LPSC GRENOBLE | MODANE
CNRS IN2P3 Les deux infinis

Sabine Kraml

Experience with LLP likelihoods from SModelS

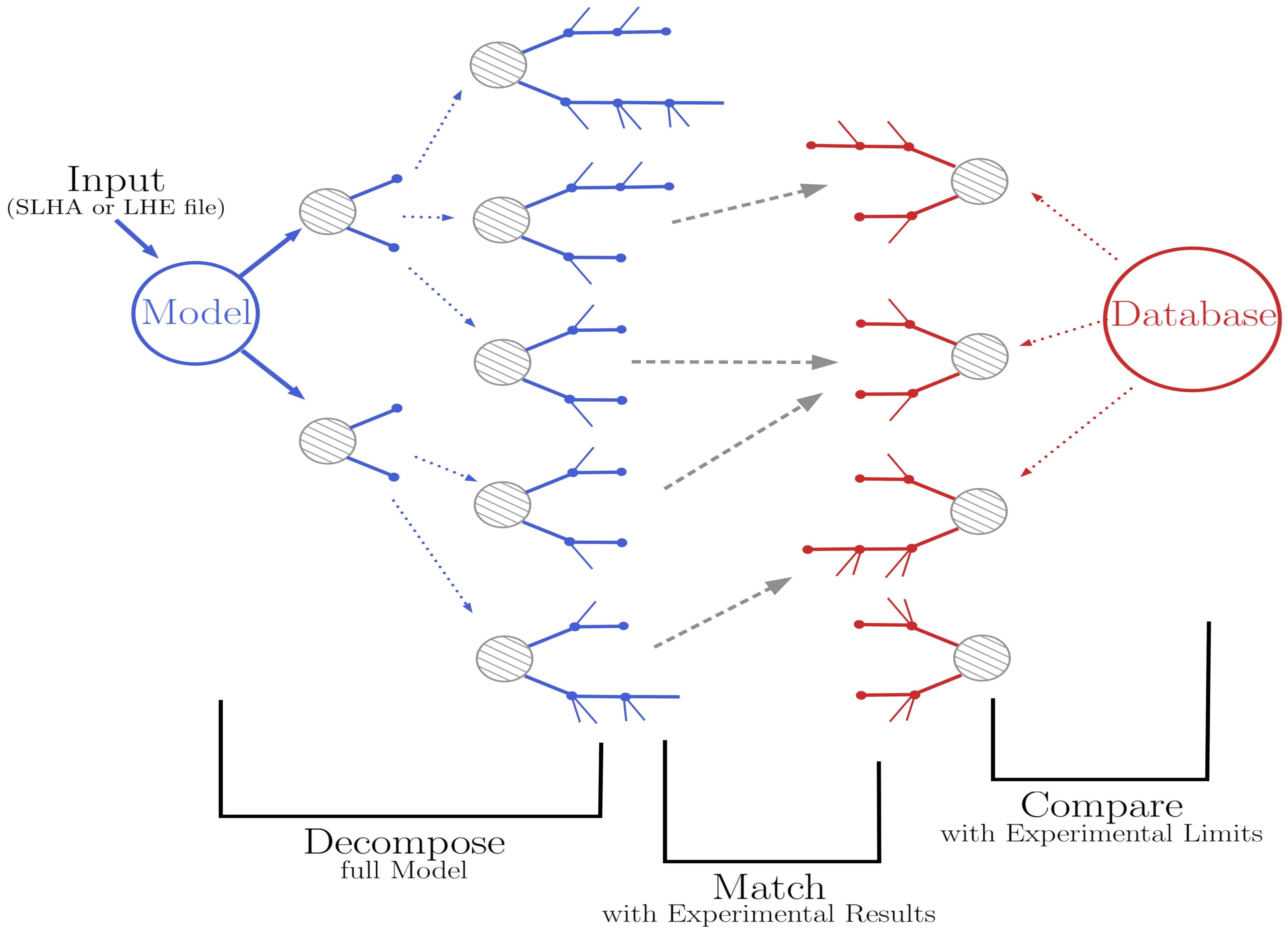
in collaboration with G. Alguero, J. Heisig, C.K. Khosa, A. Lessa, T. Pascal, H. Reyes-Gonzalez, and W. Waltenberger

Searching for long-lived particles at the LHC and beyond: Tenth workshop of the LLP Community
— 11 Nov 2021, Joint session with Reinterpretation Forum "Publication of Statistical Models" hands-on workshop —

SModelS — a public tool for interpreting simplified-model results from the LHC

- Based on a general procedure to decompose BSM collider signatures featuring a Z_2-like symmetry into simplified-model topologies.
- Large database of simplified-model results (currently 62 ATLAS & CMS searches from Run 2; lots of Run 1 results).
- Simultaneous treatment of prompt and LLP signatures
- Independent of exp. analysis approach: cut-based, MVA, BDT selections
- Very fast b/c no need for MC simulation.

☞ **talk by Jan Heisig at 9th LLP workshop**



https://smodels.github.io/

ATLAS and CMS Run 2 results in SModelS 2.1.0 database

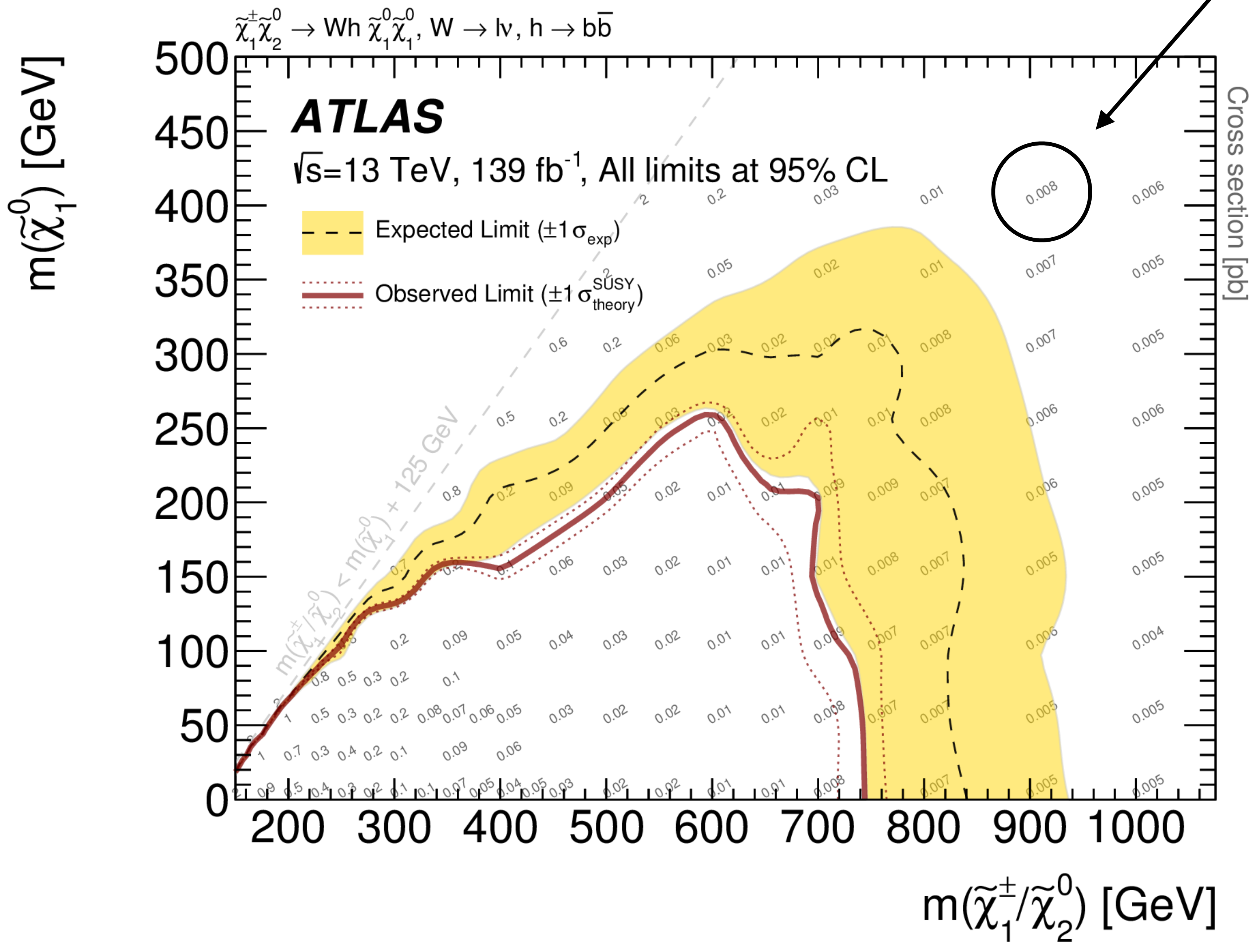
LLP searches

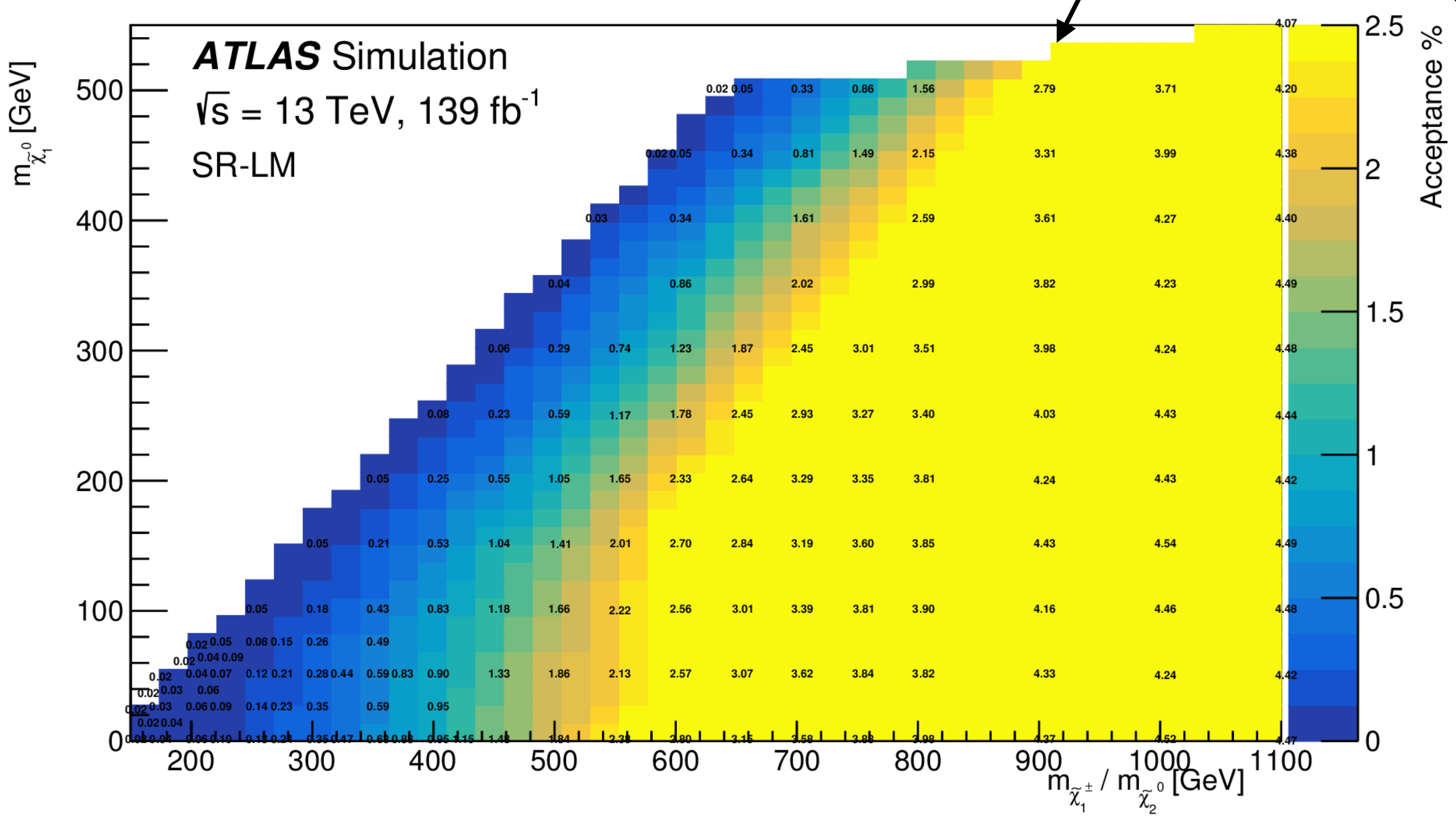
ID	Short Description	$\mathcal{L}$ [fb^{-1}]	UL_{obs}	UL_{exp}	EM	comb.
ATLAS-SUSY-2015-01 [62]	2 b-jets	3.2	✓			
ATLAS-SUSY-2015-02 [63]	1ℓ stop	3.2	✓		✓	
ATLAS-SUSY-2015-06 [64]	0ℓ + 2–6 jets	3.2			✓	
ATLAS-SUSY-2015-09 [65]	jets + 2 SS or $\geq 3\ell$	3.2	✓			
ATLAS-SUSY-2016-06 [66]	disappearing tracks	36.1			✓	
ATLAS-SUSY-2016-07 [67]	0ℓ + jets	36.1	✓		✓	
ATLAS-SUSY-2016-08 [68]	displaced vertices	32.8	✓			
ATLAS-SUSY-2016-14 [69]	2 SS or 3 ℓ's + jets	36.1	✓			
ATLAS-SUSY-2016-15 [70]	0ℓ stop	36.1	✓			
ATLAS-SUSY-2016-16 [71]	1ℓ stop	36.1	✓		✓	
ATLAS-SUSY-2016-17 [72]	2 OS leptons	36.1	✓			
ATLAS-SUSY-2016-19 [73]	2 b-jets + τ's	36.1	✓			
ATLAS-SUSY-2016-24 [74]	2–3 ℓ's, EWino	36.1	✓		✓	
ATLAS-SUSY-2016-26 [75]	$\geq 2\,c$-jets	36.1	✓			
ATLAS-SUSY-2016-27 [76]	jets + γ	36.1	✓		✓	
ATLAS-SUSY-2016-28 [77]	2 b-jets	36.1	✓			
ATLAS-SUSY-2016-32 [44]	HSCP	31.6	✓	✓	✓	
ATLAS-SUSY-2016-33 [78]	2 OSSF ℓ's	36.1	✓			
ATLAS-SUSY-2017-01 [79]	$WH(bb)$, EWino	36.1	✓			
ATLAS-SUSY-2017-02 [80]	0ℓ + jets	36.1	✓	✓		
ATLAS-SUSY-2017-03 [21]	multi-ℓ EWino	36.1	✓		✓	
ATLAS-SUSY-2018-04 [81]	2 hadronic taus	139.0	✓		✓	JSON
ATLAS-SUSY-2018-06 [22]	3 leptons, EWino	139.0	✓	✓	✓	
ATLAS-SUSY-2018-10 [17]	1ℓ + jets	139.0	✓		✓	
ATLAS-SUSY-2018-12 [19]	0ℓ + jets	139.0	✓	✓	✓	
ATLAS-SUSY-2018-14 [15]	displaced leptons	139.0			✓	JSON
ATLAS-SUSY-2018-22 [18]	multi-jets	139.0	✓		✓	
ATLAS-SUSY-2018-23 [20]	$WH(\gamma\gamma)$, EWino	139.0	✓	✓		
ATLAS-SUSY-2018-31 [82]	$2b + 2H(bb)$	139.0	✓		✓	JSON
ATLAS-SUSY-2018-32 [59]	2 OS leptons	139.0	✓			
ATLAS-SUSY-2019-08 [60]	$1\ell + H(bb)$, EWino	139.0	✓		✓	JSON

