Killing the CMSSM softly

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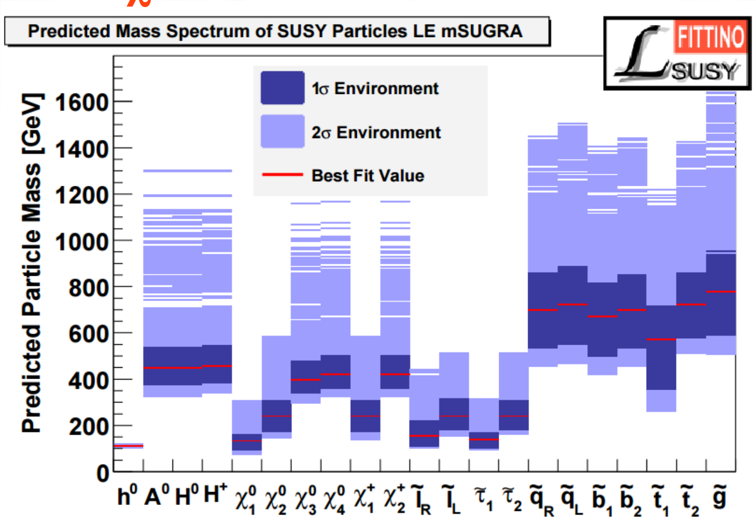
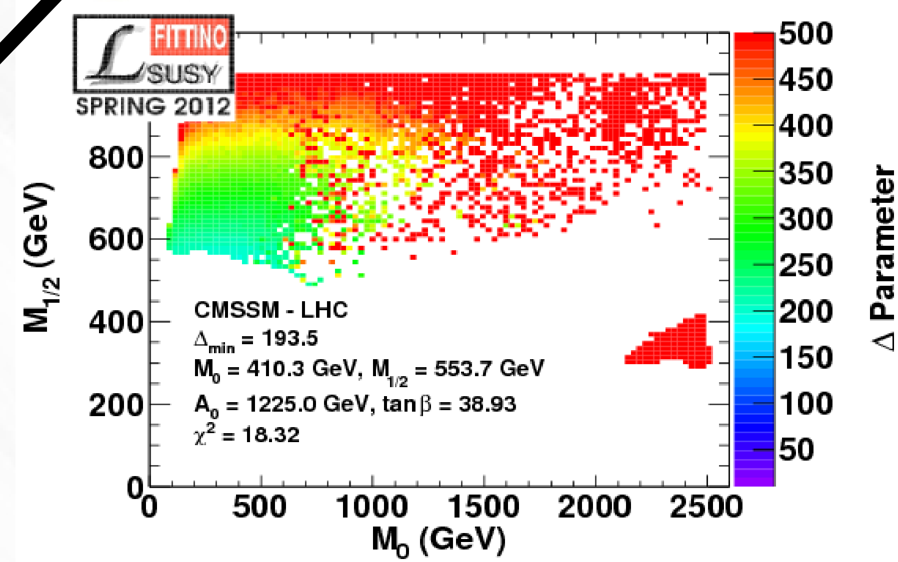
Introduction – The Evolution of the CMSSM

1. Before the LHC
arxiv:0907.2589
χ^2 / ndf: 20.6 / 22



2. After the 7 TeV run
arxiv:1204.4199
χ^2 / ndf: 13.1/9



3. After the 8 TeV run
this talk (i.a.)

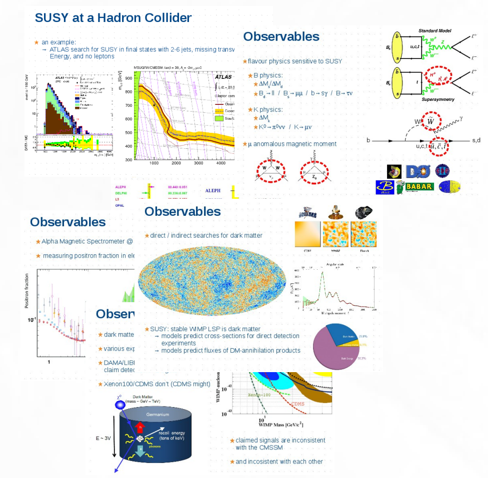
Outline

- The Fittino Framework for Global Fits of SUSY models
  → Observables & Observable Sets
  → Scanning and Constraining the Parameter Space

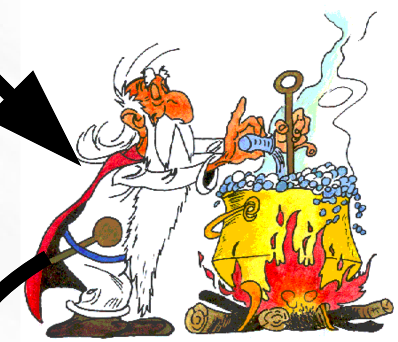
- The CMSSM after the LHC 8 TeV Run
  → Best Fit Points & Preferred Parameter Space
  → The lightest Higgs in the CMSSM
  → The p-Value of the CMSSM

The Fittino Framework & Outline

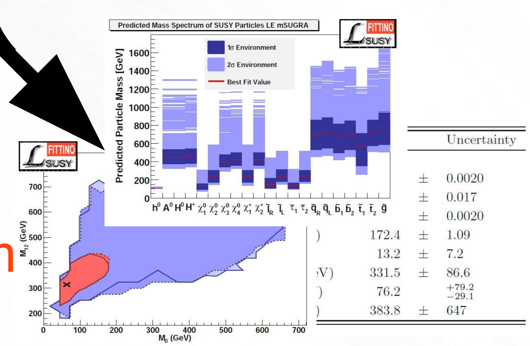
- select sensitive observables
  - low energy observables
  - Higgs boson properties
  - collider searches for sparticle production
  - direct/indirect dark matter searches



- scan the parameter space
  - public codes for calculation of model predictions
  - χ^2 as a measure for level of agreement
  - Markov Chain Monte Carlo for smart sampling

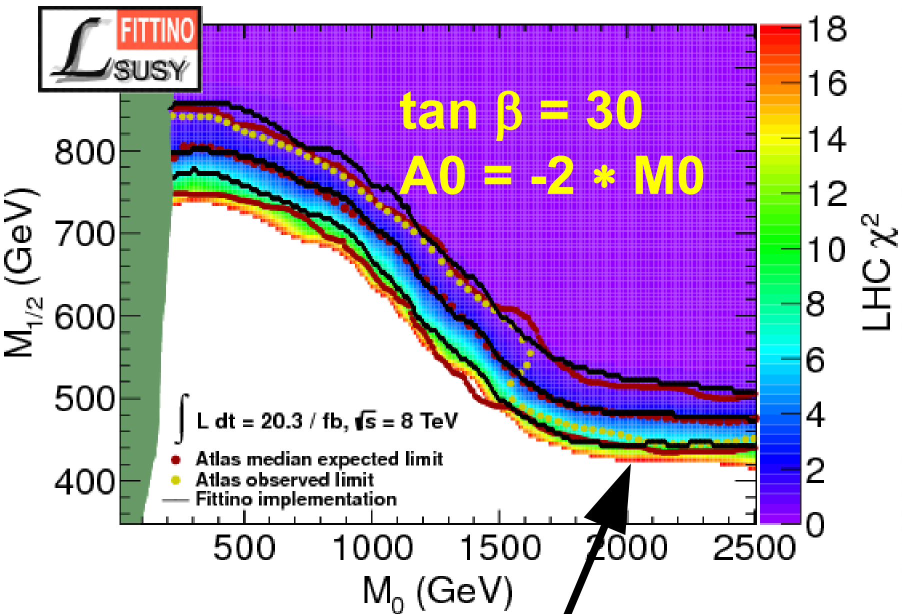


- statistical analysis
  - frequentist interpretation
  - preferred parameter regions and mass spectrum
  - calculation of p-value with pseudo experiments



