Higgs searches beyond the Standard Model at the Large Hadron Collider

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OUTLINE

- Run I at the LHC: the birth of the Higgs physics
- Precision Higgs physics as a way to probe BSM
- BSM Higgs decays
- Searches for additional Higgs bosons
- Perspectives for Run2 & beyond

Disclaimer: my personal selection of the most significant results from Run 1

THE 2 MAIN OUTCOMES OF THE LHC, SO FAR

Discovery of the Higgs boson

$$M_H = (125.09 \pm 0.21 \pm 0.11)\ \mathrm{GeV}$$

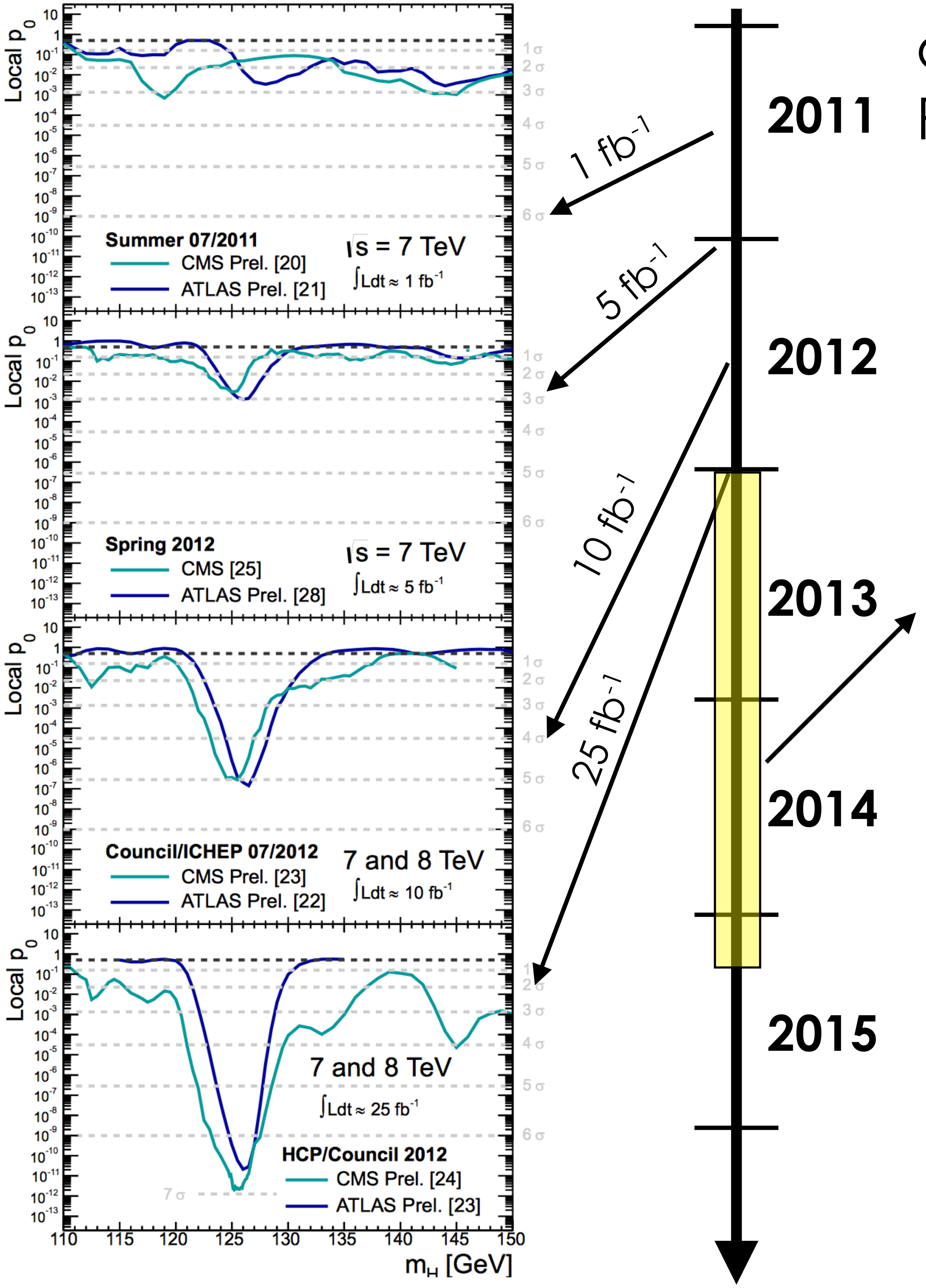
8th October 2013

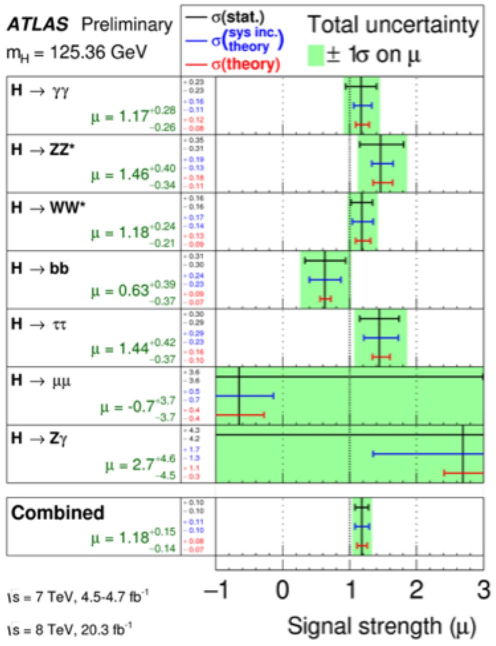
THE BEH-MECHANISM,
INTERACTIONS WITH SHORT RANGE FORCES
AND
SCALAR PARTICLES

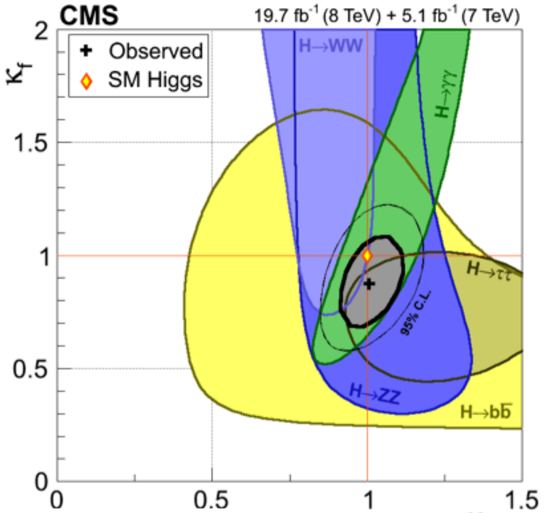
No direct sign of new physics… yet

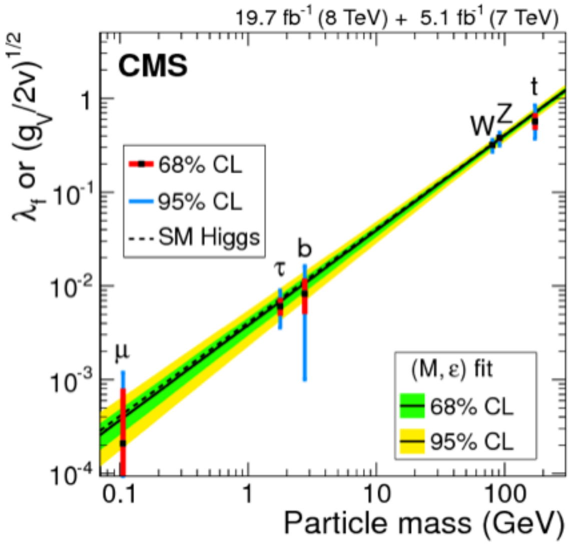
RUN I: THE BIRTH OF THE HIGGS PHYSICS

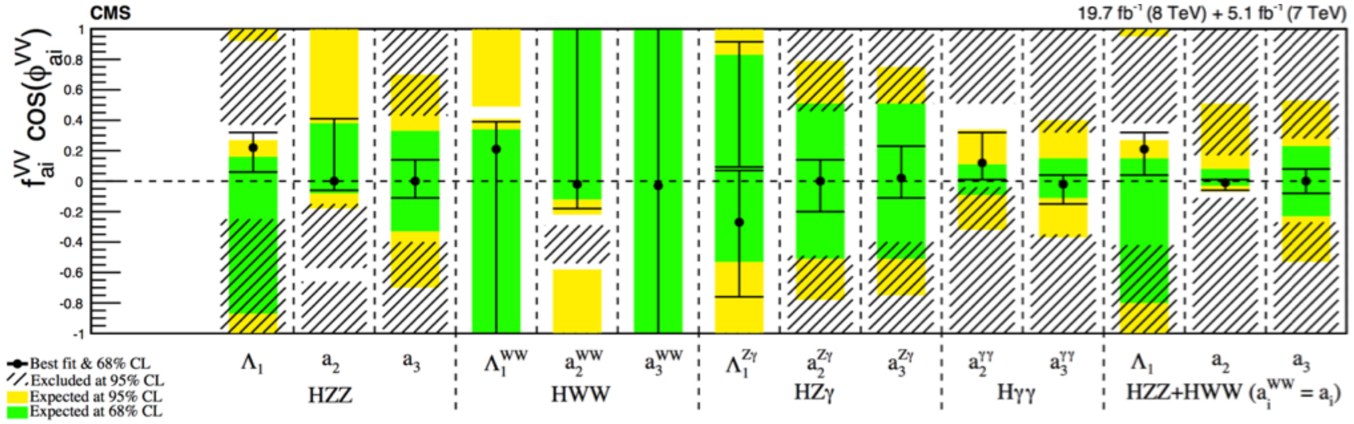
From a text-book discovery to the start of the precision Higgs physics with full Run I statistics:



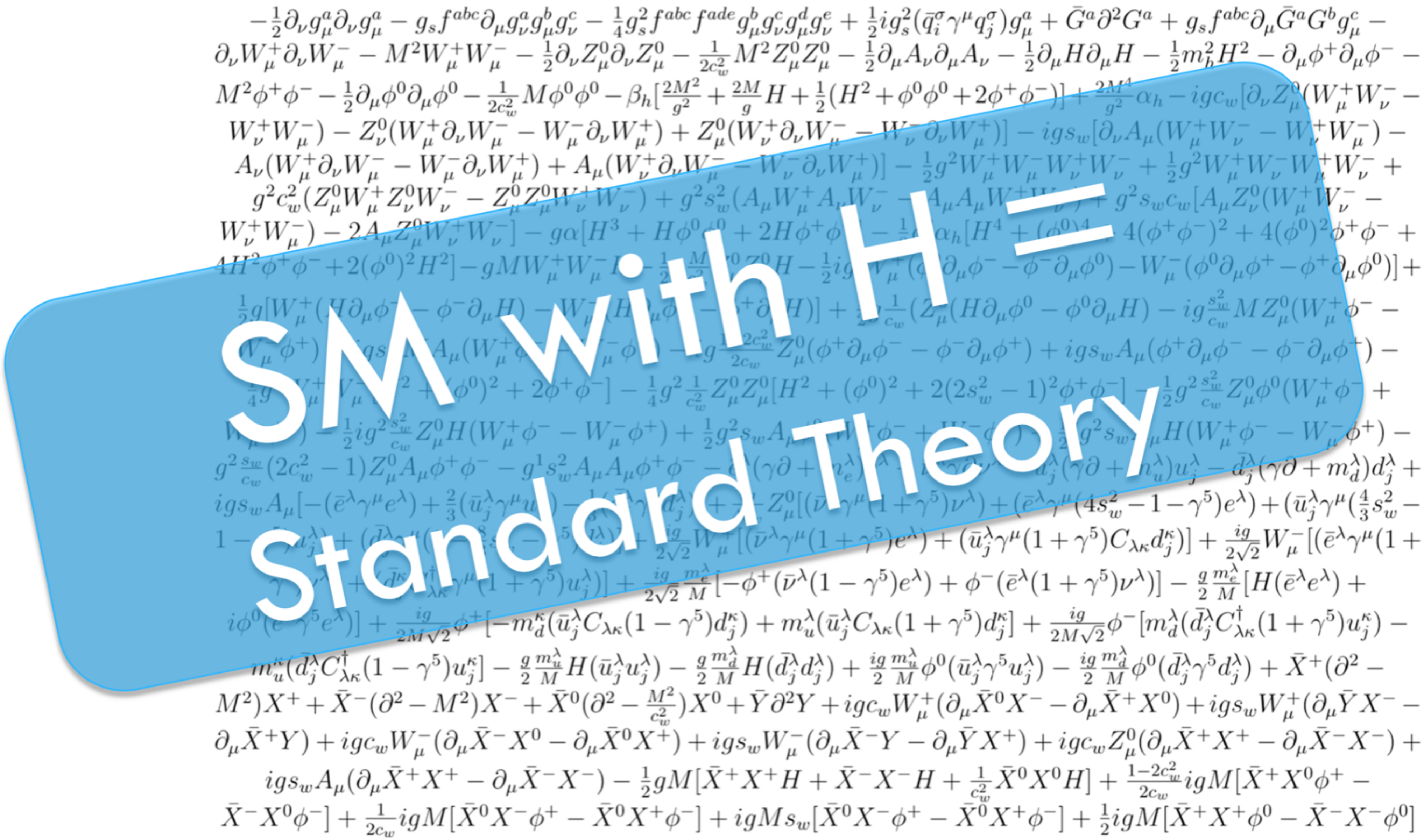








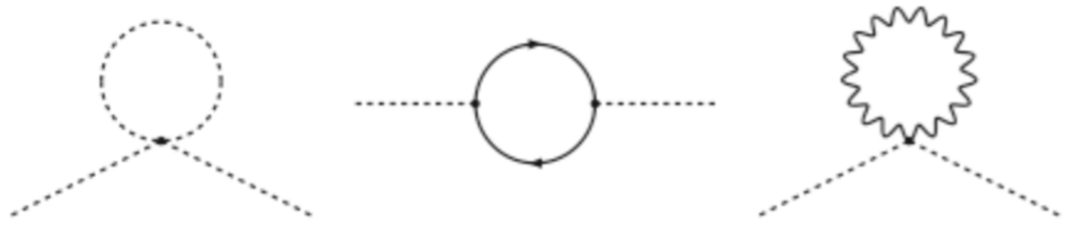
THE "STANDARD THEORY"



Self consistent up to large scales [JHEP 1208 (2012) 098]

EWSB: THE NATURALNESS PUZZLE

Higgs potential is renormalizable, however loop corrections to the Higgs boson mass quadratically divergent



$$\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi^2}$$

Not an issue if cut-off Λ not far from TeV, instead if SM→Planck scale fine-tuning

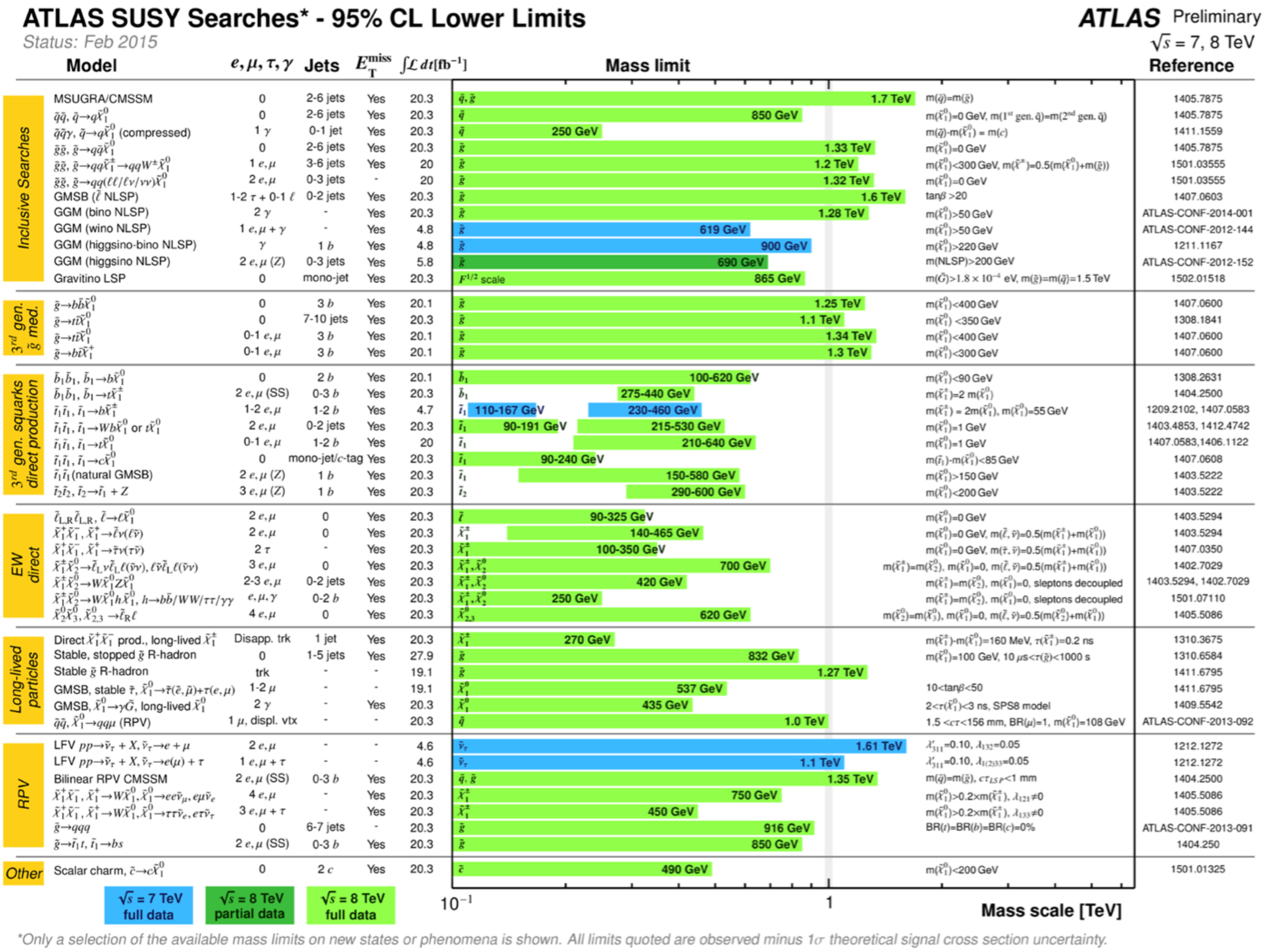
Elegant Solutions (some including dark matter candidates):

- **Additional symmetries**: supersymmetry
- **Composite Higgs**, Higgs as a "π^0" of a new strong interaction
- **Extra-dimensions**, "move the Planck scale"
- **New ideas**: arXiv:1504.07551

Or:

- **Deal with it**, anthropic principle/multiverse

SUPERSYMMETRY SEARCHES

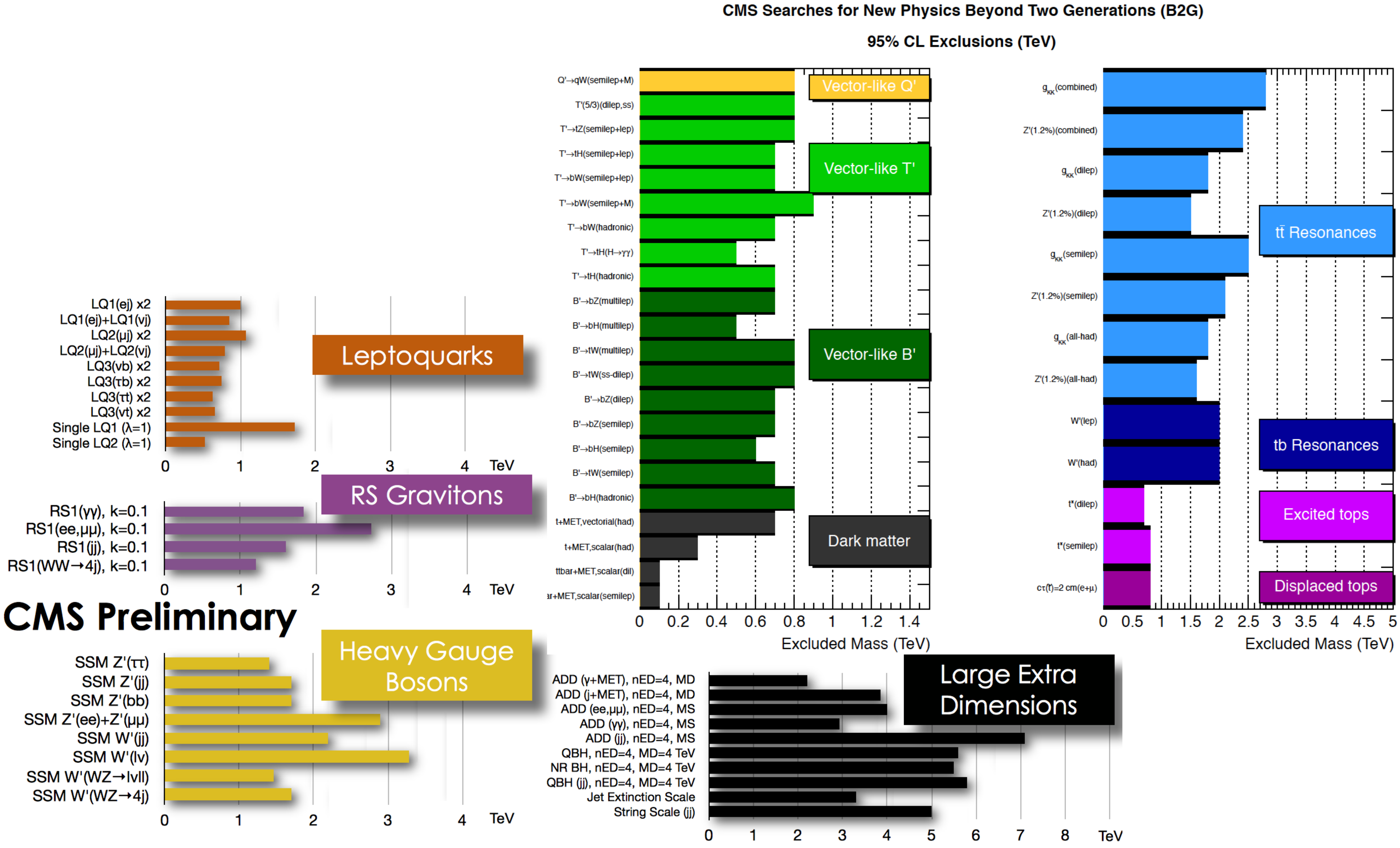


*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

EXOTICS SEARCHES



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https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

BSM HIGGS PHYSICS

Complementary directions to look for BSM physics in Higgs sector

Precision
mass
scalar couplings
spin/CP
differential cross sections
off shell couplings/width

Rare/new H decays
$Z\gamma, \gamma\gamma^*$
$\mu\mu$
$J/\Psi\gamma$
lepton flavour violation

H

Extended Higgs sector
2HDM
MSSM,NMSSM
double charged Higgs

H as a tool for discovery
portal to DM: invisible Higgs decays
portal to hidden sectors
portal to BSM physics: decays to HH, WH, ZH, tH, …
FCNC: t→cH

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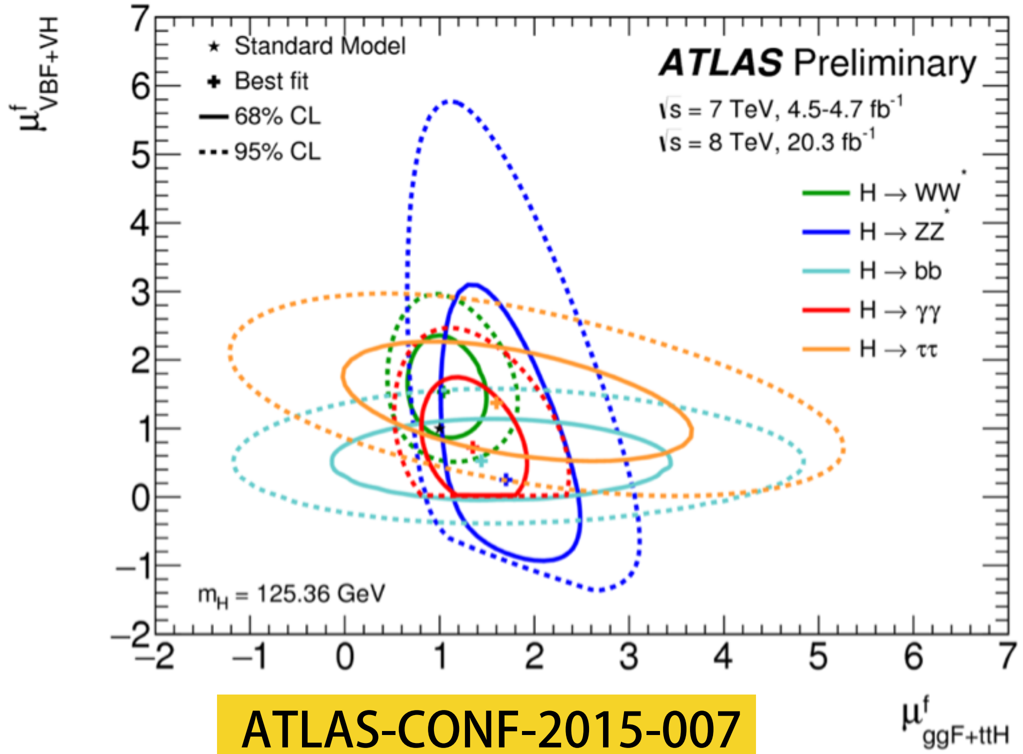
THE HIGGS PICTURE FROM RUN I

$$\mu \equiv \sigma \cdot \mathrm{Br} / (\sigma \cdot \mathrm{Br})_{\mathrm{SM}}$$



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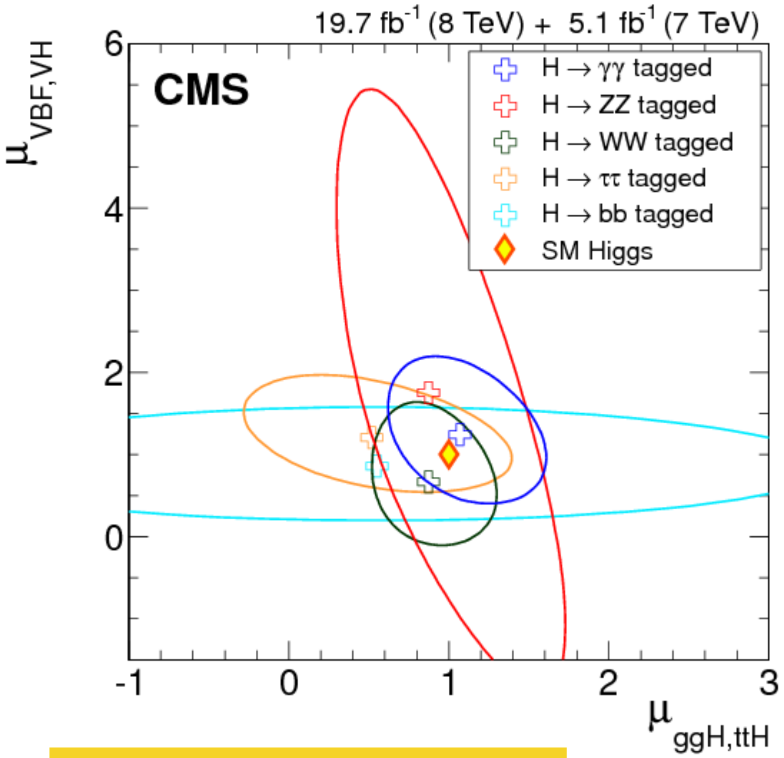
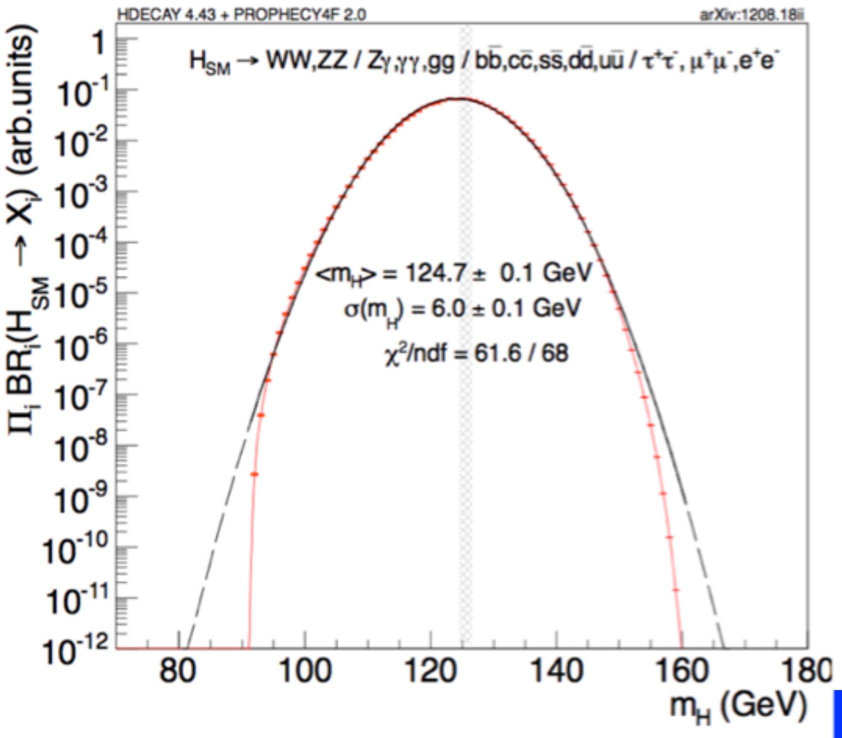


CMS arXiv:1412.8662



Nature was very kind with us

product of BR ~ max @ 125 GeV

PRECISION: COUPLINGS DEVIATIONS

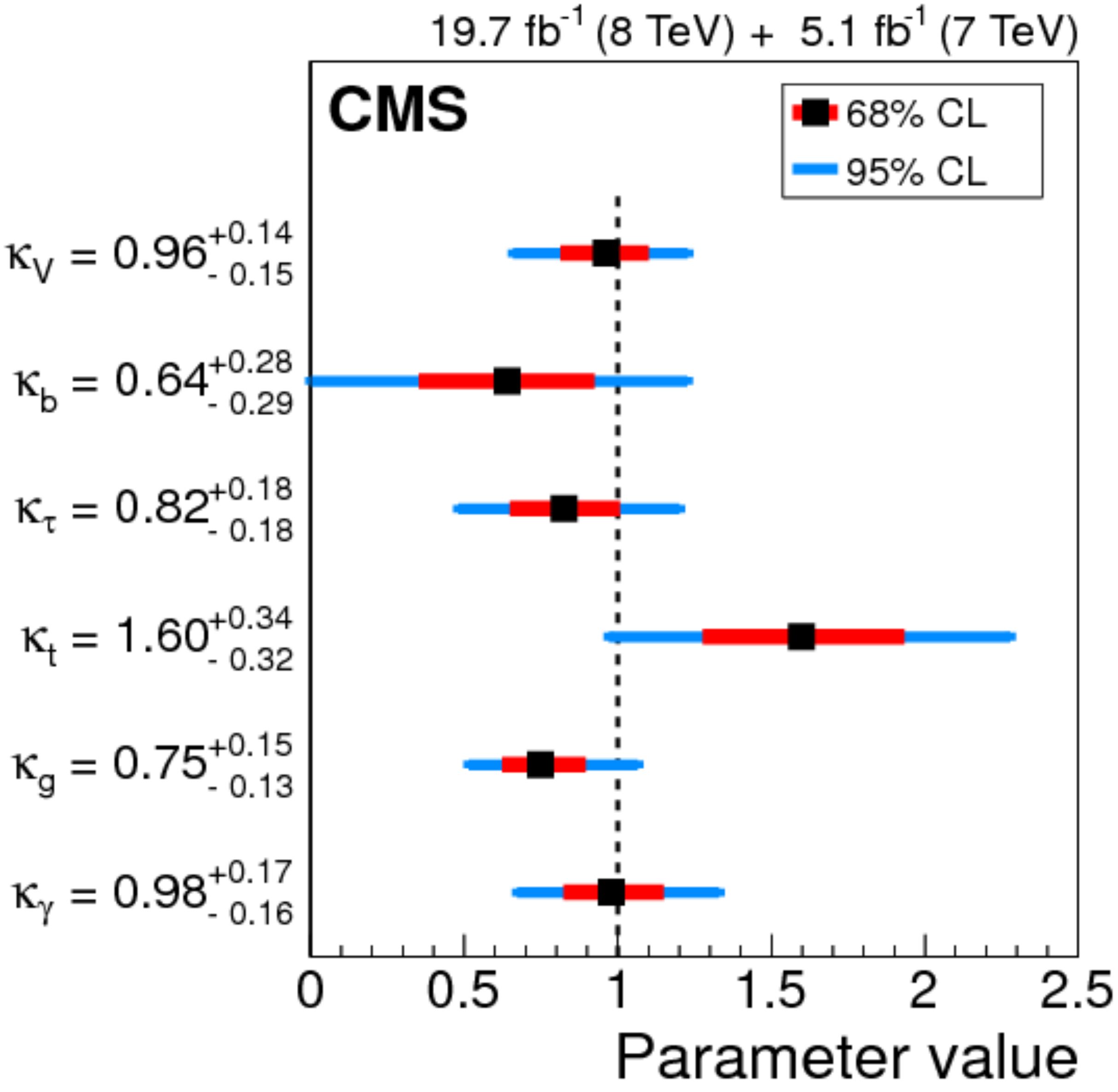
Looking for Higgs couplings deviations: use an "effective approach"

- parametrize deviation from SM with coupling modifiers, "kappa", $k_x^{SM}=1$
  - tensor structure kept as SM
  - ok for Run1 precision

e.g. signal strength in $H\rightarrow\gamma\gamma$:

	$H \rightarrow \gamma\gamma$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$
$t\bar{t}H$	$\frac{\kappa_t^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$
VBF	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_W) \cdot \kappa_\gamma^2}{\kappa_H^2}$
WH	$\frac{\kappa_W^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$
ZH	$\frac{\kappa_Z^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$

LHC Run I probe Higgs couplings @ 15-30% level



Still large room for BSM

"CLASSIC" HIGGS BSM SCENARIOS

Extended Higgs sector: E.g. 2HDM/MSSM, EWSB via 2 Higgs doublets.

