Exotic Di-Higgs Resonances in Neutral Naturalness

Particle Physics Seminar

DESY

June 12, 2023

Rodolfo Capdevilla
Fermilab

***RC**, Roni Harnik, Adam Martin, JHEP **03** (2020) 117*
*Mario Barela, **RC**, ArXiv: 2306.xxxxx*

Outline

1. Introduction
   - Fundamental questions in HEP
   - The Higgs boson and beyond
2. Naturalness
   - Where are the stops?
   - A little hierarchy?
3. Neutral Naturalness
   - Folded Supersymmetry
   - Quirky collider signatures
   - Di-Higgs signals
4. Results
5. Summary/Conclusions

1. Introduction

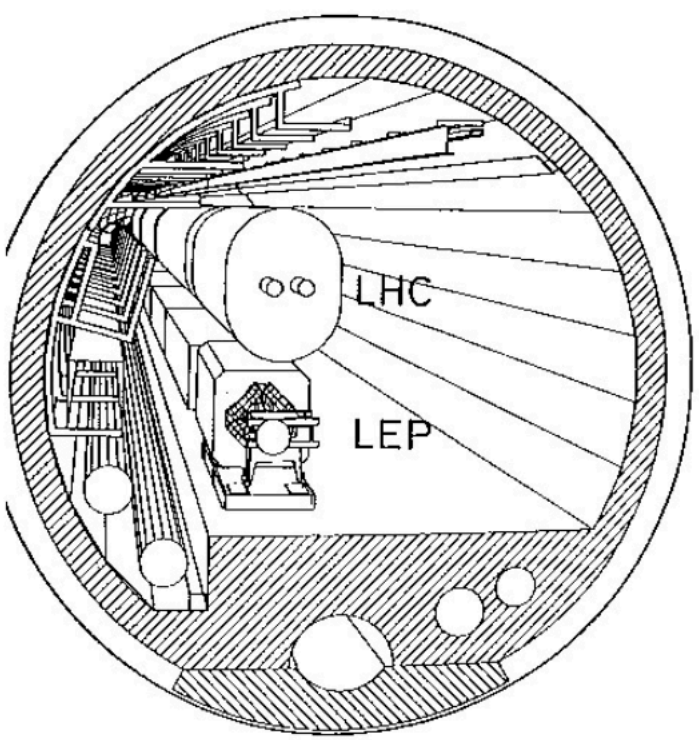
- Before the LHC:

Satisfied with these successes, we have now to face deeper questions such as:

what is the origin of mass?
what kind of unification may exist beyond the standard model?
what is the origin of flavour?
is there a deeper reason for gauge symmetry?

We have simply too many a priori plausible hypotheses concerning the nature of symmetry breaking in the standard model. Experimentation in the TeV range at the constituent level is bound to provide most essential clues, and the present successes of the $p\bar{p}$ collider are a very strong encouragement to go to higher energies and to higher luminosities in hadron-hadron collisions.

ECFA 84/85
CERN 84-10
5 September 1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984

1. Introduction

- Before the LHC:

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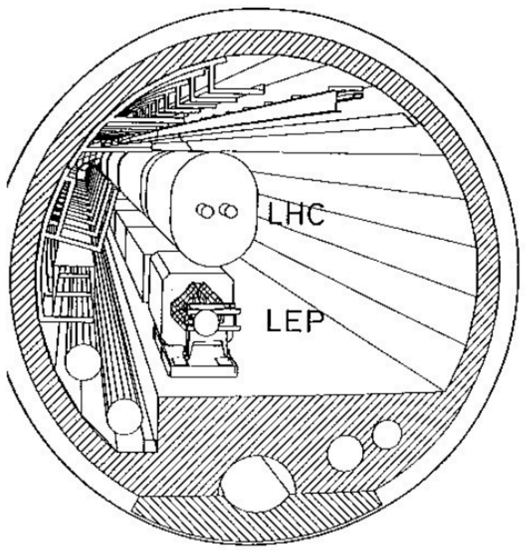

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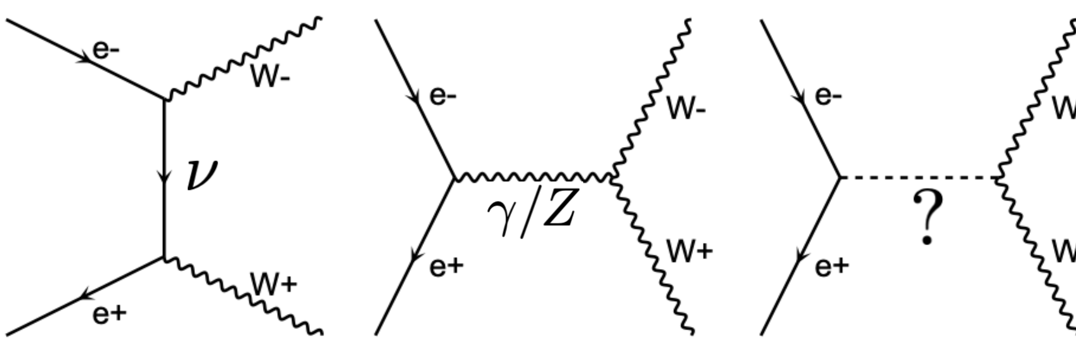
We have simply too many a priori plausible hypotheses concerning the nature of symmetry breaking in the standard model. Experimentation in the TeV range at the constituent level is bound to provide most essential clues, and the present successes of the $p\bar{p}$ collider are a very strong encouragement to go to higher energies and to higher luminosities in hadron-hadron collisions.

(*) A no-lose theorem for the LHC:



“If the Higgs boson did not exist, we should have to invent something very much like it”

- Chris Quigg

We give an S-matrix theoretic demonstration that if the Higgs boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{\frac{1}{2}}$ partial-wave unitarity is not respected by the tree diagrams for two-body scattering of gauge bosons, and the weak interactions must become strong at high energies. We exhibit the relation

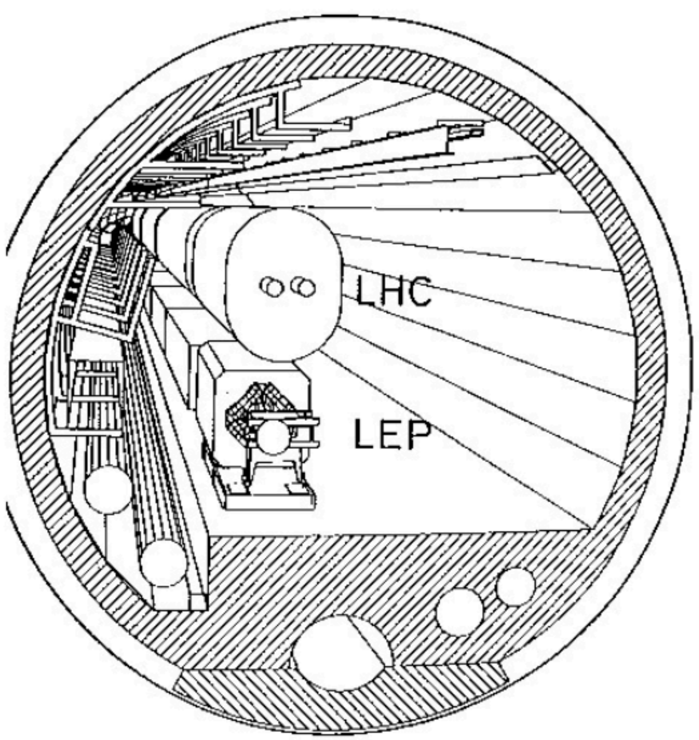
$$M_h \leq M_c = (8\pi\sqrt{2}/3G_F)^{\frac{1}{2}} \simeq 1\ \mathrm{TeV}/c^2$$

Lee, Quigg, Thacker, Phys. Rev. D **16** (1977) 1519

1. Introduction

- Now:

ECFA 84/85
CERN 84-10
5 September 1984



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Satisfied with these successes, we have now to face deeper questions such as:

~~what is the origin of mass?~~ → Yes, the Higgs! … yet (*)

what kind of unification may exist beyond the standard model?

what is the origin of flavour?

is there a deeper reason for gauge symmetry?

We have simply too many a priori plausible hypotheses concerning the nature of symmetry breaking in the standard model. Experimentation in the TeV range at the constituent level is bound to provide most essential clues, and the present successes of the $p\bar{p}$ collider are a very strong encouragement to go to higher energies and to higher luminosities in hadron-hadron collisions.

(*) We only got more questions:

Is there a more fundamental description of EWSB?
What mechanism sets the scale and stabilizes the Higgs mass?

Other questions include:

What is the nature of Dark Matter?
What is the mechanism for Baryogenesis?
What is the mechanism for neutrino masses?
The unknown! How can nature surprise us?

1. Introduction

- Higgs precision program:

What kind of unification may exist beyond the SM?
What is the origin of flavor?
Is there a deeper reason for gauge symmetry?
Is there a more fundamental description of EWSB?
What mechanism sets the scale and stabilizes the Higgs mass?

What is the nature of Dark Matter?
What is the mechanism for Baryogenesis?
What is the mechanism for neutrino masses?
The unknown! How can nature surprise us?

The Higgs is the key!

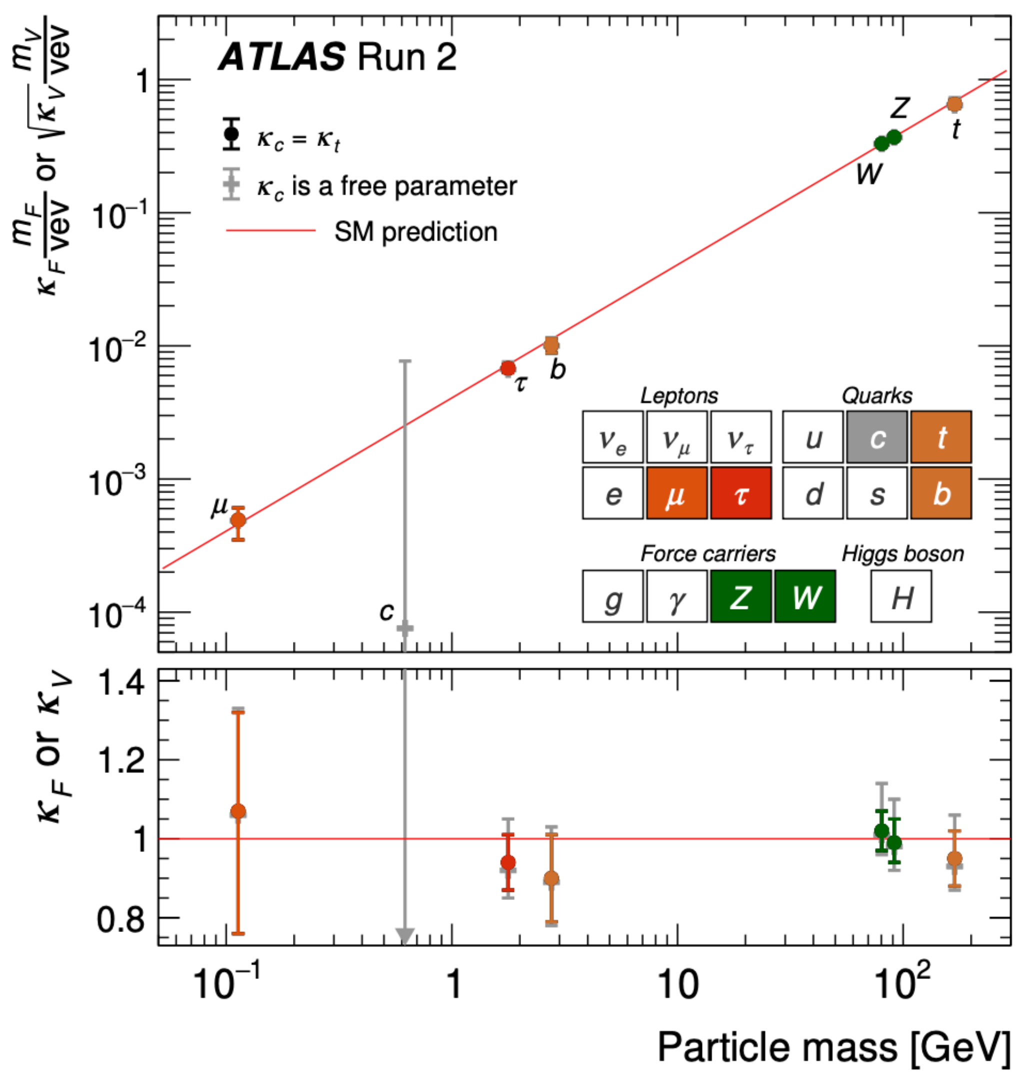
*Measuring **Higgs couplings** might answer some of the fundamental questions!*

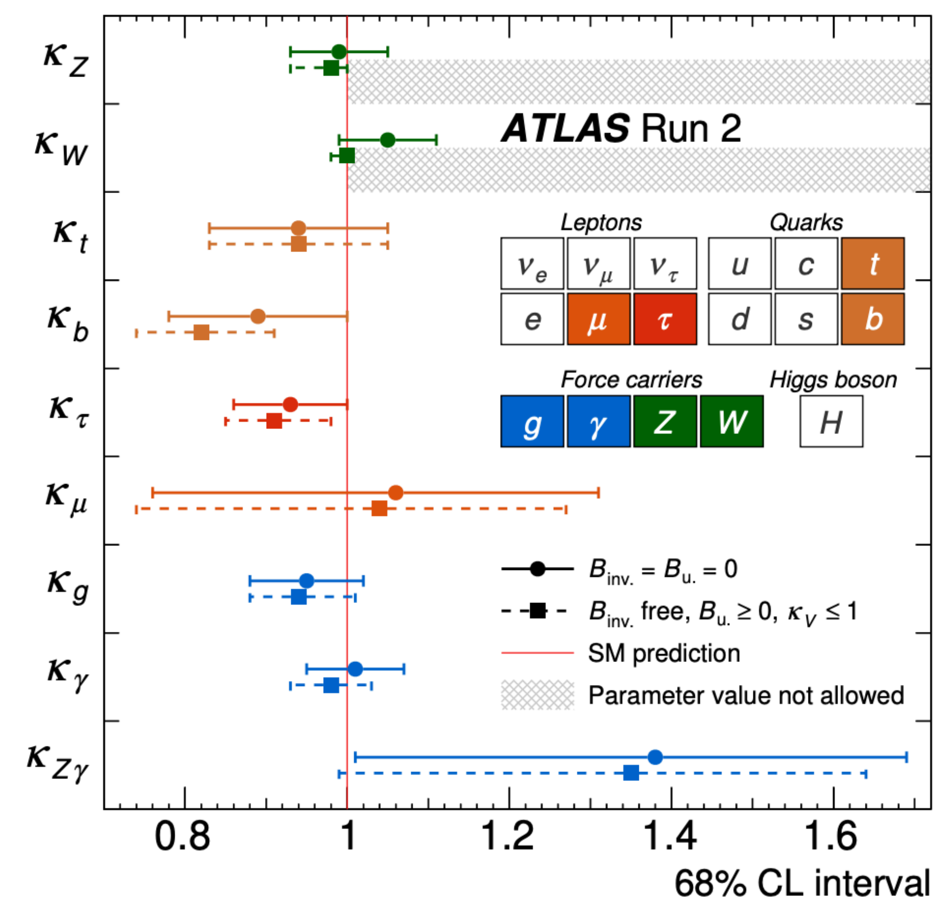
*The **Higgs** might be the **portal** to new physics!*

1. Introduction

- Higgs couplings:

Measuring ***Higgs couplings*** *might answer some of the fundamental questions!*



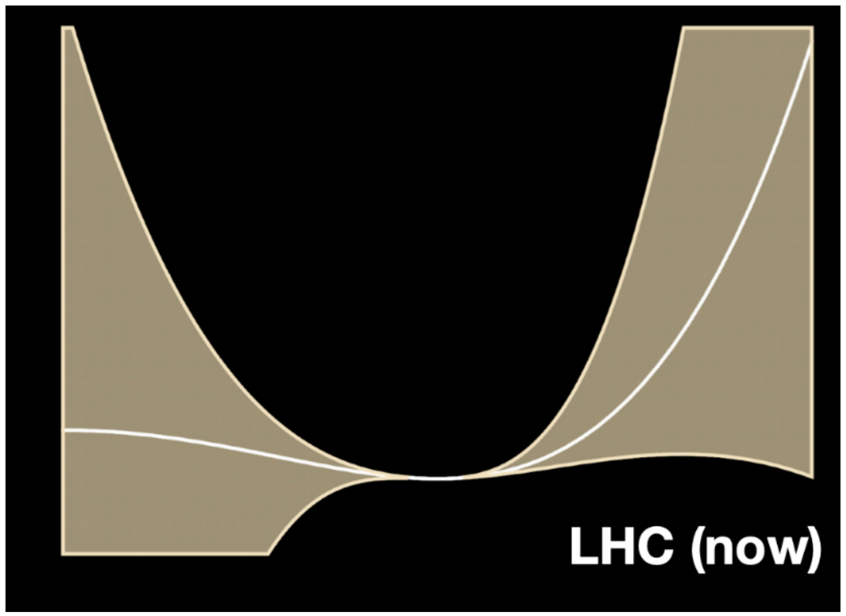


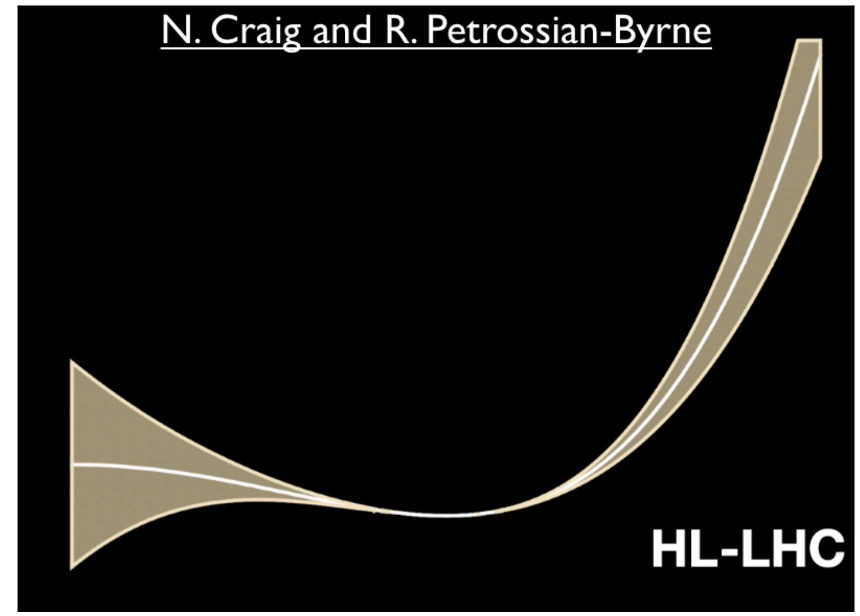
ATLAS Collaboration, Nature 607 (2022) 7917

1. Introduction

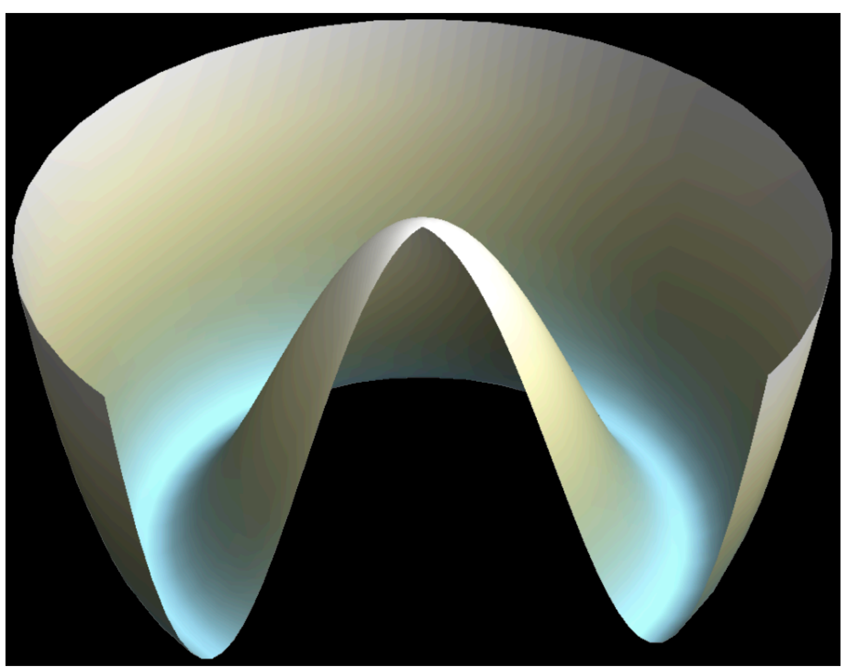
- Higgs couplings:

What is the exact shape to the Higgs potential?

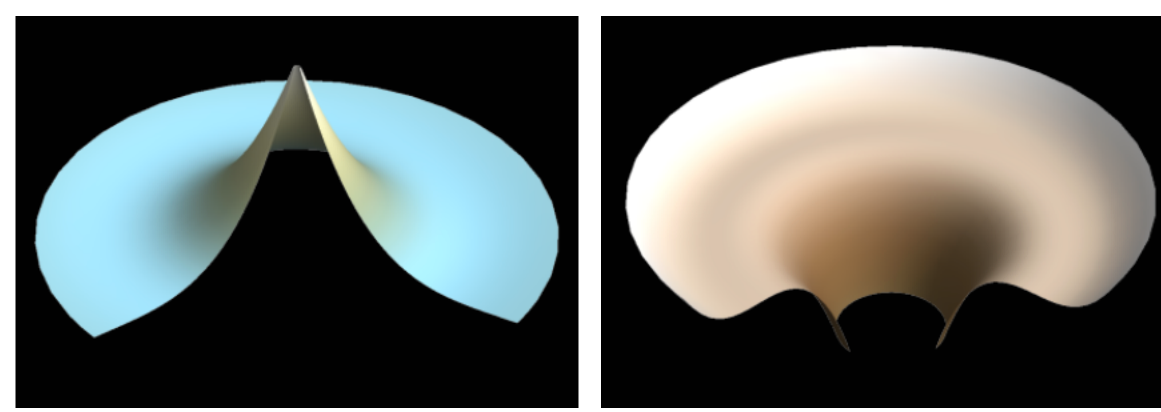




Standard Picture!