Observables

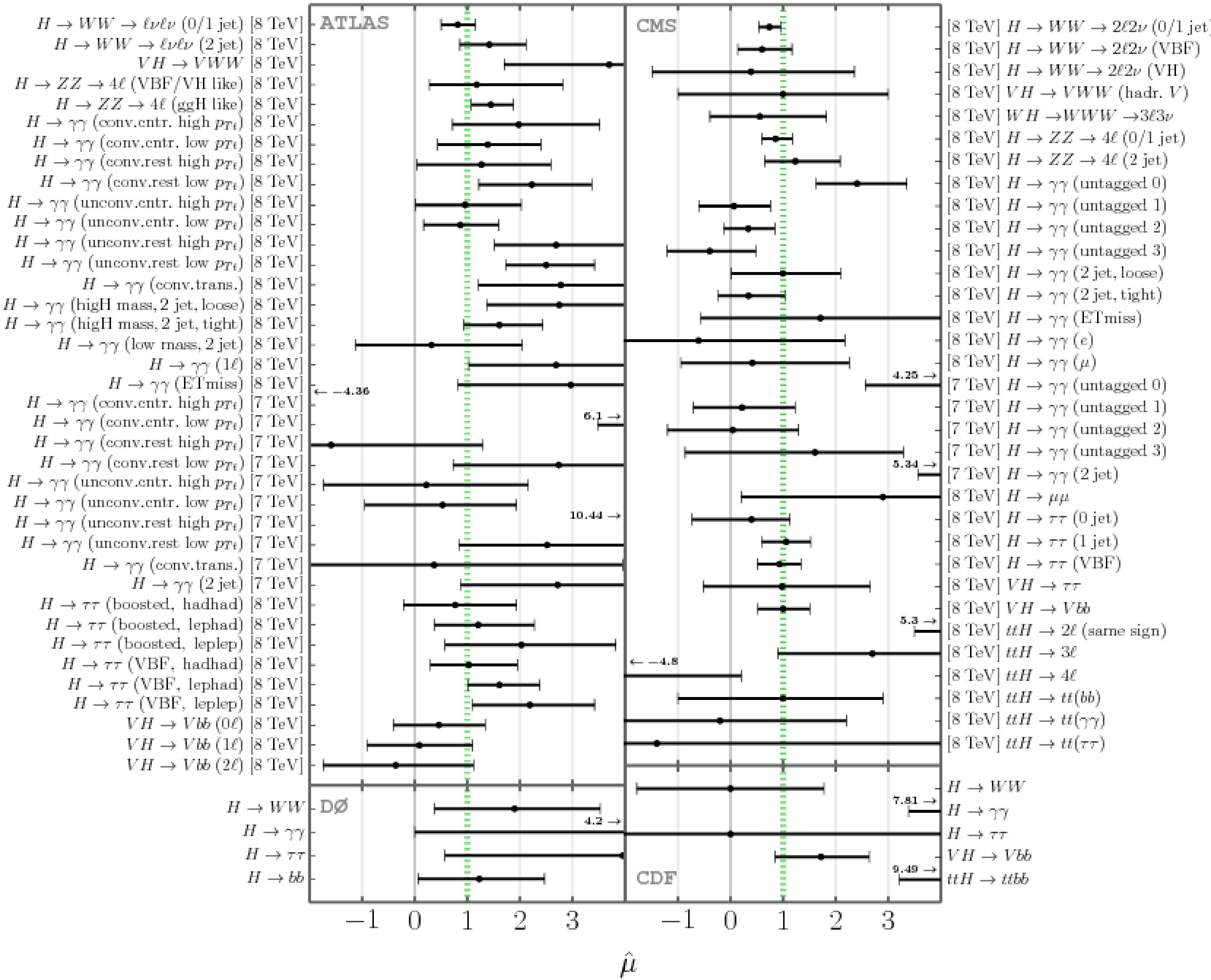
$a_\mu - a_\mu^{\mathrm{SM}}$	$(28.7 \pm 8.0) \times 10^{-10}$
$\sin^2 \theta_{\mathrm{eff}}$	0.23113 ± 0.00021
m_t	$(173.34 \pm 0.27 \pm 0.71)\,\mathrm{GeV}$
m_W	$(80.385 \pm 0.015)\,\mathrm{GeV}$
Δm_s	$(17.719 \pm 0.036 \pm 0.023)\,\mathrm{ps}^{-1}$
$\mathscr{B}(B_s \to \mu\mu)$	$(2.90 \pm 0.70) \times 10^{-9}$
$\mathscr{B}(b \to s\gamma)$	$(3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$
$\mathscr{B}(B \to \tau\nu)$	$(1.05 \pm 0.25) \times 10^{-4}$
Ωh^2	0.1187 ± 0.0017



correction in A0 and tan β via scaling factor

limits on
→ direct detection cross-section (LUX)
→ chargino mass from LEP
→ SUSY production at the LHC