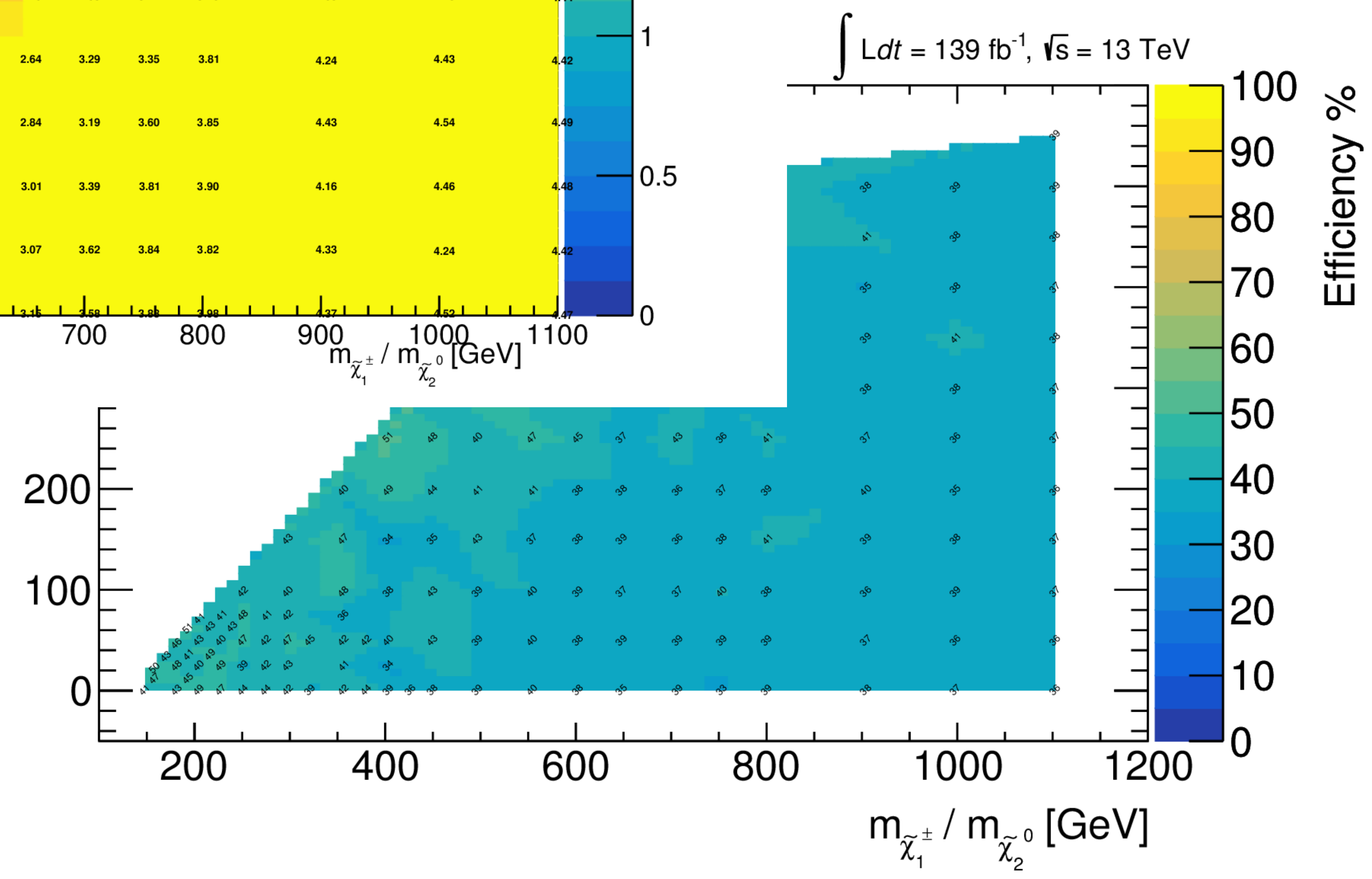
ID	Short Description	$\mathcal{L}$ [fb^{-1}]	UL_{obs}	UL_{exp}	EM	comb.
CMS-PAS-EXO-16-036 [83]	HSCP	12.9	✓			
CMS-PAS-SUS-16-052 [84]	ISR jet + soft ℓ	35.9	✓		✓	Cov.
CMS-SUS-16-009 [85]	0ℓ + jets, top tag	2.3	✓	✓		
CMS-SUS-16-032 [86]	2 b- or 2 c-jets	35.9	✓			
CMS-SUS-16-033 [87]	0ℓ + jets	35.9	✓	✓	✓	
CMS-SUS-16-034 [88]	2 OSSF leptons	35.9	✓			
CMS-SUS-16-035 [89]	2 SS leptons	35.9	✓			
CMS-SUS-16-036 [90]	0ℓ + jets	35.9	✓	✓		
CMS-SUS-16-037 [91]	1ℓ + jets with MJ	35.9	✓			
CMS-SUS-16-039 [92]	multi-ℓ, EWino	35.9	✓			
CMS-SUS-16-041 [93]	multi-ℓ + jets	35.9	✓			
CMS-SUS-16-042 [94]	1ℓ + jets	35.9	✓			
CMS-SUS-16-043 [95]	$WH(bb)$, EWino	35.9	✓			
CMS-SUS-16-045 [96]	$2\,b + 2\,H(\gamma\gamma)$	35.9	✓			
CMS-SUS-16-046 [97]	high-p_T γ	35.9	✓			
CMS-SUS-16-047 [98]	γ + jets, high H_T	35.9	✓			
CMS-SUS-16-049 [99]	0ℓ stop	35.9	✓	✓		
CMS-SUS-16-050 [100]	0ℓ + top tag	35.9	✓	✓		
CMS-SUS-16-051 [101]	1ℓ stop	35.9	✓	✓		
CMS-SUS-17-001 [102]	2ℓ stop	35.9	✓			
CMS-SUS-17-003 [103]	2 taus	35.9	✓			
CMS-SUS-17-004 [58]	EWino combination	35.9	✓			
CMS-SUS-17-005 [104]	1ℓ + jets, top tag	35.9	✓	✓		
CMS-SUS-17-006 [105]	jets + boosted $H(bb)$	35.9	✓	✓		
CMS-SUS-17-009 [106]	SFOS leptons	35.9	✓	✓		
CMS-SUS-17-010 [107]	2ℓ stop	35.9	✓	✓		
CMS-SUS-18-002 [108]	γ + (b-)jets, top tag	35.9	✓	✓		
CMS-SUS-19-006 [109]	0ℓ + jets, MHT	137.0	✓	✓		
CMS-SUS-19-009 [110]	1ℓ + jets, MHT	137.0	✓			
CMS-EXO-19-001 [111]	non-prompt jets	137.0			✓	
CMS-EXO-19-010 [10]	disappearing tracks	101.0			✓	

SModelS uses two types of experimental results:

upper limit (UL) maps and **A×ε ‘efficiency’ maps (EM)**







Efficiency map results allow us to sum different contributions to the same signal region, and to ***compute a likelihood***.

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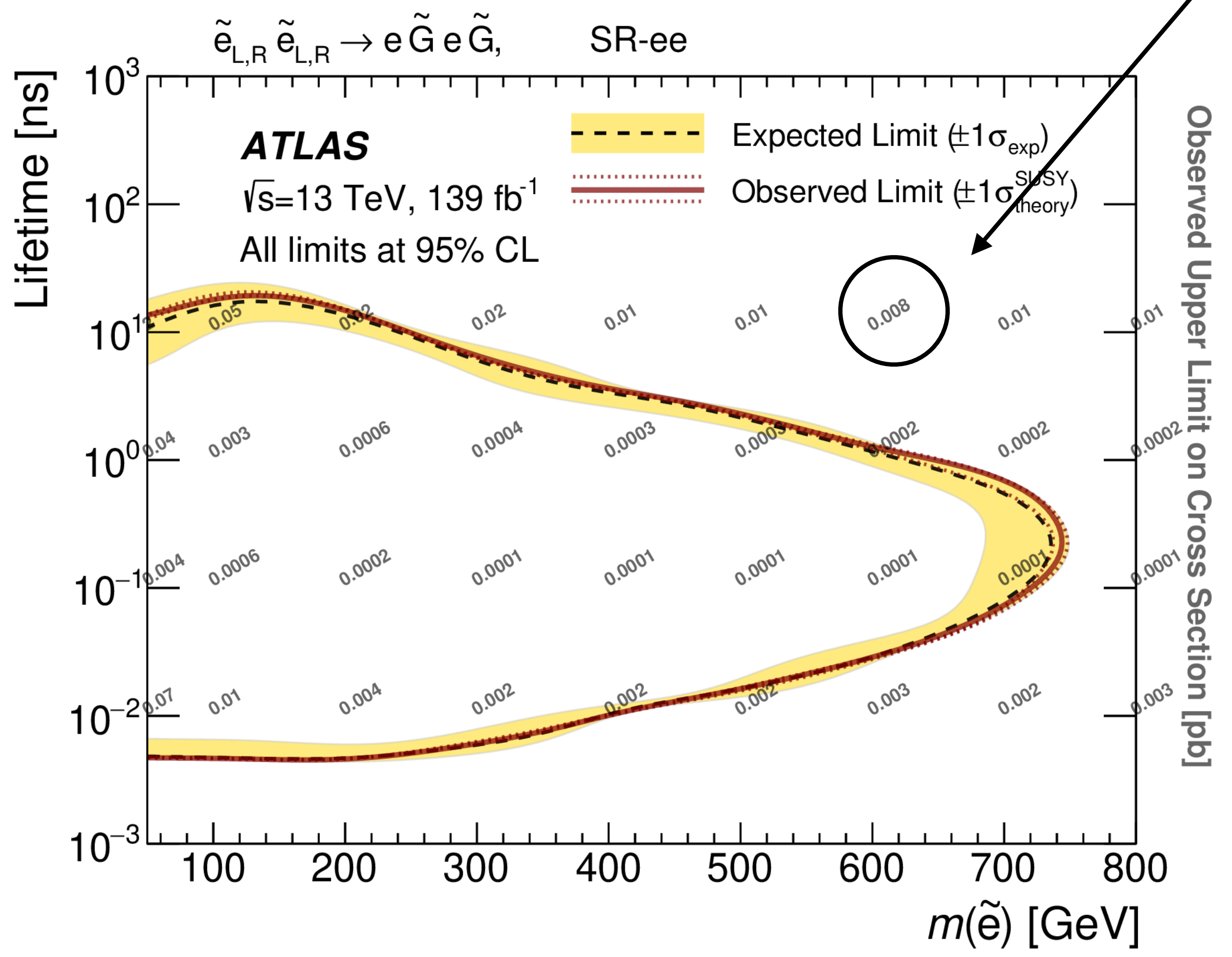

