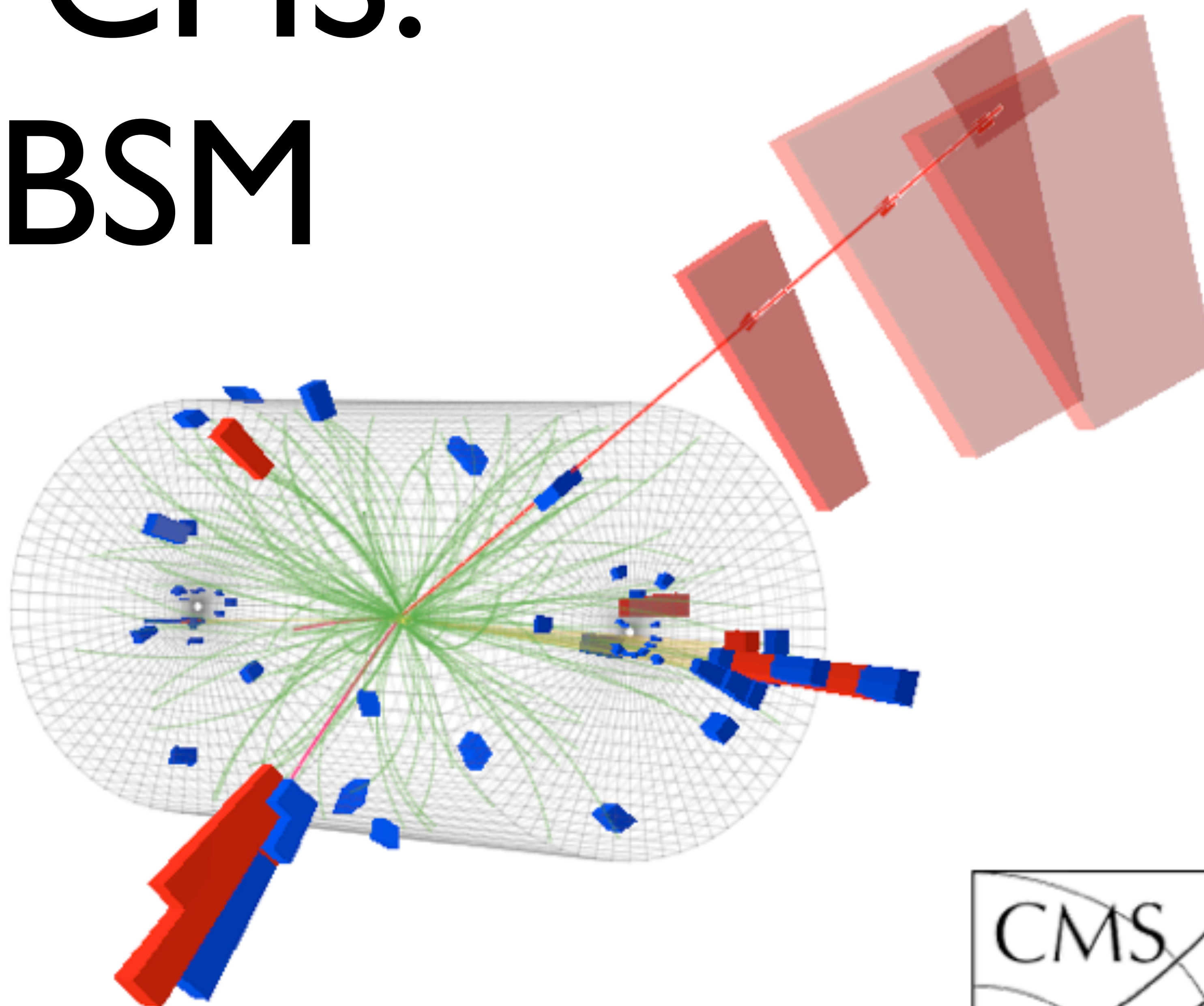
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

ETH Institute for Particle Physics

$H \rightarrow \tau\tau$ in CMS: SM and BSM



L. Bianchini

ETH Zurich

On behalf of the CMS Collaboration

Higgs Hunting 2013, Orsay

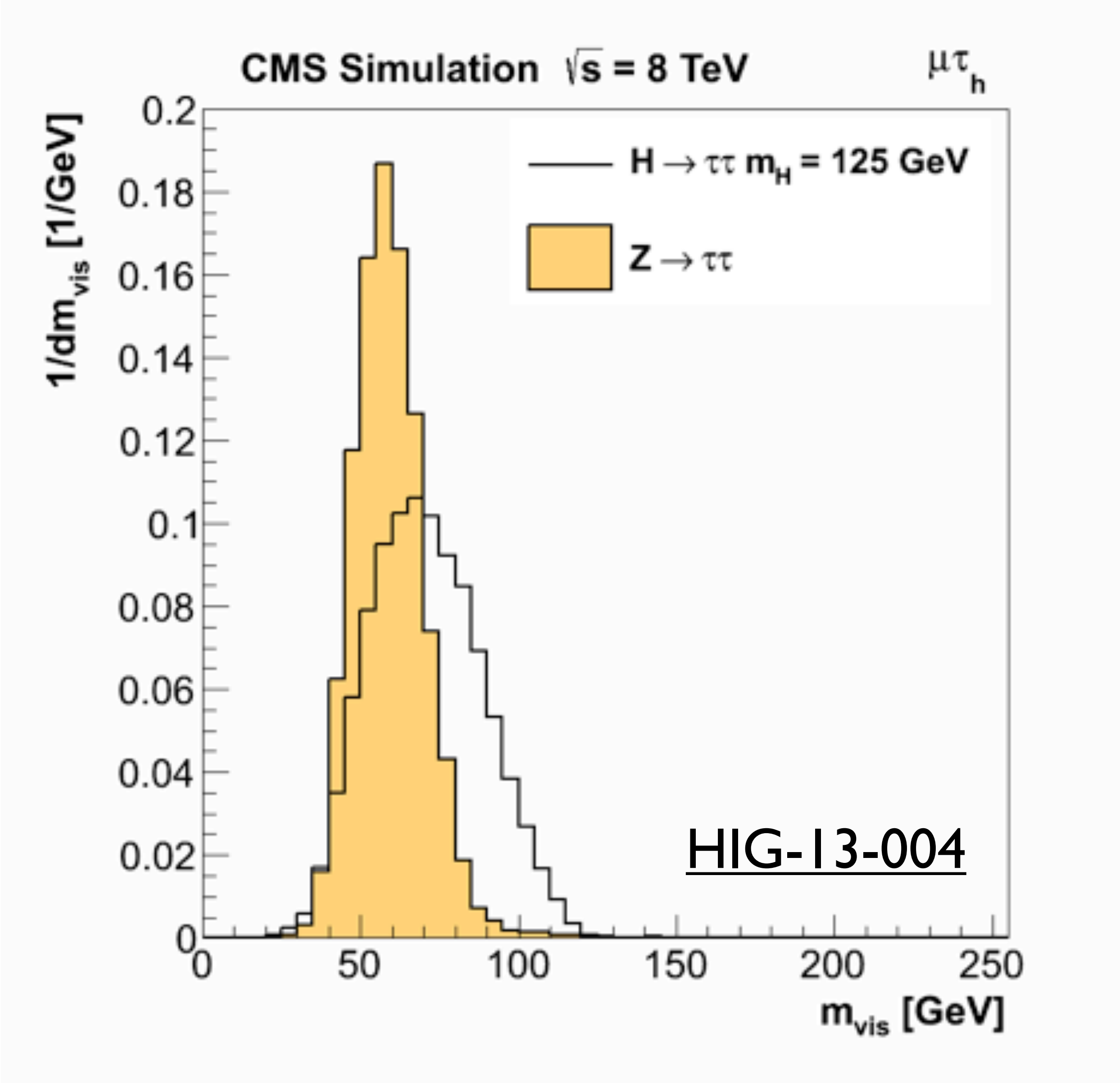
Outline

- Introduction
  - Key di-τ observables
  - Di-τ mass reconstruction
- Searches
  - Inclusive $H \to \tau\tau$ (SM)
  - VH, $H \to \tau\tau$ (SM)
  - MSSM $\Phi \to \tau\tau$
- Conclusions
  - Summary & prospects

Introduction

Di-tau key-observables

- Visible di-τ mass
  - Simplest M_H estimator
  - Robust, but ~poor resolution
- Di-τ boost (⇔ extra jets)
  - Jets ⇒ production mechanism
  - Boost ⇒ better mass resolution
- Collinear Approximation
  - Motivates topological cuts on E_T^{miss}
  - Superseeded as "mass estimator"
- Full di-tau mass (aka "SVfit")...



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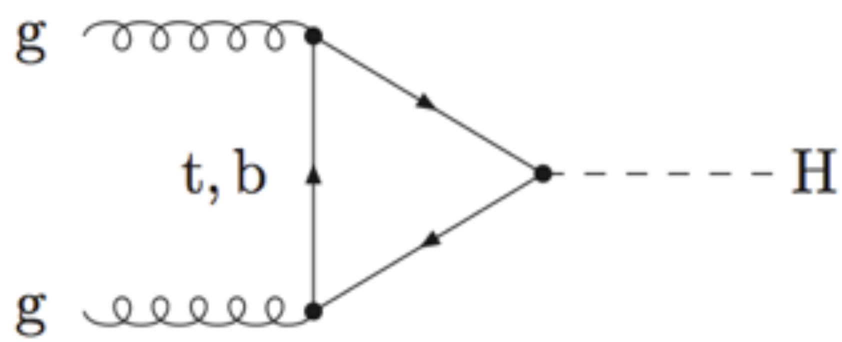

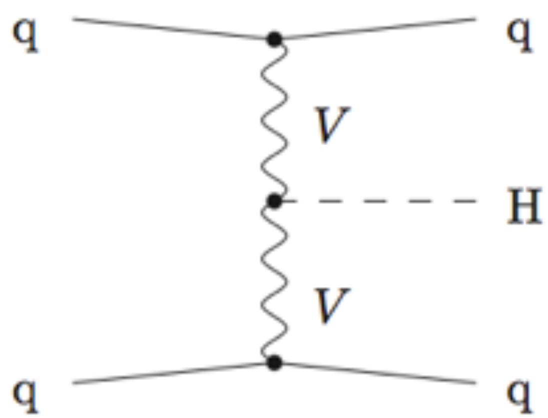

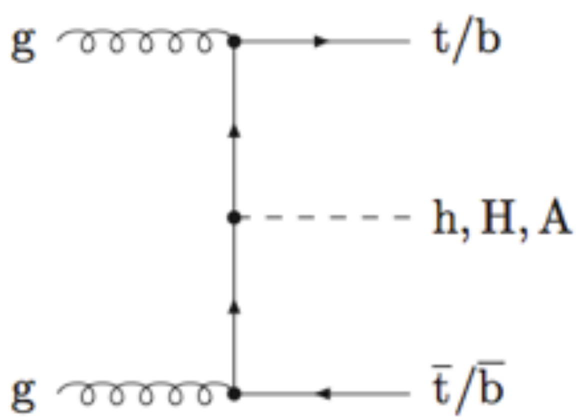

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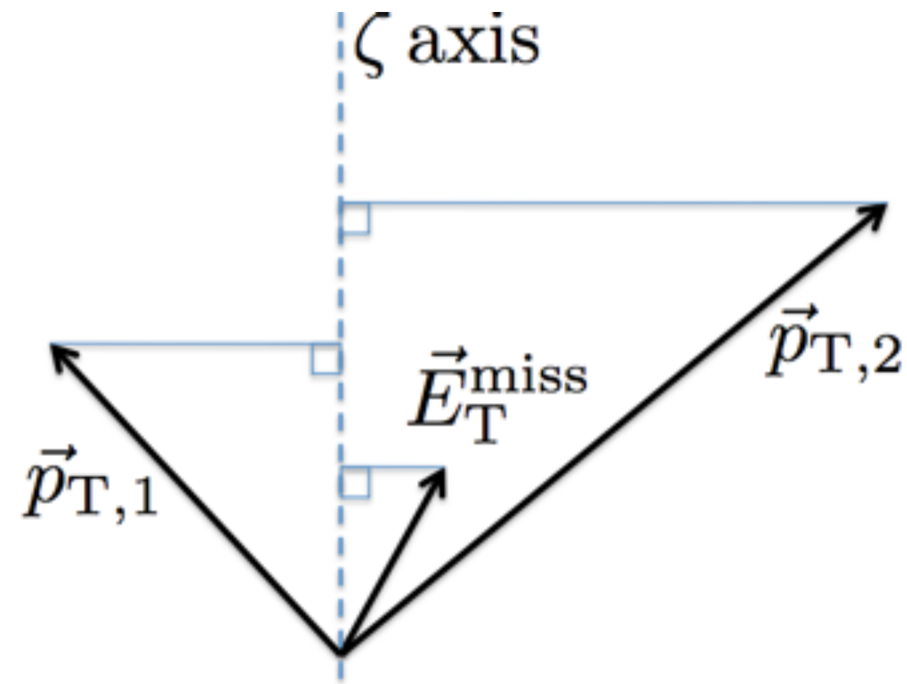

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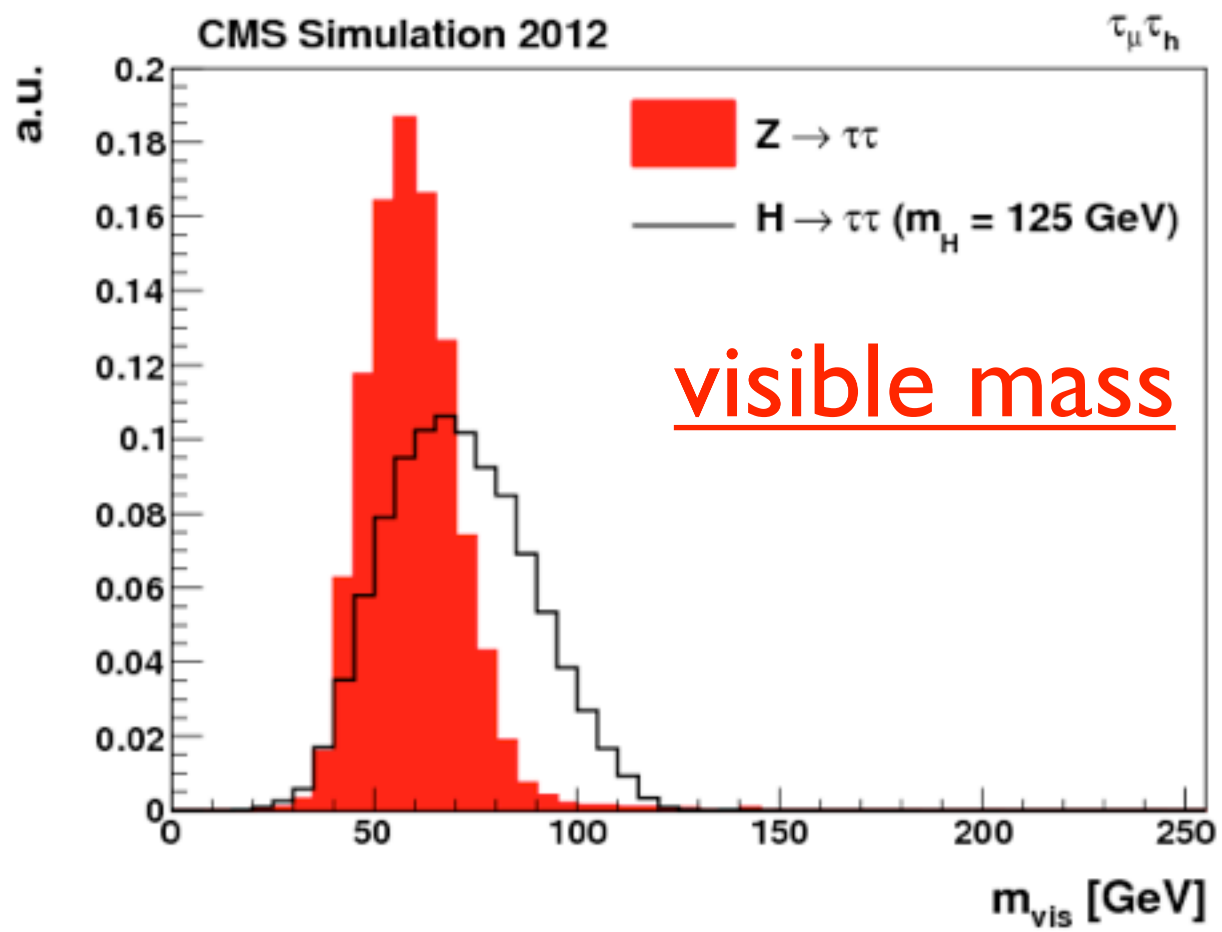
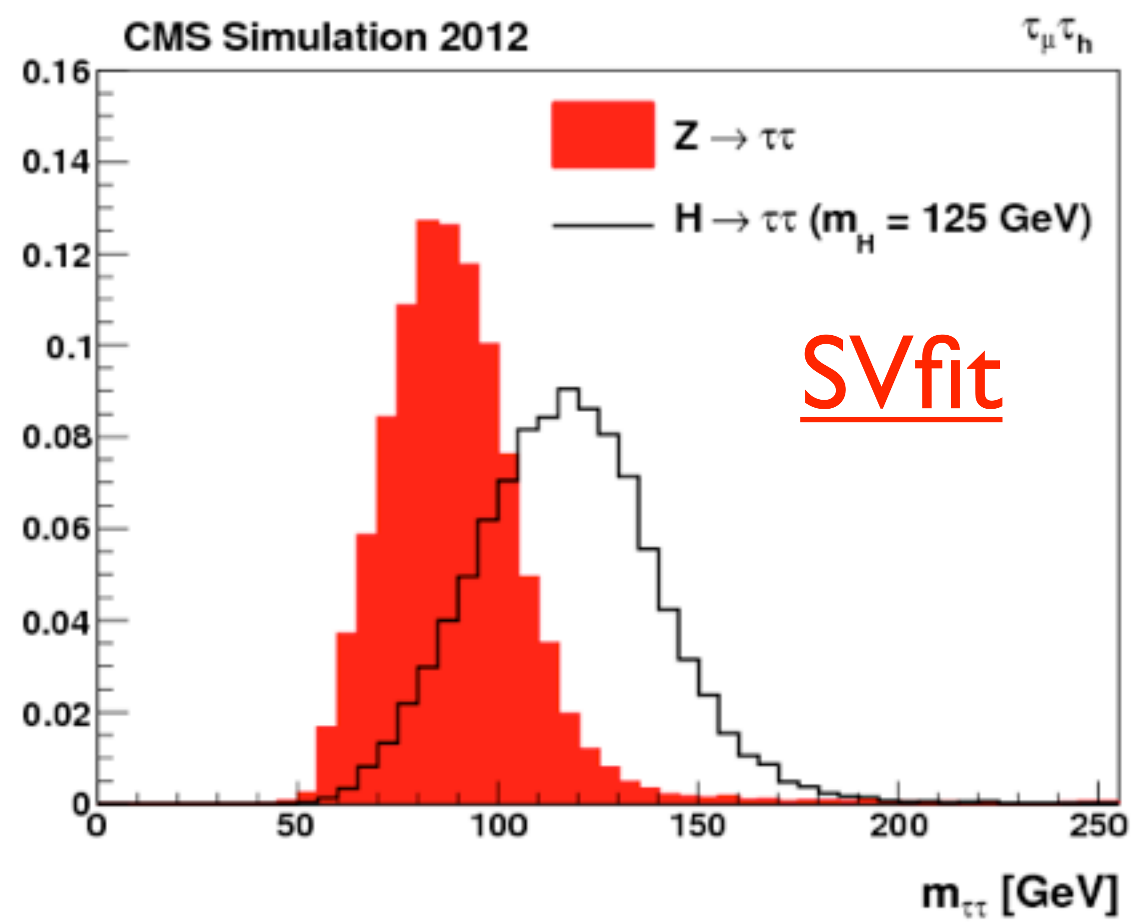
The SVfit mass

HEP 06 (2013) 081

- Dynamical Likelihood estimator
  - Marginalization of unobserved neutrinos d.o.f.
  - Constraints from <u>theory</u> (tau decay kinematics) and <u>experiment</u> (E_T^{miss})
  - Works for all tau decay modes





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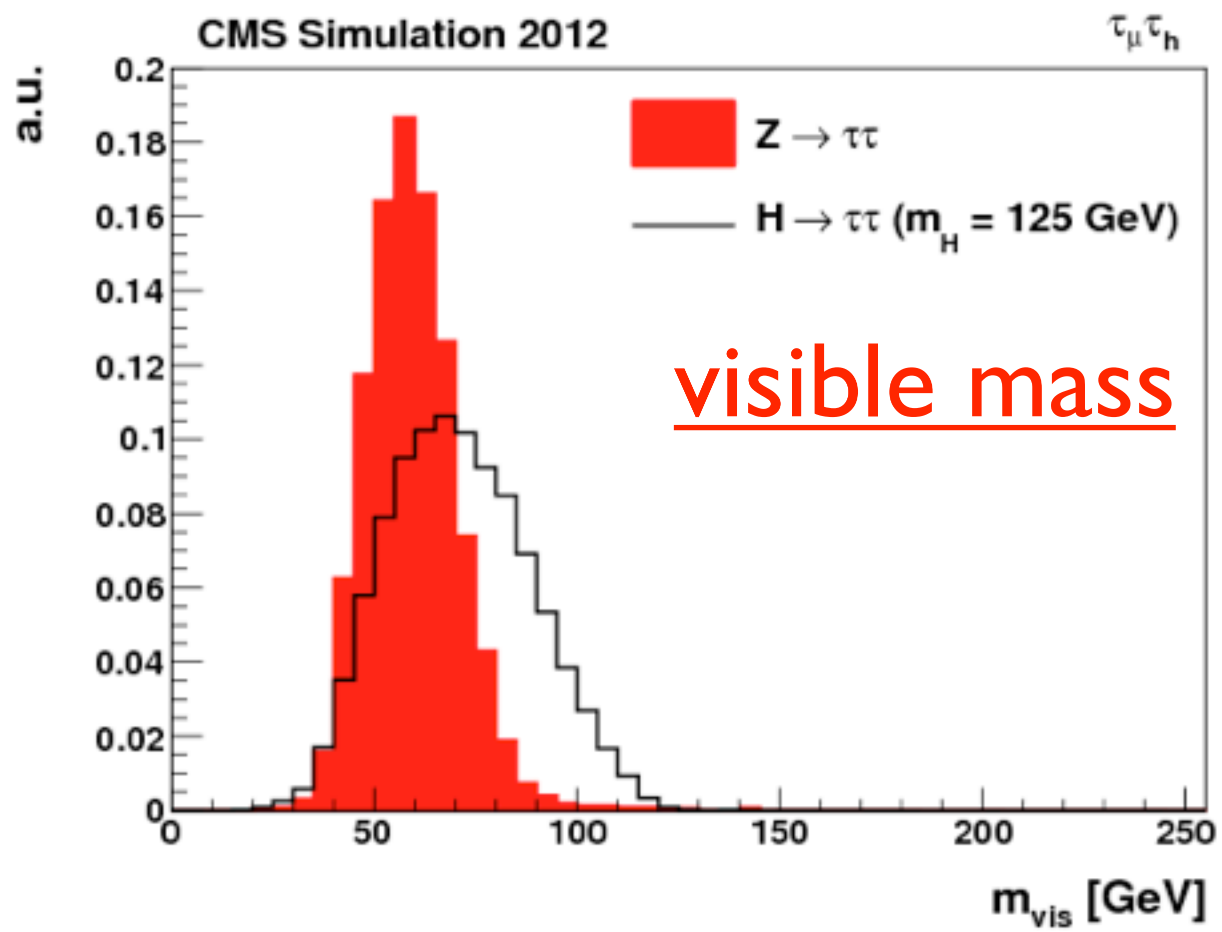

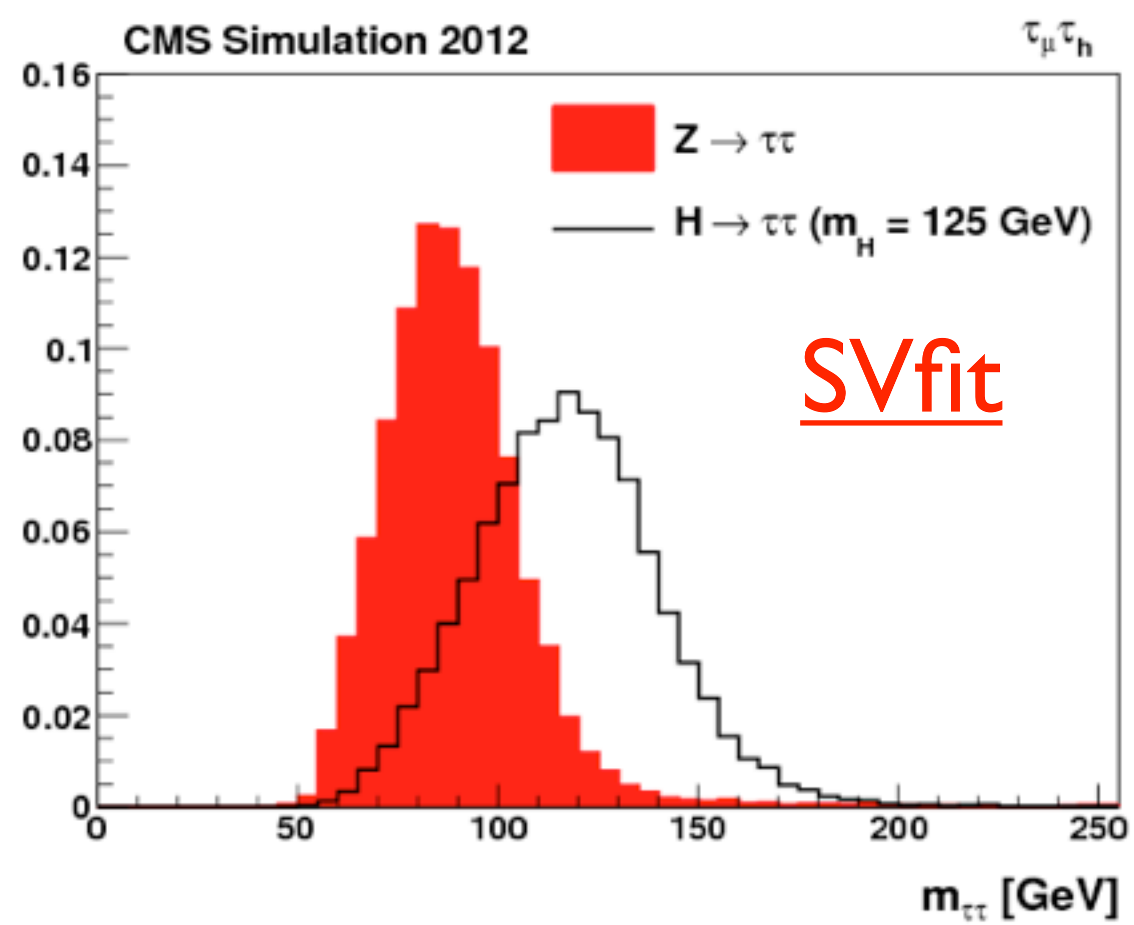

✓mass resolution

$\Rightarrow \sigma/M \lesssim 20\%$

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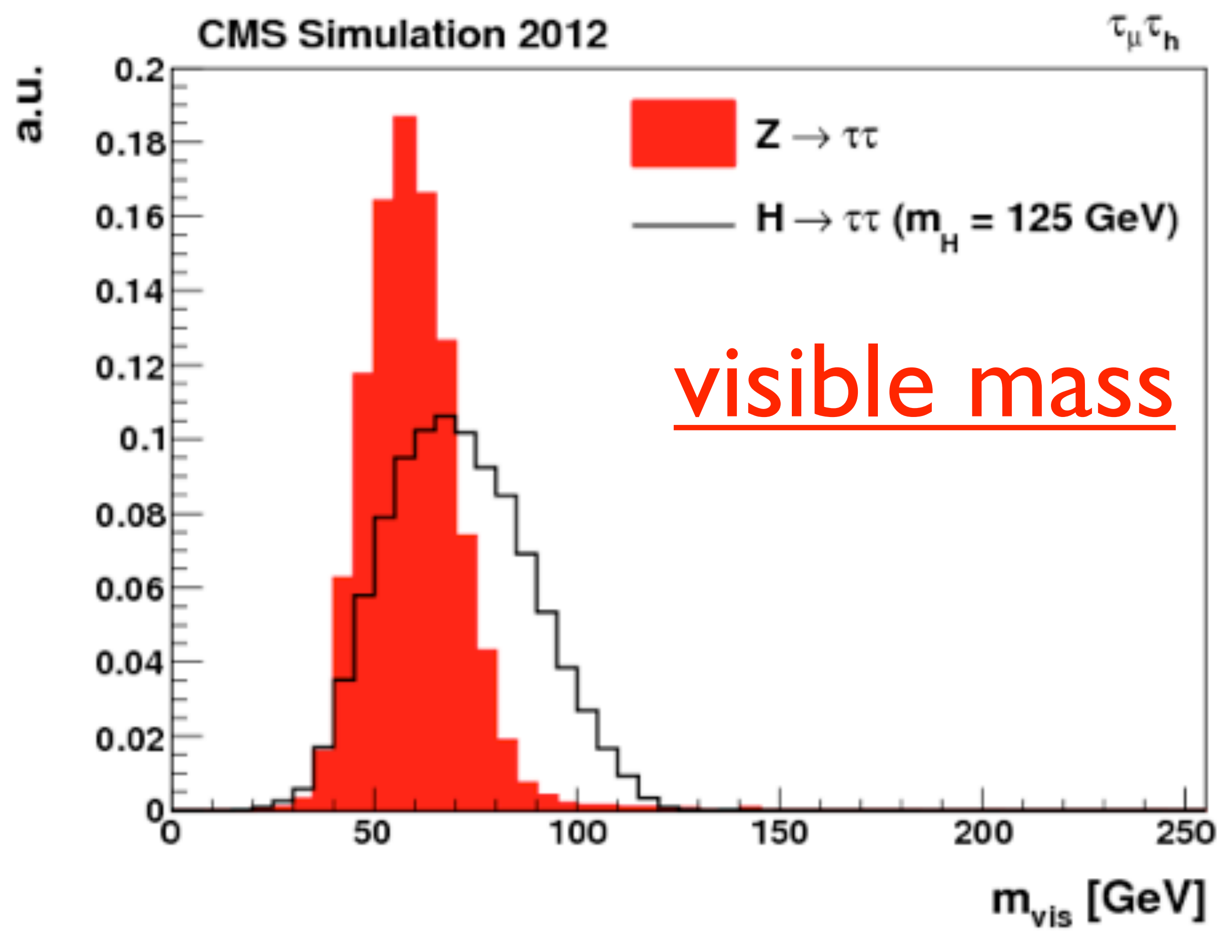

