Karlsruher Institut für Technologie

MSSM $\phi \to \tau\tau$

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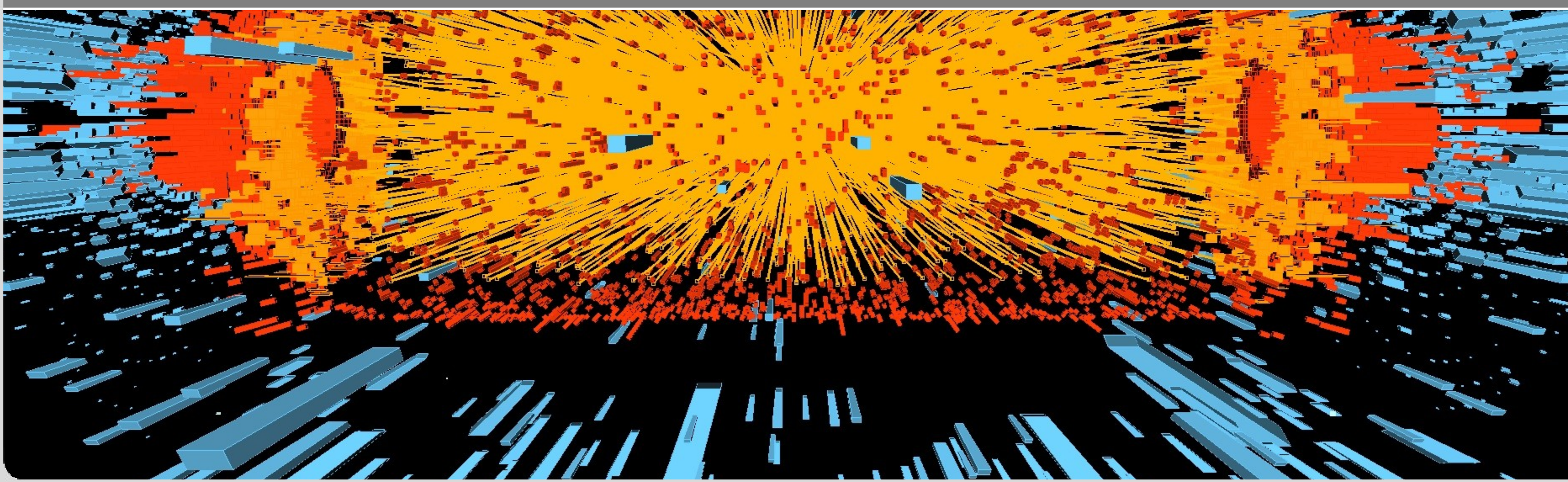


Quelle: http://www.interactions.org/cms/

Agenda

Standardmodel
- Gauge theories
- Higgs mechanism
- Yukawa coupling

→ **Higgs discovery**

→ **Extensions of the SM**
- SUSY
- MSSM

→ **Higgs searches** $\phi \to \tau\tau$
- Model independent
- Model dependent (MSSM)

Recap – The Standardmodel

- QED Lagrangian and Gauge Invariance

$$L_{Dirac} = \overline{\Psi}\,(i\gamma^{\mu}\partial_{\mu} - m)\,\Psi$$

Invariant under global U(1) transformation

$$\Psi \rightarrow \Psi' = \exp(i\Theta)\Psi$$
$$\overline{\Psi} \rightarrow \overline{\Psi}' = \overline{\Psi}\exp(-i\Theta)$$

$$L \rightarrow L' = L \quad \checkmark$$

Demand invariance under local U(1) transformation!

$$\Psi \rightarrow \Psi' = \exp(i\Theta(x))\Psi$$
$$\overline{\Psi} \rightarrow \overline{\Psi}' = \overline{\Psi}\exp(-i\Theta(x))$$

$$\partial_{\mu} \rightarrow D_{\mu} = \partial_{\mu} + iqA_{\mu}$$

$$A_{\mu} \rightarrow A'_{\mu} = A_{\mu} - \frac{1}{q}\partial_{\mu}\Theta(x)$$

$$L_{QED} = \overline{\Psi}(i\gamma^{\mu}D_{\mu} - m)\Psi = \overline{\Psi}(i\gamma^{\mu}\partial_{\mu})\Psi - m\overline{\Psi}\Psi - q(\overline{\Psi}\gamma^{\mu}\Psi)A_{\mu} + \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Full QED lagrangian

$$L \rightarrow L' = L \quad \checkmark$$

Recap – The Standardmodel

The demad of gauge invariance under local U(1) transofrmation gives rise to the covariant derivative D_μ and a new field A_μ which works as a massless messenger particle between different points in spacetime.

Massless?

- Terms like $m^2 A_\mu A^\mu$ are not gauge invariant
- Euler-Lagrange equation for A_μ leads to massless Klein-Gordon equation

$$(\partial_\mu \partial^\mu) A_\mu = 0$$

→ Gauge field is a boson with zero mass

Recap – The Standardmodel

Special**U**nitary

- U(1) use same procedure to non-abelian Lie groups SU(N) (generators of the group don't commute)

$G \in SU(N)$

$G_{fin} = (I + i\frac{\vartheta^a_{fin}}{m} T^a)^m \xrightarrow{m \to \infty} e^{i\vartheta^a T^a}$

ϑ^a Continuous parameter

T^a Generator of the group

$(N^2 - 1)$ Generators

- SM : $SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$
- SU(3): QCD
  - 8 massless gluons
  - No need for spontaneous symmetry breaking
- SU(2) x U(1): Electroweak sector
  - Parity violation (weak force couples only to lh particles and rh antiparticles)
  - Massterms of the form $m^2\overline{\Psi}\Psi$ / $m^2 W^\mu W_\mu$ not invariant under symmetry transformations (lh and rh fields transform differently)

Solution → Yukawa Coupling

Solution → Higgs Mechanism

Higgs Mechanism

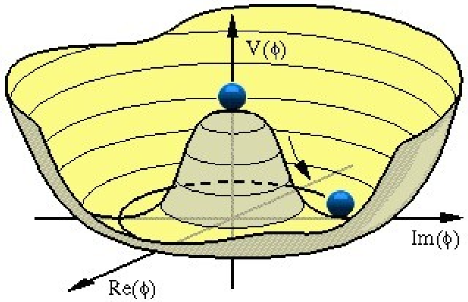
- Sponateous symmetry breaking + local Gauge theory
  - Groundstate has less symmetries than the corresponding e.o.m
  - Breaking of global symmetries → Goldstone theorem

> There is one massless scalar particle (goldstone boson) for every spontaneously broken symmetry

Higgs Mechanism

- e.g. Lagrangian for complex scalar field (global U(1) symmetry)

$$L = (\partial_\mu \Phi)^* (\partial^\mu \Phi) - \mu^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2$$



- Groundstate for $\mu^2 < 0 \;\rightarrow\; \Phi^* \Phi = -\frac{\mu^2}{2\lambda}$

- Expand around minima $|\Phi| = \sqrt{-\frac{\mu^2}{2\lambda}} = v$

$$\Phi = v + \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$

$$\rightarrow L = \frac{1}{2}(\partial_\mu \phi_1)^2 + \frac{1}{2}(\partial_\mu \phi_2)^2 - 2\lambda v^2 \phi_1^2 - \sqrt{2} v \lambda \phi_1 (\phi_1^2 + \phi_2^2) - \frac{\lambda}{4}(\phi_1^2 + \phi_2^2)^2$$

Interaction terms: $\phi^4 \quad \phi^3$

Massterms: $m_{\phi_1} = 2v\sqrt{\lambda} \qquad m_{\phi_2} = 0$ (Goldstone Boson)

