



Sometimes I drive recklessly, just to kill off  
close copies of me in the multiverse.

# SUSY Predictions for ILC and CLIC

*Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)*

Fukuoka, 05/2017

- 1.** Introduction
- 2.** The MasterCode
- 3.** SUSY Fit Results for the ILC and CLIC
- 4.** New Theory Predictions for the ILC and CLIC
- 5.** Conclusions

# 1. Introduction

Some “recent” measurements:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

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Simple SUSY models predicted correctly:

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# 1. Introduction

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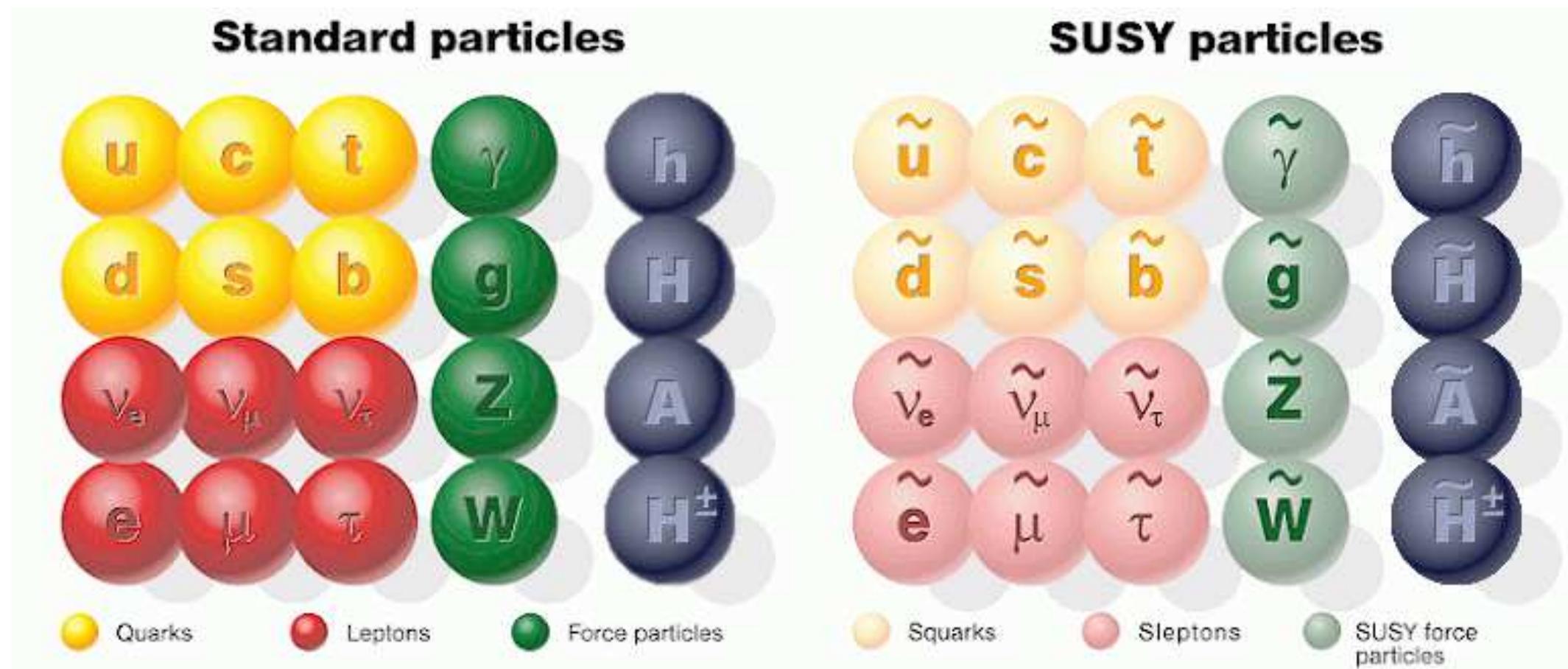
Simple SUSY models predicted correctly:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

⇒ good motivation to look at SUSY!

# The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature has so many free parameters!

## GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

$$m_0, m_{1/2}, A_0, \tan\beta, \text{sign } \mu$$

$m_0$  : universal scalar mass parameter

$m_{1/2}$  : universal gaugino mass parameter

$A_0$  : universal trilinear coupling

$\tan\beta$  : ratio of Higgs vacuum expectation values

$\text{sign}(\mu)$  : sign of supersymmetric Higgs parameter

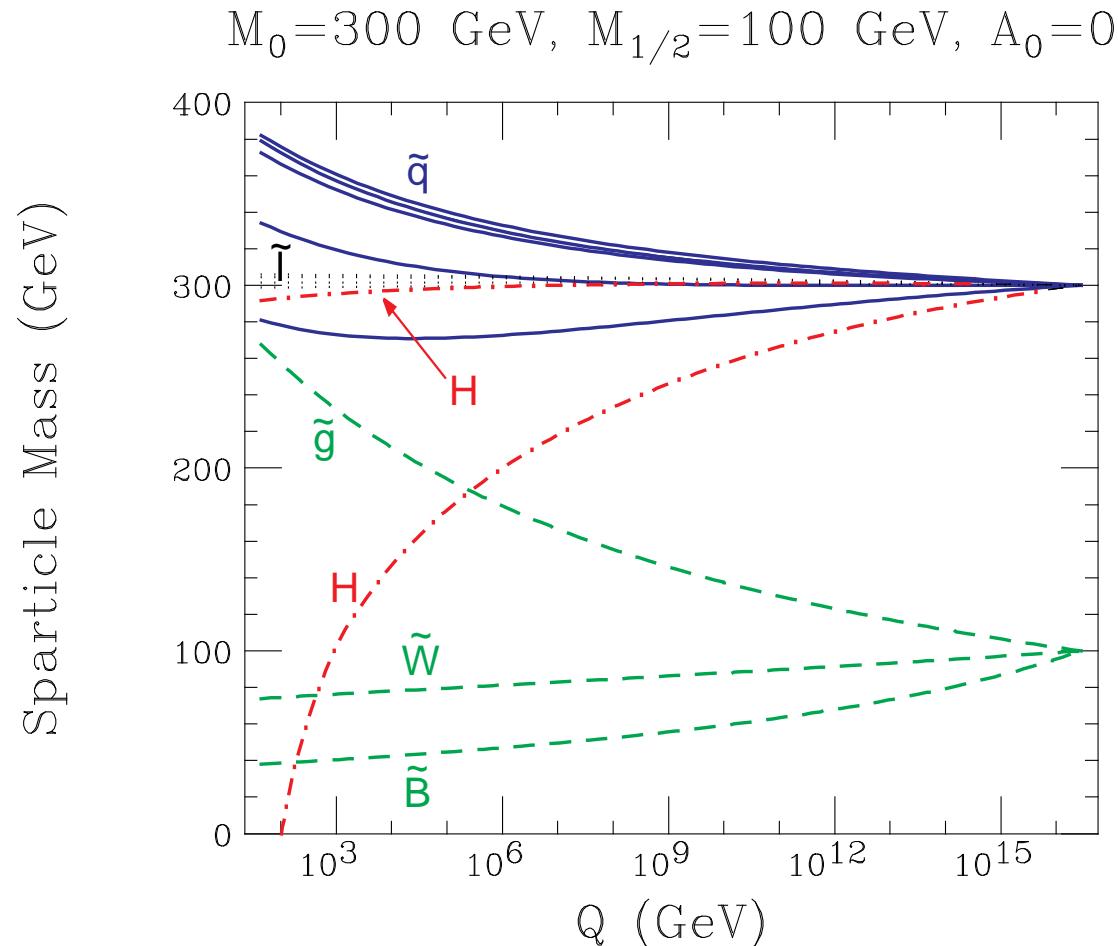
} at the GUT scale

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino ⇒ DM!

## GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

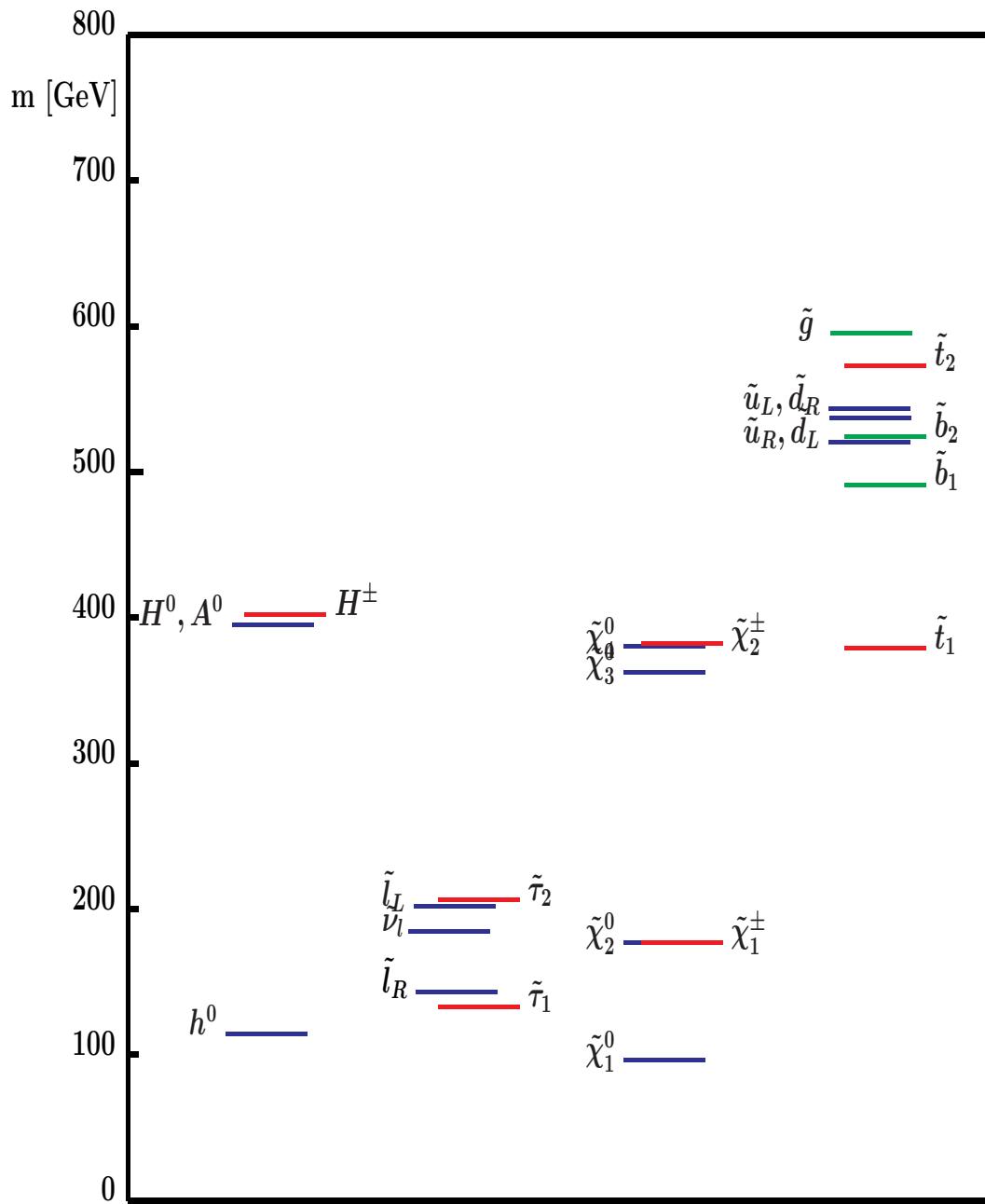
⇒ particle spectra from renormalization group running to weak scale



⇒ one parameter turns negative ⇒ Higgs mechanism for free

“Typical” CMSSM scenario  
(SPS 1a benchmark scenario):

Strong connection between  
all the sectors



## GUT based models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

⇒ effectively  $M_A$  as free parameters at the EW scale

⇒ Scenario characterized by

$$m_0, m_{1/2}, A_0, \tan\beta, \text{sign } \mu \text{ and } M_A$$

## GUT based models: 3.) NUHM2: (Non-universal Higgs mass model 2)

Assumption: no unification of scalar Higgs parameter at the GUT scale

⇒ effectively  $M_A$  and  $\mu$  as free parameters at the EW scale

⇒ Scenario characterized by

$$m_0, m_{1/2}, A_0, \tan\beta, \mu \text{ and } M_A$$

## GUT based models: 4.) SU(5) GUT:

Assumption I:

no unification of **scalar Higgs** parameter at the GUT scale

( $\Rightarrow$  effectively  $M_A$  and  $\mu$  as free parameters at the EW scale)

Assumption II:

$$(q_L, u_L^c, e_L^c)_i \in \mathbf{10}_i, (\ell_L, d_L^c)_i \in \bar{\mathbf{5}}_i$$

$\Rightarrow$  Scenario characterized by

$$m_5, m_{10}, m_{1/2}, A_0, \tan \beta, m_{H_u}, m_{H_d}$$

## GUT based models: 5.) mAMSB:

mAMSB scenario characterized by

$$m_{3/2}, m_0, \tan \beta, \text{sign}(\mu)$$

$m_{3/2} = \langle F \rangle / M_{\text{Planck}}$ : overall scale of SUSY particle masses

$m_0$ : phenomenological parameter: universal scalar mass term introduced in order to keep squares of slepton masses positive

typical feature: very small neutralino–chargino mass difference  
 $\Rightarrow \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi^\pm$  with very soft pions

## GUT based models: 6.) sub-GUT:

Based on CMSSM with unification at  $M_{\text{GUT}} \sim 2 \cdot 10^{16}$  GeV:

⇒ Scenario characterized by

$$m_0, m_{1/2}, A_0, \tan \beta, \text{sign } \mu$$

Unification is assumed at  $M_{\text{in}} \leq M_{\text{GUT}}$ :

⇒ Scenario characterized by

$$M_{\text{in}}, m_0, m_{1/2}, A_0, \tan \beta, \text{sign } \mu$$

Possible realization in “mirage unification”  
warped extra dimensions

...

## Problem: We cannot be sure about the SUSY-breaking mechanism

- ⇒ it is possible that with the CMSSM, NUHM, SU(5), mAMSB, sub-GUT we missed the “correct” mechanism
- ⇒ hint: strong connection between colored and uncolored sector tension between low-energy EW effects and (colored) LHC searches

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## Solution: investigate also the “general MSSM”

⇒ 11 parameters are manageable ⇒ pMSSM11

- squark mass parameters:  $m_{\tilde{q}_{1,2}} =: m_{\tilde{q}}$ ,  $m_{\tilde{q}_3}$
- slepton mass parameter(s):  $m_{\tilde{l}}$ ,  $m_{\tilde{\tau}}$
- gaugino masses:  $M_1$ ,  $M_2$ ,  $M_3$
- trilinear coupling:  $A$
- Higgs sector parameters:  $M_A$ ,  $\tan \beta$
- Higgs mixing parameter:  $\mu$

## 2. The Mastercode

⇒ collaborative effort of theorists and experimentalists

[*Bagnaschi, Borsato, Buchmüller, Cavanaugh, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Liu, Lucio, Martinez Santos, Olive, Richards, Sakurai, Weiglein*]

Über-code for the combination of different tools:

- Über-code original in Fortran, now re-written in C++
- tools are included as **subroutines**
- **compatibility** ensured by collaboration of authors of “MasterCode” and authors of “sub tools” **/SLHA(2)**
- sub-codes in Fortran or C++

⇒ evaluate observables of one parameter point consistently with various tools

[cern.ch/mastercode](http://cern.ch/mastercode)

## Data we have:

- Higgs boson mass/couplings/... (LHC)  $\Rightarrow$  FeynHiggs

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- SUSY searches (LHC)  $\Rightarrow$  own re-cast
- electroweak precision data  $\Rightarrow$  FeynWZ, FeynHiggs
- flavor data  $\Rightarrow$  SuperIso, SuFla
- astrophysical data (DM properties)  $\Rightarrow$  MicrOMEGAs, SSARD

The  $\chi^2$  evaluation:



## Global fits of SUSY

Experimental  
constraints

SUSY model

Mastercode

$$\chi^2 = \sum_i^{N_{meas}} \left( \frac{P_i - \mu_i}{\sigma_i} \right)$$

parameters

compatibility

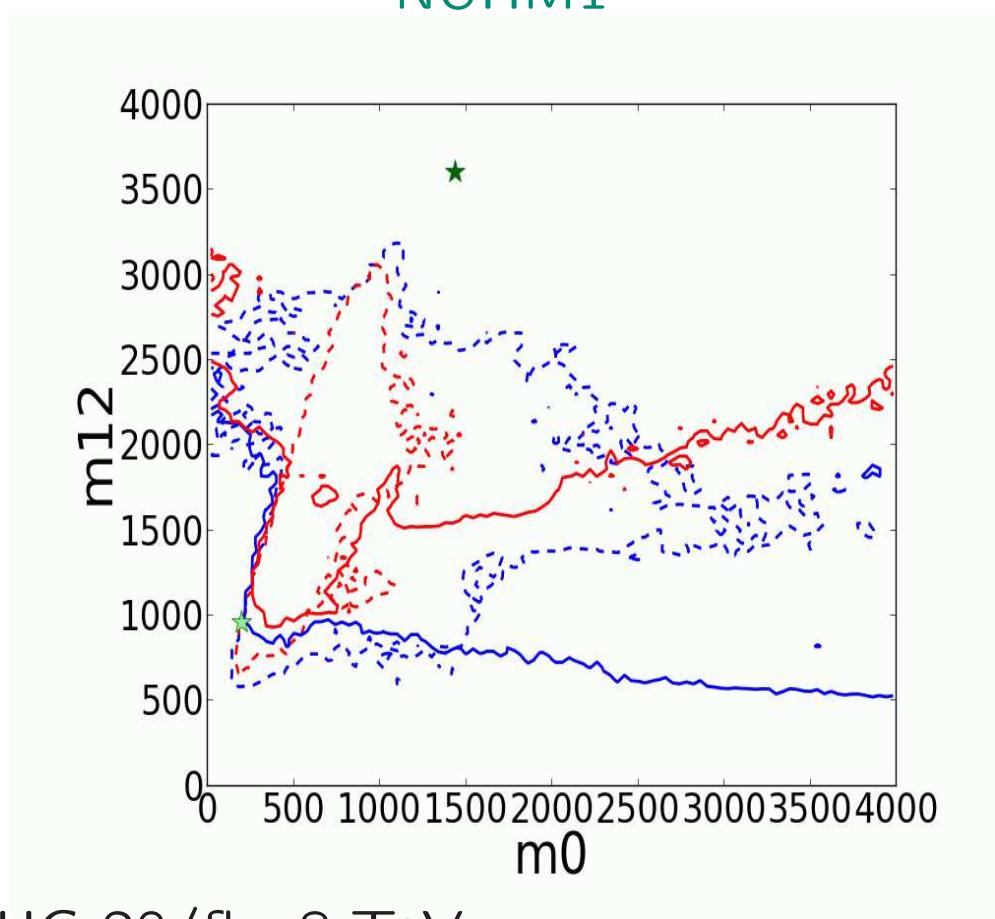
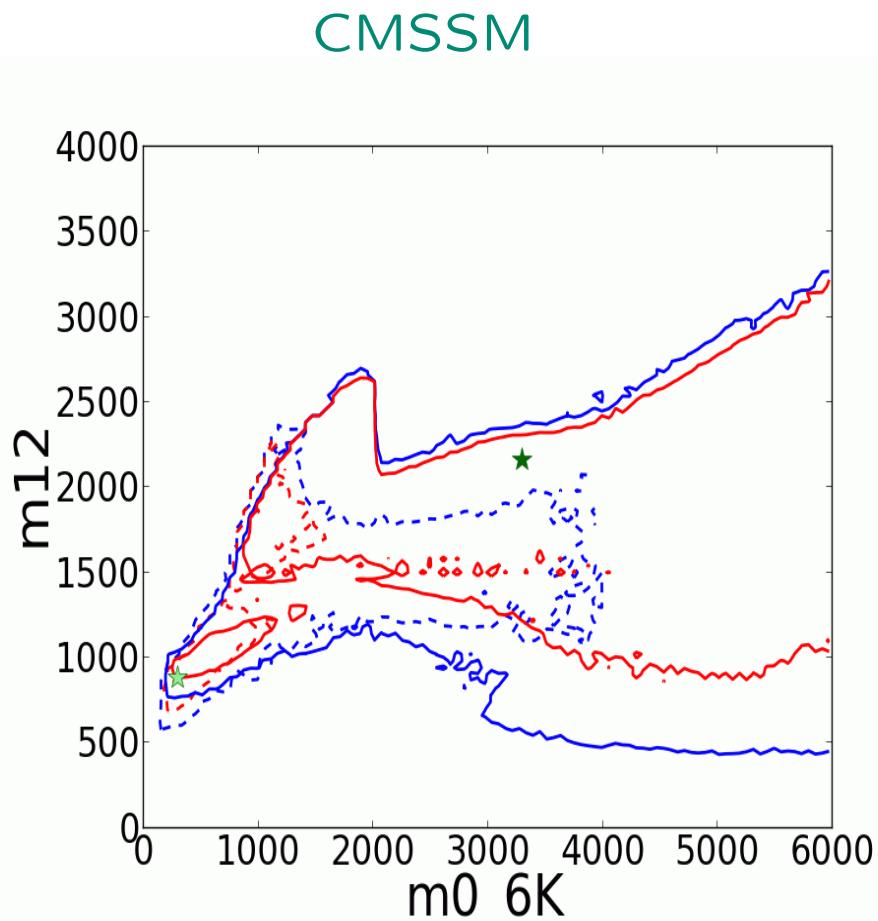
predictions

### 3. Predictions for the ILC and CLIC

$m_0$ - $m_{1/2}$  plane including LHC 20/fb:



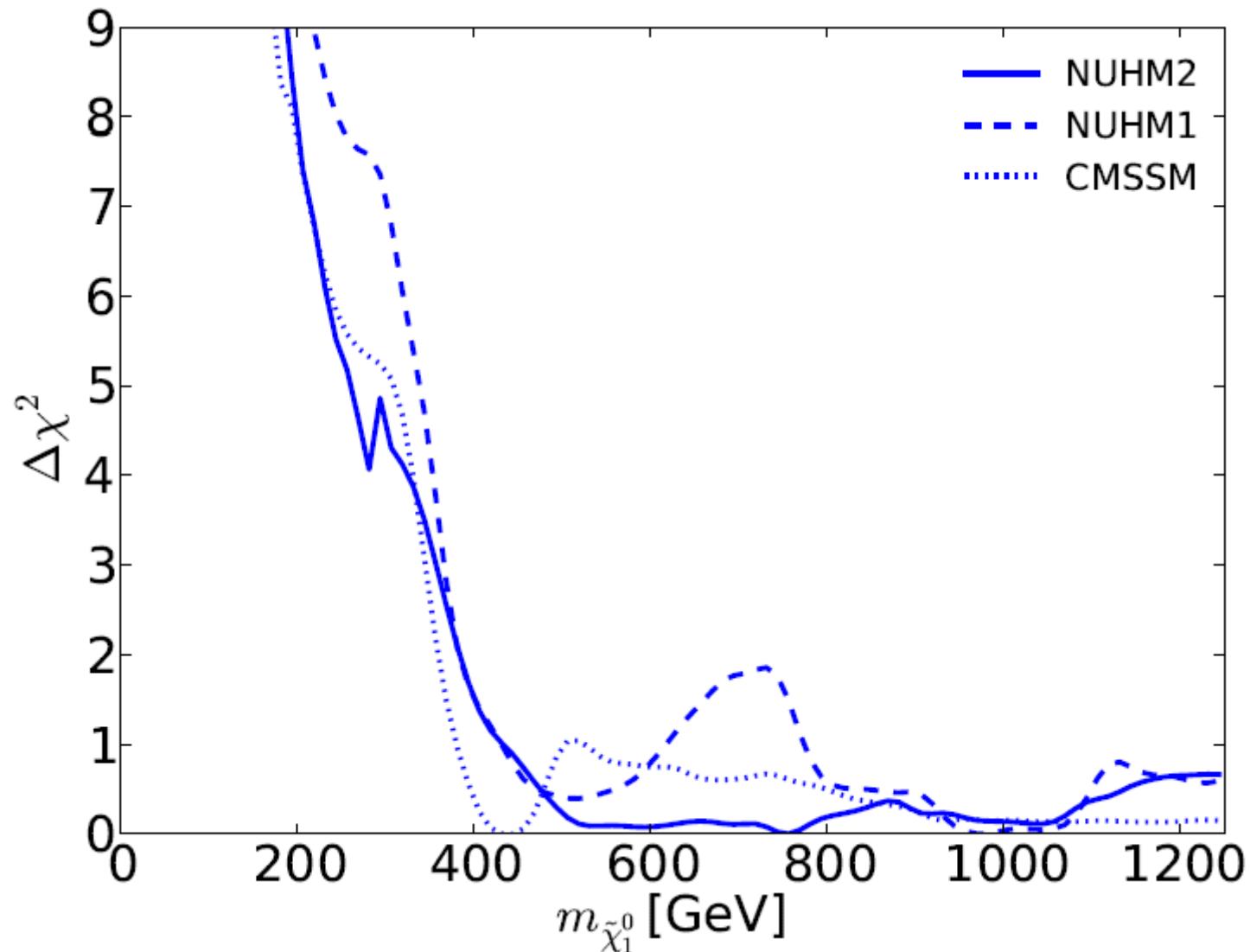
[2013]



dotted: LHC 5/fb 7 TeV, solid: LHC 20/fb 8 TeV

⇒ very high masses favored!

