

## Particle and Astroparticle Physics Colloquium Hamburg June 28, 2022

Four Jet Events in  $e^+ e^-$   
M. Bengtsson (Aachen, )  
Mar, 1988

In the past decades we have observed an increasing understanding of the theory of matter. The picture is summarized in the Standard Model of Particle Physics. The model is complete except for the structure of the scalar sector. Governed by asymptotic unitarity, the Higgs self-couplings are finally fixed.

The Higgs sector -- phenomenological as well as collider aspects -- is discussed in today's colloquium. We are looking forward to **Margarete Mühlleitner's (Karlsruhe Institute of Technology)** presentation.

Scaling Violations in Inclusive  $e^+ e^-$  Annihilation  
C. Peterson (SLAC), D. Schlatter (SLAC), J. Schmitt (SLAC), Peter M. Zerwas (Aachen, Tech. Hochsch.)  
Apr, 1982

LEP  
Apr, 1979

LEP colliders: QCD corrections  
C. Peterson (Aachen, Tech. Hochsch.), P.M. Zerwas (Aachen, Tech. Hochsch.)

Neutrino Production by Neutrinos  
C. Peterson (Aachen, Tech. Hochsch.), P.M. Zerwas (Aachen, Tech. Hochsch.)

T.F. Walsh (DESY), P.M.

Peter Fest  
Or  
What is the  
True Theory  
Underlying Nature



---

# Our Driving Force

---

- ♦ Peter Zerwas in a very rare outburst of emotions during coffee in the DESY canteen at lunch time:

We have the most wonderful job in the world!



- ♦ We would certainly all agree on that!

We are all driven by the endeavor to understand what holds the world together in its inmost folds.

---

# Facts

---

- ♦ Peter Zerwas followed this endeavor with enthusiasm and dedication

---

# Facts

---

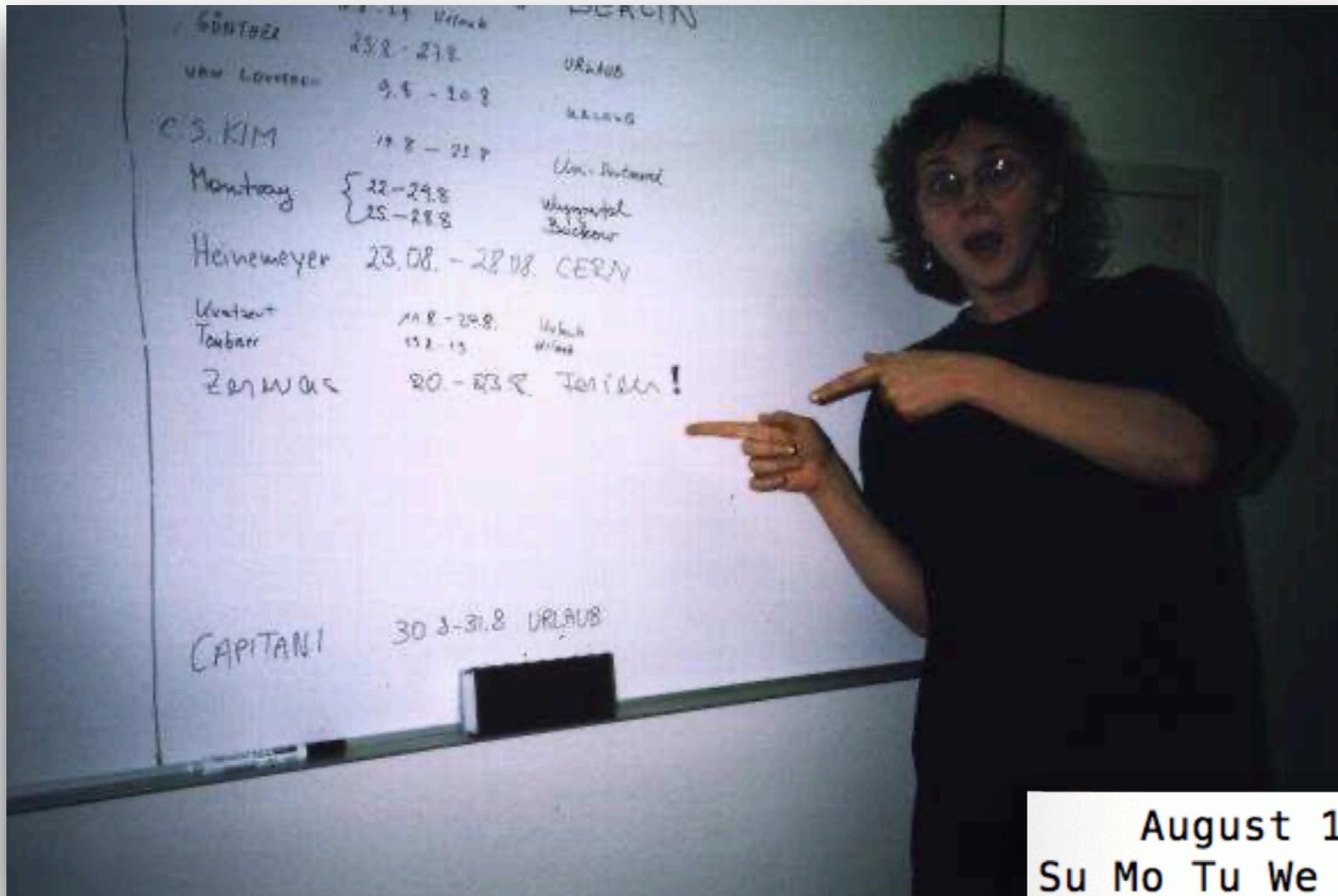
♦ Peter Zerwas followed this endeavor with enthusiasm and dedication

... and assumed that everybody of his students and collaborators had the same 24/24 on 7/7 dedication



# Facts

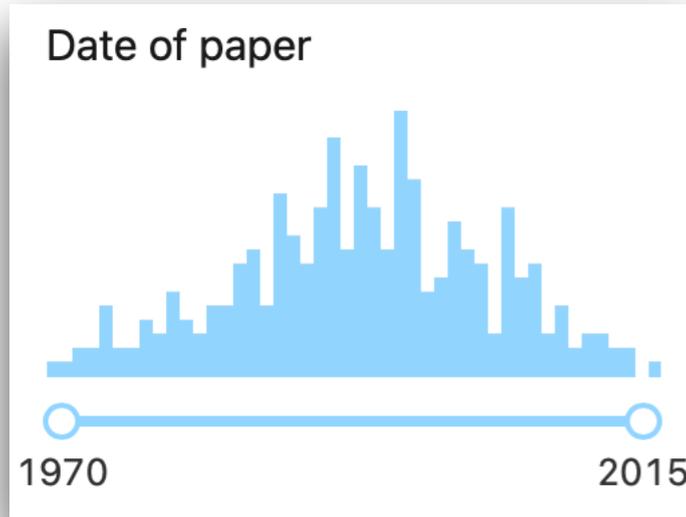
- ♦ Peter Zerwas followed this endeavor with enthusiasm and dedication



August 1999						
Su	Mo	Tu	We	Th	Fr	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

# Facts

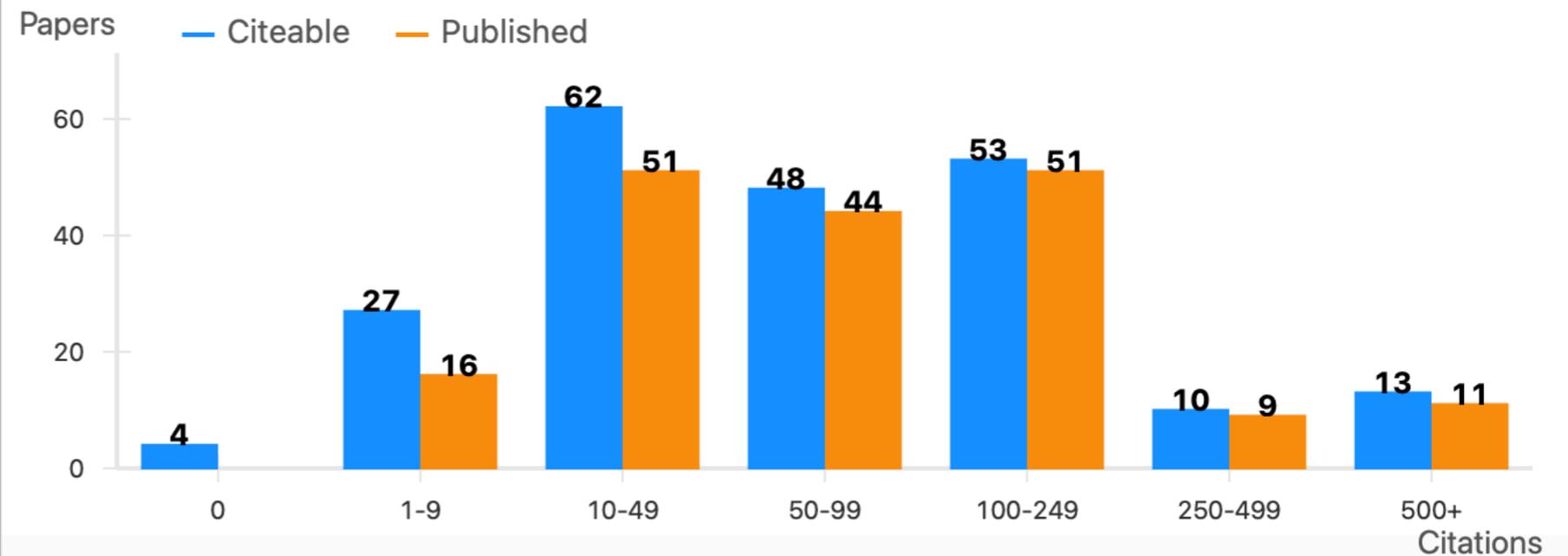
♦ Peter Zerwas followed this endeavor with enthusiasm and dedication



## Citation Summary

Exclude self-citations (?)

	Citeable (?)	Published (?)
Papers	217	182
Citations	29,664	25,719
h-index (?)	86	84
Citations/paper (avg)	136.7	141.3



# Facts

♦ Peter Zerwas followed this endeavor with enthusiasm and dedication



# Facts

## ♦ Short Curriculum Vitae:

1970 Dissertation on *Chiral Symmetry*

Postdoc at DESY/Hamburg, SLAC Stanford/California

1976 Professor for Theoretical Physics in Aachen

1991 Leading Scientist in DESY Theory Group &  
Professor at the University of Hamburg

2007 Retirement

- Guest Professor/Research Visits: CERN, SLAC, FNAL, KEK
- Leader of „Experiments Committee“ at LEP/CERN
- Member of Particle Data Group Advisory Board at LBNL
- Co-Editor of „Zeitschrift für Physik“, „Eur. Phys. Journal“, „Reports on Progress in Physics“



# Outline



- ♦ Overview of Peter's research early and later years
- ♦ The Legacy
  - Higgs physics - relation to today's LHC physics program  
what can be learnt
- ♦ Higgs discovery
  - detour to supersymmetry
- ♦ The Higgs program
  - Higgs boson mass
  - Higgs boson couplings
  - Higgs boson quantum numbers
  - Higgs pair production
- ♦ Higgs Portal to Hidden Sector
- ♦ Varia 😊



*Peter's  
Research*

---

# Research

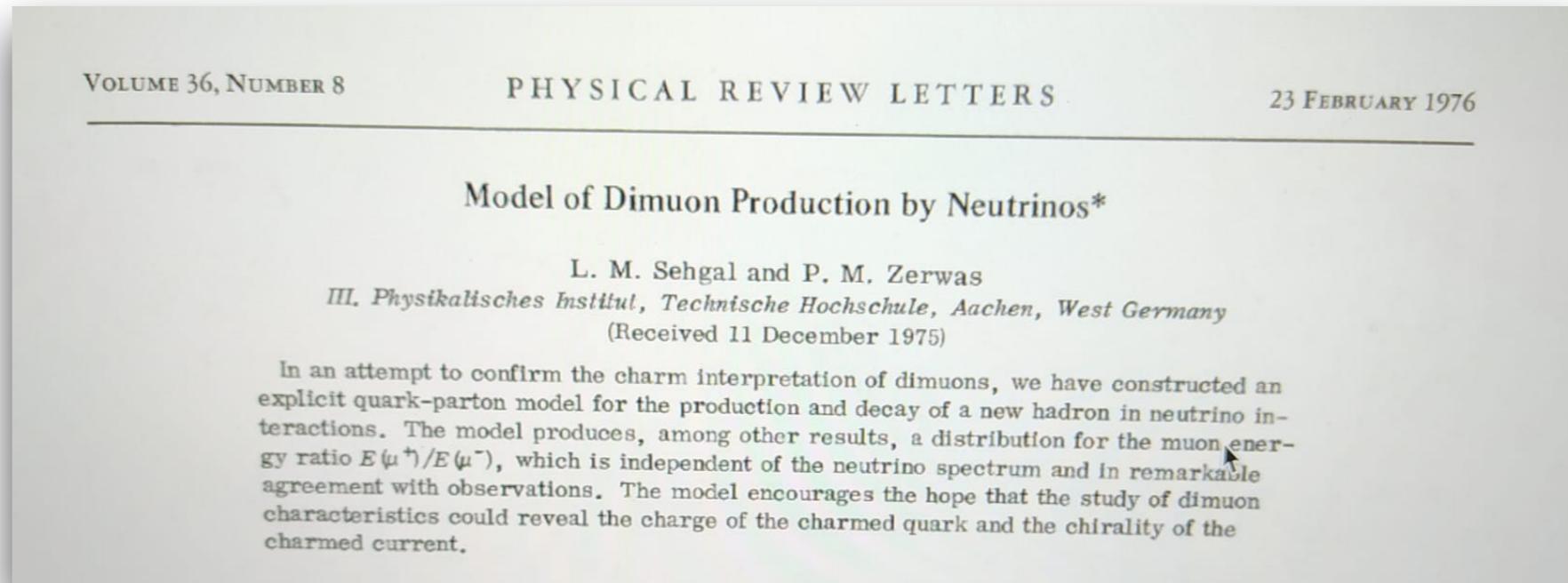
---

♦ **Early years:** Main research field: [Quantum Chromodynamics](#)

# Research

♦ **Early years:** Main research field: **Quantum Chromodynamics**

**Determination of charm quark mass** first time from neutrino data



# Research

✦ **Early years:** Main research field: **Quantum Chromodynamics**

**Determination of charm quark mass** first time from neutrino data

**Peterson Fragmentation** - transition of heavy quarks into jets

SLAC-PUB-2912  
April 1982  
(T/E)

SCALING VIOLATIONS IN INCLUSIVE  $e^+e^-$  ANNIHILATION SPECTRA\*

C. Peterson\*\*, D. Schlatter, I. Schmitt\*\*\* and P. M. Zerwas\*\*\*\*  
Stanford Linear Accelerator Center  
Stanford University, Stanford, California 94305

ABSTRACT

The origin of the observed scaling violations in inclusive  $e^+e^-$  annihilation is investigated. Perturbative jet evolution is not necessarily the only reason for scale breaking in the hadron spectra at

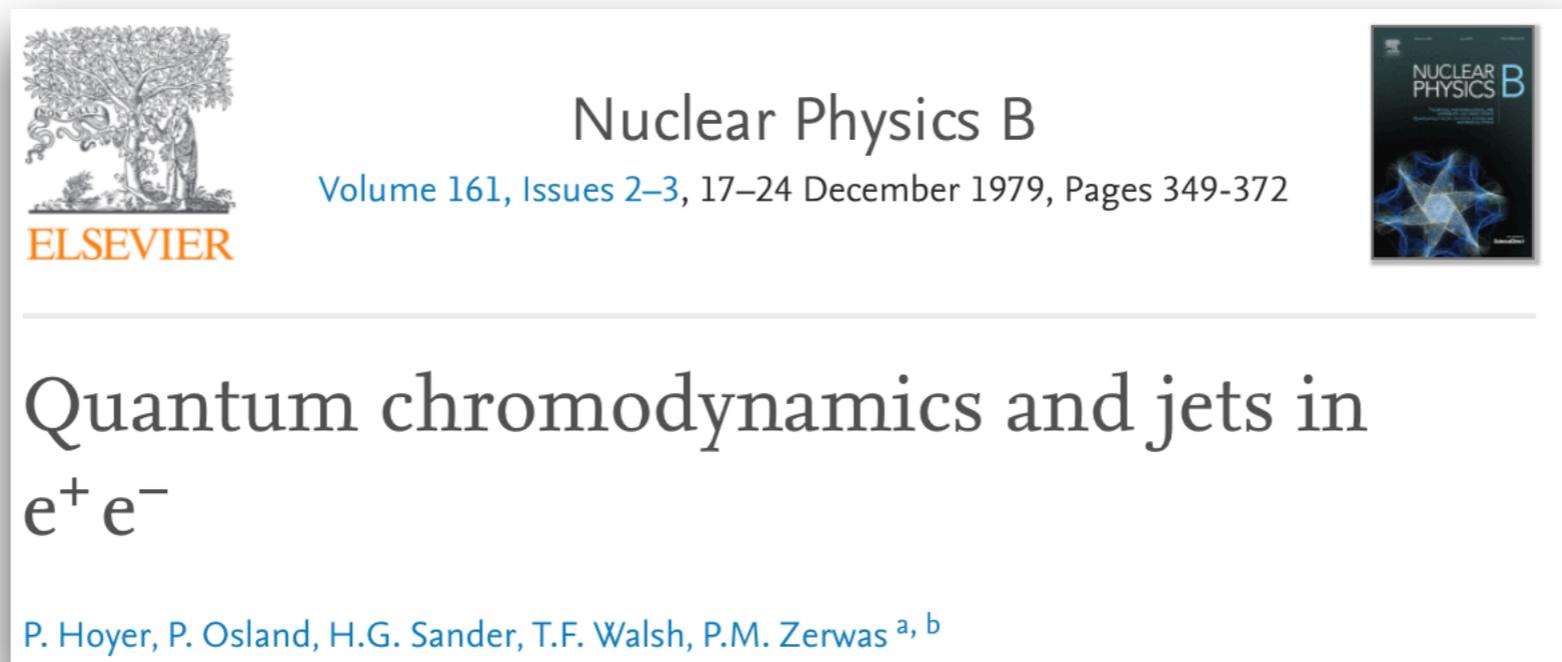
# Research

♦ **Early years:** Main research field: **Quantum Chromodynamics**

**Determination of charm quark mass** first time from neutrino data

**Peterson Fragmentation** - transition of heavy quarks into jets

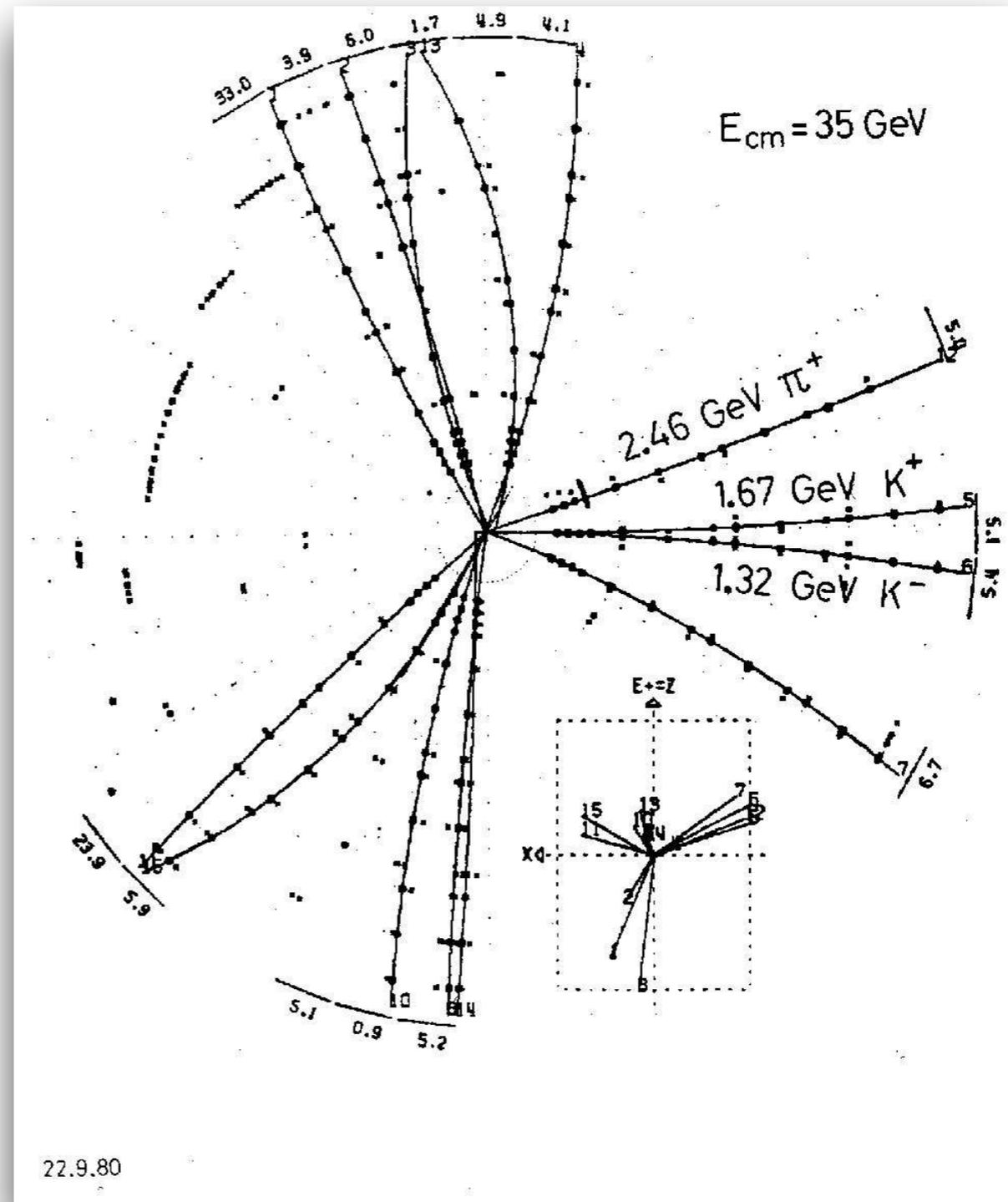
**Hoyer Model** - fragmentation of gluons in hadron jet  
discovery of hadron jets at PETRA (DESY) experimentally  
established the existence of gluons



# Discovery of the Gluon

Typical 3 jet event in the TASSO detector: Two quarks produced in an electron-positron collision emit a gluon; each of the particles turn into a jet of particles.