Institute of Experimental Particle Physics (IEKP)

Higgs mechanism for U(1) gauge theory

$$L = (D_\mu \phi)^*(D^\mu \phi) - \mu^2 \phi^* \phi - \lambda(\phi^*\phi)^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

- Spontaneous symmetry breaking: expand ϕ around $\mathrm{v} = \sqrt{-\frac{\mu^2}{2\lambda}}$

$$\phi(x) = v + \frac{1}{\sqrt{2}}(\varphi_1 + i\varphi_2) = \left(v + \frac{H(x)}{\sqrt{2}}\right) \exp\left(i \frac{\chi(x)}{\sqrt{2}v}\right)$$

- Kinetic term changes to

$$|D_\mu \phi|^2 = \frac{1}{2}\partial_\mu H \partial^\mu H + e^2 v^2 A'_\mu A^{\mu\prime} \left(1 + \frac{H}{v\sqrt{2}}\right)^2$$ with $$A'_\mu = A_\mu + \frac{\partial_\mu \chi}{\sqrt{2} v e}$$

- Which leads to the lagrangian

$$L = \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - 2\lambda v^2 H^2 - \lambda\sqrt{2} v H^3 - \frac{\lambda}{v} H^4 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + e^2 v^2 A'_\mu A^{\mu\prime} + e^2 A'_\mu A^{\mu\prime}\left(\sqrt{2} v H + \frac{H^2}{2}\right)$$

Massive scalar particle (Higgs)

Massive gauge boson
In this case a massive photon

Higgs Mechanism

- Sponateous symmetry breaking + local Gauge theory
  - Groundstate has less symmetries than the corresponding e.o.m
  - Breaking of global symmetries → Goldstone theorem
  - No Goldstone bosons but one more d.o.f (longitudinal polarization) for the gauge fields
  - In SU(2)xU(1) gauge theory W and Z gauge bosons aquire mass
  - Photon stays massless

- This shuffling of d.o.f is the Higgs mechanism

Yukawa coupling

- $m\overline{\Psi}\Psi$ not gauge invariant under $SU(2)_L xU(1)_Y$ (different charges)

$$m\overline{\Psi}\Psi = m(\overline{\Psi_L}\Psi_R + \overline{\Psi_R}\Psi_L)$$

- Idea is to write interaction between $\Psi_L,\ \Psi_R \text{ and } \phi$ (for simple down type electron case)

$$L_Y = g(\overbrace{\underbrace{\overline{\Psi_L}\ \phi}_{SU(2)_L \text{ invariant}}\ e_R}^{U(1)_Y \text{ invariant}} + h.c)$$

e_R: Singlet under $SU(2)_L$

Charges w.r.t $U(1)_Y$

$$Y_R = -2$$
$$Y_\phi = 1$$
$$Y_L = -1$$

- L_Y invariant under $SU(2)_L xU(1)_Y$
- May become a mass term after ssb

$$\phi = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

Lorentz invariant
Gauge invariant
Renormalizable
Dimension 4

✓

Yukawa coupling

$$\phi = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Rightarrow$$

$$L_Y = g[(\overline{\nu_L}\ \overline{e_L}) \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} e_R + h.c] = g(\overline{e_L} \cdot e_R + h.c)\frac{v+h}{\sqrt{2}}$$

$$= \frac{gv}{\sqrt{2}}(\overline{e_L}e_R + \overline{e_R}e_L) + \frac{gh}{\sqrt{2}}(\overline{e_L}e_R + \overline{e_R}e_L)$$

$$= m_e(\overline{e_L}e_R + \overline{e_R}e_L) + \frac{m_e}{v}h(\overline{e_L}e_R + \overline{e_R}e_L)$$

→ $$L_Y = m_e\bar{e}e + \frac{m_e h\bar{e}e}{v}$$

Fermion mass

Higgs fermion interaction ~ $\frac{m_e}{v}$

- Quark masses: same procedure but need Higgs doublet with Y=-1 for down type quarks $\phi^\dagger$ (later)

SM Lagrangian

$$L_{SM} = L_F + L_{gauge} + L_\phi + L_Y$$

$$L_F = \sum_\Psi \overline{\Psi} i \gamma^\mu D_\mu \Psi \qquad D_\mu \Psi = (\partial_\mu - \underbrace{i g_s T^a G^a_\mu}_{\text{SU(3)}} - \underbrace{i g \frac{\tau^i}{2} W^i_\mu}_{\text{SU(2)}} - \underbrace{i g' \frac{1}{2} B_\mu}_{\text{U(1)}}) \Psi$$

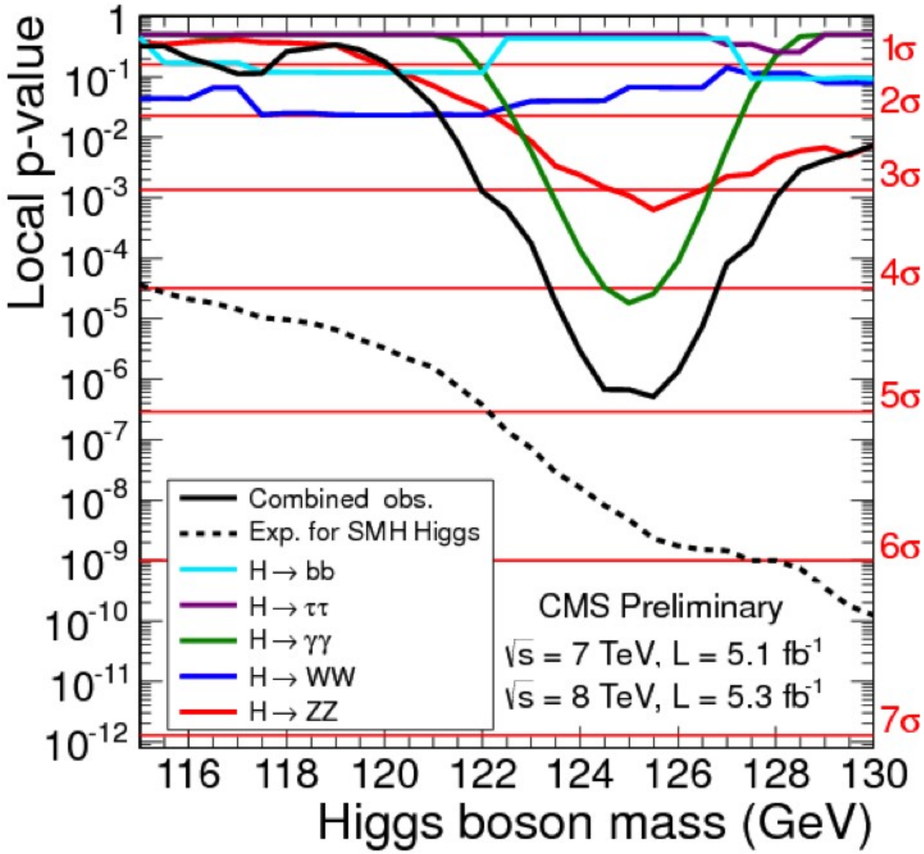
$$L_{gauge} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu} W^{\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$$

$$L_\phi = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi)$$

$$D_\mu \phi = (\partial_\mu - \underbrace{i g \frac{\tau^i}{2} W^i_\mu}_{\text{SU(2)}} - \underbrace{i g' \frac{1}{2} B_\mu}_{\text{U(1)}}) \phi$$

Higgs Discovery

arXiv:1207.7235



P-value:

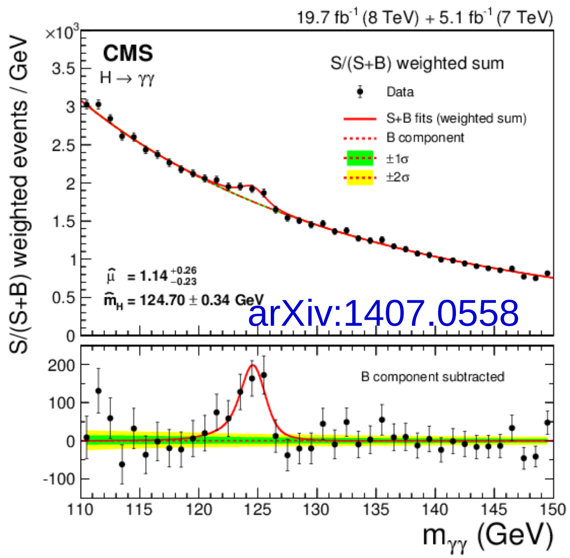
$$p = \int_{t_m}^{\infty} g(t|H_0)dt$$

Probability to measure values t > t_m if H_0 is true

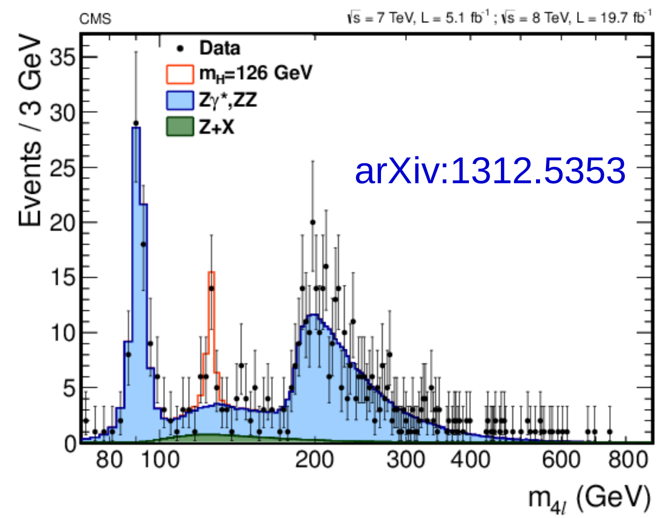
..so there's a chance of less than 10^{-6}

First LHC run 2010-2012

$H \to \gamma\gamma$



$H \to ZZ$



- It is a boson
- Spin 0 (Landau Yang Theorem)
- Mass at ~125 GeV
- CP even : $J^P=0^+$ (very likely)
- BUT: Is it **THE** SM Higgs Boson or could it be something else?

Problems of the SM

- Higgs mechanism “deus ex machina”
- Gravitation not included
- Dark Matter
- Neutrino masses
- Matter anti-matter asymmetry
- No strong & weak & em unification
- ...

Extensions of the SM - SUSY

- every boson as a fermion as superpartner and vice verca
- Same mass, same quantum numbers (except spin)
- Must be broken (same mass particles not observed)

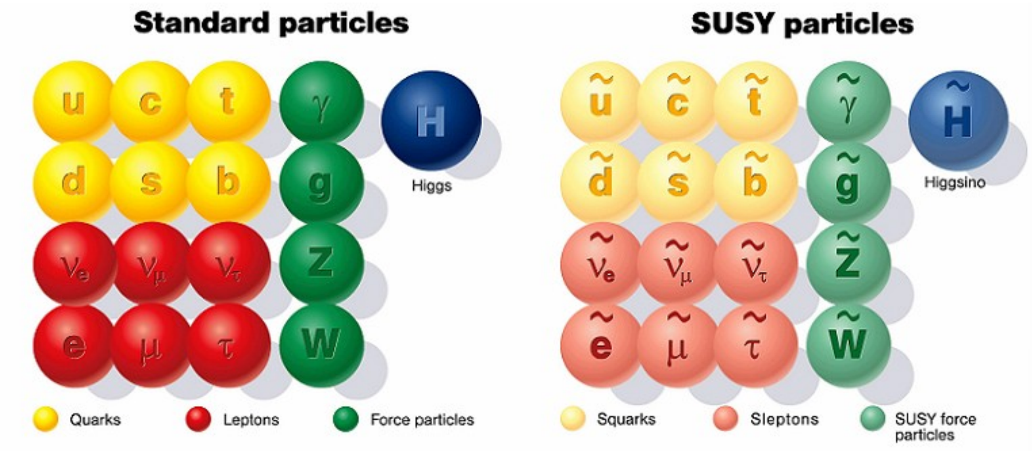


Illustration by CERN & IES de SAR

- Hidden sector and visible sector → what is the messenger?
- R-Parity: LSP possible DM candidate

MSSM

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- Same symmetry group, SU(3)xSU(2)xU(1), as SM
- Need second Higgs doublet with Y=-1 for down type quark masses in Yukawa coupling

$$L_Y = g\overline{\Psi}\Phi\Psi \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \qquad H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$$

$VEV_1=v_1$, $VEV_2=v_2$

- In SM $H_2^\dagger$ gives rise to down type quark masses. But is not allowed in SUSY.
- 8 d.o.f – 3 (W,Z) → 5 physical states
- 2 CP-even neutral Higgs bosons: H,h
- 1 CP-odd neutral Higgs boson: A
- 2 charged Higgs bosons: H^+,H^-

MSSM

- Two free parameters: $\tan\beta = \frac{v_1}{v_2} \qquad m_A$

$$\tan\beta = \frac{v_2}{v_1}, \quad {v_1}^2 + {v_2}^2 = v^2 = 4\frac{m_Z^2}{g^2 + g'^2} \approx 246\text{GeV}$$

- All MSSM Higgs masses can be expressed through $\tan\beta = \frac{v_1}{v_2} \qquad m_A$

$$m^2_{H+-} = m_A^2 + m_W^2 \qquad m^2_{H,\,h} = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}\right)$$

- Other parametrs fixed to benchmark scenarios

- **Tree level:** e.g. upper bound on m_h(light scalar Higgs boson mass)

  $m_h \leq m_Z \cos 2\beta$ After radiative corrections: $m_h \approx 135$ GeV

- e.g. Benchmark scenario m_h^{max} : allow m_h to reach 135 GeV

- More benchamrk scenarios..(e.g. m_H,m_h compatible with SM Higgs mass)

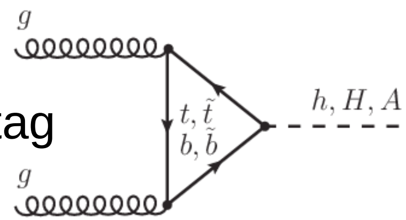
Production and decay

- LHC: Upper mass bound on SM like Higgs (h) with higher order corrections

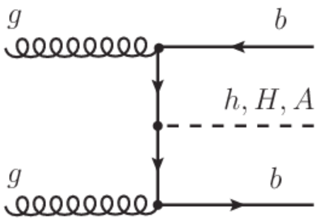
$$m_h^2 \approx M_Z^2 \cos^2(2\beta) + \Delta m_h^2 \quad m_h \approx 125\mathrm{GeV} \rightarrow \Delta \mathrm{m_h} \approx 85\mathrm{GeV} \rightarrow \mathrm{large} \tan\beta$$

- Gluon fusion dominant at small tanβ
- Large tanβ (>>1)→ stronger Yukawa coupling to down type fermions→ b-quark associated production dominant