⇒ prospects for ILC and CLIC?

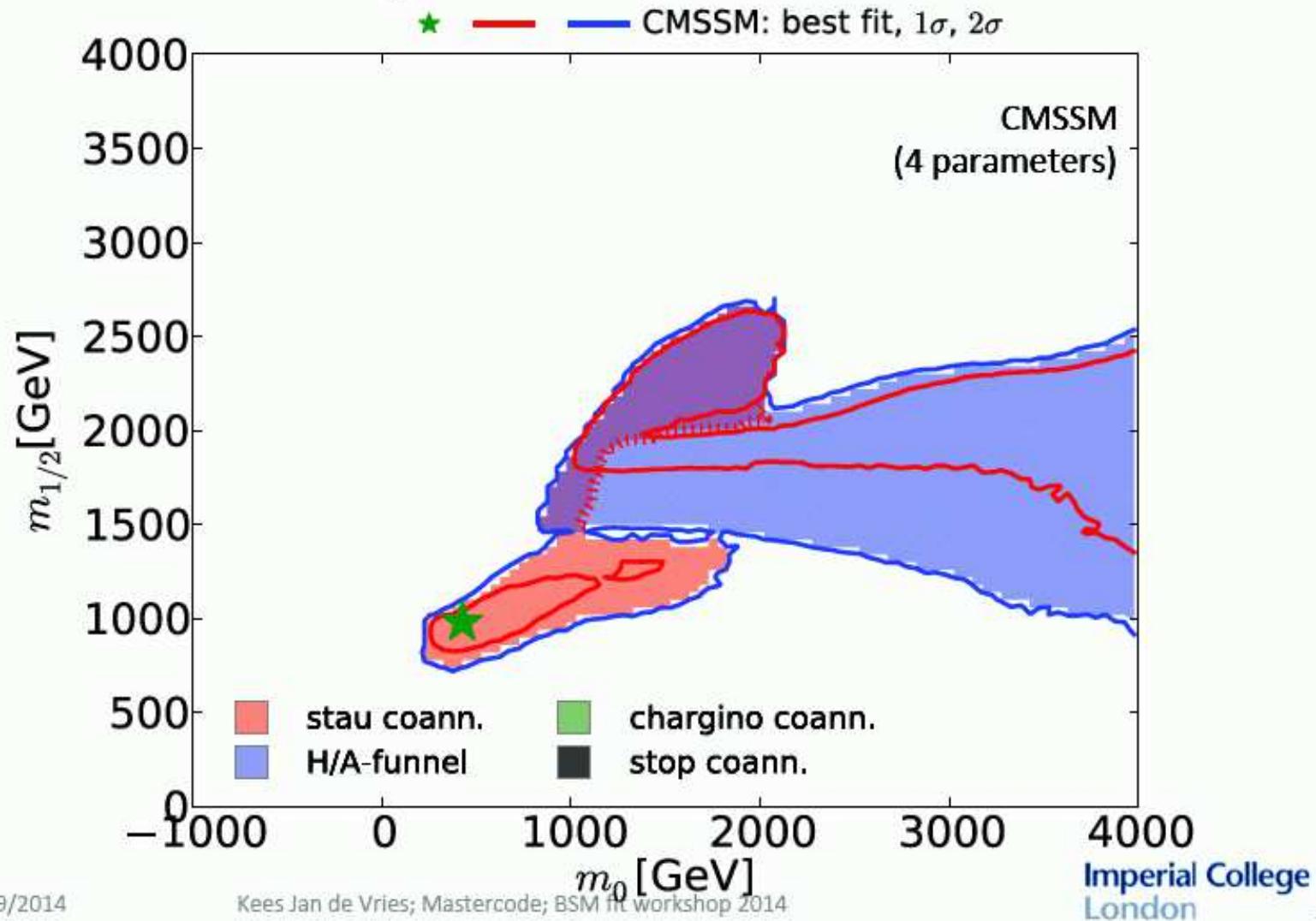


⇒ only very large values are favored

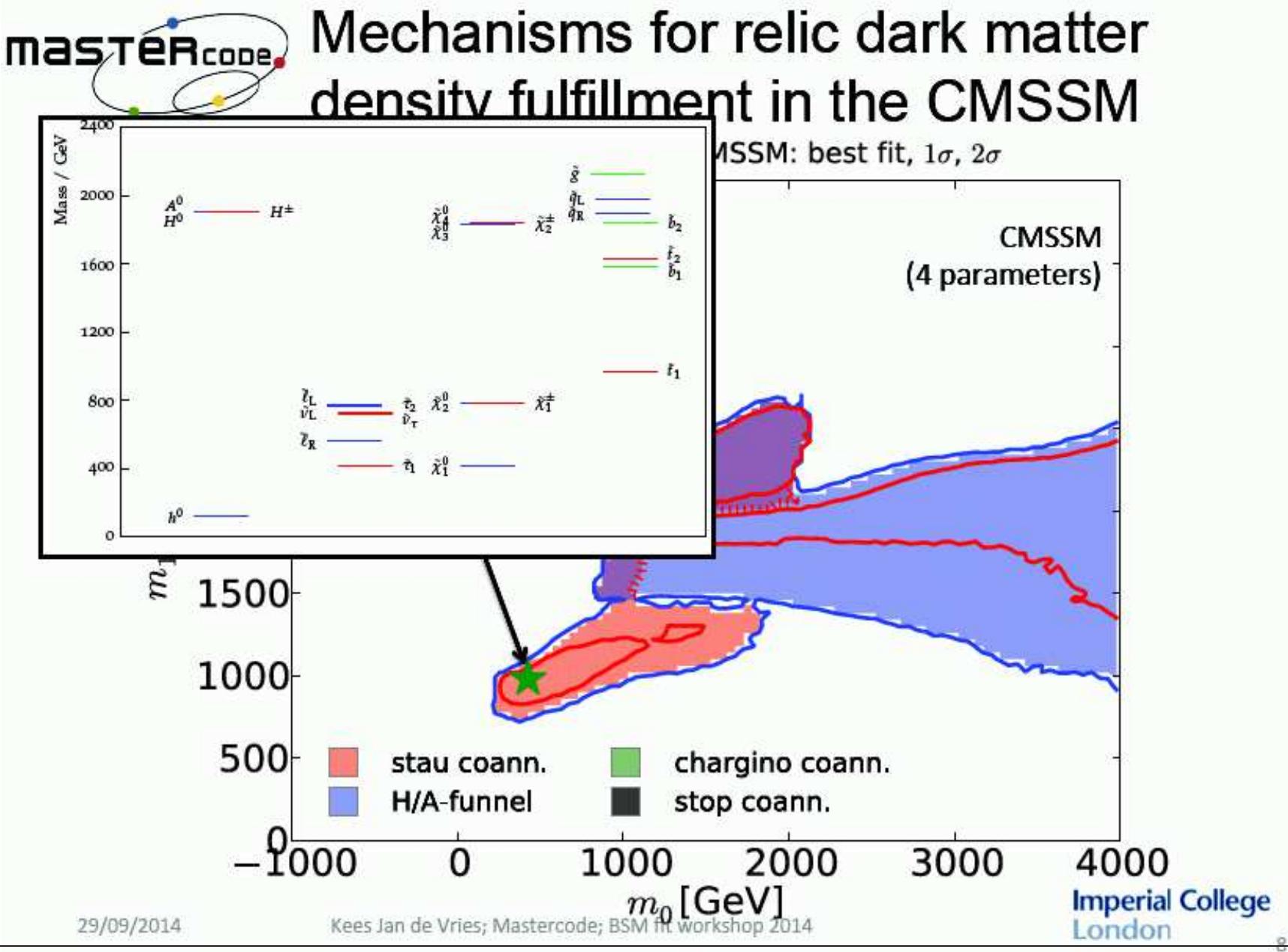
## CMSSM best-fit point prediction



## Mechanisms for relic dark matter density fulfillment in the CMSSM



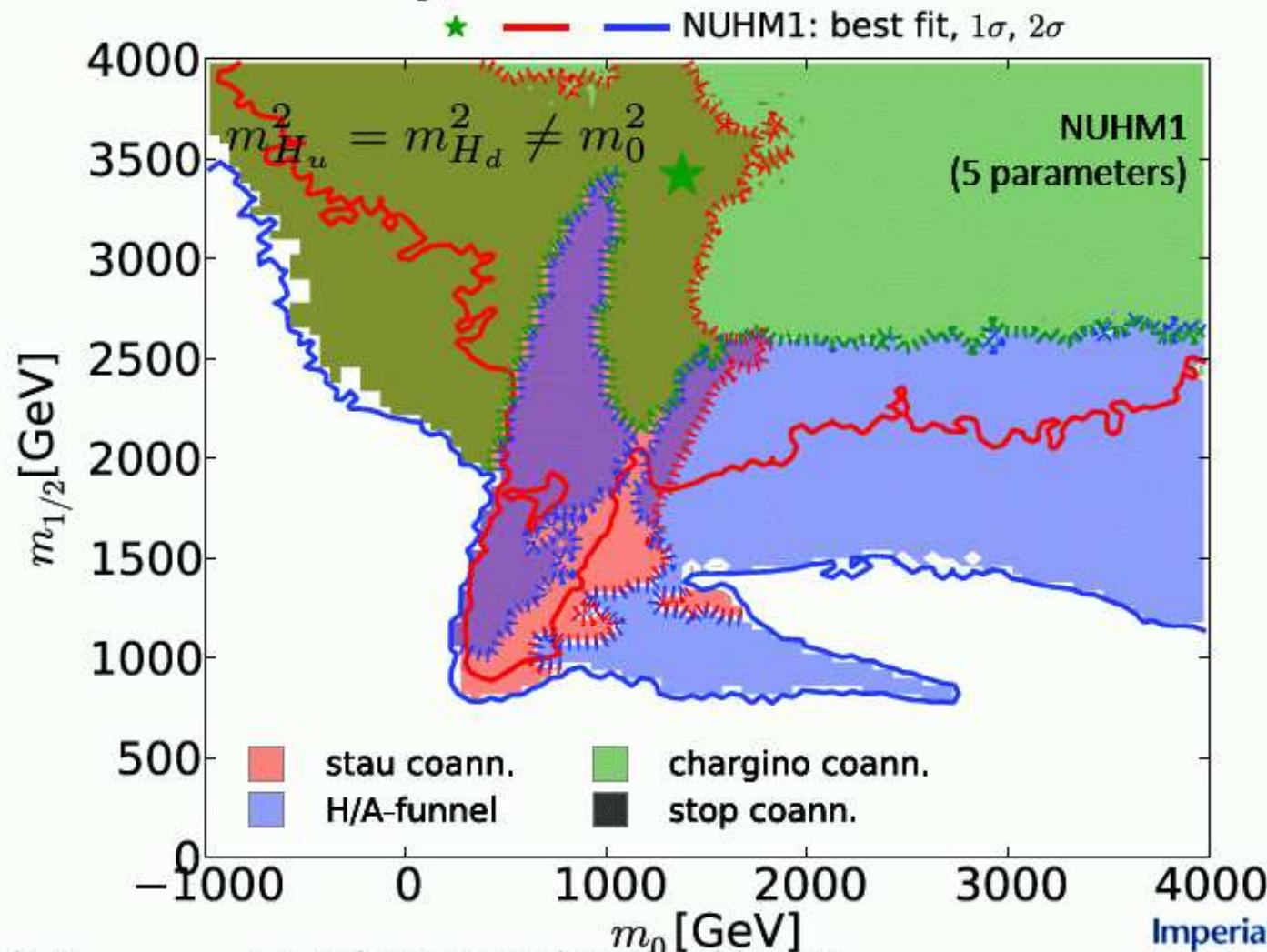
## CMSSM best-fit point prediction



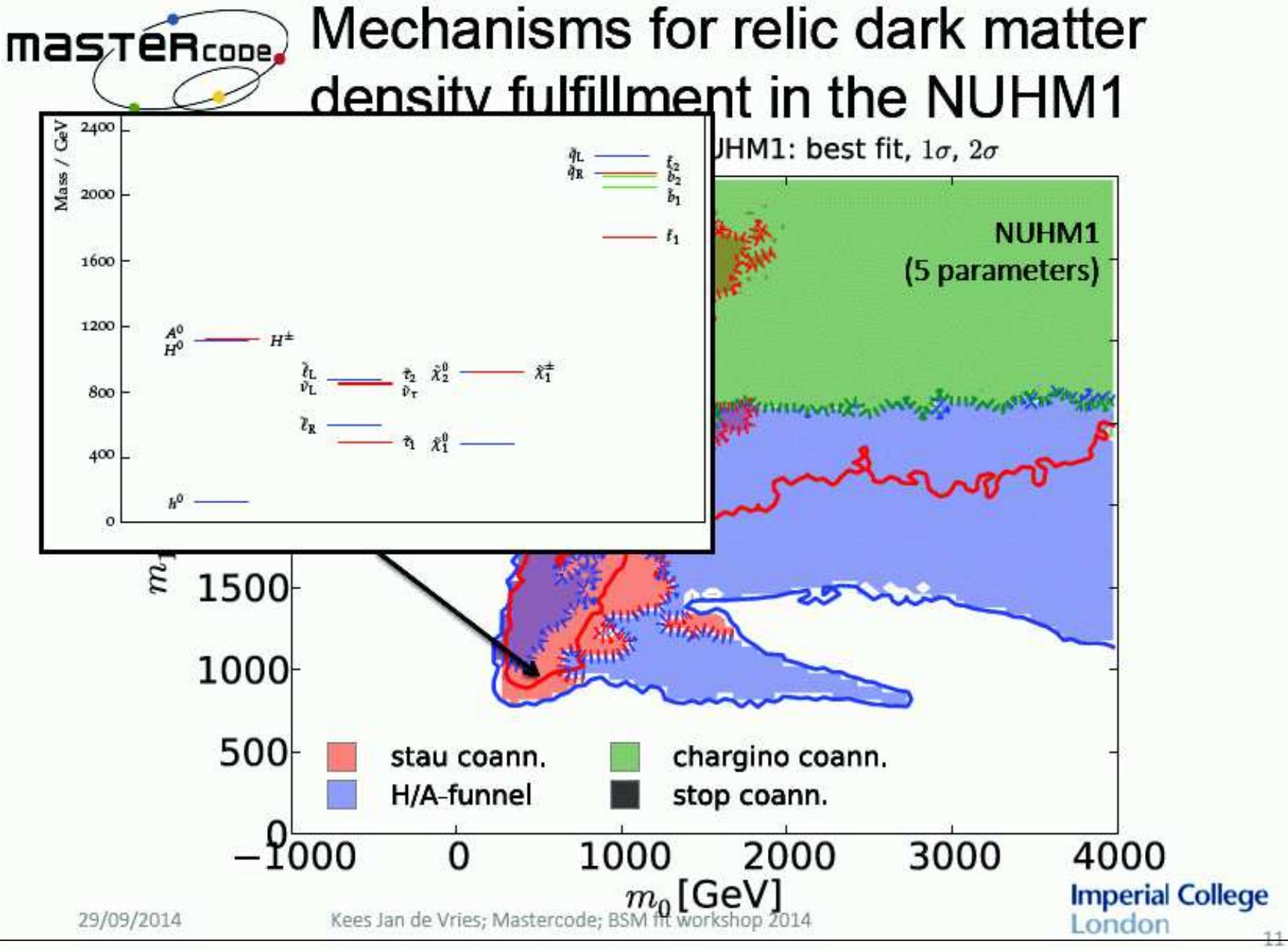
## NUHM1 best-fit point prediction



# Mechanisms for relic dark matter density fulfillment in the NUHM1



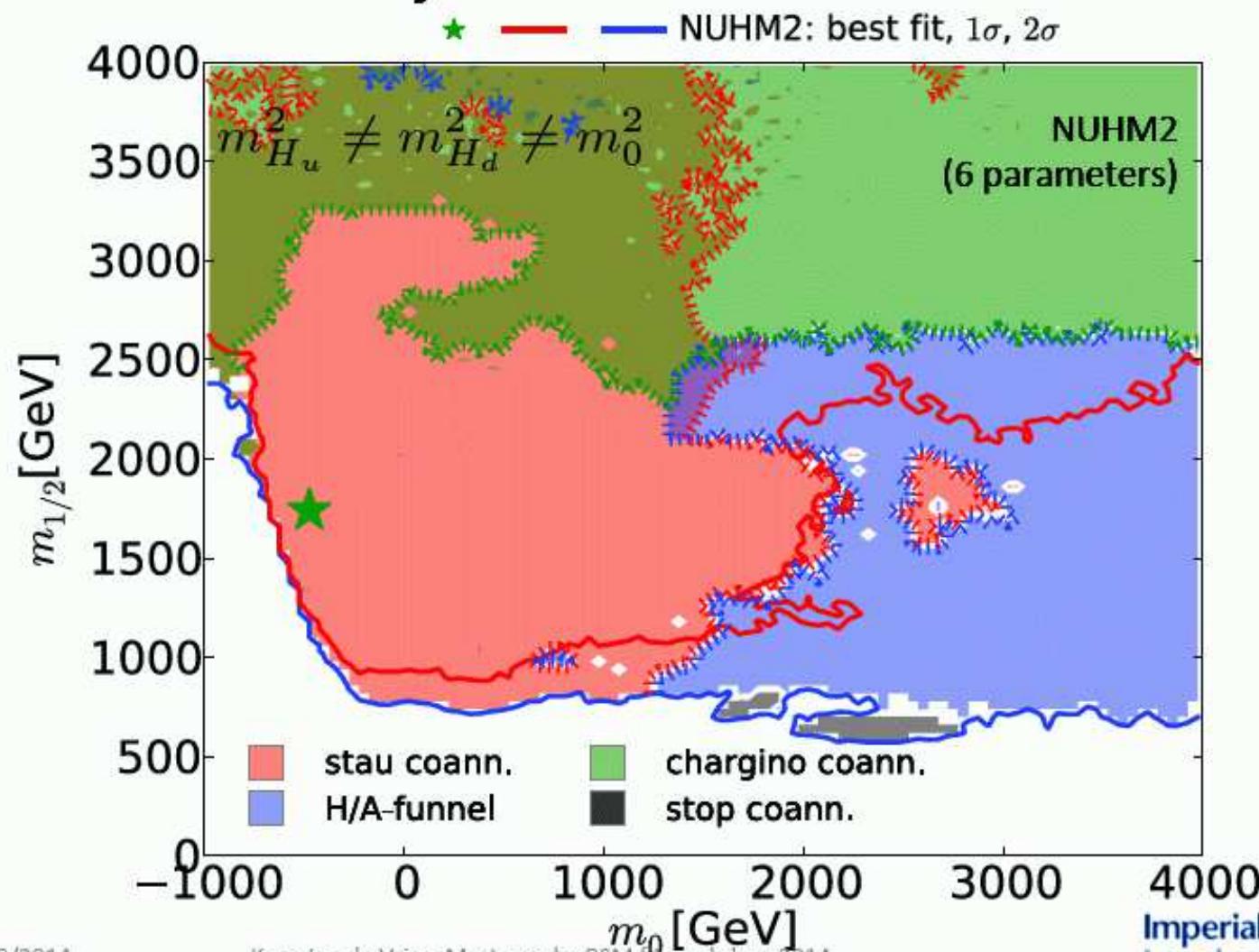
## NUHM1 best-fit point prediction



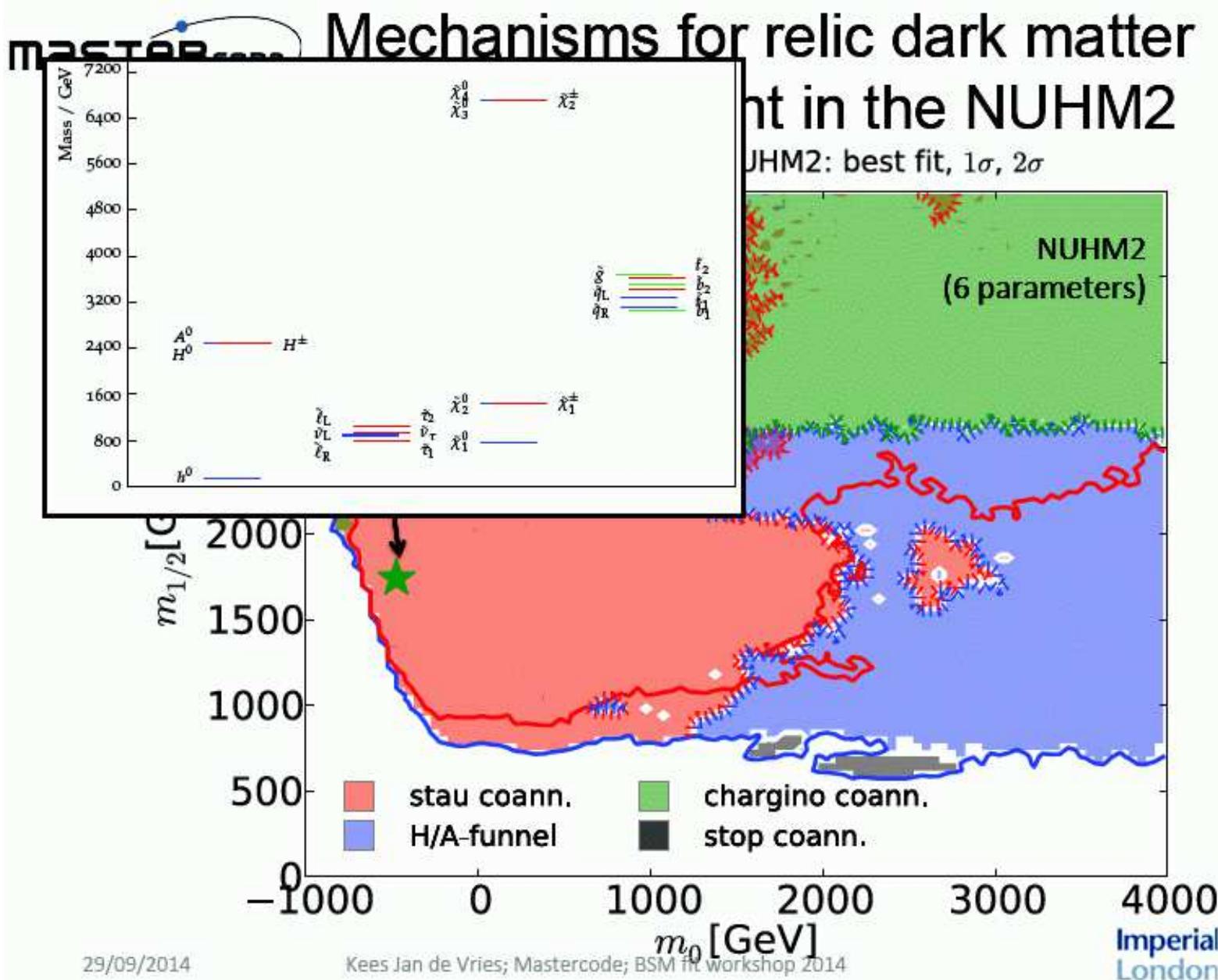
## NUHM2 best-fit point prediction



# Mechanisms for relic dark matter density fulfillment in the NUHM2



## NUHM2 best-fit point prediction

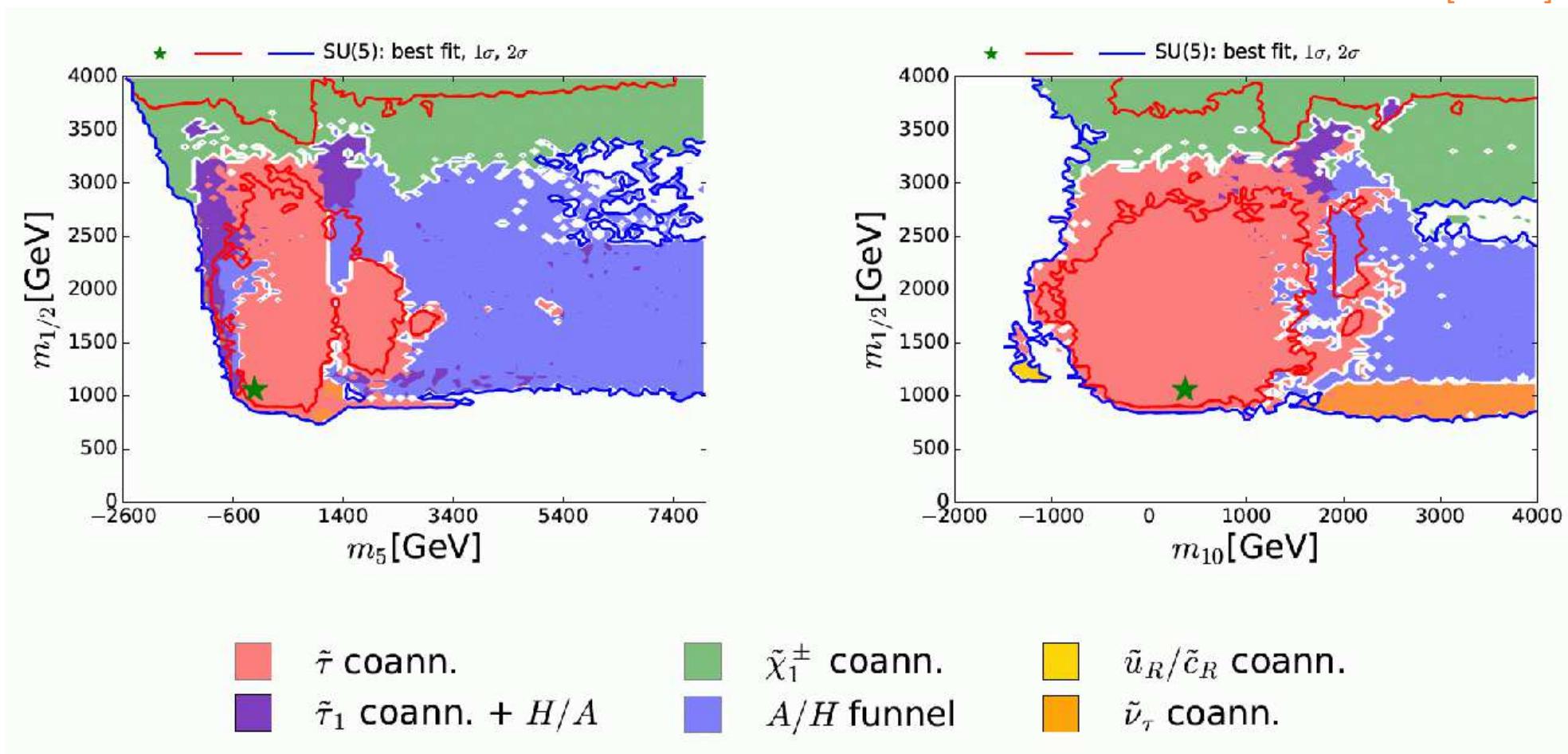


# Results in the SU(5)



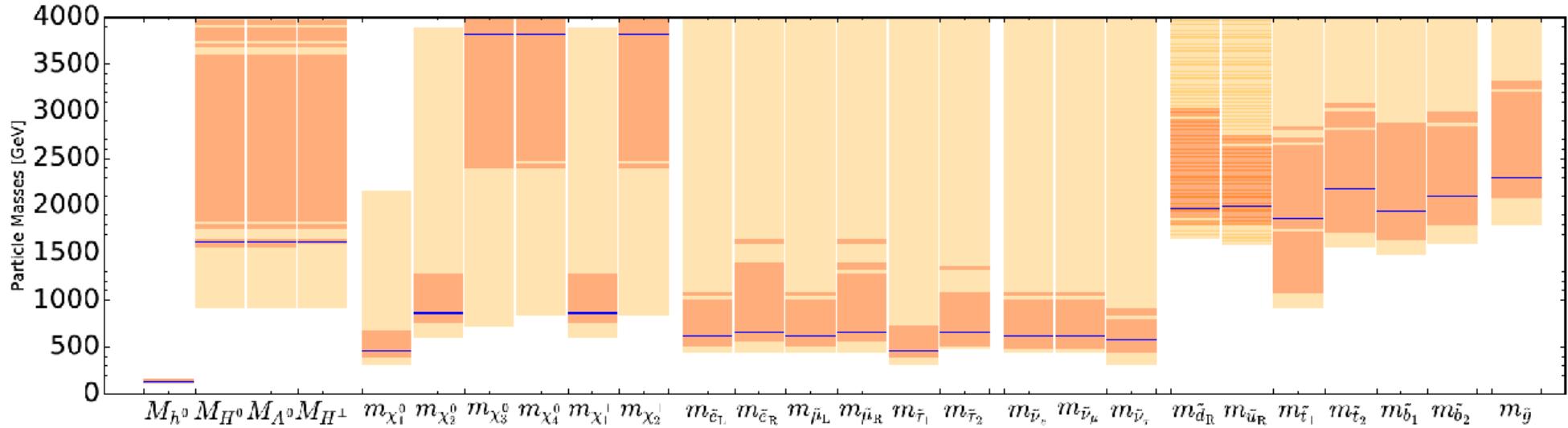
[2016]

## Dark Matter annihilation mechanism:



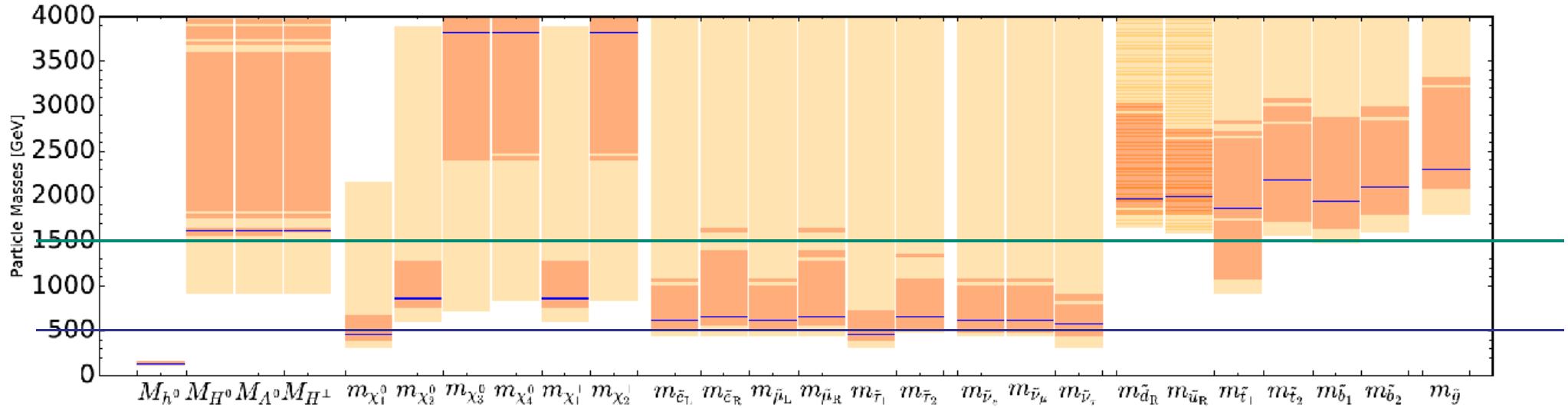
$\Rightarrow \tilde{u}_R/\tilde{c}_R/\tilde{\nu}_\tau$  co-ann. possible  $\Rightarrow$  but  $\tilde{\tau}_1$  co-ann. dominant!

## SU(5) prediction: best-fit masses



- ⇒ high colored masses
- ⇒ lower electroweak masses  
partially with not too large  $1\sigma$  ranges
- ⇒ clear prediction for ILC and CLIC