Direct searches: look for additional scalars (neutral or charged), if SUSY direct searches for SUSY partners

Indirect searches: b-physics ($B \rightarrow \tau\nu$, $B \rightarrow D^{(*)}\tau\nu$, $b \rightarrow s\gamma$, $B_s \rightarrow \mu\mu$), H(125) couplings

Composite Higgs: Higgs as pseudo Goldstone boson of a new strong interaction

Direct searches: new vector resonances, new "light" fermion partner states

Indirect searches: stringent constraints from EWPT, H(125) couplings (controlled by $\xi = (v/f)^2$ compositeness parameter)

INTERPRETATION EXAMPLE: 2HDM

Effective theory with 2 complex scalar doublets

- **5 physical scalar fields after EWSB**
  - ➡neutral: h,H CP even, A CP odd
  - ➡charged: $H^{\pm}$

Couplings described by 2 mixing angles

- tanβ=v_1/v_2, α mixing angle h/H

$$g_{hVV}^2 + g_{HVV}^2 + g_{AVV}^2 = \left(g_{hVV}^{\mathrm{SM}}\right)^2$$

Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

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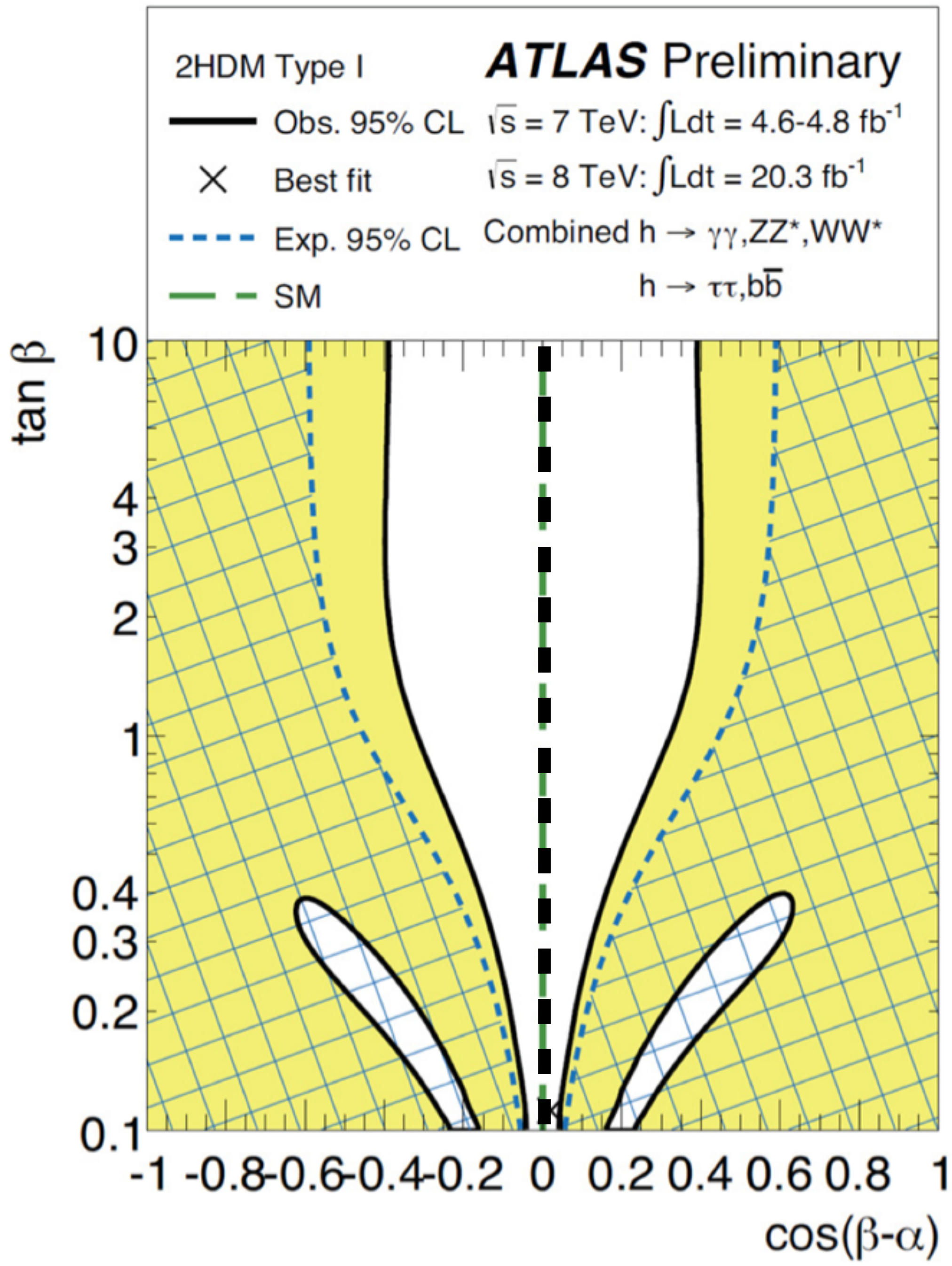


Decoupling region: Higgs very close to SM or $m_{A,H} >> m_h$ not probed given current precision

INTERPRETATION EXAMPLE: MSSM

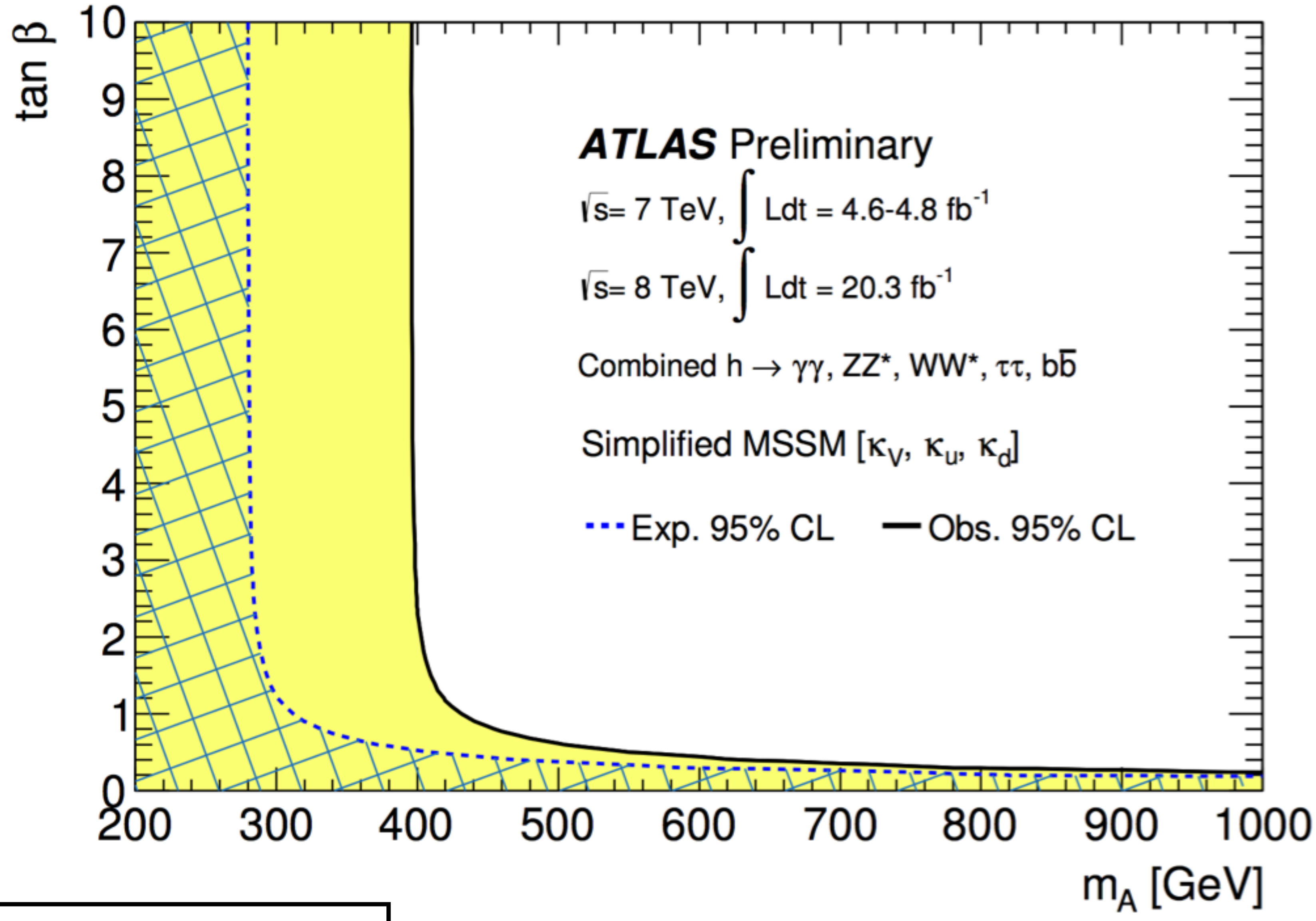
MSSM: a particular 2HDM Type II model

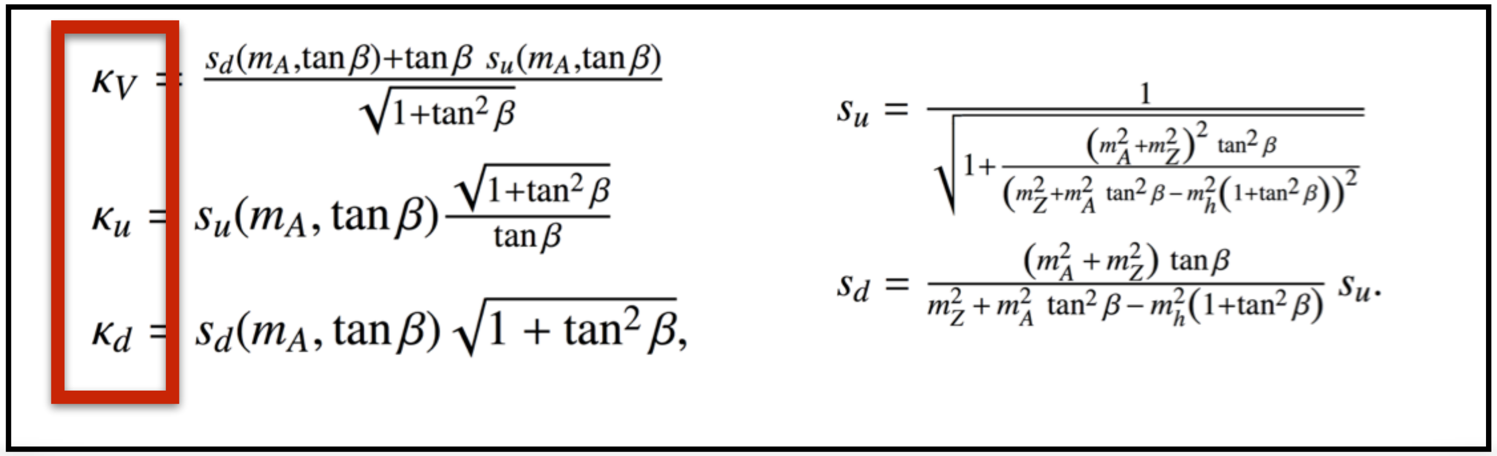
Simplified MSSM: m_h used to parametrise radiative corrections

Djouadi et al. arXiv:1305.2172

At low tanβ implies a very large M_S SUSY scale

ATLAS-CONF-2014-010





$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\ s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta},$$

$$s_u = \frac{1}{\sqrt{1+\frac{(m_A^2+m_Z^2)^2\tan^2\beta}{\left(m_Z^2+m_A^2\tan^2\beta-m_h^2(1+\tan^2\beta)\right)^2}}}$$

$$s_d = \frac{(m_A^2+m_Z^2)\tan\beta}{m_Z^2+m_A^2\tan^2\beta-m_h^2(1+\tan^2\beta)}\,s_u.$$

m_A >~ 400 GeV

INTERPRETATION EXAMPLE: COMPOSITE HIGGS

MCHM: SO(5)/SO(4) symmetry breaking

Coupling k$_V$ "universally" modified, proportional to $\xi = v^2/f^2$

Coupling k$_F$ depends on the actual model implementation

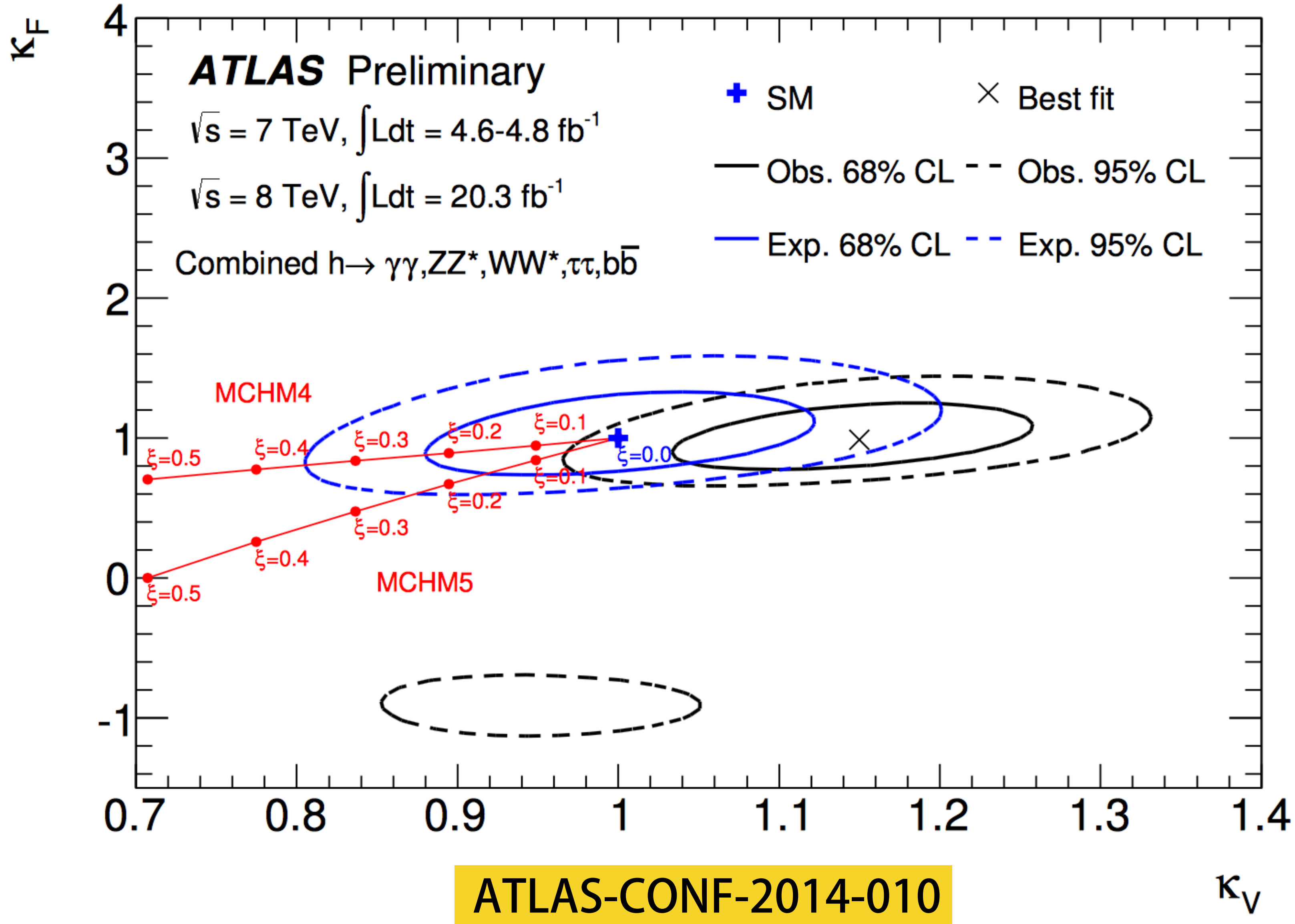
arXiv:hep-ph/0412089

MCHM4

$$\boxed{\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi},}$$

MCHM5

$$\boxed{\begin{aligned}\kappa_V &= \sqrt{1-\xi}\\ \kappa_F &= \frac{1-2\xi}{\sqrt{1-\xi}}.\end{aligned}}$$



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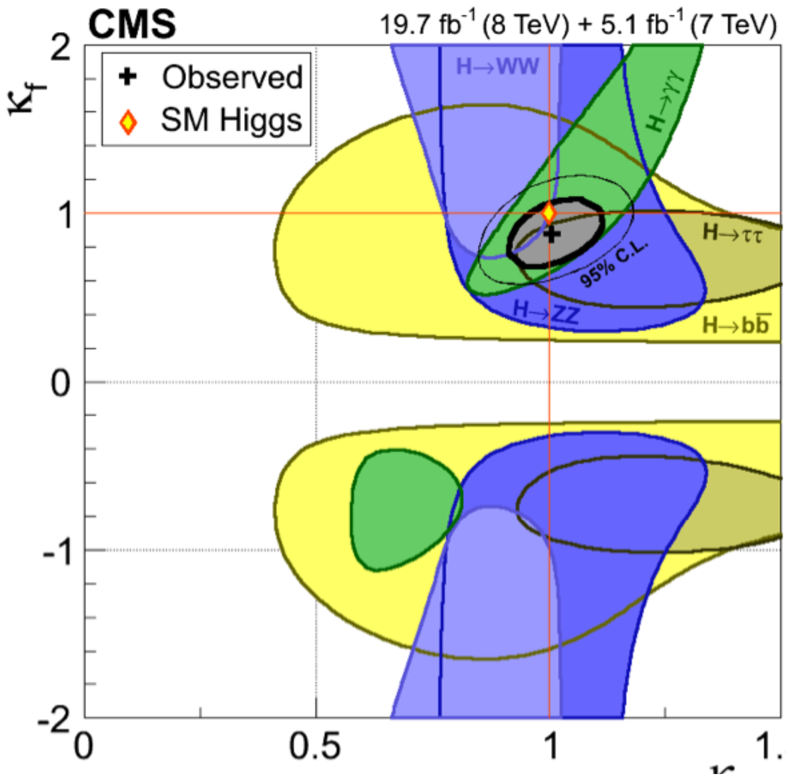
f >~ 1 TeV

PROBING k_V/k_F RELATIVE PHASE

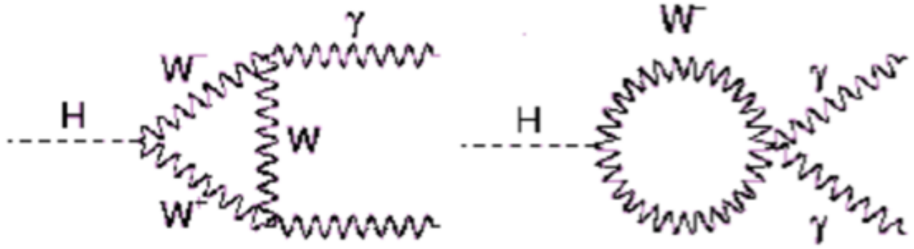
Reversed phase for fermion coupling

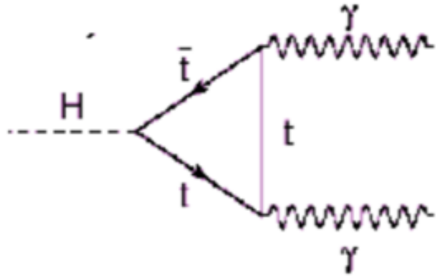
K_f=-1 disfavoured by k_V/k_F couplings fit



Most channels constraints independent from relative phase

Degeneracy broken by H→γγ: BR enhanced if phase is reversed

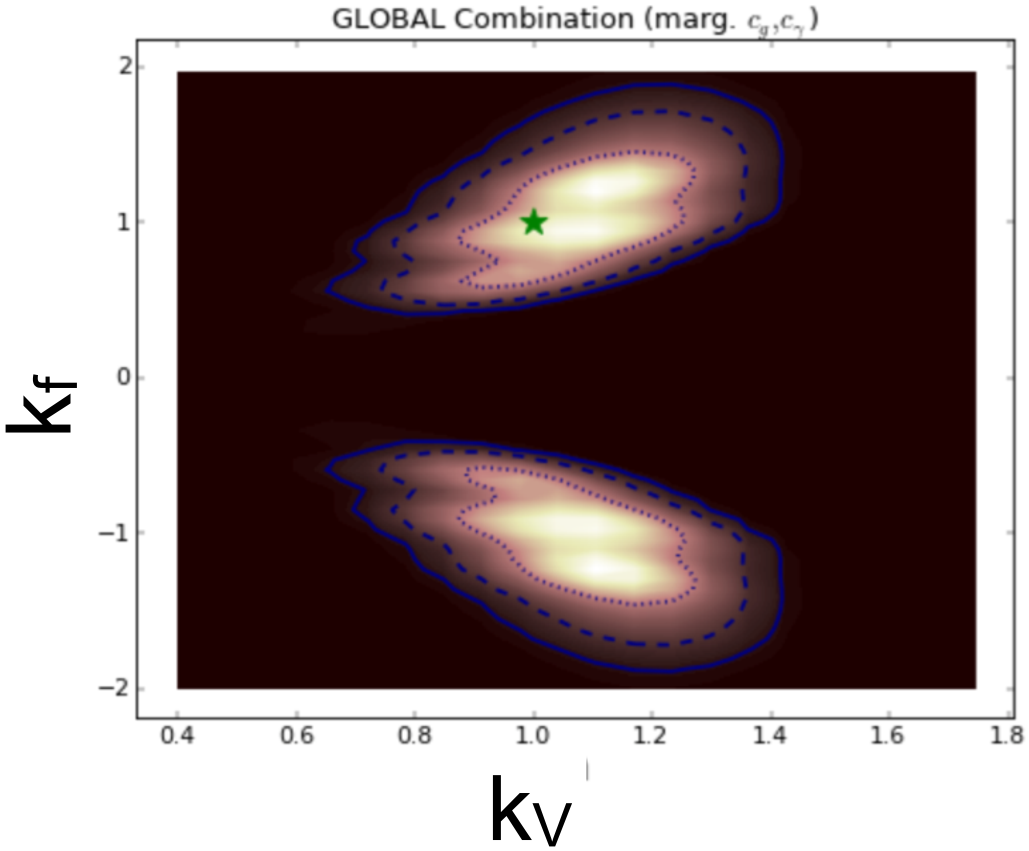




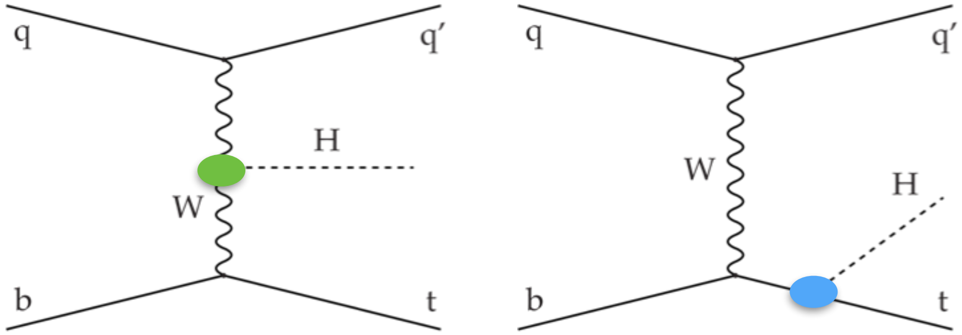
$\sim \kappa_\gamma^2 = |1.28\,\kappa_W - 0.28\,\kappa_t|^2$

However, when assuming BSM contributions in k_g & $k_{\gamma\gamma}$, still degeneracy in k_V/k_f plane

[J.Ellis, T.You, JHEP 06 (2013) 103]



A BETTER INTERFEROMETER: T+H



t+H: SM tree level cancellation

σ(t+H)=**18 fb** @ 8 TeV(σ ~ 1/10 of ttH)

x15 σ if Y_t relative sign reversed wrt SM

t+H: first proposed by Biwas, Mele, Gabrielli as a probe for Htt sign [JHEP 01 (2013) 088]

Strong involvement of CMS Rome group

Analysis testing k_t=-1 hypothesis, assuming rest of SM still valid

- not realistic, but allows easy interpretation
- test also other BSM models where t+H enhanced

Combination to be published soon: sensitivity to exclude ~ x 2 σ(k_t=-1)

Potential to exclude k_t=-1 with <20 fb^{-1} @ 13 TeV

95% CL exclusion limits on σ/σ(k_t=-1)

CMS HIG-14-001 **t+H(→γγ)**	**Obs 4.1(Exp 4.1)**
CMS HIG-14-015 **t+H(→bb)**	**Obs 7.6(Exp 5.2)**
CMS **HIG-14-026** **t+H(WW,ττ)**	**Obs 6.7 (Exp 5.0)**

H→γγ final state most sensitive thanks to BR enhancement

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HIGGS BSM DECAYS

$$\Gamma_H = \Sigma_i \kappa_i^2 \Gamma_i^{SM}$$

Undetected/invisible Higgs decays indirect constraint at ~<30% at 95% CL.

$$\Gamma_H^{SM} = 4.2\ \mathrm{MeV}$$

total width very small. Even small couplings implies sizeable BRs!