No b-tag



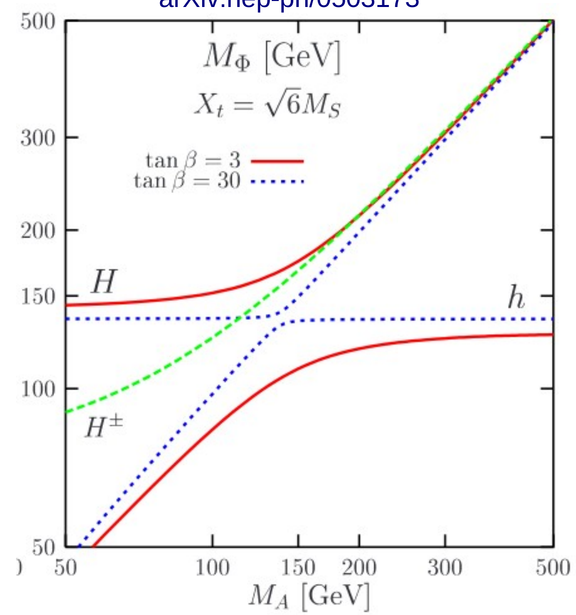
$(gg\Phi)$



$(bb\Phi)$

b-tag

arXiv:hep-ph/0503173

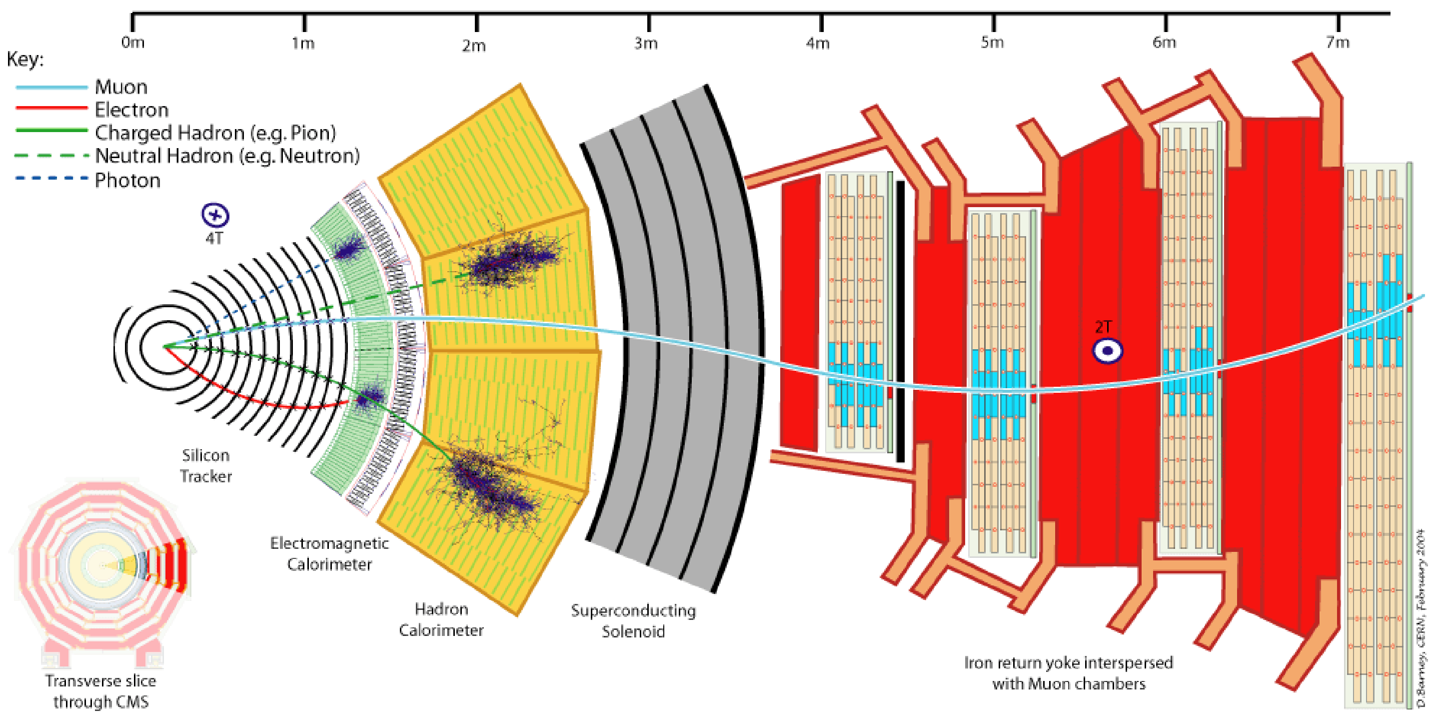


- Interesting decay channels (for large tanβ)

$H \rightarrow \tau\tau$ $\quad$ $H \rightarrow bb$

Experimental setup **C**ompact **MUON** **S**elenoid

- CMS detector can detect e,μ,p,n,γ,K,π → no τ



CMS-doc-4172-v2

- One needs to reconstruct τ events from decay products

τ decays

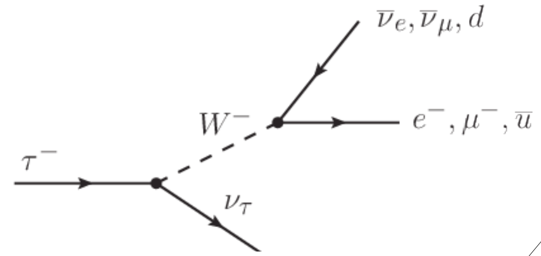
- Decays in lighter leptons and hadrons $m_\tau \approx 1776\ \mathrm{GeV}$

$$\tau \rightarrow e + \nu_e + \nu_\tau$$
$$\tau \rightarrow \mu + \nu_\mu + \nu_\tau$$

$$\left.\begin{array}{l}\tau^- \rightarrow \pi^- + \pi^0 + \nu_\tau \\ \tau^- \rightarrow \pi^- + \nu_\tau\end{array}\right\} \quad \tau \rightarrow \tau_h$$

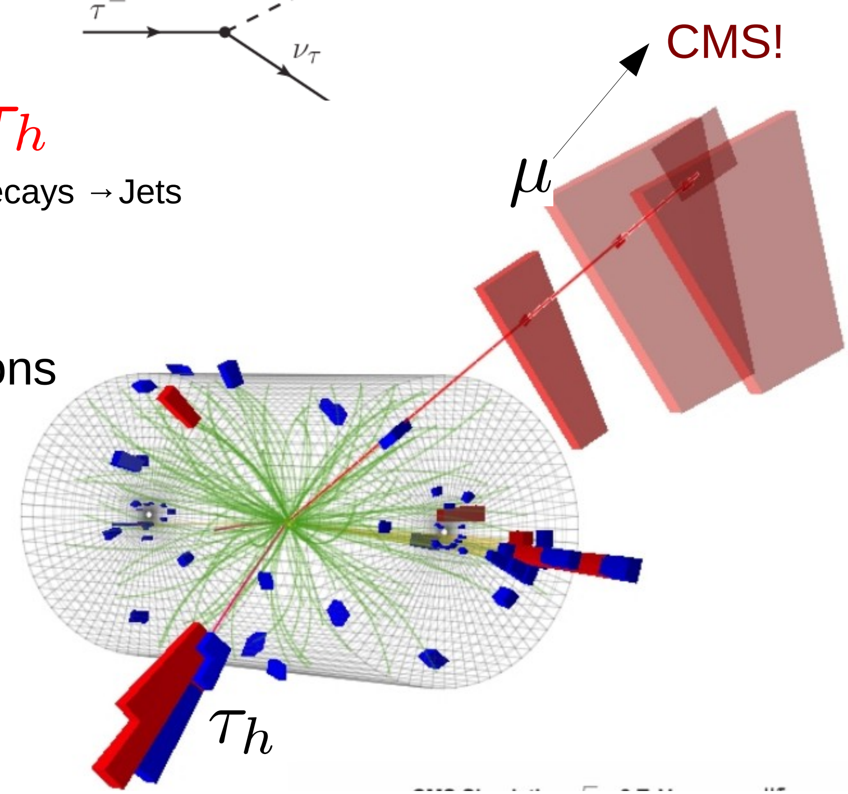
...