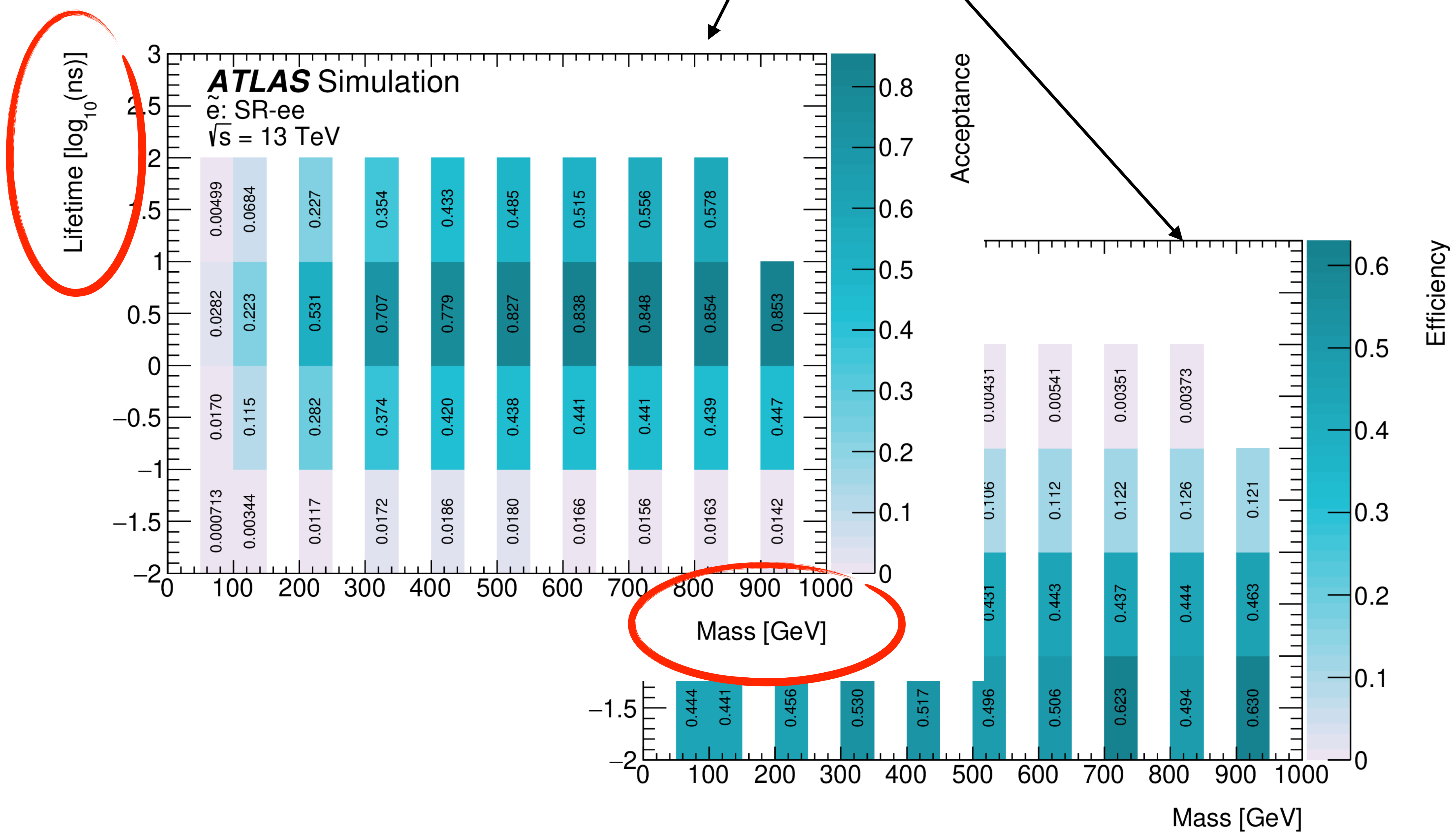

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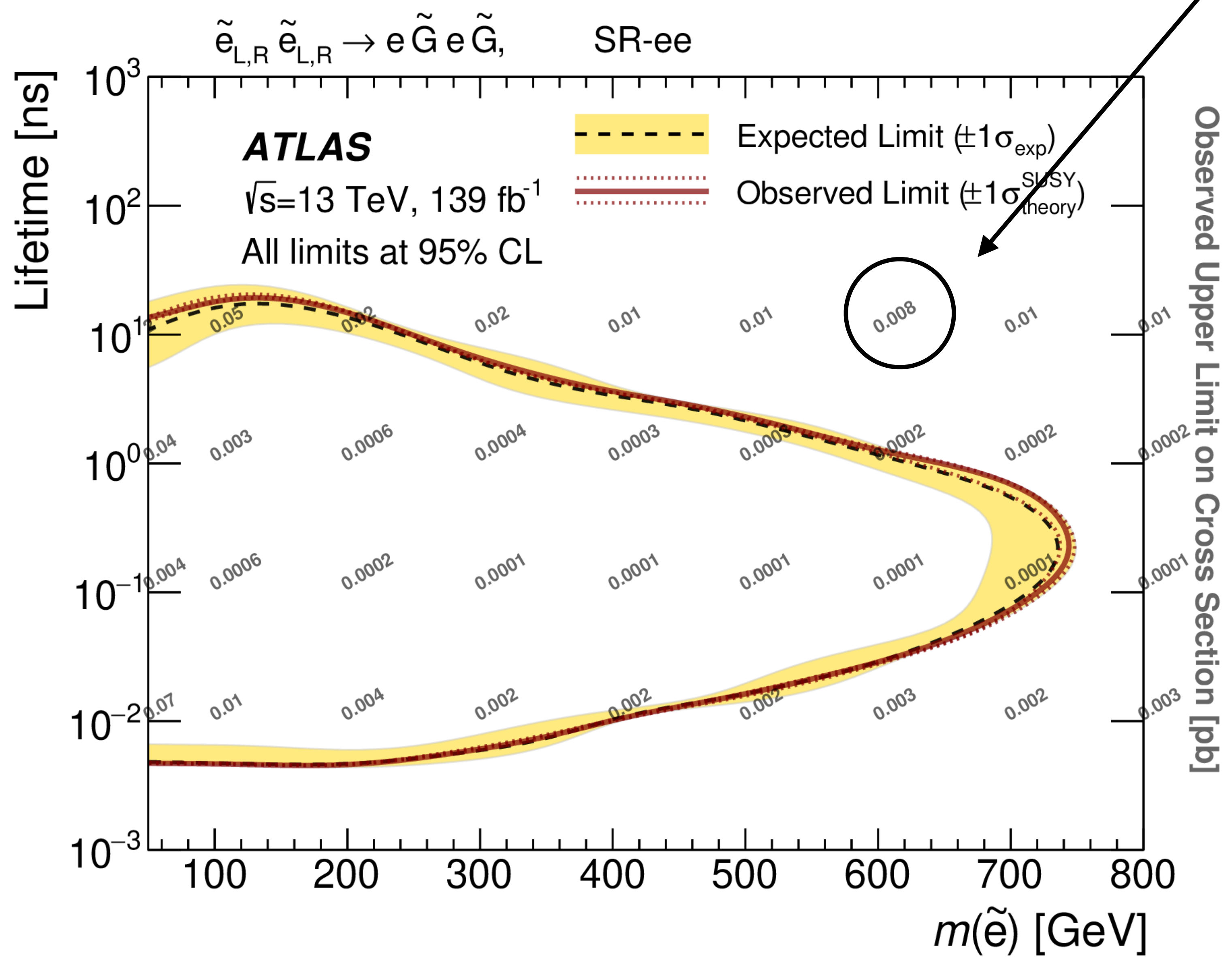
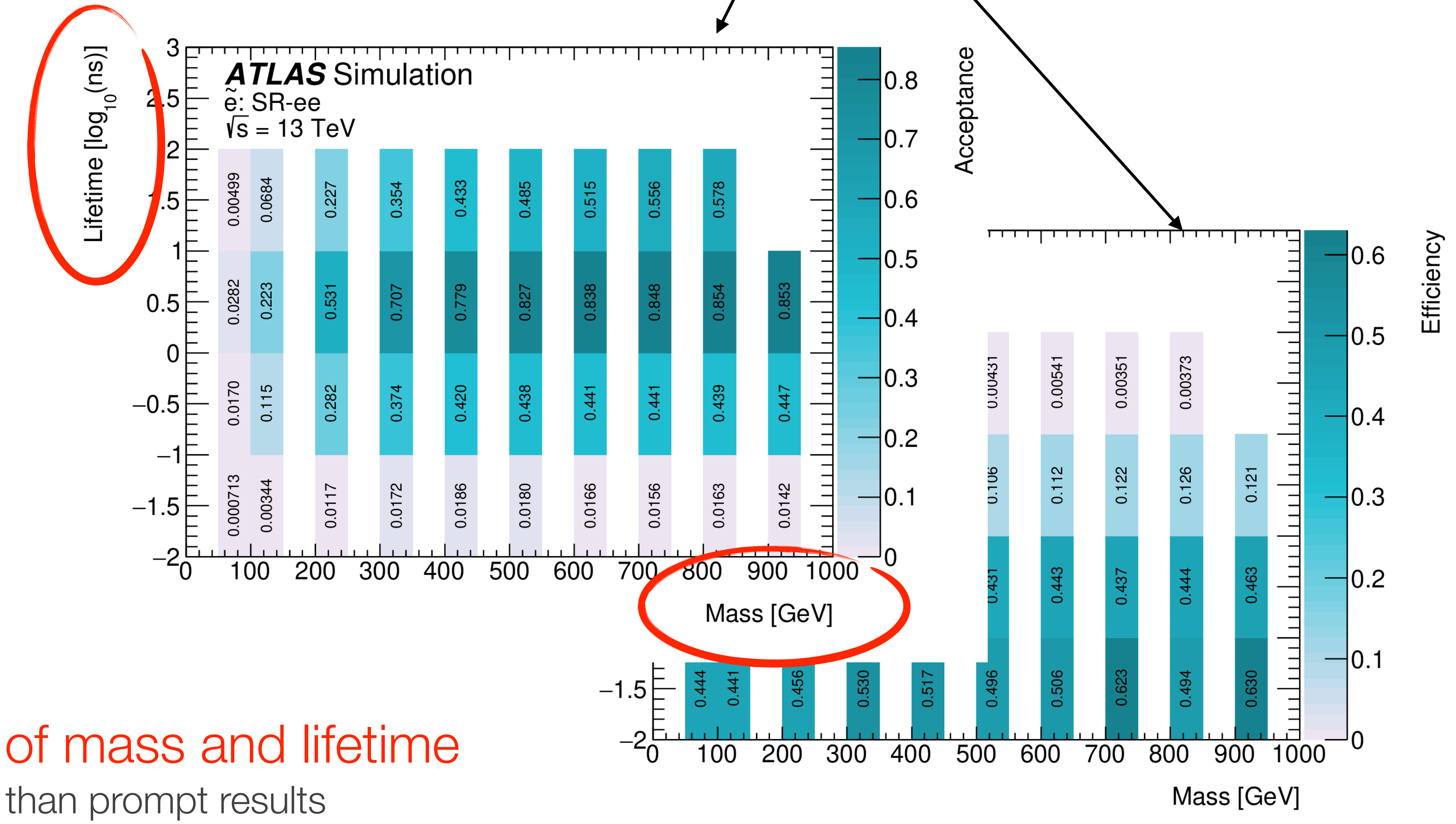
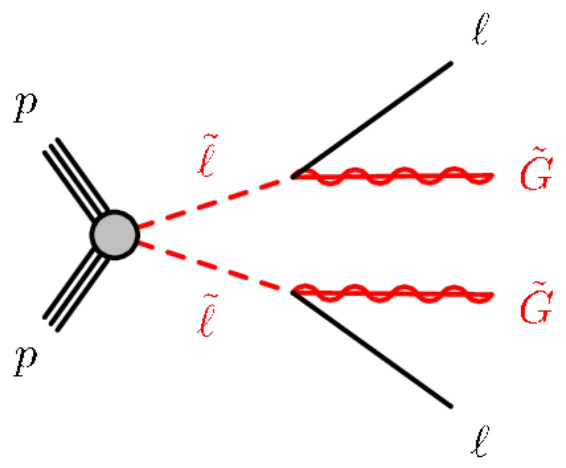






LLP results are ‘maps’ in terms of mass and lifetime

→ in principle higher dimensionality than prompt results

Efficiency map results allow us to sum different contributions to the same signal region, and to ***compute a likelihood***.