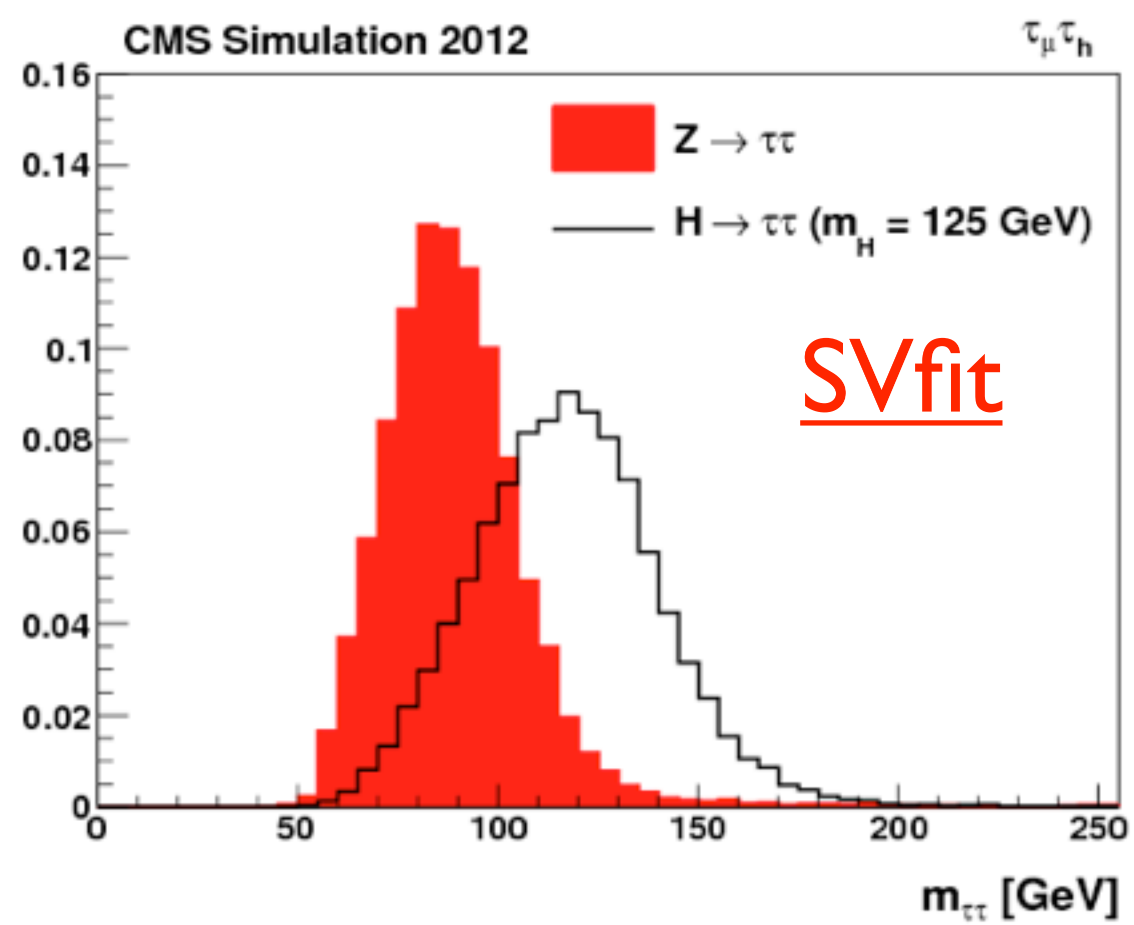

✓**mass resolution** ⇒ $\sigma/M \lesssim 20\%$

✓ Z/H **separation**

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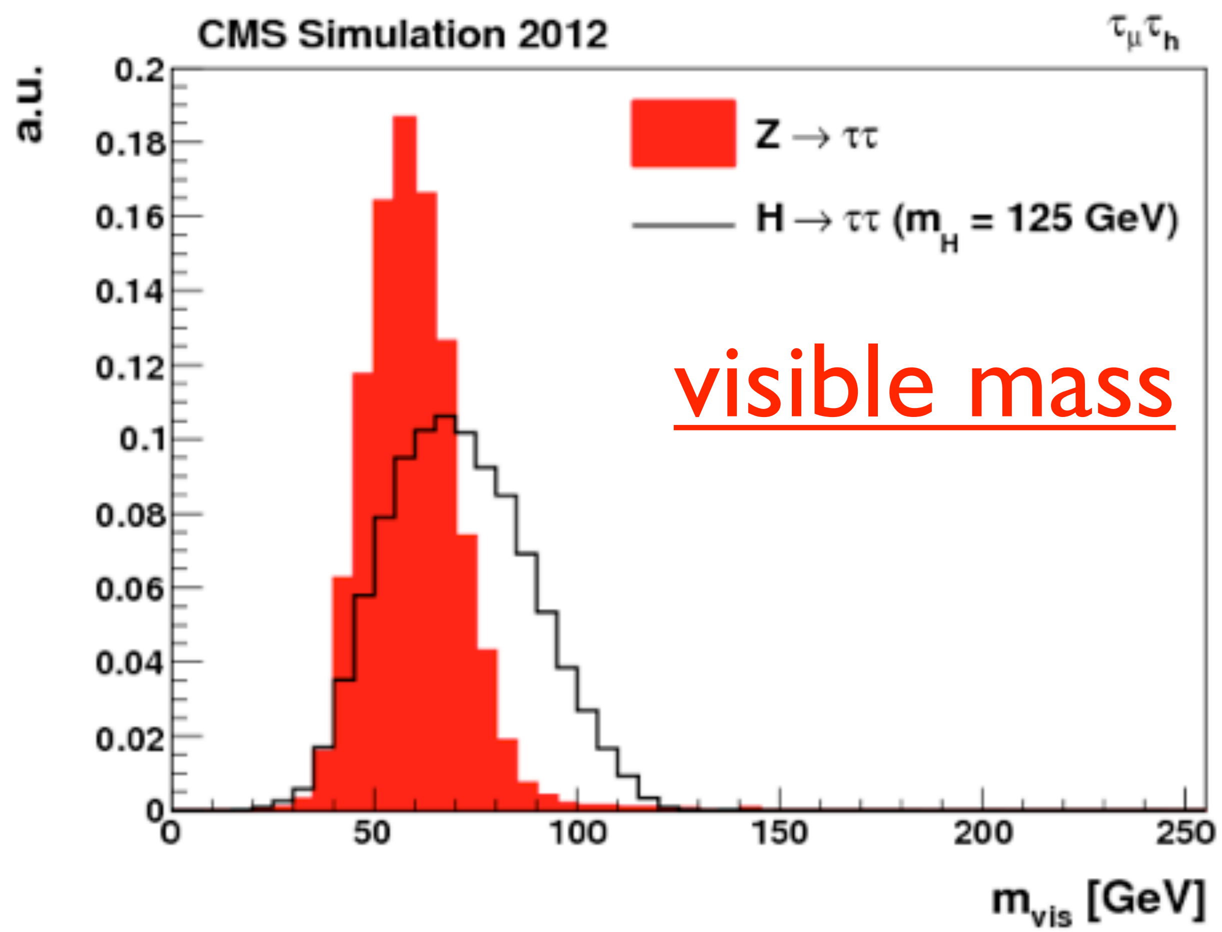
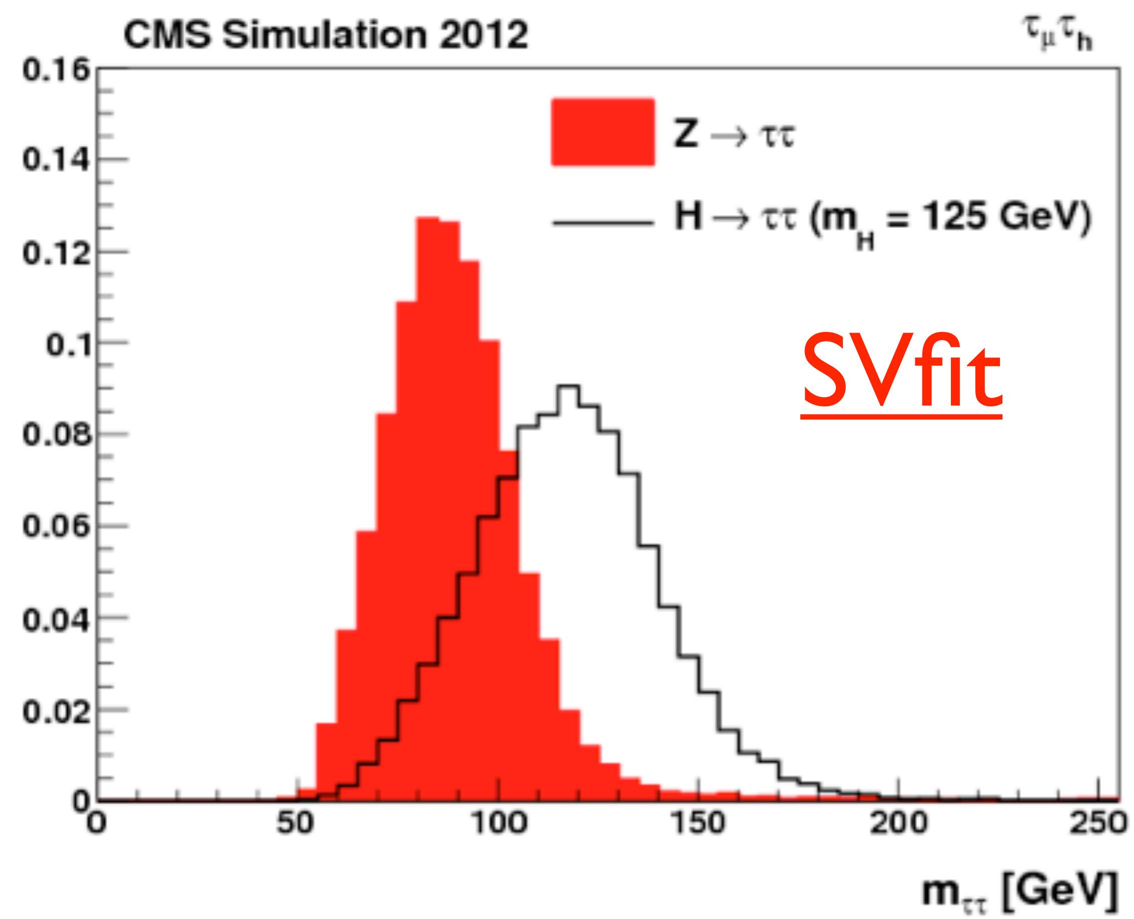




✓**mass resolution** $\Rightarrow \sigma/M \lesssim 20\%$

✓ Z/H **separation**

➜ Impact on limit/sign: **+ 30%**

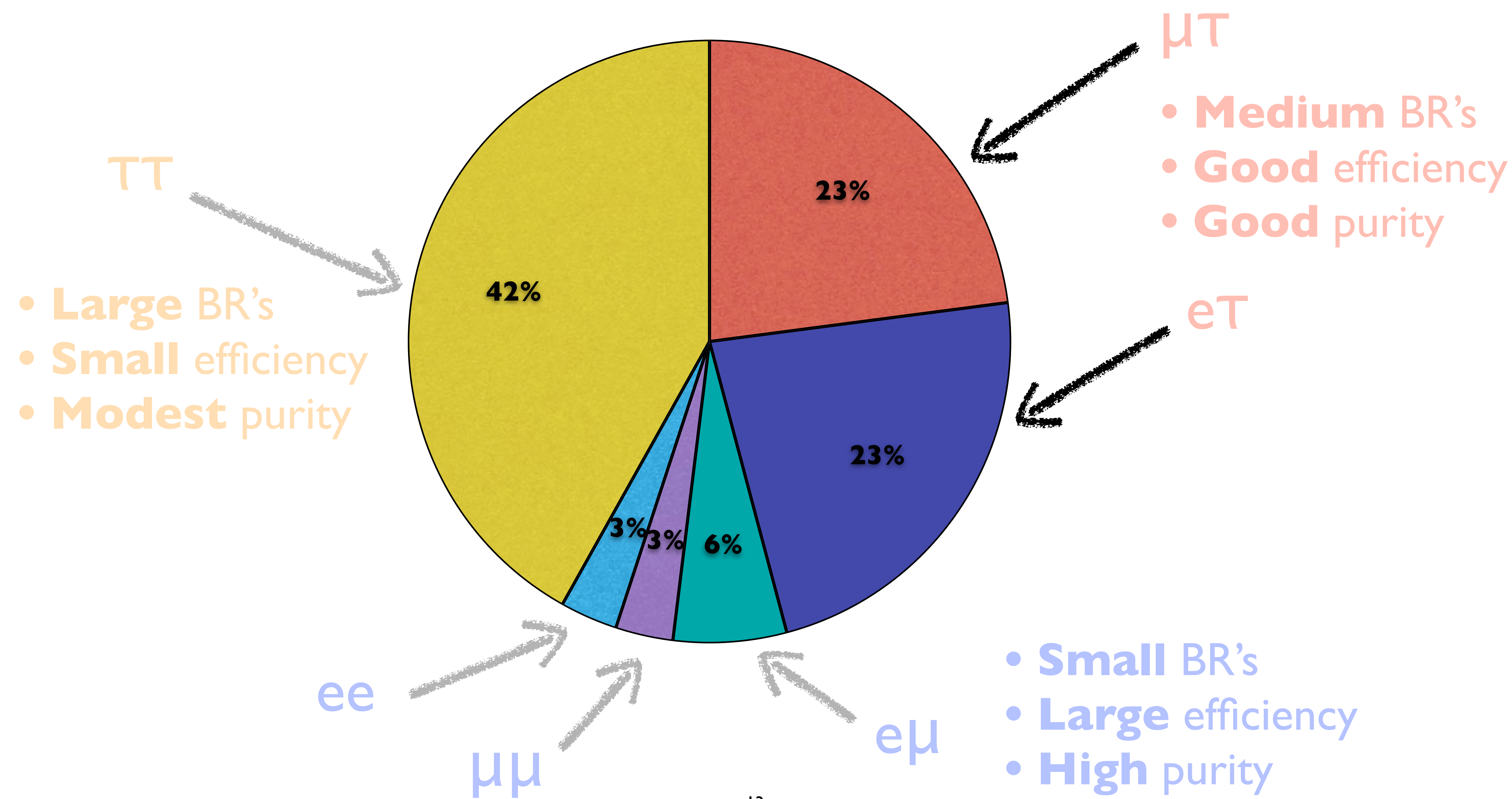
Searches:
gg,qq → H → ττ

(24.3 fb^{-1}, 7+8 TeV)

PAS HIG-13-004

Decay modes

- Search for $\Phi \to \tau\tau$ is several decay modes
  - Not merged
  - Results statistically combined to maximise sensitivity



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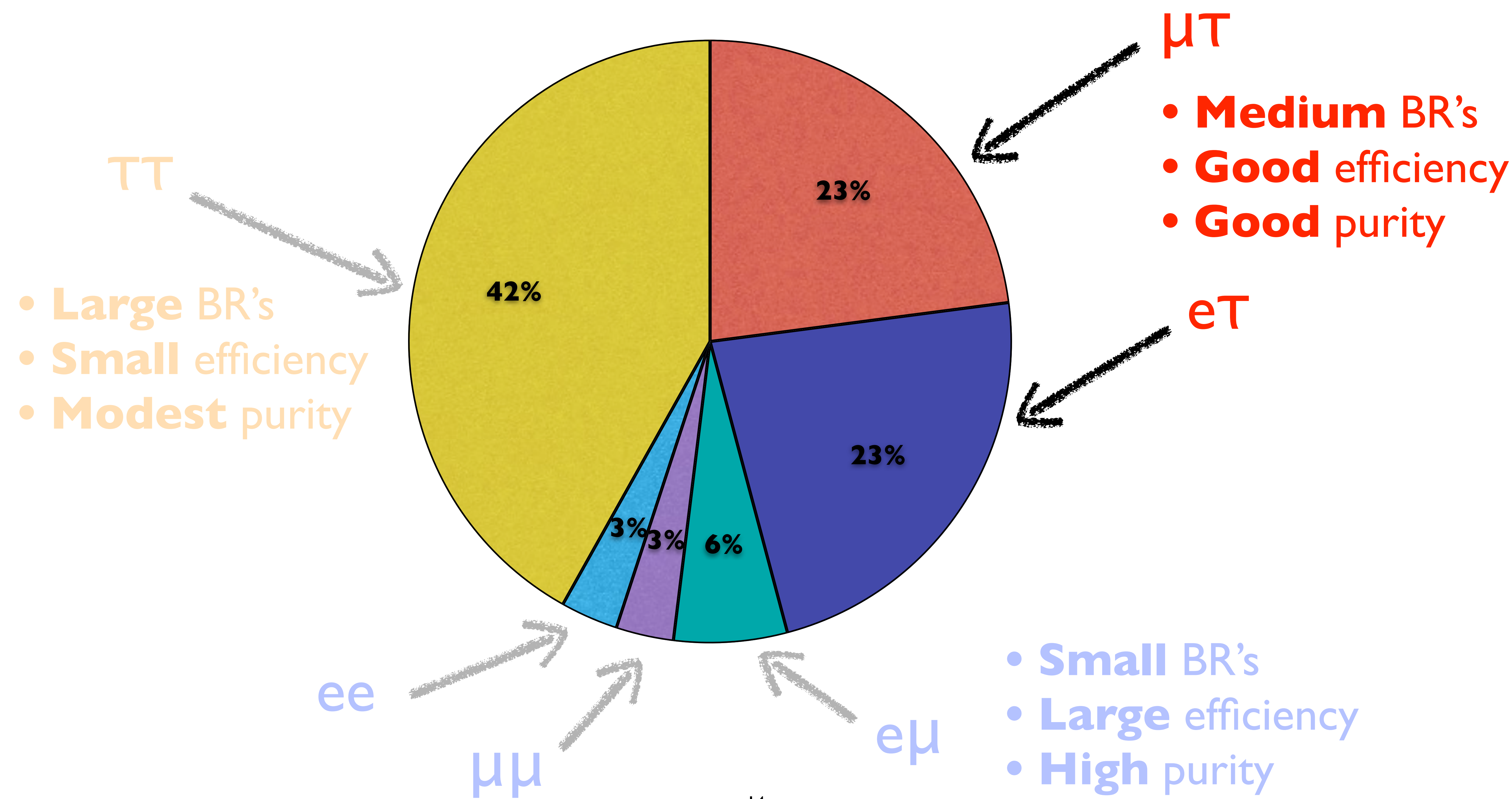

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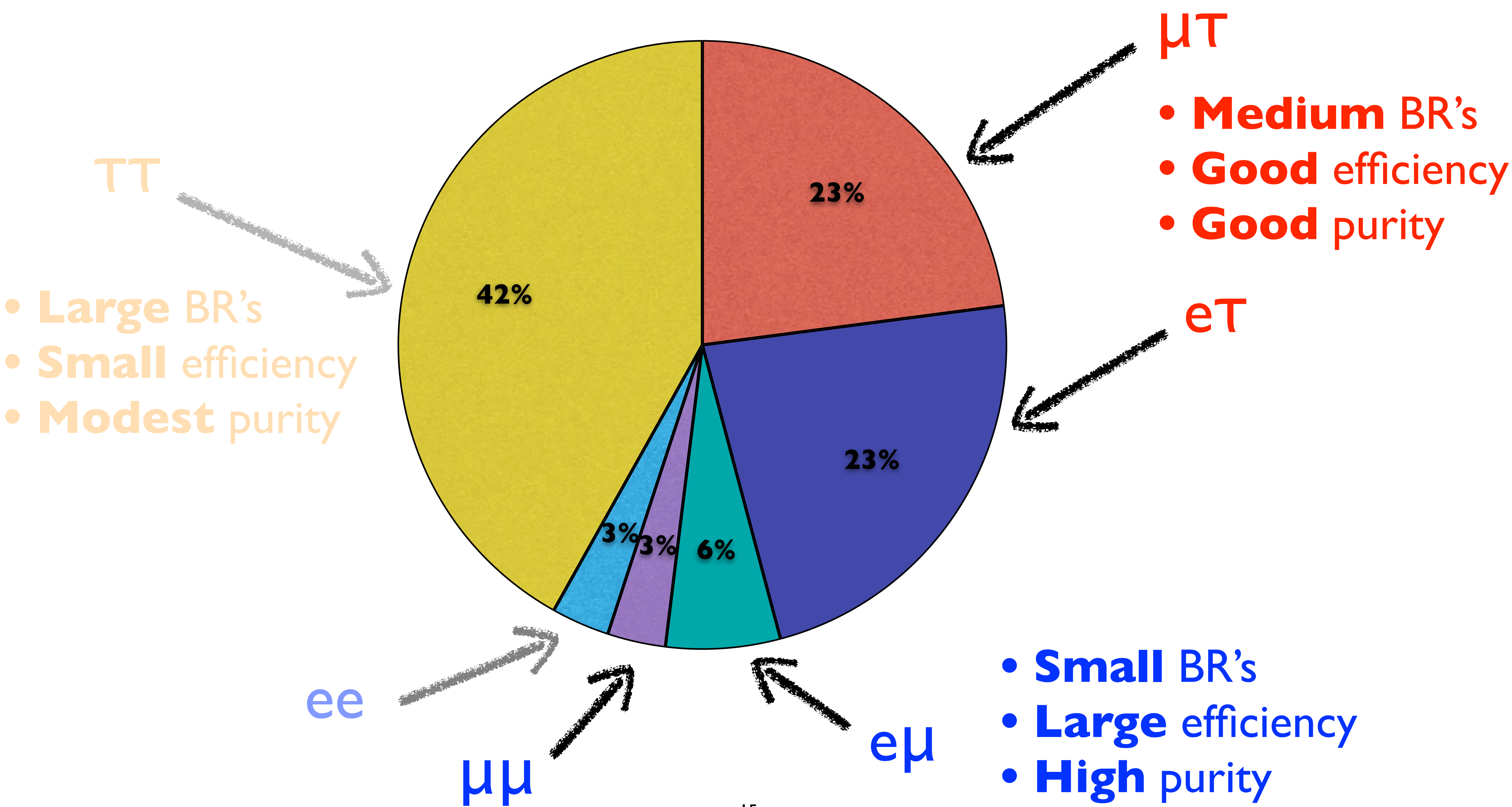

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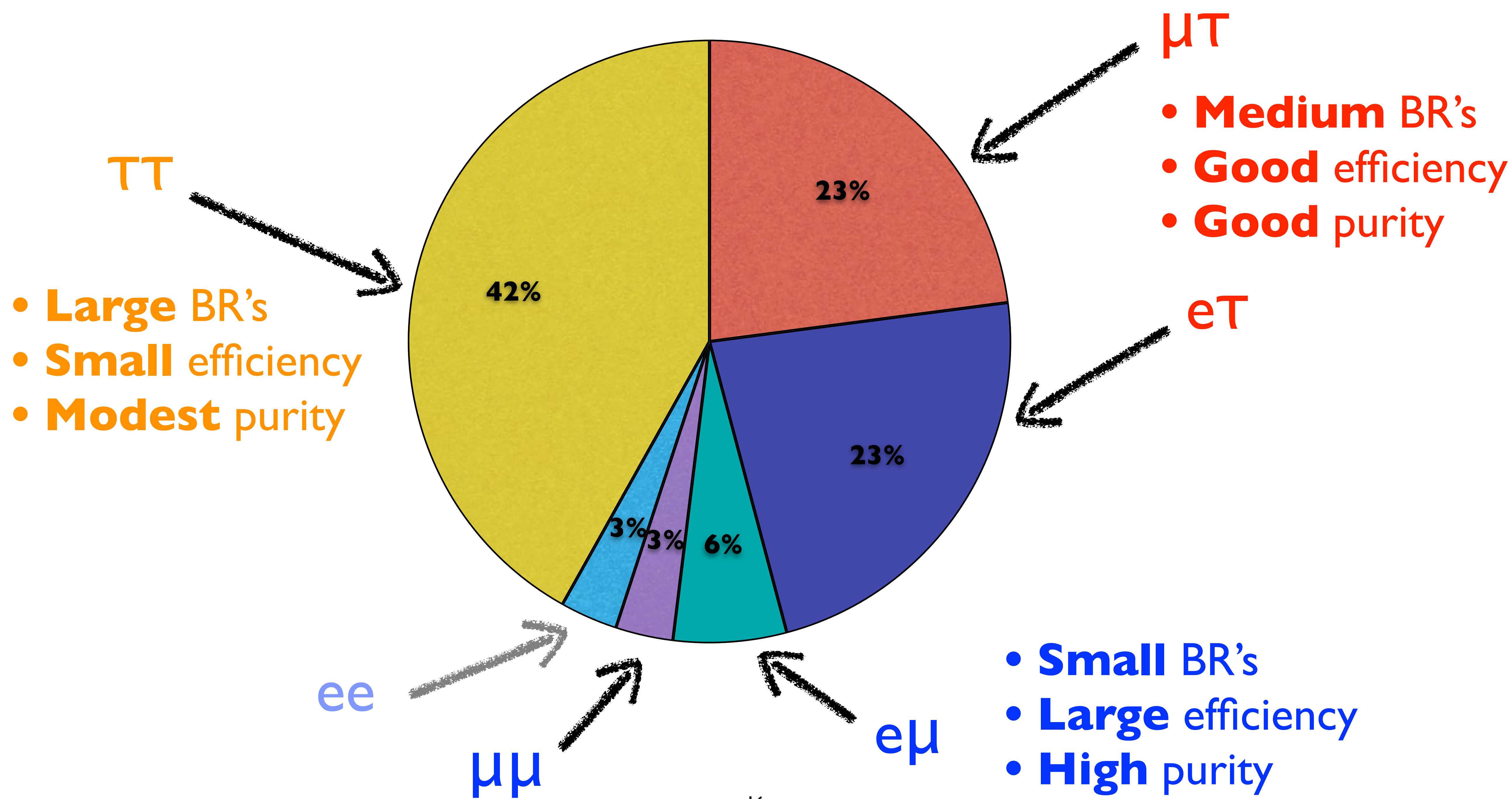
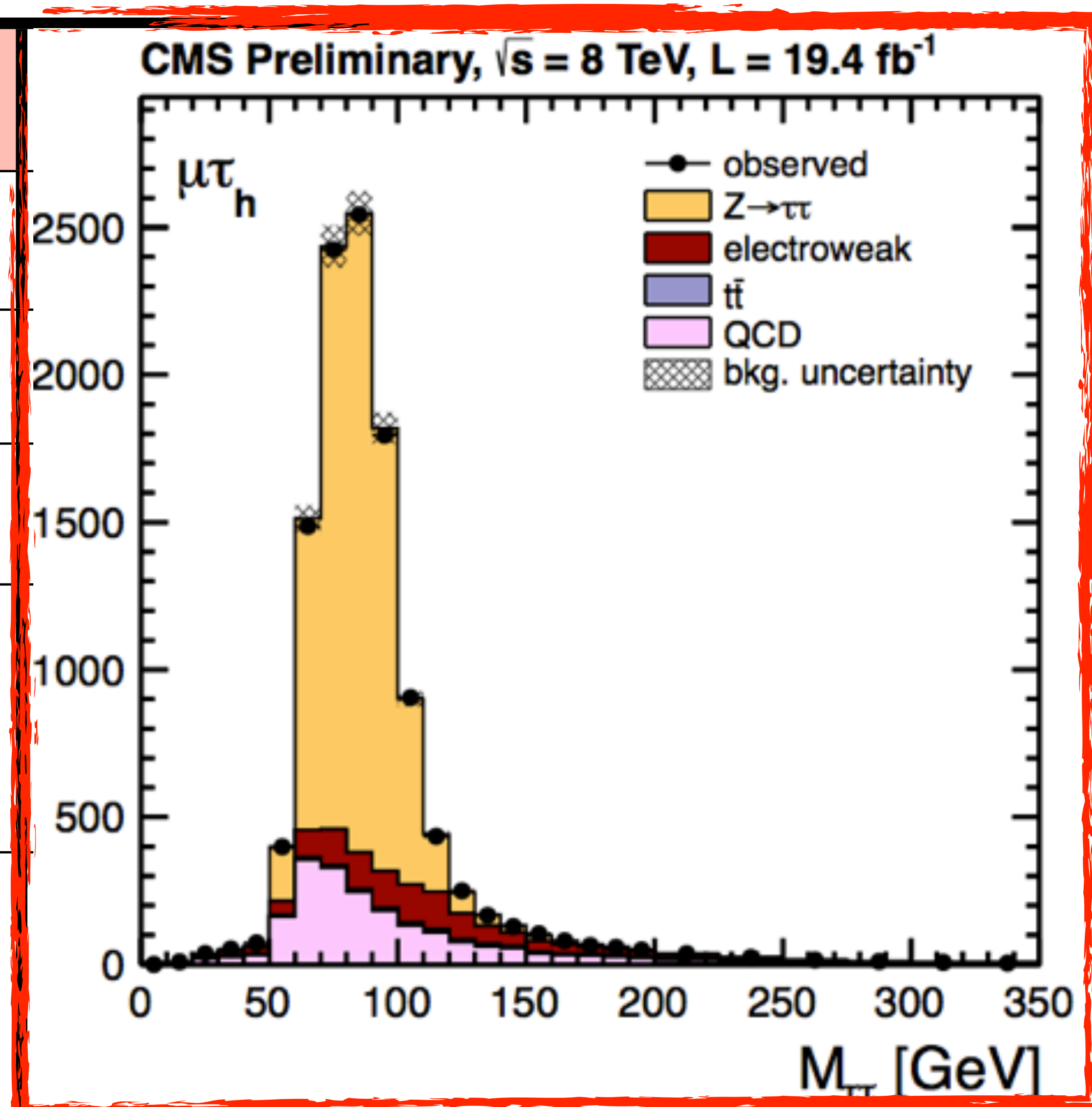


