Global fits of neutrino and dark matter models with GAMBIT

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Outline

1. Global Fits
   - What?
   - Why?
   - How?
2. GAMBIT
3. Results
   - Right-handed Neutrinos
   - Higgs portal DM
4. Summary and outlook

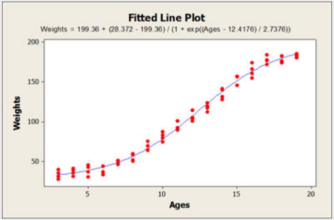
What are global fits?

What are global fits?

Global fit in statistics

Statistical fit of one or more **models** to several **data** sets simultaneously

- Generalisation of non-linear regression
- **Goodness-of-fit**
- **Parameter estimation**
- **Comparison of models**



Why do we need global fits?

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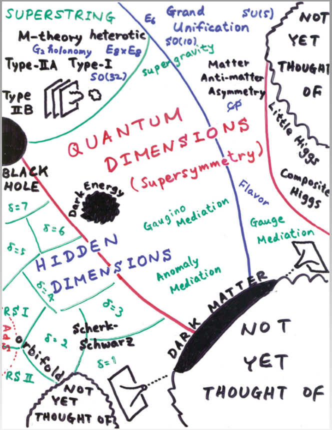
- Many BSM theories
  - → Which one is better?
- BSM models have a large amount of parameters
  - → Explore full parameter space
  - → Where is my theory valid?
- Many experimental constraints
  - → Collider searches, dark matter, precision observables, flavour anomalies,...
  - → Simultaneously include all constraints
  - → Does my theory fit the experimental data?



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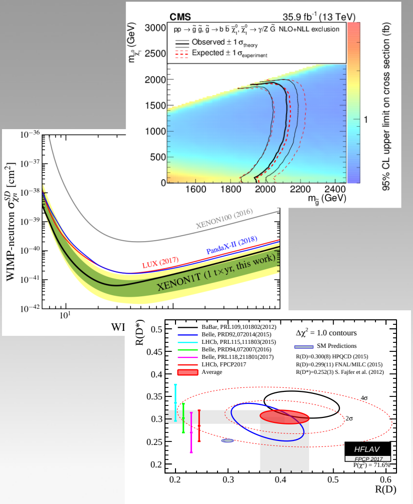

How do we do global fits?

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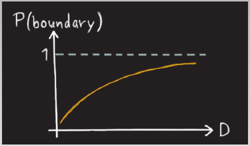
- Combine all constraints into a **composite likelihood**

$$\mathcal{L} = \mathcal{L}_{Collider}\mathcal{L}_{Higgs}\mathcal{L}_{DM}\mathcal{L}_{Flavour}\cdots$$

- Perform an extensive **parameter scan**
  - → Old-school sampling methods (random, grid) are inefficient
  - → Impossible to make statement about statistics
  - → Need **smart sampling strategies** (differential, nested, genetic,. . .)



- **Rigorous** statistical interpretation (frequentist/Bayesian)
  - → Goodness-of-fit
  - → Parameter estimation
  - → Model comparison

GAMBIT

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GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org EPJC **77** (2017) 784 arXiv:1705.07908

- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source

Members of:
ATLAS, Belle-II, CLiC, CMS, CTA, *Fermi*-LAT, DARWIN, IceCube, LHCb, SHiP, XENON
Authors of:
DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaTols, nulike, PolyChord, Rivet, SoftSUSY, SuperISO, SUSY-AI, WIMPSim

- Fast definition of new datasets and theories
- Plug and play scanning, physics and likelihood packages

Recent collaborators:
Peter Athron, Csaba Balázs, Ankit Beniwal, Sanjay Bloor, Torsten Bringmann, Andy Buckley, José Eliel Camargo-Molina, Marcin Chrząszcz, Jonathan Cornell, Matthias Danninger, Joakim Edsjö, Ben Farmer, Andrew Fowlie, Tomás E. Gonzalo, Will Handley, Sebastian Hoof, Selim Hotinli, Felix Kahlhoefer, Anders Kvellestad, Julia Harz, Paul Jackson, Farvah Mahmoudi, Greg Martinez, Are Raklev, Janina Renk, Chris Rogan, Roberto Ruiz de Austri, Pat Scott, Patrick Stöcker, Aaron Vincent, Christoph Weniger, Martin White, Yang Zhang

40+ participants in 11 experiments and 14 major theory codes

Structure of GAMBIT

MODULES (Bits)

- Physics Modules
  - → **ColliderBit**: collider searches [GAMBIT, Eur.Phys.J. C77 (2017) no.11, 795]
  - → **DarkBit**: relic density, dd,... [GAMBIT, Eur.Phys.J. C77 (2017) no.12, 831]
  - → **FlavBit**: flavour observables [GAMBIT, Eur.Phys.J. C77 (2017) no.11, 786]
  - → **SpecBit**: spectra, RGE running [GAMBIT, Eur.Phys.J. C78 (2018) no.1, 22]
  - → **DecayBit**: decay widths [GAMBIT, Eur.Phys.J. C78 (2018) no.1, 22]
  - → **PrecisionBit**: precision tests [GAMBIT, Eur.Phys.J. C78 (2018) no.1, 22]
  - → **NeutrinoBit**: neutrino likelihoods [GAMBIT, upcoming]
- **ScannerBit** : stats and sampling [GAMBIT, Eur.Phys.J. C77 (2017) no.11, 761]

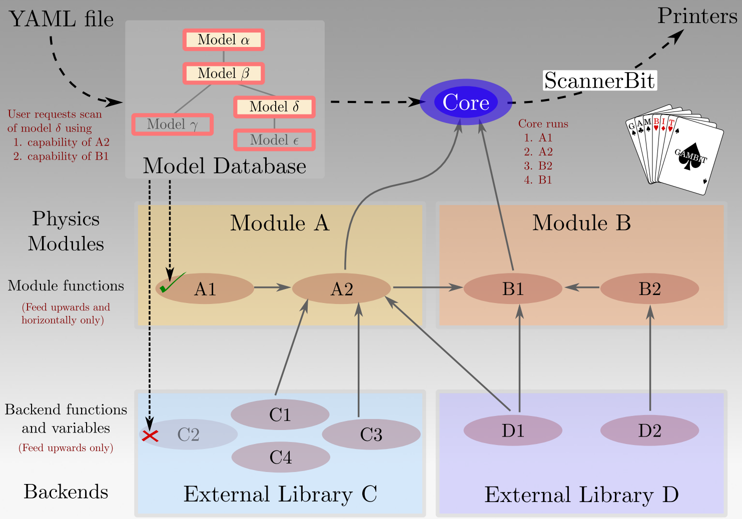
  (Diver, GreAT, Multinest, ...)

BACKENDS (Pythia, DarkSUSY, MicrOMEGAs, SPheno, SuperISO,...)

CORE [GAMBIT, Eur.Phys.J. C78 (2018) no.2, 98]

- Models
- Dependency resolution

Structure of GAMBIT



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Backends

- External tools and libraries to calculate observables
- C, C++, Fortran, Mathematica, Python

HiggsBounds	4.2.1	Backends/installed/higgsbounds/4.2.1/lib/libhiggsbounds.so	absent/broken	10	0	0
	4.3.1	Backends/installed/higgsbounds/4.3.1/lib/libhiggsbounds.so	OK	10	0	0
HiggsSignals	1.4	Backends/installed/higgssignals/1.4.0/lib/libhiggssignals.so	OK	12	0	0
LibFarrayTest	1.0	Backends/examples/libFarrayTest.so	OK	10	0	0
LibFirst	1.0	Backends/examples/libfirst.so	OK	8	0	0
	1.1	Backends/examples/libfirst.so	OK	15	0	0
LibFortran	1.0	Backends/examples/libfortran.so	OK	6	0	0
LibSecond	1.0	Backends/examples/libsecond/1.0/libsecond_1_0.py	OK	6	0	0
	1.1	Backends/examples/libsecond/1.1/libsecond_1_1.py	needs Python 3	6	0	0
	1.2	Backends/examples/libsecond/1.2/libsecond_1_2.py	OK	6	0	0
LibThird	1.0	Backends/examples/libthird/1.0/libthird_1_0	OK	8	0	0
	1.1	Backends/examples/libthird/1.1/libthird_1_1	needs Python 3	6	0	0
	1.2	Backends/examples/libthird/1.2/libthird_1_2	OK	6	0	0
MicrOmegas_DiracSingletDM_Z2	3.6.9.2	Backends/installed/micromegas/3.6.9.2/DiracSingletDM_Z2/libmicromegas.so	OK	20	0	0
MicrOmegas_MSSM	3.6.9.2	Backends/installed/micromegas/3.6.9.2/MSSM/libmicromegas.so	OK	19	0	0
MicrOmegas_MajoranaSingletDM_Z2	3.6.9.2	Backends/installed/micromegas/3.6.9.2/MajoranaSingletDM_Z2/libmicromegas.so	OK	20	0	0
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MicrOmegas_VectorSingletDM_Z2	3.6.9.2	Backends/installed/micromegas/3.6.9.2/VectorSingletDM_Z2/libmicromegas.so	OK	20	0	0
Pythia	8.212	Backends/installed/pythia/8.212/lib/libpythia8.so	OK	0	28	109
Pythia_EM	8.212	no path in config/backend_locations.yaml.default	absent/broken	0	28	109
SPheno	3.3.8	Backends/installed/spheno/3.3.8/lib/libSPheno.so	OK	282	0	0
SUSYHD	1.0.2	Backends/installed/susyhd/1.0.2/SUSYHD.m	Mathematica absent	3	0	0
SUSYPOPE	0.2	no path in config/backend_locations.yaml.default	absent/broken	3	0	0
SUSY_HIT	1.5	Backends/installed/susyhit/1.5/libsusyhit.so	OK	55	0	0
SuperIso	3.6	Backends/installed/superiso/3.6/libsuperiso.so	OK	55	0	0
gamLike	1.0.0	Backends/installed/gamlike/1.0.0/lib/gamLike.so	OK	4	0	0
gm2calc	1.2.0	Backends/installed/gm2calc/1.2.0/src/libgm2calc.so	absent/broken	5	11	14
	1.3.0	Backends/installed/gm2calc/1.3.0/src/libgm2calc.so	OK	5	11	14
libMathematicaTest	1.0	Backends/examples/libMathematicaTest.m	Mathematica absent	14	0	0
nulike	1.0.4	Backends/installed/nulike/1.0.4/lib/libnulike.so	absent/broken	4	0	0

Gambit diagnostic backend line 23 (press h for help or q to quit)

Results

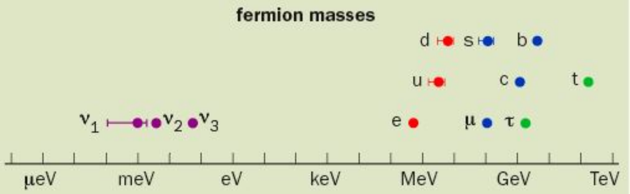
Right-handed Neutrinos

[M.Chrzaszcz, M.Drewes, T.G., J.Harz, S.Krishnamurthy, C.Weniger, upcoming]