Alternative pictures allowed by uncertainties!



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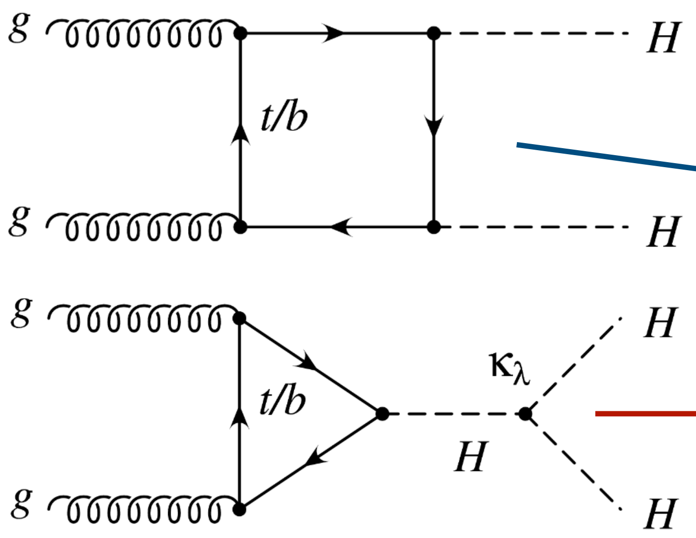
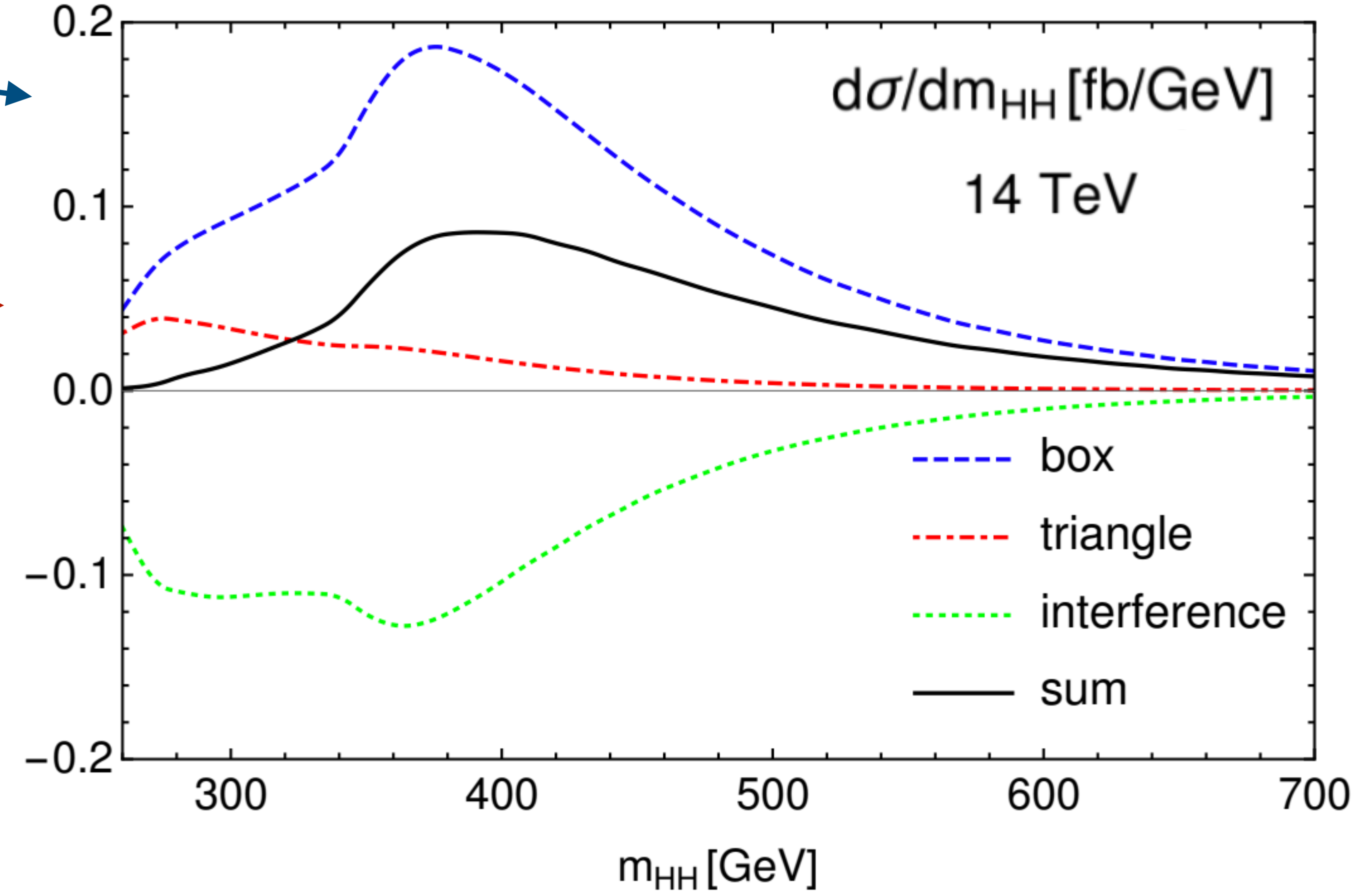


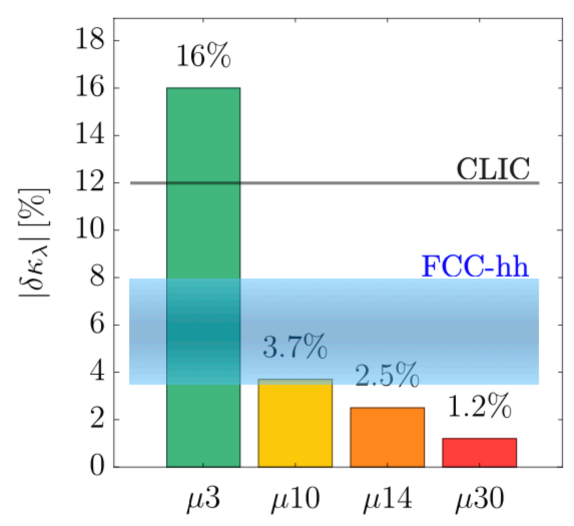
Double Higgs Production at Colliders, Rev. Phys. 5 (2020) 100045



collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
$CEPC_{240}$	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
FCC-hh	-	5%	5%

A task for future colliders?

We already started!



1. Introduction

- Higgs portal:

*The **Higgs** might be the **portal** to new physics!*

$$|H|^2\mathcal{O}$$

→ *Extended Higgs sector*

→ *Singlet scalar DM*

→ *Electroweak Baryogenesis*

⋮

$$HL^\alpha\mathcal{O}_\alpha$$

→ *Heavy neutral leptons*

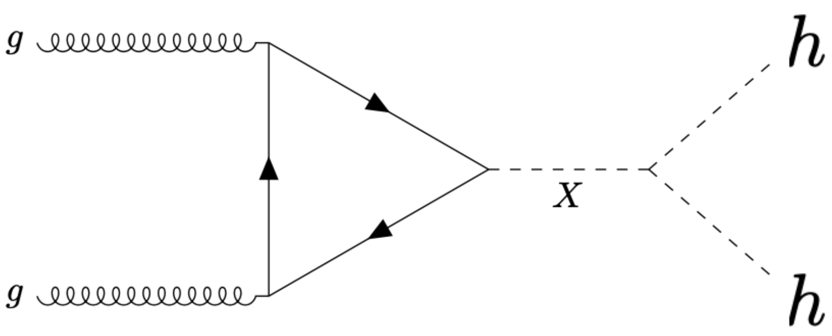
→ *Sterile neutrino DM*

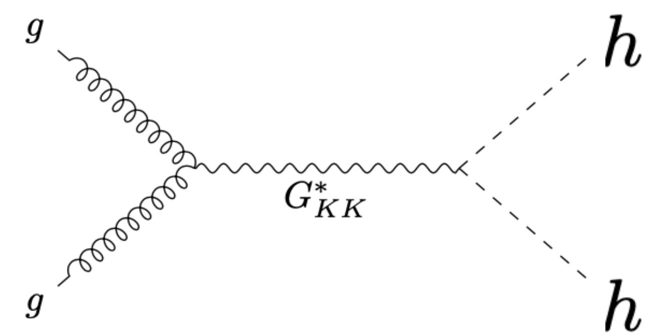
⋮

1. Introduction

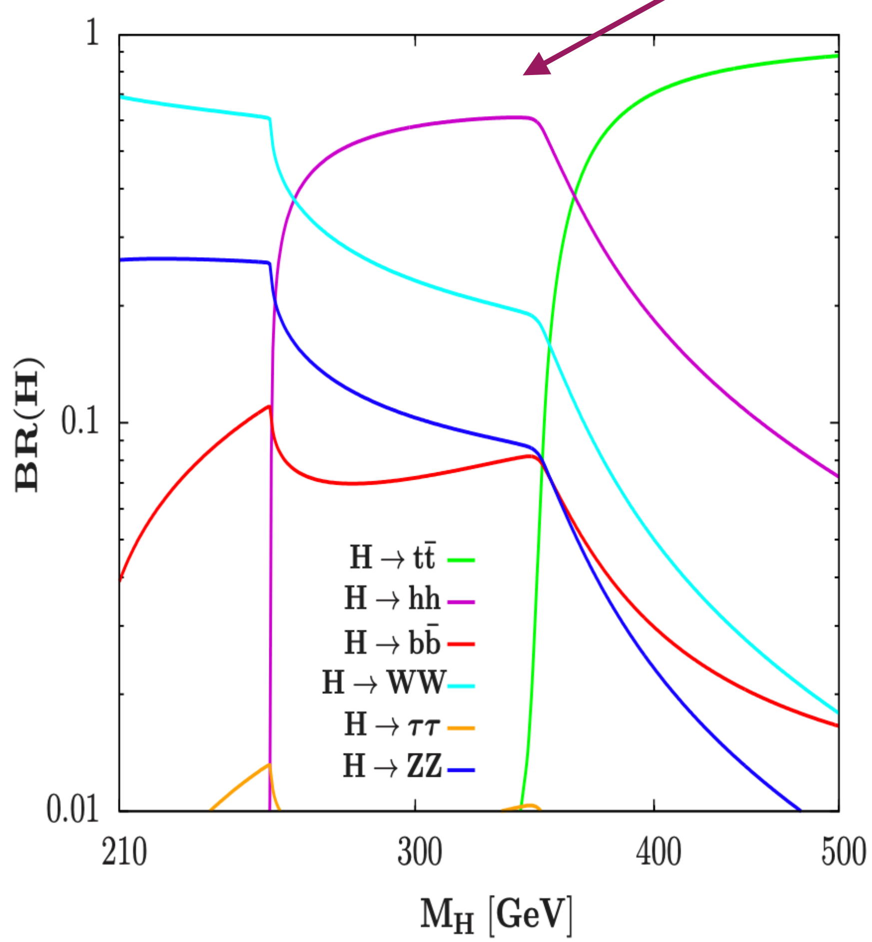
- Higgs portal:

Search for exotic resonances!

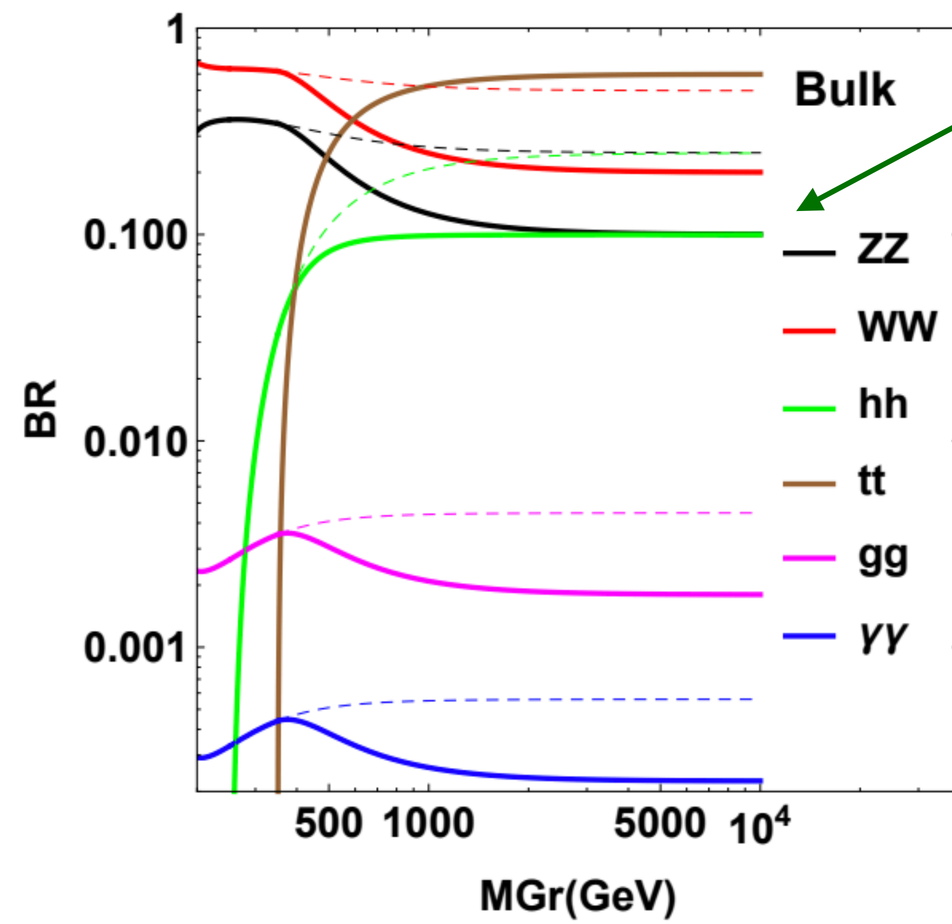




Dominant decay channel hh



Sizeable hh Branching ratio



Djouadi, Quevillon, JHEP 10 (2013) 028

Alexandra Carvalho, ArXiv:1404.0102

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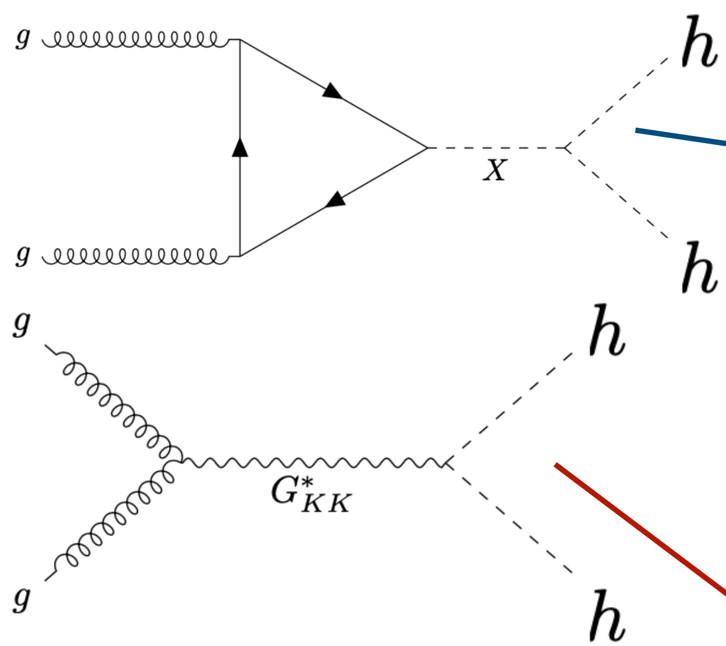

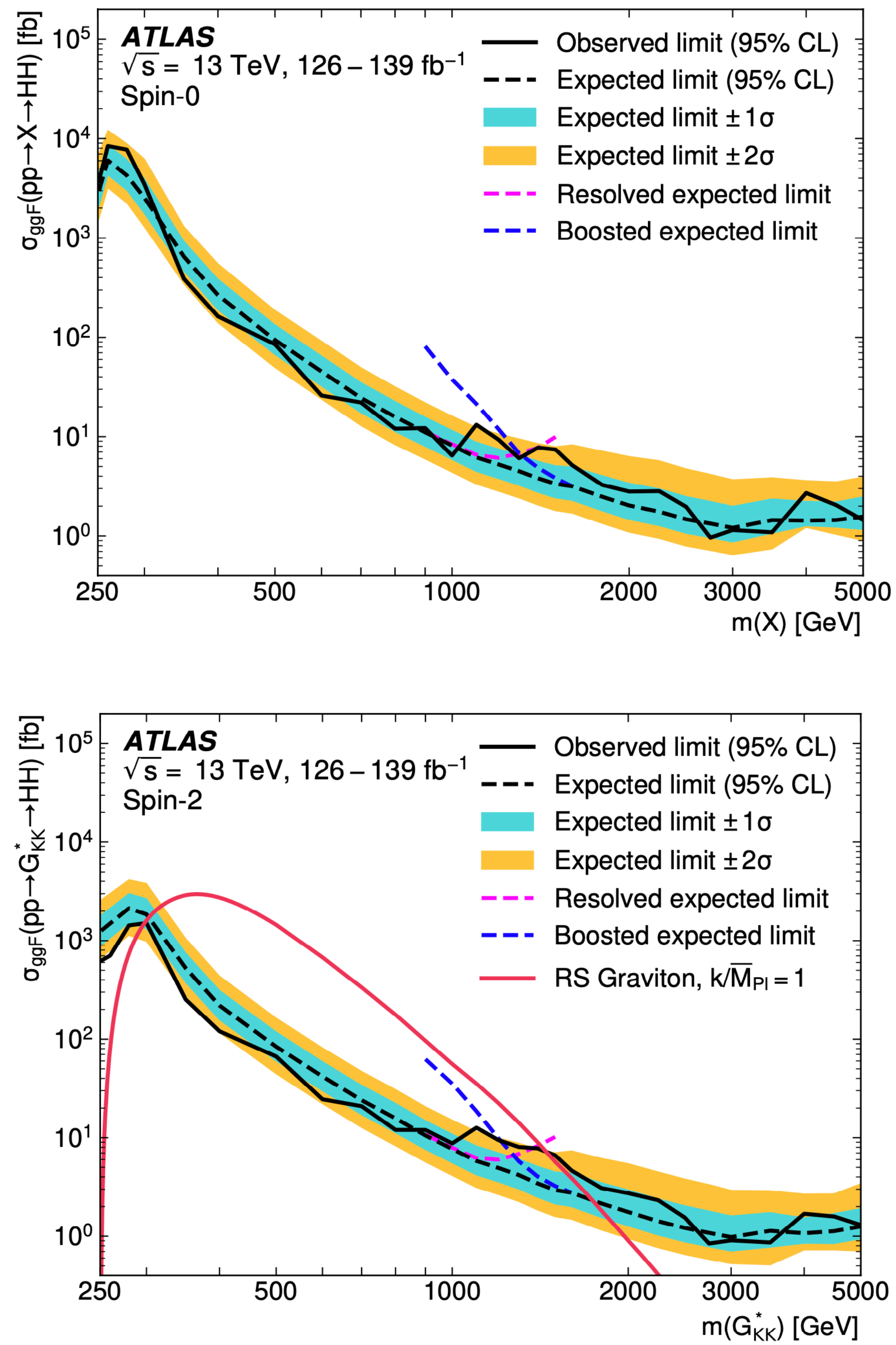

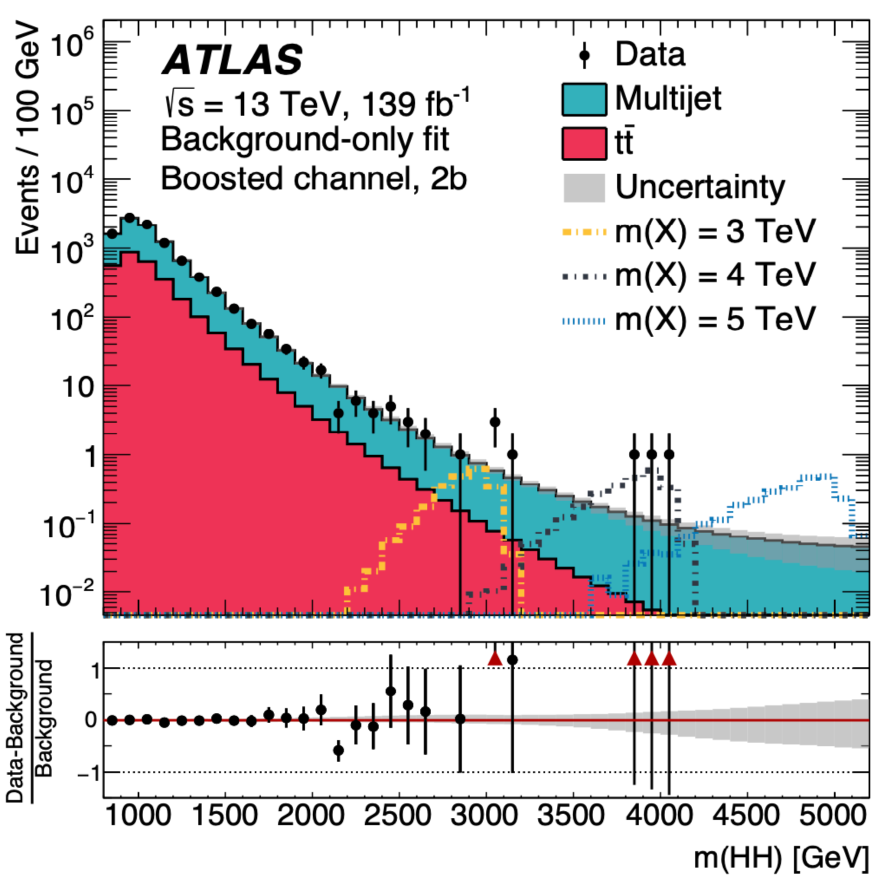

ATLAS Collaboration, Phys. Rev. D 105 (2022) 9, 092002

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Fundamental questions

↓

Higgs precision program

↙ ↘

Higgs couplings ↓ *Shape of the potential, Trilinear coupling, …*

Higgs portal ↓ *Extra scalars, Di-Higgs resonances, …*

Rodolfo Capdevilla, Fermilab

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Higgs precision program

Higgs couplings

Shape of the potential, Trilinear coupling, …

Higgs portal

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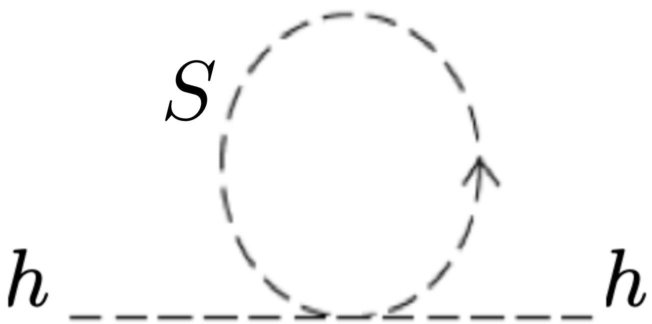
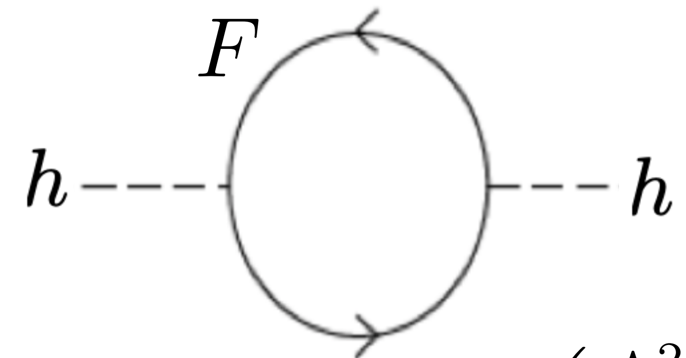
Rodolfo Capdevilla, Fermilab

2. Naturalness

- The hierarchy problem:





$$\delta m_h^2 \sim \Lambda^2 - m_S^2 \log\left(\frac{\Lambda^2}{m_S^2}\right) + \ldots$$

$$\delta m_h^2 \sim -\Lambda^2 + m_F^2 \log\left(\frac{\Lambda^2}{m_F^2}\right) + \ldots$$

Supersymmetry can solve this!