μτ: overview

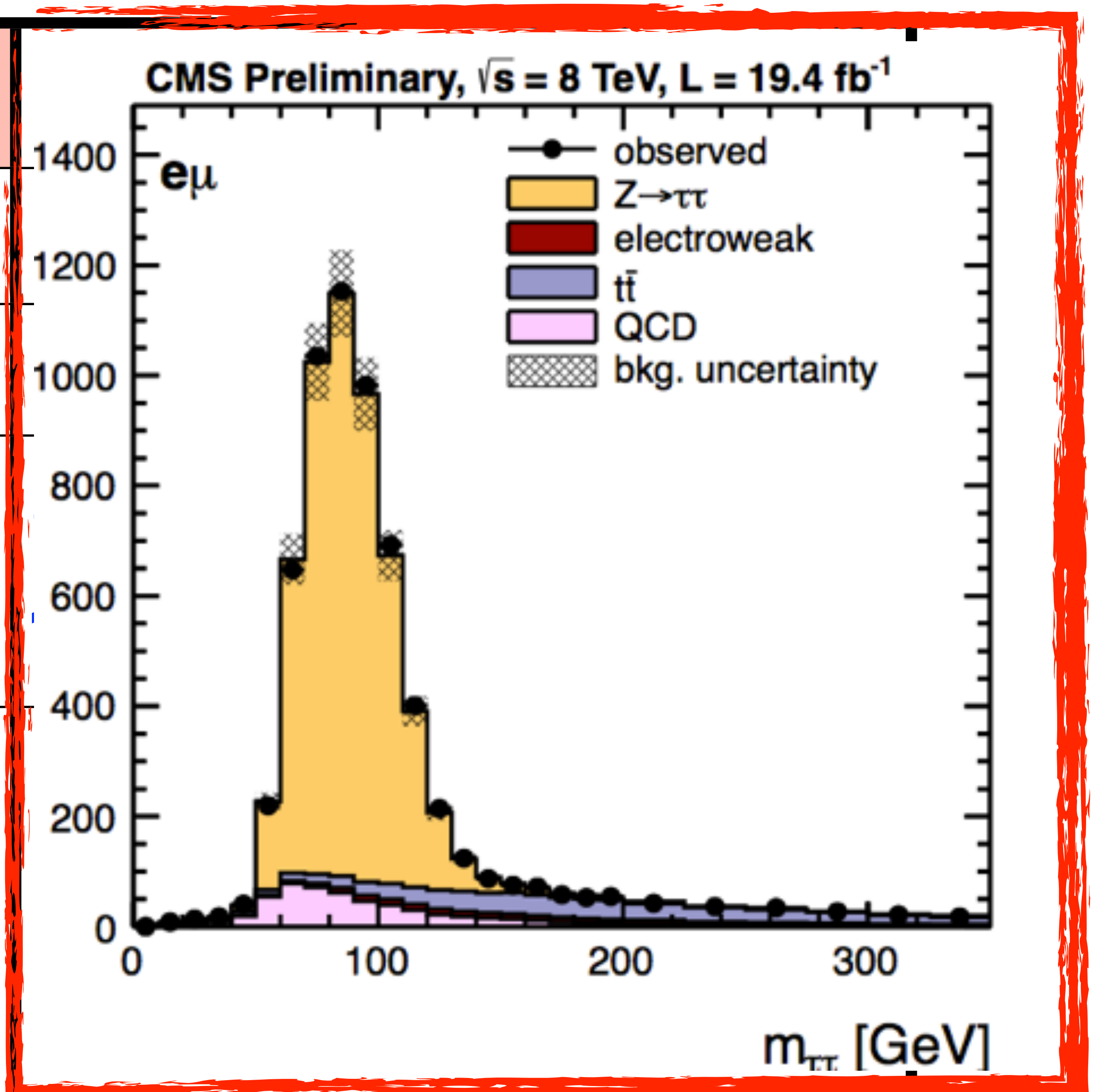
μ+τ
L1 Mu
HLT_IsoMu_PFTau
discr. against $Z\rightarrow\mu\mu$
μ: p_T>17-20, $\|\eta\|$<2.1 τ: p_T>20, $\|\eta\|$<2.3
$M_T(\mu, E_T^{miss})$ <20



Main backgrounds: **$Z\rightarrow\tau\tau$** **QCD** **W+jets**

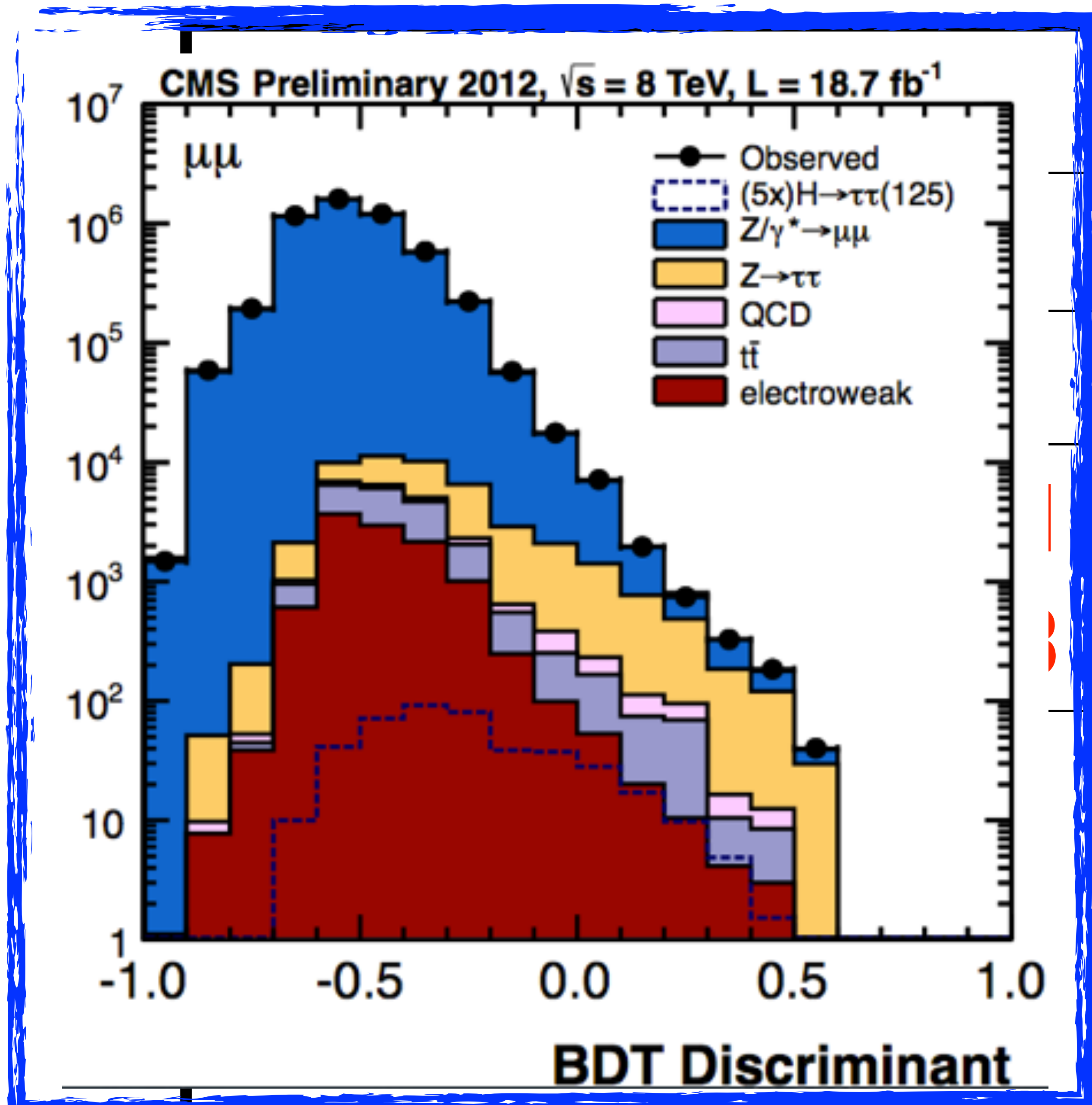
eμ: overview

e+μ
L1 Mu Ele
HLT_Mu_Ele
μ: p_T>20(10), $\vert\eta\vert$<2.1 **e**: p_T>10(20), $\vert\eta\vert$<2.3
$D\zeta$ > -20



Main backgrounds: **Z→ττ** **QCD** **Top** **Di-boson**

μμ: overview



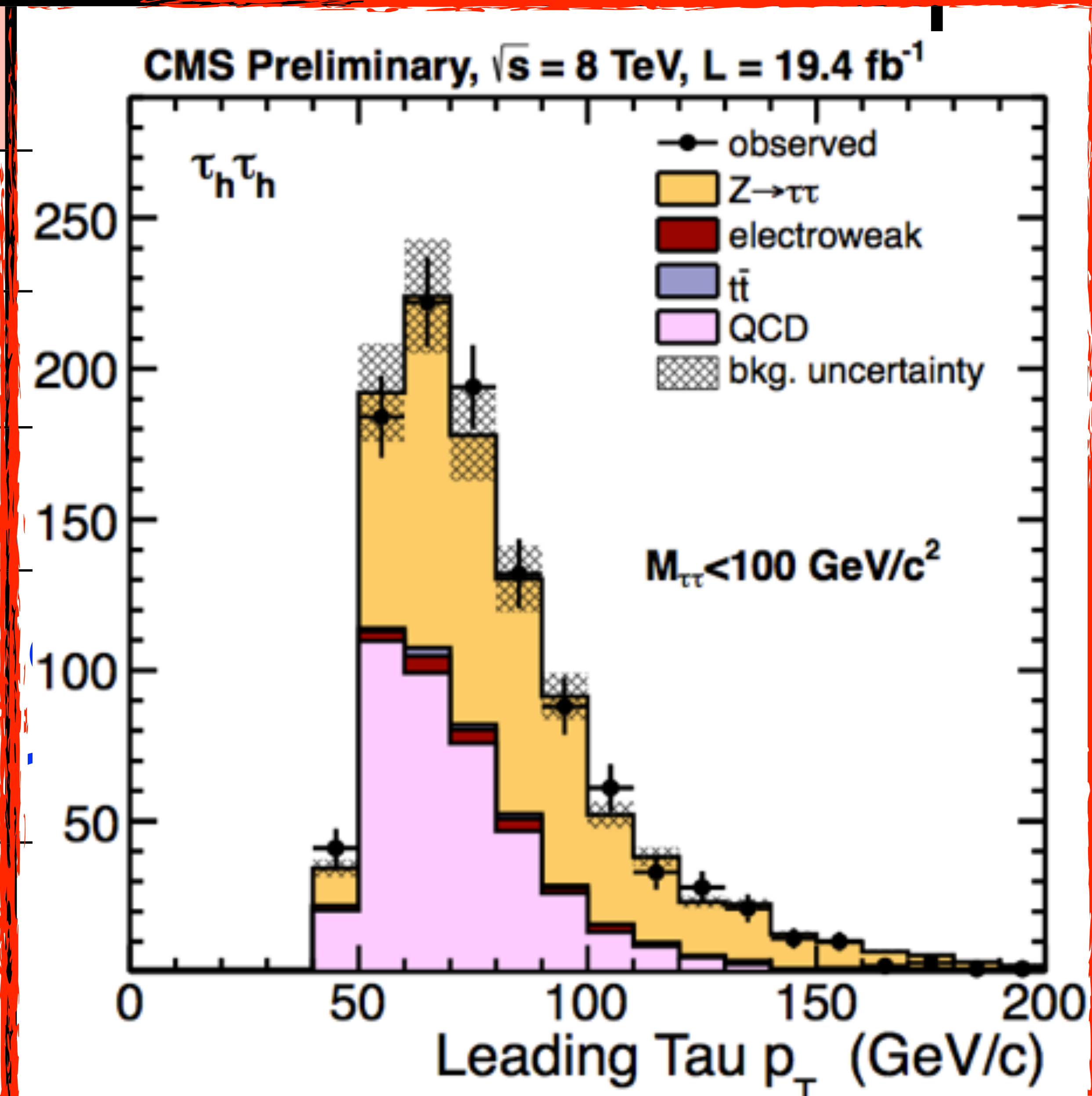
μ+μ
L1 Double Mu
HLT_DoubleMu
μ: p_T>20(10), |η|<2.1 μ: p_T>10(20), |η|<2.1
BDT discriminant against Z→ μμ

Main backgrounds: Z→μμ Z→ττ Top Di-boson

Thursday, July 25, 13

ττ: overview

τ+τ
L1 tau
HLT_DoubleTau_Jet
≥1 jet p_T>50
τ: p_T>45, |η|<2.3 τ: p_T>45, |η|<2.3
Transverse Boost* p_T^H>110-140



Main backgrounds: Z→ττ QCD W+jets

* only in analysis cat. See later

Event Categories

	0-jet	1-jet*	2-jets* (VBF enhanced)
Low "τ" p_T	**Sideband**	✓resolution	• M_{jj}>500 GeV • $\lvert\Delta\eta_{jj}\rvert$>3.5 • CJV
High "τ" p_T	**Sideband**	✓resolution ✓purity	
ττ-specific:		• $p_T^{\tau\tau}$>110 GeV	• M_{jj}>250 GeV • $\lvert\Delta\eta_{jj}\rvert$>2.5 • $p_T^{\tau\tau}$>140 GeV • CJV

* p_T>30 GeV, anti-PU jet id

Main backgrounds estimation

$Z \to \tau\tau$

Kinematics: **$Z \to \mu\mu$ data**
[muons replaced with MC taus]

Normalization: **$Z \to \mu\mu$** *yield in same data set*

W+jets

Kinematics: MC

Normalization: high-M_T **sideband**

Top

Kinematics: MC

Normalization: **sideband** *(b-tags)*

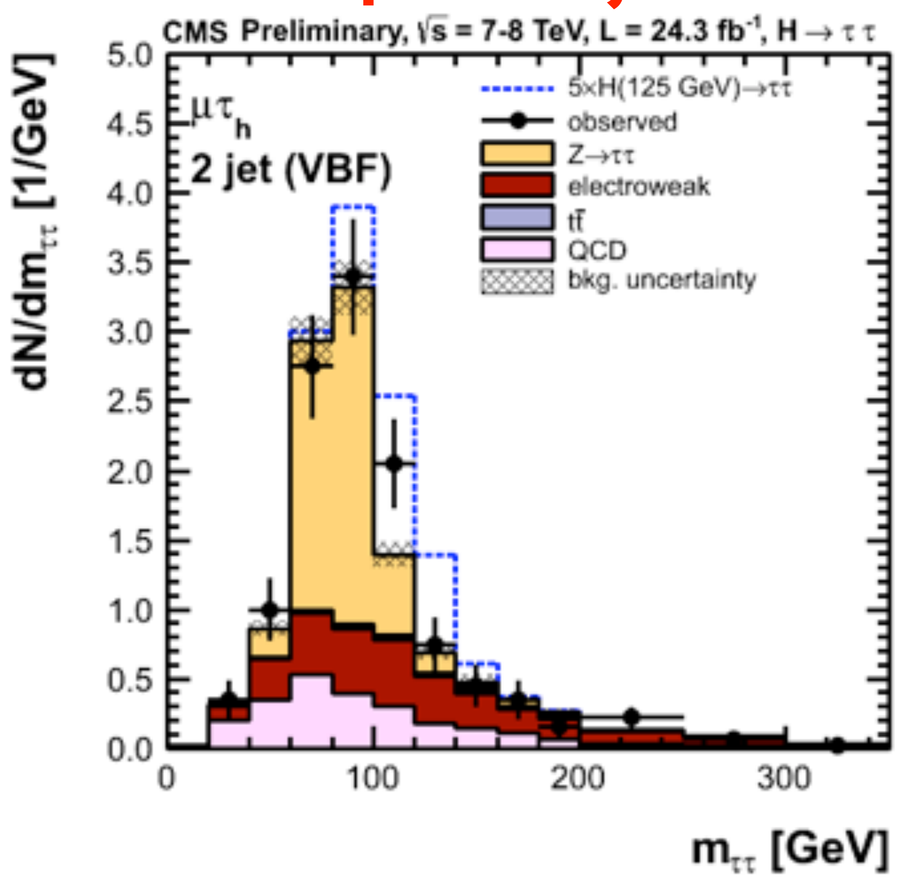
QCD

Kinematics and *normalization:*

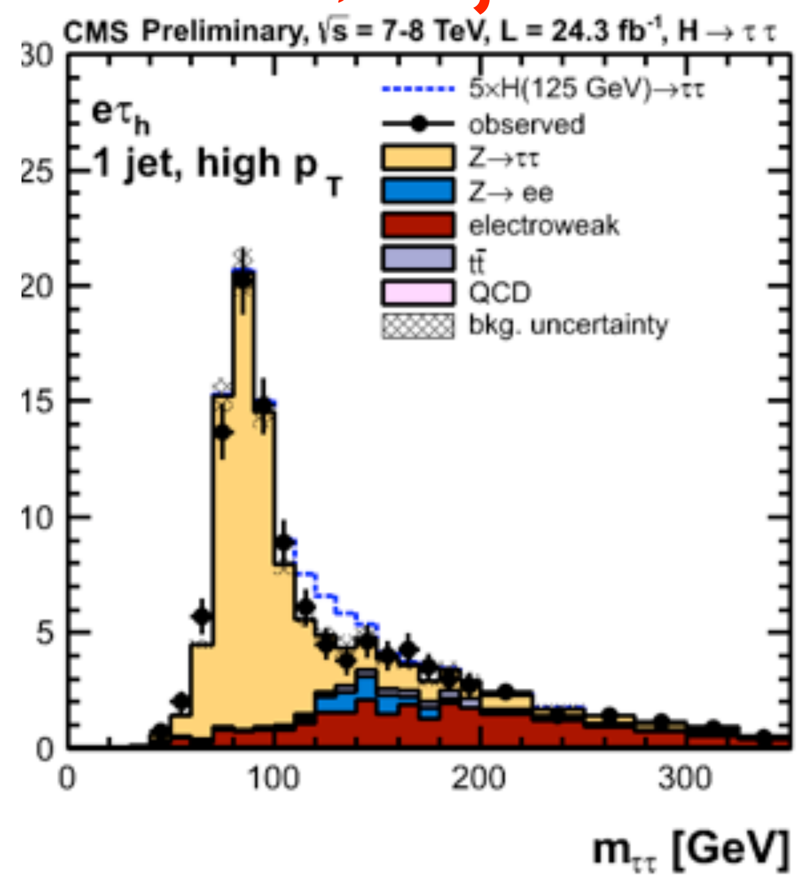
- Same-sign **sideband**, or
- Fake-rate method

Mass spectra

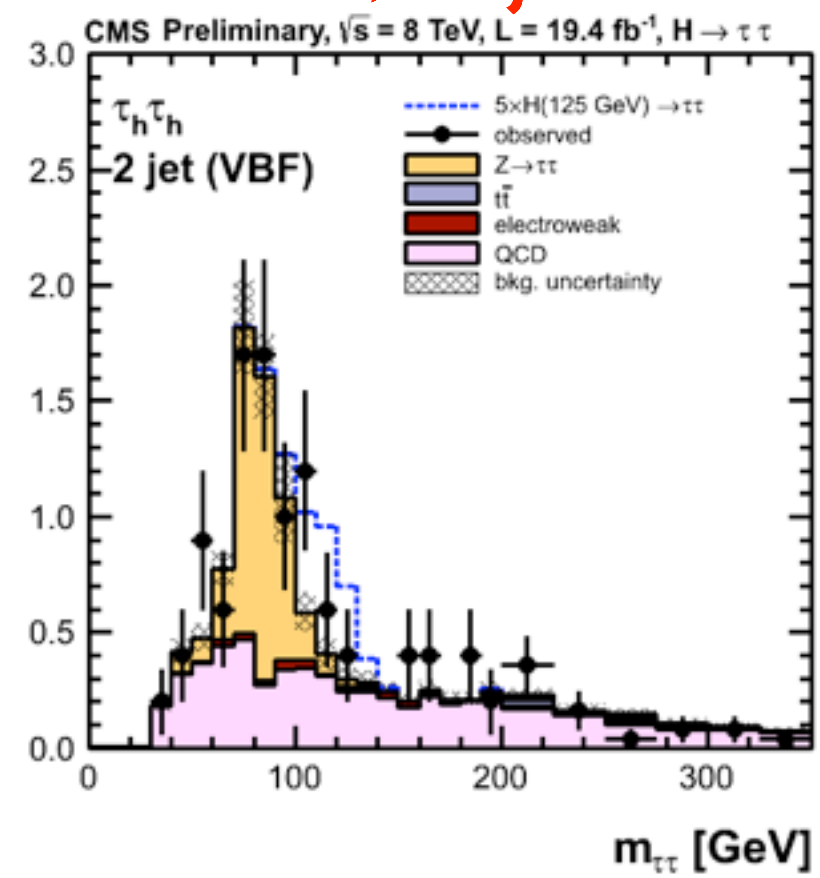
μτ, 2-jet



eτ, 1-jet



ττ, 1-jet



... and many more!

Systematic uncertainties

systematics	relative unc.	affects...	...by...
τ ID+trigger	8%	norm.	±8%
τ energy scale	3%	norm., shape	±3%
jet energy scale	2-5%	norm.	±(1-6)% ±(5-20)%
Z→ττ in cat.	-	norm.	±(3-13)%
QCD	-	norm.	±(6-35)%
W+jets/ l→τ fakes	-	norm.	±(10-30)%
Th. unc. (scale)	-	norm.	±4% ±(10-30)%
Stat. unc. templates	-	bin norm.	≤10%

- Over-constrained system
  - Mostly from 0-jet category
  - Fit for nuisances. E.g.

τ-ID: (0.0±**8.0**)%→ (-5.5±**1.9**)%

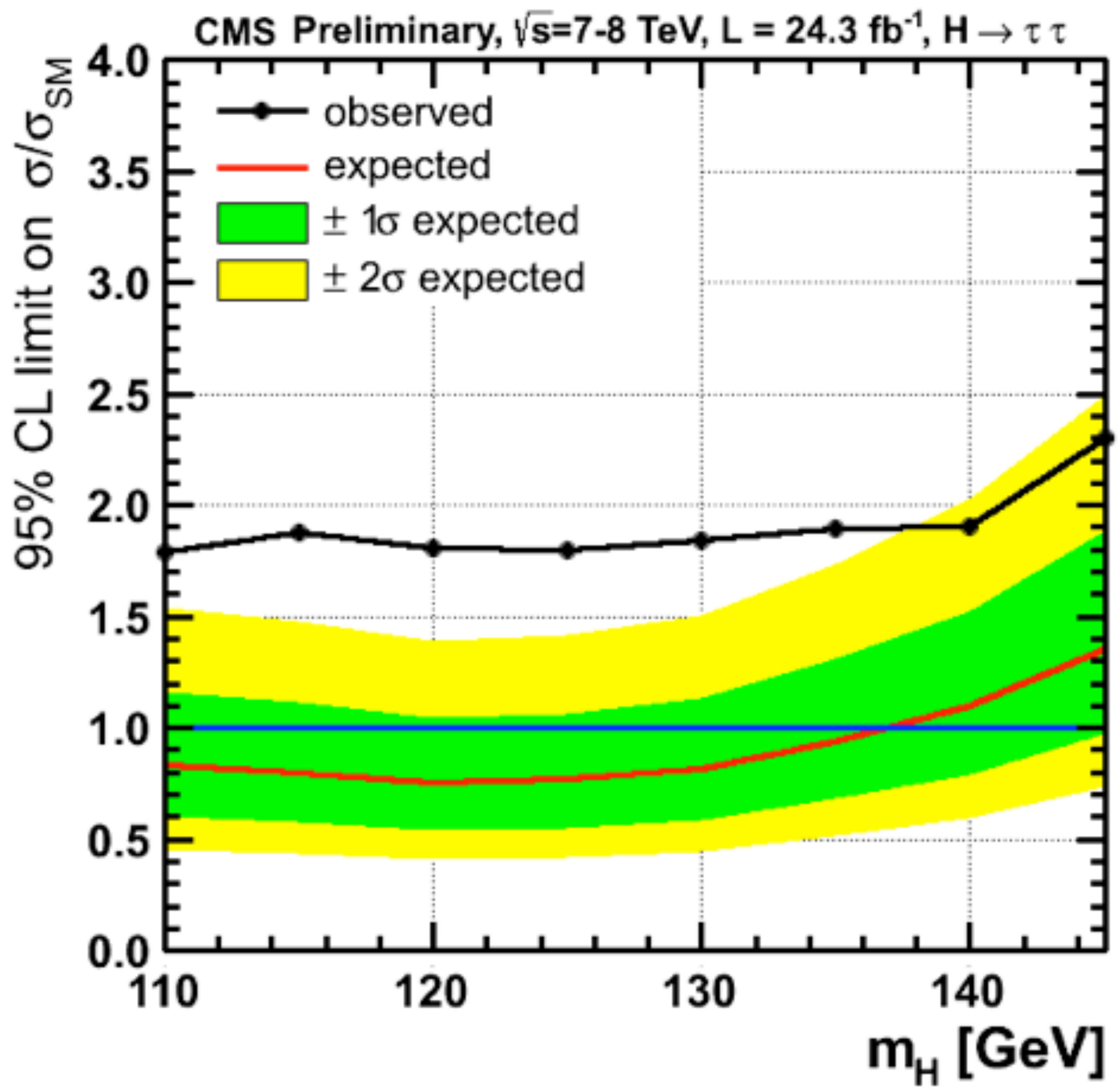
μ →τ: (0.0±**30**)%→ (-10 ±**16**)%

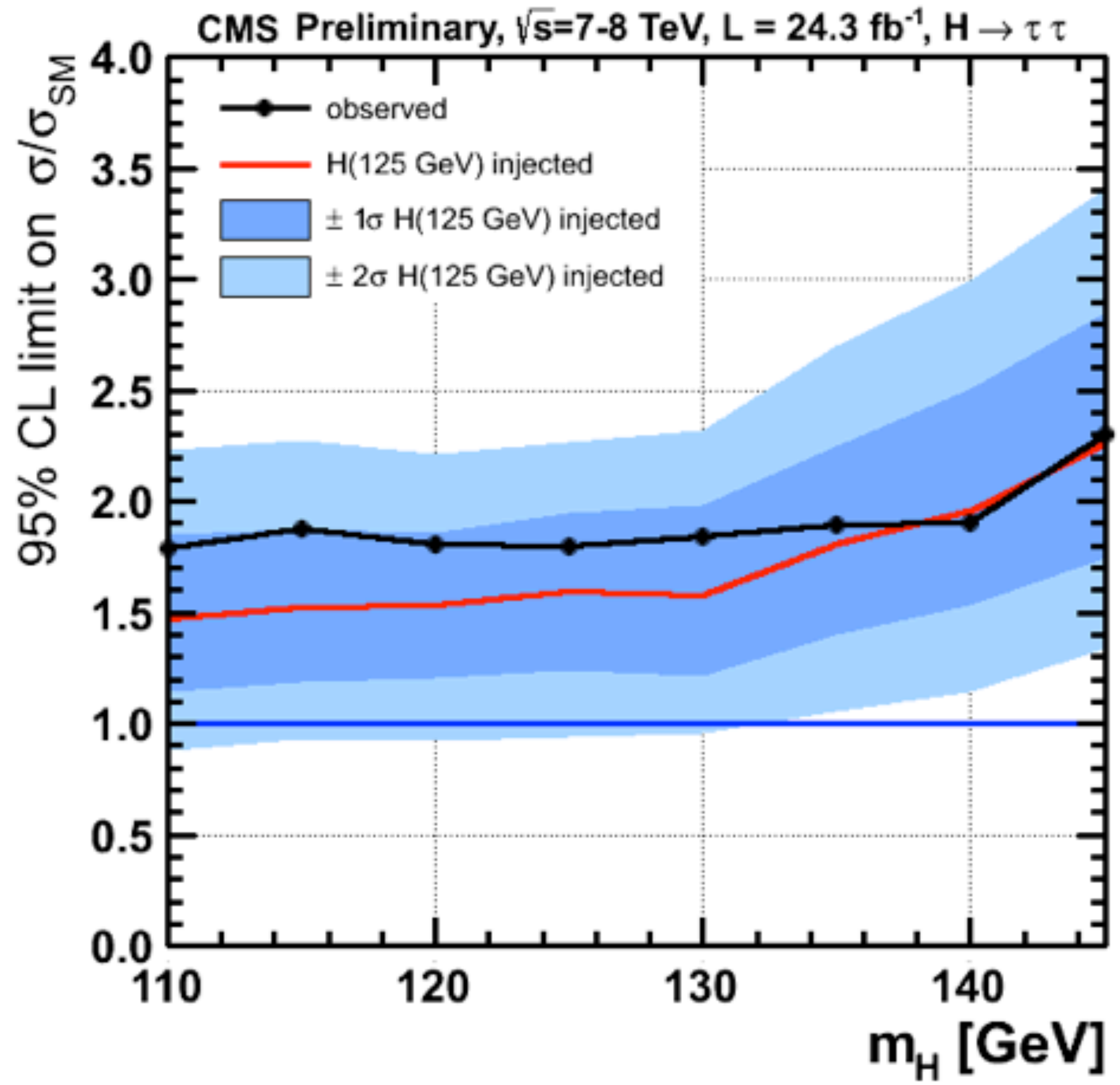
τ-ES: (0.0±**3.0**)%→ (-0.8±**0.2**)%

N.B. can't take them as **real** measurements (large correlations!!!)