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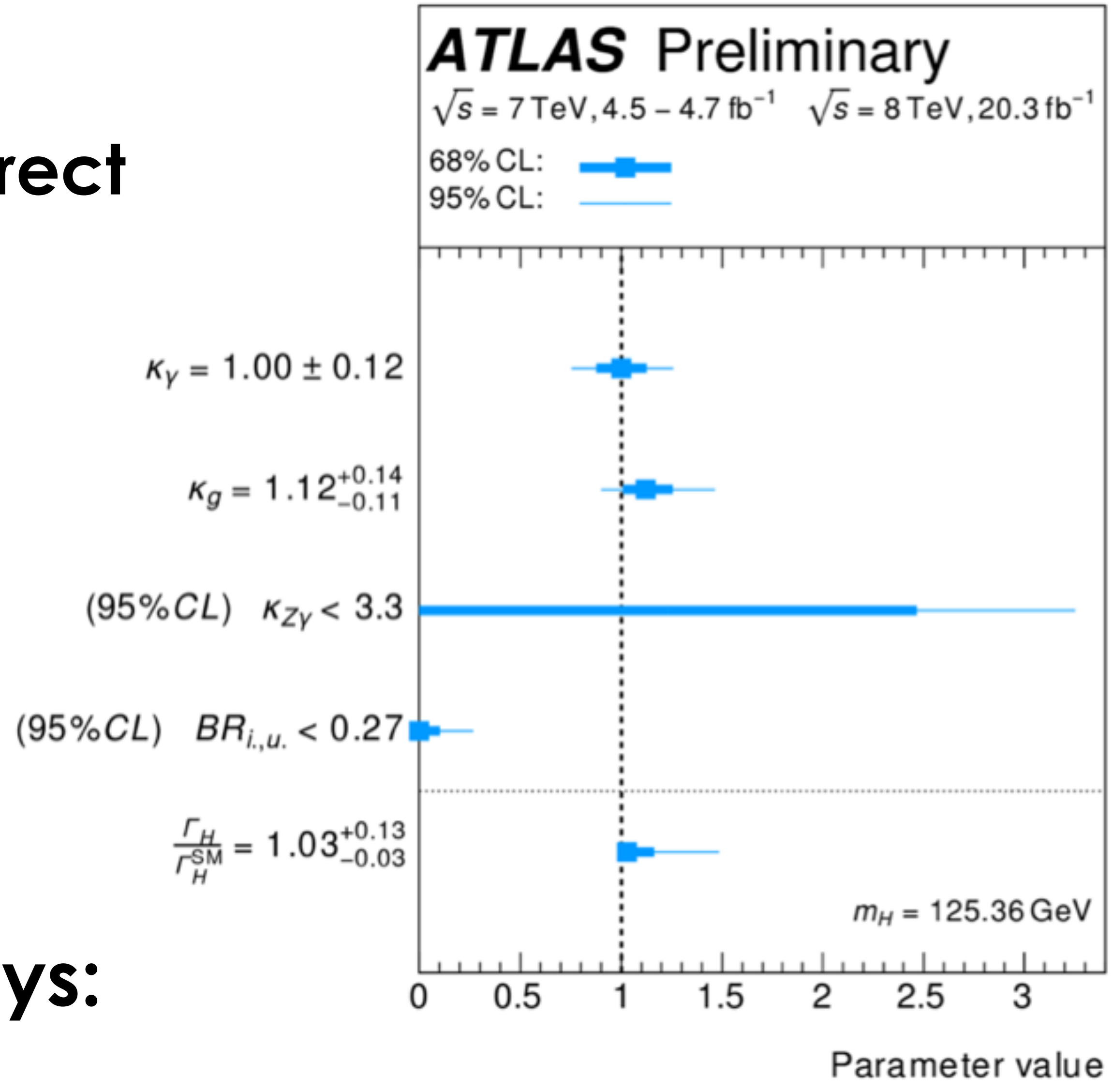


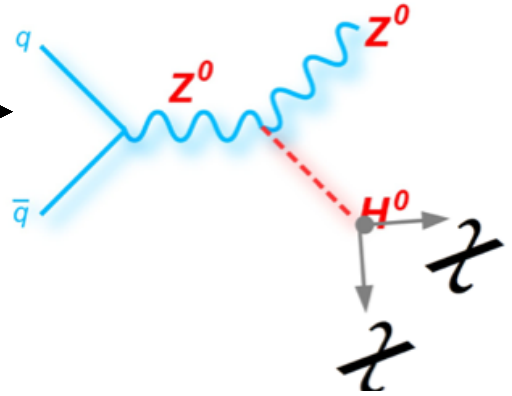
Direct searches for BSM Higgs decays:

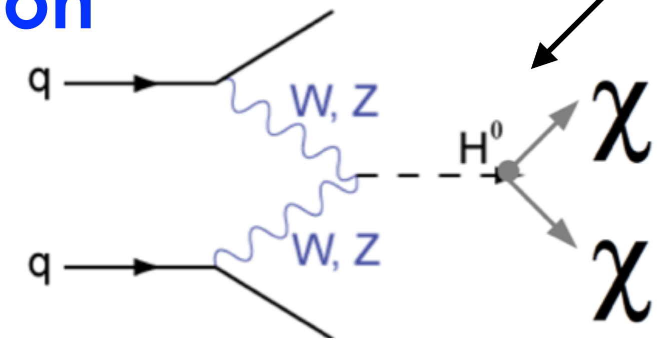
- h → Invisible (MET), h → γ + MET
- h → μτ (lepton flavour violation)
- h → ϕϕ→ xx yy
- h → long lived particles
- h → …

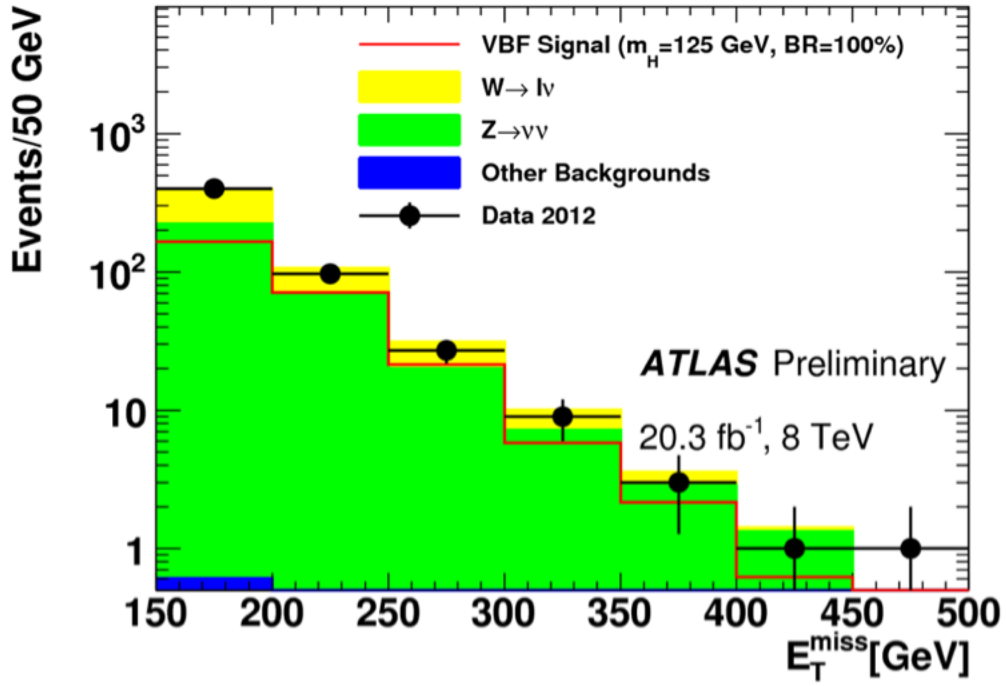
H→INVISIBLE

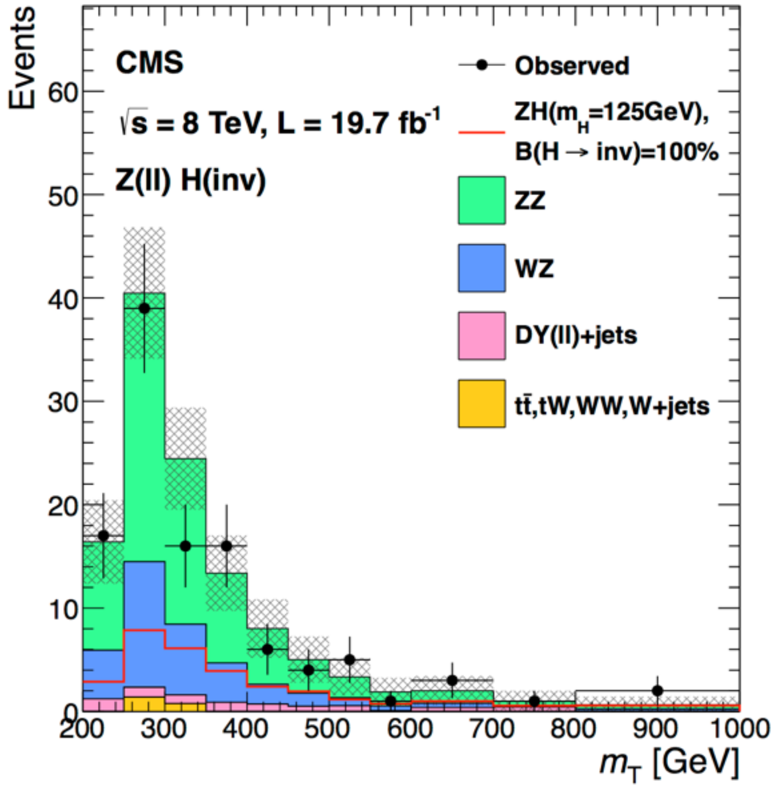
Direct search for invisible Higgs: interesting in the context of Dark Matter

Exploit associated Vector Boson Fusion and VH production →









Most sensitive channel. H(125) BR upper limits:

ATLAS: 29% (exp 35%), CMS: 57% (exp 40%)

H(125) BR upper limits

ATLAS: Z(→ll)+H 75% (exp 62%)

ATLAS: Z(→jj)+H 78% (exp 86%)

CMS: Z(→ll,→bb)+H 81% (exp 83%)

H→INVISIBLE

Complementary search wrt direct dark matter experiments for low mass DM: $m_X<m_H/2$

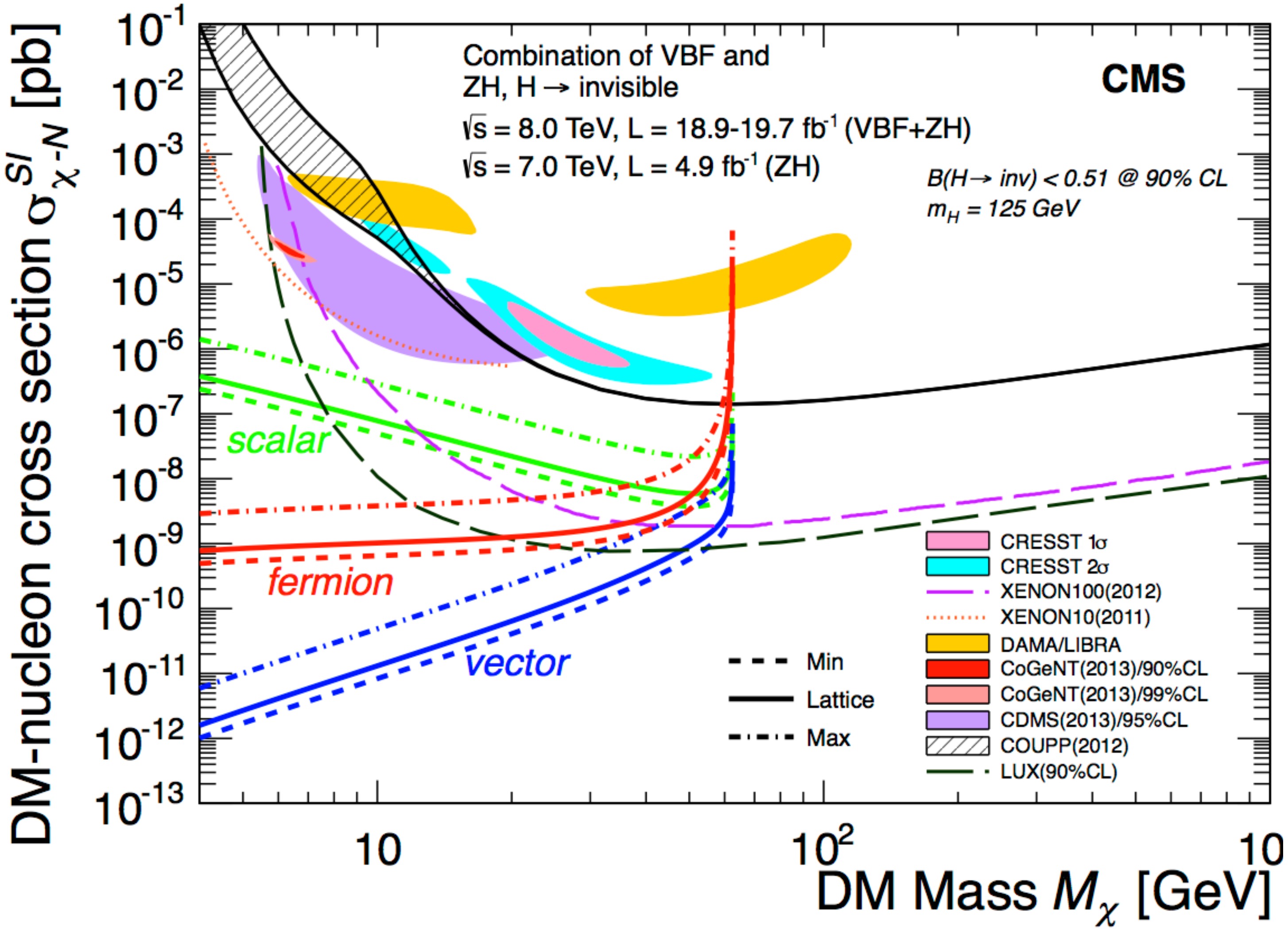
Higgs portal models: direct interactions of Higgs with DM candidate

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \boxed{\frac{\lambda_{HS}}{2} H^\dagger H S^2} - \frac{\lambda_S}{4} S^4$$

E.g. spin independent nucleon-scalar DM cross section

$$\sigma^{\rm SI}_{\rm S-N} = \frac{4\Gamma_{\rm inv}}{m_{\rm H}^3 v^2 \beta} \frac{m_{\rm N}^4 f_{\rm N}^2}{(M_\chi + m_{\rm N})^2},$$

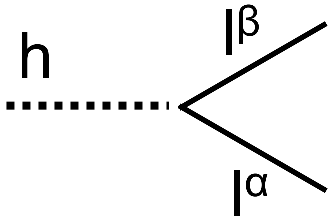
f_N: Higgs-nucleon form factor from lattice QCD



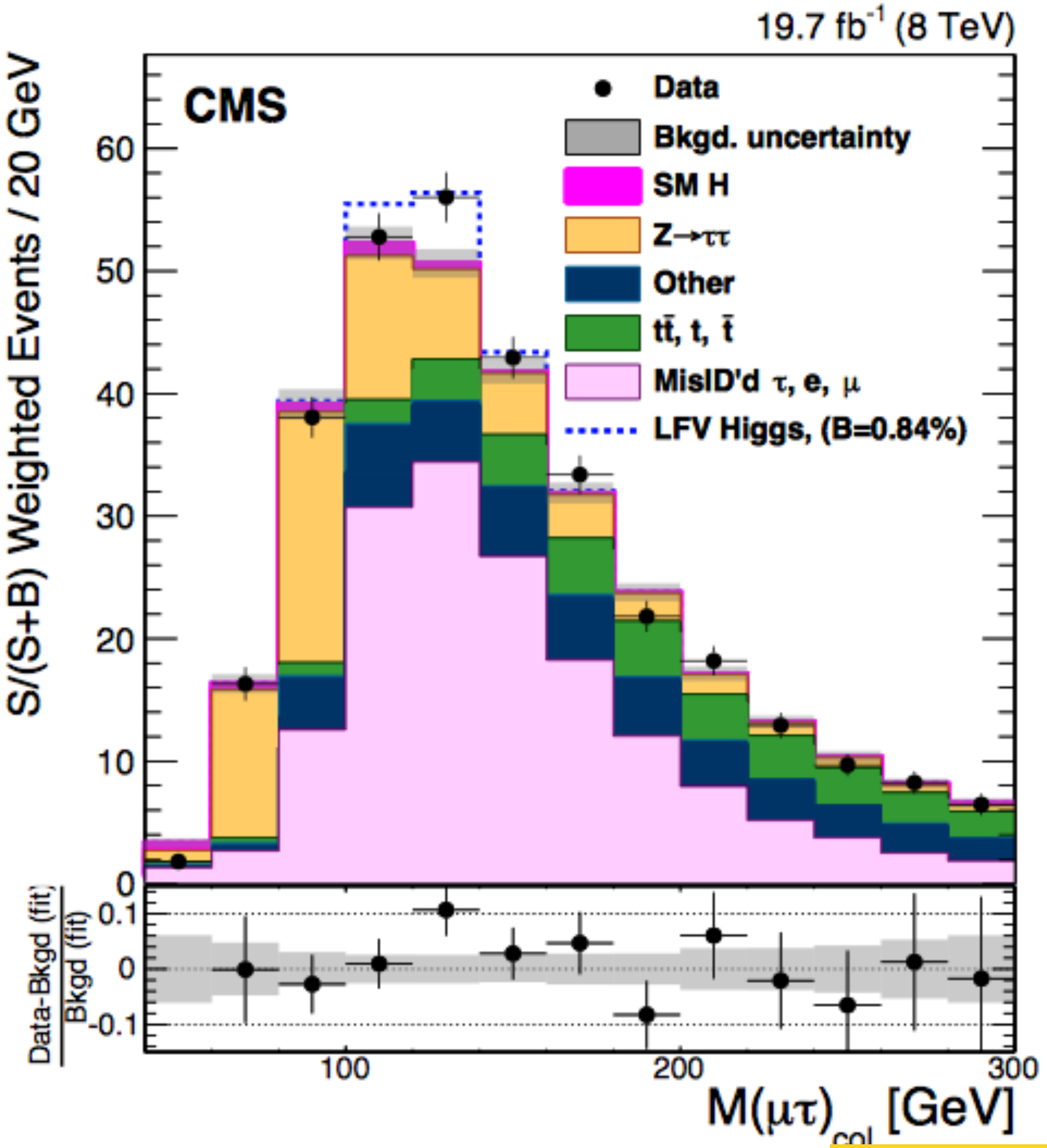
H→μτ: LEPTON FLAVOUR VIOLATION

FCNC heavily constrained in the quark sector, but lepton sector less constrained

Indirect limits on BR(H→μτ) from τ rare decays search (τ→3μ,τ→μγ): ~10%



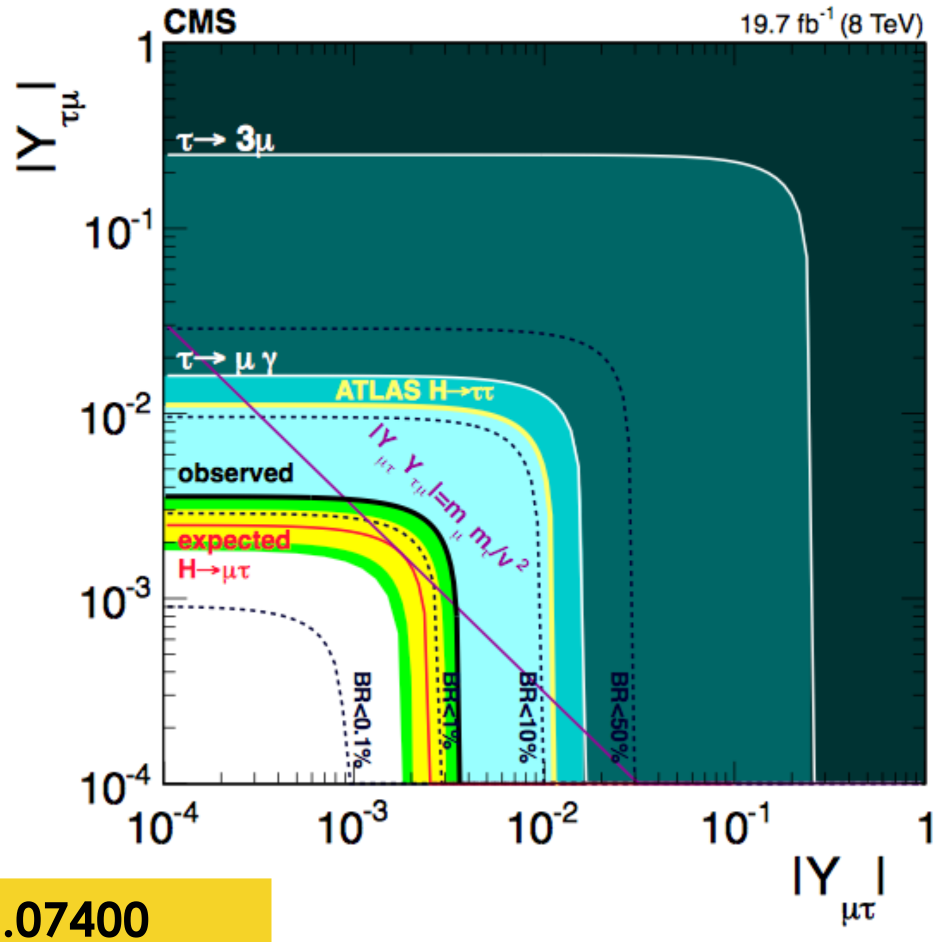
$$\Gamma(H \to \ell^\alpha \ell^\beta) = \frac{m_H}{8\pi}\left(|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2\right)$$



Direct limit on BR(H→μτ) < 1.57%

(2.4σ excess…)

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$$



CMS: arXiv:1502.07400

LIGHT SCALARS: H→ϕϕ

Search for light scalars mostly motivated in the NMSSM (Next-to Minimal SSM) context

MSSM: μ-problem, higgsino mass parameter μ imposed at EWSB scale

NMSSM: generate μ dinamically, adding a singlet super field S

$\mu = \lambda\langle S\rangle$ from: $\lambda\hat{S}\hat{H}_u\hat{H}_d$

Less fine-tuning then in MSSM

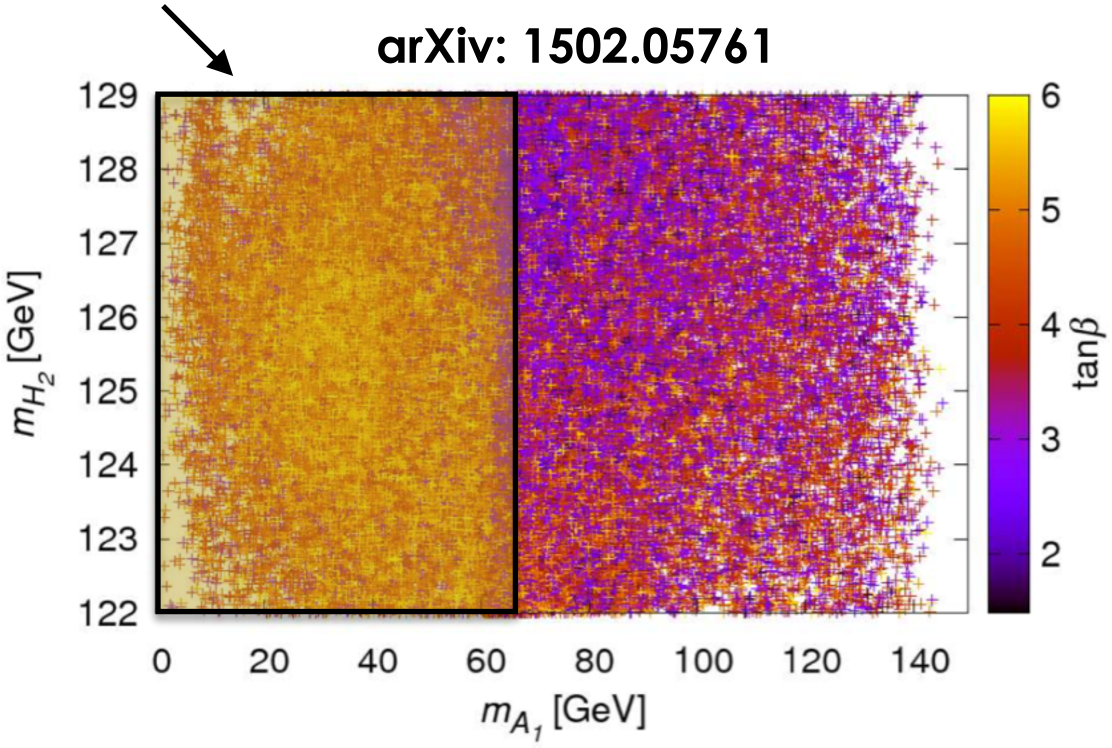
MSSM: $m_h^2 \approx M_Z^2\cos^2 2\beta + \Delta m_h^2$

NMSSM: $m_h^2 \approx M_Z^2\cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$

NMSSM: larger Higgs sector: 3 CP-even H, 2 CP-odd A, 2 charged H±. **H(125) not necessarily the lightest scalar**

Include constraints from b-physics, dark matter relic density, LEP & LHC Higgs searches

arXiv: 1502.05761

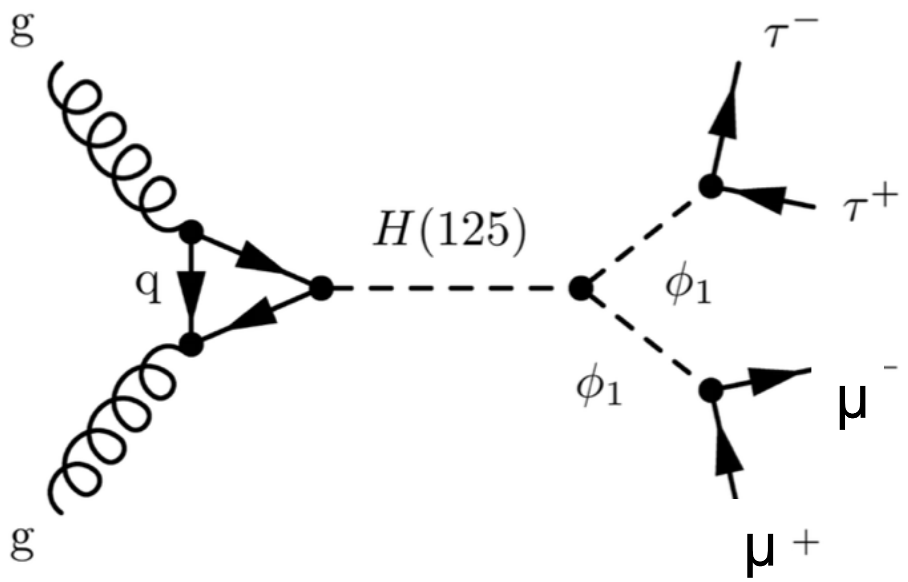


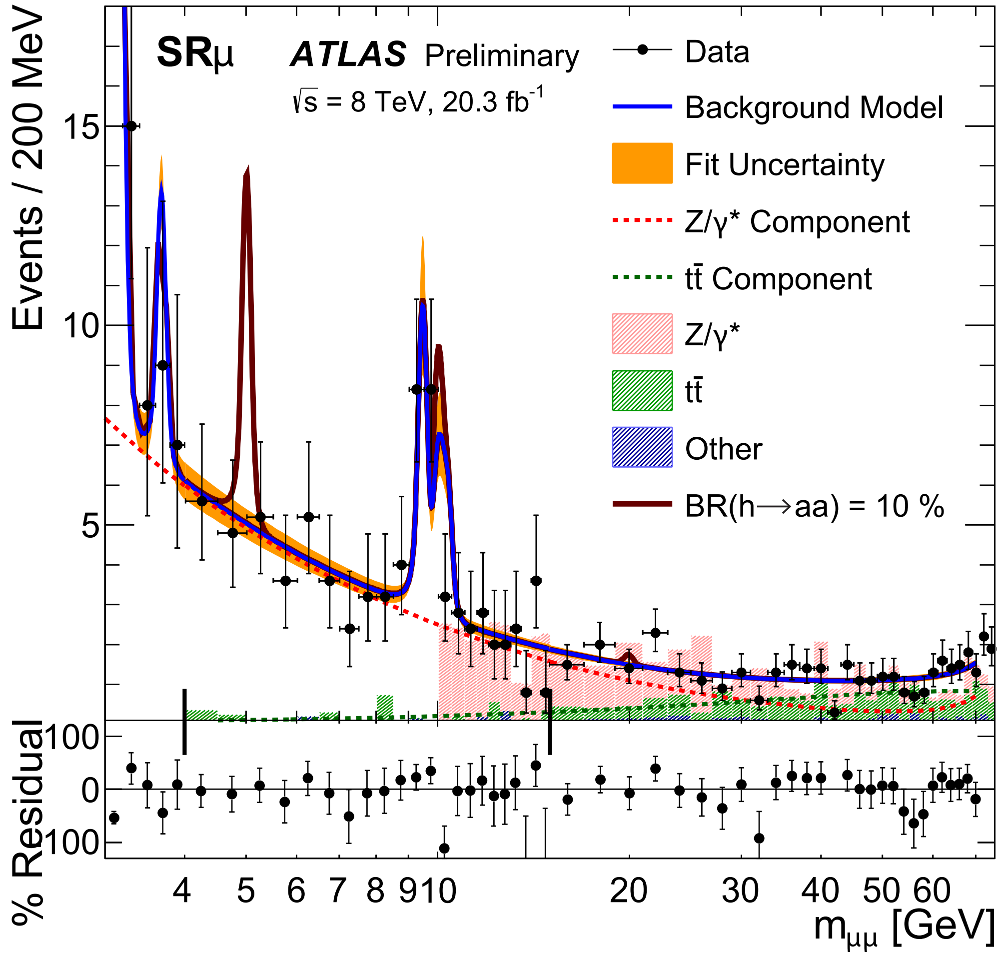
Light Scalars: $H\to\phi\phi\to 2\mu 2\tau$

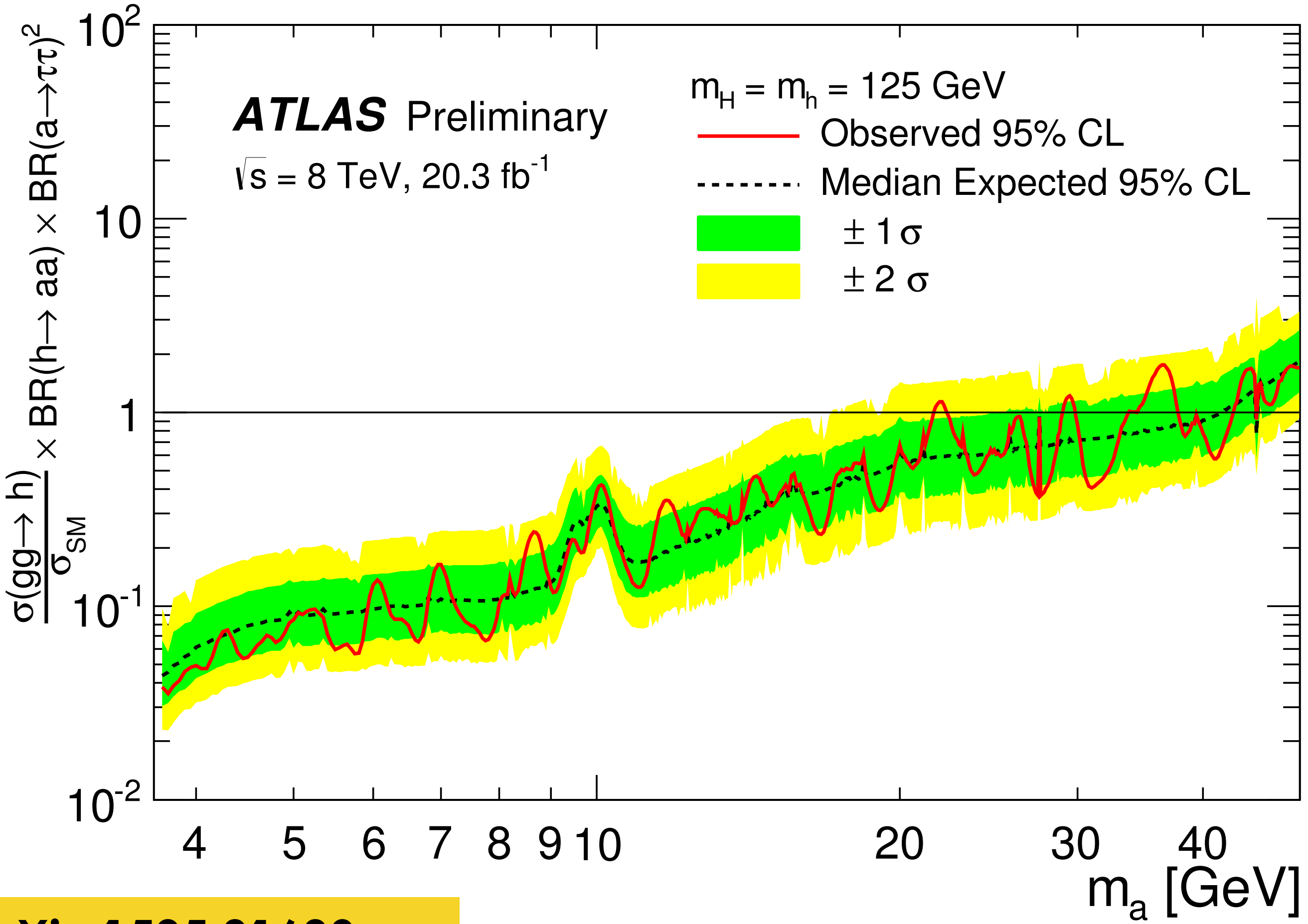
Searches performed so far:
$H\to\phi\phi\to 4\mu,4\tau,2\mu 2\tau$