## SU(5) prediction: best-fit masses



ILC:  $\sqrt{s} = 1000$  GeV  $\Rightarrow$  only few EW particles possibly accessible

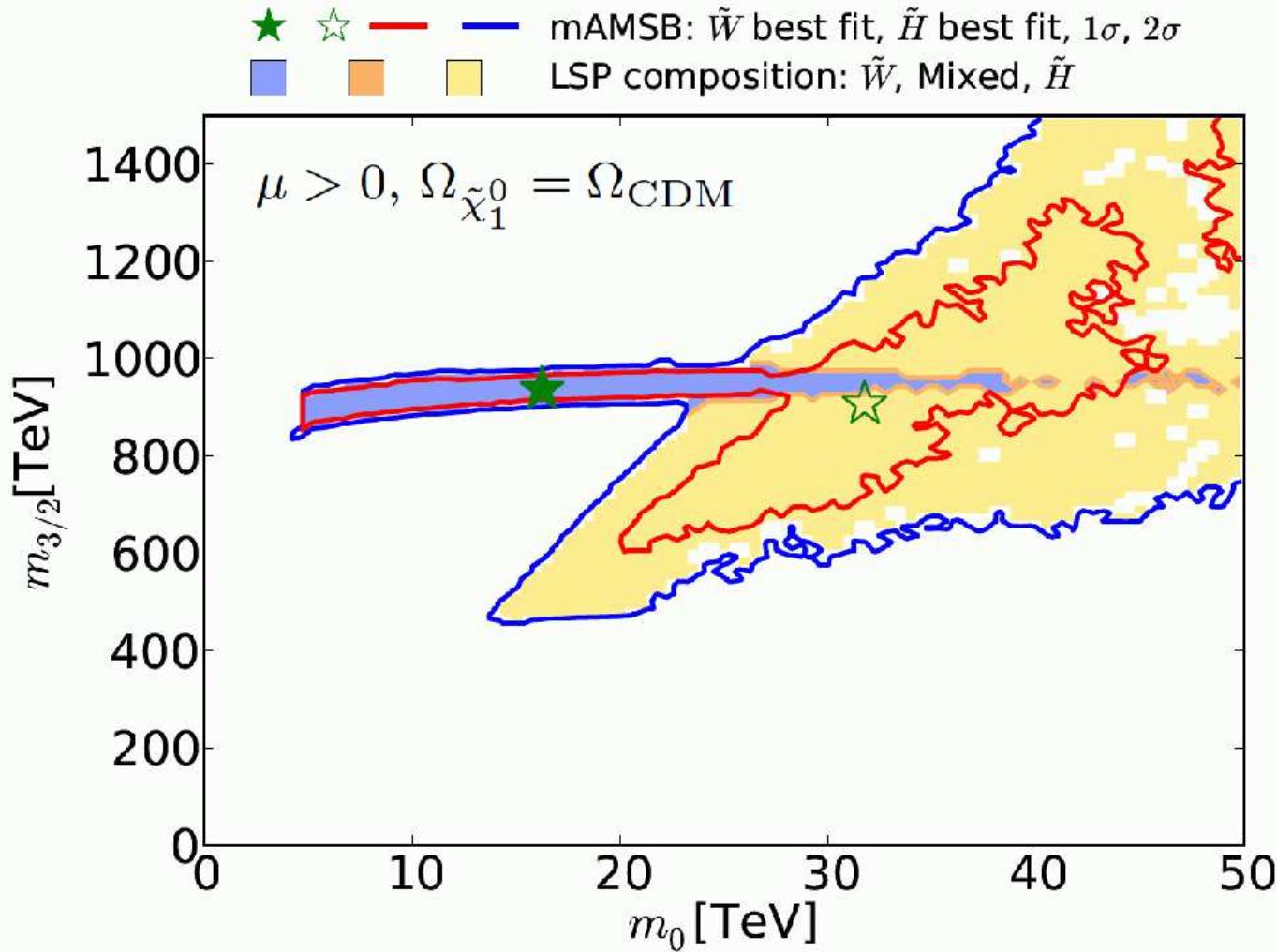
CLIC:  $\sqrt{s} = 3000$  GeV  $\Rightarrow$  pair production of many SUSY particles “likely”  
 $\Rightarrow$  no access to colored particles

## Results in the mAMSB



[2016]

### Dark Matter composition:

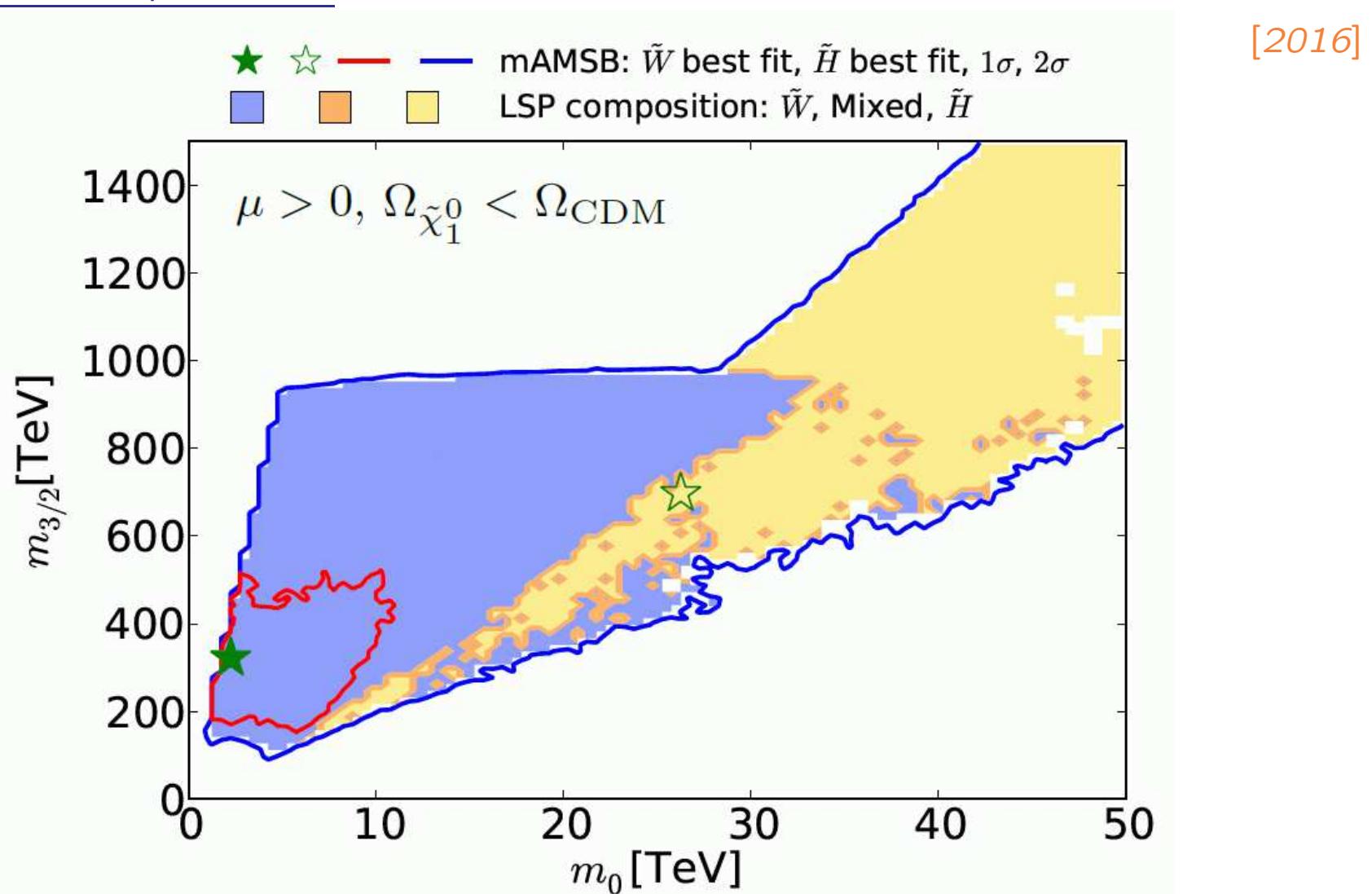


⇒  $m_{\tilde{\chi}_1^0} \sim 2.9 \pm 0.1 \text{ TeV}$  (wino),  $\sim 1.1 \pm 0.02 \text{ TeV}$  (higgsino)

## Results in the mAMSB



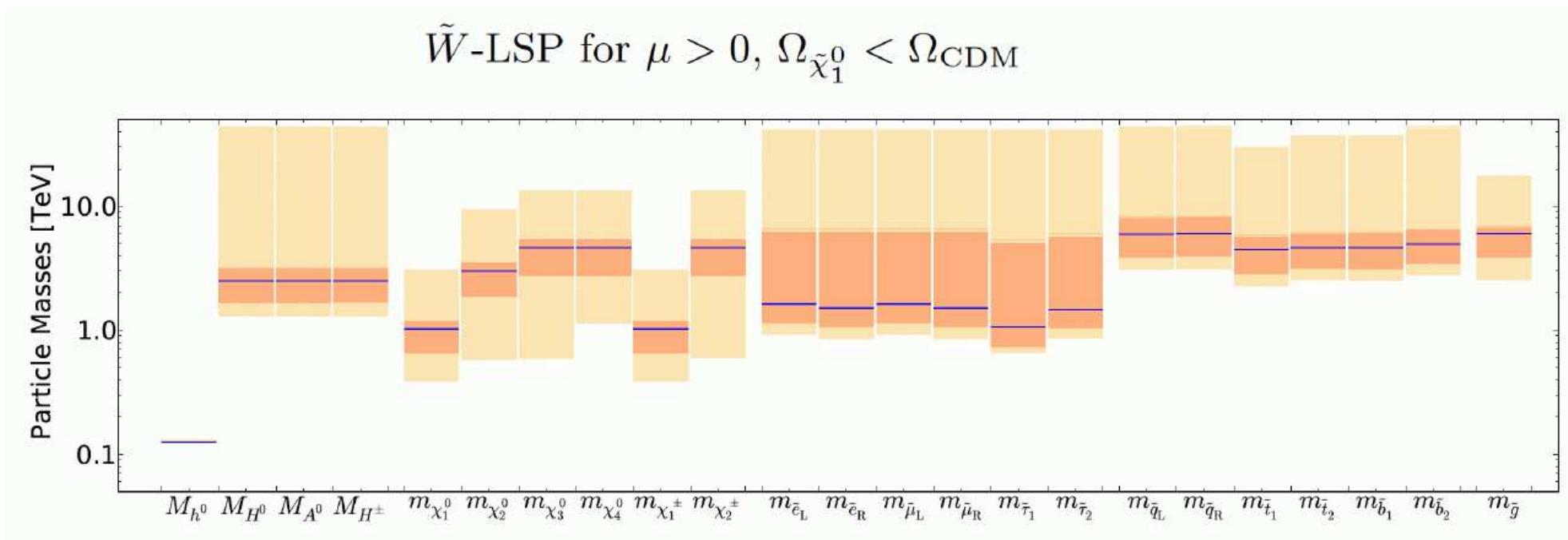
Dark Matter composition:



⇒ very relaxed limits ⇒ lower masses

## mAMSB prediction: best-fit masses (wino)

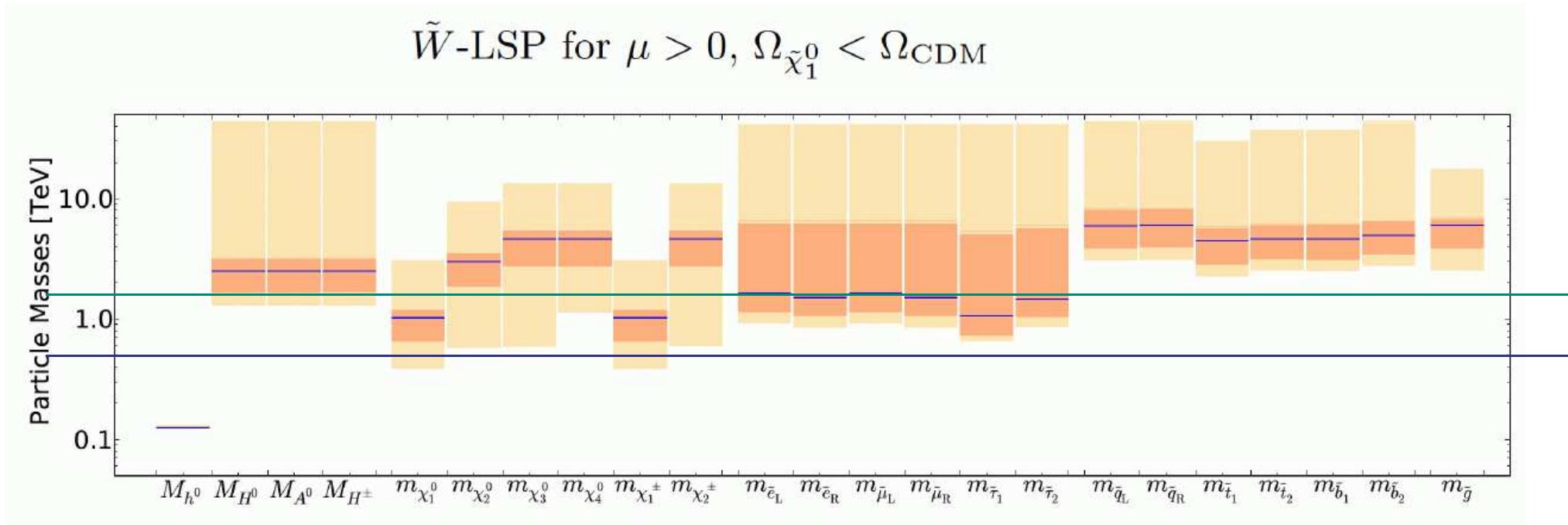
[2016]



- high colored masses
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partially with not too large  $1\sigma$  ranges
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## mAMSB prediction: best-fit masses (wino)

[2016]

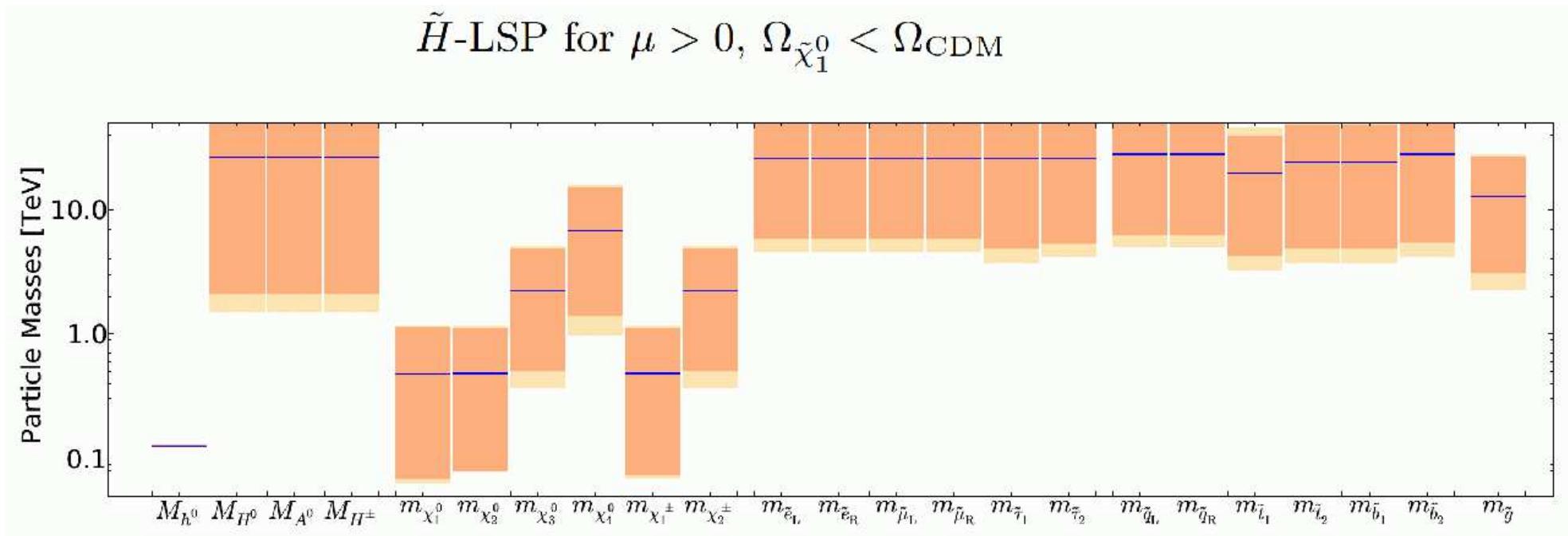


ILC:  $\sqrt{s} = 1000 \text{ GeV} \Rightarrow \text{bad prospects}$

CLIC:  $\sqrt{s} = 3000 \text{ GeV} \Rightarrow \text{pair production of few SUSY particles "likely"} \\ \Rightarrow \text{no access to colored particles}$

