Global Fits to Dark Matter

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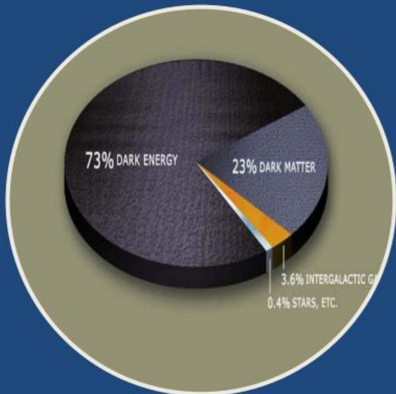
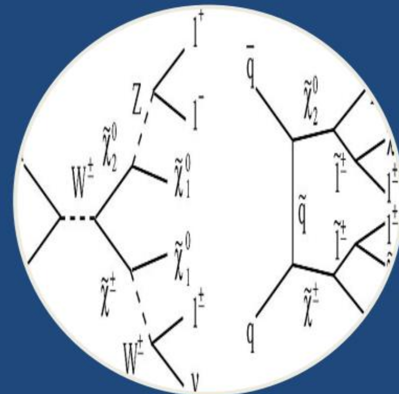
Global Fits to Dark Matter

- Why global fits ?
- Models and Code
- Global fits SUSY models with a few parameters
- Global fits SUSY models with many paramters
- Global fits and Fermi-LAT GeV excess
- Forecasting for the LHC: A recent example
- New developments for global fits



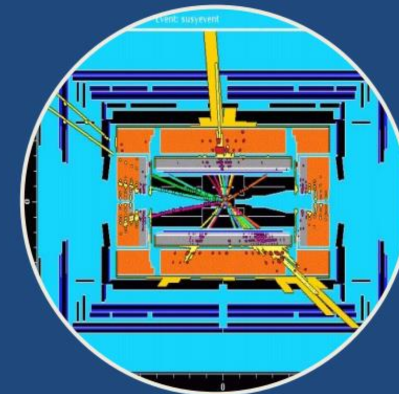
Evidence from Astroparticle physics

- Dark Matter
- Assumptions



Theoretical connections

- Supersymmetry
- Extra Dimensions
- … , ??



Consequences for LHC

- LHC phenomenology
- Model testing

Why global fits?

- Simplified models (1-3 parameters)
- Simple models (e.g. mSUGRA, 4-6 parameters)
- Models (MSSM, 7-20 parameters)
- Full models (SUSY ?, >20 parameters)

Why global fits?

- Simplified models (1-3 parameters) * number of models
- Simple models (e.g. mSUGRA, 4-6 parameters) * number of models
- Models (MSSM, 7-20 parameters)
- Full models (SUSY ?, >20 parameters)

- Complexity
- Curse of dimensionality

(Volume increases so much that data becomes sparse)

Simple

Simplified models * number of models

not equal

Full model

Curse of dimensionality and random sampling

- Volume of some solutions is 10^(-20) of parameter space (see later)
- Random sampling will not work to find solutions
- Random sampling good to get first (iteration) overview of parameter space

Statistical inference

Goals:

- Determine Likelihood (model | world data)

Frequentist:

- Likelihood-based methods: determine the best fit parameters by finding the minimum of -2 Log(Likelihood) = chi-squared
- Determine Confidence Interval

Metric dependent…

Statistical inference

Goals:

- Determine Likelihood (model | world data)

…or Bayesian

$$P(H \mid E) = \frac{P(E \mid H) \cdot P(H)}{P(E)}$$

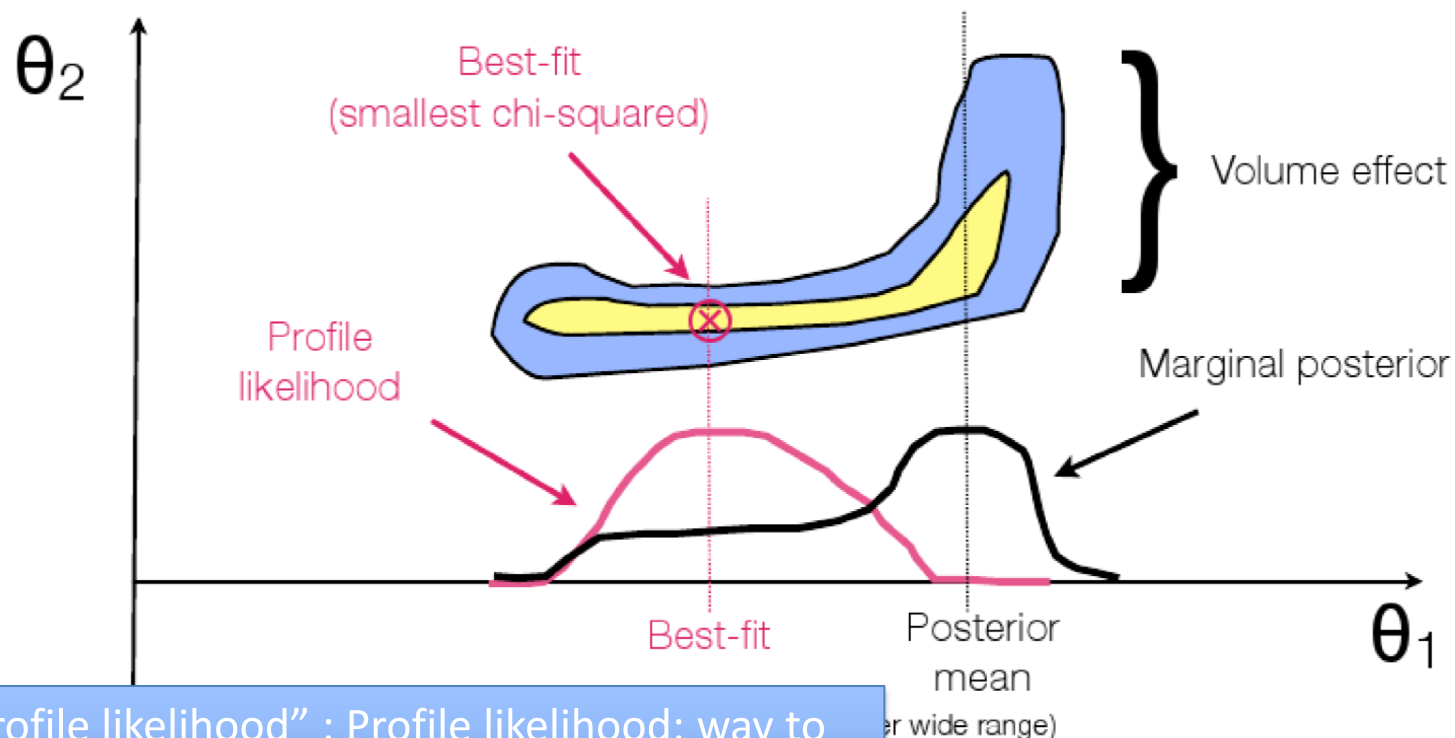
Posterior probability = Prob. of observing E given H * Prior (H)

Determine P(E|H)

Assume Prior ➔ Hope that result is prior independent

Profiling versus Marginalizing

$$P(\theta_1|D) = \int L(\theta_1, \theta_2) p(\theta_1, \theta_2) d\theta_2 \quad L(\theta_1) = max_{\theta_2} L(\theta_1, \theta_2)$$



"Profile likelihood" : Profile likelihood: way to treat nuisance

$L(x,y) \Rightarrow PL(x) = \max. L(x,y)$ for fixed x in y

Models

Today:

- Simple SUSY models status
- MSSM (no galactic center excess)
- MSSM (galactic center excess)
- EFTs
- More models done and needed !

Worldwide data

Observable	Mean value μ	Standard deviation σ (exper.)	τ (theor.)	Ref.
M_W [GeV]	80.385	0.015	0.01	[48]
$\sin^2 \theta_{\text{eff}}$	0.23153	0.00016	0.00010	[48]
Γ_Z [GeV]	2.4952	0.0023	0.001	[48]
σ^0_{had} [nb]	41.540	0.037	-	[48]
R^0_l	20.767	0.025	-	[48]
R^0_b	0.21629	0.00066	-	[48]
$BR(\overline{B}_s \to \mu^+\mu^-) \times 10^9$	3.2	1.5	0.38	[52]
$\Omega_{\tilde{\chi}^0_1} h^2$	0.1186	0.0031	0.012	[56]
m_h [GeV]	125.66	0.41	2.0	[66, 67]
$^\dagger \mu_{\gamma\gamma}$	0.78	0.27	15%	[69]
$^\dagger \mu_{W^+W^-}$	0.76	0.21	15%	[70]

Usually:
Electroweak precision measurements, rare decays, relic Dark Matter density,
Higgs mass, Higgs couplings, sigma_DM_SD, sigma_DM_SI