1979



# Research

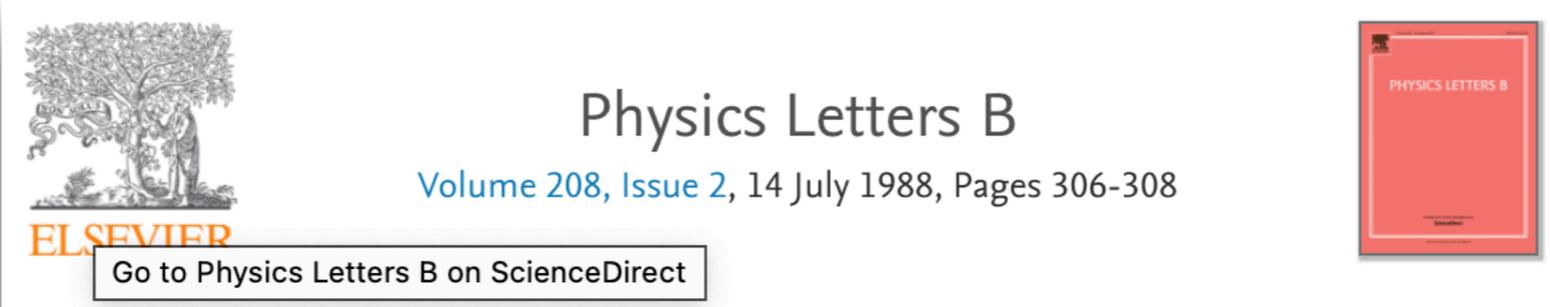
♦ **Early years:** Main research field: **Quantum Chromodynamics**

**Determination of charm quark mass** first time from neutrino data

**Peterson Fragmentation** - transition of heavy quarks into jets

**Hoyer Model** - fragmentation of gluons in hadron jet  
discovery of hadron jets at PETRA (DESY) experimentally  
established the existence of gluons

**Bengtsson-Zerwas Winkel** - signal of the self-interaction of  
the gluons -> asymptotic freedom of the QCD



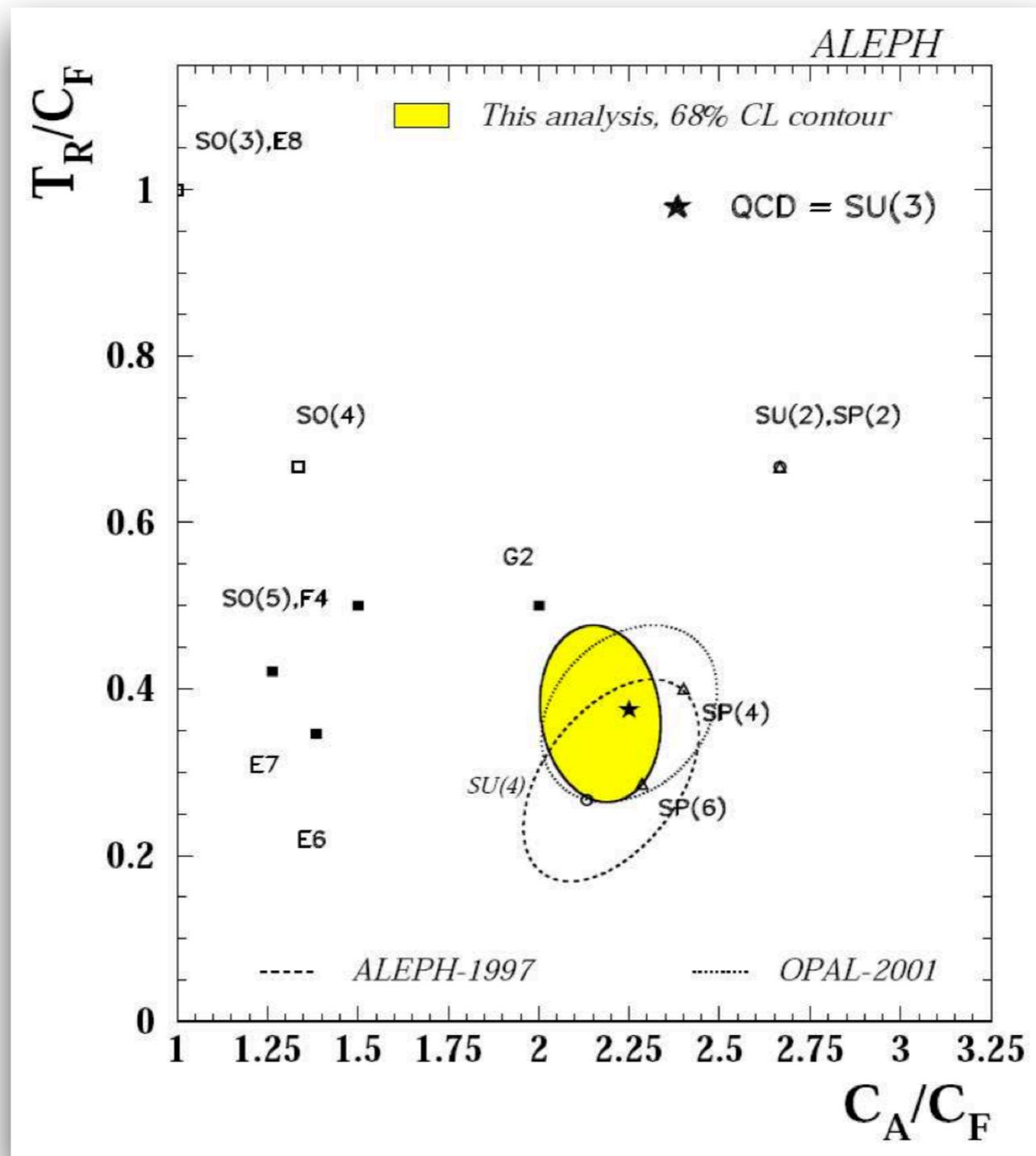
Physics Letters B  
Volume 208, Issue 2, 14 July 1988, Pages 306-308

Go to Physics Letters B on ScienceDirect

Four-jet events in  $e^+e^-$  annihilation:  
Testing the three-gluon vertex ☆

M. Bengtsson \*, P.M. Zerwas \*

# Establish Colour SU(3)



---

# Research

---

✦ **Early years:** Main research field: **Quantum Chromodynamics**

**Determination of charm quark mass** first time from neutrino data

**Peterson Fragmentation** - transition of heavy quarks into jets

**Hoyer Model** - fragmentation of gluons in hadron jet  
discovery of hadron jets at PETRA (DESY) experimentally  
established the existence of gluons

**Bengtsson-Zerwas Winkel** - signal of the self-interaction of  
the gluons -> asymptotic freedom of the QCD

**Photon Fragmentation Function** - transition of hadronic jet into  
a single highly energetic photon

---

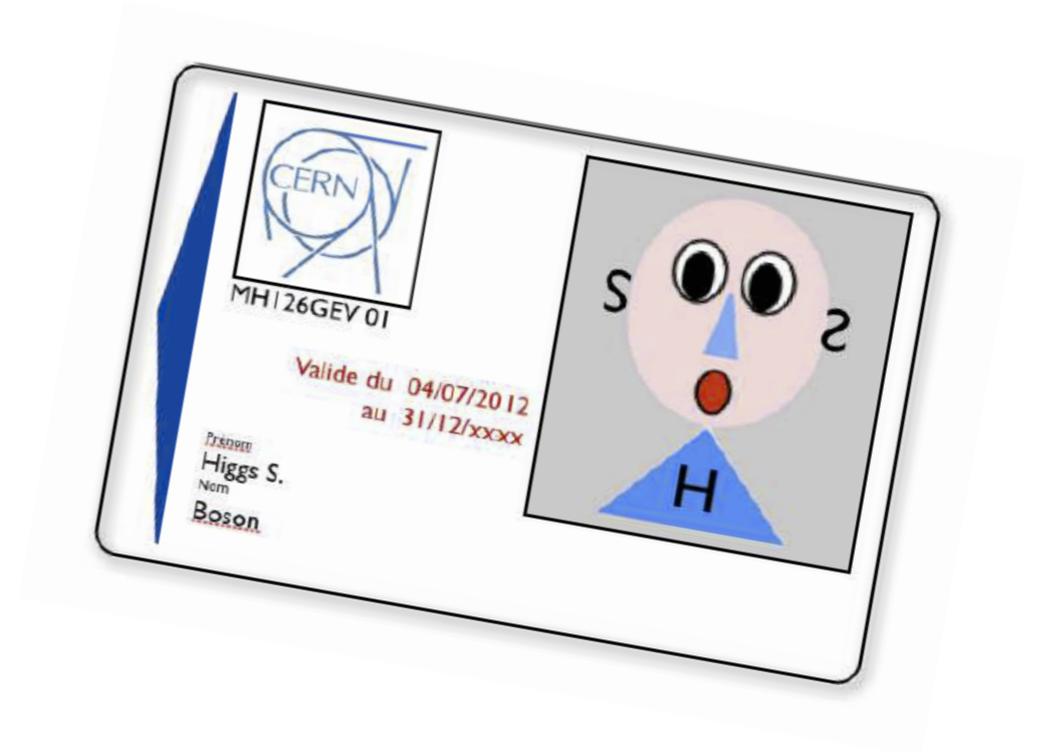
# Research

---

♦ Later years:

♦ Later years:

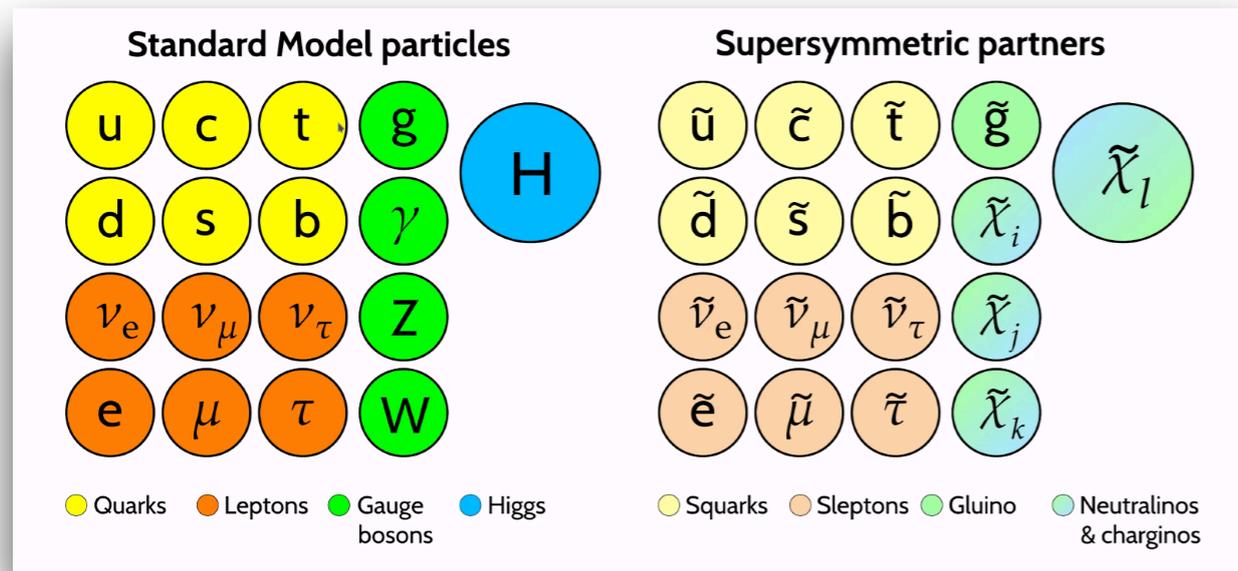
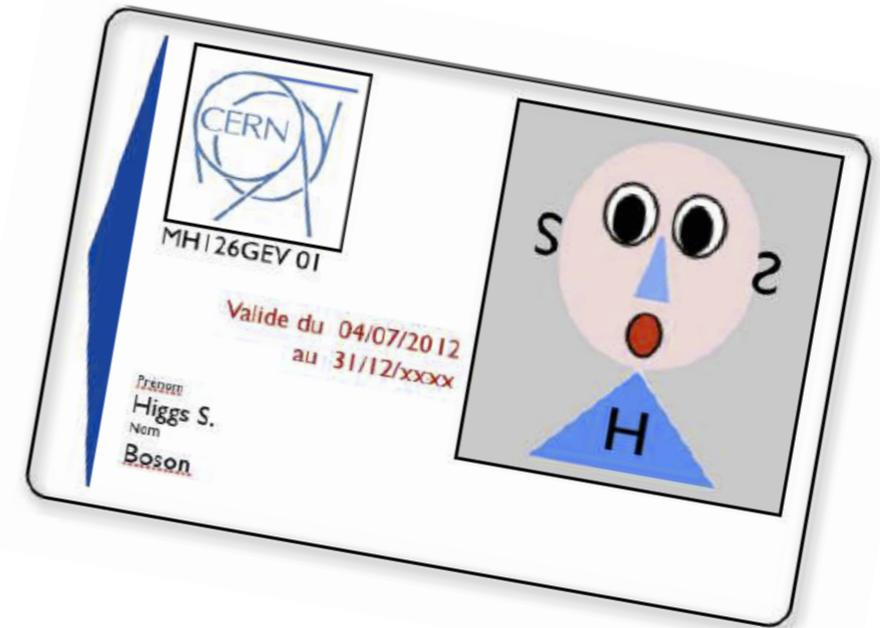
Higgs Physics



✦ Later years:

Higgs Physics

Supersymmetry

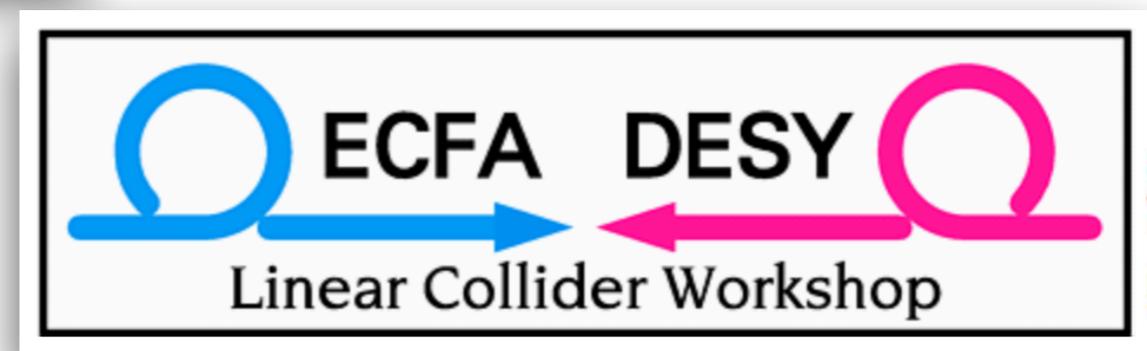
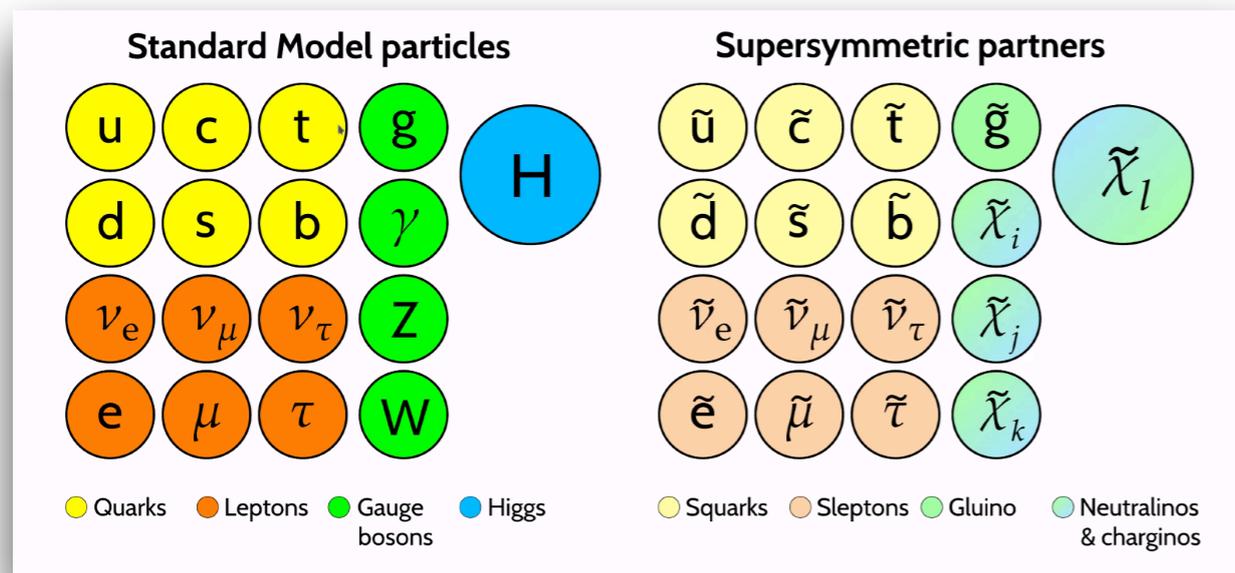
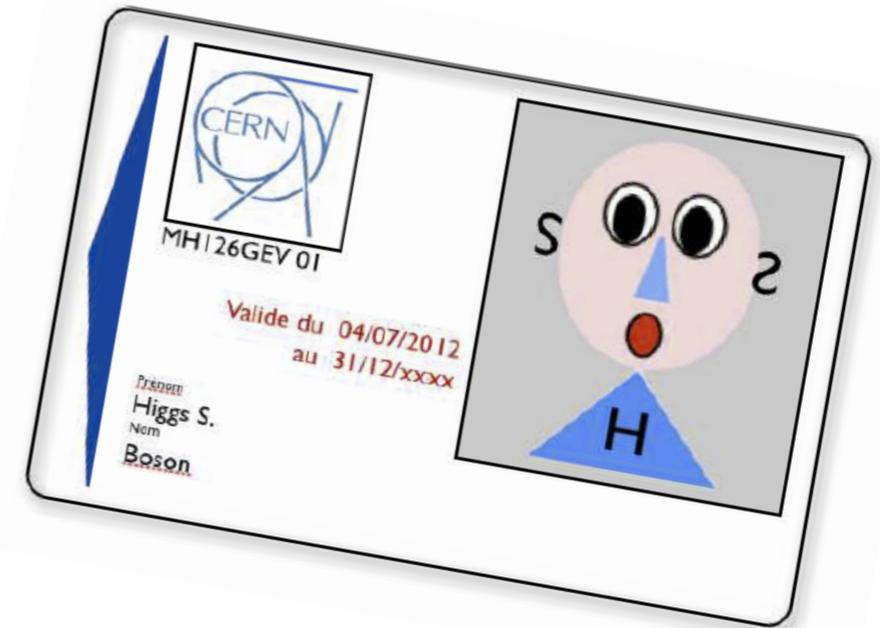


♦ Later years:

Higgs Physics

Supersymmetry

Physics Potential of an  $e^+e^-$  collider



# Dedication to the $e^+e^-$ Linear Collider

**Extended Study**

**NEWS**

**TDR**

**LC Notes**

**WGs**

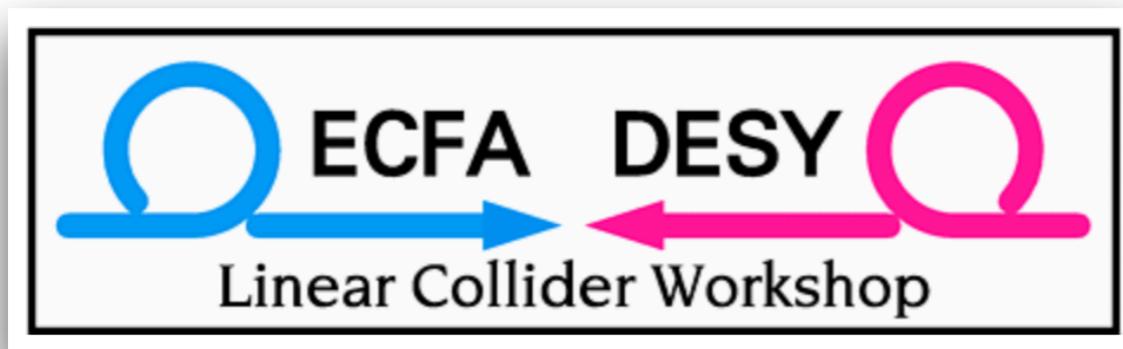
**TESLA Colloquium**

- [Goals of the Study.](#)
- [Organizing committee.](#)
- [Milestones.](#)
- [News Page](#)
- [Review process for a detector R&D program](#)
- Workshops:
  - [First Workshop, Orsay April 1998. Speakers slides.](#)
  - [Second Workshop, Lund 28-30 June 1998. Speakers slides.](#)
  - [Third Workshop, Frascati 7-10 Nov 1998. Speakers slides.](#)
  - [Fourth Workshop, Oxford 20-23 March 1999. Speakers slides.](#)
  - [International Workshop on Linear Colliders \(LCWS99\) at Sitges, near Barcelona, 1-5 Nov 1999. Speakers slides.](#)
  - [Fifth Workshop, Obernai 16-19 October 1999. Speakers slides.](#)
  - [Sixth Workshop, Padova 5-8 May 2000. Speakers slides - sorted by program. Speakers slides - sorted by author.](#)
  - [Seventh Workshop, DESY, 22-25 September 2000. Speakers slides.](#)
  - [5th International  \$e^+e^-\$  Linear Collider Workshop on Physics and Detector R&D, DESY, 2-4 October 2000. Speakers slides.](#)
- [Meetings of working groups between main ECFA/DESY Workshops and other workshops.](#)

TESLA Technical Design Report

## Part III Physics at an $e^+e^-$ Linear Collider

March 2001

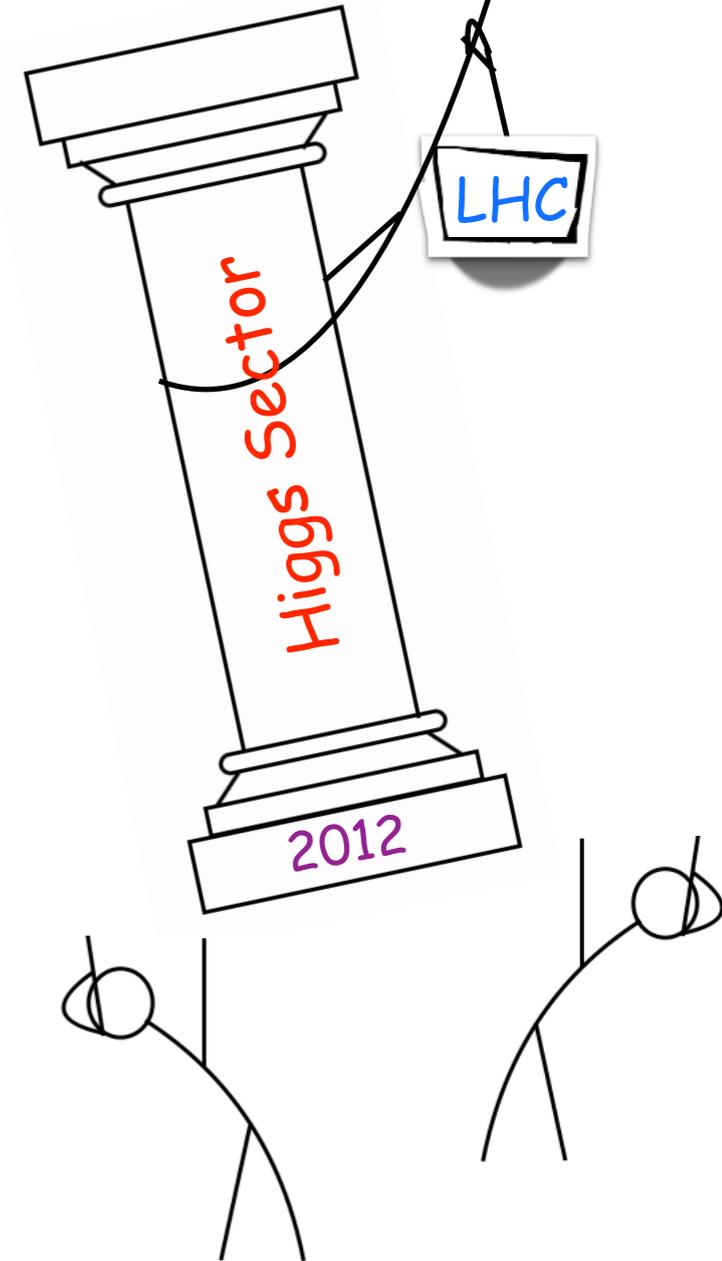
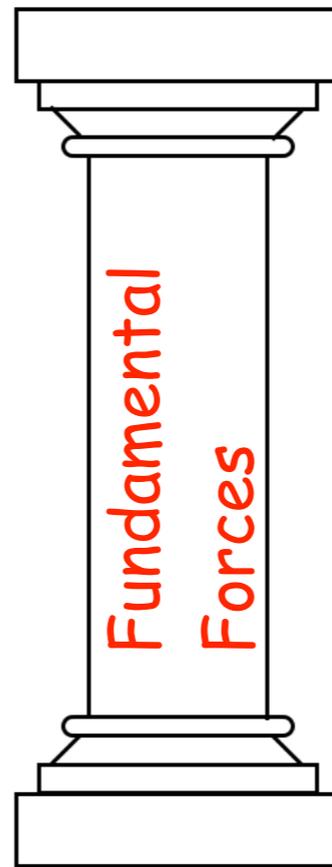
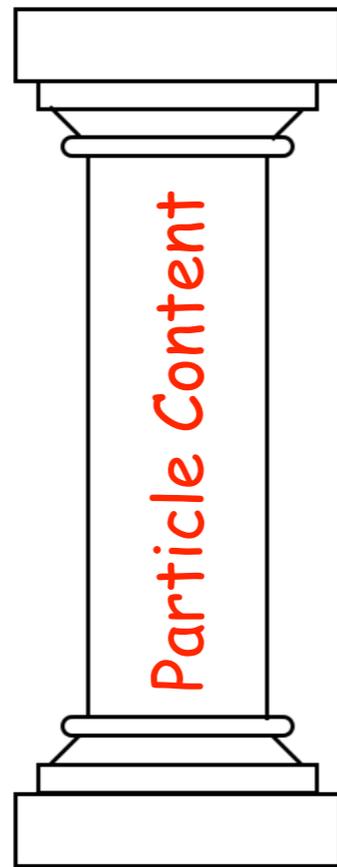
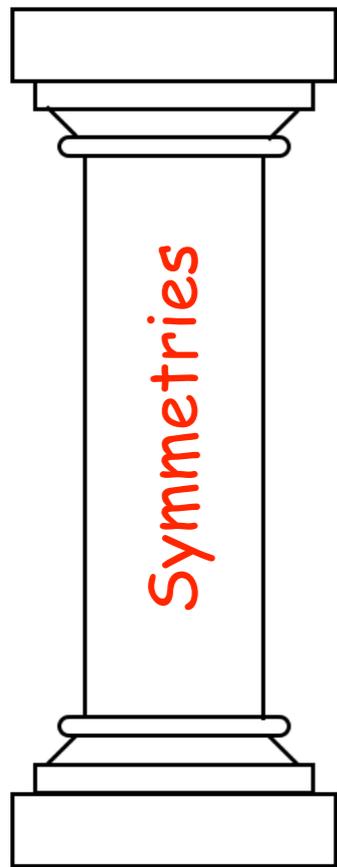