Results: CL upper limits

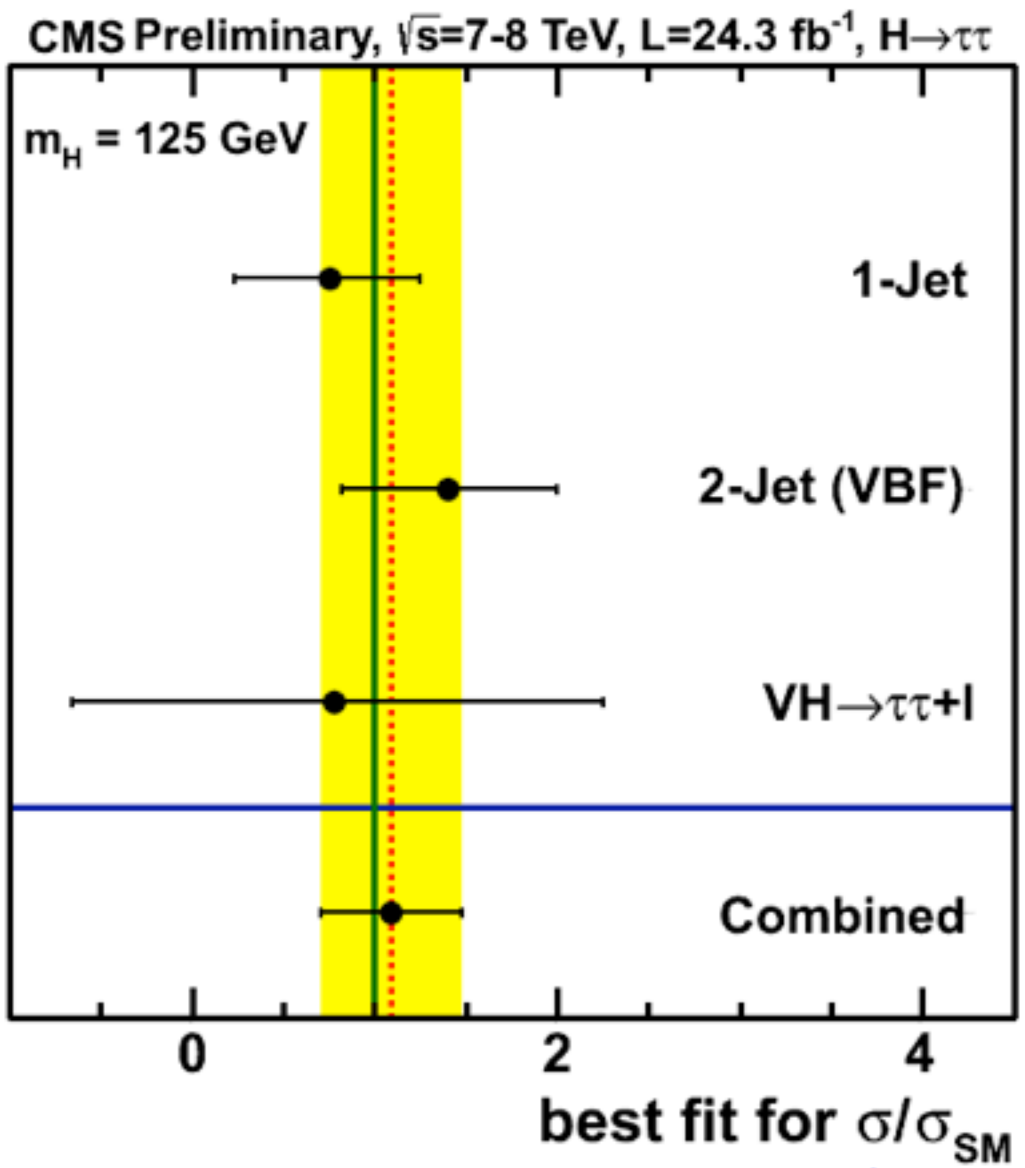
- Exclusion limits
  - Broad **excess** makes the exclusion weaker than expected
  - Consistency improves under **signal+background** hypothesis

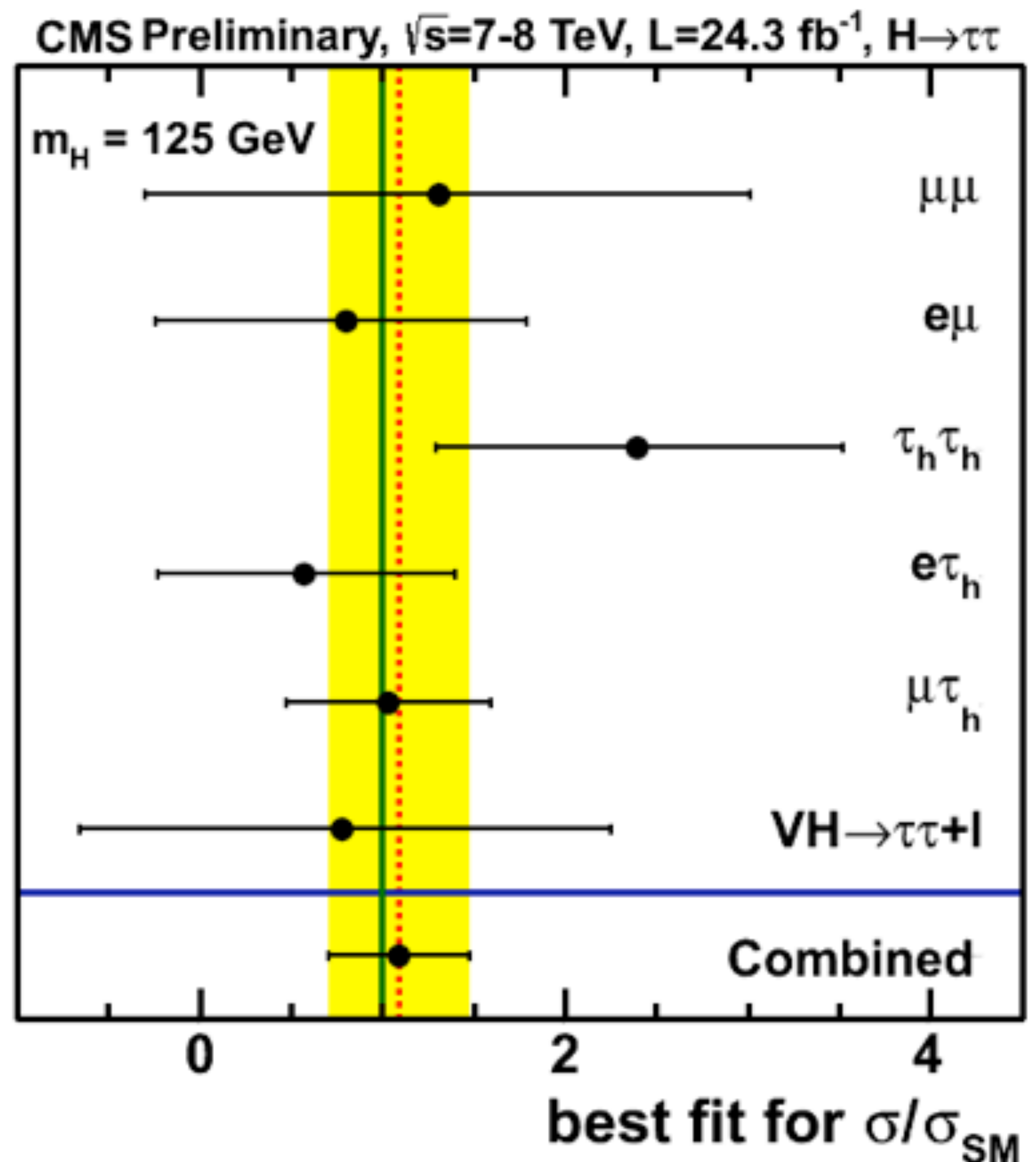




Results: ML fit to strength modifier

- Anatomy of the excess
  - Consistent among categories / channels

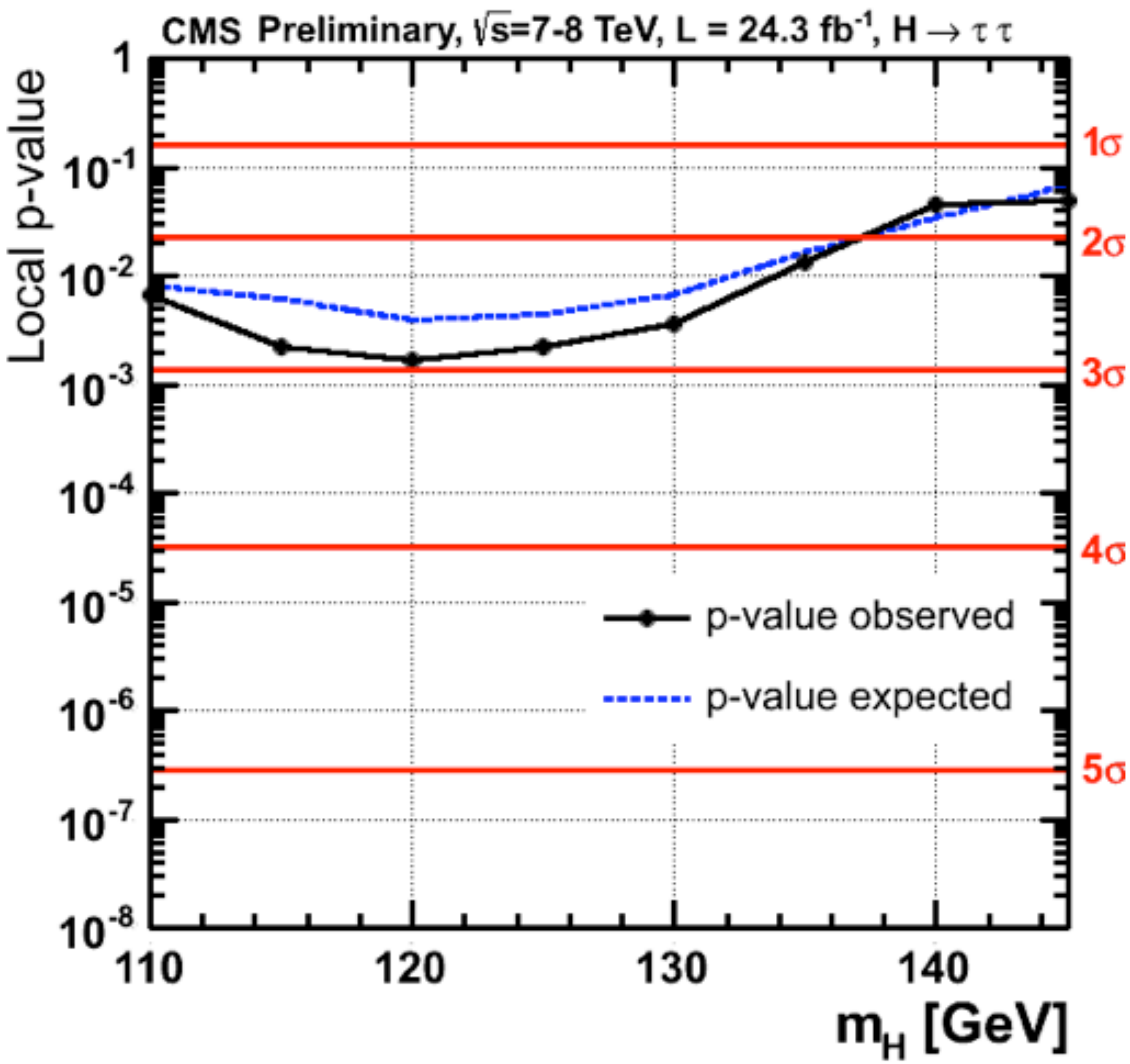


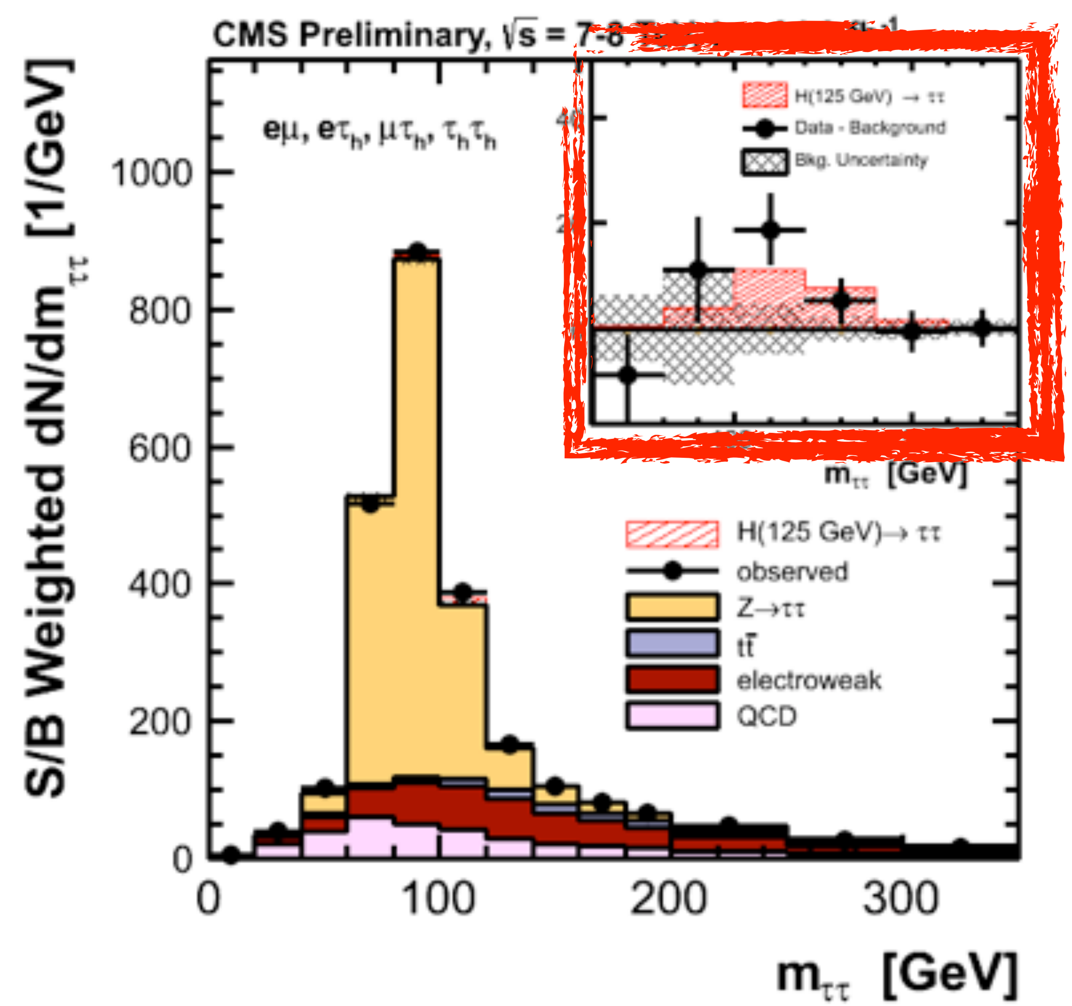


μ(SM) = 1.1 ± 0.4 at M_H = **125** GeV

Results: significance of the excess

- Probability for a background fluctuation
  - Minimum p-value of **2.93σ** at $\mathbf{M_H}$ **=120** GeV
  - Measured p-value of **2.85σ** at $\mathbf{M_H}$ **=125.8** GeV (expected from SM: **2.6σ**)





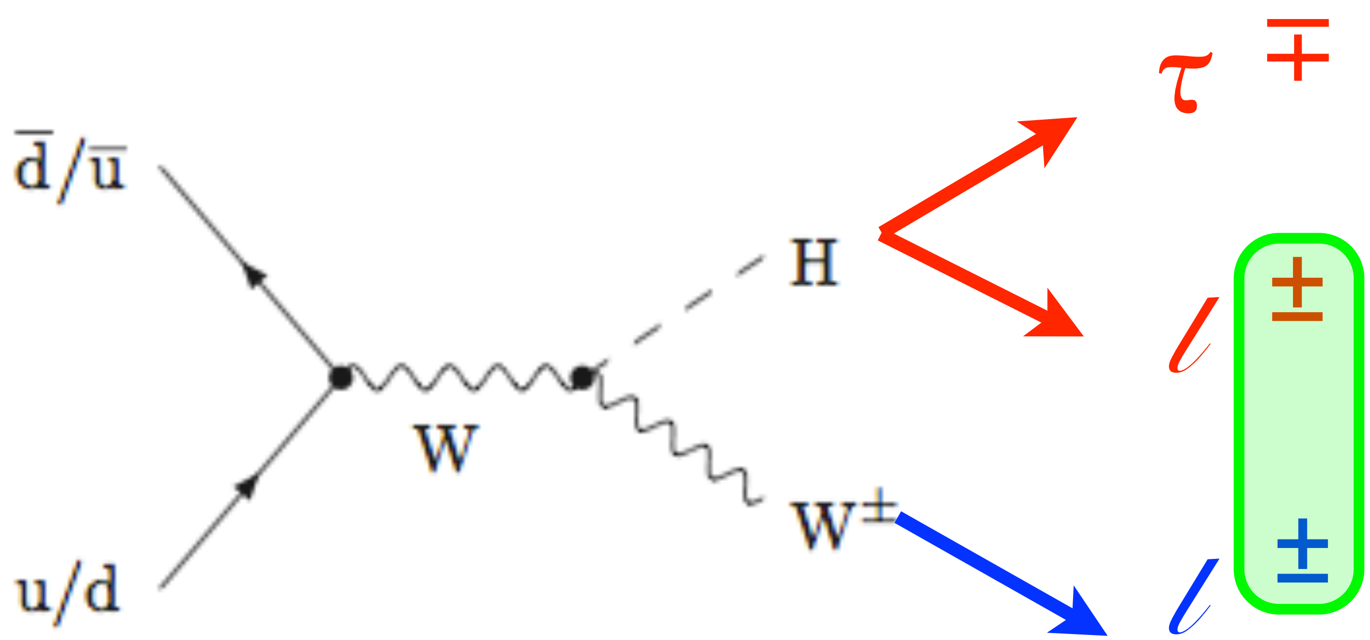
Searches: VH, $H \rightarrow \tau\tau$

($24.5\ fb^{-1}$, 7+8 TeV)

PAS HIG-12-053

Event Selection

- Search for $H \rightarrow \tau\tau$ plus ≥ 1 prompt leptons
  - Orthogonal to inclusive di-τ search

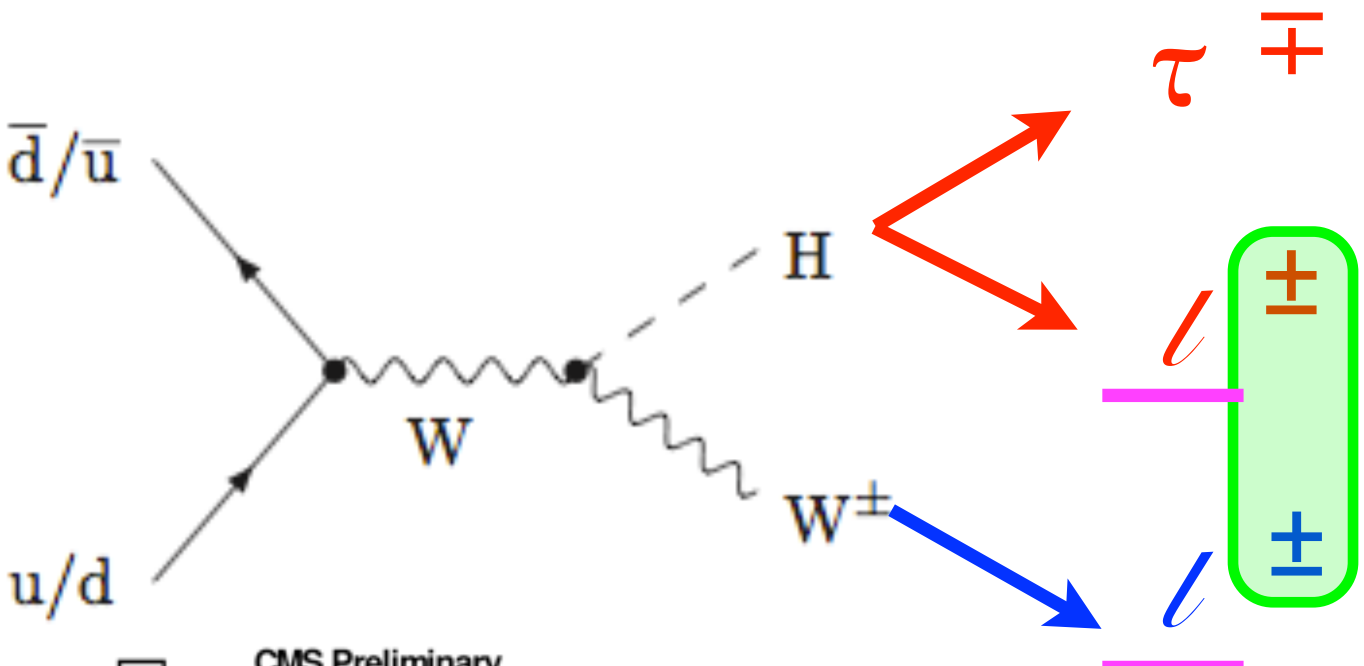


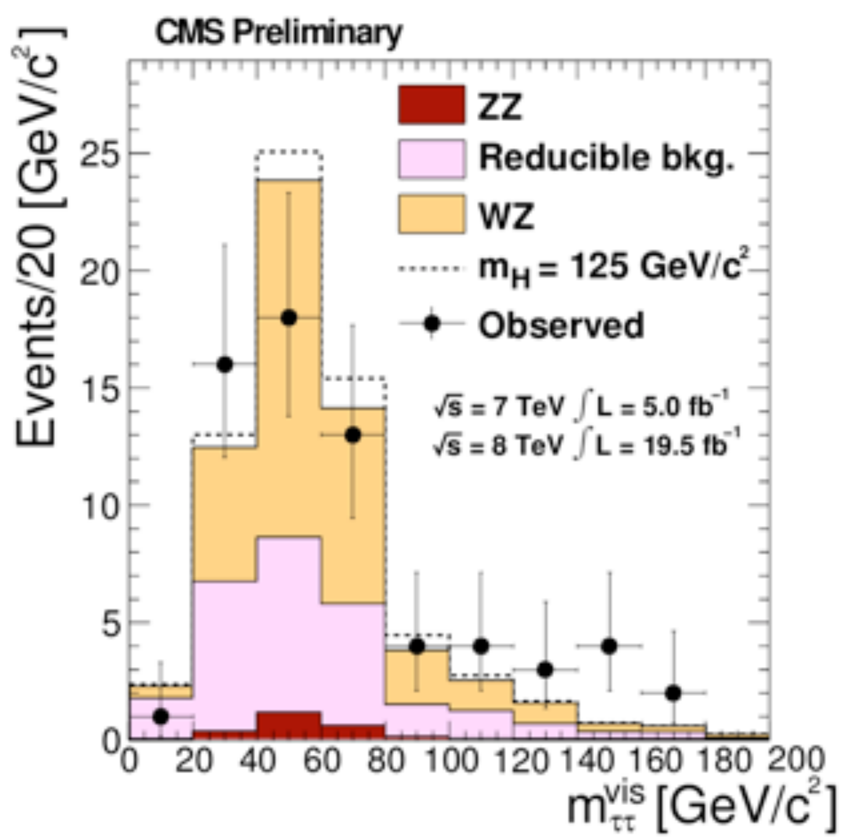
$\ell\ \ell\ \tau$

- Same-sign leptons
- Backgrounds:
  - ✓Irreducible:
    WZ
  - ✓Reducible:
    $j \rightarrow \ell$

Event Selection

- Search for H → ττ plus ≥ 1 prompt leptons
  - Orthogonal to inclusive di-τ search





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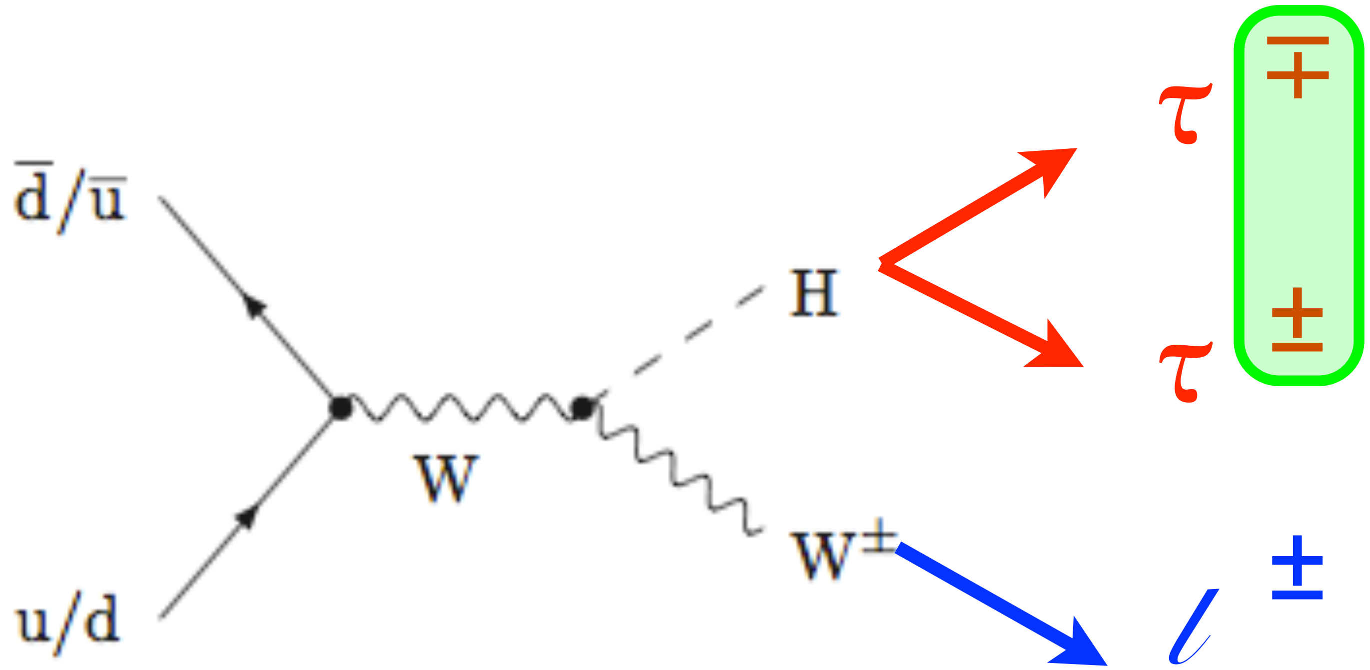

ℓ τ τ

- Opposite-sign taus
- Backgrounds:
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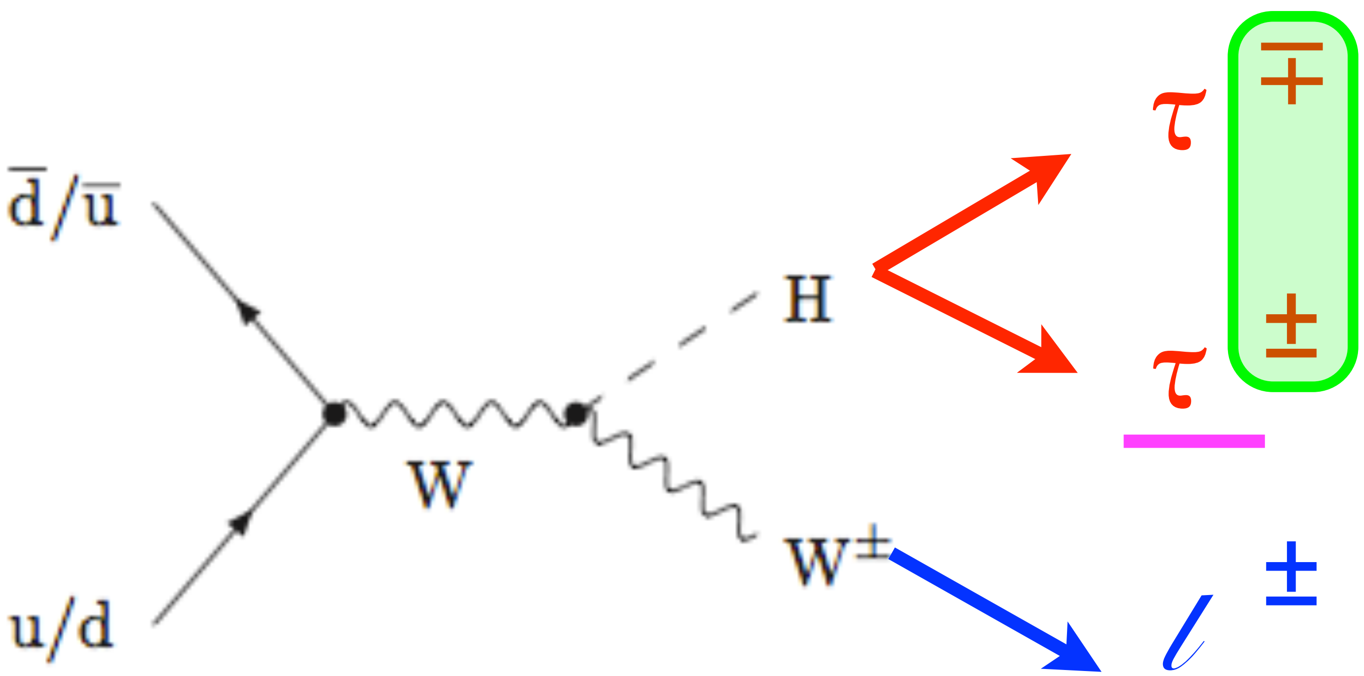