Choice:
Fermi-LAT excess and spheroidal dwarf limits

Difficult:
LHC SUSY limits

Simple models status

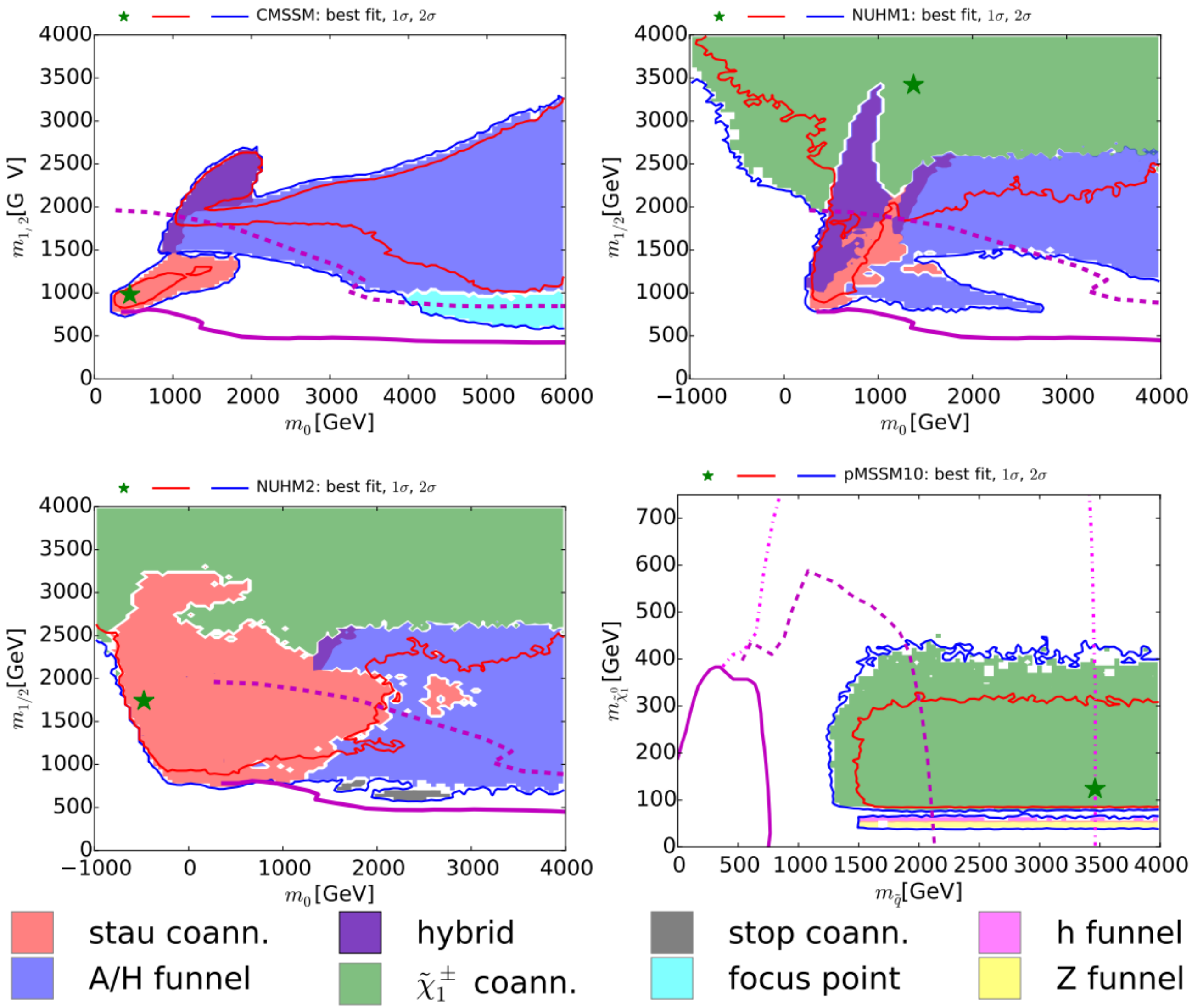
- Various attempts:

  Mastercode, sFitter, Fittino,

  Gambit, Bayesfits …
- Example next slide …

  (see also other talks at this conference)

Mastercode exploring 4 models



The red and blue contours correspond approximately to the 68 and 95% CL contours, with the green stars indicating the best-fit points, and the **solid purple contours show the current LHC 95% exclusions from MET searches**

http://arxiv.org/pdf/1508.01173.pdf

Simple model summary

- cMSSM etc. not dead … but mass scale increased also by Higgs mass and LHC direct detection
- … models not killed yet… larger mass scales can decrease naturalness…
- Various interesting results to steer DM searches (especially LHC e.g. stau1 long lived in NUHM2)

MSSM 10-19

MSSM-15 parameters and priors			
Flat priors		Log priors	
M_1 [TeV]	(-5, 5)	$\text{sgn}(M_1)\log\|M_1\|/\text{GeV}$	$(-3.7, 3.7)$
M_2 [TeV]	(0.1, 5)	$\log M_2/\text{GeV}$	$(2, 3.7)$
M_3 [TeV]	(-5, 5)	$\text{sgn}(M_3)\log\|M_3\|/\text{GeV}$	$(-3.7, 3.7)$
m_L [TeV]	(0.1,10)	$\log m_L/\text{GeV}$	$(2, 4)$
m_{L_3} [TeV]	(0.1,10)	$\log m_{L_3}/\text{GeV}$	$(2, 4)$
m_{E_3} [TeV]	(0.1,10)	$\log m_{E_3}/\text{GeV}$	$(2, 4)$
m_Q [TeV]	(0.1,10)	$\log m_Q/\text{GeV}$	$(2, 4)$
m_{Q_3} [TeV]	(0.1,10)	$\log m_{Q_3}/\text{GeV}$	$(2, 4)$
m_{U_3} [TeV]	(0.1,10)	$\log m_{U_3}/\text{GeV}$	$(2, 4)$
m_{D_3} [TeV]	(0.1,10)	$\log m_{D_3}/\text{GeV}$	$(2, 4)$
A_t [TeV]	(-10, 10)	$\text{sgn}(A_t)\log\|A_t\|/\text{GeV}$	$(-4, 4)$
A_0 [TeV]	(-10,10)	$\text{sgn}(A_0)\log\|A_0\|/\text{GeV}$	$(-4, 4)$
μ [TeV]	(-5,5)	$\text{sgn}(\mu)\log\|\mu\|/\text{GeV}$	$(-3.7, 3.7)$
m_A [TeV]	(0.01, 5)	$\log m_A/\text{GeV}$	$(1, 3.7)$
$\tan\beta$	$(2, 62)$	$\tan\beta$	$(2, 62)$
M_t [GeV]	173.2 ± 0.87 [17] (Gaussian prior)		

LHC constrains on squark and gluinos not severe !

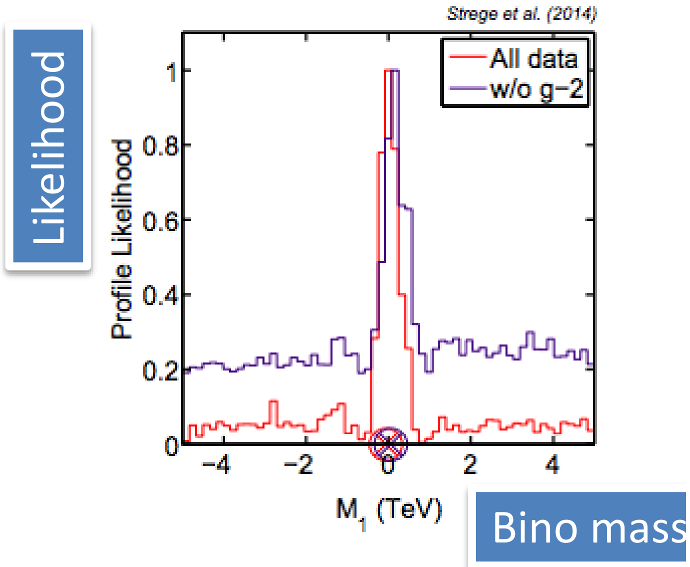
Global MSSM fits

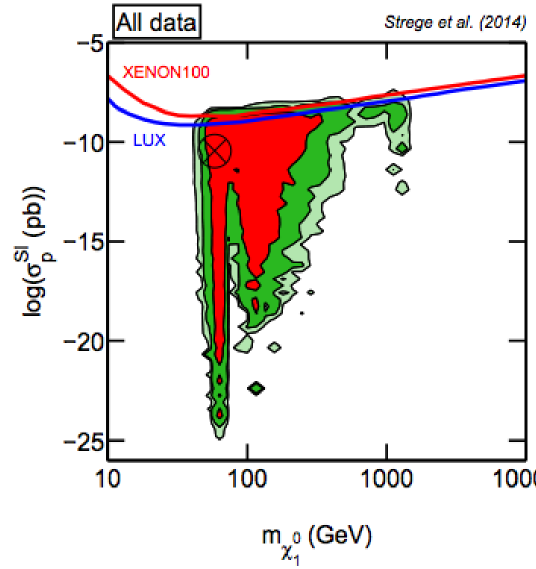
- All world data
- Attempts to include SUSY LHC limits
- 8-18 pMSSM parameters
- GC excess not included here…

Global MSSM Fits for Dark Matter

JHEP 1409 (2014) 081

Fit in MSSM model with 18 parameters using all worldwide data, but no LHC and Fermi-LAT





