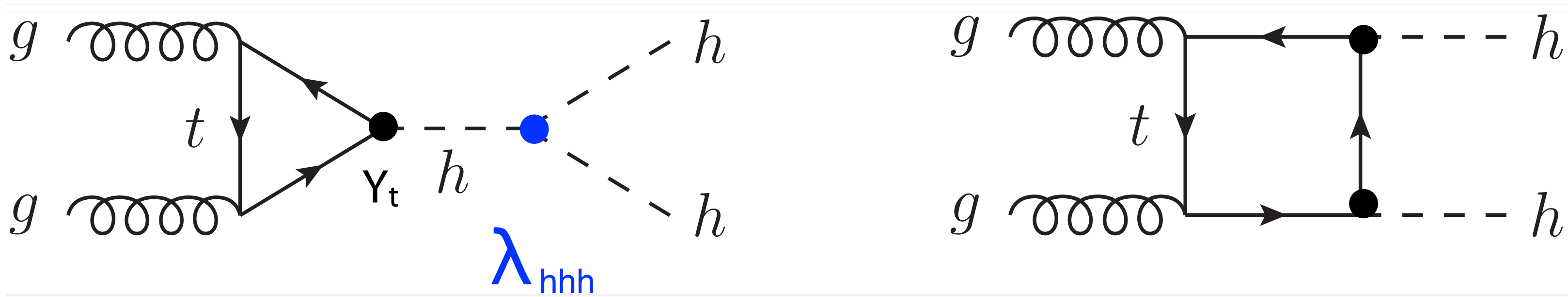
$H^{\pm} \to \tau\nu$ - results in MSSM m_h^{mod+} scenario



- **light H± almost ruled out in this** (and most of other) **scenario**(s)

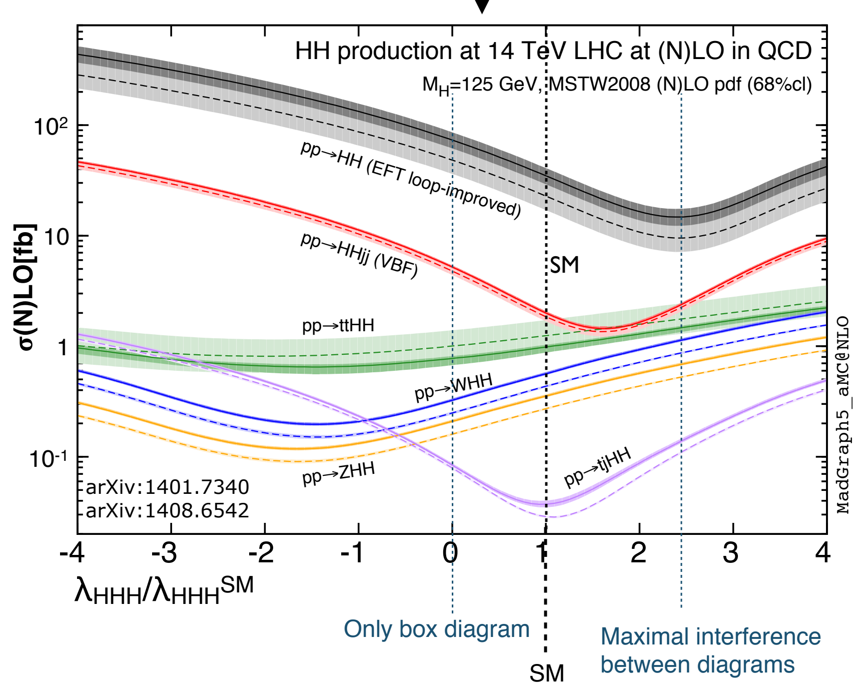
Non-resonant h→hh - theory motivation

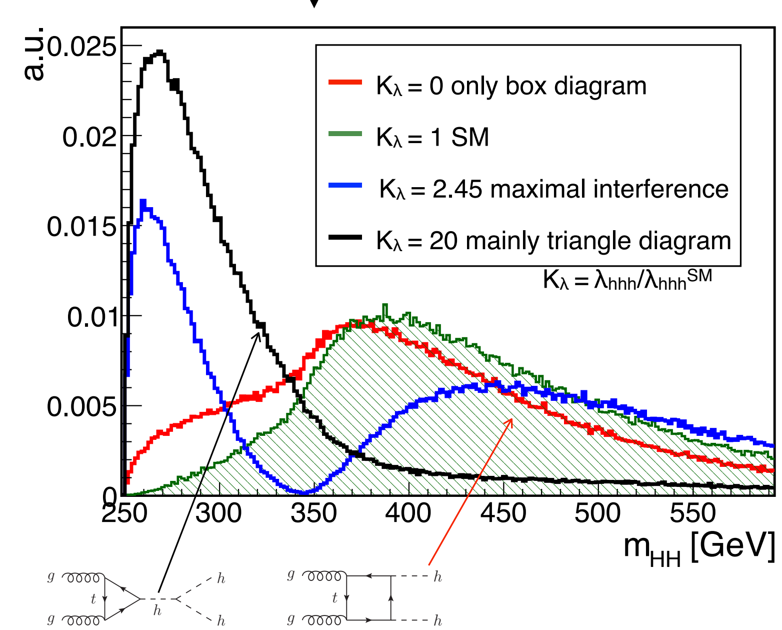
- **in the SM this arises from the interference of these two processes**