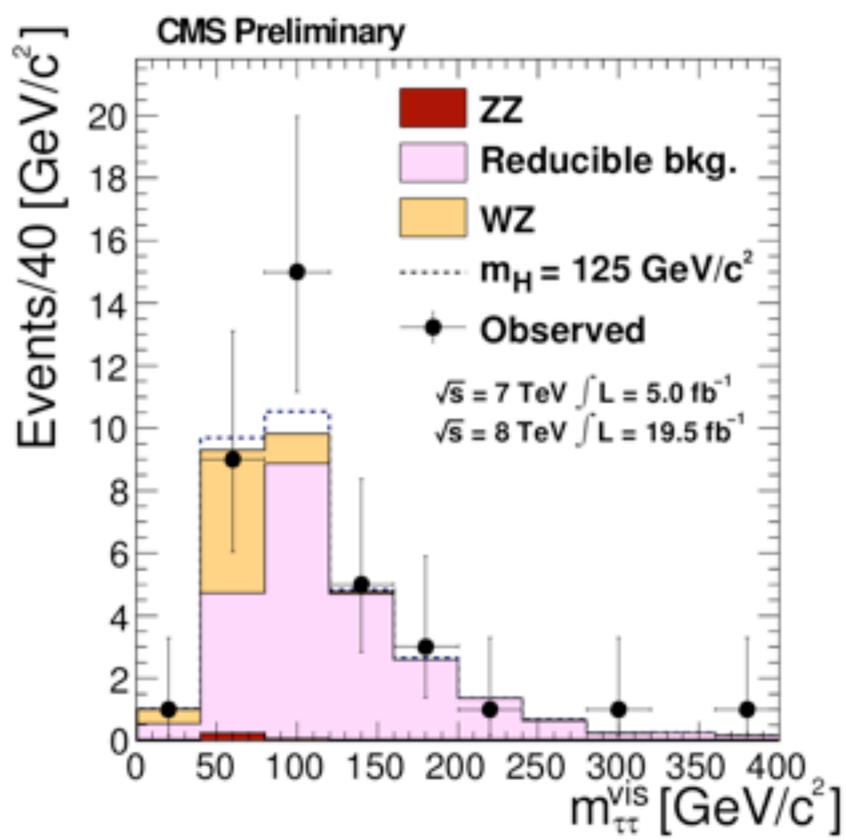

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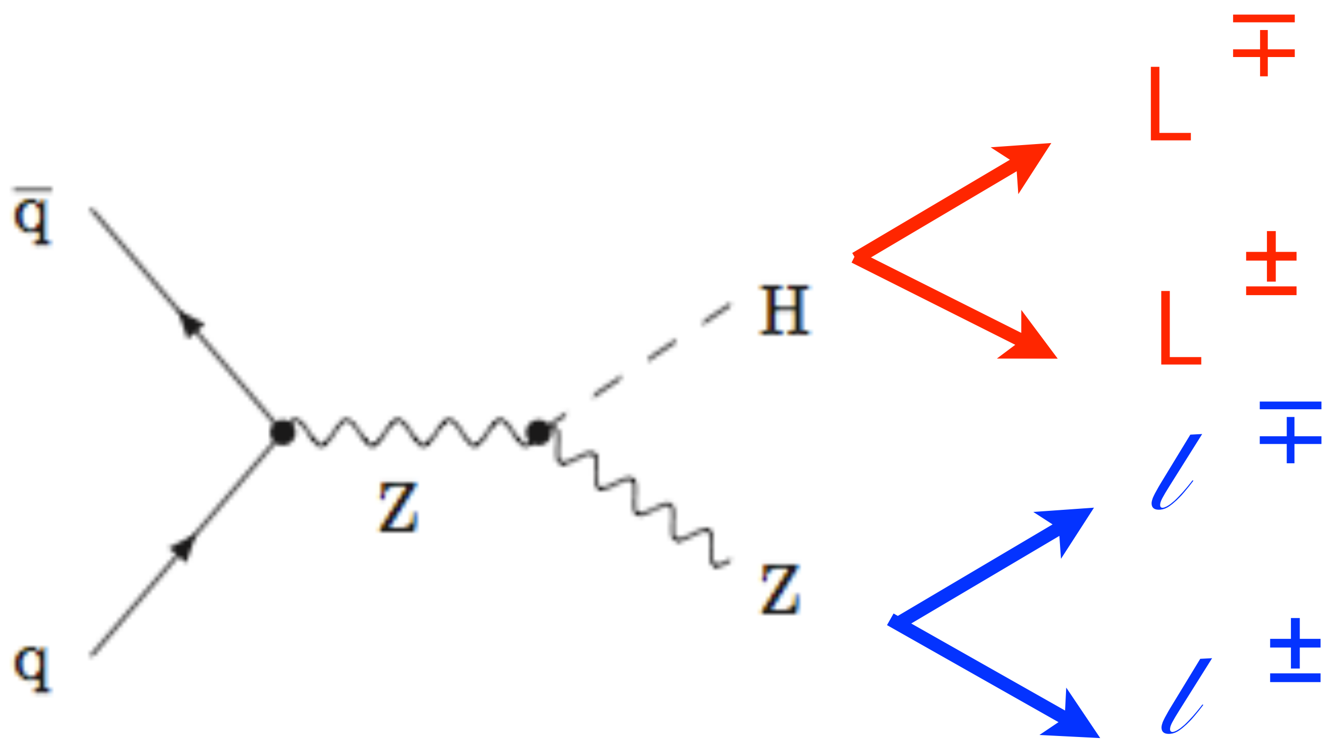
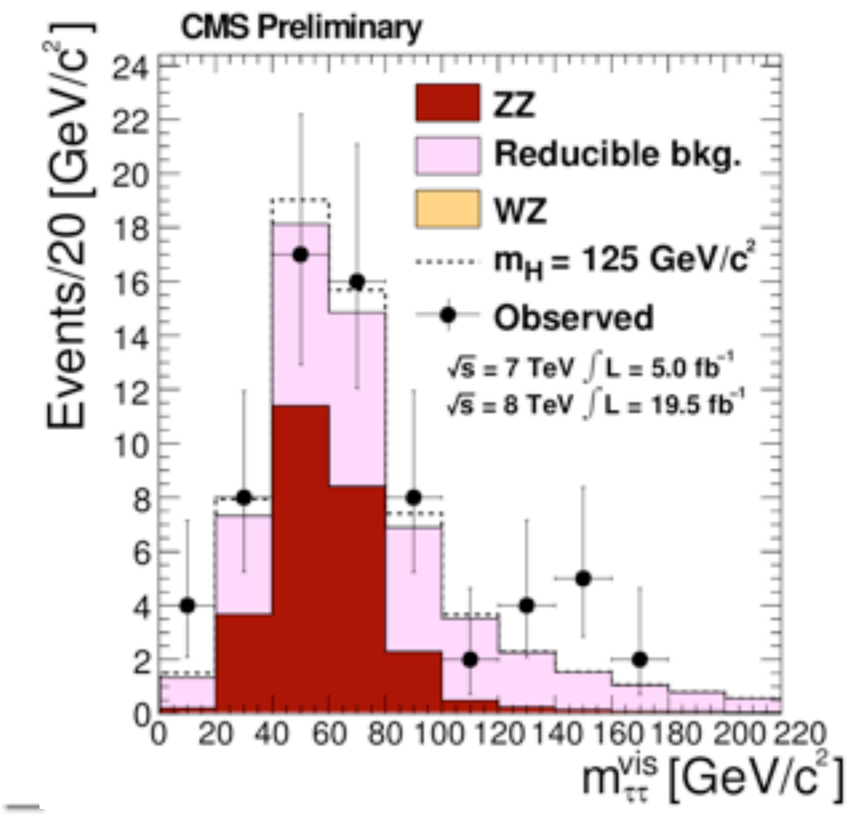


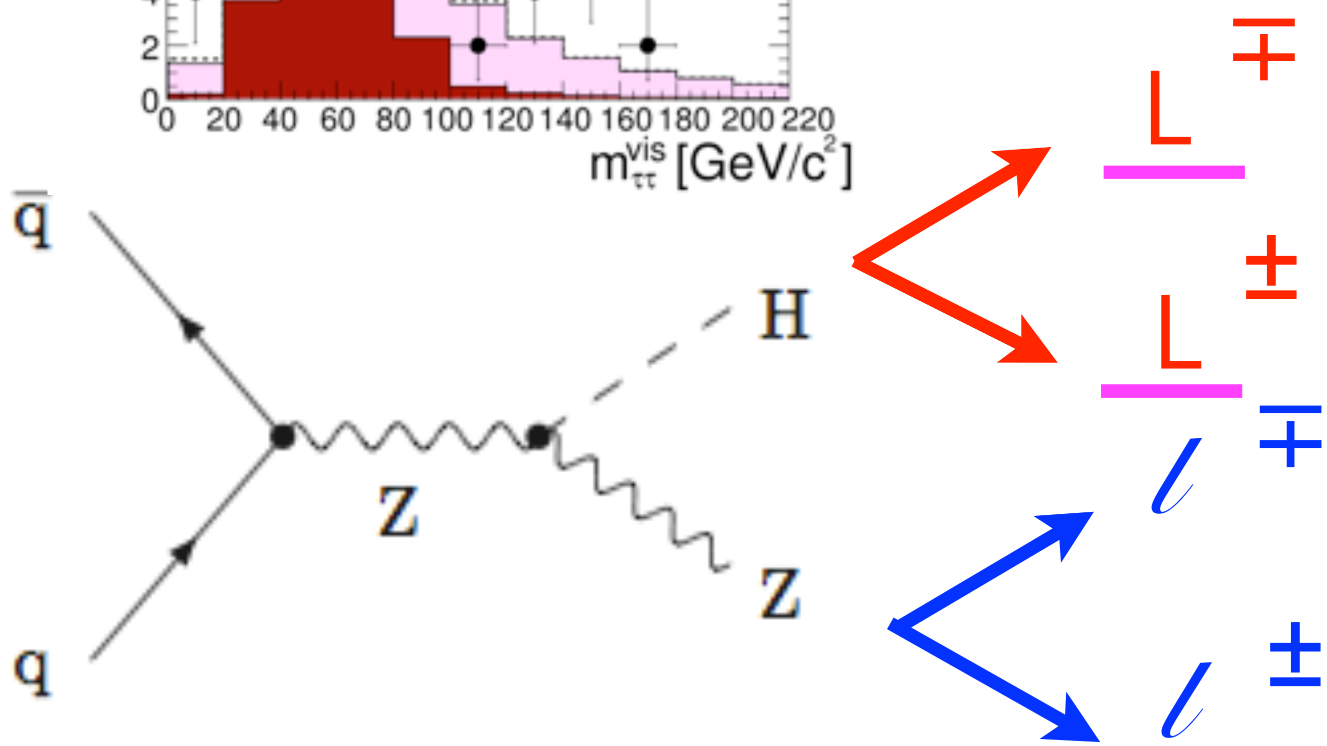
$\ell\,\ell$ LL

- LL = $\mu\tau$, $e\tau$, $\tau\tau$, $e\mu$
- Backgrounds:
    - ✓ Irreducible: ZZ
    - ✓ Reducible: $jj \rightarrow$ LL

Event Selection

- Search for $H \to \tau\tau$ plus ≥ 1 prompt leptons
  - Orthogonal to inclusive di-τ search



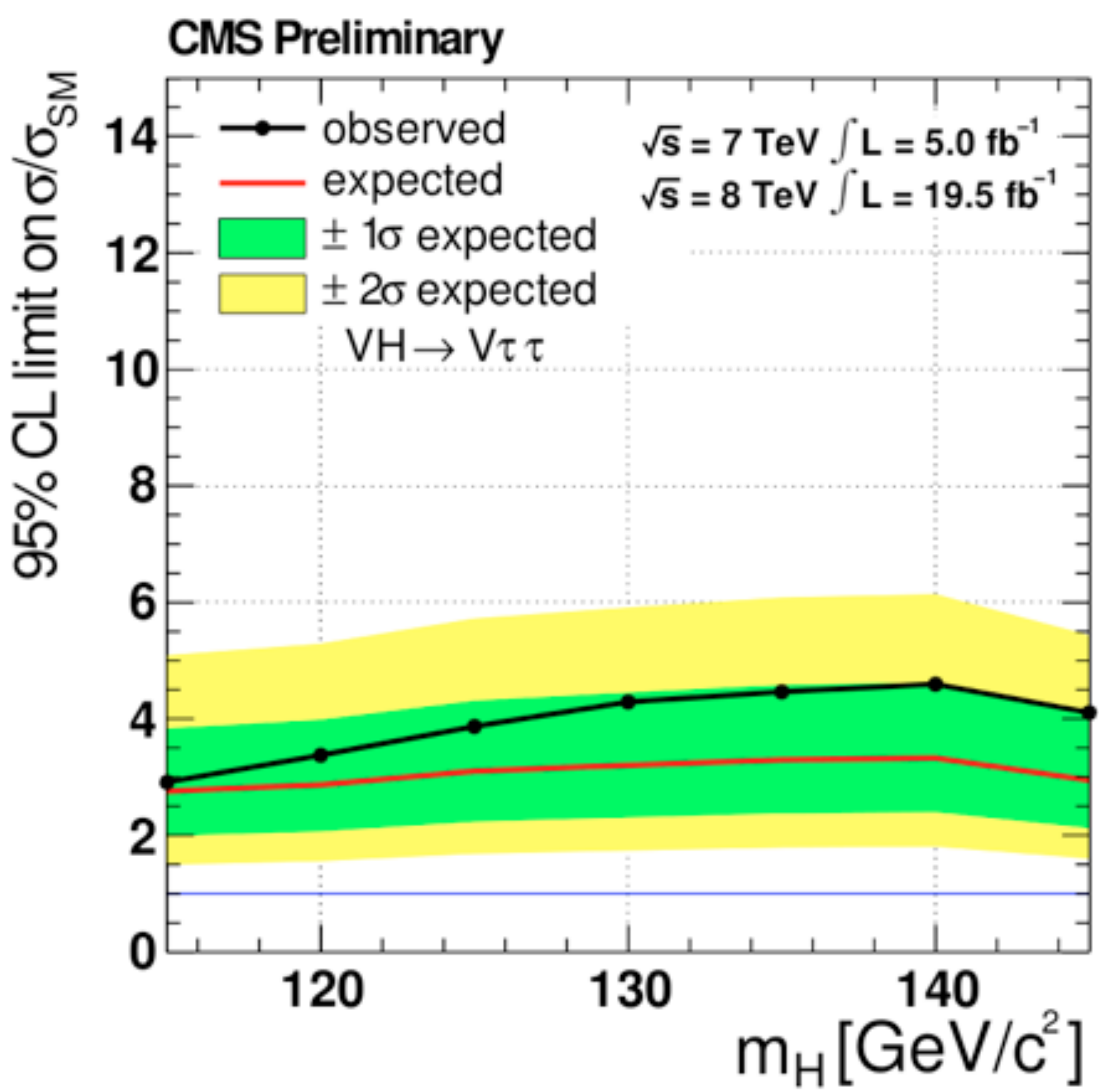


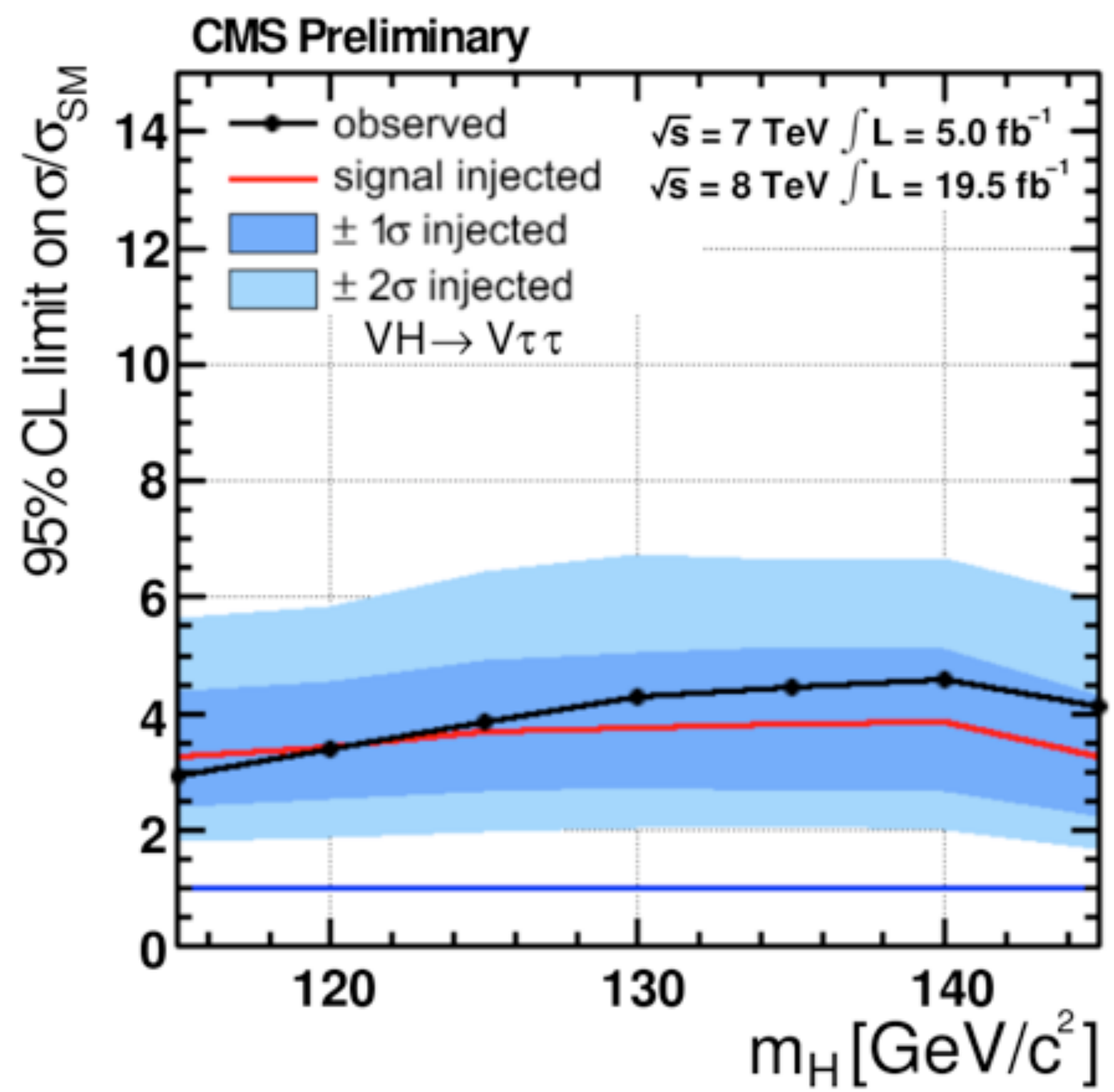
$\ell\,\ell$ LL

- LL = $\mu\tau$, $e\tau$, $\tau\tau$, $e\mu$
- Backgrounds:
  - ✓ Irreducible:
    ZZ
  - ✓ Reducible:
    $jj \to$ LL

Results: CL upper limit

- Binned fit to di-τ visible mass
- Not yet sensitive to SM Higgs. No excess observed
  - Consistent with both S+B and B hypothesis





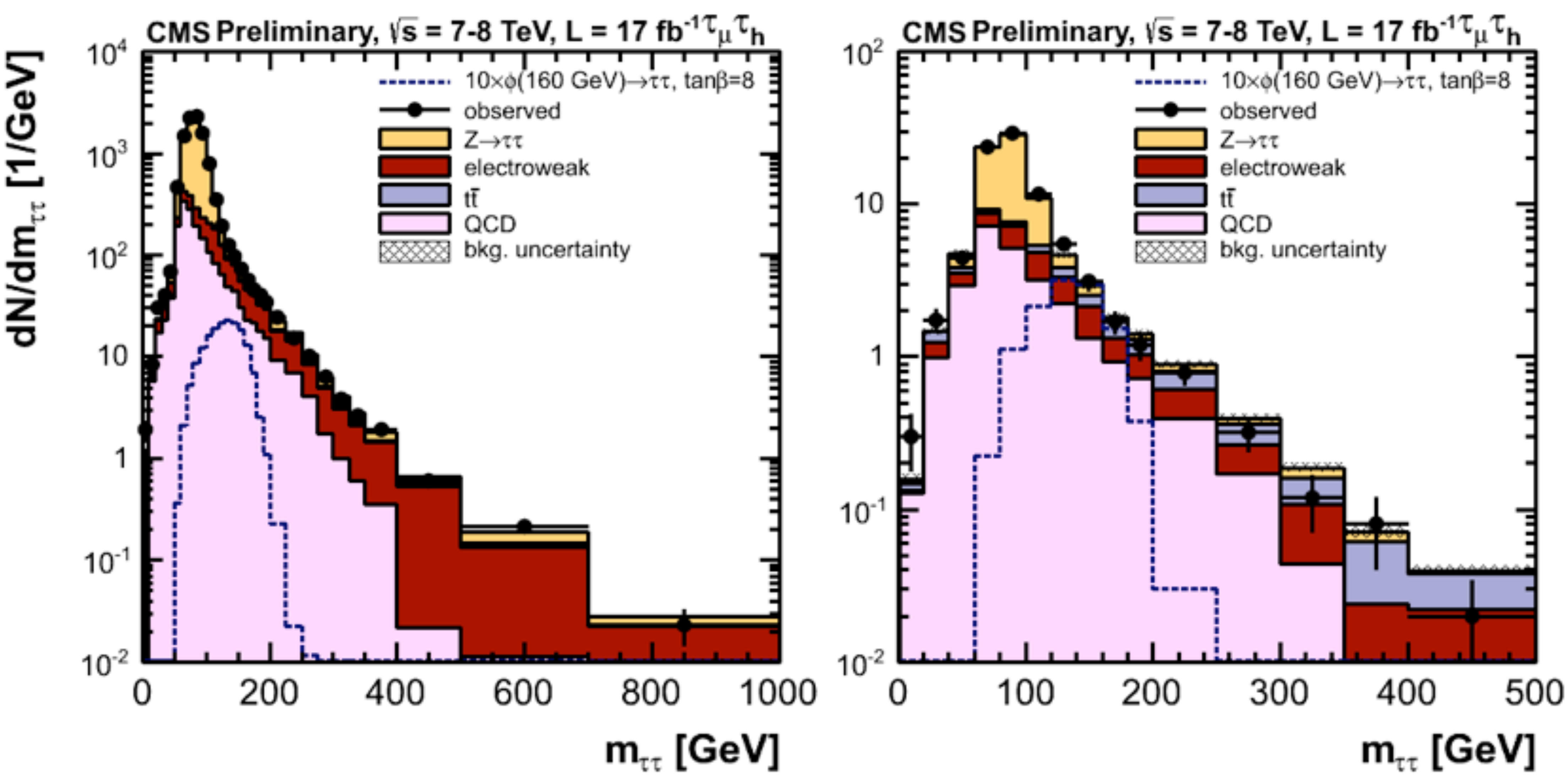
Searches: MSSM $\Phi \rightarrow \tau\tau$

($17\ fb^{-1}$, 7+8 TeV)

CMS HIG-12-050

The signature

- MSSM: <u>three</u> neutral Higgs bosons (Φ=h,H,A)
  - BR(Φ → ττ) sizeable even for large M_Φ : **scan $M_{\tau\tau}$ tails for bumps**

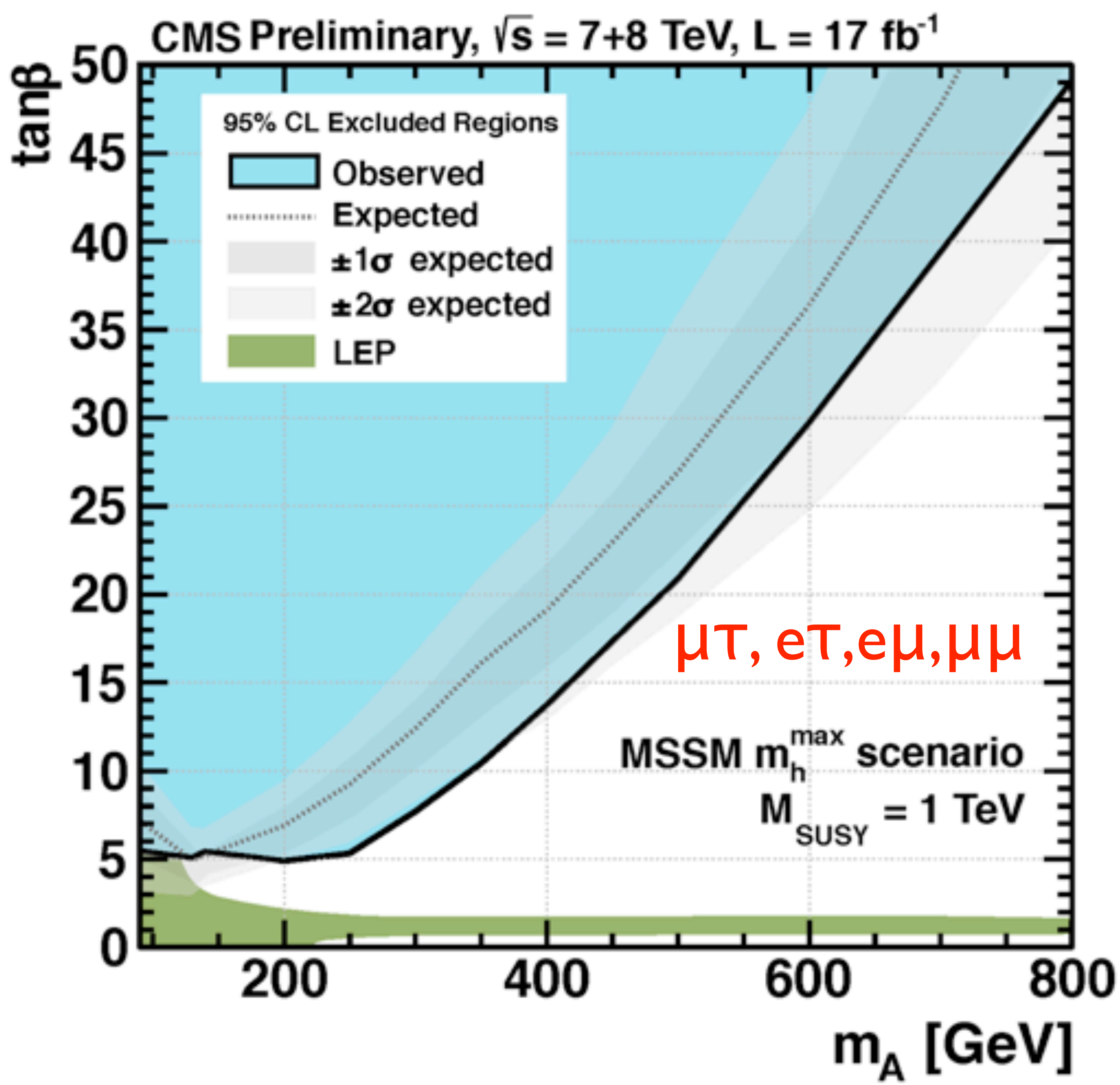


- Depending on model parameters (tanβ), associated production with <u>*b*-quarks</u> important
  - **b-tagging**

<u>arXiv:1101.0593</u>

Results

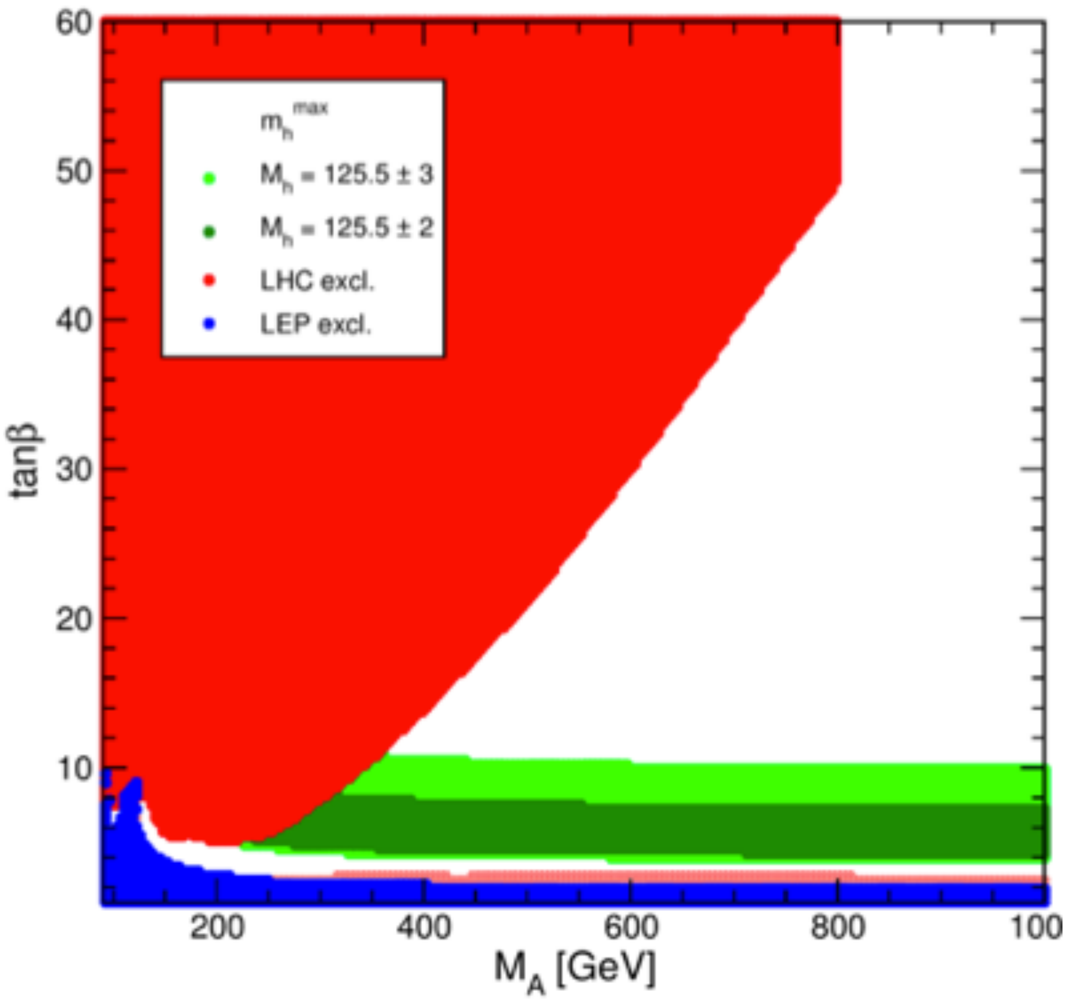
- Two event categories: **0 b-tag, 1 b-tag**
- As customary, results interpreted in benchmark scenario



- Simulateneous fit for h,H,A → ττ
    - with masses, xsec, and BR functions of (M_A, tanβ)
- Excluding as low as tanβ~5

MSSM confronted with present data

- For $M(\Phi=h)=(125\pm2)$ GeV, not much room left in m_h^{max}



Carena et al. arXiv:1302.7033

- New benchmark scenarios have been proposed
  - can still accomodate much of the unexplored parameter space
- For the future:
  - **new decay channels** (ττ)
  - model dependent interpretation in new benchmark models
  - model independent bbΦ/ggΦ xsec limits
  - extension to $\mathbf{M_A} \lesssim$ **1 TeV**

Conclusions

Summary

- Excess in the gg/qq H → ττ search observed
  - **2.85σ** at 125 GeV, consistent with SM expected of **2.6σ**
- VH channel approaching SM sensitivity
  - Results consistent with either hypothesis
- Not covered here: ttH, H → ττ (CMS HIG-13-019)
  - Preliminary results recently presented; still far from SM sensitivity
- MSSM search to be updated soon
  - Many improvements in the pipeline
  - **N.B:** Φ→ττ as a direct probe of the MSSM Higgs sector