## mAMSB prediction: best-fit masses (higgsino)

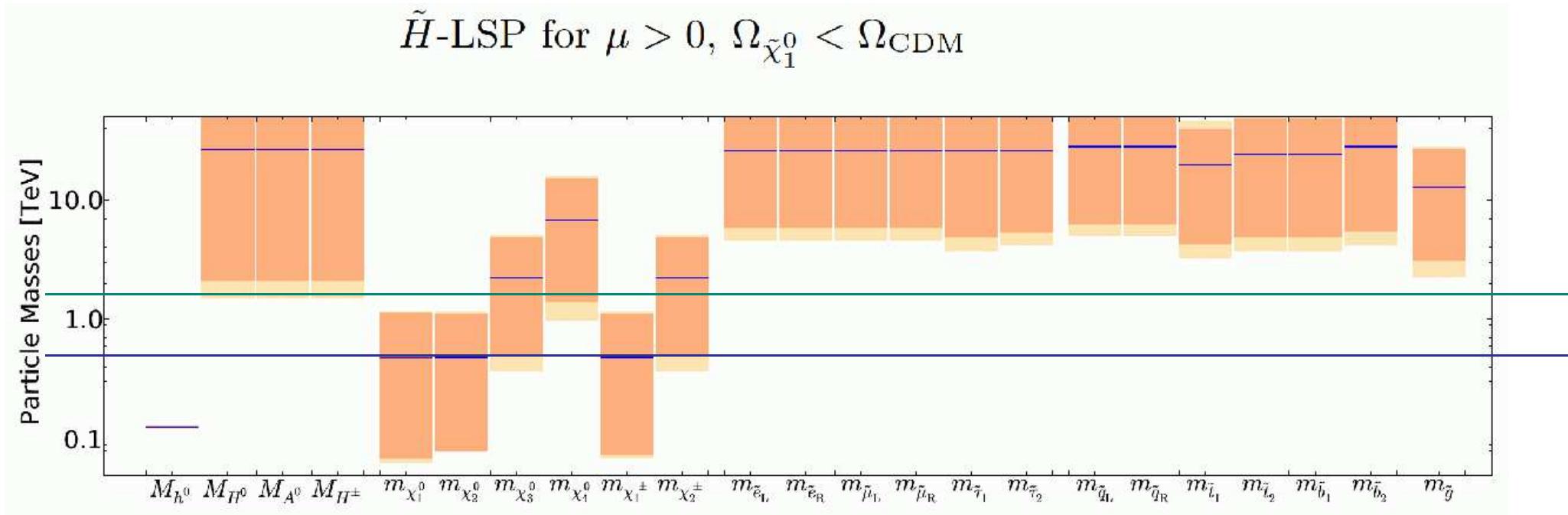
[2016]



- ⇒ high colored masses
- ⇒ some(!) lower electroweak masses  
partially with not too large  $2\sigma$  ranges
- ⇒ clear prediction for ILC and CLIC

## mAMSB prediction: best-fit masses (higgsino)

[2016]

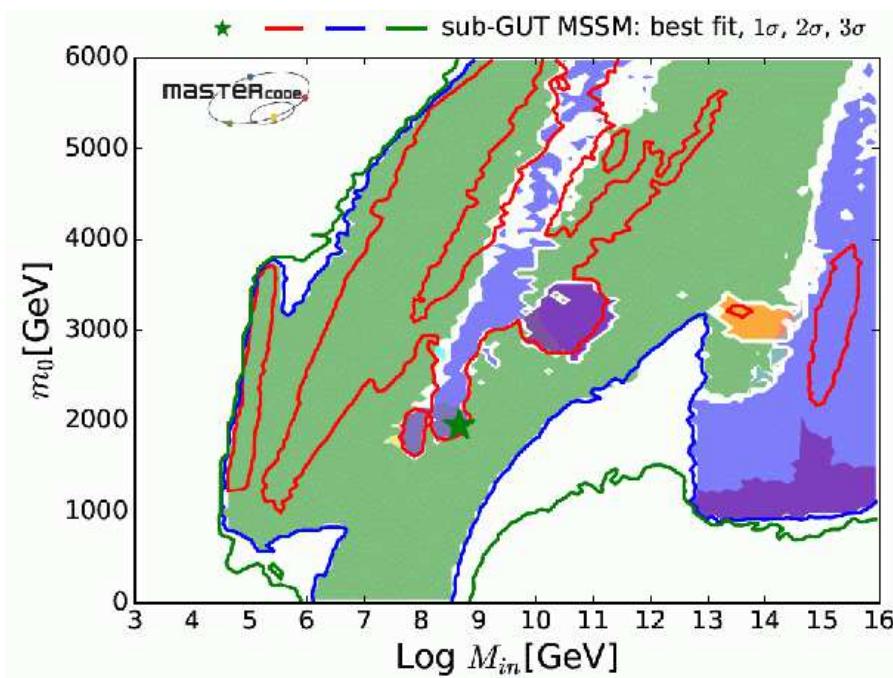


ILC:  $\sqrt{s} = 1000 \text{ GeV} \Rightarrow$  few EW particles possibly accessible

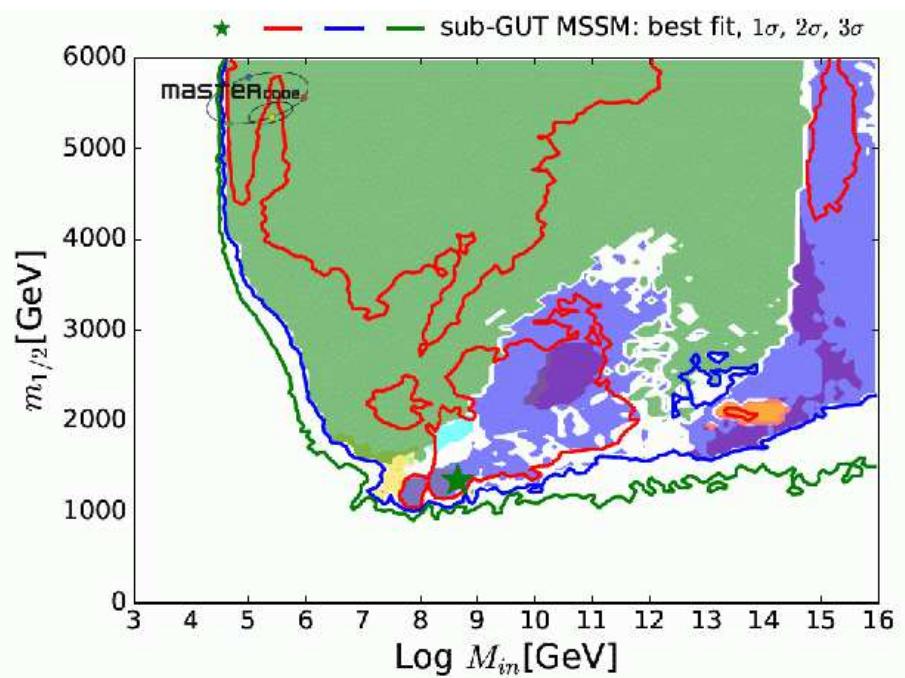
CLIC:  $\sqrt{s} = 3000 \text{ GeV} \Rightarrow$  pair production of few SUSY particles  
 “guaranteed”  
 $\Rightarrow$  no access to colored particles

## Results in sub-GUT

[2017]



$\tilde{\chi}_1^\pm$ coann.	$\tilde{\tau}_1$ coann.
$A/H$ funnel	focus point
$\tilde{t}_1$ coann.	$\tilde{t}_1$ coann. + $H/A$ funnel



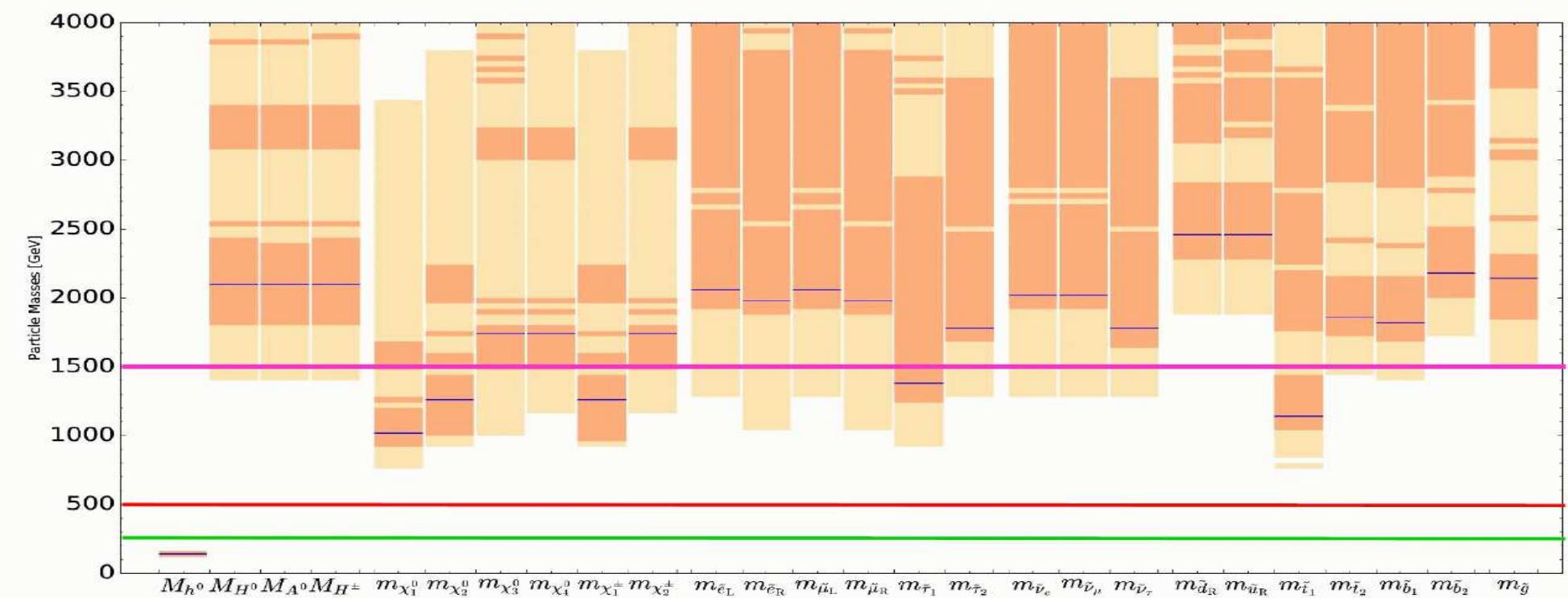
$\tilde{\tau}_1 + \tilde{t}_1$ coann.
$\tilde{t}_1 + \tilde{\chi}_1^\pm$ coann.
$\tilde{\tau}_1$ coann. + $\tilde{t}_1$ coann. + $H/A$

⇒ low  $M_{in}$  possible/favored

⇒ mainly due to  $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$

## sub-GUT prediction: best-fit masses

[2017]



⇒ high colored masses  
⇒ high electroweak masses

ILC:  $\sqrt{s} = 1000 \text{ GeV}$  ⇒ nothing

CLIC:  $\sqrt{s} = 3000 \text{ GeV}$  ⇒ pair production of few SUSY particles  
⇒ no access to colored particles

## Intermediate summary (simplified):

- data: Higgs, LHC searches, DM measurements/searches, EW, flavor
- GUT based models exhibit a heavy spectrum
- very difficult for the LHC
- ILC has to be “lucky” (I did not discuss it’s great Higgs/EW capabilities)
- CLIC has some particles in reach
- colored spectrum could partially be covered at FCC-hh

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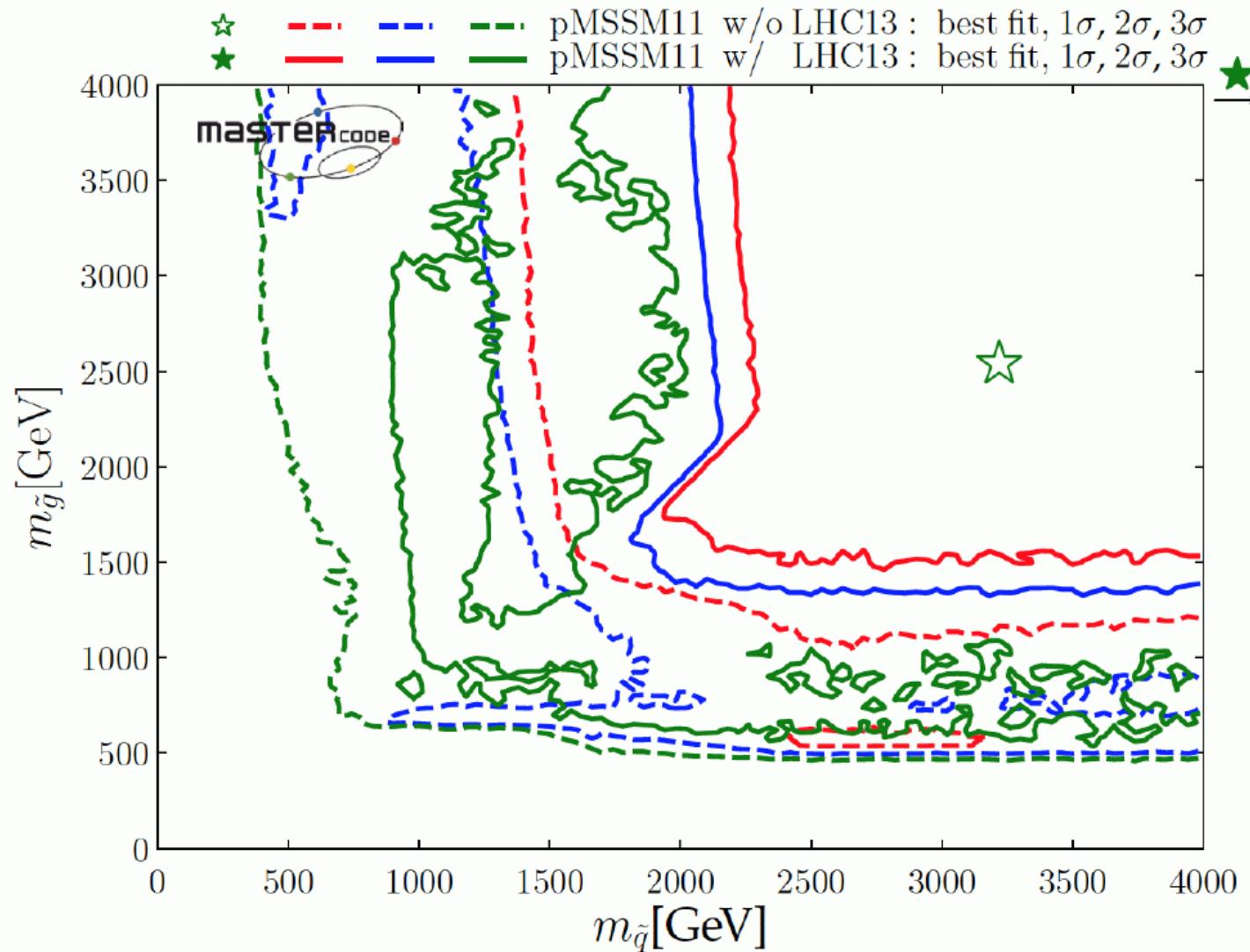
Let's look at the more general pMSSM11!

## Results and predictions in the pMSSM11

Parameter	Range	Number of segments
$M_1$	(-4 , 4 ) TeV	6
$M_2$	( 0 , 4 ) TeV	2
$M_3$	(-4 , 4 ) TeV	4
$m_{\tilde{q}}$	( 0 , 4 ) TeV	2
$m_{\tilde{q}_3}$	( 0 , 4 ) TeV	2
$m_{\tilde{l}}$	( 0 , 2 ) TeV	1
$m_{\tilde{\tau}}$	( 0 , 2 ) TeV	1
$M_A$	( 0 , 4 ) TeV	2
$A$	(-5 , 5 ) TeV	1
$\mu$	(-5 , 5 ) TeV	1
$\tan \beta$	( 1 , 60)	1
Total number of boxes		384

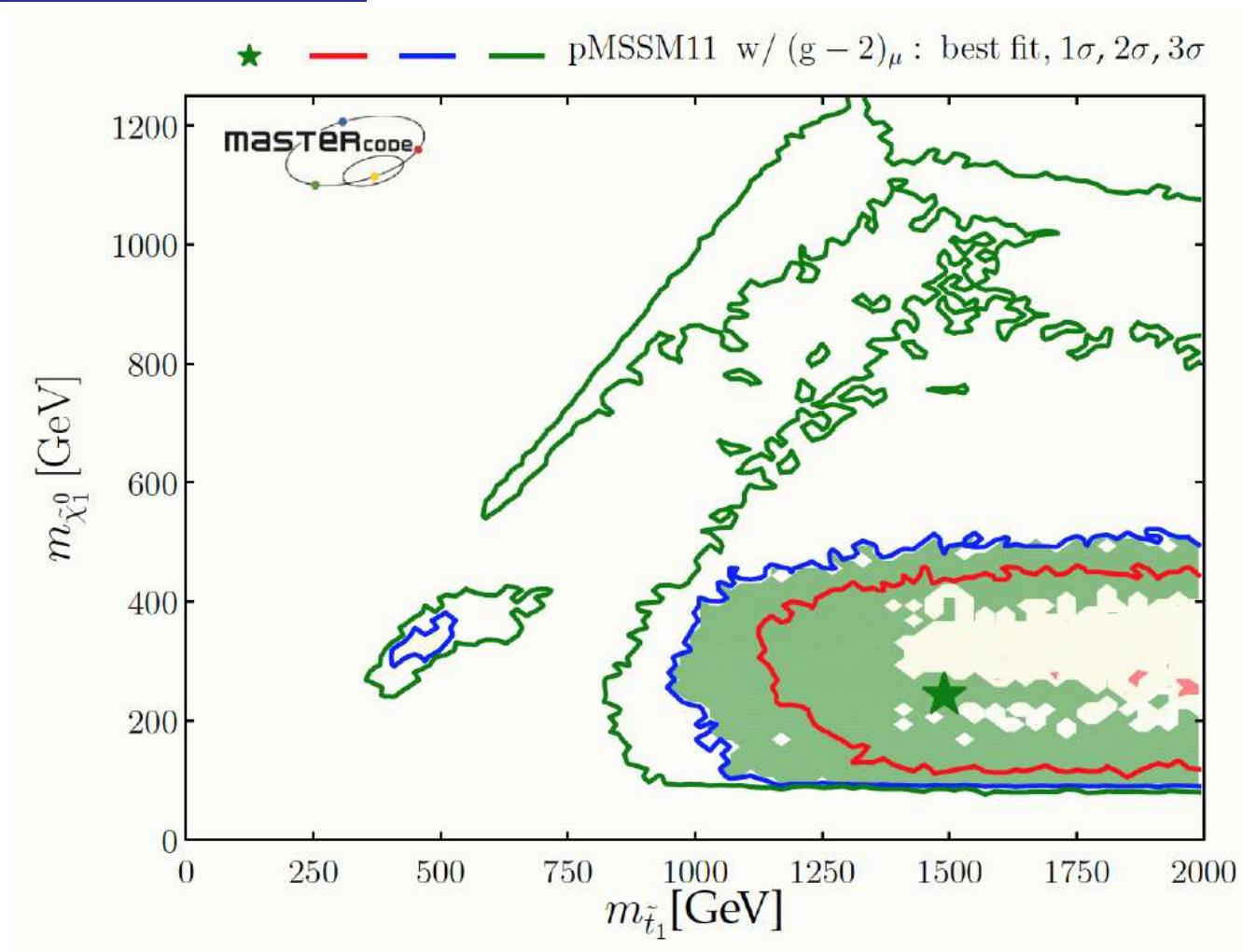
# pMSSM11: Going from 8 TeV to 13 TeV (and adding latest DM limits)

[2017]



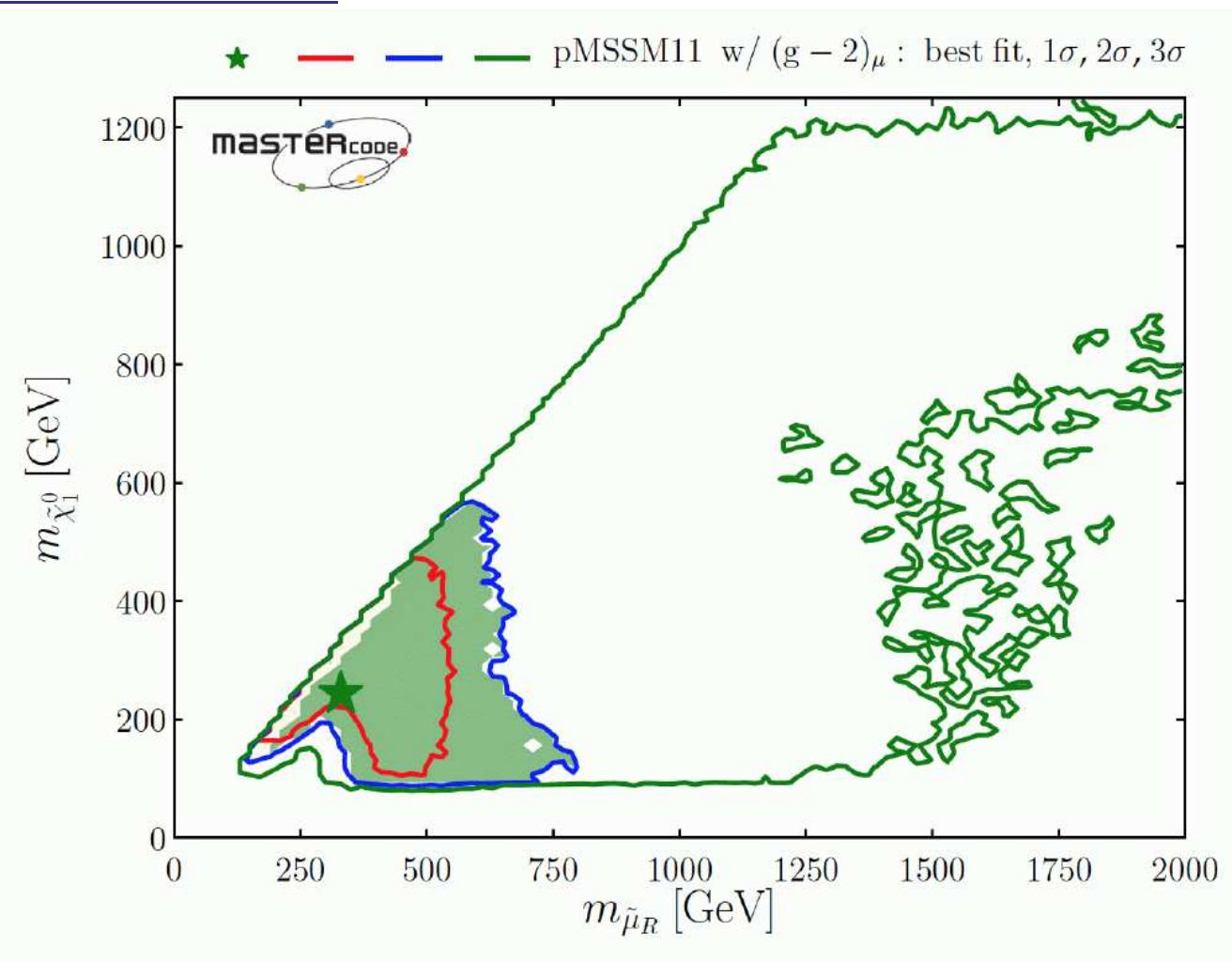
⇒ substantial move to higher masses!

⇒ notice the “nose”!