Global MSSM Fits for Dark Matter

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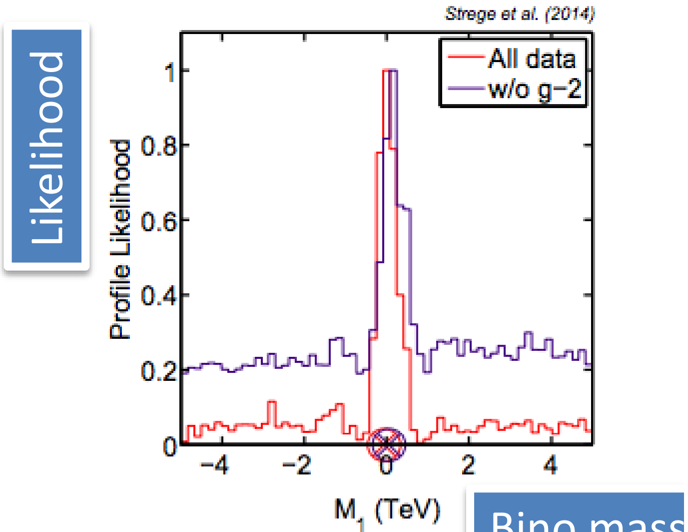
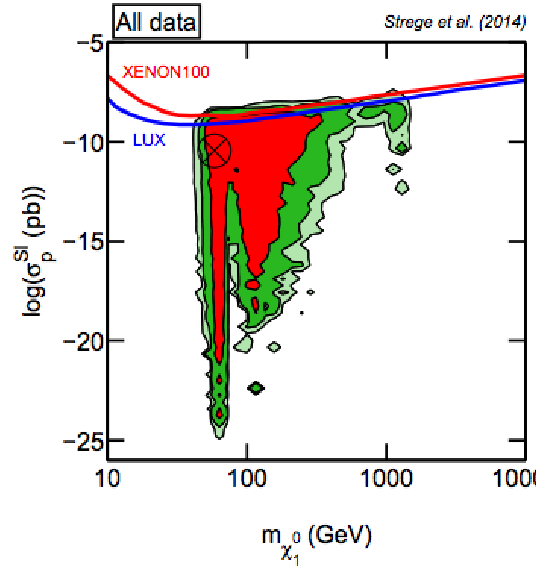
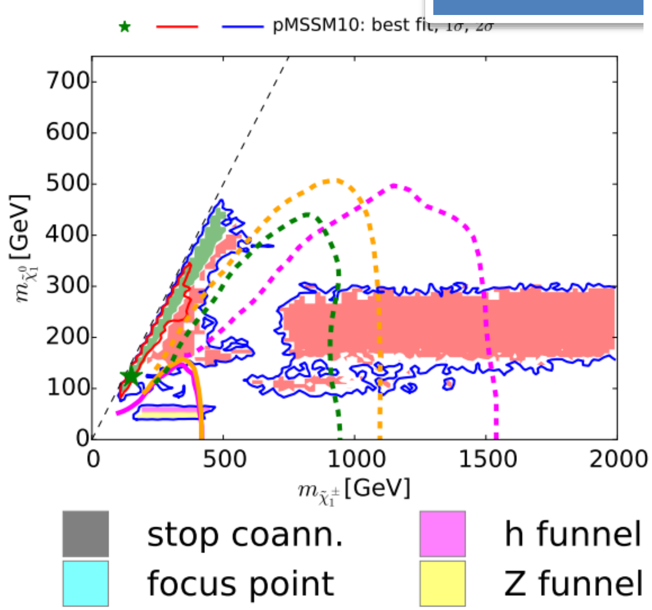


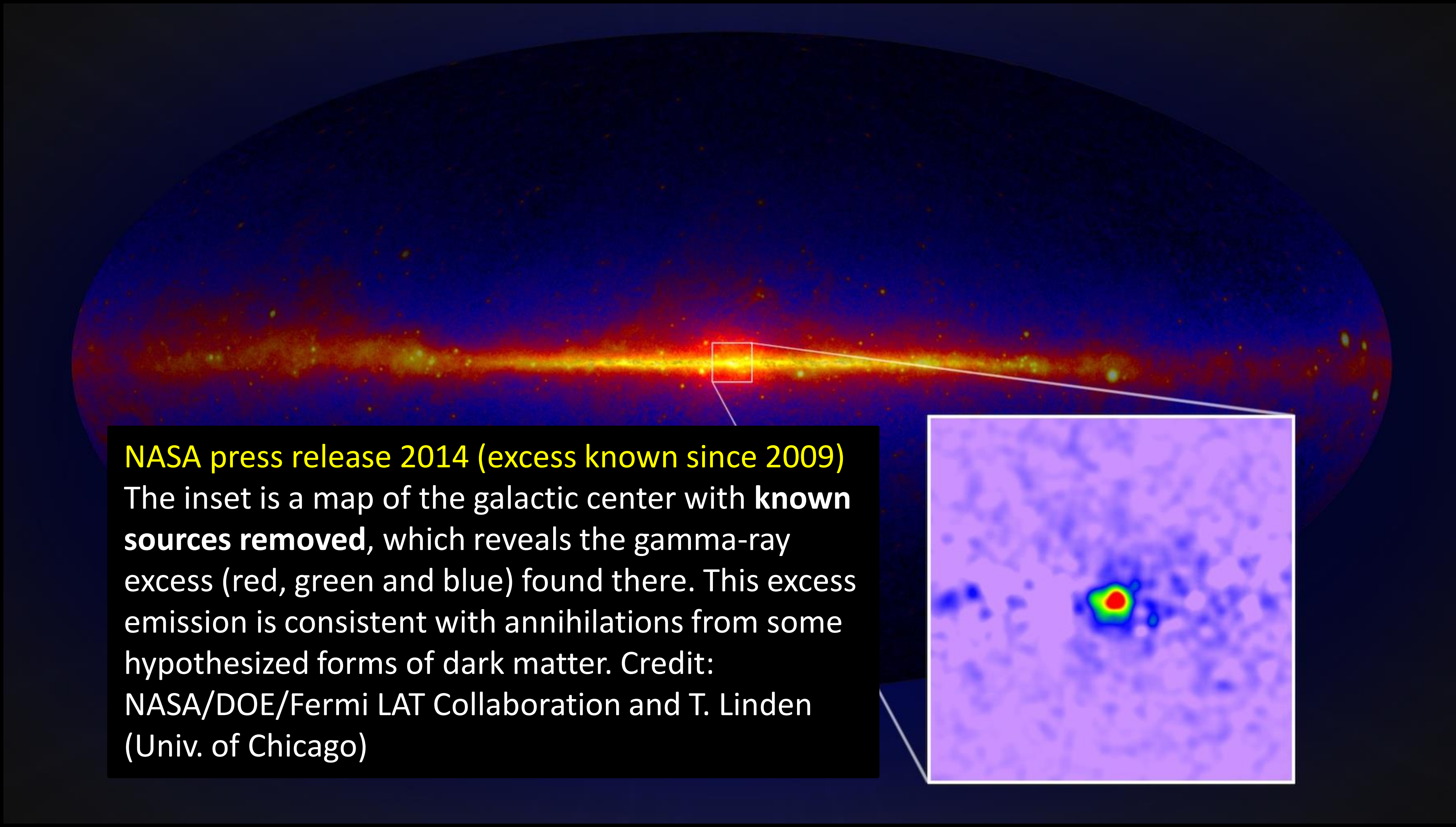


Eur.Phys.J. C75 (2015) 500
Mastercode collaboration:

Fit in MSSM model with 10 parameters using all worldwide data, but no Fermi-LAT



Very similar conclusions



NASA press release 2014 (excess known since 2009)

The inset is a map of the galactic center with **known sources removed**, which reveals the gamma-ray excess (red, green and blue) found there. This excess emission is consistent with annihilations from some hypothesized forms of dark matter. Credit: NASA/DOE/Fermi LAT Collaboration and T. Linden (Univ. of Chicago)

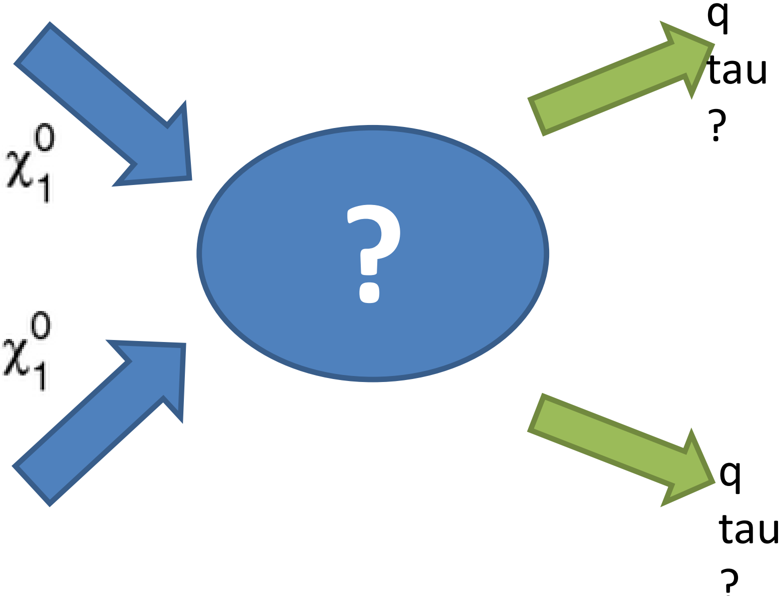
Official paper in 2015

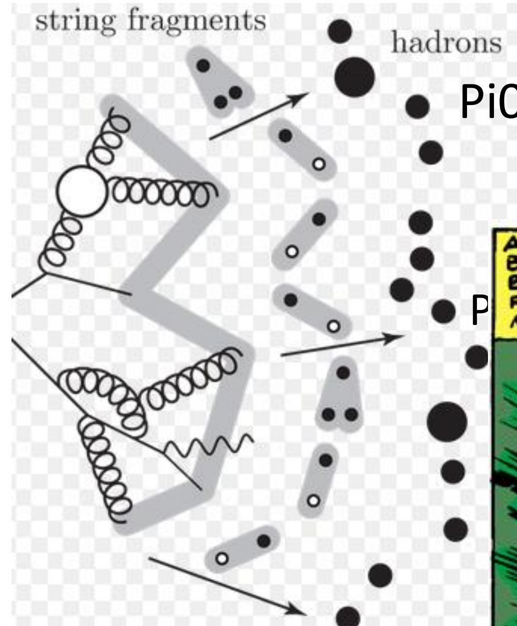
Fermi-LAT Observations of High-Energy Gamma-Ray Emission Toward the Galactic Center

Fermi-LAT Collaboration (M. Ajello (Clemson U.) *et al.*). Nov 9, 2015. 29 pp.