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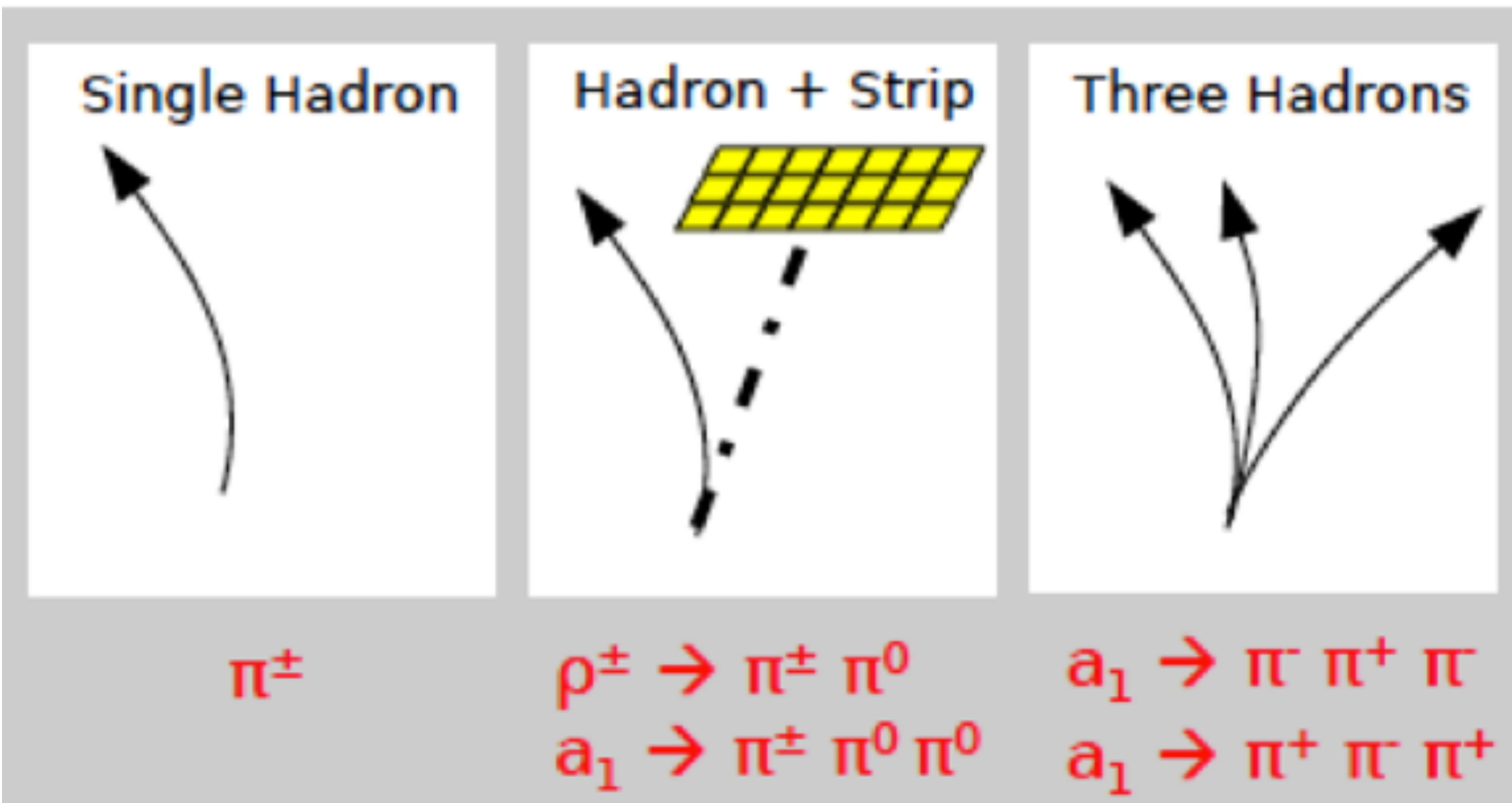
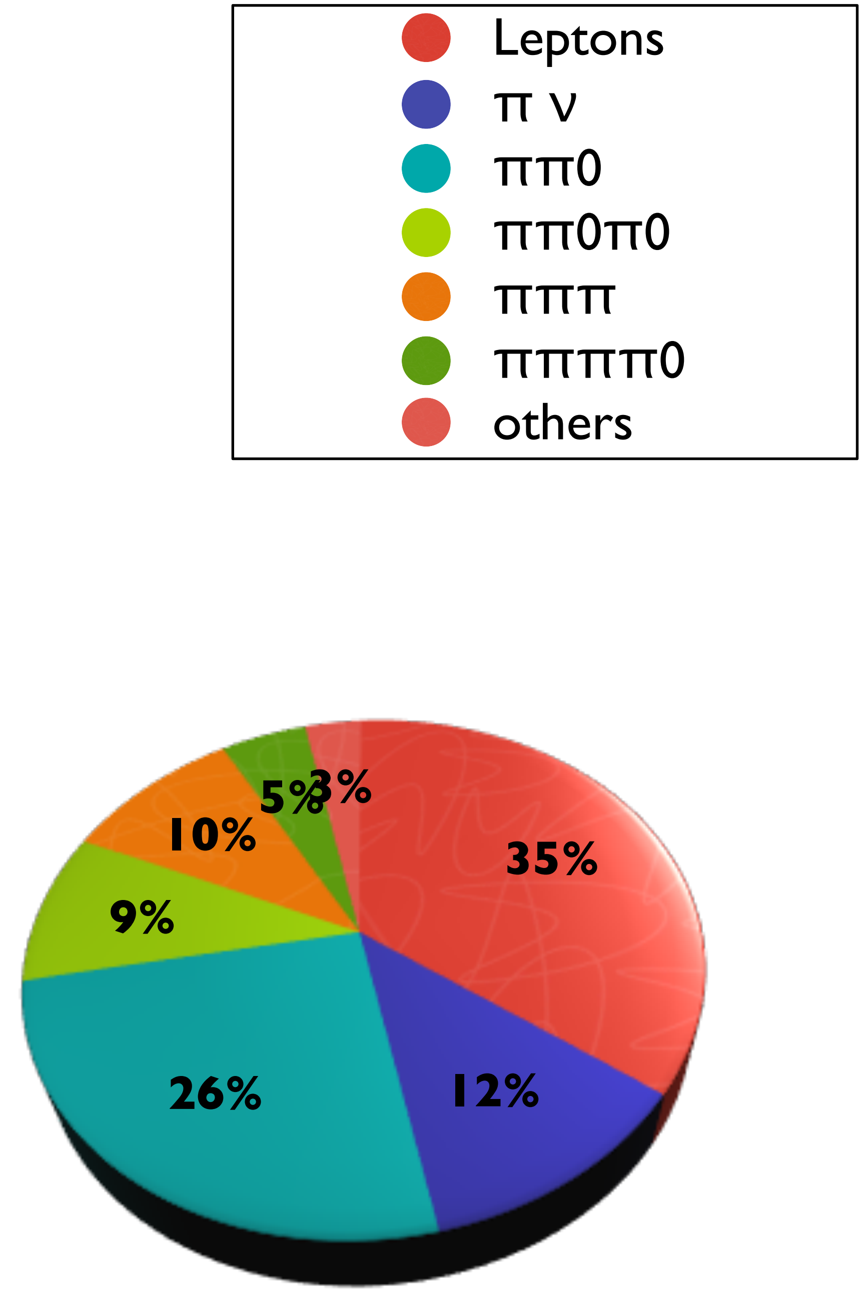
... to make sure we are not missing the "***H A***" (→ ττ)!

Back up

Taus in CMS

- Hadronic tau reconstruction
  - Seeded by the GED (PFlow)
  - KEY FEATURE: Decay mode reconstruction



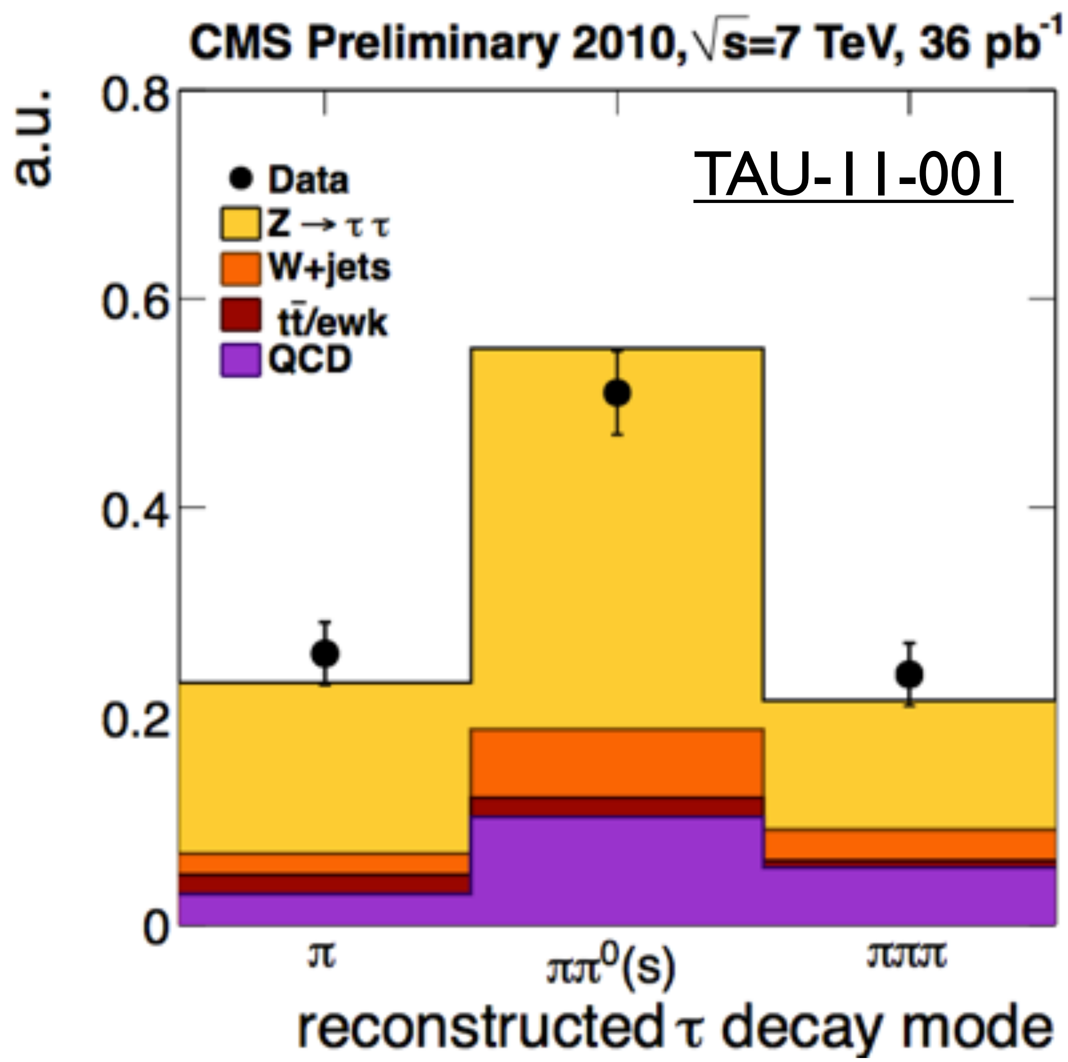


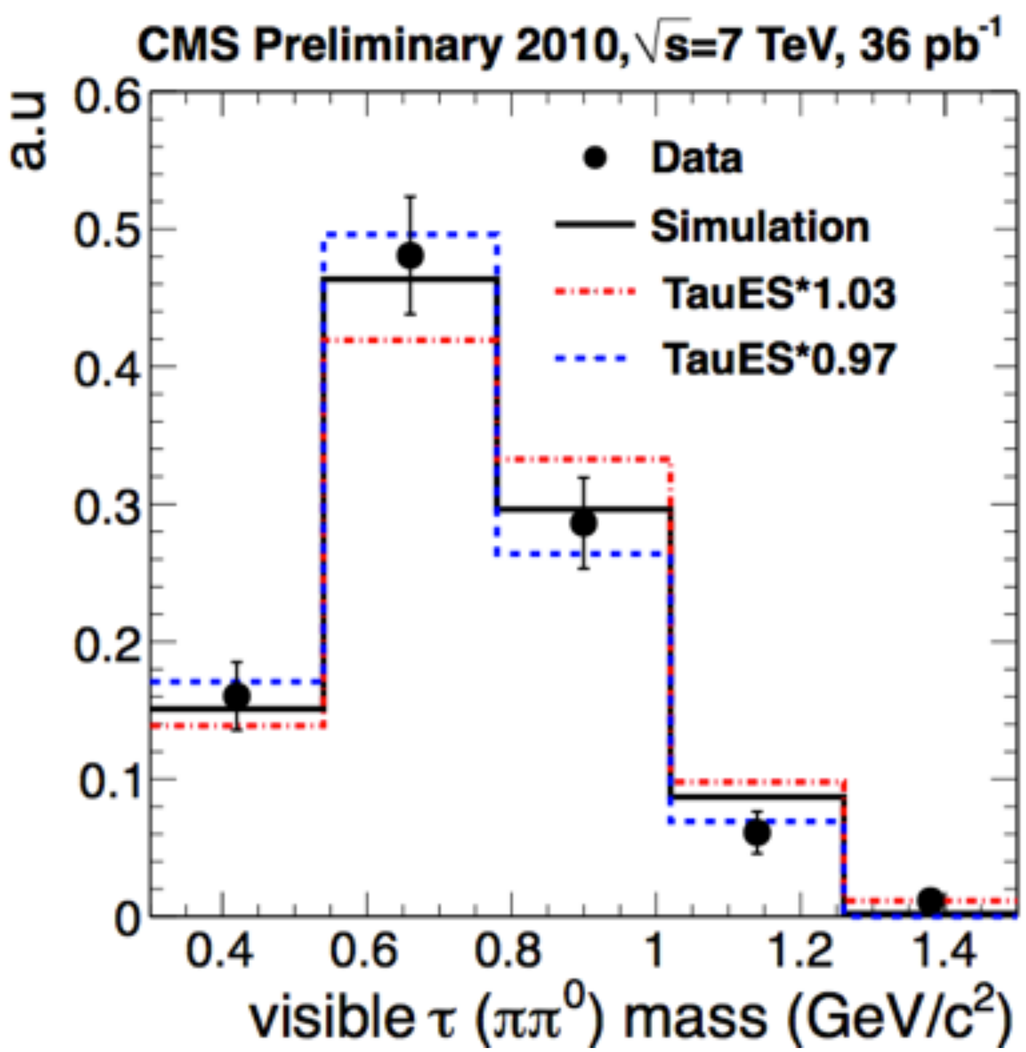
- NB: PFlow Taus also @ HLT
  - Regional PFlow at HLT garantees
    - ✓ higher efficiency and online/offline consistency

Tau key-observables

- Decay mode multiplicity
  - discrimination against electrons/muons
- Visible tau mass
  - provides in-situ calibration of tau-ES

"Polarimeters" observables not yet deployed in $\Phi \rightarrow \tau\tau$ searches

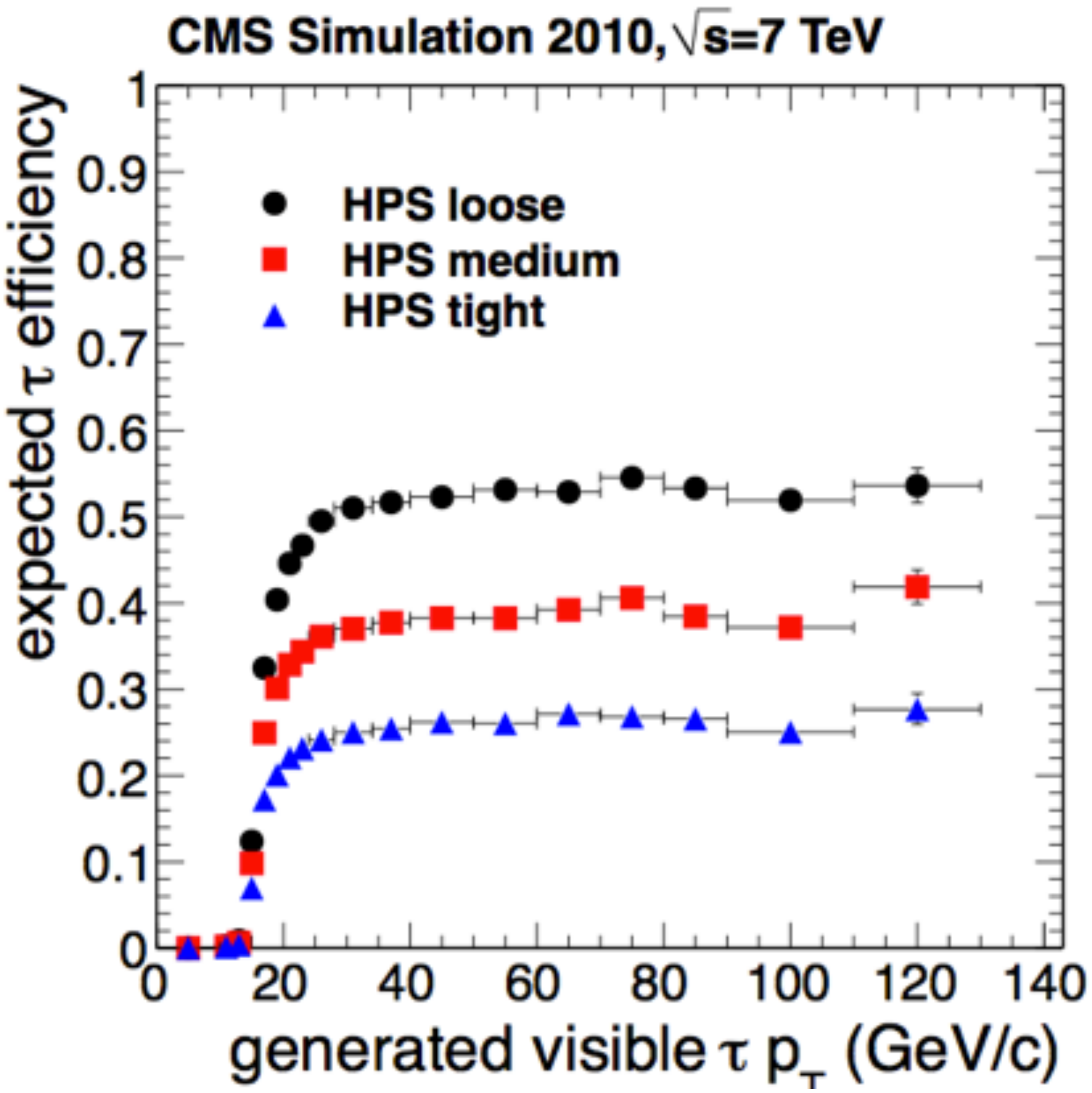


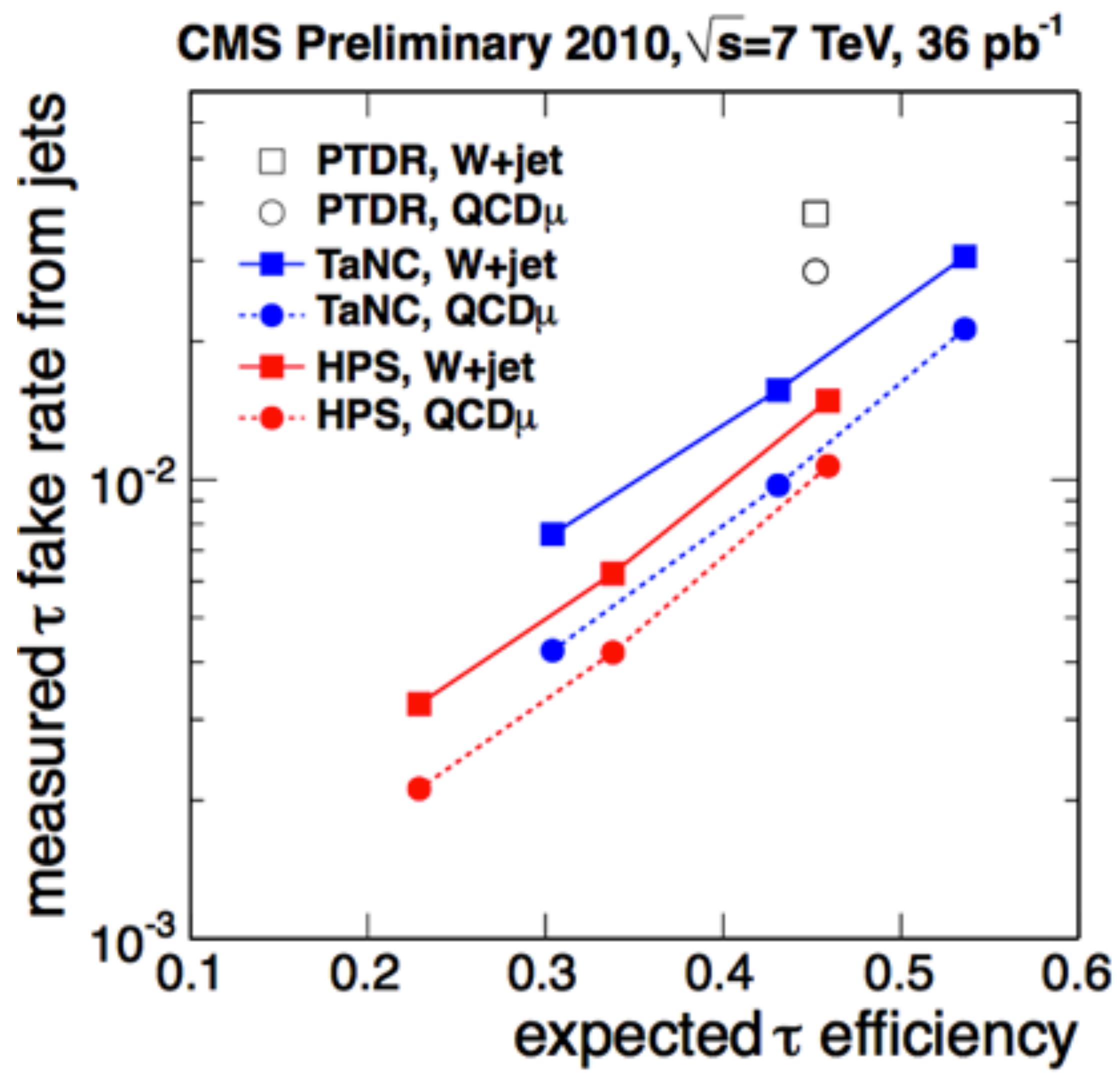


Tau performances

- State-of-the-art performances
  - Tau-ID efficiency: **60-65%** -- measured with T&P
  - Fake rate from jets: **2-3%**
  - Efficiency flat vs pt

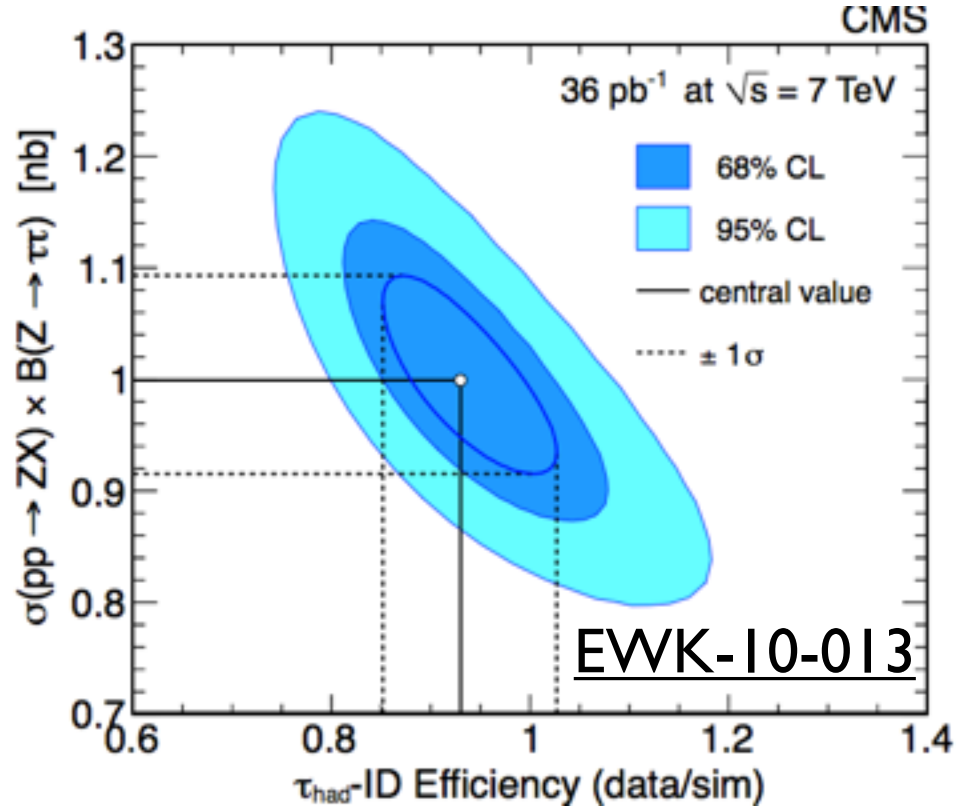
TAU-11-001



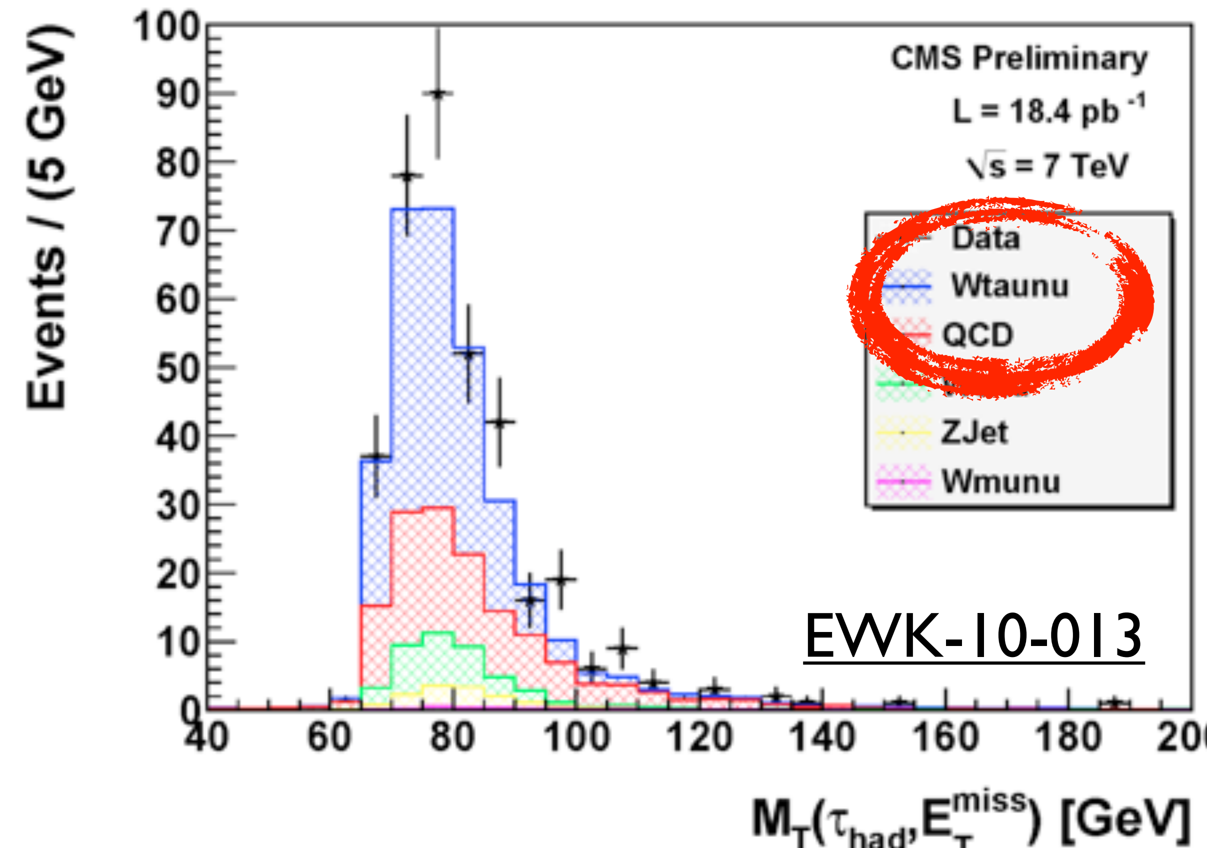


The candles

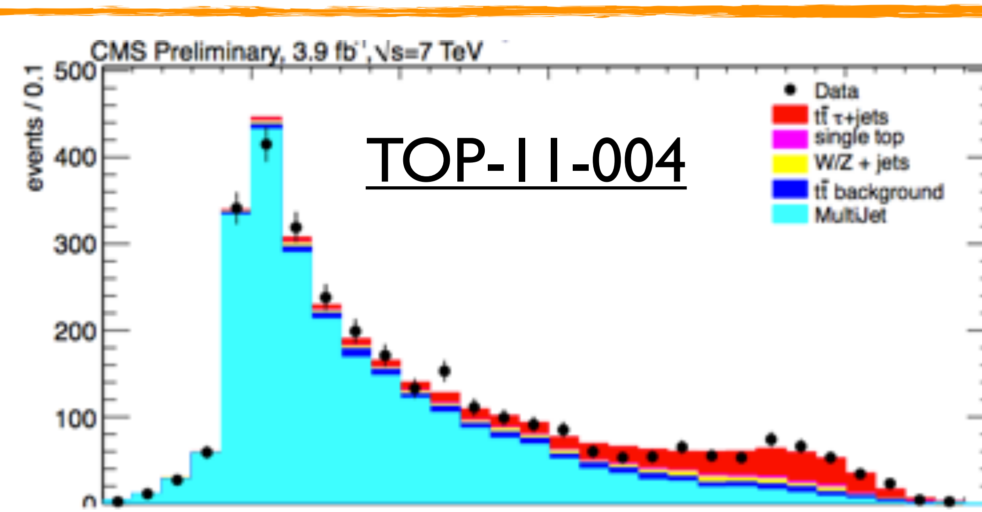
- Z→ττ
  - X-section with 36 pb-1
  - ✓ final-states: **μτ eτ eμ μμ**
    - ✦ eμ+μμ ⇒ insitu calibration of tauID



- W→τν
  - Evidence of W→τν with early data
  - Limited by trigger since then



- Top
  - Final states with τ's extensively studied
  - Not yet assessed as τ candle