Editors: R.-D.Heuer, D.Miller, F.Richard, P.M.Zerwas

*The Legacy*



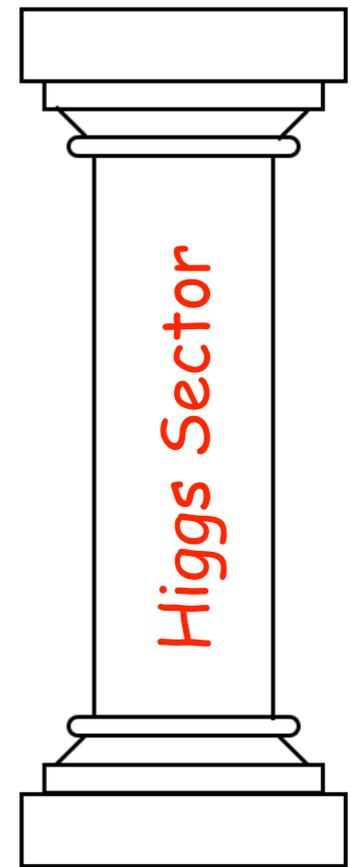
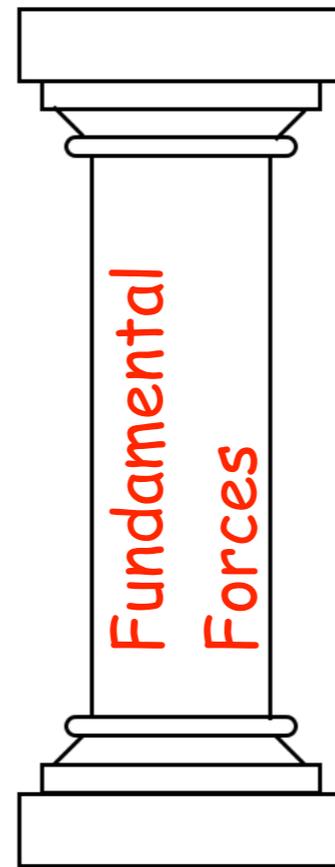
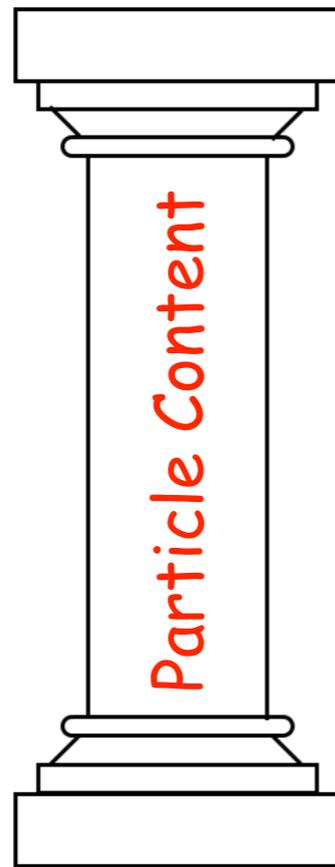
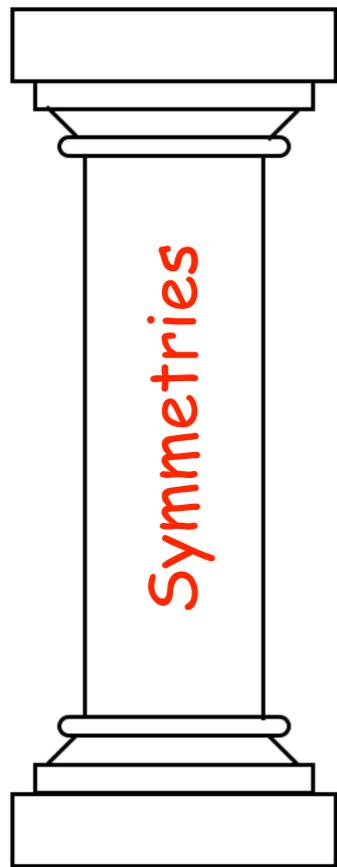
# The Four Pillars of the Standard Model



---

# The Four Pillars of the Standard Model

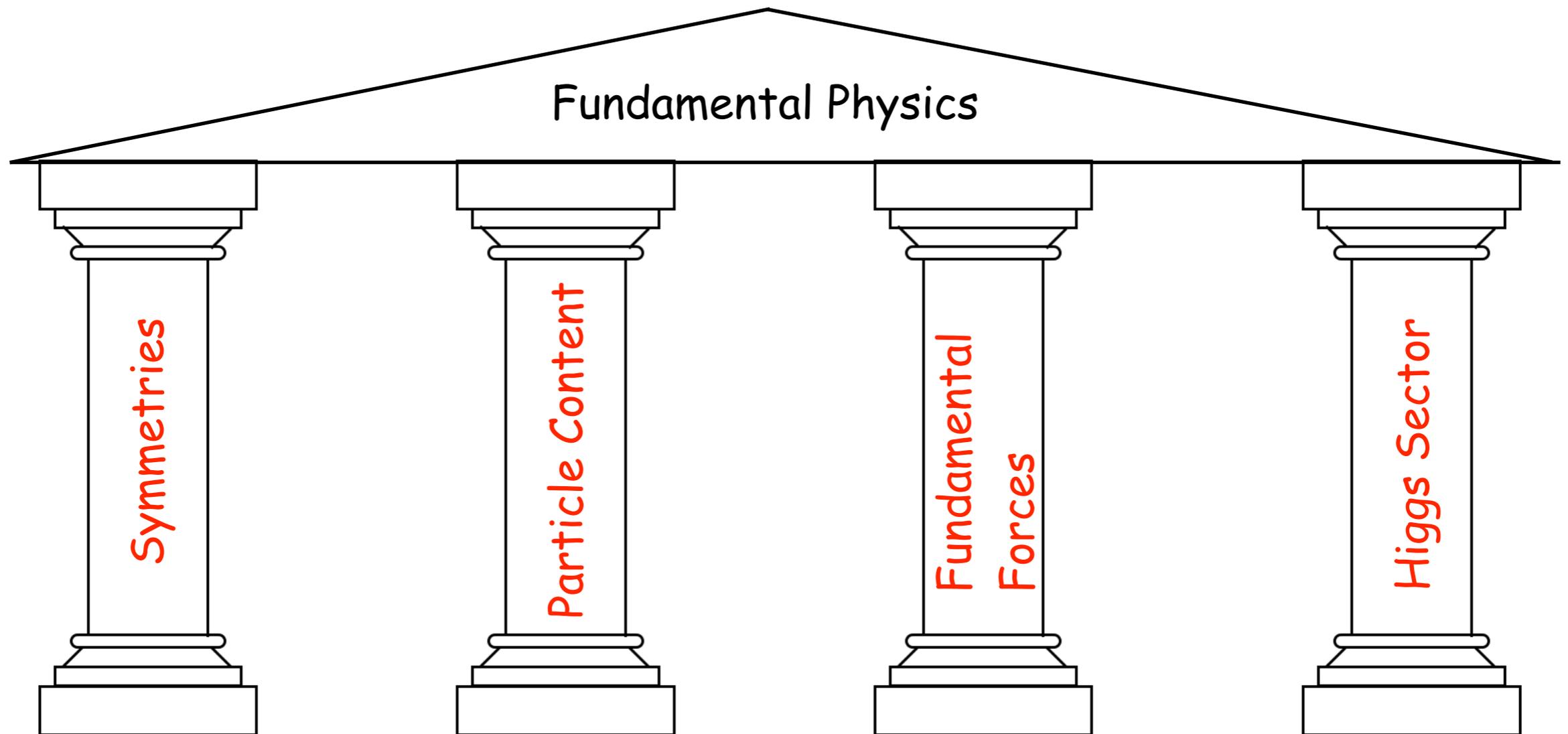
---



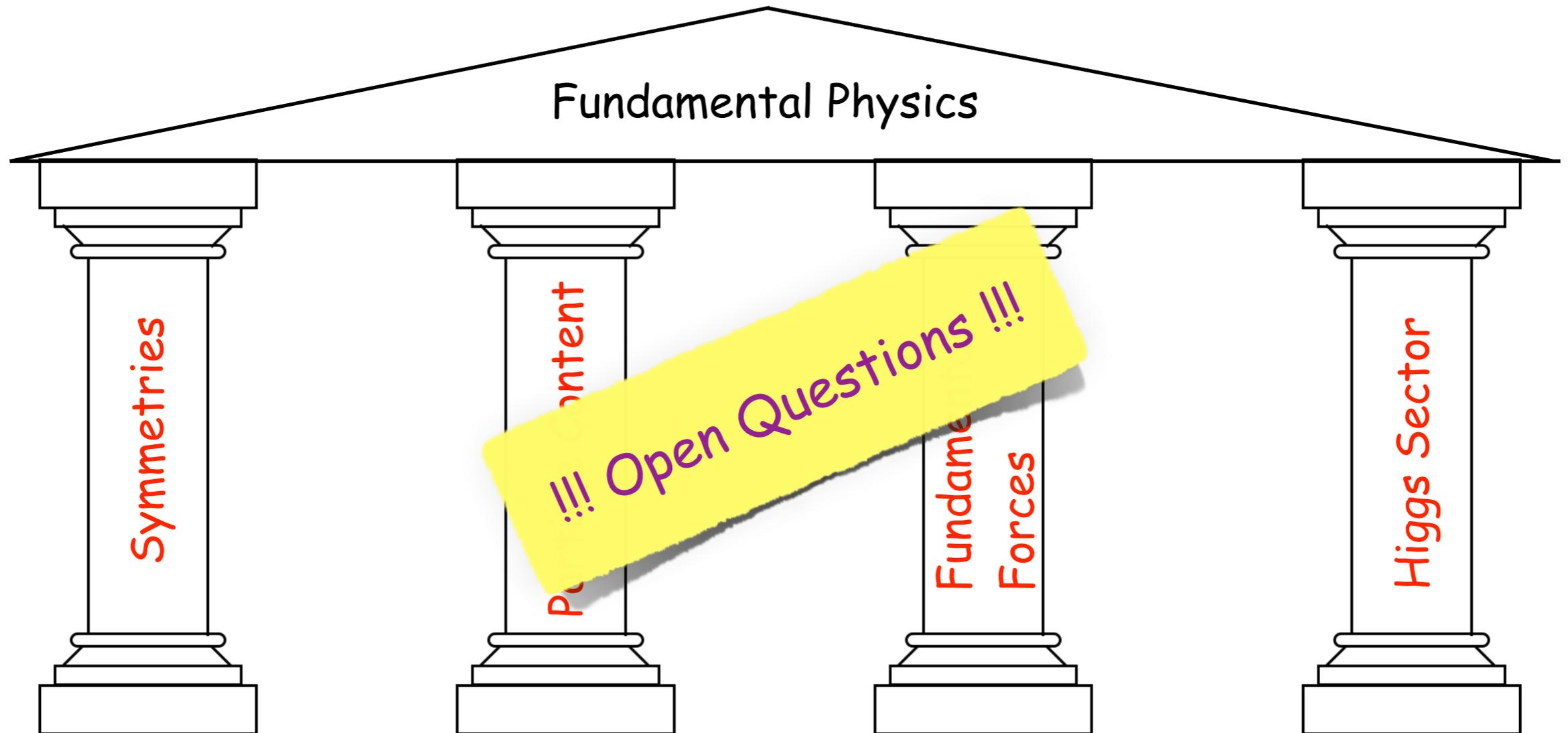
---

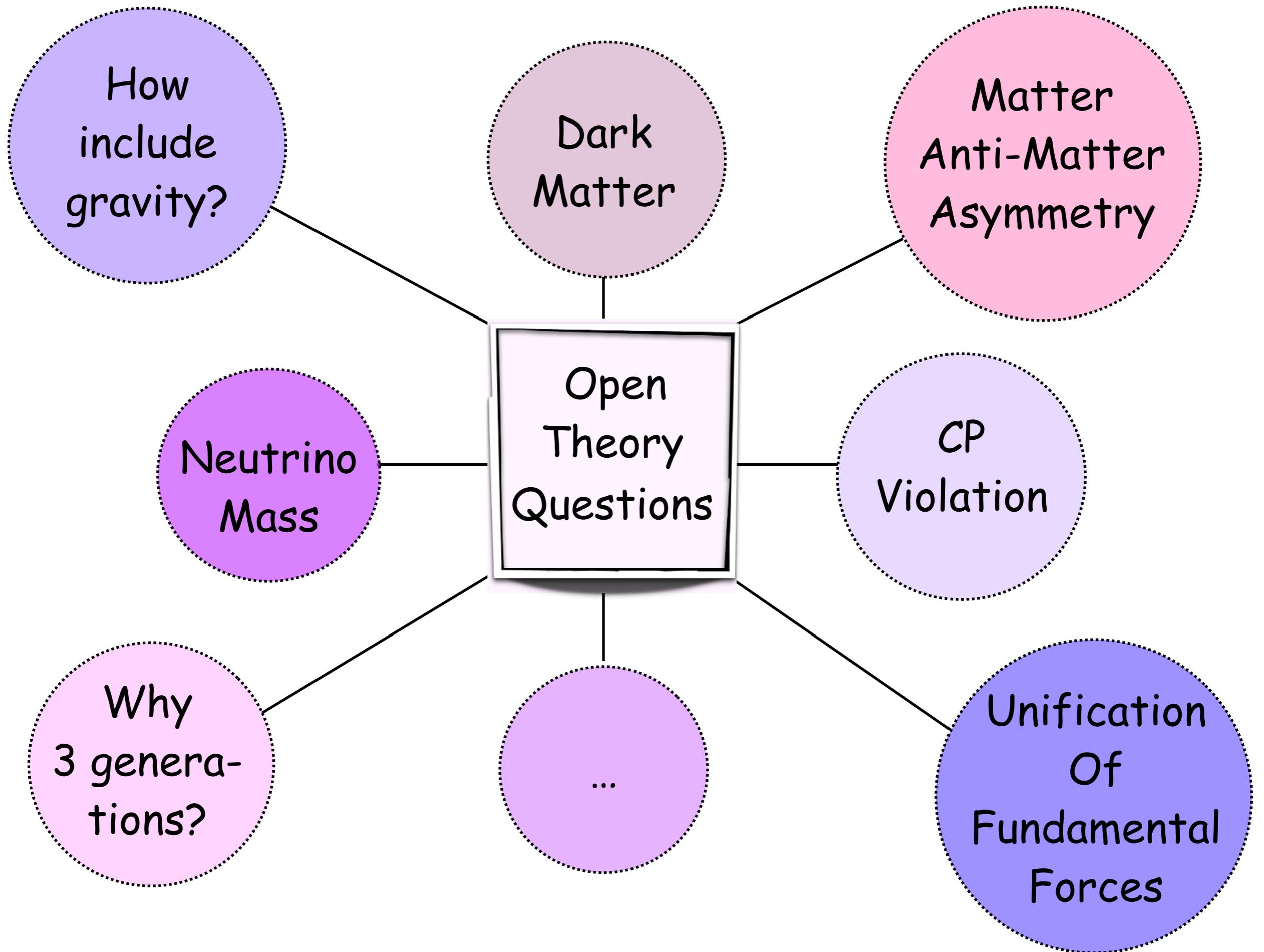
# The Standard Model is Structurally Complete

---



# The Standard Model is Structurally Complete - But





How include gravity?

Dark Matter

Matter Anti-Matter Asymmetry

Neutrino Mass

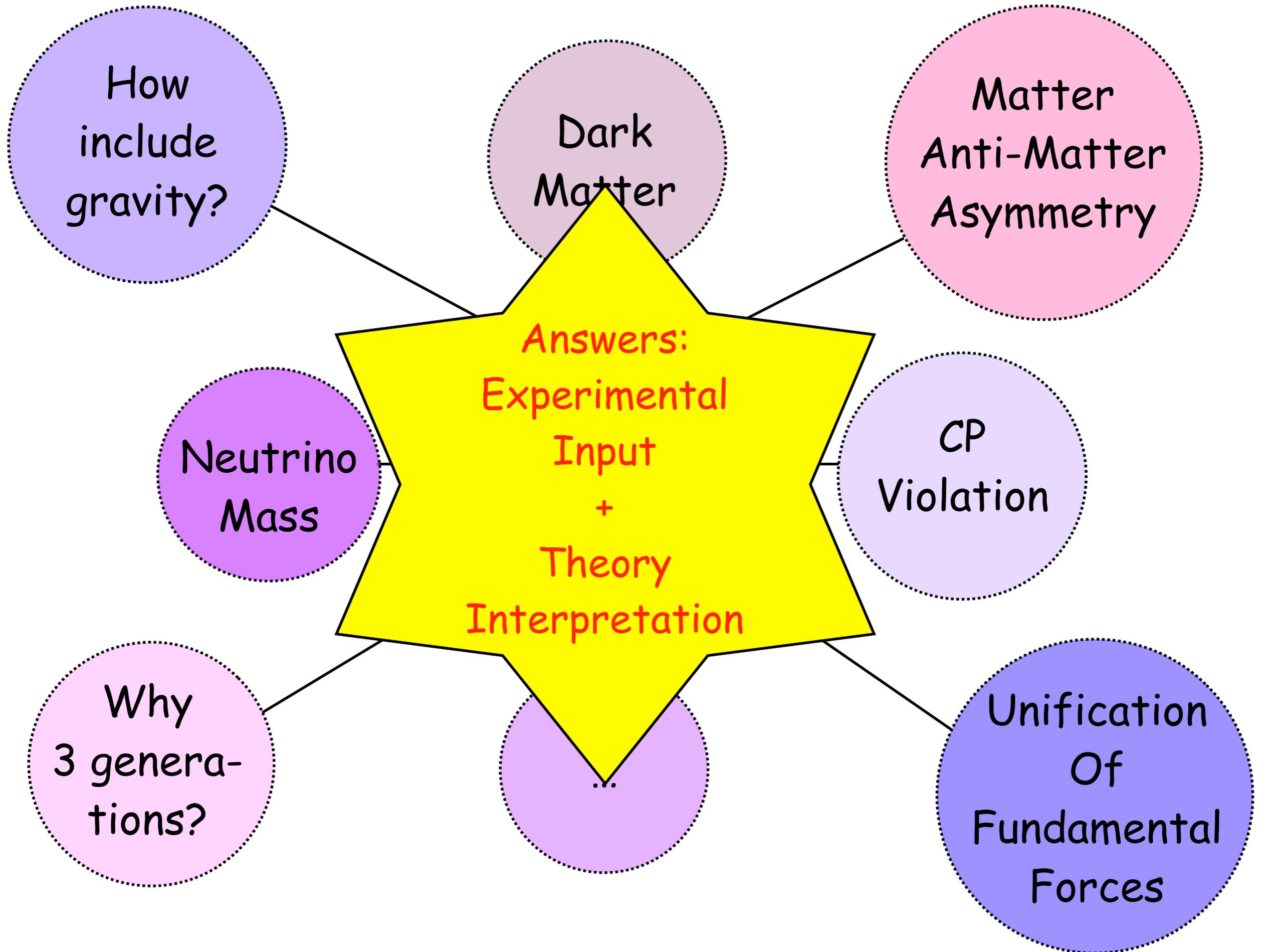
Open Theory Questions

CP Violation

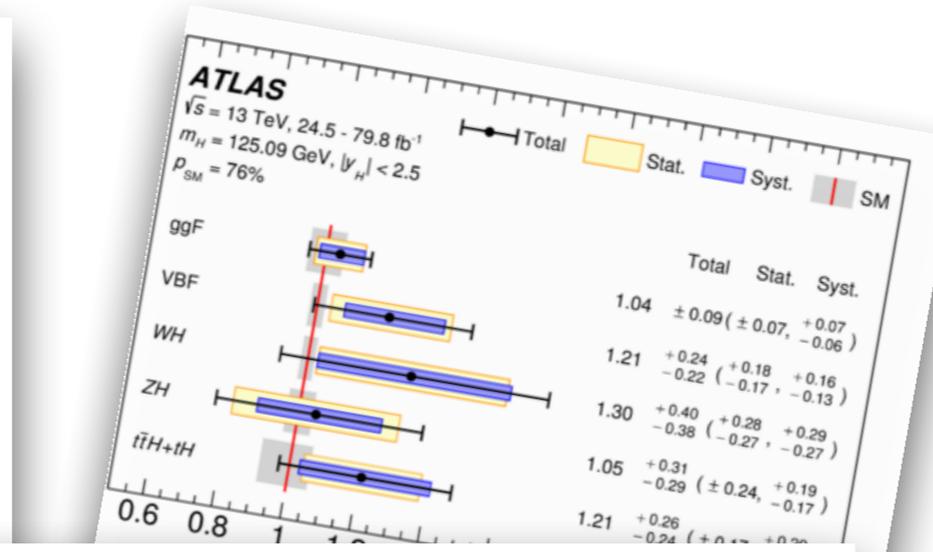
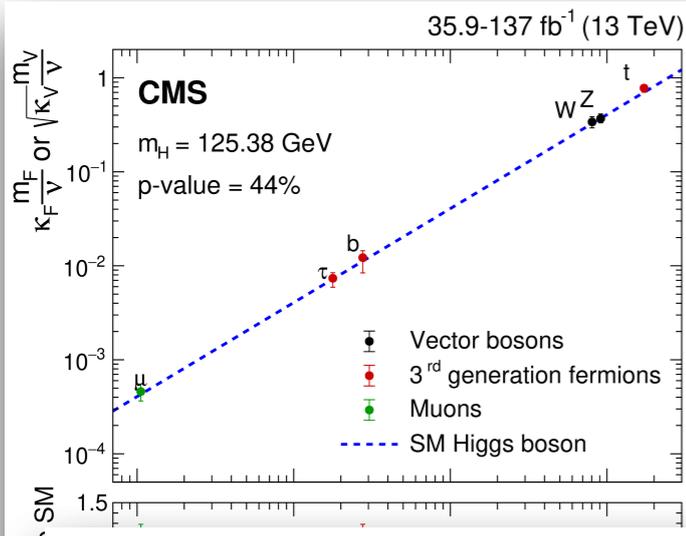
Unification Of Fundamental Forces

...

