Beyond the (already observed) Higgs

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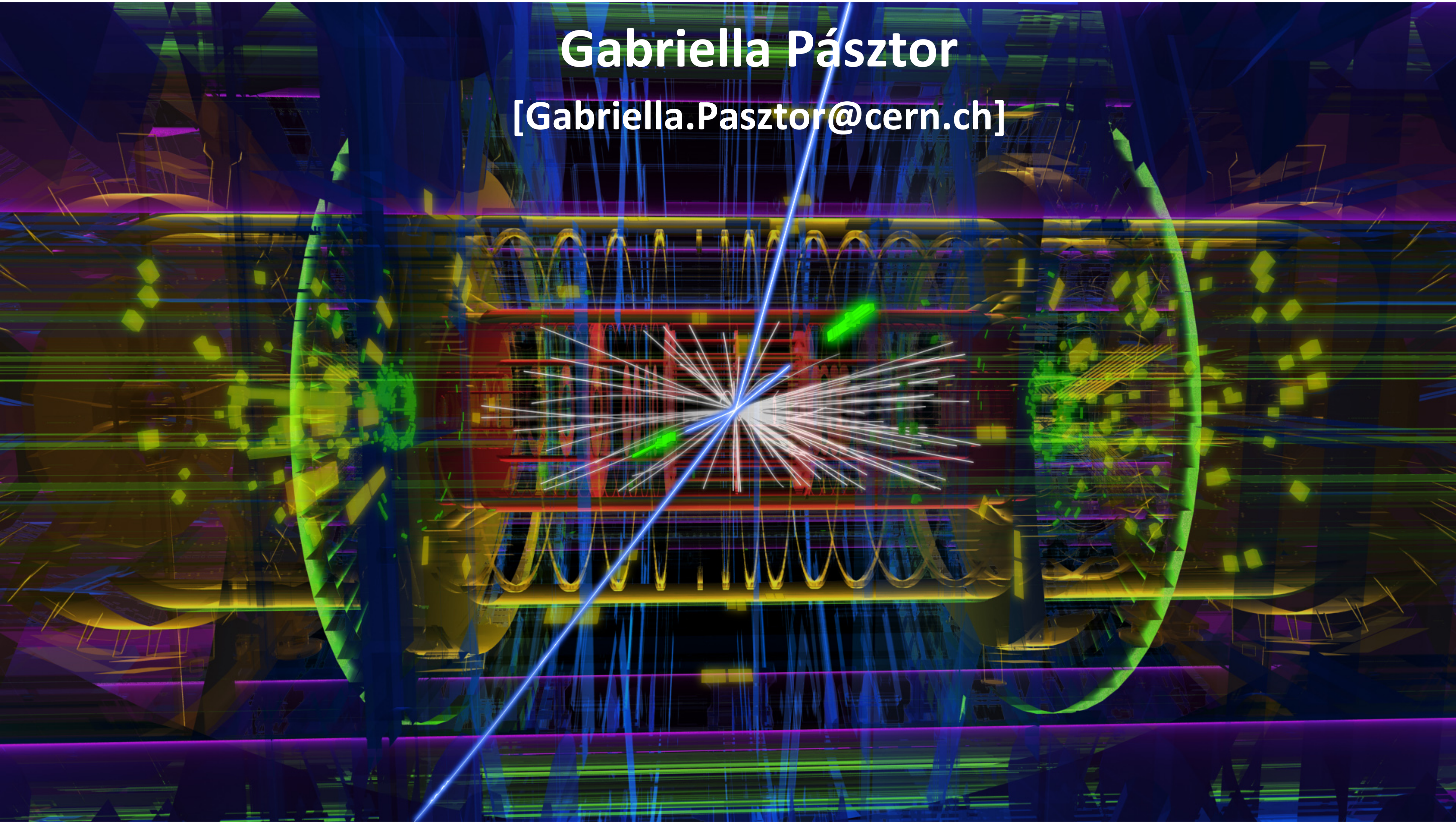
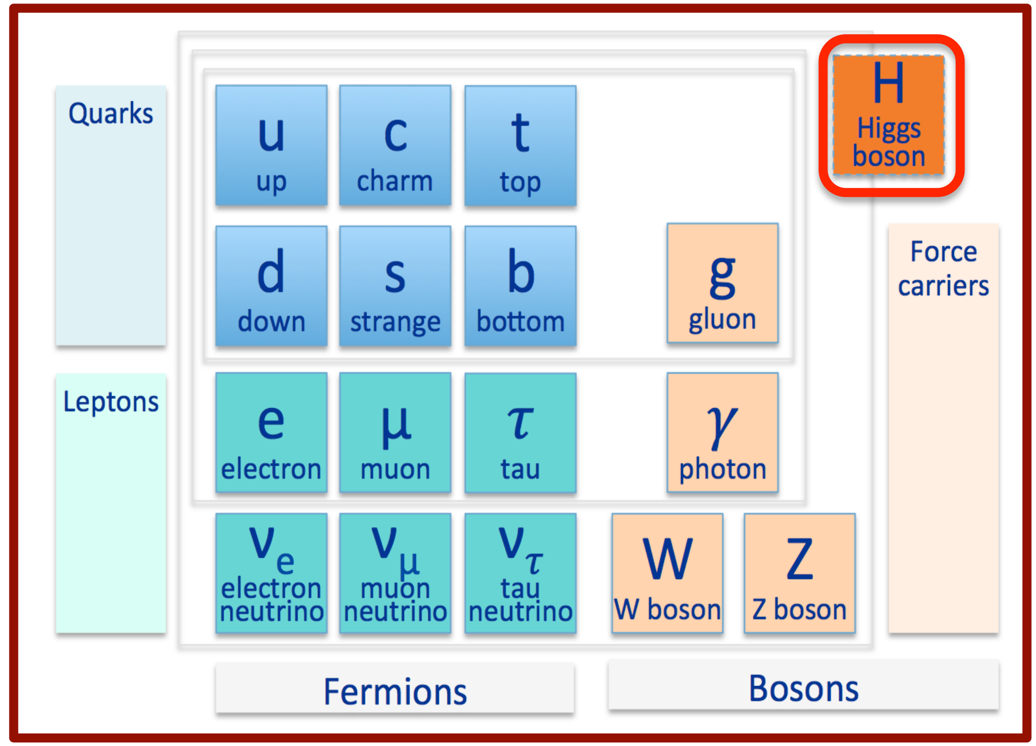


Zimányi School, Budapest, 6 December 2013

Status quo: the Standard Model after LHC Run1

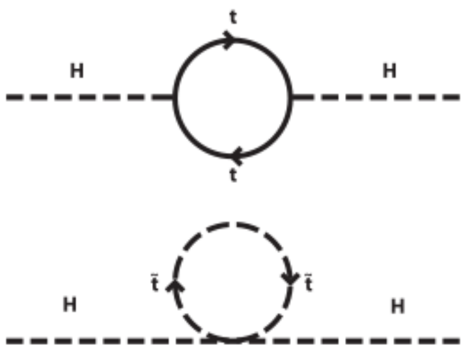
- ATLAS and CMS discovered a Higgs boson with m = 125.5 GeV, so far compatible with SM
- No other new particle seen at LHC
- SM complete and describes with huge success phenomena observed in collider experiments
- SM can not be the final theory!
- Deviations due to new physics (in the Higgs sector and elsewhere) might be subtle
- Precision measurements might give the key to discoveries
- ... parallel to direct searches for new physics!



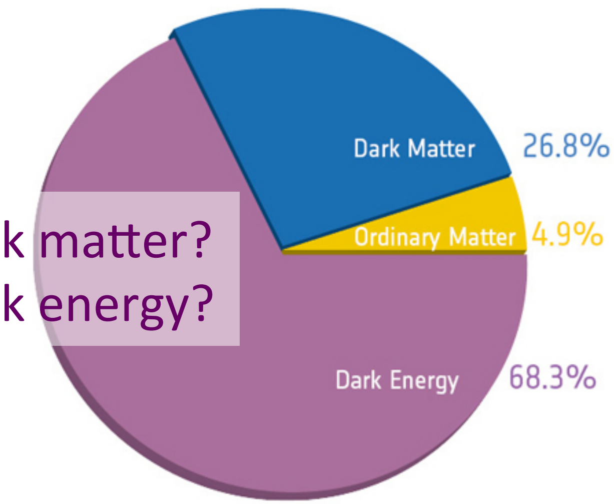
- BEH mechanism provides mass to the W and Z bosons
- Higgs boson regularizes weak vector-boson scattering and makes the theory consistent

Why go beyond the Standard Model?

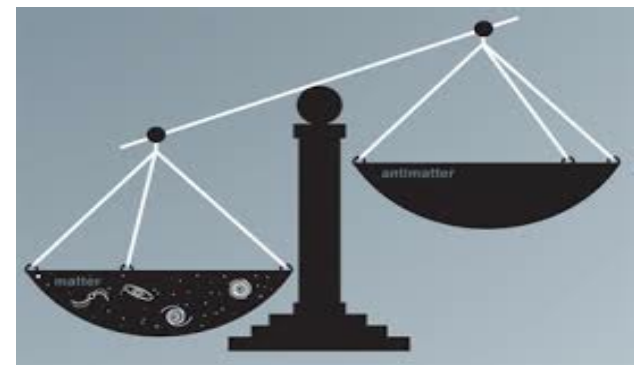
Conceptual weaknesses, observational hints!



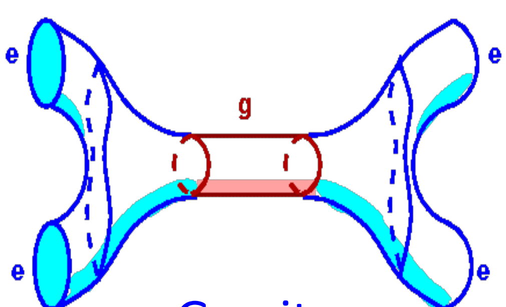
Higgs mass stability?
(Hierarchy problem)



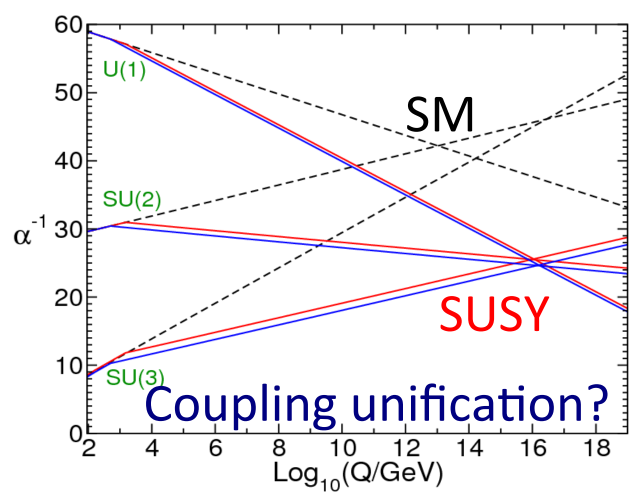
Dark matter?
Dark energy?



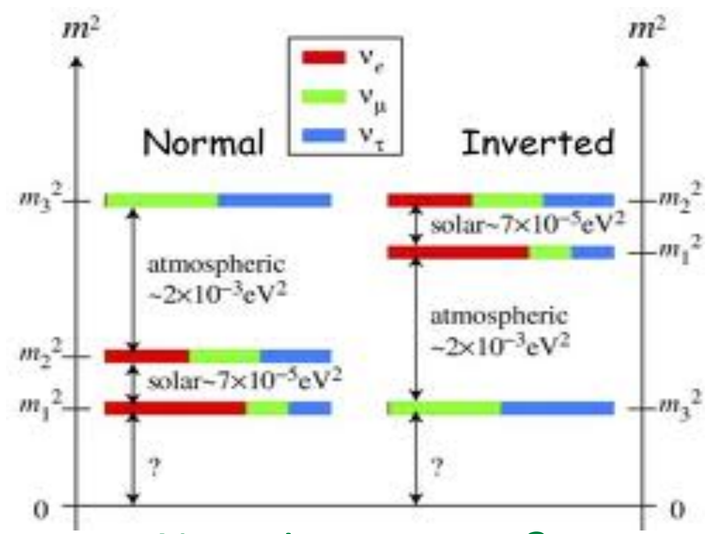
Matter – anti-matter asymmetry? (CP violation)



Gravity +
gauge interactions (ToE)?



Coupling unification?



Neutrino masses?

The way ahead
to understand EWSB and discover the more fundamental theory

Some questions after the Higgs discovery:

- Properties as predicted by SM? Spin, parity, CP violation, couplings? With what precision can we extract them?
- Can we measure couplings to 2nd generation fermions (muon, c quark)?
- Can we reconstruct the Higgs potential? Can we measure Higgs self coupling, i.e. di-Higgs production?
- Does the Higgs boson regularize the VV scattering fully? Do other processes beyond the SM contribute?
- Is the new boson alone? Can we discover its (neutral and/or charged) partners?
- Is it a fundamental scalar or a composite particle?
- What stabilizes the Higgs mass against radiative corrections? SUSY? ED? Something else?
- Does the Higgs open a window to new physics?

The program:

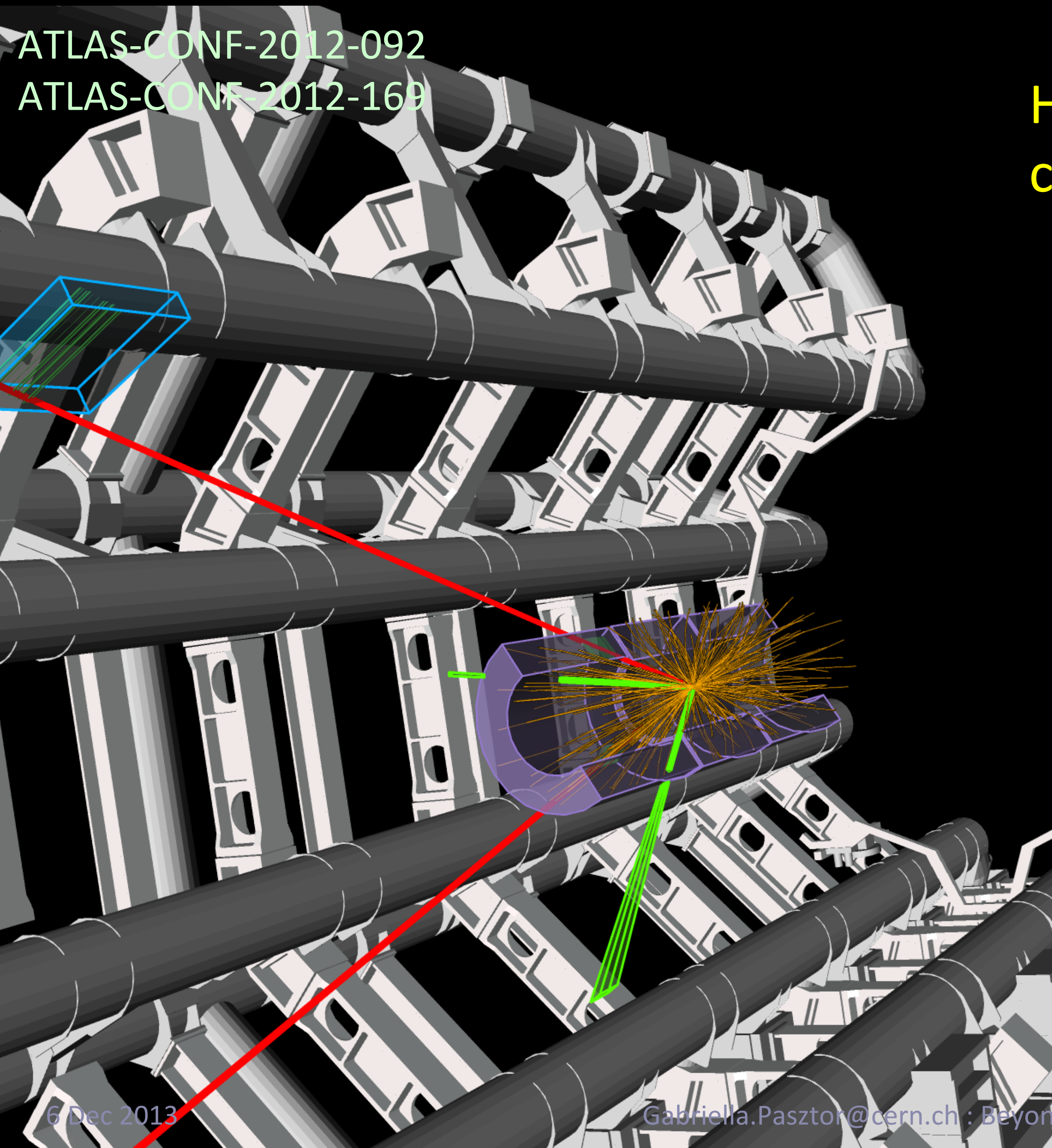
1) Measure precisely the properties of the Higgs boson
2) Look for additional Higgs bosons
3) Study massive EW vector boson scattering and triple gauge boson production
   - measure Quartic Gauge Couplings / test the SM gauge structure
   - sensitive to the scalar sector / EWSB model
4) Look directly for new phenomena
   (SUSY, new gauge bosons W'/Z', extra dimensions... and the unexpected!)

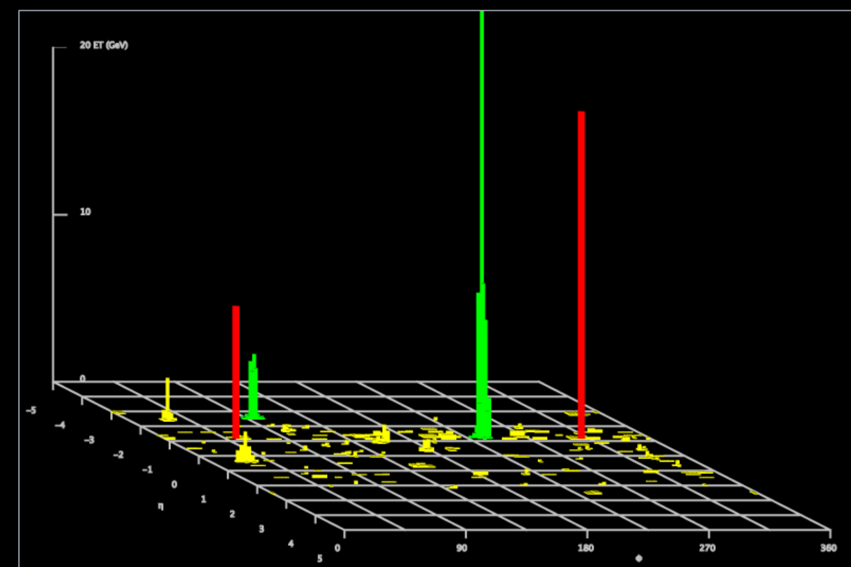
Higgs property measurements

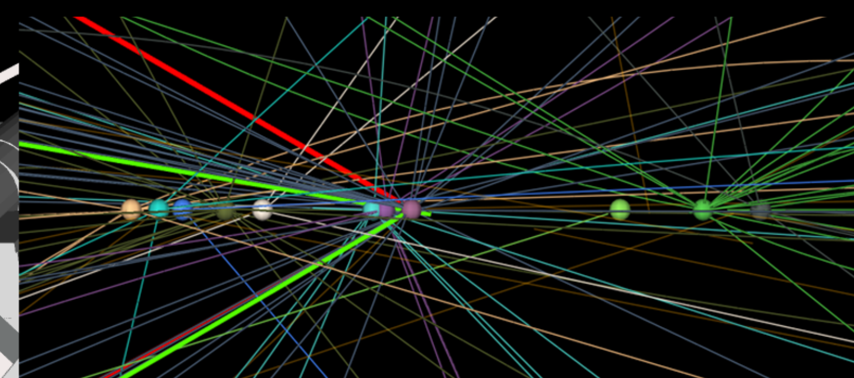
ATLAS-CONF-2012-092
ATLAS-CONF-2012-169

$H \rightarrow ZZ^{*} \rightarrow ee\,\mu\mu$ candidate

ATLAS EXPERIMENT
http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST





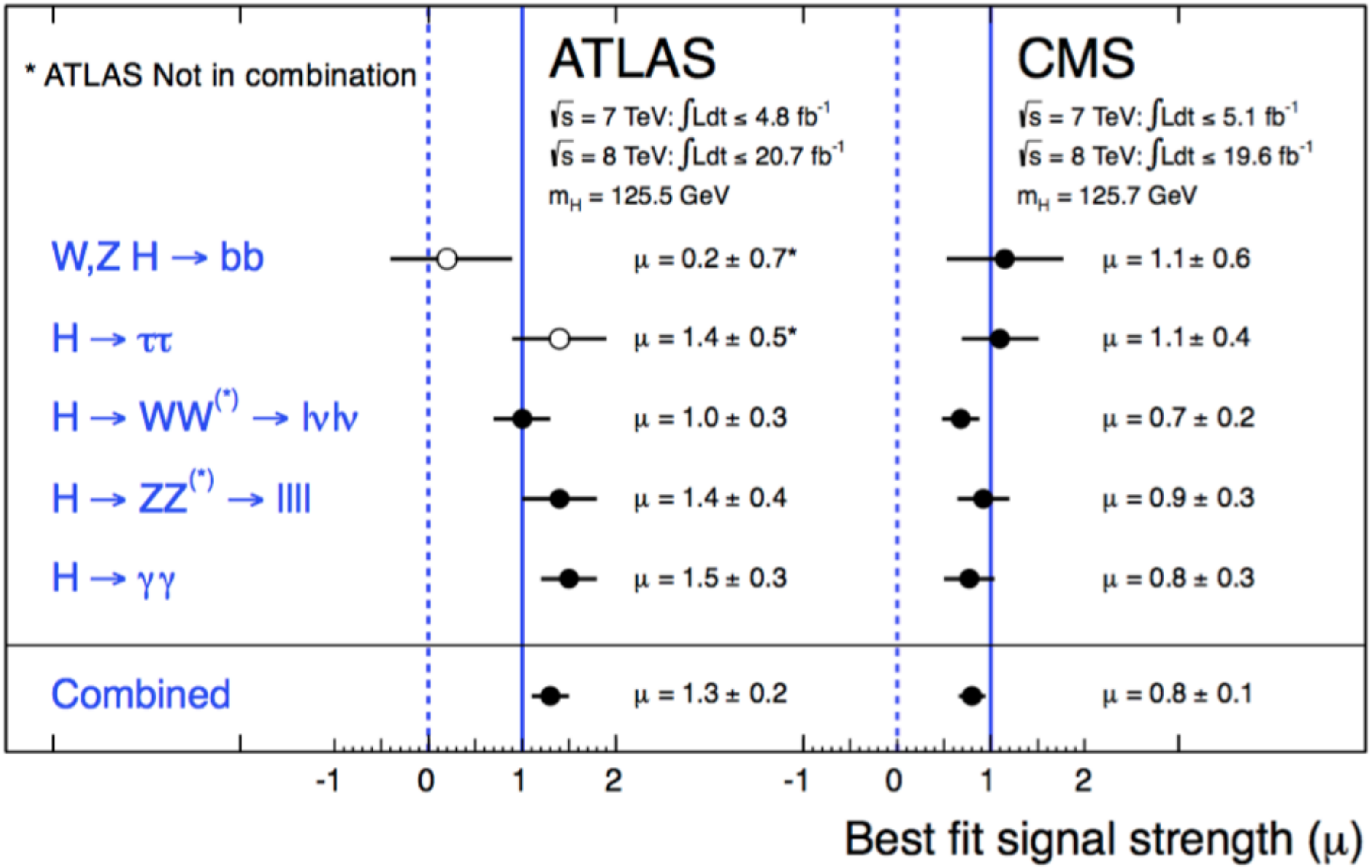


Higgs production cross-section

$$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$

PLB 726 (2013) 88-119

CMS-PAS-HIG-13-005



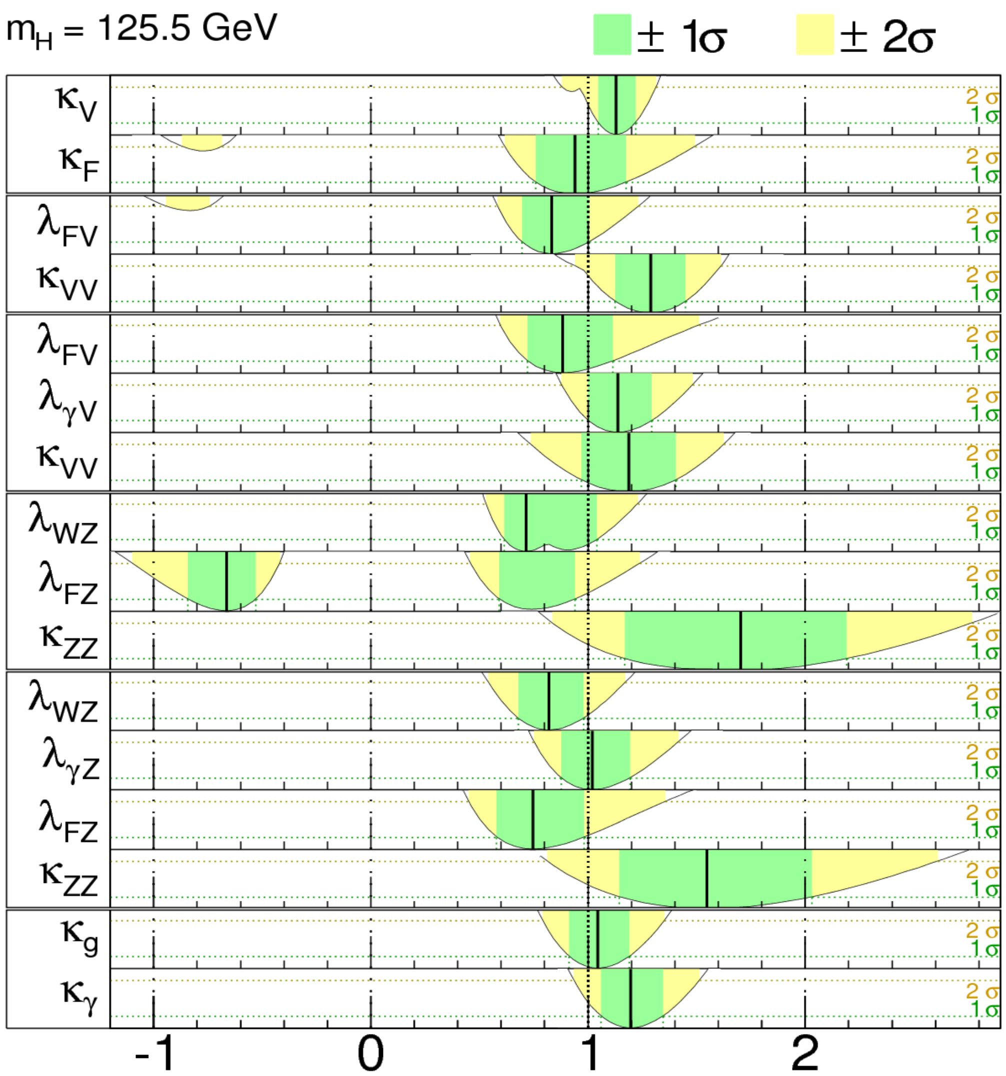
Tevatron combined (bb, $\tau\tau$, $\gamma\gamma$, WW^*):
$\mu = 1.44 \pm 0.6$

Excellent agreement with SM within current precision of 10-20%

Coupling constant scale factors

$\kappa_i \equiv g_i / g_i^{SM}$

Measuring diffeent production and decay channels....



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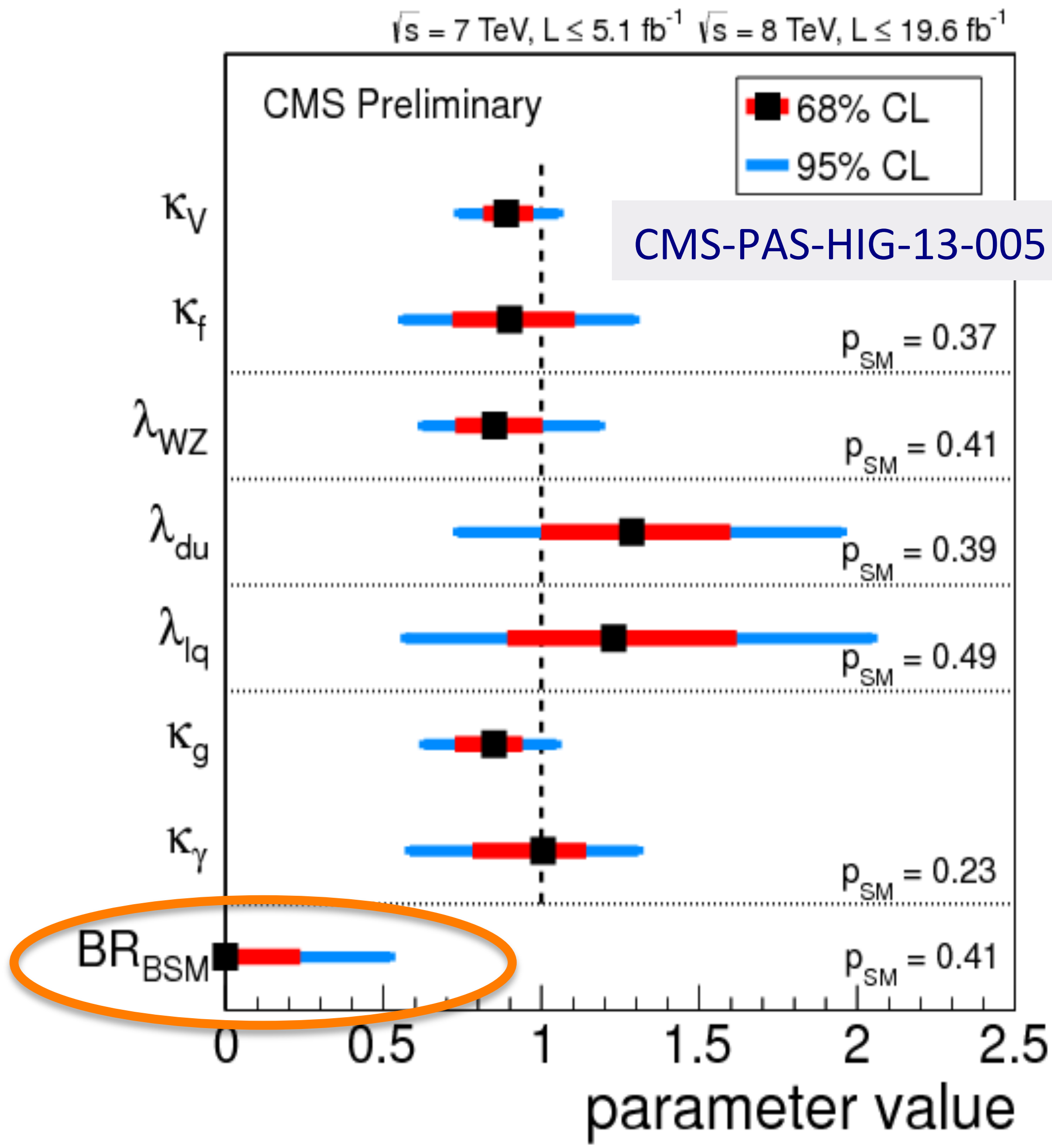
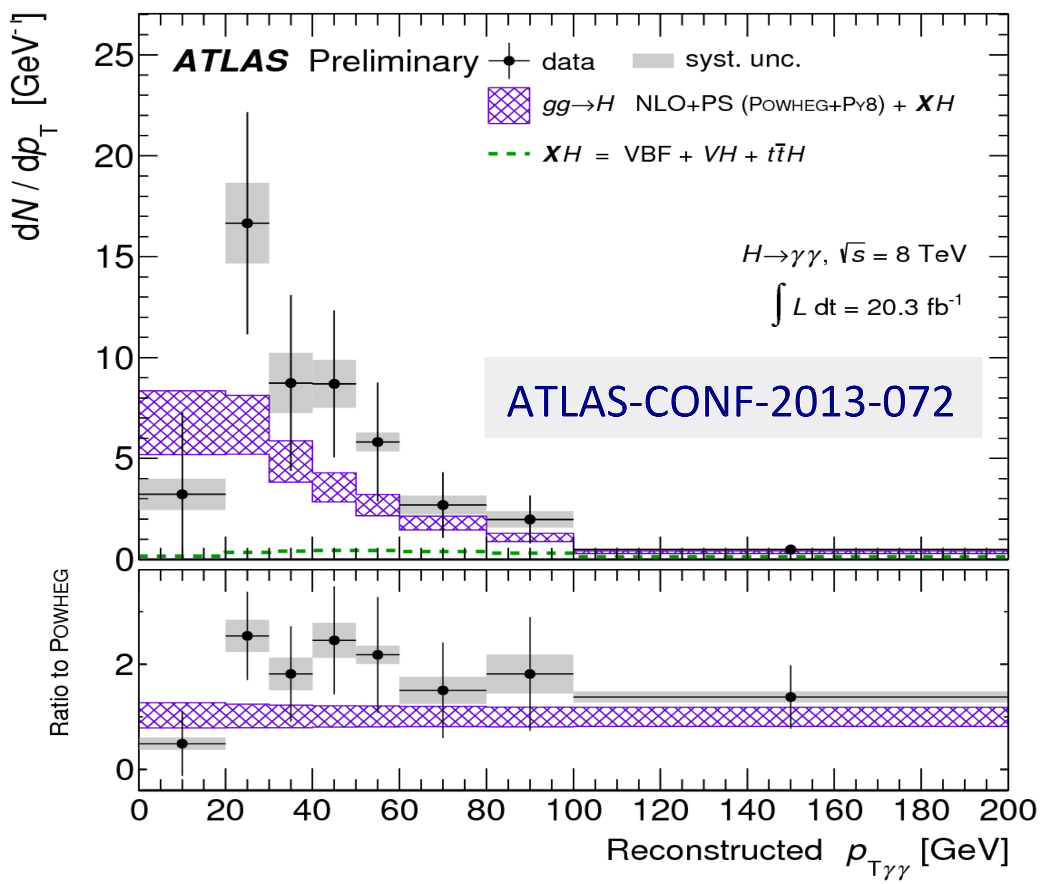


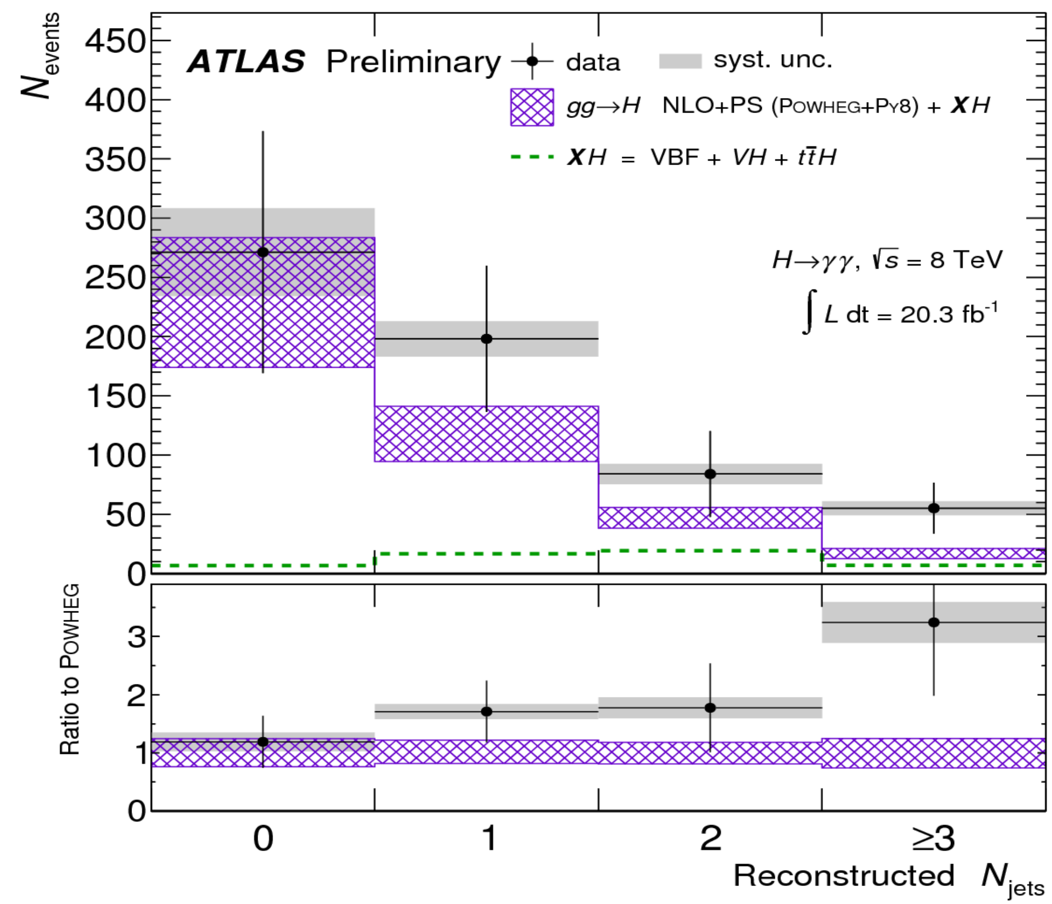
There is still place for new physics, exotic decays!