Hadronic decays → Jets



- Important decay modes for two τ -leptons

$\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$,
$e\mu$, $\mu\mu$, ee



DESY-Seminar 2014 Roger Wolf

Searches for $A/H/h \to \tau\tau$

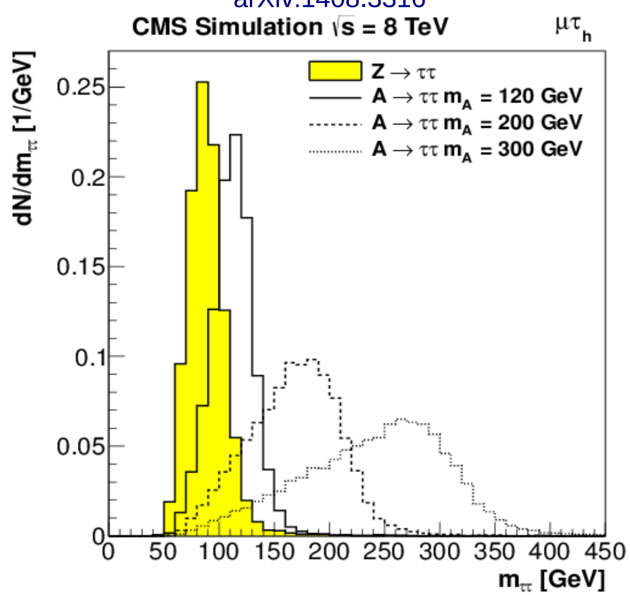
- Expect two isolated high p_T leptons $\underbrace{(e, \mu, \tau_h)}_{\text{Trigger objects}}$

  τ From Higgs decays should be isolated (not inside jets)

- Reduce backgrounds

- Reconstruct $m_{\tau\tau}$
  - ML technique
  - Distinguish Higgs signal from bkg

arXiv:1408.3316



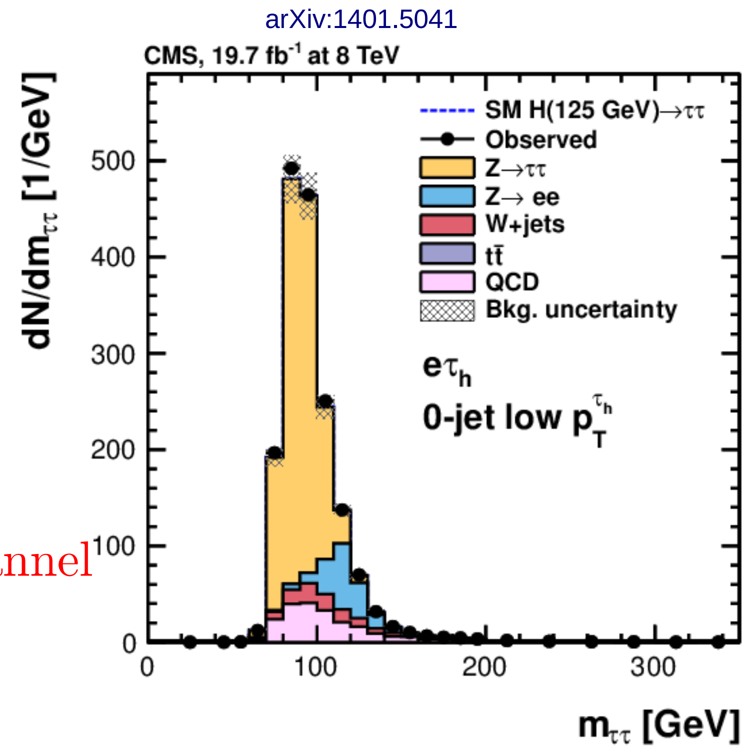
- Enhance sensitivity to MSSM Higgs bosons with b-tag associated Higgs productio $(\text{large} \tan\beta)$

Background

- Largest source of bkg $Z \to \tau\tau$

  ⟶ Embedding method

Take $Z \to \mu\mu$ from data
Replace reconstructed μ by simulated τ decays
(lepton universality)



- QCD multijet events:
  - 2J misidentified as τ_h decays → $\tau_h\tau_h$ channel
  - 1J misidentified as τ_h decay → $e\tau_h$ and $\mu\tau_h$ channel

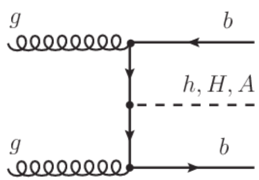
- W+Jets: contributes to $e\tau_h$ and $\mu\tau_h$ channel

- Drell-Yan production of μ pairs

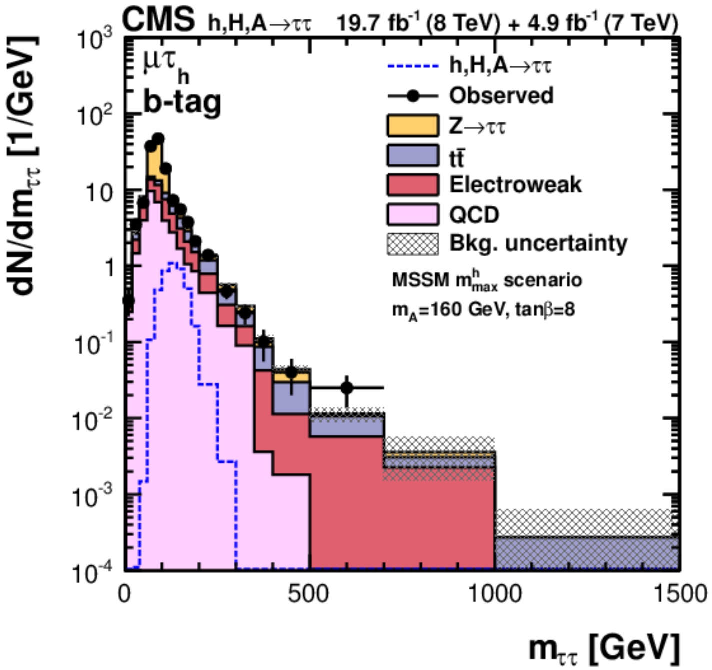
$\mu\tau_h$ channel				
	$\sqrt{s} = 7$ TeV		$\sqrt{s} = 8$ TeV	
Process	no b-tag	b-tag	no b-tag	b-tag
$Z \rightarrow \tau\tau$	26838 ± 244	284 ± 8	87399 ± 497	1118 ± 31
QCD	5495 ± 258	131 ± 18	18056 ± 811	552 ± 62
W+jets	2779 ± 201	55 ± 14	12845 ± 793	237 ± 52
Z+jets (e, μ or jet faking τ)	716 ± 109	11 ± 2	3704 ± 454	54 ± 9
$t\bar{t}$	82 ± 6	36 ± 5	564 ± 41	194 ± 22
Di-bosons + single top	94 ± 11	12 ± 2	506 ± 51	60 ± 7
Total background	36004 ± 205	530 ± 18	123075 ± 407	2214 ± 44
A+H+h $\rightarrow \tau\tau$	226 ± 23	17 ± 2	929 ± 85	67 ± 9
Observed data	36055	542	123239	2219
Efficiency $\times$ acceptance				
gluon fusion Higgs	$2.34 \cdot 10^{-2}$	$2.49 \cdot 10^{-4}$	$1.78 \cdot 10^{-2}$	$2.32 \cdot 10^{-4}$
b-quark associated Higgs	$1.96 \cdot 10^{-2}$	$3.54 \cdot 10^{-3}$	$1.53 \cdot 10^{-2}$	$2.66 \cdot 10^{-3}$