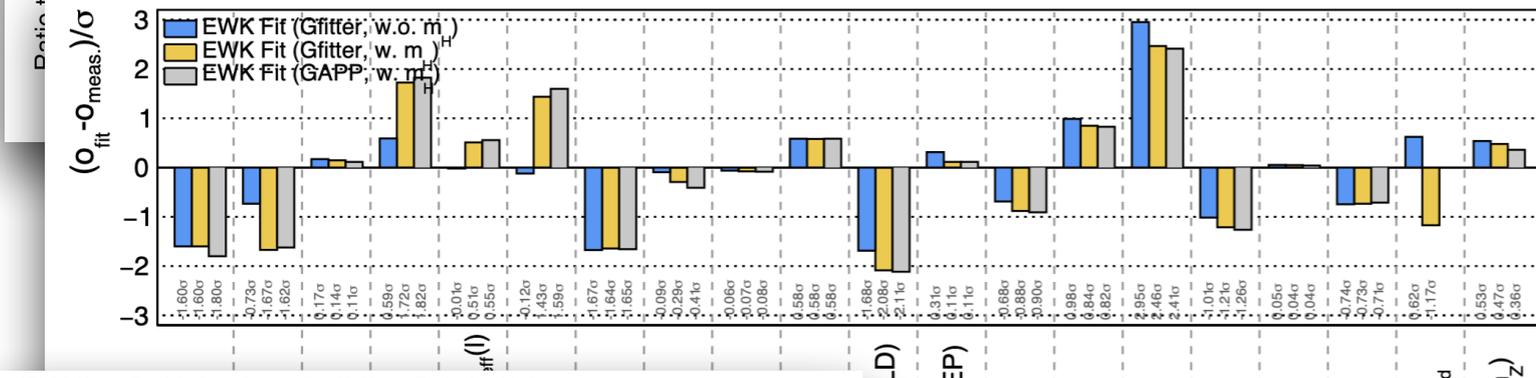
Why 3 generations?



# Status



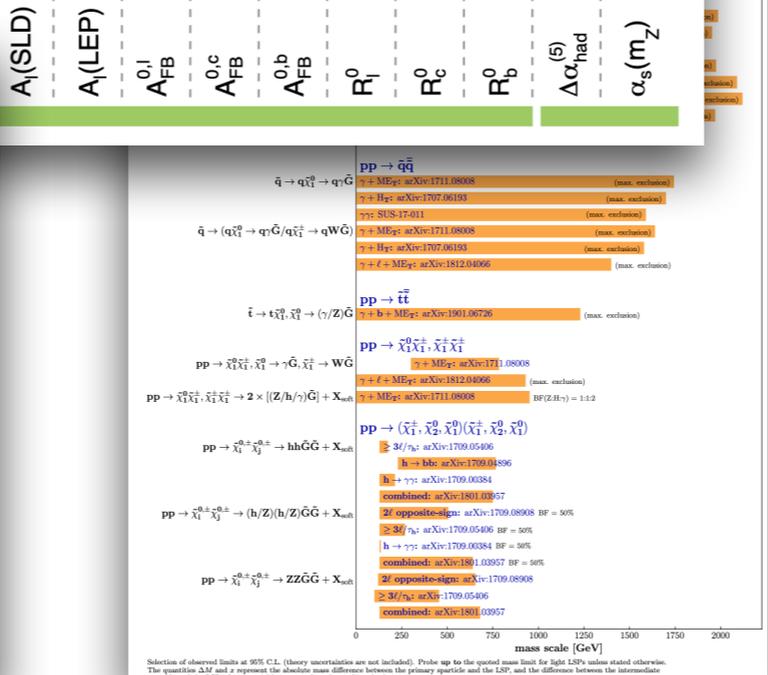
Discovered Higgs Boson behaves very SM-like



Consistency Test of the SM at the quantum level

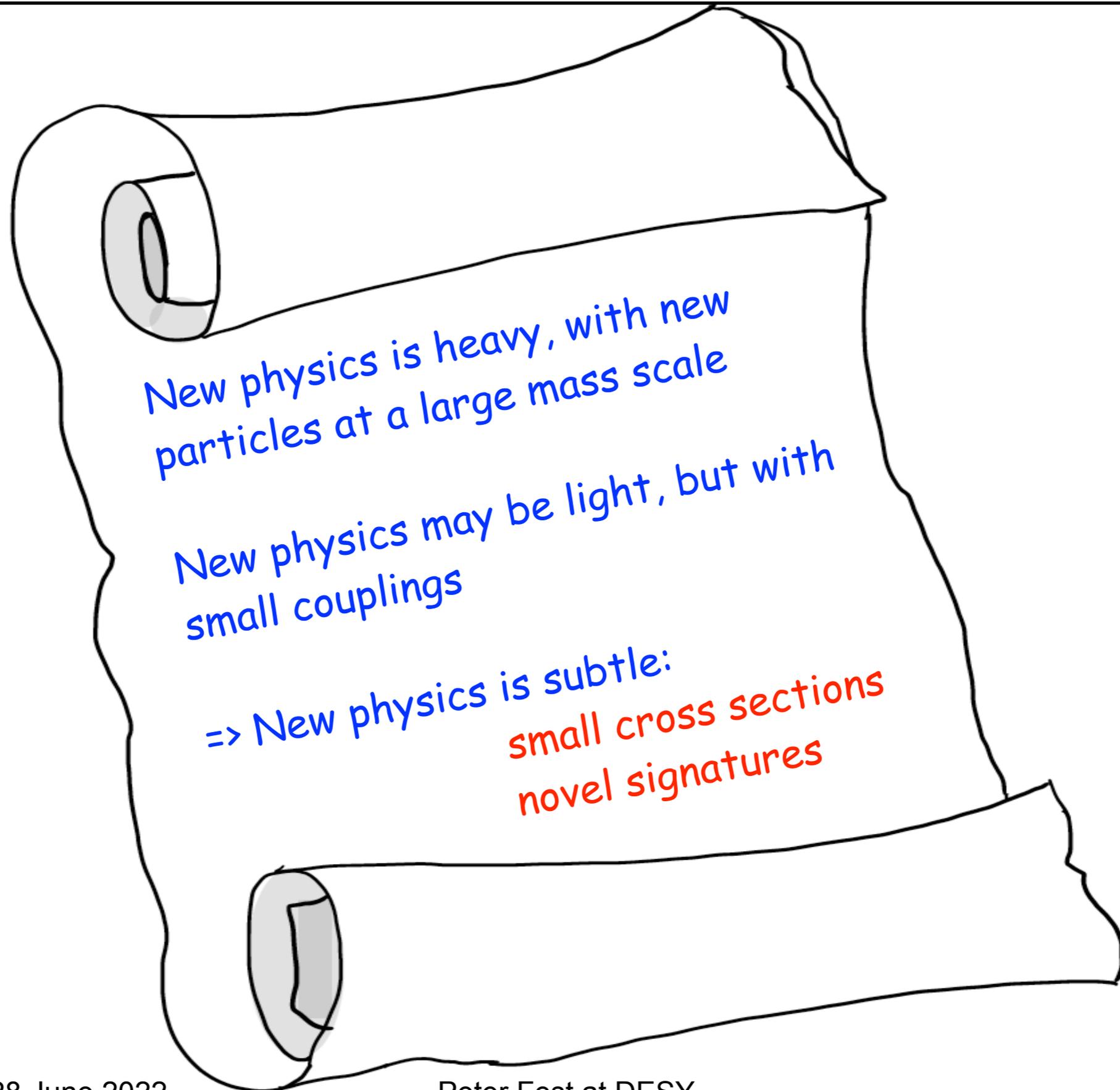
**ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits**  
 Status: July 2021

Model	$f, \gamma$	Jets	$E_{miss}$	Limit	Reference
ADD $G_{UV} + g/g$	$0 < \mu_{UV} < \gamma$	1-4	Yes	139	2102.10874
ADD non-resonant $\gamma\gamma$	$2\gamma$	-	Yes	362	1702.04147
ADD QSH	-	2j	-	370	1703.09127
ADD BH multijet	-	-	-	36	1612.05586
RS1 $G_{UV} \rightarrow \gamma\gamma$	$2\gamma$	-	Yes	139	2102.13495
Bulk RS $G_{UV} \rightarrow WW/ZZ$	multi-channel	-	Yes	361	1608.02380
Bulk RS $G_{UV} \rightarrow WW \rightarrow f\nu_{qg}$	$1 < \mu_{UV} < 2j/1j$	Yes	139	2004.14636	
Bulk RS $G_{UV} \rightarrow tt$	$1 < \mu_{UV} > 1b, 3j/2j$	Yes	361	1804.10823	
GUED/RSPP	$1 < \mu_{UV} < 2b, 2j$	Yes	361	1602.06273	
SSM $Z' \rightarrow \ell\ell$	$2 < \mu_{UV} < \gamma$	-	Yes	139	1902.06248
SSM $Z' \rightarrow \tau\tau$	$2\tau$	-	Yes	361	1709.07262
Leptophobic $Z' \rightarrow bb$	$2b$	-	Yes	361	1605.06239
Leptophobic $Z' \rightarrow \tau\tau$	$0 < \mu_{UV} > 1b, 3j/2j$	Yes	139	2005.05138	
SSM $W' \rightarrow \ell\nu$	$1 < \mu_{UV} < \gamma$	Yes	139	1605.06239	
SSM $W' \rightarrow \nu\nu$	$1 < \mu_{UV} < \gamma$	Yes	139	1605.06239	
SSM $W' \rightarrow \ell b$	$1 < \mu_{UV} < 2j/1j$	Yes	139	1605.06239	
HVT $W' \rightarrow WZ \rightarrow f\nu_{qg}$ model B	$0 < \mu_{UV} < 2j/1j$	Yes	139	2004.14636	
HVT $Z' \rightarrow ZH$ model B	$0 < \mu_{UV} < 1b, 3j/2j$	Yes	139	1605.06239	
HVT $W' \rightarrow WW$ model B	$0 < \mu_{UV} < 1b, 3j/2j$	Yes	139	1605.06239	
LRSM $W_{2/3} \rightarrow \mu\nu_{\ell}$	$2\mu$	1j	-	80	1904.12879
Cl eeee	$2 < \mu_{UV} < 2j$	-	Yes	370	1702.09127
Cl ee $\mu\mu$	$2 < \mu_{UV} < 2j$	-	Yes	139	2006.12546
Cl ee $\tau\tau$	$2 < \mu_{UV} < 2j$	-	Yes	139	2105.13847
Cl ee $\tau\nu$	$2 < \mu_{UV} < 2j$	-	Yes	139	2105.13847
Cl ee $\tau\nu$	$2 < \mu_{UV} < 2j$	-	Yes	361	1811.02395
Axisial-vector med. (Dirac DM)	$0 < \mu_{UV} < \gamma$	1-4	Yes	139	1605.06239
Pseudo-scalar med. (Dirac DM)	$0 < \mu_{UV} < \gamma$	1-4	Yes	139	1605.06239
Vector med. $Z'$ (Dirac DM)	$0 < \mu_{UV} < \gamma$	2b	Yes	139	1605.06239
Pseudo-scalar med. 2HDM	multi-channel	-	Yes	139	1605.06239
Scalar reson. $\phi \rightarrow \ell\ell$ (Dirac DM)	$0 < \mu_{UV} < 1b, 0-1j$	Yes	361	1605.06239	
Scalar LQ 1 <sup>st</sup> gen	$2 < \mu_{UV} < 2j$	Yes	139	1605.06239	
Scalar LQ 2 <sup>nd</sup> gen	$2 < \mu_{UV} < 2j$	Yes	139	1605.06239	
Scalar LQ 3 <sup>rd</sup> gen	$1 < \mu_{UV} < 2j$	Yes	139	1605.06239	
Scalar LQ 3 <sup>rd</sup> gen	$0 < \mu_{UV} < 3j, 3j/2j$	Yes	139	1605.06239	
Scalar LQ 3 <sup>rd</sup> gen	$3 < \mu_{UV} < 3j, 3j/2j$	Yes	139	1605.06239	
Scalar LQ 3 <sup>rd</sup> gen	$0 < \mu_{UV} < 1 < 0-2j, 2b$	Yes	139	1605.06239	
VLO $T \rightarrow Z + X$	$2 < \mu_{UV} < 3 < 2j, 1 < 1-4j$	Yes	139	1605.06239	
VLO $BB \rightarrow WZ, Z\gamma + X$	multi-channel	-	Yes	361	1605.06239
VLO $T \rightarrow \tau + X$	$2 < \mu_{UV} < 3 < 2j, 1 < 1-4j$	Yes	361	1605.06239	
VLO $T \rightarrow \mu + X$	$1 < \mu_{UV} < 1 < 1b, 3j/2j$	Yes	361	1605.06239	
VLO $V \rightarrow W\gamma$	$1 < \mu_{UV} < 1 < 1b, 3j/2j$	Yes	361	1605.06239	
VLO $B \rightarrow H\gamma$	$0 < \mu_{UV} < 2b, 2j, 2j/1j$	Yes	139	1605.06239	
Excluded quark $q \rightarrow q\gamma$	$1 < \mu_{UV} < 2j$	-	Yes	139	1910.20447
Excluded quark $q' \rightarrow q\gamma$	$1 < \mu_{UV} < 2j$	-	Yes	361	1709.10440
Excluded quark $q \rightarrow q\gamma$	$1 < \mu_{UV} < 1 < 1b, 3j/2j$	-	Yes	361	1605.06239
Excluded lepton $\ell \rightarrow \ell\gamma$	$3 < \mu_{UV} < \tau$	-	Yes	20.3	1411.2921
Excluded lepton $\ell' \rightarrow \ell\gamma$	$3 < \mu_{UV} < \tau$	-	Yes	20.3	1411.2921
Type III Seesaw	$2.3 < \mu_{UV} < 2j$	Yes	139	1605.06239	
LRSM Majorana	$2.3 < \mu_{UV} < 2j$	Yes	139	1605.06239	
Higgs triplet $H^{\pm\pm} \rightarrow W^+W^+$	$2.3 < \mu_{UV} < 2j$	Yes	139	1605.06239	
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2.3 < \mu_{UV} < 2j$	Yes	139	1605.06239	
Higgs triplet $H^{\pm\pm} \rightarrow \tau\tau$	$3 < \mu_{UV} < \tau$	-	Yes	20.3	1411.2921
Multi-charged particles	-	-	Yes	361	1605.06239
Magnetic monopoles	-	-	Yes	34.4	1905.10130



No direct discovery of New Physics so far

# Where is New Physics?



*The Higgs  
Discovery*



---

# The Higgs Discovery 4th July 2012

---

# The Higgs Discovery 4th July 2012



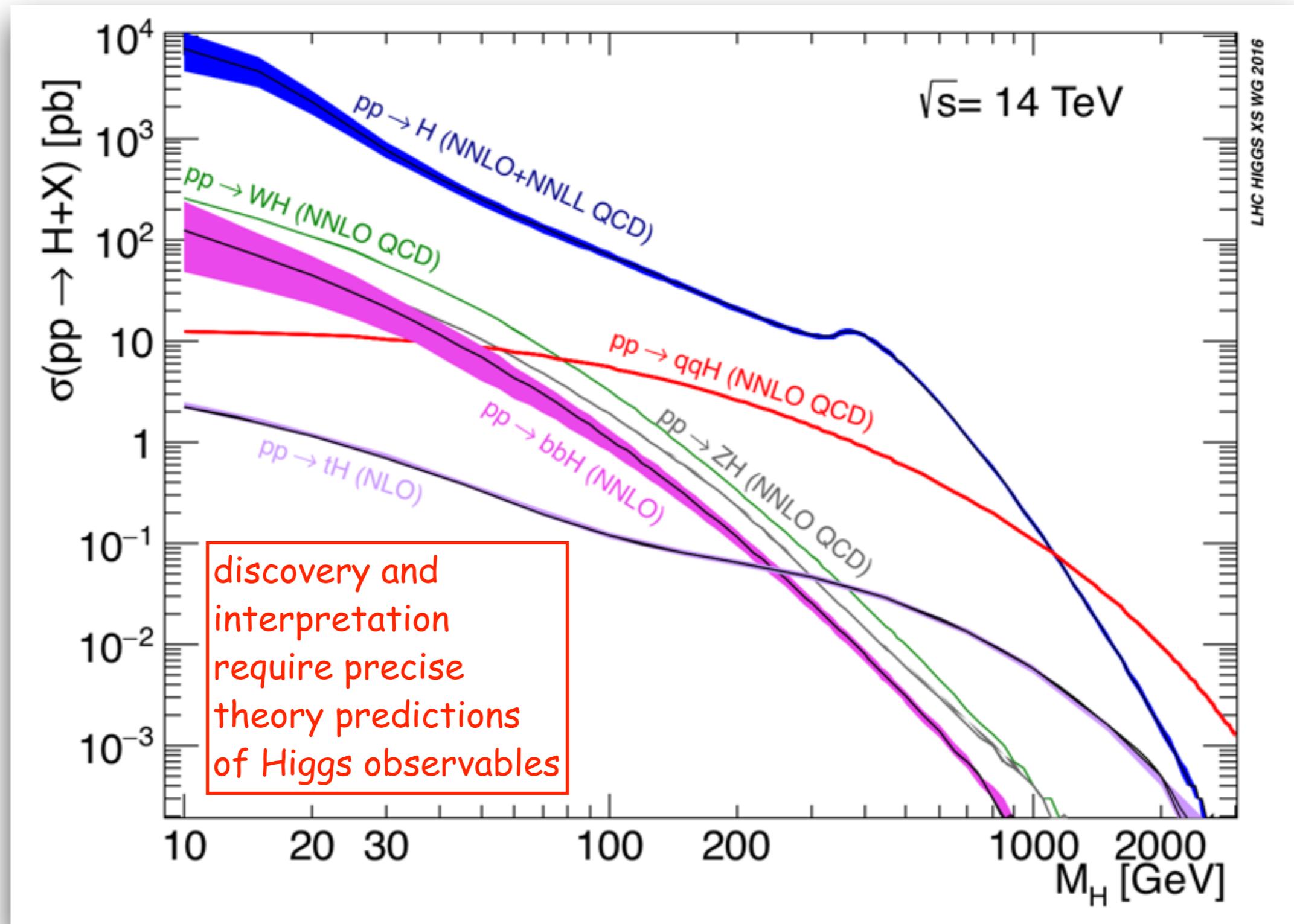
# The Higgs Discovery 4th July 2012



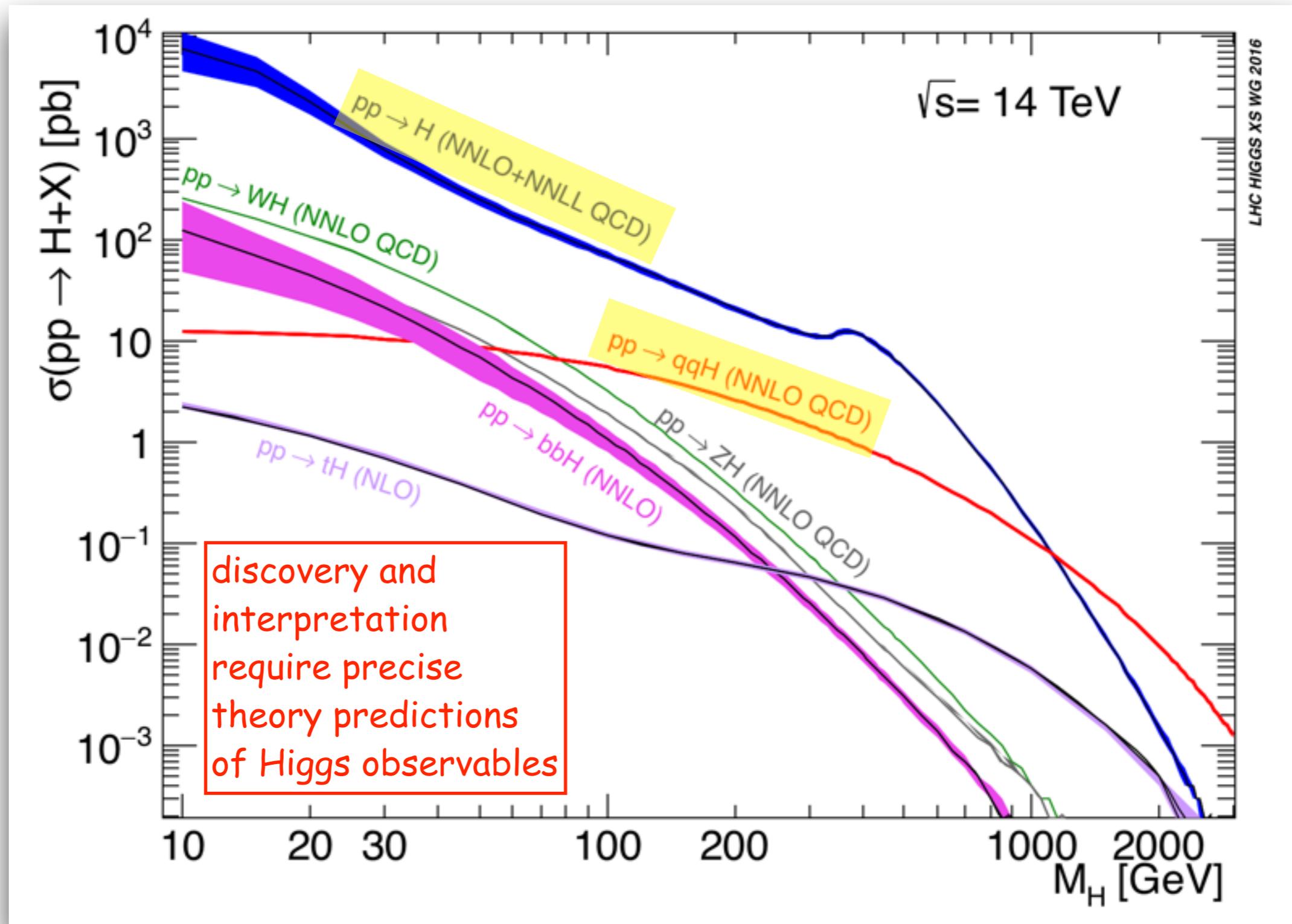
# The Higgs Discovery 4th July 2012



# LHC Higgs Production Cross Sections



# LHC Higgs Production Cross Sections



---

# Gluon Fusion in H at NLO QCD w/ full Top Mass Effects

---

## Higgs boson production at the LHC

#46

M. Spira (Hamburg U.), A. Djouadi (Montreal U. and DESY), D. Graudenz (CERN), P.M. Zerwas (DESY)  
(Feb, 1995)

Published in: *Nucl.Phys.B* 453 (1995) 17-82 • e-Print: [hep-ph/9504378](https://arxiv.org/abs/hep-ph/9504378) [hep-ph]