a lot of Higgs measurements
→ implemented via HiggsSignals and HiggsBounds


ATLAS
CMS
DØ
CDF
$H \to WW \to \ell\nu\ell\nu$ (0/1 jet) [8 TeV]
$H \to WW \to \ell\nu\ell\nu$ (2 jet) [8 TeV]
$VH \to VWW$ [8 TeV]
$H \to ZZ \to 4\ell$ (VBF/VH like) [8 TeV]
$H \to ZZ \to 4\ell$ (ggH like) [8 TeV]
$H \to \gamma\gamma$ (conv.cntr. high p_{Tt}) [8 TeV]
$H \to \gamma\gamma$ (conv.cntr. low p_{Tt}) [8 TeV]
$H \to \gamma\gamma$ (conv.rest high p_{Tt}) [8 TeV]
$H \to \gamma\gamma$ (conv.rest low p_{Tt}) [8 TeV]
$H \to \gamma\gamma$ (unconv.cntr. high p_{Tt}) [8 TeV]
$H \to \gamma\gamma$ (unconv.cntr. low p_{Tt}) [8 TeV]
$H \to \gamma\gamma$ (unconv.rest high p_{Tt}) [8 TeV]
$H \to \gamma\gamma$ (unconv.rest low p_{Tt}) [8 TeV]
$H \to \gamma\gamma$ (conv.trans.) [8 TeV]
$H \to \gamma\gamma$ (higH mass, 2 jet, loose) [8 TeV]
$H \to \gamma\gamma$ (higH mass, 2 jet, tight) [8 TeV]
$H \to \gamma\gamma$ (low mass, 2 jet) [8 TeV]
$H \to \gamma\gamma$ (1ℓ) [8 TeV]
$H \to \gamma\gamma$ (ETmiss) [8 TeV]
$H \to \gamma\gamma$ (conv.cntr. high p_{Tt}) [7 TeV]
$H \to \gamma\gamma$ (conv.cntr. low p_{Tt}) [7 TeV]
$H \to \gamma\gamma$ (conv.rest high p_{Tt}) [7 TeV]
$H \to \gamma\gamma$ (conv.rest low p_{Tt}) [7 TeV]
$H \to \gamma\gamma$ (unconv.cntr. high p_{Tt}) [7 TeV]
$H \to \gamma\gamma$ (unconv.cntr. low p_{Tt}) [7 TeV]
$H \to \gamma\gamma$ (unconv.rest high p_{Tt}) [7 TeV]
$H \to \gamma\gamma$ (unconv.rest low p_{Tt}) [7 TeV]
$H \to \gamma\gamma$ (conv.trans.) [7 TeV]
$H \to \gamma\gamma$ (2 jet) [7 TeV]
$H \to \tau\tau$ (boosted, hadhad) [8 TeV]
$H \to \tau\tau$ (boosted, lephad) [8 TeV]
$H \to \tau\tau$ (boosted, leplep) [8 TeV]
$H \to \tau\tau$ (VBF, hadhad) [8 TeV]
$H \to \tau\tau$ (VBF, lephad) [8 TeV]
$H \to \tau\tau$ (VBF, leplep) [8 TeV]
$VH \to Vbb$ (0ℓ) [8 TeV]
$VH \to Vbb$ (1ℓ) [8 TeV]
$VH \to Vbb$ (2ℓ) [8 TeV]
$H \to WW$
$H \to \gamma\gamma$
$H \to \tau\tau$
$H \to bb$
← −4.36
6.1 →
10.44 →
4.2 →
[8 TeV] $H \to WW \to 2\ell 2\nu$ (0/1 jet)
[8 TeV] $H \to WW \to 2\ell 2\nu$ (VBF)
[8 TeV] $H \to WW \to 2\ell 2\nu$ (VH)
[8 TeV] $VH \to VWW$ (hadr. V)
[8 TeV] $WH \to WWW \to 3\ell 3\nu$
[8 TeV] $H \to ZZ \to 4\ell$ (0/1 jet)
[8 TeV] $H \to ZZ \to 4\ell$ (2 jet)
[8 TeV] $H \to \gamma\gamma$ (untagged 0)
[8 TeV] $H \to \gamma\gamma$ (untagged 1)
[8 TeV] $H \to \gamma\gamma$ (untagged 2)
[8 TeV] $H \to \gamma\gamma$ (untagged 3)
[8 TeV] $H \to \gamma\gamma$ (2 jet, loose)
[8 TeV] $H \to \gamma\gamma$ (2 jet, tight)
[8 TeV] $H \to \gamma\gamma$ (ETmiss)
[8 TeV] $H \to \gamma\gamma$ (e)
[8 TeV] $H \to \gamma\gamma$ (μ)
[7 TeV] $H \to \gamma\gamma$ (untagged 0)
[7 TeV] $H \to \gamma\gamma$ (untagged 1)
[7 TeV] $H \to \gamma\gamma$ (untagged 2)
[7 TeV] $H \to \gamma\gamma$ (untagged 3)
[7 TeV] $H \to \gamma\gamma$ (2 jet)
[8 TeV] $H \to \mu\mu$
[8 TeV] $H \to \tau\tau$ (0 jet)
[8 TeV] $H \to \tau\tau$ (1 jet)
[8 TeV] $H \to \tau\tau$ (VBF)
[8 TeV] $VH \to \tau\tau$
[8 TeV] $VH \to Vbb$
[8 TeV] $ttH \to 2\ell$ (same sign)
[8 TeV] $ttH \to 3\ell$
[8 TeV] $ttH \to 4\ell$
[8 TeV] $ttH \to tt(bb)$
[8 TeV] $ttH \to tt(\gamma\gamma)$
[8 TeV] $ttH \to tt(\tau\tau)$
$H \to WW$
$H \to \gamma\gamma$
$H \to \tau\tau$
$VH \to Vbb$
$ttH \to ttbb$
4.25 →
5.34 →
5.3 →
← −4.8
7.81 →
9.49 →
−1 0 1 2 3
−1 0 1 2 3
$\hat{\mu}$

Higgs Observables Set

- CMSSM can't distinguish between all measurements
- use 3 additional combinations

Experiment, Channel	observed μ	observed m_h
ATLAS, $h \to WW \to \ell\nu\ell\nu$ [80]	$0.99^{+0.31}_{-0.28}$	-
ATLAS, $h \to ZZ \to 4\ell$ [80]	$1.43^{+0.40}_{-0.35}$	(124.3 ± 1.1) GeV
ATLAS, $h \to \gamma\gamma$ [80]	$1.55^{+0.33}_{-0.28}$	(126.8 ± 0.9) GeV
ATLAS, $h \to \tau\tau$ [81]	$1.44^{+0.51}_{-0.43}$	-
ATLAS, $Vh \to V(bb)$ [82]	$0.17^{+0.67}_{-0.63}$	-
CMS, $h \to WW \to \ell\nu\ell\nu$ [83]	$0.72^{+0.20}_{-0.18}$	-
CMS, $h \to ZZ \to 4\ell$ [84]	$0.93^{+0.29}_{-0.25}$	(125.6 ± 0.6) GeV
CMS, $h \to \gamma\gamma$ [85]	$0.77^{+0.30}_{-0.27}$	(125.4 ± 1.1) GeV
CMS, $h \to \tau\tau$ [86]	$0.78^{+0.27}_{-0.27}$	-
CMS, $Vh \to V(bb)$ [86]	$1.00^{+0.50}_{-0.50}$	-

Medium Obs Set

→ Baseline

Experiment, Channel	observed μ	observed m_h
ATLAS, $h \to WW, ZZ, \gamma\gamma$ [80]	$1.33^{+0.21}_{-0.18}$	(125.5 ± 0.8) GeV
ATLAS, $h \to \tau\tau$ [81]	$1.44^{+0.51}_{-0.43}$	-
ATLAS, $Vh \to V(bb)$ [82]	$0.17^{+0.67}_{-0.63}$	-
CMS, $h \to WW, ZZ, \gamma\gamma$ †	$0.80^{+0.16}_{-0.15}$	(125.7 ± 0.6) GeV
CMS, $h \to \tau\tau$ [86]	$0.78^{+0.27}_{-0.27}$	-
CMS, $Vh \to V(bb)$ [86]	$1.00^{+0.50}_{-0.50}$	-

Small Obs Set

Experiment, Channel	observed μ	observed m_h
ATLAS+CMS, $h \to WW, ZZ$	$0.94^{+0.17}_{-0.16}$	(125.73 ± 0.45) GeV
ATLAS+CMS, $h \to \gamma\gamma$	$1.16^{+0.22}_{-0.20}$	
ATLAS+CMS, $h \to \tau\tau$	$1.11^{+0.24}_{-0.23}$	-
ATLAS+CMS, $Vh, tth \to bb$	$0.69^{+0.37}_{-0.37}$	-