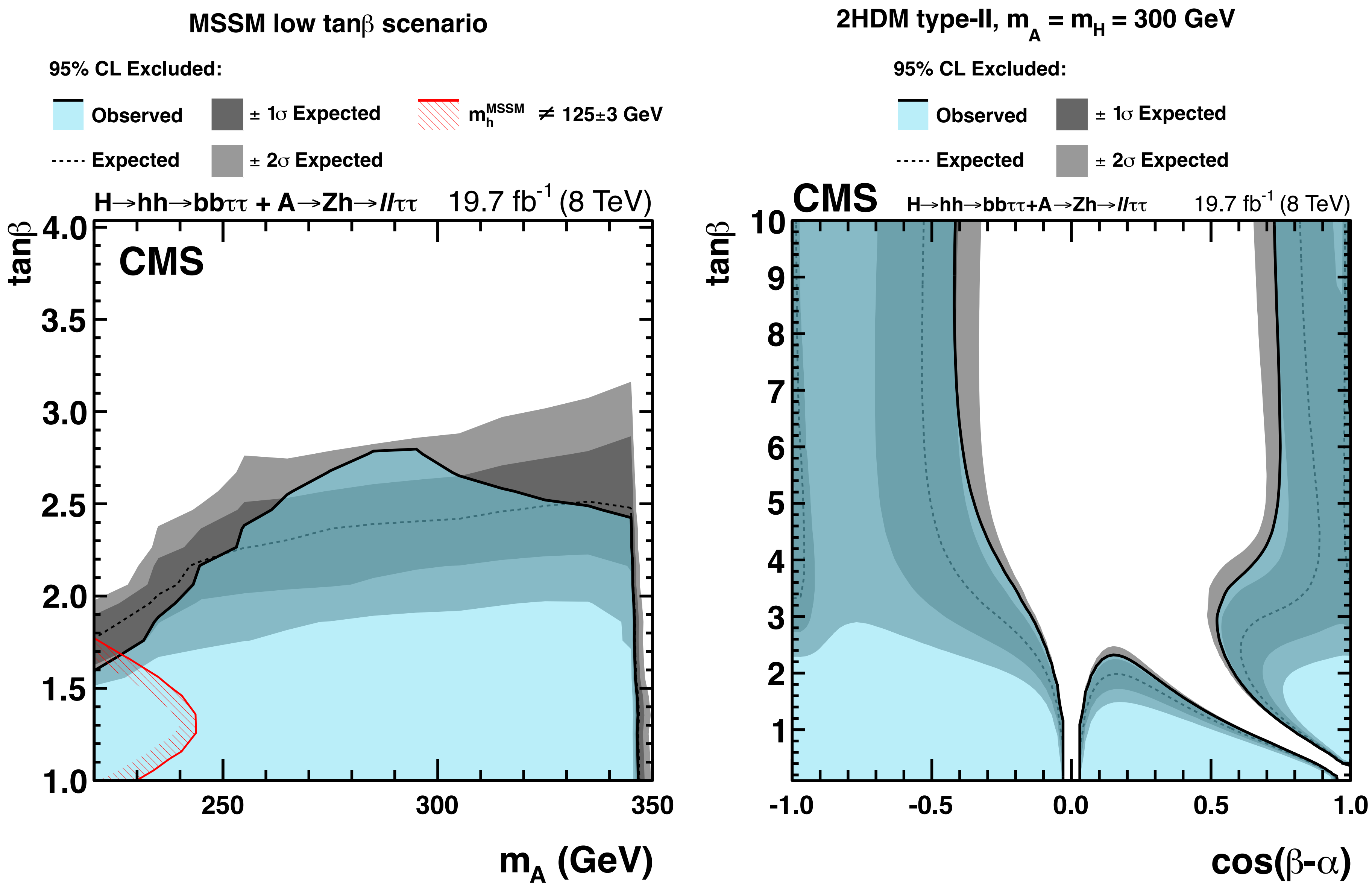
- where λ_{hhh} indicates the **trilinear Higgs coupling**
  which is expected to be too small to be measured at LHC in Run2

- **BSM contributions can be present** and are represented by
  the coupling modifier $k_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM}$
  that affects both the cross section and the kinematics of the hh process





Resonant MSSM H→hh→bbττ - 8 TeV



- the results of the 8 TeV analysis were interpreted in the MSSM (together with A→Zh→ℓℓττ), low tanβ and 2HDM type-II models, further reducing the non excluded parameter space
- update at 13 TeV foreseen for Moriond17