BR($\phi\to XX$) expected to be proportional to m_X^2

$2\mu 2\tau$ good compromise: use clean $m_{\mu\mu}$ as final observable







arXiv:1505.01609

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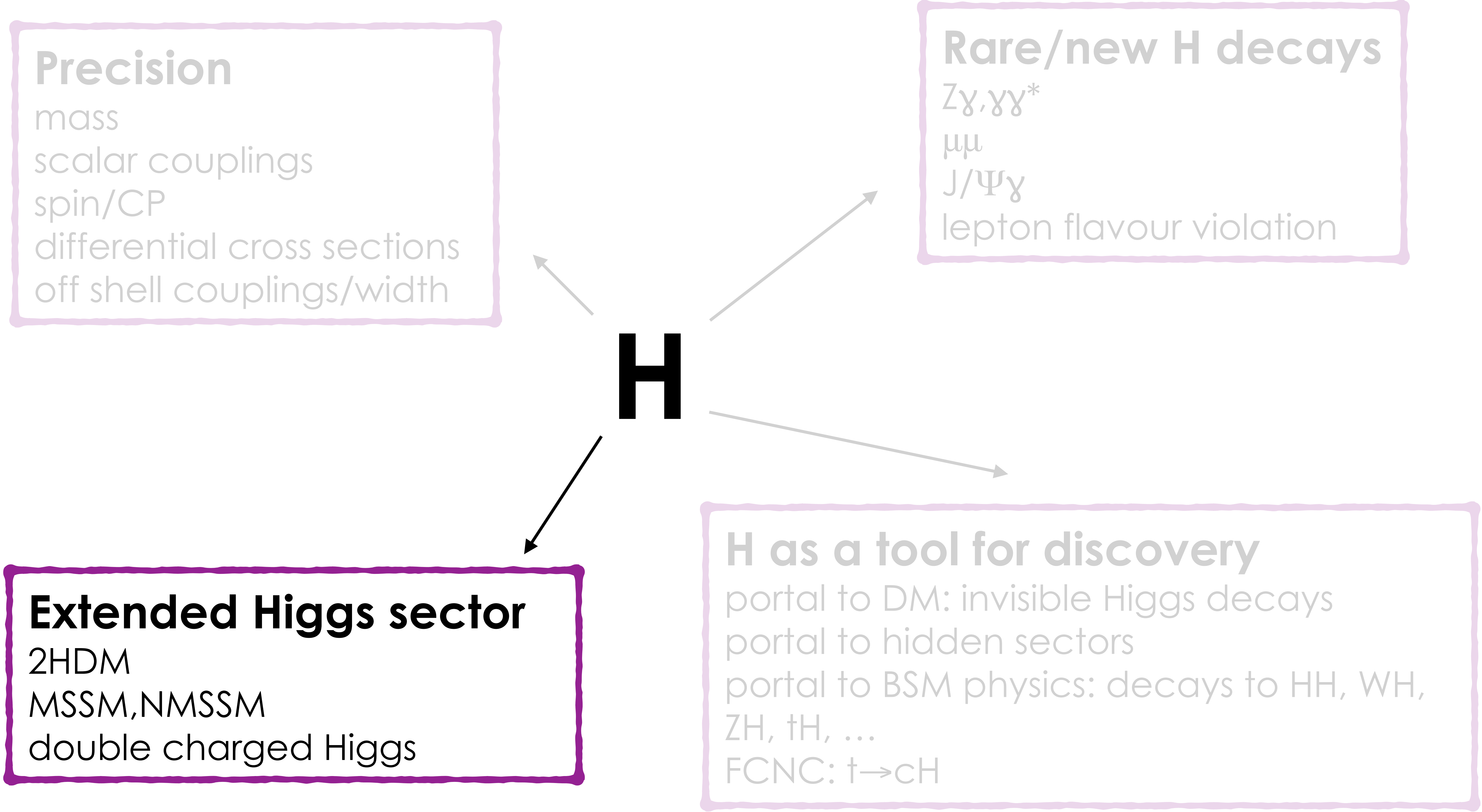

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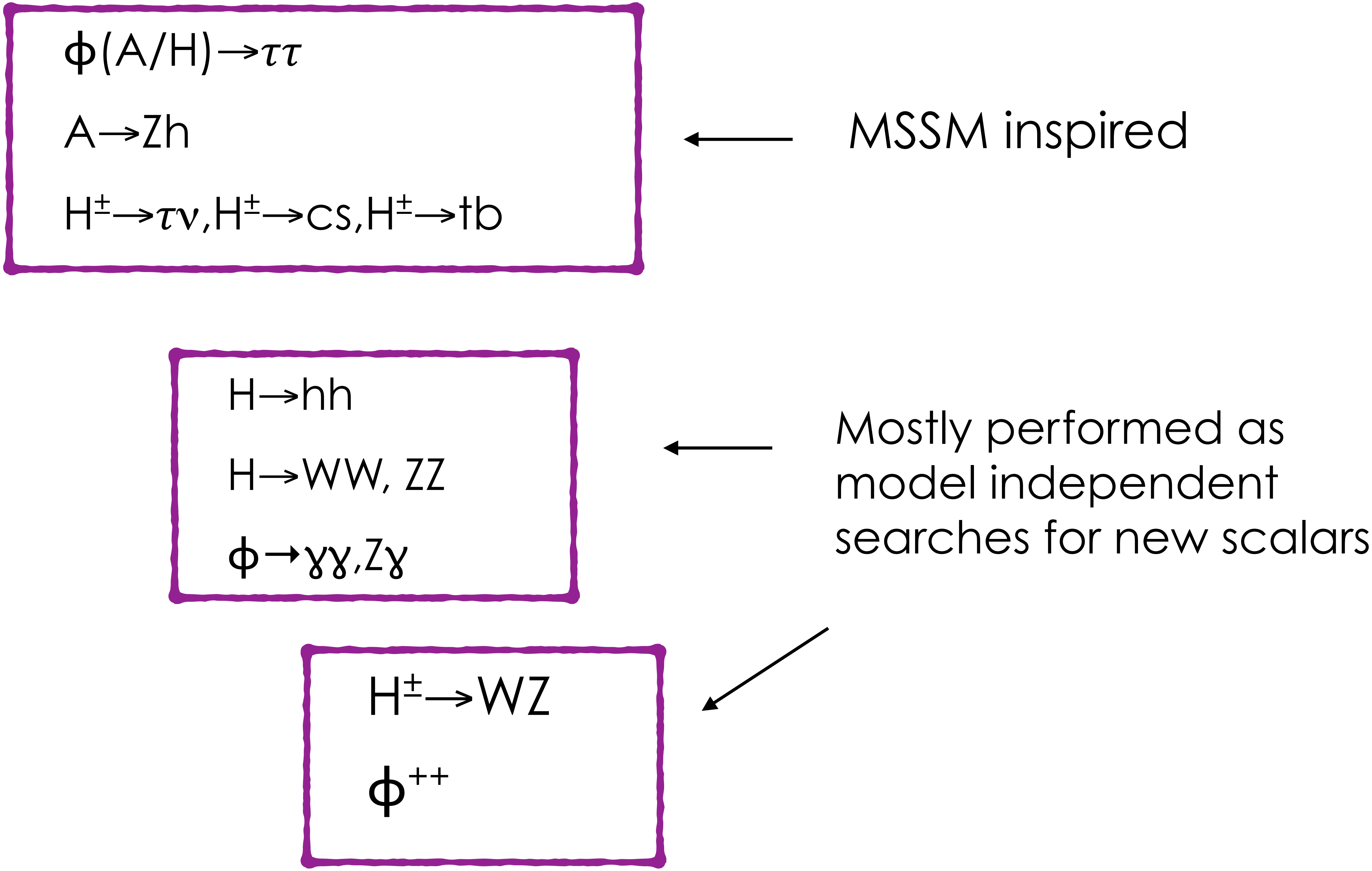
portal to DM: invisible Higgs decays
portal to hidden sectors
portal to BSM physics: decays to HH, WH, ZH, tH, …
FCNC: t→cH

HEAVY SCALAR SEARCHES



$\phi(A/H) \to \tau\tau$

$A \to Zh$

$H^{\pm} \to \tau\nu, H^{\pm} \to cs, H^{\pm} \to tb$

MSSM inspired

$H \to hh$

$H \to WW, ZZ$

$\phi \to \gamma\gamma, Z\gamma$

Mostly performed as model independent searches for new scalars

$H^{\pm} \to WZ$

ϕ^{++}

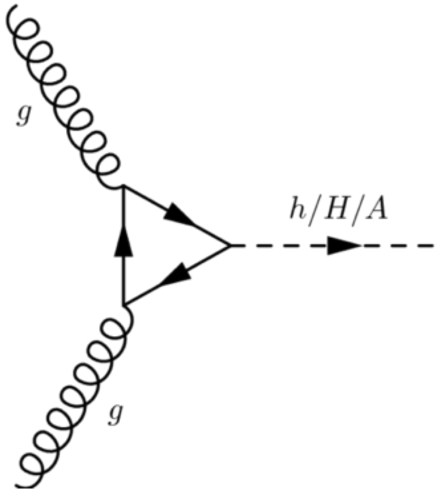
$\phi \to \tau\tau$

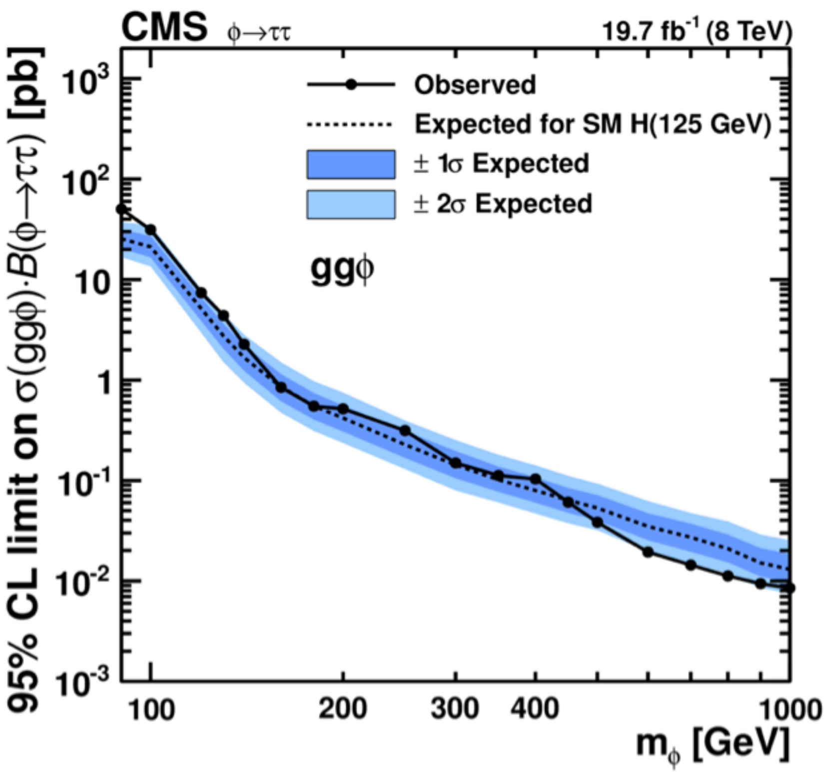
MSSM: large BR($\phi \to \tau\tau$) for for tanβ>5

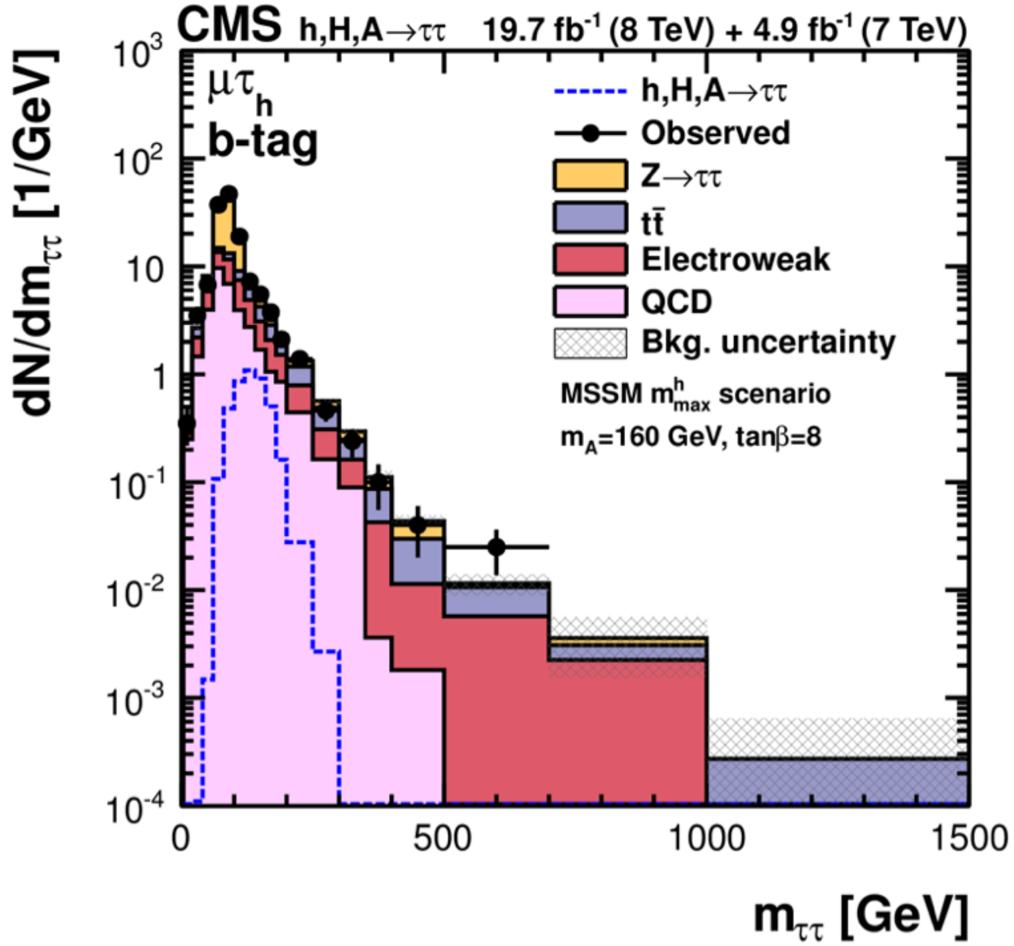
Analysis builds up on SM $h \to \tau\tau$. Bump search in reconstructed $m_{\tau\tau}$

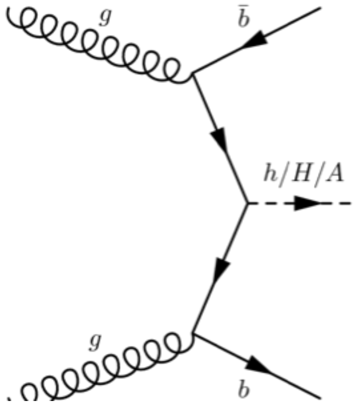
Several final states considered for the τ decay: $\tau_e, \tau_\mu, \tau_{had}$

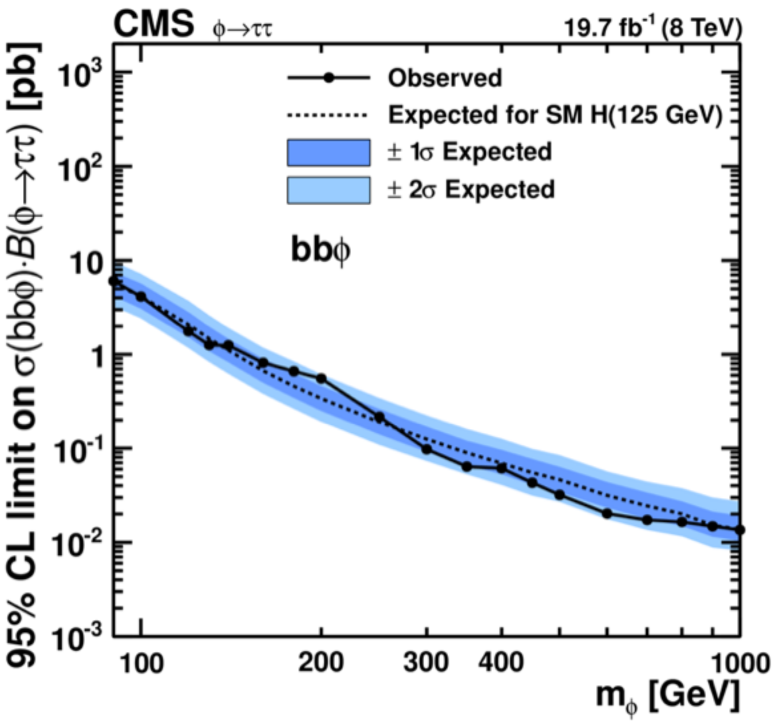
b-tag categories for bbϕ production









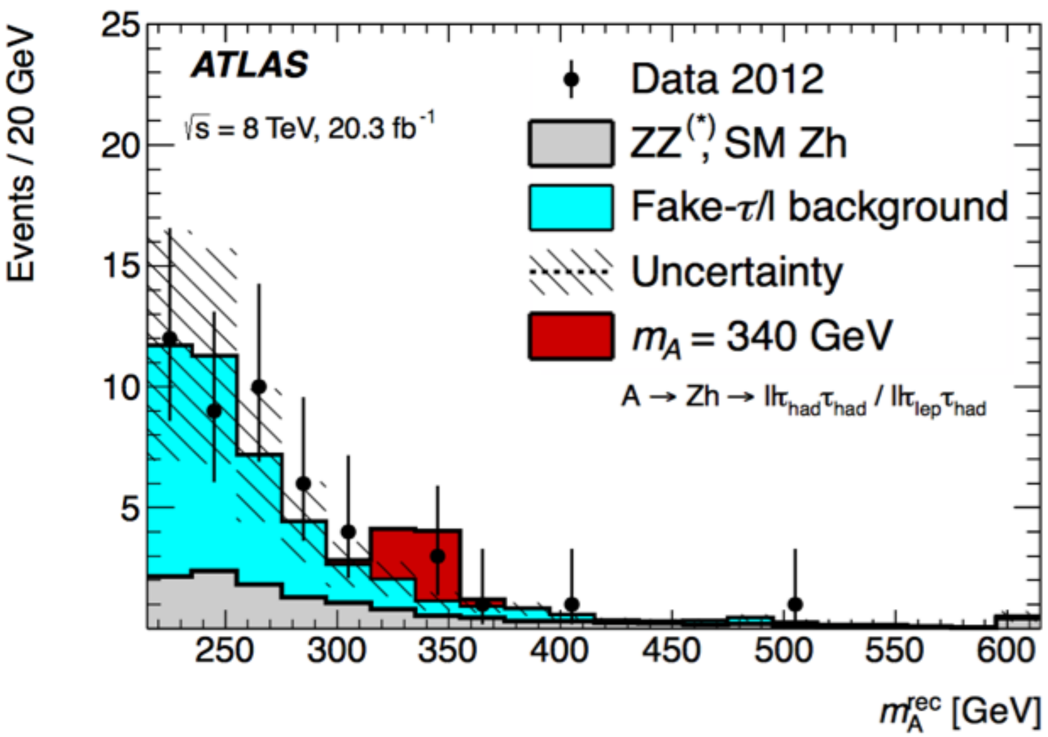


ATLAS: JHEP 11 (2014) 056

CMS: JHEP 10 (2014) 160

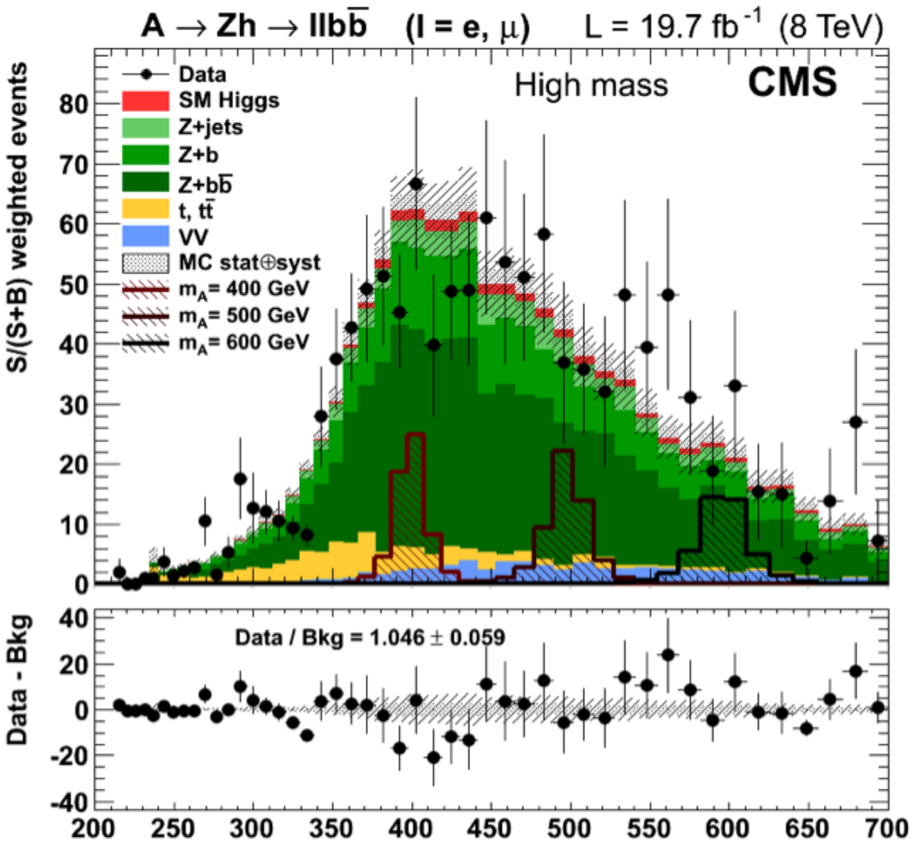
A→ZH

A→Z(→ll)h(→$\tau\tau$)

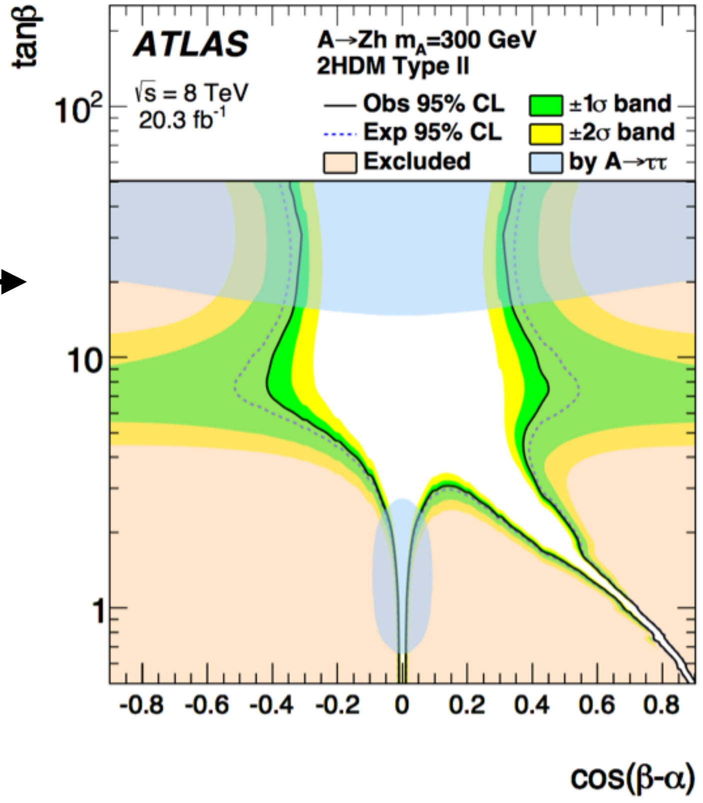


Strong involvement of ATLAS Rome group

A→Z(→ll)h(→bb)



Extend sensitivity in low tanβ for 2HDM/MSSM models not covered by the ϕ→$\tau\tau$ search ⟶

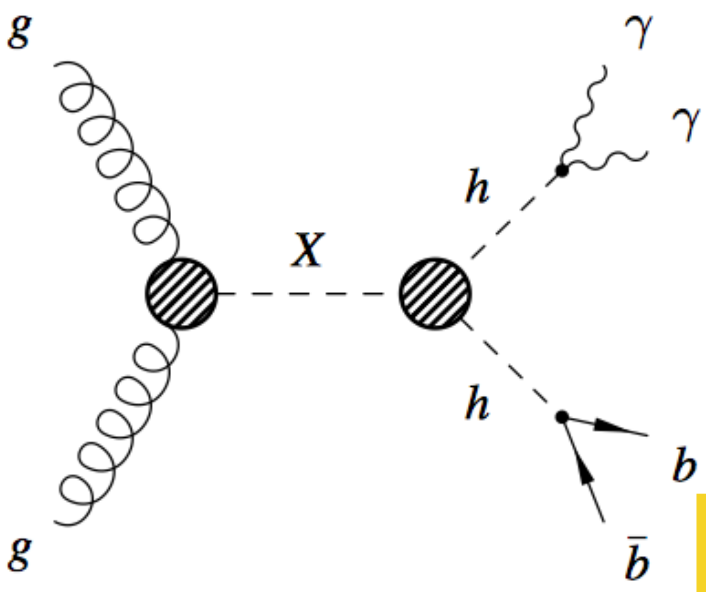


ATLAS: PLB 744 (2015) 163-183

CMS: arXiv:1504.04710

X→HH

Interesting in the context of 2HDM for low tanβ region m_H<350

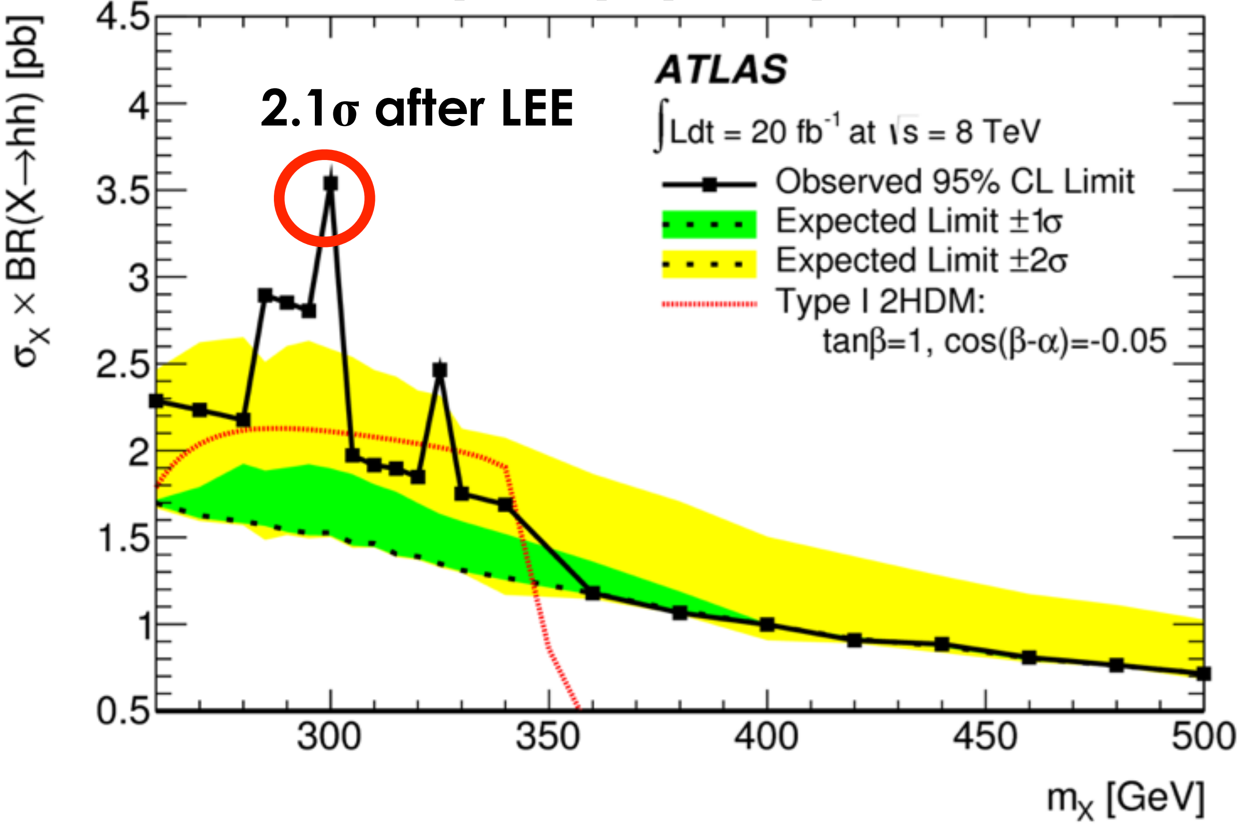


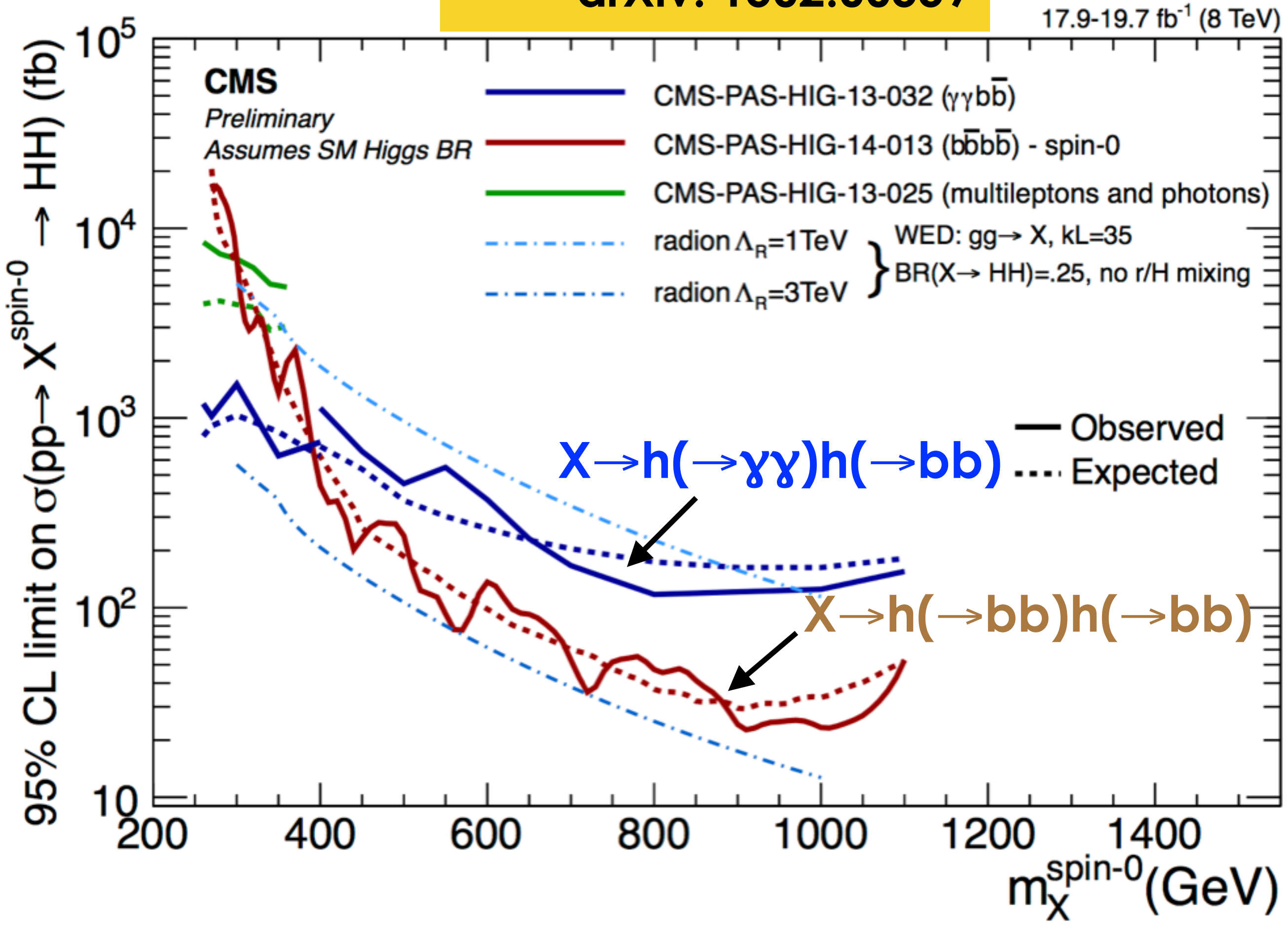
Strong involvement of ATLAS & CMS Rome group