Combined Obs Set

Calculating Model Predictions

- Fittino uses

→ **SPheno** for the mass Spectrum

→ **SuperIso** for the B-meson branching fractions

→ **FeynHiggs** for Higgs properties, m_W, $\sin\theta_{eff}$, $(g-2)_\mu$

→ **micrOMEGAs** for Ωh^2

→ **DarkSUSY** via AstroFit for direct detection cross section

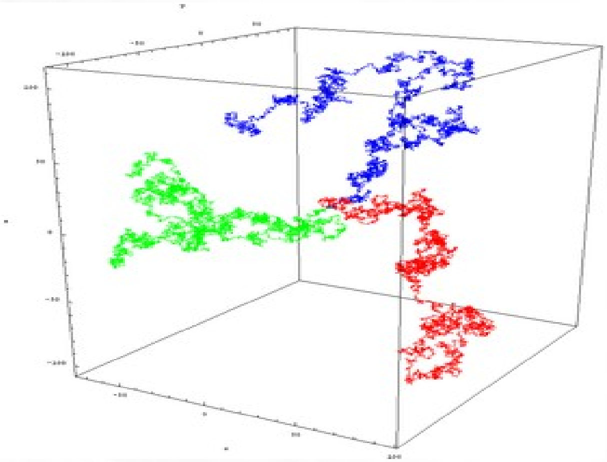
→ **Herwig++/Delphes/Prospino** for the emulation of the ATLAS 0-Lepton search

Sampling the Parameter Space

- 3 goals
  → accurate determination of best fit point
  → extensive coverage of full parameter space
  → accurate evaluation of p-value

- adaptive Markov Chain Monte Carlo
  → proposal densities adjusted regularly
  → 20 independent chains

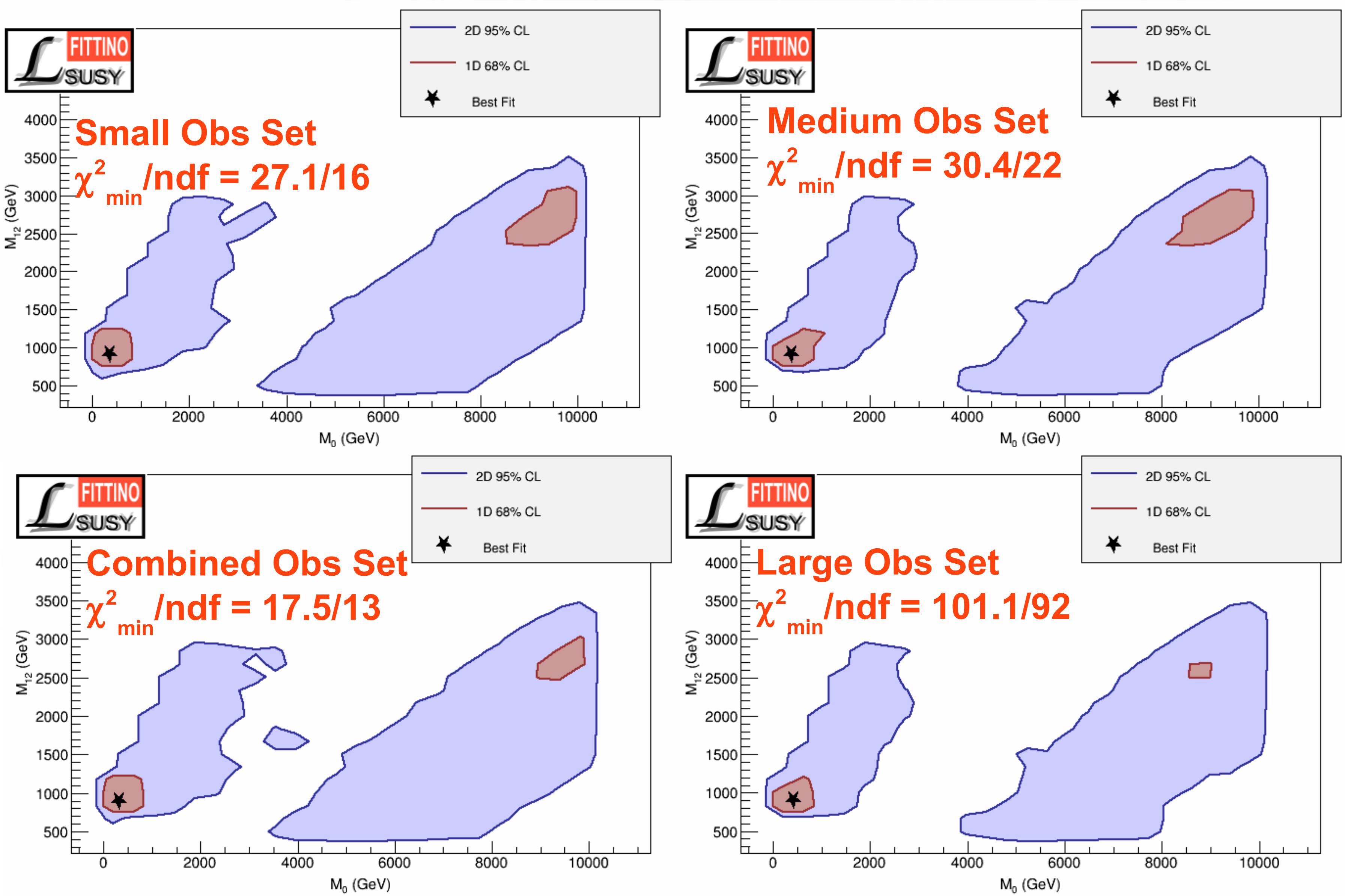
  → 850 million valid points
  → 100 million points with $\chi^2 < 100$