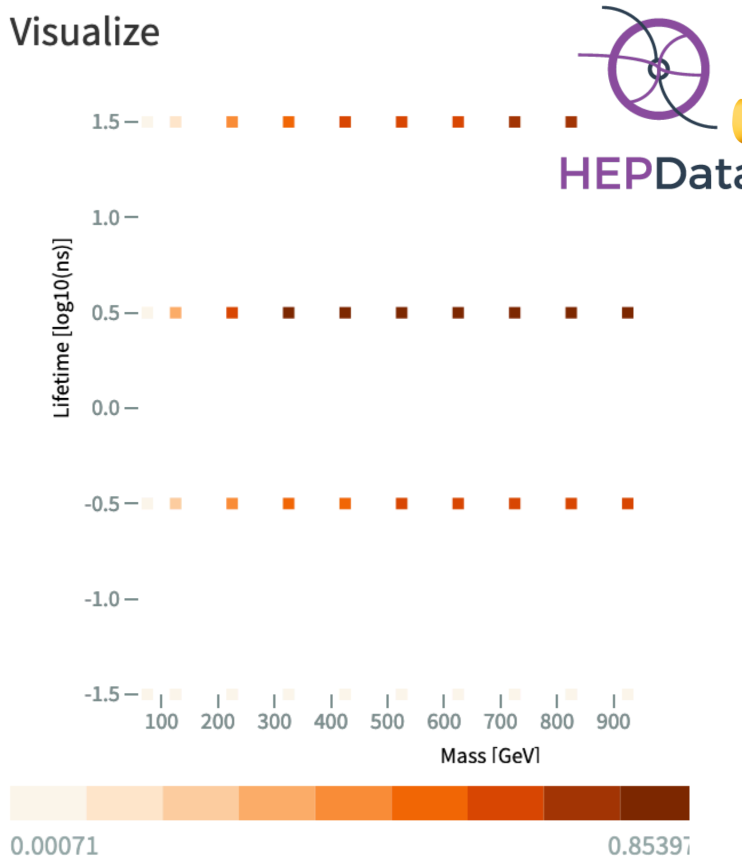
Computing likelihoods from EM results

Acceptance × efficiency values allow us to determine the signal contributions in each signal region (SR)

$$s = \Sigma\, \sigma \times \mathrm{BR} \times L \times A \times \epsilon$$

L = integrated luminosity

Mass [GeV]	Lifetime [log10(ns)]	Acceptance
75.0	-1.5	0.00071316
75.0	-0.5	0.017015
75.0	0.5	0.028157
75.0	1.5	0.0049927
125.0	-1.5	0.0034405
125.0	-0.5	0.11465
125.0	0.5	0.22332
125.0	1.5	0.068424
225.0	-1.5	0.011696



HEPData

Given the number of observed events, expected backgrounds and uncertainties thereon, we can compute from this a **simplified likelihood**

$$\mathcal{L}(\mu, \theta) = \frac{(\mu s + b + \theta)^{n_{\rm obs}}\, e^{-(\mu s + b + \theta)}}{n_{\rm obs}!}\; exp\left(-\frac{\theta^2}{2\delta^2}\right)$$

$$\delta^2 = \delta_s^2 + \delta_b^2$$

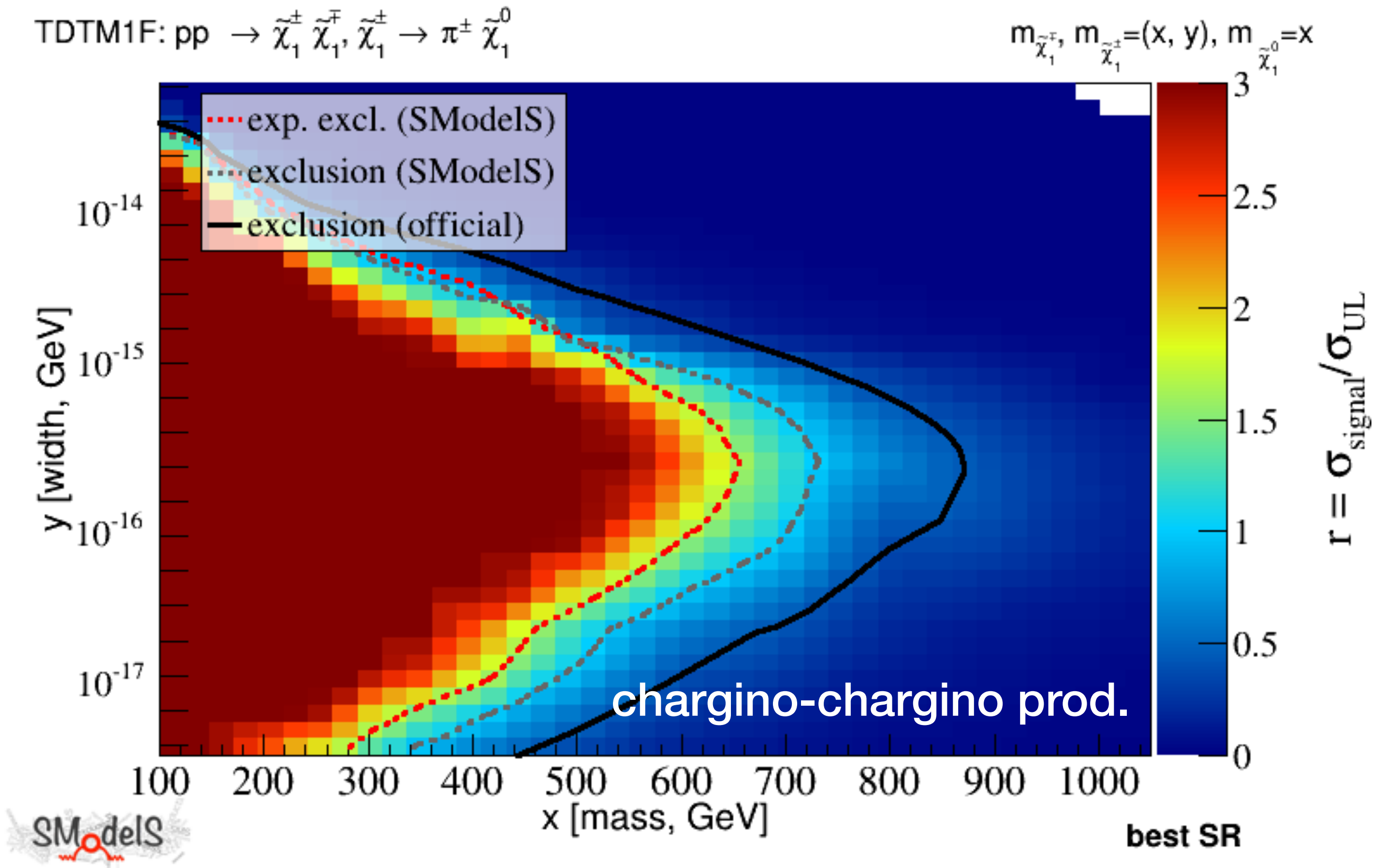
signal+background uncertainties

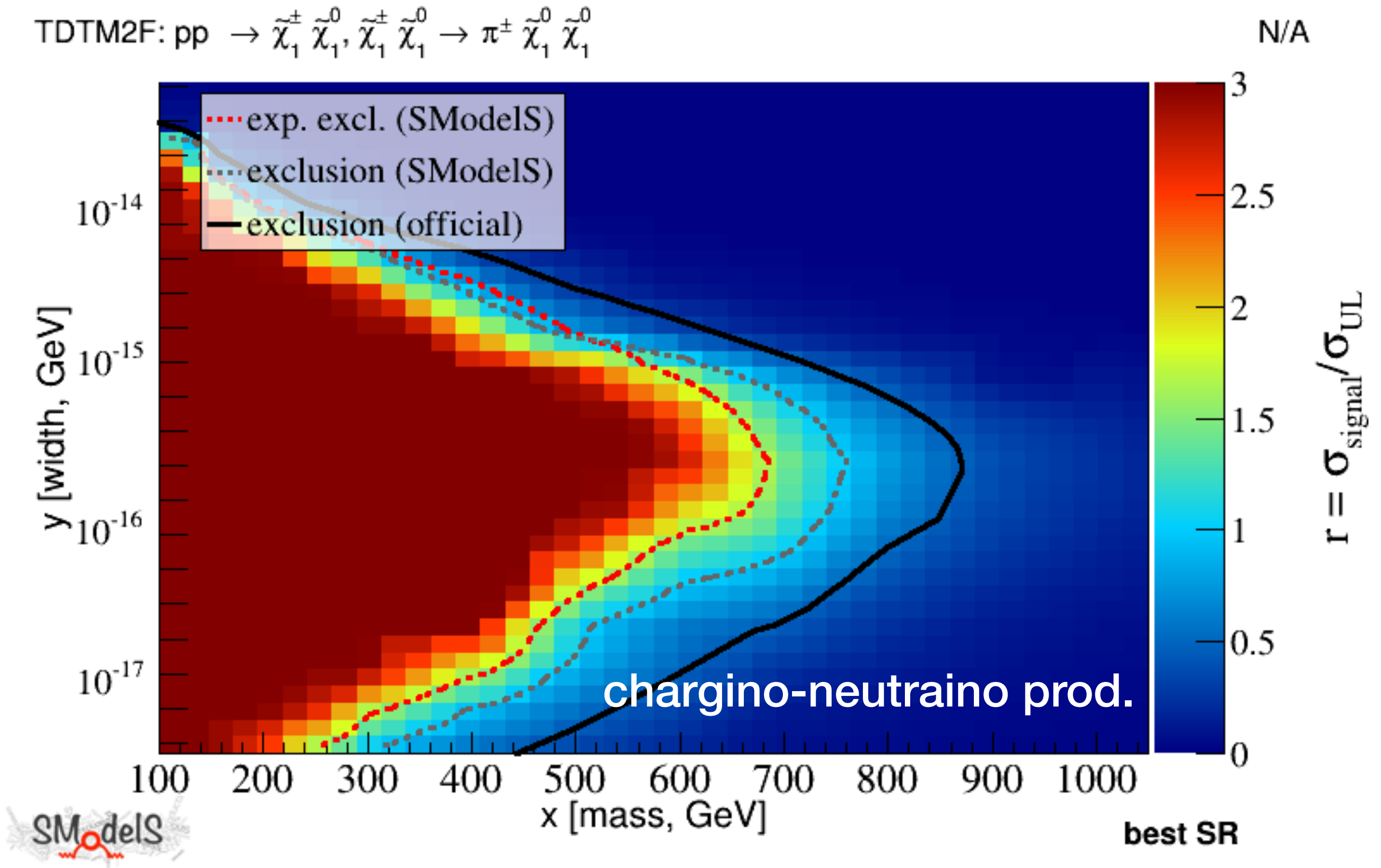
assuming a Poisson distribution for the data and a Gaussian with variance of δ^2 for the nuisances, p(θ)

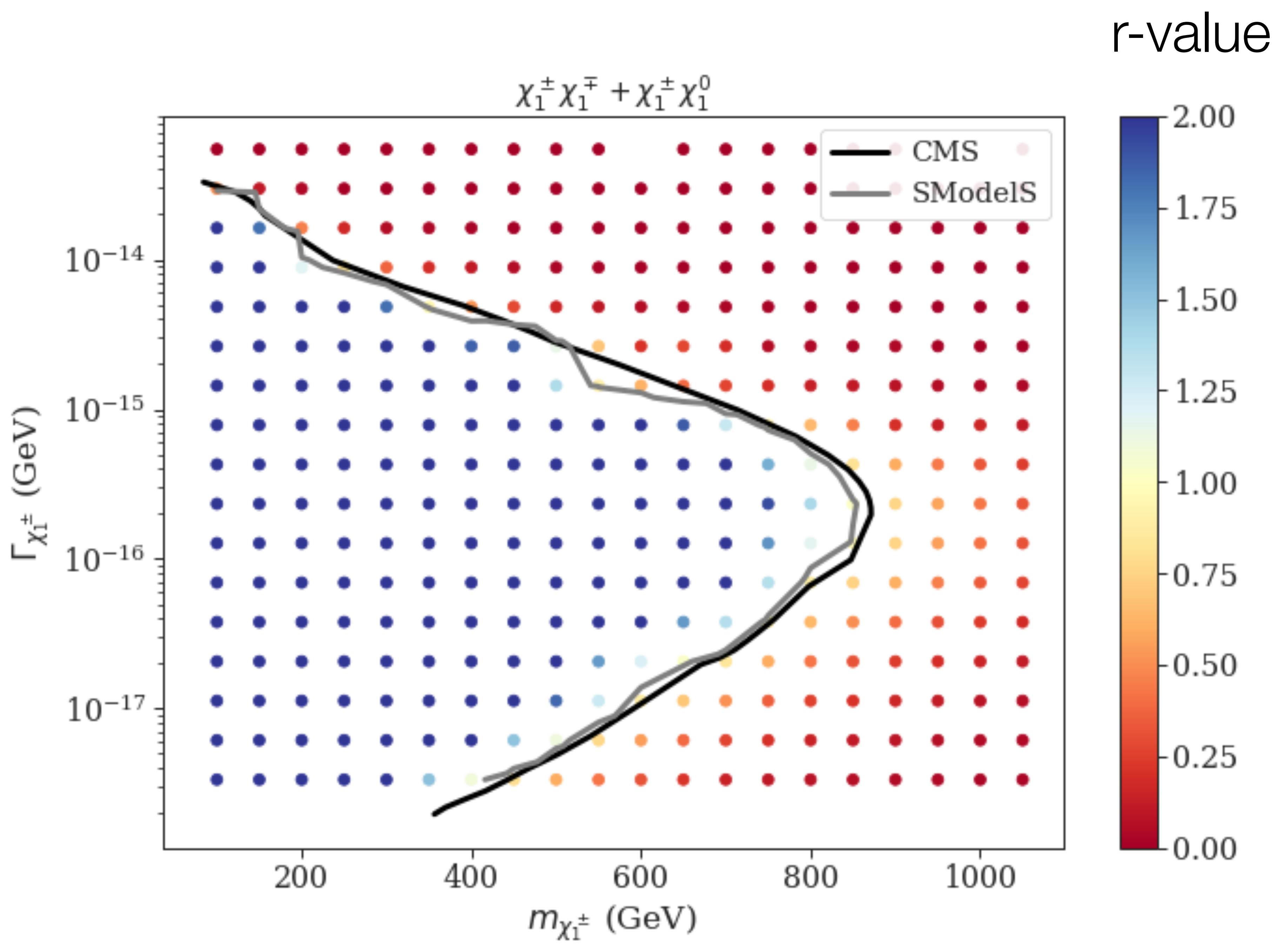
Example for combination of topologies (for the same SR)

CMS disappearing track search

CMS-EXO-19-010 (efficiencyMap)