It can also answer some of these questions!

What kind of unification may exist beyond the SM?
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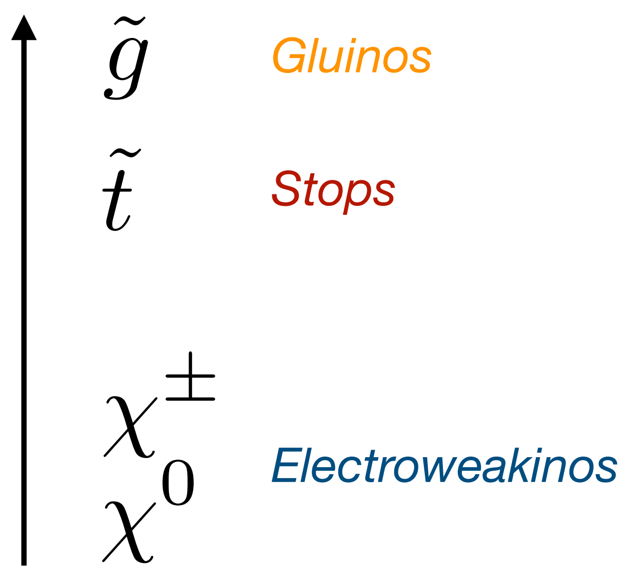
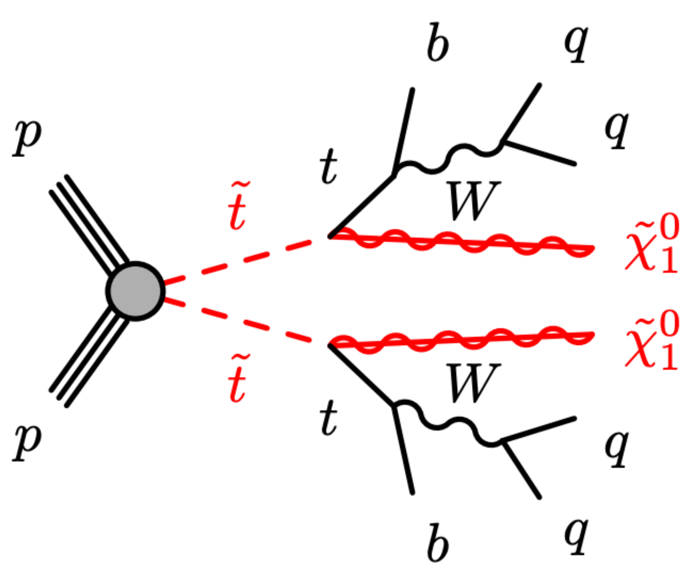
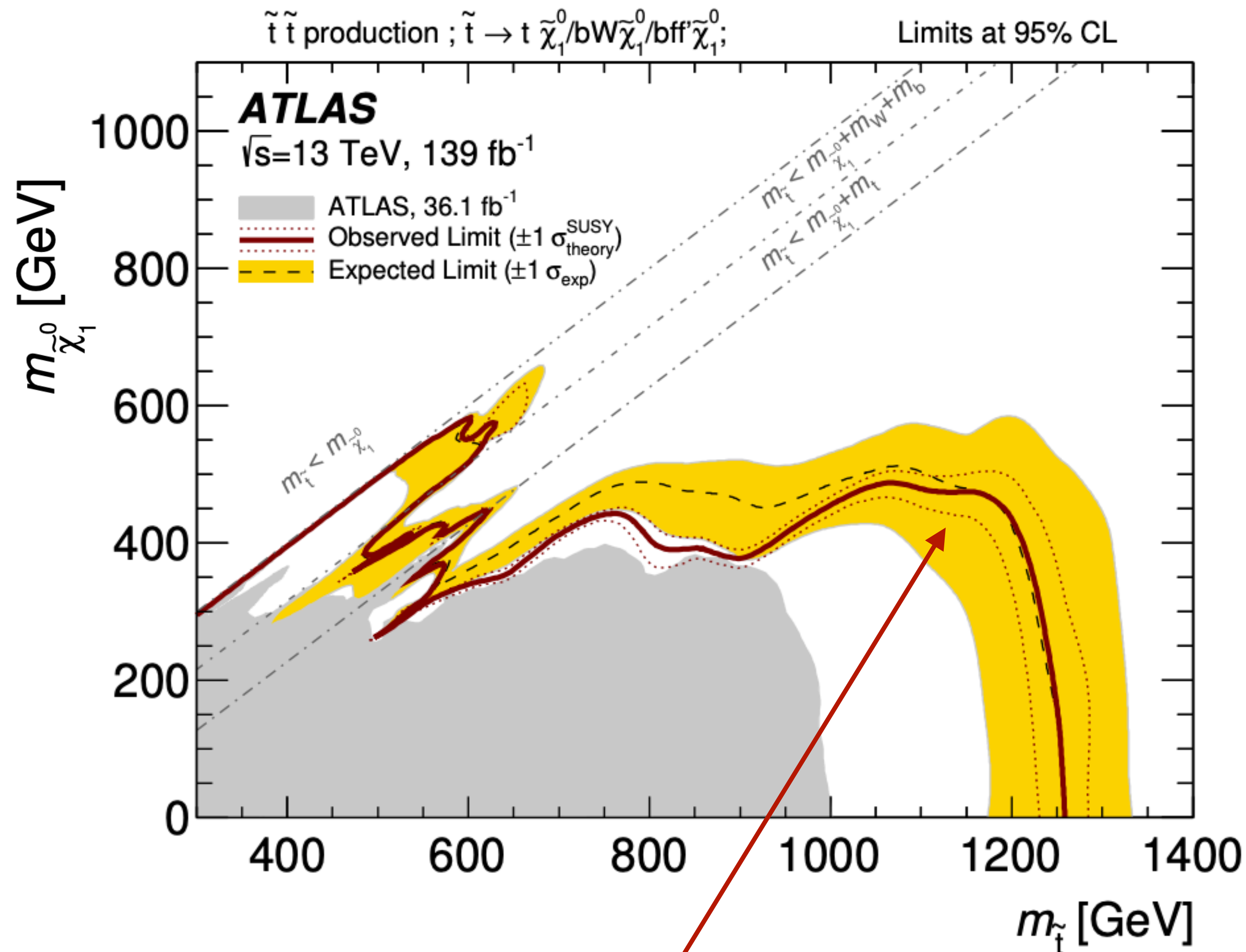
2. Naturalness

- Benchmarks:





ATLAS Collaboration, Eur. Phys. J. C 80 (2020) 8

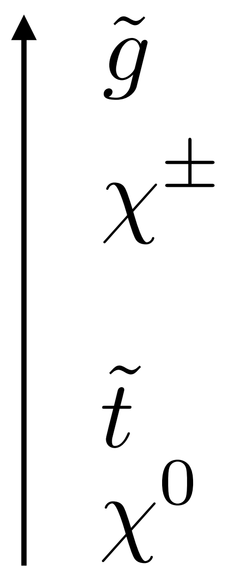


Direct searches are pushing stops above the TeV scale

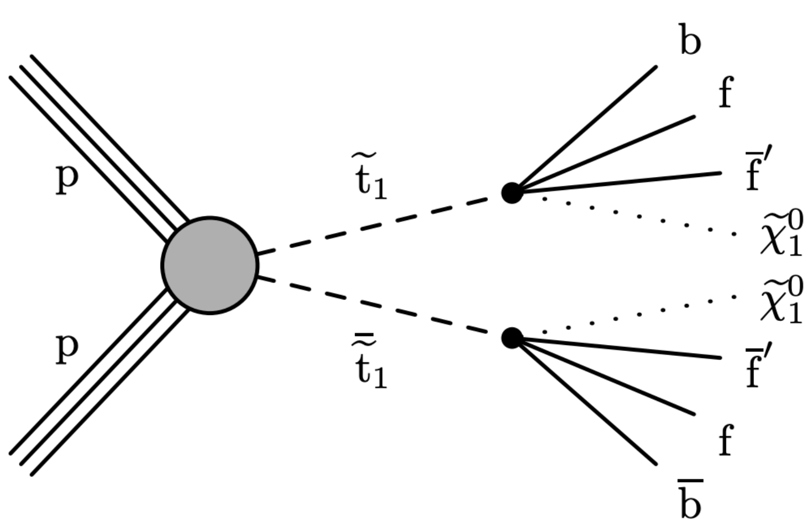
2. Naturalness

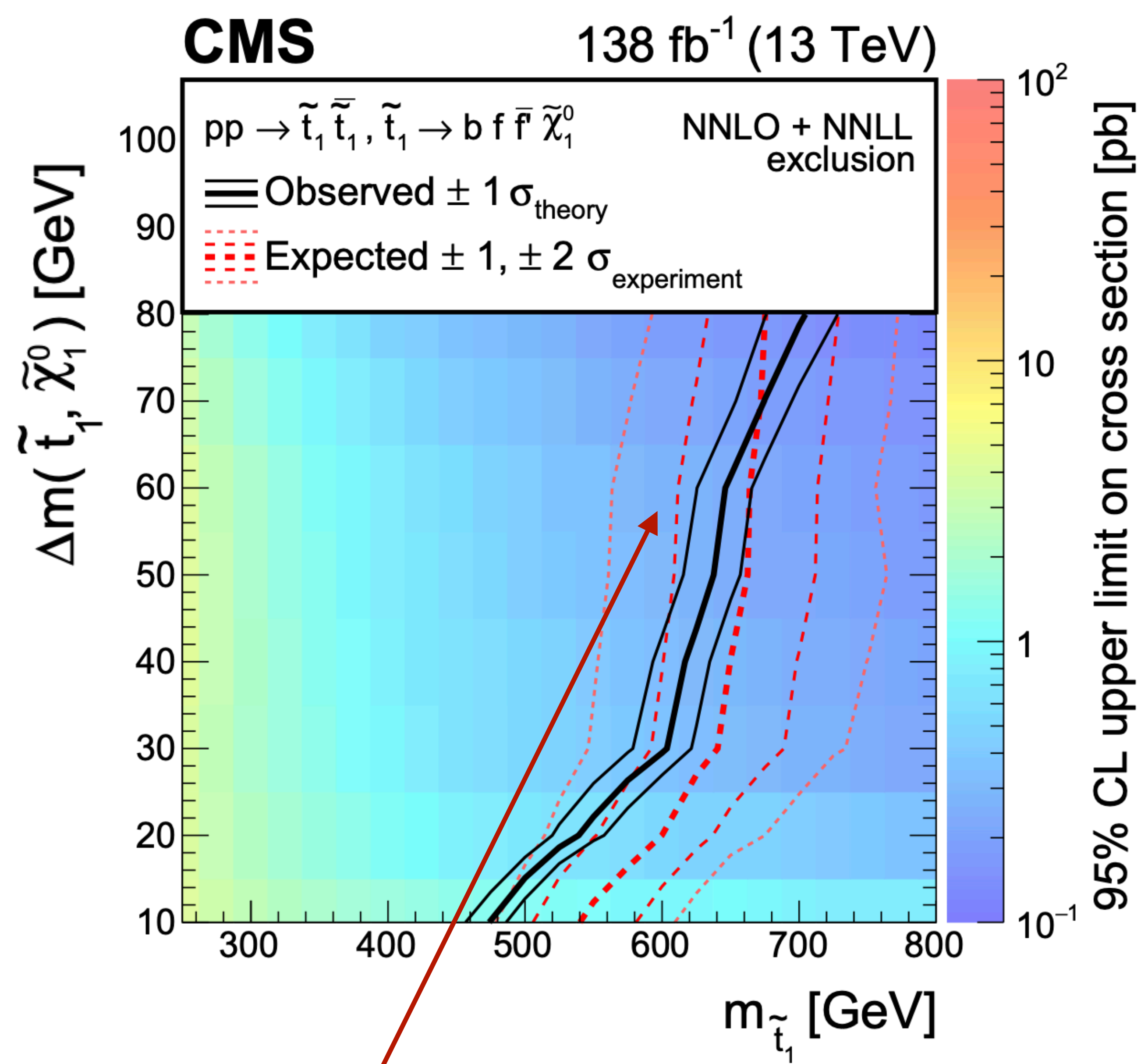
- Benchmarks:

CMS Collaboration, ArXiv:2301.08096



Compressed!





Bounds for the compressed spectrum are not as high!

2. Naturalness

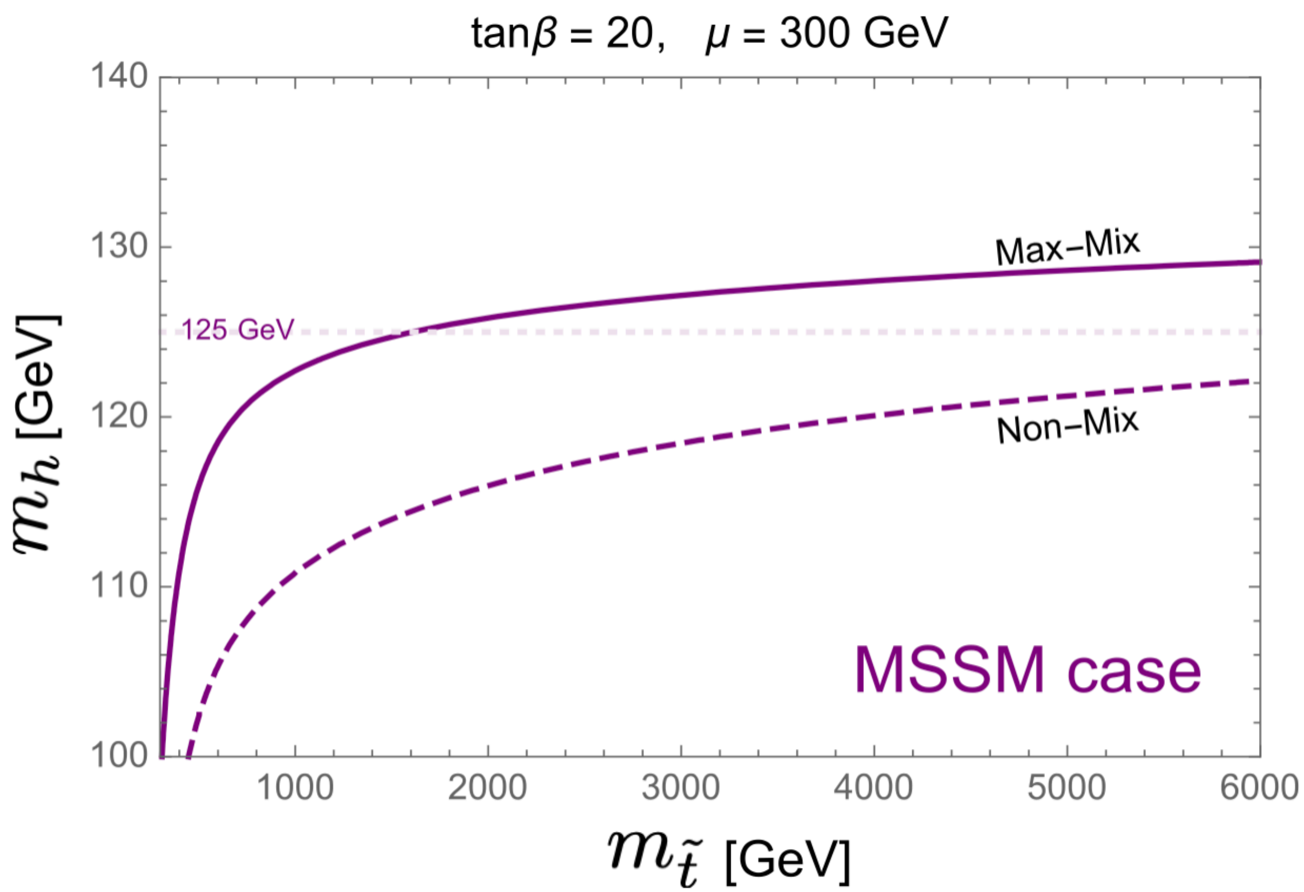
- Where are the stops?

$$m_h \sim m_Z \cos(2\beta)$$

The minimal model predicts a very light SM-like Higgs boson!

$$m_h^2 \sim m_Z^2 \cos^2(2\beta) + \frac{3m_t^4}{8\pi^2 v^2} \log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

Loop contributions can increase the Higgs mass!



The vanilla version points at stop masses above the TeV scale!

A little hierarchy?

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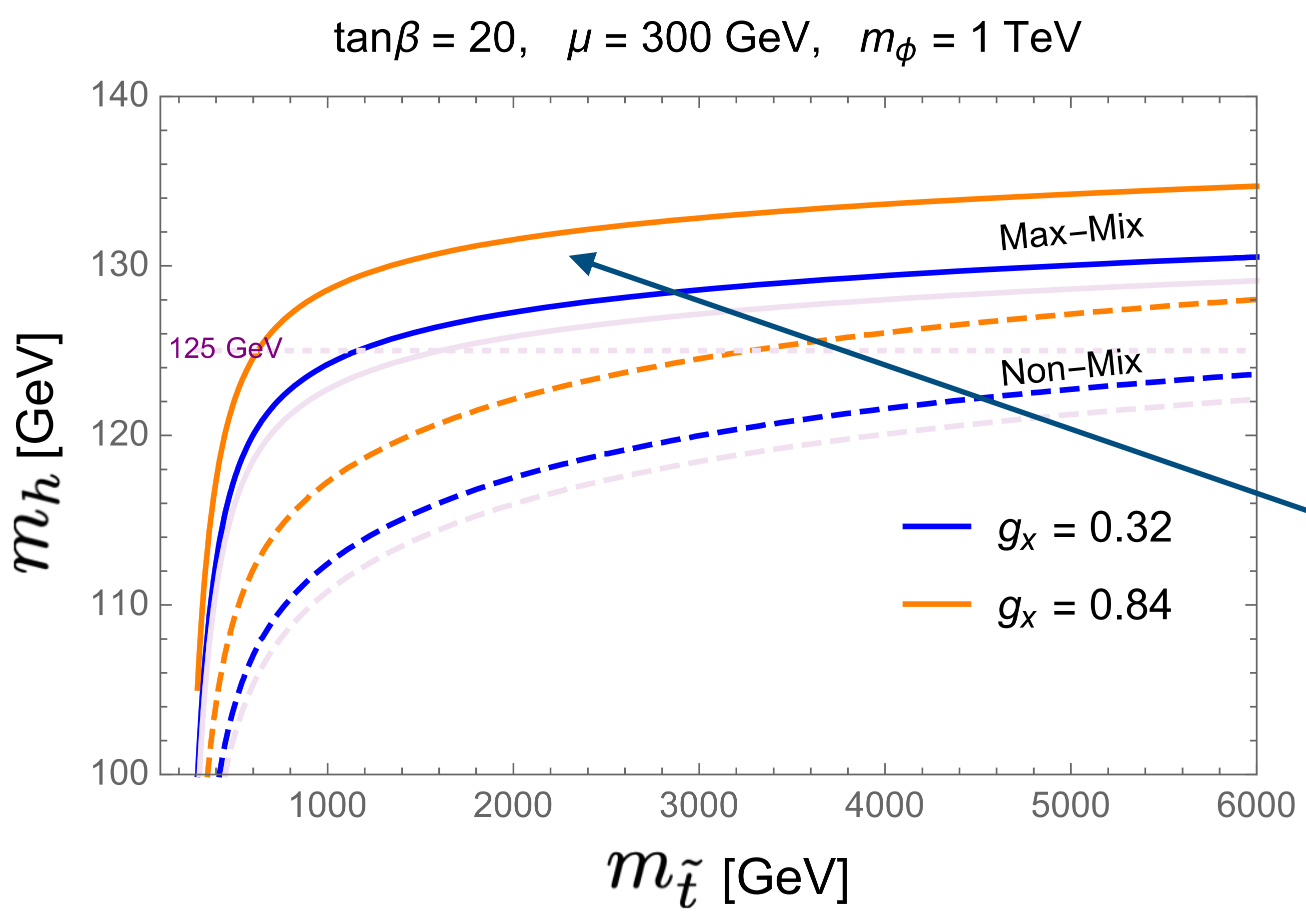

The vanilla version predicts stop masses above the TeV scale!