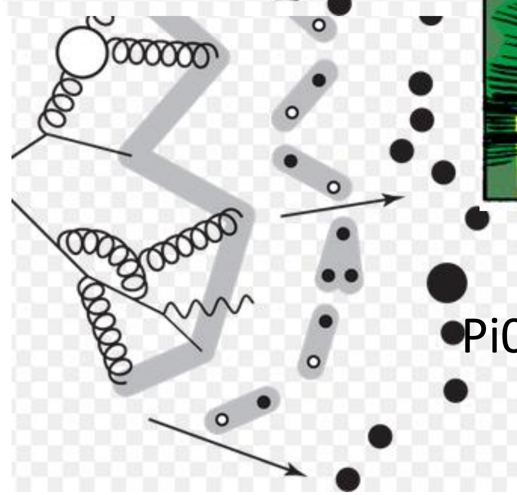
e-Print: **arXiv:1511.02938** **[astro-ph.HE]** | **PDF**

DM Signal Modelling



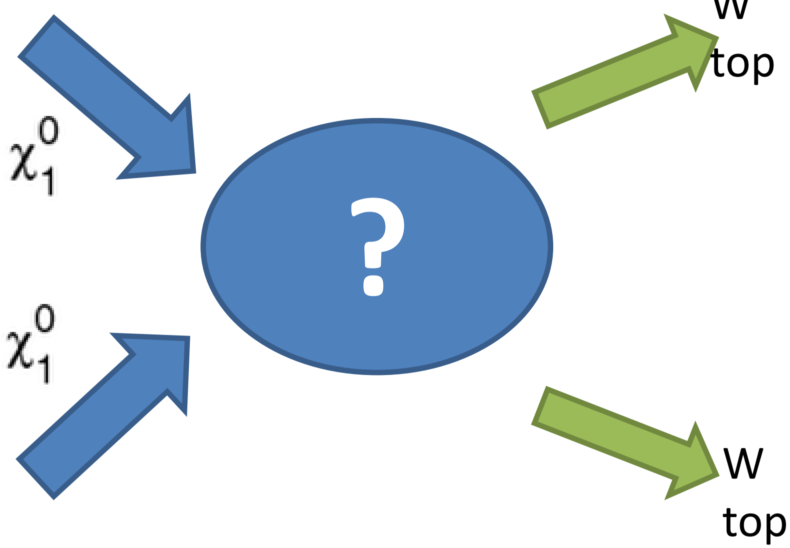


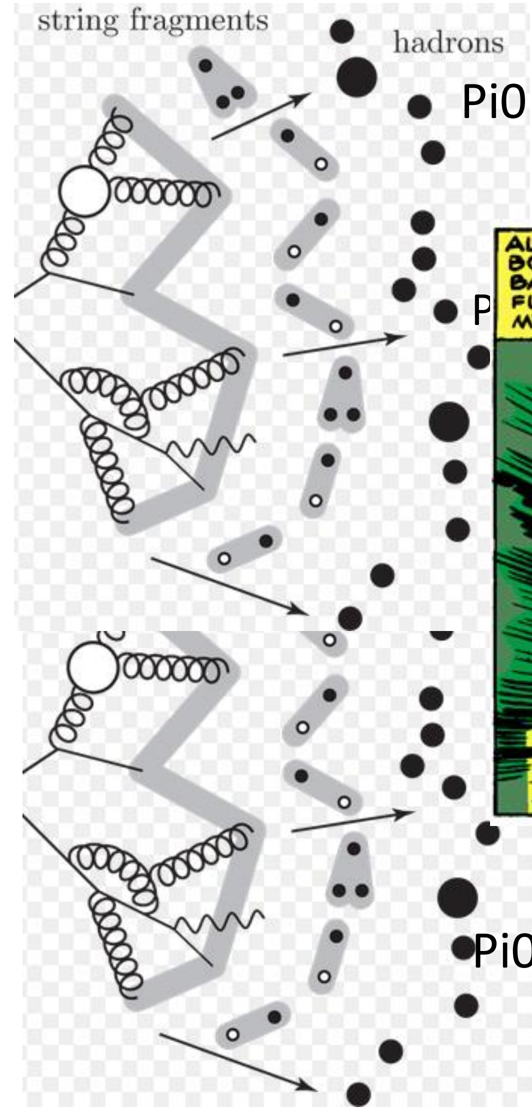
Pi0 => gamma gamma



Pi0 => gamma gamma

DM Signal Modelling



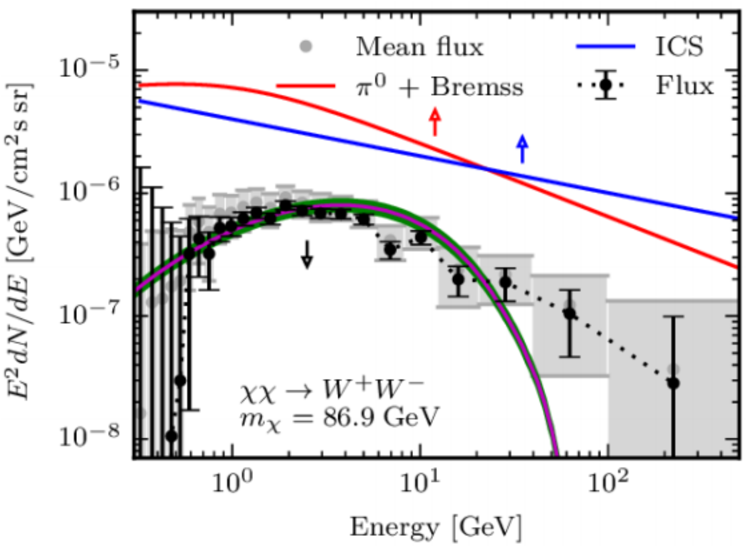


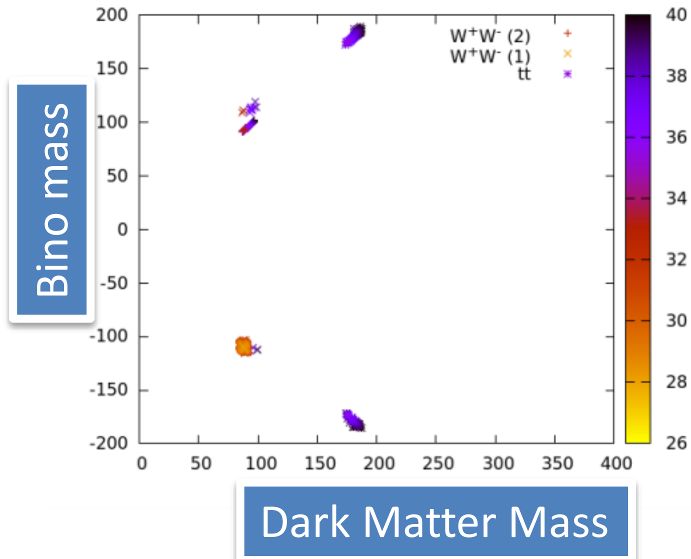
Pi0 => gamma gamma

Pi0 => gamma gamma

MSSM and Galactic Center excess

JCAP 1508 (2015) 08, 006 and arxiv1507.07008





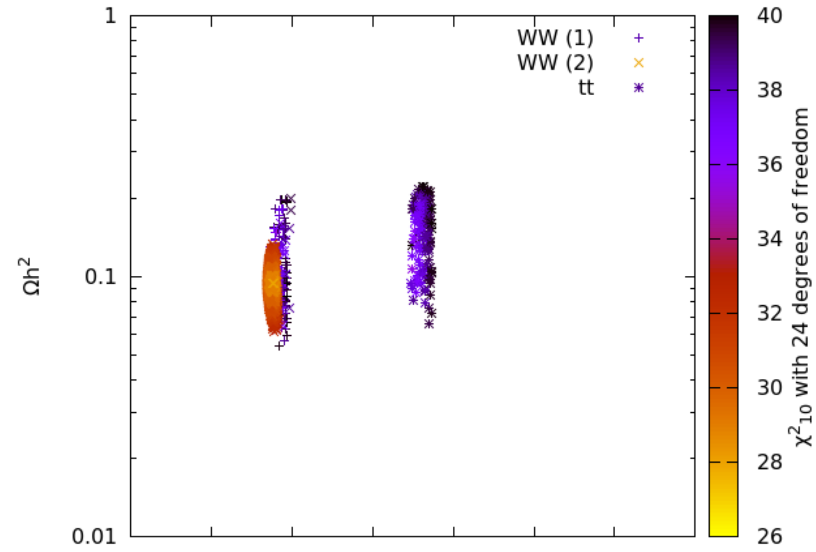
Galactic Center gamma-ray excess can be described with Neutralino DM of approx. 80-90 GeV annihilating into W+W-

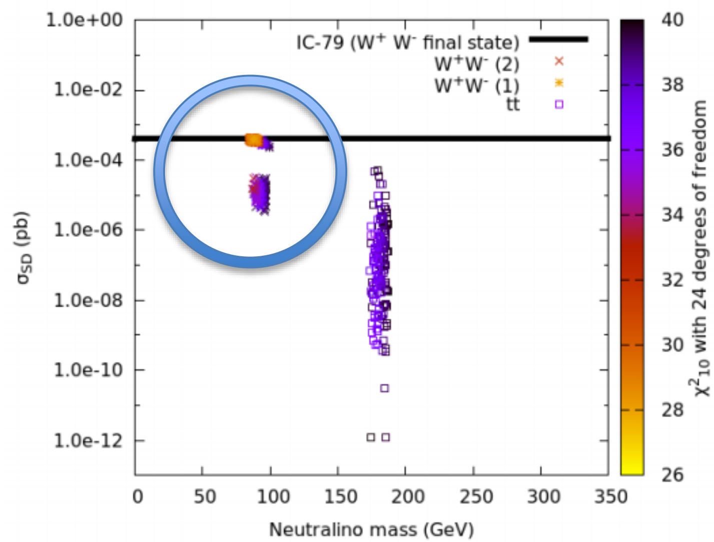
Fit using GC excess
Higgs, LEP, Lux, Icecube data
“only” !
➔ Right DM relic density

Best solution is 85 GeV Bino-Higgsino or Bino-Wino….