ATLAS: Phys. Rev. Lett. 114, 081802 (2015)

CMS: PRD 90, 112013
HIG-13-032
arXiv: 1502.00559

X→h(→γγ)h(→bb)





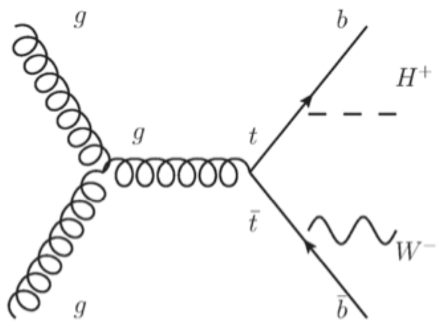
CHARGED HIGGS: $H^{\pm} \to \tau^{\pm}\nu$

$M_{H^{\pm}} < m_{top}$: production in tt decay [tt→HbWb]

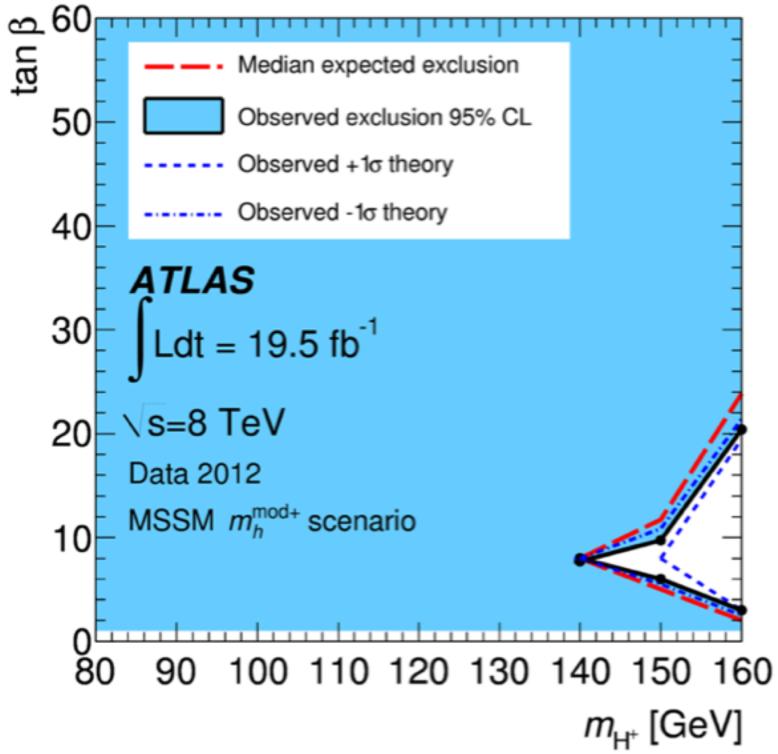
$M_{H^{\pm}} > m_{top}$: associated production with top [tH(b)]

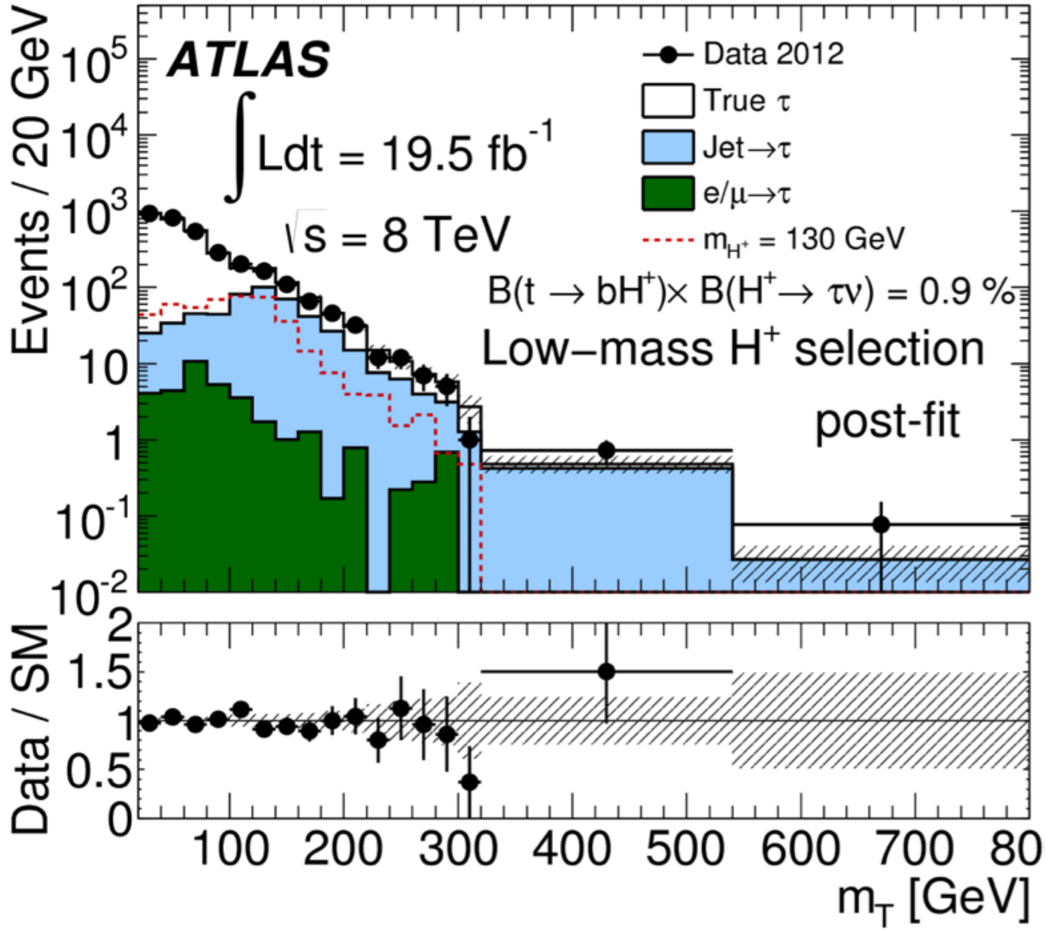
τ_{had}+MET+b-jets final state

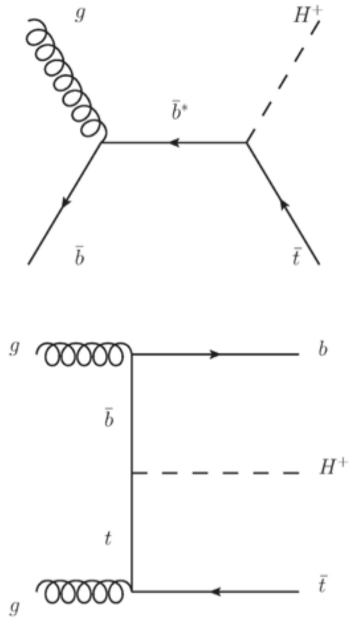
able to exclude full MSSM phase space for $m_{H\pm}$<160 GeV



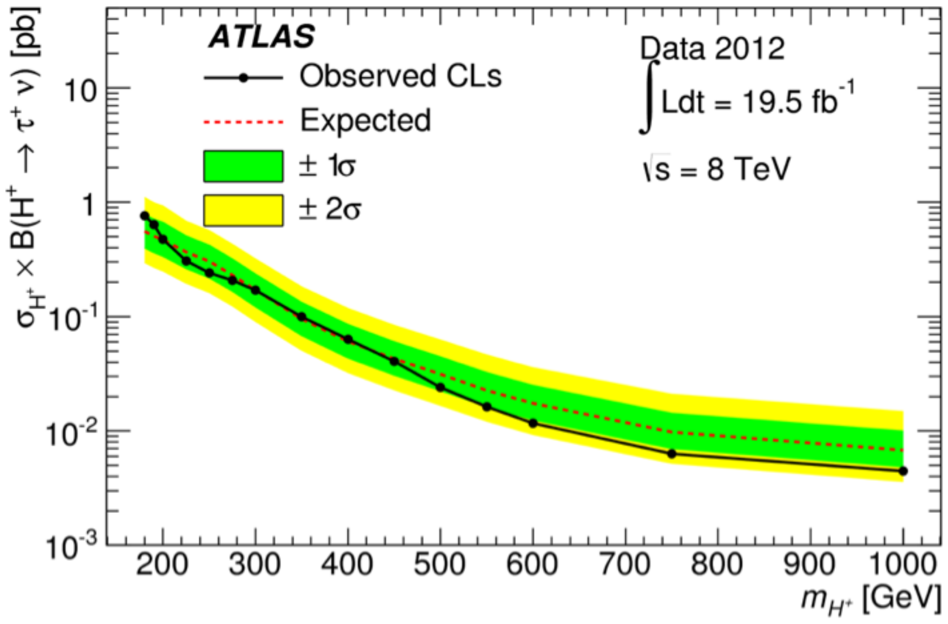
low $m_{H\pm}$







high $m_{H\pm}$

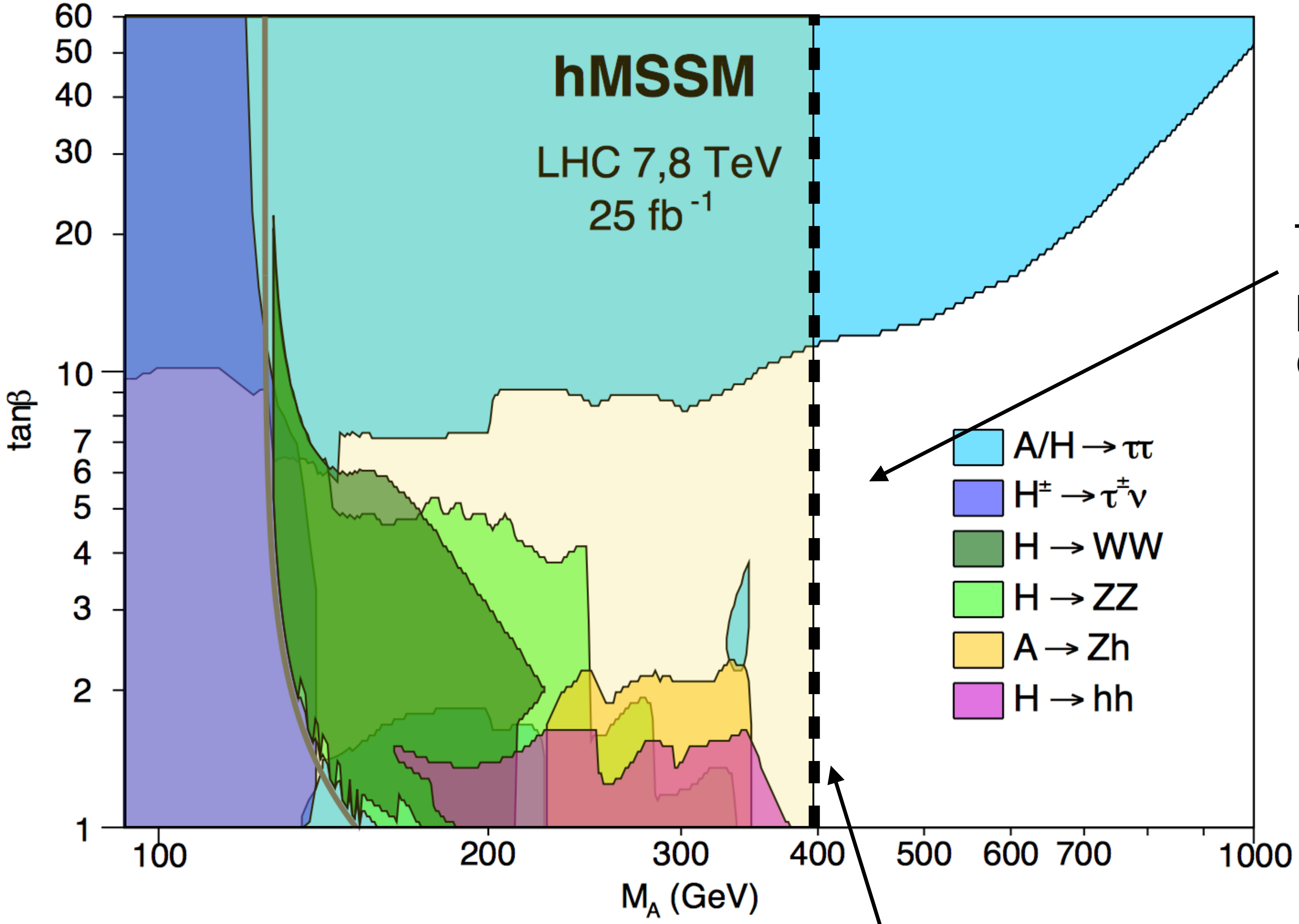


ATLAS: JHEP 03 (2015) 88

CMS-HIG-14-020

hMSSM: RUN I SUMMARY

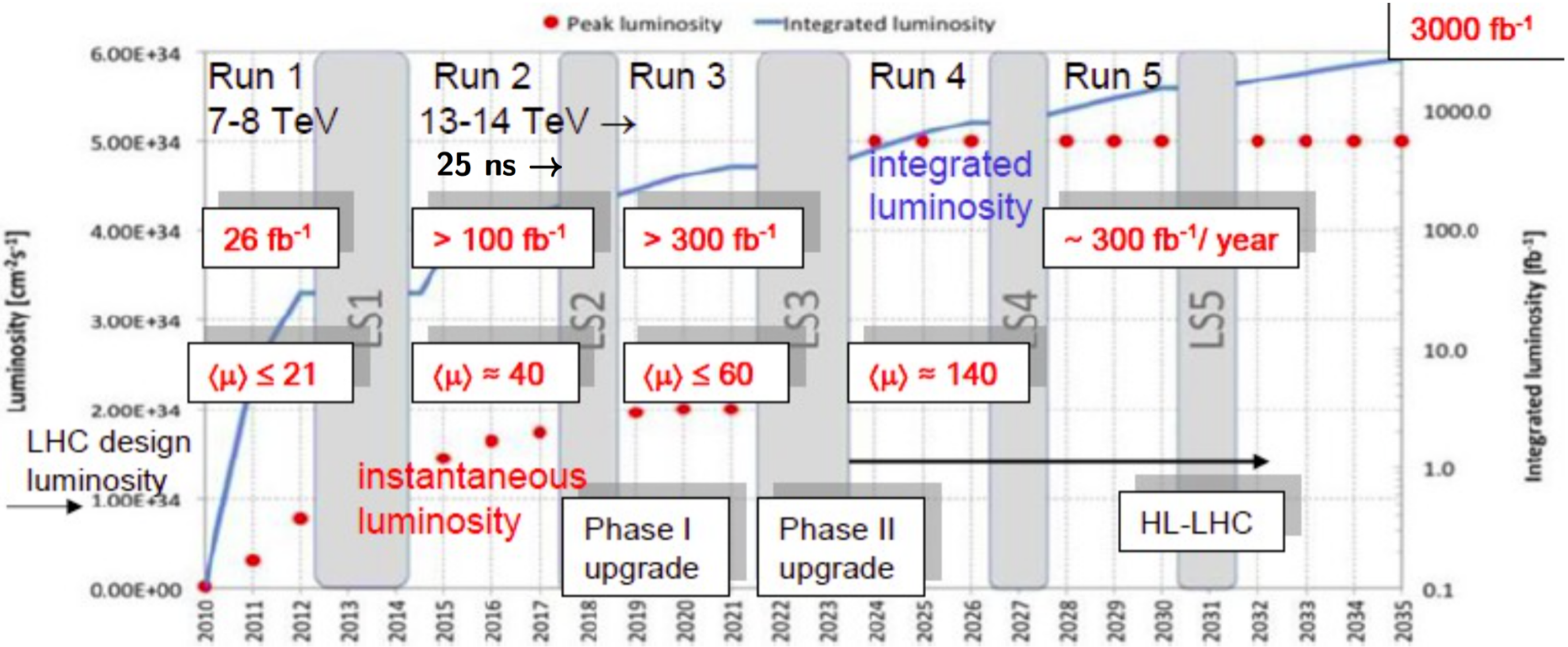
A. Djouadi et al: arXiv:1502.05653



This region can be probed also looking @ $\phi \rightarrow tt$

Indirect limit from Higgs couplings

BEYOND RUN1



Target for 2015: 5-10 fb^{-1} First stable collisions: 03.06.2015

>100 fb^{-1} by 2018, >300 fb^{-1} by 2023

HL-LHC: ~3000 fb-1, 5 x 10^{34} cm^{-2}s^{-1} requires detector+DAQ+trigger upgrades

PERSPECTIVES FOR HIGGS PHYSICS @ RUN 2

13 TeV: H cross section ~ x 2, ttH ~ x4

Run I sensitivity/precision will be reached for H analyses ~10 fb^{-1} @ 13 TeV

	σ(8 TeV)	σ(13 TeV)	ratio
gg→H	19.3	43.9	**2.3**
VBF	1.58	3.75	**2.4**
WH	0.70	1.38	**2.0**
ZH	0.42	0.87	**2.1**
ttH	0.13	0.51	**3.9**

Full Run2+3 statistics (~300 fb^{-1}):

~10M H produced
~400k H useful for precision measurements

Rare processes: **$H\to\mu\mu$ @ &** 3σ, **$H\to Z\gamma$** @ > 2σ
Direct ttH coupling could be established @ ~ 5σ

Higgs couplings can be tested at levels better then 10%

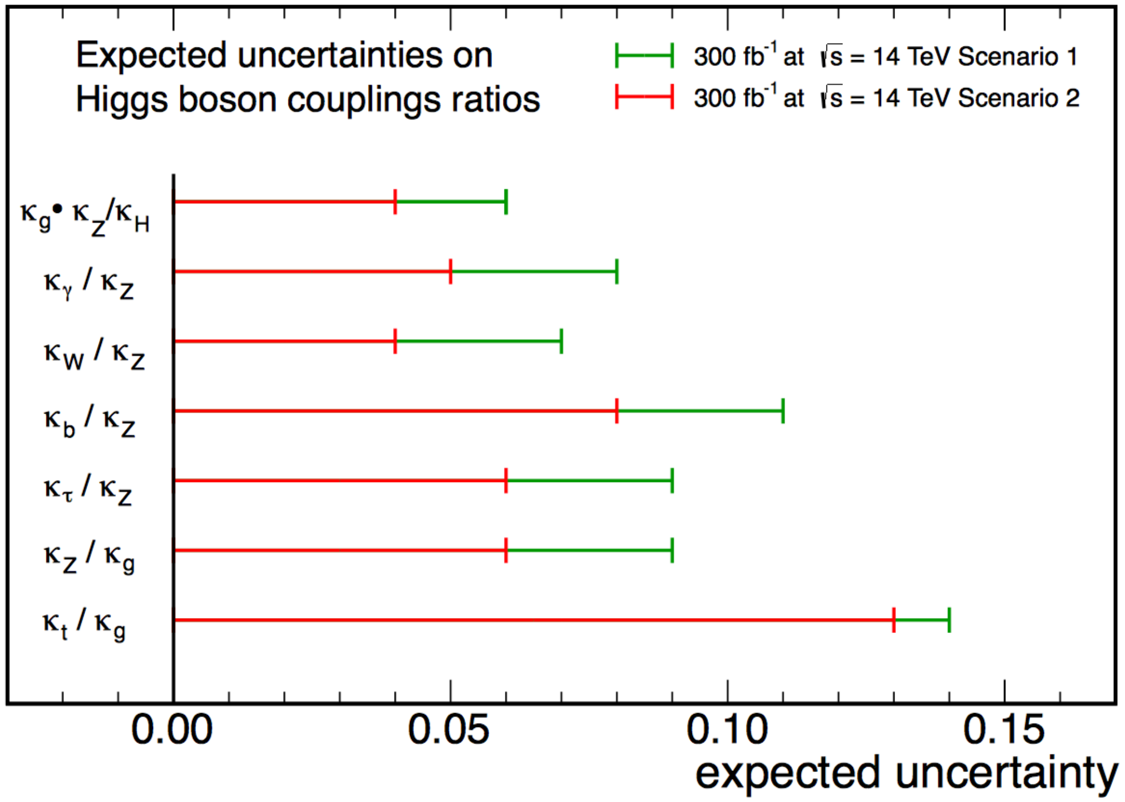
Differential cross-sections for $H\to\gamma\gamma$,$H\to ZZ$,$H\to WW$ improving sensitivity for new physics looking also at kinematic deviations

RUN 2: A NEW ERA FOR HIGGS MEASUREMENTS

Transition from statistically limited to systematically limited in the Higgs precision physics

Reaching the ultimate precision will require new tools and new ideas, paving the grounds for HL-LHC.

Theory and experiment working together
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

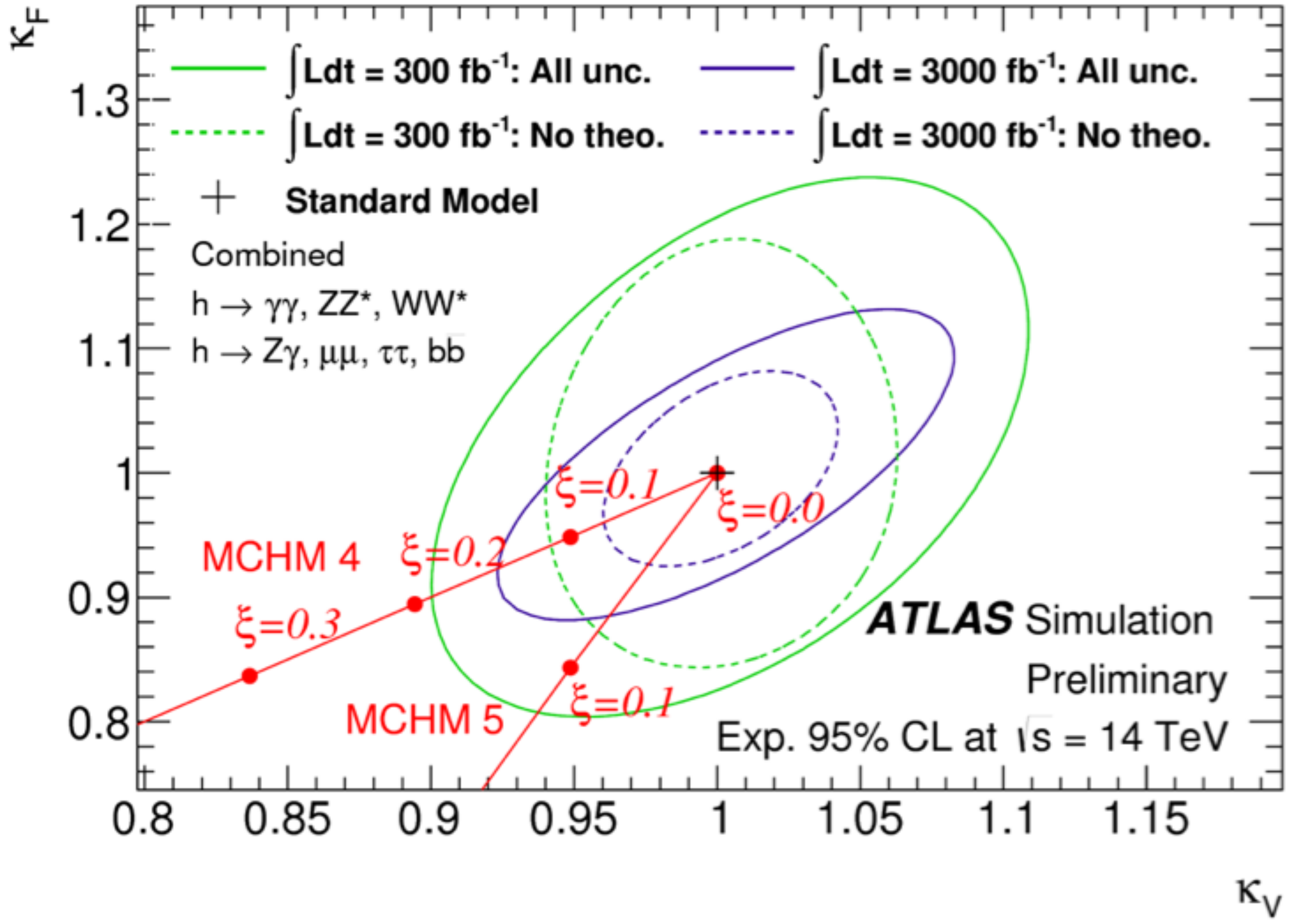

CMS Projection

- We are organized in 3 working groups.