A little hierarchy?

Discovering stops below 1TeV might indicate the existence of an extended gauge U(1)MSSM or scalar sector NMSSM

RC, Antonio Delgado, Adam Martin, Phys. Rev. D **92** (2015) 11

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Where are the stops?

Below 1TeV? → *U(1)MSSM*, *NMSSM*

What if stops are not (fully) charged under the SM gauge group?

(Neutral Naturalness)

Beyond LHC reach? → *Little Hierarchy*

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Where are the stops? → *Below 1TeV?* → *U(1)MSSM*, *NMSSM*

Where are the stops? → *Beyond LHC reach?* → *Little Hierarchy*, *What if stops are not charged under the SM gauge group?*

(Neutral Naturalness)

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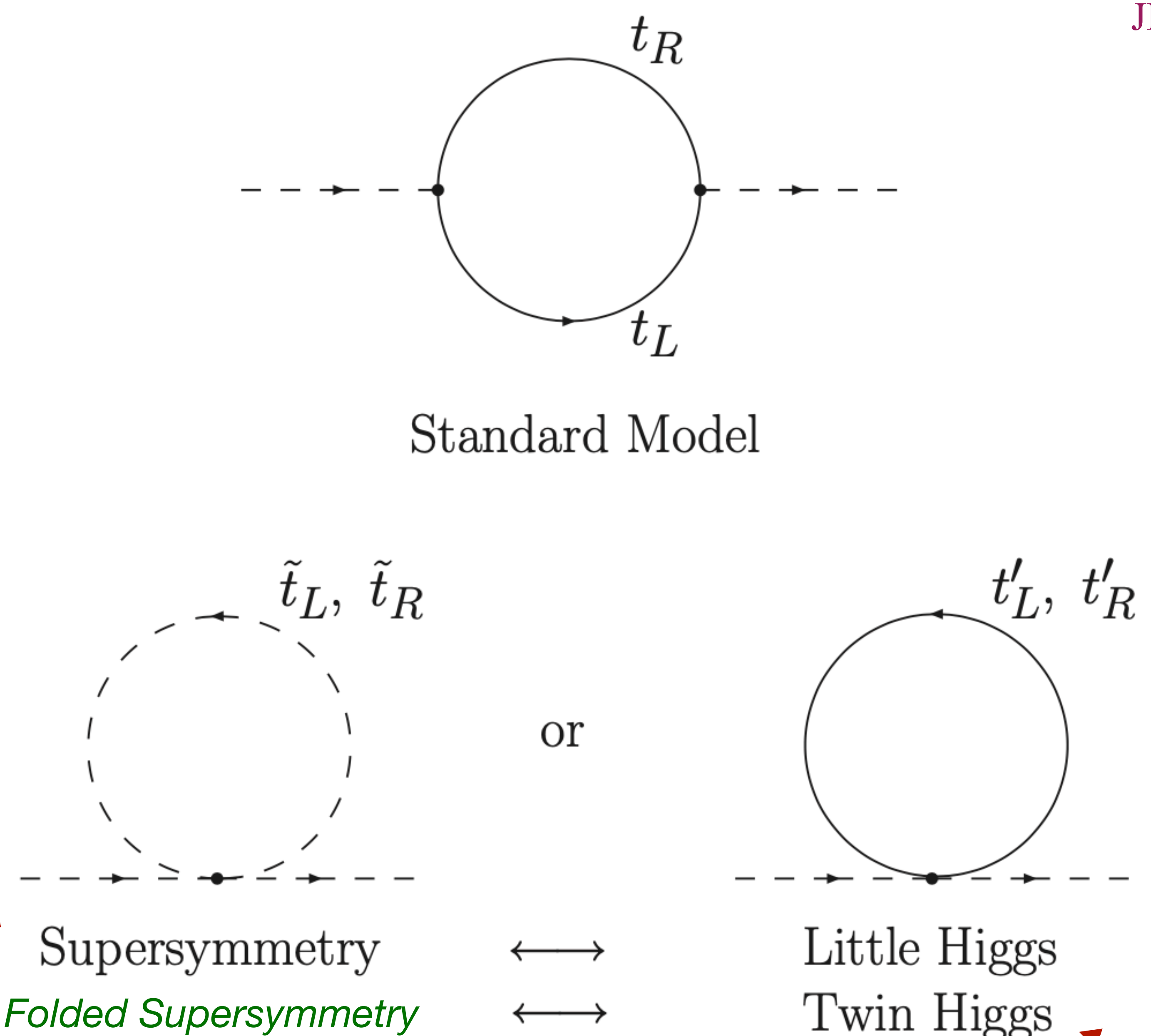
3. Neutral Naturalness

- Top partners:

Burdman, Chacko, Goh, Harnik, JHEP **02** (2007) 009

Top partners are charged under the SM group



Folded Supersymmetry

Top partners (scalar) have electroweak charge but not SM color charge!

Top partners (fermionic) are completely neutral under the SM group

3. Neutral Naturalness

- Folded Supersymmetry:

Burdman, Chacko, Goh, Harnik, JHEP **02** (2007) 009

Effective theory In the IR

$SU(3)_c \times SU(2)_L \times U(1)_Y$ $\qquad$ $SU(3)_{c'} \times SU(2)_L \times U(1)_Y$

t_L, t_R $\qquad$ $\tilde{t}_L, \tilde{t}_R$

Top quark $\qquad$ *Top partners*

Related in the UV

$$Z_2$$

$$SU(3)_c \leftrightarrow SU(3)_{c'}$$

$$\Lambda_{\rm QCD} \sim \Lambda_{\rm QCD'}$$

TeV

$\tilde{t}$

t

$\Lambda_{\rm QCD'}$

$\Lambda_{\rm QCD}$

Very close!

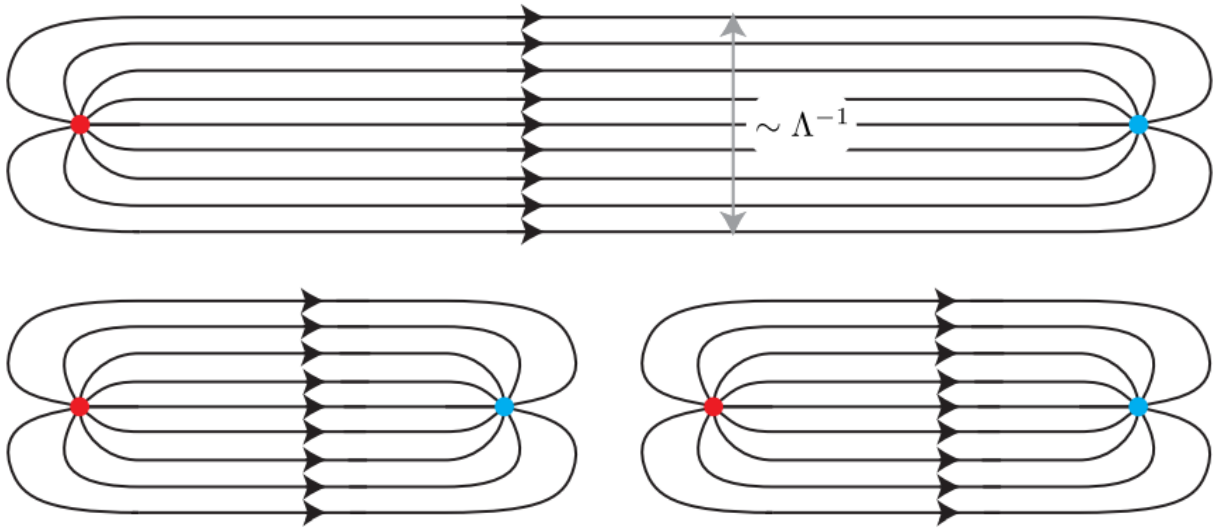
Note! The lightest particle colored under c' is heavier than confining scale!

Quirks! Prediction of the model

3. Neutral Naturalness

- (s)Quirks:

Kang, Luty, JHEP 11 (2009) 065

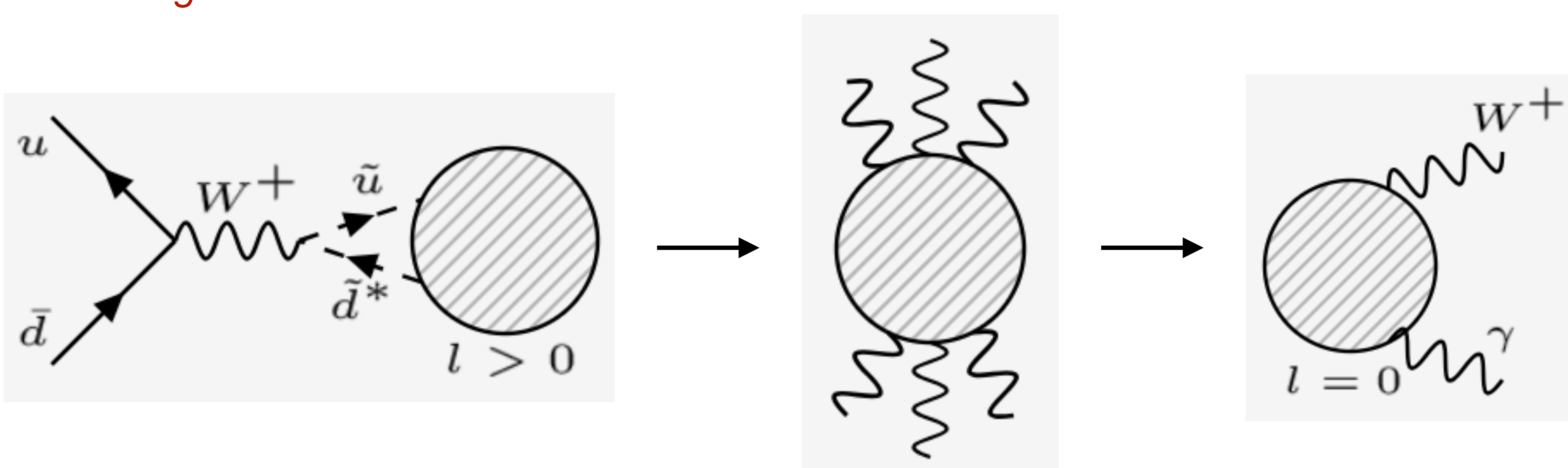


The string breaks as long as

$$\Lambda > 2m_Q$$

$$\Gamma \sim \frac{m_Q}{4\pi^3} e^{-m_Q^2/\Lambda^2} \qquad (m_Q \gg \Lambda)$$

Quirky collider signatures:



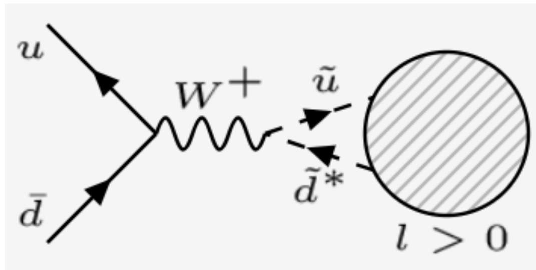
Production *Relaxation* *Decay*

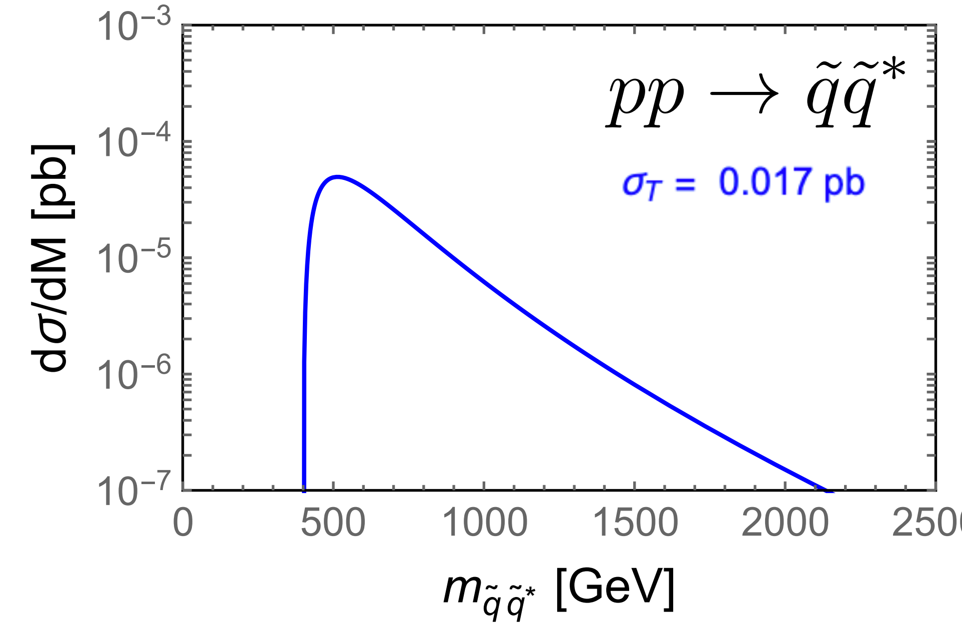
Burdman, Chacko, Goh, Harnik, Krenke, Phys. Rev. D 78 (2008) 075028

3. Neutral Naturalness

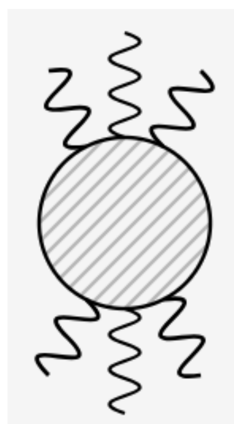
- (s)Quirks:

Production



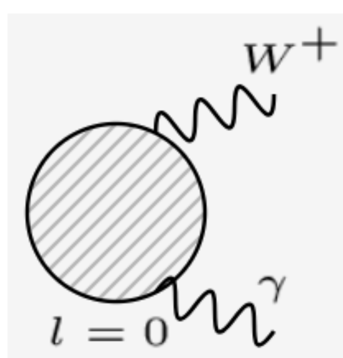


Relaxation

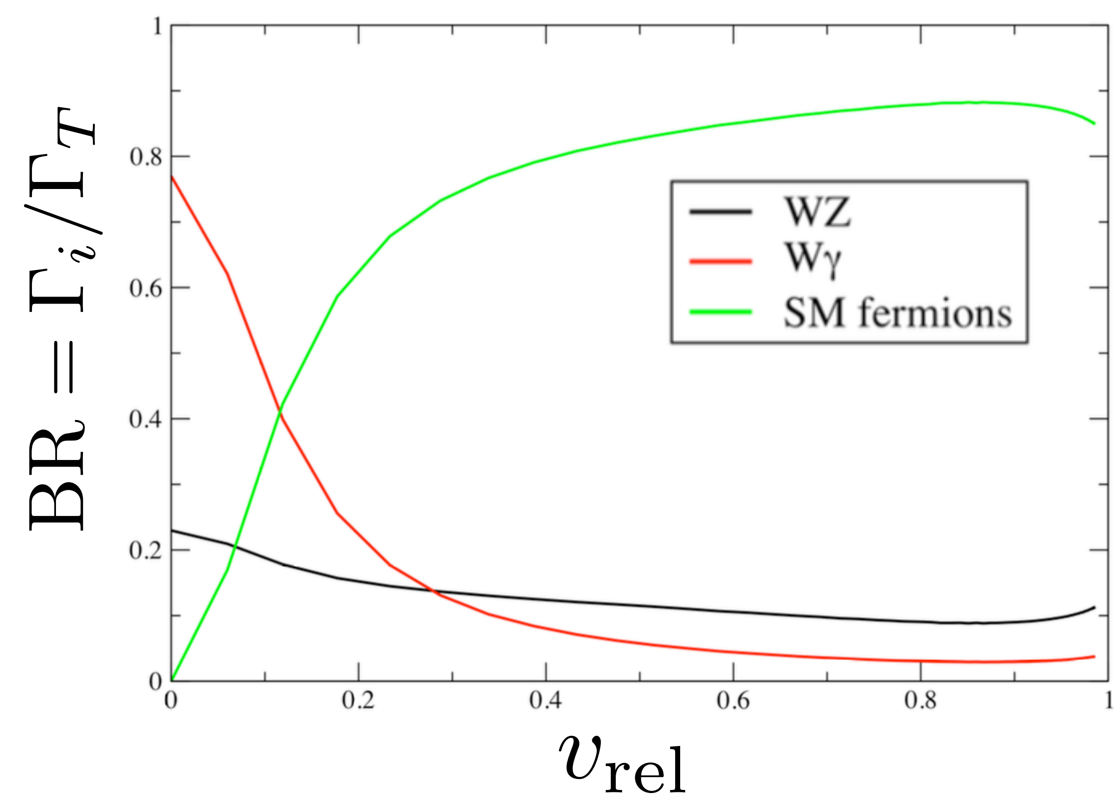


$$t_{rad} \sim \frac{3}{8\pi\alpha}\frac{m_{q'}^3}{\Lambda'^4} = \left(\frac{m_{q'}}{500\text{ GeV}}\right)^3\left(\frac{5\text{ GeV}}{\Lambda'}\right)^4 10^{-18}\,\text{sec}$$

Decay



$$\sigma v_{\rm rel} \sim \frac{\pi\alpha^2}{18 s_W^2 E^2}$$

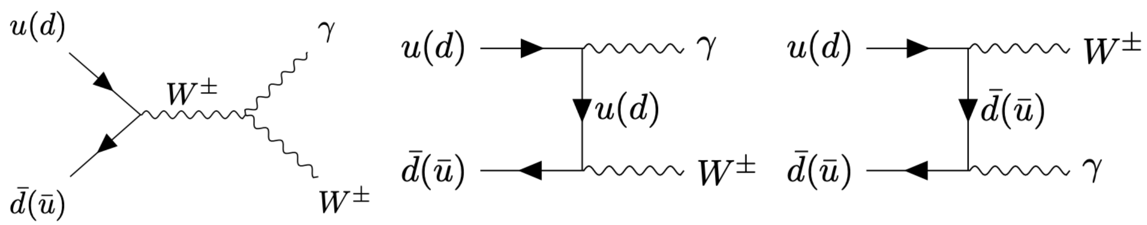


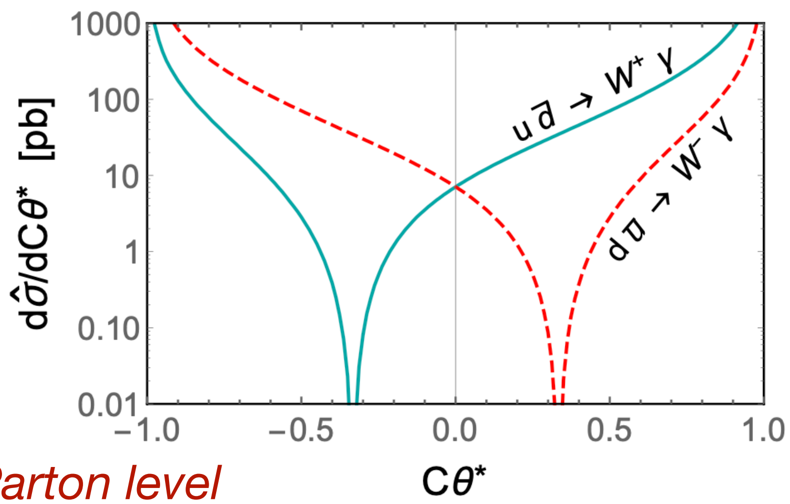
Burdman, Chacko, Goh, Harnik, Krenke,
Phys. Rev. D 78 (2008) 075028

3. Neutral Naturalness

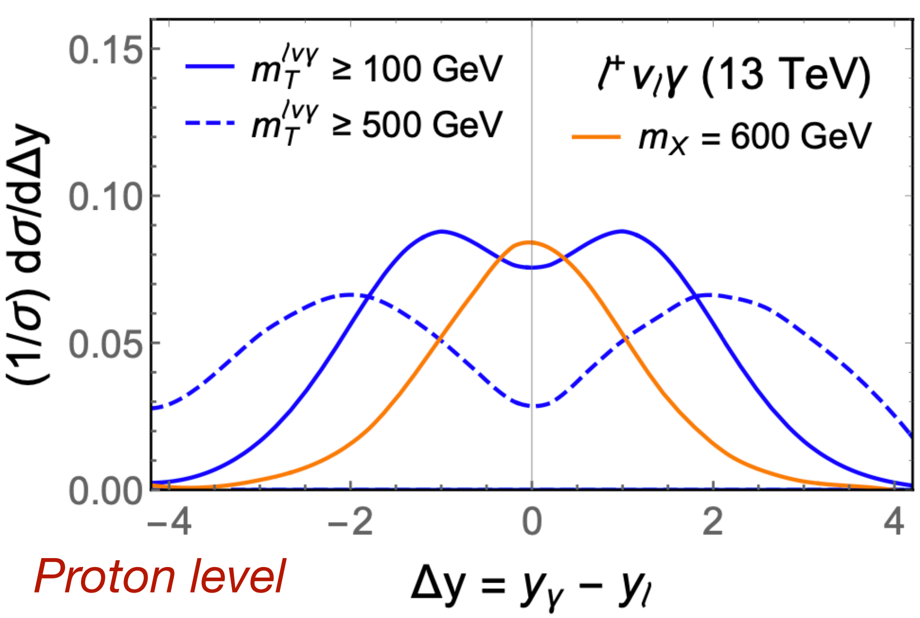
- (s)Quirks:

Advantages in the search for the charged state: Radiation Amplitude Zero (RAZ)