Entering the Higgs measurement era: H→ $\gamma\gamma$ differential cross-sections

Test perturbative QCD calculations for the dominant ggH process

Sensitive to relative rate of production via different mechanisms

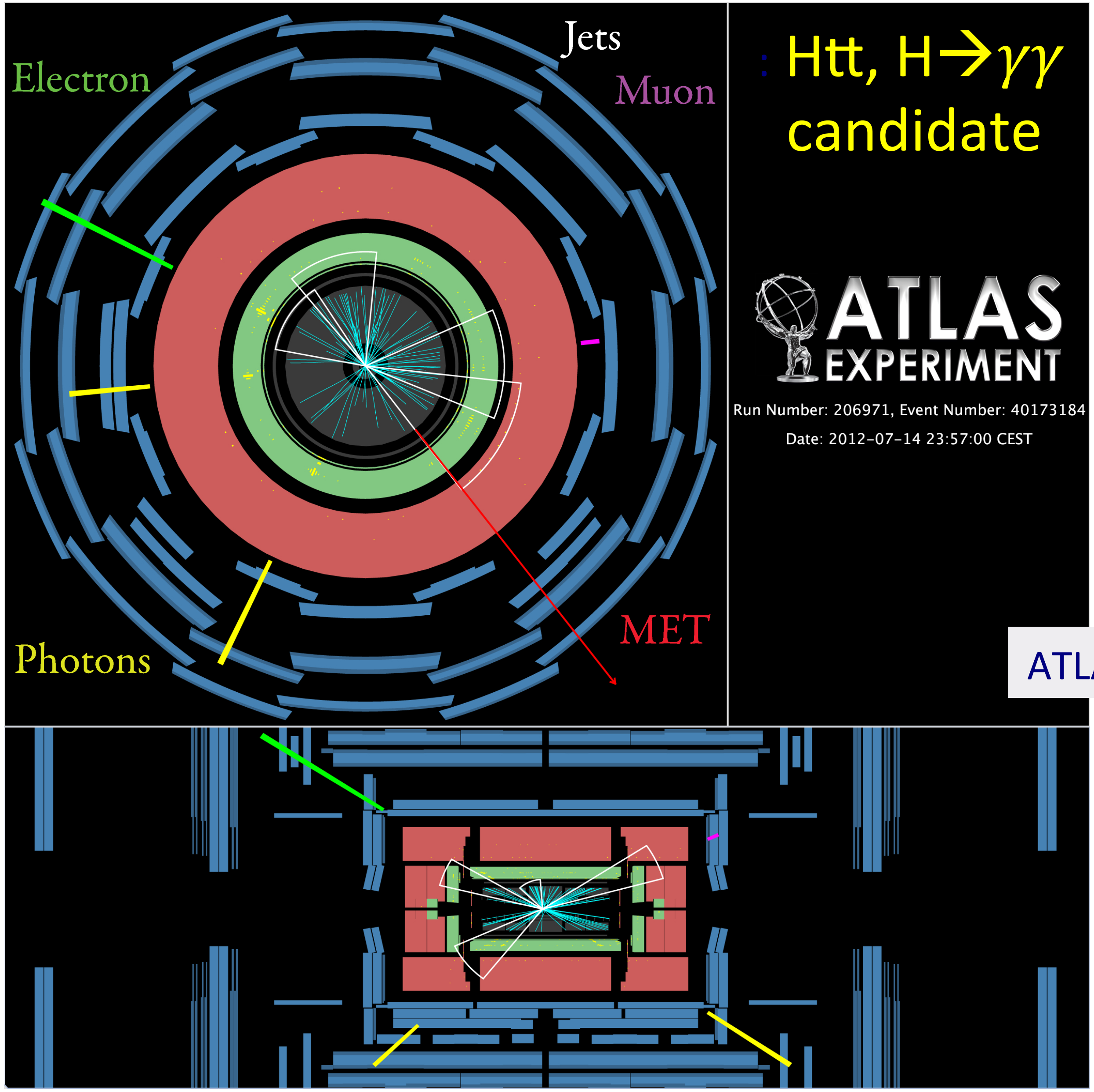




Reduced model dependence!

If the BSM model has non-SM like tensor structure, i.e. predicts different detector acceptances, selection efficiencies, fiducial cross-sections unfolded to particle level provide a better source of information

Measuring rare processes

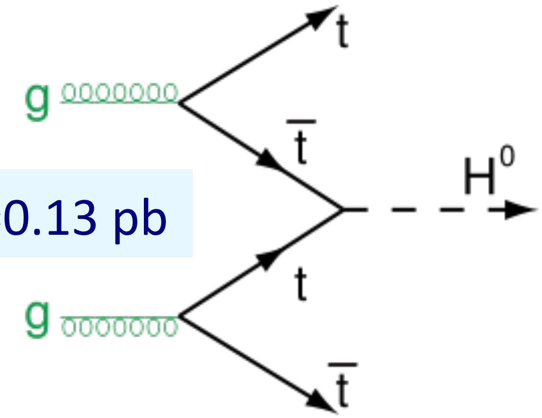


ATLAS-CONF-2013-080

S/B = 0.45 (leptonic)

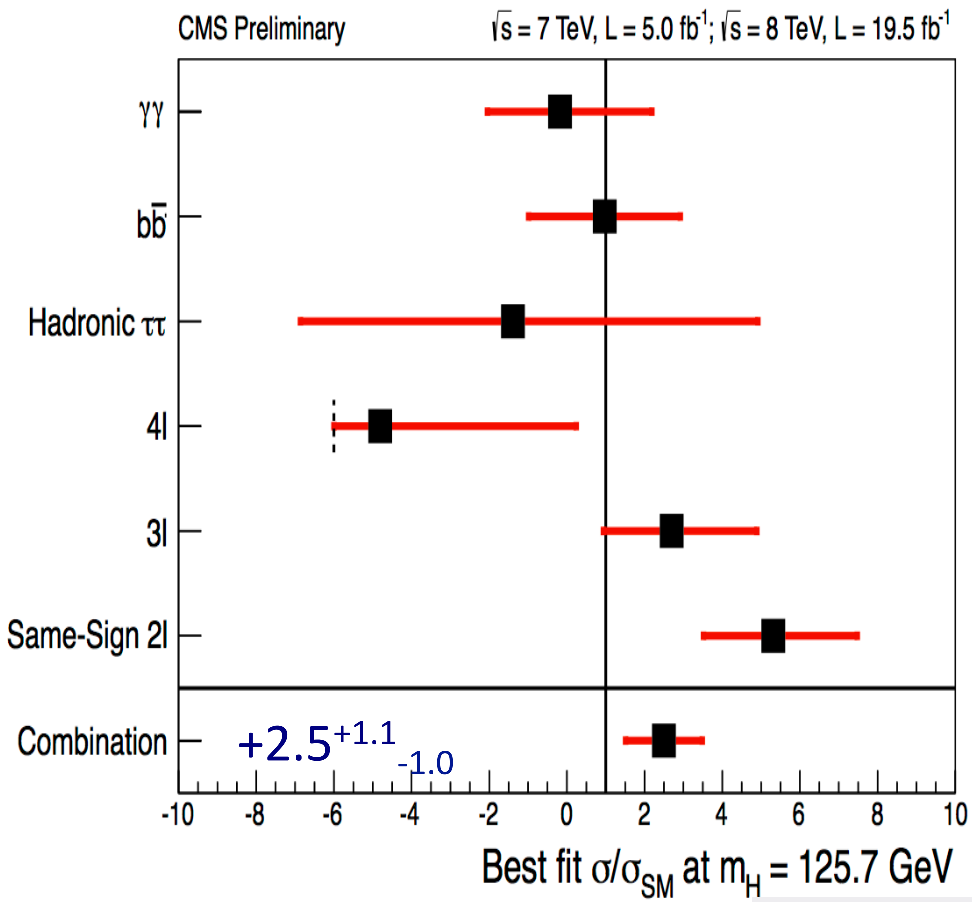
S/B = 0.19 (hadronic)

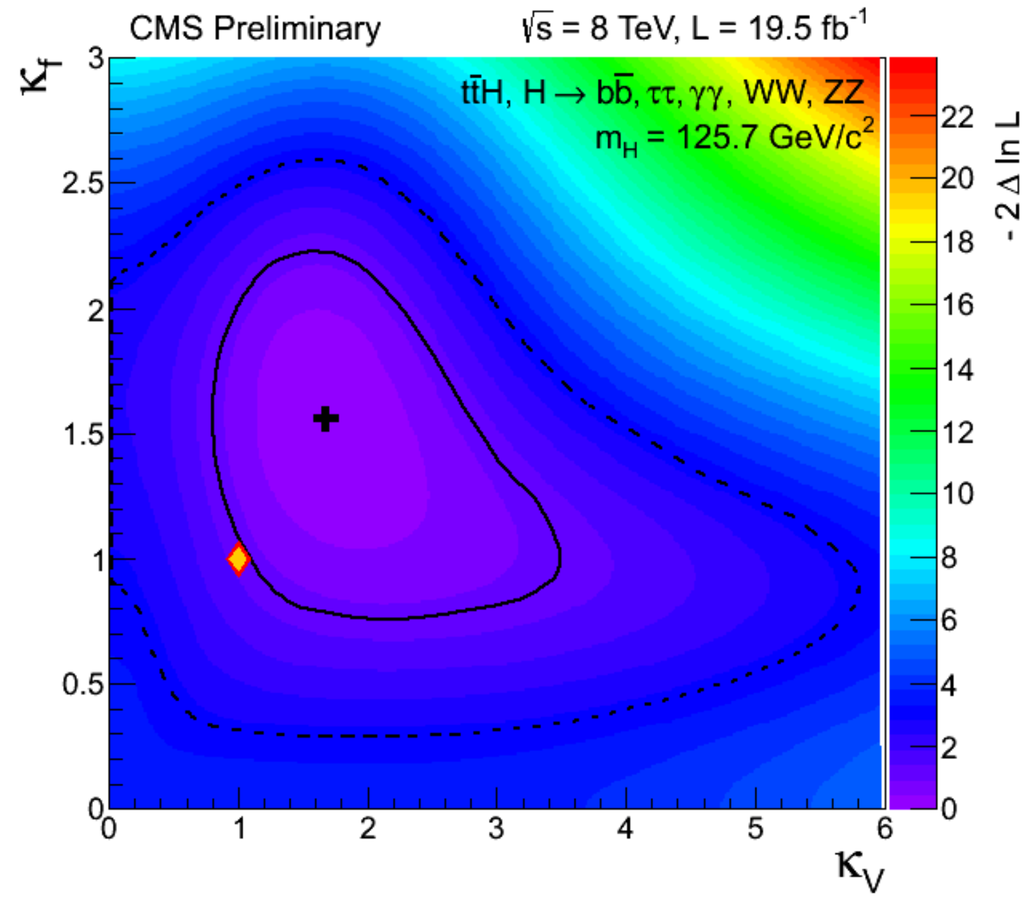
Search for ttH production



$\sigma \approx 0.13$ pb

Direct acces to Htt coupling
Large background, small cross-section → very challenging!

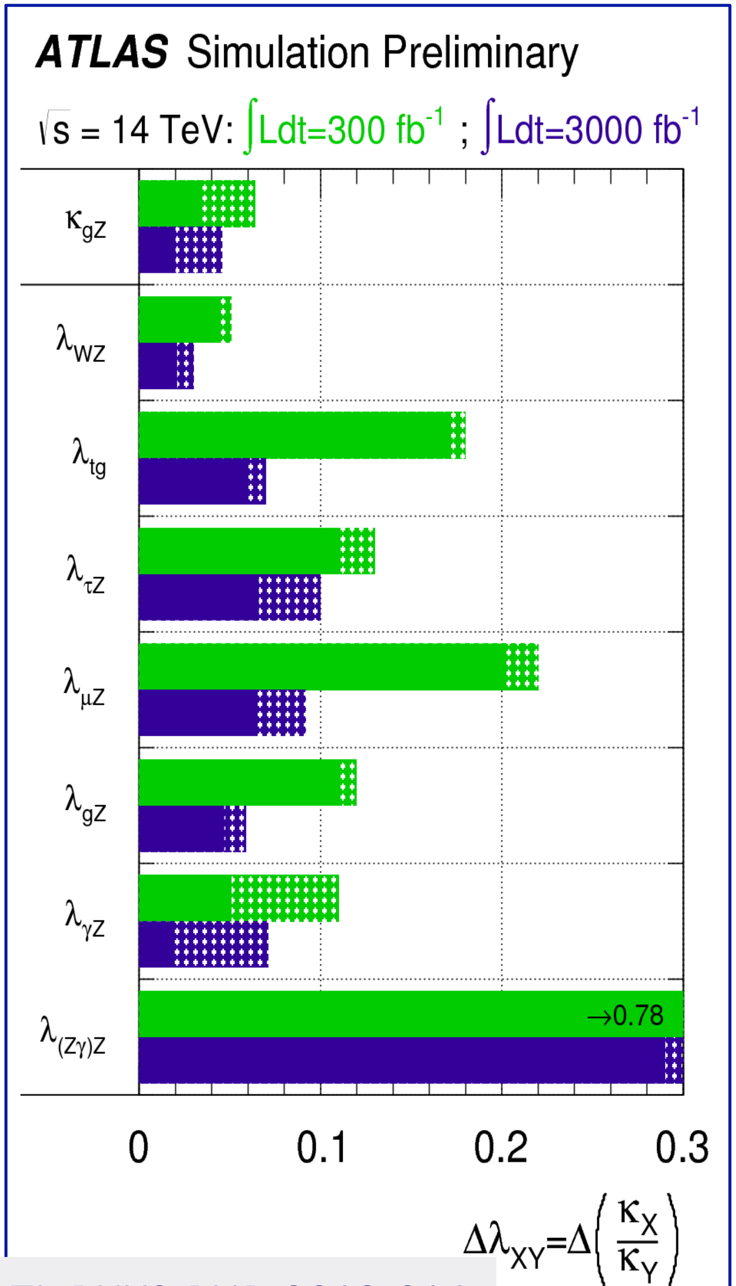




https://twiki.cern.ch/twiki/bin/view/CMSPublic/ttHCombinationTWiki

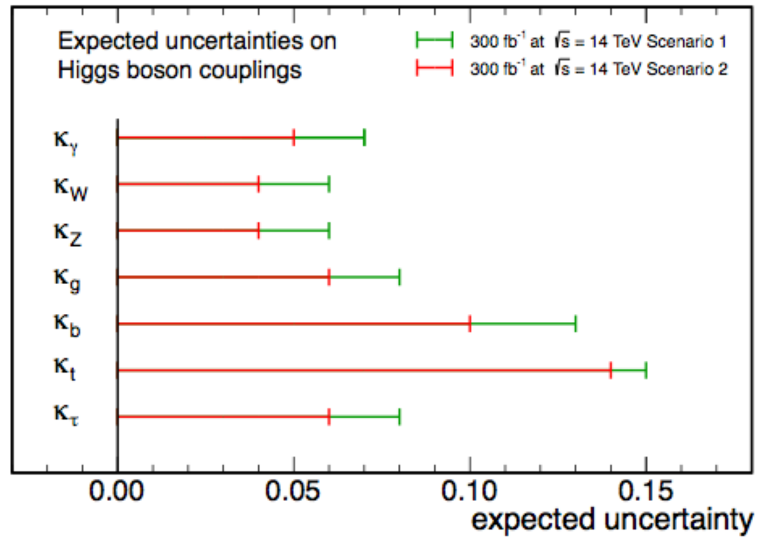
☆ Can we access Hcc coupling at LHC? Recent suggestion for HL-LHC: H→ J/ψ γ

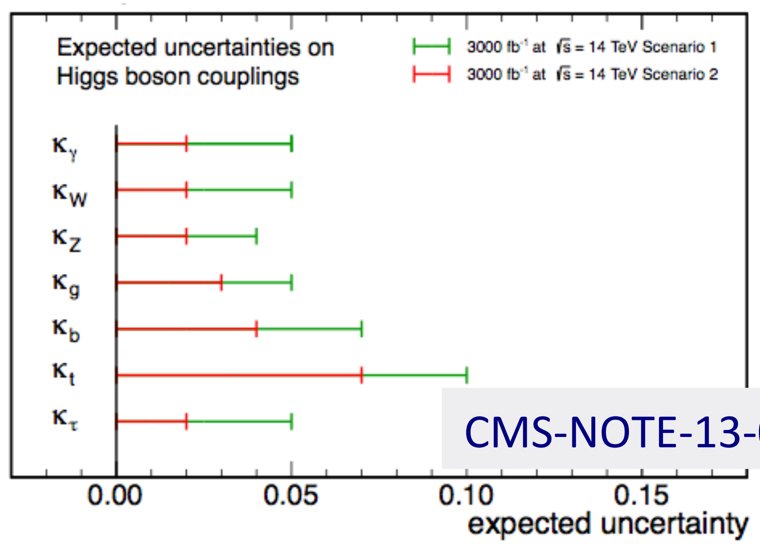
Projections for Run 2 and HL-LHC (E_{cm}=14 TeV)



ATL-PHYS-PUB-2013-014

CMS Projection





CMS-NOTE-13-002

Most difficult task: Measurement of Higgs self-interaction CMS+ATLAS combined: ~30%

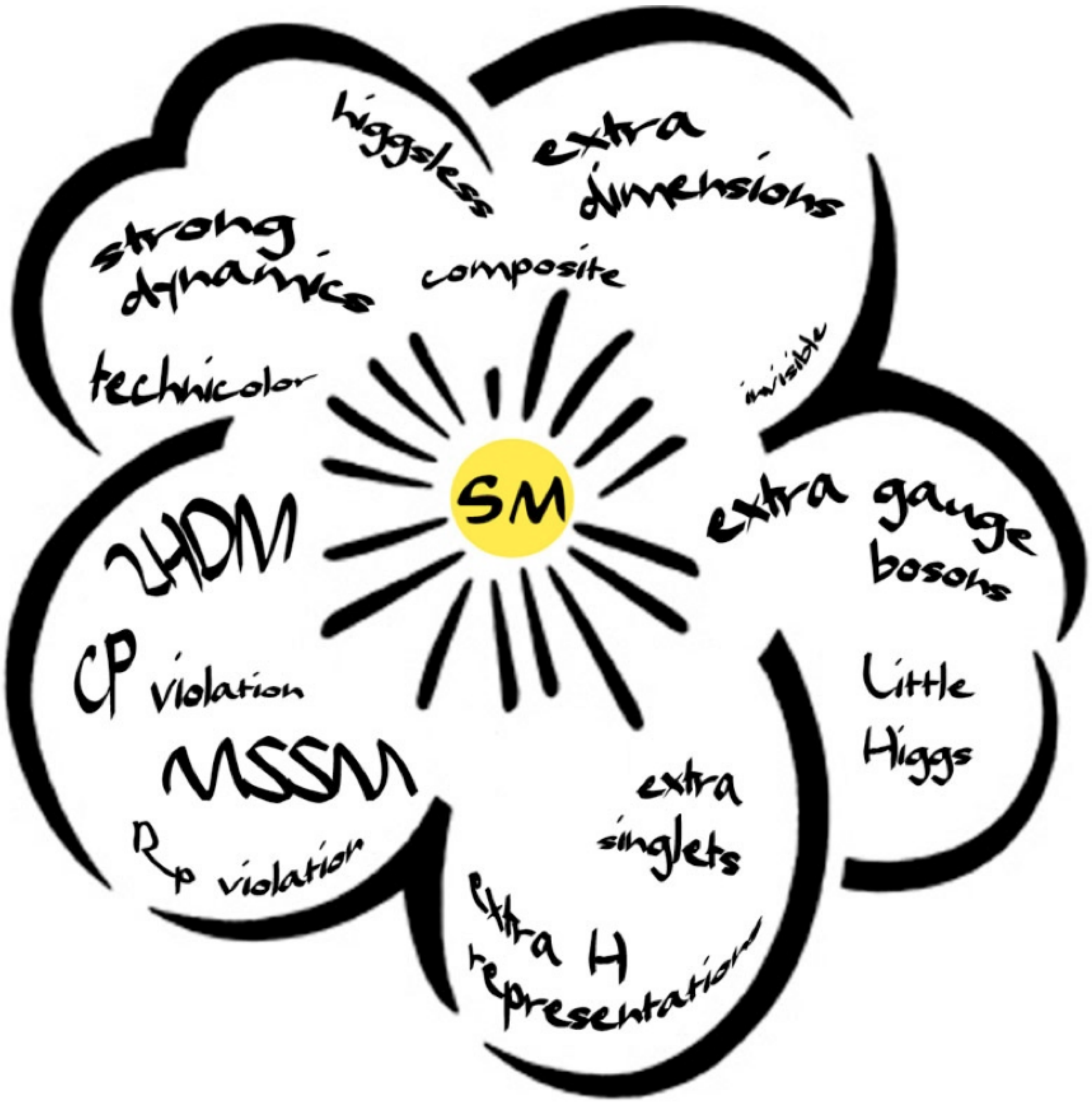
- Theory „requires" <20% typically to see SUSY contributions

arXiv:1305.6397v2 [hep-ph]

CMS scenario 1: syst uncertanities as in Run1

scenario 2: etheory syst x 0,5; experimental ~ 1/√L

Going beyond...



Extended Higgs sector

Standard Model
1 complex scalar doublet
1 physical Higgs boson: H

2HDM
2 complex scalar doublets
5 physical Higgs bosons: h, H, A, H^+, H^-

MSSM (Type-II 2HDM)
2 complex scalar doublets
5 physical Higgs bosons: h, H, A, H^+, H^-

NMSSM (~~μ-problem of MSSM~~)
2 complex scalar doublets + 1 singlet
7 physical Higgs bosons:
h_1, h_2, h_3, a_1, a_2, h^+, h^-

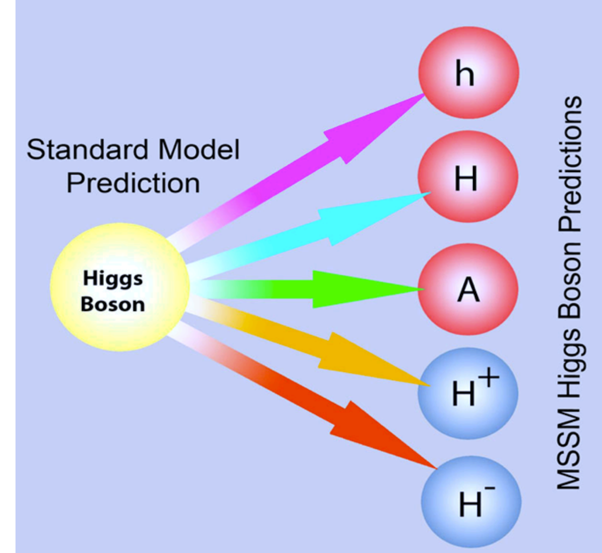
Additional SM-like Higgs
(→ high-mass searches)

Fermiophobic Higgs

Invisible Higgs
e.g. decaying to neutral LSP

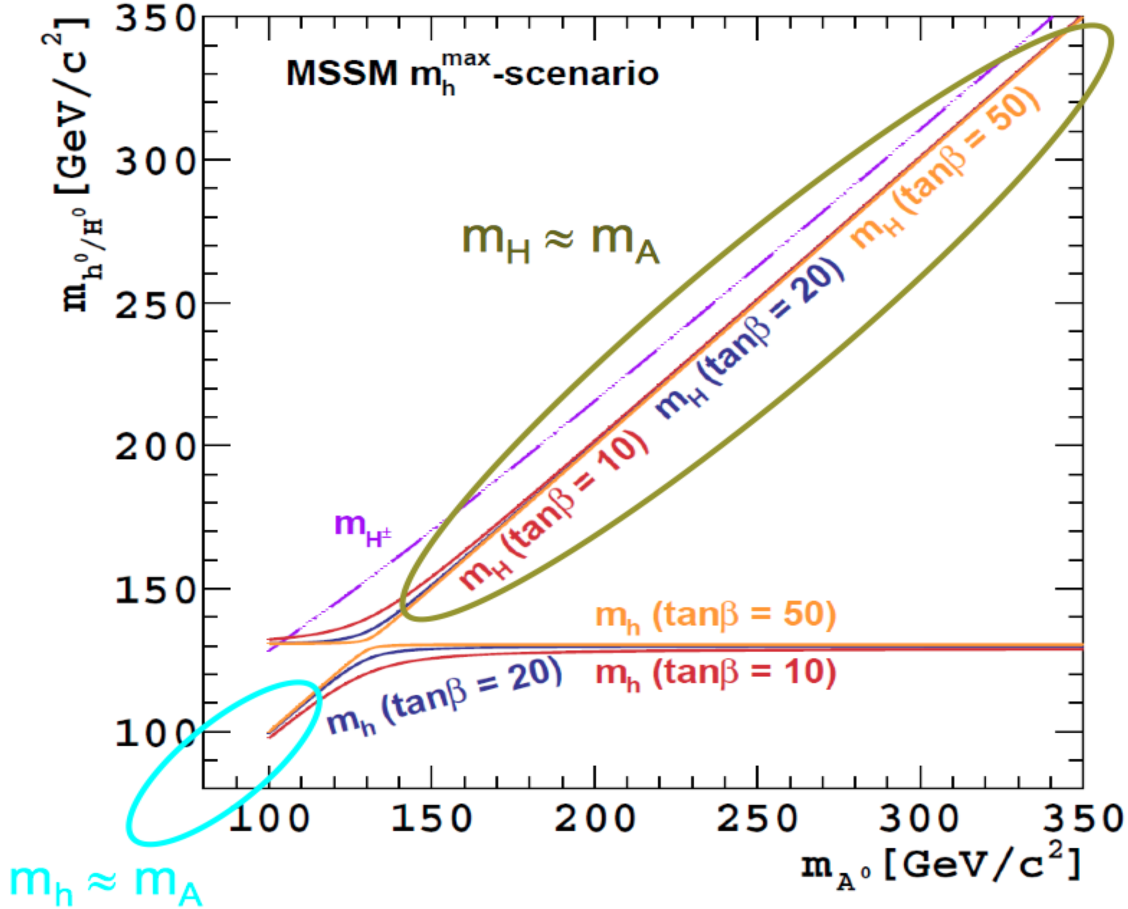
„Exotic" Higgs
e.g. decaying to lepton-jets in hidden-valley SUSY

MSSM Higgs sector



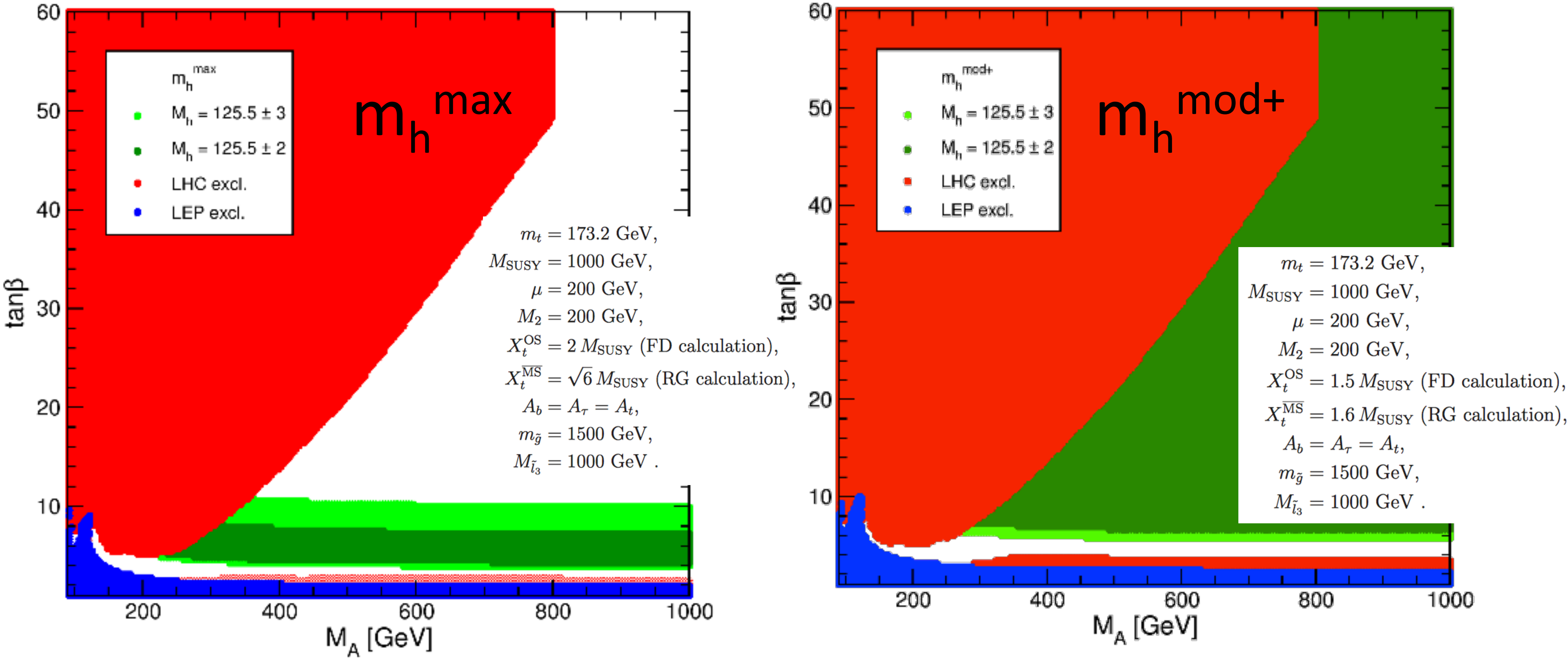
- 2 complex scalar doublets → 5 physical Higgs bosons
- Tree-level parameters: m_A, tanβ
- Many more parameters after radiative corrections
  → need benchmark scenarios
- Show only m_h^{max} in this talk

- In MSSM, at large m_A ($>>m_Z$), h usually becomes SM-like (decoupling limit)
  → Direct search for additional Higgs states important!
- Rise of phenomenological-MSSM (pMSSM-*n*): general scan of the *n* most important parameters (while fixing the less important ones to fit precision data)
- Remember: while general MSSM has 100+ parameters from the soft susy breaking terms of the Lagrangian, relations are expected among them depending on how SUSY is broken)