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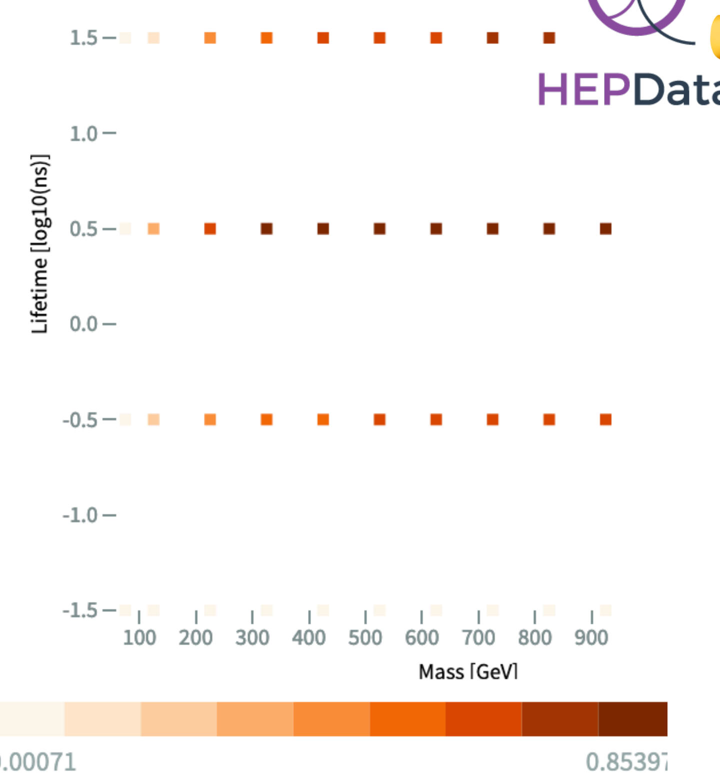
Visualize



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$$\mathcal{L}(\mu,\theta) = \frac{(\mu s + b + \theta)^{n_{\mathrm{obs}}}\, e^{-(\mu s + b + \theta)}}{n_{\mathrm{obs}}!} \, exp\left(-\frac{\theta^2}{2\delta^2}\right)$$

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75.0	-0.5	0.017015
75.0	0.5	0.028157
[illegible]	[illegible]	0.0049927
225.0		

Visualize

HEPData

Caveat: unless information on background correlations is provided, only the most sensitive ("best") SR can be used.
→ **If signal splits up over several SR, a large part of it may be lost** ←

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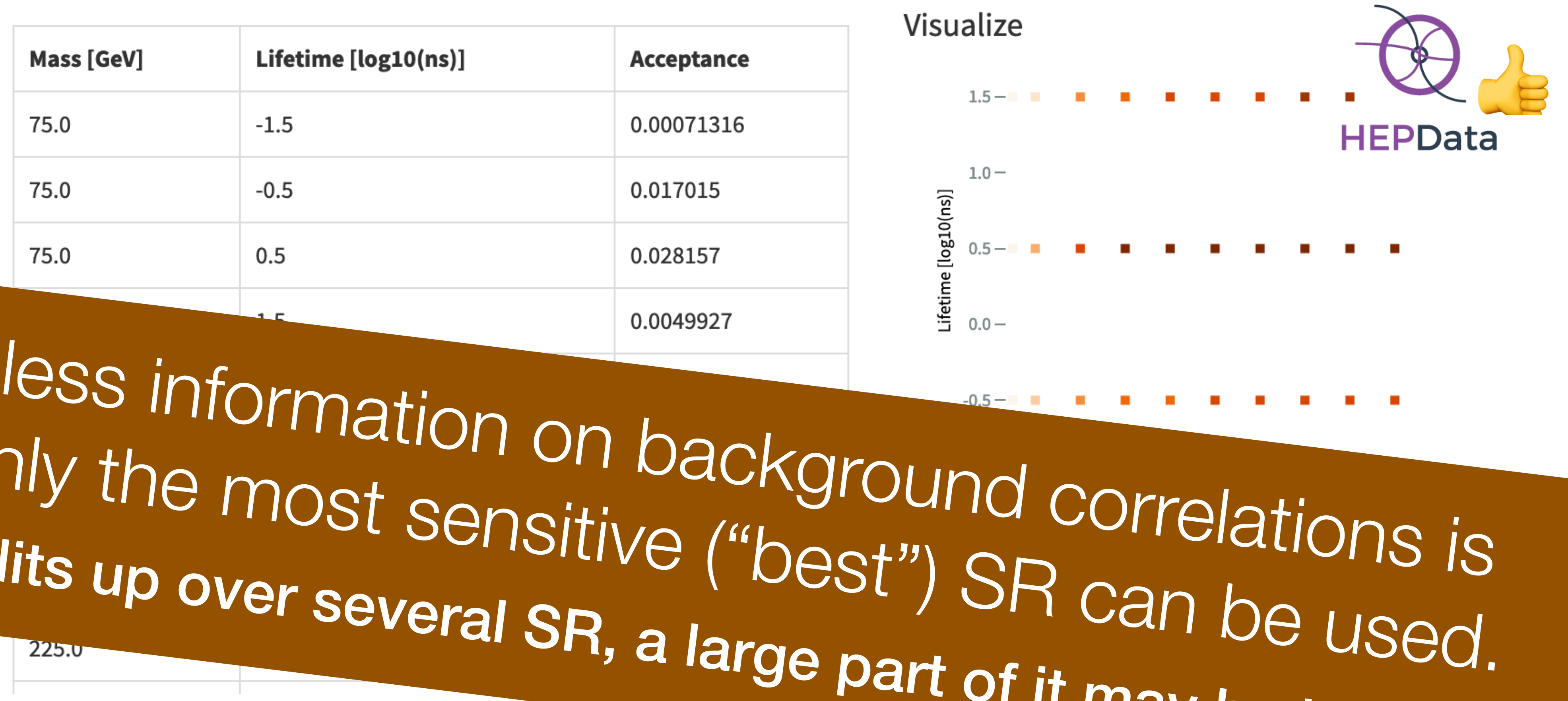

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$$\mathcal{L}_S(\mu, \boldsymbol{\theta}) = \prod_{i=1}^{N} \frac{(\mu \cdot s_i + b_i + \theta_i)^{n_i} e^{-(\mu \cdot s_i + b_i + \theta_i)}}{n_i!} \cdot \exp\left(-\frac{1}{2}\boldsymbol{\theta}^T \mathbf{V}^{-1} \boldsymbol{\theta}\right)$$

← *covariance matrix*

See CMS NOTE-2017/001

assuming a Poisson distribution for the data and a Gaussian with variance of δ^2 for the nuisances, $p(\theta)$

Full statistical model in JSON format

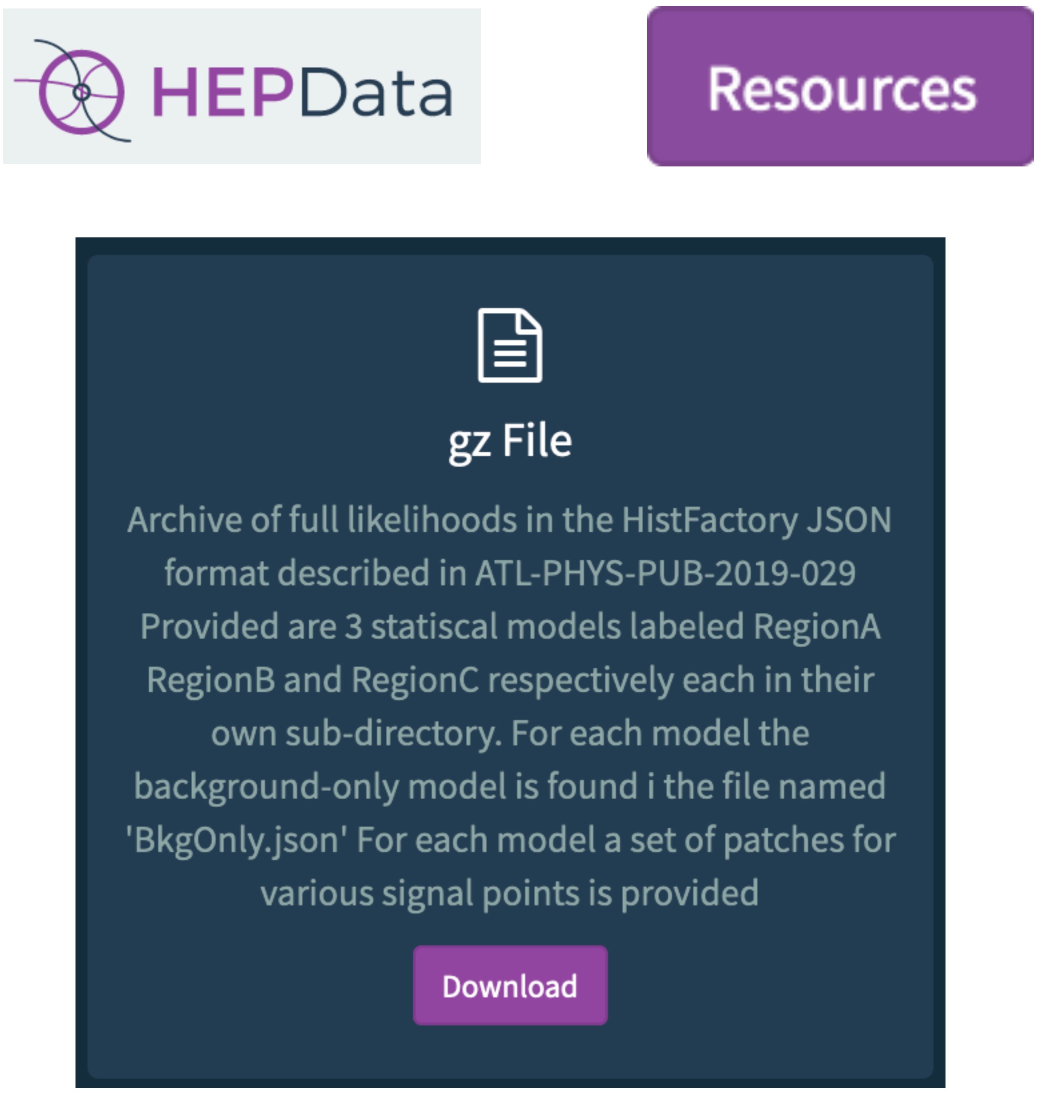
ATL-PHYS-PUB-2019-029

ATLAS: plain-text serialisation of HistFactory workspaces, JSON format

- Provides background estimates, changes under systematic variations, and observed data counts at the same fidelity as used in the experiment.

	Description	Modification	Constraint Term c_χ	Input
constrained	Uncorrelated Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \text{Pois}\left(r_b = \sigma_b^{-2} \mid \rho_b = \sigma_b^{-2}\gamma_b\right)$	σ_b
	Correlated Shape	$\Delta_{scb}(\alpha) = f_p\left(\alpha \mid \Delta_{scb,\alpha=-1}, \Delta_{scb,\alpha=1}\right)$	$\text{Gaus}\,(a = 0 \mid \alpha, \sigma = 1)$	$\Delta_{scb,\alpha=\pm1}$
	Normalisation Unc.	$\kappa_{scb}(\alpha) = g_p\left(\alpha \mid \kappa_{scb,\alpha=-1}, \kappa_{scb,\alpha=1}\right)$	$\text{Gaus}\,(a = 0 \mid \alpha, \sigma = 1)$	$\kappa_{scb,\alpha=\pm1}$
	MC Stat. Uncertainty	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \text{Gaus}\left(a_{\gamma_b} = 1 \mid \gamma_b, \delta_b\right)$	$\delta_b^2 = \sum_s \delta_{sb}^2$
	Luminosity	$\kappa_{scb}(\lambda) = \lambda$	$\text{Gaus}\,(l = \lambda_0 \mid \lambda, \sigma_\lambda)$	$\lambda_0, \sigma_\lambda$
free	Normalisation	$\kappa_{scb}(\mu_b) = \mu_b$		
	Data-driven Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$		

Rate modifications defined in HistFactory for bin *b*, sample *s*, channel *c*.



- Usage: RooFit, **pyhf**

✔ **SModelS includes since v1.2.4 an interface to pyhf**

`combineSR = True/False` in the parameters.ini file

G. Alguero, SK, W. Waltenberger, arXiv:2009.01809

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```
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in the parameters.ini file

G. Alguero, SK, W. Waltenberger, arXiv:2009.01809

Likelihood available

Search for charginos and neutralinos in all-hadronic final states	SUSY	Accepted by PRD	17-AUG-21	13	139 fb^{-1}
4-top xsec measurement	TOPQ	Accepted by JHEP	22-JUN-21	13	139 fb^{-1}
Search for gluinos, stops and electroweakinos in RPV models in final states with 1L and many jets	SUSY	Accepted by EPJC	17-JUN-21	13	139 fb^{-1}
Search for charginos and neutralinos in final states with 3L and MET	SUSY	Accepted by EPJC	03-JUN-21	13	139 fb^{-1}
Measurement of ttZ cross sections in Run 2	TOPQ	Eur. Phys. J. C 81 (2021) 737	23-MAR-21	13	139 fb^{-1}
Search for third-generation scalar leptoquarks decaying to a top quark and a tau lepton	EXOT	JHEP 06 (2021) 179	27-JAN-21	13	139 fb^{-1}
Search for squarks and gluinos in final states 1L, jets and MET	SUSY	Eur. Phys. J. C 81 (2021) 600	05-JAN-21	13	139 fb^{-1}
Search for charginos and neutralinos in RPV models in final states with 3L (or more)	SUSY	Phys. Rev. D 103, (2021) 112003	20-NOV-20	13	139 fb^{-1}
Search for displaced leptons	SUSY	Phys. Rev. Lett. 127 (2021) 051802	13-NOV-20	13	139 fb^{-1}
Search for squarks and gluinos in final states with 0L, jets and MET	SUSY	JHEP 02 (2021) 143	27-OCT-20	13	139 fb^{-1}
Measurement of the ttbar production cross-section in the lepton+jets channel at 13 TeV	TOPQ	Phys. Lett. B 810 (2020) 135797	24-JUN-20	13	139 fb^{-1}
Stop pair, long-lived; displaced vertex and displaced muon	SUSY	Phys. Rev. D 102 (2020) 032006	26-MAR-20	13	136 fb^{-1}
Chargino-neutralino pair; 3 leptons, weak-scale mass splittings	SUSY	Phys. Rev. D 101 (2020) 072001	18-DEC-19	13	139 fb^{-1}
Chargino-neutralino pair, slepton pair; soft leptons	SUSY	Phys. Rev. D 101 (2020) 052005	28-NOV-19	13	139 fb^{-1}
Staus; taus	SUSY	Phys. Rev. D 101 (2020) 032009	15-NOV-19	13	139 fb^{-1}
Chargino-neutralino pair; Higgs boson in final state, 2 b-jets and 1 lepton	SUSY	Eur. Phys. J. C 80 (2020) 691	19-SEP-19	13	139 fb^{-1}
Stop pair, sbottom pair, gluino pair; two same-sign leptons or three leptons	SUSY	JHEP 06 (2020) 46	18-SEP-19	13	139 fb^{-1}
Sbottom; b-jets	SUSY	JHEP 12 (2019) 060	08-AUG-19	13	139 fb^{-1}