Right-handed neutrinos

- **Right-handed neutrinos** $N_{1,2,3}$
- N_j are **SM singlets** $\quad N_j \in \{\mathbf{1}, \mathbf{1}, 0\}$
- Yukawa couplings $\to$ **Dirac** mass terms

$$\mathcal{L} \supset Y_\nu^{ij} L_i N_j \phi = M_D^{ij} \nu_i N_j$$



- $Y_\nu / Y_t \lesssim 10^{12-15}$

Type I Seesaw

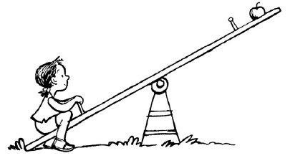
- **Majorana** mass term for N_j

$$\mathcal{L} \supset Y_\nu^{ij} L_i N_j \phi + M^{ij} N_i N_j$$
$$= M_D^{ij} \nu_i N_j + M_M^{ij} N_i N_j$$

$$M_\nu = \begin{pmatrix} \delta m_\nu^{1-loop} & M_D \\ M_D^T & M_M \end{pmatrix}$$

- "Naturally" **light neutrino masses**

$$m_\nu \sim M_D^T M_M^{-1} M_D, \quad m_N \sim M_M$$



- Neutrino **mixing** matrix

$$\mathcal{U}_\nu = \begin{pmatrix} V_\nu & \Theta \\ \Theta^T & V_N \end{pmatrix} \approx \begin{pmatrix} 1 - \frac{1}{2}\theta\theta^\dagger & \theta \\ -\theta^\dagger & 1 - \frac{1}{2}\theta^\dagger\theta \end{pmatrix} \begin{pmatrix} U_\nu & 0 \\ 0 & U_N \end{pmatrix}$$

The Casas-Ibarra parametrization

- Θ parametrizes the active - sterile neutrino **mixing**
- CI parametrization [J. A. Casas & A. Ibarra, Nuc. Phys. B618, (1-2), 2001]

$$\Theta = iU_\nu \sqrt{m_\nu^{diag}} \mathcal{R} \sqrt{\tilde{M}^{diag}}^{-1}$$

$$\tilde{M}_{IJ} \simeq \tilde{M}_{IJ}^{\text{diag}} = M_I \delta_{IJ} \left(1 - \frac{M_I^2}{v^2} l(M_I)\right)$$

- Rotation matrix $\mathcal{R} = \mathcal{R}^{23}\mathcal{R}^{13}\mathcal{R}^{12}$

$$\mathcal{R}_{ii}^{ij} = \mathcal{R}_{jj}^{ij} = \cos\omega_{ij}$$
$$\mathcal{R}_{ij}^{ij} = -\mathcal{R}_{ji}^{ij} = \sin\omega_{ij}$$

- Permutations of $\mathcal{R}^{ij}$ to remove bias

Symmetry protected limit

- Approximate $B - L$ symmetry $\qquad F_{\alpha I} = \Theta_{\alpha I} M_I / v$

$$M_M = \begin{pmatrix} M(1-\mu) & 0 & 0 \\ 0 & M(1+\mu) & 0 \\ 0 & 0 & M' \end{pmatrix},$$

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix},$$

- Two-degenerate RHNs $\rightarrow$ pseudo-Dirac fermion $\qquad \mu, \epsilon_\alpha, \epsilon'_\alpha \ll 1$

$$M_1 \sim M_2, \quad \Theta_{\alpha 1} \sim i\Theta_{\alpha 2}$$

- Oscillation data does not constraint $|U_{\alpha_I}|^2 \equiv |\Theta_{\alpha I}|^2$
- Upper limit purely from other experimental constraints
- Necessary and sufficient $m_{\nu_0} \rightarrow 0$ [Moffat, Pascoli, Weiland, arXiv:1712.07611]

Model parameters

- Light (left-handed) neutrino masses

$$m_{\nu_i} \quad i \in \{1,2,3\} \quad \rightarrow \quad m_{\nu_0},\ \Delta m^2_{12},\ \Delta m^2_{3l}$$

- Heavy (right-handed) neutrino masses

$$M_I \quad I \in \{1,2,3\} \quad \rightarrow \quad M_1,\ \Delta M_{21},\ M_3$$

- Active neutrino mixing parameters

$$\{\theta_{12},\ \theta_{13},\ \theta_{23}, \quad \alpha_1,\ \alpha_2, \quad \delta_{CP}\}$$

- Active-sterile neutrino mixing angles

$$\Re(\omega_{ij}), \Im(\omega_{ij})$$

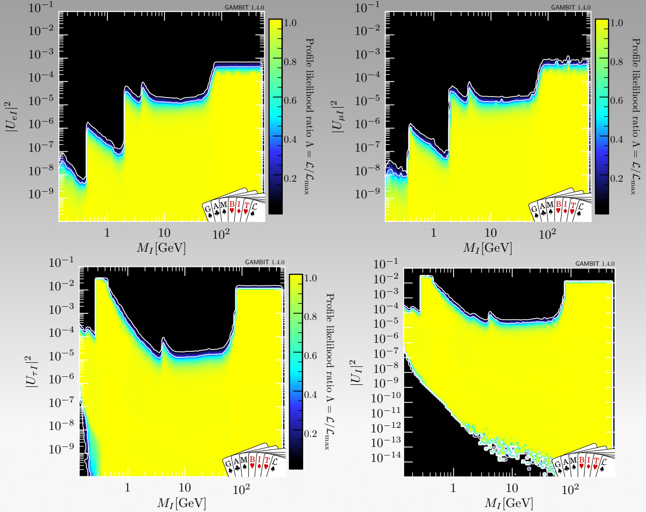
Likelihoods and observables

- Active neutrino parameters [NuFit, JHEP **1608** (2016) 033]
- Sum of neutrino masses $\sum m_\nu < 0.23$ eV
- Electroweak precision observables $\sin^2\theta_{\text{eff}}, m_W, \Gamma_{Z\to\text{inv}}, \Gamma_{W\to l\nu}$
- Direct searches

  PIENU, PS-191, E949, CHARM, NuTeV, DELPHI, ATLAS, CMS
- Lepton flavour violating decays $l \to l\gamma$, $l \to 3l$, $\mu - e$
- Big Bang Nucleosynthesis $\tau_N < 0.1s$
- Neutrinoless Double β decay GERDA, KamLAND-Zen
- Lepton Universality $R^X_{\alpha\beta}$, R_K, R^*_K
- CKM Unitarity $|V^{CKM}_{us}|^2 + |V^{CKM}_{ud}|^2 = 1$
- Perturbativity of Yukawas $F < 4\pi$

Results

- Profile likelihood plots M_I vs $|U_{\alpha I}|^2$



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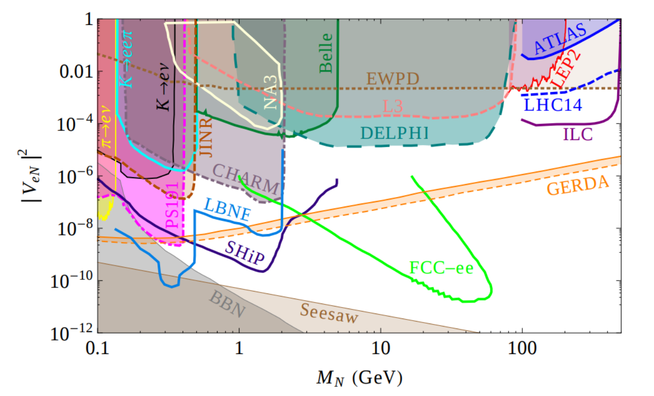
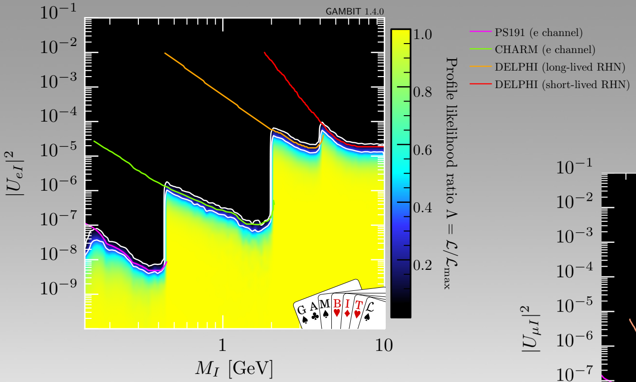
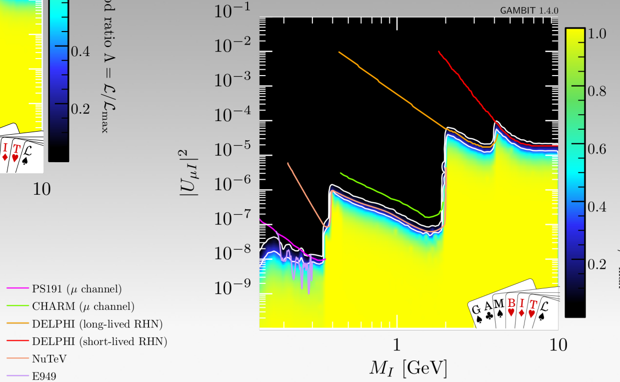


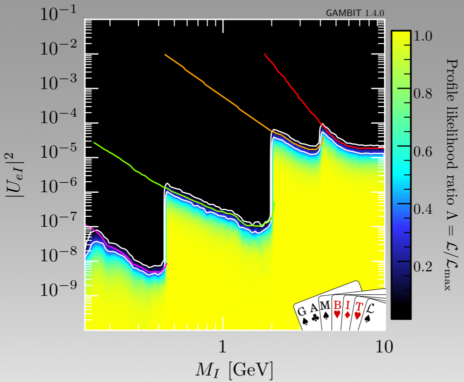
[Deppisch, Dev, Pilaftsis, New J.Phys. 17 (2015) no.7, 075019]

Results


GAMBIT 1.4.0
$|U_{eI}|^2$
M_I [GeV]
Profile likelihood ratio $\Lambda = \mathcal{L}/\mathcal{L}_{\max}$
PS191 (e channel)
CHARM (e channel)
DELPHI (long-lived RHN)
DELPHI (short-lived RHN)


GAMBIT 1.4.0
$|U_{\mu I}|^2$
M_I [GeV]
PS191 (μ channel)
CHARM (μ channel)
DELPHI (long-lived RHN)
DELPHI (short-lived RHN)
NuTeV
E949