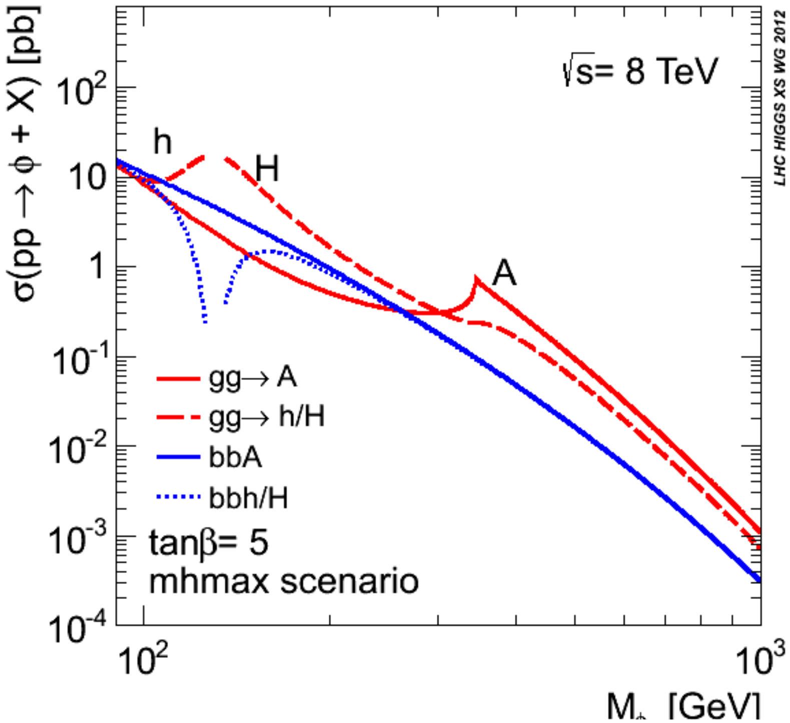


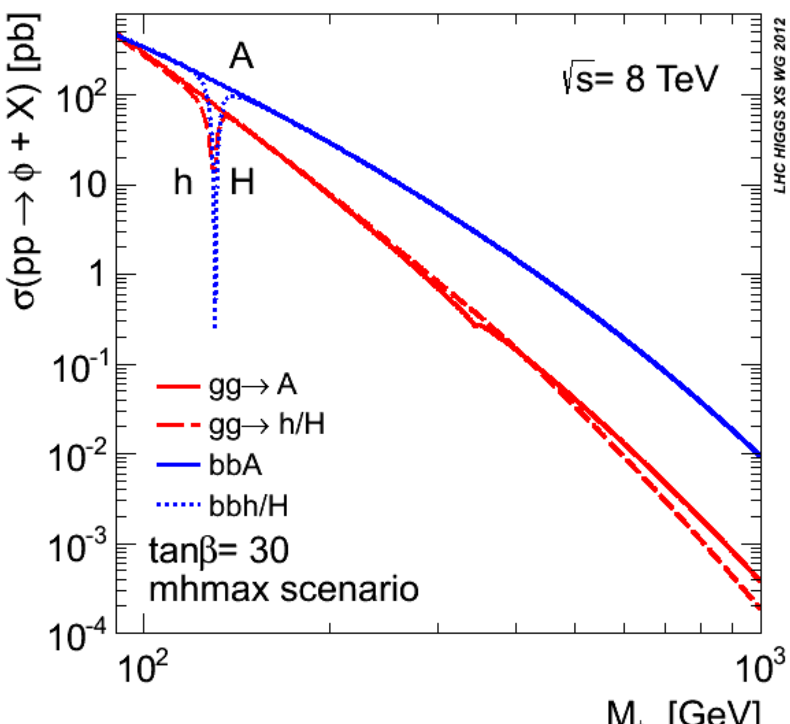
Consistency with m_h = 125 GeV

arXiv:1302.7033 [hep-ph]



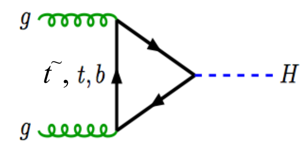
arXiv: 1307.1347[hep-ph]

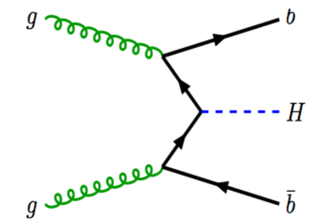




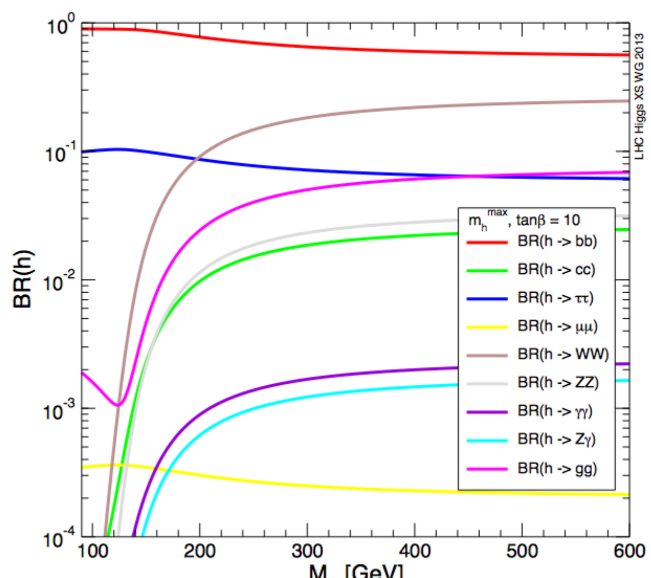
Production and decay

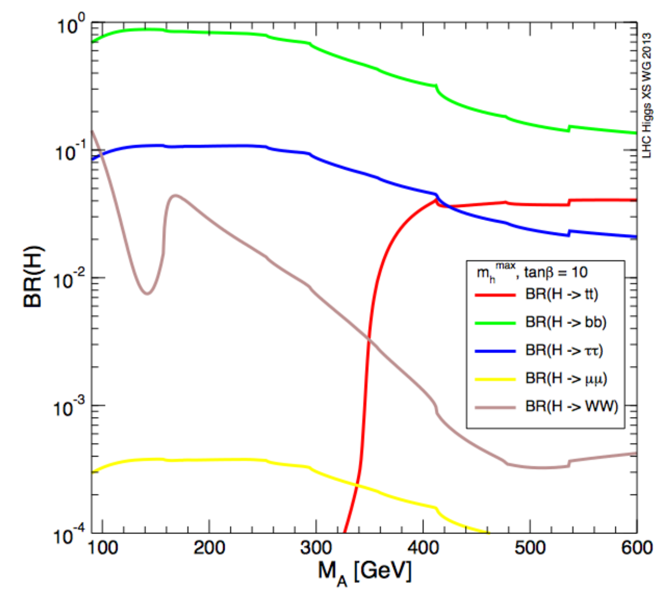
- Associated bbϕ production plays an important role





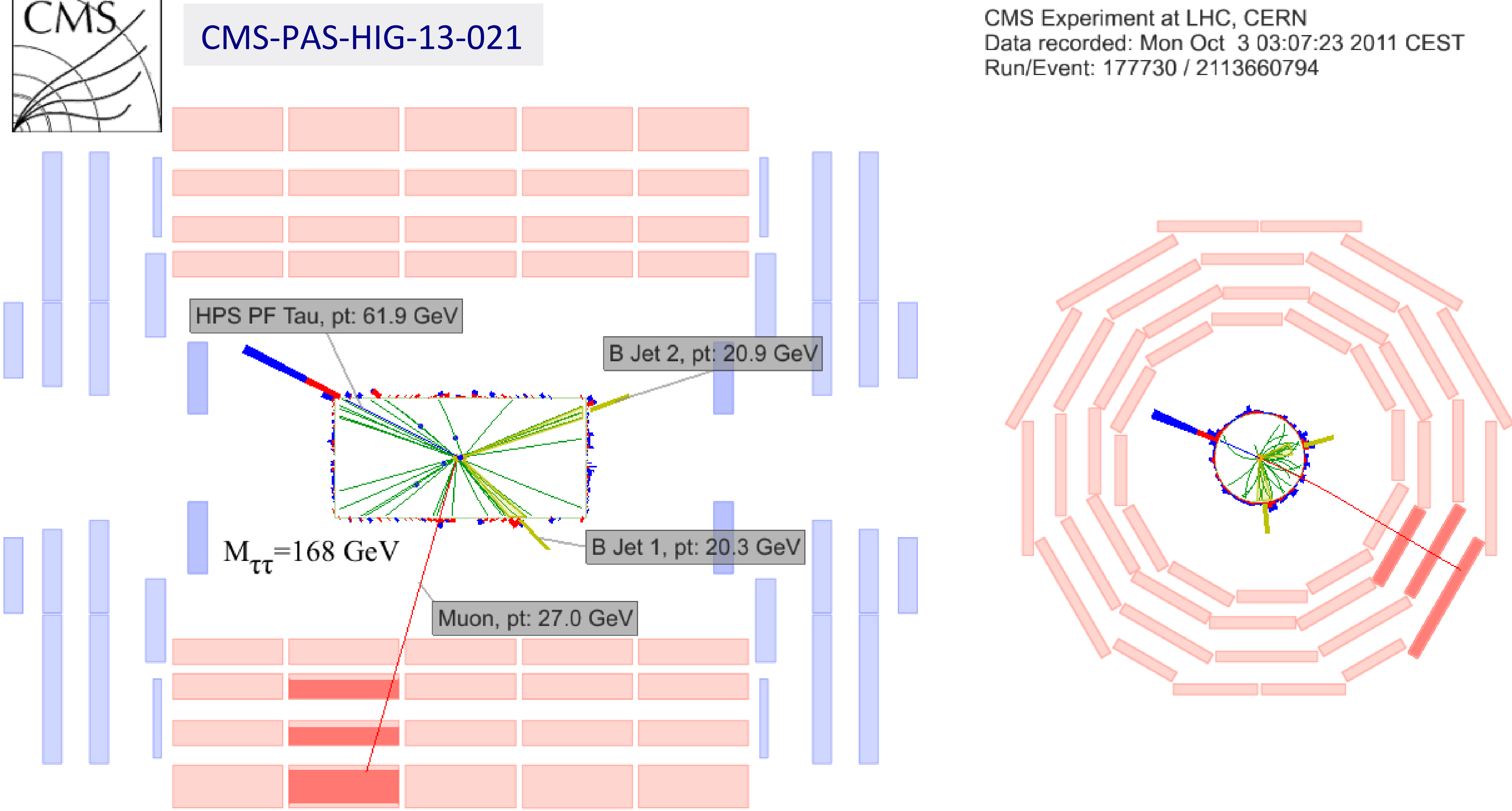
- Strongly enhanced cross-section at high tanβ
- Decays ϕ→bb, $\tau\tau$ are important also at high mass
- ϕ→bb very challenging (huge background)
- ϕ→μμ very low BR but excellent resolution (could separate H / A when degenerate)





Search for bbϕ → bb ($\tau\tau$)

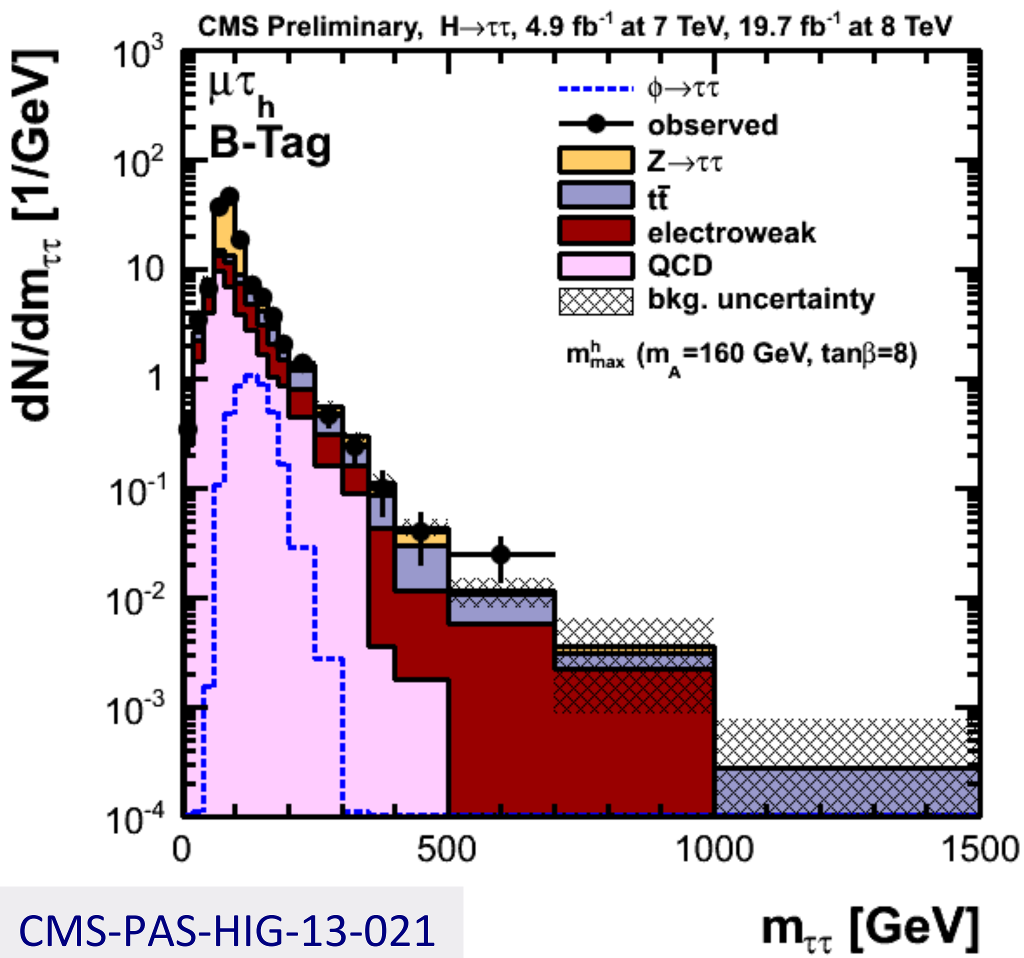
CMS-PAS-HIG-13-021

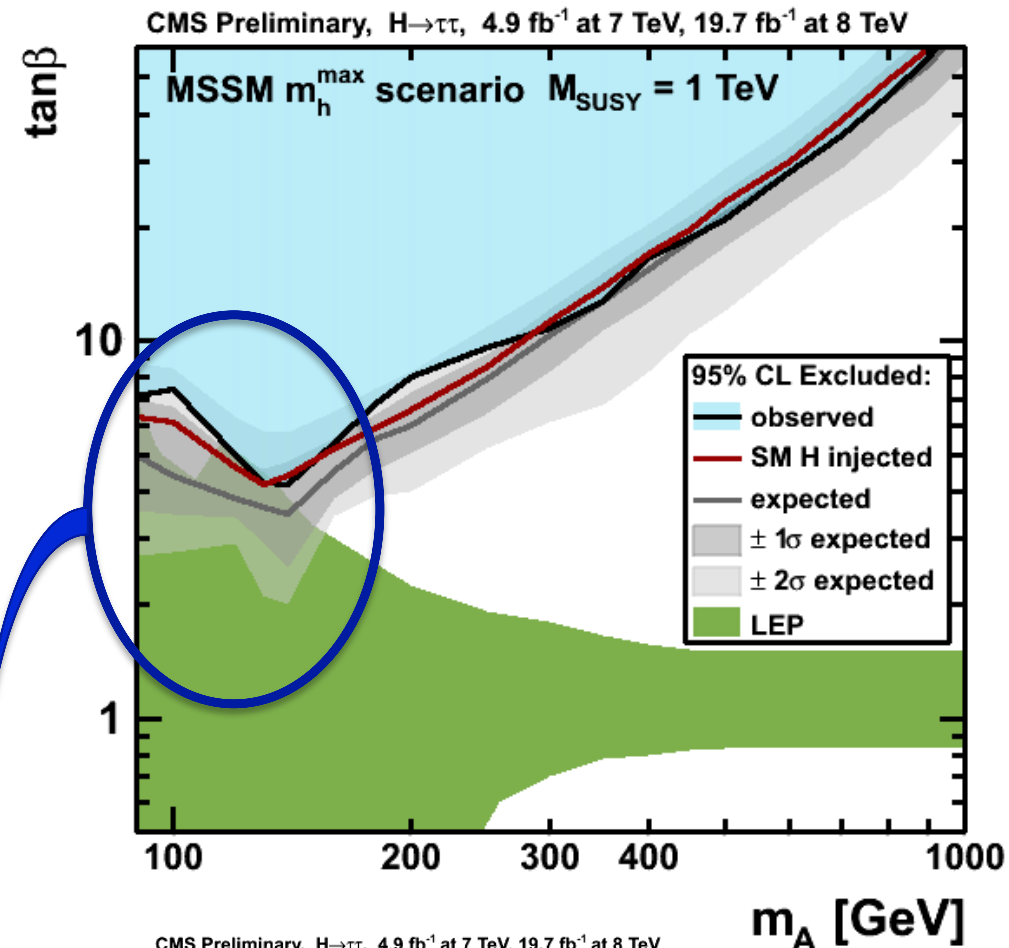


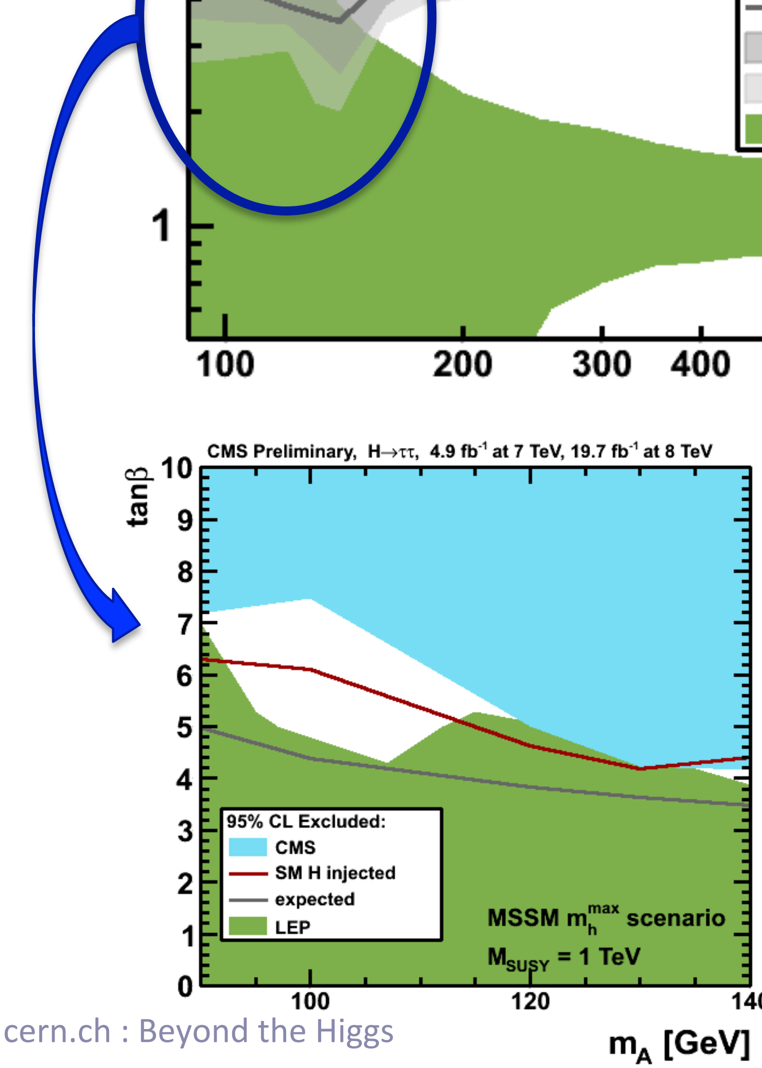
bbϕ → bb ($\tau\tau$) → bb (had μ) candidate

Search for $\phi \rightarrow \tau\tau$

Background composition differs significantly from tau final state to tau final state, but all distributions are well described by background only hypothesis

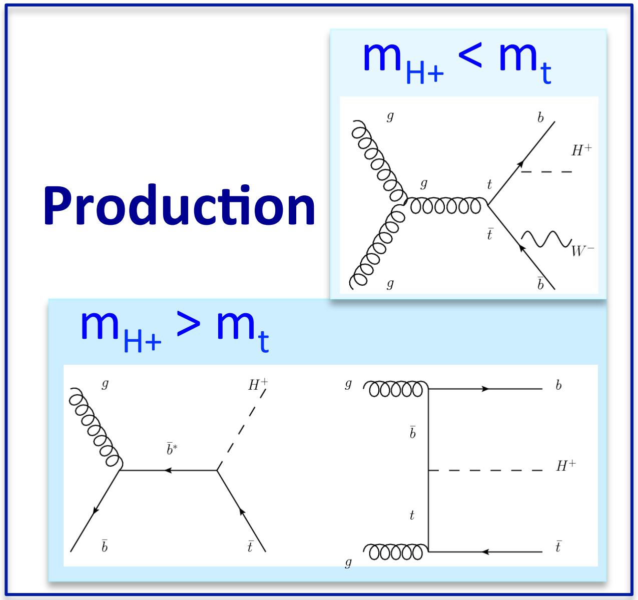


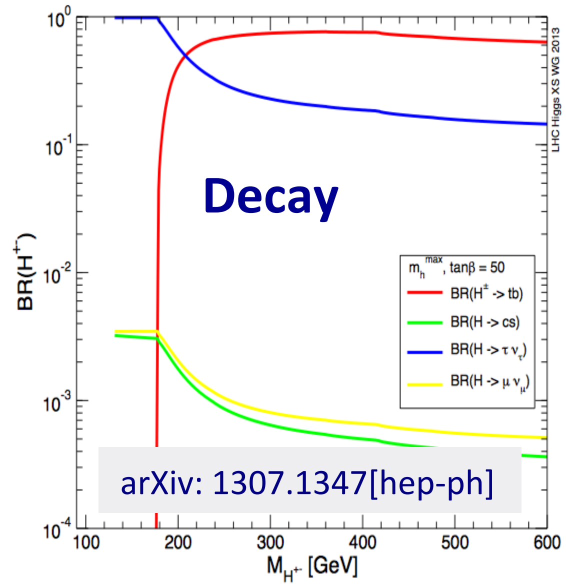


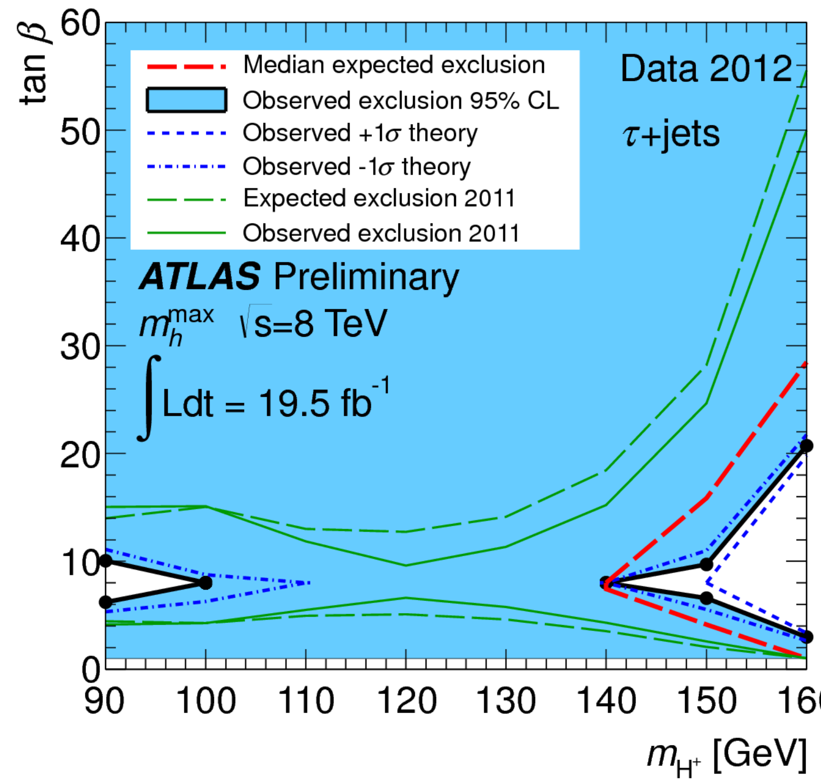


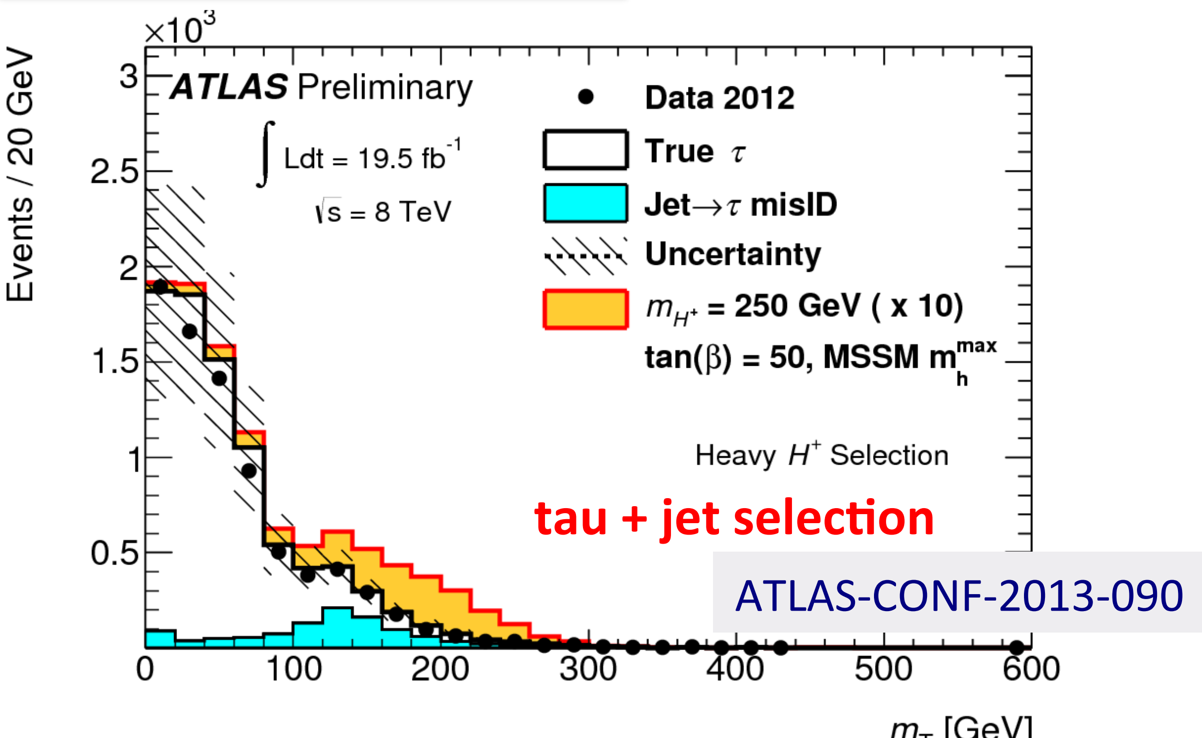
CMS-PAS-HIG-13-021

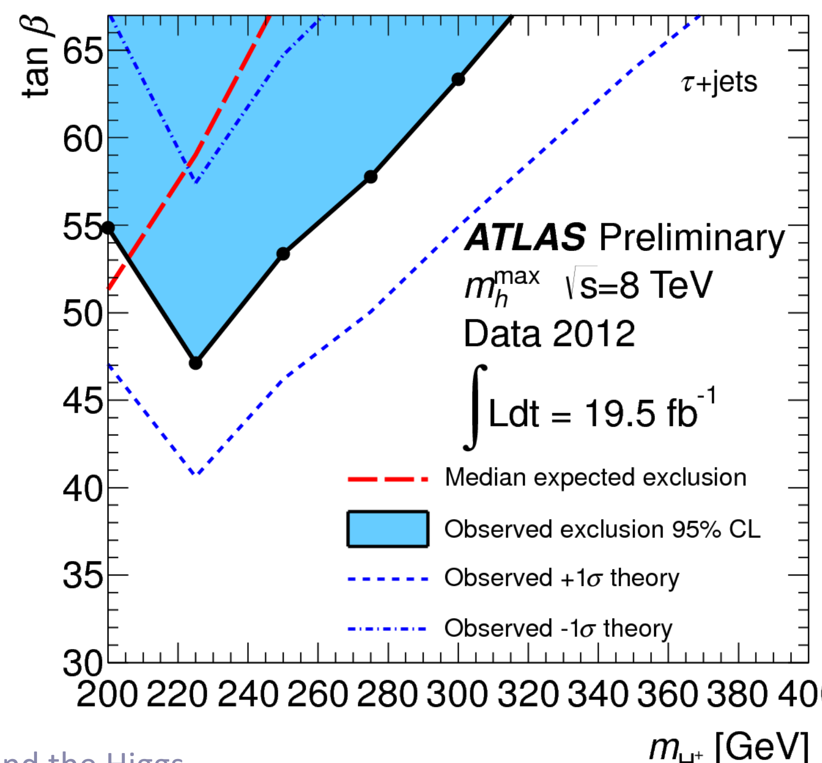
Search for Charged Higgs











Searching for exotic Higgs decays

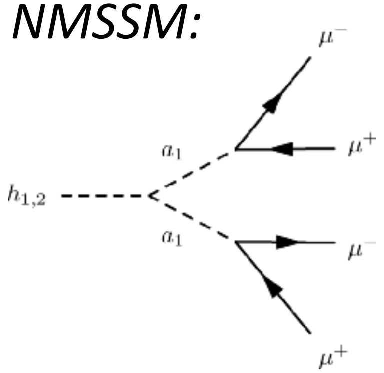
Many „beyond MSSM” extensions, e.g.

- NMSSM (to solve the μ-problem of MSSM): 7 physical Higgs bosons: h_1, h_2, h_3, a_1, a_2, h^+, h^-
- Hidden-valley theories with a dark sector (dark-particles can have low mass!)

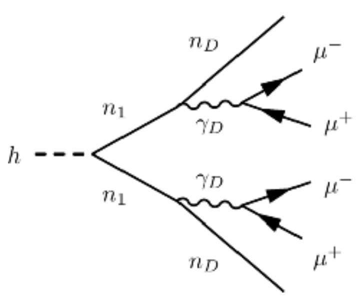
Exotic decay modes open, e.g.