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G. Alguero, SK, W. Waltenberger, arXiv:2009.01809

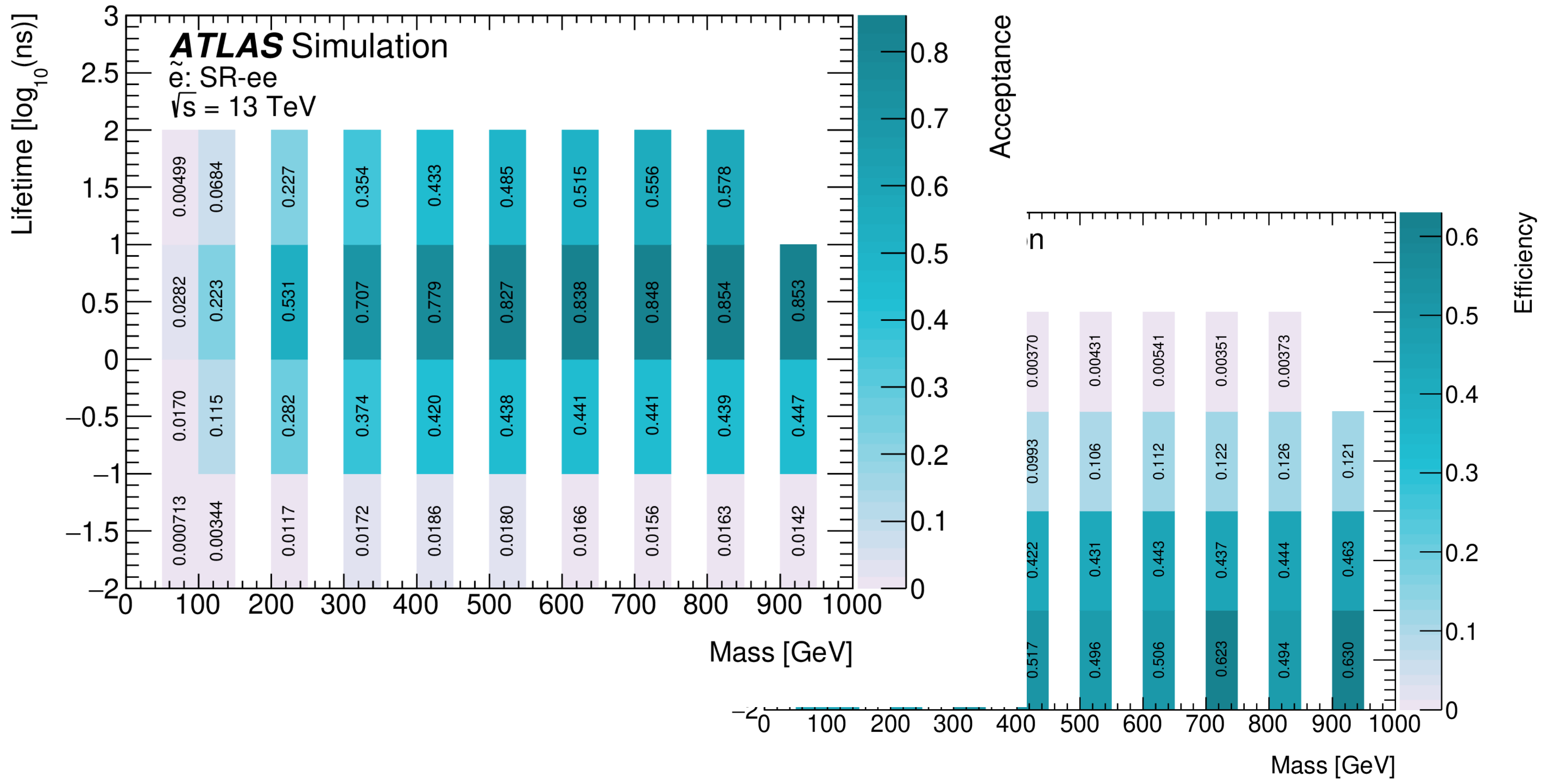
Likelihood available

Search for charginos and neutralinos in all-hadronic final states	SUSY	Accepted by PRD	17-AUG-21	13	139 fb^{-1}
4-top xsec measurement	TOPQ	Accepted by JHEP	22-JUN-21	13	139 fb^{-1}
Search for gluinos, stops and electroweakinos in RPV models in final states with 1L and many jets	SUSY	Accepted by EPJC	17-JUN-21	13	139 fb^{-1}
Search for charginos and neutralinos in final states with 3L and MET	SUSY	Accepted by EPJC	03-JUN-21	13	139 fb^{-1}
Measurement of ttZ cross sections in Run 2	TOPQ	Eur. Phys. J. C 81 (2021) 737	23-MAR-21	13	139 fb^{-1}
Search for third-generation scalar leptoquarks decaying to a top quark and a tau lepton	EXOT	JHEP 06 (2021) 179	27-JAN-21	13	139 fb^{-1}
Search for squarks and gluinos in final states 1L, jets and MET	SUSY	Eur. Phys. J. C 81 (2021) 600	05-JAN-21	13	139 fb^{-1}
Search for charginos and neutralinos in RPV models in final states with 3L (or more)	SUSY	Phys. Rev. D 103, (2021) 112003	20-NOV-20	13	139 fb^{-1}
Search for displaced leptons	SUSY	Phys. Rev. Lett. 127 (2021) 051802	13-NOV-20	13	139 fb^{-1}
Search for squarks and gluinos in final states with 0L, jets and MET	SUSY	JHEP 02 (2021) 143	27-OCT-20	13	139 fb^{-1}
Measurement of the ttbar production cross-section in the lepton+jets channel at 13 TeV	TOPQ	Phys. Lett. B 810 (2020) 135797	24-JUN-20	13	139 fb^{-1}
Stop pair, long-lived; displaced vertex and displaced muon	SUSY	Phys. Rev. D 102 (2020) 032006	26-MAR-20	13	136 fb^{-1}
Chargino-neutralino pair; 3 leptons, weak-scale mass splittings	SUSY	Phys. Rev. D 101 (2020) 072001	18-DEC-19	13	139 fb^{-1}
Chargino-neutralino pair, slepton pair; soft leptons	SUSY	Phys. Rev. D 101 (2020) 052005	28-NOV-19	13	139 fb^{-1}
Staus; taus	SUSY	Phys. Rev. D 101 (2020) 032009	15-NOV-19	13	139 fb^{-1}
Chargino-neutralino pair; Higgs boson in final state, 2 b-jets and 1 lepton	SUSY	Eur. Phys. J. C 80 (2020) 691	19-SEP-19	13	139 fb^{-1}
Stop pair, sbottom pair, gluino pair; two same-sign leptons or three leptons	SUSY	JHEP 06 (2020) 46	18-SEP-19	13	139 fb^{-1}
Sbottom; b-jets	SUSY	JHEP 12 (2019) 060	08-AUG-19	13	139 fb^{-1}

Statistical model from ATLAS displaced lepton search

Simple structure: single background source, Gaussian

Region	SR-ee	SR-$\mu\mu$	SR-$e\mu$
Fake + heavy-flavor	0.46 ± 0.10	$< 10^{-4}$	$0.007^{+0.019}_{-0.007}$
Cosmic-ray muons	–	$0.11^{+0.20}_{-0.11}$	–
Expected background	0.46 ± 0.10	$0.11^{+0.20}_{-0.11}$	$0.007^{+0.019}_{-0.007}$
Observed events	0	0	0



Comb_bkgonly.json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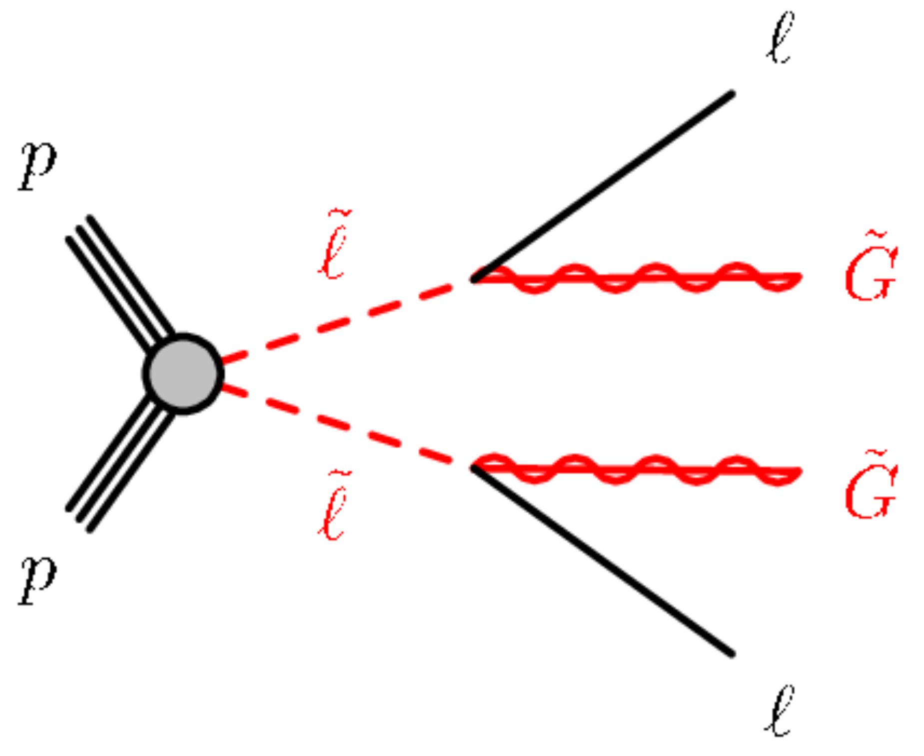
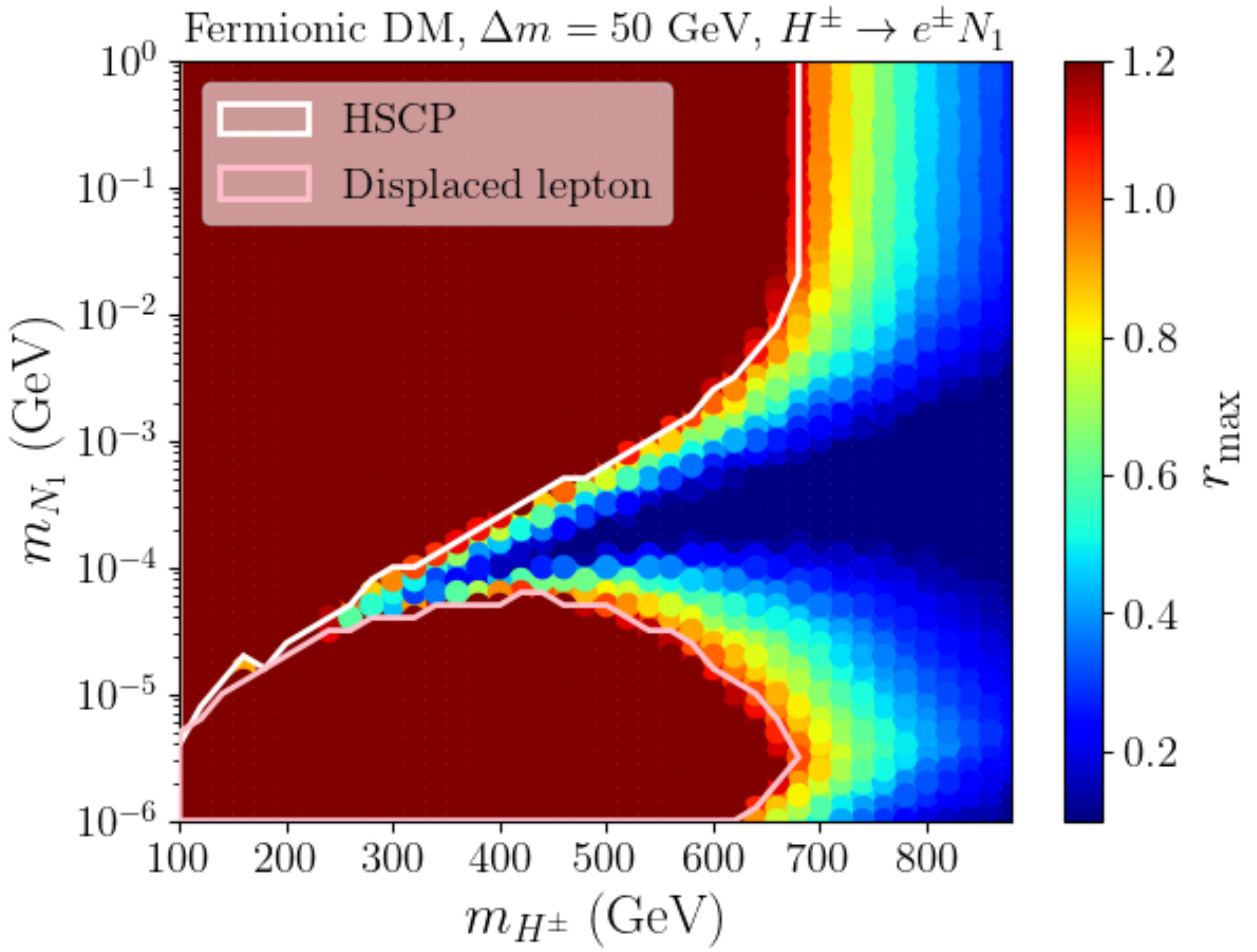
Reinterpretation: long-lived charged scalars in scotogenic model