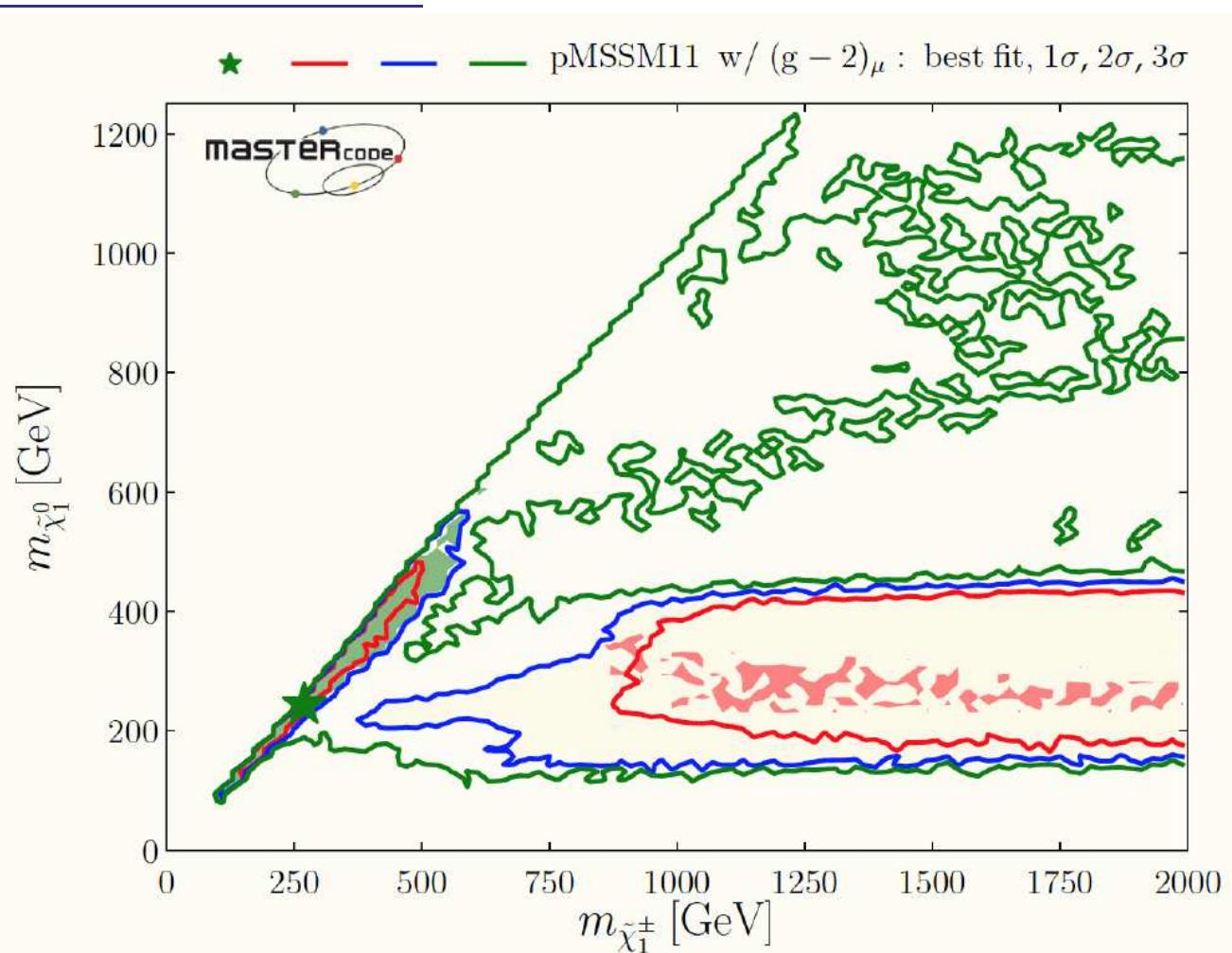


$\tilde{\chi}_1^\pm$ coann.	slep coann.	gluino coann.	stop coann.
A/H funnel	stau coann.	squark coann.	sbot coann.

⇒ high (low) stop (neutralino) masses ⇒ notice the compressed region!



⇒ all masses low!!



⇒ chargino co-annihilation

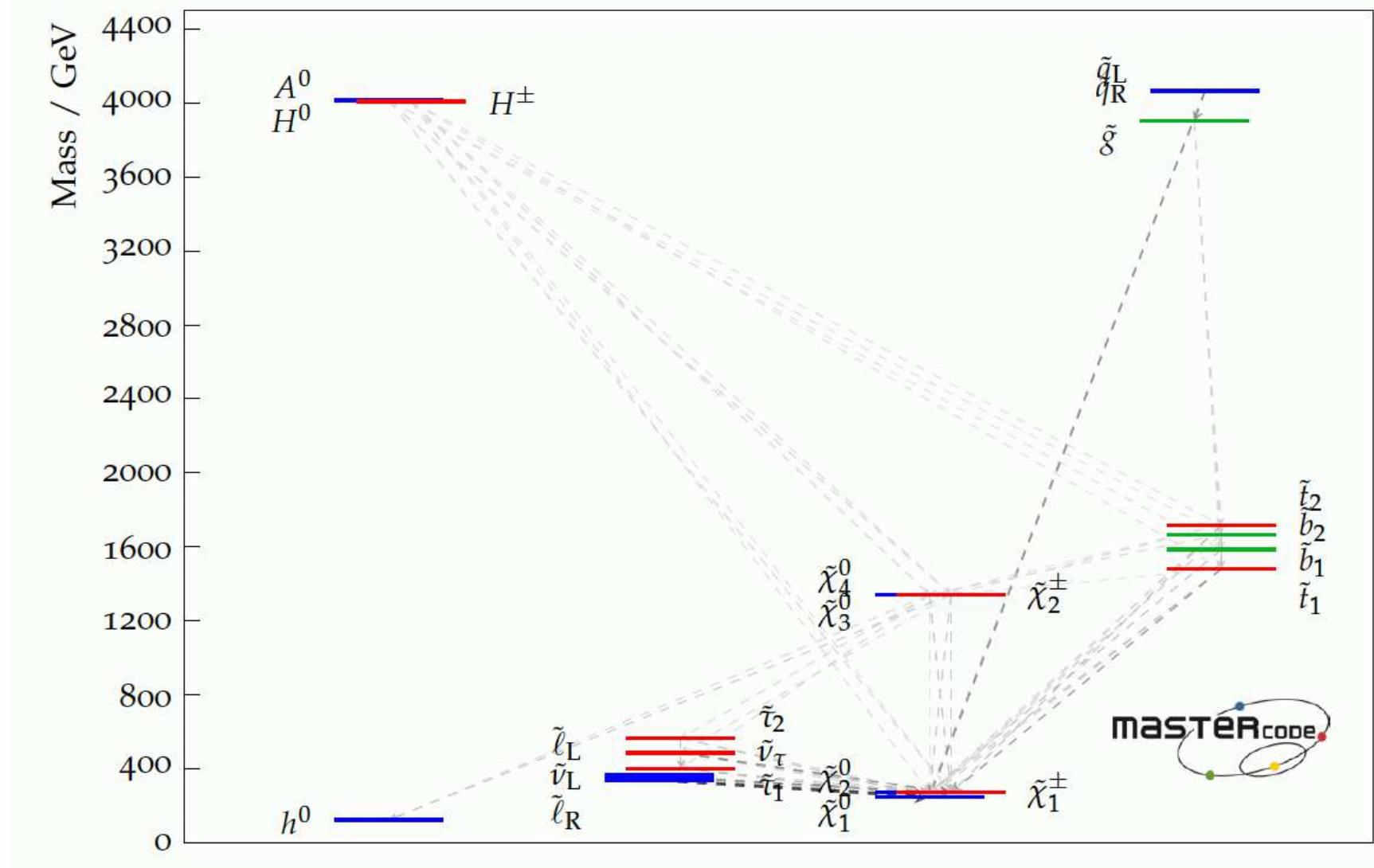
⇒  $M_1 \sim M_2$

## pMSSM11: best-fit point parameters

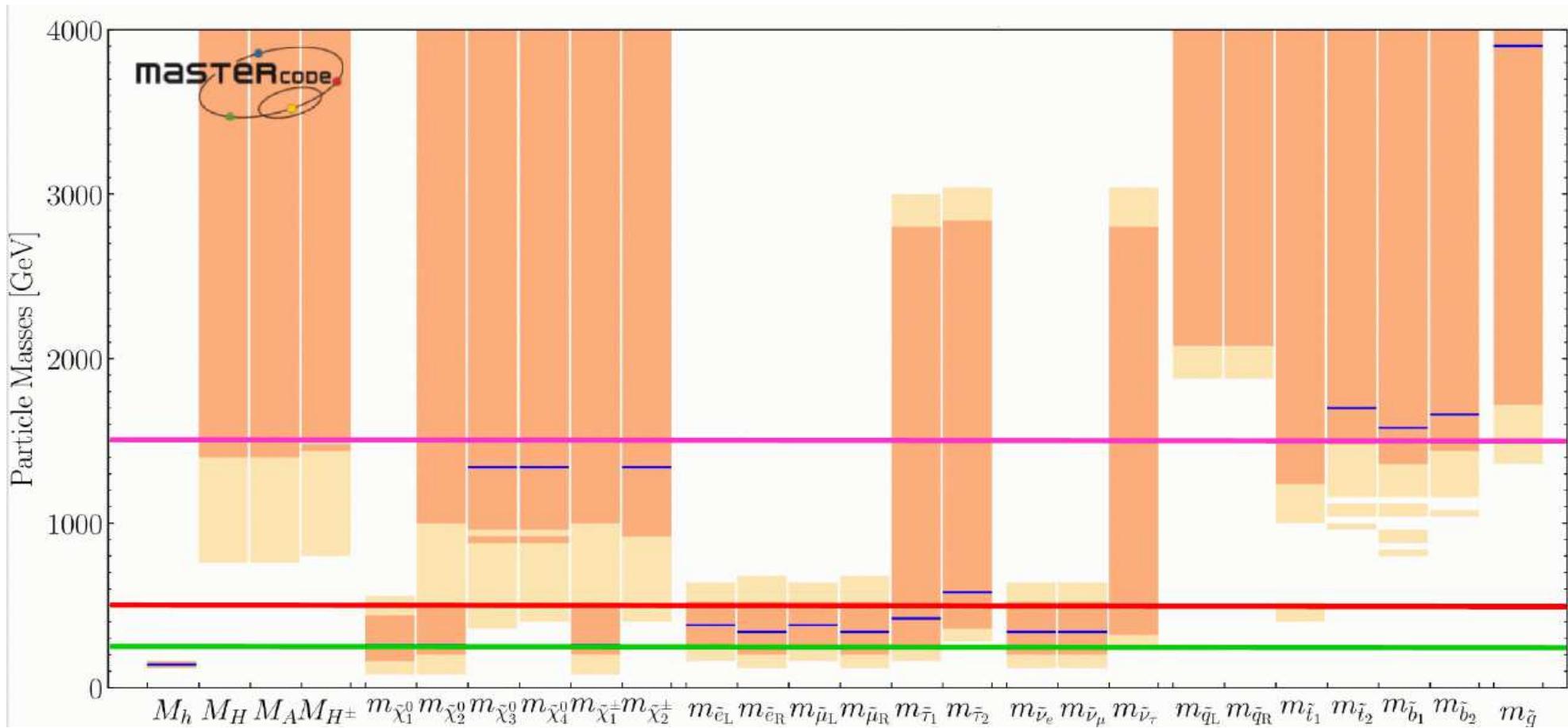
[2017]

Parameter	With LHC 13 TeV and $(g - 2)_\mu$	
	Best fit	'Nose' region
$M_1$	0.25 TeV	- 0.39 TeV
$M_2$	0.25 TeV	1.2 TeV
$M_3$	- 3.86 TeV	- 1.7 TeV
$m_{\tilde{q}}$	4.0 TeV	2.00 TeV
$m_{\tilde{q}_3}$	1.7 TeV	4.1 TeV
$m_{\tilde{\ell}}$	0.35 TeV	0.36 TeV
$m_{\tilde{\tau}}$	0.46 TeV	1.4 TeV
$M_A$	4.0 TeV	4.2 TeV
$A$	2.8 TeV	5.4 TeV
$\mu$	1.33 TeV	- 5.7 TeV
$\tan \beta$	36	19
$\chi^2/\text{d.o.f.}$	22.1/20	24.46/20
p-value	0.33	0.22
$\chi^2(HS)$	68.01	67.97

⇒ excellent  $p$  value!



⇒ heavy colored, light uncolored spectrum



ILC:  $\sqrt{s} = 1000$  GeV  $\Rightarrow$  precision analysis of EW particle and DM easy!

CLIC:  $\sqrt{s} = 3000$  GeV  $\Rightarrow$  precision analysis of EW particles and DM easy!

## What to conclude?

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⇒ Look at the *p* values!

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⇒ Look at the  $p$  values!

Model	Min. $\chi^2/\text{dof}$	$\chi^2$ -prob. ( $p$ -value)
CMSSM	32.8/18	11%
NUHM1	31.1/23	12%
NUHM2	30.3/22	11%
SU(5)	32.4/23	9%
mAMSB	36.5/27	11%
sub-GUT	28.9/24	23%
pMSSM11	21.0/20	33%

Which model is more likely??

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⇒ pMSSM11: model with higher  $\chi^2$ -probability  
model with good ILC/CLIC prospects  
detailed LHC analysis tbd!

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⇒ Are we ready (from the TH side) for EW particle production?

## 4. New Theory Predictions for the ILC and CLIC

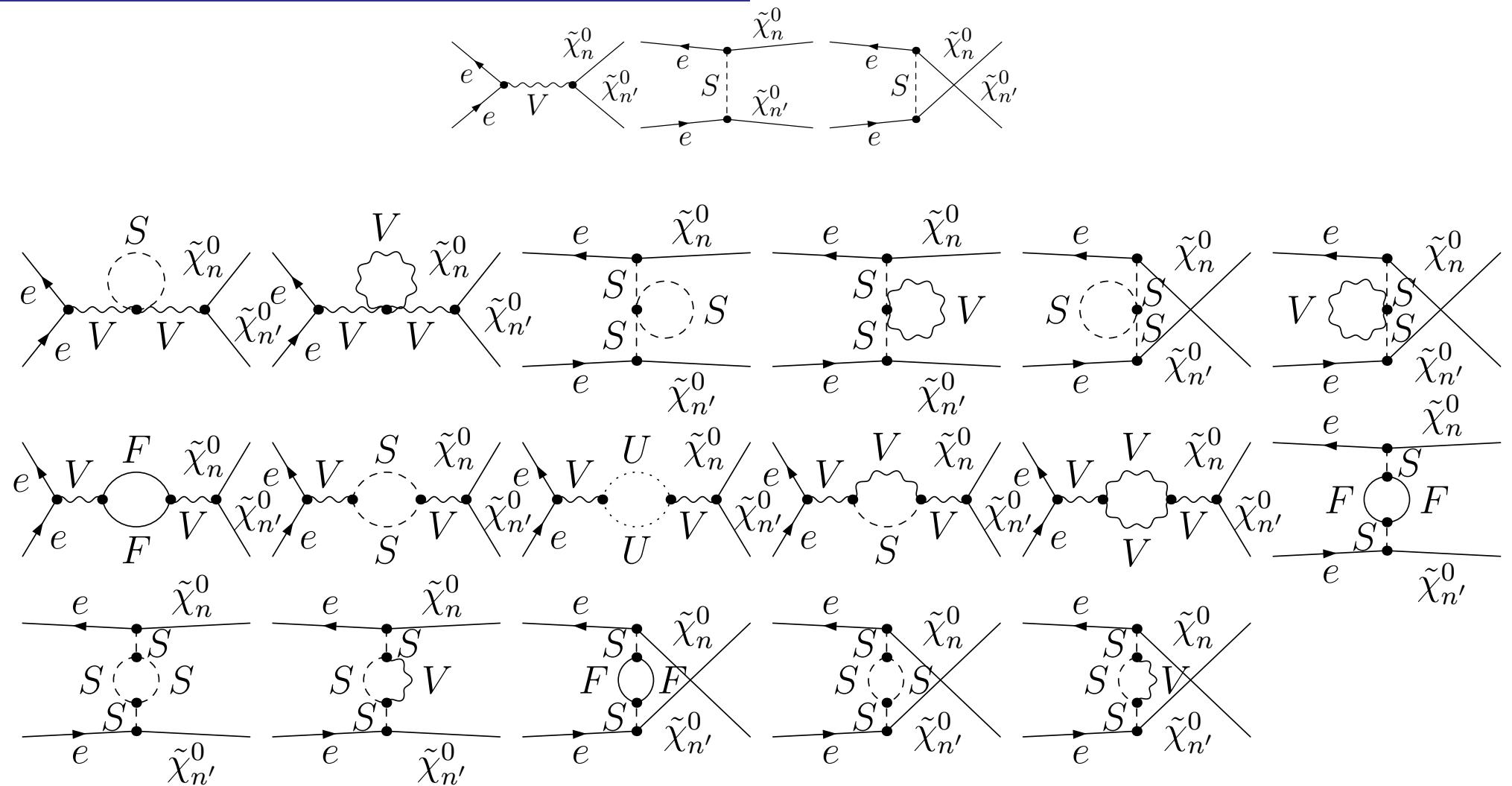
Extensive program for SUSY production and decay:

[S.H., C. Schappacher et al. 08'-18']

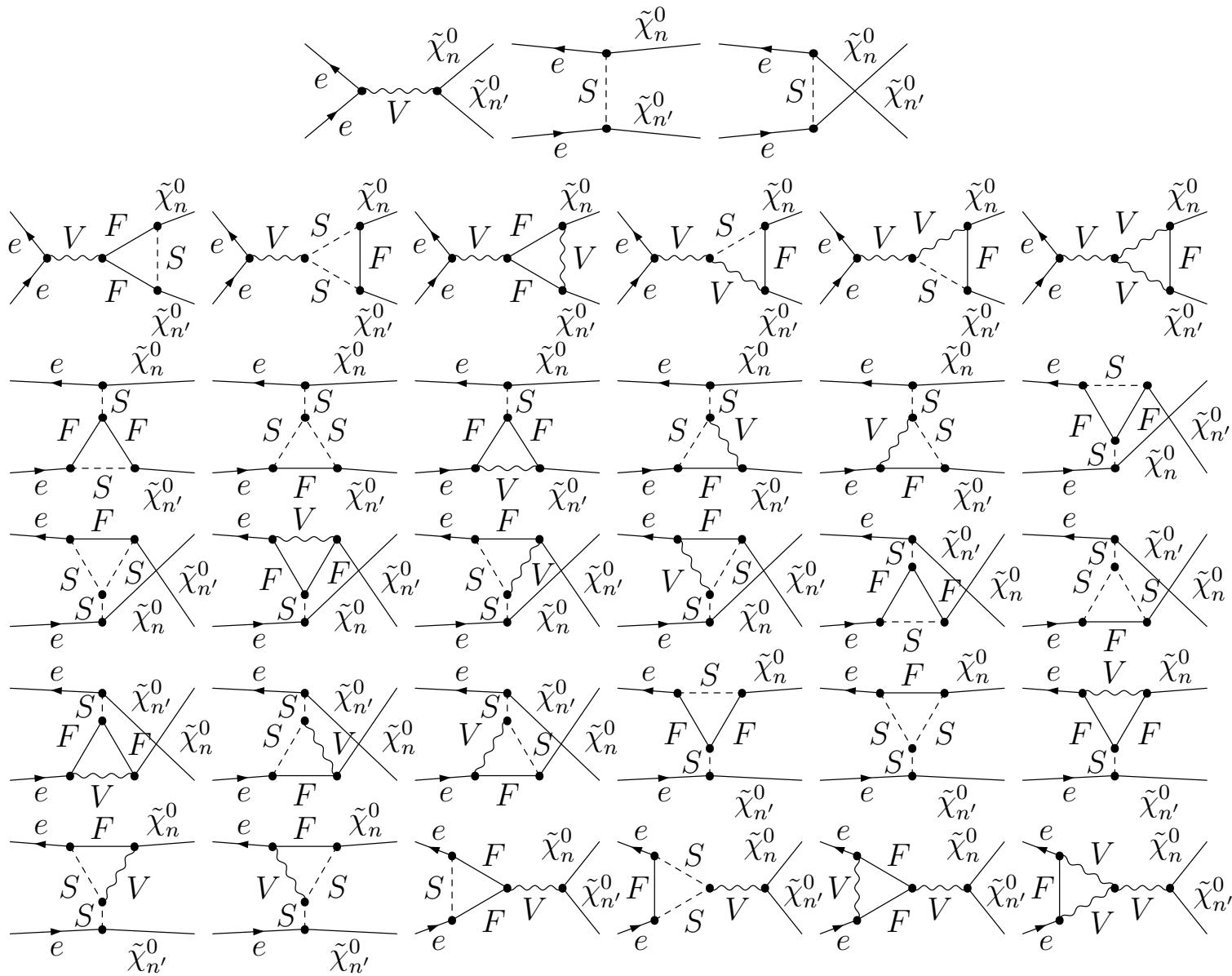
- full one-loop
- real and complex parameters
- soft and hard (and collinear) QED/QCD radiation
- renormalization (finally) fully under control
  
- stop/sbottom/stau decays
- gluino/chargino/neutralino decays
- Higgs decays
- Higgs production ( $2 \rightarrow 2$ )
- chargino/neutralino production
- slepton production

## Chargino/neutralino production:

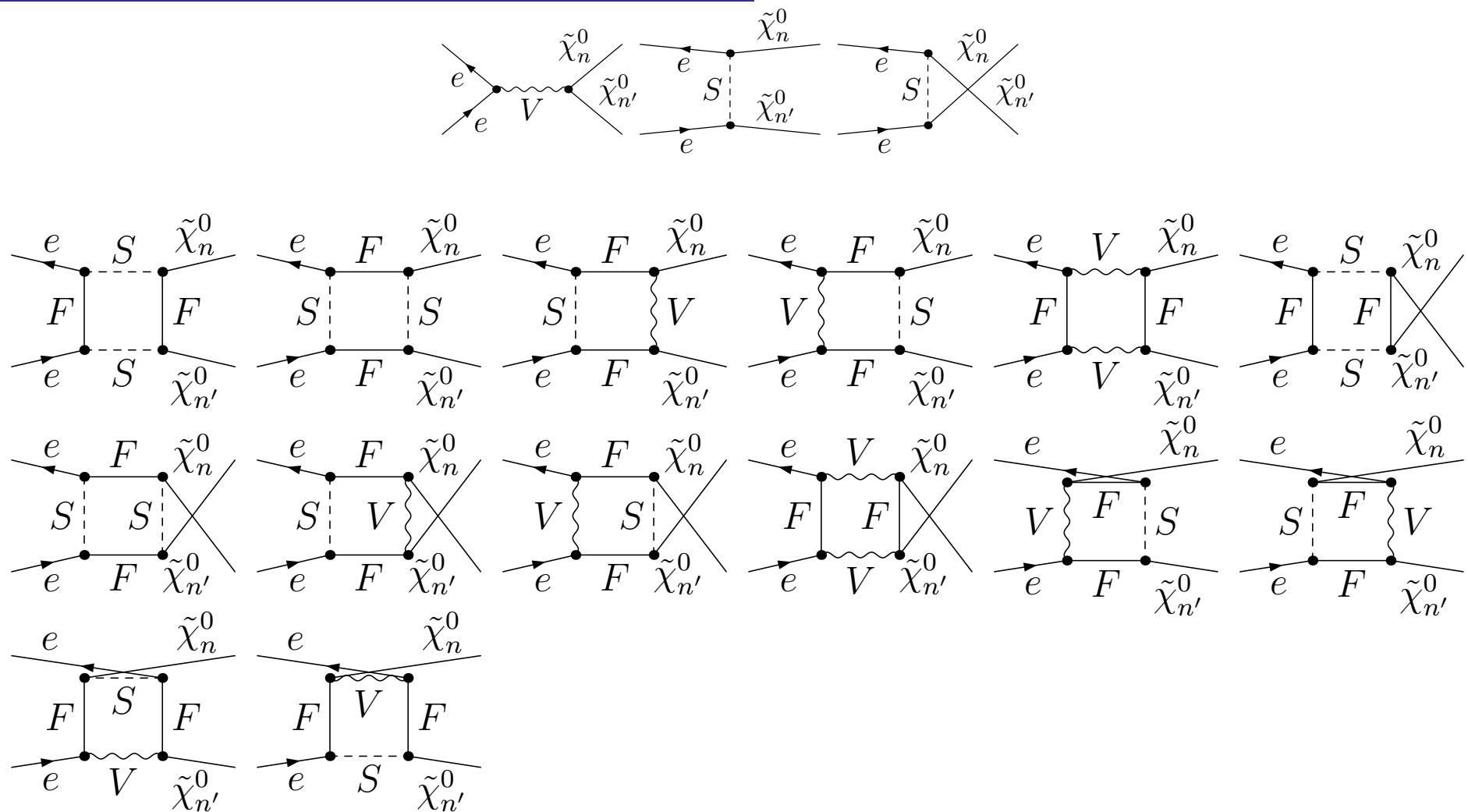
$e^+e^- \rightarrow \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0$  ( $e^+e^- \rightarrow \tilde{\chi}_c^\pm \tilde{\chi}_{c'}^\mp$  similar):