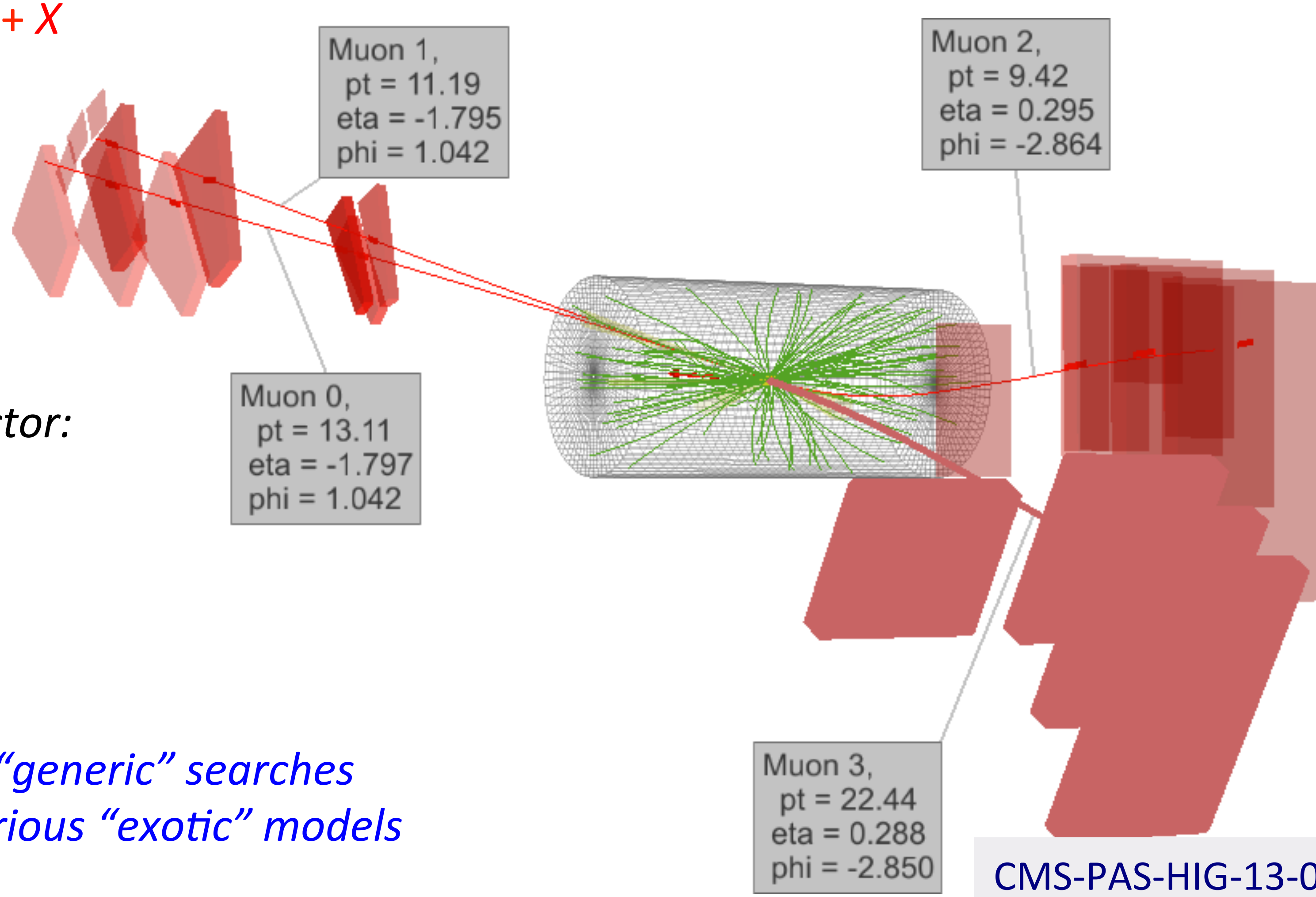
$h \to 2a + X \to 4\mu + X$

NMSSM:



SUSY with a dark sector:





→ *Topology-based, “generic” searches interpreted In various “exotic” models*

CMS-PAS-HIG-13-010

Search for h→ 2a + X → 4μ + X at low m_a

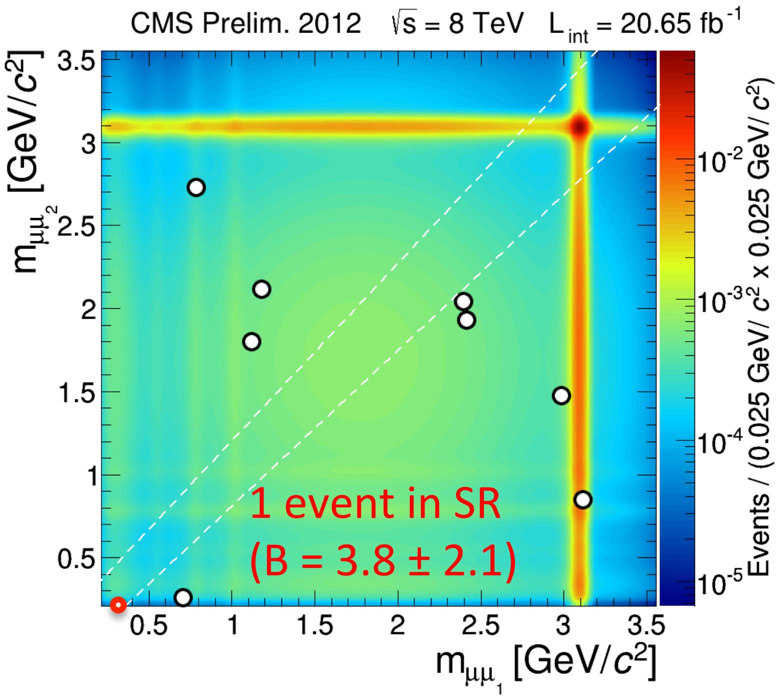
Search for decays into two very light bosons ($m < 2\, m_\tau$) decaying to OS, boosted muon pairs

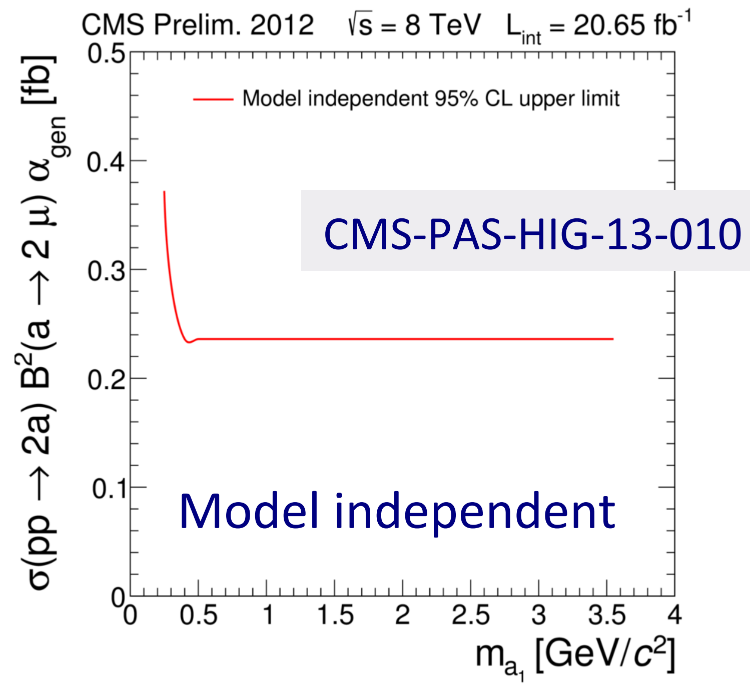
NMSSM

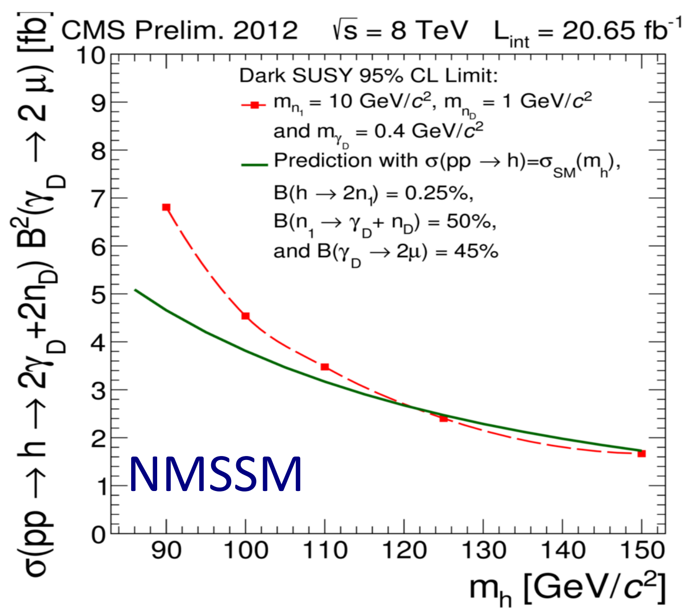
- h_1 or h_2 corresponds to 125 GeV Higgs
- a new CP-odd Higgs

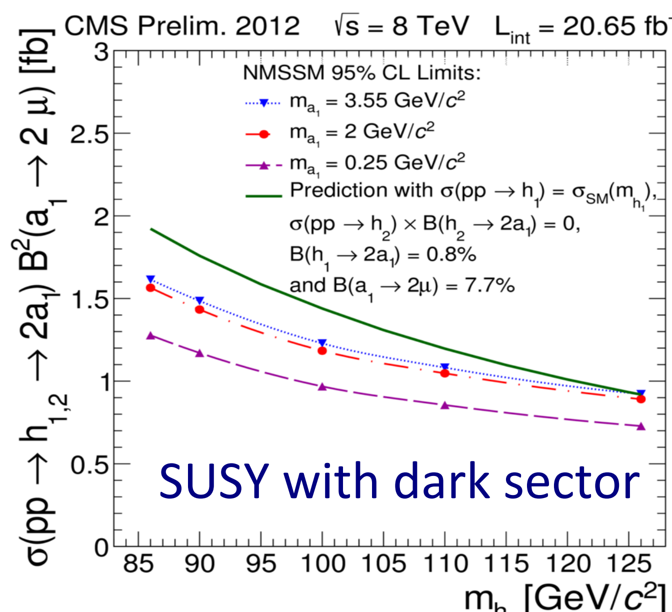
Hidden-valley

- h decays to lightest neutralino, which decays to a dark fermion + a (low-mass) dark photon that weakly couples to SM fermions
- cascades of dark particle decays might lead to larger multiplicity lepton-jets

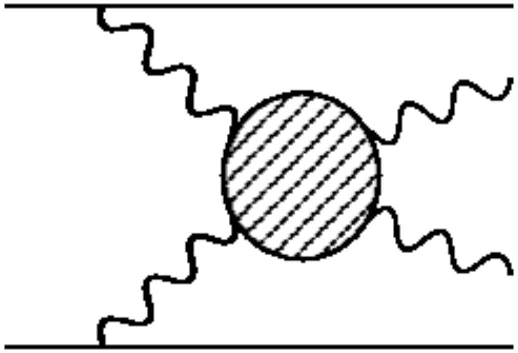


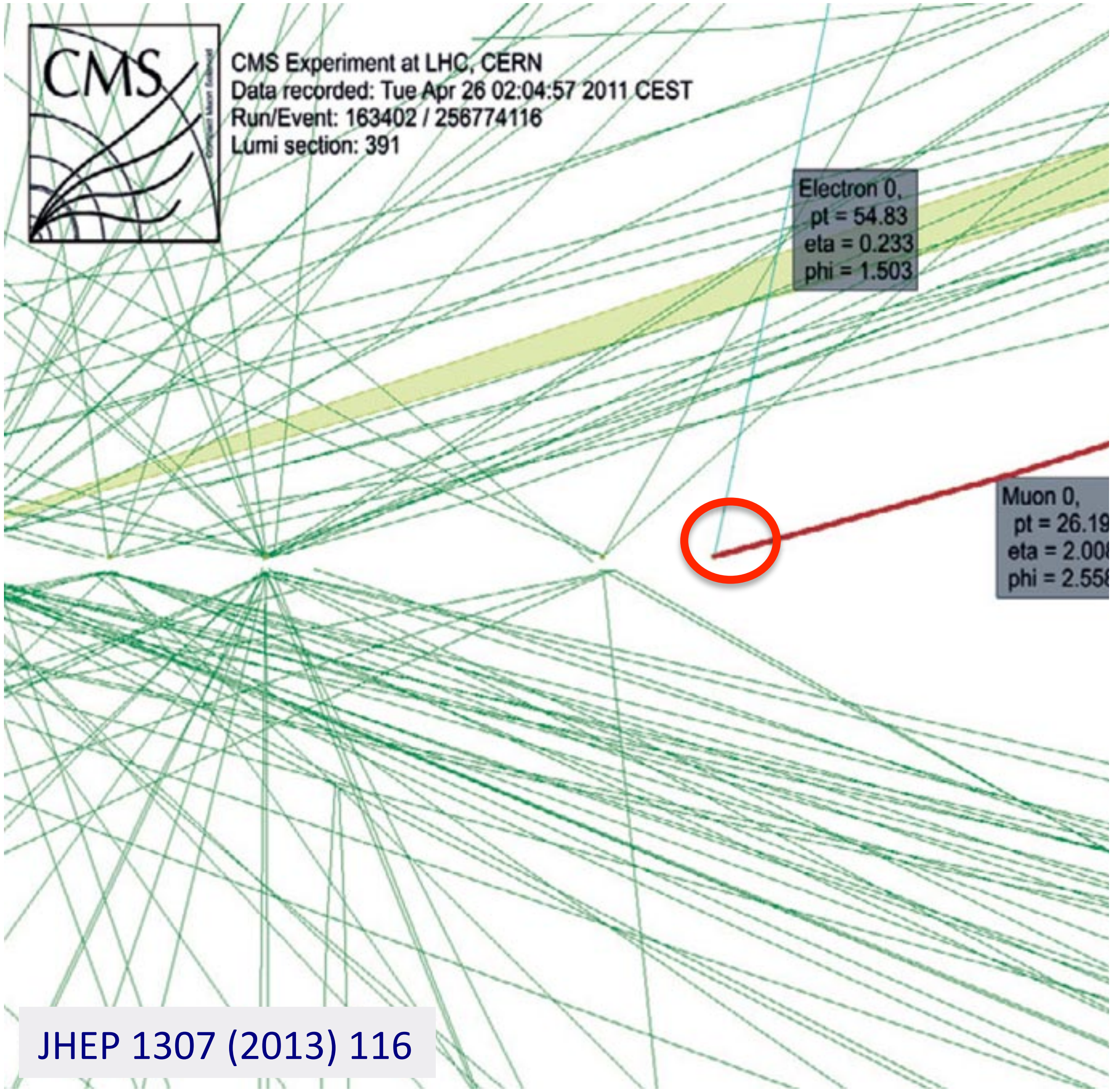






What if no additional state is seen?





Exclusive $\gamma\gamma \rightarrow$ WW production candidate

VV scattering: a probe of EWSB

Vector boson scattering is „intimately" connected to EWSB and new physics

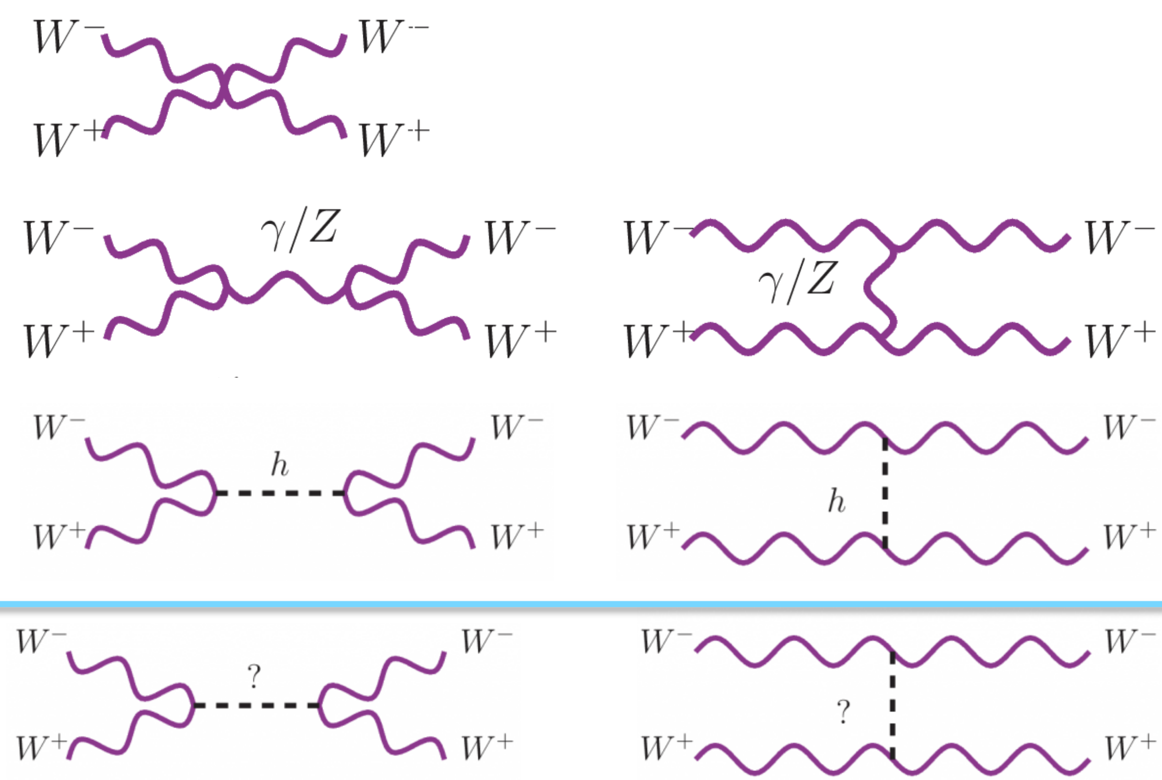
- In SM, unitarity in VV scattering is restored by Higgs exchange: $\sigma \sim O(E^2) - O(E^2) \rightarrow O(E^0)$
- If HVV coupling is not exactly the SM value, unitarity is not realized [$\sigma \sim O(E^2)$] or „delayed" until a new high-mass state enters

Even if no new physics is observed directly (finite energy reach, large backgrounds), VV scattering can reveal its existence

SM gauge bosons:

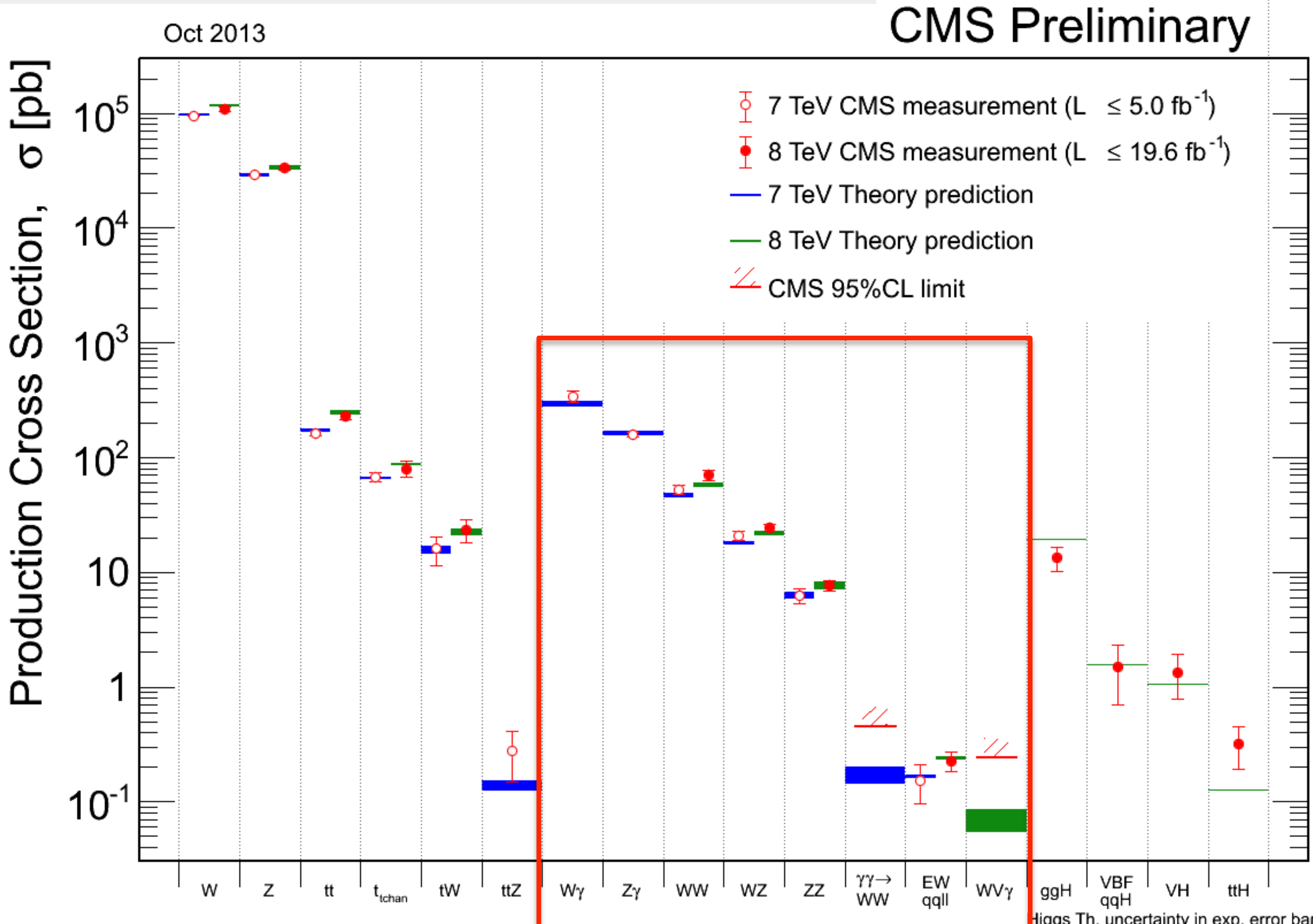
Higgs:

New scalar
(or new gauge boson):



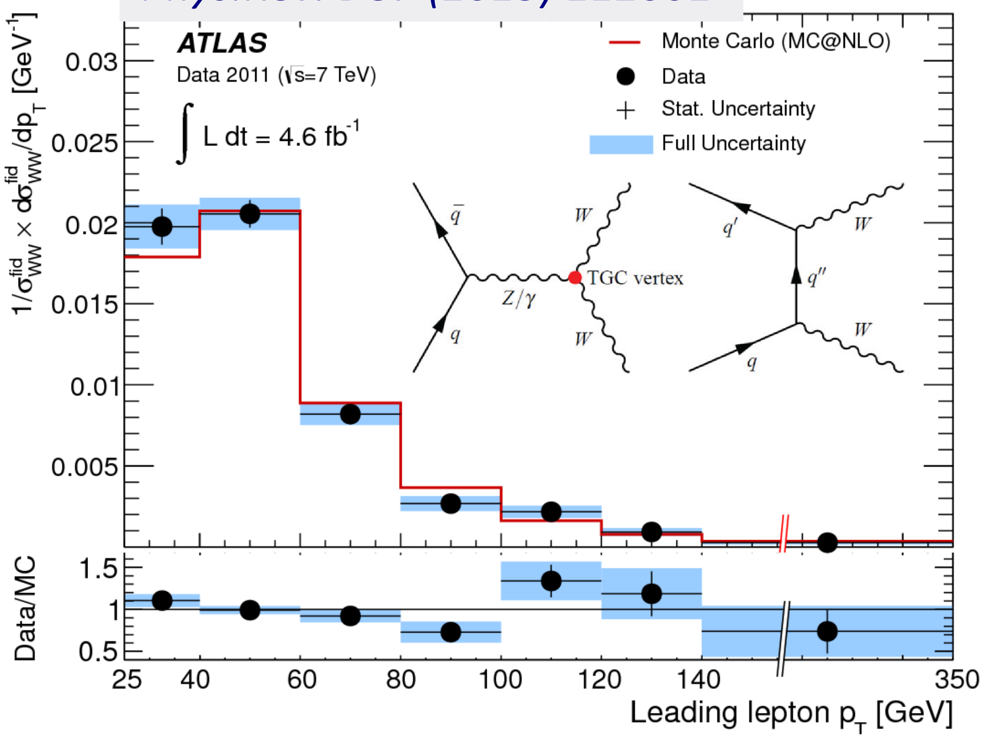
State-of-the-art in multi-boson studies

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

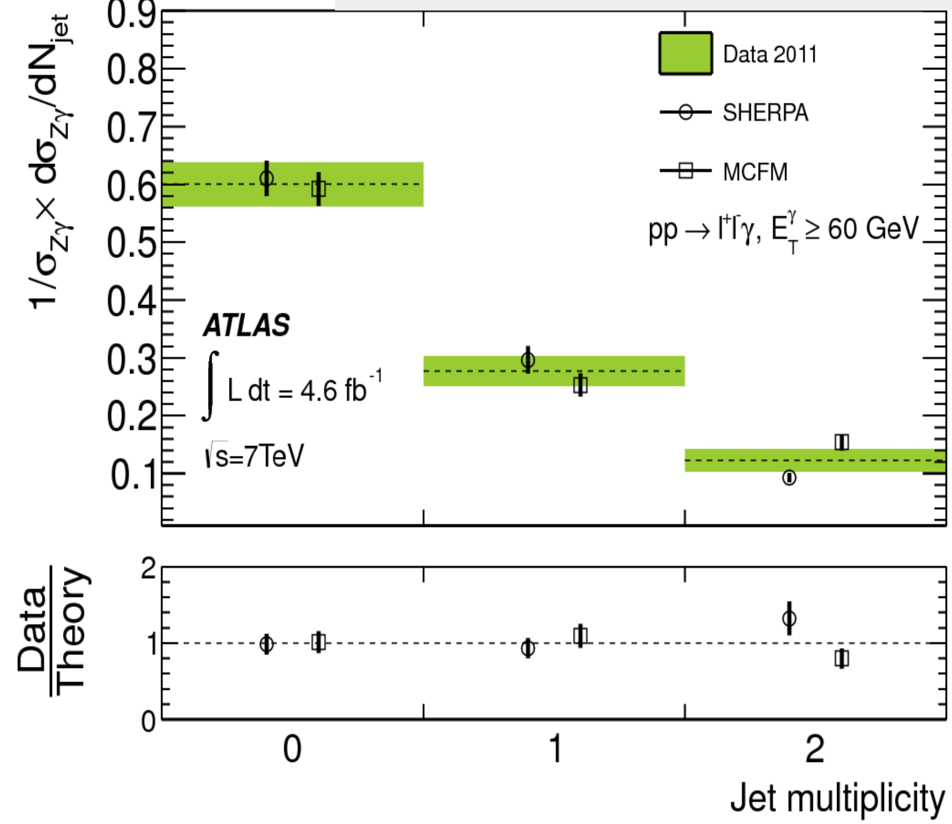


Diboson measurements going differential…

Phys.Rev. D87 (2013) 112001

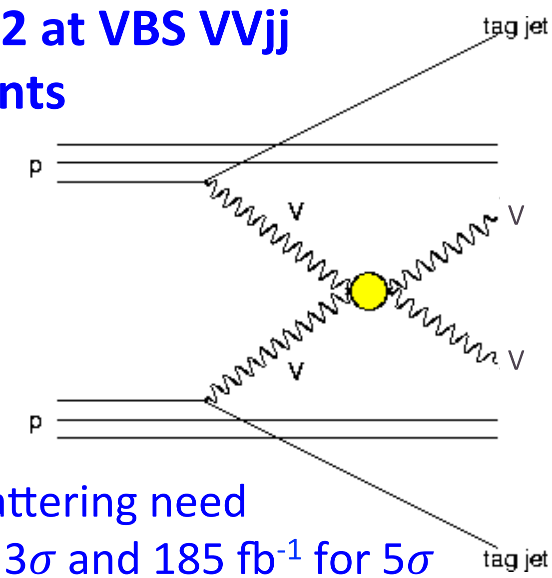


Phys.Rev. D87 (2013) 112003



- Jet multiplicity distribution only available for llγ and l$\nu\gamma$ measurements
- Especial interesting for inclusive VVjj as a step towards vector boson scattering measurements, where forward jets tag the event

Aim in Run 2 at VBS VVjj measurements

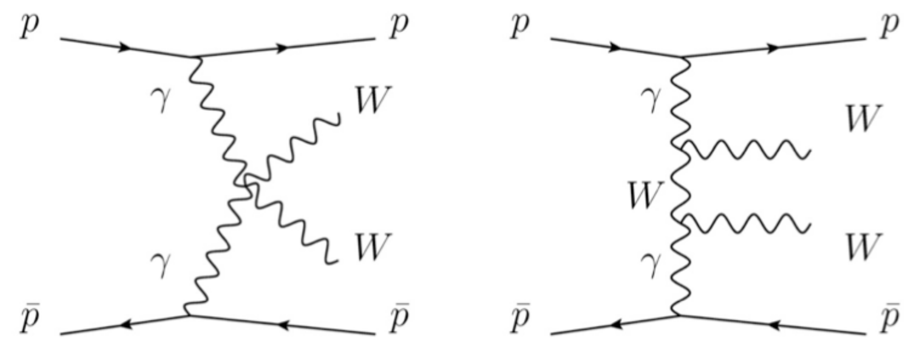


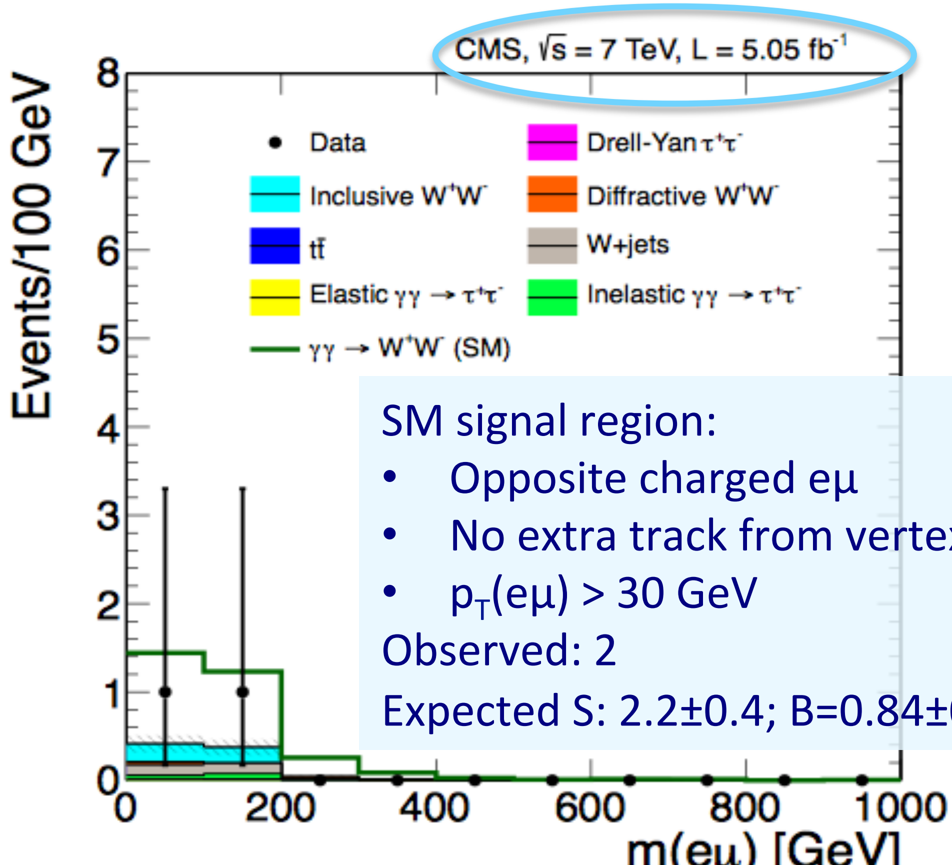
SM WZ scattering need
75 fb-^{1} for 3σ and 185 fb^{-1} for 5σ

CMS-PAS-FTR-13-006

Exclusive $\gamma\gamma \rightarrow WW \rightarrow e\nu\mu\nu$

- Acess $\gamma\gamma WW$ quartic coupling
- Statistics limited measurement
- High $p_T(e\mu)$ sensitive to anomalous couplings from new physics

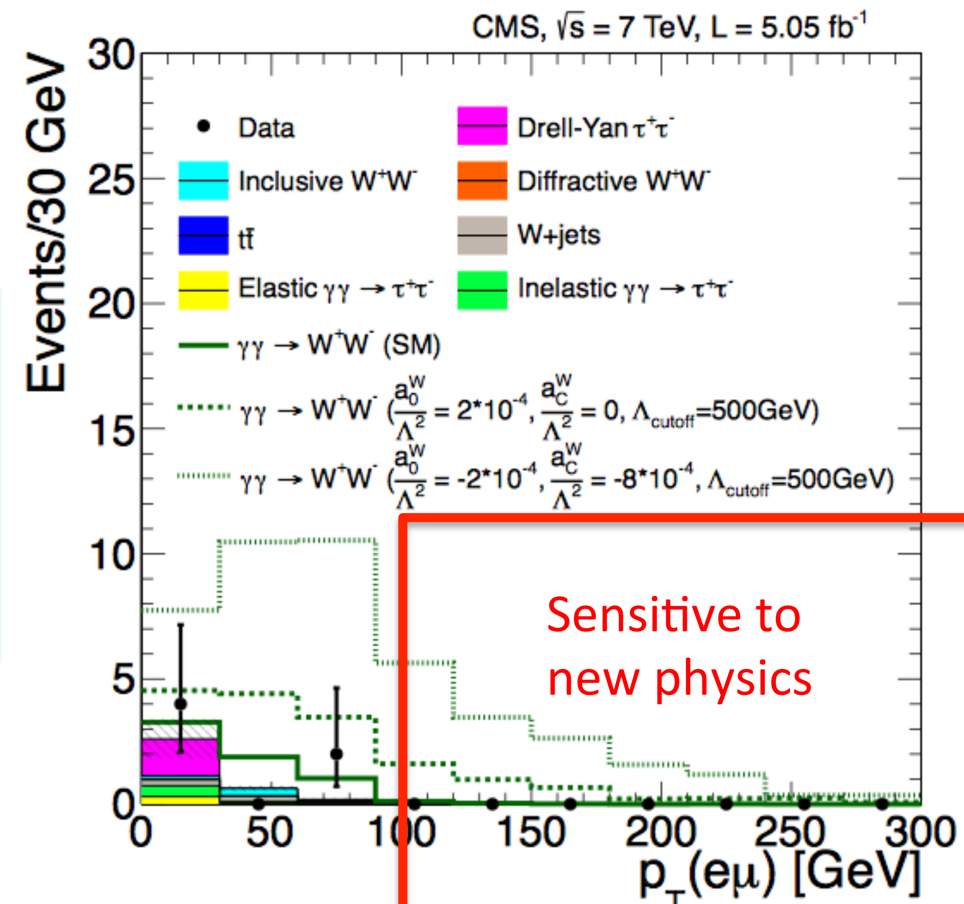




SM signal region:
- Opposite charged eμ
- No extra track from vertex
- $p_T(e\mu) > 30$ GeV

Observed: 2

Expected S: 2.2±0.4; B=0.84±0.15

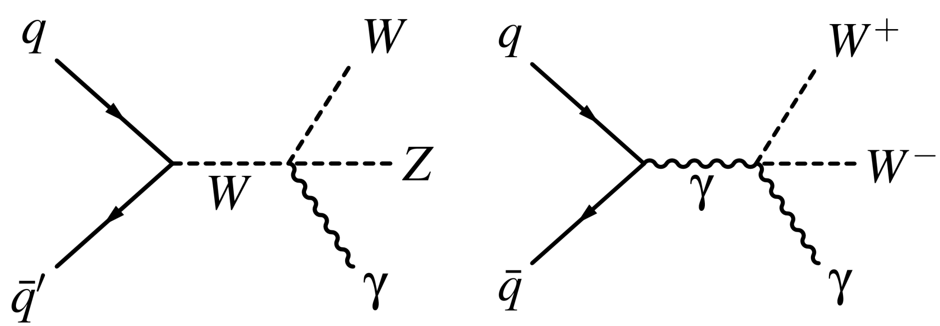


$\sigma = 2.2^{+3.3}_{-2.0}$ fb (<10.6 fb @ 95%CL)