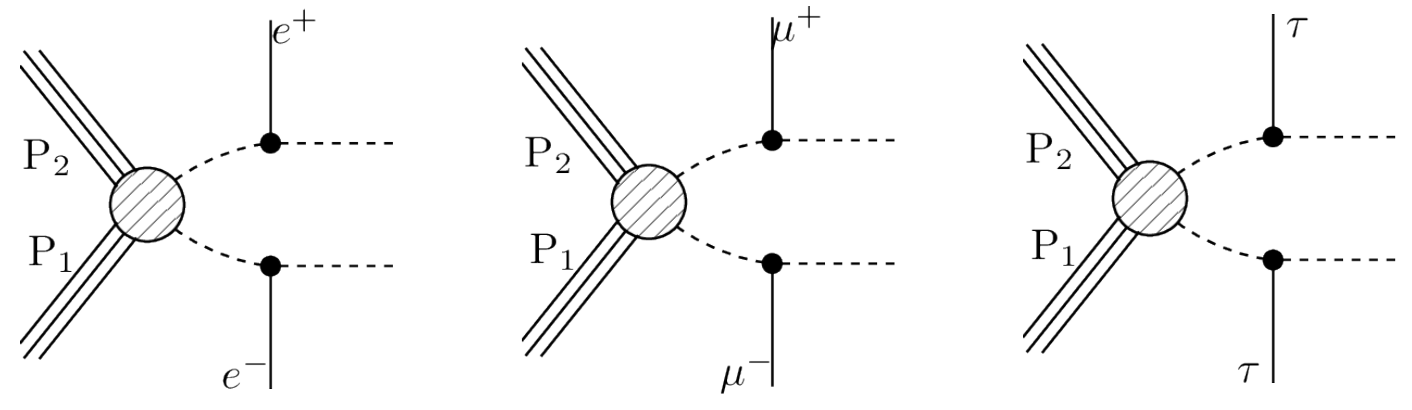
Scotogenic model with light sterile neutrino DM: can have long-lived charged Higgs



BR = 100% electrons



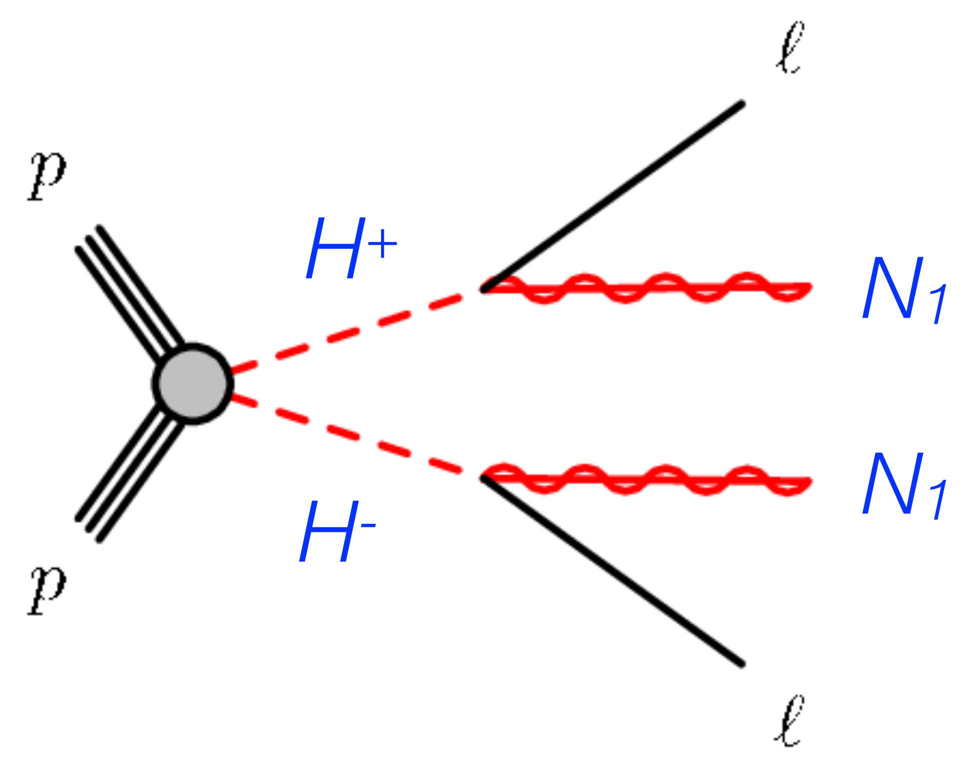
Efficiency maps available for:



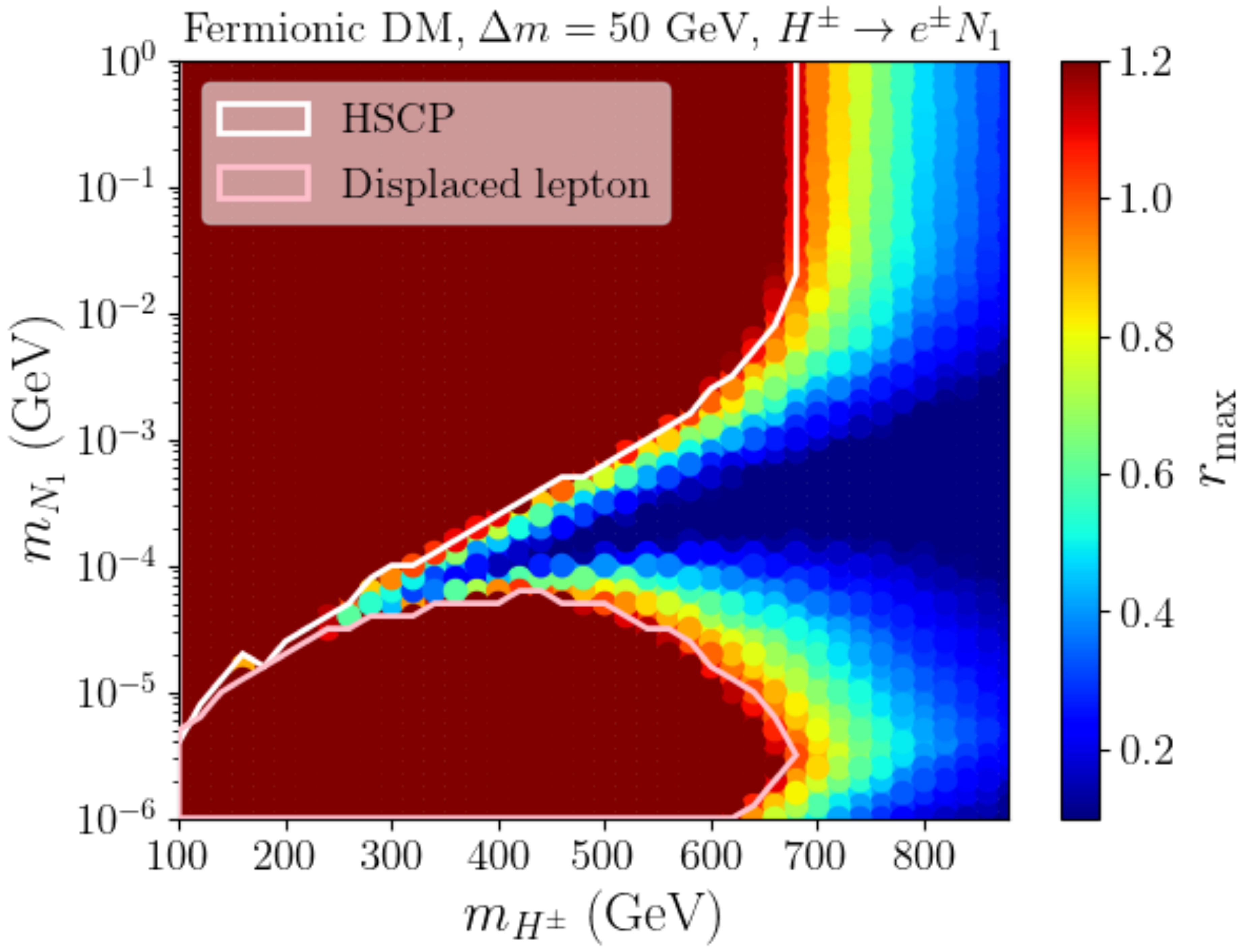
but not for different-flavour cases

Reinterpretation: long-lived charged scalars in scotogenic model

Scotogenic model with light sterile neutrino DM: can have long-lived charged Higgs



BR = 100% electrons



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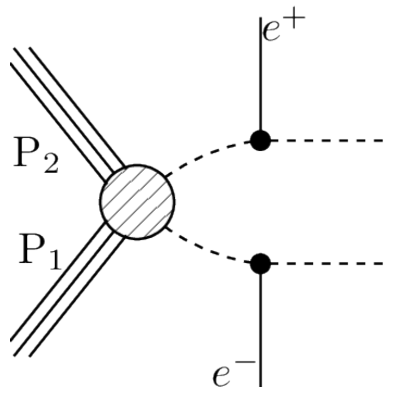
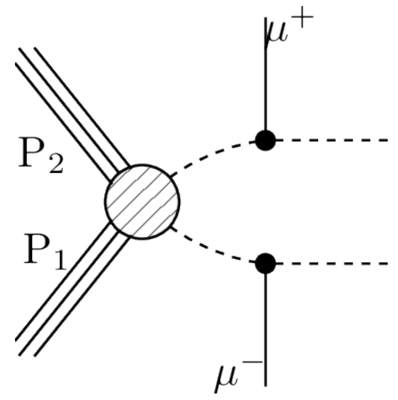
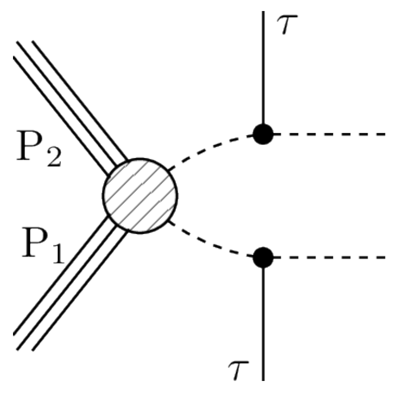