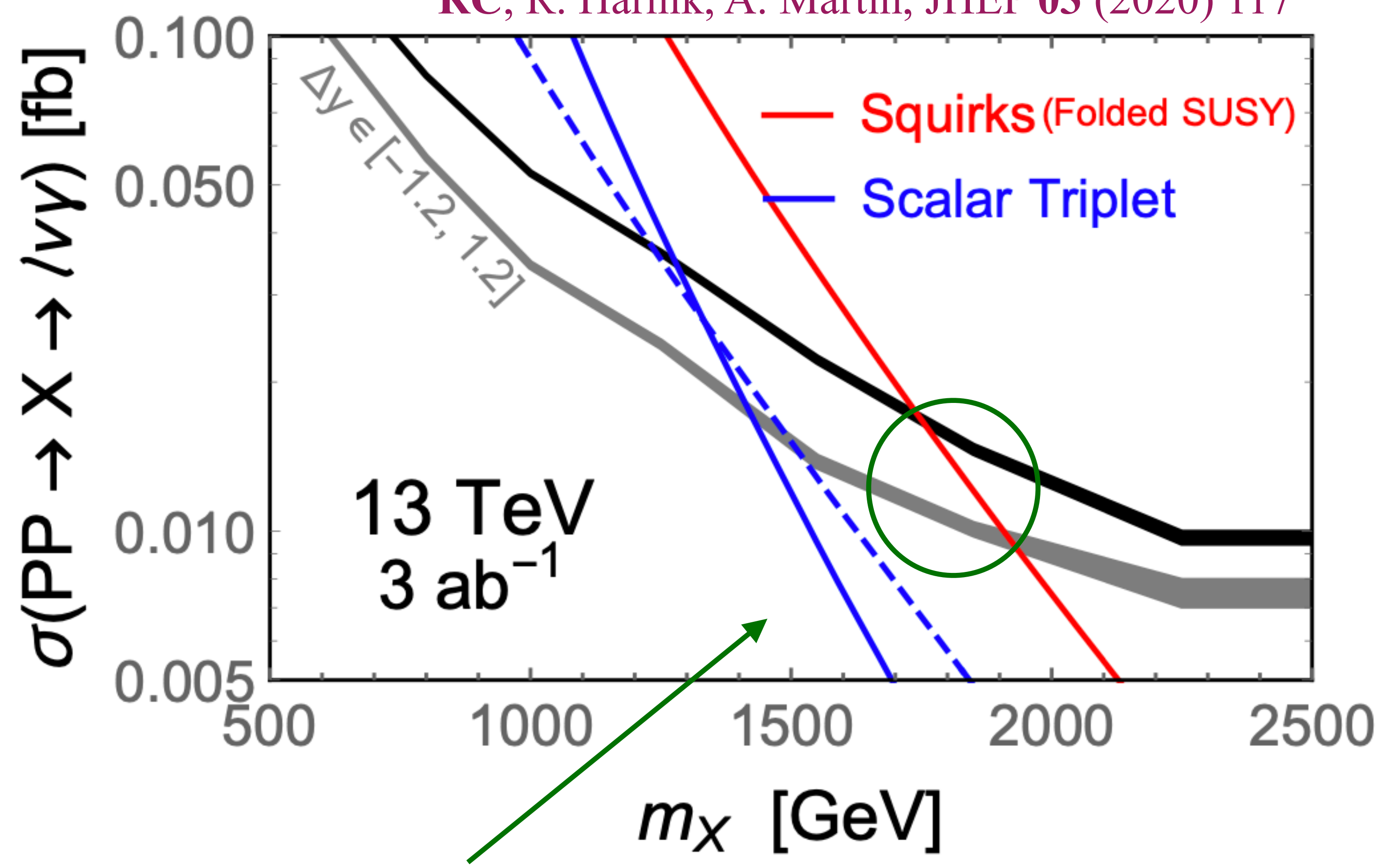


Parton level



Proton level

RC, R. Harnik, A. Martin, JHEP **03** (2020) 117



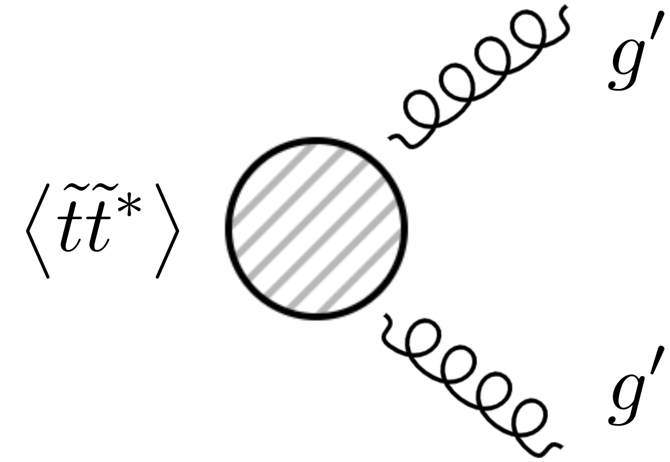
Exploiting the RAZ one can increase the reach by ~200GeV

Rodolfo Capdevilla, Fermilab

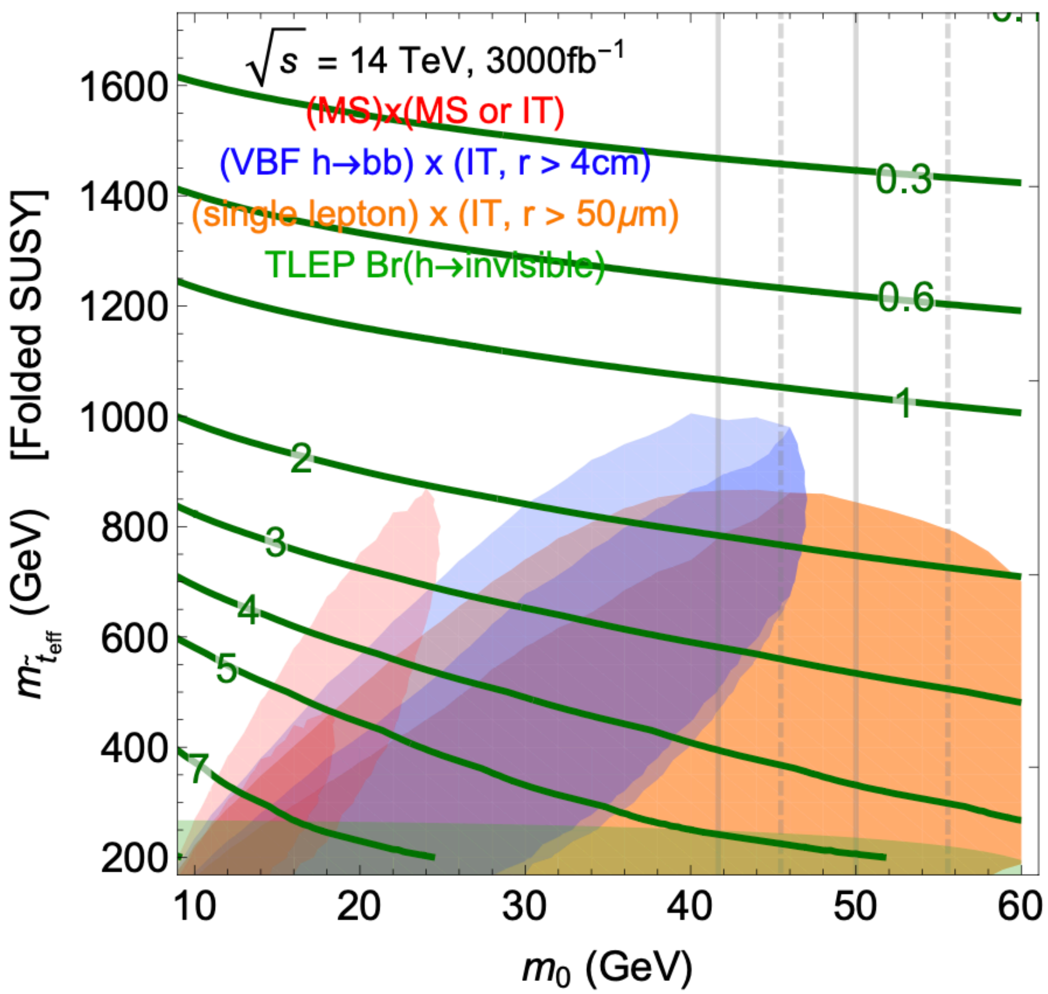
3. Neutral Naturalness

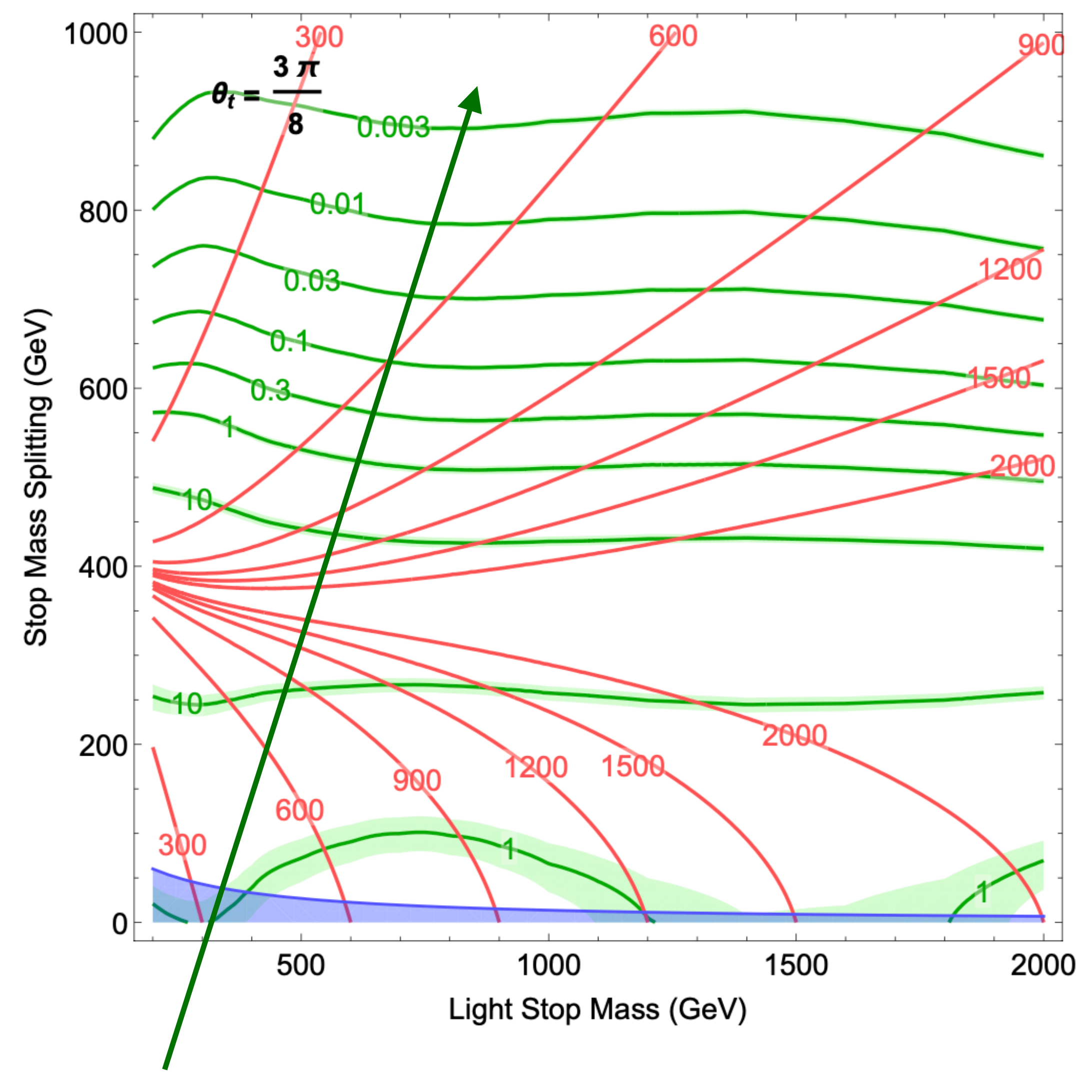
- (s)Quirks:

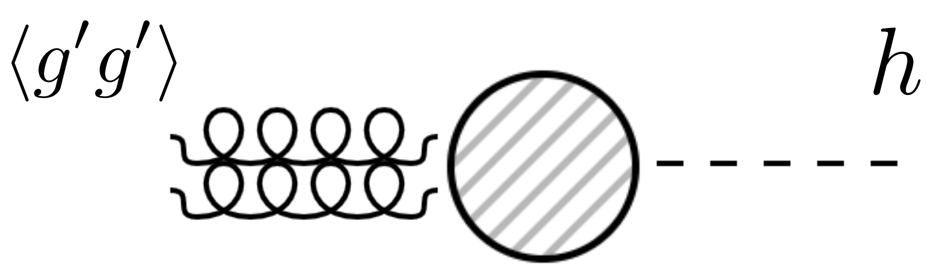
What happens with the neutral state?
It mostly decays to glueballs!



Dark glueballs
Hidden valleys
Exotic Higgs decays
Displaced signals…







Dark glueball - Higgs mixing!

will help probe the sub-cm glueball regime. Note, however, that the annihilation branching fraction to mirror gluons becomes small for large mass splittings. In that case, di-higgs searches may have greater sensitivity. For purely LH stops,

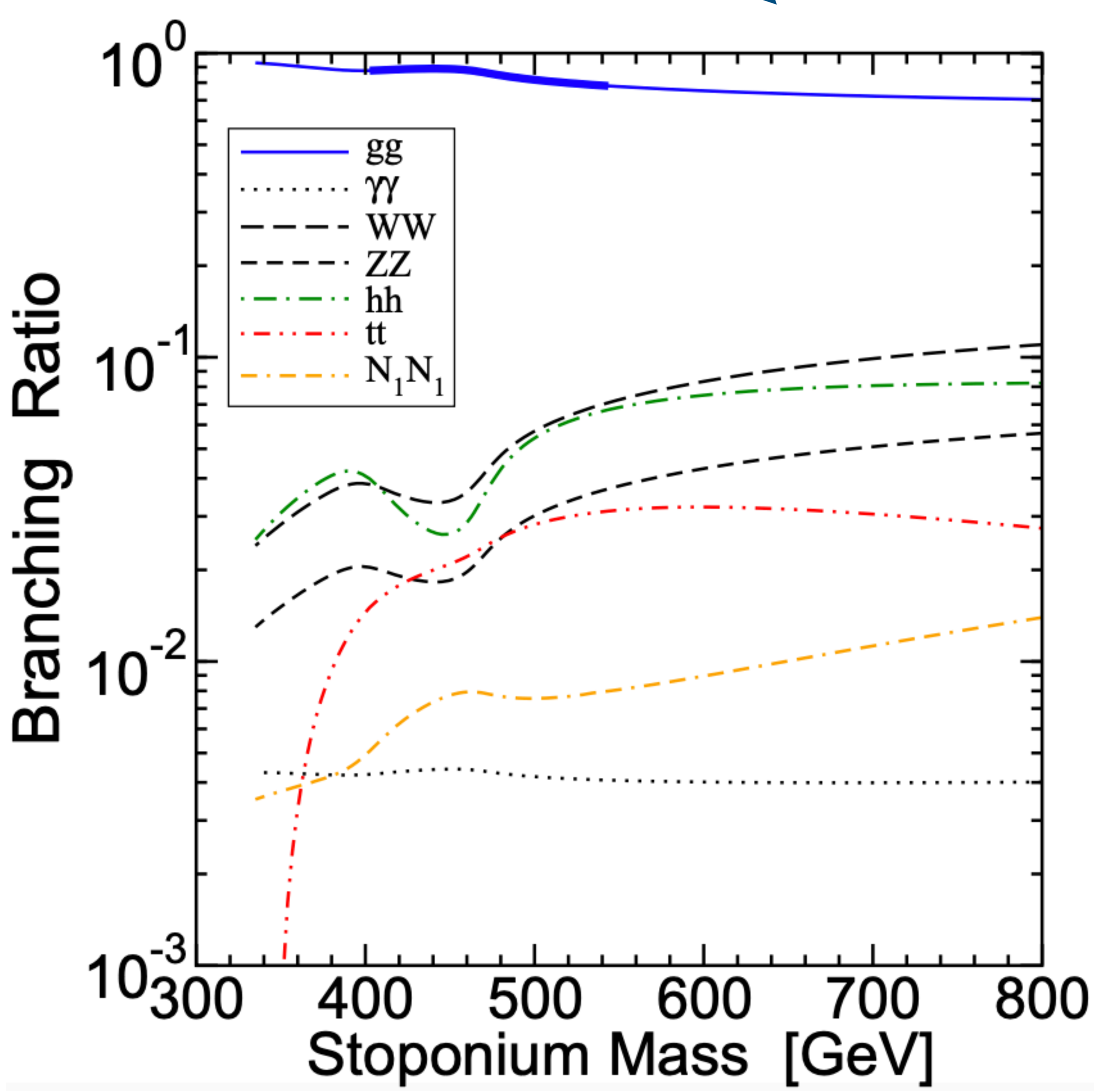
Chacko, Curtin, Verhaaren,
Phys. Rev. D **94** (2016) 1, 011504

3. Neutral Naturalness

- Di-Higgs signal:

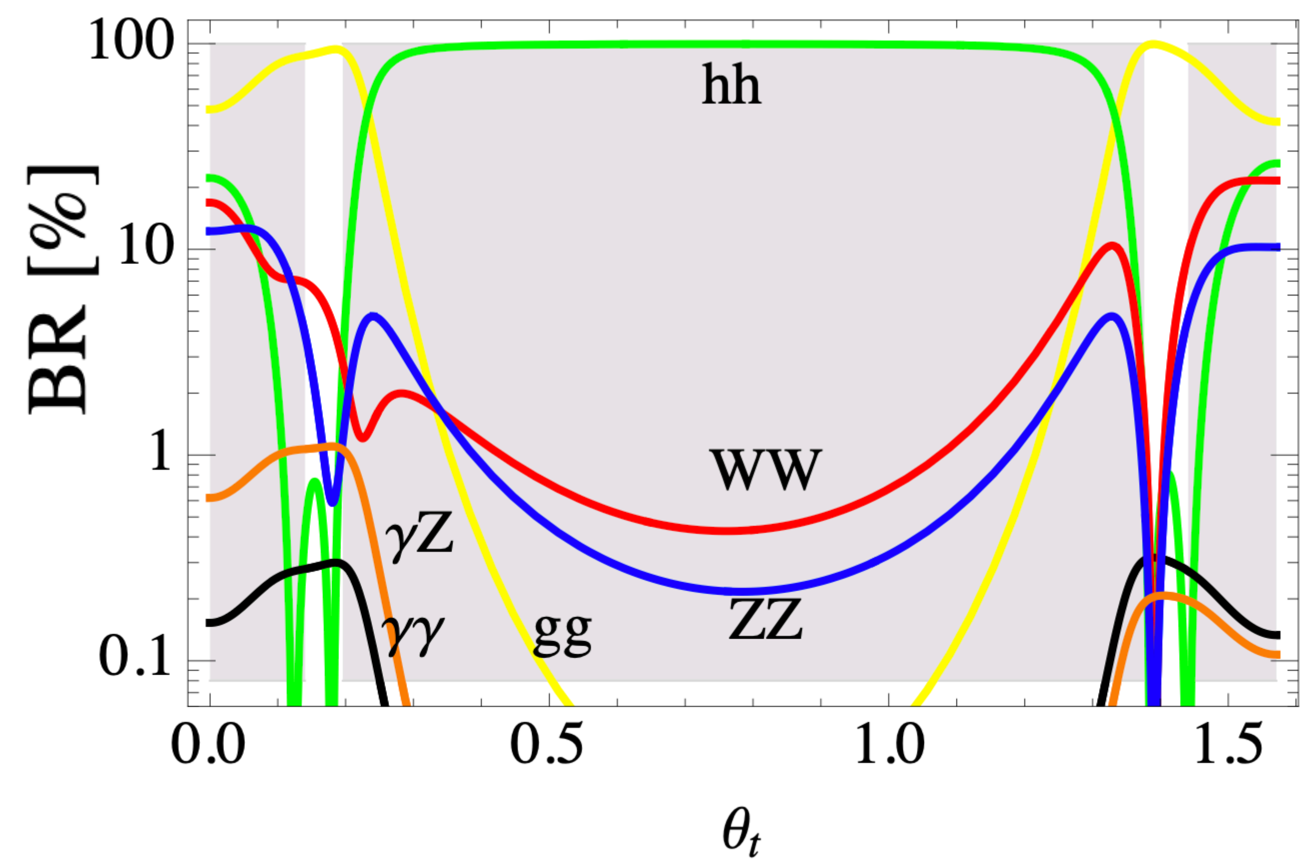
An example from stoponium!

Dominant decay mode to gluons!



S. Martin, Phys. Rev. D **77** (2008) 075002

Di-Higgs dominates as splitting increases!



B. Batell, S. Jung, JHEP **07** (2015) 061

Outline

1. Introduction

- Fund
- The H

2. Naturaln

- Wher
- A littl

3. Neutral Naturalness

- Folded Supersymmetry
- Quirky collider signatures
- Di-Higgs signals

Results

Summary/Conclusions

Higgs self coupling!

Higgs portal!

Neutral Naturalness!