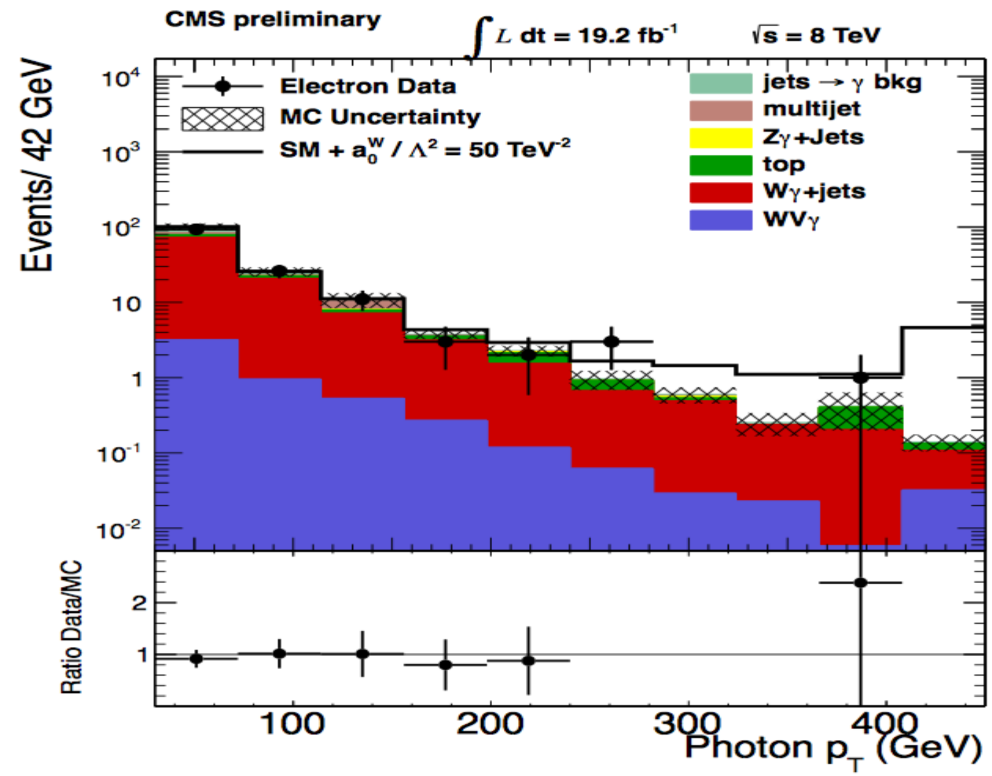
$\sigma_{SM} = 4.0 \pm 0.7$ fb

JHEP 1307 (2013) 116

Tri-boson production



- Leptonic W decay → e, μ
- Hadronic W/Z → 2 jets
- Photon with pT>10 GeV



Process	muon channel number of events	electron channel number of events
$W\gamma$+jets	$136.9 \pm 3.5 \pm 9.2 \pm 0.0$	$101.6 \pm 2.9 \pm 8.0 \pm 0.0$
WV+jet, jet$\to\gamma$	$33.1 \pm 1.3 \pm 4.6 \pm 0.0$	$21.3 \pm 1.0 \pm 3.1 \pm 0.0$
MC $t\bar{t}\gamma$	$12.5 \pm 0.8 \pm 2.9 \pm 0.5$	$9.1 \pm 0.7 \pm 2.1 \pm 0.4$
MC single top	$2.8 \pm 0.8 \pm 0.2 \pm 0.1$	$1.7 \pm 0.6 \pm 0.1 \pm 0.1$
MC $Z\gamma$+jets	$1.7 \pm 0.1 \pm 0.1 \pm 0.1$	$1.5 \pm 0.1 \pm 0.1 \pm 0.1$
multijets	$<0.2 \pm 0.0 \pm 0.1 \pm 0.0$	$7.2 \pm 3.6 \pm 3.6 \pm 0.0$
SM $WW\gamma$	$6.3 \pm 0.1 \pm 1.5 \pm 0.3$	$4.7 \pm 0.1 \pm 1.1 \pm 0.2$
SM $WZ\gamma$	$0.6 \pm 0.0 \pm 0.1 \pm 0.0$	$0.5 \pm 0.0 \pm 0.1 \pm 0.0$
Total predicted	$193.9 \pm 3.9 \pm 10.8 \pm 1.0$	$147.6 \pm 4.8 \pm 9.6 \pm 0.7$
Data	183	139

Cross-section not yet accessible
Upper limit: 241 fb
(3.4 x SM)

CMS-PAS-SMP-13-009

Anomalous quartic gauge coupling limits

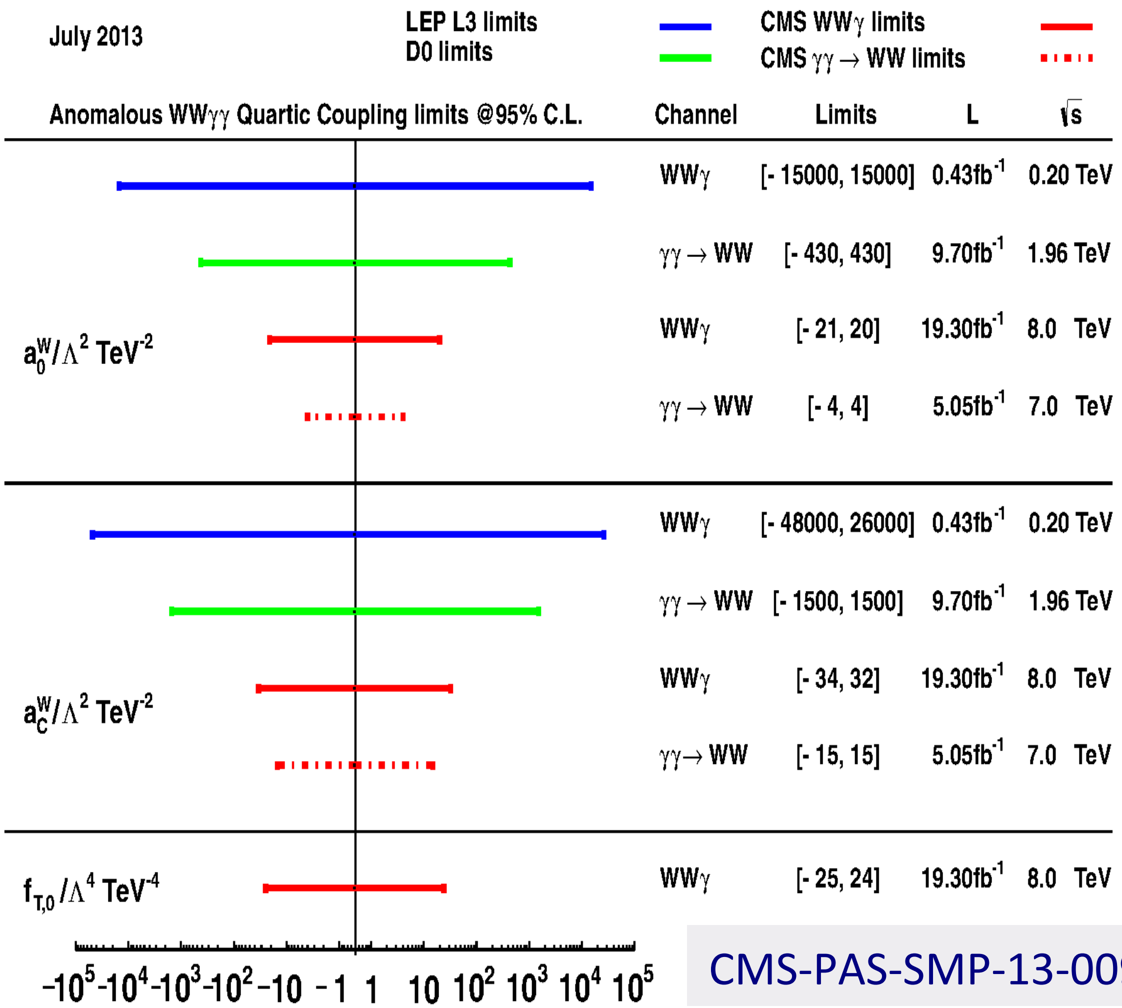
- EFT Lagrangian parametrizing possible new physics

$$L = L_{SM} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}$$

- Dim-6 and dim-8 operators by integrating out the new degrees of freedom
- Coefficients to be calculated from more complete high-energy theory
- Unitarity violation → form-factors, cut-off
- Large theoretical uncertainties

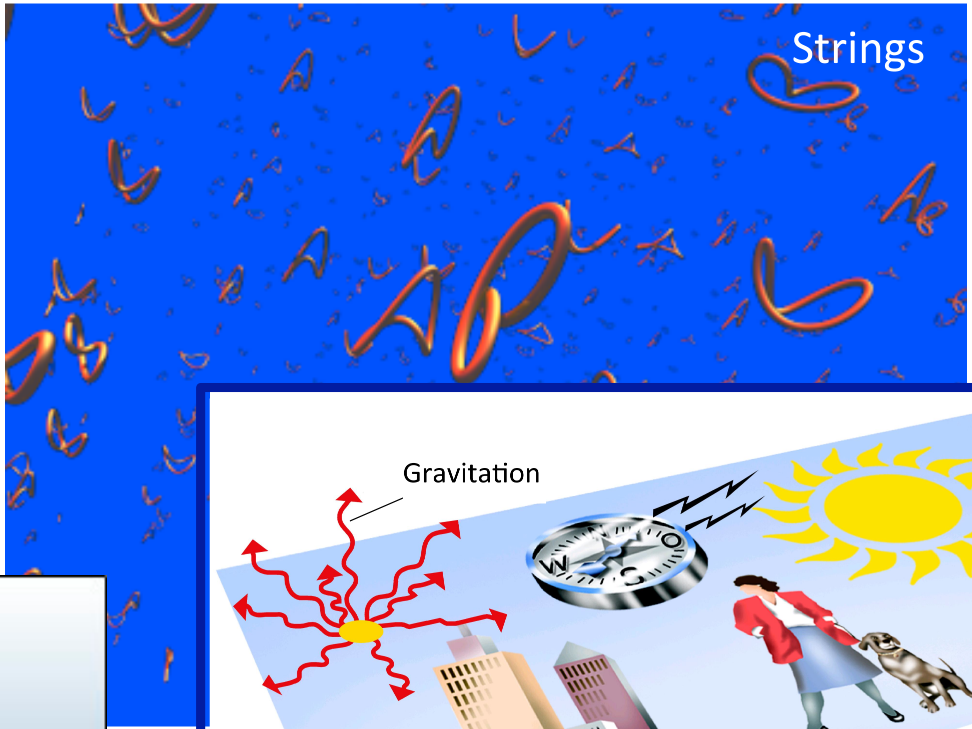
$$L_6^0 = \frac{e^2}{8}\frac{a_0^W}{\Lambda^2} F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W_\alpha^- - \frac{e^2}{16\cos^2\Theta_W}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha$$

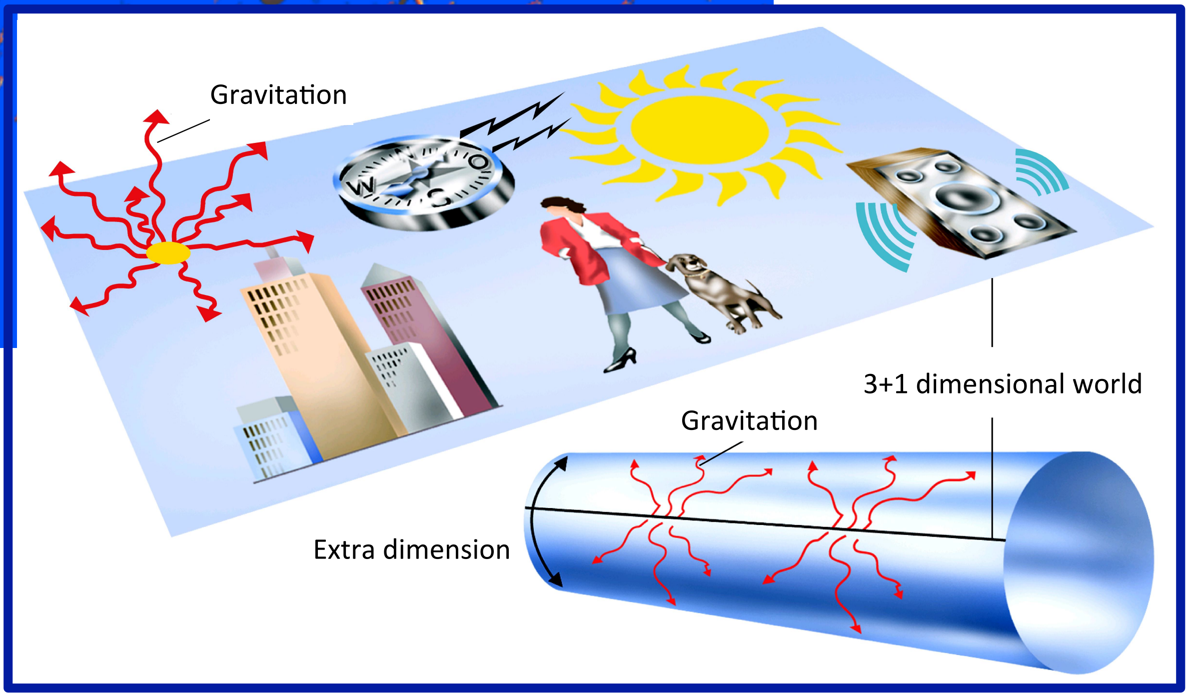
$$L_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2} F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W_\beta^- + W^{-\alpha}W_\beta^+) - \frac{e^2}{16\cos^2\Theta_W}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

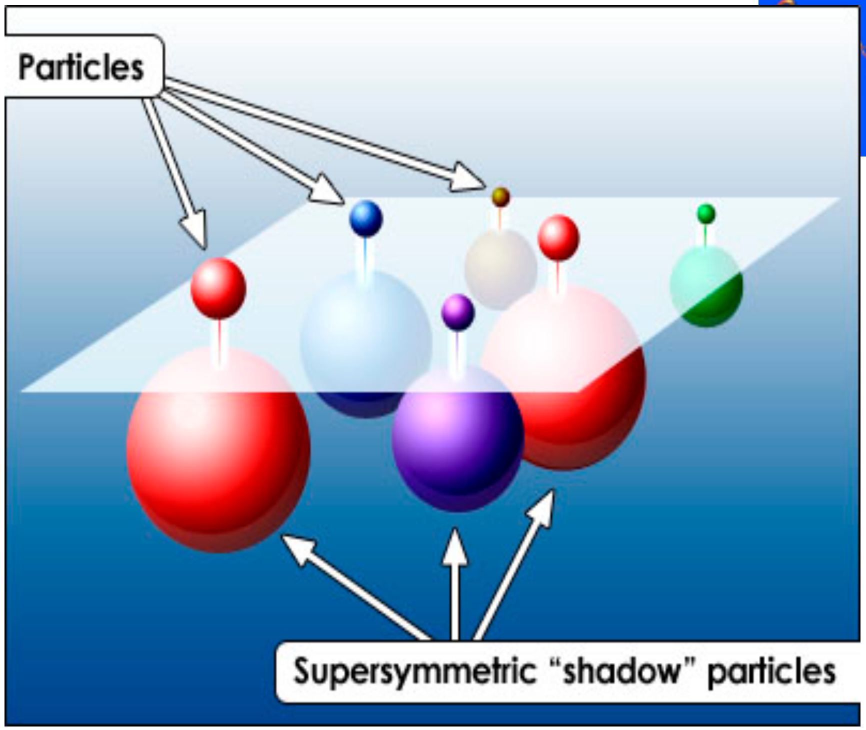


CMS-PAS-SMP-13-009

Beyond the Higgs sector







ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.6 - 22.9)\ \text{fb}^{-1}$ $\sqrt{s} = 7,\ 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [\text{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta$>18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 275-430 GeV	$m(\tilde{\chi}_1^\pm)=2\,m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 271-520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	1 b	Yes	14.3	sgluon 800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

Mass scale [TeV] (axis: 10^{-1}, 1)

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

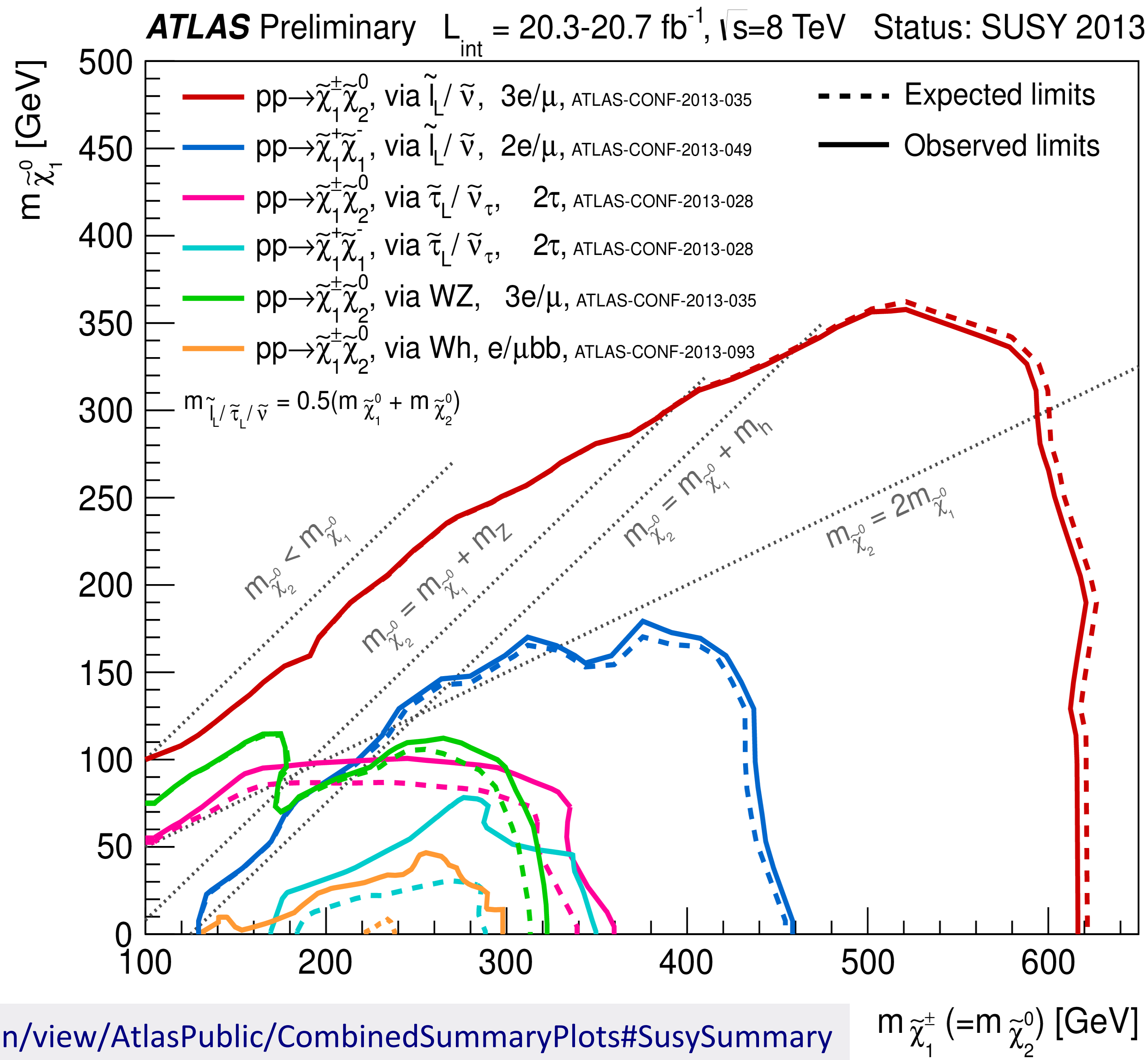
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots#SusySummary

Constraints on gaugino production

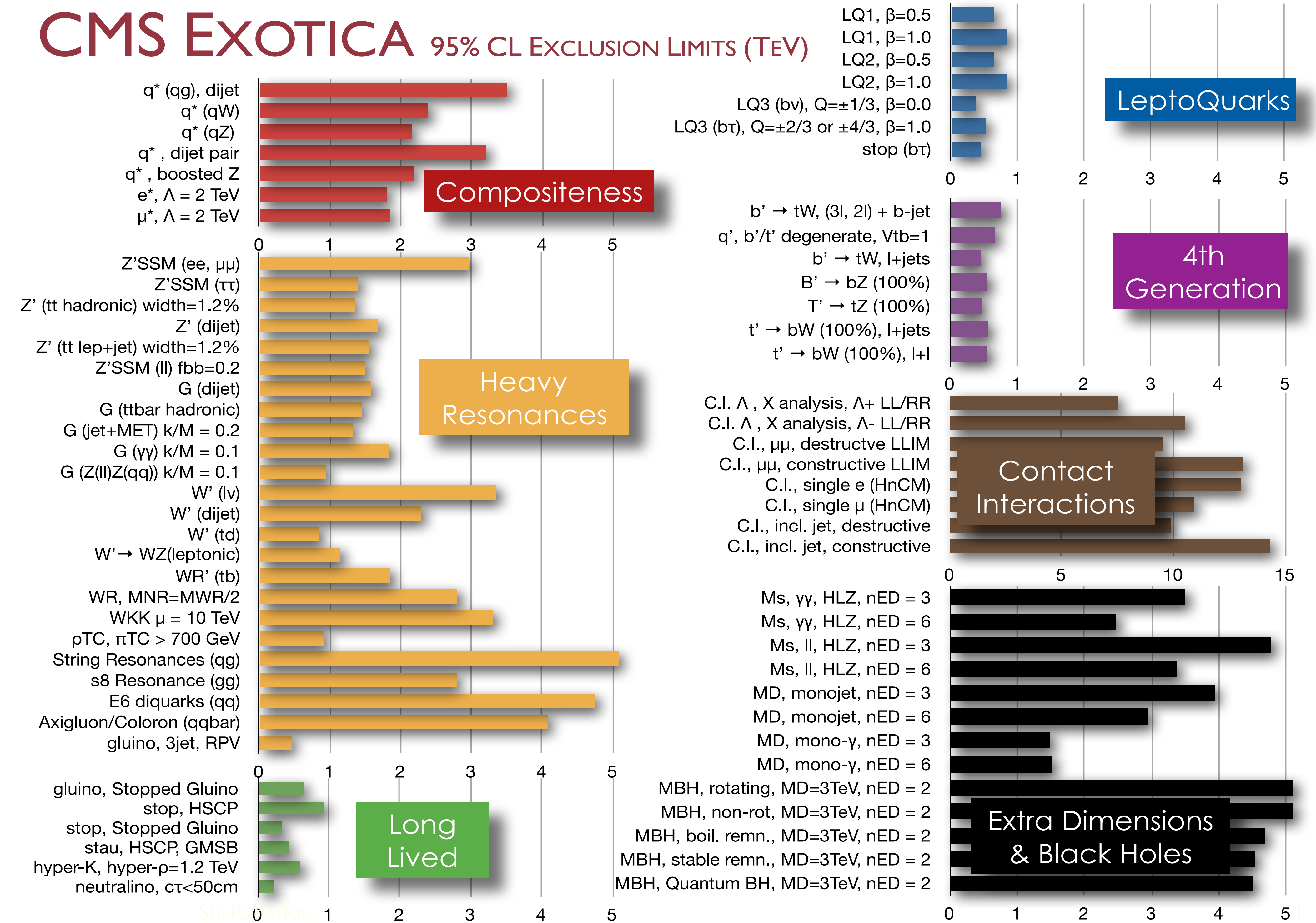
No hint anywhere for new SUSY phenomena

Natural-SUSY seems less and less probable (Higgs mass & direct search results)



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots#SusySummary

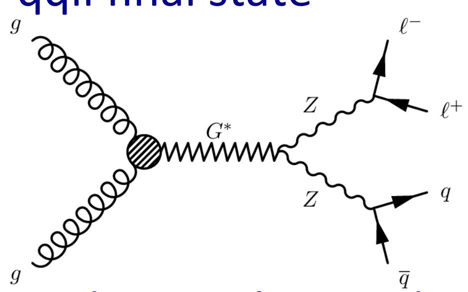
CMS Exotica 95% CL Exclusion Limits (TeV)



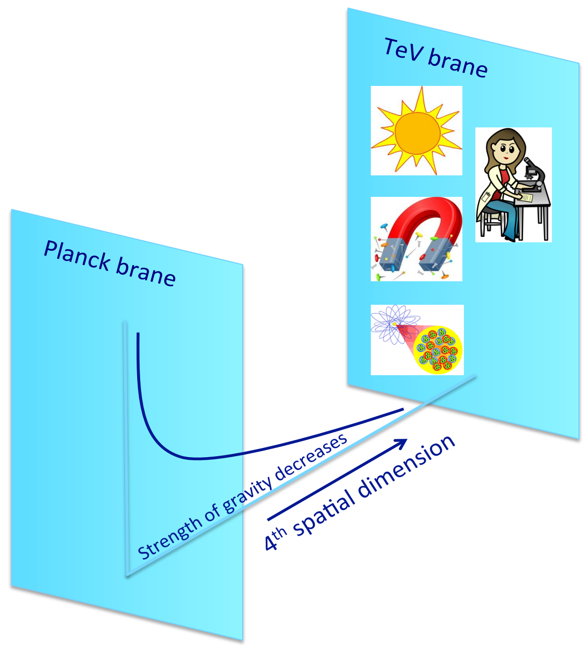
https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/CMS-EXO-Moriond2013.pdf

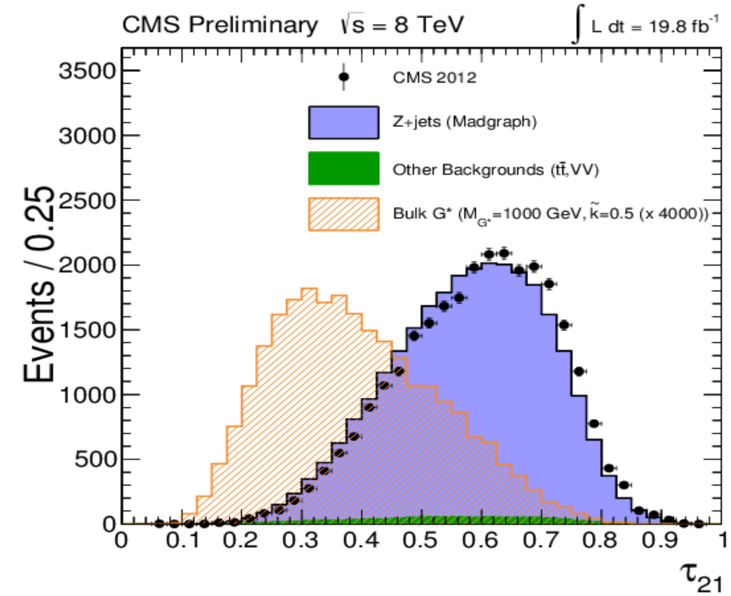
Search for extra dimensions: RS graviton

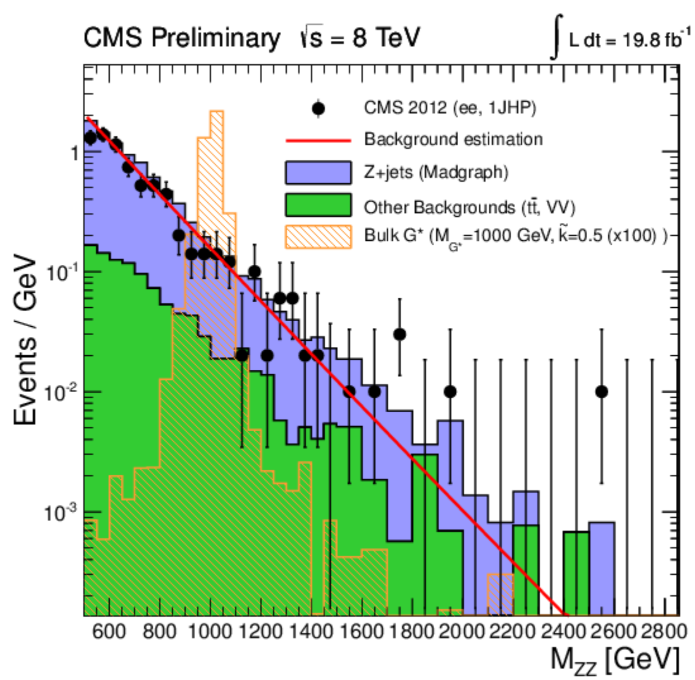
- Randall-Sundrum model proposed to solve the hierarchy problem assuming a 5th dimension with a warped geometry
- Only gravity can propagate in the ED
- In 3+1 D, KK graviton resonances appear
- Search for $G_{KK} \rightarrow ZZ$ in qqll final state

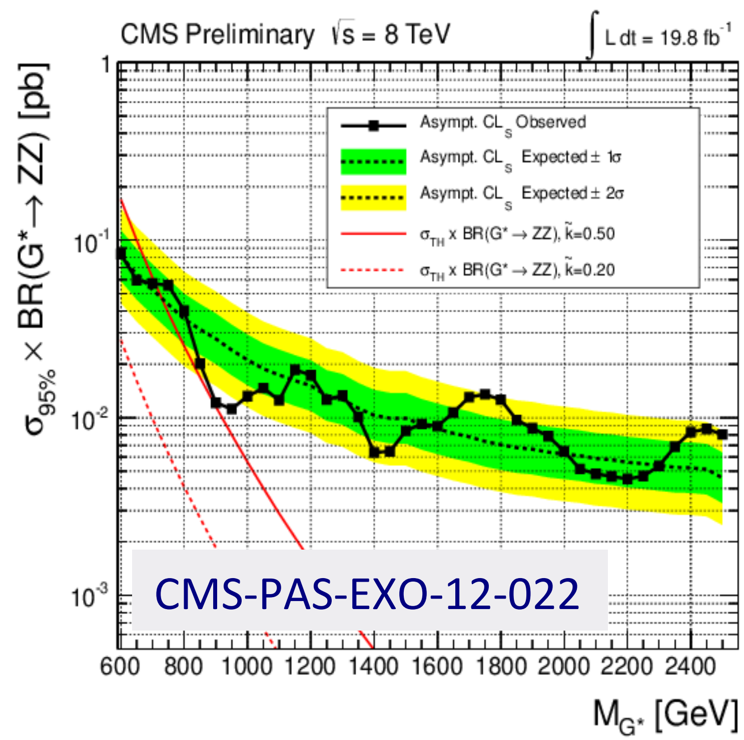


- Hadronic Z boosted: jet substructure techniques





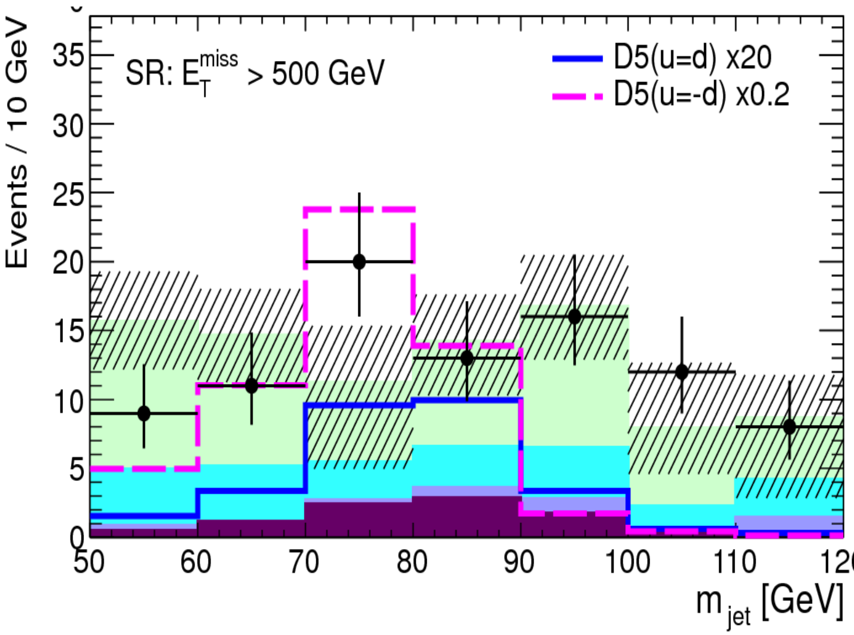


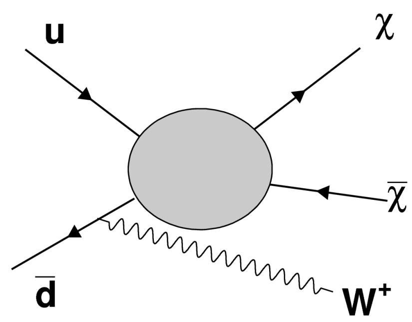


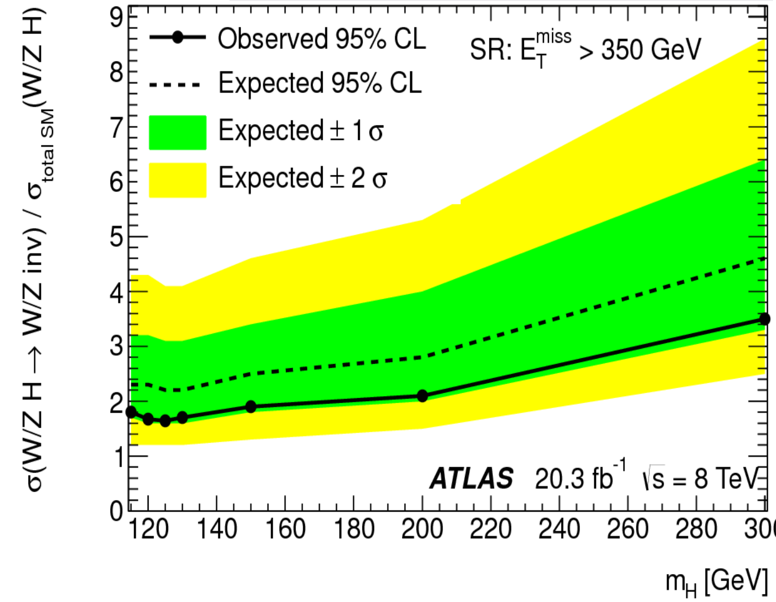
Search for dark matter

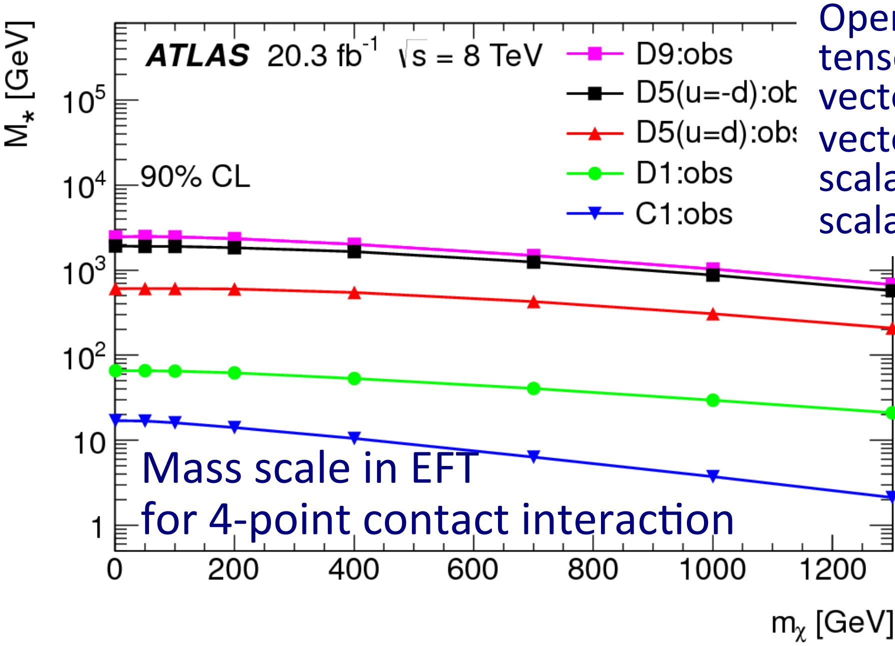
arXiv:1309.4017 [hep-ex]

Pair-produced dark matter tagged by initial-state W/Z emission in boosted hadronic final state



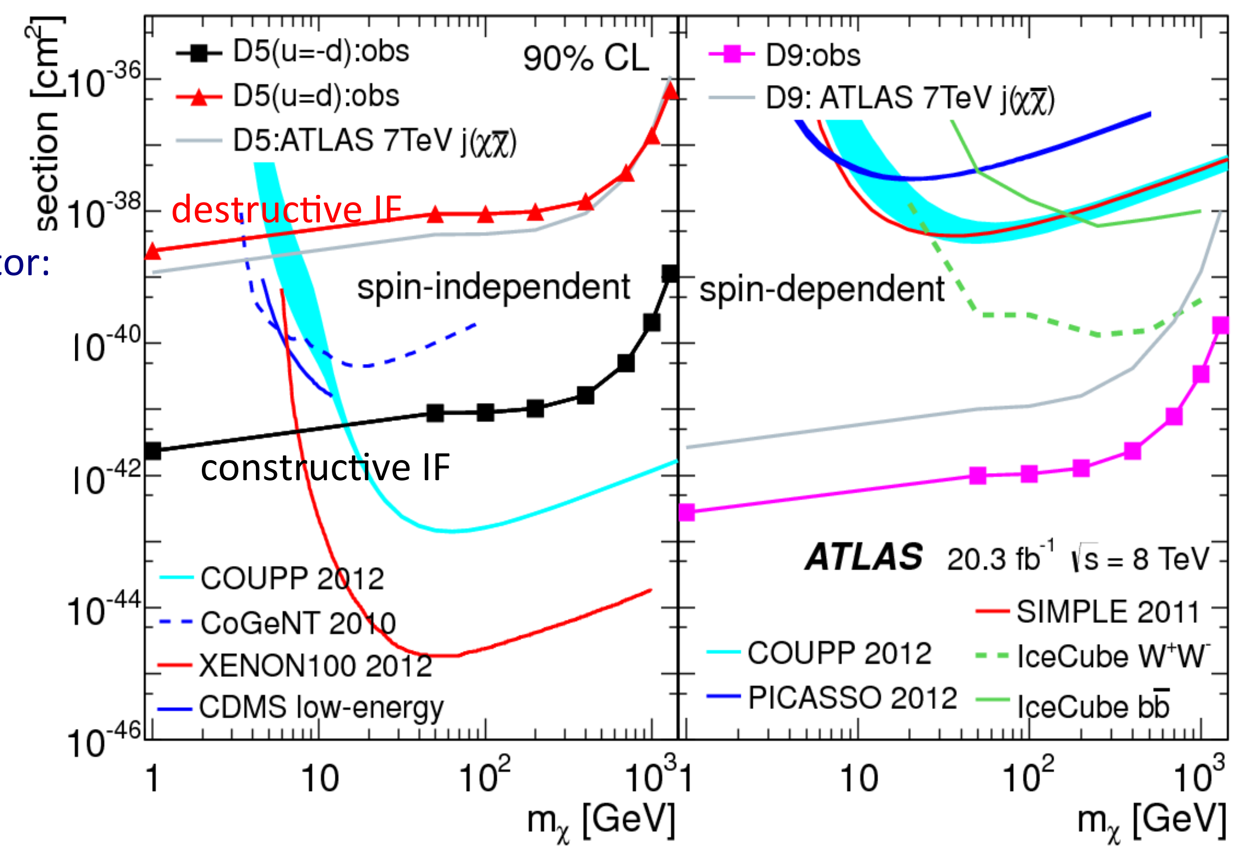






Operator:
tensor
vector
vector
scalar
scalar

Mass scale in EFT
for 4-point contact interaction



As exiting as ever...