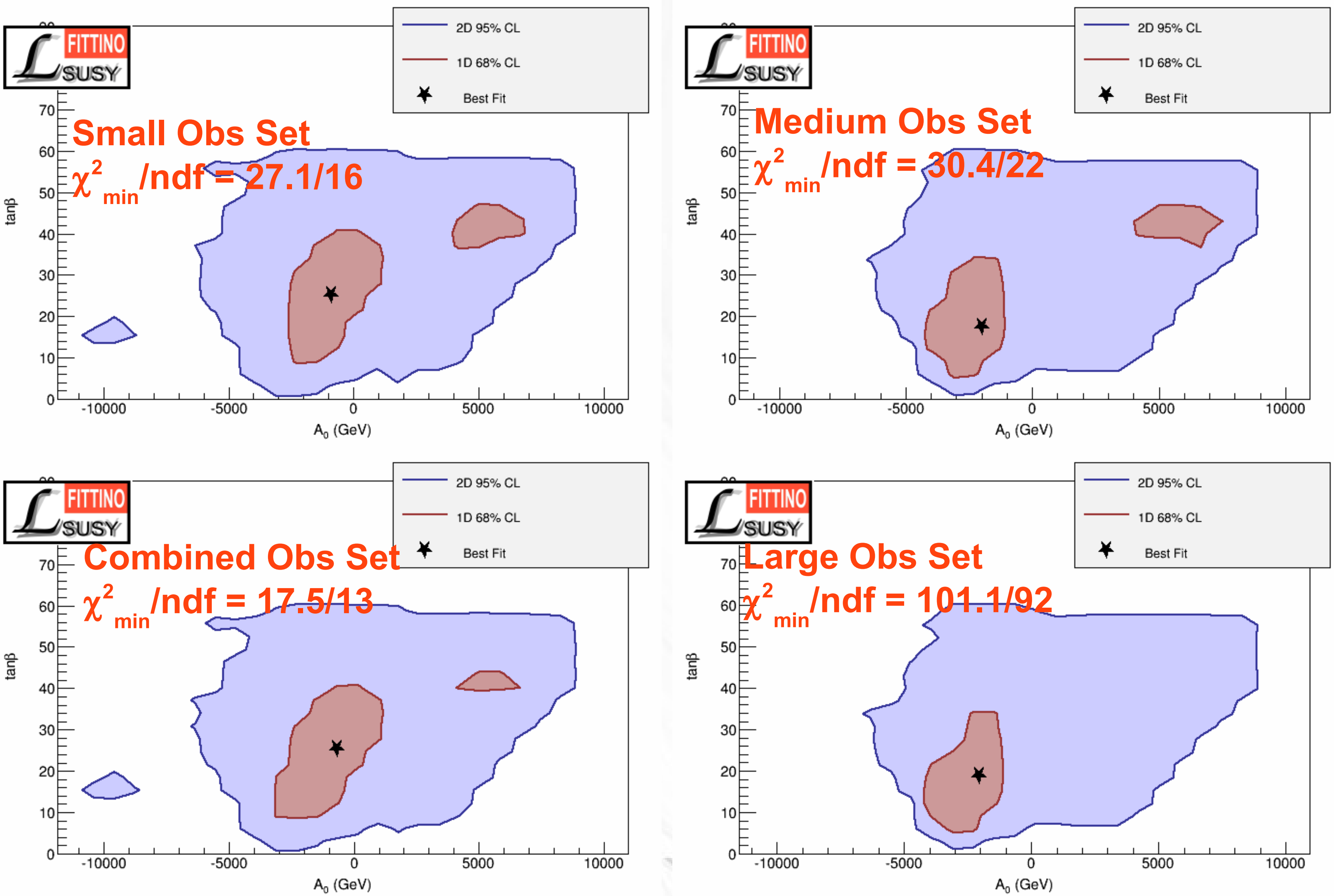
- determination of p-Value
  → full fit too demanding in terms of CPU time
  → use original MCMC to find best fit points

    → conservative estimation of model p-value

Results I: Parameter Regions & Best Fit Points



Results I: Parameter Regions & Best Fit Points



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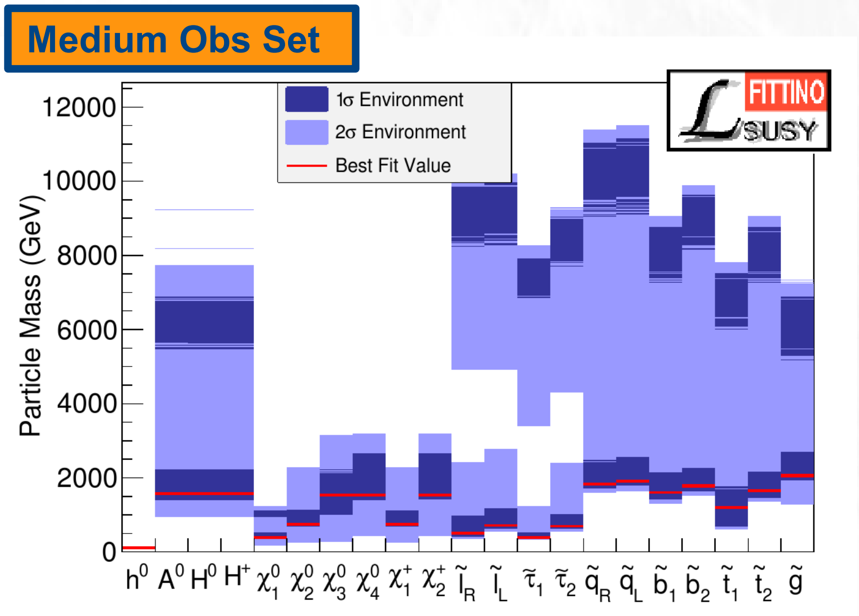
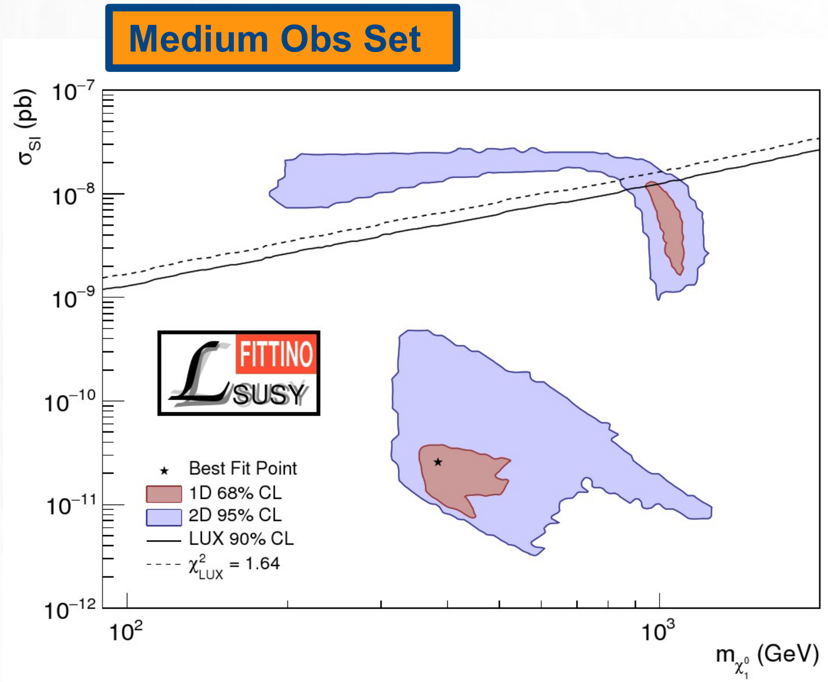
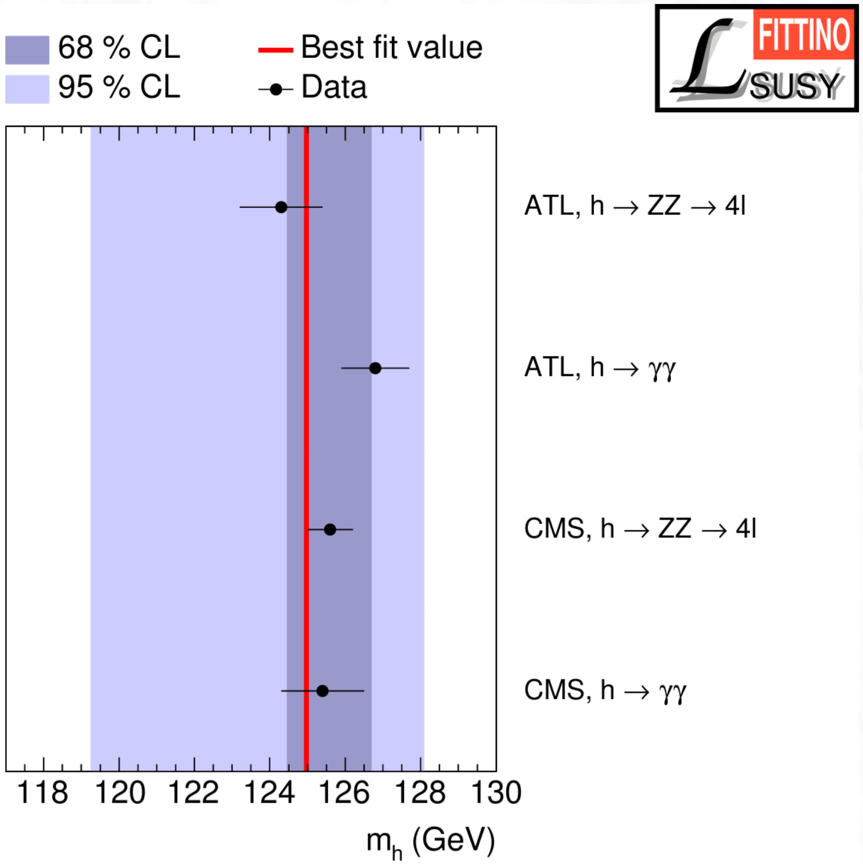