Group TWiki	Mail to conveners	ATLAS	CMS	THEORY	
Higgs XS&BR	Mail	Bruce Mellado (Witwatersrand)	Pasquale Musella (CERN)	Massimiliano Grazzini (Zürich)	Robert Harlander (Wuppertal)
Higgs Properties	Mail	Michael Dührssen (CERN)	Andre David (CERN)	Adam Falkowski (Orsay-LPT)	Gino Isidori (Zürich)
BSM Higgs	Mail	Nikolaos Rompotis (Washington)	Mario Pelliccioni (Torino)	Ian Low (Argonne and Northwestern)	Margarete Mühlleitner (Karlsruhe)

BEYOND RUN2: HL-LHC

ATLAS-PHYS-PUB-2014-017



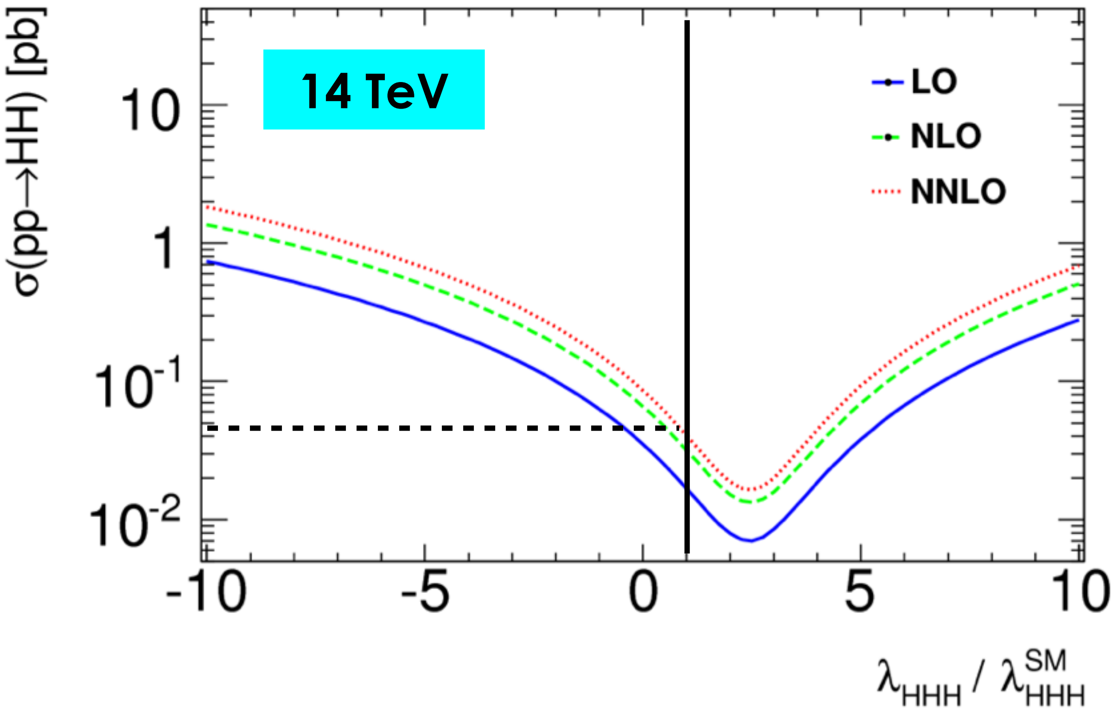
HL-LHC (3000 fb^{-1}): ultimate precision for the Higgs coupling measurements

If no direct sign of BSM found, Higgs precision physics will be the most important tool to look for new physics

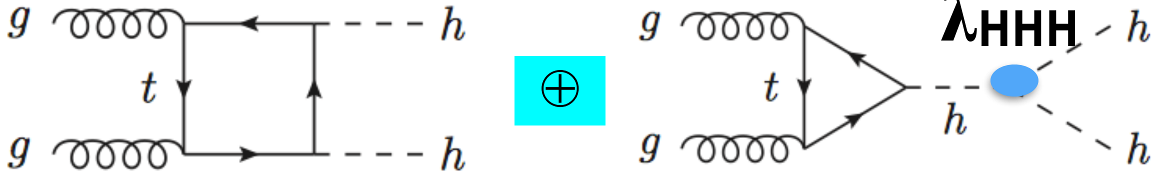
HL-LHC: PROBING HIGGS SELF COUPLING

hh non-resonant production: small cross-section in the SM **~40fb @ 14 TeV**

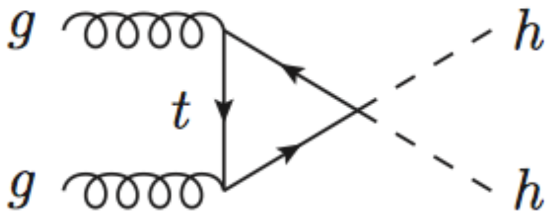
- potential to measure the Higgs self coupling
- can reveal anomalous hh couplings

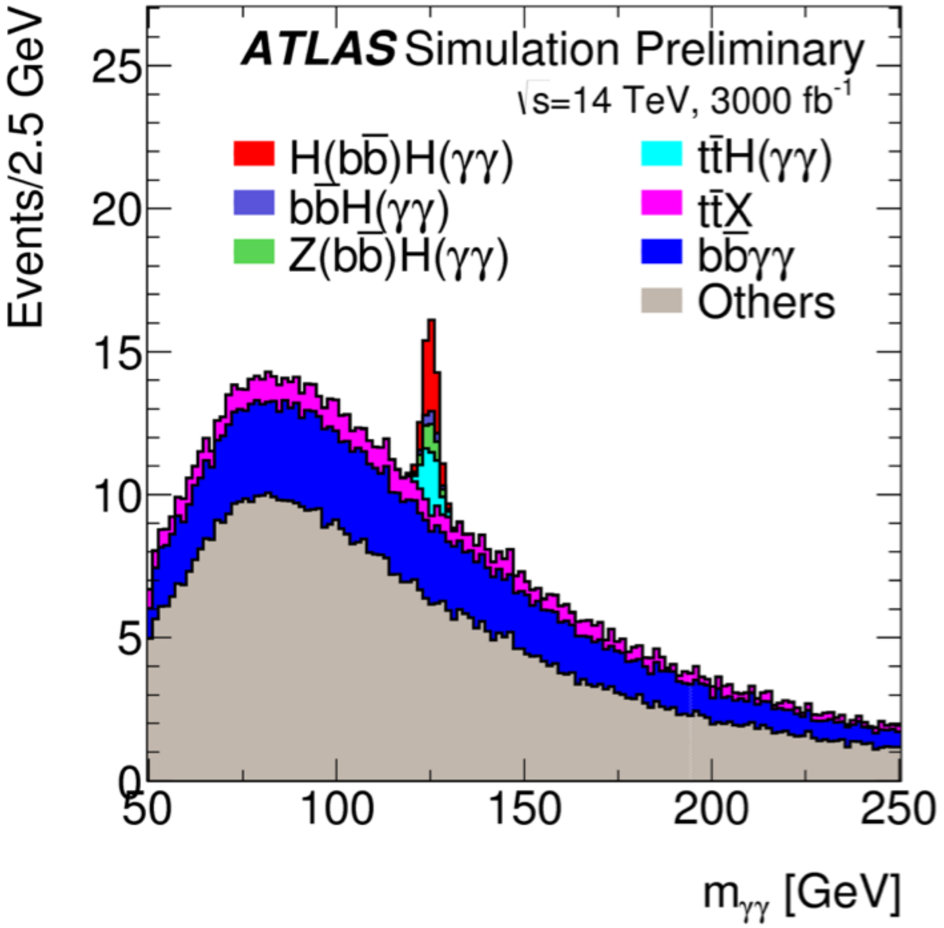


SM hh production



Anomalus BSM hh production





h(→γγ)h(→bb) the most promising channel @ HL-LHC: ~2σ per experiment according to current projections

h(→ττ)h(→bb) also being studied

SUMMARY

Run 1: from Higgs discovery, to the start of the Higgs physics

we have a new toy to play

Run 2: pushing the Higgs physics into the precision era

~10 fb^{-1} @ 13 TeV needed to achieve Run I sensitivity

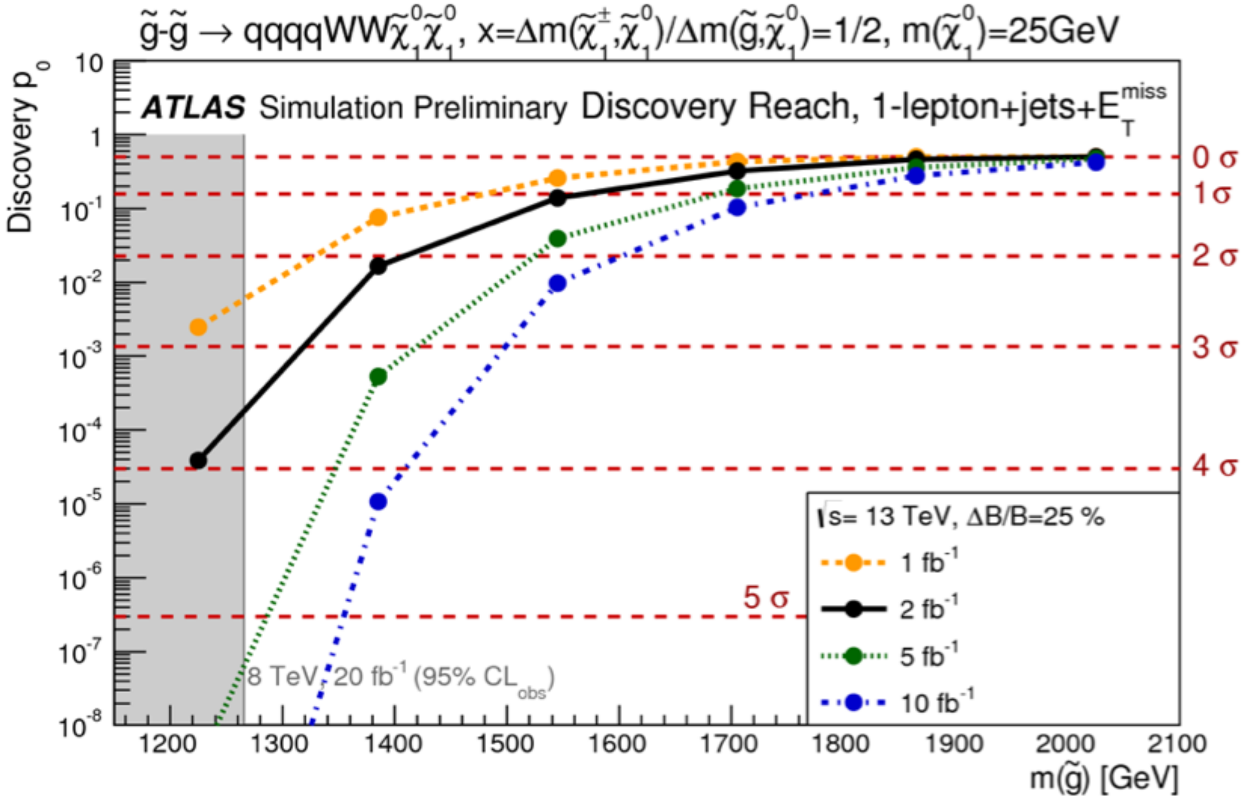
<10% precision on Higgs couplings at the end of Run 2

prepare grounds for HL-LHC where ultimate precision will be reached

General feeling of "Higgs and no BSM". However:

Wait for Run2! Direct searches reach increase very rapidly thanks to increase in sqrt(s)

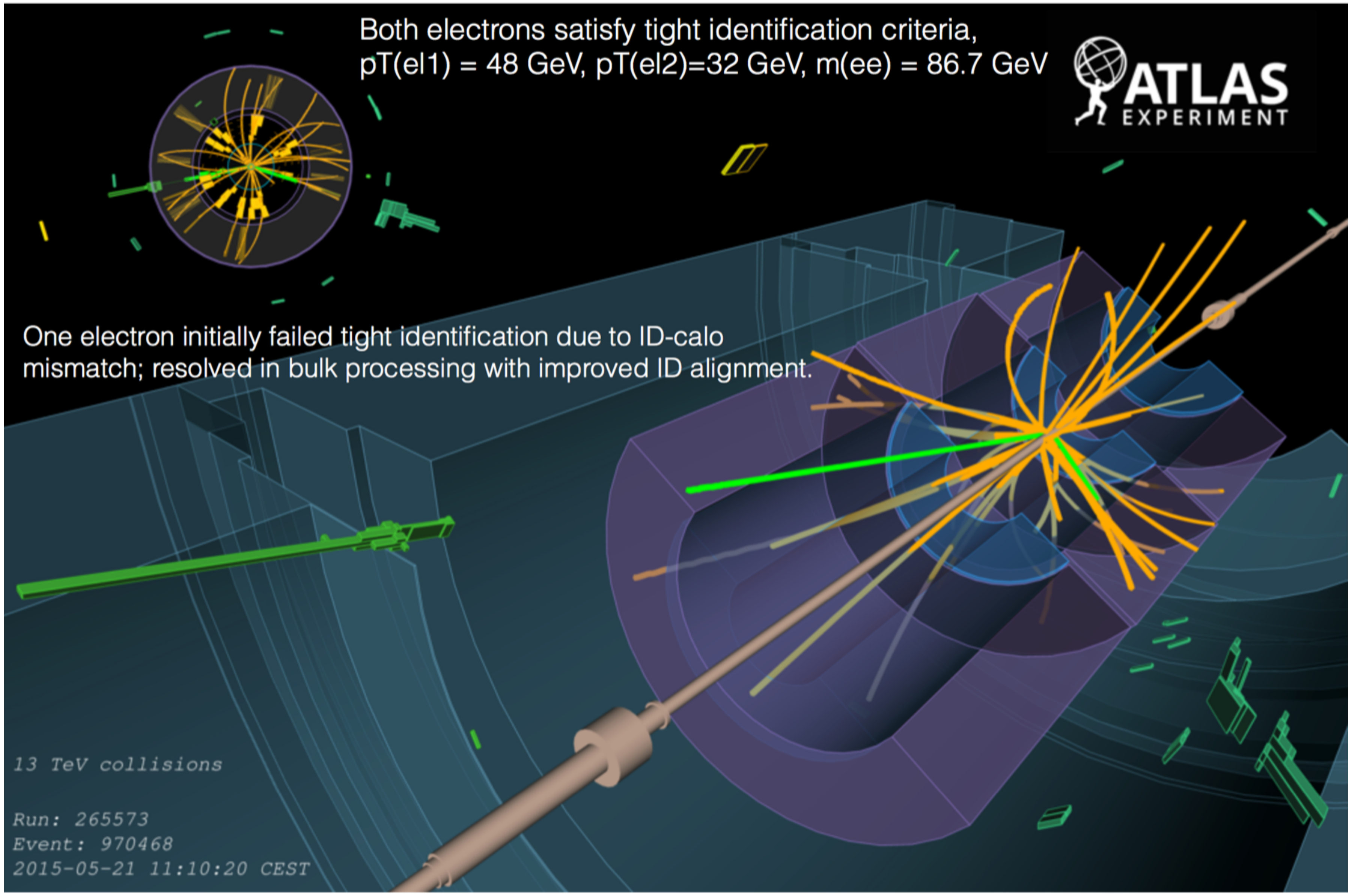
Smaller BSM cross-sections can be probed later-on thanks to the Run 2 statistics



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

RUN2 HAS STARTED!

Z→e^+e^- candidate



Both electrons satisfy tight identification criteria, pT(el1) = 48 GeV, pT(el2)=32 GeV, m(ee) = 86.7 GeV

One electron initially failed tight identification due to ID-calo mismatch; resolved in bulk processing with improved ID alignment.

13 TeV collisions

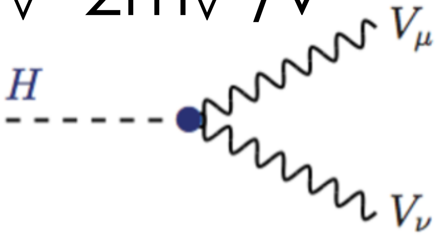
Run: 265573
Event: 970468
2015-05-21 11:10:20 CEST

BACKUP

THE HIGGS IN THE SM

$|D_\mu \phi|^2$

$g_{HVV}=2m_V^2/v$



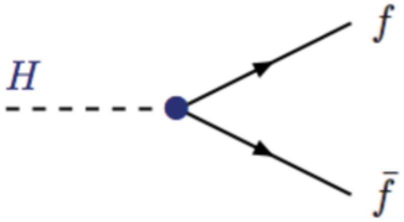
$$\frac{M_W}{M_Z}=\rho\frac{g^2}{g^2+g'^2}=\rho\cos^2\theta_W$$

$$\rho = 1$$

Discovery not really a surprise: LEP legacy

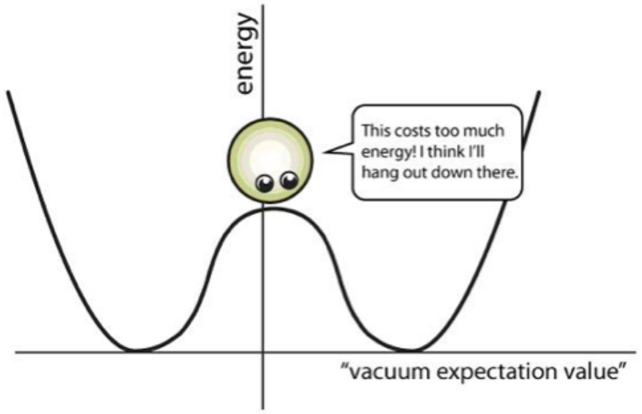
$\chi_i\, y_{ij}\, \chi_j \phi + h.c.$

$g_{Hff}=\sqrt{2}m_f/v$



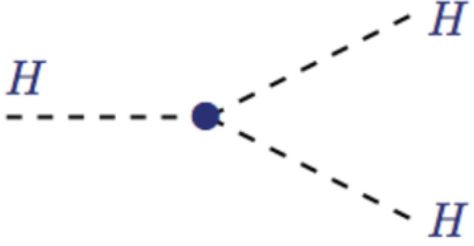
Flavour hierarchy unexplained

$V(\phi)$



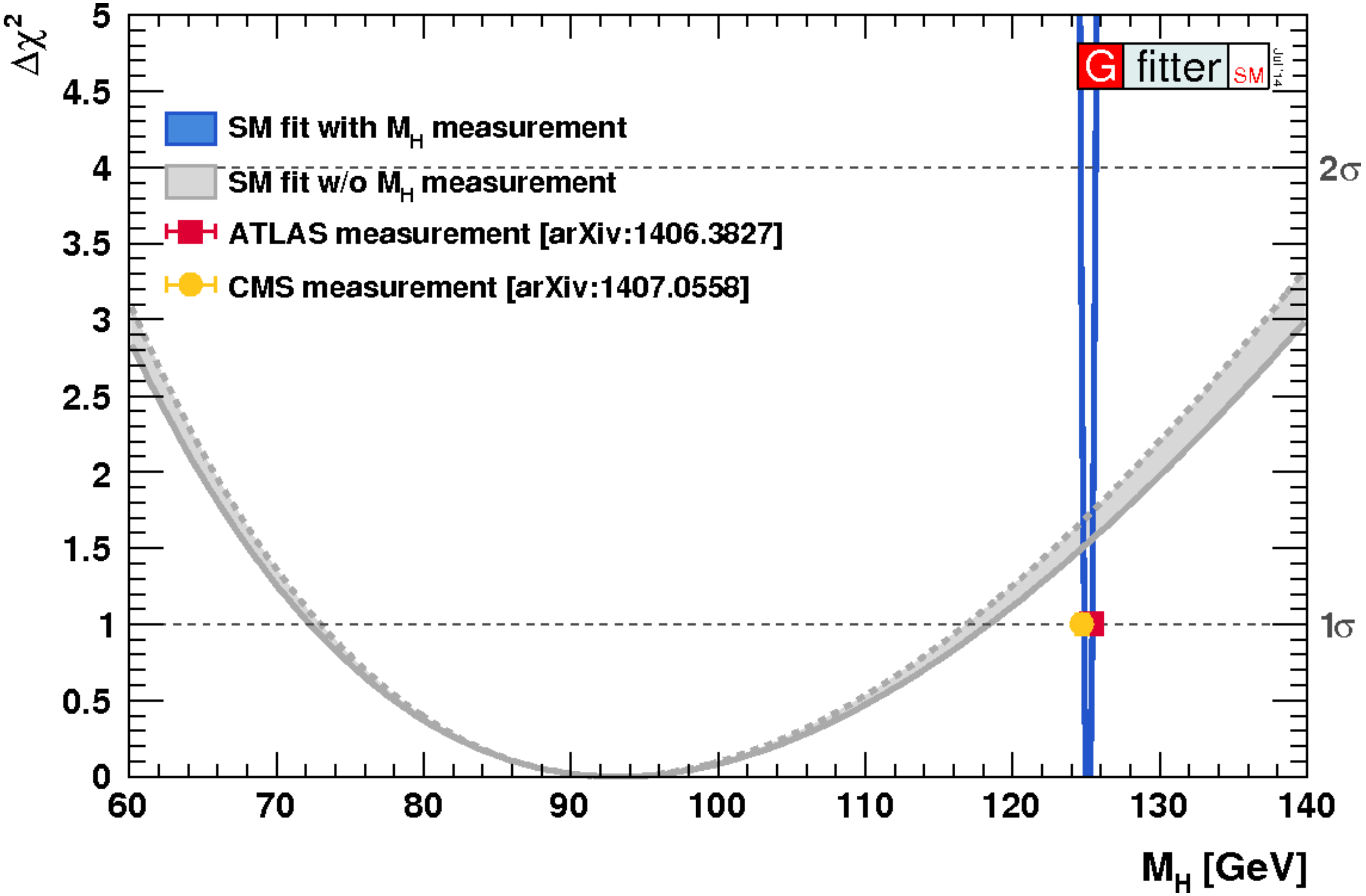
$$V = \mu^2\Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$

$g_{HHH}=3m_H^2/v$



The most challenging coupling to be tested at the LHC

LOOKING FOR SM DEVIATION: MASS



Consistent with SM EWK precision tests

H→μμ & H→ee

BR(H→μμ)=2.2x10^{-4} ~ 1/10 x BR(H→γγ)

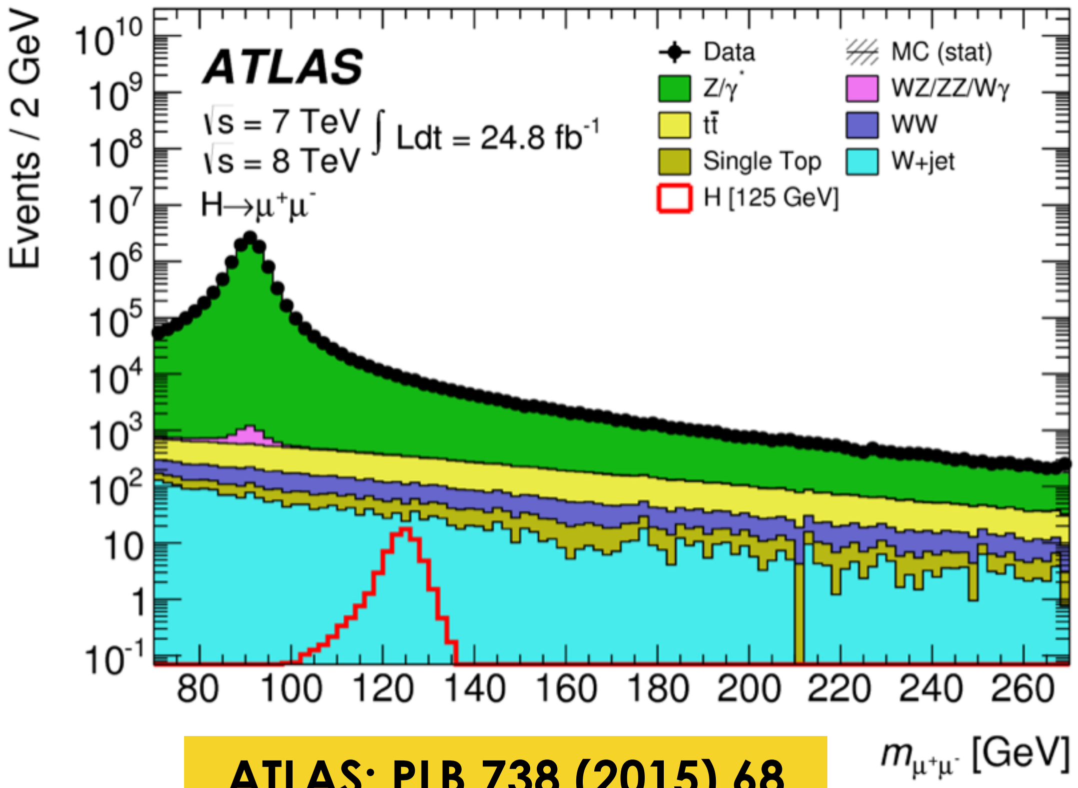
H(125)→μμ 95% CL observed (expected) limits on σ/σ$_{SM}$

ATLAS: PLB 738 (2015)	**7.0(7.2)**
CMS: arXiv:1410.6679	**7.4(6.5)**

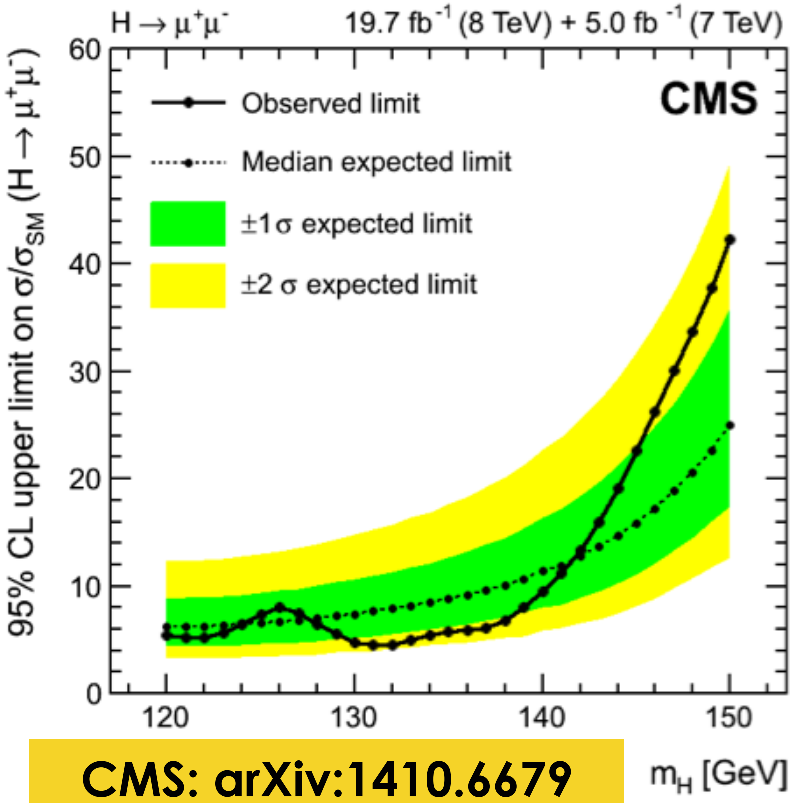
Together with evidence of H→ττ, confirm lepton non-universality

With 300 fb^{-1} @ 13 TeV sensitivity to ~exclude H→μμ

H→ee: CMS put 95% CL exclusion limit on σ x BR(H(125)→ee)=41fb



ATLAS: PLB 738 (2015) 68

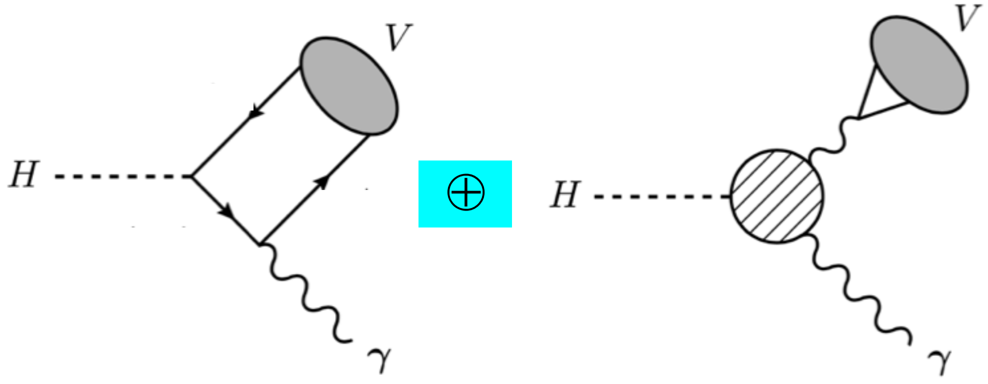


CMS: arXiv:1410.6679

H→J/ψγ,ϒγ

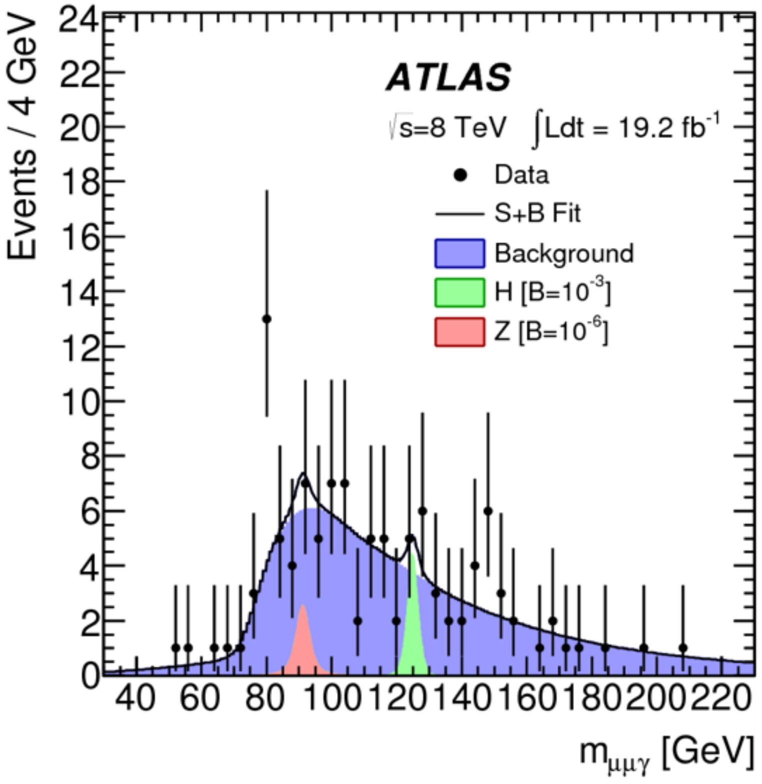
Very small BR

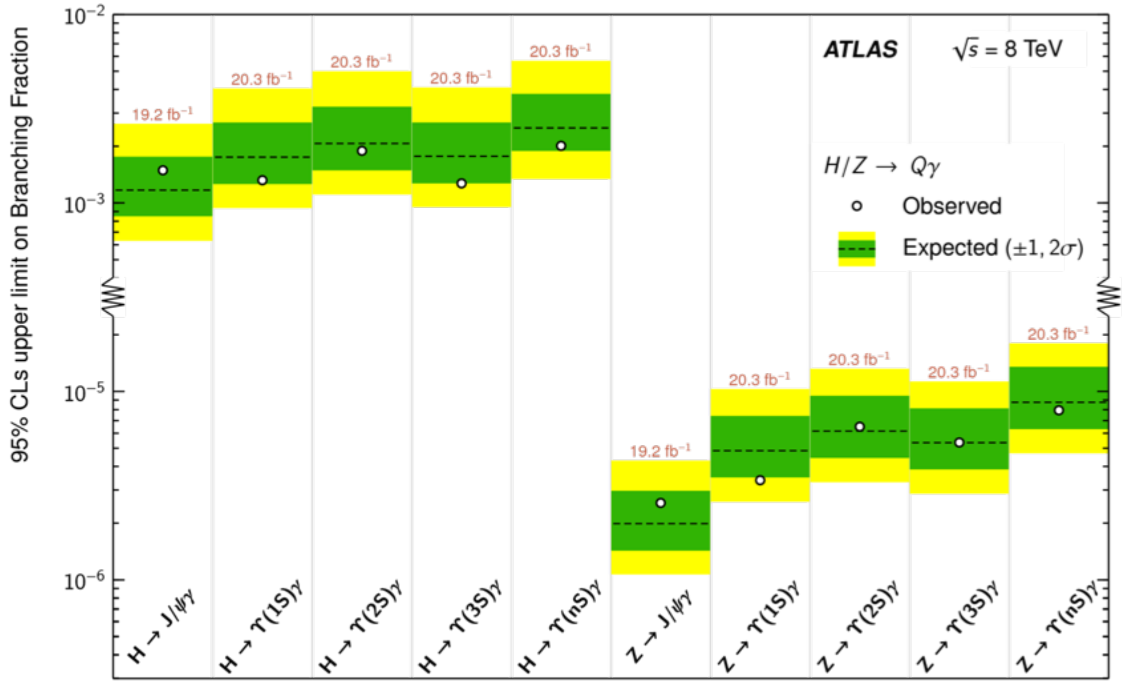
BR(H→J/ψγ) ~ 3x10^{-6}



Limit on H(→J/ψγ) ~ x 540 SM

J/ψ+γ candidates

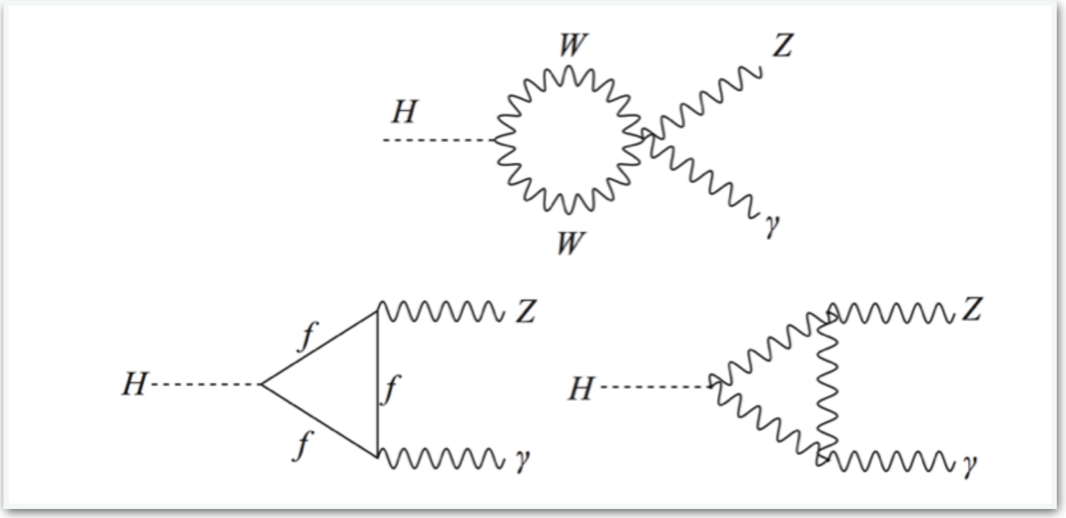




ATLAS: arXiv:1501.03276 NEW

RARE HIGGS DECAYS: $H\to Z\gamma$ & $H\to\gamma^*\gamma\to\mu\mu\gamma$

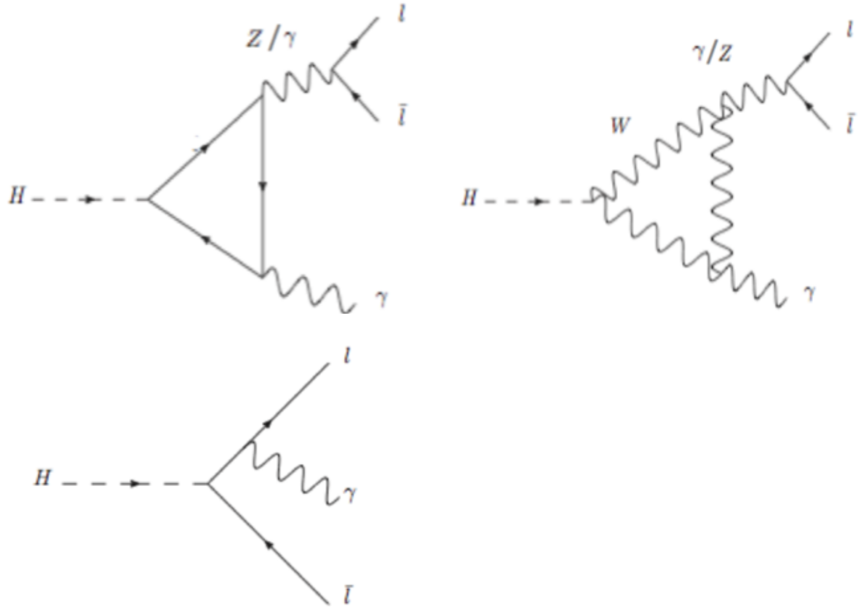
- **Search performed in $Z(\to ee)+\gamma$ and $Z(\to\mu\mu)+\gamma$ channel**