We are only at the beginning....
What waits
behind the Higgs?

Extra

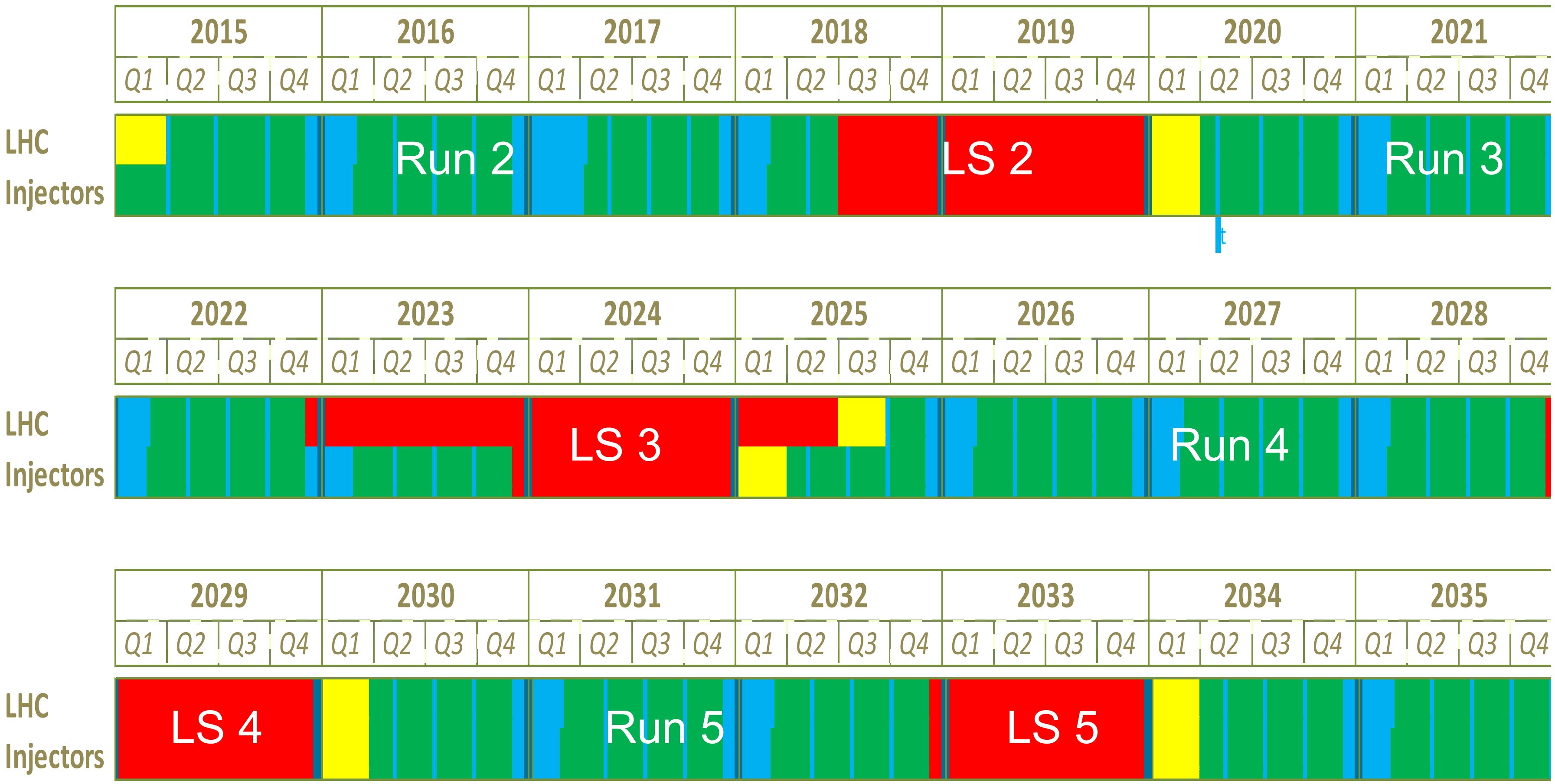
LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)

LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)

LS3 LHC: starting in 2023 => 30 months + 3 BC

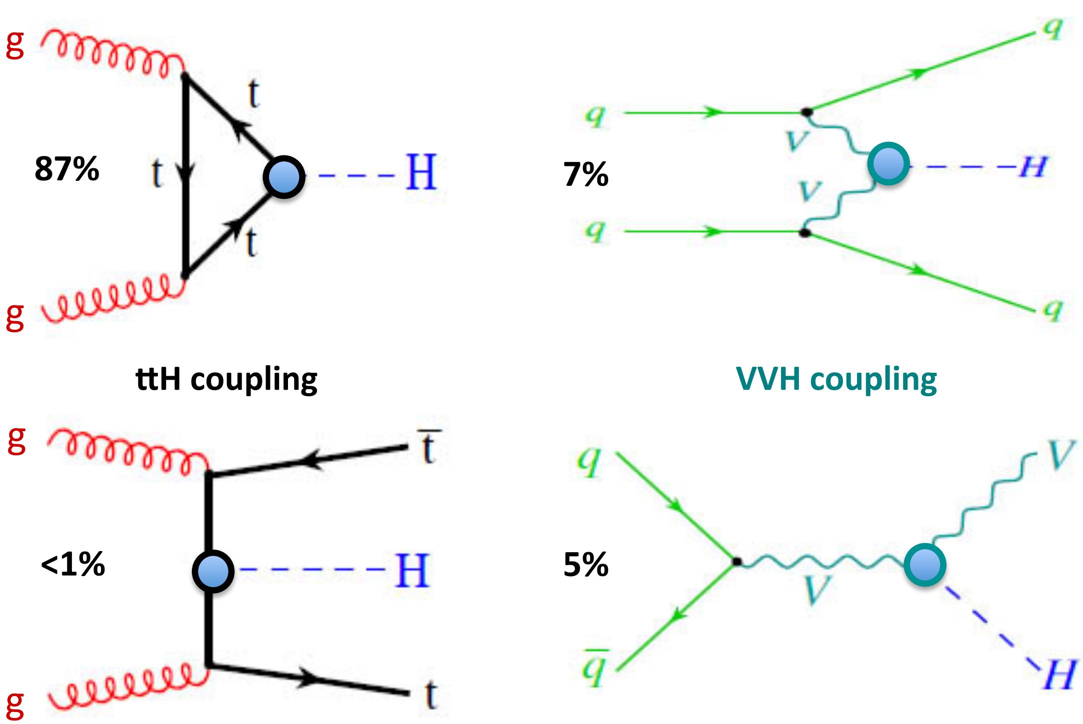
injectors: in 2024 => 13 months + 3 BC

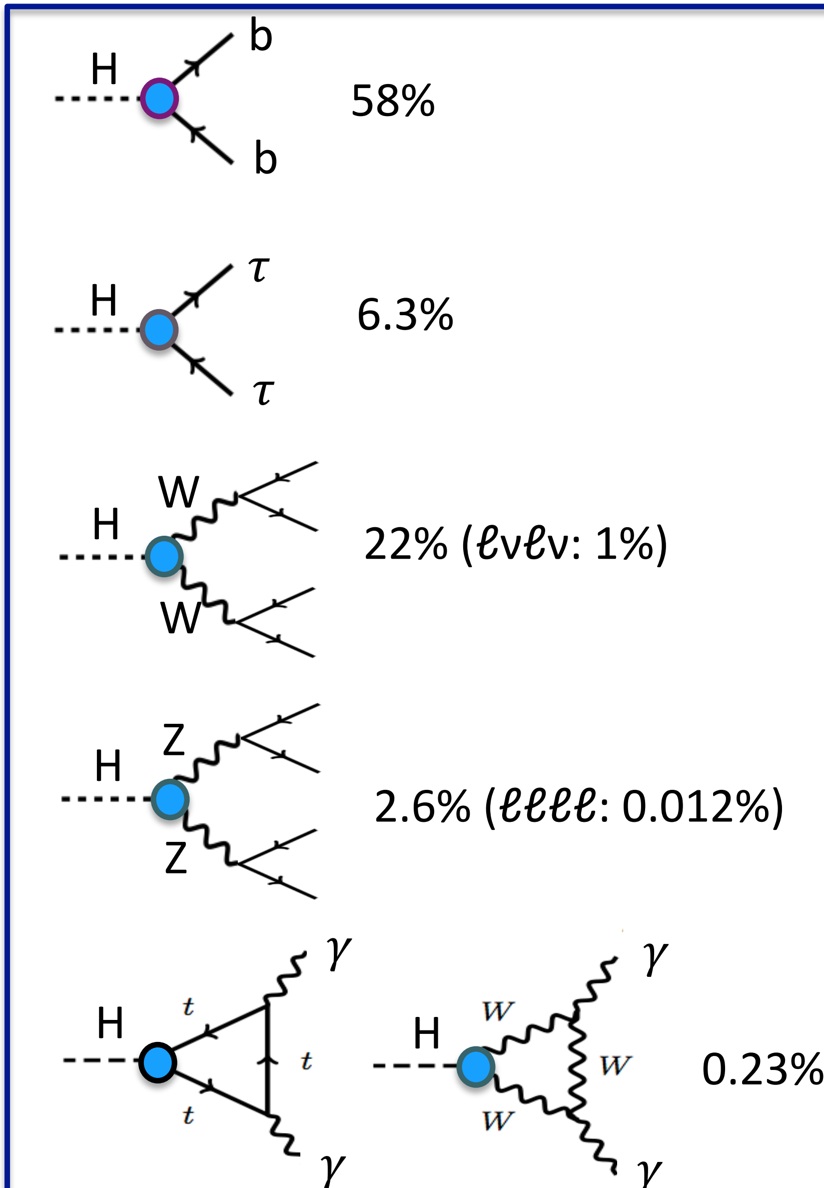


LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

Higgs production and decay

σ_{total} = 22 pb @ √s = 8 TeV, m_H = 125 GeV

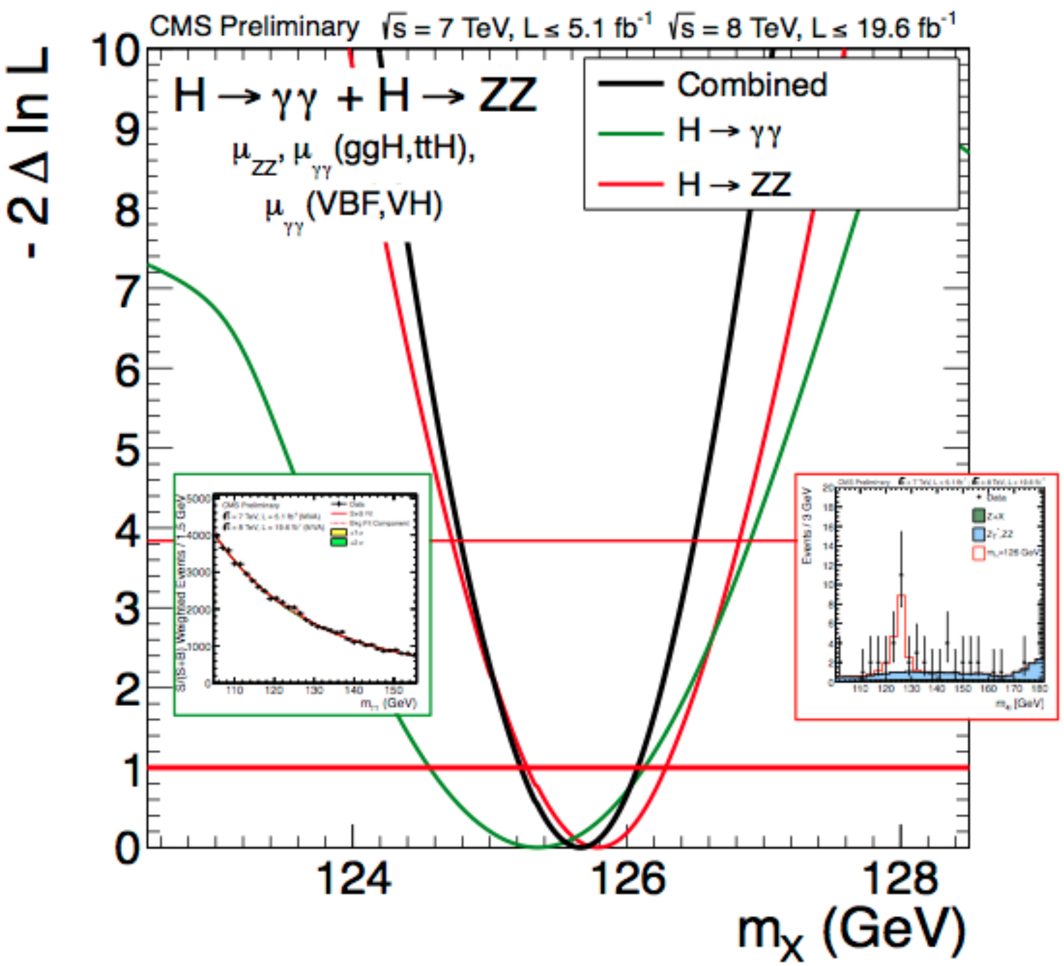


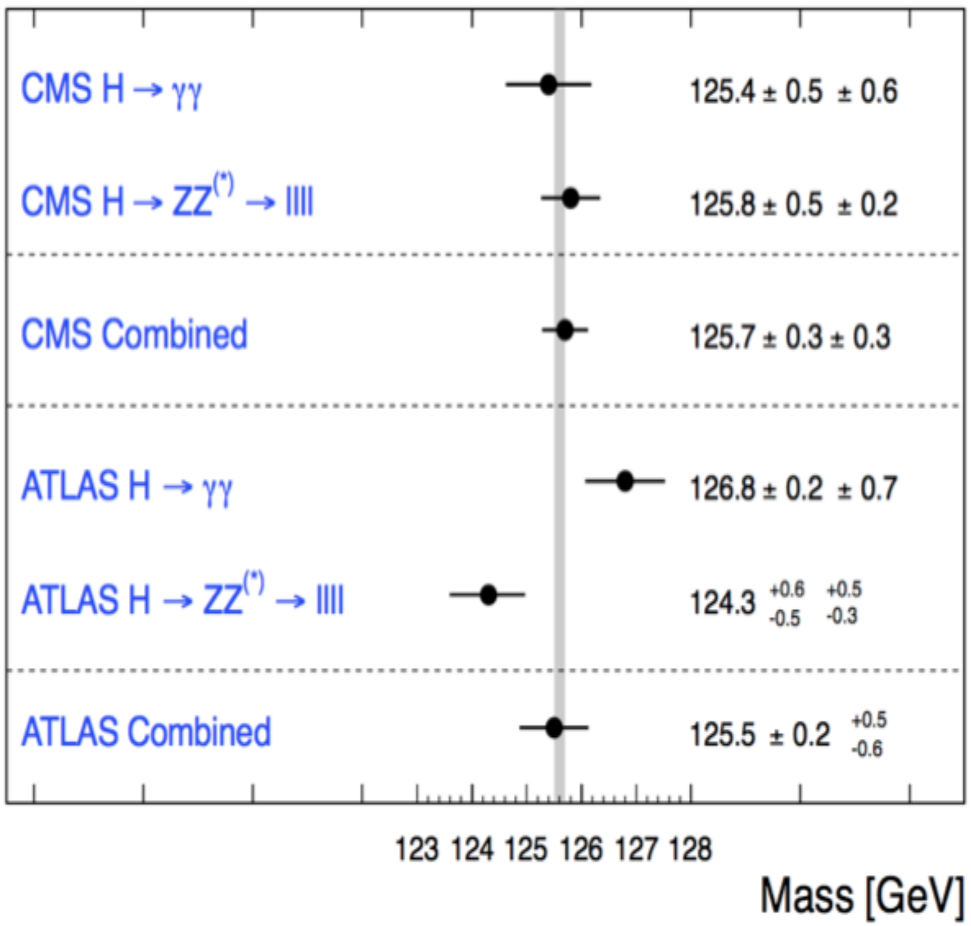


Measuring different production and decay modes, the different coupling constants can be determined

g(Hff) ∝ $m_{fermion}$
g(HVV) ∝ m_{bozon}^2

Higgs mass





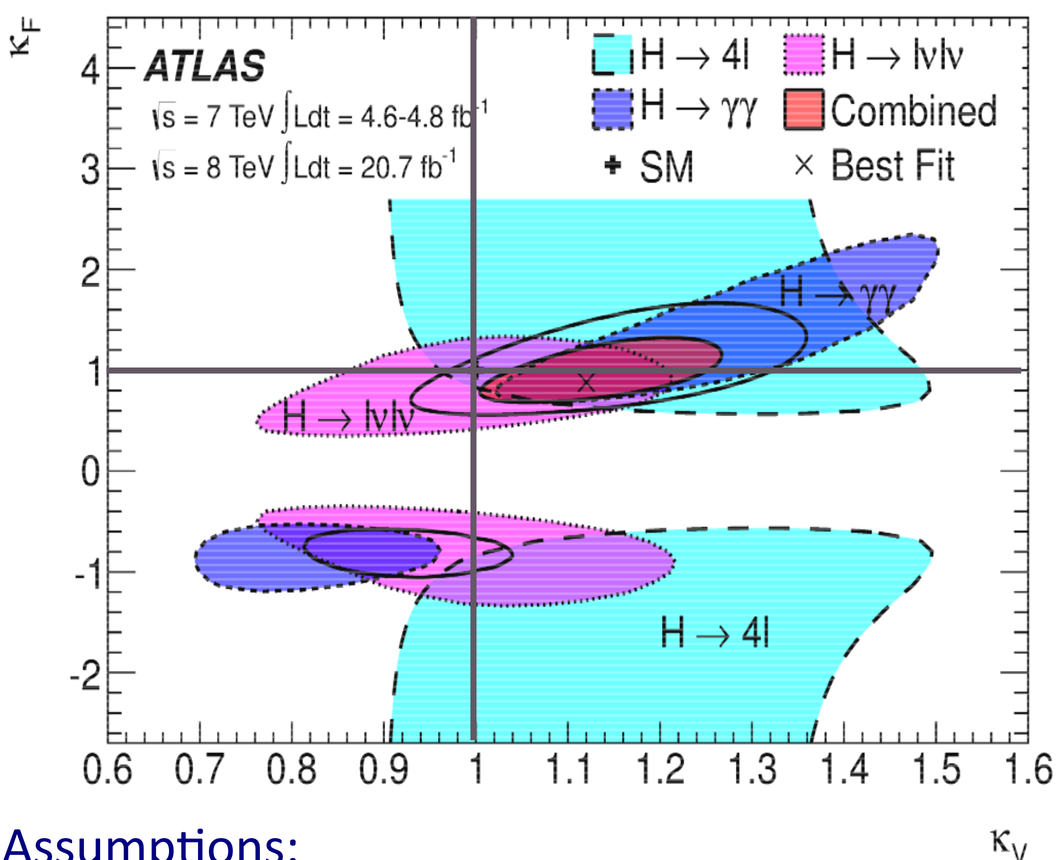
Final results require final Run1 calibration

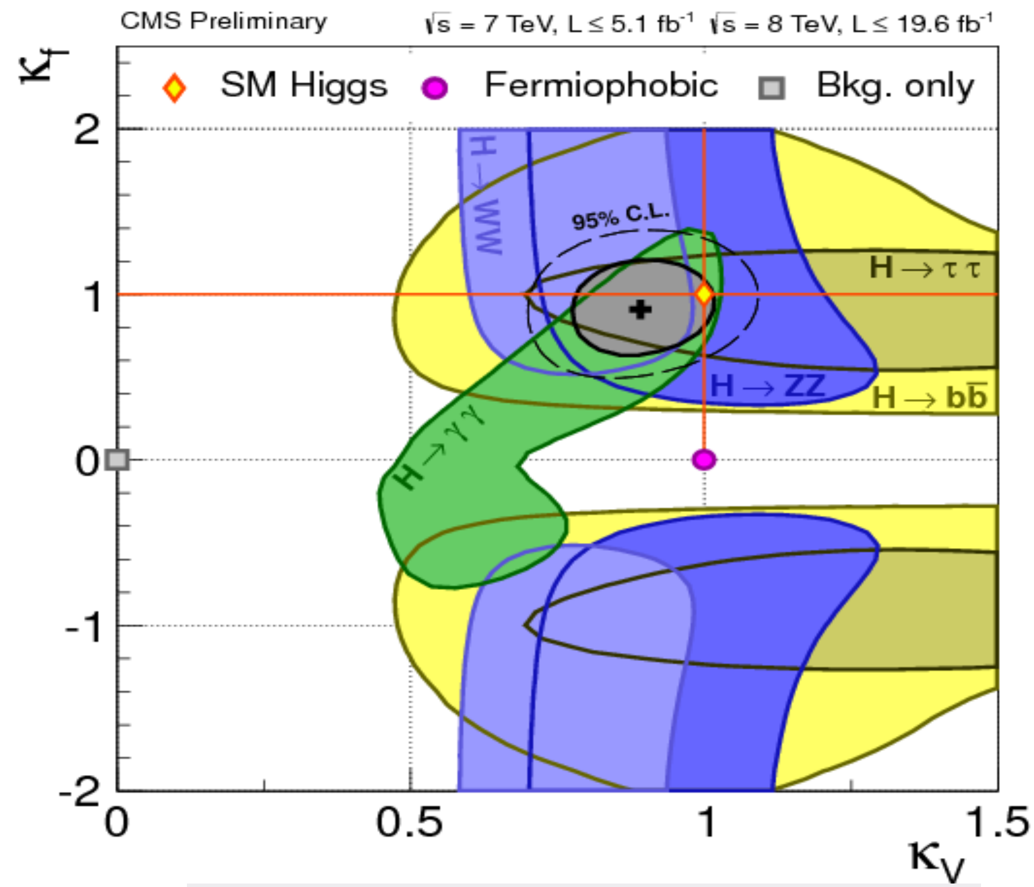
Constrains both SUSY and composite-Higgs models! (See an example later...)

Coupling constant scale factors

$\kappa_i \equiv g_i / g_i^{SM}$

κ_V vs. κ_F

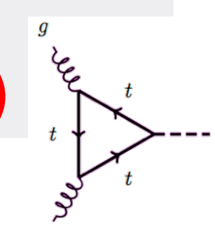




Assumptions:

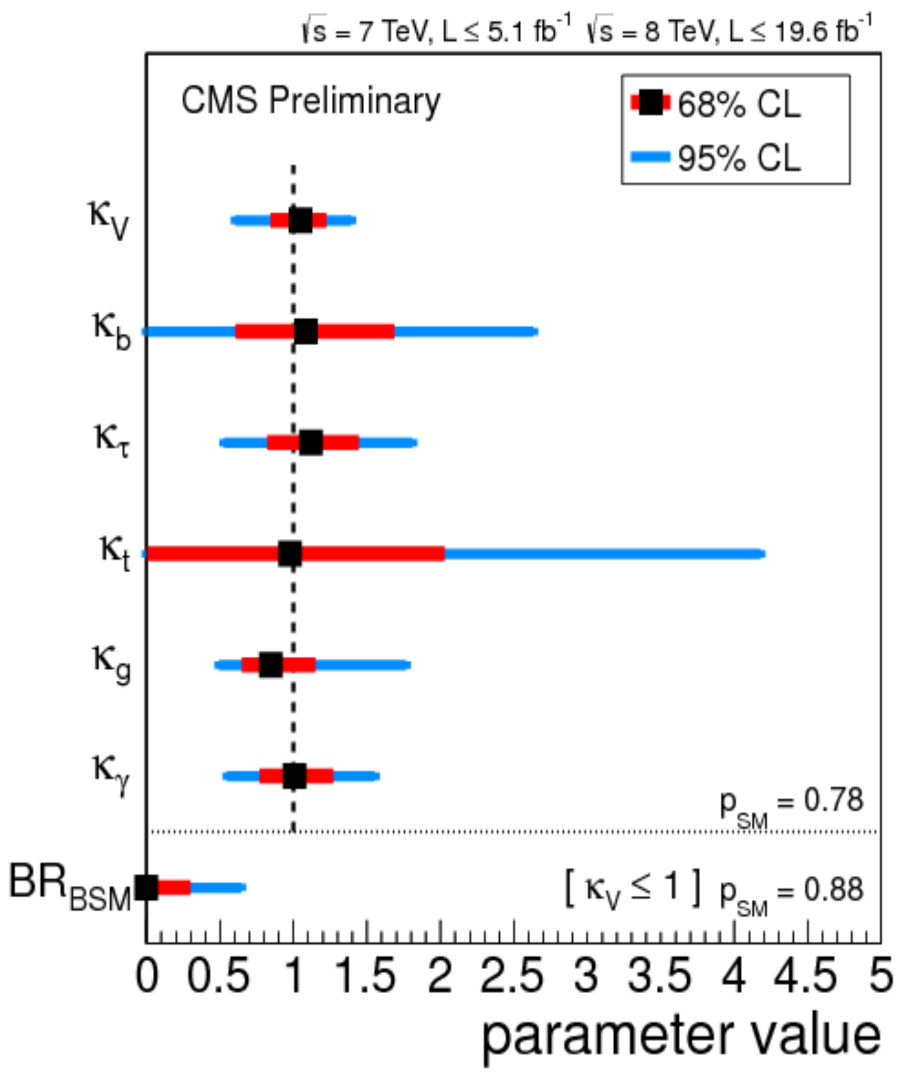
- All fermion (t,b, τ, ..) couplings scale with κ_F
- All heavy vector boson (W, Z) couplings scale with κ_V
- No other new physics contributes to the total width: $\kappa_g(\kappa_F\ \kappa_V)$, $\kappa_\gamma(\kappa_F\ \kappa_V)$
- Total width Γ_H scales with $\kappa_H^2 \approx 0.7\ \kappa_F^2 + 0.3\ \kappa_V^2$

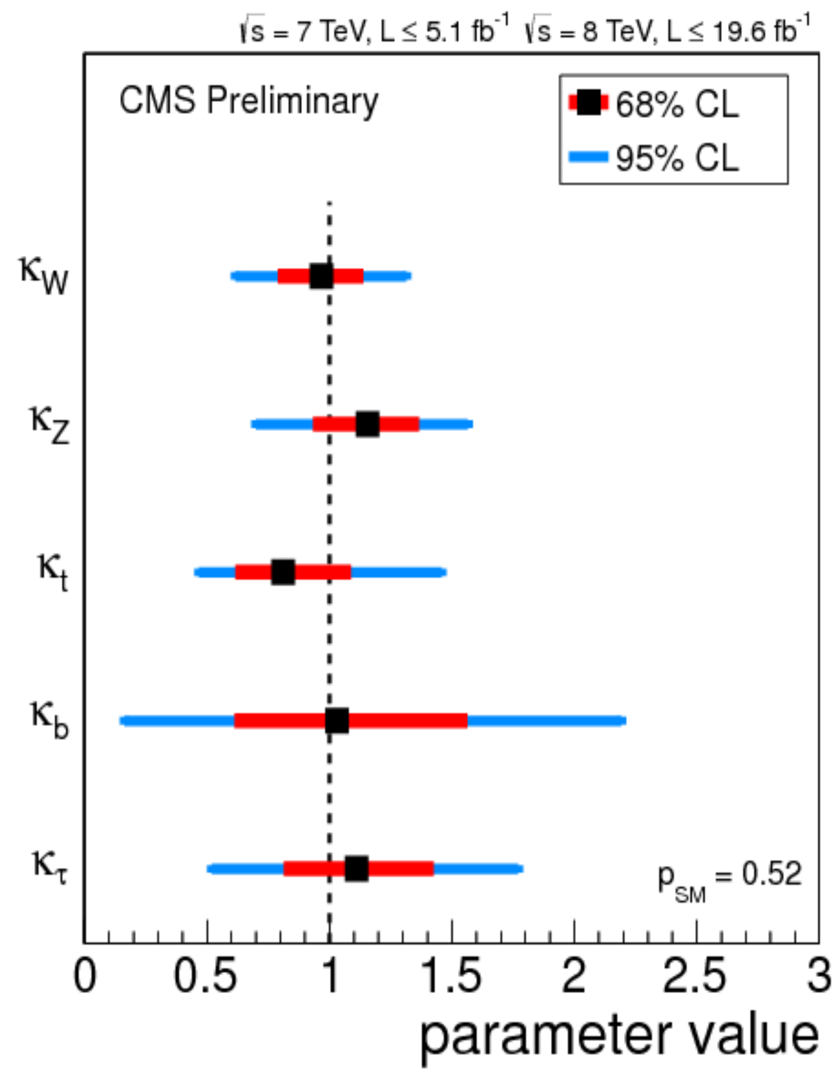
- **Agreement with SM within 10-20% precision**
- **κ_F=0 excluded with >5σ (from indirect ggH loop)**