Are these solutions interesting?

- Solutions are “spot on” (bino-wino and bino-higgsino DM)
- Right relic DM density (non trivial for MSSM due to co-annihilation)
- Not excluded by any experiment worldwide! (also not from LHC, not included into the fit)
- Bino-Higgsino solution has tiny fine tuning…. Icecube excess?



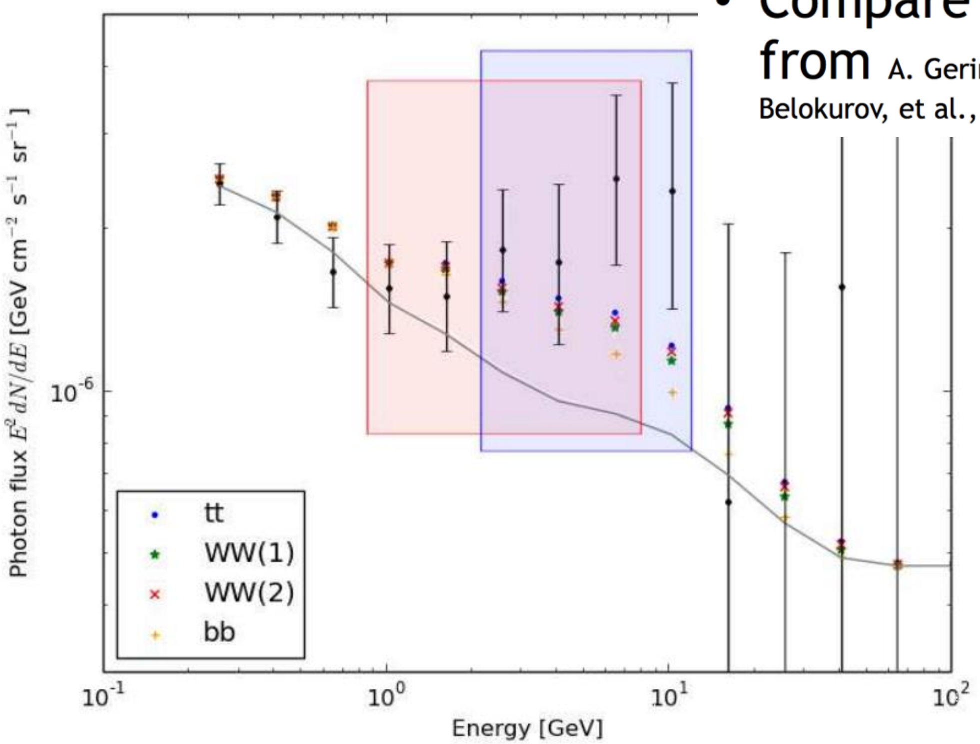


arXiv:1502.05703

Reticulum 2 and MSSM

- Small excess (2-3 sigma) reported for dwarf galaxy Reticulum-2
- Official Fermi-LAT paper reports p=0.06 including trial factors (for DM mass and shape) with updated dataset (pass8)
- Compare our solutions to data pass7 data from A. Geringer-Sameth, M. G. Walker, S. M. Koushiappas, S. E. Koposov, V. Belokurov, et al., arXiv:1503.02320.

JCAP12(2015)013

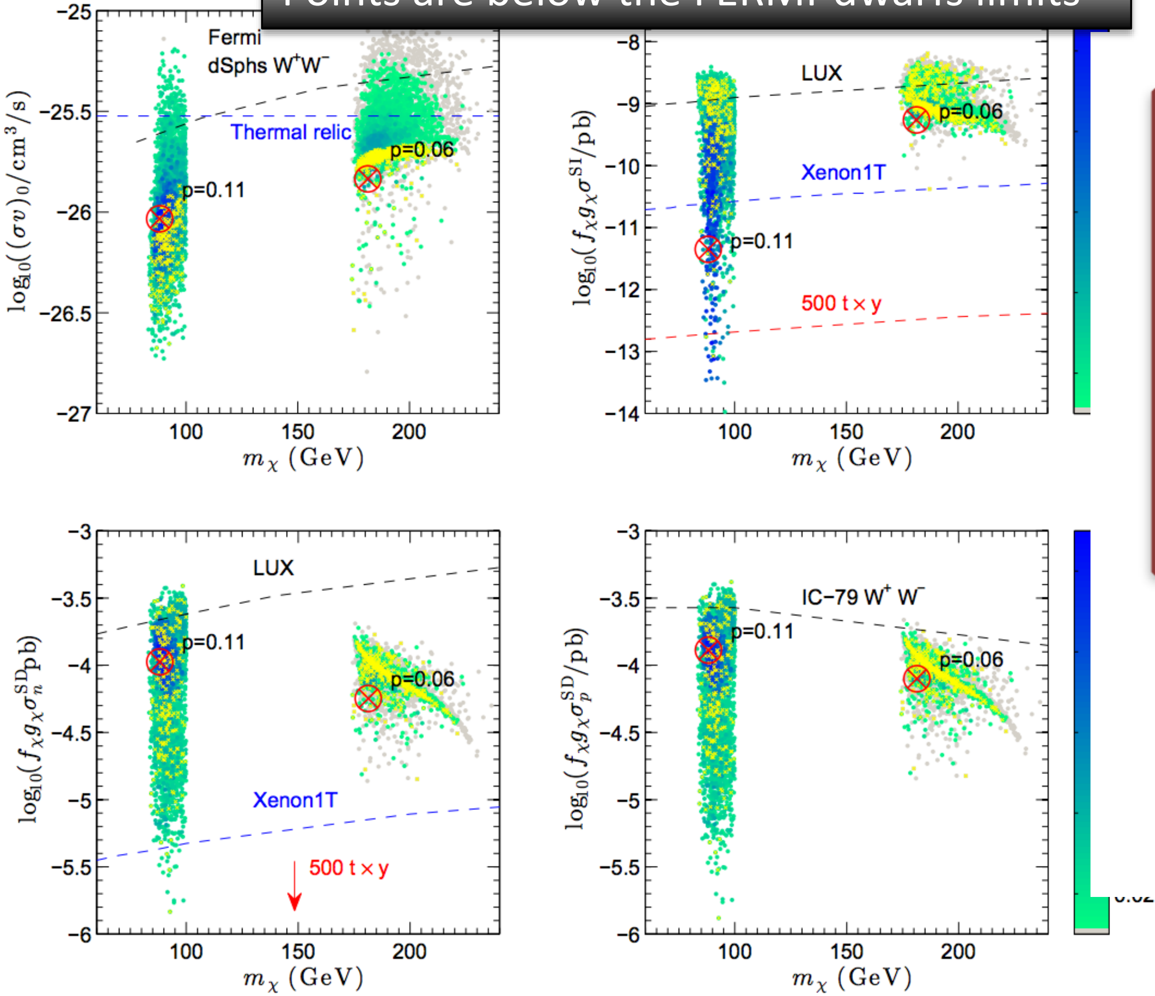


Slightly better fit
Than bb solution

J-factor consistent with value determined by jeans analysis

Full MSSM19 fit (including GC excess)

Points are below the FERMI-dwarfs limits



colour indicates p-value of the fit **yellow** means that points have right Omega*h2 within 2 sigma

$$\rho_\chi/\rho_{\rm DM} = \Omega_\chi/\Omega_{\rm DM} \equiv f_\chi$$

Best fit points

- Best fit region of MSSM 19 fit with GC excess overlaps with MSSM 10 Mastercode solutions

Interesting:

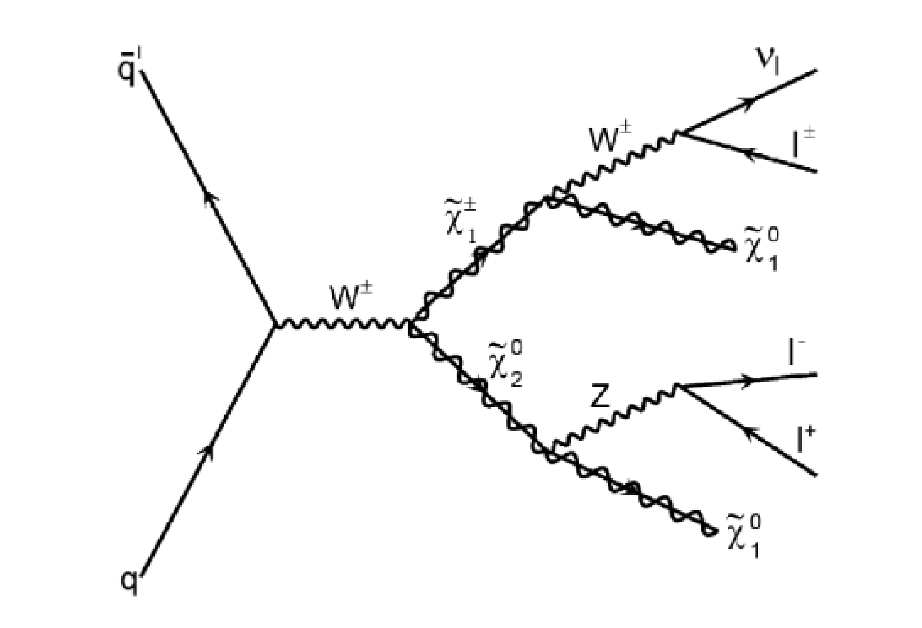
- Solutions not excluded yet at LHC
- **Even worse: No sensitivity** at LHC with 3000 fb-1
- Unless dedicated search done…