Results


GAMBIT 1.4.0
$|U_{eI}|^2$
10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9}
1 10
M_I [GeV]
1.0 0.8 0.6 0.4 0.2
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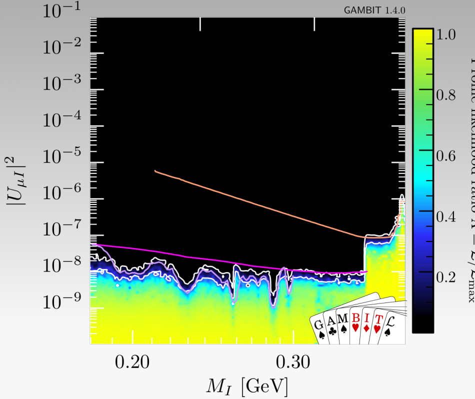
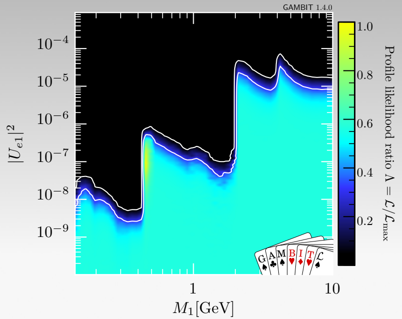
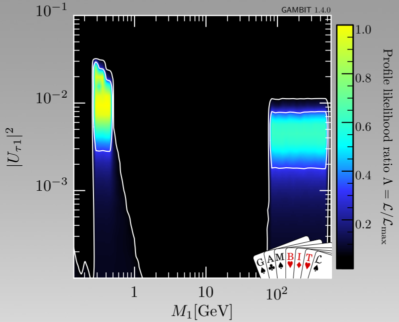

GAMBIT 1.4.0
$|U_{\mu I}|^2$
10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9}
0.20 0.30
M_I [GeV]
1.0 0.8 0.6 0.4 0.2
PS191 (μ channel)
CHARM (μ channel)
NuTeV
E949

Results

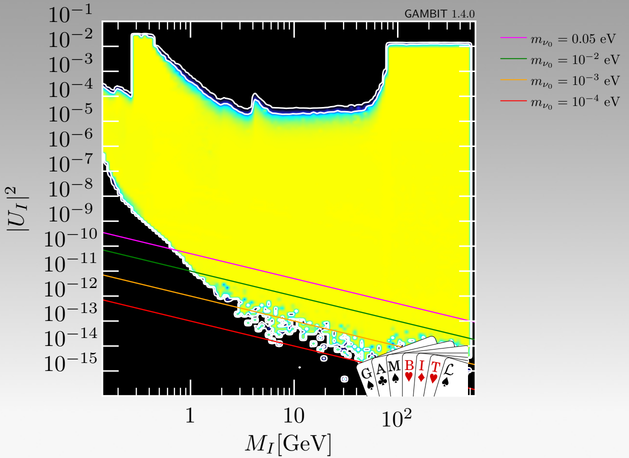
- Full likelihood
- Excess in lnL at large $|U_\tau|^2$
  - $\rightarrow$ Invisible width Γ_Z
  - $\rightarrow$ Fit to CKM entries
  - $\rightarrow$ Lepton universality R_τ





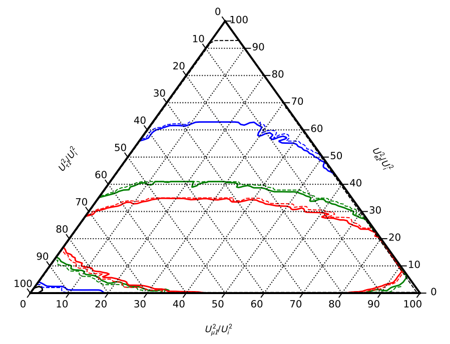
- Excess in lnL at large $|U_e|^2$
  - $\rightarrow$ Lepton universality R_K
- Low significance $\lesssim 1\sigma$

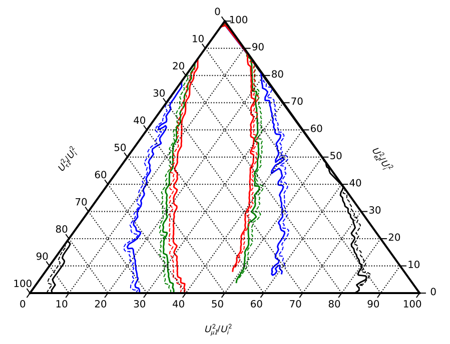
- Seesaw and BBN limits



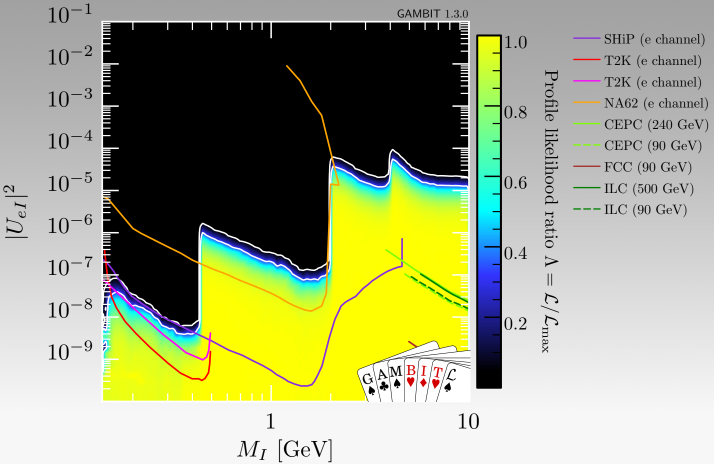
Results

- Massless neutrino limit $m_{\nu_0} \to 0 \rightsquigarrow$ approximate $B - L$





- Future constraints



Results

Higgs portal DM

[GAMBIT, Eur.Phys.J. C77 (2017) no.8, 568]

[GAMBIT, Eur.Phys.J. C79 (2019) no.1, 38]

Models of Higgs-portal DM

- **Scalar** singlet S with $\mathbb{Z}_2$

$$\mathcal{L}_S = \frac{1}{2}\mu_S^2|S|^2 + \frac{1}{4}\lambda_S|S|^4 + \frac{1}{2}\lambda_{hS}|S|^2|H|^2$$

- **Vector** singlet V with $\mathbb{Z}_2$

$$\mathcal{L}_S = \frac{1}{2}\mu_V^2 V_\mu V^\mu + \frac{1}{4!}\lambda_V(V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{hV}V_\mu V^\mu|H|^2$$

- **Fermion** singlet with $\mathbb{Z}_2$. Dirac ψ or Majorana χ

$$\mathcal{L}_\psi = -\mu_\psi\bar{\psi}\psi - \frac{\lambda_{h\psi}}{\Lambda_\psi}\left(\cos\theta\bar{\psi}\psi + \sin\theta\bar{\psi}i\gamma_5\psi\right)|H|^2$$

$$\mathcal{L}_\chi = -\frac{1}{2}\mu_\chi\bar{\chi}\chi - \frac{1}{2}\frac{\lambda_{h\chi}}{\Lambda_\chi}\left(\cos\theta\bar{\chi}\chi + \sin\theta\bar{\chi}i\gamma_5\chi\right)|H|^2$$

Model parameters

- **Scalar** singlet S with $\mathbb{Z}_2$ $\{m_S, \lambda_{hS}\}$
- **Vector** singlet V with $\mathbb{Z}_2$ $\{m_V, \lambda_{hV}\}$, $m_V^2 = \mu_V^2 + \frac{1}{2}\lambda_{hV} v_0^2$
- **Fermion** singlet with $\mathbb{Z}_2$. Dirac ψ or Majorana χ $\{m_{\psi/\chi}, \lambda_{h\psi/\chi}/\Lambda_{\psi/\chi}, \xi\}$

$$m_{\psi/\chi}^2 = \left(\mu_{\psi/\chi}^2 + \frac{1}{2}\frac{\lambda_{h\psi/\chi}}{\Lambda_{\psi/\chi}} v_0^2 \cos\theta\right)^2 + \left(\frac{1}{2}\frac{\lambda_{h\psi/\chi}}{\Lambda_{\psi/\chi}} v_0^2 \sin\theta\right)^2,$$

$$\cos\xi = \frac{\mu_{\psi/\chi}}{m_{\psi/\chi}}\left(\cos\theta + \frac{1}{2}\frac{\lambda_{h\psi/\chi}}{\Lambda_{\psi/\chi}}\frac{v_0^2}{\mu_{\psi/\chi}}\right)$$

- Nuisance parameters

$$\{\rho_0, v_{\rm peak}, v_{\rm esc}\}, \quad \{\sigma_s, \sigma_l\}, \quad \{m_h, \alpha_s^{\overline{MS}}(m_Z)\}$$

Model parameters

- **Scalar** singlet S

$$\{m_S, \lambda_{hS}\}$$

Parameter	Minimum	Maximum	Prior
λ_{hs}	10^{-4}	10	log
m_s (full-range scan)	45 GeV	10 TeV	log
m_s (low-mass scan)	45 GeV	70 GeV	flat

- **Vector** singlet V

$$\{m_V, \lambda_{hV}\}$$

Parameter	Minimum	Maximum	Prior type
λ_{hV}	10^{-4}	10	log
m_V (low mass)	45 GeV	70 GeV	flat
m_V (high mass)	45 GeV	10 TeV	log

- **Fermion** singlet χ/ψ

$$\{m_{\psi/\chi}, \lambda_{h\psi/\chi}/\Lambda_{\psi/\chi}, \xi\}$$

Parameter	Minimum	Maximum	Prior type
$\lambda_{h\chi,h\psi}/\Lambda_{\chi,\psi}$	10^{-6} GeV^{-1}	1 GeV^{-1}	log
ξ	0	π	flat
$m_{\chi,\psi}$ (low mass)	45 GeV	70 GeV	flat
$m_{\chi,\psi}$ (high mass)	45 GeV	10 TeV	log

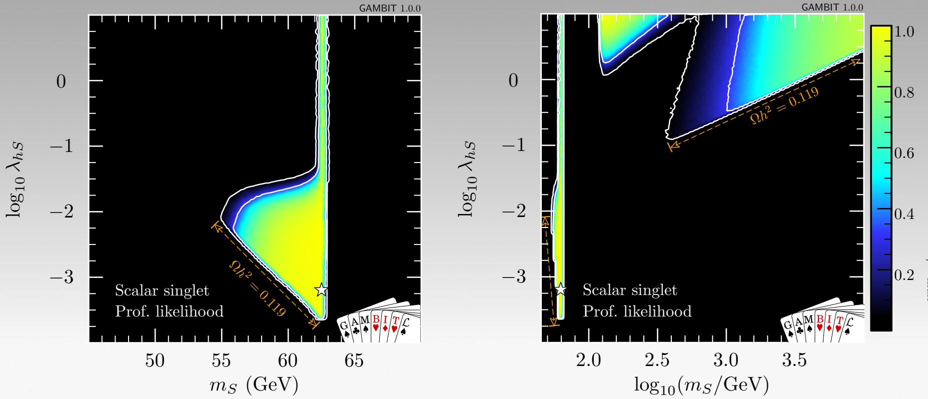
Constraints and likelihoods

- Thermal relic density of DM $\Omega_{\rm DM} h^2 < 0.1188$ [Planck, 2015]
  `DarkSUSY`
- Higgs invisible width $\mathrm{BR}(H \to \mathrm{inv.}) < 0.19$
- Direct detection constraints
  - → S: LUX 2016, PandaX 2016, SuperCDMS, Xenon100
  - → V/F: PandaX 2017, CDMSlite, CRESST-II, PICO-60, DarkSide-50, Xenon1T