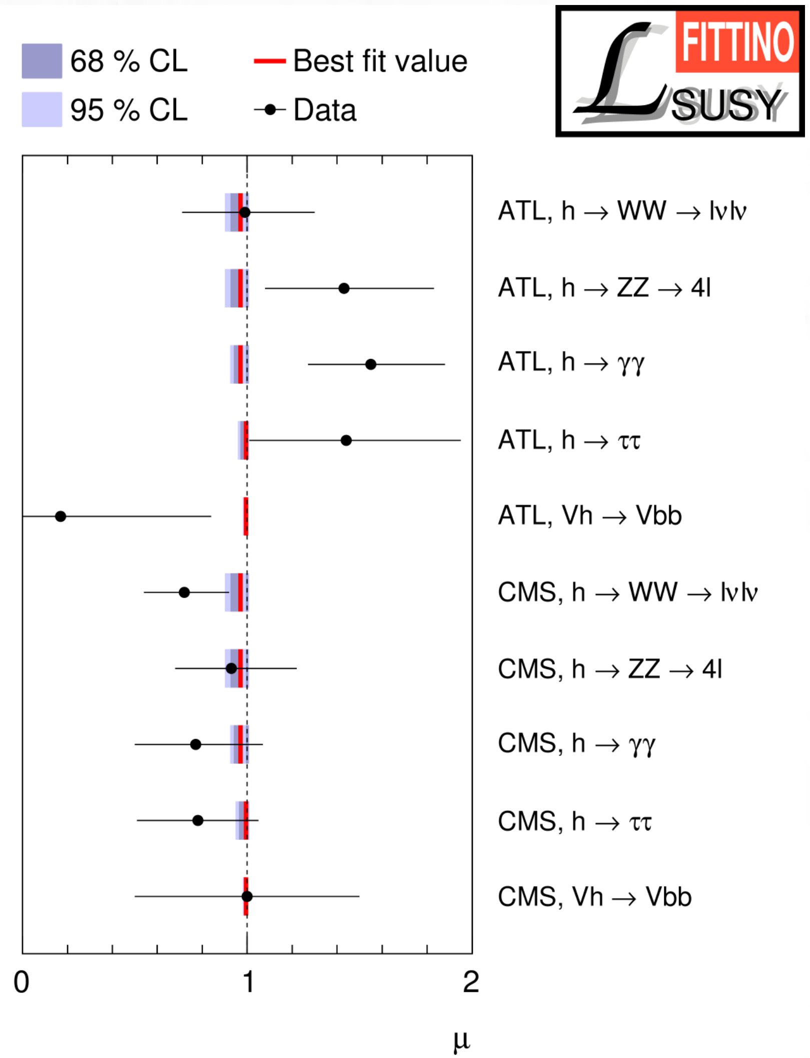


Observable Set	M_0	$M_{1/2}$	A_0	$\tan\beta$
Combined	327.4 GeV	900.5 GeV	-679.6 GeV	25.6
Small	361.5 GeV	926.3 GeV	-907.9 GeV	25.3
Medium	387.4 GeV	918.2 GeV	-2002.8 GeV	17.7
Large	418.6 GeV	910.6 GeV	-2041.6 GeV	19.2