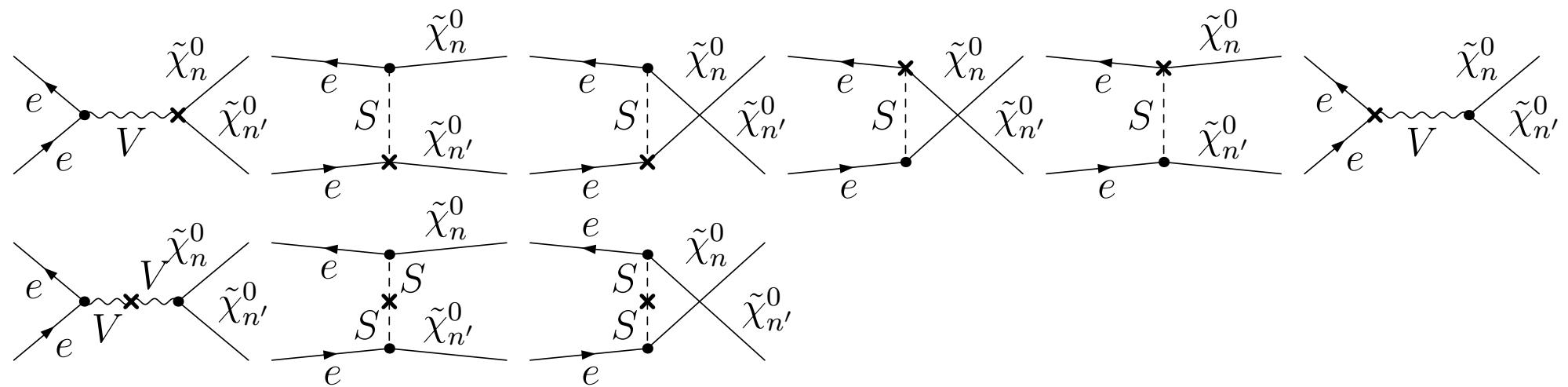
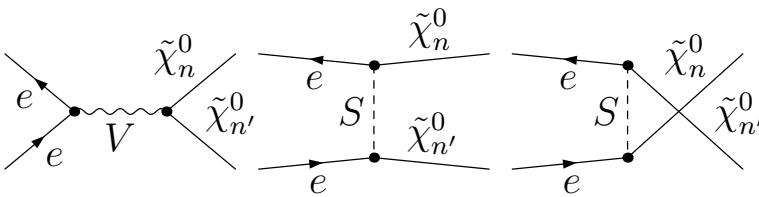
$e^+e^- \rightarrow \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0$  ( $e^+e^- \rightarrow \tilde{\chi}_c^\pm \tilde{\chi}_c^\mp$  similar):



$e^+e^- \rightarrow \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0$  ( $e^+e^- \rightarrow \tilde{\chi}_c^\pm \tilde{\chi}_c^\mp$  similar):



$e^+e^- \rightarrow \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0$  ( $e^+e^- \rightarrow \tilde{\chi}_c^\pm \tilde{\chi}_c^\mp$  similar):



+ soft and hard QED radiation

## cMSSM parameters:

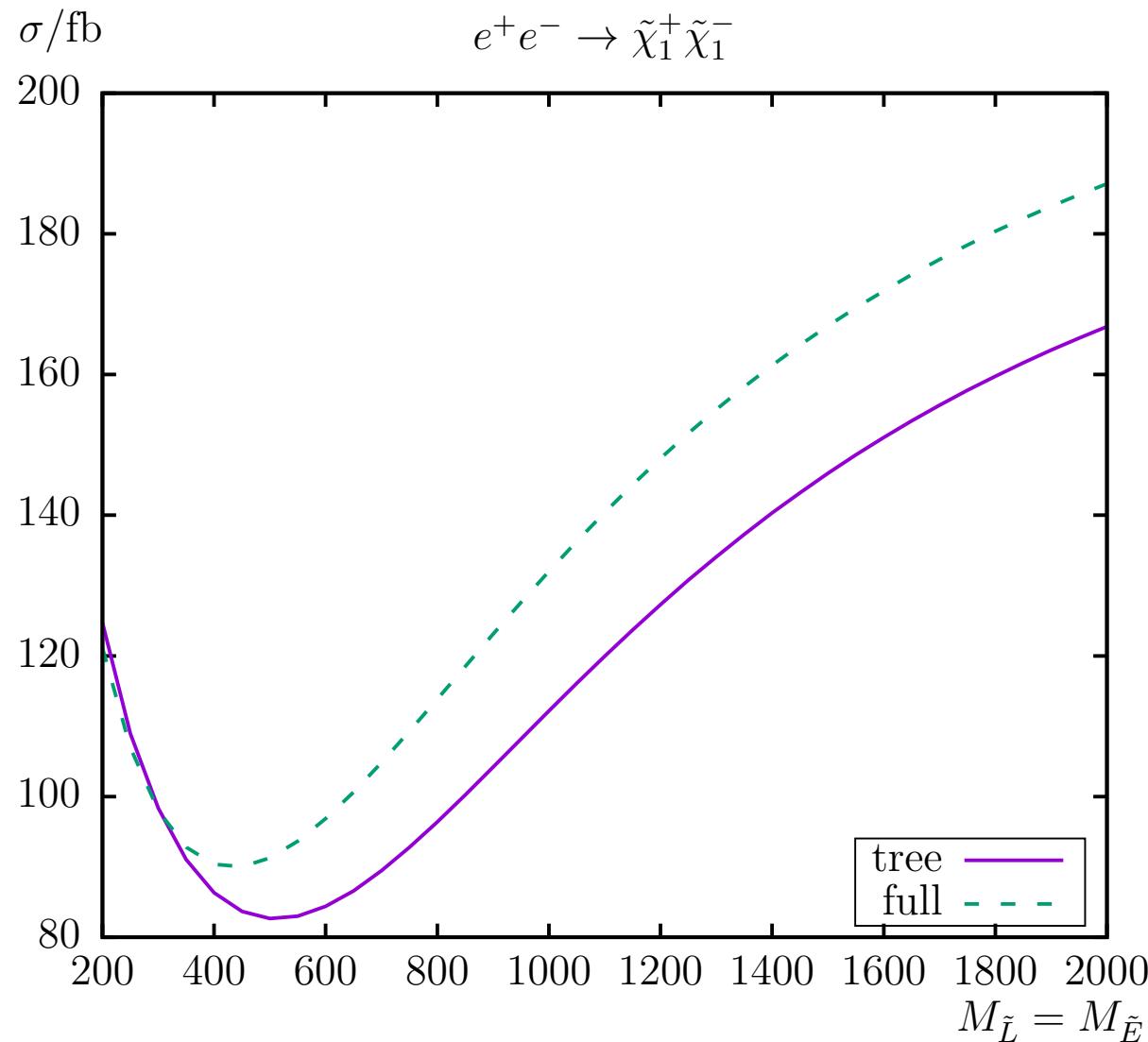
Scen.	$\sqrt{s}$	$t_\beta$	$\mu$	$M_{H^\pm}$	$M_{\tilde{Q}, \tilde{U}, \tilde{D}}$	$M_{\tilde{L}, \tilde{E}}$	$ A_t $	$A_b$	$A_\tau$	$ M_1 $	$M_2$	$M_3$
$\mathcal{S}$	1000	10	450	500	1500	1500	2000	$ A_t $	$M_{\tilde{L}}$	$\mu/4$	$\mu/2$	2000
<hr/>												
	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$		$m_{\tilde{\chi}_1^0}$		$m_{\tilde{\chi}_2^0}$		$m_{\tilde{\chi}_3^0}$		$m_{\tilde{\chi}_4^0}$		
tree	212.760	469.874		110.434		213.002		455.162		469.226		
CCN [1]	212.760	469.874		110.434		212.850		455.195		469.560		

with  $\sqrt{s}$ ,  $M_{H^\pm}$ ,  $\tan \beta$ ,  $M_{\tilde{L}}$ ,  $|M_1|$  varied

- Scenario chosen such that many processes are possible at the same time
- not chosen to maximize loop corrections

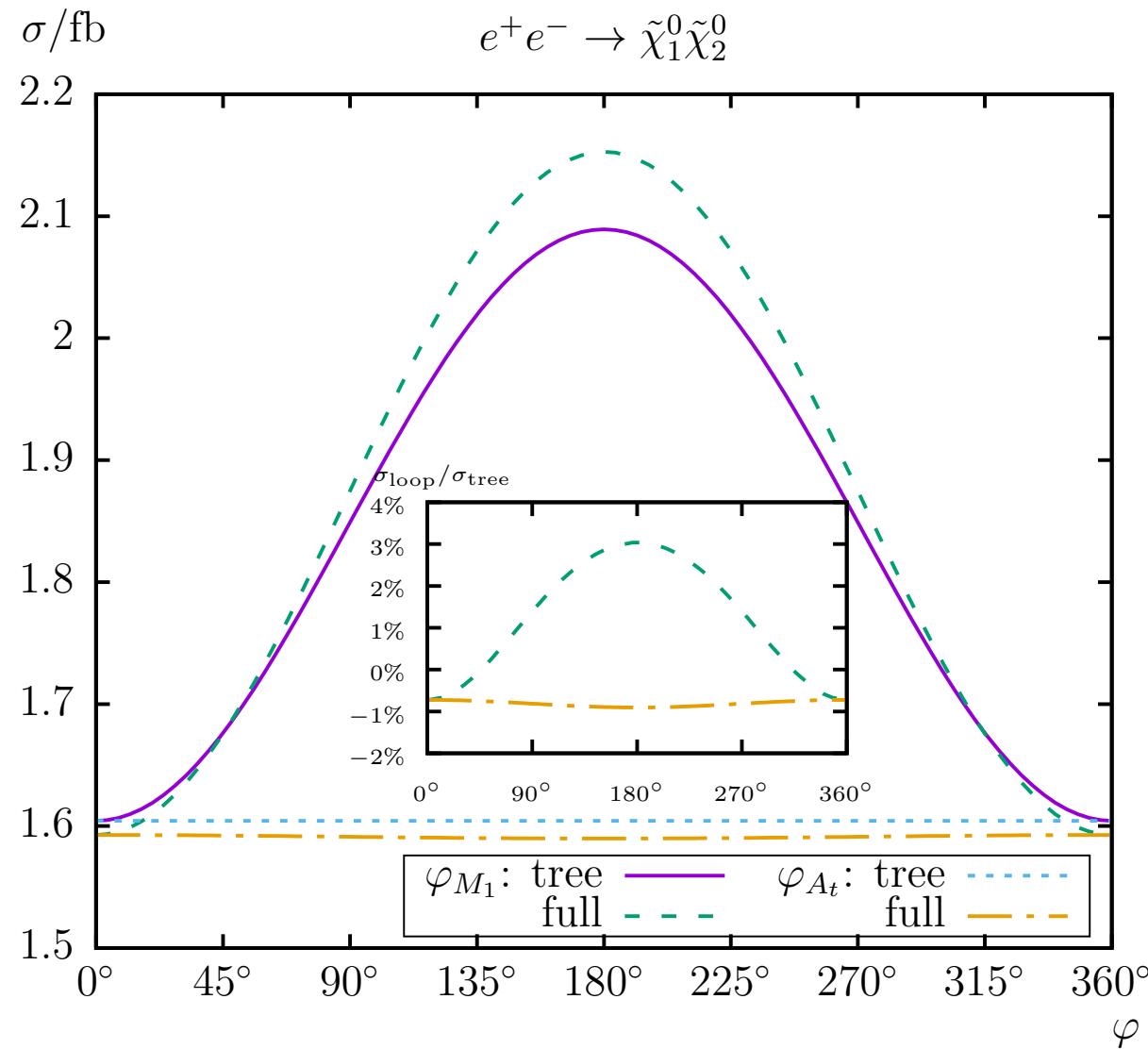
⇒ few example plots

$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$ :



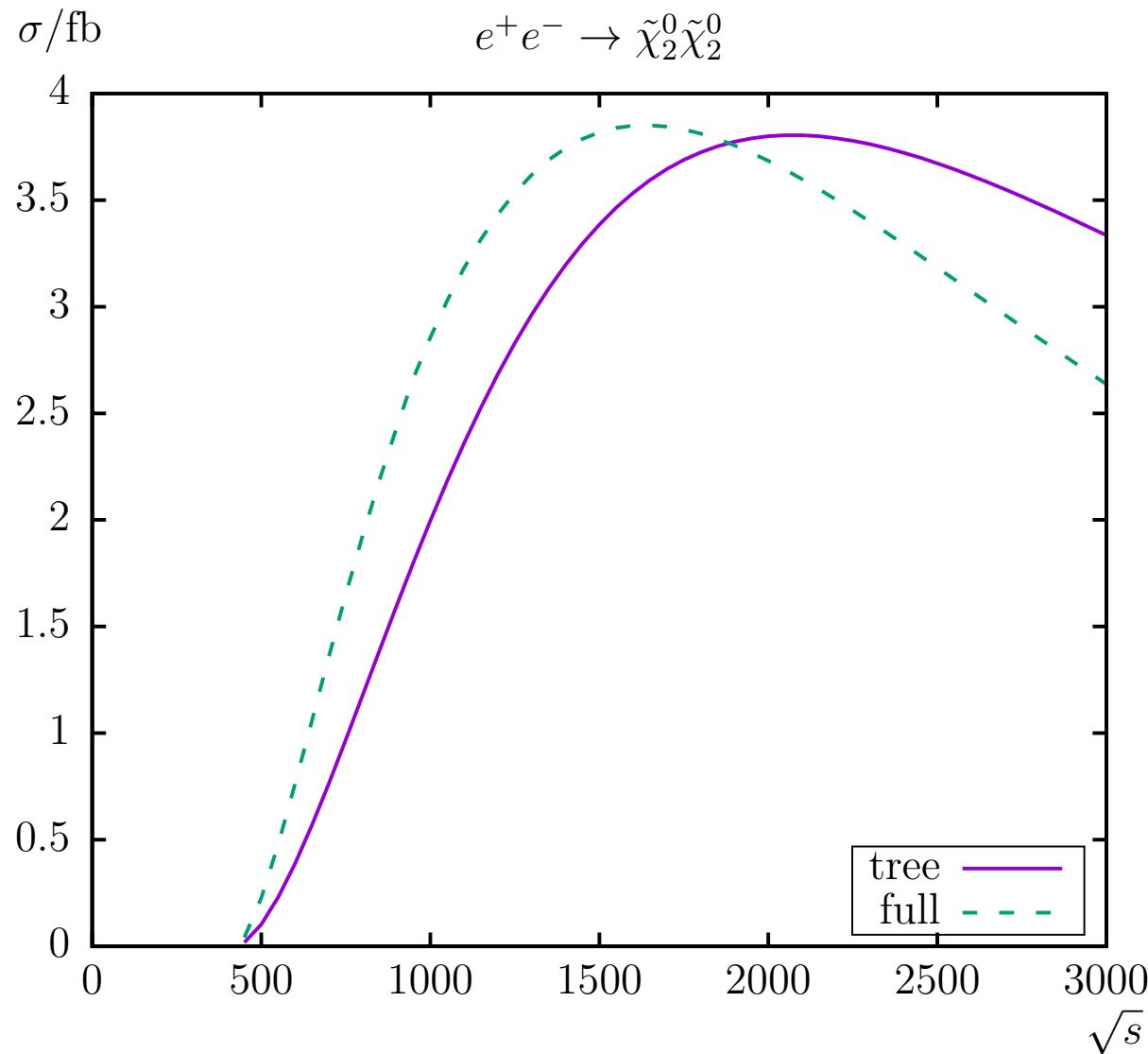
⇒ loop corrections crucial!

$e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0$ :



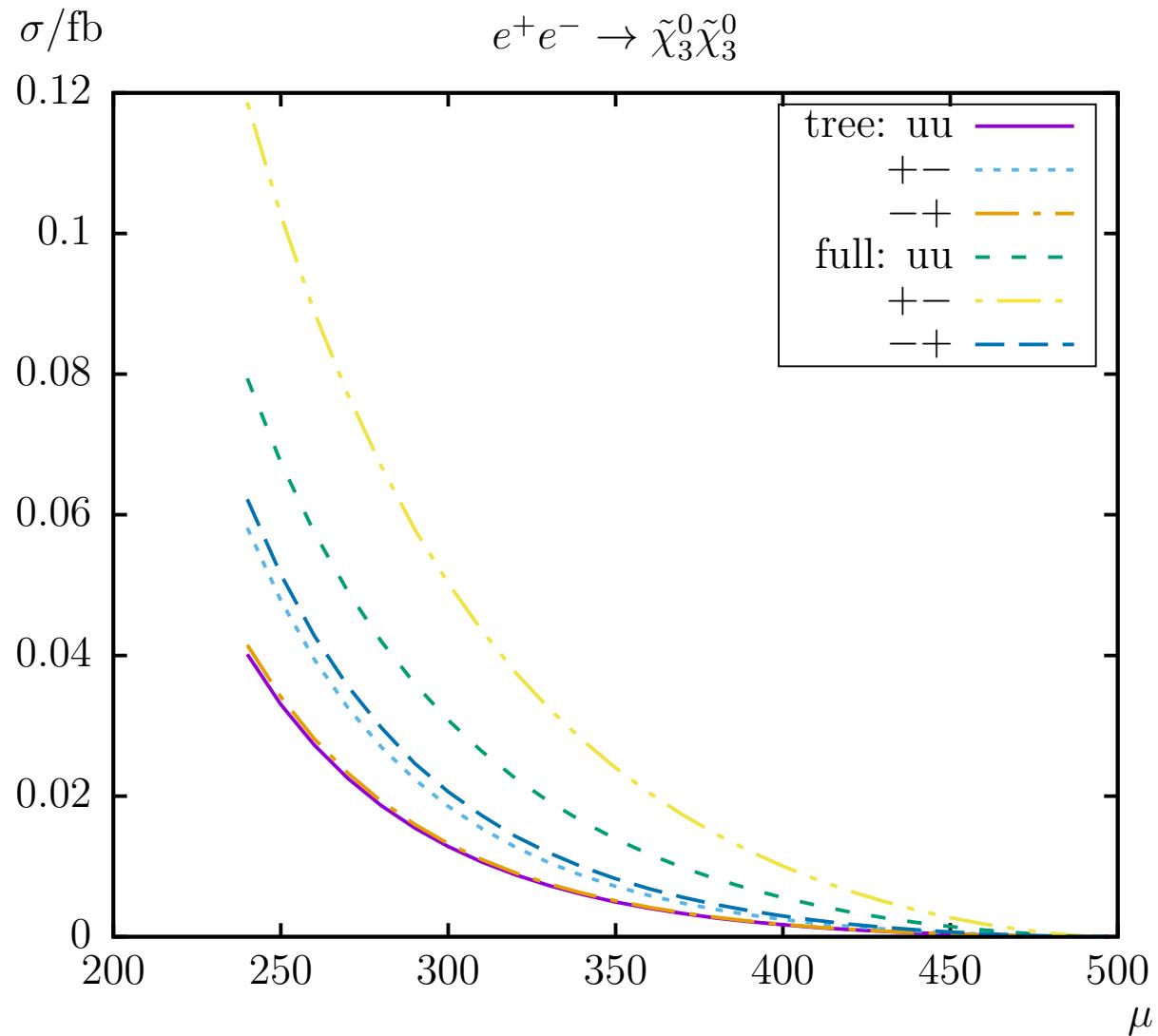
⇒  $M_1$  phase dependence large, loop corrections crucial!

$$\underline{e^+ e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0}:$$



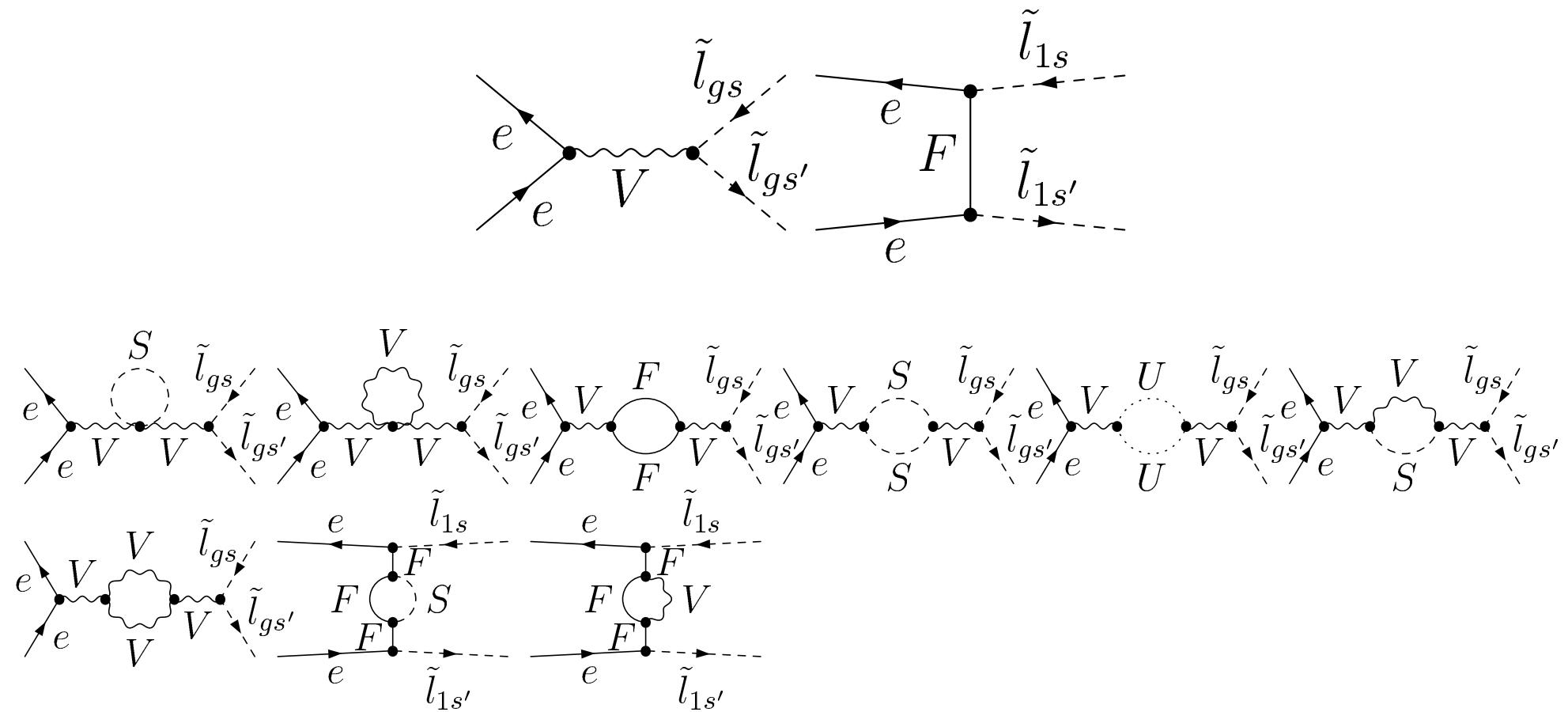
⇒ loop corrections depend strongly on  $\sqrt{s}$

$$e^+ e^- \rightarrow \tilde{\chi}_3^0 \tilde{\chi}_3^0$$



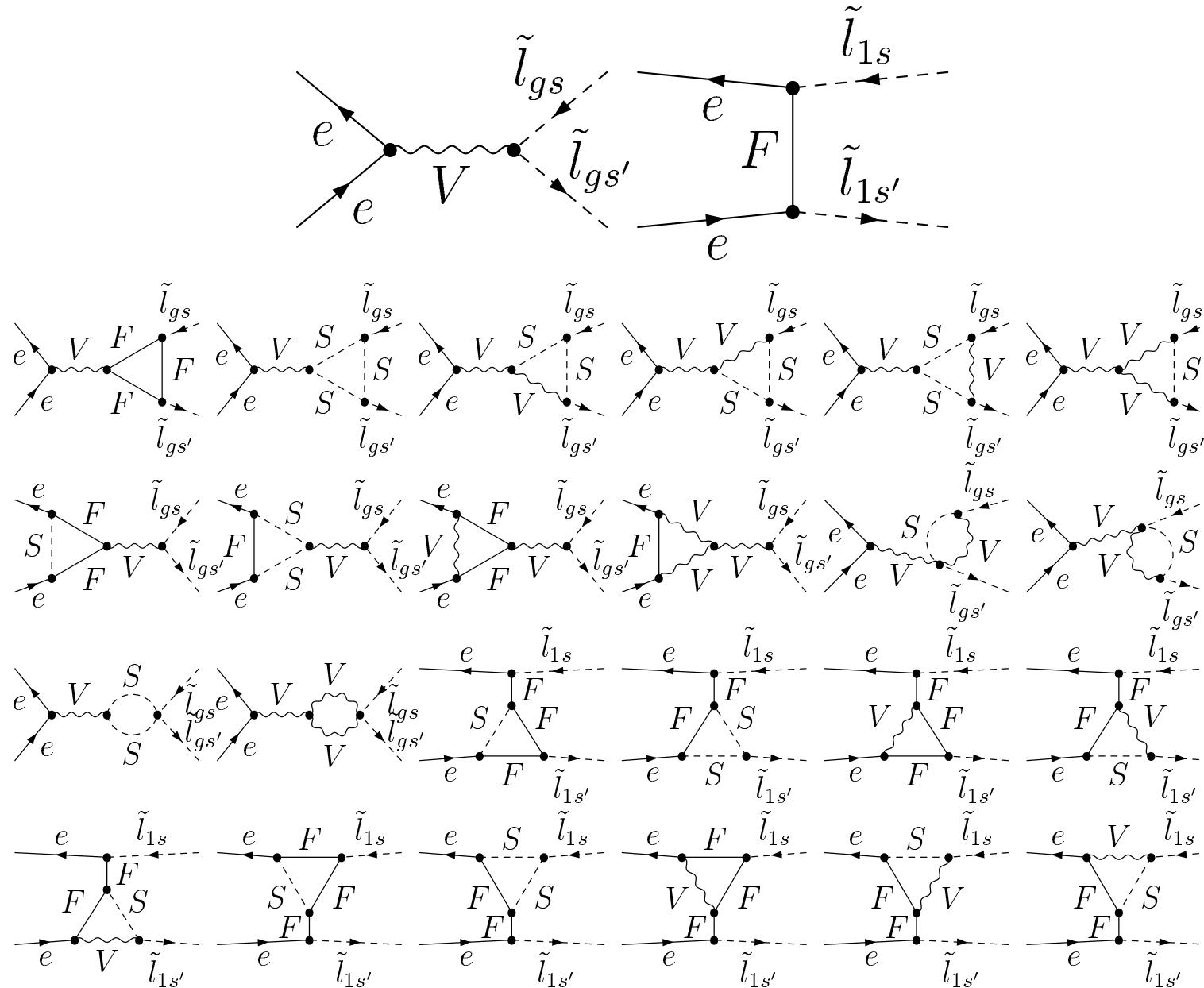
⇒ polarization could be crucial for some processes!