Outline

1. Introduction
    - Fundamental questions in HEP
    - The Higgs boson and beyond
2. Naturalness
    - Where are the stops?
    - A little hierarchy?
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    - Quirky collider signatures
    - Di-Higgs signals
4. Results
5. Summary/Conclusions

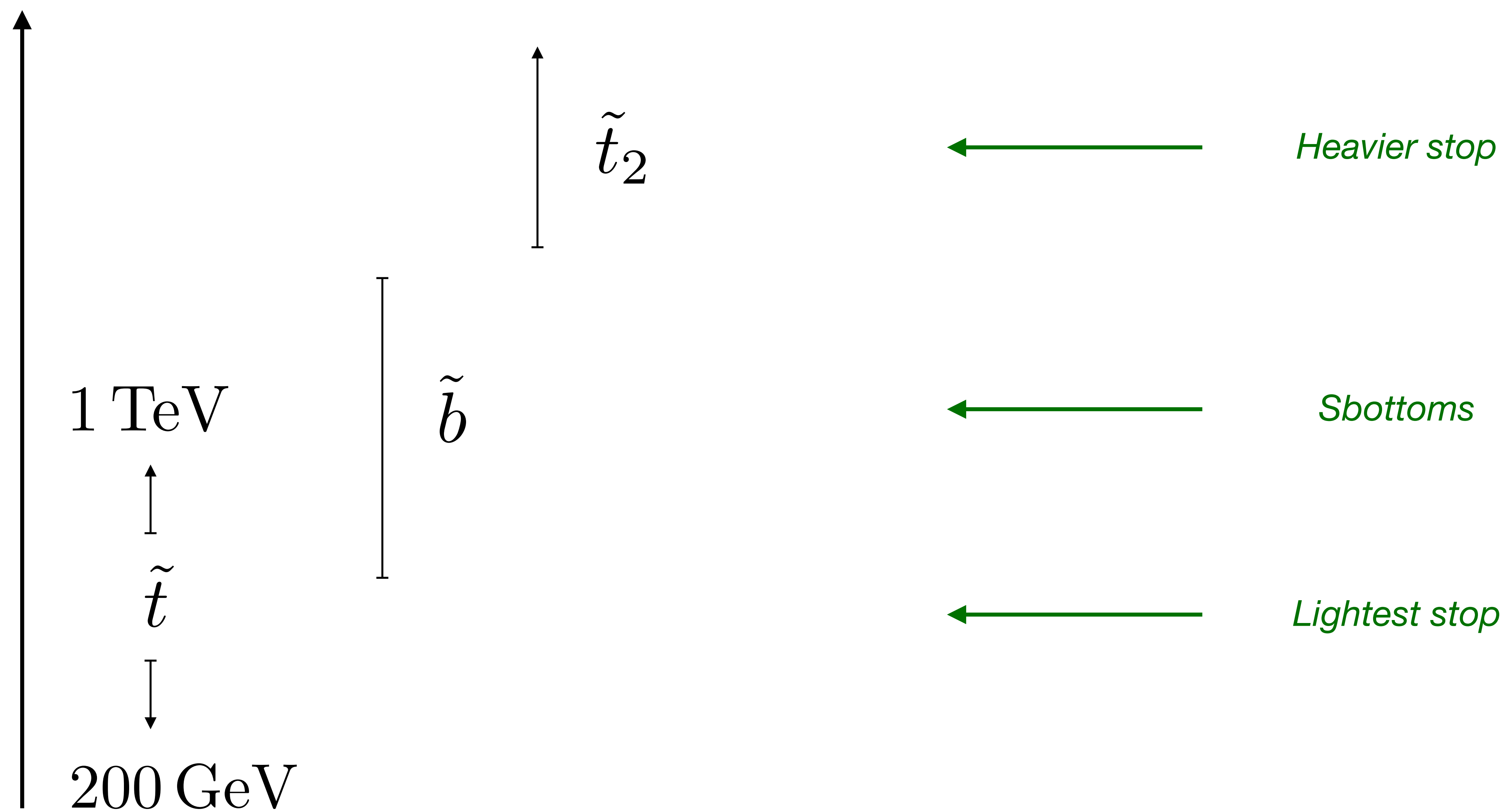
4. Results

- Considerations:

Free parameters:

$\tan\beta = \frac{v_u}{v_d}$	*Ratio of vevs*	$m_{\tilde{t}} \equiv m_{\tilde{t}_1}$	*Mass of lightest stop*
A_t	*Trilinear soft parameter*	$m_{\tilde{Q}_L} = m_{\tilde{t}_R}$	*Soft masses*
μ	*Mu term*	$m_{\tilde{b}} = m_{\tilde{b}_R}$	*Sbottom masses*

Spectrum:



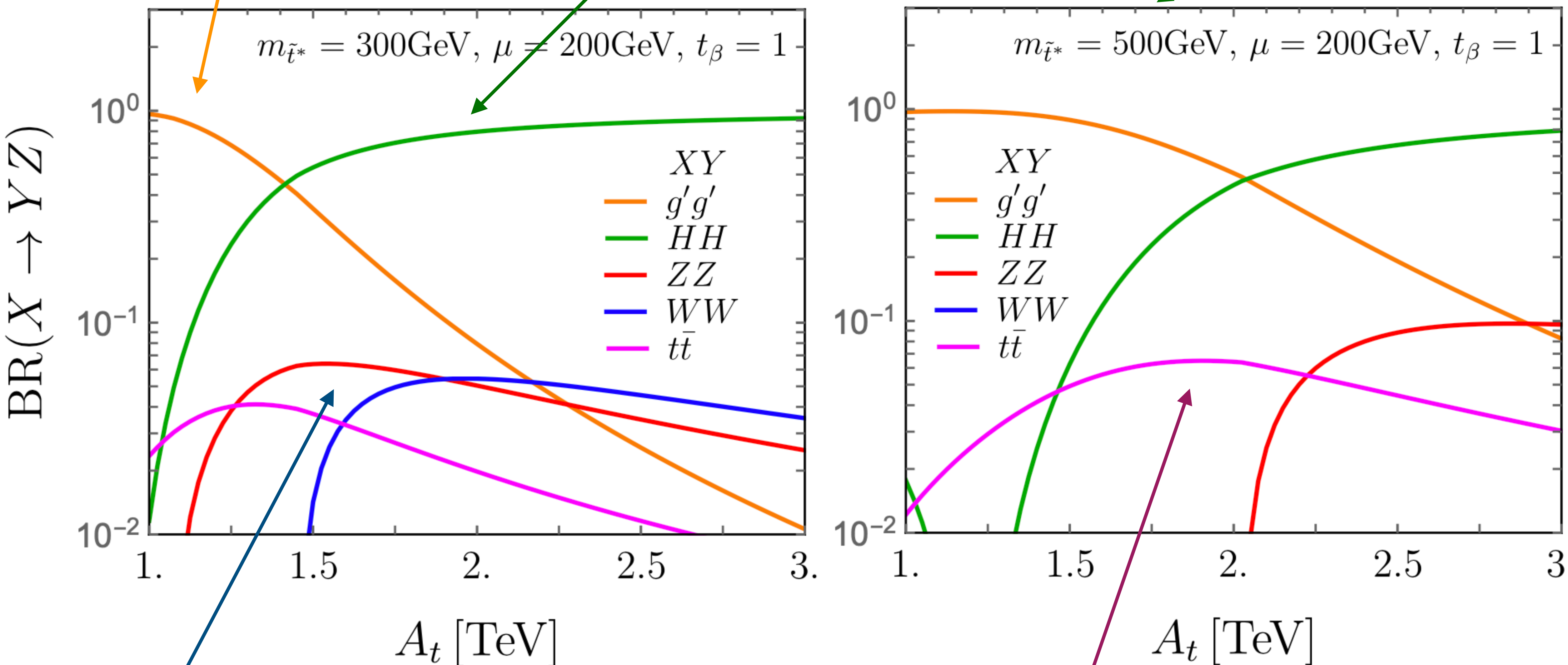
4. Results

- F-sQuirks BR:

(dark) gluons dominate at small At

Di-Higgs dominates for large At

Heavier stops require larger At for HH to dominate!

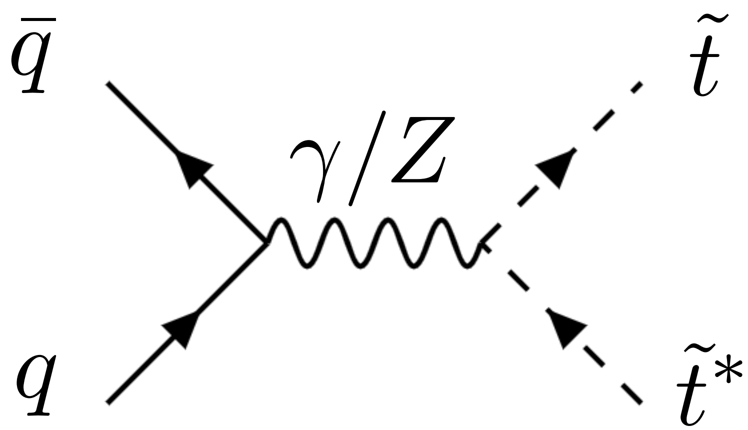


VV decay modes stay at the 1-10% level

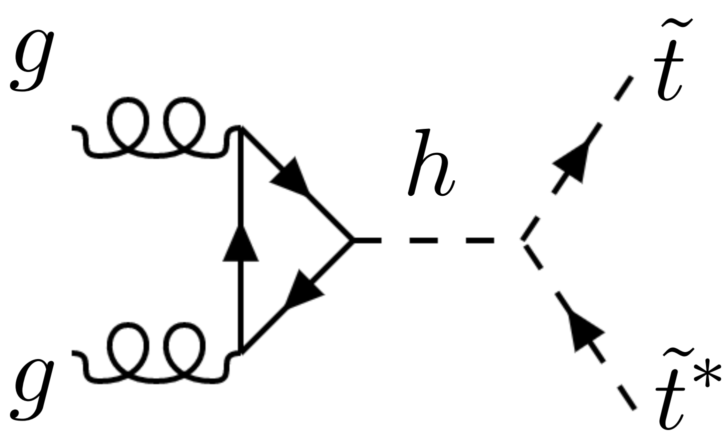
Interesting di-top mode with also a 1-10% BR

4. Results

- F-sQuirks production:

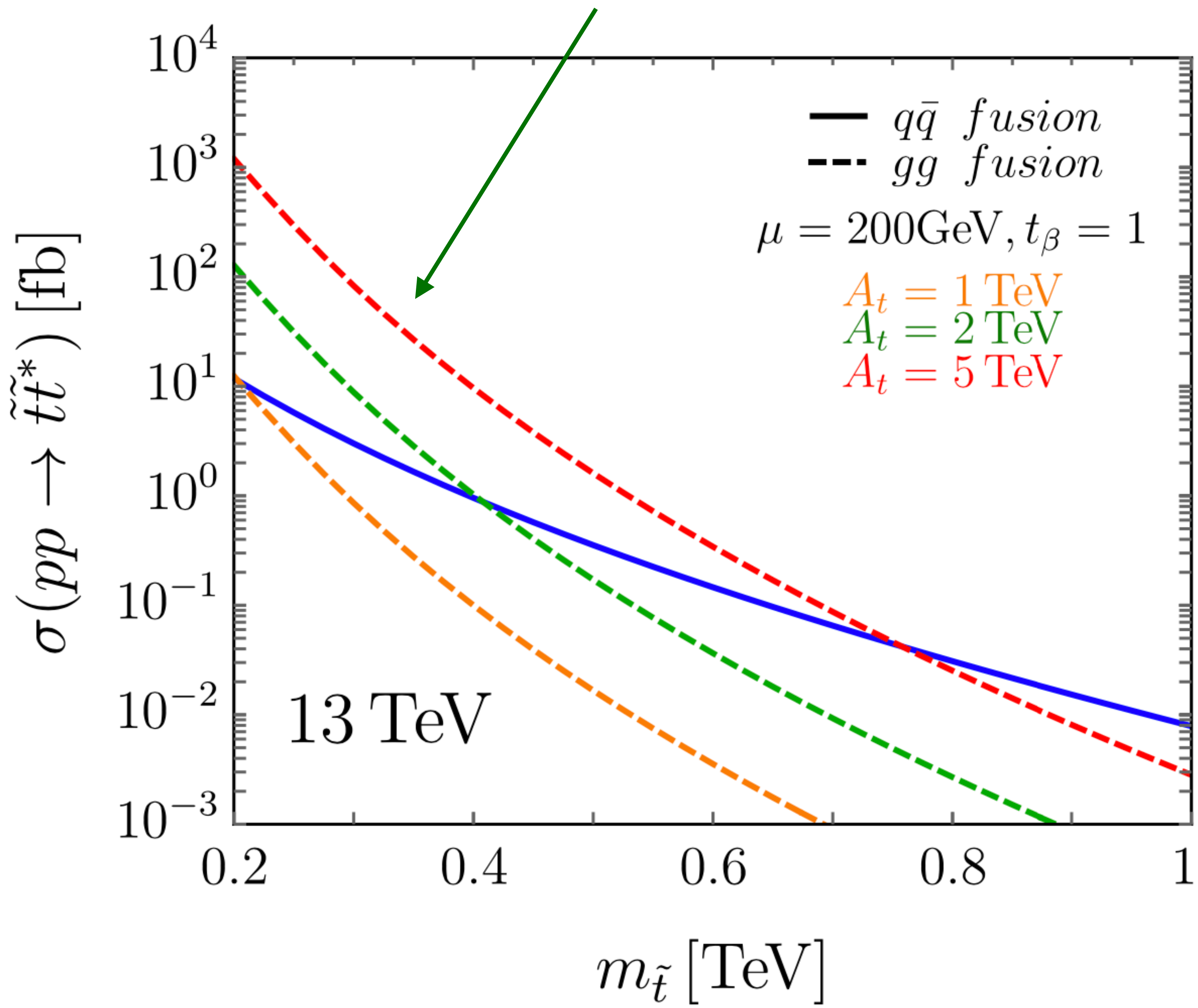


Quark fusion



Gluon fusion

*Increasing At not only increases BR but **also** production rates!*



Rodolfo Capdevilla, Fermilab

4. Results

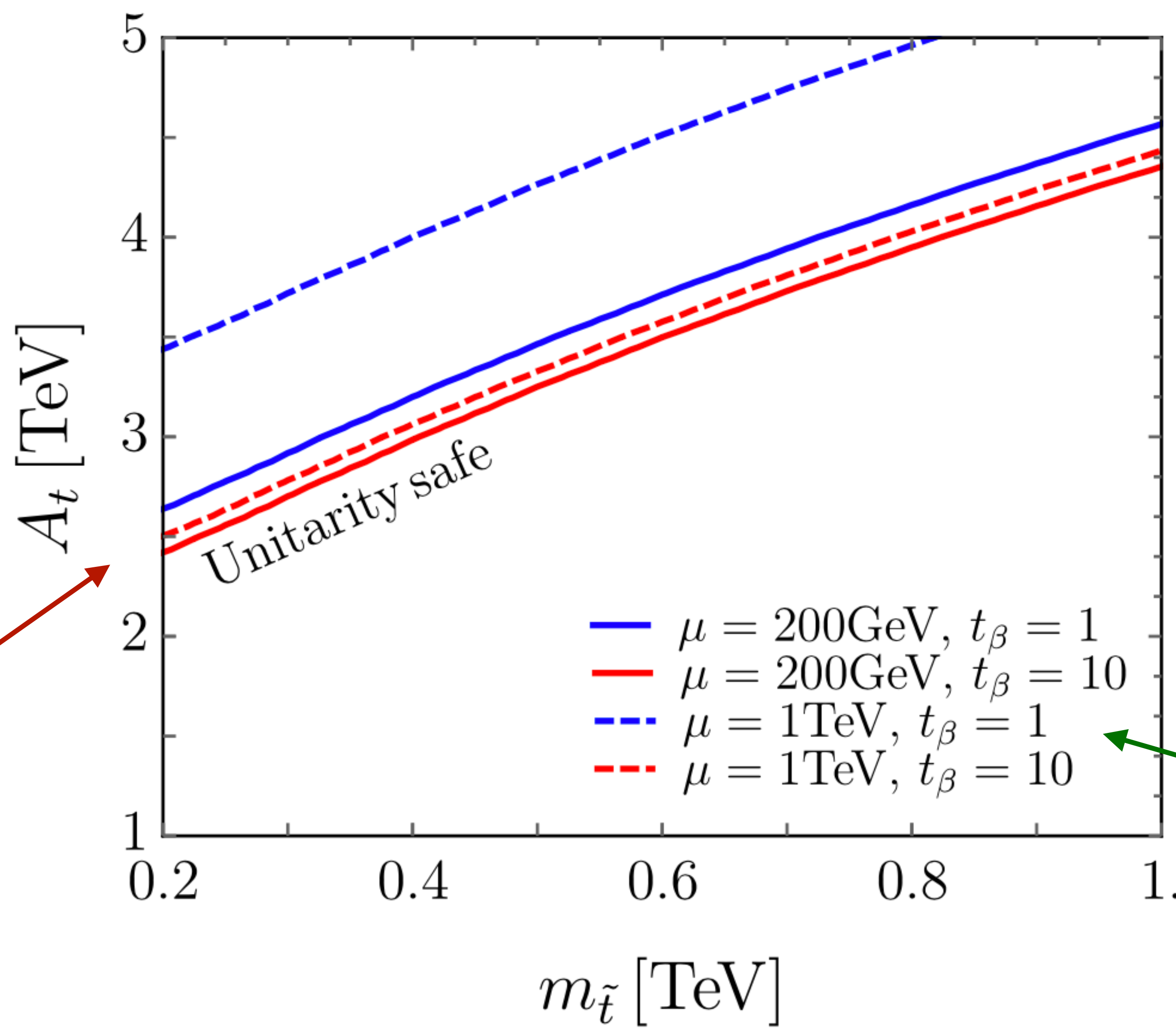
- F-sQuirks production:

DANGER!
No free lunch!

Trilinear couplings are known to be dangerous!

$$A_t \tilde{t}_L \tilde{t}_R h$$

- *Vacuum instability*
- *Tachyonic states*
- *Patial wave unitarity*
- *...*

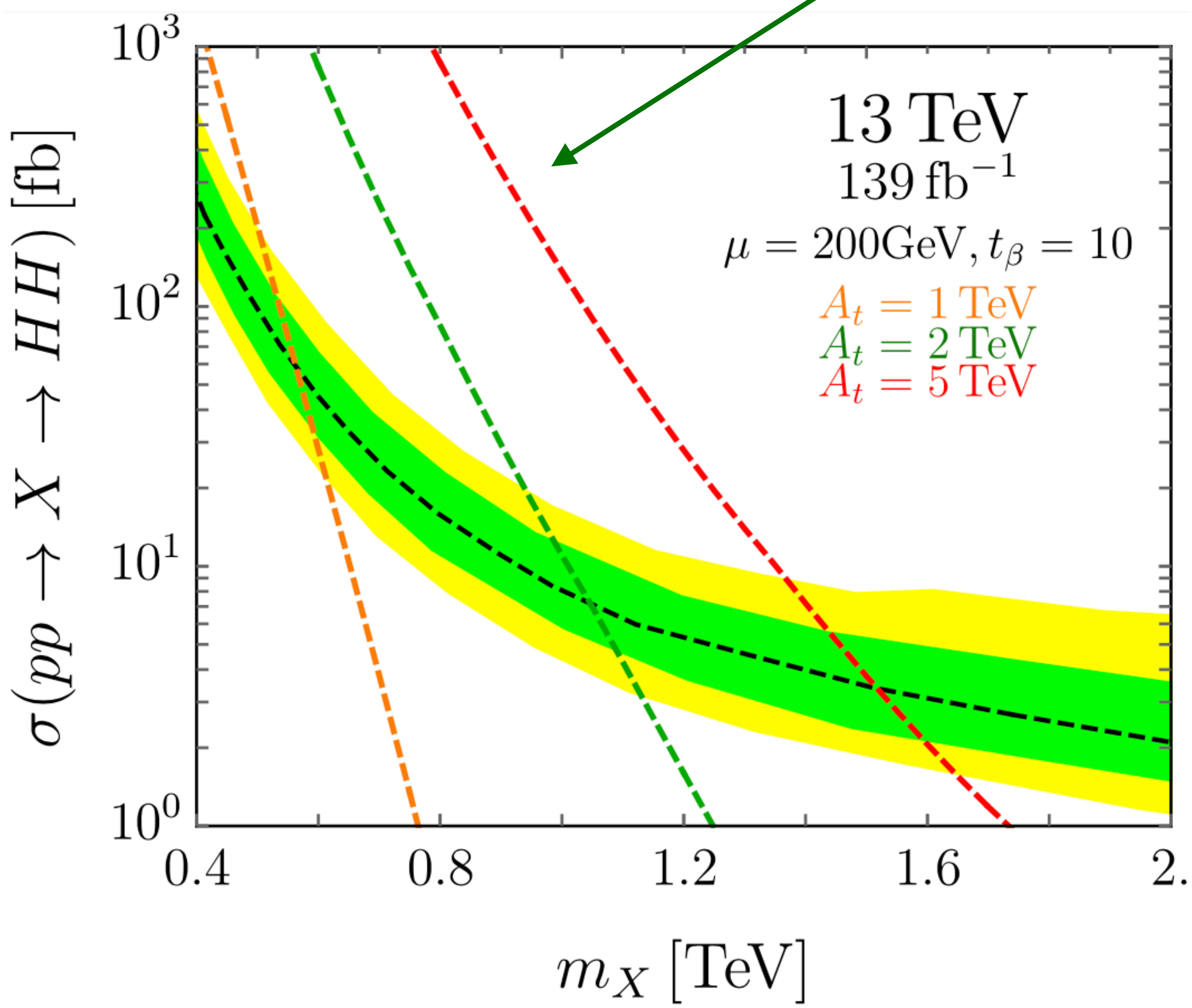


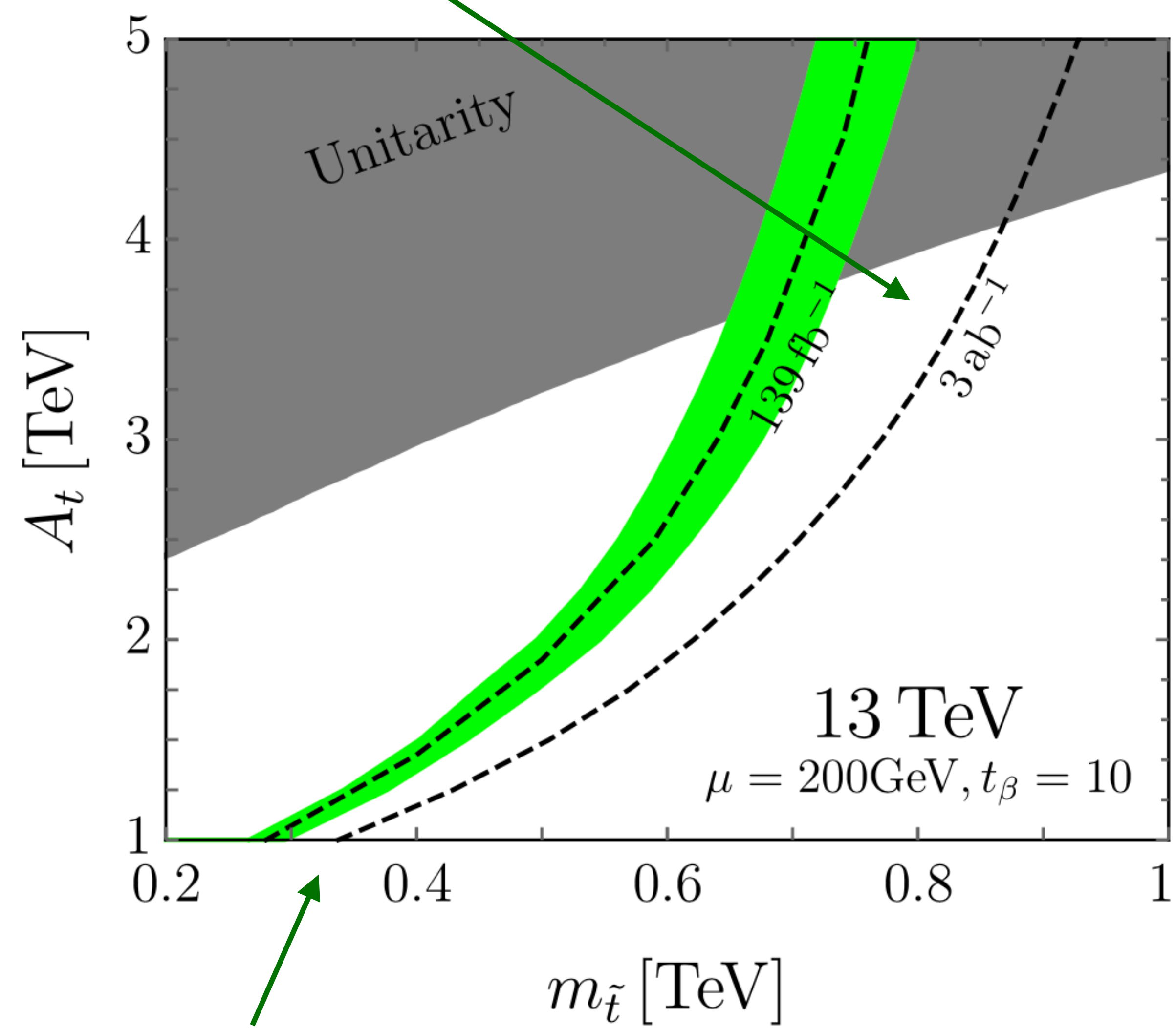
Region above the lines are excluded by unitarity

We explore a few benchmarks

- F-sQuirks searches:

Benchmarks where tb is large enough show promising results!