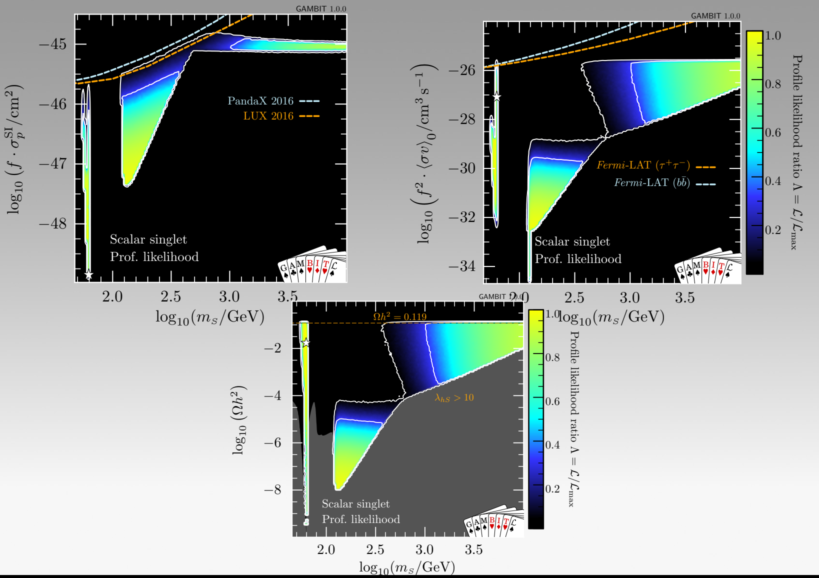
  `DDCalc`
- Capture and annihilation of DM in the Sun IceCube
  `Capt'n General`, `nulike`
- Indirect detection through gamma rays Fermi-LAT
  gamLike
- Nuisance likelihoods $\{\rho_0, v_{\rm peak}, v_{\rm esc}\}, \{\sigma_s, \sigma_l\}, \{m_h, \alpha_s^{\overline{MS}}(m_Z)\}$

Results

- Scalar DM



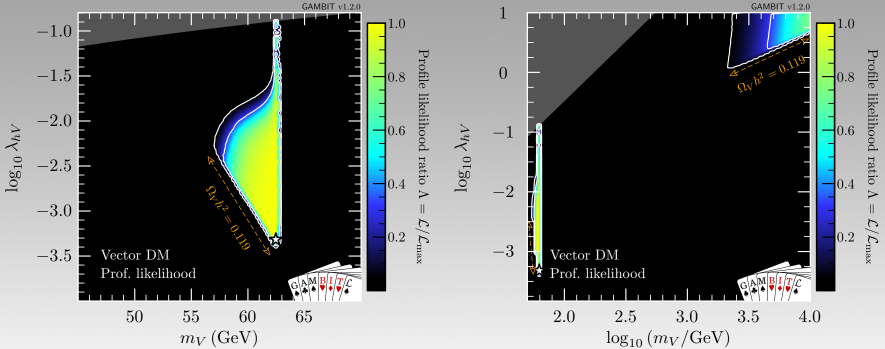
Results



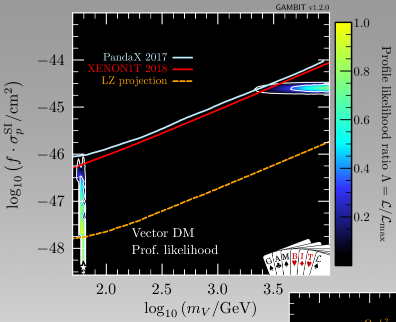
GAMBIT 1.0.0
PandaX 2016
LUX 2016
Scalar singlet
Prof. likelihood
$\log_{10}\left(f \cdot \sigma_p^{\rm SI}/{\rm cm}^2\right)$
$\log_{10}(m_S/{\rm GeV})$
-45
-46
-47
-48
2.0
2.5
3.0
3.5
GAMBIT 1.0.0
Fermi-LAT ($\tau^+\tau^-$)
Fermi-LAT ($b\bar{b}$)
Scalar singlet
Prof. likelihood
$\log_{10}\left(f^2 \cdot \langle\sigma v\rangle_0/{\rm cm}^3\,{\rm s}^{-1}\right)$
$\log_{10}(m_S/{\rm GeV})$
-26
-28
-30
-32
-34
Profile likelihood ratio $\Lambda = \mathcal{L}/\mathcal{L}_{\rm max}$
1.0
0.8
0.6
0.4
0.2
GAMBIT 1.0.0
$\Omega h^2 = 0.119$
$\lambda_{hS} > 10$
Scalar singlet
Prof. likelihood
$\log_{10}(\Omega h^2)$
$\log_{10}(m_S/{\rm GeV})$
-2
-4
-6
-8
Profile likelihood ratio $\Lambda = \mathcal{L}/\mathcal{L}_{\rm max}$

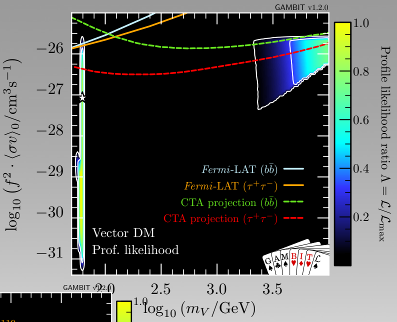
Results

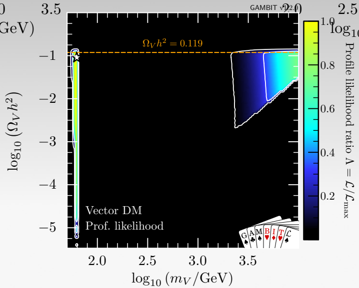
- Vector DM



Results

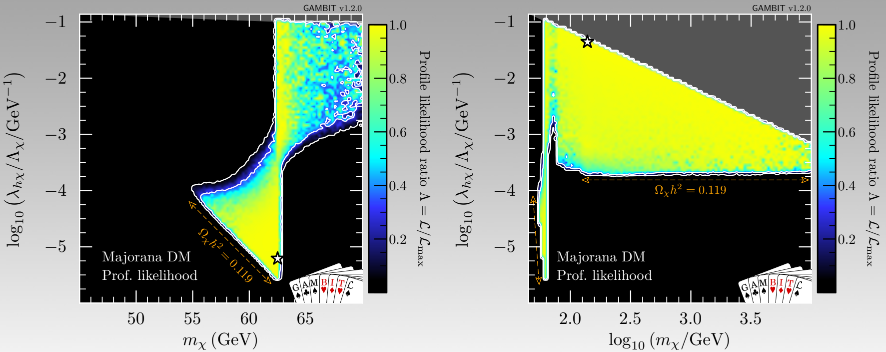

GAMBIT v1.2.0
PandaX 2017
XENON1T 2018
LZ projection
Vector DM
Prof. likelihood
$\log_{10}\left(f \cdot \sigma_p^{SI}/\mathrm{cm}^2\right)$
$\log_{10}\left(m_V/\mathrm{GeV}\right)$
Profile likelihood ratio $\Lambda = \mathcal{L}/\mathcal{L}_{max}$


GAMBIT v1.2.0
Fermi-LAT ($b\bar{b}$)
Fermi-LAT ($\tau^+\tau^-$)
CTA projection ($b\bar{b}$)
CTA projection ($\tau^+\tau^-$)
Vector DM
Prof. likelihood
$\log_{10}\left(f^2 \cdot \langle\sigma v\rangle_0/\mathrm{cm}^3\mathrm{s}^{-1}\right)$
$\log_{10}\left(m_V/\mathrm{GeV}\right)$
Profile likelihood ratio $\Lambda = \mathcal{L}/\mathcal{L}_{max}$


GAMBIT v1.2.0
$\Omega_V h^2 = 0.119$
Vector DM
Prof. likelihood
$\log_{10}\left(\Omega_V h^2\right)$
$\log_{10}\left(m_V/\mathrm{GeV}\right)$
Profile likelihood ratio $\Lambda = \mathcal{L}/\mathcal{L}_{max}$

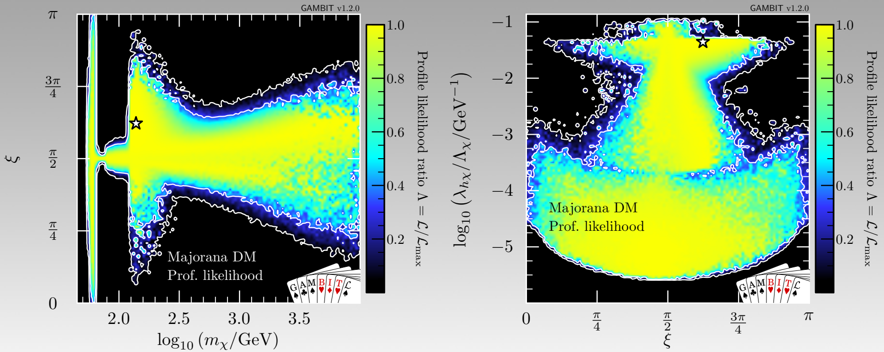
Results

- Fermion DM (both Majorana and Dirac)

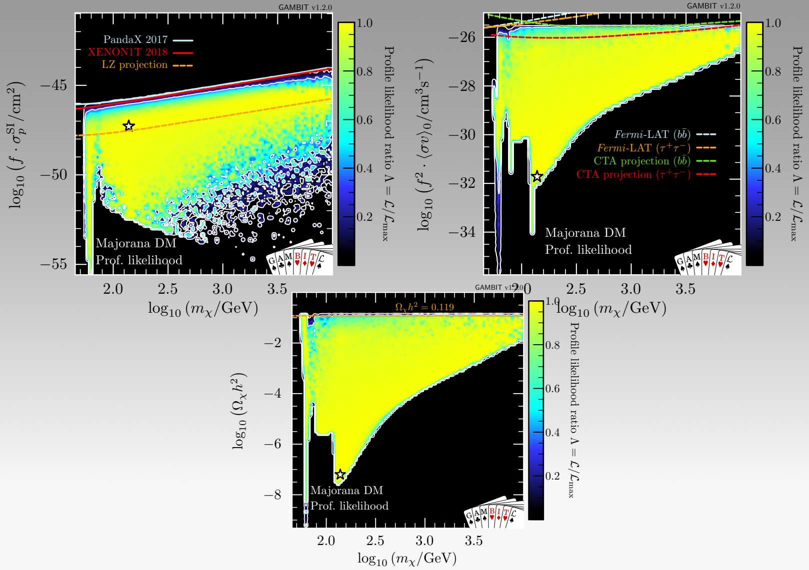


Results

- Fermion DM (both Majorana and Dirac)