- **Very small BR expected in SM ~0.1%.**
  - New particles/couplings (e.g composite higgs) can be revealed in decays involving loop
- **For h(125) excluding BR enhancement >~ x10 @ 95% CL**

ATLAS: arXiv:1402.3051	>11(9)
CMS: Phys. Lett. B 726(2013) 587	>9.5(10)

- **Dalitz decay**
  - different contributions to the same final state, not yet disentangled
  - wrt to $Z\gamma$: $m_{\mu\mu}<20$ GeV

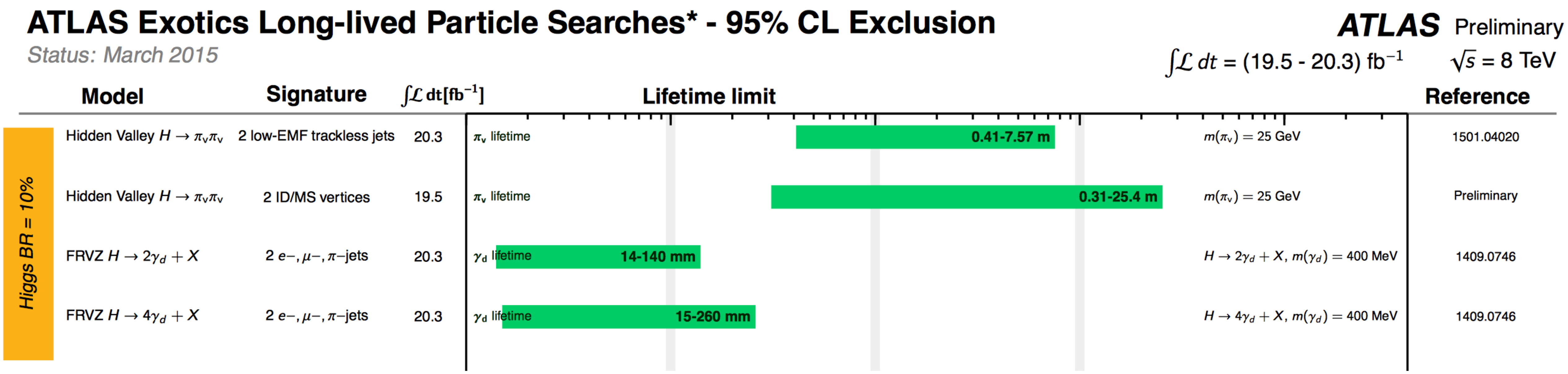


- **Sensitivity similar to $Z\gamma$: excluding >x11 @ 95% CL**

CMS HIG-14-003	>11(7)

NEW

H→DARK/HIDDEN SECTOR



ATLAS Exotics Long-lived Particle Searches* - 95% CL Exclusion

Status: March 2015

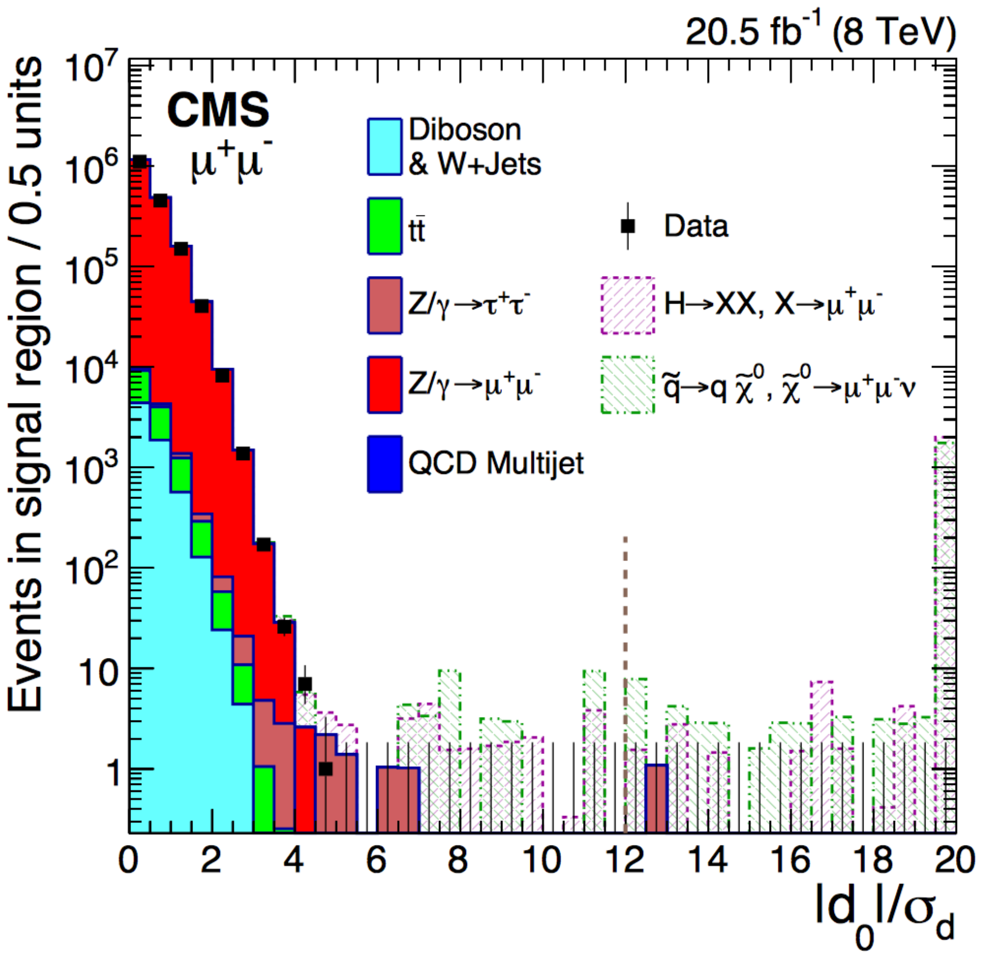
ATLAS Preliminary

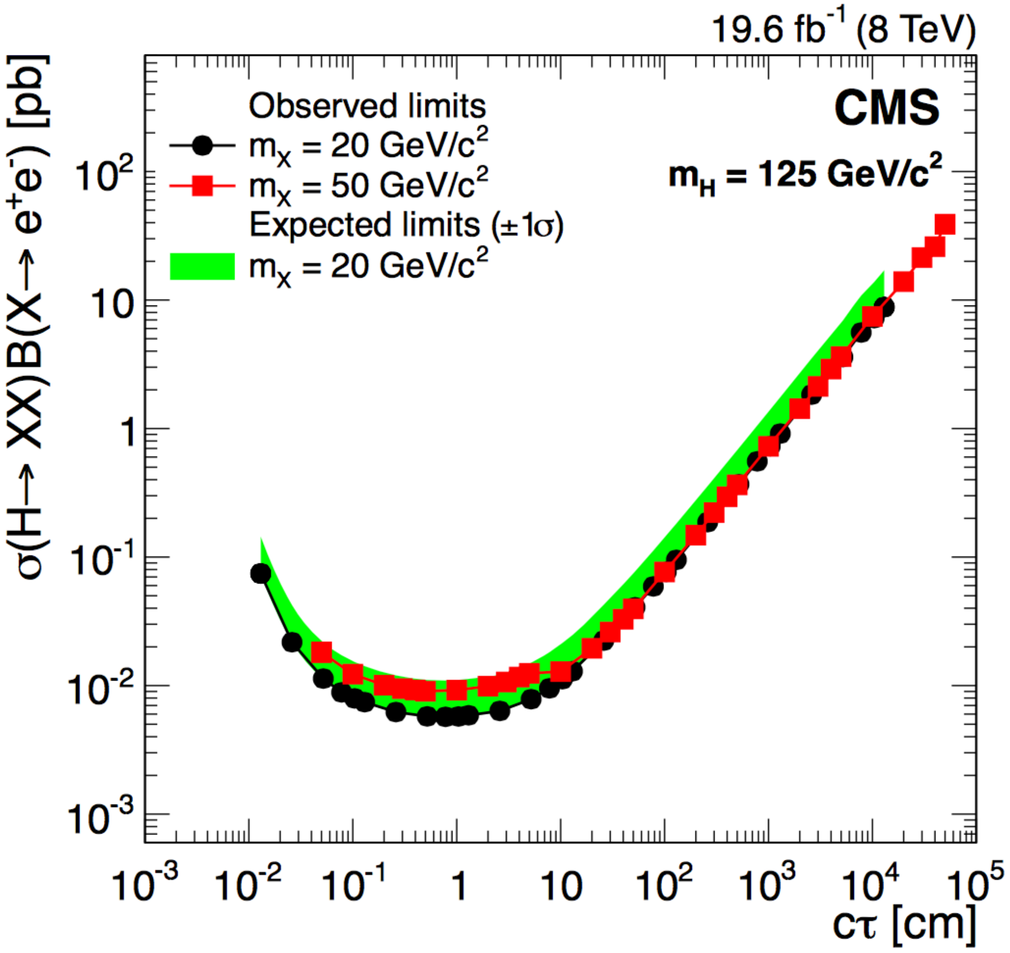
$\int \mathcal{L}\, dt = (19.5 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 8$ TeV

Higgs BR = 10%

Model	Signature	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Lifetime limit		Reference
Hidden Valley $H \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime 0.41-7.57 m	$m(\pi_v) = 25$ GeV	1501.04020
Hidden Valley $H \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.31-25.4 m	$m(\pi_v) = 25$ GeV	Preliminary
FRVZ $H \to 2\gamma_d + X$	$2\ e-, \mu-, \pi-$jets	20.3	γ_d lifetime 14-140 mm	$H \to 2\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
FRVZ $H \to 4\gamma_d + X$	$2\ e-, \mu-, \pi-$jets	20.3	γ_d lifetime 15-260 mm	$H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746

Displaced lepton pairs





H→ DARK SECTOR

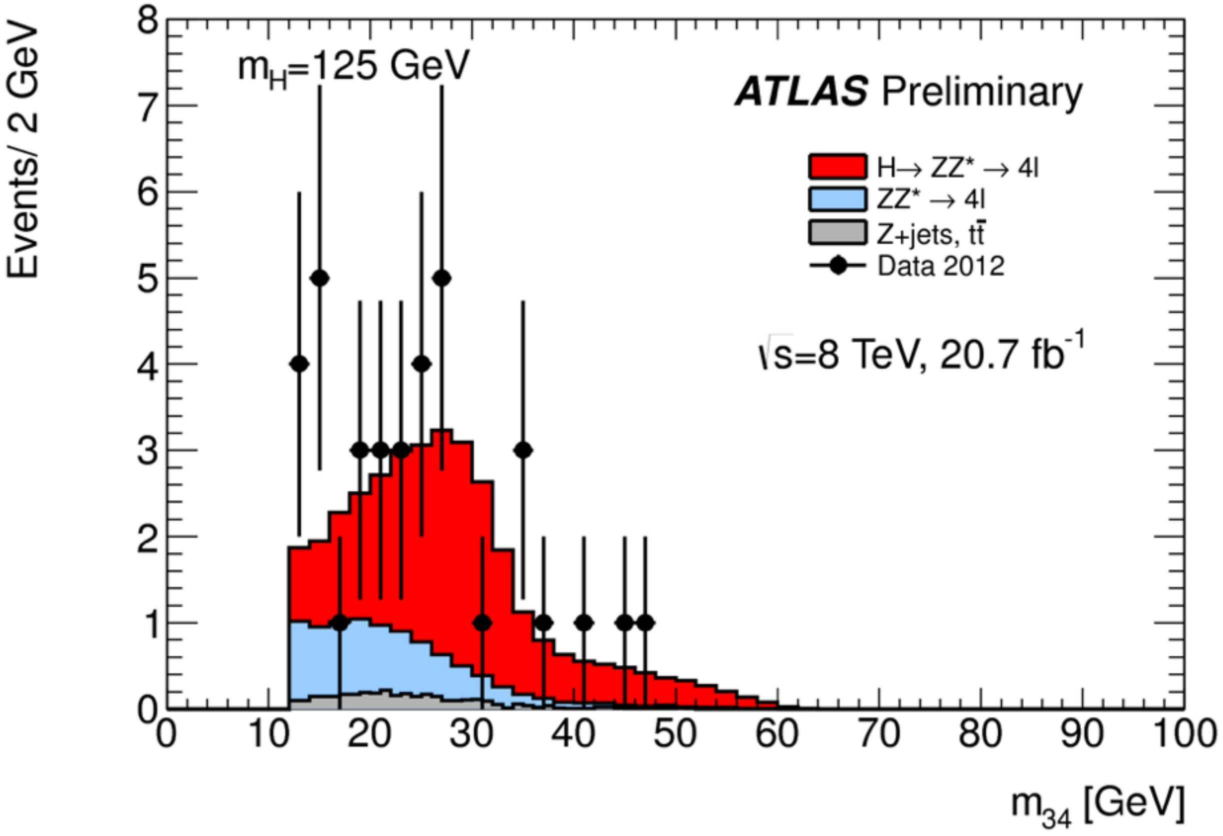
If dark sector, e.g. new a $U(1)_d$ gauge boson, Higgs could decay to its dark boson Z_d

$U(1)_d$ unbroken: $H \to ZZ_d$, coupling via kinematic mixing

$U(1)_d$ broken: H mixing with dark Higgs, $H \to Z_dZ_d$

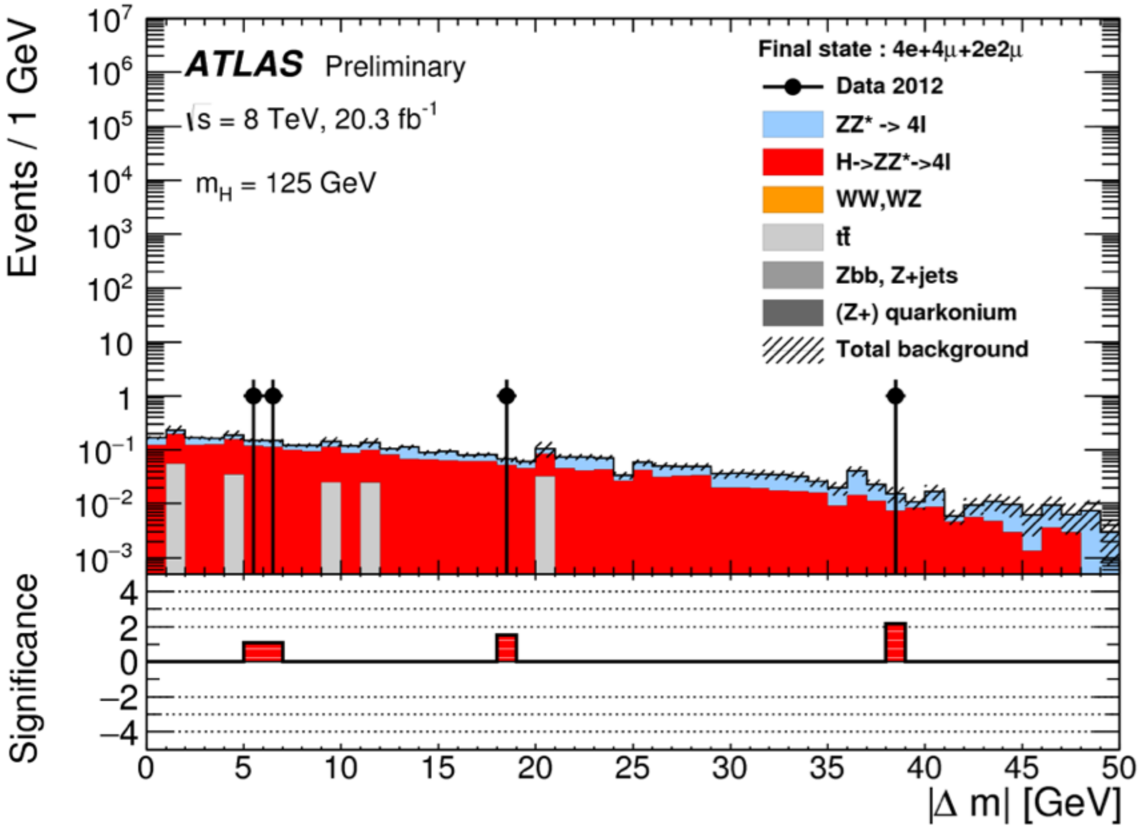
ATLAS-CONF-2015-003

$H \to ZZ_d \to 4l$: same selection as Higgs $H \to ZZ^* \to 4l$, look for a bump in m_{34}



Limit on $BR(H \to ZZ_d)$ ~10-40% for m_{Zd} in 15-60 GeV range

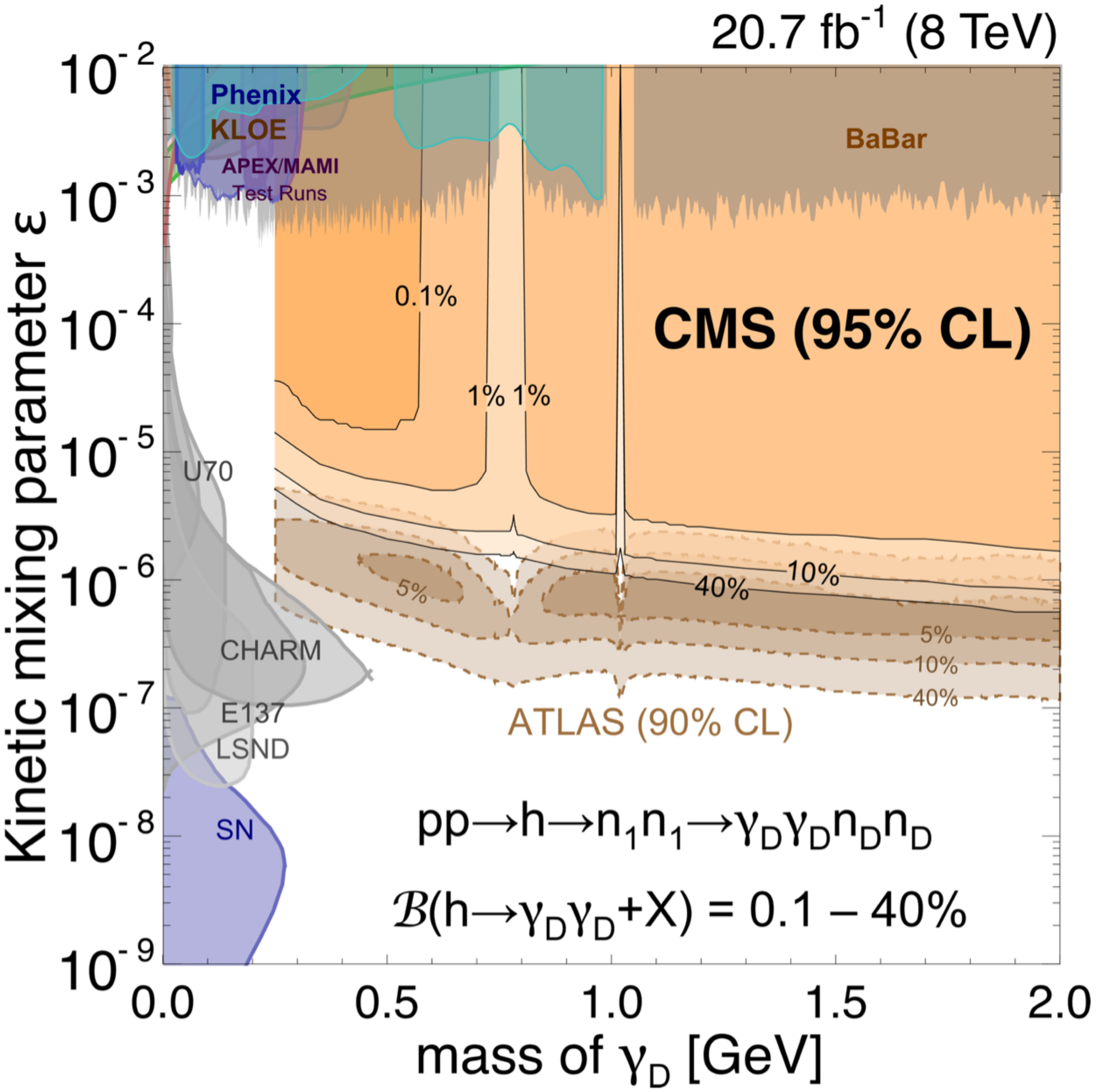
$H \to Z_dZ_d \to 4l$: small Δm between pairs of opposite sign same flavour leptons



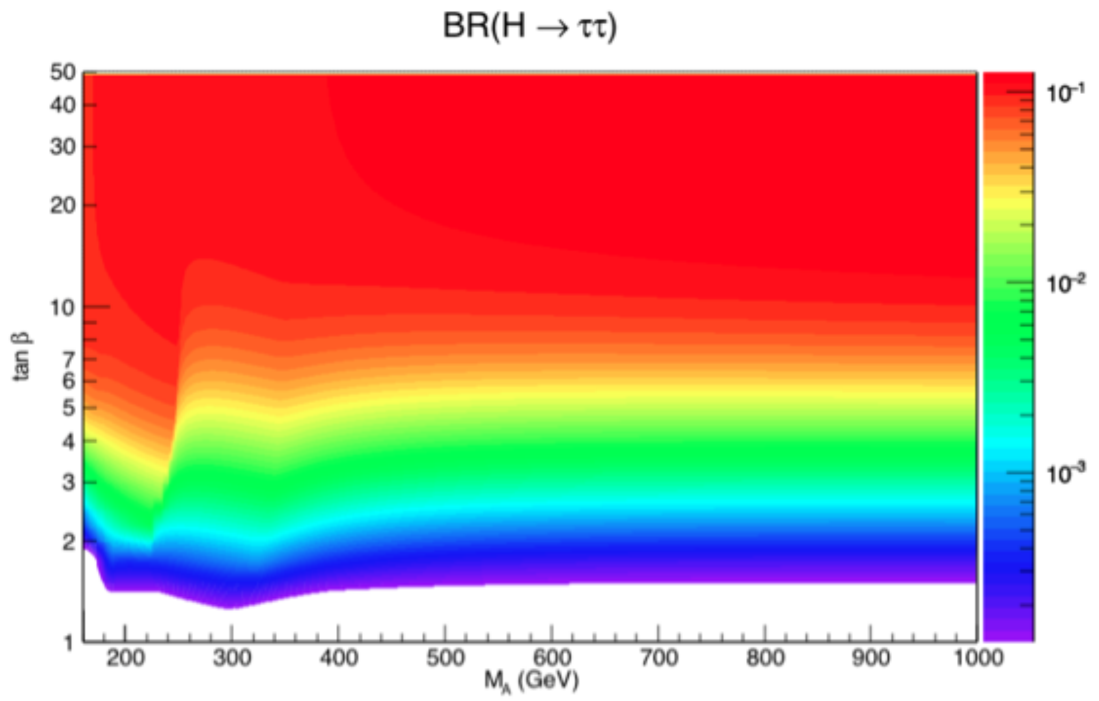
Limit on $BR(H \to Z_dZ_d)$ ~20% for m_{Zd} in 15-60 GeV range