pdf



DOI



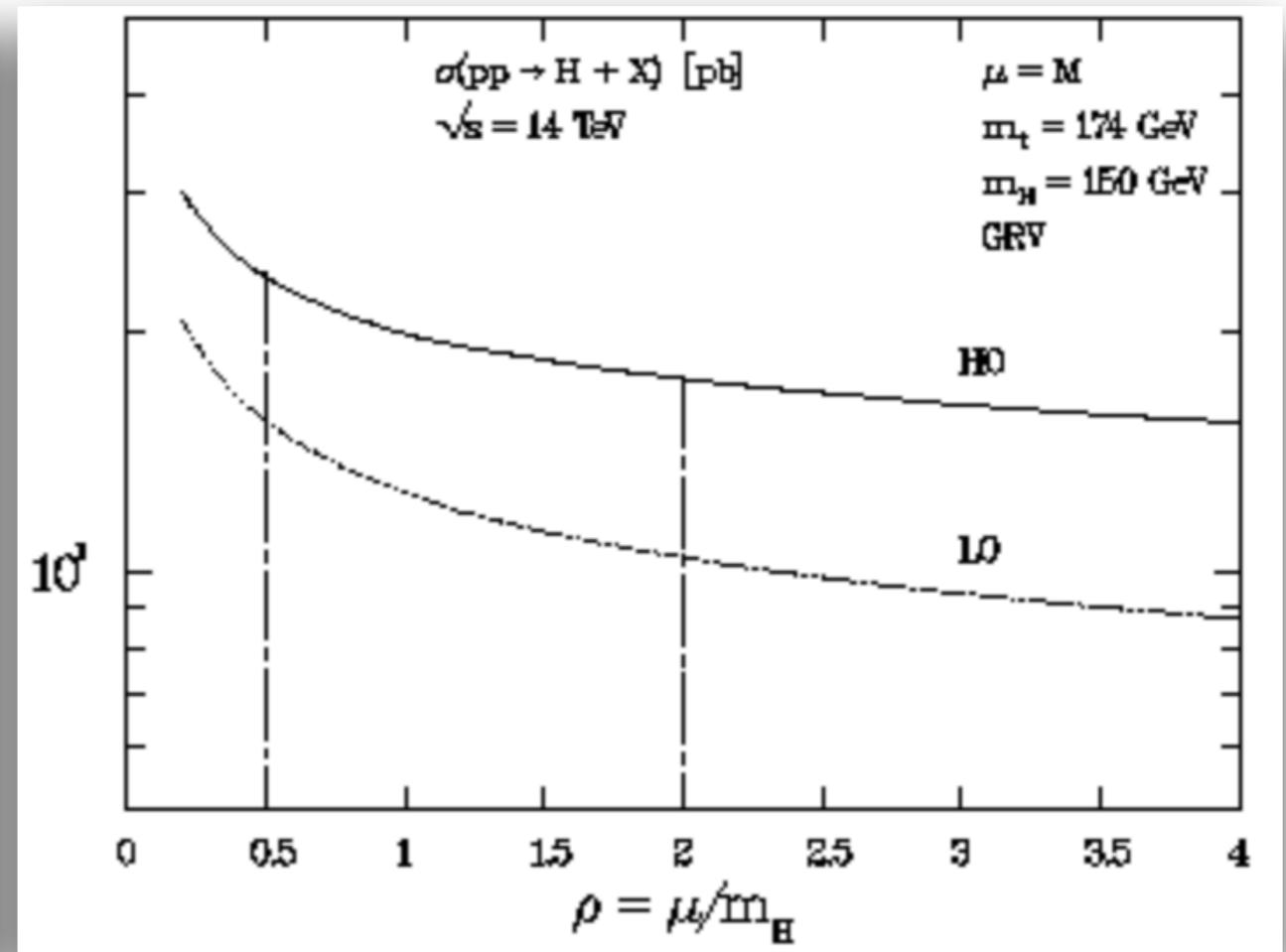
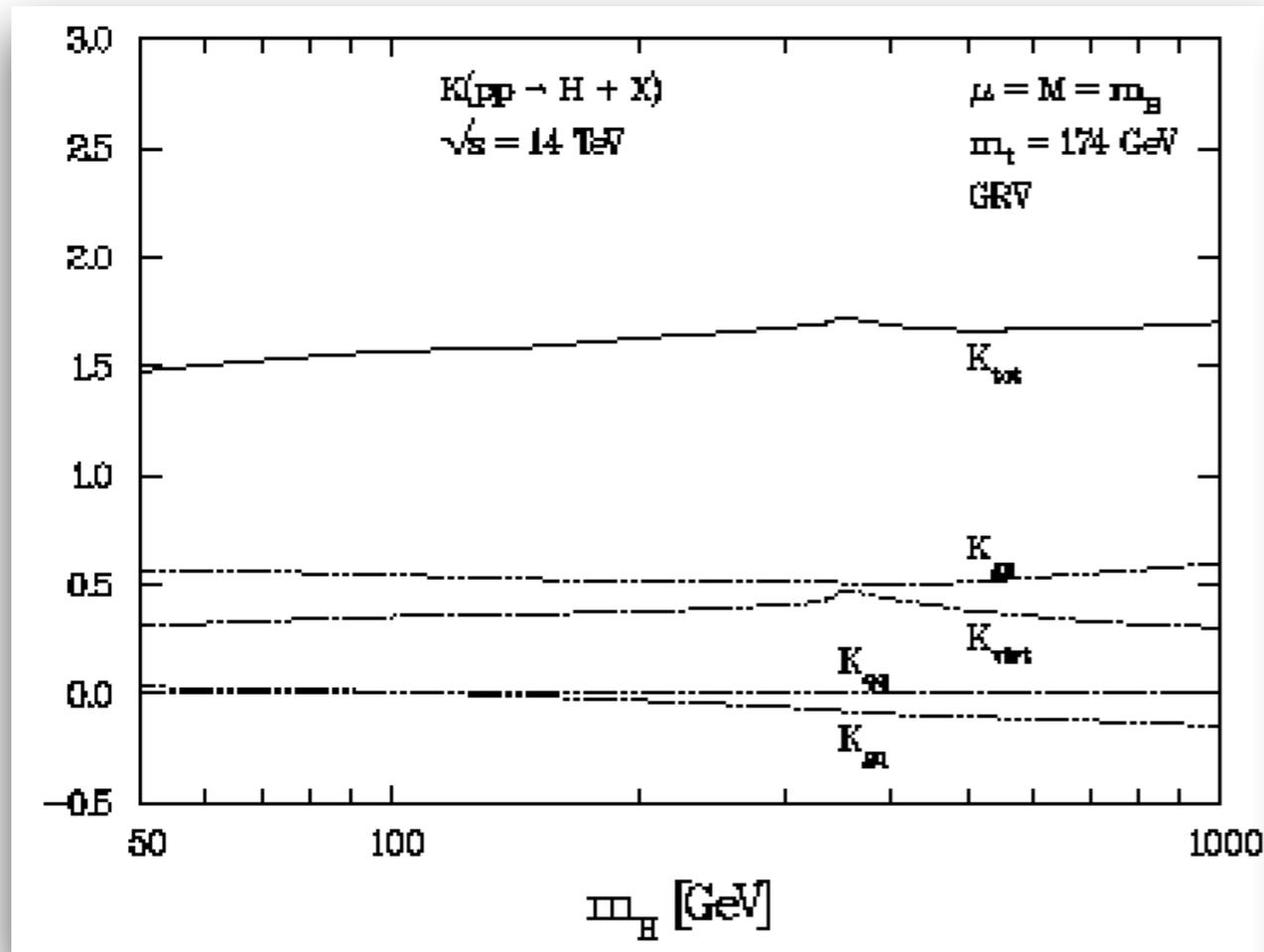
cite



1,516 citations

# Gluon Fusion in H at NLO QCD w/ full Top Mass Effects

[Spira,Djouadi,Graudenz,Zerwas,'95]



- ◆ NLO QCD corrections are significant
- ◆ renormalization scale dependence: reduction of theoretical uncertainty

---

# $t\bar{t}H+X$ Production at NLO QCD

---

## NLO QCD corrections to $t$ anti- $t$ $H$ production in hadron collisions

#1

[W. Beenakker](#) (Nijmegen U., IMAPP), [S. Dittmaier](#) (DESY and Munich, Max Planck Inst.), [M. Kramer](#) (Edinburgh U.), [B. Plumper](#) (DESY), [M. Spira](#) (PSI, Villigen) et al. (Nov, 2002)

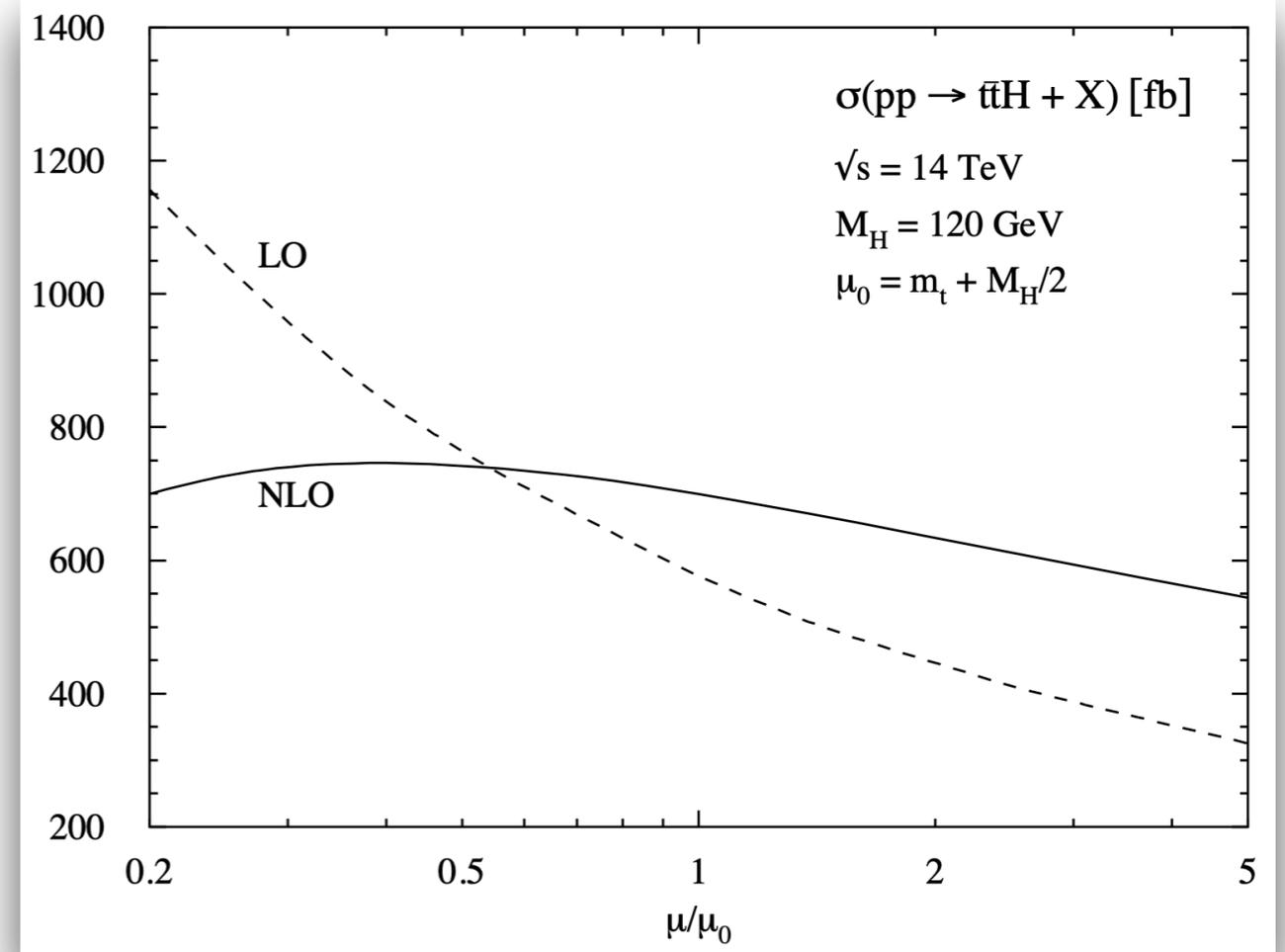
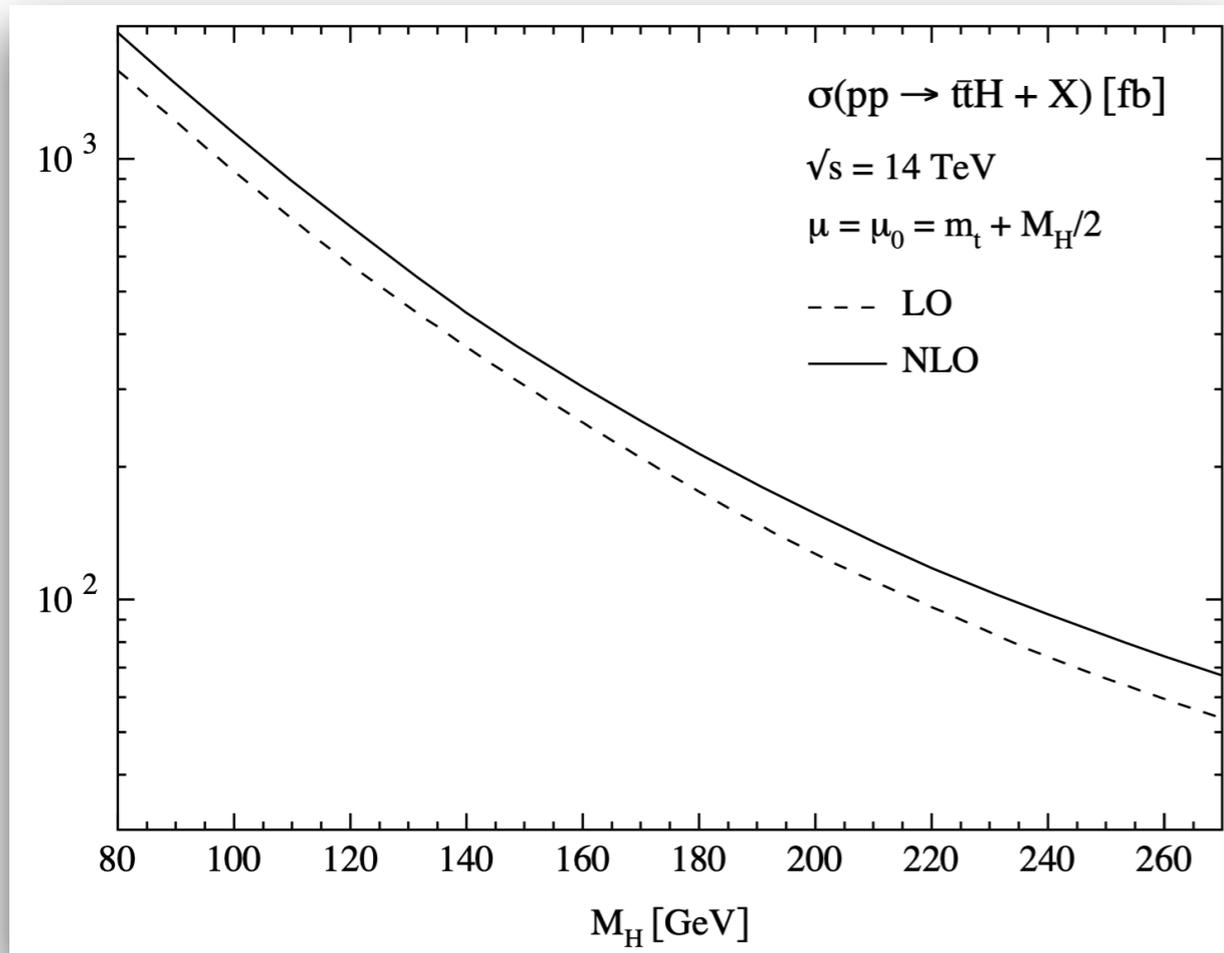
Published in: *Nucl.Phys.B* 653 (2003) 151-203 • e-Print: [hep-ph/0211352](#) [hep-ph]

 pdf    DOI    cite

 598 citations

# $t\bar{t}H+X$ Production at NLO QCD

[Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas, '02]



- ◆ NLO QCD corrections increase cross section @LHC by 20%
- ◆ renormalization scale dependence: reduction of theoretical uncertainty

---

## Where we are

---

- ✦ **Experimental reality:** No Beyond the Standard Model Physics discovered so far!

# Where we are - Example SUSY Search Limits

CMS (preliminary)

Moriond 2021

## Overview of SUSY results: squark pair production

137 fb<sup>-1</sup> (13 TeV)

### pp → $\tilde{t}\tilde{t}$

$\tilde{t} \rightarrow t\tilde{\chi}_1^0$

Combination: SUS-20-002

0 $\ell$ : arXiv:1909.03460;1908.04722,2103.01290

1 $\ell$ : arXiv:1912.08887

2 $\ell$  opposite-sign: arXiv:2008.05936

$\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^\pm\tilde{\chi}_1^0$

Combination: SUS-20-002

$x = 0.5$

0 $\ell$ : arXiv:1909.03460;2103.01290

$x = 0.5$

1 $\ell$ : arXiv:1912.08887

$x = 0.5$

2 $\ell$  opposite-sign: arXiv:2008.05936

$x = 0.5$

$\tilde{t} \rightarrow (t\tilde{\chi}_1^0/b\tilde{\chi}_1^\pm \rightarrow bW\tilde{\chi}_1^0)$

Combination: SUS-20-002

$\Delta M_{\tilde{\chi}_1^\pm} = 5$  GeV, BF=50%

0 $\ell$ : arXiv:1909.03460;2103.01290

$\Delta M_{\tilde{\chi}_1^\pm} = 5$  GeV, BF=50%

1 $\ell$ : arXiv:1912.08887

$\tilde{t} \rightarrow b\tilde{f}'\tilde{\chi}_1^0$

0 $\ell$ : arXiv:1909.03460;2103.01290

$\Delta M < 80$  GeV (max. exclusion)

$\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow b\tilde{f}'\tilde{\chi}_1^0$

0 $\ell$ : arXiv:1909.03460;2103.01290

$\Delta M < 80$  GeV (max. exclusion),  $x = 0.5$

$\tilde{t} \rightarrow c\tilde{\chi}_1^0$

0 $\ell$ : arXiv:2103.01290

$\Delta M < 80$  GeV (max. exclusion)

$\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow b\nu\tilde{l} \rightarrow b\nu\ell\tilde{\chi}_1^0$

2 $\ell$ : arXiv:2008.05936

$x = 0.5$

### pp → $\tilde{b}\tilde{b}$

$\tilde{b} \rightarrow b\tilde{\chi}_1^0$

0 $\ell$ : arXiv:1909.03460;1908.04722

$\tilde{b} \rightarrow t\tilde{\chi}_1^\pm \rightarrow tW^\pm\tilde{\chi}_1^0$

2 $\ell$  same-sign and  $\geq 3\ell$ : arXiv:2001.10086

$M_{\tilde{\chi}_1^0} = 50$  GeV

### pp → $\tilde{q}\tilde{q}$

$\tilde{q} \rightarrow q\tilde{\chi}_1^0$

0 $\ell$ : arXiv:1909.03460;1908.04722

$\tilde{q}_R + \tilde{q}_L (\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s})$

0 $\ell$ : arXiv:1909.03460;1908.04722

one light squark ( $\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}$ )

mass scale [GeV]

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless stated otherwise. The quantities  $\Delta M$  and  $x$  represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to  $\Delta M$ , respectively, unless indicated otherwise.

# Where we are - Example SUSY Search Limits

CMS (preliminary)

Moriond 2021

## Overview of SUSY results: squark pair production

137 fb<sup>-1</sup> (13 TeV)

### pp → t $\bar{t}$

t $\bar{t}$  → t $\bar{t}$ χ<sub>1<sup>0</sup></sub>

Combination: SUS-20-002

0ℓ: arXiv:1909.03460;1908.04722,2103.01290

1ℓ: arXiv:1912.08887

2ℓ opposite-sign: arXiv:2008.05936

t $\bar{t}$  → bχ<sub>1<sup>±</sup> → bW<sup>±</sup>χ<sub>1<sup>0</sup></sub></sub>

Combination: SUS-20-002

0ℓ: arXiv:1909.03460;2103.01290

1ℓ: arXiv:1912.08887

2ℓ opposite-sign: arXiv:2008.05936

t $\bar{t}$  → (tχ<sub>1<sup>0</sup>/bχ<sub>1<sup>±</sup> → bWχ<sub>1<sup>0</sup>)</sub></sub></sub>

Combination: SUS-20-002

0ℓ: arXiv:1909.03460;2103.01290

1ℓ: arXiv:1912.08887

t $\bar{t}$  → bff $\bar{f}$ χ<sub>1<sup>0</sup></sub>

0ℓ: arXiv:1909.03460;2103.01290

t $\bar{t}$  → bχ<sub>1<sup>±</sup> → bff $\bar{f}$ χ<sub>1<sup>0</sup></sub></sub>

0ℓ: arXiv:1909.03460;2103.01290

t $\bar{t}$  → cχ<sub>1<sup>0</sup></sub>

0ℓ: arXiv:2103.01290

t $\bar{t}$  → bχ<sub>1<sup>±</sup> → bνℓ → bνℓχ<sub>1<sup>0</sup></sub></sub>

2ℓ: arXiv:2008.05936

### pp → b $\bar{b}$

b $\bar{b}$  → bχ<sub>1<sup>0</sup></sub>

0ℓ: arXiv:1909.03460;1908.04722

b $\bar{b}$  → tχ<sub>1<sup>±</sup> → tW<sup>±</sup>χ<sub>1<sup>0</sup></sub></sub>