## Slepton production



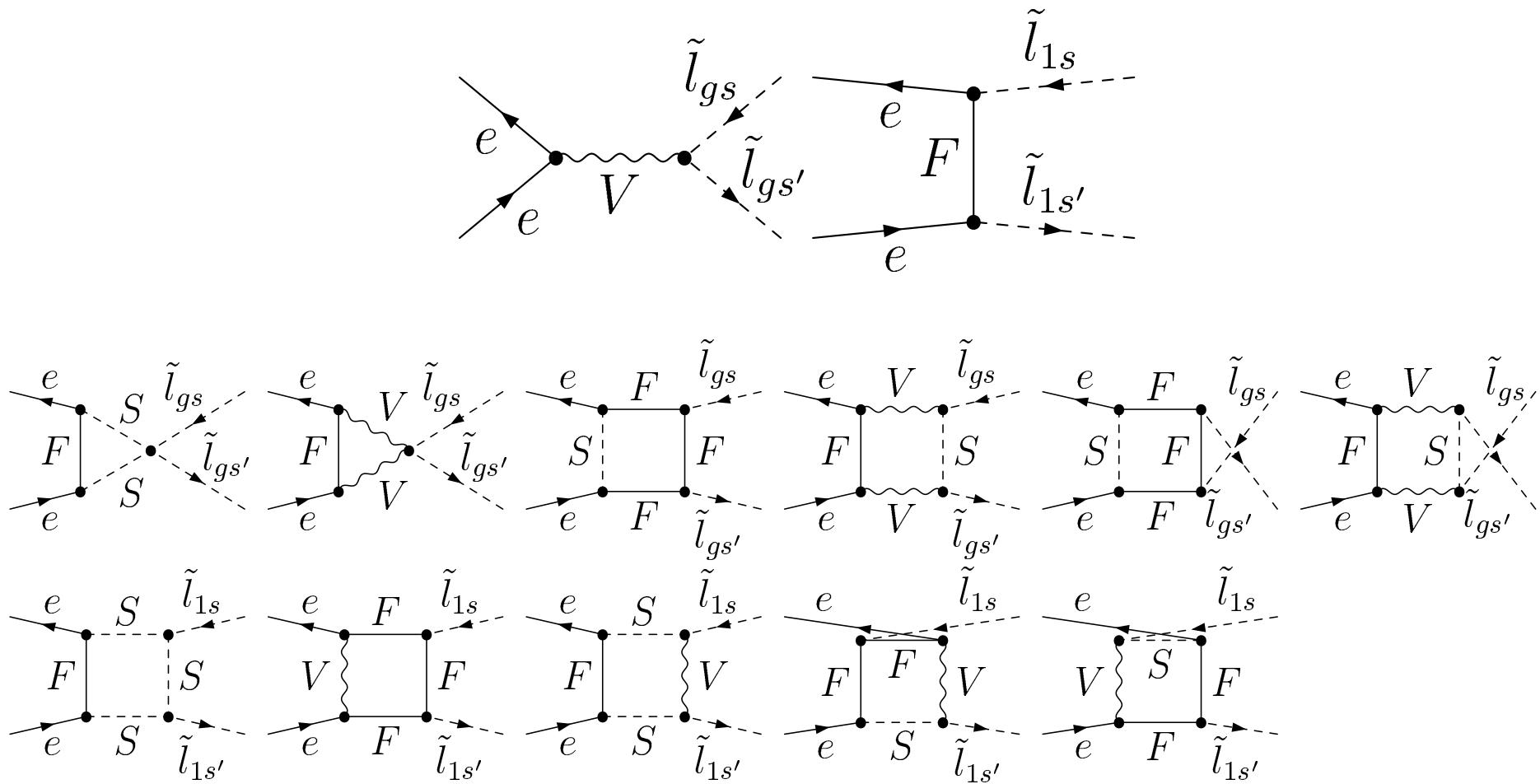
$$e^+ e^- \rightarrow \tilde{e}_{gs}^\pm \tilde{e}_{gs'}^\mp$$


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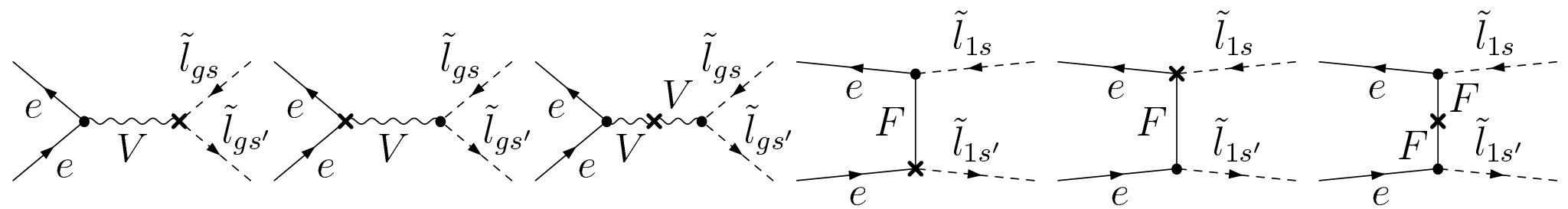
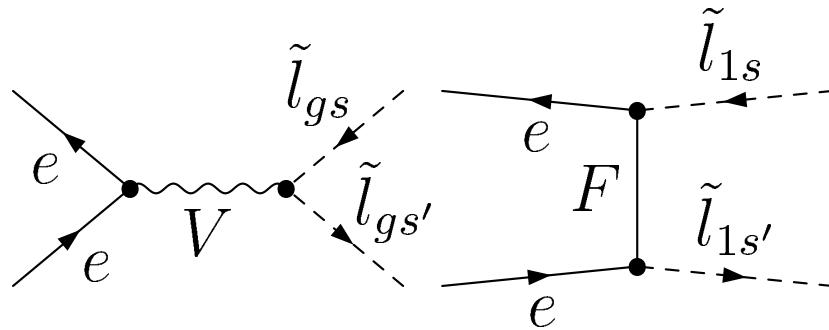
$$e^+ e^- \rightarrow \tilde{e}_{gs}^\pm \tilde{e}_{gs'}^\mp$$


---



$$e^+ e^- \rightarrow \tilde{e}_{gs}^\pm \tilde{e}_{gs'}^\mp$$


---



+ soft and hard QED radiation

## Numerical example scenario:

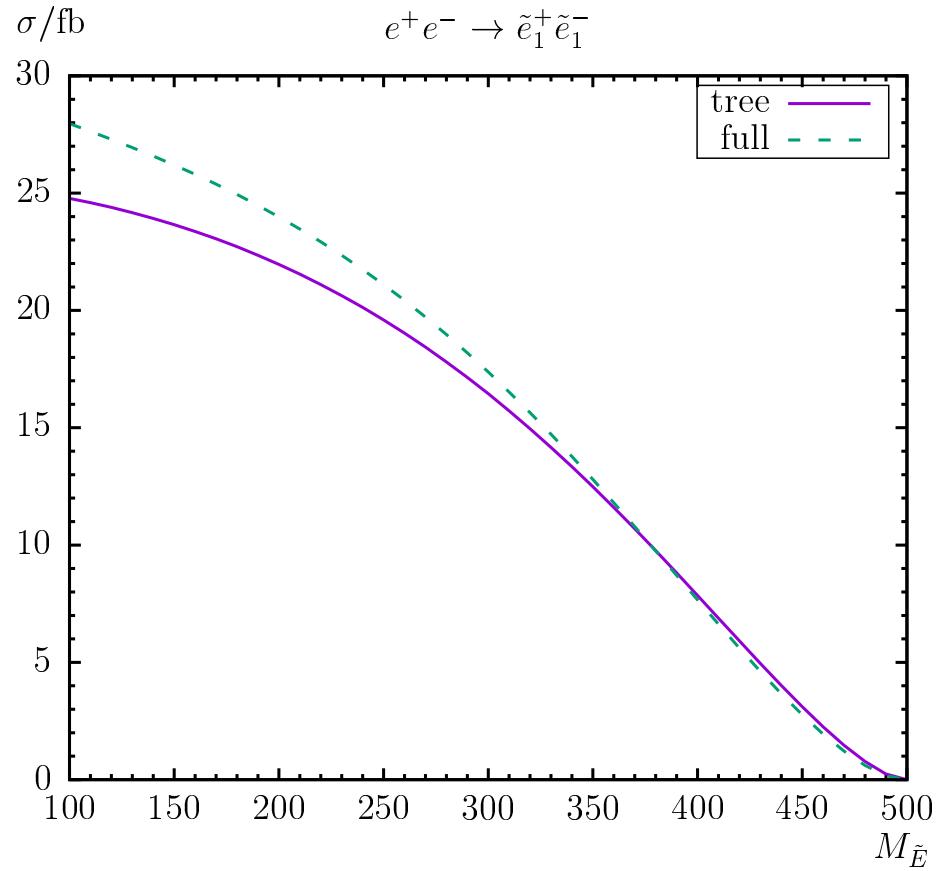
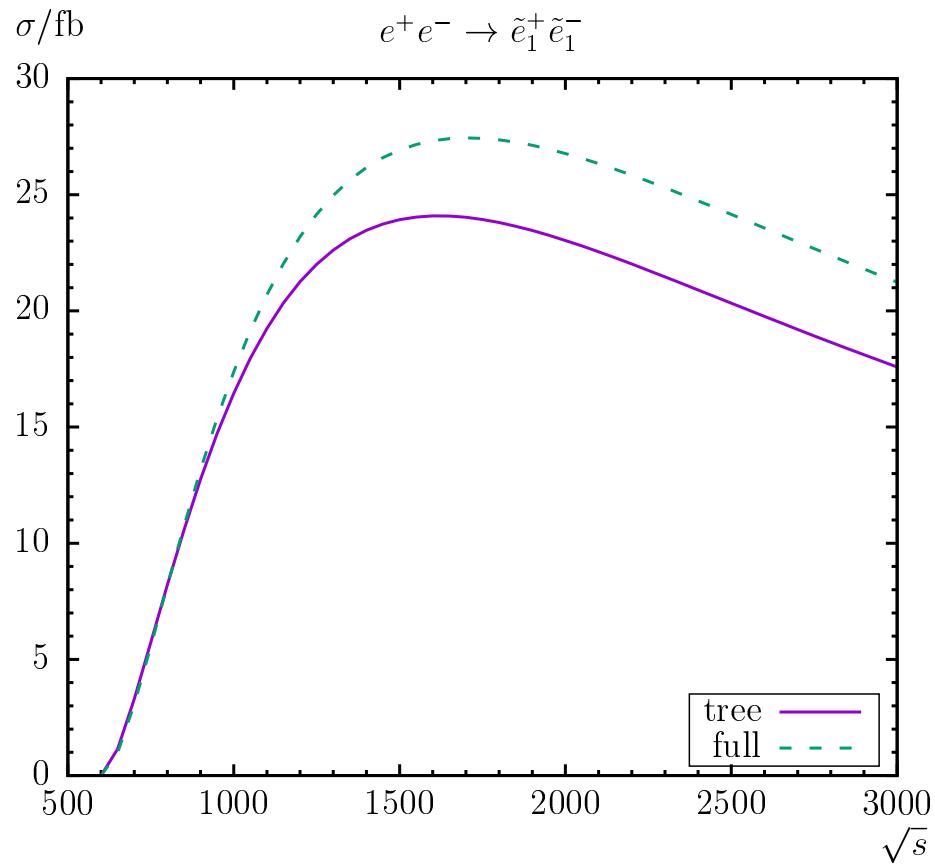
$\sqrt{s}$	$\tan \beta$	$\mu$	$M_{H^\pm}$	$M_{\tilde{Q}, \tilde{U}, \tilde{D}}$	$M_{\tilde{L}} = M_{\tilde{E}} + 50$	$A_{u_g}$	$A_{d_g}$	$ A_{e_g} $	$ M_1 $	$M_2$	$M_3$	
1000	10	350	1200	2000		300	2600	2000	2000	400	600	2000

Parameters varied:  $\sqrt{s}$ ,  $\mu$ ,  $M_{\tilde{L}}$ ,  $\tan \beta$ ,  $M_1$ ,  $M_2$ ,  $\varphi_{M_1}$ ,  $\varphi_{A_{eg}}$

- in agreement with exp. data
- opens up many (all) production channels
- relevant parameters varied
- ...

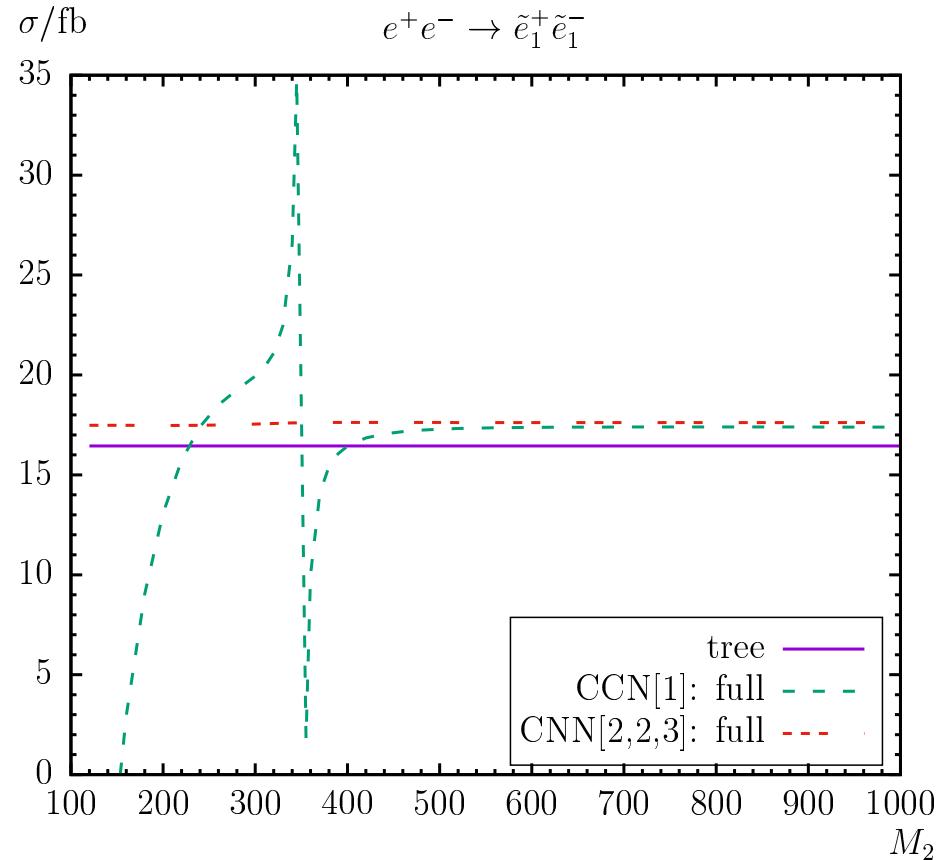
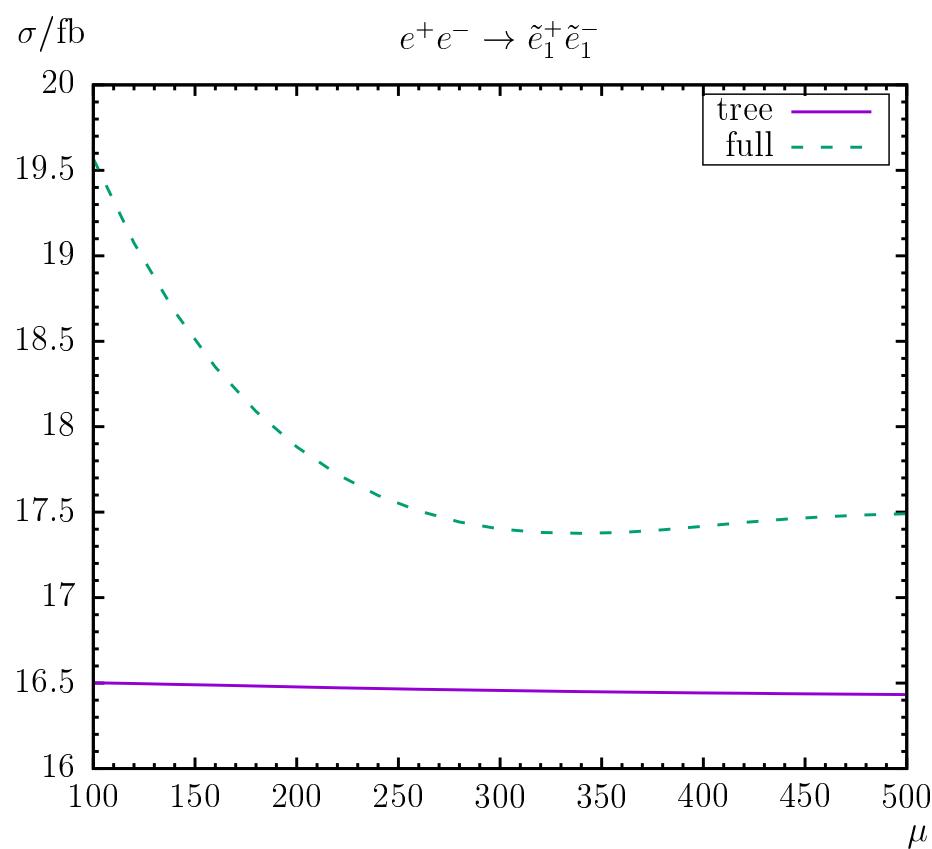
⇒ show some relevant examples

## $\tilde{e}_1 \tilde{e}_1$ production (I):



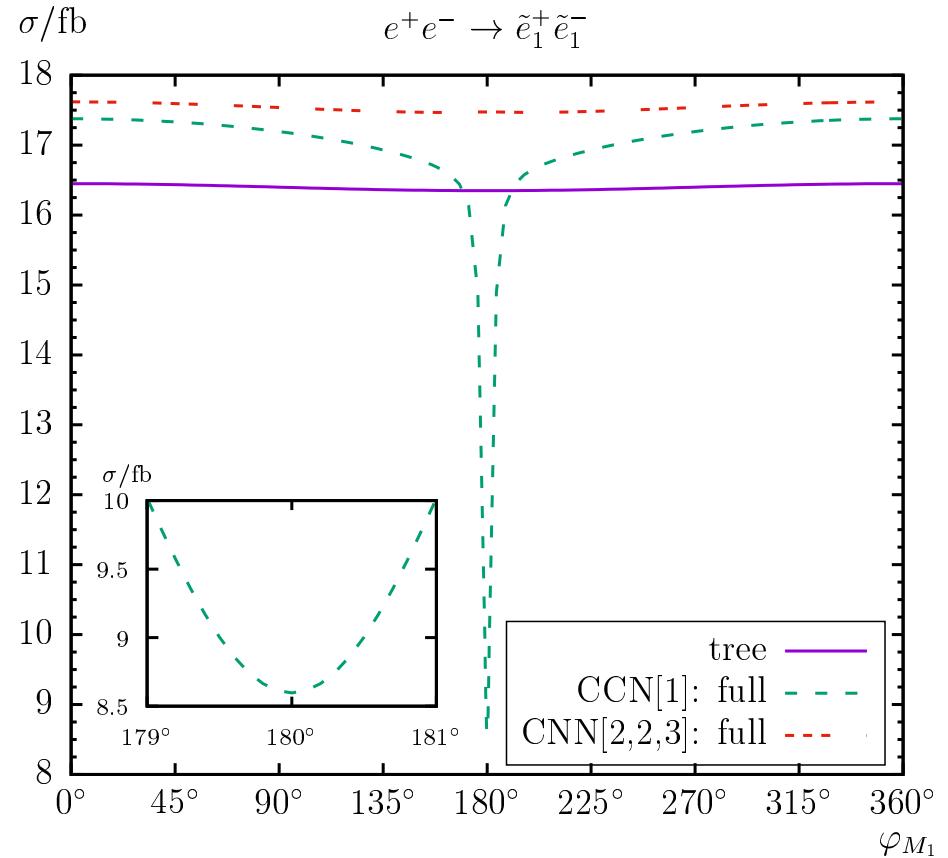
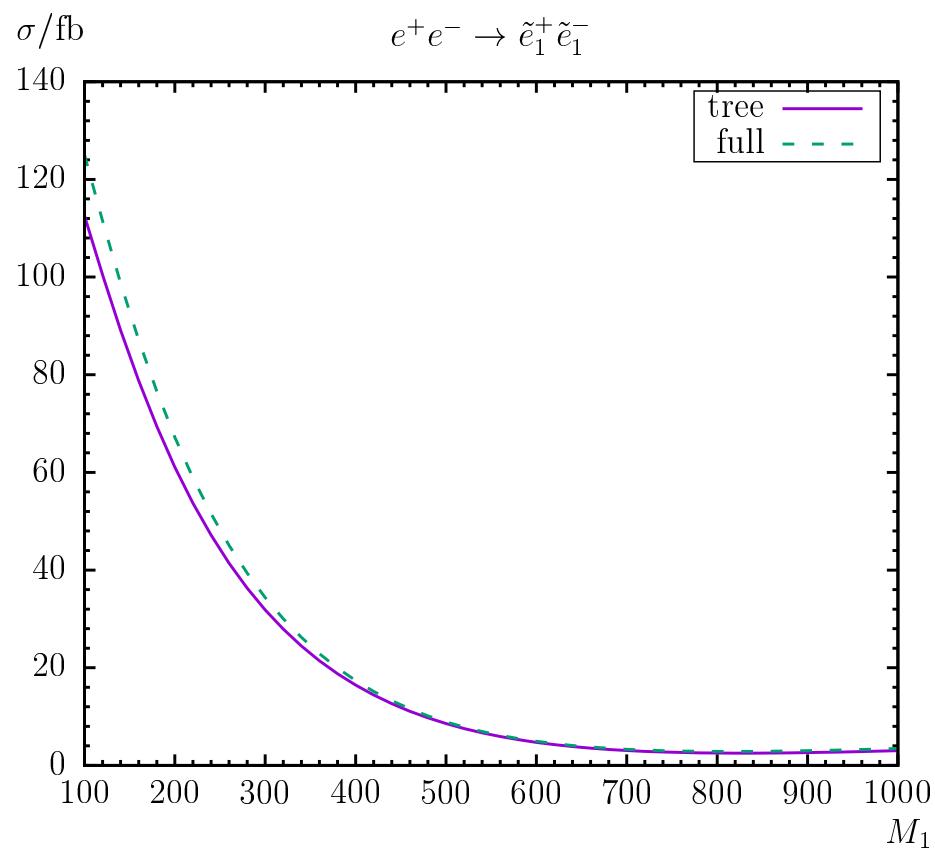
⇒ loop corrections  $\sim 20\%$