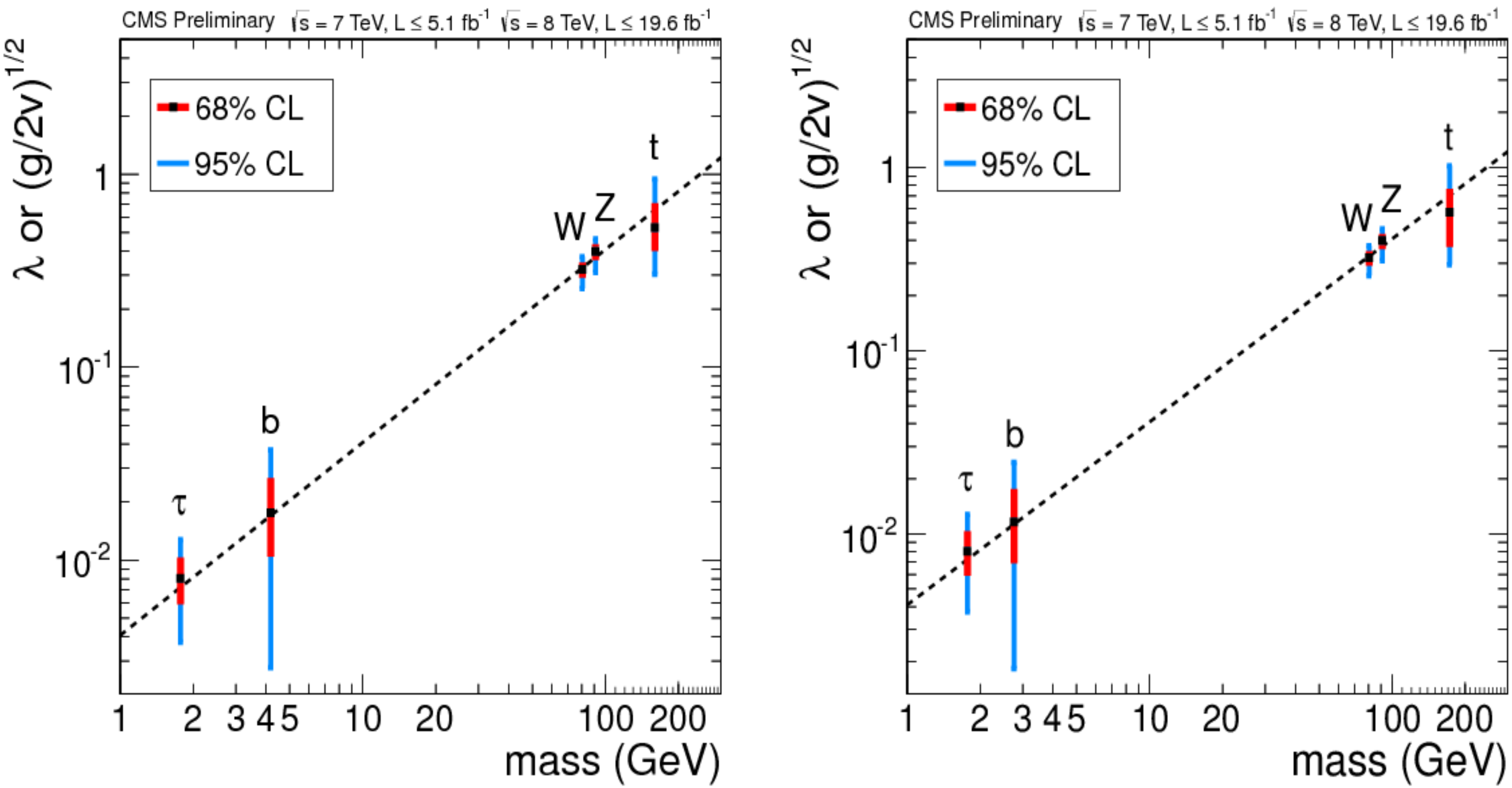
Coupling constant scale factors

$\kappa_i \equiv g_i / g_i^{SM}$

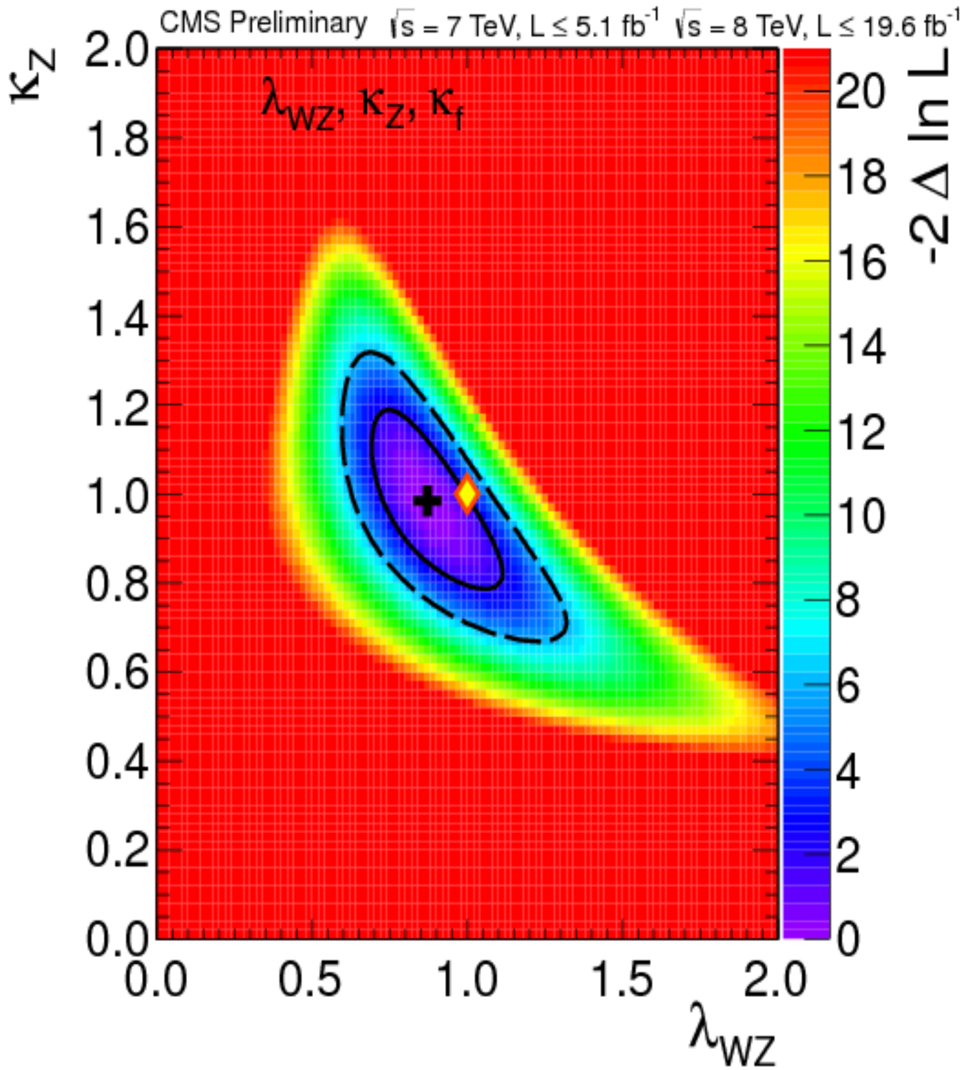


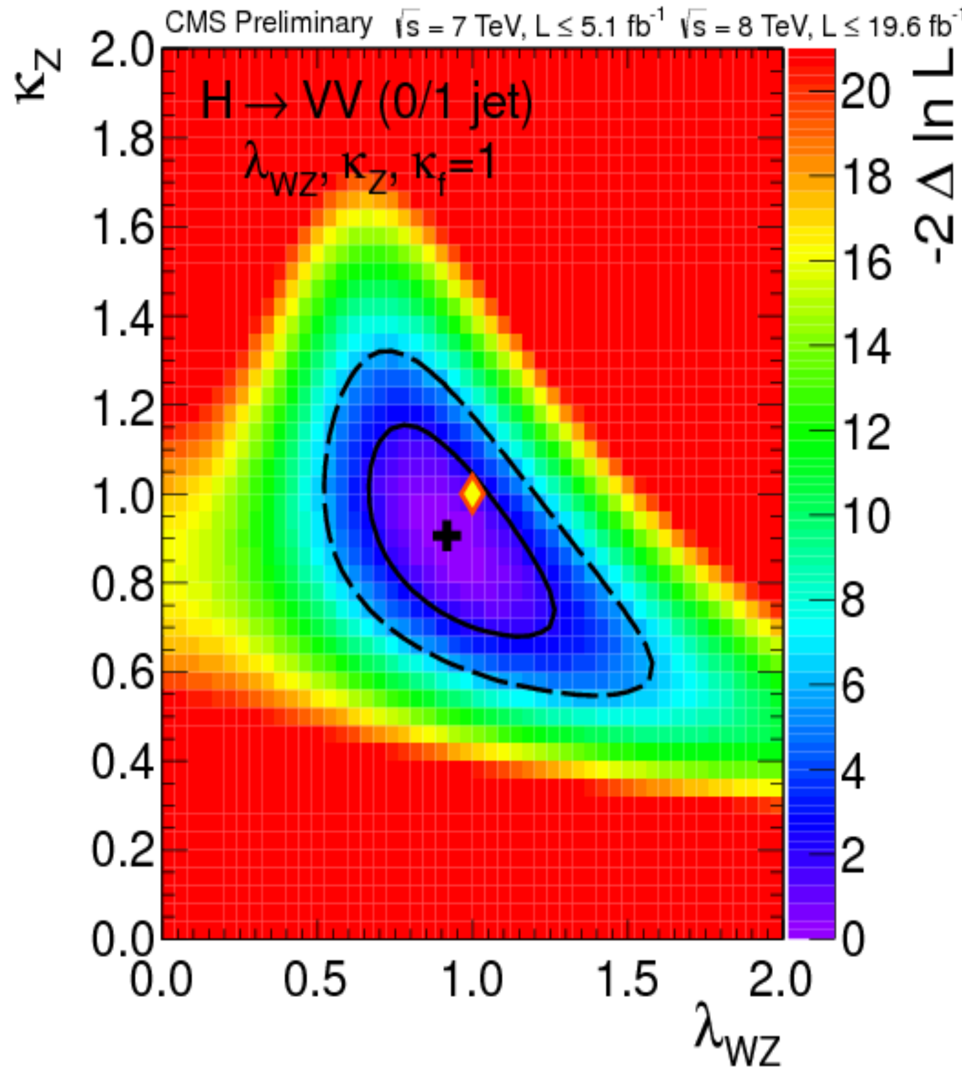


Higgs coupling vs. mass



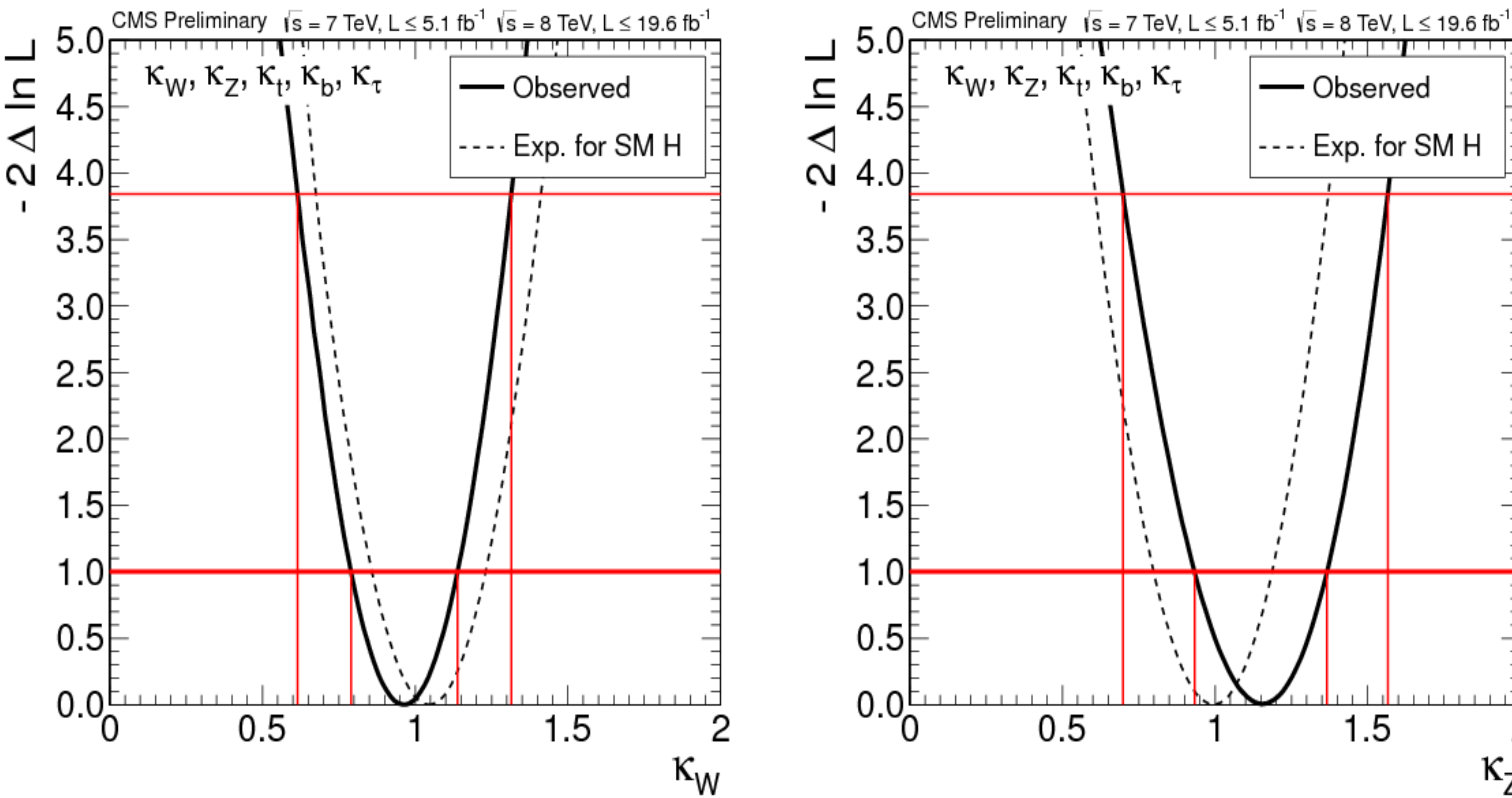
Test of custodial symmetry



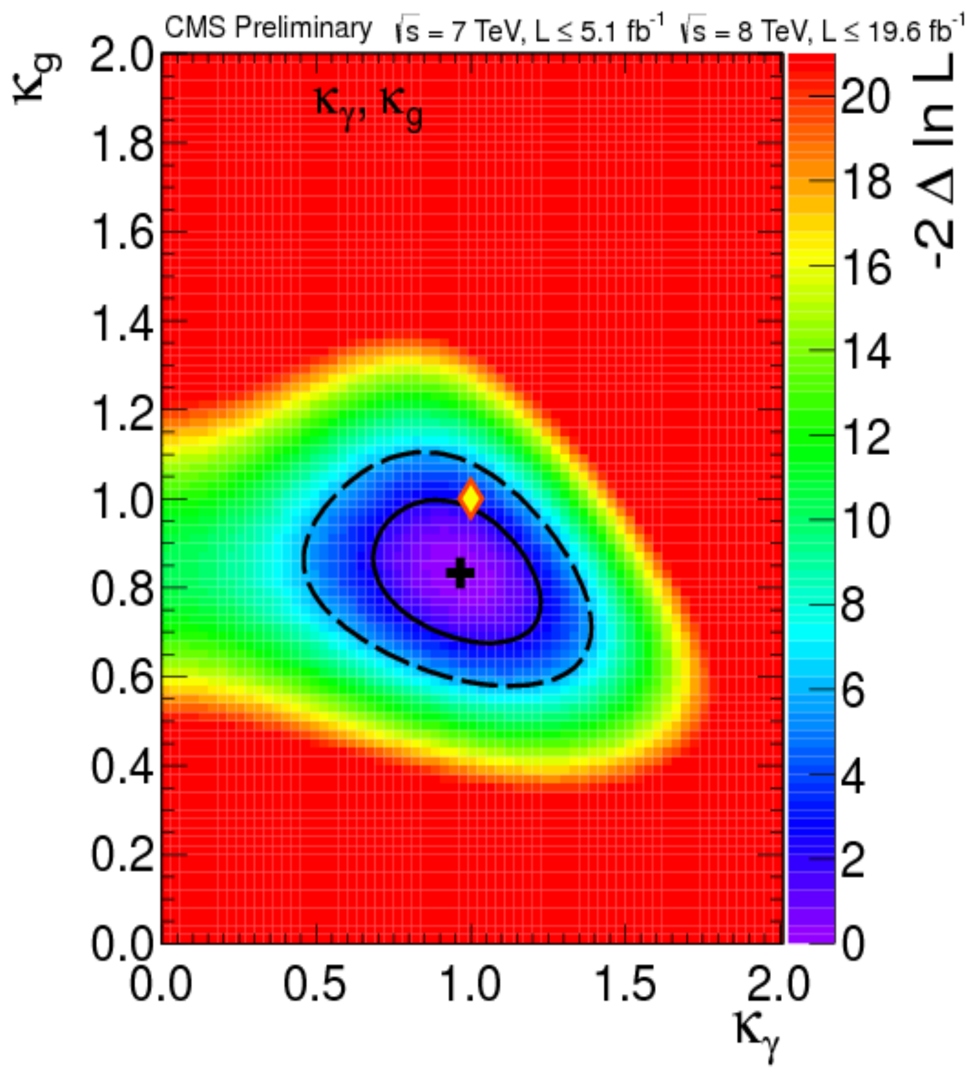


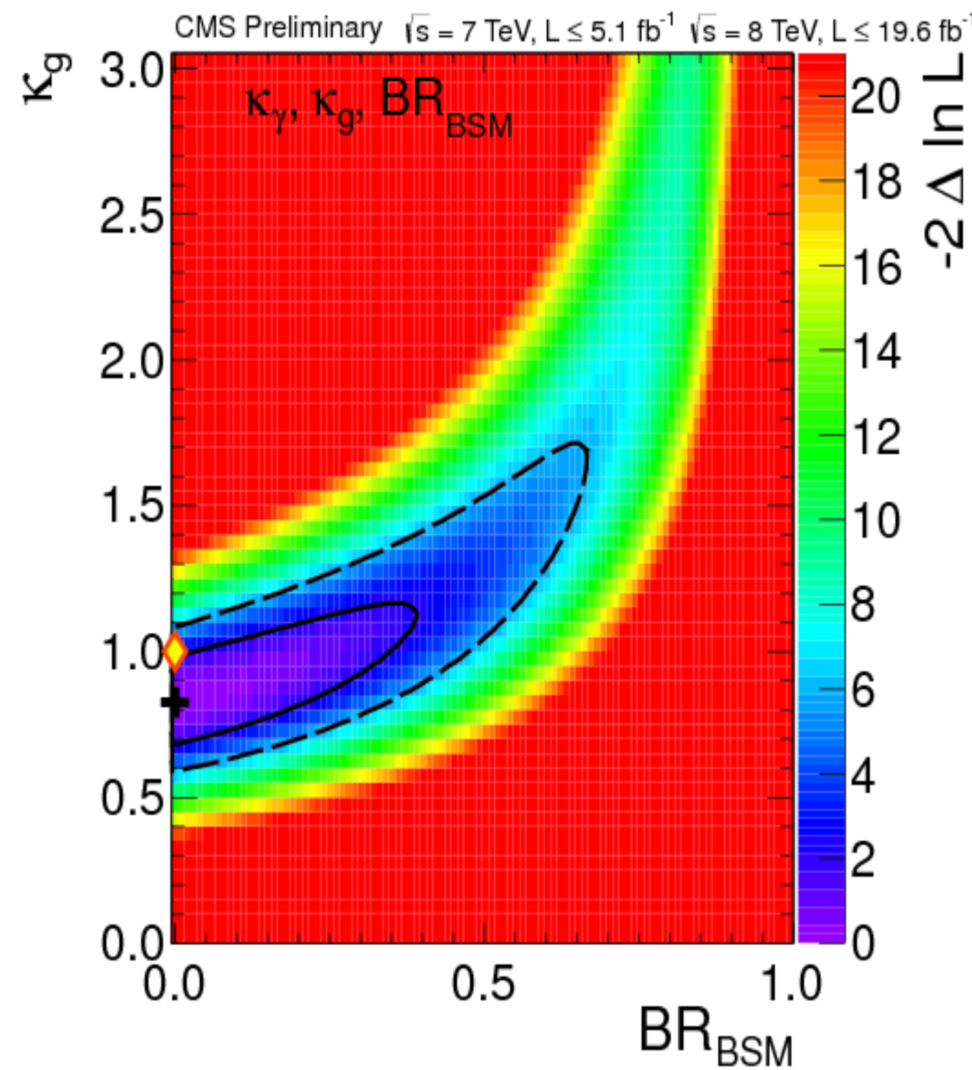
Generic search for deviation from SM

by profiling the other coupling modifiers

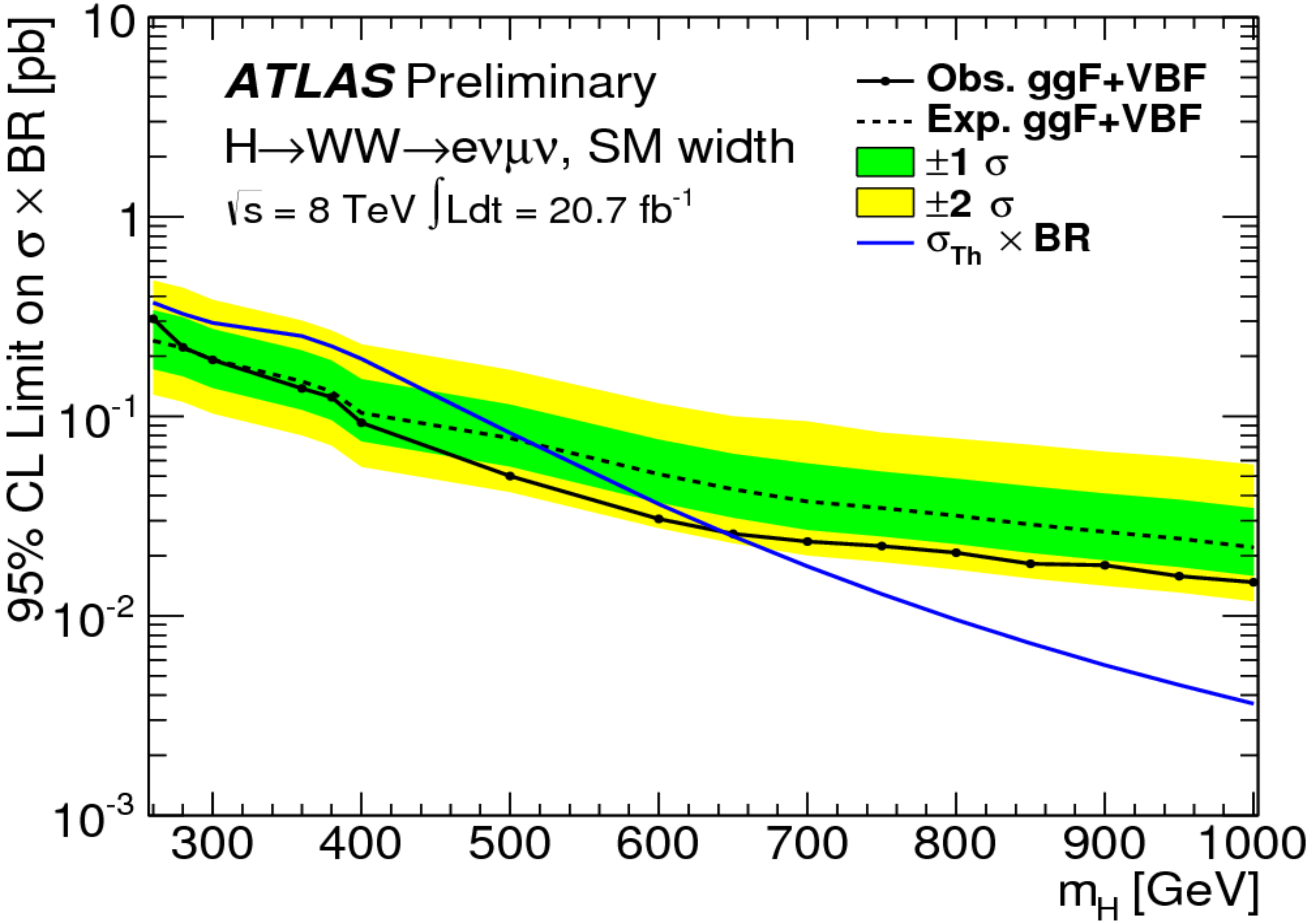


Search for new physics in loops





High-mass searches: an example

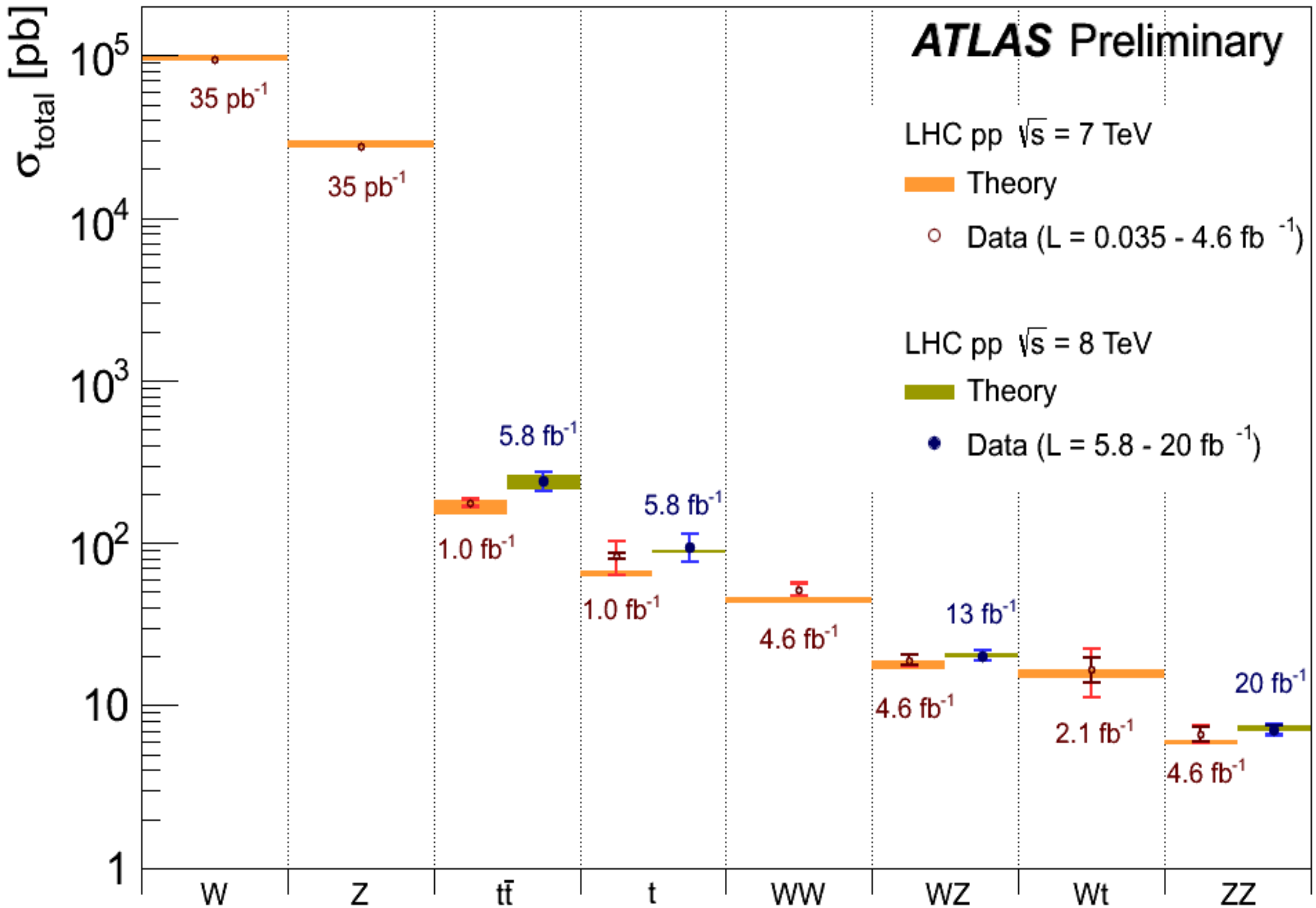


The μ-problem of SUSY

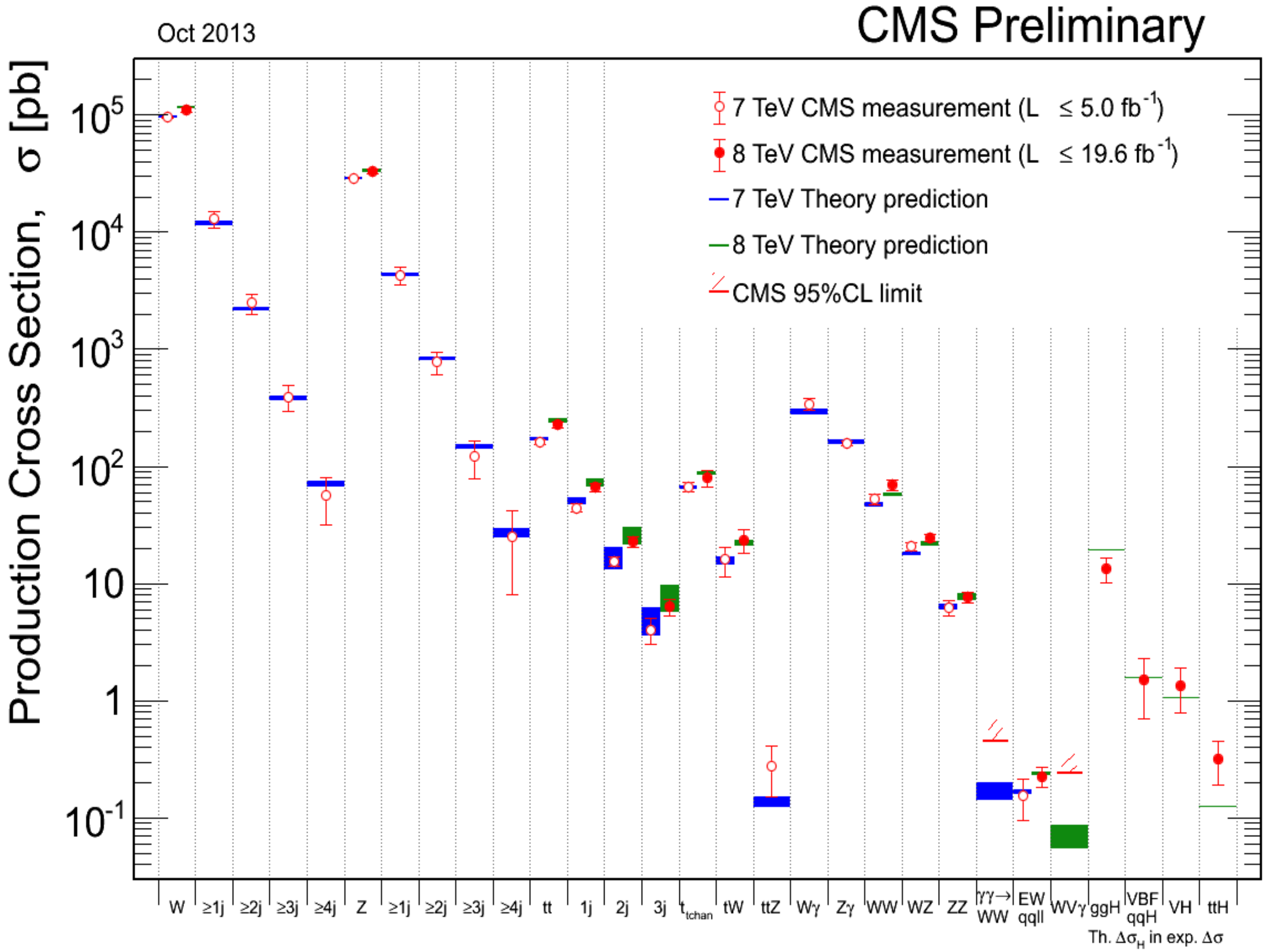
$$W_{\mathsf{MSSM}} = \widehat{Q}\widehat{H}_u \mathbf{h_u} \widehat{U}^C + \widehat{H}_d \widehat{Q} \mathbf{h_d} \widehat{D}^C + \widehat{H}_d \widehat{L} \mathbf{h_e} \widehat{E}^C + \mu \widehat{H}_u \widehat{H}_d$$

- μ is in the superpotential, so it is present before supersymmetry breaking (via soft terms). **μ should know nothing about the electroweak scale.**
- If $\mu = 0$ then there is no mixing between the two Higgs doublets. Any breaking of electroweak symmetry generated in the up-quark sector (by $M_H^2 < 0$) could not be communicated to the down-quark sector. The down-type quarks and leptons would remain massless.
- If $\mu = M_{Planck}$ then the Higgs bosons and their higgsino partners would gain Planck scale masses, in contradiction with upper bounds from triviality and precision electroweak data.
- For phenomenologically acceptable supersymmetry, the μ-parameter must be of the order of the electroweak scale.
- One way to link the μ-parameter with the electroweak scale is to make it a vacuum expectation value. Introduce a new iso-singlet neutral colorless chiral superfield $\widehat{S}$ coupling together the usual two Higgs doublet superfields. The scalar part of this is $\lambda S H_u H_d$. If S gains a vacuum expectation value we generate and effective μ-term. → NMSSM