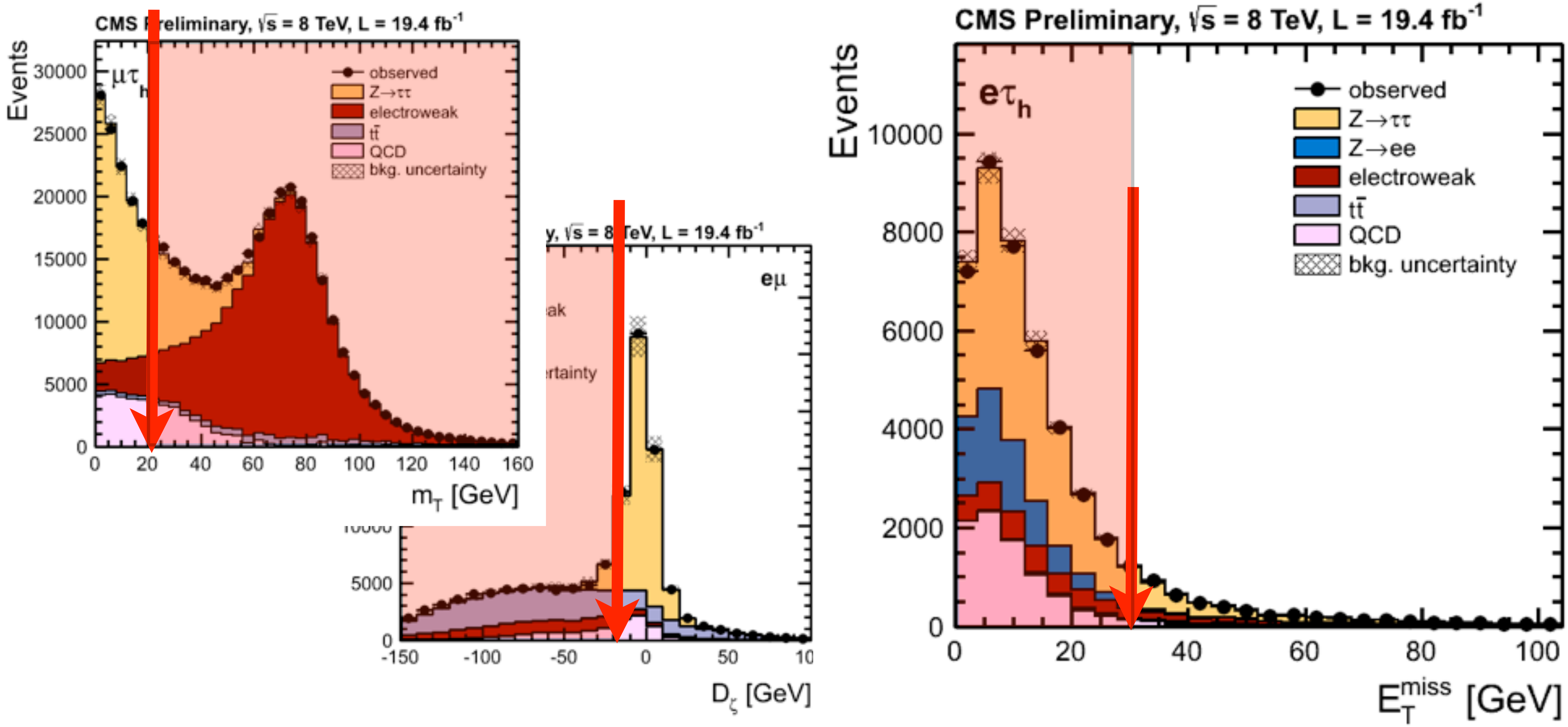
Common "topological" cuts (μτ, eτ, eμ)

$M_T(l, E_T^{miss})$, D_ζ*

reduction of W+jets and top

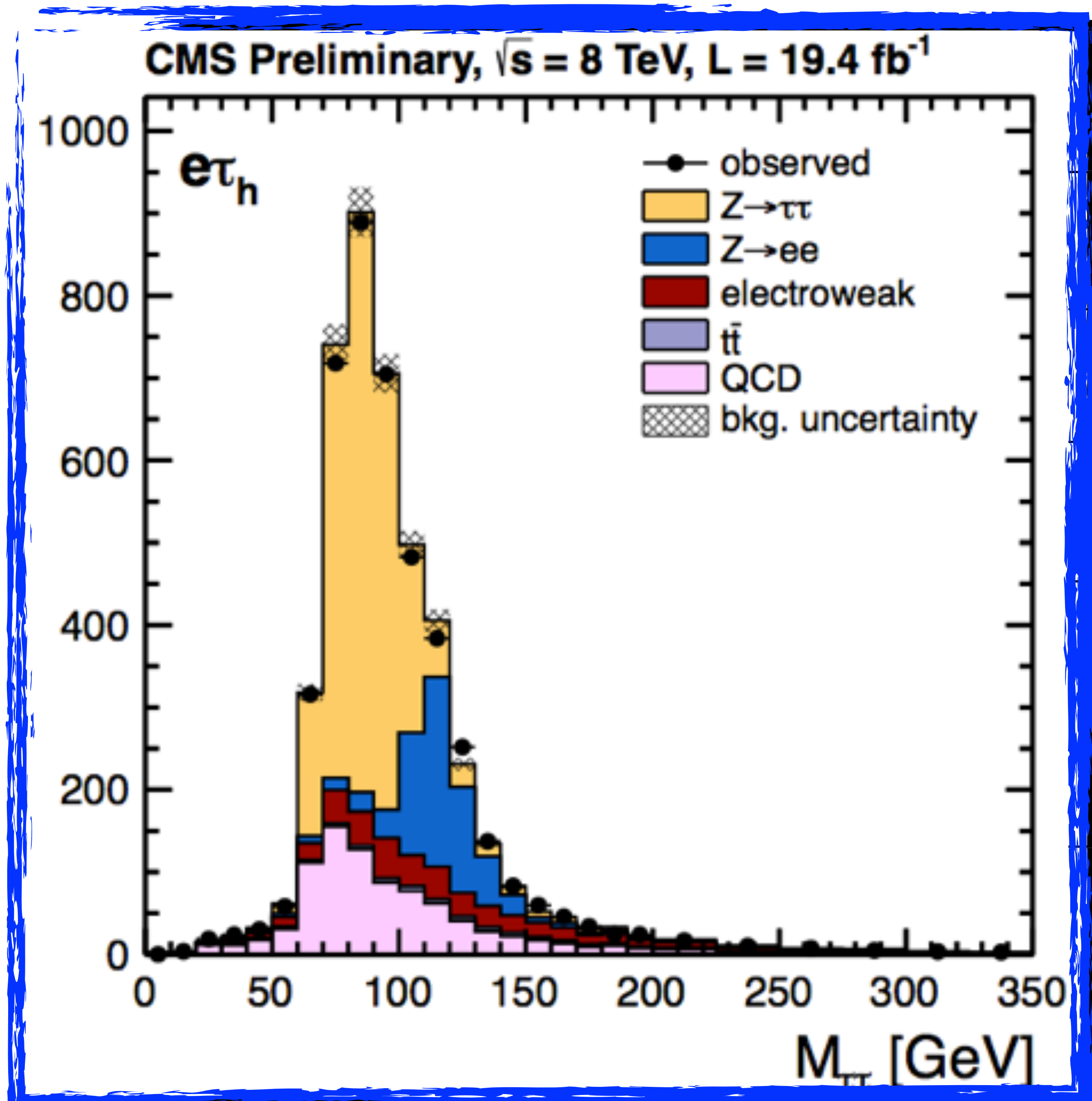
E_T^{miss}

reduction of Z→ee/μμ



* Ref. HIG-13-004

eT: overview



e+τ
L1 Ele
HLT_IsoEle_PFTau
discr. against $Z\rightarrow ee$
e: p_T>20-24, $\vert\eta\vert$<2.1 **τ**: p_T>20, $\vert\eta\vert$<2.3
$M_T(e, E_T^{miss})$ <20, (E_T^{miss} >30)*

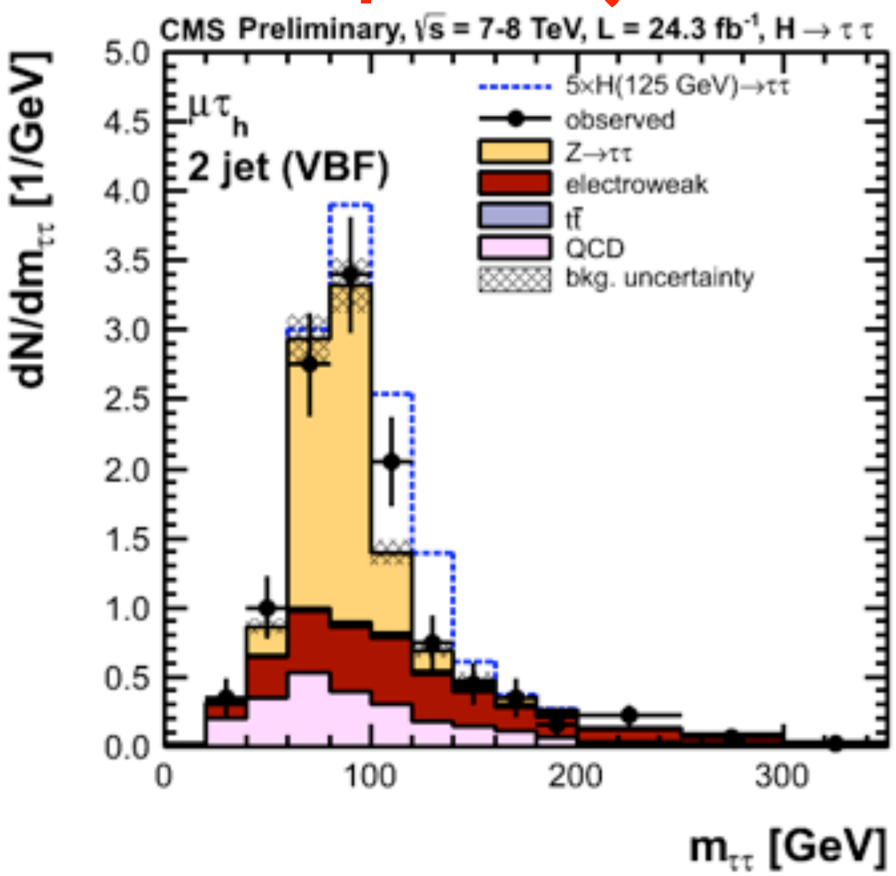
Main backgrounds: **$Z\rightarrow\tau\tau$** **QCD** **W+jets** **$Z\rightarrow ee$**

* only in 1-jet cat.
See later

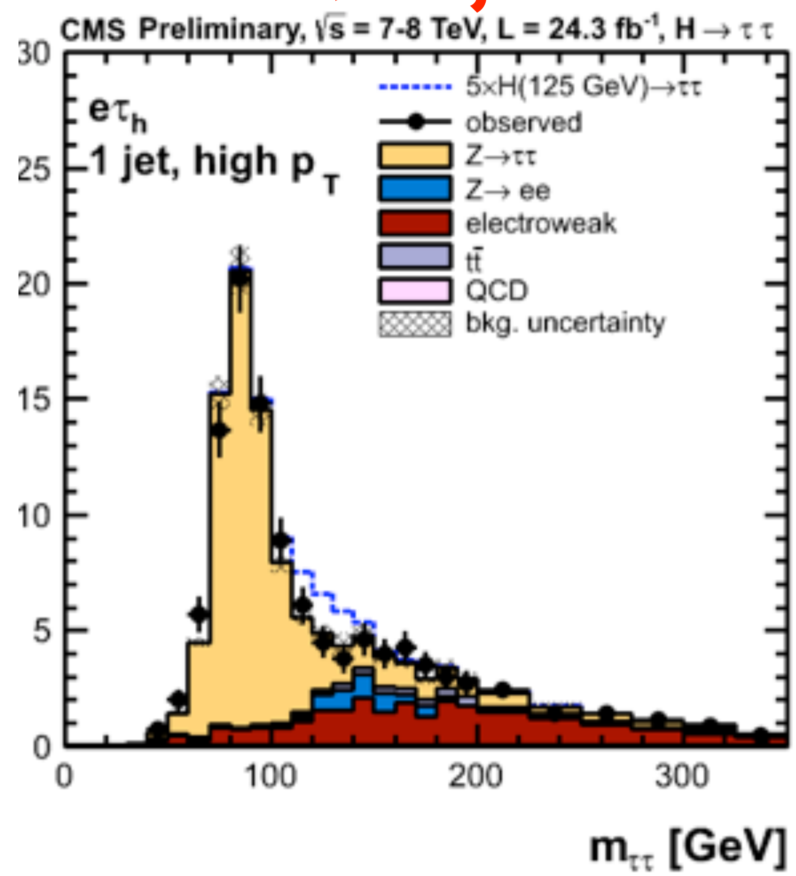
Statistical interpretation

- Test statistic based on profile-likelihood ratio
  - Likelihood built with SVfit mass histograms
  - Systematics incorporated as nuisance parameters
- Example of after-fit plots:

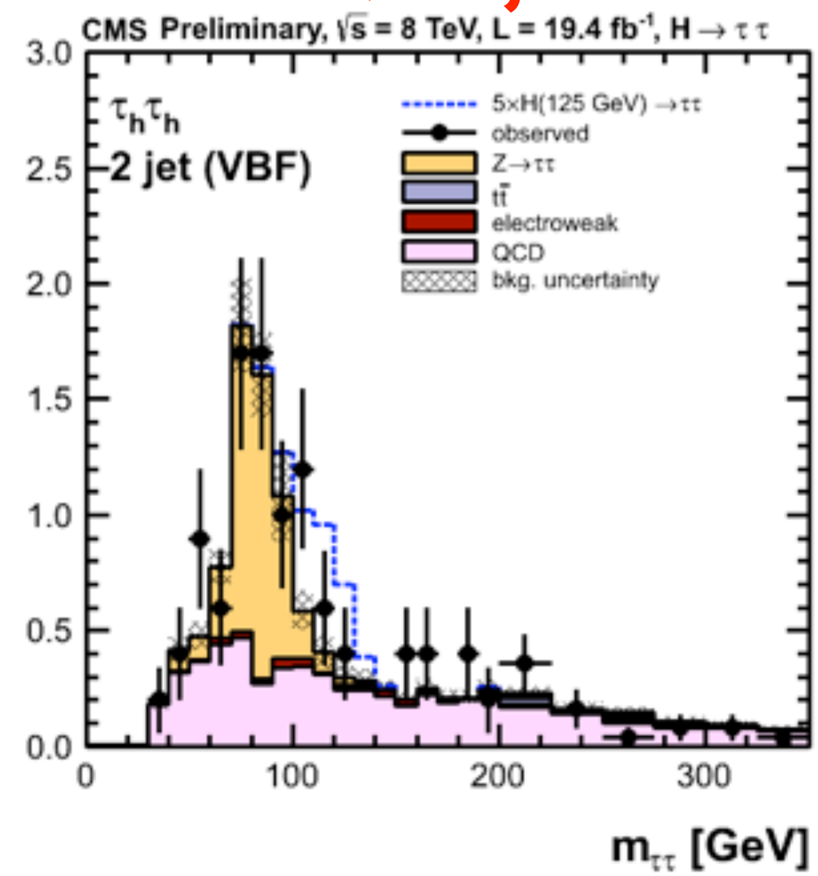
μτ, 2-jet



eτ, 1-jet



ττ, 1-jet



Experimental Uncertainties		Propagation into Event Categories		
Uncertainty	Uncert.	*0-Jet*	*1-Jet*	*VBF*
Electron ID & Trigger (†*)	±2%	±2%	±2%	±2%
Muon ID & Trigger (†*)	±2%	±2%	±2%	±2%
Tau ID & Trigger (†)	±8%	±8%	±8%	±8%
Tau Energy Scale (†)	±3%	±3%	±3%	±3%
Electron Energy Scale (†)	±1%	±1%	±1%	±1%
JES (Norm.) (†*)	±2.5 – 5%	∓3 – 15%	±1 – 6%	±5 – 20%
MET (Norm.) (†*)	±5%	±5 – 7%	±2 – 7%	±5 – 8%
b-Tag Efficiency (†*)	±10%	∓2%	∓2 – 3%	∓3%
Mis-Tagging (†*)	±30%	∓2%	∓2%	∓2 – 3%
Norm. Z production (†*)	±3%	±3%	±3%	±3%
$Z \to \tau\tau$ Category	±3%	±0 – 5%	±3 – 5%	±10 – 13%
Norm. $t\bar{t}$ (†* ex.vbf)	±10%	±10%	±10%	±12 – 33%
Norm. Diboson (†* ex. vbf)	±15 – 30%	±15 – 30%	±15 – 30%	±15 – 100%
Norm. QCD Multijet	±6 – 32%	±6 – 32%	±9 – 30%	±19 – 35%
Lumi 7 TeV (8 TeV)	±2.2(4.2)%	±2.2(4.2)%	±2.2(4.2)%	±2.2(4.2)%
Norm. *W*+jets	±10 – 30%	±20 – 27%	±10 – 33%	±12.4% – 30%
Norm. $Z \to \ell\ell$: e fakes τ_h (†)	±20%	±20%	±36%	±22%
Norm. $Z \to \ell\ell$: μ fakes τ_h (†)	±30%	±30%	±30%	±30%
Norm. $Z \to \ell\ell$: jet fakes τ_h	±20%	±20%	±20%	±40%

Theory Uncertainties (SM)		Propagation into Limit Calculation		
Uncertainty	Uncert.	*0-Jet*	*1-Jet*	*VBF*
PDF (†*)	-	-	±2 – 8%	±2 – 8%
$\mu_r/\mu_f(gg \to H)$ (†*)	-	-	±10%	±30%
$\mu_r/\mu_f(qq \to H)$ (†*)	-	-	±4%	±4%
$\mu_r/\mu_f(qq \to VH)$ (†*)	-	-	±4%	±4%
UE & PS (†*)	-	-	±4%	±4%

Results: S/B weighted plot

- The global picture (for visual purposes only)
  - All channels and categories weighted by **S/B** and combined
  - Excess around ~120 GeV most striking

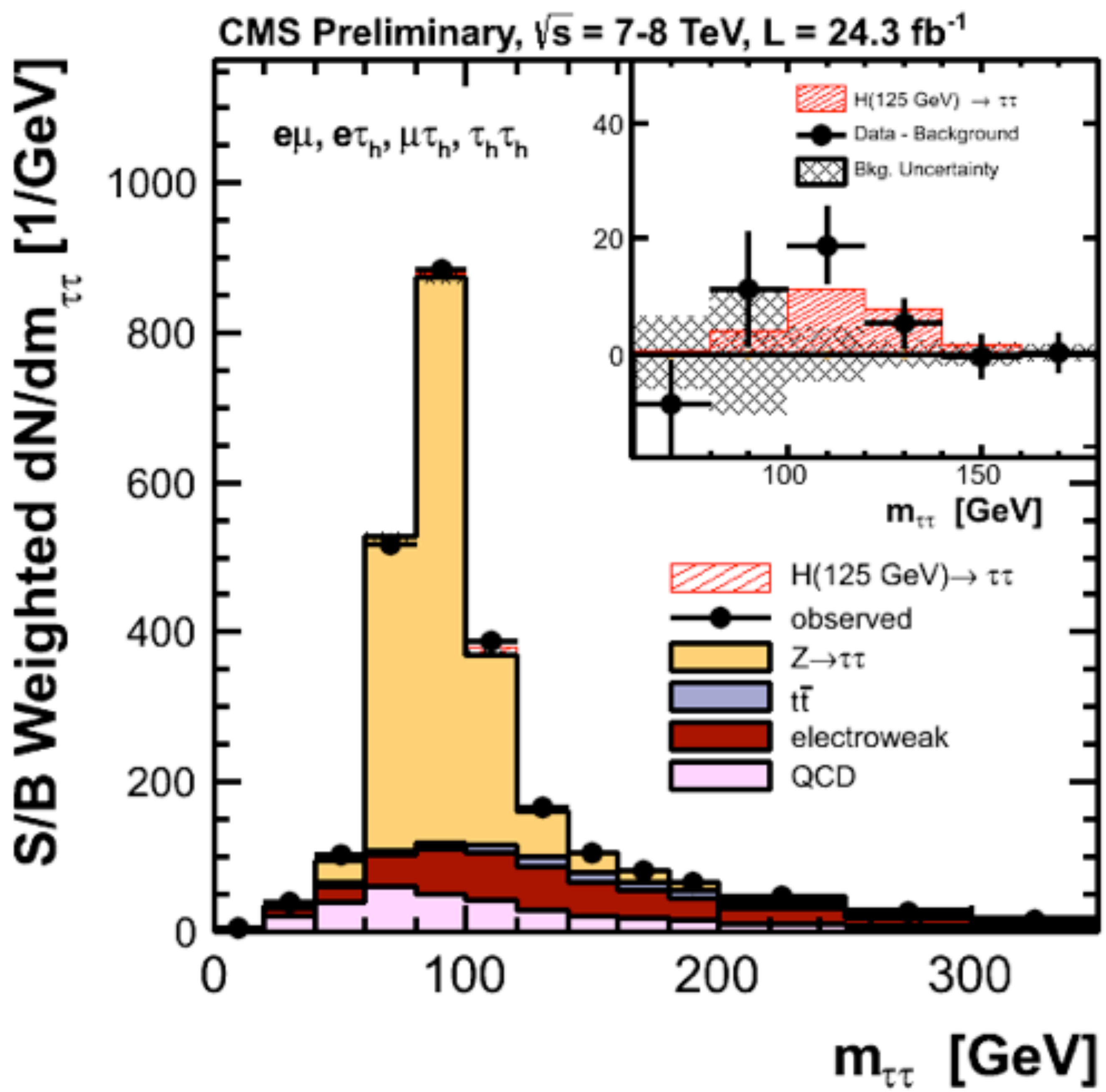


Table 3: Observed and expected event yields, and expected signal efficiency in the $\mu\tau_h$ channel.

Process	*0-Jet*	*1-Jet high p_T*	*VBF*
Z→ $\tau\tau$	84833 ± 1927	4686 ± 232	109 ± 11
QCD	18313 ± 478	481 ± 38	48 ± 7
EWK	8841 ± 653	1585 ± 153	63 ± 9
$t\bar{t}$	11 ± 1	155 ± 11	5 ± 1
Total Background	111998 ± 2090	6908 ± 281	225 ± 16
H→ $\tau\tau$	- ± -	73 ± 13	11 ± 2
Observed	112279	7011	240

Signal Eff.

gg→ H	-	$1.99 \cdot 10^{-3}$	$8.51 \cdot 10^{-5}$
qq→ H	-	$4.09 \cdot 10^{-3}$	$3.46 \cdot 10^{-3}$
qq→ H$t\bar{t}$ or VH	-	$3.00 \cdot 10^{-3}$	$1.60 \cdot 10^{-5}$

Table 4: Observed and expected event yields, and expected signal efficiency in t

Process	*0-Jet*	*1-Jet high p_T*	*VBF*
Z→ $\tau\tau$	25161 ± 708	792 ± 62	47 ± 6
QCD	7706 ± 307	3 ± 0.3	17 ± 4
EWK	9571 ± 510	365 ± 53	44 ± 6
$t\bar{t}$	4 ± 0.5	47 ± 4	4 ± 1
Total Background	42443 ± 924	1207 ± 82	113 ± 9
H→ $\tau\tau$	- ± -	15 ± 3	5 ± 1
Observed	42481	1217	117

Signal Eff.

gg→ H	-	$3.94 \cdot 10^{-4}$	$3.33 \cdot 10^{-5}$
qq→ H	-	$1.10 \cdot 10^{-3}$	$1.78 \cdot 10^{-3}$
qq→ H$t\bar{t}$ or VH	-	$8.30 \cdot 10^{-4}$	$1.46 \cdot 10^{-6}$

Process	*1-Jet*	*VBF*
Z→ $\tau\tau$	428 ± 90	47 ± 28
QCD	210 ± 31	61 ± 10
EWK	41 ± 9	4 ± 1
$t\bar{t}$	29 ± 6	2 ± 2
Total Background	709 ± 95	114 ± 30
H→ $\tau\tau$	9 ± 4	4 ± 2
Observed	718	120

Signal Eff.

gg→ H	$2.52 \cdot 10^{-4}$	$4.99 \cdot 10^{-5}$
qq→ H	$5.93 \cdot 10^{-4}$	$1.20 \cdot 10^{-3}$
qq→ H$t\bar{t}$ or VH	$9.13 \cdot 10^{-4}$	$3.59 \cdot 10^{-5}$

Table 5: Observed and expected event yields, and expected signal efficiency in the $e\mu$ channel.

Process	*0-Jet*	*1-Jet high p_T*	*VBF*
Z→ $\tau\tau$	48882 ± 1282	1830 ± 105	61 ± 6
QCD	4374 ± 249	395 ± 36	19 ± 2
EWK	1185 ± 89	461 ± 44	7 ± 1
$t\bar{t}$	74 ± 5	1100 ± 66	19 ± 2
Total Background	54514 ± 1309	3785 ± 137	105 ± 7
H→ $\tau\tau$	- ± -	23 ± 4	5 ± 0.6
Observed	54694	3774	118

Signal Eff.

gg→ H	-	$6.04 \cdot 10^{-4}$	$3.27 \cdot 10^{-5}$
qq→ H	-	$1.37 \cdot 10^{-3}$	$1.80 \cdot 10^{-3}$
qq→ H$t\bar{t}$ or VH	-	$1.38 \cdot 10^{-3}$	$1.32 \cdot 10^{-5}$

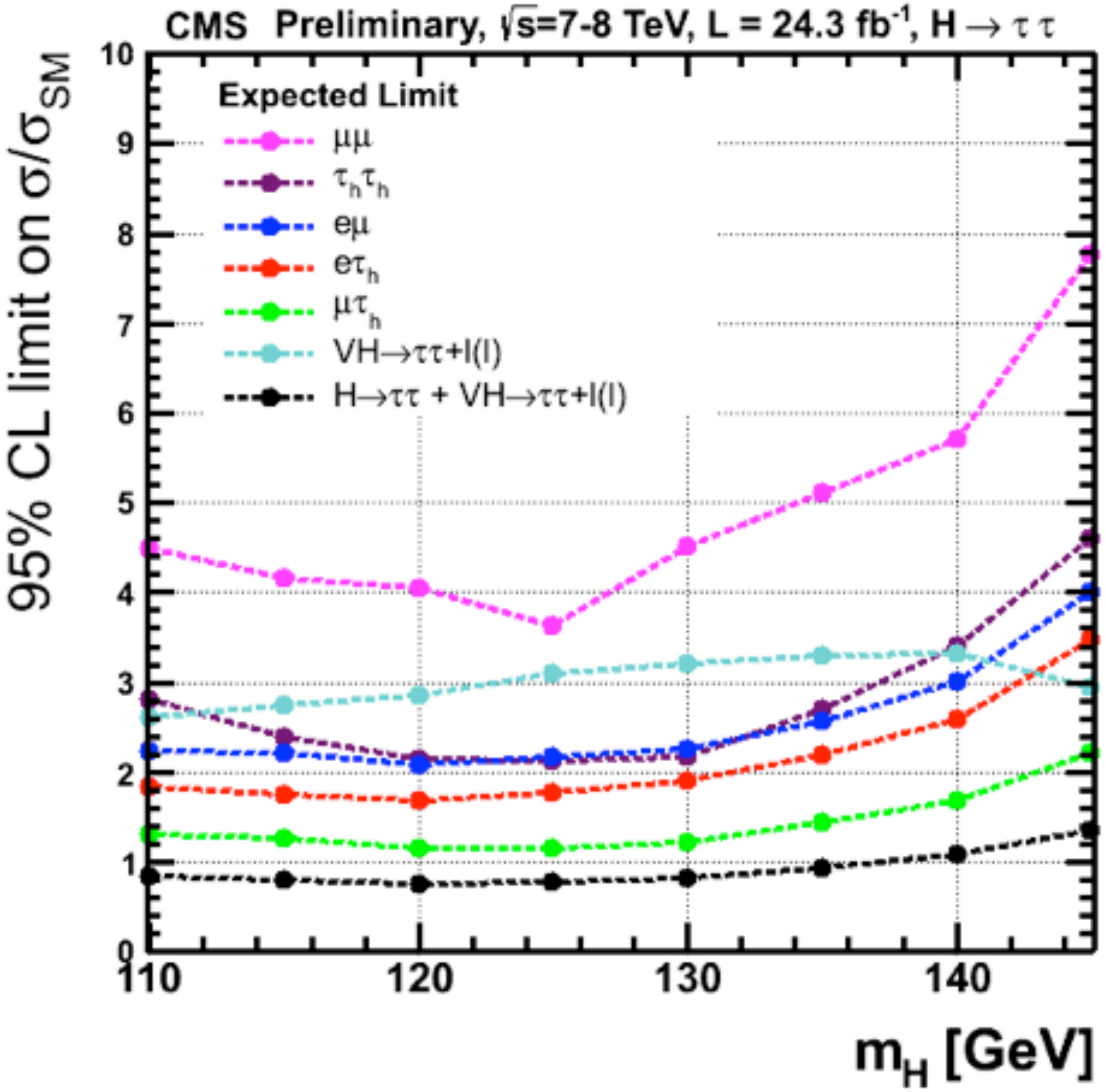
Table 6: Observed and expected event yields, and expected signal efficiency in the $\mu\mu$ channel.