arXiv:1408.3316

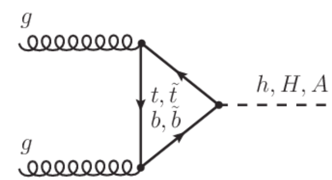
Signal extraction



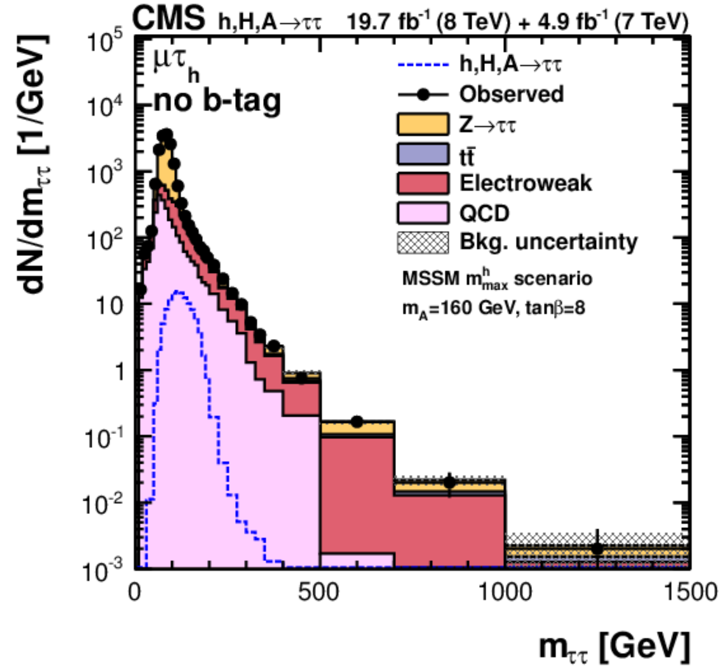
arXiv:1408.3316



b-tag



arXiv:1408.3316



No b-tag

Model independent searches

- Search for a narrow ϕ resonance
- Test statistic q based on profile likelihood ratio

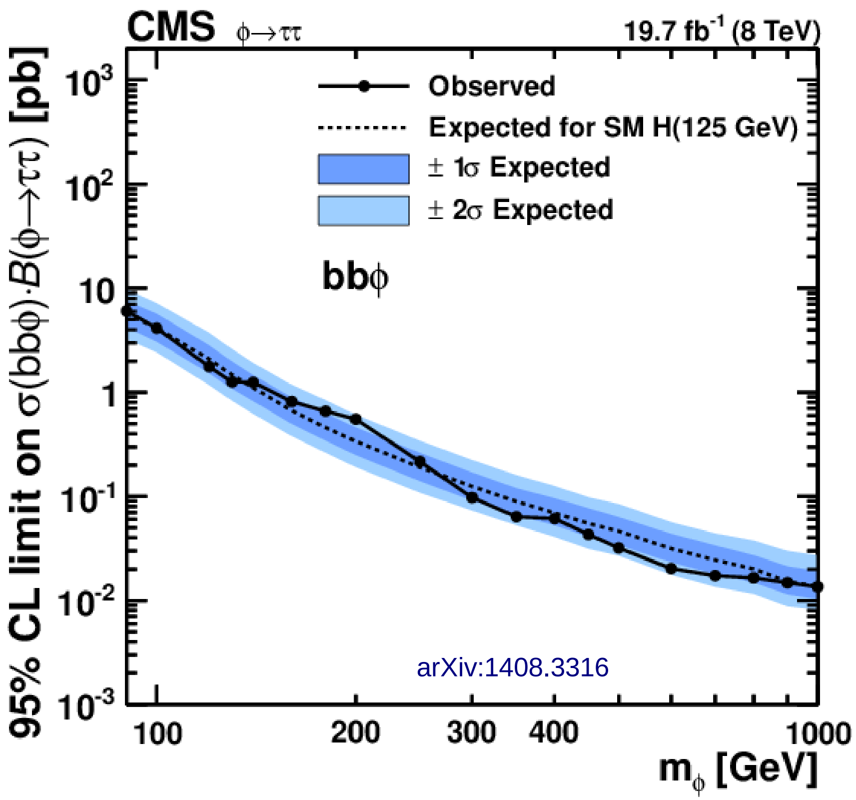
Signal or bkg like data?

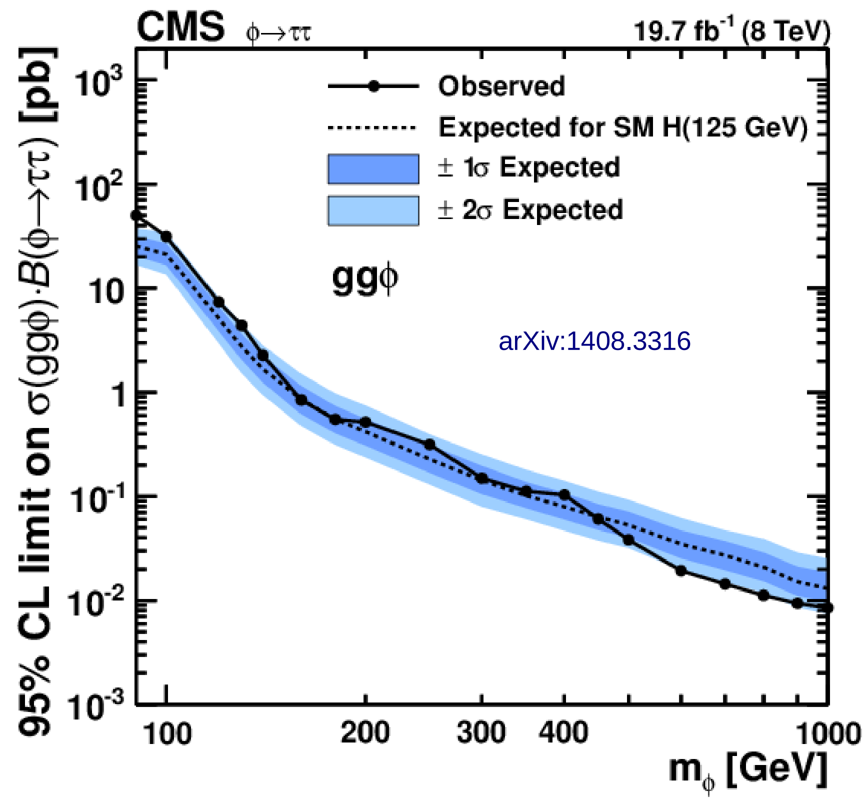
$$q_\mu = -2\ln\frac{L(N_{obs}|\mu\cdot s+b,\hat{\theta}_\mu)}{L(N_{obs}|\hat{\mu}\cdot s+b,\hat{\theta})} \quad , \quad 0\leq\hat{\mu}\leq\mu$$

- $\hat{\theta}_\mu$ maximizes likelihood in the numerator for given μ
- $\hat{\theta}$ and $\hat{\mu}$ define the point where the likelihood reaches its global maximum

→ Upper limits on $\sigma\cdot B(\phi\to\tau\tau)$ for $\sigma(gg\phi)$ and $\sigma(\mathrm{bb}\phi)$