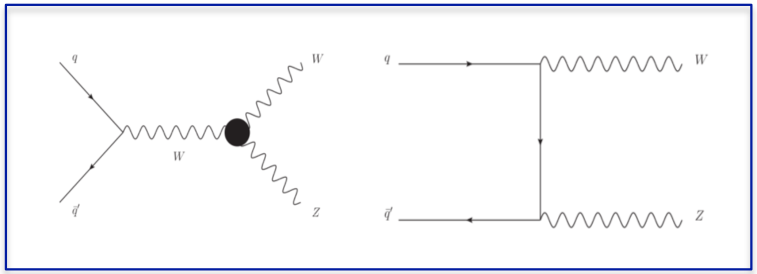
The SM strairway

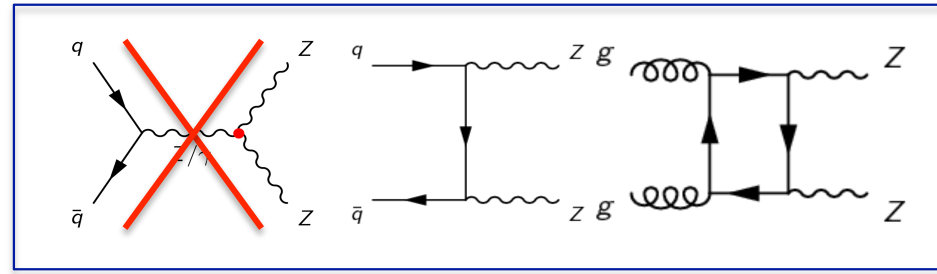


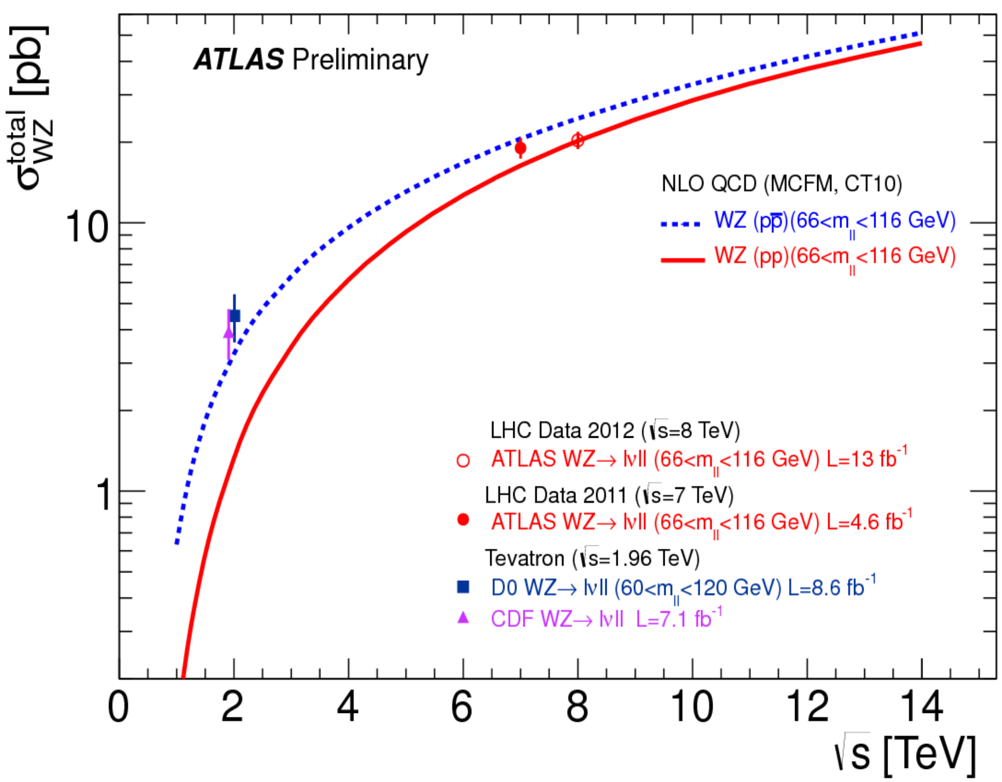
The SM strairway

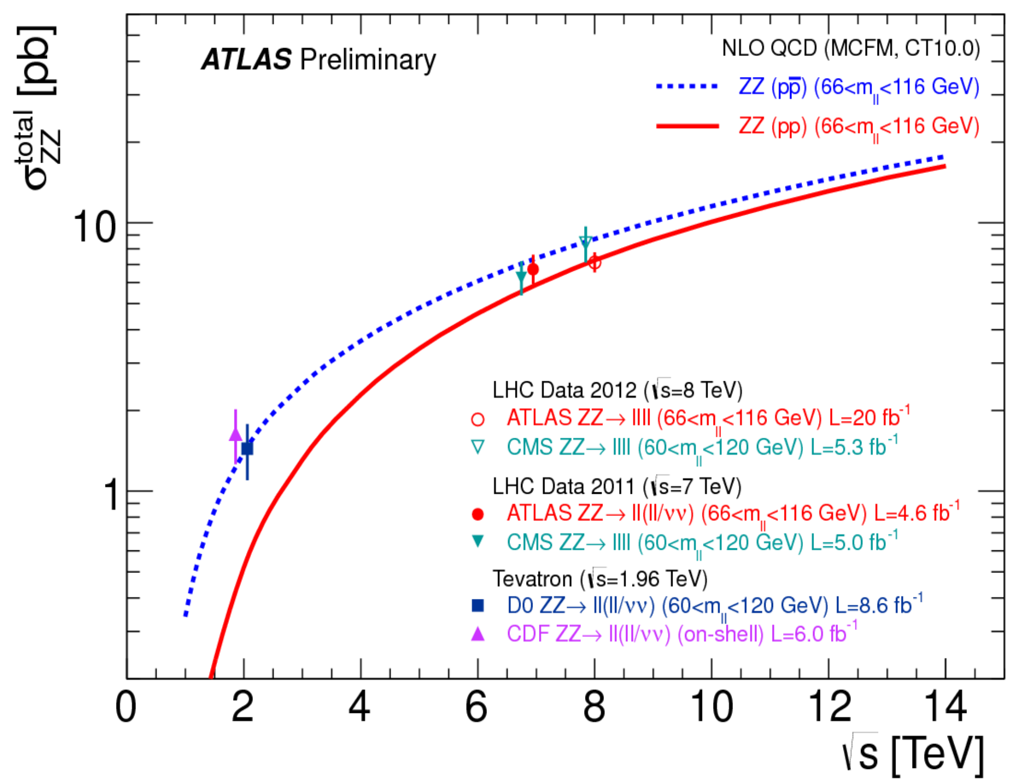


Diboson measurements

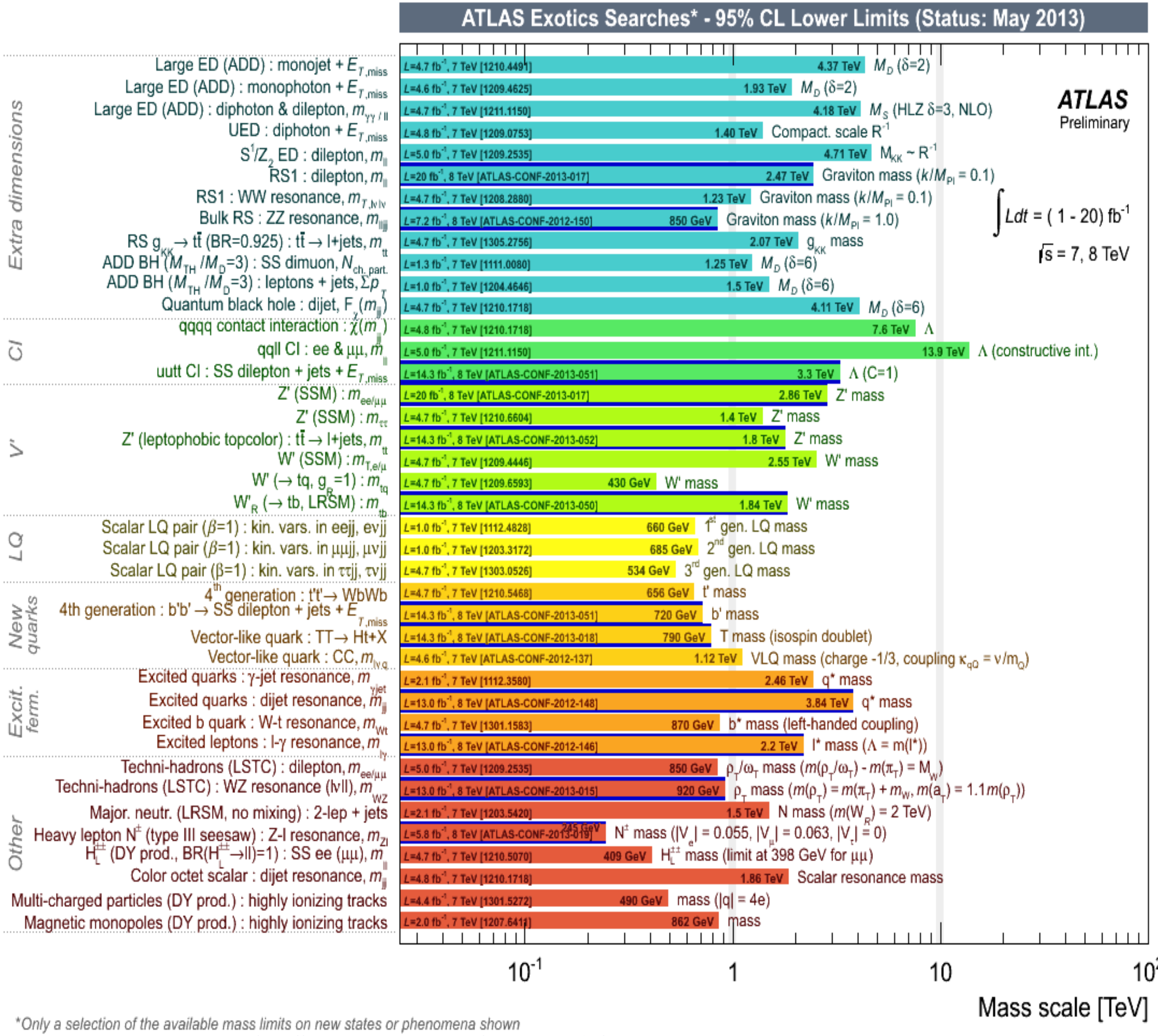




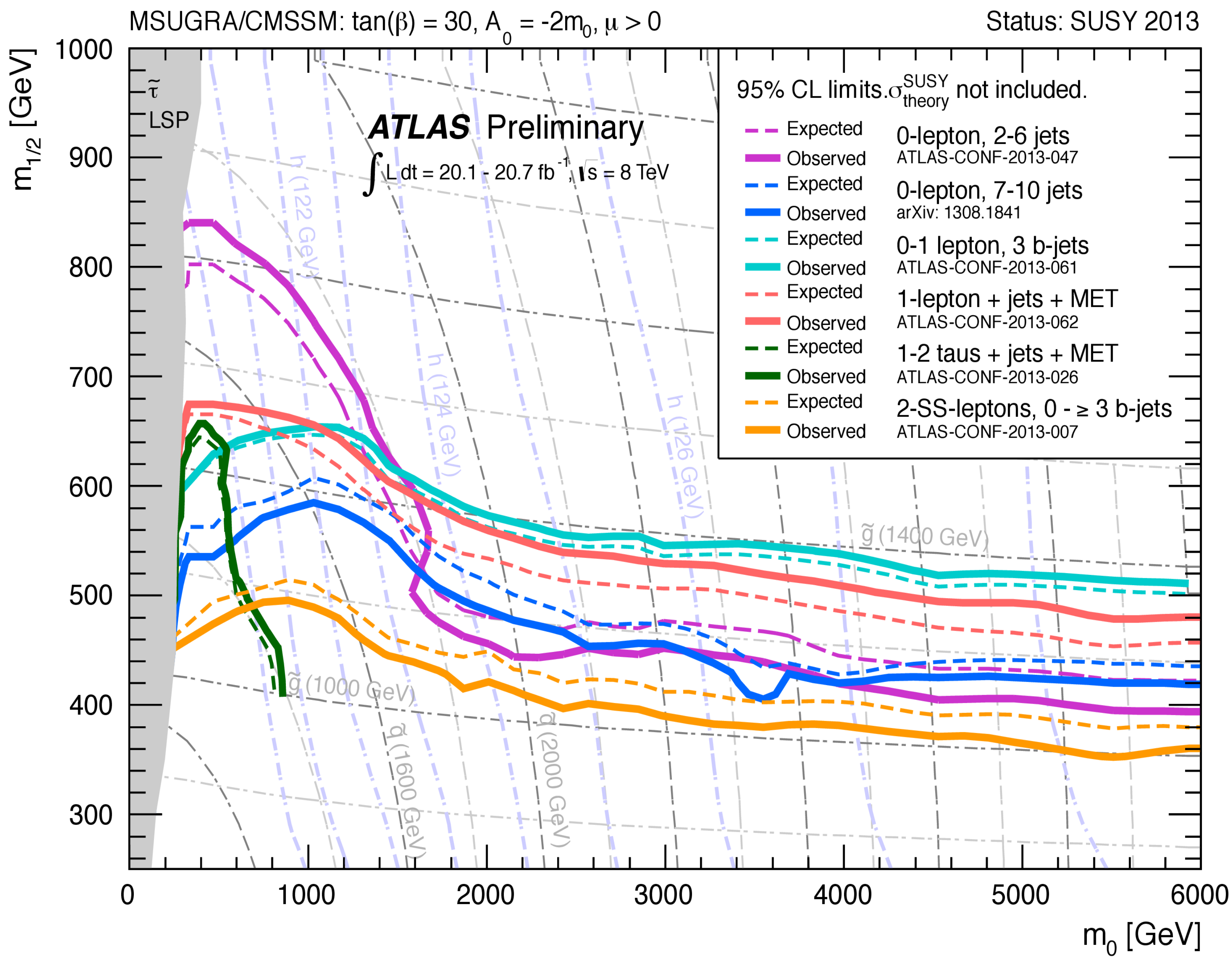




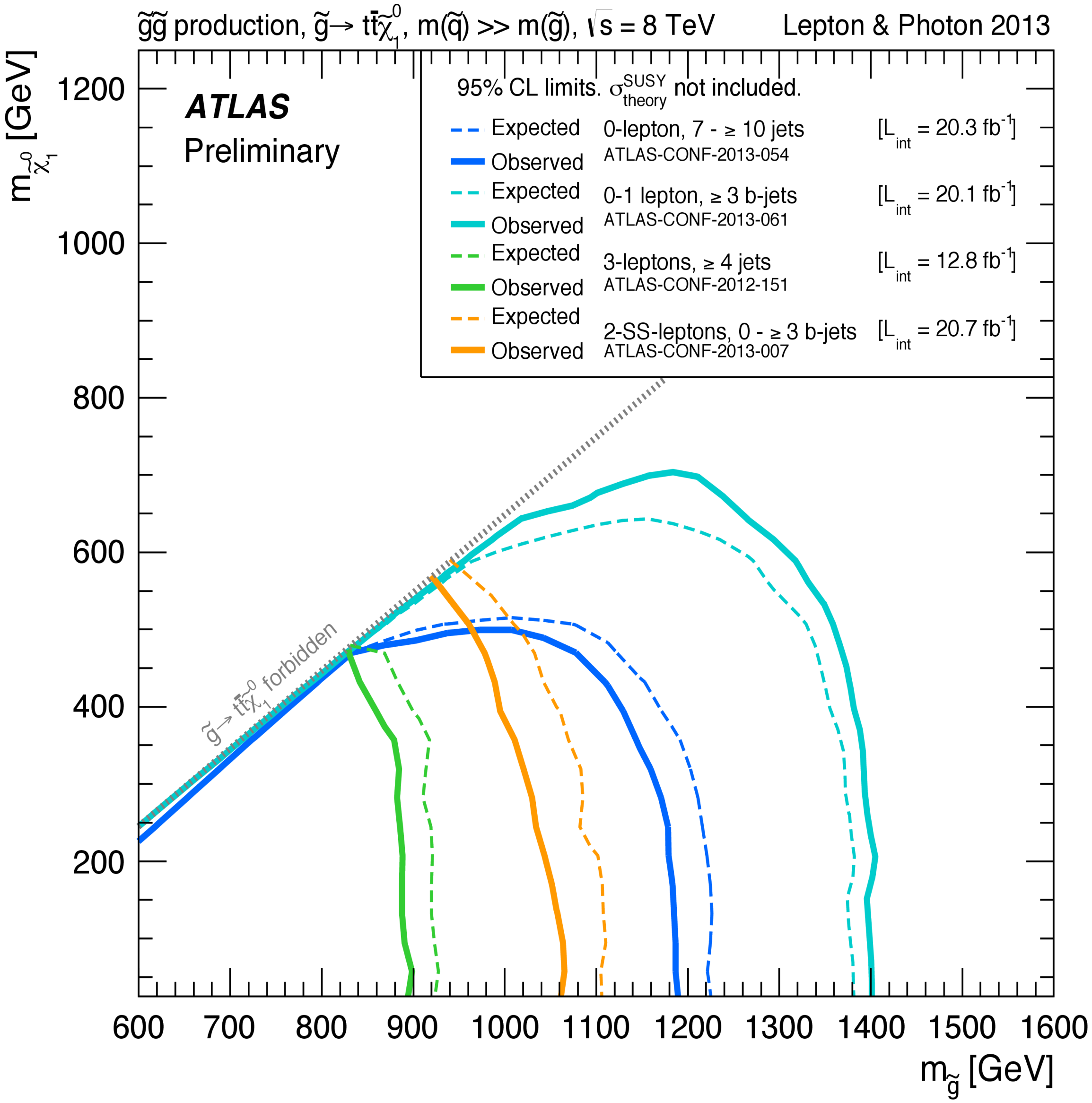
Testing „exotic” models



MSUGRA / CMSSM constraints

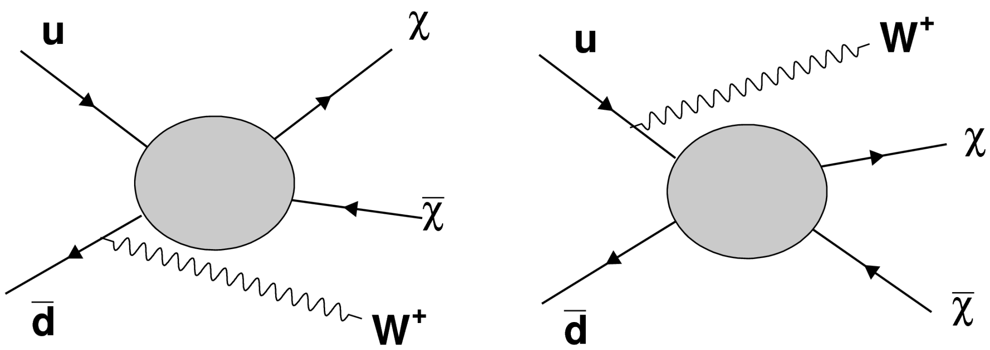


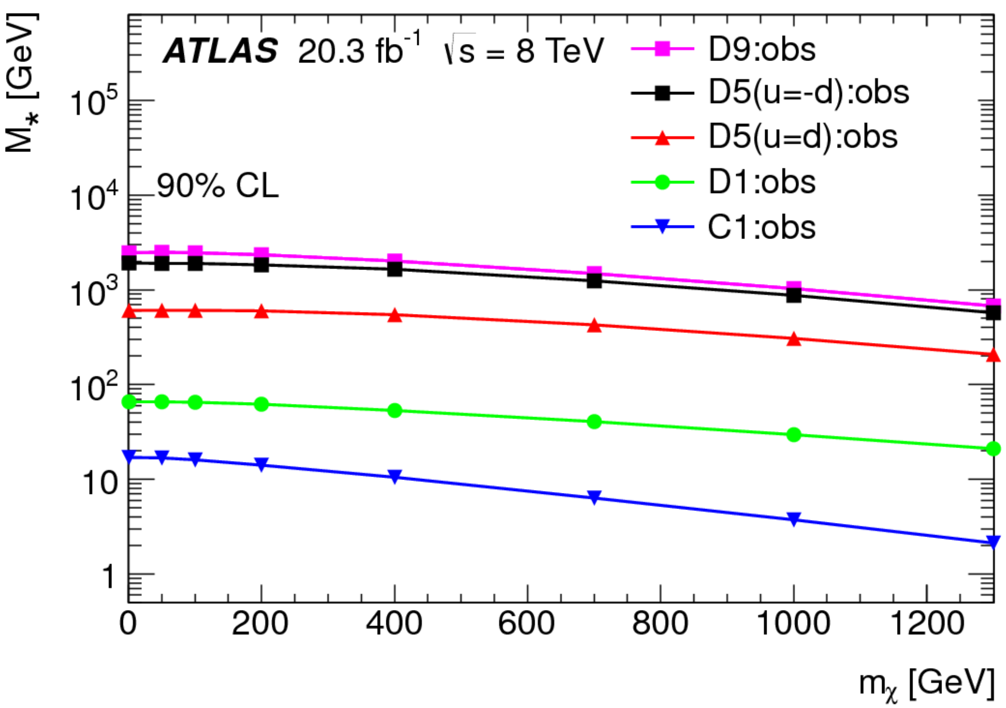
Stop searches

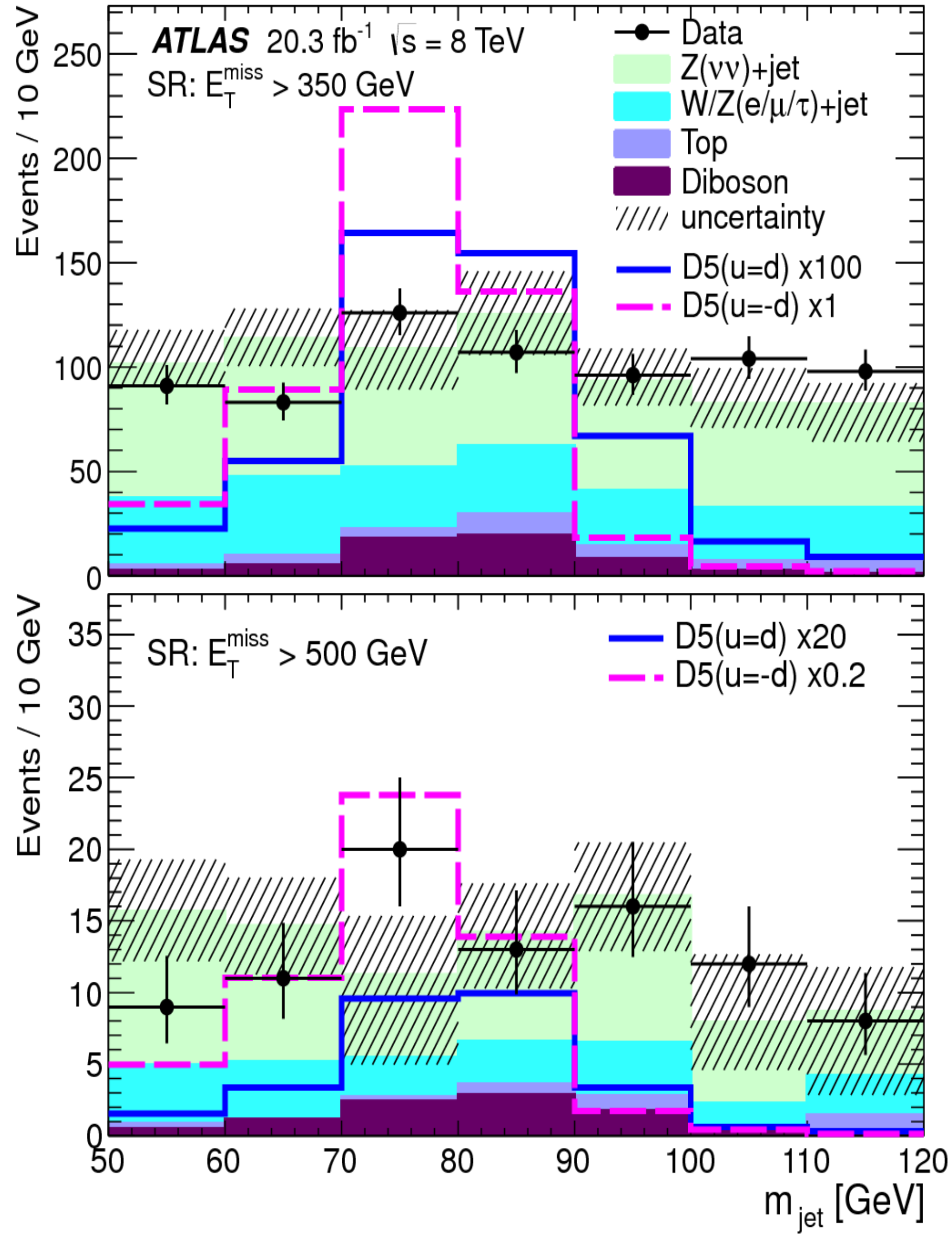


Search for dark matter

Search for pair-produced dark matter using initial state W/Z emission in hadronic final state

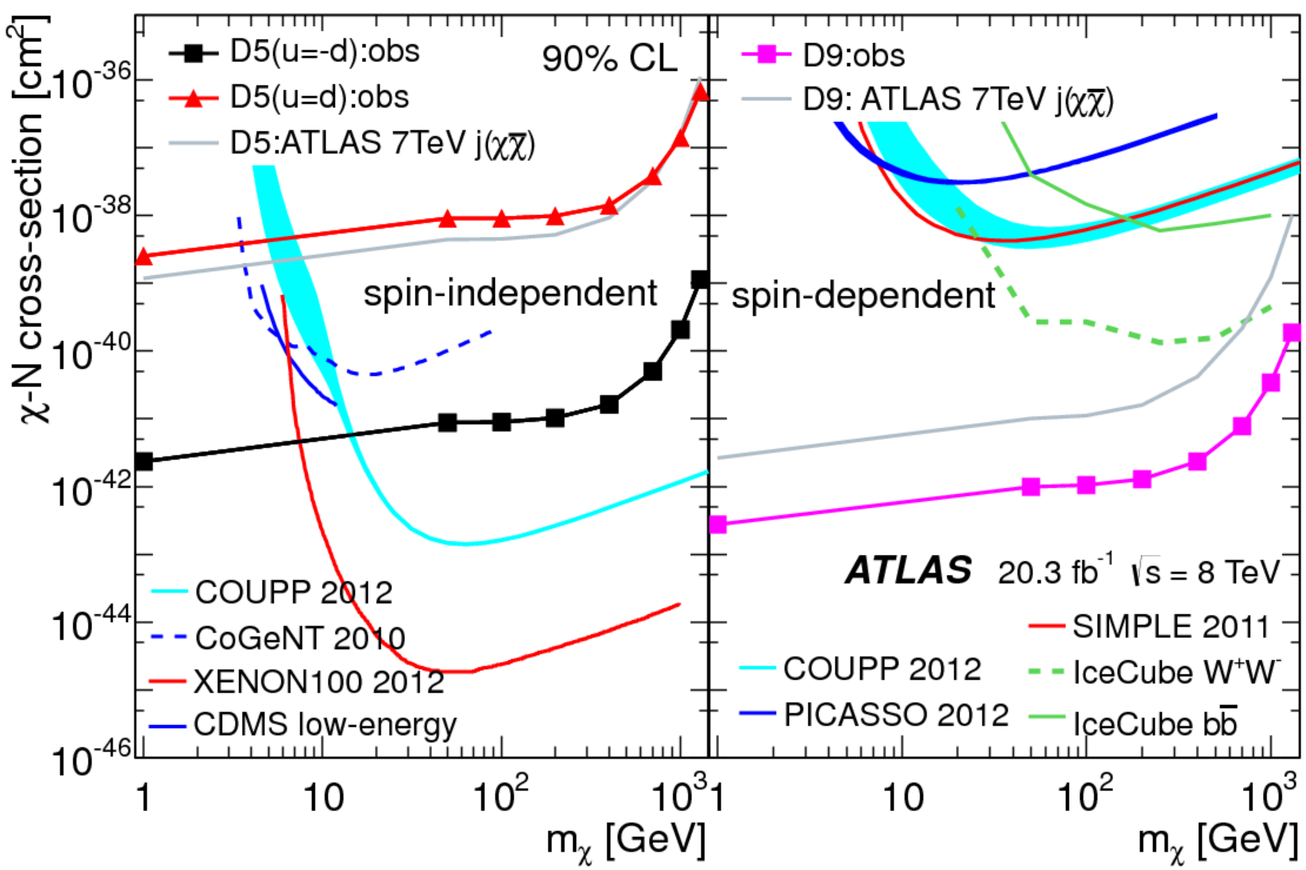


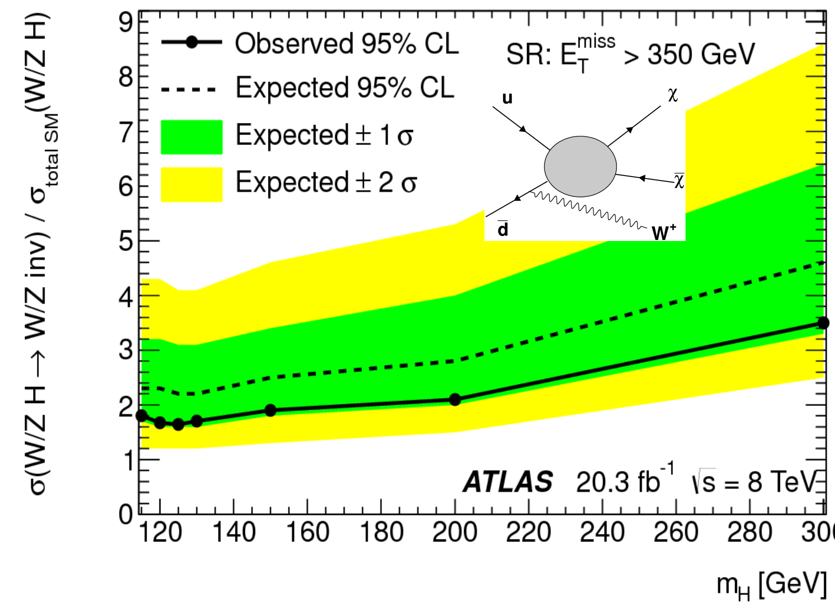


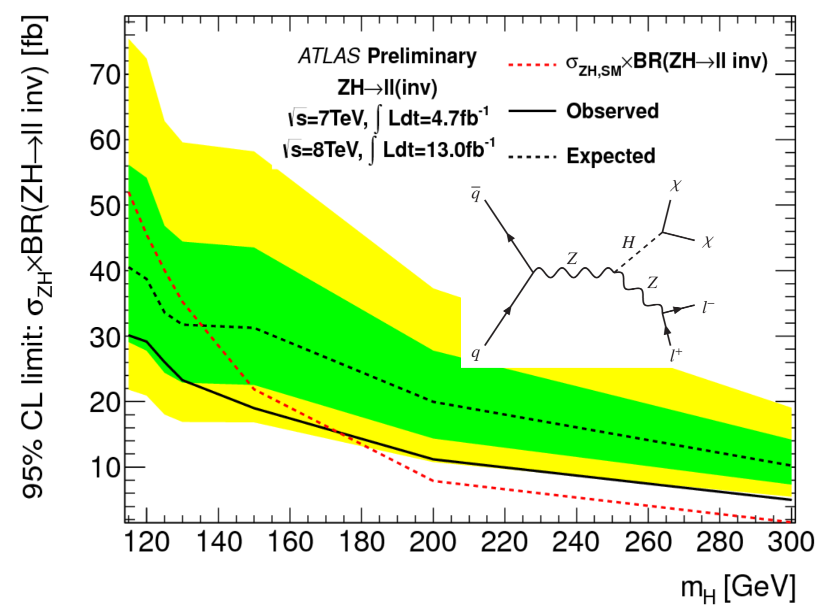


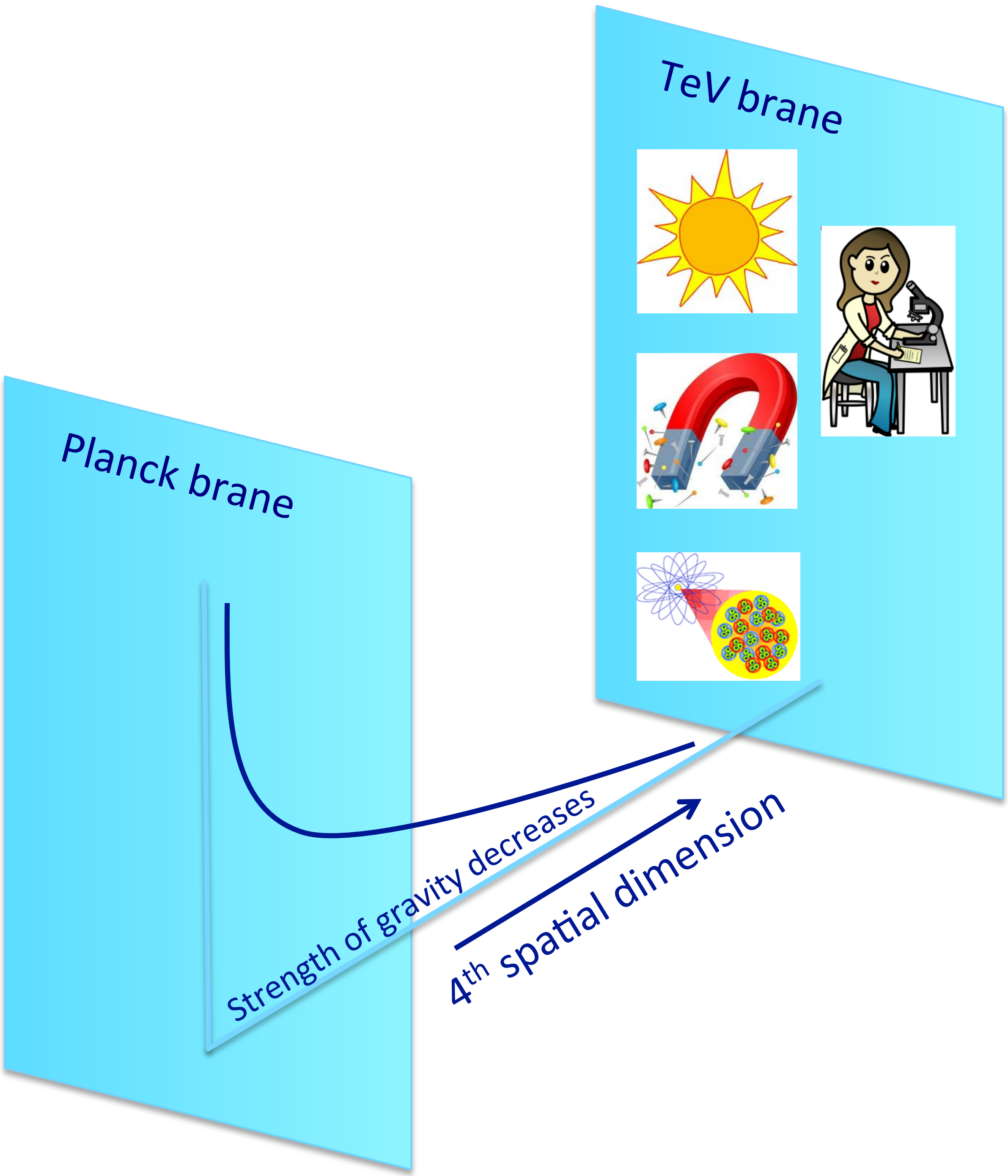
Search for dark matter

- Compare to direct dark matter detection experiments: best sensitivity at low masses
- Can be interpreted in models with invisibly decaying Higgs boson: complementary to dedicated searches









TeV brane
Planck brane
Strength of gravity decreases
4th spatial dimension