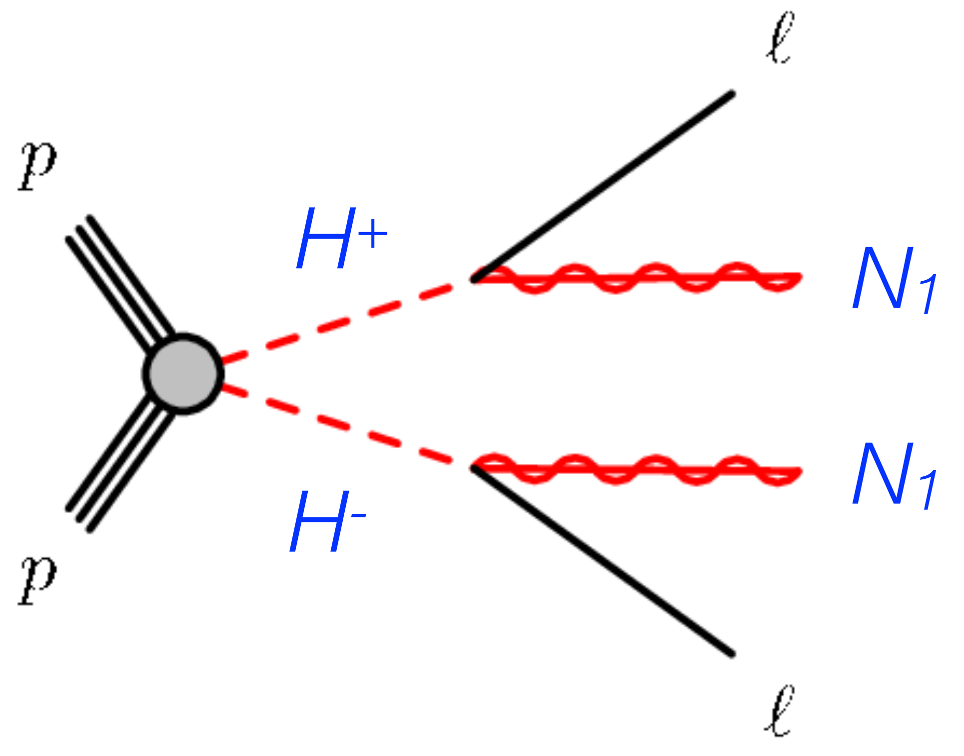




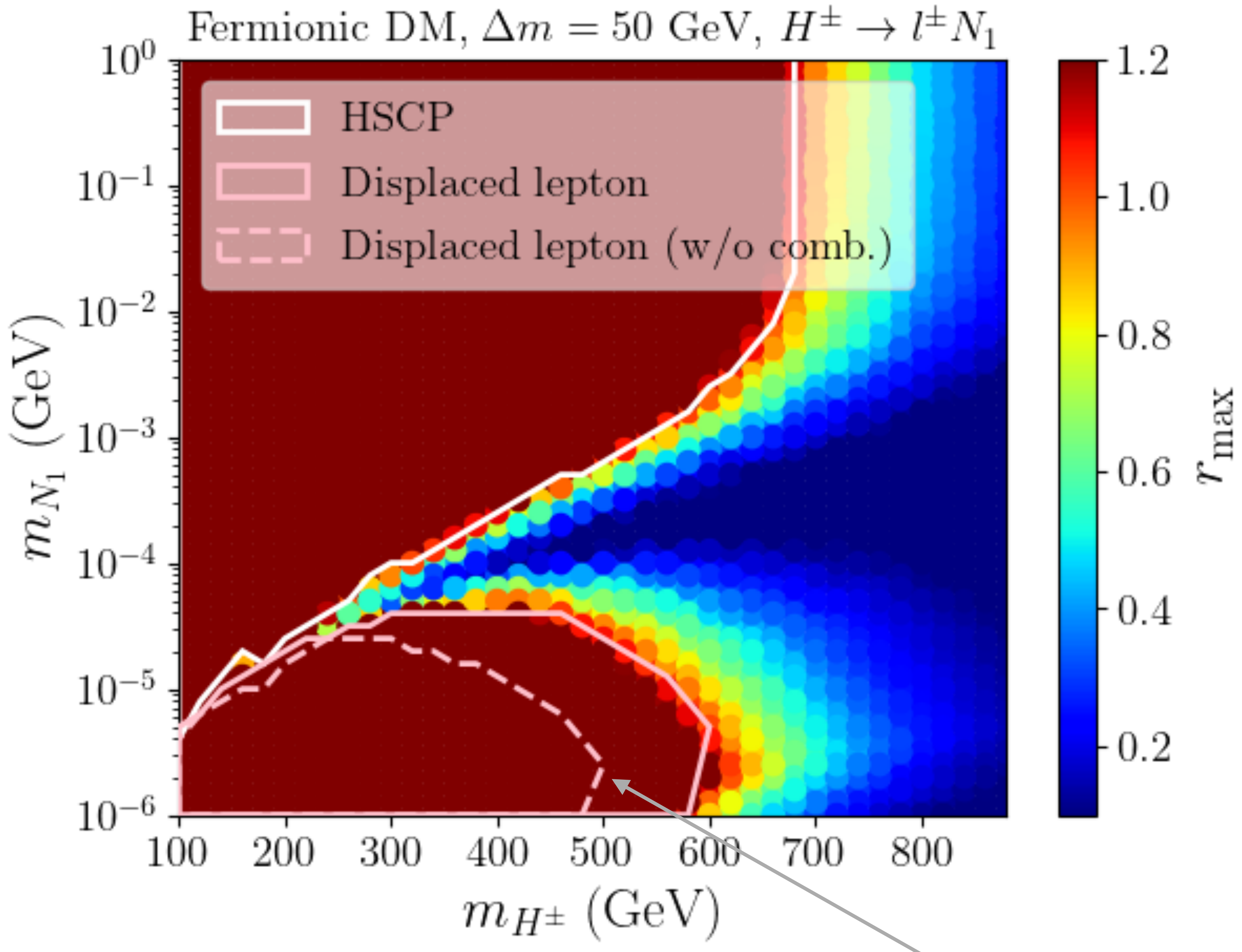
but not for different-flavour cases

Reinterpretation: long-lived charged scalars in scotogenic model

Scotogenic model with light sterile neutrino DM: can have long-lived charged Higgs



BR = 50% electrons, 50% muons



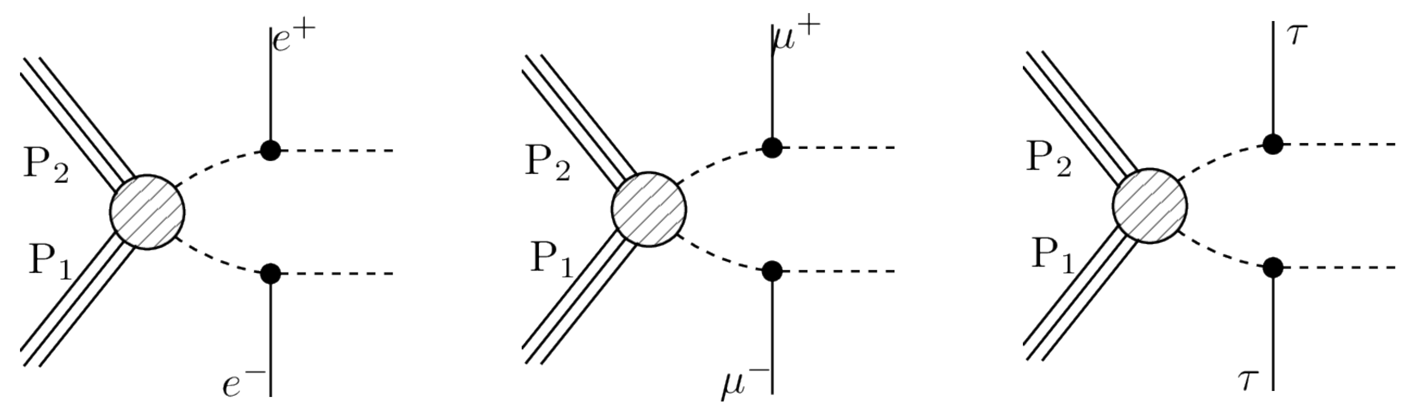
Signal is:

$25\%\ e^+e^-$

$25\%\ \mu^+\mu^-$

$50\%\ e^\pm\mu^\mp$

Efficiency maps available for:



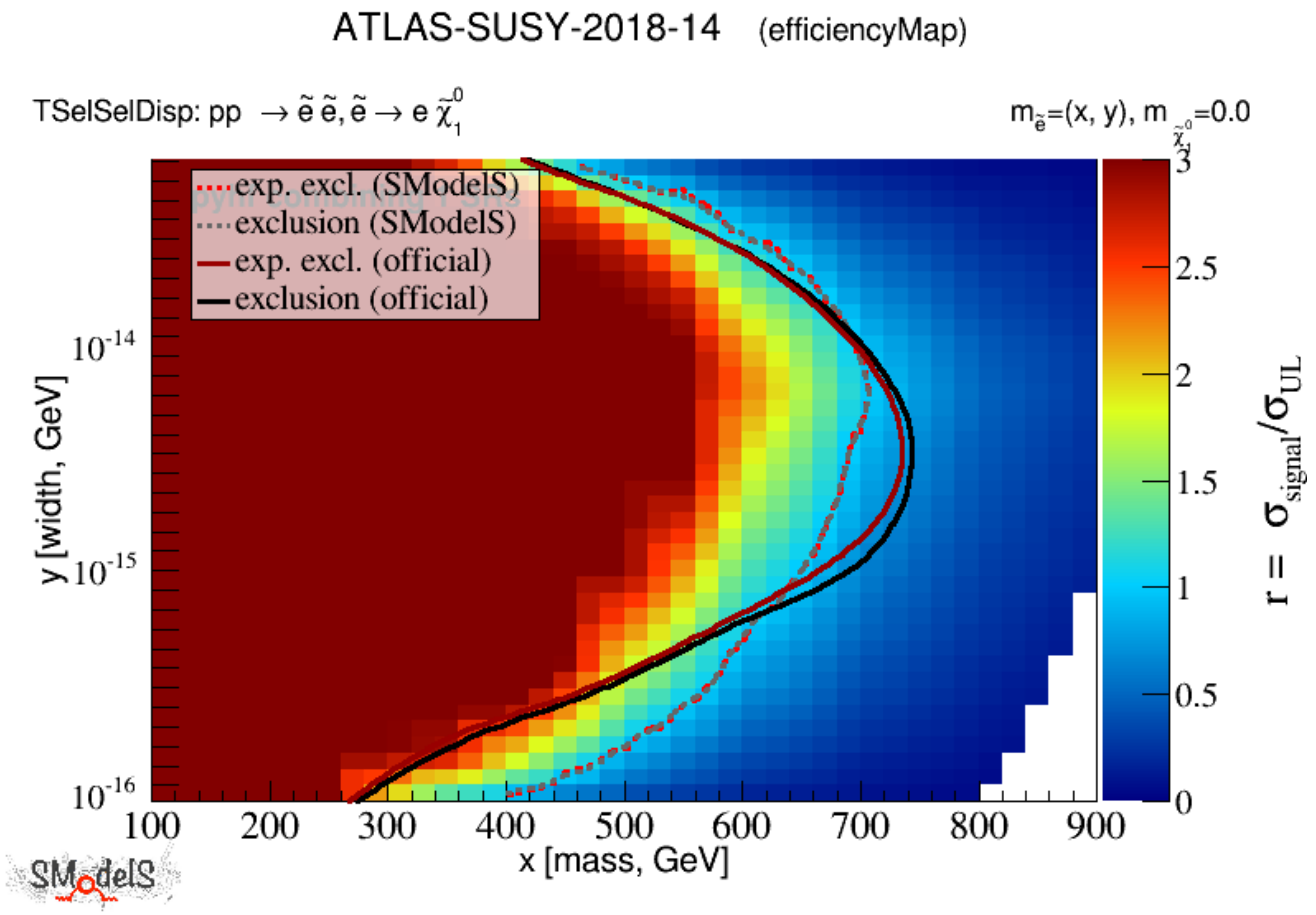
but not for different-flavour cases

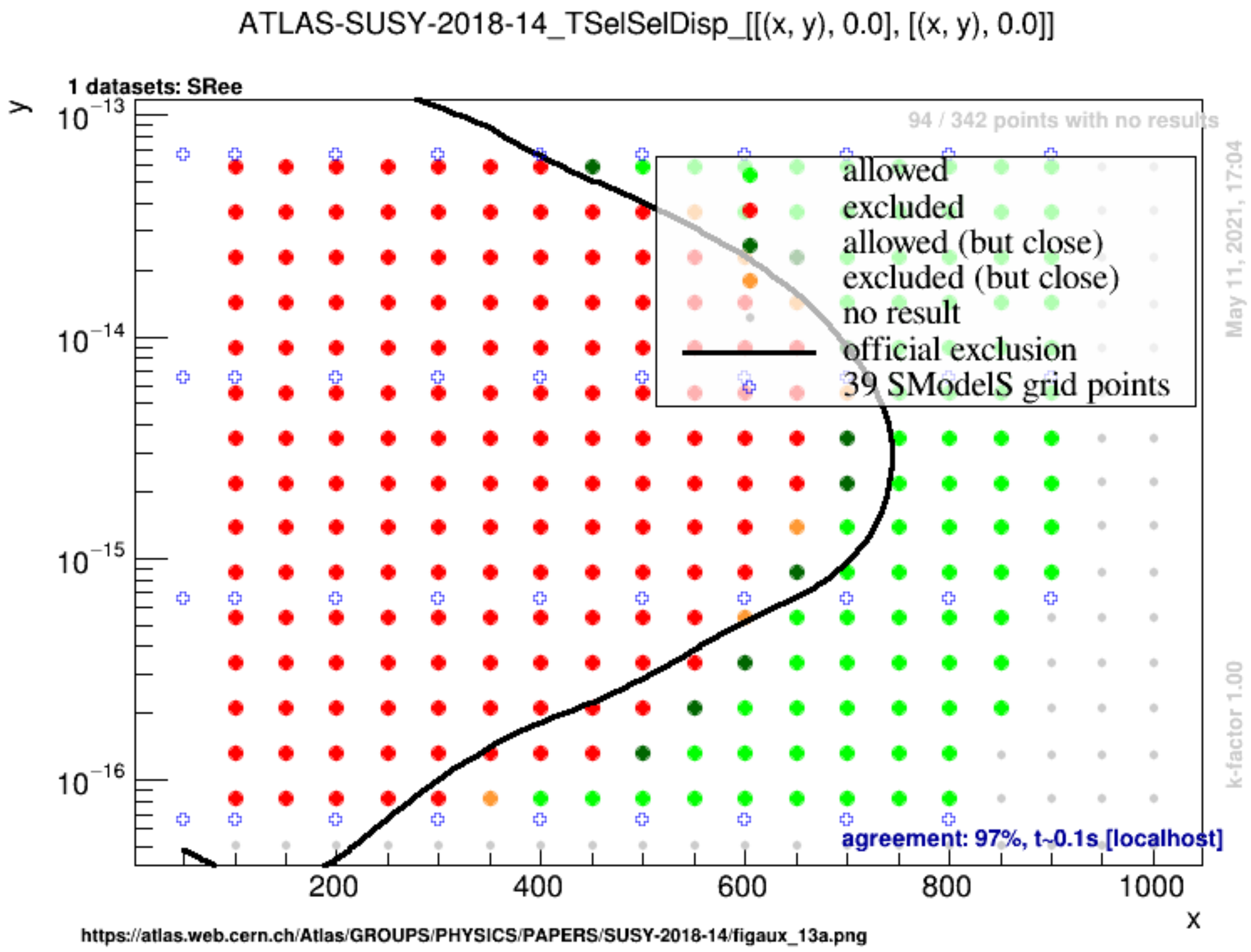
Limit without combining SRee and SRmm
>100 GeV weaker

Conclusions

- SModelS v2 can treat a large variety of LLP results: HSCP, DT, DV, …
- Lifetime-dependent efficiency maps are important to be able to
  - sum different contributions to the same signal region
  - compute likelihoods
- Statistical models in pyhf JSON formats allow us to combine signal regions
  → greatly improves reinterpretations !!
- pyhf patchsets can be used to extract efficiency maps!

Some comments/observations





Available lifetime grid is too coarse for the interpolation we need to do