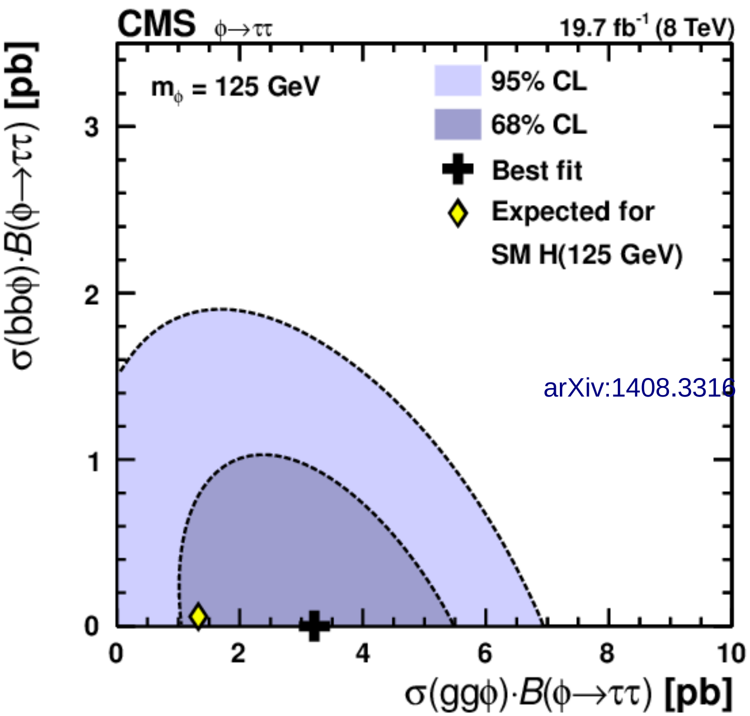
Model independent searches 1D





- Treat other production channel as nuissance parameter

Model independent searches 2D



- Likelihood contour plots for SM Higgs mass
- Result compatible with SM Higgs

MSSM model dependent searches

- Modified CL approach (MSSM vs bkg only is not valid anymore)
- Test compatibility of the data to h, H, A signal compared to SM Higgs signal

$$M(\mu) = [\mu \cdot s(\mathrm{MSSM}) + (1-\mu) \cdot \mathrm{s(SM)}] + \mathrm{b}$$

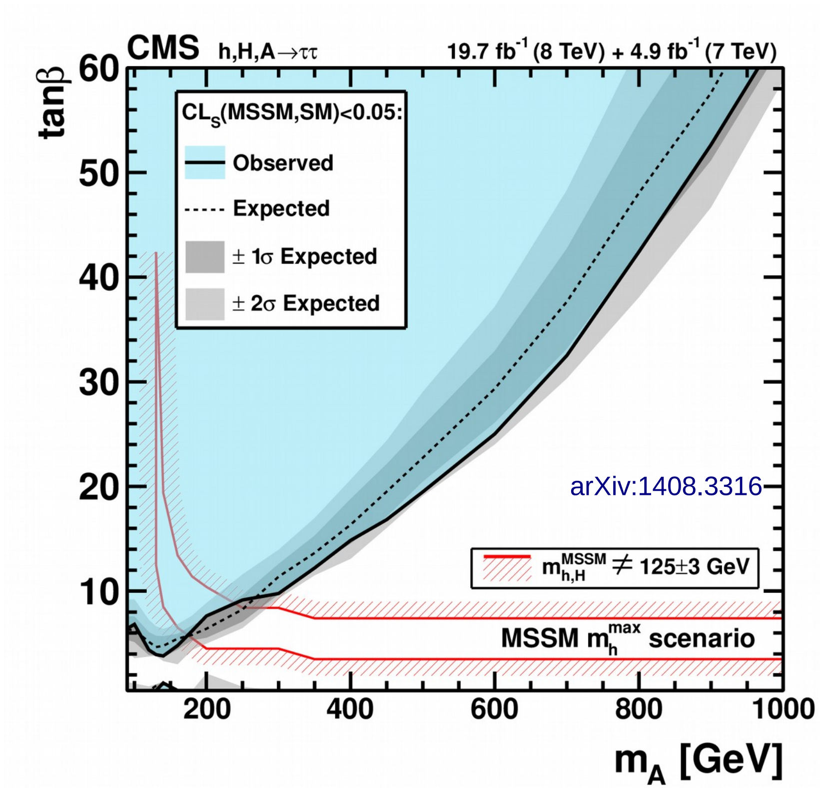
Physical model

$$q_{MSSM/SM} = -2 \ln \frac{L(N_{obs}|M(1), \hat{\theta}_\mu)}{L(N_{obs}|M(0), \hat{\theta}_0)}$$

Maximized by finding the Corresponding nuissance parameters for M(1) and M(0)

- Expectation for every benchmark scenario is determined at each point of the parameter space tanβ, m_A

MSSM model dependent searches



Uncertainties

- **Experimental uncertainties**
  - Integrated Luminosity ~2%
  - Jet energy scale 1-10%
  - Identification and trigger efficiencies ~2%
  - τ Uncertainty ~8%
  - B-tagging 2-7%
  - Mistag for light flavor partons 10-20%

- **Theoretical uncertainties**
  - σ depends on tanβ, m_A and benchmark scenario
  - up to 20%