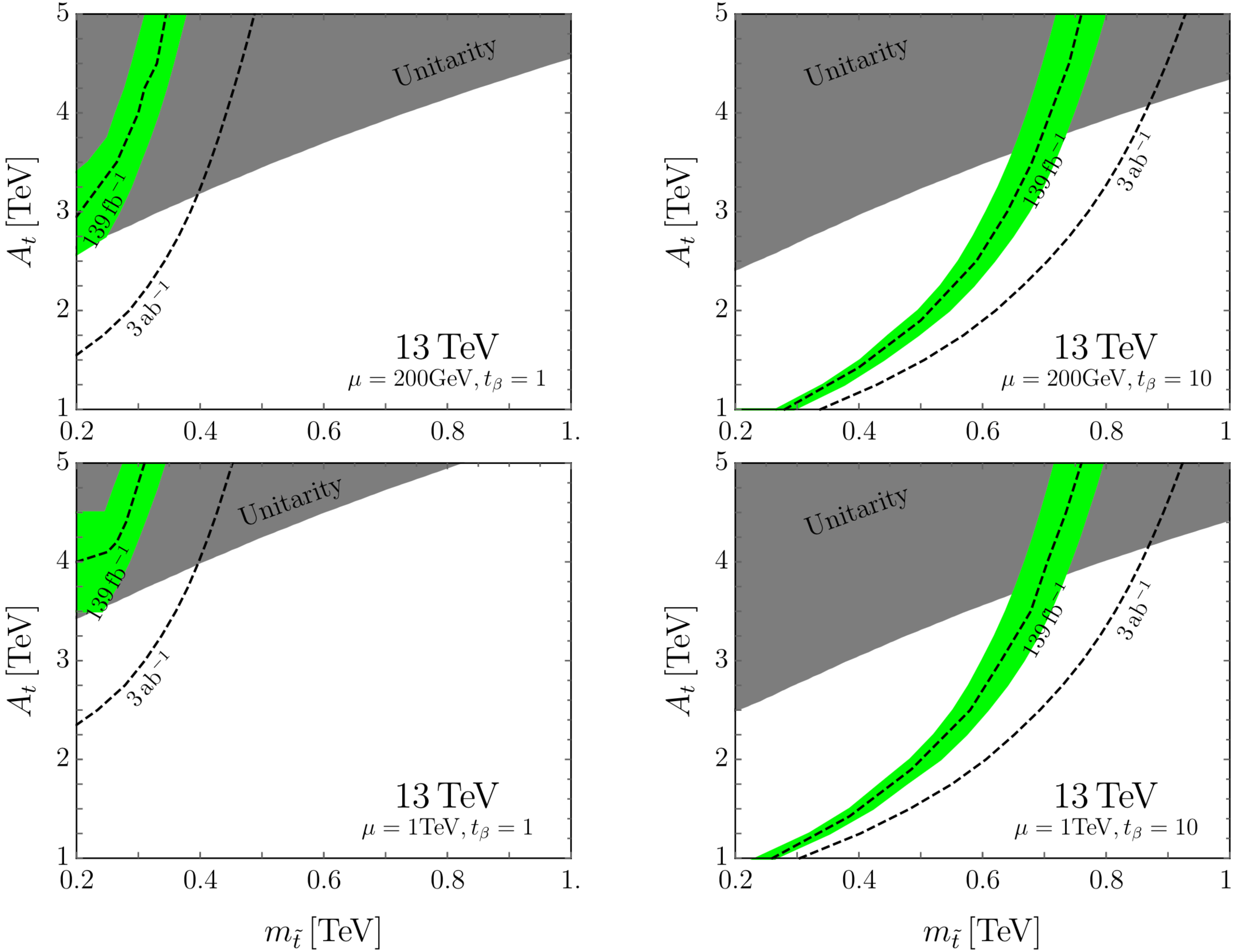


HH resonances between 600 - 1700 GeV can be found in incoming runs at the LHC!

$$m_X = 2m_{\tilde{t}}$$

$$m_X = 2m_{\tilde{t}}$$

- F-sQuirks searches:



Rodolfo Capdevilla, Fermilab

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Summary/Conclusions

1. Higgs precision program -> Trilinear coupling -> Di-Higgs searches

2. Higgs portal to new physics -> Exotic resonances -> Di-Higgs searches

3. Stop searches -> Neutral naturalness -> Di-Higgs searches

4. Future runs of the LHC could discover Di-Higgs resonances in the range of 0.6 - 1.7 TeV. This in the context of Folded supersymmetry and under reasonable assumptions.

Thanks!

Minimal Dark Matter

- Higgsinos and Winos
- Disappearing Tracks

Federico Meloni, DESY

Rosa Simoniello, CERN

Jose Zurita, U. Valencia

2. Minimal Dark Matter

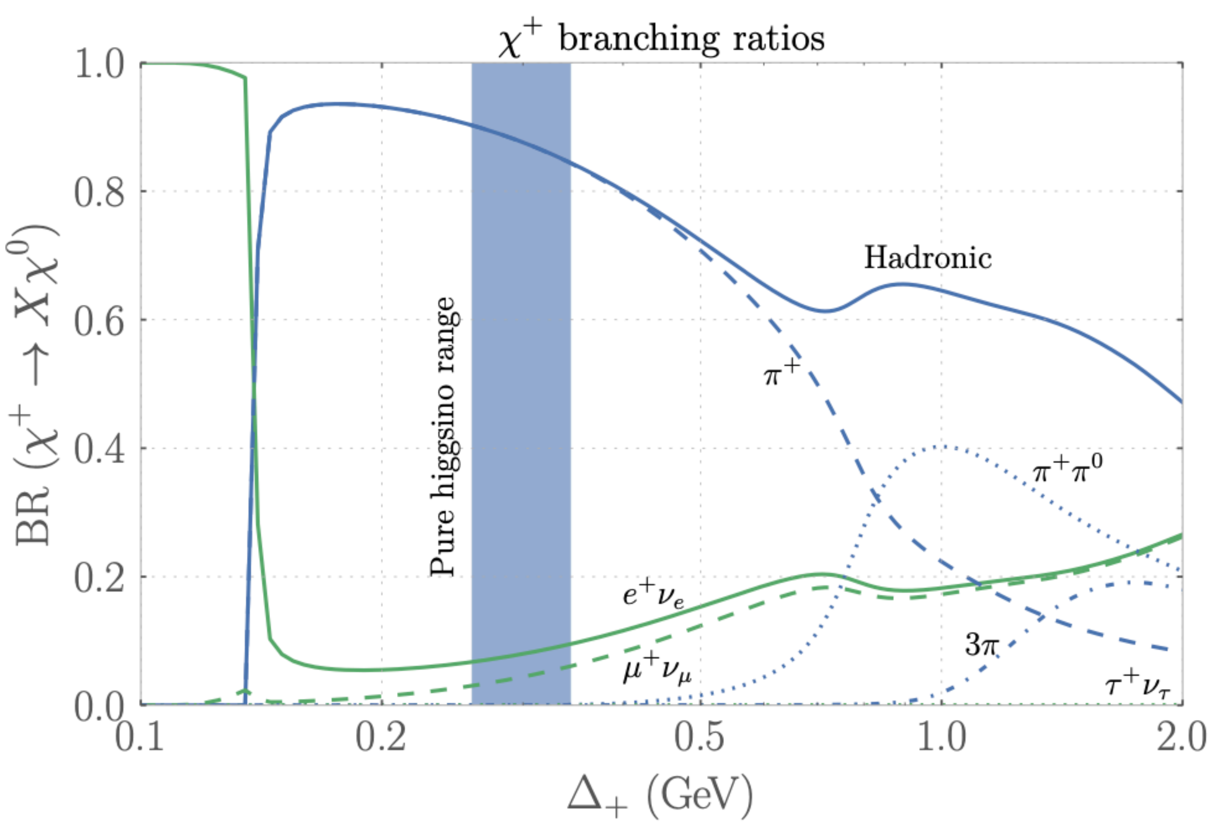
- Small mass splitting from radiative corrections

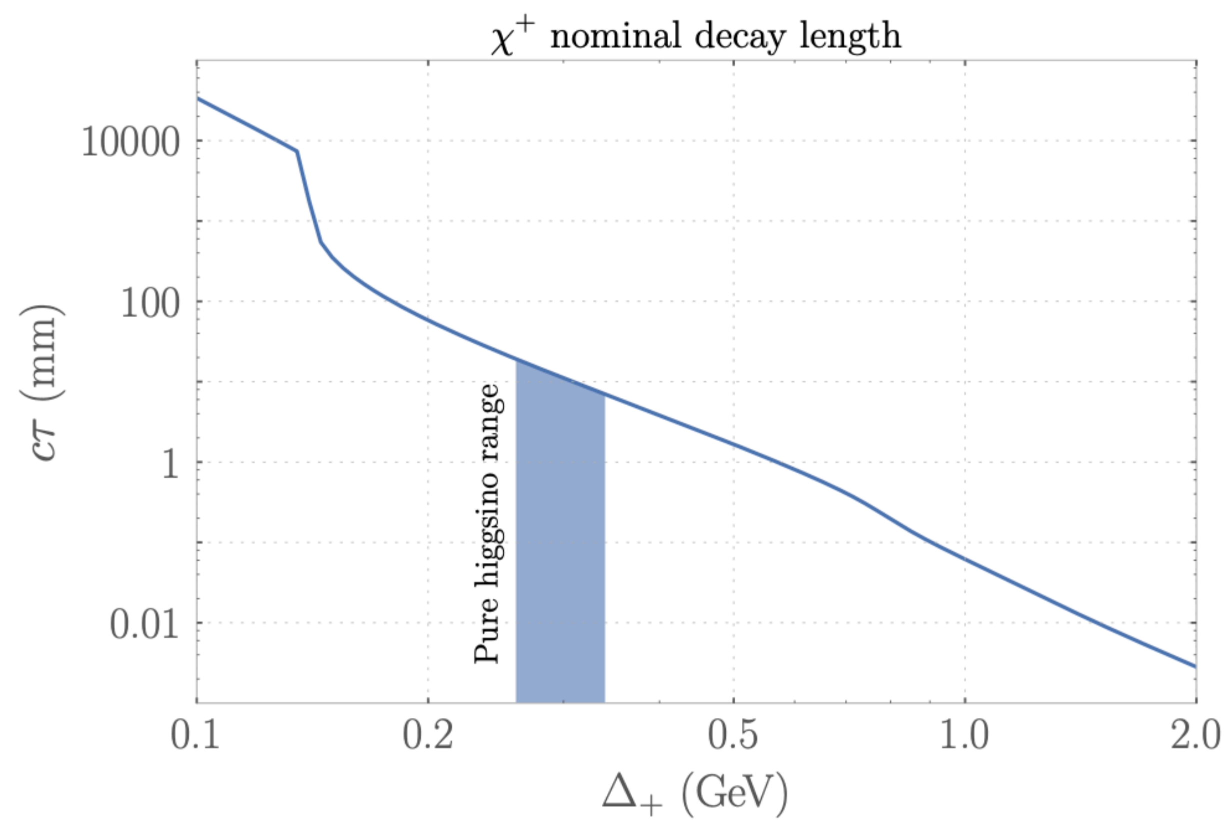
$$\chi_{\tilde{H}} = \begin{pmatrix} \chi^+_{\tilde{H}} \\ \chi^0_{\tilde{H}} \end{pmatrix}$$

$$\Delta m = m_{\chi^+} - m_{\chi^0} > 0$$

Feature of the model!

- DM candidate stable
- Charged states are long-lived



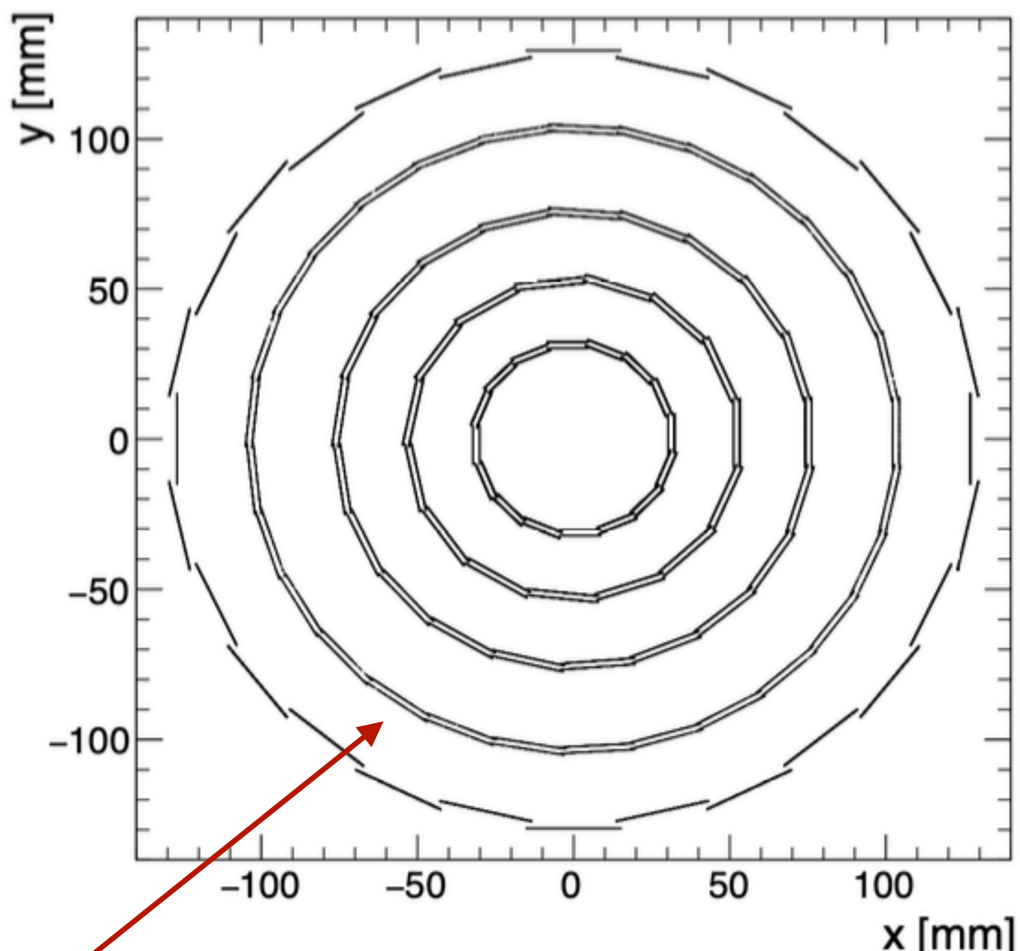


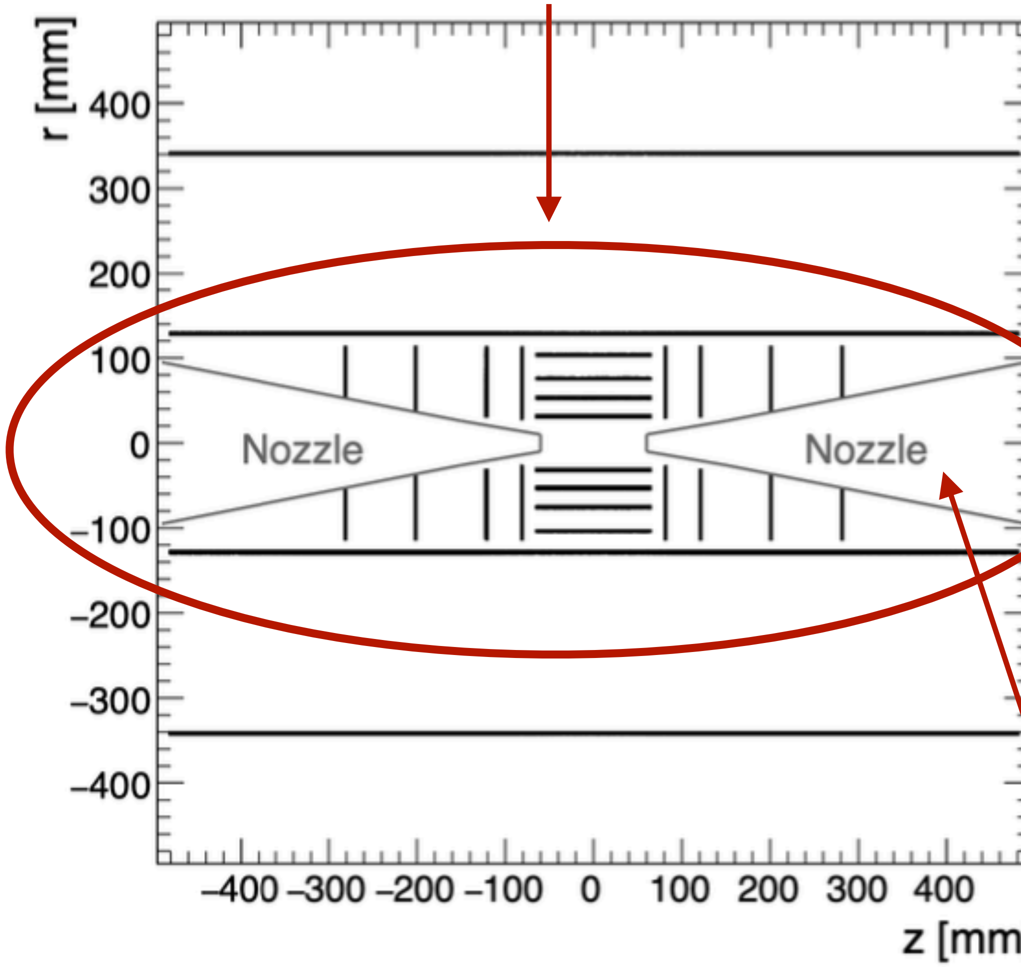
R. Mahbubani, P. Schwaller, J. Zurita, JHEP 06 (2017) 119

2. Minimal Dark Matter

- Muon colliders: Detector Geometry

Vertex Detector





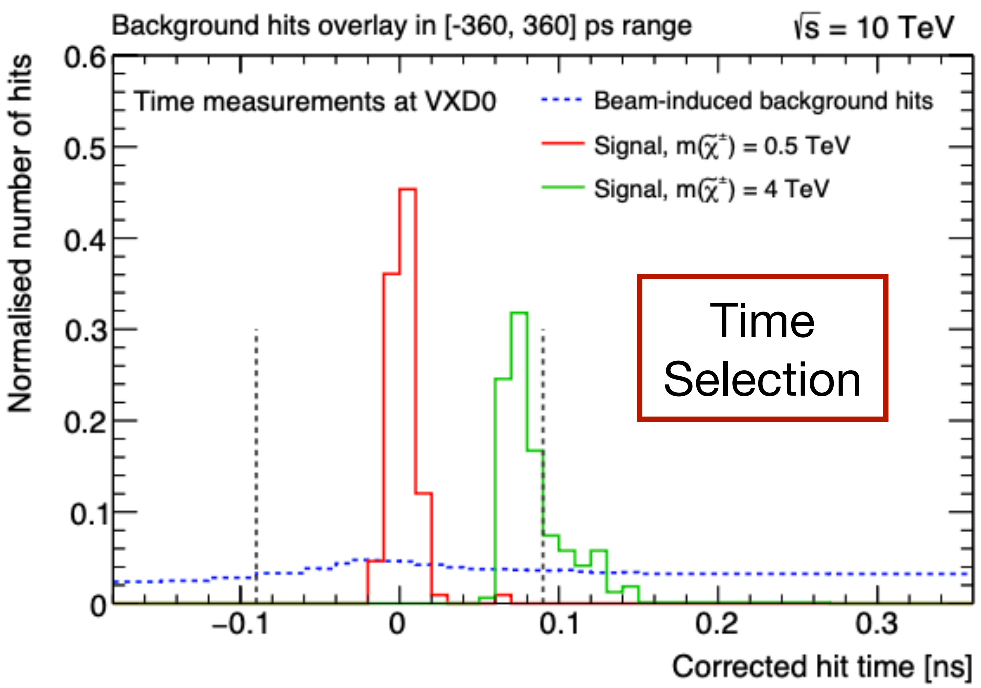
Double layer structure!