2ℓ same-sign and ≥ 3ℓ: arXiv:2001.10086

### pp → q $\bar{q}$

q $\bar{q}$  → qχ<sub>1<sup>0</sup></sub>

0ℓ: arXiv:1909.03460;1908.04722

0ℓ: arXiv:1909.03460;1908.04722

## ATLAS SUSY Searches\* - 95% CL Lower Limits

March 2022

ATLAS Preliminary

√s = 13 TeV

Model	Signature	∫L dt [fb <sup>-1</sup> ]	Mass limit	Reference								
Inclusive Searches	q $\bar{q}$ , q → qχ <sub>1<sup>0</sup></sub>	0 e, μ mono-jet	2-6 jets 1-3 jets	E <sub>T</sub> <sup>miss</sup> E <sub>T</sub> <sup>miss</sup>	139 139	q $\bar{q}$ [1x, 8x Degen.] q [8x Degen.]	1.0 0.9	1.85	m(χ <sub>1<sup>0</sup>) &lt; 400 GeV m(q<math>\bar{q}</math>)-m(χ<sub>1<sup>0</sup>) = 5 GeV</sub></sub>	2101.14293 2102.10874		
	g $\bar{g}$ , g → gχ <sub>1<sup>0</sup></sub>	0 e, μ	2-6 jets	E <sub>T</sub> <sup>miss</sup>	139	g	Forbidden	2.3	m(χ <sub>1<sup>0</sup>) = 0 GeV m(χ<sub>1<sup>0</sup>) = 1000 GeV</sub></sub>	2101.14293 2101.14293		
	g $\bar{g}$ , g → q $\bar{q}$ Wχ <sub>1<sup>0</sup></sub>	1 e, μ	2-6 jets	E <sub>T</sub> <sup>miss</sup>	139	g	Forbidden	2.2	m(χ <sub>1<sup>0</sup>) = 600 GeV</sub>	2101.01629		
	g $\bar{g}$ , g → q $\bar{q}$ (ℓℓ)χ <sub>1<sup>0</sup></sub>	ee, μμ	2 jets	E <sub>T</sub> <sup>miss</sup>	139	g	Forbidden	2.2	m(χ <sub>1<sup>0</sup>) &lt; 700 GeV</sub>	CERN-EP-2022-014		
	g $\bar{g}$ , g → qqWZχ <sub>1<sup>0</sup></sub>	0 e, μ	7-11 jets	E <sub>T</sub> <sup>miss</sup>	139	g	Forbidden	1.97	m(χ <sub>1<sup>0</sup>) &lt; 600 GeV</sub>	2008.06032		
	g $\bar{g}$ , g → qqWZχ <sub>1<sup>0</sup></sub>	SS e, μ	6 jets	E <sub>T</sub> <sup>miss</sup>	139	g	Forbidden	1.15	m(g $\bar{g}$ )-m(χ <sub>1<sup>0</sup>) = 200 GeV</sub>	1909.08457		
	g $\bar{g}$ , g → t $\bar{t}$ χ <sub>1<sup>0</sup></sub>	0-1 e, μ SS e, μ	3 b 6 jets	E <sub>T</sub> <sup>miss</sup>	79.8 139	g	Forbidden	2.25	m(χ <sub>1<sup>0</sup>) &lt; 200 GeV m(g<math>\bar{g}</math>)-m(χ<sub>1<sup>0</sup>) = 300 GeV</sub></sub>	ATLAS-CONF-2018-041 1909.08457		
	g $\bar{g}$ , g → t $\bar{t}$ χ <sub>1<sup>0</sup></sub>	0 e, μ	2 b	E <sub>T</sub> <sup>miss</sup>	139	b $\bar{b}$	Forbidden	1.255	m(χ <sub>1<sup>0</sup>) &lt; 400 GeV 10 GeV &lt; Δm(b<math>\bar{b}</math>, χ<sub>1<sup>0</sup>) &lt; 20 GeV</sub></sub>	2101.12527 2101.12527		
	b $\bar{b}$ , b $\bar{b}$ → bχ <sub>1<sup>0</sup></sub>	0 e, μ 2 τ	6 b 2 b	E <sub>T</sub> <sup>miss</sup> E <sub>T</sub> <sup>miss</sup>	139 139	b $\bar{b}$ b $\bar{b}$	Forbidden	0.68	0.23-1.35	Δm(χ <sub>1<sup>0</sup>, χ<sub>1<sup>±</sup>) = 130 GeV, m(χ<sub>1<sup>0</sup>) = 100 GeV Δm(χ<sub>1<sup>0</sup>, χ<sub>1<sup>±</sup>) = 130 GeV, m(χ<sub>1<sup>0</sup>) = 0 GeV</sub></sub></sub></sub></sub></sub>	1908.03122 2103.08189	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup></sub>	0-1 e, μ	≥ 1 jet	E <sub>T</sub> <sup>miss</sup>	139	τ $\bar{τ}$	Forbidden	0.65	1.25	m(χ <sub>1<sup>0</sup>) = 1 GeV</sub>	2004.14060, 2012.03799	
3 <sup>rd</sup> gen. squarks direct production	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup></sub>	1 e, μ	3 jets/1 b	E <sub>T</sub> <sup>miss</sup>	139	τ $\bar{τ}$	Forbidden	0.65	1.25	m(χ <sub>1<sup>0</sup>) = 500 GeV</sub>	2012.03799	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup></sub>	1-2 τ	2 jets/1 b	E <sub>T</sub> <sup>miss</sup>	139	τ $\bar{τ}$	Forbidden	1.4		m(τ $\bar{τ}$ ) = 0 GeV	2108.07665	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup></sub>	0 e, μ	2 c	E <sub>T</sub> <sup>miss</sup>	36.1	c $\bar{c}$	Forbidden	0.85		m(χ <sub>1<sup>0</sup>) = 0 GeV</sub>	1805.01649	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup></sub>	0 e, μ	mono-jet	E <sub>T</sub> <sup>miss</sup>	139	τ $\bar{τ}$	Forbidden	0.55	0.85	m(τ $\bar{τ}$ )-m(χ <sub>1<sup>0</sup>) = 5 GeV</sub>	2102.10874	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup></sub>	1-2 e, μ	1-4 b	E <sub>T</sub> <sup>miss</sup>	139	τ $\bar{τ}$	Forbidden	0.067-1.18		m(χ <sub>1<sup>0</sup>) = 500 GeV</sub>	2006.05880	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup></sub>	3 e, μ	1 b	E <sub>T</sub> <sup>miss</sup>	139	τ $\bar{τ}$	Forbidden	0.86		m(χ <sub>1<sup>0</sup>) = 360 GeV, m(τ<math>\bar{τ}</math>)-m(χ<sub>1<sup>0</sup>) = 40 GeV</sub></sub>	2006.05880	
	χ <sub>1<sup>±</sup>χ<sub>2<sup>0</sup> via WZ</sub></sub>	Multiple ℓ/jets ee, μμ	≥ 1 jet	E <sub>T</sub> <sup>miss</sup> E <sub>T</sub> <sup>miss</sup>	139 139	χ <sub>1<sup>±</sup>χ<sub>2<sup>0</sup> χ<sub>1<sup>±</sup>χ<sub>2<sup>0</sup></sub></sub></sub></sub>	0.205	0.96	m(χ <sub>1<sup>0</sup>) = 0, wino-bino m(χ<sub>1<sup>±</sup>)-m(χ<sub>1<sup>0</sup>) = 5 GeV, wino-bino</sub></sub></sub>	2106.01676, 2108.07586 1911.12606		
	χ <sub>1<sup>±</sup>χ<sub>1<sup>±</sup> via WW</sub></sub>	2 e, μ		E <sub>T</sub> <sup>miss</sup>	139	χ <sub>1<sup>±</sup>χ<sub>1<sup>±</sup></sub></sub>	0.42		m(χ <sub>1<sup>0</sup>) = 0, wino-bino</sub>	1908.08215		
	χ <sub>1<sup>±</sup>χ<sub>2<sup>0</sup> via Wh</sub></sub>	Multiple ℓ/jets		E <sub>T</sub> <sup>miss</sup>	139	χ <sub>1<sup>±</sup>χ<sub>2<sup>0</sup></sub></sub>	Forbidden	1.06		m(χ <sub>1<sup>0</sup>) = 70 GeV, wino-bino</sub>	2004.10894, 2108.07586	
	χ <sub>1<sup>±</sup>χ<sub>1<sup>±</sup> via ℓ<sub>L</sub>/ν</sub></sub>	2 e, μ		E <sub>T</sub> <sup>miss</sup>	139	χ <sub>1<sup>±</sup>χ<sub>1<sup>±</sup></sub></sub>	Forbidden	1.0		m(ℓ, ν) = 0.5(m(χ <sub>1<sup>±</sup>) + m(χ<sub>1<sup>0</sup>))</sub></sub>	1908.08215	
EW direct	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup></sub>	2 τ		E <sub>T</sub> <sup>miss</sup>	139	τ $\bar{τ}$	[τ <sub>L</sub> , τ <sub>R</sub> , L]	0.16-0.3	0.12-0.39	m(χ <sub>1<sup>0</sup>) = 0</sub>	1911.06660	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup></sub>	2 e, μ	0 jets	E <sub>T</sub> <sup>miss</sup>	139	τ $\bar{τ}$		0.7		m(χ <sub>1<sup>0</sup>) = 0</sub>	1908.08215	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup></sub>	ee, μμ	≥ 1 jet	E <sub>T</sub> <sup>miss</sup>	139	τ $\bar{τ}$		0.256		m(τ $\bar{τ}$ )-m(χ <sub>1<sup>0</sup>) = 10 GeV</sub>	1911.12606	
	H $\bar{H}$ , H → Hχ <sub>1<sup>0</sup>/ZG</sub>	0 e, μ	≥ 3 b	E <sub>T</sub> <sup>miss</sup>	36.1	H $\bar{H}$		0.13-0.23	0.29-0.88	BR(H <sub>1</sub> <sup>0</sup> → Hχ <sub>1<sup>0</sup>) = 1 BR(H<sub>2</sub><sup>0</sup> → ZG) = 1 BR(H<sub>1</sub><sup>±</sup> → ZG) = 1</sub>	1806.04030 2103.11684 2108.07586	
	H $\bar{H}$ , H → Hχ <sub>1<sup>0</sup>/ZG</sub>	4 e, μ	0 jets	E <sub>T</sub> <sup>miss</sup>	139	H $\bar{H}$		0.55	0.45-0.93			
	H $\bar{H}$ , H → Hχ <sub>1<sup>0</sup>/ZG</sub>	0 e, μ	≥ 2 large jets	E <sub>T</sub> <sup>miss</sup>	139	H $\bar{H}$						
	Long-lived particles	Direct χ <sub>1<sup>±</sup>χ<sub>1<sup>±</sup> prod., long-lived χ<sub>1<sup>±</sup></sub></sub></sub>	Disapp. trk	1 jet	E <sub>T</sub> <sup>miss</sup>	139	χ <sub>1<sup>±</sup>χ<sub>1<sup>±</sup></sub></sub>	0.21	0.66	Pure Wino Pure higgsino	2201.02472 2201.02472	
		Stable g R-hadron	pixel dE/dx		E <sub>T</sub> <sup>miss</sup>	139	g		2.05			CERN-EP-2022-029
		Metastable g R-hadron, g → qqχ <sub>1<sup>0</sup></sub>	pixel dE/dx		E <sub>T</sub> <sup>miss</sup>	139	g	[τ(g) = 10 ns]	2.2		m(χ <sub>1<sup>0</sup>) = 100 GeV</sub>	CERN-EP-2022-029
		ℓℓ, ℓ → ℓG	Displ. lep		E <sub>T</sub> <sup>miss</sup>	139	ℓ $\bar{ℓ}$ , μ $\bar{μ}$		0.7		τ(ℓ) = 0.1 ns τ(ℓ) = 0.1 ns	2011.07812 2011.07812
ℓℓ, ℓ → ℓG		pixel dE/dx		E <sub>T</sub> <sup>miss</sup>	139	ℓ $\bar{ℓ}$		0.34	0.36	τ(ℓ) = 10 ns	CERN-EP-2022-029	
RPV	χ <sub>1<sup>±</sup>χ<sub>1<sup>±</sup>/χ<sub>1<sup>0</sup>χ<sub>1<sup>0</sup>, χ<sub>1<sup>±</sup> → Zℓ → ℓℓℓ</sub></sub></sub></sub></sub>	3 e, μ		E <sub>T</sub> <sup>miss</sup>	139	χ <sub>1<sup>±</sup>χ<sub>1<sup>±</sup>/χ<sub>1<sup>0</sup>χ<sub>1<sup>0</sup></sub></sub></sub></sub>	[BR(Zτ)=1, BR(Ze)=1]	0.625	1.05	Pure Wino	2011.10543	
	χ <sub>1<sup>±</sup>χ<sub>1<sup>±</sup>/χ<sub>1<sup>0</sup>χ<sub>1<sup>0</sup> → WW/Zℓℓνν</sub></sub></sub></sub>	4 e, μ	0 jets	E <sub>T</sub> <sup>miss</sup>	139	χ <sub>1<sup>±</sup>χ<sub>1<sup>±</sup>/χ<sub>1<sup>0</sup>χ<sub>1<sup>0</sup></sub></sub></sub></sub>	[A <sub>133</sub> ≠ 0, A <sub>124</sub> ≠ 0]	0.95	1.55	m(χ <sub>1<sup>0</sup>) = 200 GeV</sub>	2103.11684	
	g $\bar{g}$ , g → qqχ <sub>1<sup>0</sup>, χ<sub>1<sup>0</sup> → qq</sub></sub>	4-5 large jets		E <sub>T</sub> <sup>miss</sup>	36.1	g	[m(χ <sub>1<sup>0</sup>) = 200 GeV, 1100 GeV]</sub>	1.3	1.9	Large A <sub>1<sub>12</sub></sub>	1804.03568	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup>, χ<sub>1<sup>0</sup> → tbs</sub></sub>	Multiple		E <sub>T</sub> <sup>miss</sup>	36.1	τ $\bar{τ}$	[A <sub>1<sub>22</sub></sub> = 2e-4, 1e-2]	0.55	1.05	m(χ <sub>1<sup>0</sup>) = 200 GeV, bino-like</sub>	ATLAS-CONF-2018-003	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup>, χ<sub>1<sup>0</sup> → tbs</sub></sub>	≥ 4 b		E <sub>T</sub> <sup>miss</sup>	139	τ $\bar{τ}$	Forbidden	0.95		m(χ <sub>1<sup>0</sup>) = 500 GeV</sub>	2010.01015	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup>, χ<sub>1<sup>0</sup> → tbs</sub></sub>	2 jets + 2 b		E <sub>T</sub> <sup>miss</sup>	36.7	τ $\bar{τ}$	[qq, bs]	0.42	0.61		1710.07171	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup>, χ<sub>1<sup>0</sup> → tbs</sub></sub>	2 e, μ	2 b	E <sub>T</sub> <sup>miss</sup>	36.1	τ $\bar{τ}$			0.4-1.45	BR(τ $\bar{τ}$ → b $\bar{b}$ /bμ) > 20%	1710.05544	
	τ $\bar{τ}$ , τ → τχ <sub>1<sup>0</sup>, χ<sub>1<sup>0</sup> → tbs</sub></sub>	1 μ	DV	E <sub>T</sub> <sup>miss</sup>	136	τ $\bar{τ}$	[1e-10 < A <sub>1<sub>22</sub></sub> < 1e-8, 3e-10 < A <sub>1<sub>23</sub></sub> < 3e-9]	1.0	1.6	BR(τ $\bar{τ}$ → qμ) = 100%, cosθ = 1	2003.11956	
	χ <sub>1<sup>±</sup>χ<sub>2<sup>0</sup>/χ<sub>1<sup>±</sup>χ<sub>1<sup>±</sup>, χ<sub>1<sup>0</sup>χ<sub>1<sup>0</sup> → tbs, χ<sub>1<sup>±</sup> → bbs</sub></sub></sub></sub></sub></sub></sub>	1-2 e, μ	≥ 6 jets	E <sub>T</sub> <sup>miss</sup>	139	χ <sub>1<sup>±</sup>χ<sub>2<sup>0</sup> χ<sub>1<sup>±</sup>χ<sub>1<sup>±</sup></sub></sub></sub></sub>		0.2-0.32		Pure higgsino	2106.09609	

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10<sup>-1</sup> 1 Mass scale [TeV]

# Let's talk about Supersymmetry

## ♦ Motivation:

- \* **maximal possible symmetry** compatible with Poincaré group (space-time symmetry)
- \* **solves some of the open problems** of the SM:
  - candidate for Dark Matter
  - inclusion of gravity
  - unification of fundamental forces



*Two SUSY-Gurus*

# Supersymmetry

## ♦ Motivation:

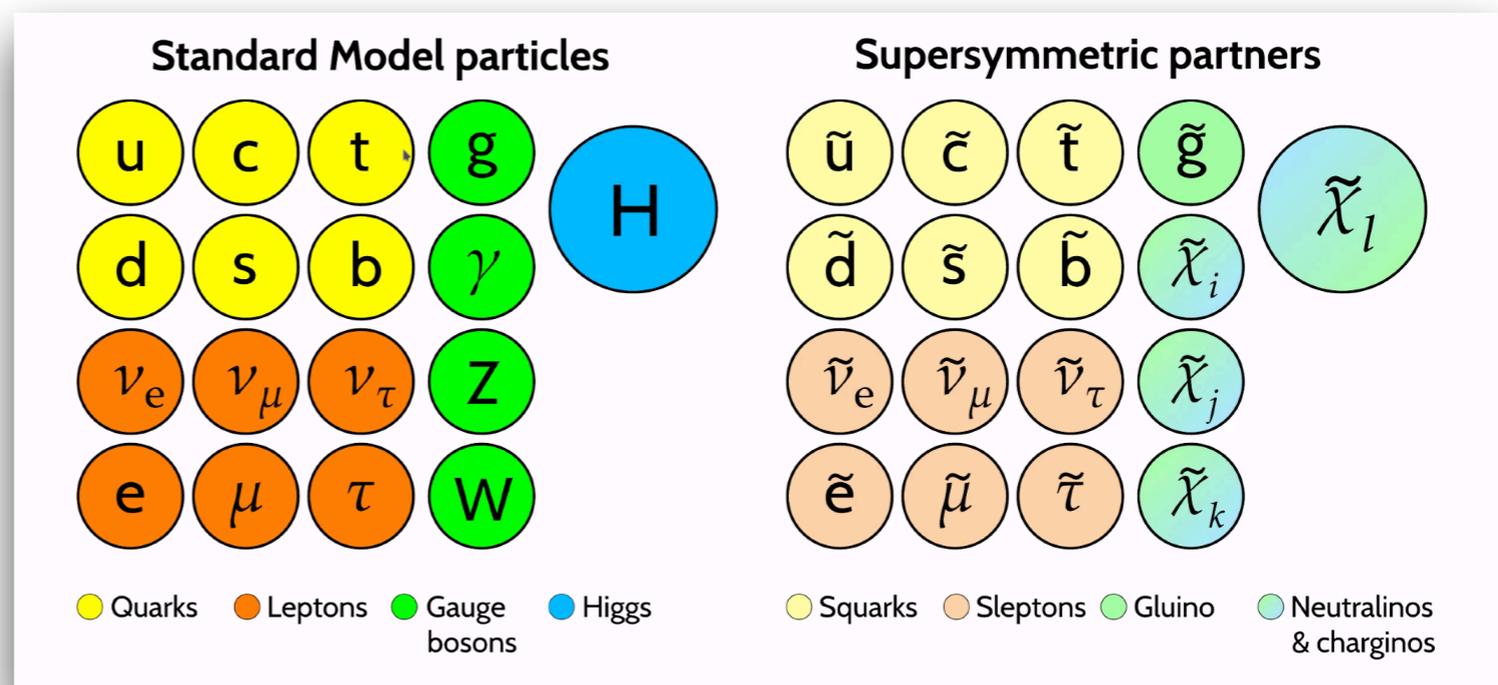
- \* **maximal possible symmetry** compatible with Poincaré group (space-time symmetry)
- \* **solves some of the open problems** of the SM:
  - candidate for Dark Matter
  - inclusion of gravity
  - unification of fundamental forces

## ♦ Implications:

- \* **enlarged particle spectrum:** each SM particle has supersymmetric partner particle
- \* **enlarged Higgs sector**



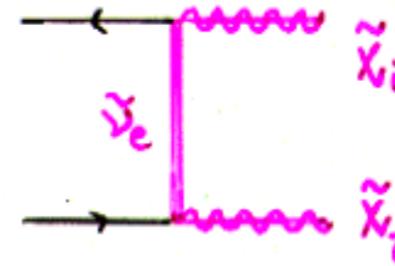
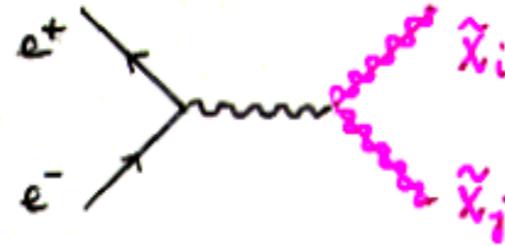
Two SUSY-Gurus



# Discovery Requires Precise Theory Predictions

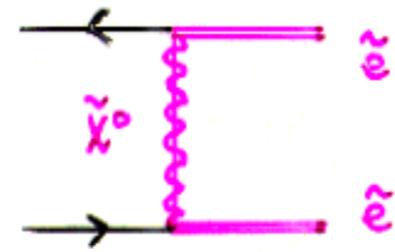
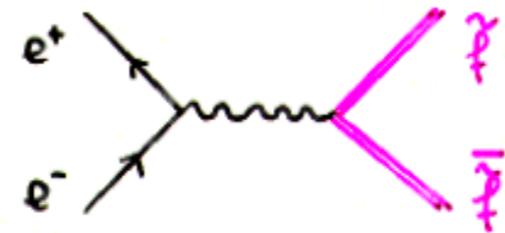
## Production :

- Charginos / neutralinos



$$\sigma \sim \beta$$

- Sleptons / squarks



$$\sigma \sim \beta^3$$

$$1/\beta$$

Markus

# Discovery Requires Precise Theory Predictions

## The Production of charginos / neutralinos and sleptons at hadron colliders

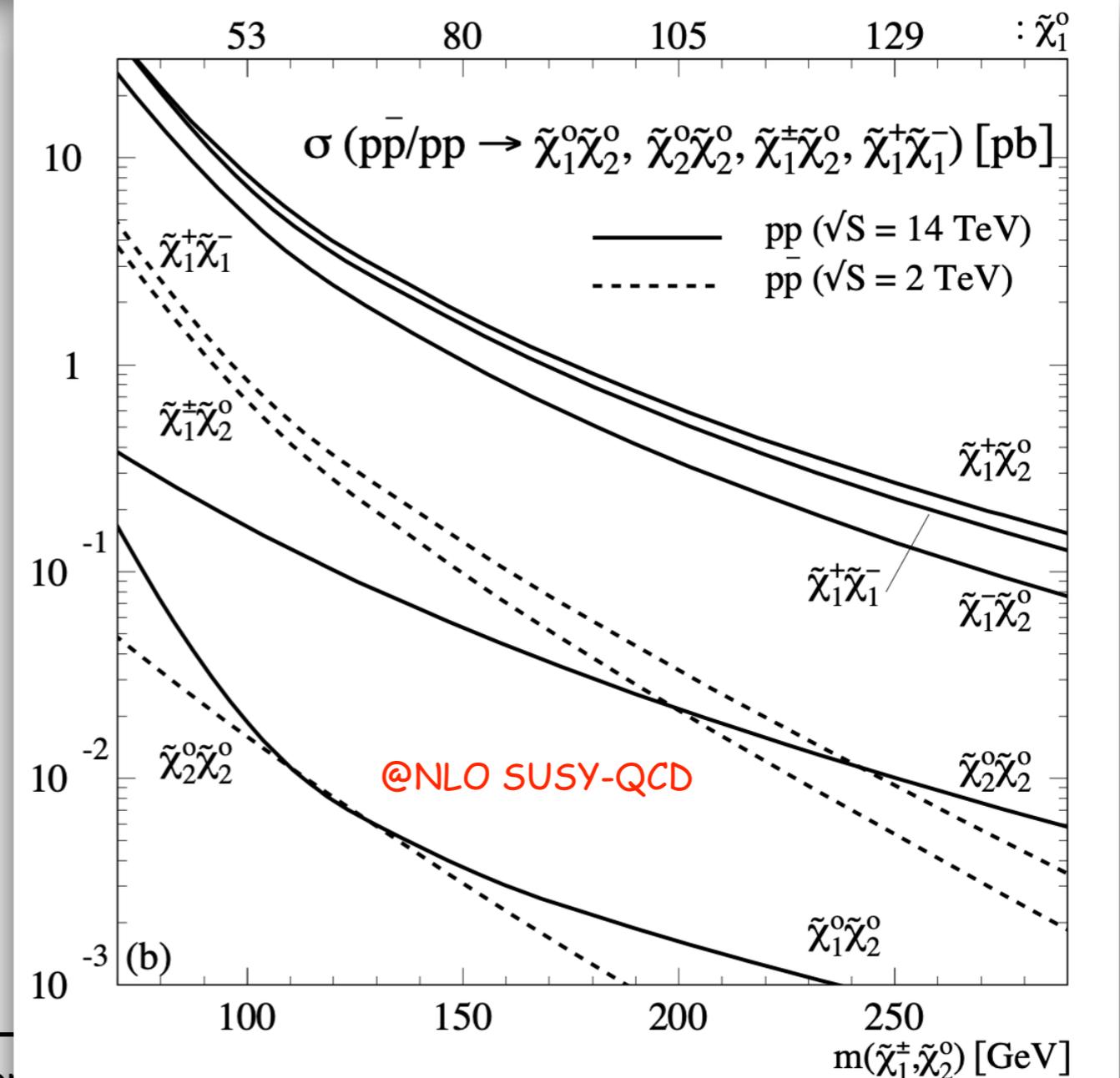
#8

W. Beenakker (Durham U.), M. Klasen (Argonne), M. Kramer (CERN), T. Plehn (Wisconsin U., Madison), M. Spira (Hamburg U.) et al. (Jun, 1999)