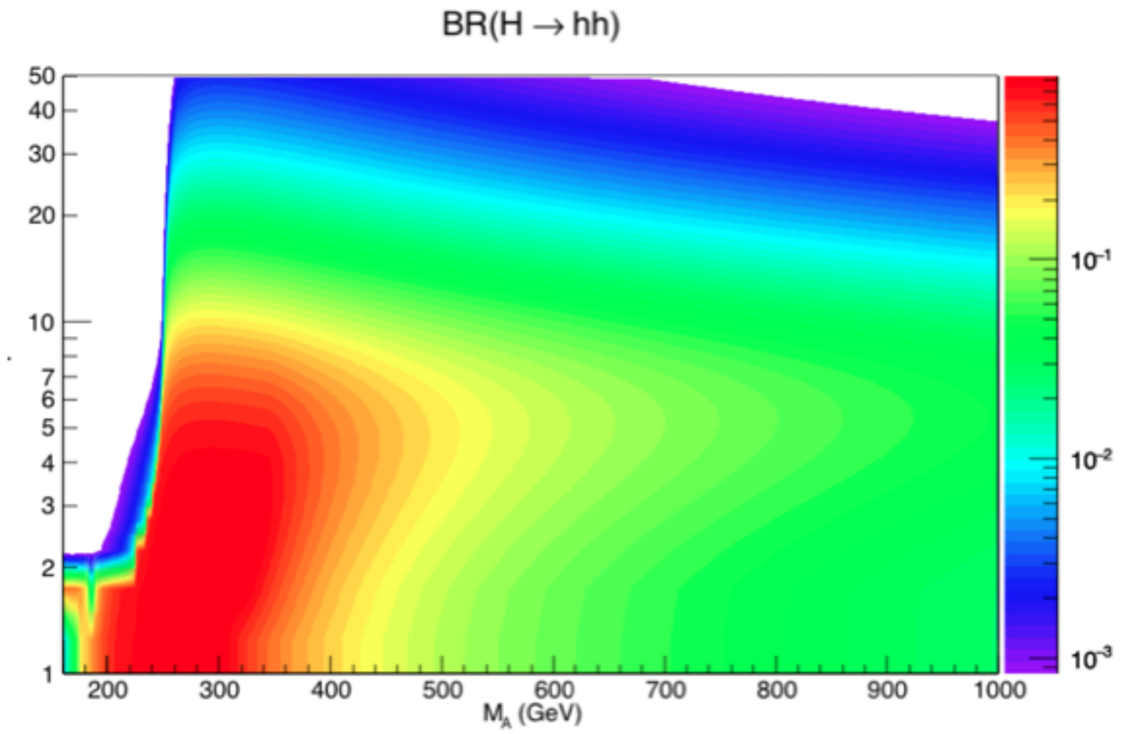
H→ DARK SECTOR

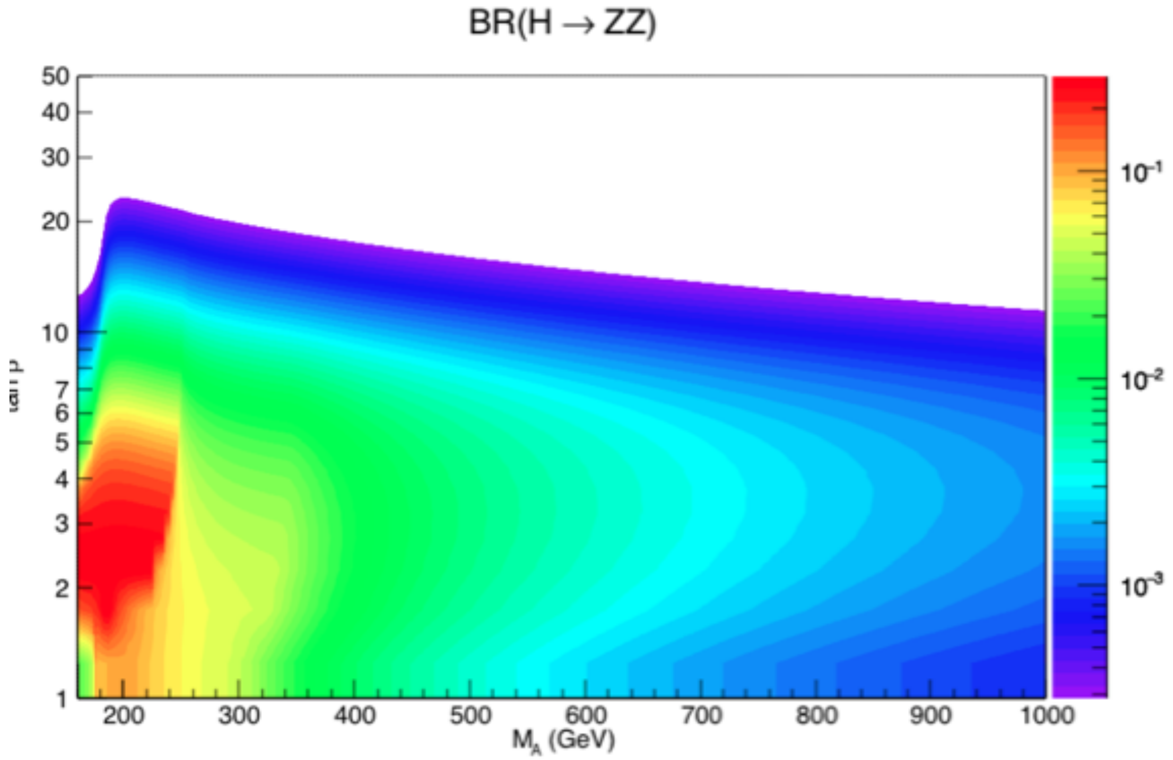
H→2γ_d(→μμ)+X

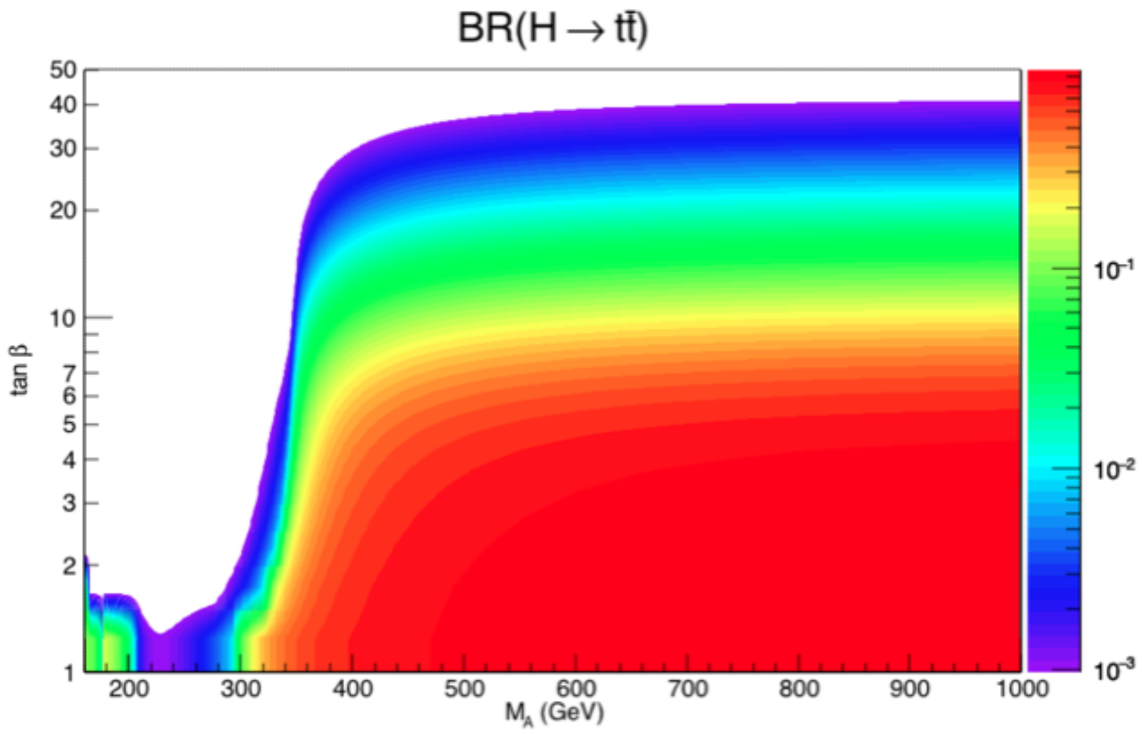


HMSSM: Heavy Higgs Decays

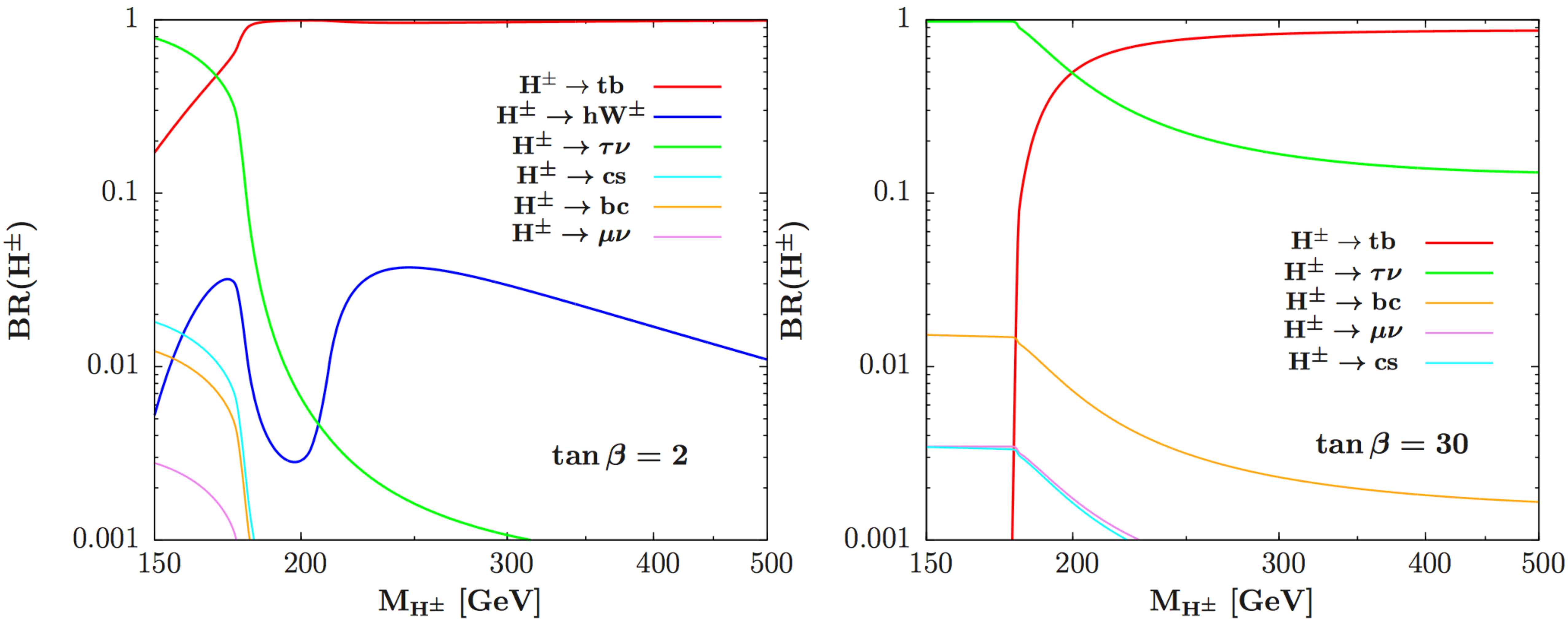

BR(H → ττ)


BR(H → hh)


BR(H → ZZ)


BR(H → tt̄)

MSSM: CHARGED HIGGS DECAY



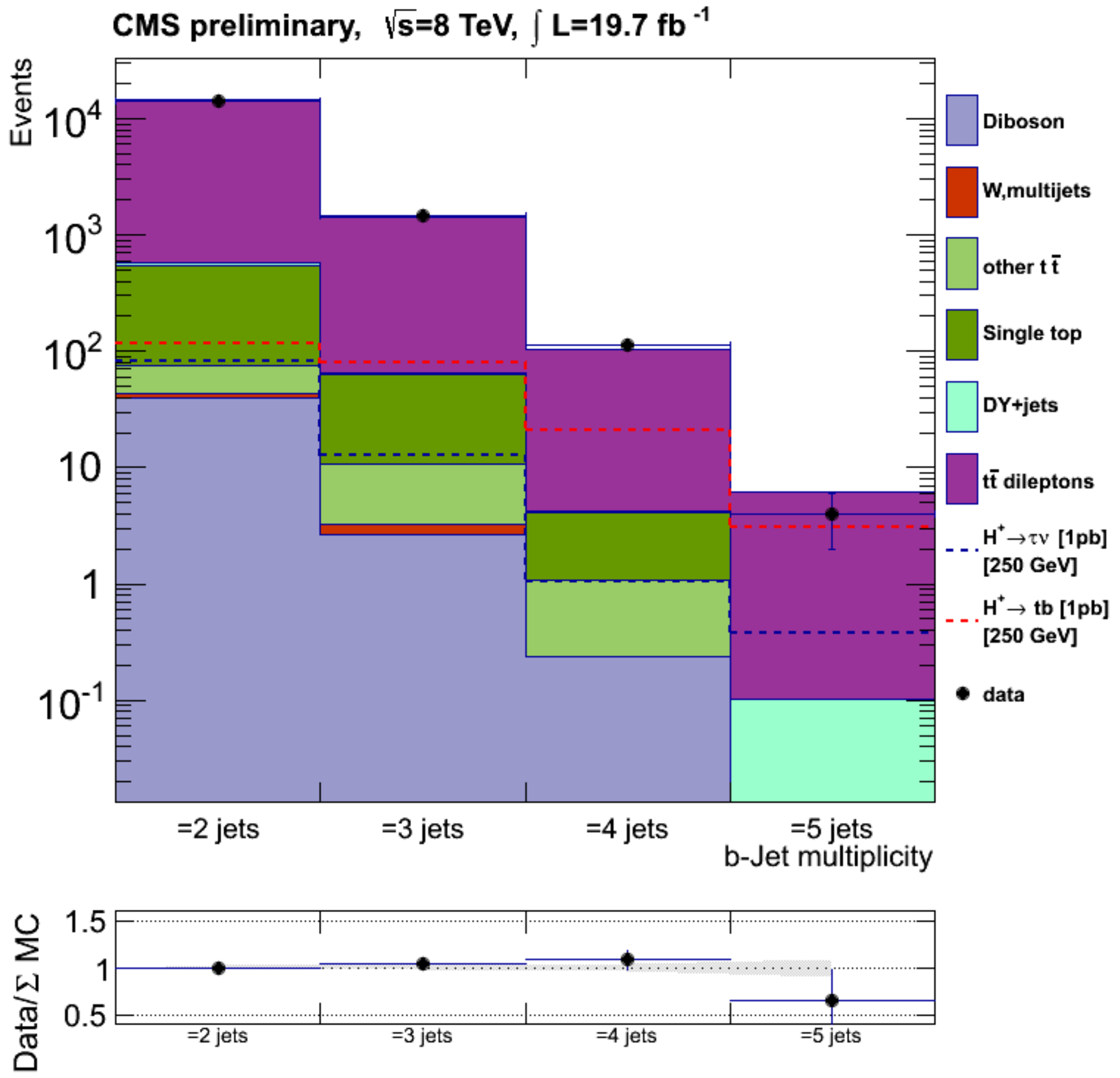
CHARGED HIGGS

High m_{H+} mass: $H^+ \to tb$

di-lepton + b-jets final state

sensitive to both $H^+ \to tb$ & $H^+ \to \tau\nu$

interpretation provided for $BR(H^+ \to tb)=1$ or $BR(H^+ \to \tau\nu)=1$



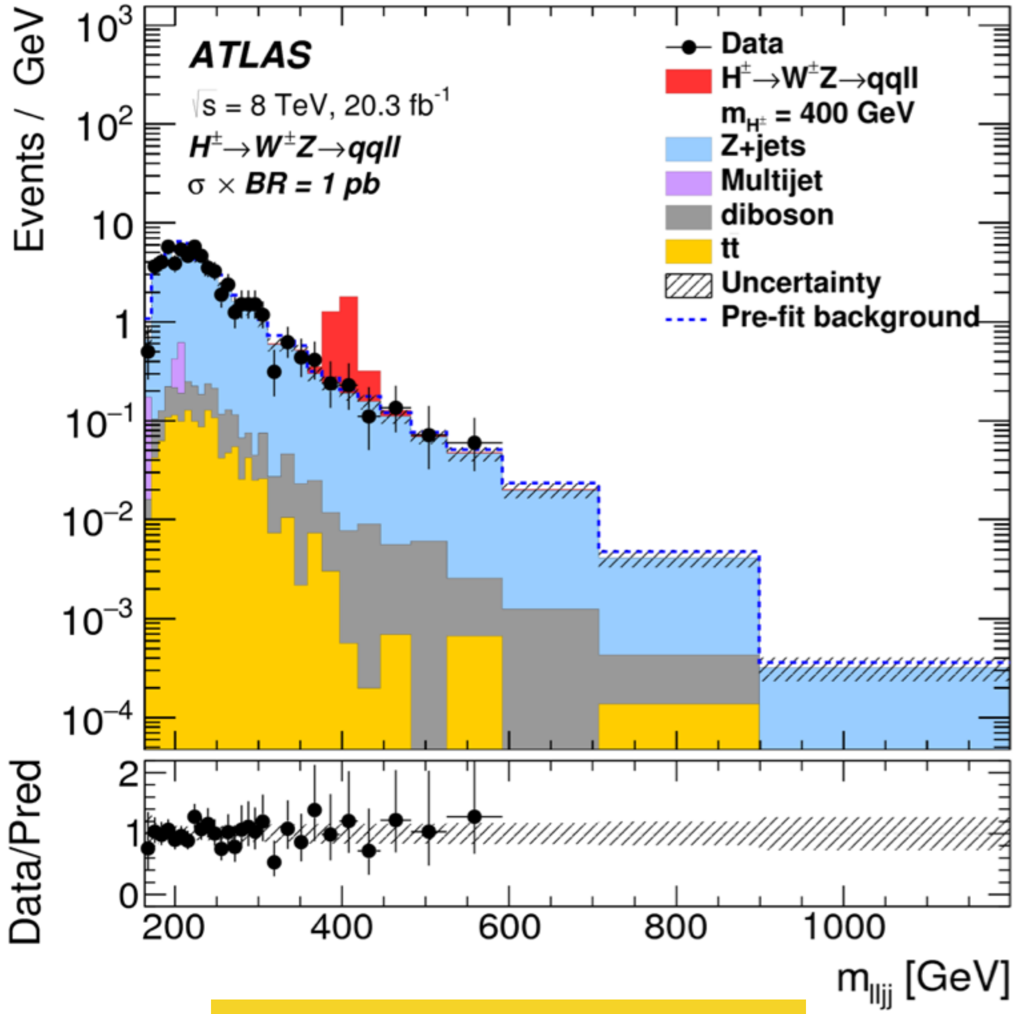
CMS-HIG-13-026

Higgs triplet model: $H^\pm \to W^\pm Z$

allowed at tree level

Search performed with VBF production of charged Higgs

2 jets (VBF topology), 2 central jets (W decay), 2 leptons (Z)

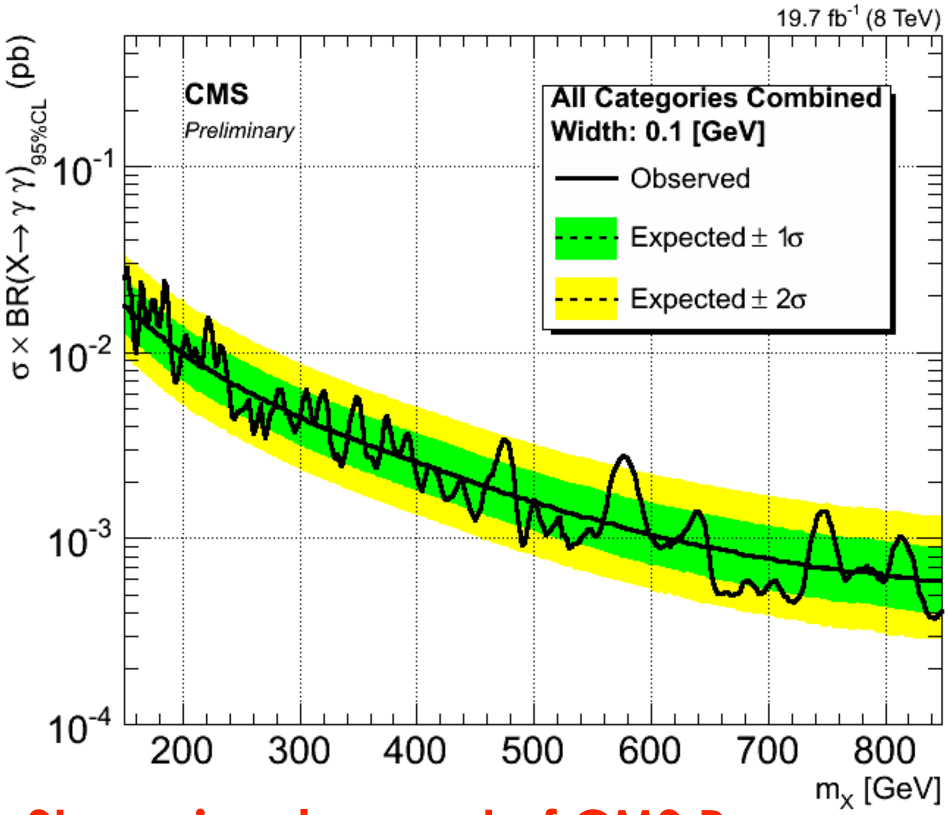


ATLAS-HIGG-2014-13

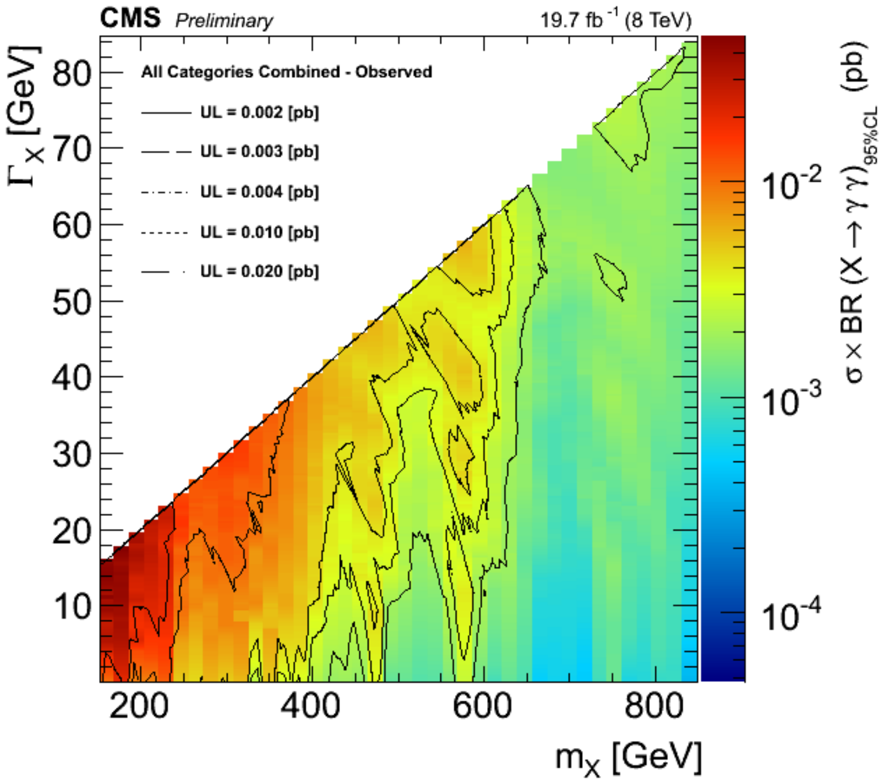
$\phi \to \gamma\gamma, \phi \to Z\gamma$

$\phi \to \gamma\gamma$

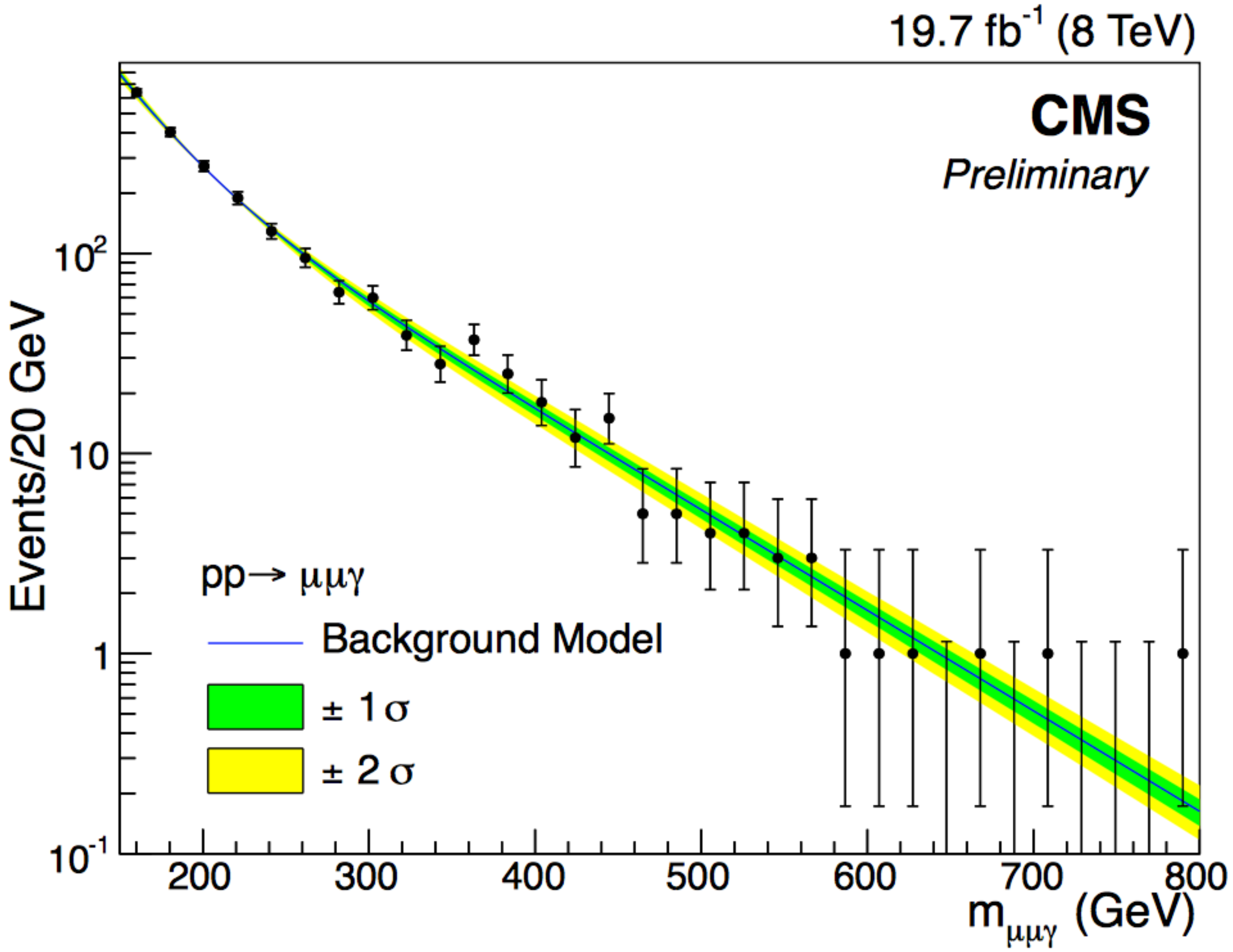
CMS-HIG-14-006



Strong involvement of CMS Rome group



$A \to Z(\to \mu\mu)\gamma$



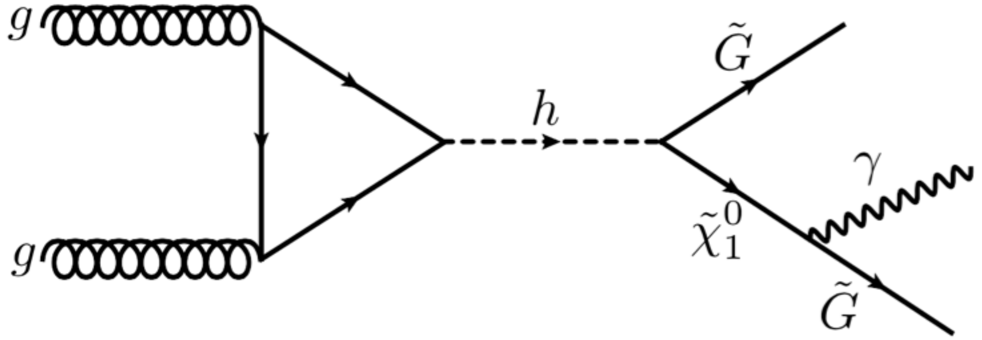
CMS-HIG-14-031

H→γ+MET

Higgs decays to neutralinos/gravitinos: γ+MET final state

GMSB $h \to \tilde{G}\,\tilde{\chi}^0 \to \tilde{G}\,\tilde{G}\,\gamma$

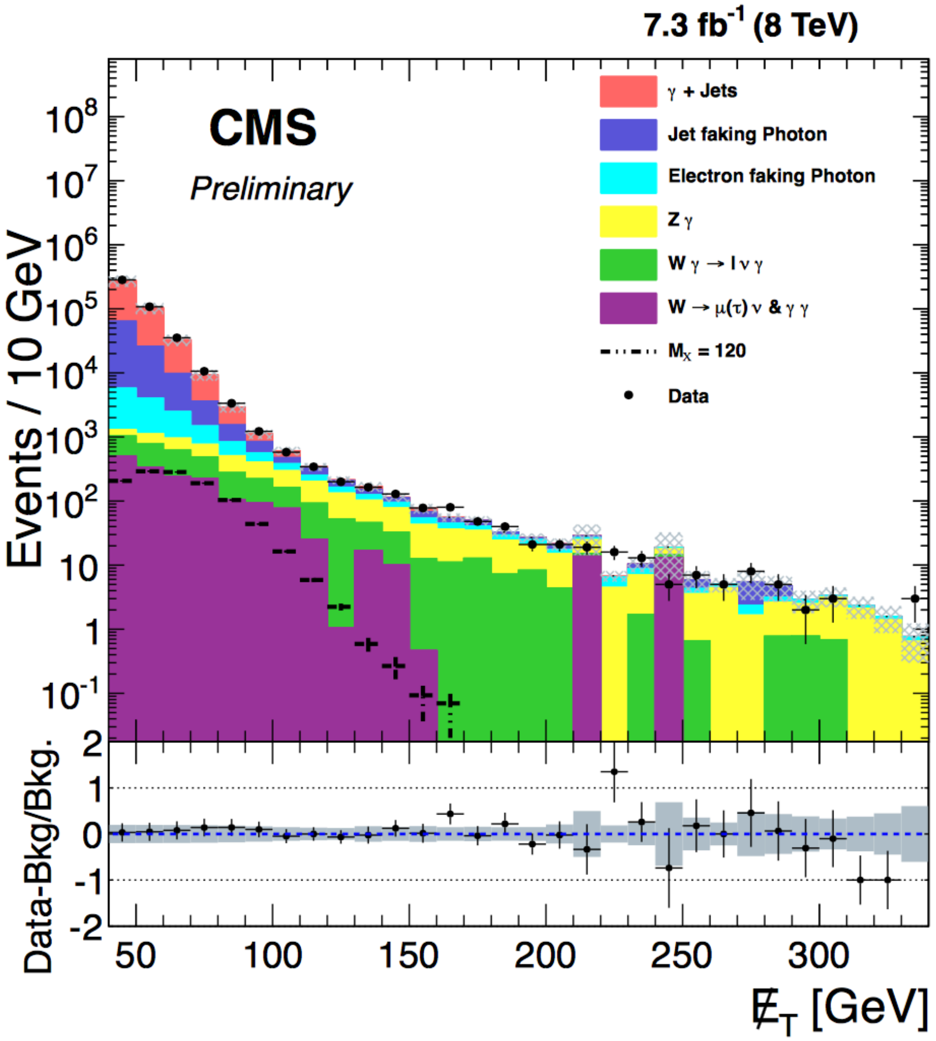
NMSSM $h \to \tilde{\chi}^0_2\,\tilde{\chi}^0_1 \to \tilde{\chi}^0_1\,\tilde{\chi}^0_1\,\gamma$

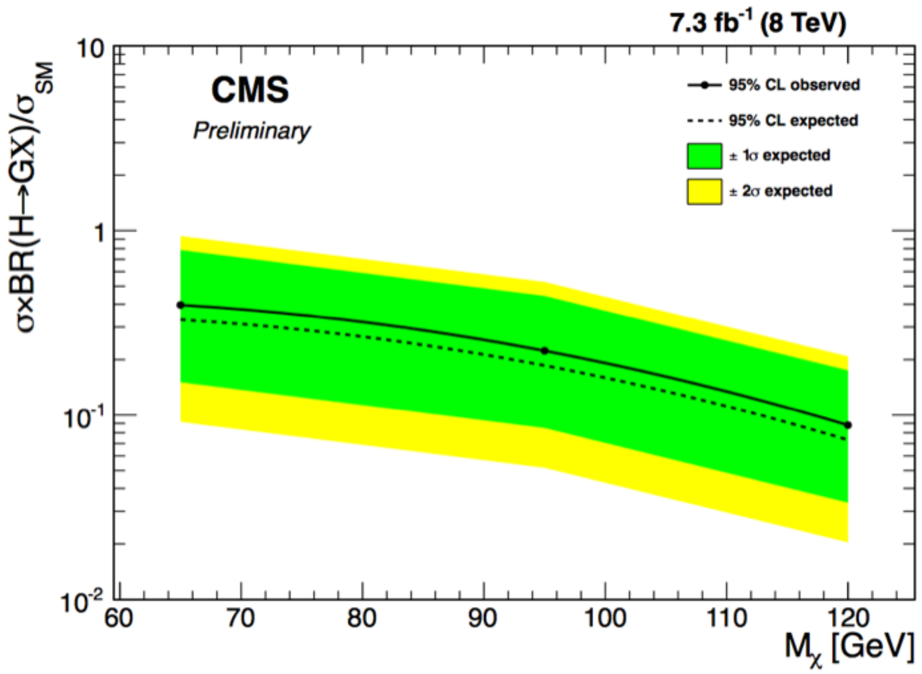


CMS: inclusive analysis

γ p_T>45 GeV

ATLAS: associated VBF production





Optimized for
$m_h/2 < m_{\tilde{\chi}^0_1} < m_h$
below γγ+MET will dominate

CMS: HIG-14-024