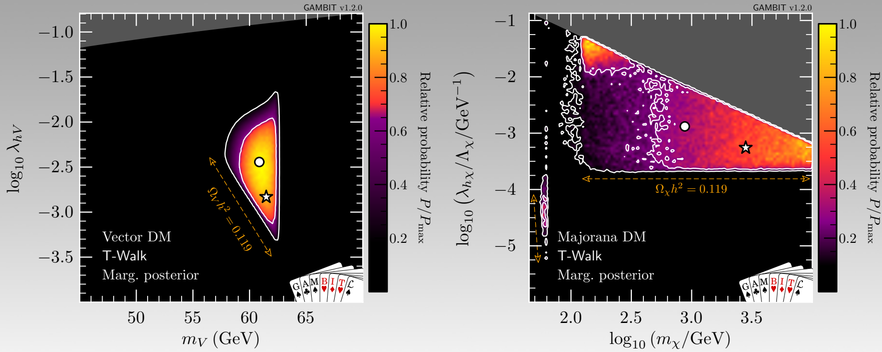
Results



GAMBIT v1.2.0
PandaX 2017
XENON1T 2018
LZ projection
Majorana DM
Prof. likelihood
$\log_{10}\left(f \cdot \sigma_p^{SI}/\mathrm{cm}^2\right)$
$\log_{10}(m_\chi/\mathrm{GeV})$
Profile likelihood ratio $\Lambda = \mathcal{L}/\mathcal{L}_{max}$
Fermi-LAT ($b\bar{b}$)
Fermi-LAT ($\tau^+\tau^-$)
CTA projection ($b\bar{b}$)
CTA projection ($\tau^+\tau^-$)
$\log_{10}\left(f^2 \cdot \langle\sigma v\rangle_0/\mathrm{cm}^3\mathrm{s}^{-1}\right)$
$\Omega_\chi h^2 = 0.119$
$\log_{10}(\Omega_\chi h^2)$

Results

- Posterior Probability



Bayesian Model Comparison

- Bayes factor

$$B = \frac{\mathcal{Z}(M1)}{\mathcal{Z}(M2)}, \qquad \mathcal{Z}(M) = \int \mathcal{L}(D|\theta)P(\theta)d\theta$$

- CP-odd vs CP-even fermion DM

Model	Comparison model and priors			Odds
$\xi = 0$	m_χ: log	$\lambda_{h\chi}/\Lambda_\chi$: log	ξ: flat	70:1
$g_{\rm p}/\Lambda_{\rm p} = 0$	m_χ: log	$g_{\rm s}/\Lambda_{\rm s}$: log	$g_{\rm p}/\Lambda_{\rm p}$: log	140:1

- Scalar vs Vector vs Fermion DM

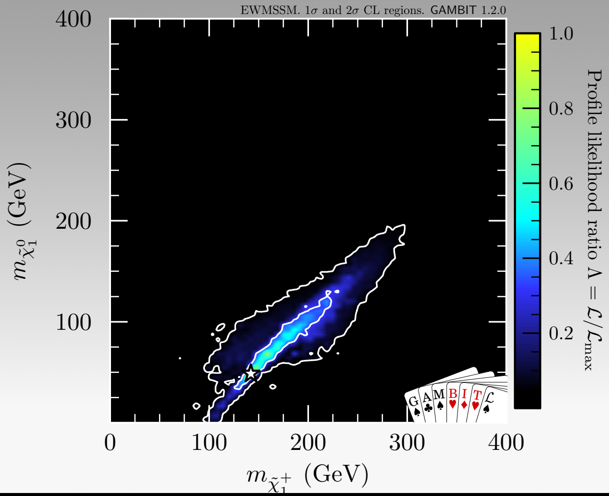
Model	Parameters and priors			Odds
S	m_S: log	λ_{hS}: log		1:1
V_μ	m_V: log	λ_{hV}: log		6:1
χ	m_χ: log	$\lambda_{h\chi}/\Lambda_\chi$: log	ξ: flat	1:1
ψ	m_ψ: log	$\lambda_{h\psi}/\Lambda_\psi$: log	ξ: flat	1:1

Summary

Summary and outlook

- **Global fits** are great!
  - → Models with many parameters → smart sampling
  - → Multitude of constraints → composite likelihoods
  - → Statistical interpretation → frequentist / Bayesian
- **GAMBIT** is well suited for this
  - → Plug-in external tools and scanning algorithms
- **Right-handed neutrinos**
  - → RHNs can explain m_ν with reasonable Yukawas
  - → Preference for an approximate B-L symmetry
  - → Strongly constrained by direct searches & BBN
- **Higgs portal Dark matter**
  - → WIMP DM is alive where DD is suppressed
  - → Slight preference for scalar/fermion over vector
  - → Strong CP-odd vs CP-even

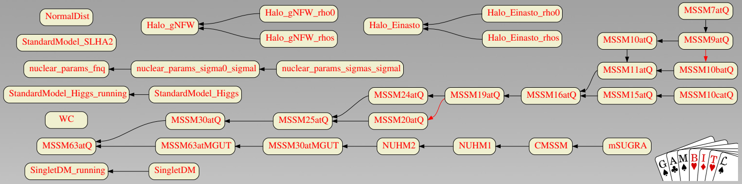
- Supersymmetric DM



Backup

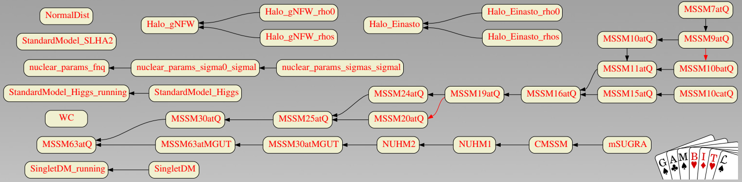
The Core

- Model hierarchy : **SUSY & Singlet DM**

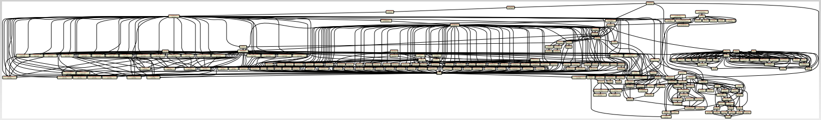


The Core

- Model hierarchy : **SUSY & Singlet DM**



- Dependency resolution : **CMSSM**



→ The core automatically determines the evaluation order

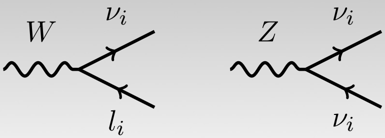
→ Each function is only run once per parameter point

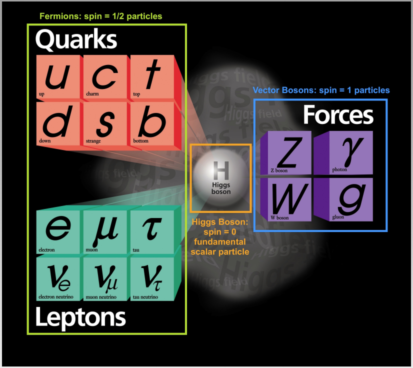
Neutrinos in the Standard Model

- The SM has 3 **active** neutrinos
- $SU(2)_L$ doublets

$$L_i \to \begin{pmatrix} \nu_i \\ l_i \end{pmatrix}$$

- Interact weakly with W or Z





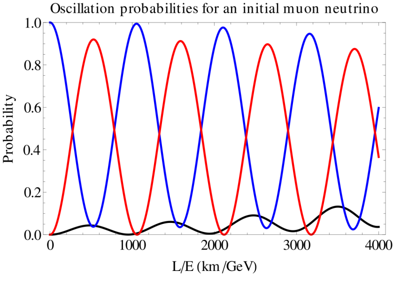
- They are **massless**: $m_{\nu_i} = 0$

- **Neutrinos have masses!**
- Super-Kamiokande observed the oscillation of atmospheric νs

  [Super-K, Phys.Rev.Lett. 81 (1998) 1562-1567]

- Neutrinos from cosmic rays

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

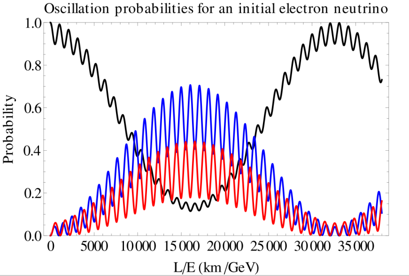


- Disappearance of ν_μ ($\to \nu_\tau$)
- Probability of oscillation $\nu_\alpha \to \nu_\beta$

$$P_{\alpha\to\beta} \approx \sin^2(2\theta)\sin^2\frac{\Delta m^2 L}{2E}$$

- Observation of oscillations $\rightsquigarrow$ evidence for massive neutrinos

Neutrino masses



- Three-neutrino **mixing**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- **Oscillations** of all flavour eigenstates $\nu_\alpha \to \nu_\beta$
- Mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 0 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\frac{\Delta m^2_{ij}L}{2E} + 2\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\frac{\Delta m^2_{ij}L}{2E}$$

Neutrino experiments

- **Solar** neutrino oscillation: ν_e disappearance ($\nu_e \to \nu_\mu$)

$$\theta_{12},\ \Delta m^2_{12}$$

[Chlorine, GALLEX/GNO, SAGE, Super-Kamiokande, SNO, Borexino]

- **Atmospheric** neutrino oscillation: ν_μ disappearance

$$\theta_{23},\ \Delta m^2_{23}$$

[IceCube, Super-Kamiokande, DeepCore]

- **Reactor** neutrino oscillation

$$\theta_{12},\ \theta_{13},\ \Delta m^2_{12}$$

[ILL, Goesgen, Krasnoyarsk, Rovno, Bugey-3, Bugey-4, SRP, NEOS, DANSS, Double Chooz, RENO, Daya Bay, KamLAND]

- **Beam** neutrino oscillation

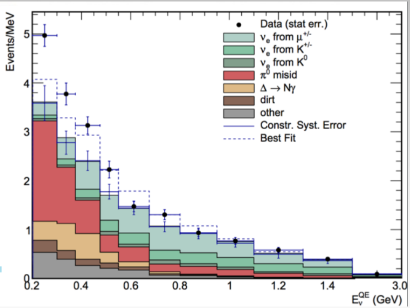
$$\theta_{13},\ \theta_{23},\ \Delta m^2_{23}$$

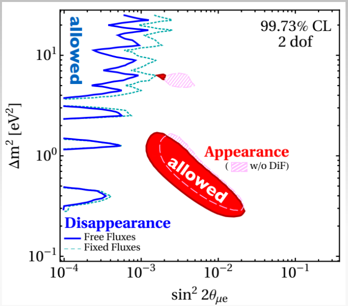
[LSND, MiniBooNE, KARMEN, NOMAD, E776, ICARUS, OPERA]

Anomalies

.