The case for a 100 GeV Bino

MSSM global fits and Galactic Center excess prefer region of approx. 100 GeV Bino Dark Matter, compressed with a chargino yielding the correct DM density

No sensitivity seen in:
- Monojets
- Or other "typical" DM searches

➔ Solution 3leptons with NO MET and special angular cuts



NEEDS FULL MODEL!!!

arXiv:1602.00590 [

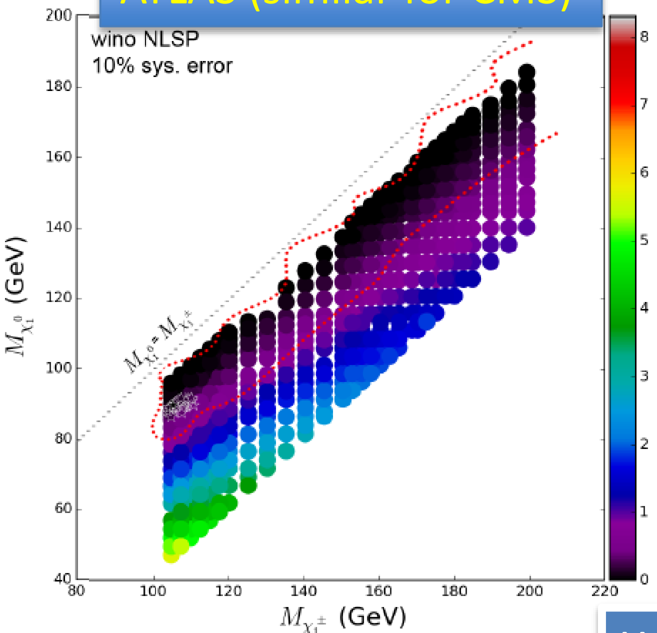
The case for a 100 GeV Bino

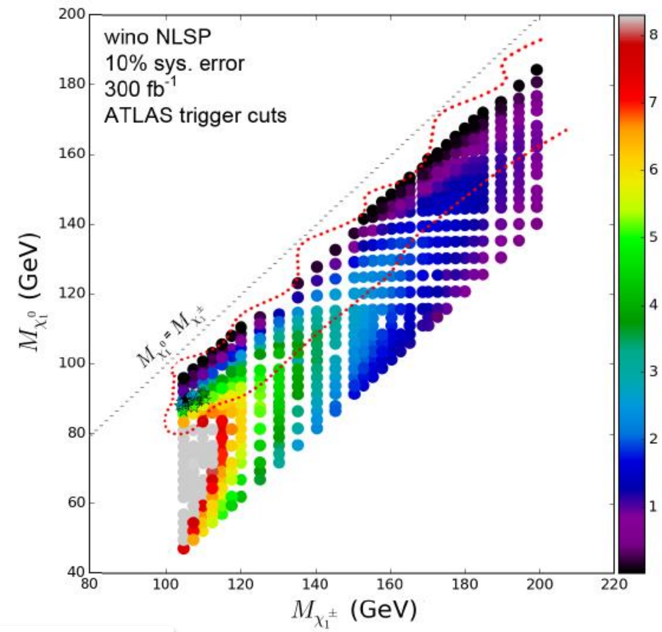
MSSM global fits and Galactic Center excess prefer region of approx. 100 GeV Bino Dark Matter, compressed with a chargino yielding the correct DM density

Dedicated new 3lepton search ("low MET") would yield sensitivity in this Region!

ATLAS (similar for CMS)

Bino mass





Wino mass

arXiv:1602.00590 [

Global EFT fits

Global EFT fits

Arxiv 1603.05994.

Recently global analysis of EFT for scalar Dark Matter

Bayesian and Frequentist fit, posterior dominated by prior

Real scalar DM operators				
Label	Coefficient	Operator	σ_{SI}	$\langle\sigma_{\text{ann}}v\rangle$
R1	$\lambda_1 \sim \frac{1}{2M^2}$	$m_q\chi^2\bar{q}q$	✓	s-wave
R2	$\lambda_2 \sim \frac{1}{2M^2}$	$im_q\chi^2\bar{q}\gamma^5 q$		s-wave
R3	$\lambda_3 \sim \frac{\alpha_s}{4M^2}$	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	✓	s-wave
R4	$\lambda_4 \sim \frac{\alpha_s}{4M^2}$	$i\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$		s-wave
Complex scalar DM operators				
Label	Coefficient	Operator	σ_{SI}	$\langle\sigma_{\text{ann}}v\rangle$
C1	$\lambda_1 \sim \frac{1}{M^2}$	$m_q\chi^\dagger\chi\bar{q}q$	✓	s-wave
C2	$\lambda_2 \sim \frac{1}{M^2}$	$im_q\chi^\dagger\chi\bar{q}\gamma^5 q$		s-wave
C3	$\lambda_3 \sim \frac{1}{M^2}$	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	✓	p-wave
C4	$\lambda_4 \sim \frac{1}{M^2}$	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$		p-wave
C5	$\lambda_5 \sim \frac{\alpha_s}{8M^2}$	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	✓	s-wave
C6	$\lambda_6 \sim \frac{\alpha_s}{8M^2}$	$i\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$		s-wave

For large momentum transfer processes such as at the LHC limits derived in an EFT context do not apply to models in which the mediator masses are < 1TeV

Global EFT fits

Quite Flat profile likelihood without GC excess, largest influence has Omega h2.

Best fit points for the real scalar DM case						
	m_χ [GeV]	$\langle\sigma_{\rm ann}v\rangle$ [cm^{3}s^{-1}]	$\sigma_{\rm SI}$ [pb]	$\chi^2_{\rm GCE}$ (p-value)	$\chi^2_{\rm dSph}$	$\chi^2_{\Omega h^2}$
w/ GCE	49.0	1.93×10^{-26}	8.52×10^{-11}	27.74 (0.15)	71.6	0.2
w/o GCE	173.3	2.47×10^{-28}	2.22×10^{-10}	–	66.7	1.5×10^{-6}
Best fit points for the complex scalar DM case						
w/ GCE	42.6	7.37×10^{-27}	8.30×10^{-11}	28.2 (0.14)	67.56	0.003
w/o GCE	2.76	4.84×10^{-28}	4.82×10^{-4}	–	65.78	0.0008

Table 2: Best fit points (i.e. minimal χ^2) for both the real and complex scalar DM candidates with and without fitting to the Galactic centre excess. The p-values are calculated only using χ^2 contribution from the Galactic centre excess, under the fairly bold assumption that the test statistic is chi-squared distributed with $24-3=21$ degrees of freedom.

Most common configuration, and therefore the most probable, is when a single operator dominates and the others are weak.

With GCE: Specific mass range (40-60 GeV) and operator R2/C2 preferred, but in tension with dwarf spheroidal limits for real scalar DM (no tension for complex scalar DM due to smaller annihilation cross section, more degrees of freedom)

Including LHC limits

- >400 signal regions to search for SUSY particles
- ATLAS/CMS give usually limits on simplified models (1-3 parameters)
- ➔ **Can we use them to make limits for non-simplified models ?**
- Needed: Cross section + Simulation + Reconstruction + Analysis code + Limit code

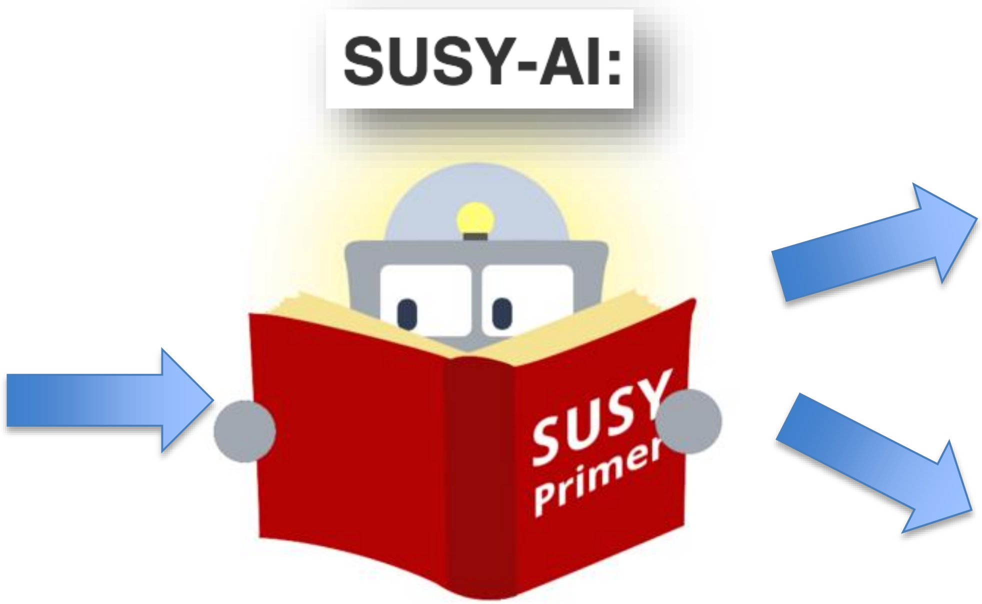
  ➔ Takes CPU hours per model point

Various attempt to recast LHC limits (Checkmate using Delphes, Atom, sModels, Mastercode etc.)