Summary

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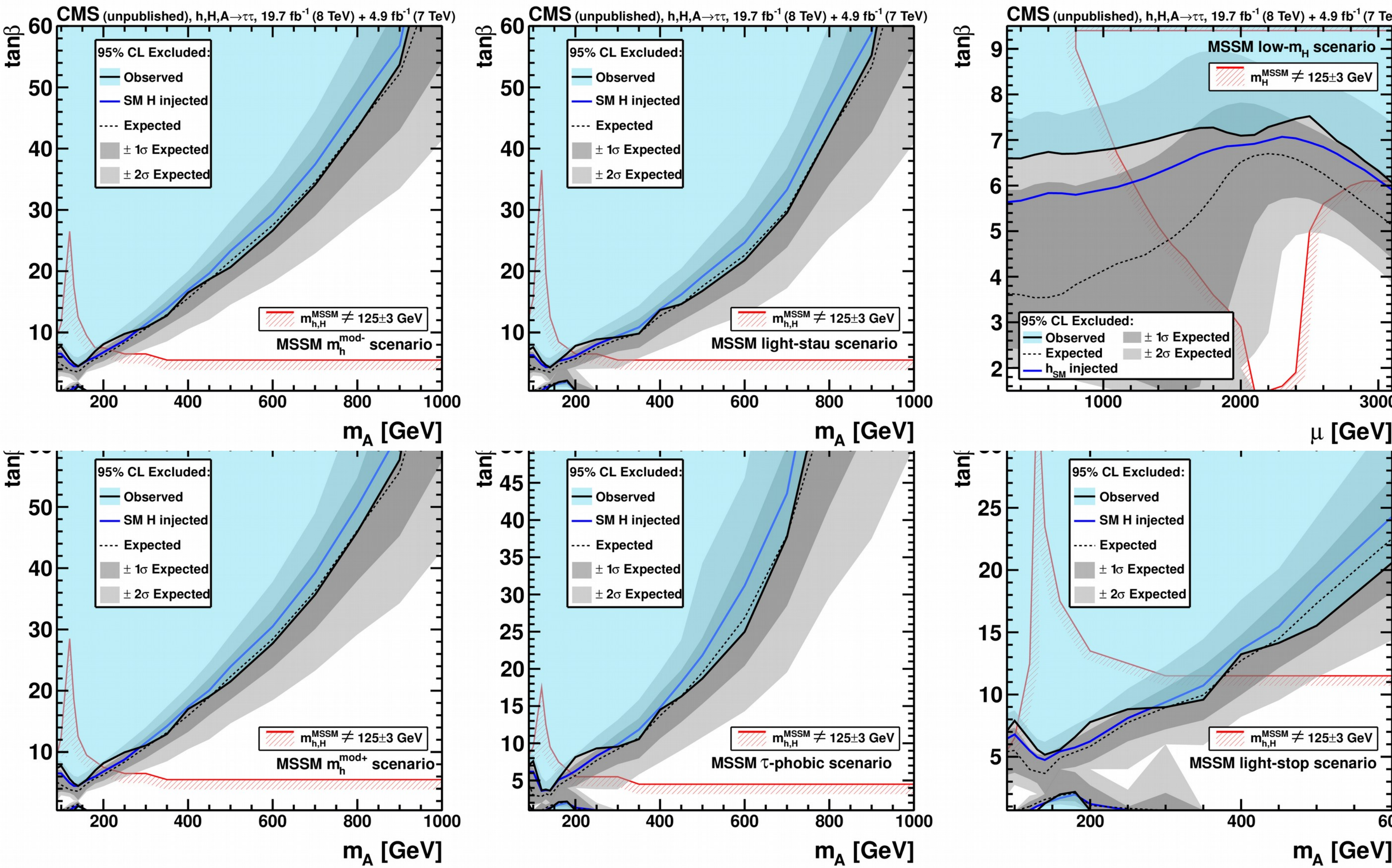
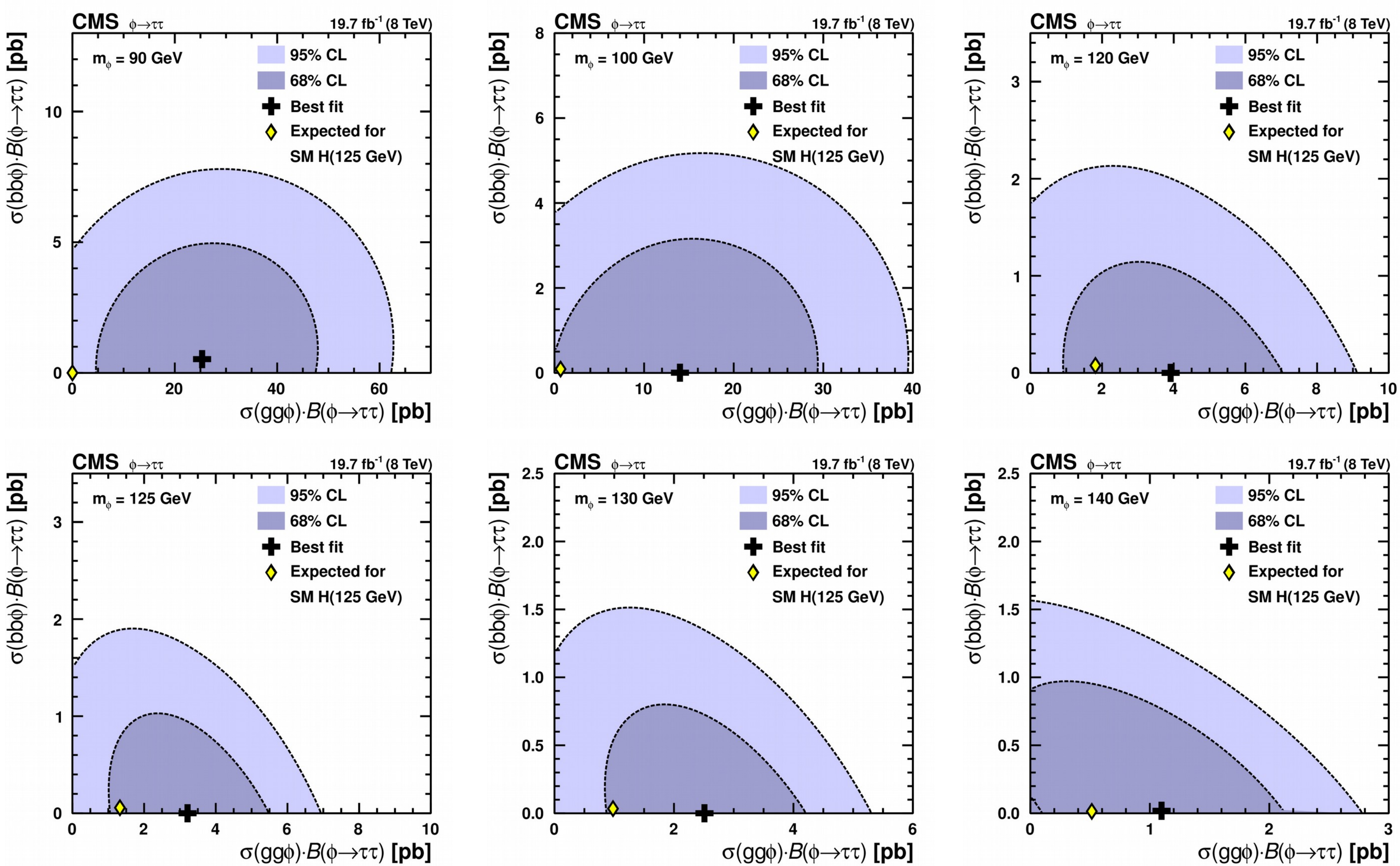
- No BSM physics in run 1
- Run 2?
- No evidenz in run 2 → What will happen to SUSY?

Backup


CMS (unpublished), h,H,A→ττ, 19.7 fb-1 (8 TeV) + 4.9 fb-1 (7 TeV)
95% CL Excluded:
Observed
SM H injected
Expected
± 1σ Expected
± 2σ Expected
m_{h,H}^{MSSM} ≠ 125±3 GeV
MSSM m_h^{mod-} scenario
MSSM light-stau scenario
MSSM low-m_H scenario
m_H^{MSSM} ≠ 125±3 GeV
h_SM injected
MSSM m_h^{mod+} scenario
MSSM τ-phobic scenario
MSSM light-stop scenario
tanβ
m_A [GeV]
μ [GeV]


CMS φ→ττ
19.7 fb-1 (8 TeV)
mφ = 90 GeV
95% CL
68% CL
Best fit
Expected for
SM H(125 GeV)
σ(bbφ)·B(φ→ττ) [pb]
σ(ggφ)·B(φ→ττ) [pb]
CMS φ→ττ
19.7 fb-1 (8 TeV)
mφ = 100 GeV
95% CL
68% CL
Best fit
Expected for
SM H(125 GeV)
σ(bbφ)·B(φ→ττ) [pb]
σ(ggφ)·B(φ→ττ) [pb]
CMS φ→ττ
19.7 fb-1 (8 TeV)
mφ = 120 GeV
95% CL
68% CL
Best fit
Expected for
SM H(125 GeV)
σ(bbφ)·B(φ→ττ) [pb]
σ(ggφ)·B(φ→ττ) [pb]
CMS φ→ττ
19.7 fb-1 (8 TeV)
mφ = 125 GeV
95% CL
68% CL
Best fit
Expected for
SM H(125 GeV)
σ(bbφ)·B(φ→ττ) [pb]
σ(ggφ)·B(φ→ττ) [pb]
CMS φ→ττ
19.7 fb-1 (8 TeV)
mφ = 130 GeV
95% CL
68% CL
Best fit
Expected for
SM H(125 GeV)
σ(bbφ)·B(φ→ττ) [pb]
σ(ggφ)·B(φ→ττ) [pb]
CMS φ→ττ
19.7 fb-1 (8 TeV)
mφ = 140 GeV
95% CL
68% CL
Best fit
Expected for
SM H(125 GeV)
σ(bbφ)·B(φ→ττ) [pb]
σ(ggφ)·B(φ→ττ) [pb]