- **LSND**, 3.8σ in ν_e appearance
- **MiniBooNE**, 4.5σ in ν_e appearance and ν_μ disappearance
- 3σ in other reactor (Daya Bay) and radiactive source experiments (Gallium) in ν_e disappearance
- Sterile neutrino cannot fully explain all excesses



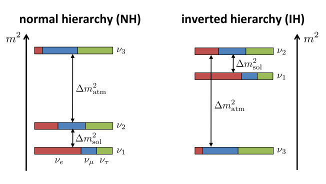


Neutrino masses

- **Fit** to neutrino oscillation data

  [NUFIT, JHEP 01 (2019) 106 [arXiv:1811.05487]]

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$



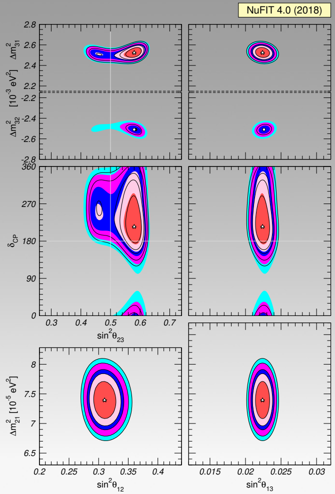
- **Neutrinos are massive** (at least two)
- **BSM** models must provide a mechanism for neutrino masses
- **RH neutrinos and type-I seesaw**

Likelihoods and observables

- Active neutrino parameters

  [E. Fernandez-Martinez, J. Hernandez-Garcia, J. Lopez-Pavon, JHEP **1608** (2016) 033]

	NH	IH
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.306^{+0.012}_{-0.012}$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.587^{+0.020}_{-0.024}$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.02179^{+0.00076}_{-0.00076}$
δ_{CP}	261^{+51}_{-59}	277^{+40}_{-46}
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.50^{+0.19}_{-0.17}$
$\frac{\Delta m^2_{3l}}{10^{-5}\ \mathrm{eV}^2}$	$2.524^{+0.039}_{-0.040}$	$-2.514^{+0.038}_{-0.041}$



- 2D gaussian likelihoods
- Planck limit $\sum m_\nu < 0.23$ eV

Likelihoods and observables

MONASH University

- Modified **Fermi constant**

$$G_\mu^2 = G_F^2(1-(\theta\theta^\dagger)_{\mu\mu}-(\theta\theta^\dagger)_{ee})$$

- EWPO parameters

$$\sin^2 2\theta_w = [\sin^2 2\theta_w]_{SM}\sqrt{1-(\theta\theta^\dagger)_{\mu\mu}-(\theta\theta^\dagger)_{ee}}$$

$$\frac{m_W^2}{[m_W^2]_{SM}} = \frac{[s_w^2]_{SM}}{s_w^2}\sqrt{1-(\theta\theta^\dagger)_{\mu\mu}-(\theta\theta^\dagger)_{ee}}\,,$$

Obs.	**Value**
m_W	$80.385(15)$
s^2_{eff}	0.23155 ± 0.00005
Γ_{inv}	0.499 ± 0.016
$\Gamma_{W\to e\bar\nu_e}$	0.223 ± 0.006
$\Gamma_{W\to \mu\bar\nu_\mu}$	0.222 ± 0.005
$\Gamma_{W\to \tau\bar\nu_\tau}$	0.237 ± 0.006

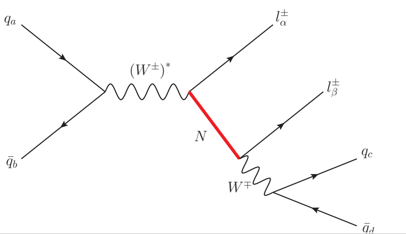
- EWPO decays

$$\Gamma_{\text{inv}} = \frac{G_\mu m_Z^3}{12\sqrt{2}\pi}\sum_{ij}\frac{(V_\nu V_\nu^\dagger)_{ij}}{\sqrt{1-(\theta\theta^\dagger)_{\mu\mu}-(\theta\theta^\dagger)_{ee})}}$$

$$\Gamma_{W\to l_\alpha\bar\nu} = \frac{G_\mu m_W^3}{6\sqrt{2}\pi}\frac{(1-\frac{1}{2}(\theta\theta^\dagger)_{\alpha\alpha})(1-x_\alpha)^2(1+x_\alpha)}{\sqrt{1-(\theta\theta^\dagger)_{\mu\mu}-(\theta\theta^\dagger)_{ee})}}$$

Likelihoods and observables

- Direct searches for RHN in **meson**, **tau** and **gauge boson** decays
- **Beam dump** and **peak search** experiments
- M_i vs $|\Theta_{\alpha i}|^2$ exclusion limits
- Poisson likelihoods

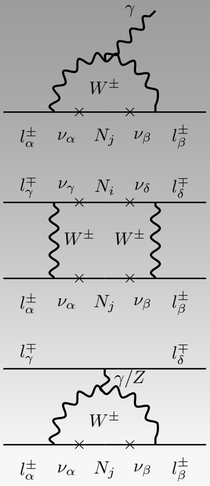


PIENU	0.06 - 0.129 GeV	Θ_{ei}	[M. Aoki et al, Phys. Rev. D, 84(5), 2011]
PS191	0.02 - 0.45 GeV	$\Theta_{ei}, \Theta_{\mu i}$	[G. Bernardi et al, Phys. Lett. B, 203(3), 1988]
E949	0.175 - 0.3 GeV	$\Theta_{\mu i}$	[A. V. Artamonov et al, Phys. Rev. D 91, 2015]
CHARM	0.01 - 2.8 GeV	$\Theta_{ei}, \Theta_{\mu i}, \Theta_{\tau i}$	[CHARM, Phys. Lett. B166(4), 1986]
NuTeV	0.25 - 2 GeV	$\Theta_{\mu i}$	[FNAL-E815, Phys. Rev. Lett. 83, 1999]
DELPHI (S)	3 - 50 GeV	$\Theta_{ei}, \Theta_{\mu i}, \Theta_{\tau i}$	[DELPHI, Z. Phys. C, 74(1), 1997]
DELPHI (L)	0.5 - 4.2 GeV	$\Theta_{ei}, \Theta_{\mu i}, \Theta_{\tau i}$	[DELPHI, Z. Phys. C, 74(1), 1997]
ATLAS	50 - 500 GeV	$\Theta_{ei}, \Theta_{\mu i}$	[ATLAS, JHEP 07:162, 2015]
CMS	1 - 10^3 GeV	$\Theta_{ei}, \Theta_{\mu i}$	[CMS, arXiv:1802.02965v1]

Likelihoods and observables

- Lepton flavour violating decays

Process	Branch. Frac.	Reference
$\mu^- \to e^-\gamma$	4.2×10^{-13}	[MEG]
$\tau^- \to e^-\gamma$	5.4×10^{-8}	[BaBar,Belle]
$\tau^- \to \mu^-\gamma$	5.0×10^{-8}	[BaBar, Belle]
$\mu^- \to e^-e^-e^+$	1.0×10^{-12}	[SINDRUM]
$\tau^- \to e^-e^-e^+$	1.4×10^{-8}	[BaBar, Belle]
$\tau^- \to \mu^-\mu^-\mu^+$	1.2×10^{-8}	[ATLAS, BaBar, Belle, LHCb]
$\tau^- \to \mu^-e^-e^+$	1.1×10^{-8}	[BaBar, Belle]
$\tau^- \to e^-e^-\mu^+$	0.84×10^{-8}	[BaBar, Belle]
$\tau^- \to e^-\mu^-\mu^+$	1.6×10^{-8}	[BaBar, Belle]
$\tau^- \to \mu^-\mu^-e^+$	0.98×10^{-8}	[BaBar, Belle]
$\mu - e$ (Ti)	1.7×10^{-12}	[SINDRUM II]
$\mu - e$ (Pb)	4.6×10^{-11}	[SINDRUM II]



- Upper bounds on $|\Theta_{\alpha I}|^2$
- One-sided gaussian likelihoods

Likelihoods and observables

- **Big Bang Nucleosynthesis** → lower bound on $|U_I|^2$

$$N_I \to \pi^0\nu_\alpha,\ N_I \to H^+ l_\alpha^-,\ N_I \to \eta\nu_\alpha,\ N_I \to \eta'\nu_\alpha,\ N_I \to \rho^+ l_\alpha^-,$$
$$N_I \to \rho^0\nu_\alpha,\ N_I \to \sum_{\alpha,\beta}\nu_\alpha\bar{\nu_\beta}\nu_\beta,\ N_I \to l^-_{\alpha\neq\beta} l^+_\beta \nu_\beta,\ N_I \to \nu_\alpha l^+_\beta l^-_\beta,$$
$$N_I \to \nu_\alpha u\bar{u},\ N_I \to \nu_\alpha d\bar{d},\ N_I \to l_\alpha u_n \bar{d_m}$$

→ Conservative limit on the lifetime $\tau_N \propto M_I^{-5} < 0.1s$

- **Neutrinoless Double β Decay**

$$[T^{0\nu}_{1/2}]^{-1} = \mathcal{A}\left| m_p \sum_I \frac{\Theta^2_{eI} M_I}{\langle p^2\rangle + M_I^2}\right|^2 ,$$

$T^{0\nu}_{1/2} \geq 2.1 \times 10^{25}$ yr, GERDA (Ge)
$T^{0\nu}_{1/2} \geq 1.07 \times 10^{26}$ yr, KamLAND-Zen (Xe)

→ Loses effectiviness in $B - L$ limit

Likelihoods and observables

- **Lepton Universality**

$$R^X_{\alpha\beta} = \frac{\Gamma(X^+ \to l^+_\alpha \nu_\alpha)}{\Gamma(X^+ \to l^+_\beta \nu_\beta)}\ , \quad X = \pi,\ K,\ \tau,\ W$$

$$R_Y = \frac{\Gamma(B^{0/\pm} \to Y^{0/\pm} l^+_\alpha l^-_\alpha)}{\Gamma(B^{0/\pm} \to Y^{0/\pm} l^+_\beta l^-_\beta)}\ , \quad Y = K,\ K^*$$