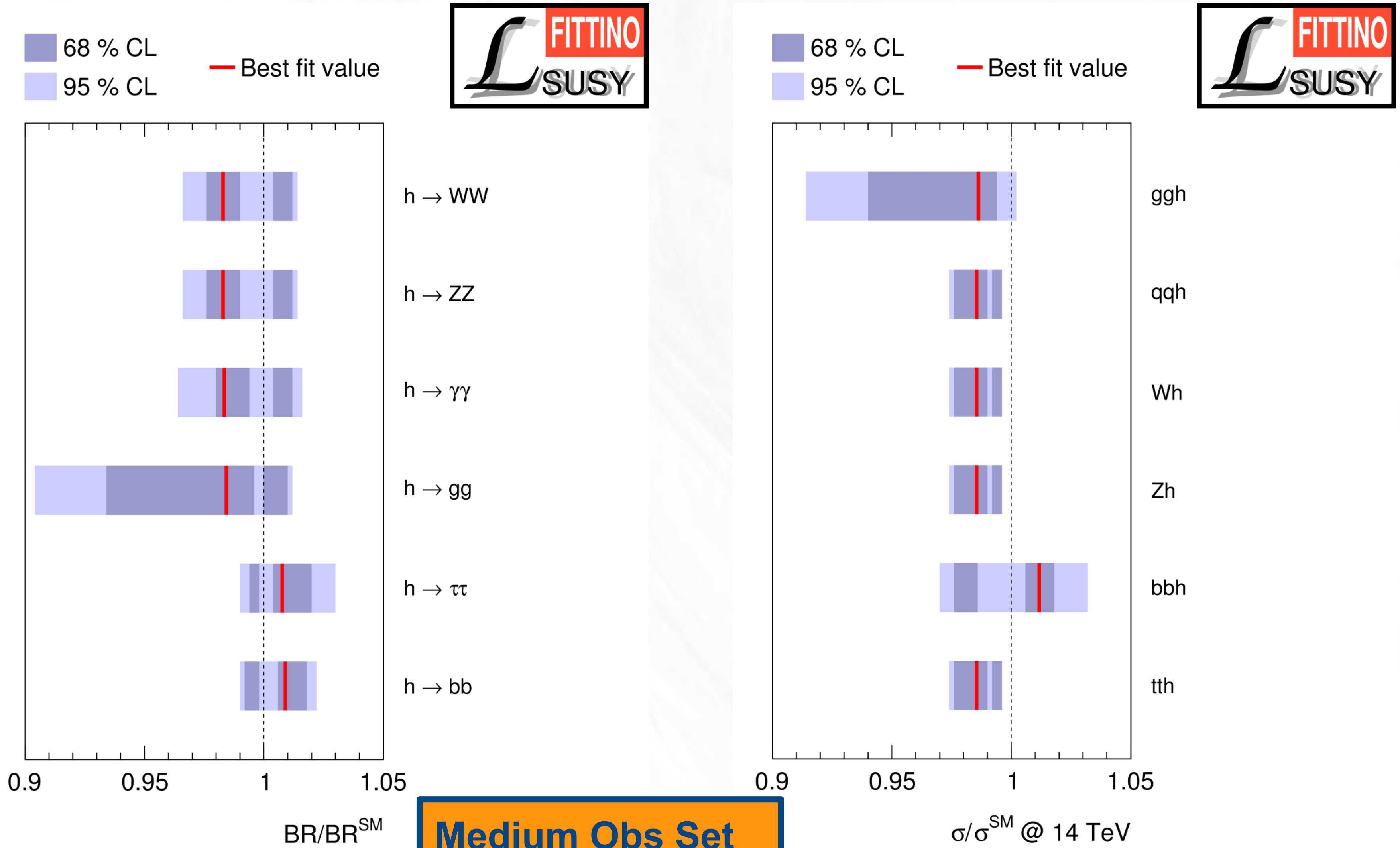
Results II: Lightest Higgs in the CMSSM



Medium Obs Set



Results II: Lightest Higgs in the CMSSM



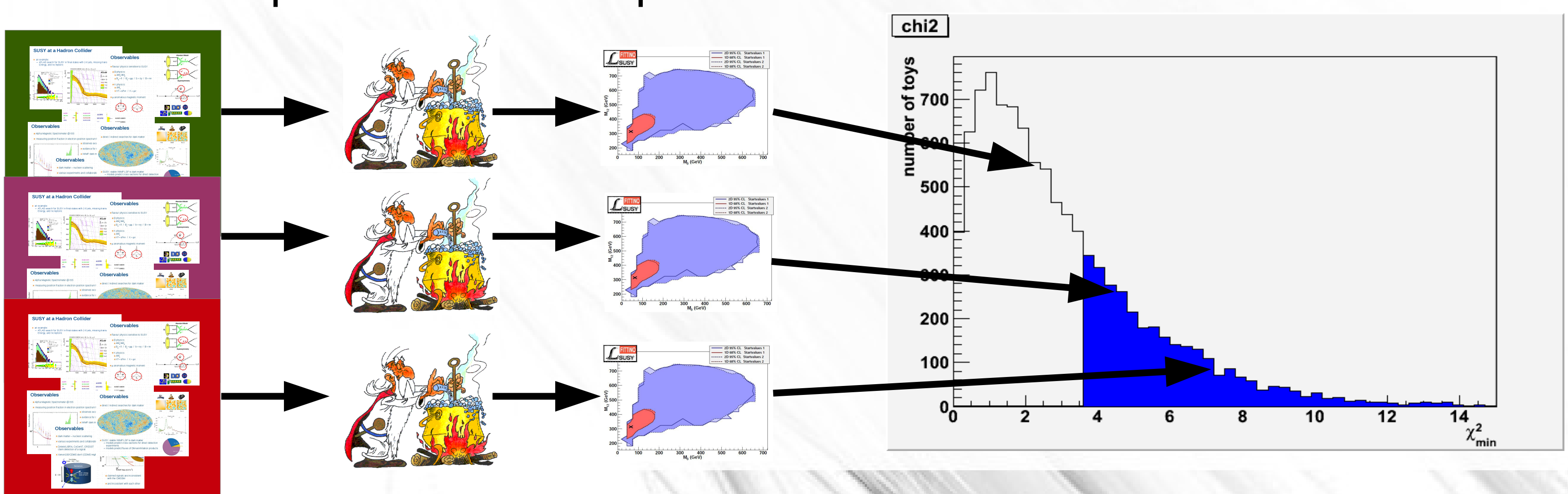
Medium Obs Set

Results III: p-Value

- non-gaussian observable set
  → 1-sided and hard limits
  → non-gaussian uncertainties
  → relative uncertainties
  → highly non-linear model

$$P_n(\chi^2) \stackrel{?}{=} \frac{(\chi^2)^{\frac{n}{2}} \cdot e^{\frac{\chi^2}{2}}}{2^{\frac{n}{2}}\Gamma(\frac{n}{2})}$$

- gaussian χ^2-distribution accurate?
  → get true χ^2-distribution from pseudo measurements
  → ~1000 pseudo datasets per obs set



Results III: p-Value

- Large Obs Set: 84 different measurements in Higgs sector
  → CMSSM makes the same prediction for several subsets

- in terms of the p-value, the model can be
  → punished for bad agreement within the data
  → rewarded for good agreement within the data

- p-value should reflect the quality of the model
  → combine measurements with same prediction
  → use combination in global fit