Machine Learning LHC results

- ATLAS (JHEP 1510 (2015) 134) released limits of 200 signal regions for about 300000 MSSM points
- We used them to construct a "Random Forest" of Decision Trees

Les Houches
Accord File



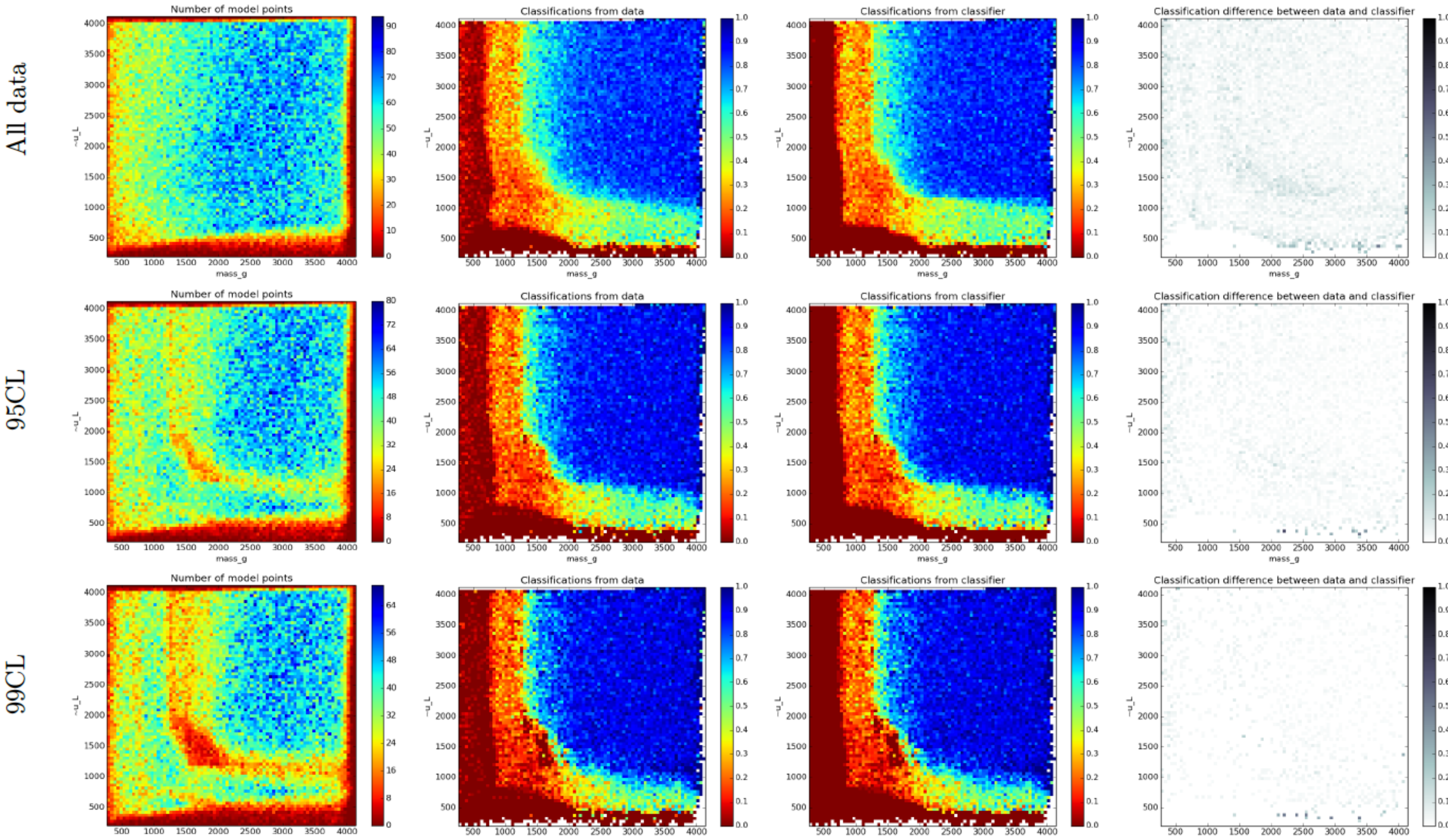
Excluded

Not Excluded

Determine
Confidence Level

> 5000 predictions / CPU second

Number of model points | True classification | Prediction by classifier | Difference between classification and prediction

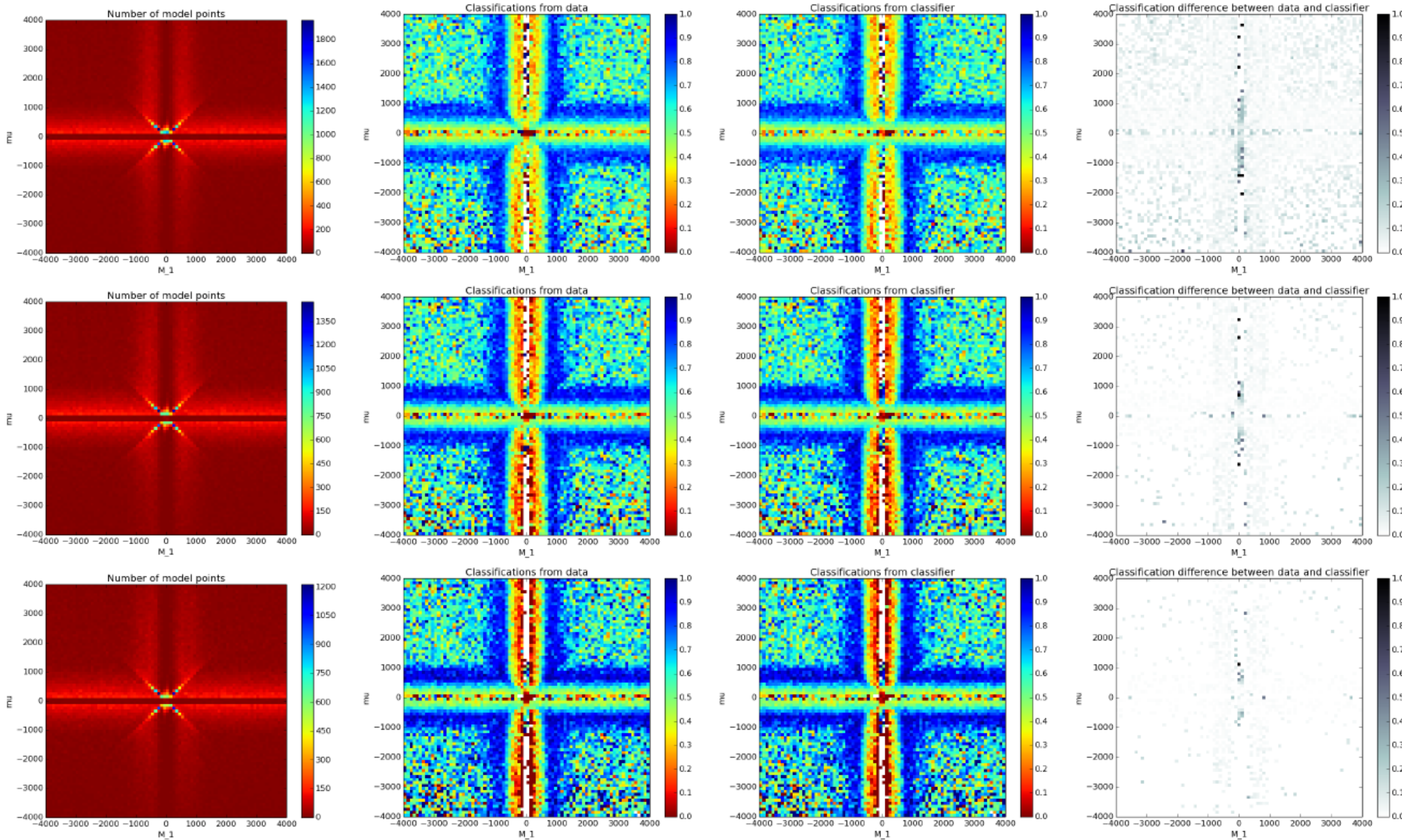


Number of model points | True classification | Prediction by classifier | Difference between classification and prediction