Published in: *Phys.Rev.Lett.* 83 (1999) 3780-3783, *Phys.Rev.Lett.* 100 (2008) 029901 (erratum) • e-Print: [hep-ph/9906298](https://arxiv.org/abs/hep-ph/9906298) [hep-ph]

pdf DOI cite

546 citations



# Discovery Requires Precise Theory Predictions

## Stop production at hadron colliders

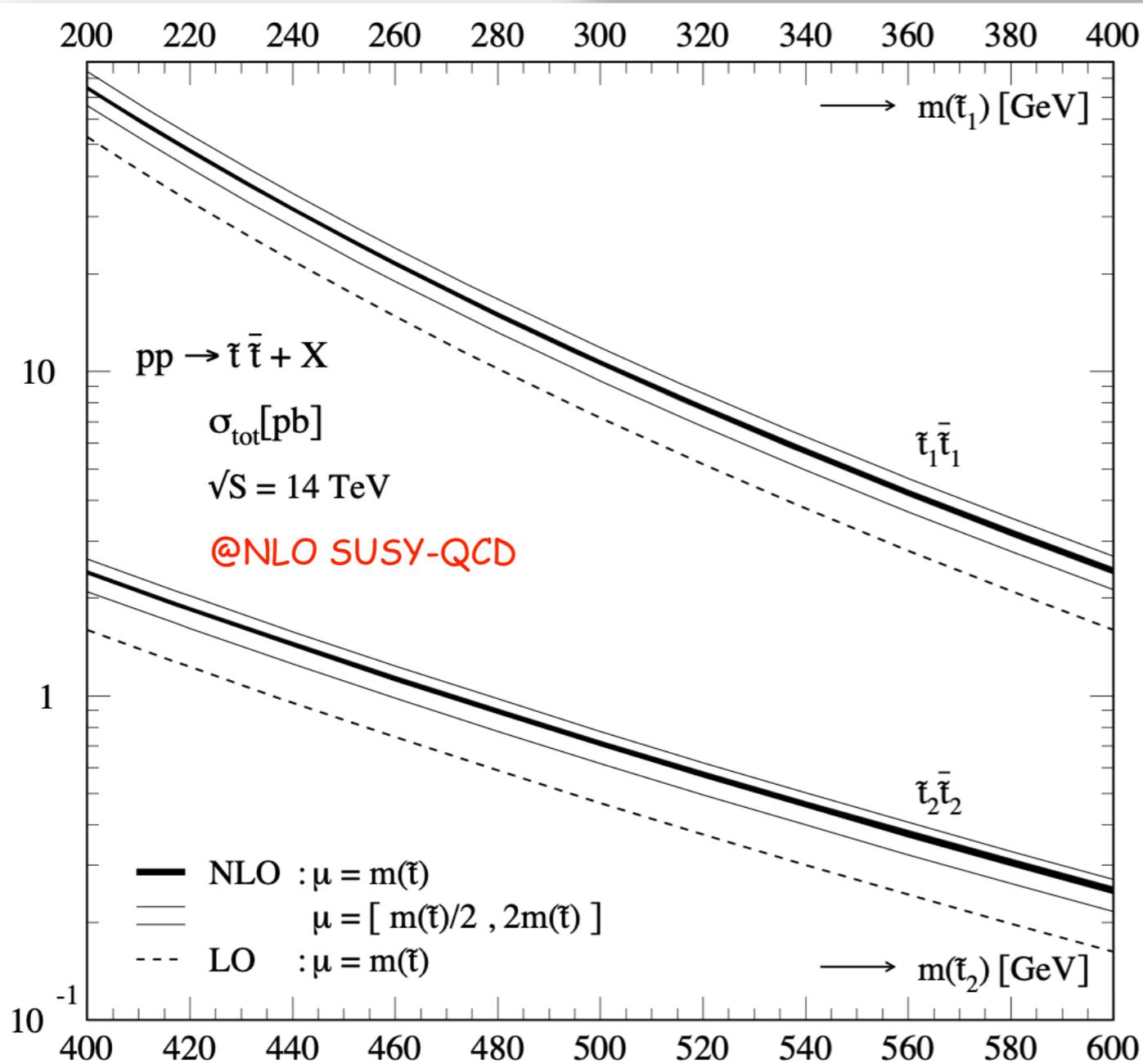
#13

W. Beenakker (Leiden U.), M. Kramer (Rutherford), T. Plehn (DESY), M. Spira (CERN), P.M. Zerwas (DESY) (Oct, 1997)

Published in: *Nucl.Phys.B* 515 (1998) 3-14 • e-Print: [hep-ph/9710451](https://arxiv.org/abs/hep-ph/9710451) [hep-ph]

[pdf](#) [DOI](#) [cite](#)

646 citations



# Discovery Requires Precise Theory Predictions

## Squark and gluino production at hadron colliders

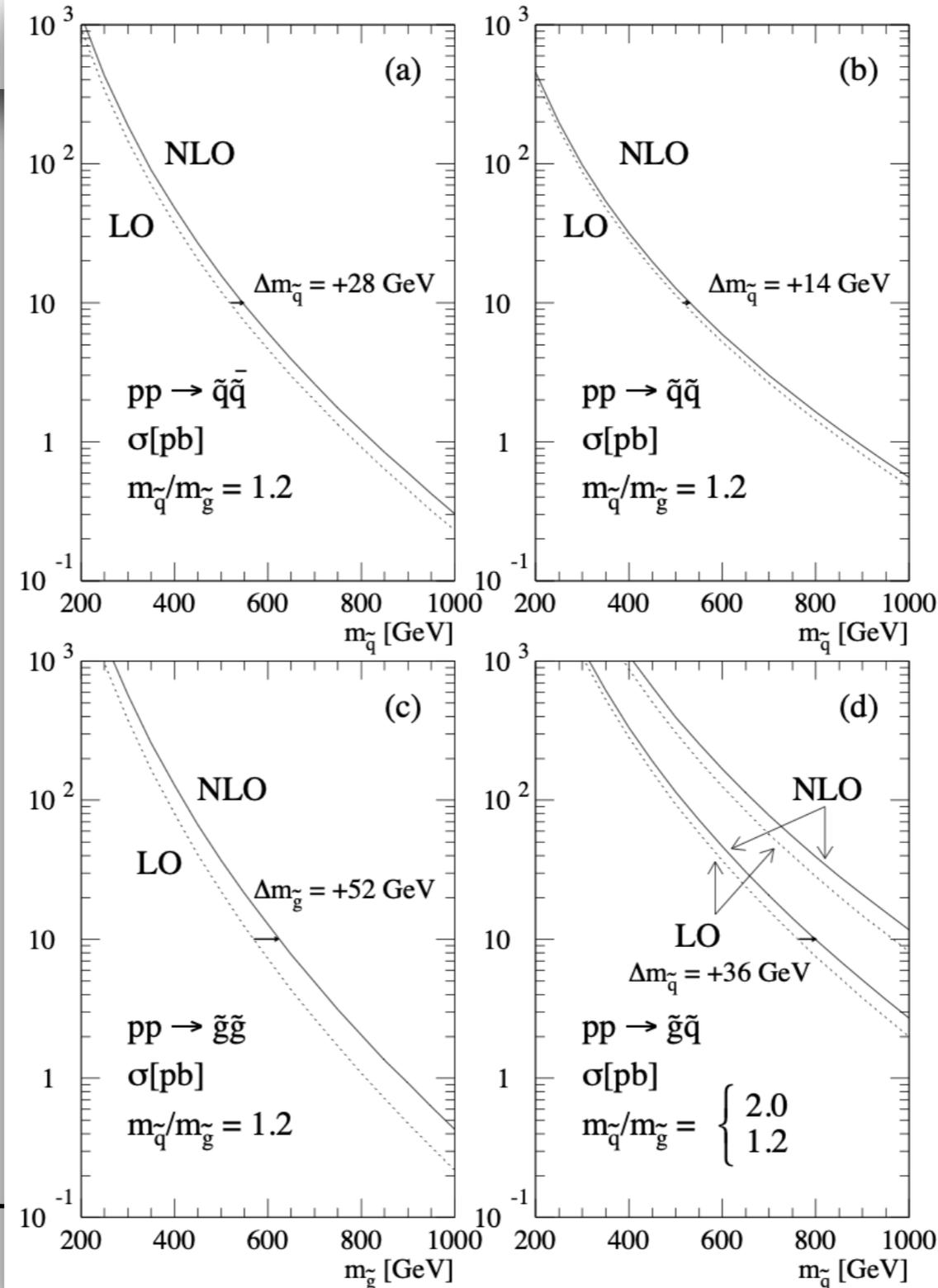
#17

W. Beenakker (Leiden U.), R. Hopker (DESY), M. Spira (CERN), P.M. Zerwas (DESY) (Oct, 1996)

Published in: *Nucl.Phys.B* 492 (1997) 51-103 • e-Print: [hep-ph/9610490](https://arxiv.org/abs/hep-ph/9610490) [hep-ph]

 pdf  DOI

 1,224 citations



# Discovery Requires Precise Theory Predictions

DECAYS :

$$\begin{aligned}\tilde{\chi}_i &\rightarrow W + \tilde{\chi}_1^0 && \oplus \text{ n cascades} \\ \tilde{l} &\rightarrow l + \tilde{\chi}_1^0 \\ \tilde{q} &\rightarrow q + \tilde{\chi}_1^0\end{aligned}$$

---

# Discovery Requires Precise Theory Predictions

---

# Discovery Requires Precise Theory Predictions

## SUSY QCD decays of squarks and gluinos

#11

W. Beenakker (Leiden U.), R. Hopker (DESY), P.M. Zerwas (DESY) (Feb, 1996)

Published in: *Phys.Lett.B* 378 (1996) 159-166 • e-Print: [hep-ph/9602378](https://arxiv.org/abs/hep-ph/9602378) [hep-ph]

 pdf  DOI  cite

 102 citations

## Stop decays in SUSY QCD

#9

W. Beenakker (Leiden U.), R. Hopker (DESY), T. Plehn (DESY), P.M. Zerwas (DESY) (Oct, 1996)

Published in: *Z.Phys.C* 75 (1997) 349-356 • e-Print: [hep-ph/9610313](https://arxiv.org/abs/hep-ph/9610313) [hep-ph]

 pdf  DOI  cite

 95 citations

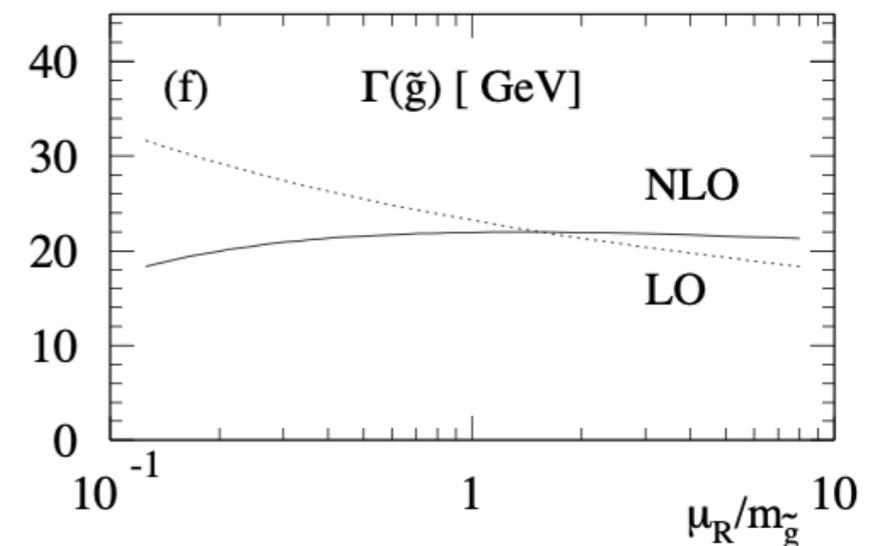
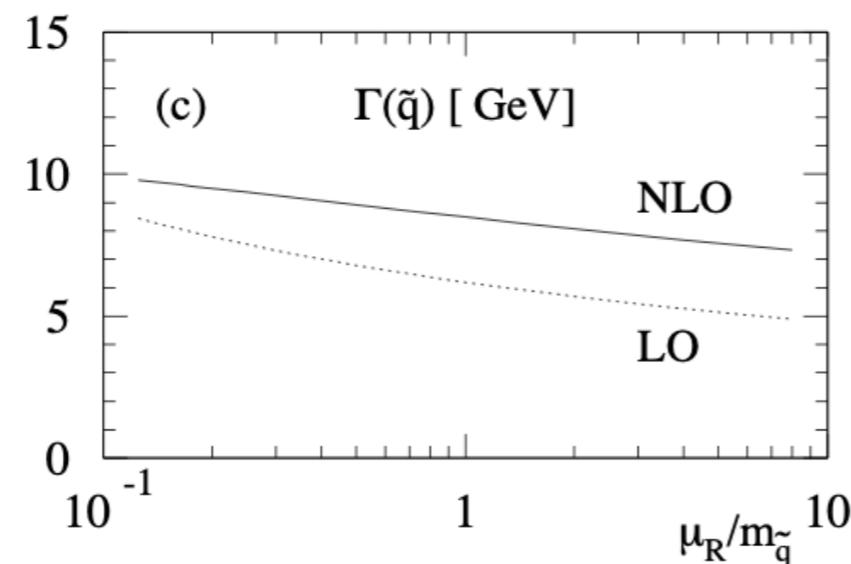
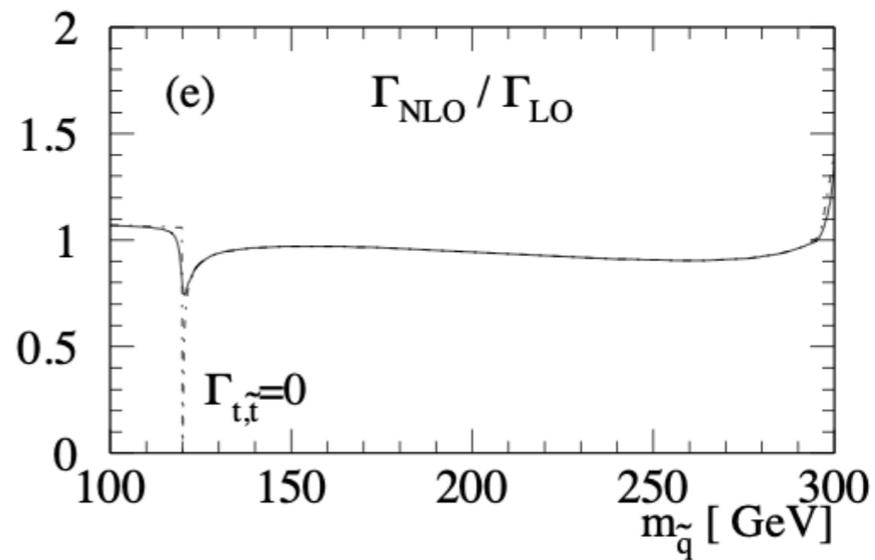
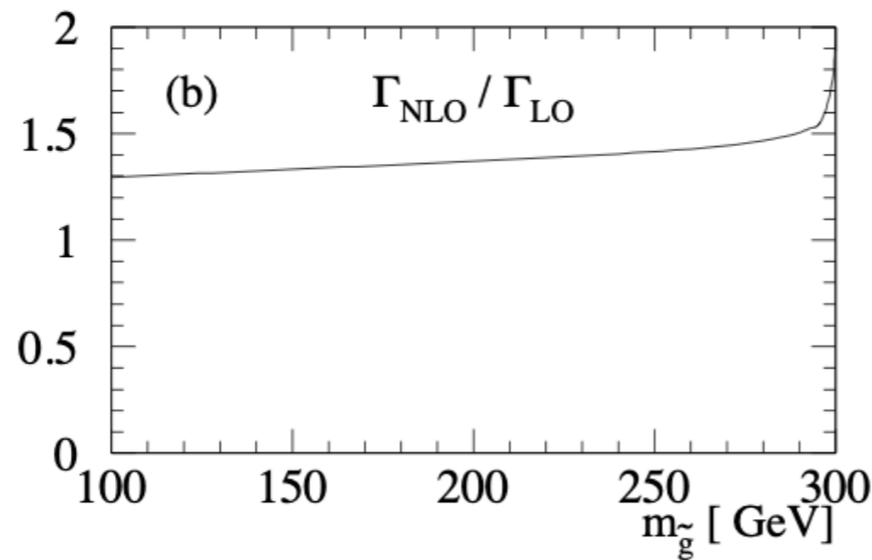
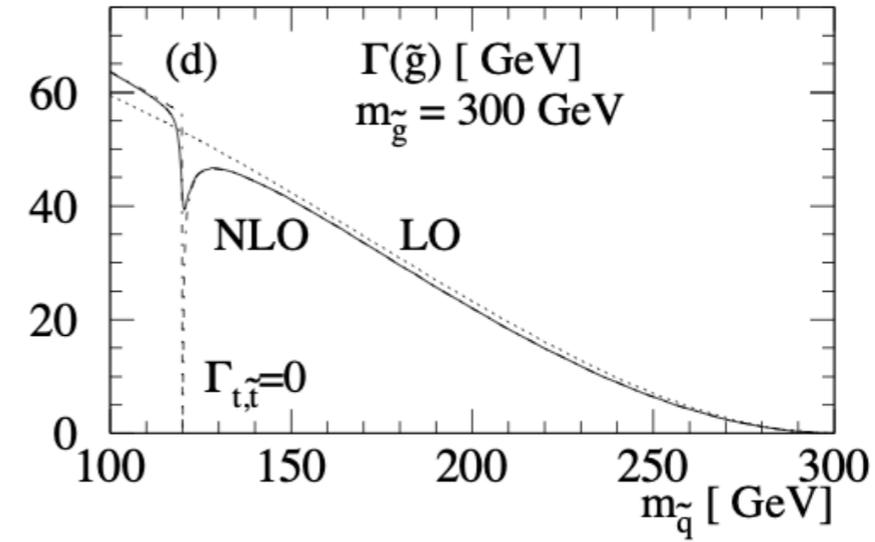
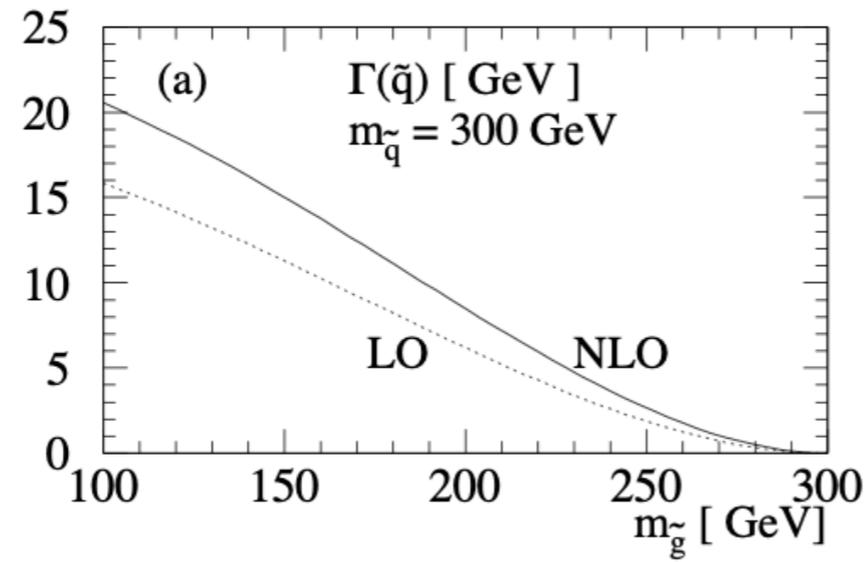
# Discovery Requires Precise Theory Predictions

## SUSY QCD decays

W. Beenakker (Leiden U)

Published in: *Phys.Lett*

pdf DOI



#9

96)

95 citations

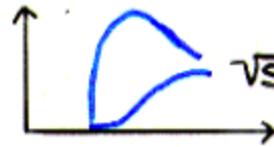
# Underlying Theory: Determination of SUSY Properties

## MASSES :

special endpts  
in continuum



scan near prod  
threshold **F**



	end pt	thresh
$\tilde{\chi}_V$	200/300	40/500
$\tilde{\ell}$	200/300	70/600
$\tilde{q}$	$\sim 3 \text{ GeV}$	$\sim 1 \text{ GeV}$

## MIXING :

$$\tilde{\chi}_i = \alpha_{ij} \tilde{W}_j + \beta_{ij} \tilde{H}_j$$

$$\tilde{t}_i = \alpha_{iL} \tilde{t}_L + \beta_{iR} \tilde{t}_R$$

prod  $e^{\pm}$  :

**F**

diag ea  
kalinovski

**F**

Uhaul ea

# Underlying Theory: Determination of SUSY Properties

## Polarization in sfermion decays: Determining tan beta and trilinear couplings #7

E. Boos (SINP, Moscow and DESY), H.U. Martyn (Aachen, Tech. Hochsch.), Gudrid A. Moortgat-Pick (DESY and Durham U., IPPP), M. Sachwitz (DESY, Zeuthen), A. Sherstnev (SINP, Moscow) et al. (Mar, 2003)

Published in: *Eur.Phys.J.C* 30 (2003) 395-407 • e-Print: [hep-ph/0303110](#) [hep-ph]

 pdf  DOI  cite

 89 citations

	Rank
00	40/500
00	70/600
V	~ 1 GeV

## Glauino Polarization at the LHC #1

M. Kramer (Aachen, Tech. Hochsch.), E. Popenda (Aachen, Tech. Hochsch.), M. Spira (PSI, Villigen), P.M. Zerwas (RWTH Aachen U. and DESY) (Feb, 2009)