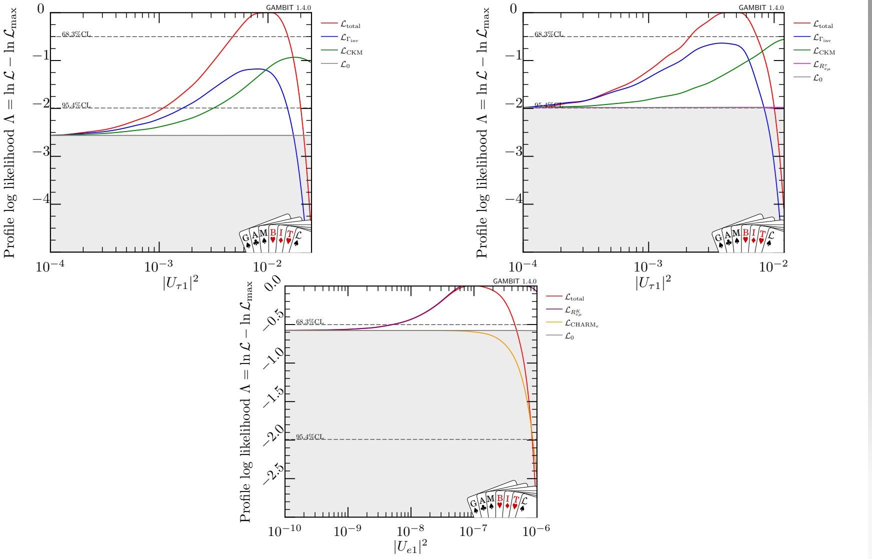
$\to$ R_D and R_{D^*} are not impacted

- **CKM Unitarity** $\quad |V^{CKM}_{us}|^2 + |V^{CKM}_{ud}|^2 = 1$

$$|(V^{exp}_{CKM})^i_{us,ud}|^2 = |(V_{CKM})_{us,ud}|^2 [1 + f^i(\Theta)]\ ,$$

$$\text{e.g. } K_L \to \pi^+ e^- \bar{\nu}_e : 1 + f^1(\Theta) = \frac{G_F^2}{G_\mu^2}[1 - (\theta\theta^\dagger)_{ee}]$$

Results


GAMBIT 1.4.0
Profile log likelihood $\Lambda = \ln\mathcal{L} - \ln\mathcal{L}_{\max}$
68.3%CL
95.4%CL
$|U_{\tau 1}|^2$
$\mathcal{L}_{\rm total}$
$\mathcal{L}_{\Gamma_{\rm inv}}$
$\mathcal{L}_{\rm CKM}$
$\mathcal{L}_0$
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Profile log likelihood $\Lambda = \ln\mathcal{L} - \ln\mathcal{L}_{\max}$
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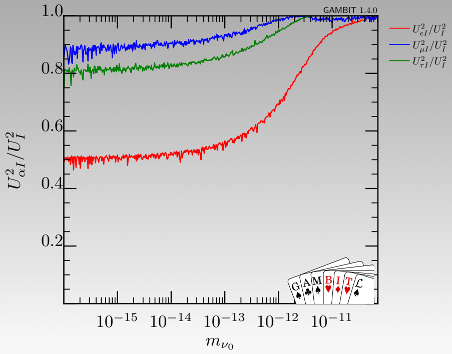
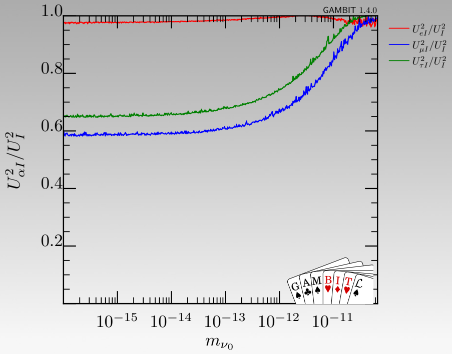
$\mathcal{L}_{\rm CKM}$
$\mathcal{L}_{R^{\tau}_{e\mu}}$
$\mathcal{L}_0$
GAMBIT 1.4.0
Profile log likelihood $\Lambda = \ln\mathcal{L} - \ln\mathcal{L}_{\max}$
68.3%CL
95.4%CL
$|U_{e1}|^2$
$\mathcal{L}_{\rm total}$
$\mathcal{L}_{R^{K}_{e\mu}}$
$\mathcal{L}_{{\rm CHARM}_e}$
$\mathcal{L}_0$

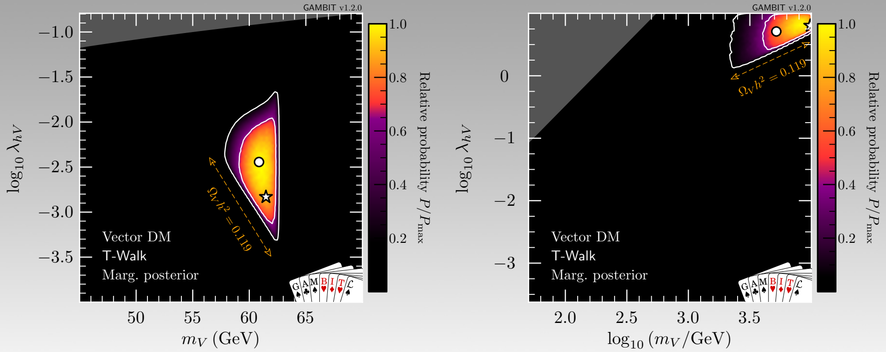
- Massless neutrino limit $m_{\nu_0} \to 0 \rightsquigarrow$ approximate $B - L$





Results

- Posterior Probability



Results

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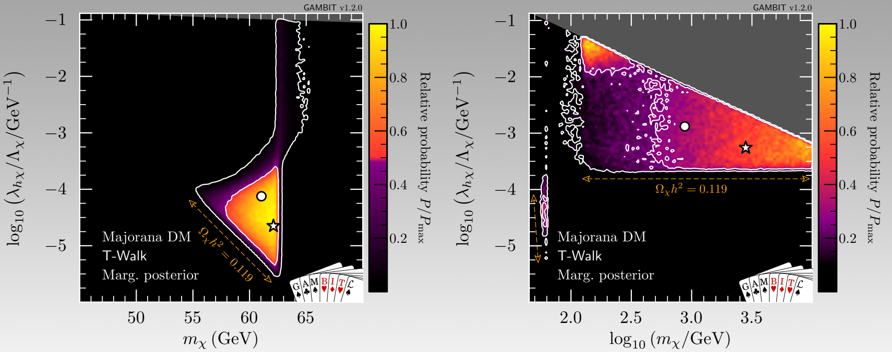
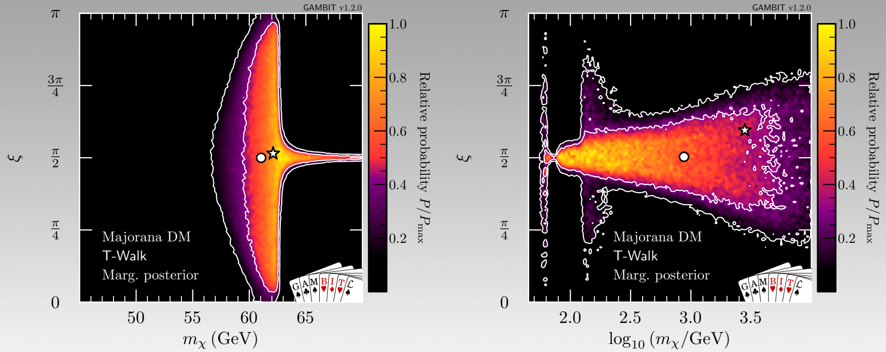
- Posterior Probability

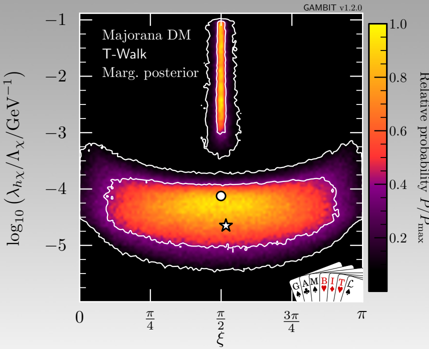


- Posterior Probability



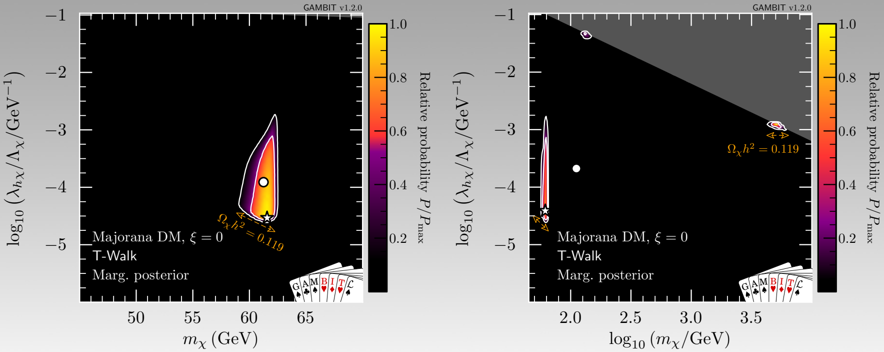
Results

- Posterior Probability



Results

- Posterior Probability



Results: EW MSSM

[arXiv:1809.02097 [hep-ph]]]

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MSSM field content

Name	Spin	Gauge ES	Mass ES
Higgs bosons	0	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h\ H\ A\ H^\pm$
squarks	0	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	-
		$\tilde{c}_L\ \tilde{c}_R\ \tilde{s}_L\ \tilde{s}_R$	-
		$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_R\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	-
		$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	-
		$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralino	1/2	$\tilde{B}\ \tilde{W}^3\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$
chargino	1/2	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{\chi}_1^\pm\ \tilde{\chi}_2^\pm$
gluino	1/2	$\tilde{g}$	-

MSSM field content

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Higgs bosons	0	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h\ H\ A\ H^\pm$
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		$\tilde{c}_L\ \tilde{c}_R\ \tilde{s}_L\ \tilde{s}_R$	-
		$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_R\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	-
		$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	-
		$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralino	1/2	$\tilde{B}\ \tilde{W}^3\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$
chargino	1/2	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{\chi}_1^\pm\ \tilde{\chi}_2^\pm$
gluino	1/2	$\tilde{g}$	-

EW MSSM

Parameters

- 4-D parameter space $(m^2_{H_d}, m^2_{H_u} \to \mu, m_A)$

$$m_h \to 125 \text{ GeV}$$
$$M_3, m_A \to 5 \text{ TeV} \qquad \{M_1, M_2, \mu, \tan\beta\}$$
$$m_{\tilde{l}}, m_{\tilde{q}} \to 3 \text{ TeV}$$
$$A_u, A_d, A_e \to 0$$

- Parameter ranges

Parameter	Range	Priors
$M_1(Q)$	[-2 TeV, 2 TeV]	hybrid, flat
$M_2(Q)$	[0, 2 TeV]	hybrid, flat
$\mu(Q)$	[-2 TeV, 2 TeV]	hybrid, flat
$\tan\beta(m_Z)$	[0, 70]	flat

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Likelihoods

- Invisible decays $\Gamma(Z \to \text{inv.}) = 499.0 \pm 1.5$ MeV $\quad \text{BF}(h \to \text{inv.}) \leq 0.19$