All data

95CL

99CL



Summary

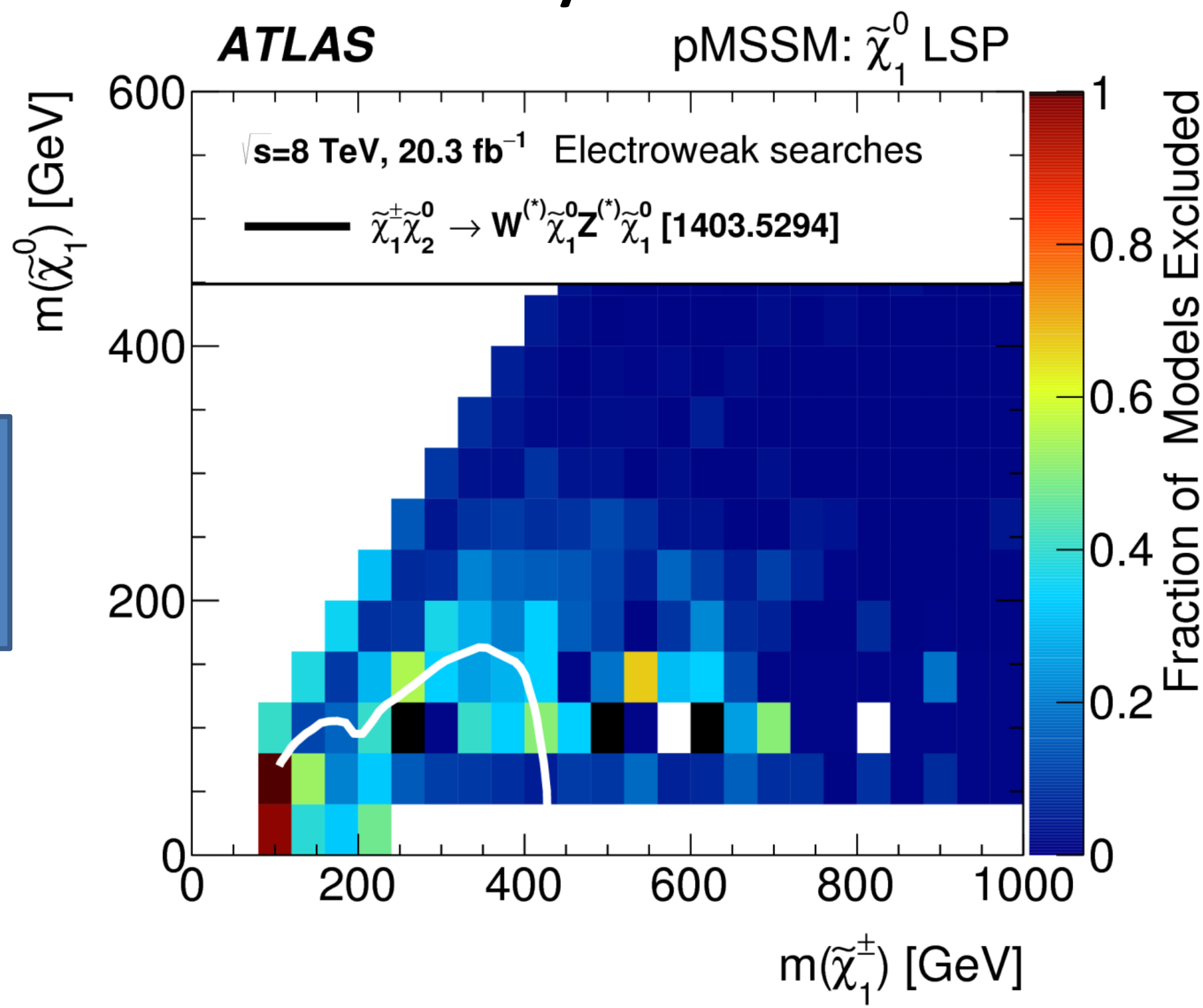
- Simplified models * n is not equal a full model
- Example: Simple model would not predict how to search for the MSSM GC solutions at LHC
- ➔ Global fits needed with generic models (also beyond SUSY…)
- **Interesting**: Best GC MSSM fits are best non-GC fits (and points with minimal fine-tuning)
- **New attempts**:

  Machine Learning, Model database

  (simple prototype www.idarksurvey.com)

Extra slides

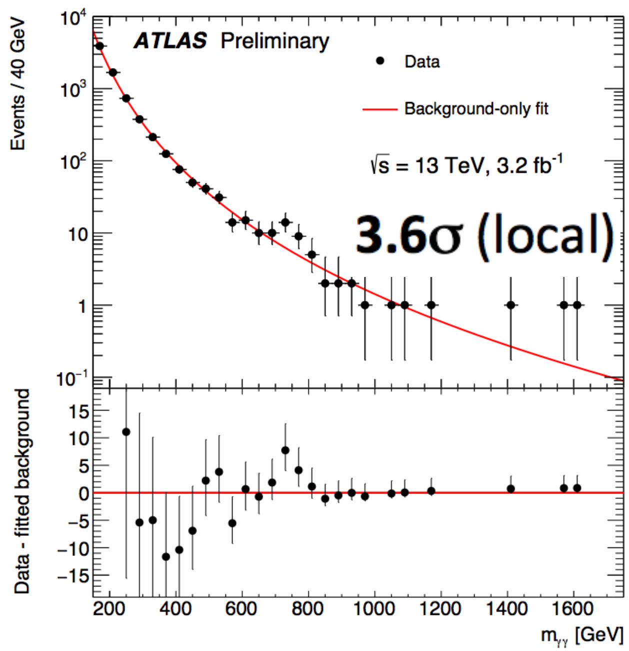
OK, what if the gluinos and squarks are heavy ?

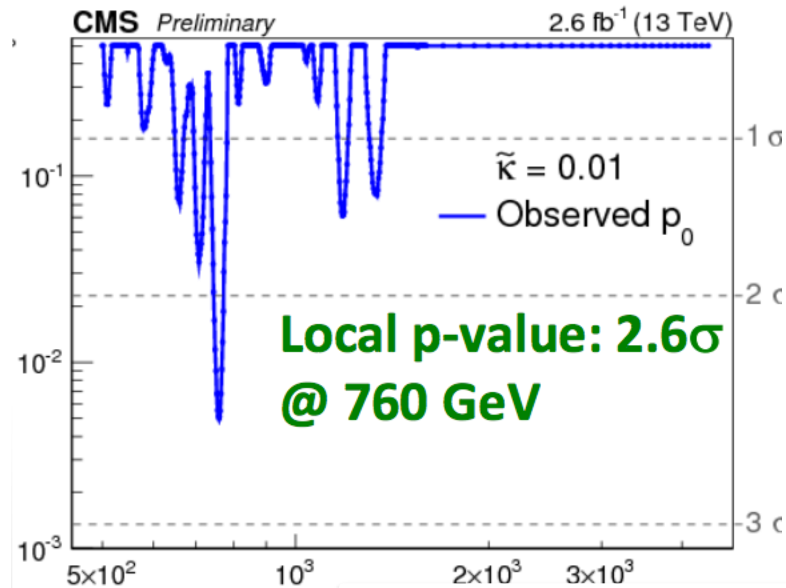


No real constrain on WIMP 100 GeV DM particles…

750 GeV resonance

End-of-year event ATLAS + CMS:





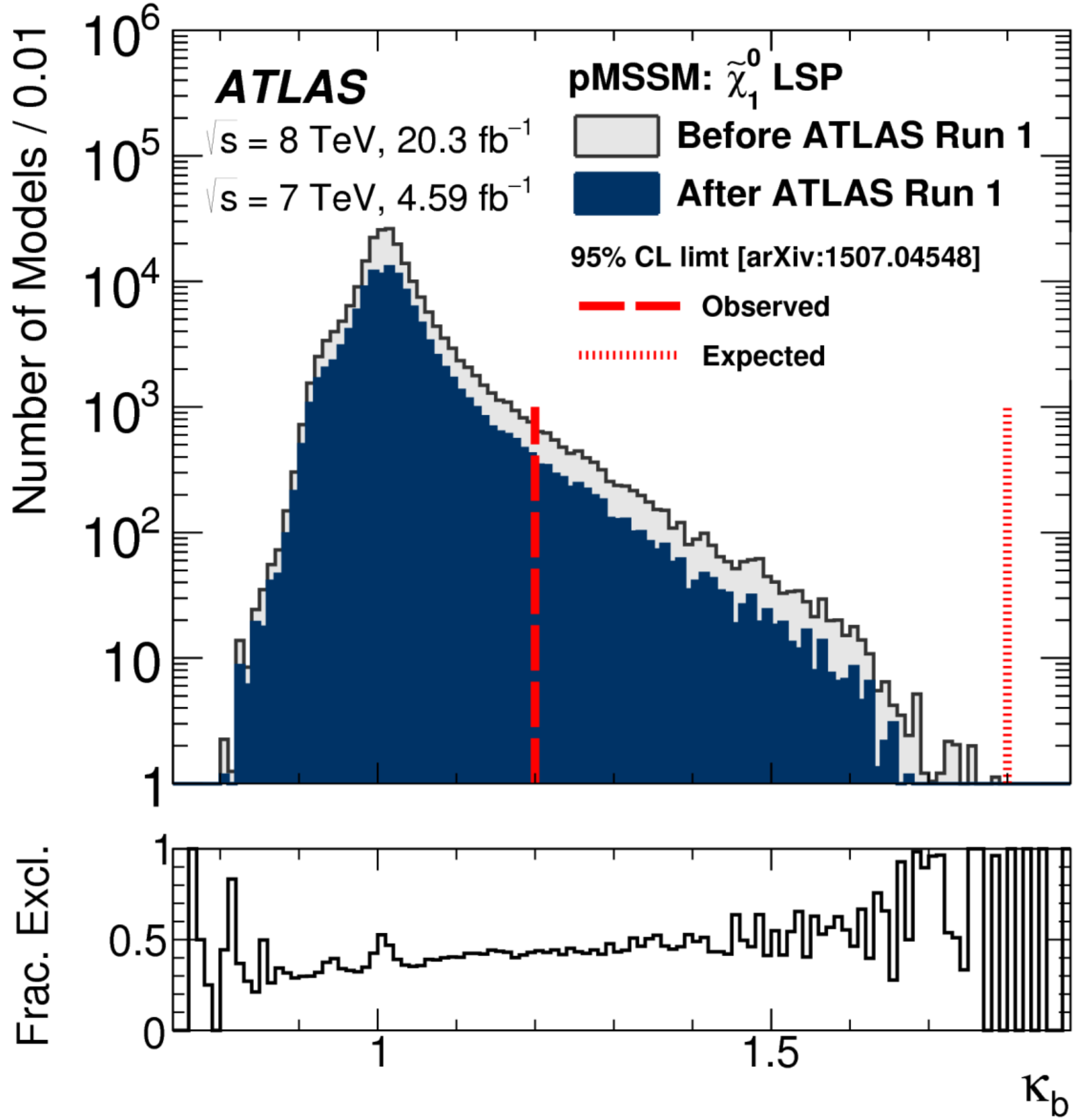
Di-photon system mass

Global p-value **2.0σ**
No signal in 8 TeV data

Global p-value < 1.2 sigma
No signal in 8 TeV data

Interesting feature in data. Not more in my view.
If correct it might be a new propagator for DM. Heavy Higgs unlikely. Wait for more data!

Higgs kappa’s and SUSY



Higgs couplings results

Many different fit assumptions
Example shown here →

Consistent with SM values within uncertainties

Sensitivity to Dark Matter ?

-If Dark Matter mass < m_H/2
-If Dark Matter has no strong coupling to Z