Experiment, Channel	observed μ	observed m_h
ATLAS, $h \to WW \to \ell\nu\ell\nu$ [80]	$0.99^{+0.31}_{-0.28}$	-
ATLAS, $h \to ZZ \to 4\ell$ [80]	$1.43^{+0.40}_{-0.35}$	(124.3 ± 1.1) GeV
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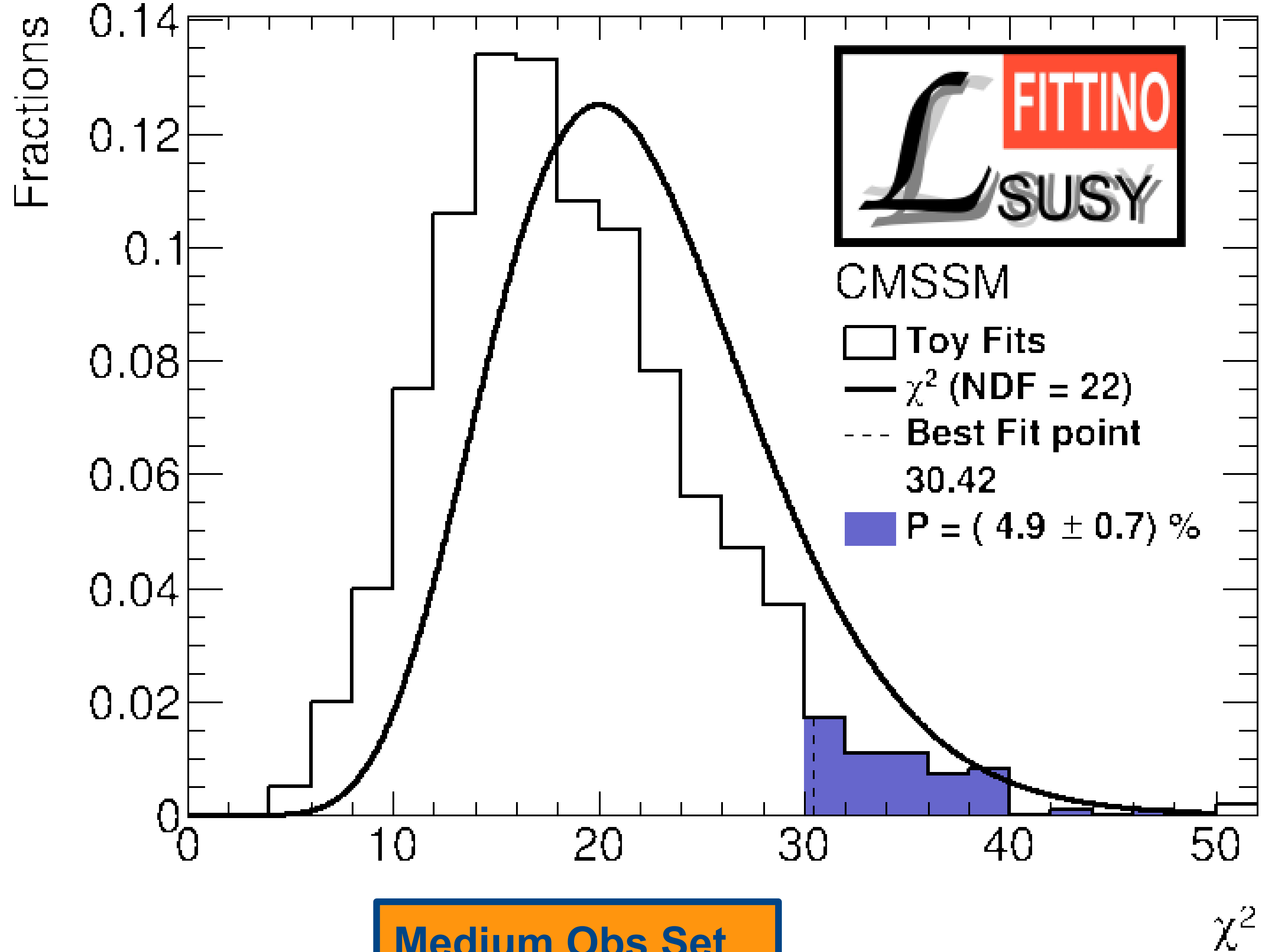
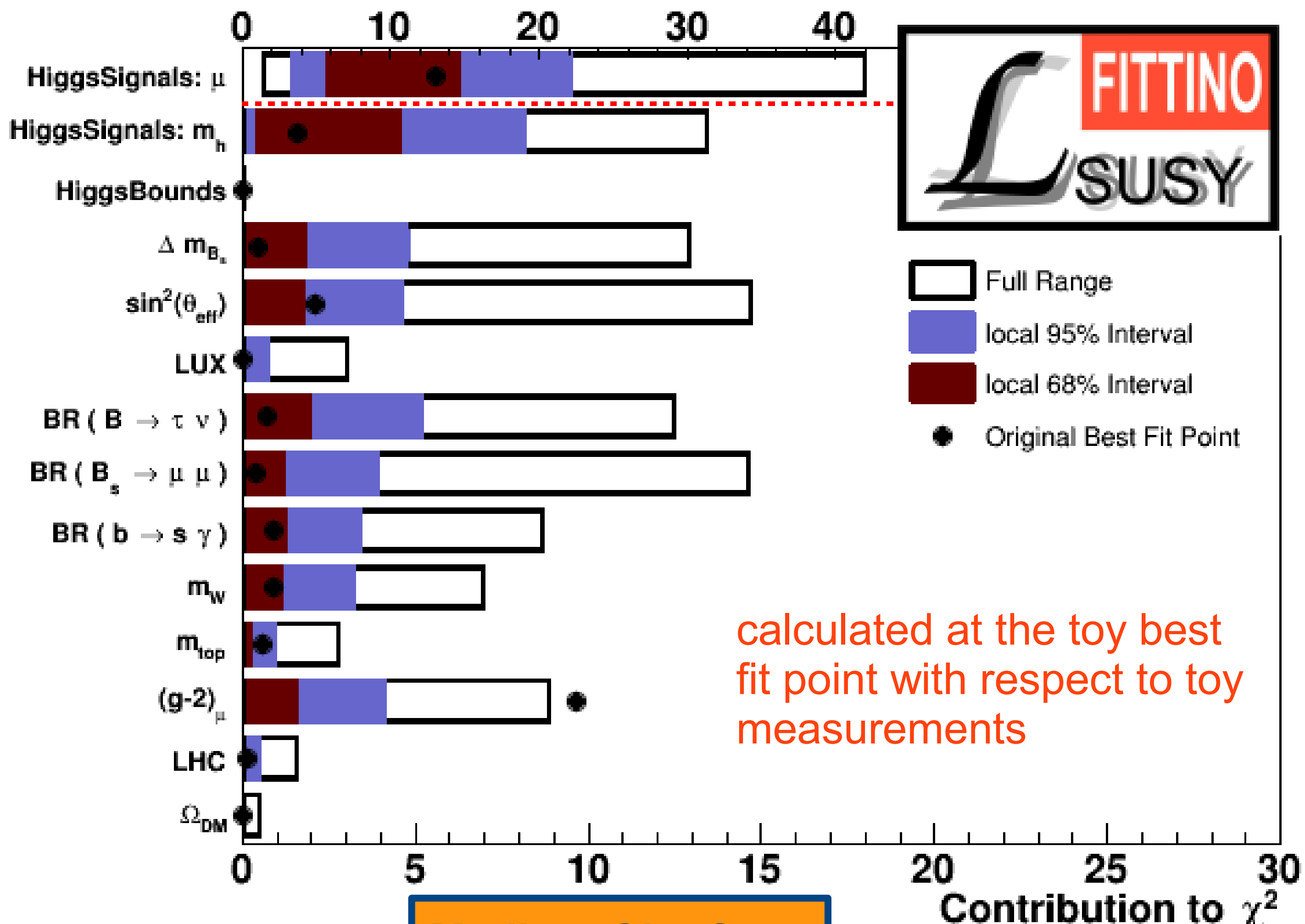
medium obs set comes closest to what we need

Results III: p-Value



Medium Obs Set

Results III: p-Value



calculated at the toy best fit point with respect to toy measurements

Medium Obs Set

Results III: p-Value

Observable Set	χ^2/ n.d.f	naive p-value	toy p-value	stat. uncert.
Combined	17.5/13	17.7%	8.3%	0.8%
Small	27.1/16	4.0%	1.9%	0.4%
Medium	30.4/22	10.8%	4.9%	0.7%
Large	101.1/92	24.3%	41.6%	4.4%
Medium / g-2	18.1/21	64.1%	51%	3%

→ naive p-value: p-value according to gaussian χ^2-distribution
→ toy p-value: p-value extracted from pseudo experiments
→ stat.uncertainty: estimated uncertainty on p-value

$$\Delta p = \sqrt{\frac{p \cdot (1-p)}{n_{\text{Toy}}}}$$

Summary

- global fit of CMSSM with updated observables
  → low energy measurements
  → measurements from cosmology/astrophysics
  → results of direct searches
  → Higgs observables

- LHC limits push the CMSSM to a region in which it can no longer accomodate $(g\text{-}2)_\mu$

- accurate determination of the p-value requires pseudo experiments

- p-value depends strongly on the choice of the observable set
  → combination of measurements with identical predictions crucial

- we exclude the CMSSM at the 95% CL with the optimal observable set