- LEP limits

Production	Signature	Experiment
$\tilde{\chi}_i^0 \tilde{\chi}_1^0$	$\tilde{\chi}_i^0 \to q\bar{q}\tilde{\chi}_1^0$	OPAL
$(i = 2, 3, 4)$	$\tilde{\chi}_i^0 \to \ell\bar{\ell}\tilde{\chi}_1^0$	L3
$\tilde{\chi}_i^+ \tilde{\chi}_i^-$	$\tilde{\chi}_i^+ \tilde{\chi}_i^- \to q\bar{q}' q\bar{q}' \tilde{\chi}_1^0 \tilde{\chi}_1^0$	OPAL
$(i = 1, 2)$	$\tilde{\chi}_i^+ \tilde{\chi}_i^- \to q\bar{q}' \ell\nu \tilde{\chi}_1^0 \tilde{\chi}_1^0$	OPAL
	$\tilde{\chi}_i^+ \tilde{\chi}_i^- \to \ell\nu\ell\nu \tilde{\chi}_1^0 \tilde{\chi}_1^0$	OPAL, L3
	ISR γ + missing energy	OPAL

- LHC searches

Likelihood label	Source
ATLAS_4b	ATLAS Higgsino search
ATLAS_4lep	ATLAS 4ℓ search
ATLAS_MultiLep_2lep_0jet	ATLAS multilepton EW search
ATLAS_MultiLep_2lep_jet	ATLAS multilepton EW search
ATLAS_MultiLep_3lep	ATLAS multilepton EW search
ATLAS_RJ_2lep_2jet	ATLAS recursive jigsaw EW search
ATLAS_RJ_3lep	ATLAS recursive jigsaw EW search
CMS_1lep_2b	CMS Wh search
CMS_2lep_soft	CMS 2 soft opposite-charge lepton search
CMS_2OSlep	CMS 2 opposite-charge lepton search
CMS_MultiLep_2SSlep	CMS multilepton EW search
CMS_MultiLep_3lep	CMS multilepton EW search

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Scan strategy

- First scans
  - → Differential evolution scanner (Diver) on jDE mode
  - → Flat & hybrid (log-flat-log) priors
  - → Targeted scans for $M_2 < 500$ GeV and $\mu < 500$ GeV
  - → Simulated 100k/500k Pythia events per parameter point
  - → Samples contain ~2.4M valid points

EW MSSM

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  - → Large MC uncertainty
  - → Signal region flip-flop

EW MSSM

Scan strategy

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  - → Simulated 100k/500k Pythia events per parameter point
  - → Samples contain ∼2.4M valid points
- Sampling issues
  - → Large MC uncertainty
  - → Signal region flip-flop
- Postprocessing
  - → More Pythia events
    - $2\sigma/3\sigma \geq$ 4M events
    - $1\sigma \geq$ 16M events
    - best 500 points $\geq$ 4M events
  - → ∼ 240k valid samples

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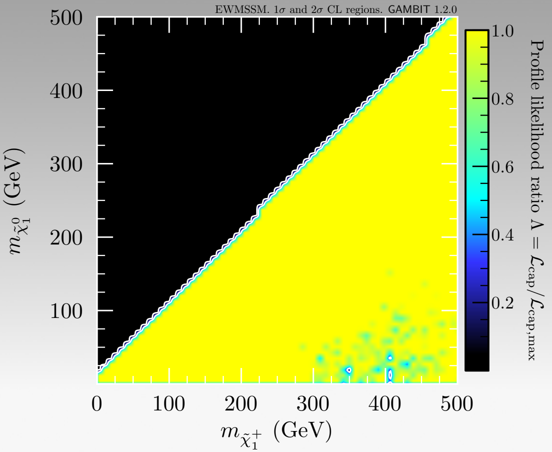
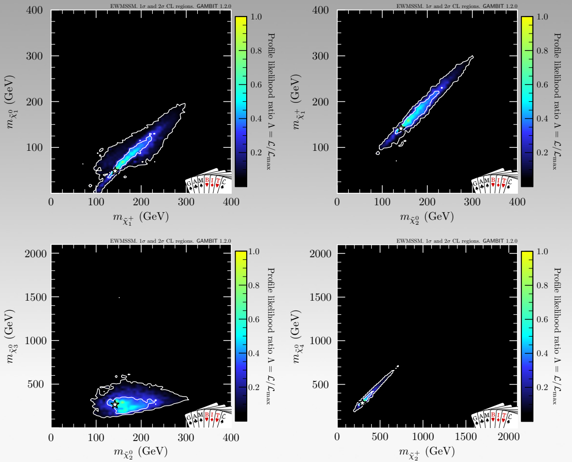
Results

- Capped likelihood

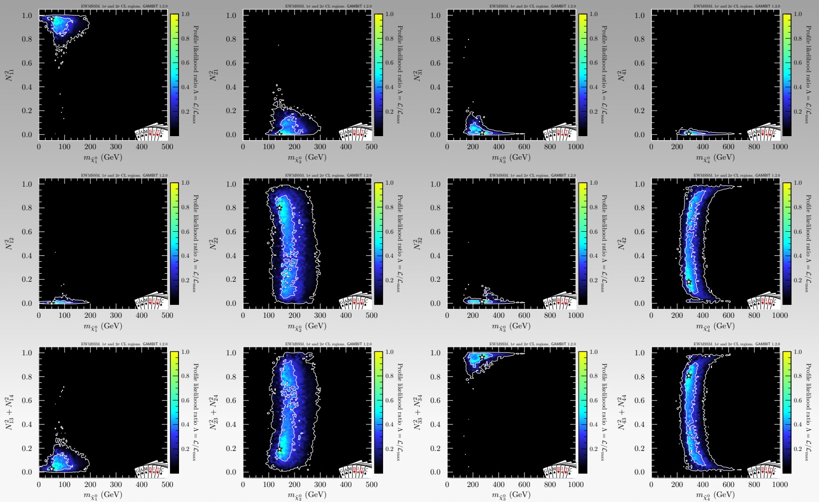


Results

- Profile likelihoods for $m_{\tilde{\chi}_i^{0,\pm}}$



Results


EWMSSM. 1σ and 2σ CL regions. GAMBIT 1.2.0
Profile likelihood ratio Λ = L/L_max
N^2_{11}
N^2_{21}
N^2_{31}
N^2_{41}
N^2_{12}
N^2_{22}
N^2_{32}
N^2_{42}
$N^2_{13} + N^2_{14}$
$N^2_{23} + N^2_{24}$
$N^2_{33} + N^2_{34}$
$N^2_{43} + N^2_{44}$
$m_{\tilde{\chi}^0_1}$ (GeV)
$m_{\tilde{\chi}^0_2}$ (GeV)
$m_{\tilde{\chi}^0_3}$ (GeV)
$m_{\tilde{\chi}^0_4}$ (GeV)

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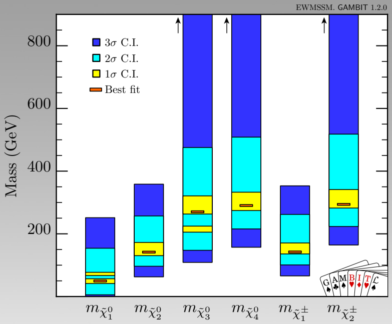
Conclusions

- No clear exclusion for light electroweakinos
  - → Careful with simplified models
- Favoured by several analyses
  - → ATLAS $4l$,
  - → ATLAS RJ $3l$,
  - → ATLAS multi-l ($2l$, $3l$)
- Minor excess
  - → $m_{\tilde{\chi}_1^0} \sim 50$ GeV
  - → Local significace 3.5σ
- Might be a hint of new physics
- Moriond?



EW MSSM

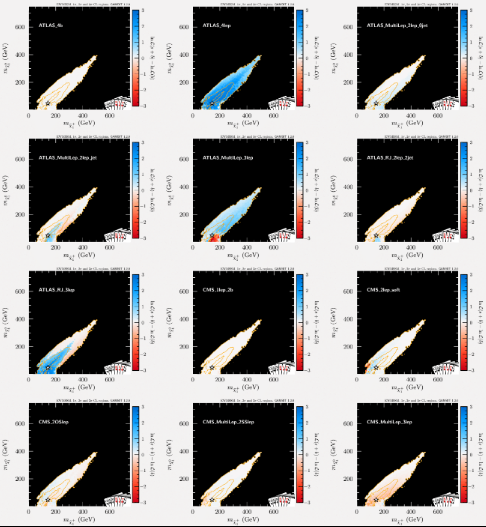
Analysis: results

- **Contribution from each analysis** to the 1σ, 2σ and 3σ best-fit regions

$$\ln \mathcal{L}(s+b) - \ln \mathcal{L}(b)$$

- **Blue**: **better** than background-only
  Red: **worse** than background-only

- Most important contributions to best-fit region:
  - ATLAS_4lep
  - ATLAS_RJ_3lep
  - ATLAS_MultiLep_2lep_jet
  - ATLAS_MultiLep_3lep
  - CMS_MultiLep_3lep



EW MSSM

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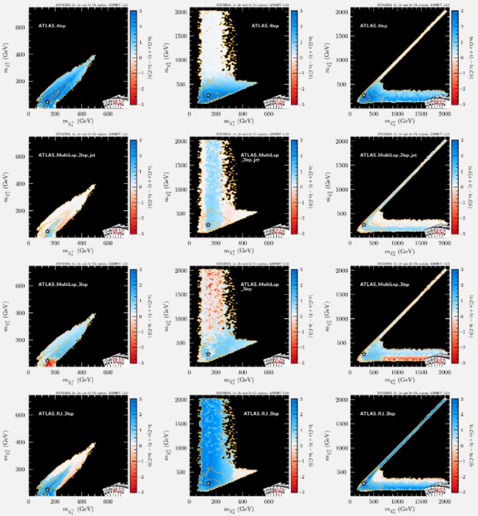
Analysis: results

- More detailed look on
  - ATLAS_4lep
  - ATLAS_RJ_3lep
  - ATLAS_MultiLep_2lep_jet
  - ATLAS_MultiLep_3lep
- Sudden changes in likelihood due to changes in most sensitive SR
- Light $\tilde{\chi}_3^0$ preferred by **ATLAS_4lep** and **ATLAS_MultiLep_3Lep**
- Heavy $\tilde{\chi}_4^0$ disfavoured by **ATLAS_MultiLep_2lep_jet** and **ATLAS_MultiLep_3Lep**
- The «expected» tension between **ATLAS_MultiLep_3Lep** and **ATLAS_RJ_3lep** observed for heavy $\tilde{\chi}_4^0$ (production of higgsino $\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_1^\pm$)



Results

Lots of processes relevant for the best-fit point:

- $\tilde{\chi}_2^0\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^- + W^+ + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_2^\mp$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \to Z + \tilde{\chi}_2^0 \to Z + Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0$,
  $\tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^- + W^+ + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0$, $\tilde{\chi}_4^0 \to Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_2^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to h + \tilde{\chi}_1^\pm \to h + W^\pm + \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_1^\pm\tilde{\chi}_3^0$ production, with e.g.
  $\tilde{\chi}_1^\pm \to W^\pm + \tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^+ + W^- + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ production, with e.g.
  $\tilde{\chi}_2^\pm \to Z + \tilde{\chi}_1^\pm \to Z + W^\pm + \tilde{\chi}_1^0$,
  $\tilde{\chi}_4^0 \to h + \tilde{\chi}_2^0 \to h + Z + \tilde{\chi}_1^0$

...