## $\tilde{e}_1 \tilde{e}_1$ production (II):



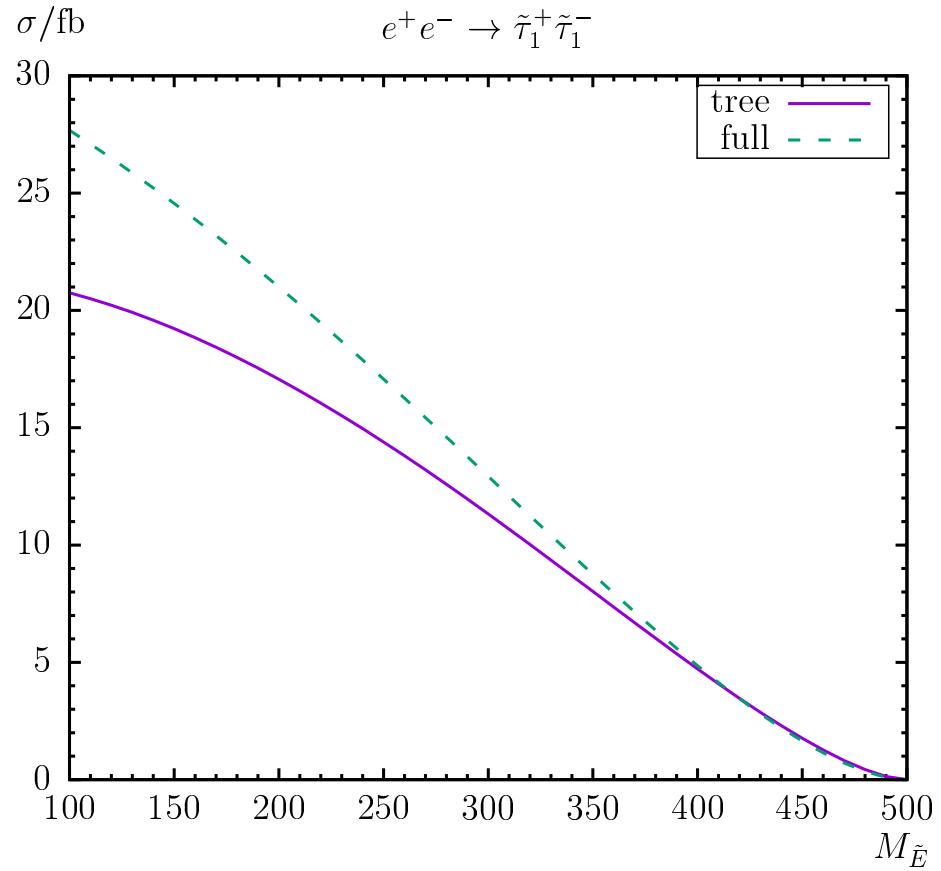
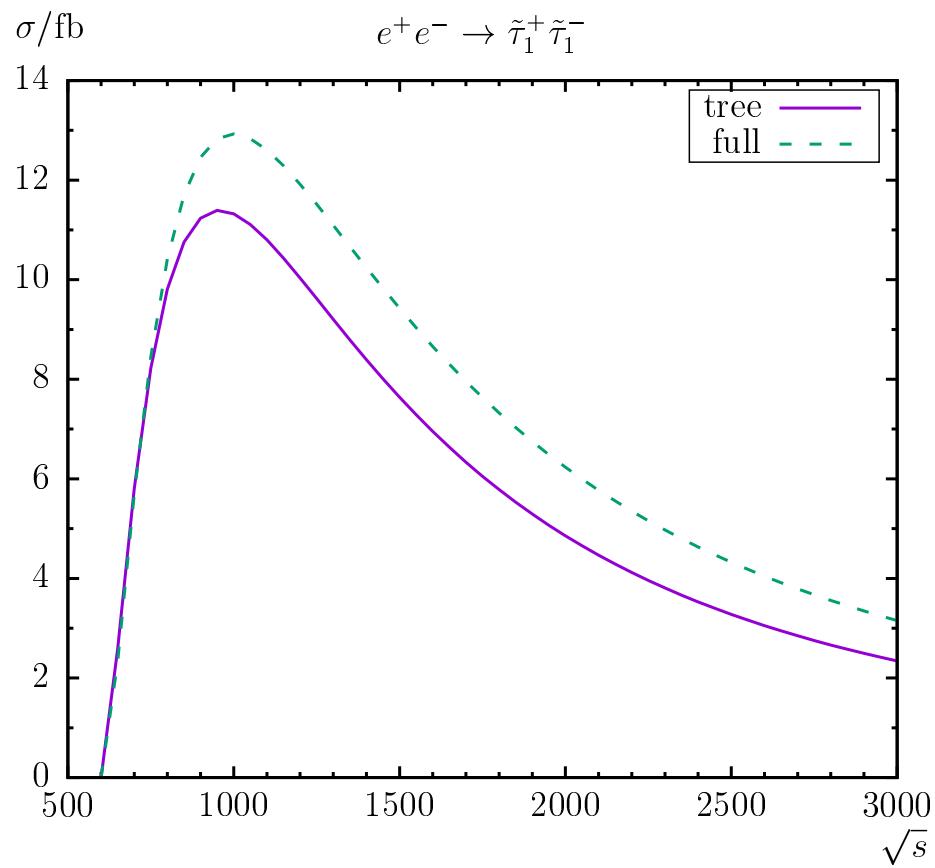
- ⇒ loop corrections  $\sim 20\%$
- ⇒ strong  $\mu$  dependence of loop corrections
- ⇒ CCN1 breaks down at  $\mu = M_2$

## $\tilde{e}_1 \tilde{e}_1$ production (III):



⇒ strong phase dependence of loop corrections

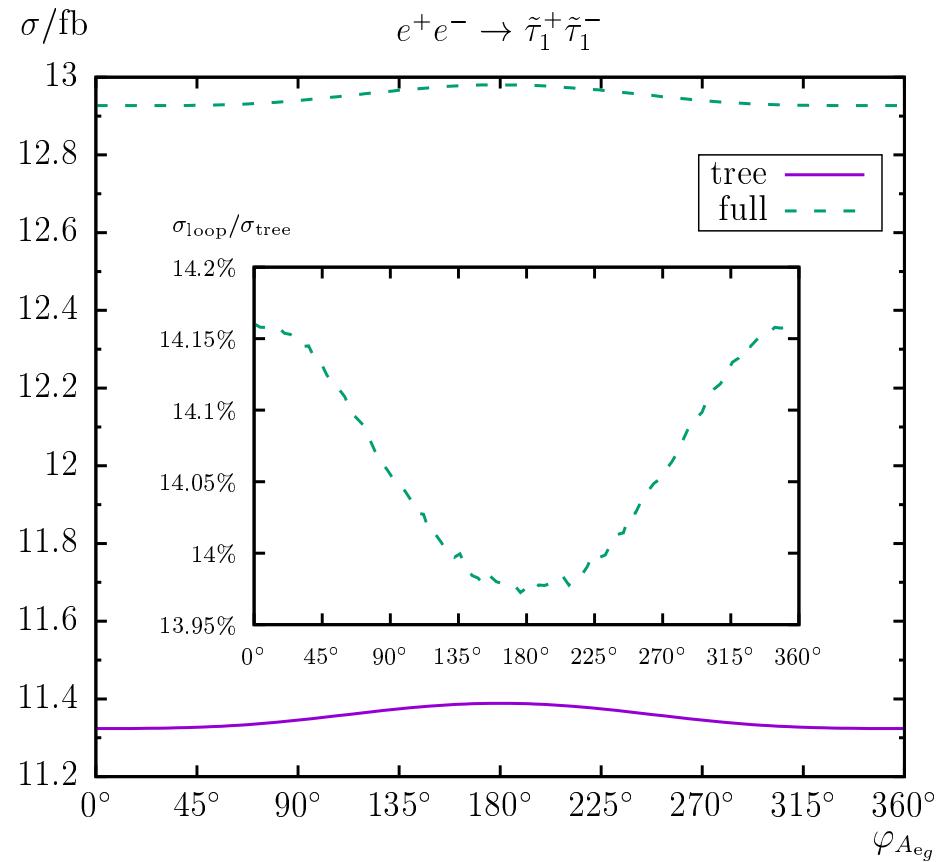
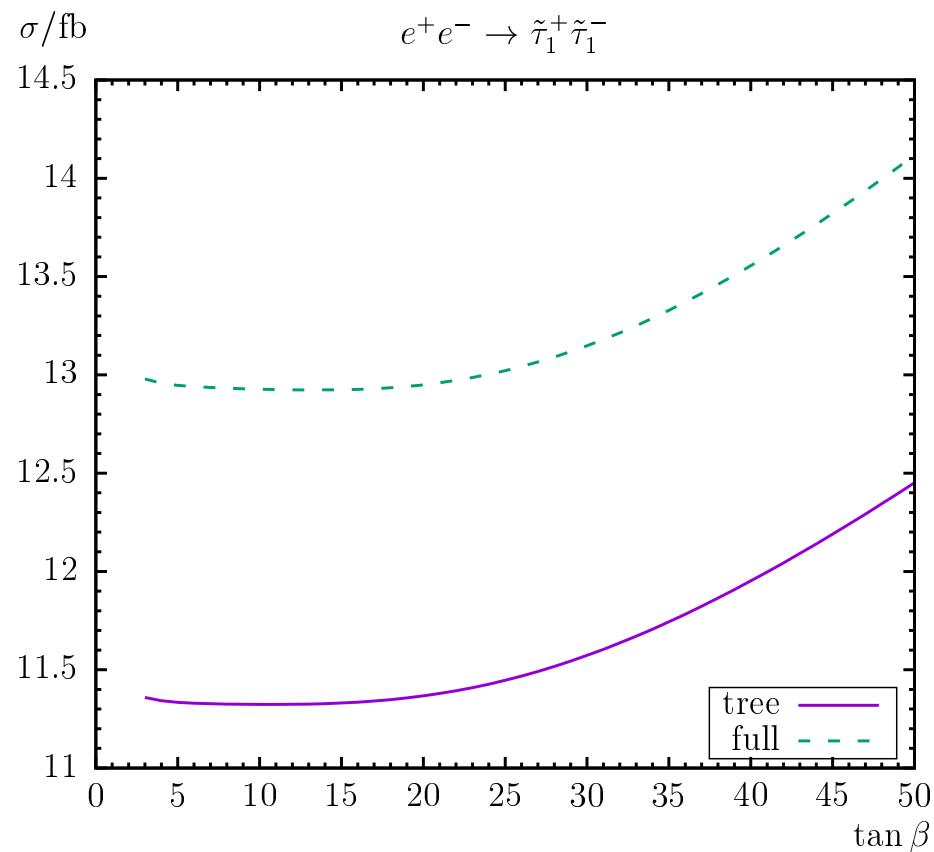
## $\tilde{\tau}_1 \tilde{\tau}_1$ production (I):



⇒ loop corrections  $\sim 20\%$

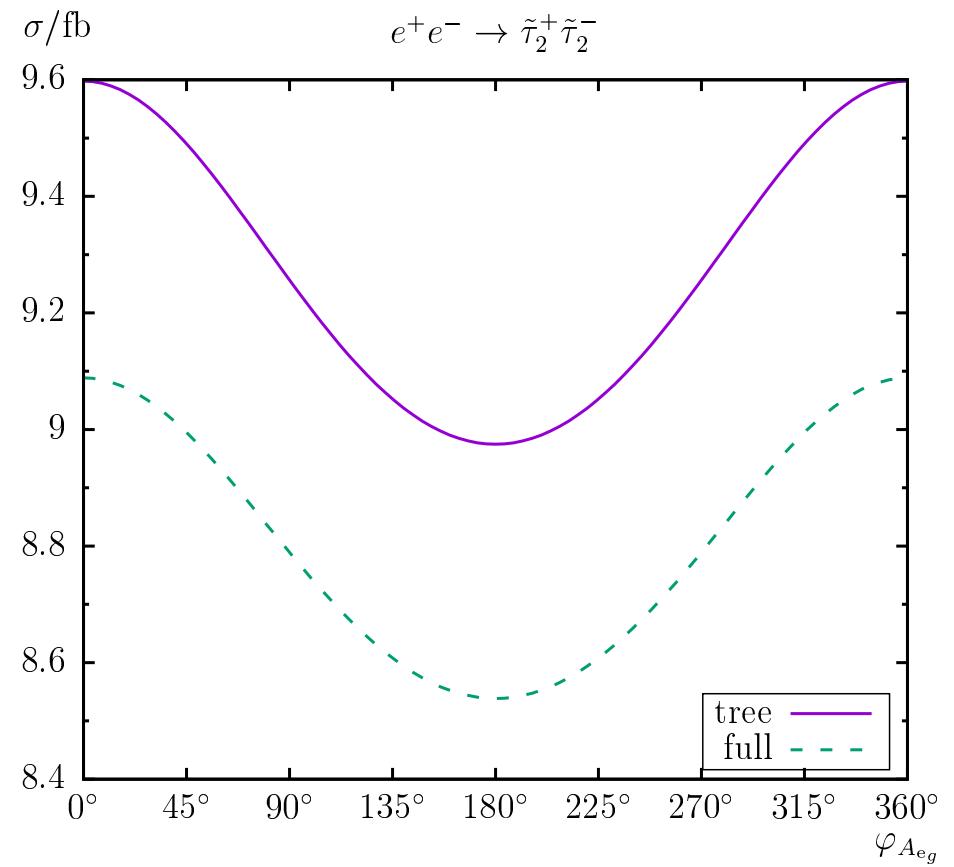
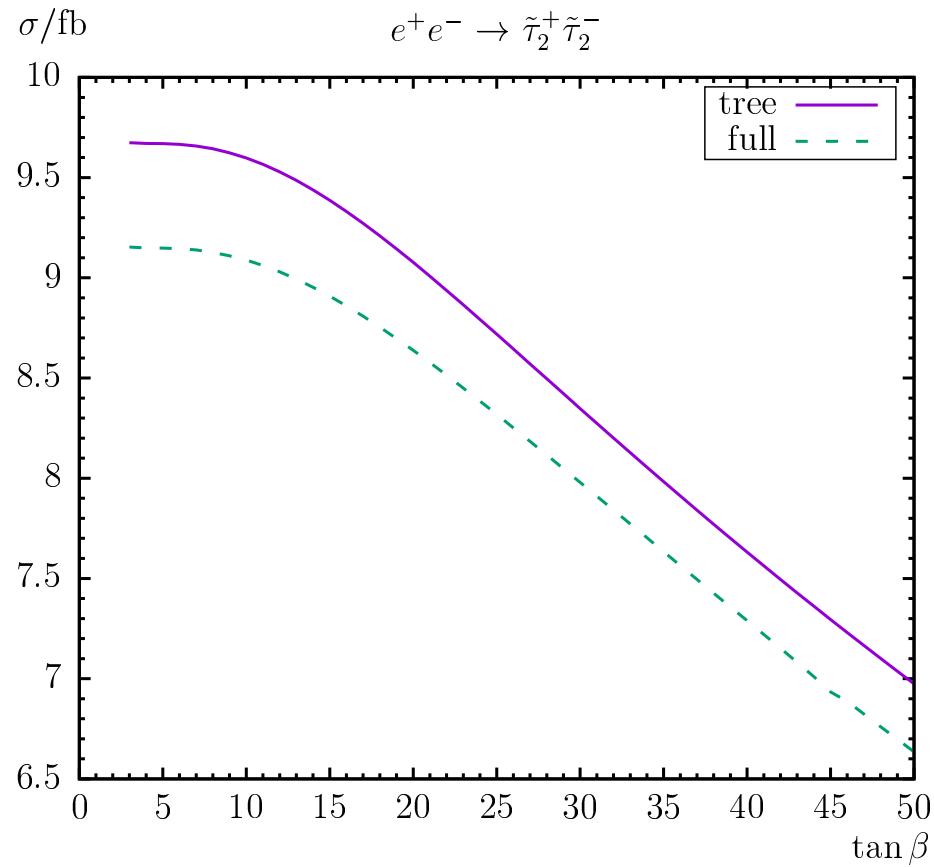
⇒ but negligible for  $\sqrt{s} \lesssim 700$  GeV

## $\tilde{\tau}_1 \tilde{\tau}_1$ production (II):



- ⇒ loop corrections  $\sim 15\%$
- ⇒ strong  $\tan \beta$  dependance
- ⇒ weak phase dependance

## $\tilde{\tau}_2 \tilde{\tau}_2$ production:



- ⇒ loop corrections  $\sim 15\%$
- ⇒ strong  $\tan \beta$  dependance
- ⇒ strong phase dependance

## 5. Conclusions

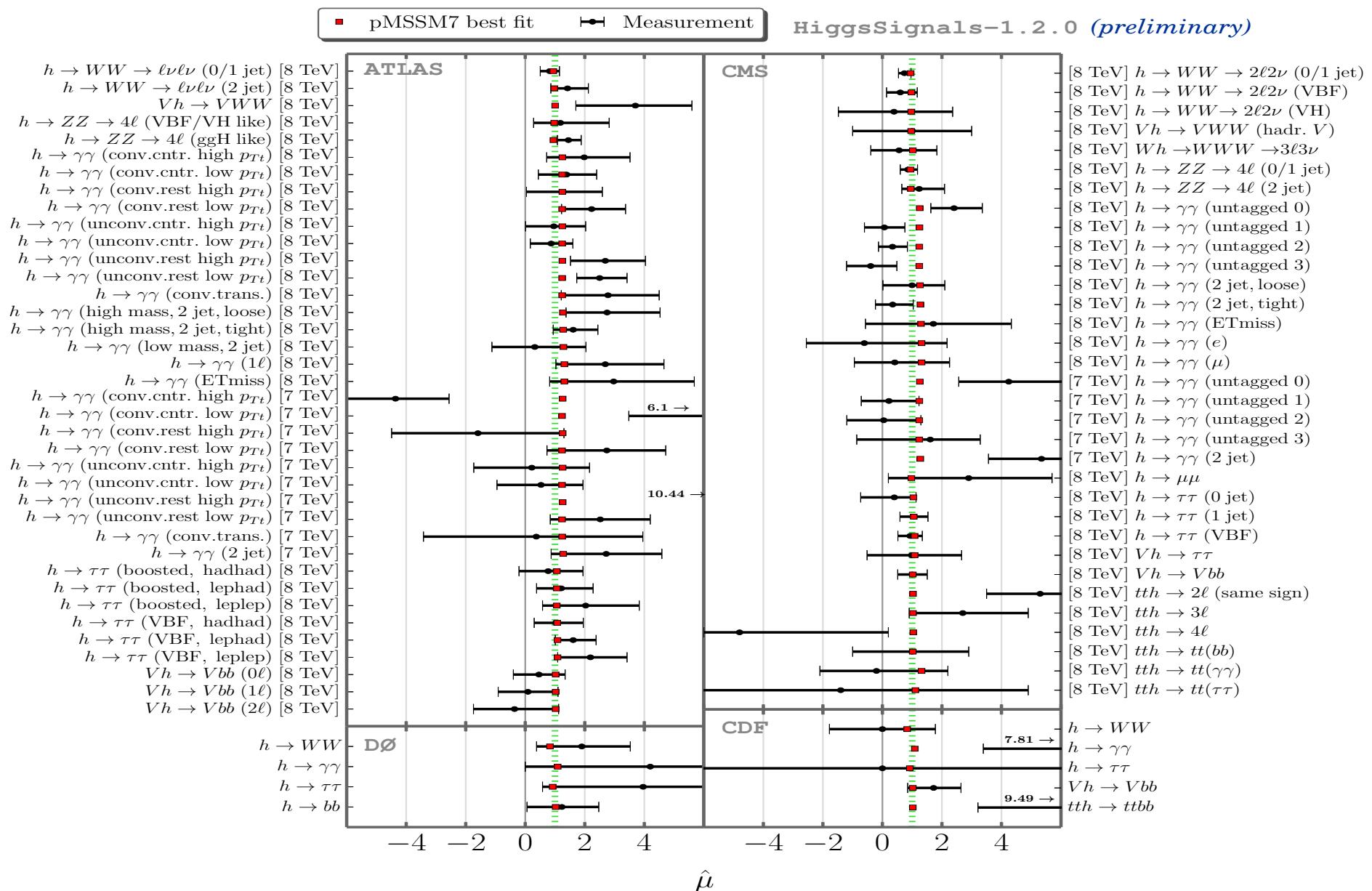
- SUSY is (still) the best-motivated BSM scenario
  - constrained models: CMSSM, NUHM1, NUHM2, SU(5), mAMSB
  - general models: pMSSM11, ...
- MasterCode: LHC, Higgs, EWPO, BPO, CDM  $\Rightarrow \chi^2$  evaluation
- | Model            | Min. $\chi^2/\text{dof}$ | $\chi^2$ -prob. ( $p$ -value) |
|------------------|--------------------------|-------------------------------|
| GUT based models | (30 … 33)/(18 … 23)      | $\sim 11\%$                   |
| pMSSM11          | 21.0/20                  | 33%                           |

$\Rightarrow$  pMSSM11: model with higher  $\chi^2$ -probability  
model with good ILC/CLIC prospects  
detailed LHC analysis tbd!
- SUSY production cross section: chargino/neutralino/sleptons ready



Further Questions?

# Higgs rate measurements: Implemented via HiggsSignals



## (Some) Electroweak precision observables in the MasterCode

(→ as for blue band analysis, except  $\Gamma_W$ )

1.  $M_W$  (LEP/Tevatron)

2.  $A_{\text{LR}}^e$  (SLD)

3.  $A_{\text{FB}}^b$  (LEP)

4.  $A_{\text{FB}}^c$  (LEP)

5.  $A_{\text{FB}}^l$

6.  $A_b, A_c$

7.  $R_b, R_c$

8.  $\sigma_{\text{had}}^0$

⇒ largest impact: (1), (2), (3)

## (Some) $B/K$ physics observables in the MasterCode

1.  $\text{BR}(b \rightarrow s\gamma)$  (MSSM/SM)
2.  $\text{BR}(B_s \rightarrow \mu^+\mu^-)$
3.  $\Delta M_s$
4.  $\mathcal{R}(\Delta M_s / \Delta M_d)$
5.  $\text{BR}(B_u \rightarrow \tau\nu_\tau)$  (MSSM/SM)
6.  $\text{BR}(B \rightarrow X_x \ell^+ \ell^-)$
7.  $\text{BR}(K \rightarrow \ell\nu)$  (MSSM/SM)
8.  $\text{BR}(\Delta M_K)$  (MSSM/SM)

⇒ largest impact: (1) and (2)

## Further low-energy observables

- anomalous magnetic moment of the muon:  $(g - 2)_\mu$

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- lightest Higgs mass:  $M_h$
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## Dark Matter observables in the MasterCode

- CDM density:  $\Omega_\chi h^2$
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## SM parameters

- top mass:  $m_t$
- $Z$  boson mass:  $M_Z$
- hadronic contribution to fine structure constant:  $\Delta\alpha_{\text{had}}$