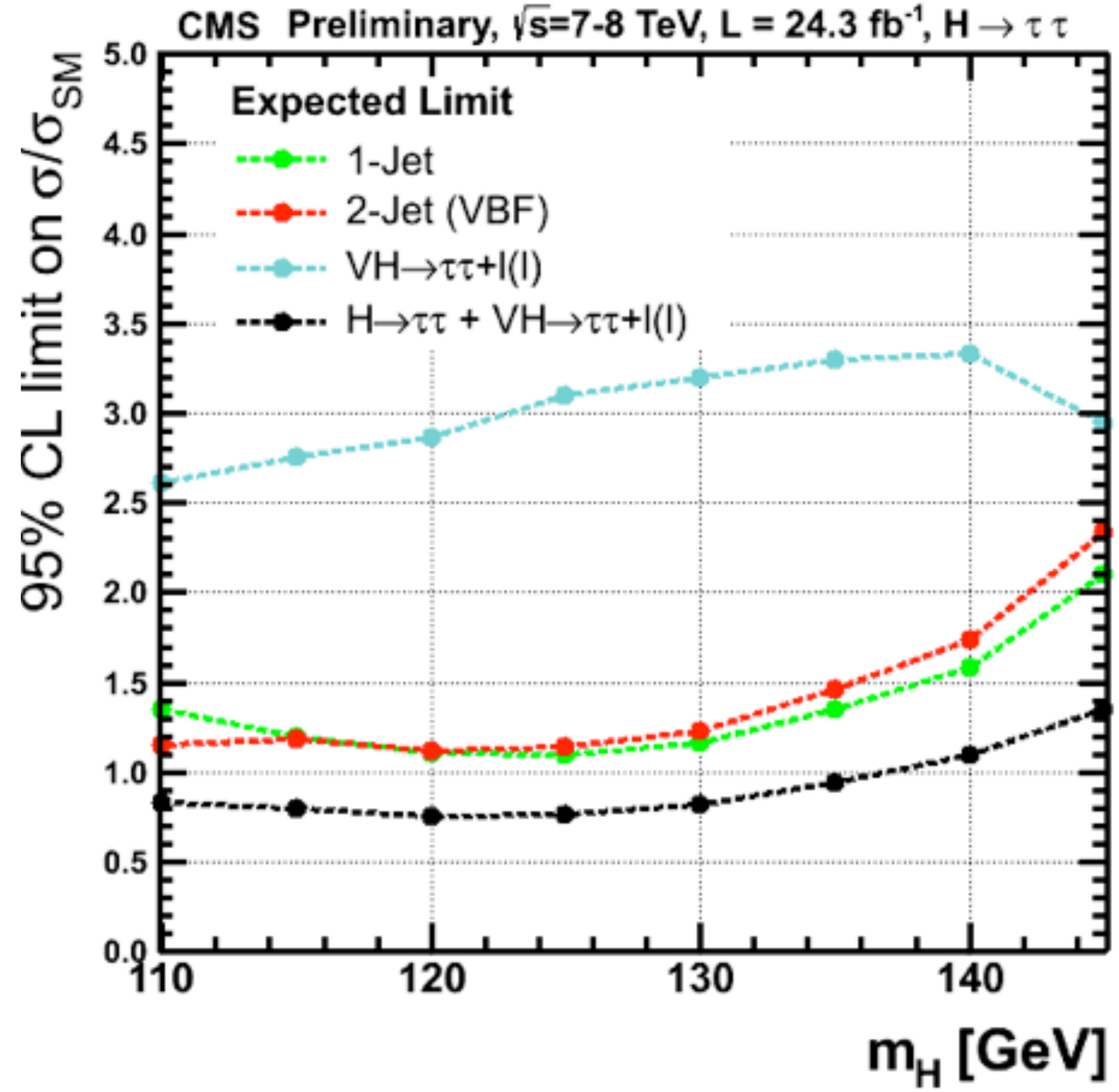
Process	*0-Jet*	*1-Jet high p_T*	*VBF*
Z→ $\mu\mu$	1925174 ± 52051	685272 ± 27303	380 ± 38
Z→ $\tau\tau$	20669 ± 470	3888 ± 157	116 ± 9
QCD	1299 ± 226	561 ± 161	6 ± 11
EWK	4732 ± 1594	7827 ± 1297	22 ± 9
$t\bar{t}$	4708 ± 2110	2168 ± 522	15 ± 5
Total Background	1956582 ± 52120	699717 ± 27418	539 ± 42
H→ $\tau\tau$	- ± -	37 ± 5	5 ± 1
Observed	1956931	700020	548

Signal Eff.

gg→ H	-	$9.50 \cdot 10^{-4}$	$7.23 \cdot 10^{-5}$
qq→ H	-	$1.85 \cdot 10^{-3}$	$1.03 \cdot 10^{-3}$
qq→ H$t\bar{t}$ or VH	-	$2.95 \cdot 10^{-3}$	$1.39 \cdot 10^{-4}$

Expected limits (SM search)



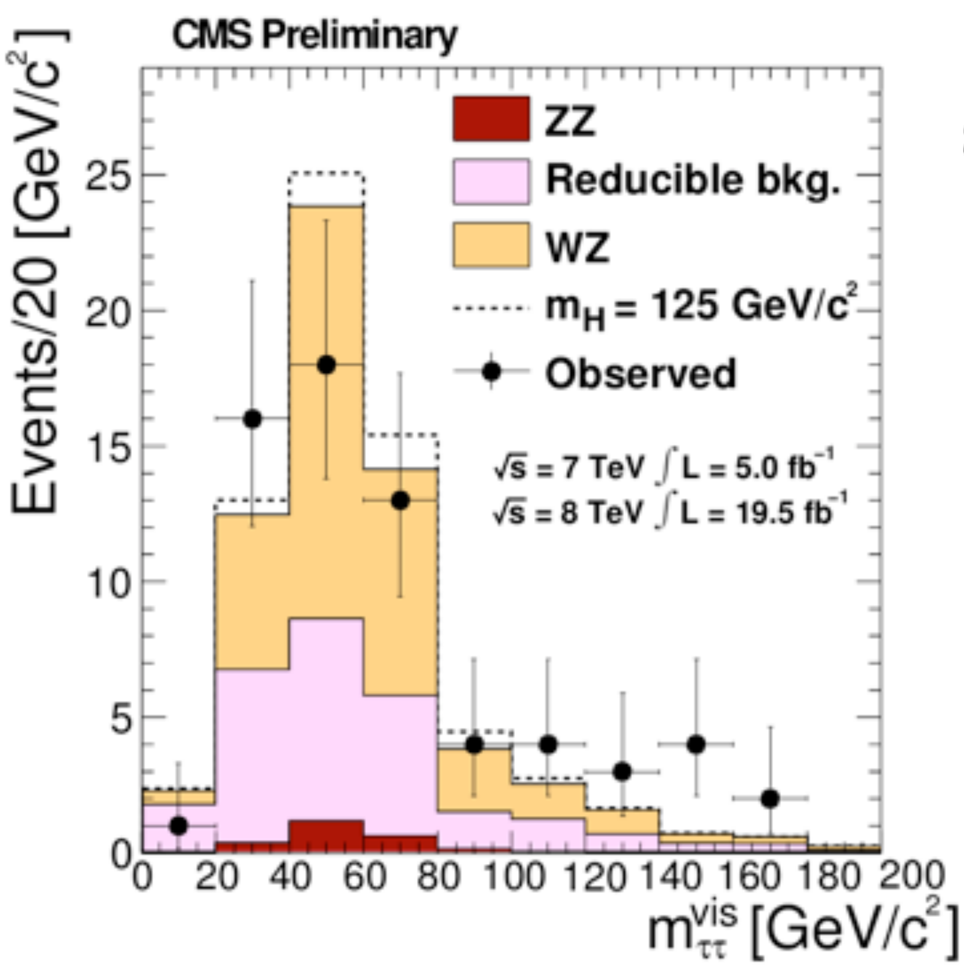


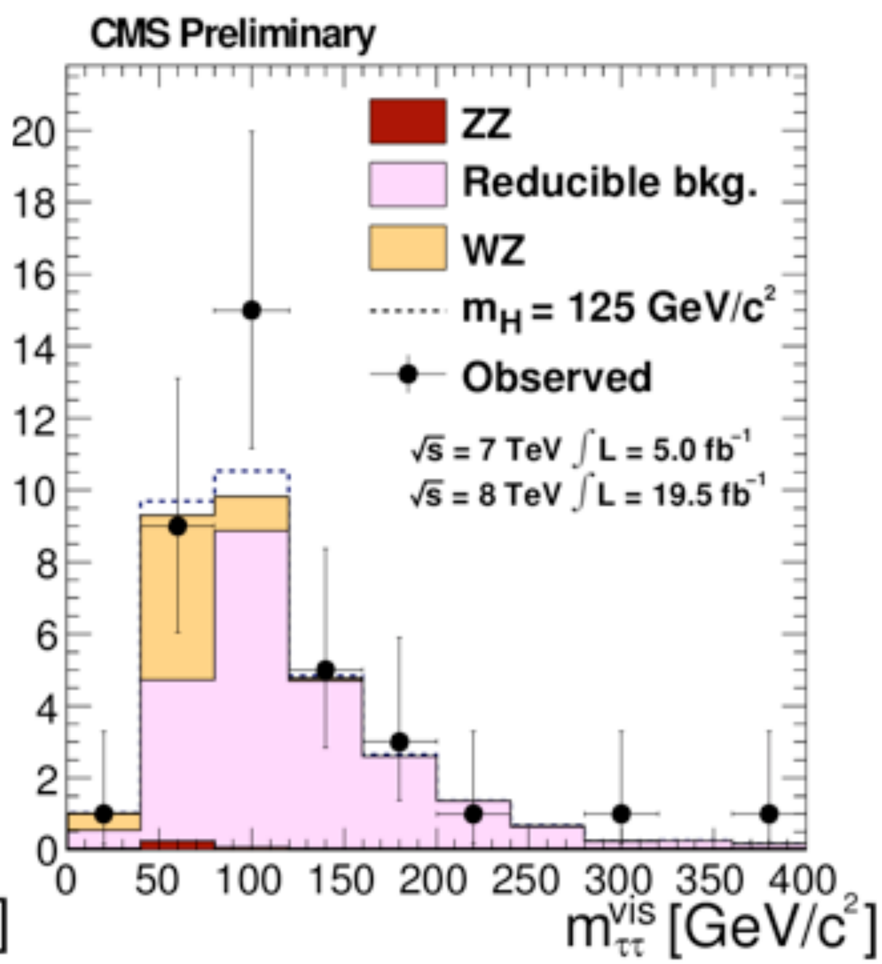
Background estimation

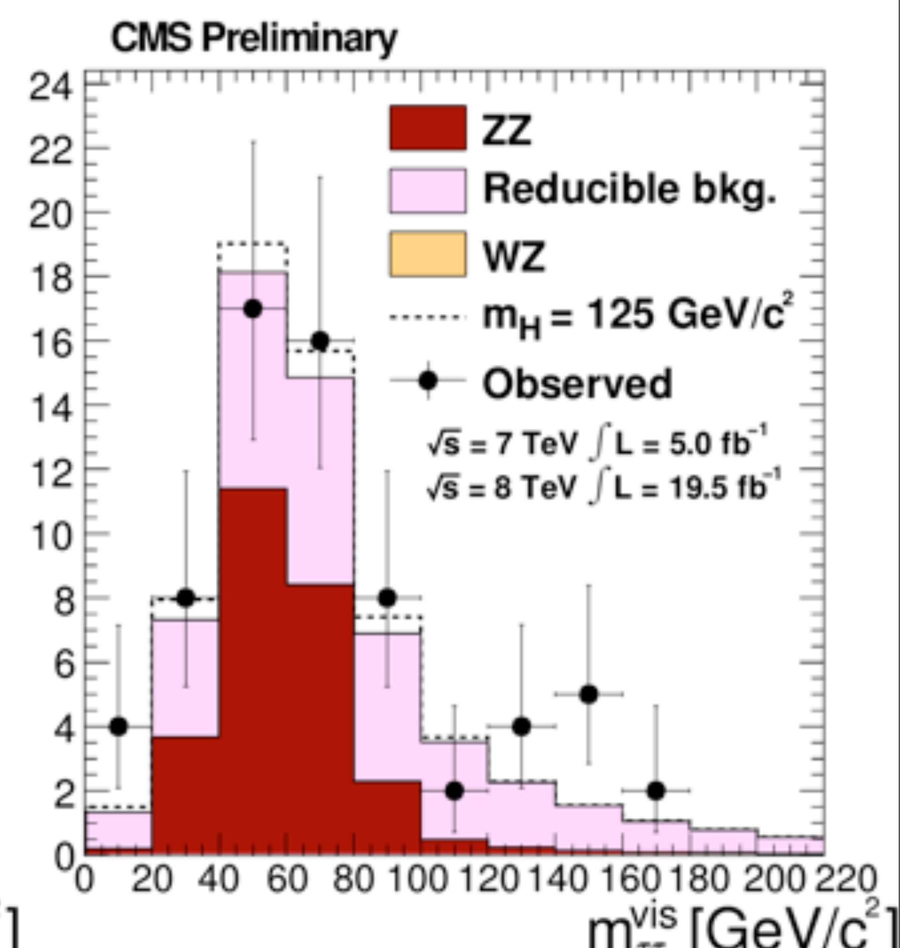
- Irreducible VV bkg from MC
  - Normalized to meas. xsec or theory
- Reducible bkg: data-driven
  - Fake-rate measured in sidebands

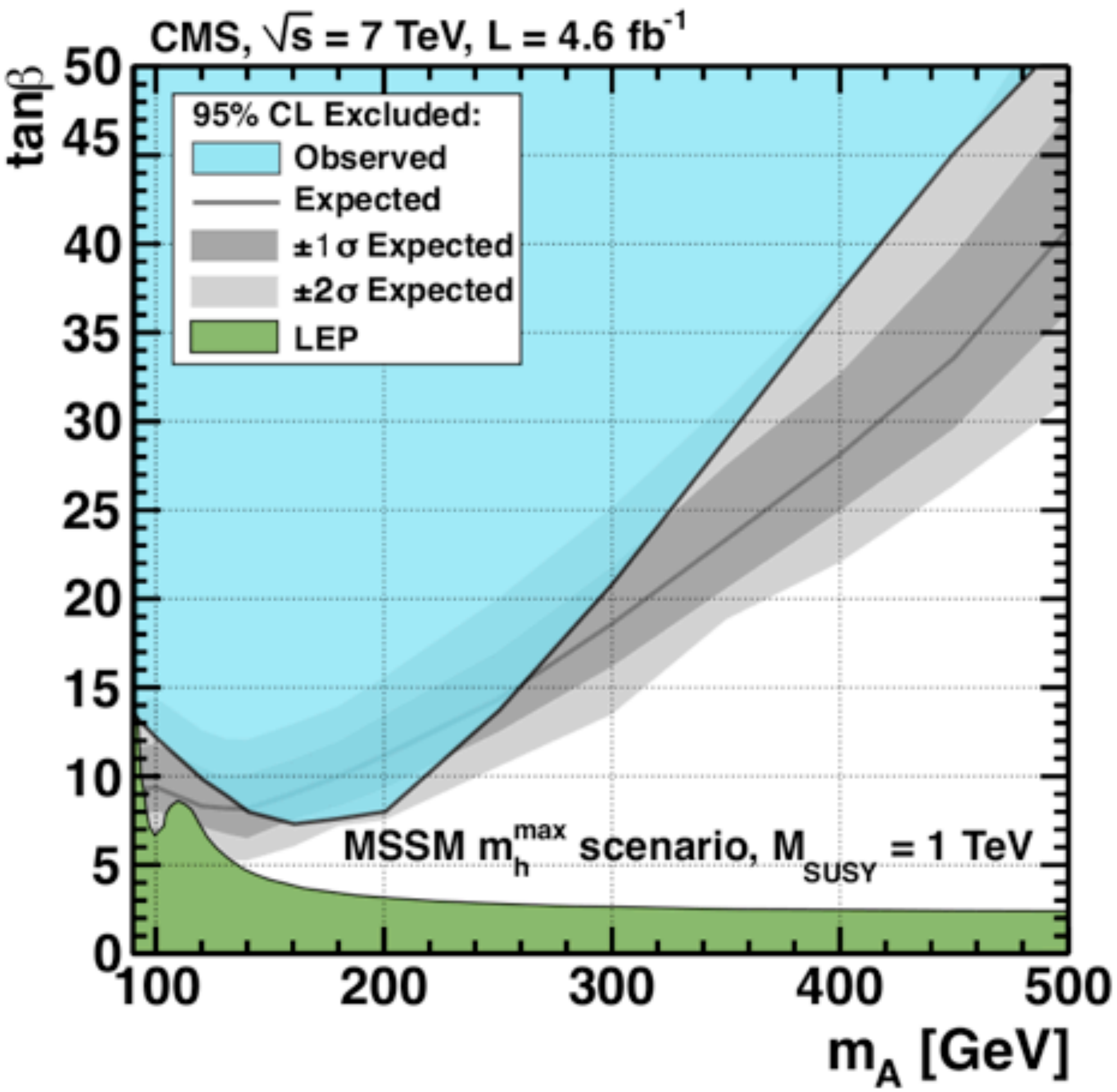
Process	$\ell\ell\tau_h$	$\ell\tau_h\tau_h$	$\ell\ell LL$
Reducible backgrounds	26.3 ± 4.7	20.8 ± 4.2	25.2 ± 10.0
WZ	35.3 ± 3.9	6.3 ± 0.9	
ZZ	2.5 ± 0.3	0.39 ± 0.08	27.2 ± 3.8
Total bkg.	64.1 ± 6.2	27.5 ± 4.3	52 ± 11
VH→V$\tau\tau$(m_H = 125 GeV/c^2)	3.6 ± 0.4	1.2 ± 0.2	2.1 ± 0.2
VH→VWW (m_H = 125 GeV/c^2)	0.50 ± 0.05	0	1.13 ± 0.09
Observed	65	36	66

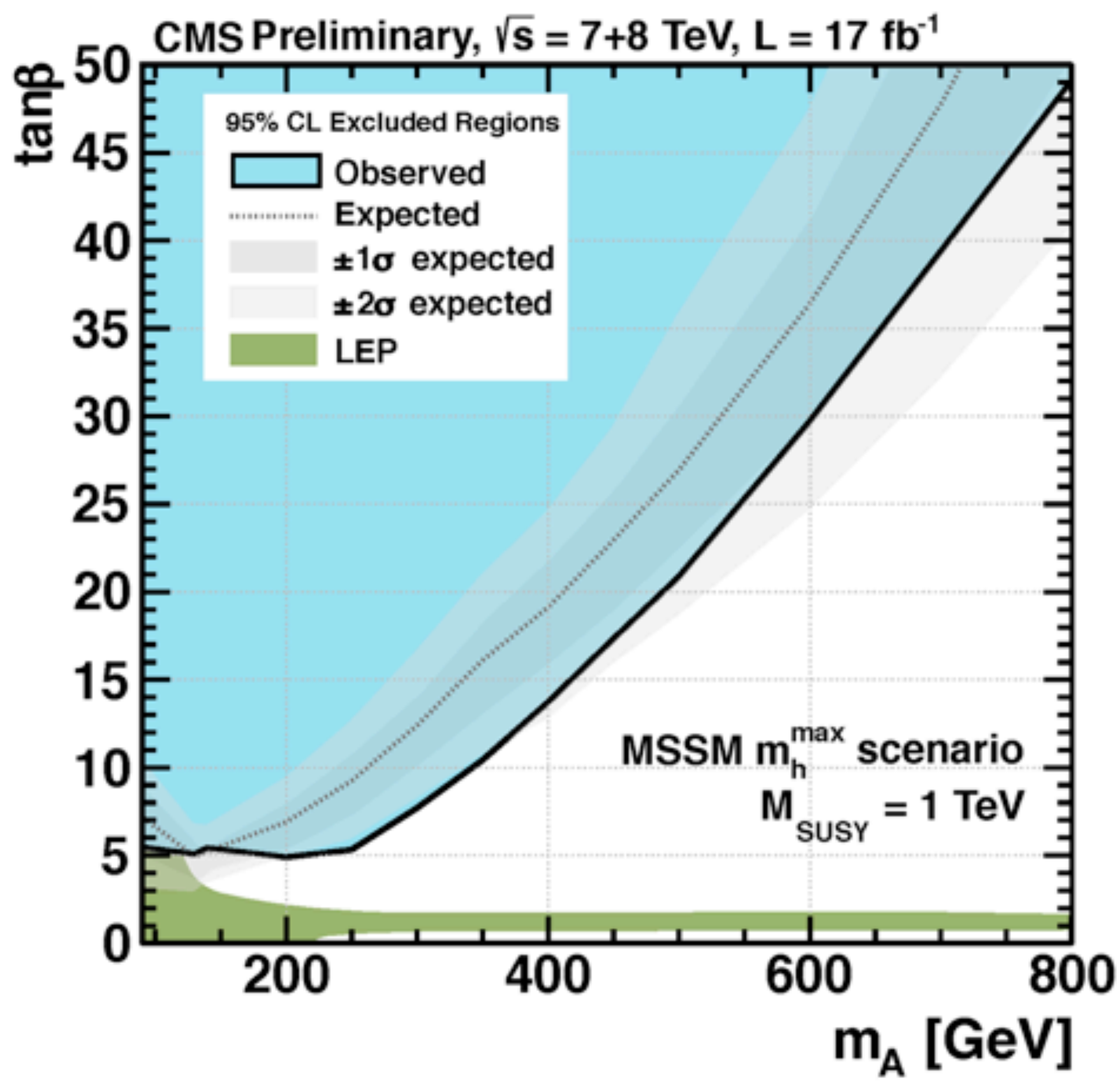
$\ell\ell\tau$ $\ell\tau\tau$ $\ell\ell$LL



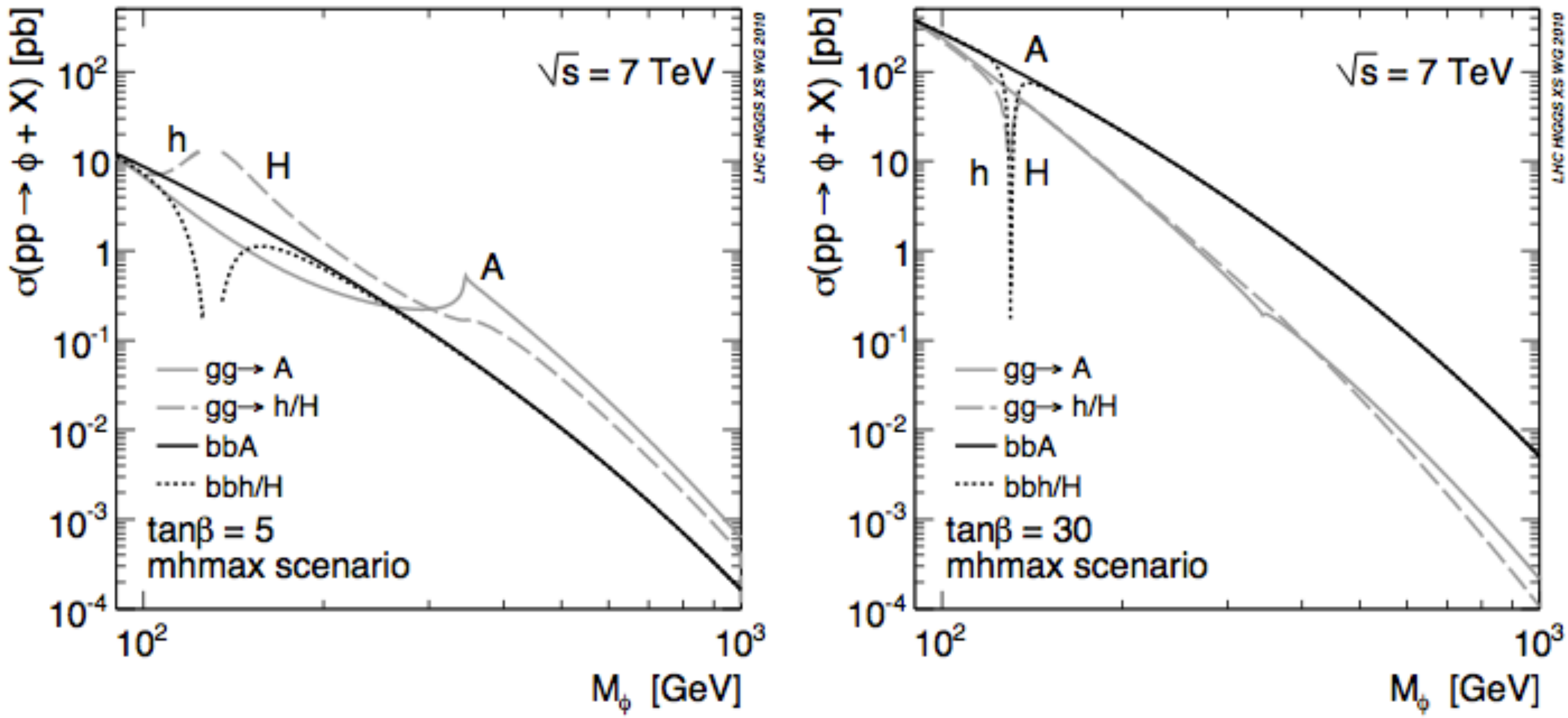




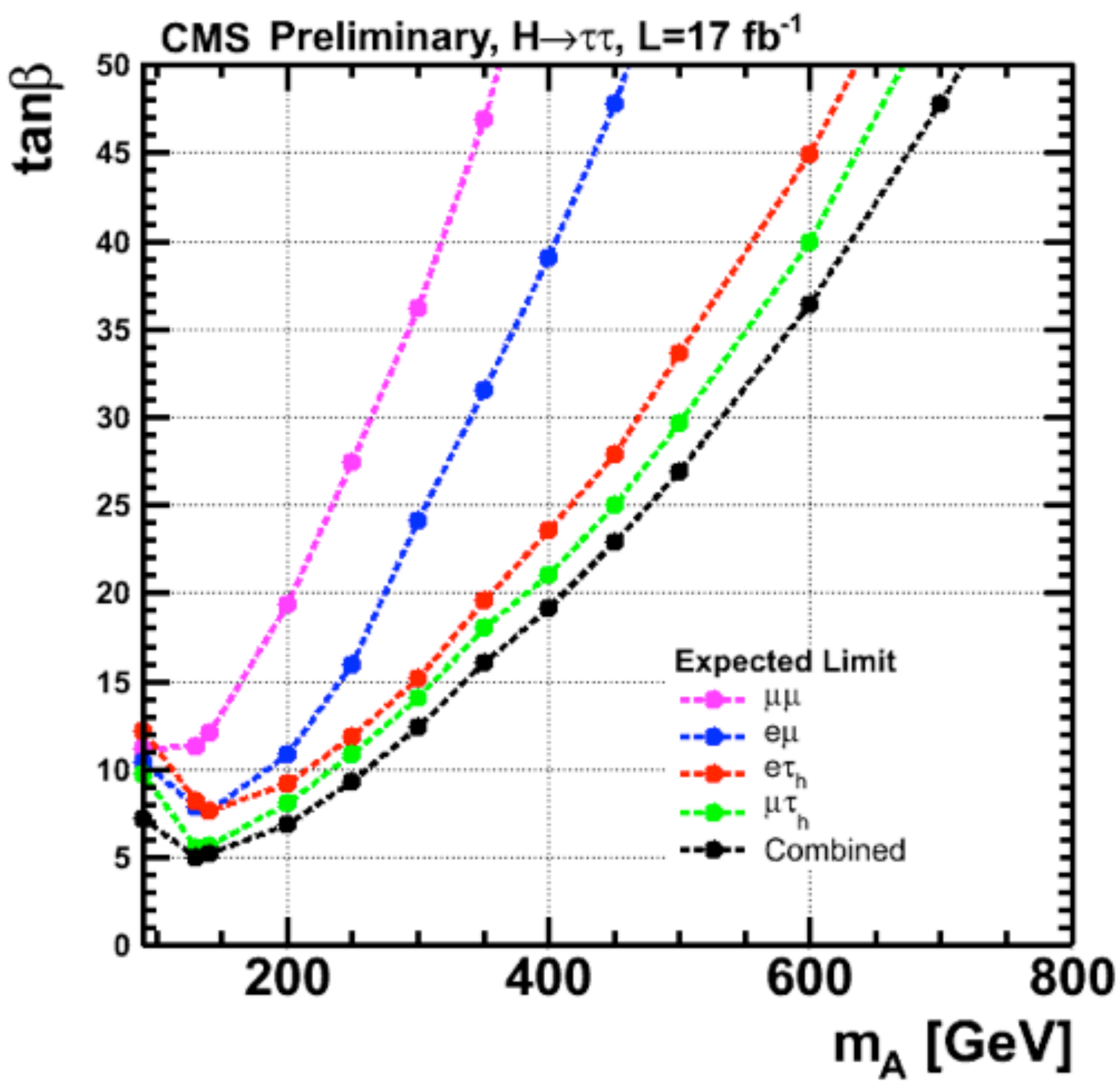

CMS, √s = 7 TeV, L = 4.6 fb-1
tanβ
95% CL Excluded:
Observed
Expected
±1σ Expected
±2σ Expected
LEP
MSSM mhmax scenario, MSUSY = 1 TeV
mA [GeV]

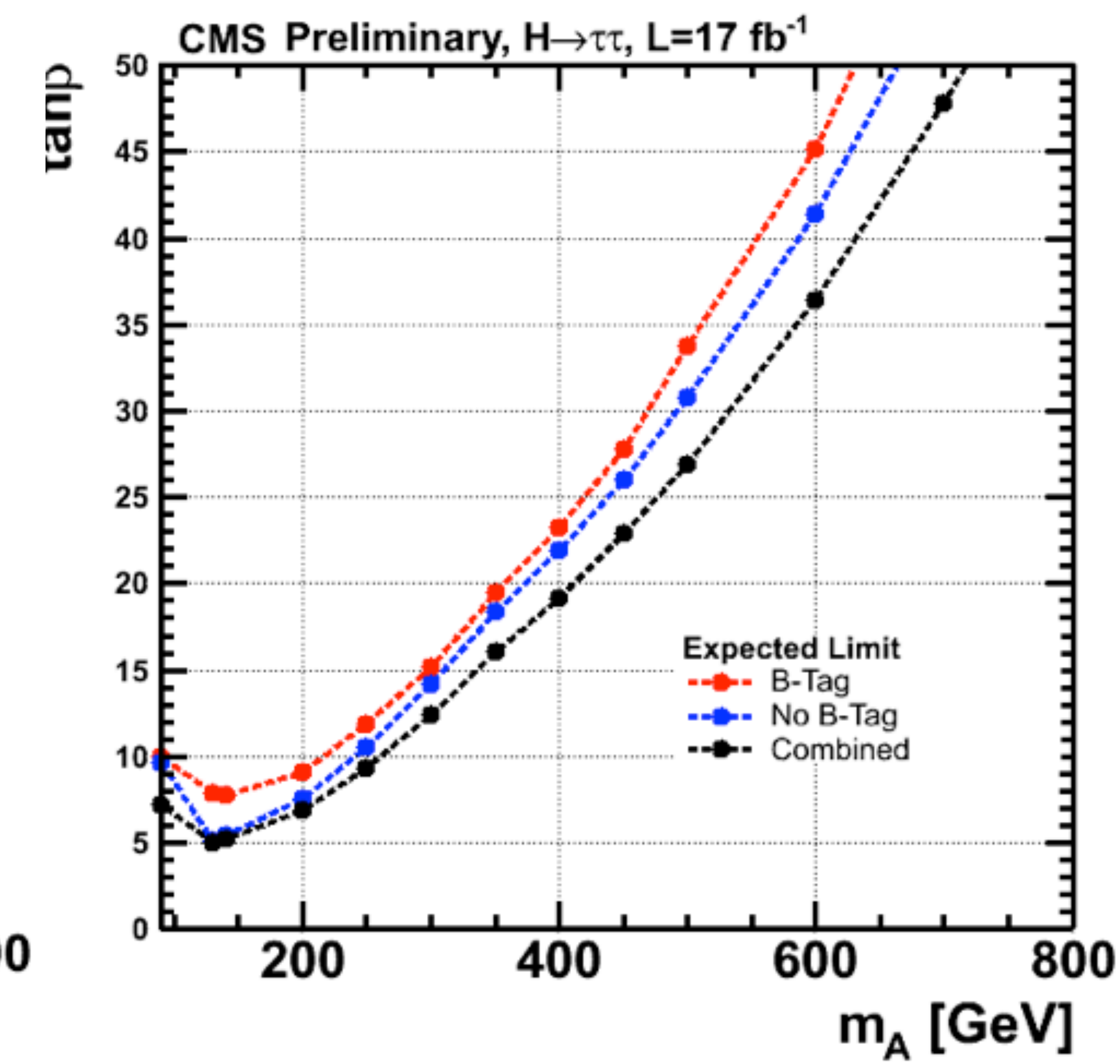

CMS Preliminary, √s = 7+8 TeV, L = 17 fb-1
tanβ
95% CL Excluded Regions
Observed
Expected
±1σ expected
±2σ expected
LEP
MSSM mhmax scenario
MSUSY = 1 TeV
mA [GeV]

MSSM xsection



Mass Spectra (MSSM search)





CMS Projection