Shielding Tungsten Nozzles!

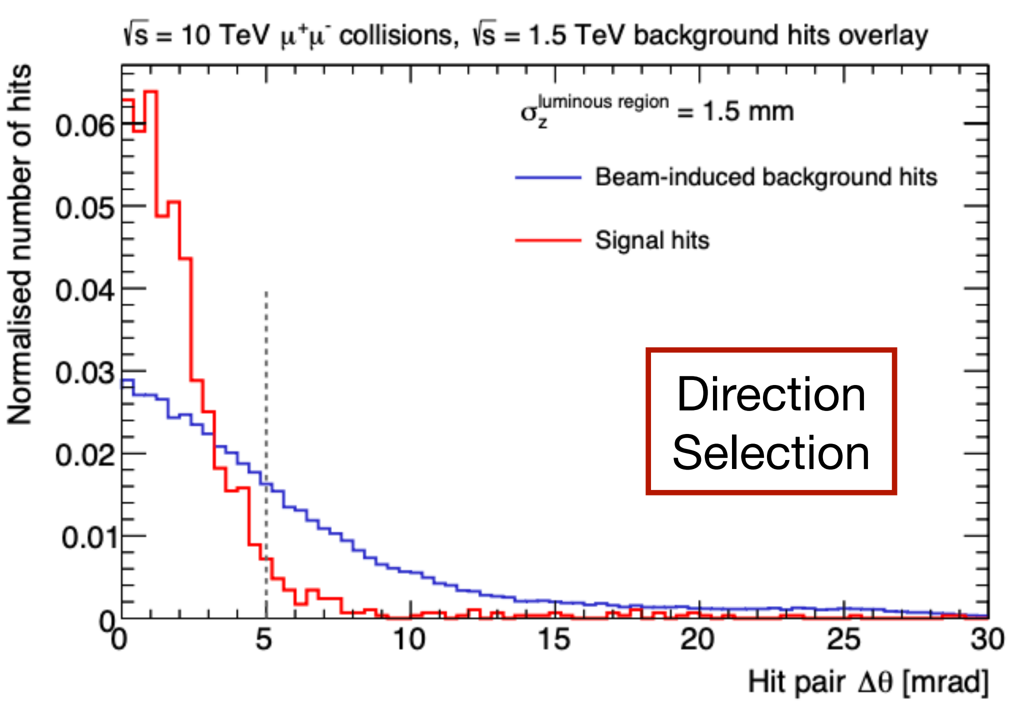
2. Minimal Dark Matter

- Muon colliders: Remember the BIB!

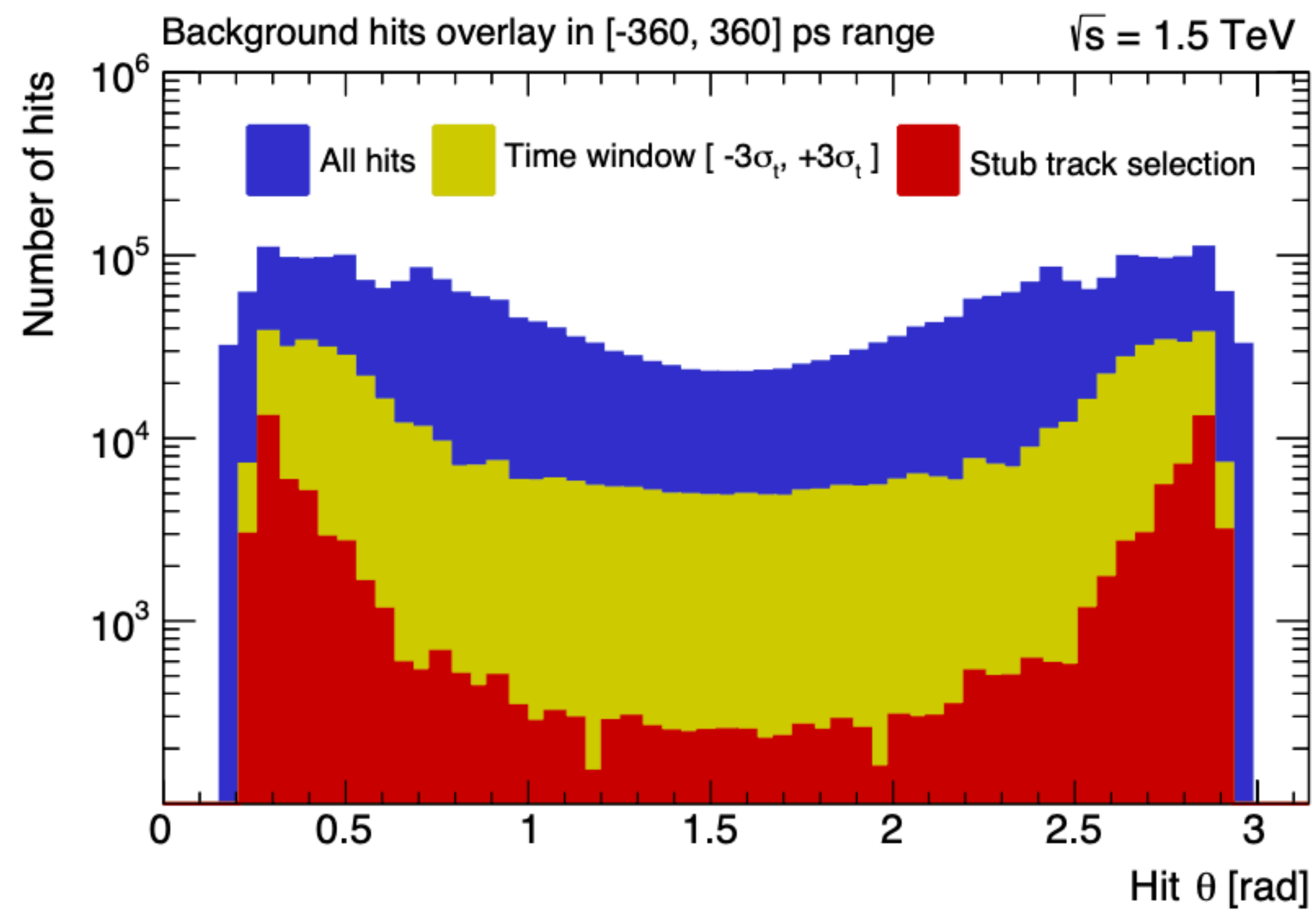
1. Soft
2. Arrives late
3. Mostly forward



Time Selection



Direction Selection



	SR^{γ}_{1t}	SR^{γ}_{2t}
Total background	187.8 ± 0.6	0.16 ± 0.05
$\tilde{W}$, 2.7 TeV, $\tau = 0.2$ ns	201 ± 5	199 ± 4
$\tilde{H}$, 1.1 TeV, $\tau = 0.02$ ns	253 ± 4	170.5 ± 2.1

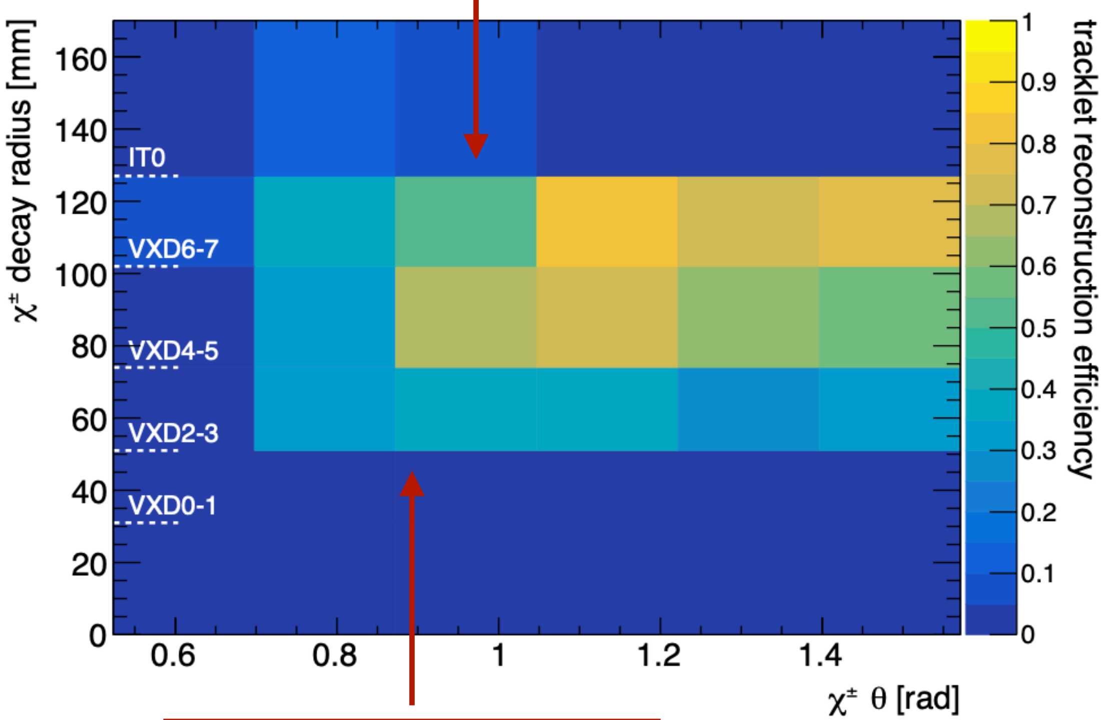
O(3) background rejection

2. Minimal Dark Matter

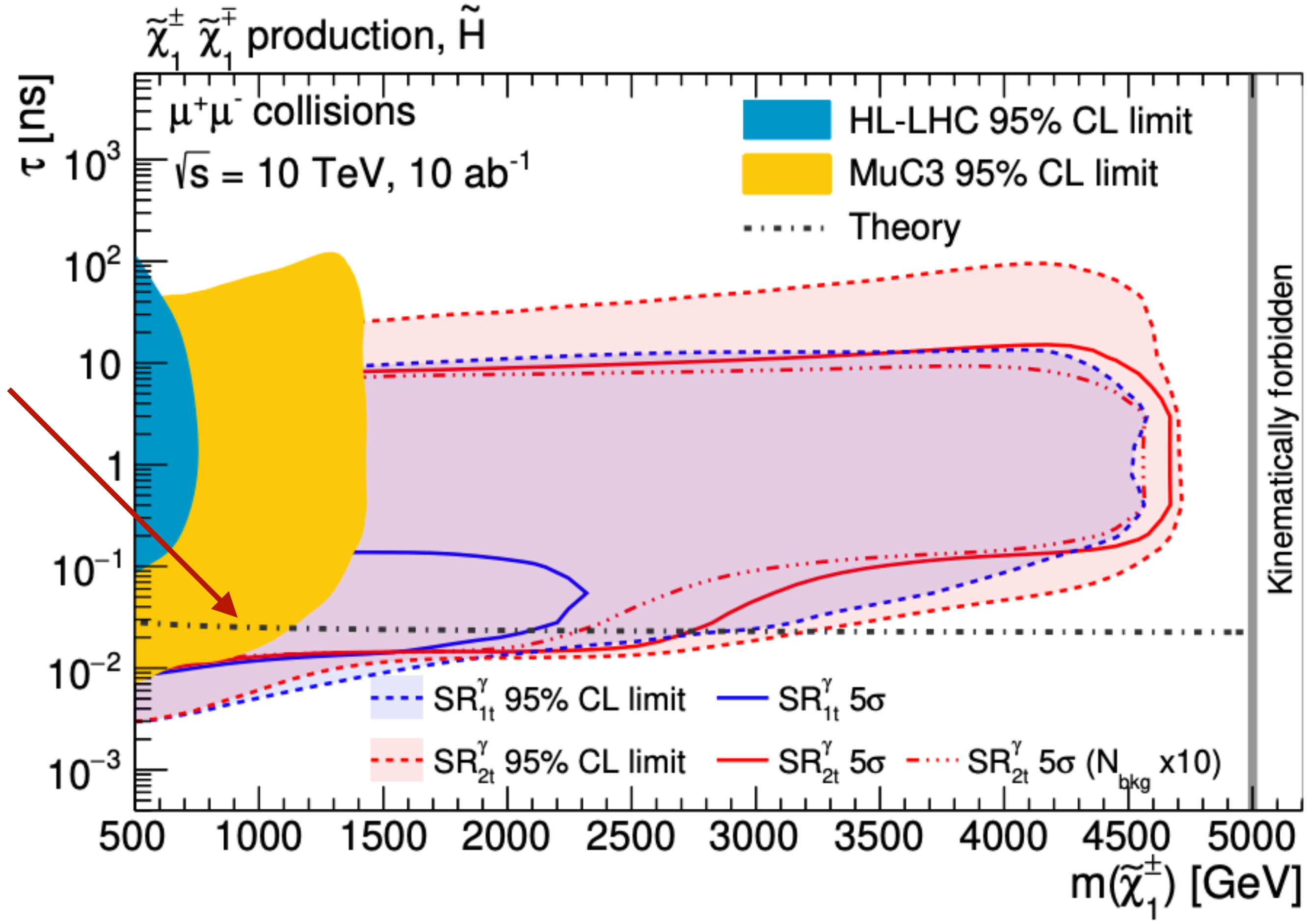
- Muon colliders

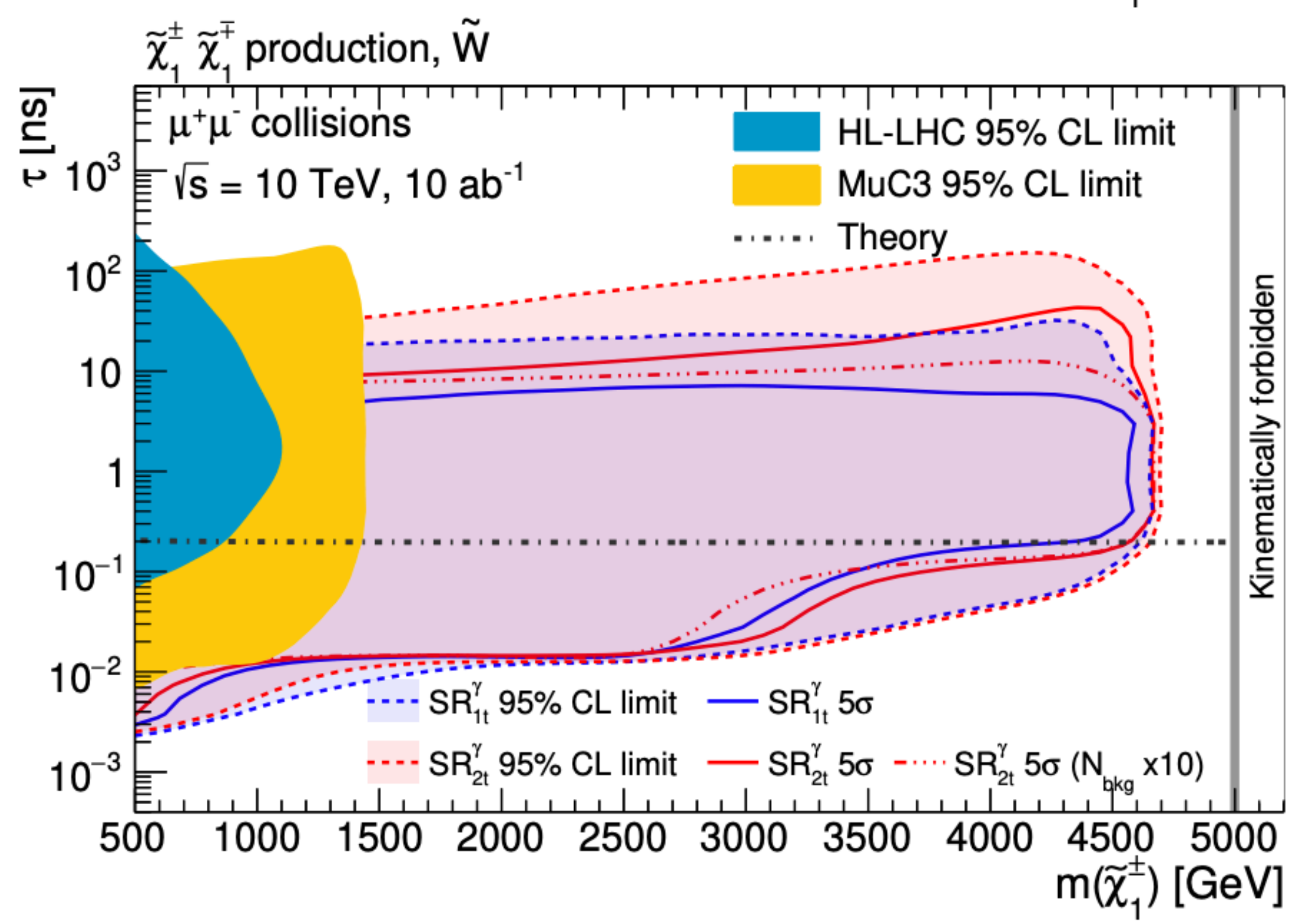
Veto layer!
(Inner tracker 1st layer)

Lifetime from
"pure" cases



Second double layer!





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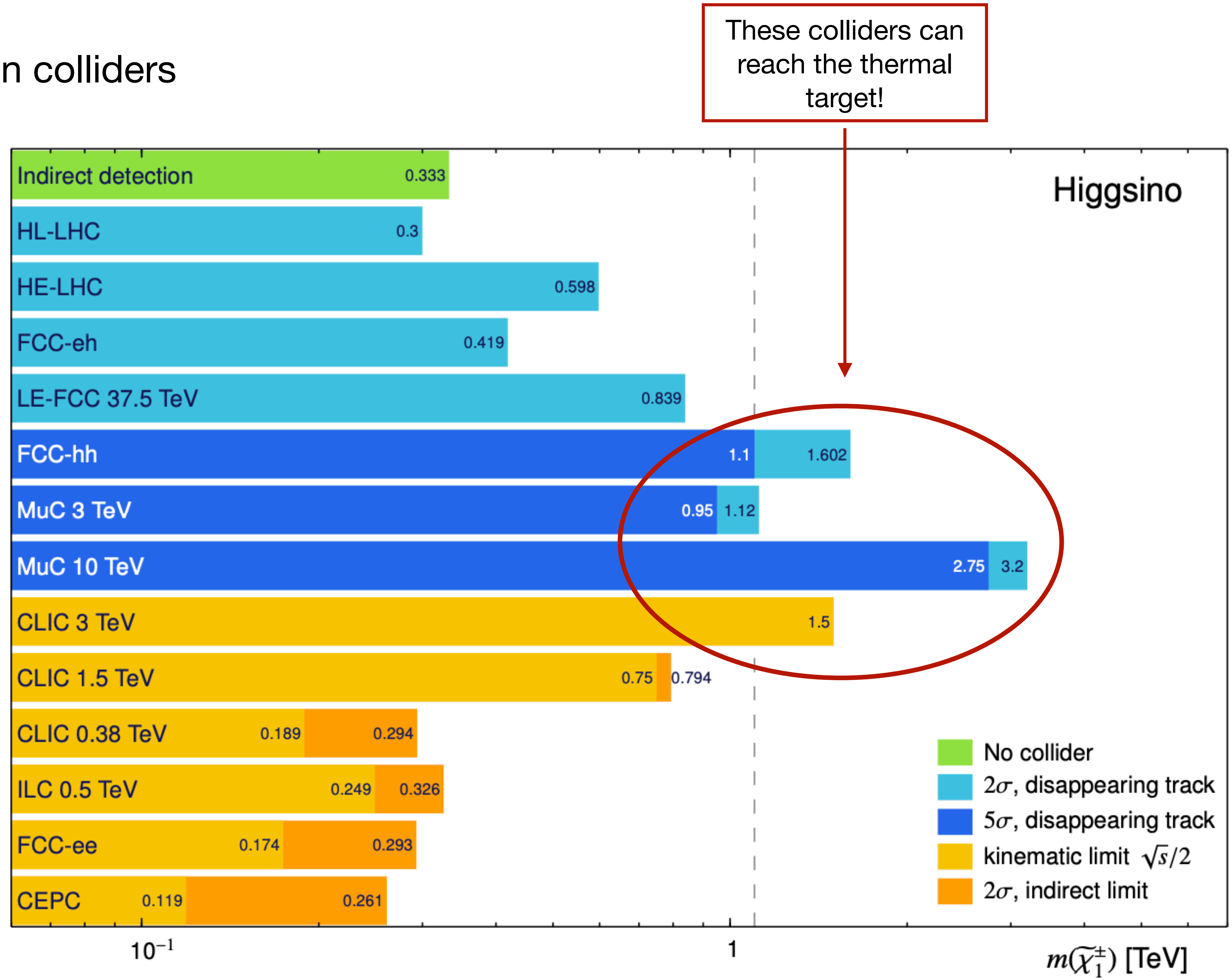
Rodolfo Capdevilla, Fermilab

2. Minimal Dark Matter

- Muon colliders



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2. Minimal Dark Matter

- Muon colliders