Published in: *Phys.Rev.D* 80 (2009) 055002 • e-Print: [0902.3795](#) [hep-ph]

 pdf  DOI  cite

 12 citations



## Analysis of the neutralino system in supersymmetric theories: Addendum #10

S.Y. Choi (Chonbuk Natl. U.), J. Kalinowski (Warsaw U.), Gudrid A. Moortgat-Pick (DESY), P.M. Zerwas (DESY) (Feb, 2002)

e-Print: [hep-ph/0202039](#) [hep-ph]

 pdf  cite

 54 citations

## Analysis of the neutralino system in supersymmetric theories #11

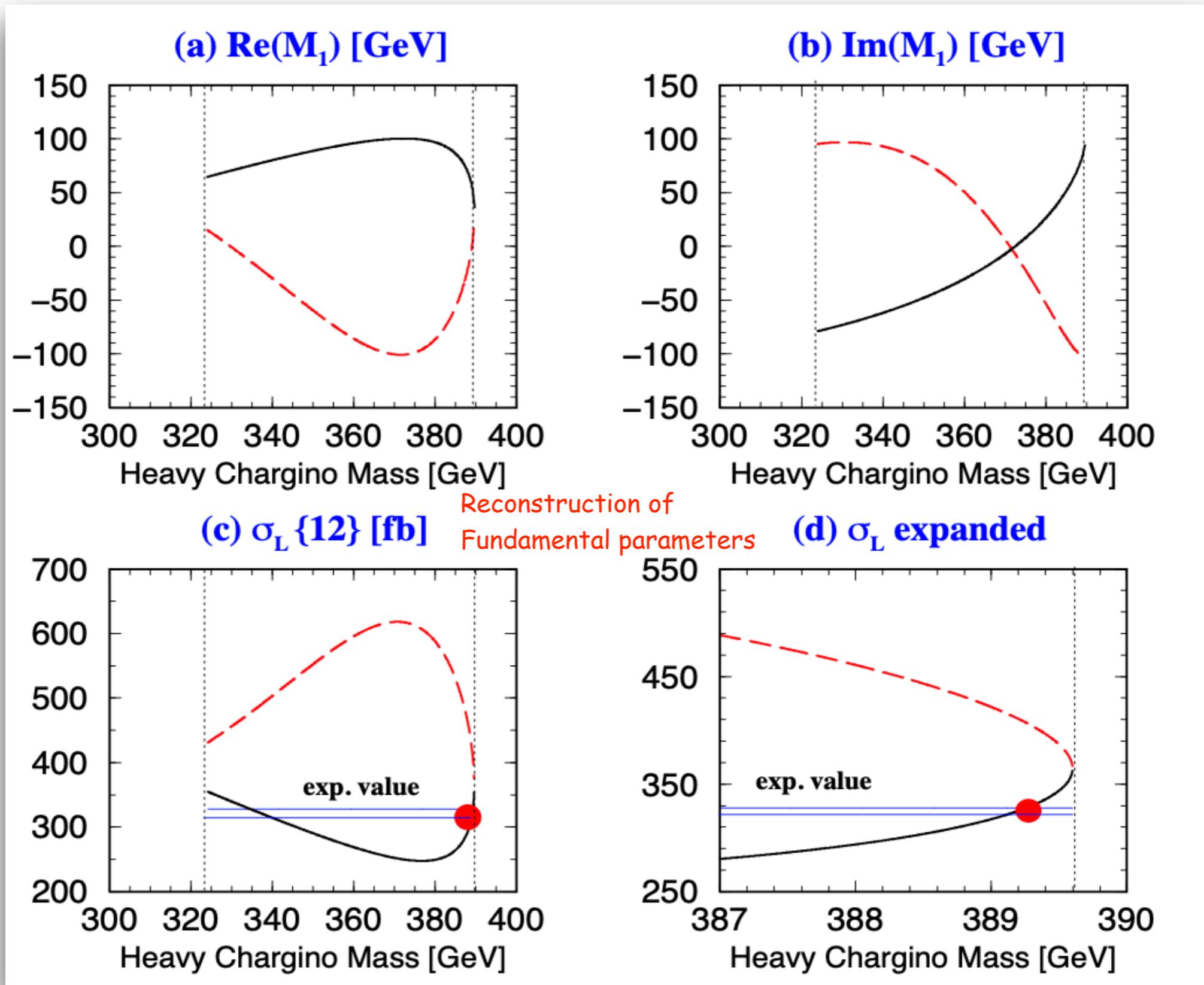
S.Y. Choi (DESY and Chonbuk Natl. U.), J. Kalinowski (DESY and Warsaw U.), Gudrid A. Moortgat-Pick (DESY), P.M. Zerwas (DESY) (Aug, 2001)

Published in: *Eur.Phys.J.C* 22 (2001) 563-579, *Eur.Phys.J.C* 23 (2002) 769-772 (addendum) • e-Print: [hep-ph/0108117](#) [hep-ph]

 pdf  links  DOI  cite

 244 citations

# Underlying Theory: Determination of SUSY Properties



# Reconstructing SUSY

(iv) reconstruction of fund. SUSY theory:



## The Reconstruction of supersymmetric theories at high-energy scales

#10

G.A. Blair (DESY and Royal Holloway, U. of London), W. Porod (Zurich U.), P.M. Zerwas (DESY) (Oct, 2002)

Published in: *Eur.Phys.J.C* 27 (2003) 263-281 • e-Print: [hep-ph/0210058](https://arxiv.org/abs/hep-ph/0210058) [hep-ph]

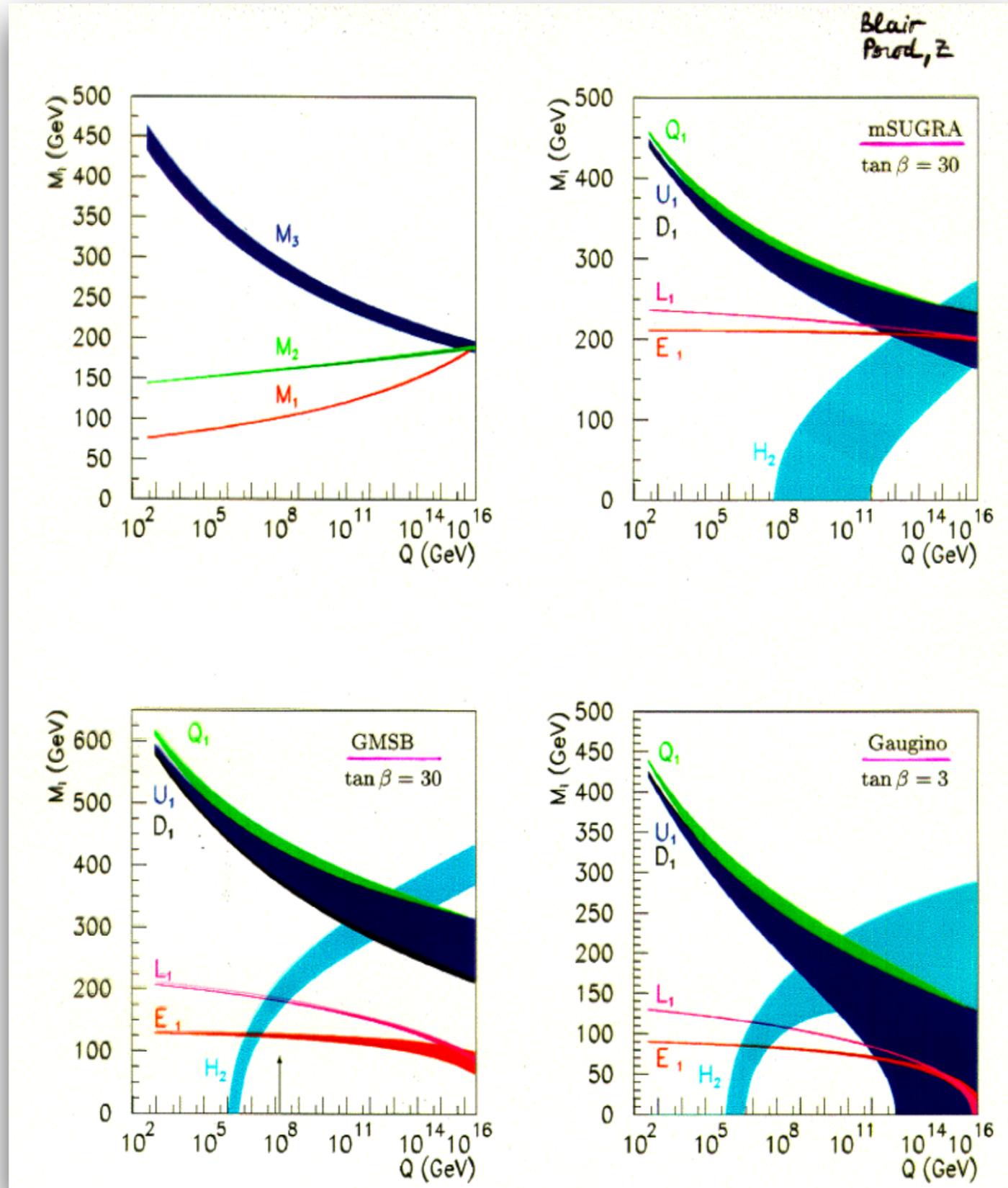
 pdf

 DOI

 cite

 130 citations

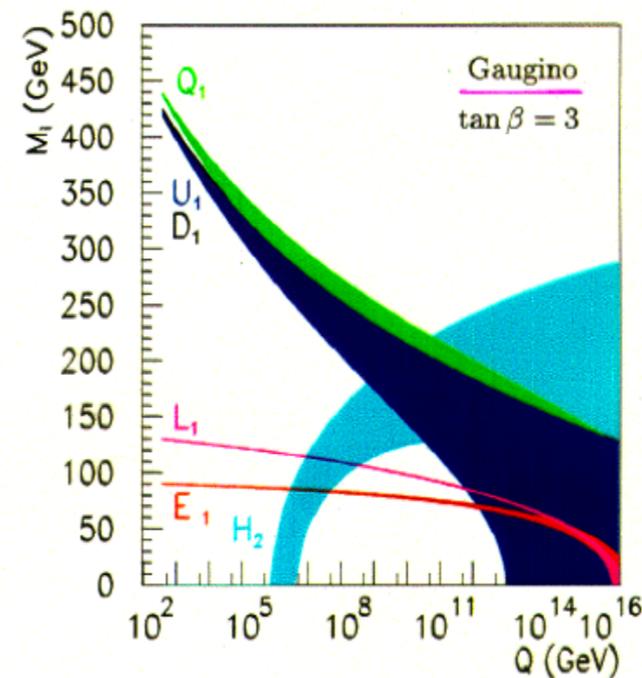
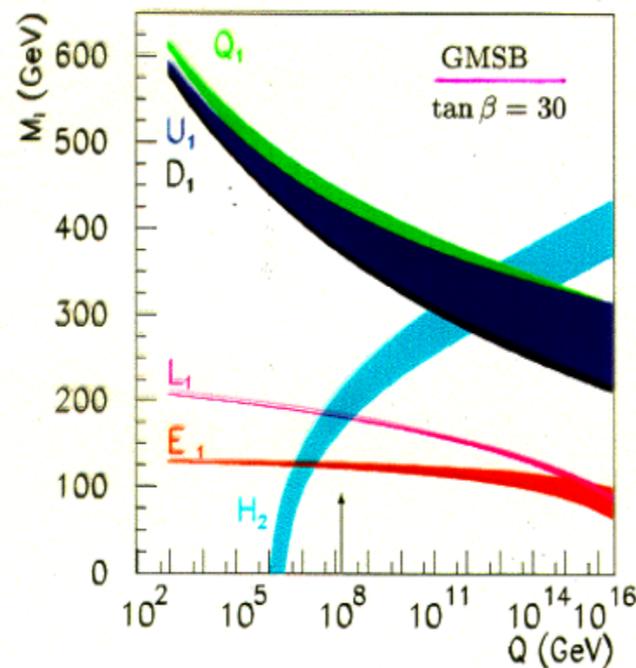
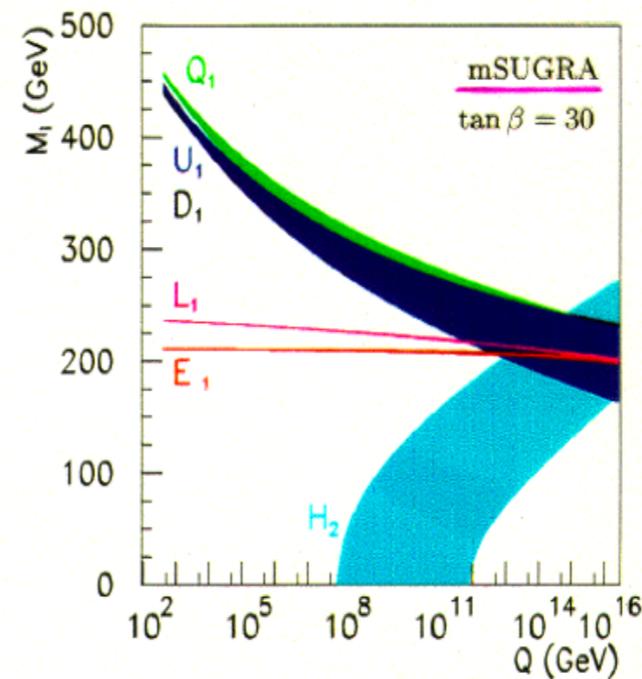
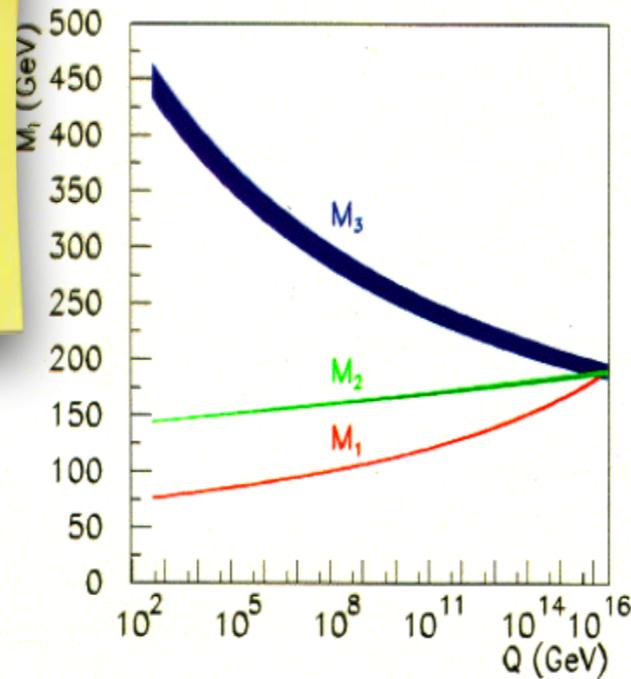
# Reconstructing SUSY



# Reconstructing SUSY

Gain insight in the underlying theory

glimpse at the early universe



# SUSY Particles at $e^+e^-$ Colliders

## Slepton production at $e^+e^-$ and $e^-e^-$ linear colliders: Addendum 😊 #2

A. Freitas (Fermilab), A. von Manteuffel (DESY), P.M. Zerwas (DESY) (Aug, 2004)

Published in: *Eur.Phys.J.C* 40 (2005) 435-445 • e-Print: [hep-ph/0408341](#) [hep-ph]

 pdf  links  DOI  cite

 30 citations

## Slepton production at $e^+e^-$ and $e^-e^-$ linear colliders #3

A. Freitas (Fermilab), A. von Manteuffel (DESY), P.M. Zerwas (DESY) (Oct, 2003)

Published in: *Eur.Phys.J.C* 34 (2004) 487-512 • e-Print: [hep-ph/0310182](#) [hep-ph]

 pdf  links  DOI 

## Chargino pair production in $e^+e^-$ collisions #12

S.Y. Choi (Yonsei U.), A. Djouadi (Montpellier U.), Herbert K. Dreiner (Rutherford), J. Kalinowski (Warsaw, CFT), P.M. Zerwas (DESY) (Jun, 1998)

Published in: *Eur.Phys.J.C* 7 (1999) 123-134 • e-Print: [hep-ph/9806279](#) [hep-ph]

 pdf  DOI  cite

 126 citations

## Determining SUSY parameters in chargino pair production in $e^+e^-$ collisions #11

S.Y. Choi (Korea Inst. Advanced Study, Seoul), A. Djouadi (Montpellier U.), H.S. Song (Seoul Natl. U.), P.M. Zerwas (DESY) (Dec, 1998)

Published in: *Eur.Phys.J.C* 8 (1999) 669-677 • e-Print: [hep-ph/9812236](#) [hep-ph]

 pdf  DOI 

 116 citations

## Squarks and gluinos at a TeV $e^+e^-$ collider: Testing the identity of Yukawa and gauge couplings in SUSY-QCD #1

A. Brandenburg (DESY), M. Maniatis (Heidelberg U.), M.M. Weber (SUNY, Buffalo), Peter M. Zerwas (RWTH Aachen U. and DESY) (Jun, 2008)

Published in: *Eur.Phys.J.C* 58 (2008) 291-300 • e-Print: [0806.3875](#) [hep-ph]

 pdf  DOI  cite

 7 citations

---

## What we have

---

✦ **Experimental reality:** No Beyond the Standard Model Physics discovered so far!

Guido Altarelli, 16/1/12, KIT: „The situation is depressing, but not desperate.“

# What we have

- ✦ Experimental reality: No Beyond the Standard Model Physics discovered so far!

Guido Altarelli, 16/1/12, KIT: „The situation is depressing, but not desperate.“

(1) Higgs excitation  $\equiv$  Higgs boson  
must be discovered

LEP2  
TeVatron  
LHC



---

## What we have

---

- ✦ Experimental reality: No Beyond the Standard Model Physics discovered so far!

Guido Altarelli, 16/1/12, KIT: „The situation is depressing, but not desperate.“

- ✦ We have the (SM-like) Higgs boson



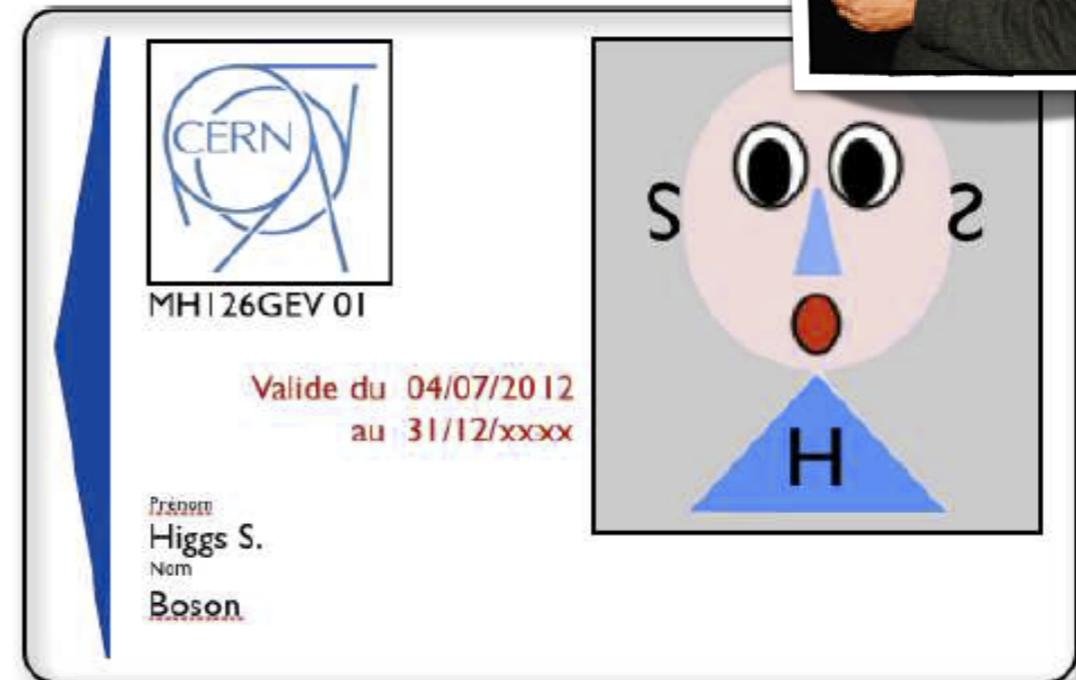
# What we have

- ♦ Experimental reality: No Beyond the Standard Model Physics discovered so far!

Guido Altarelli, 16/1/12, KIT: „The situation is depressing, but not desperate.“

- ♦ We have the (SM-like) Higgs boson

What can we learn from Higgs physics?



*The Role  
of the  
Higgs Boson  
Mass*



---

# The Role of the Higgs Boson Mass

---

♦ Combined Higgs mass value:

[ATLAS,CMS]

$$M_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)} \text{ GeV}$$

---

# The Role of the Higgs Boson Mass

---

♦ Combined Higgs mass value:

[ATLAS,CMS]

$$M_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)} \text{ GeV}$$

♦ Why precision? What can we learn?

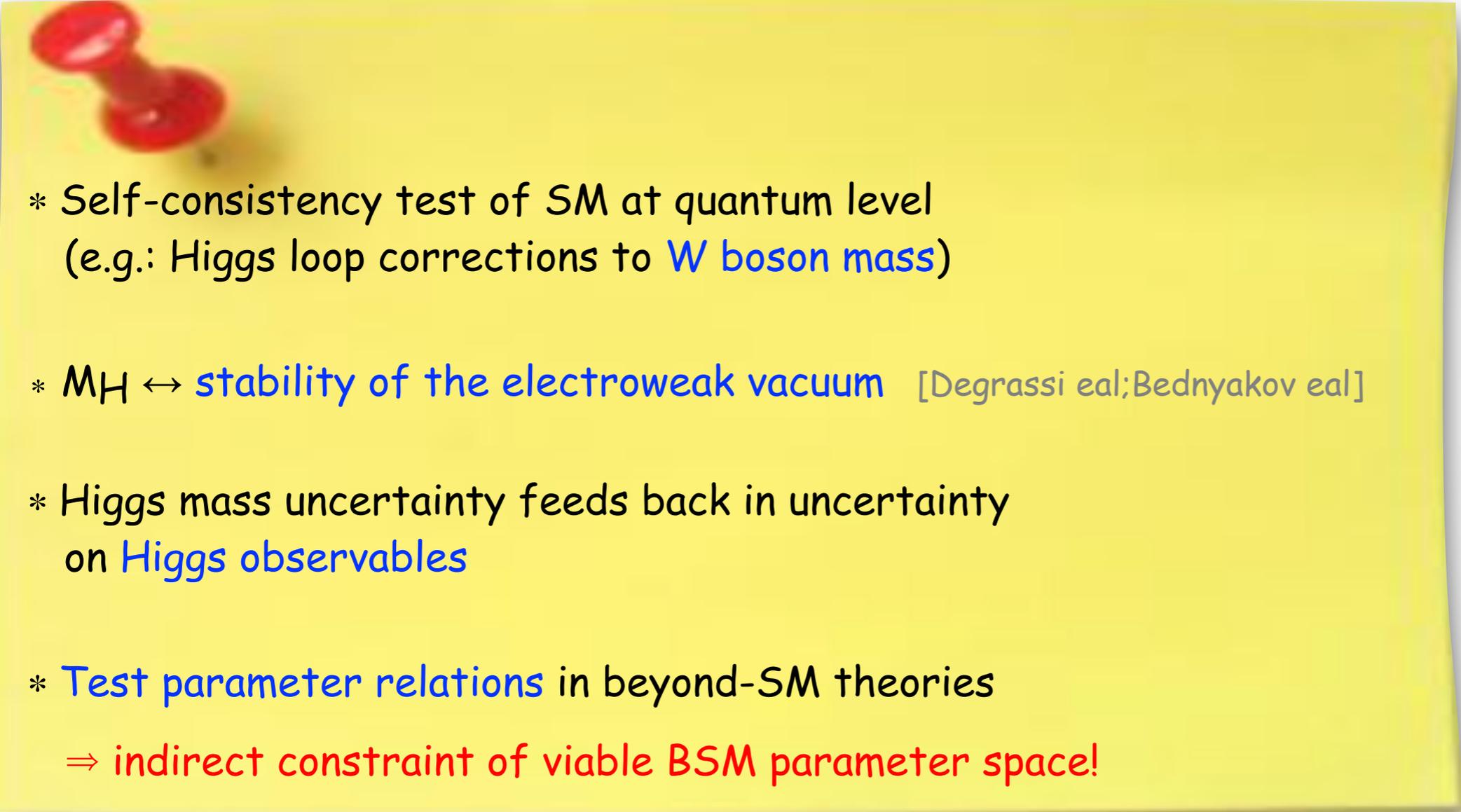
# The Role of the Higgs Boson Mass

♦ Combined Higgs mass value:

[ATLAS,CMS]

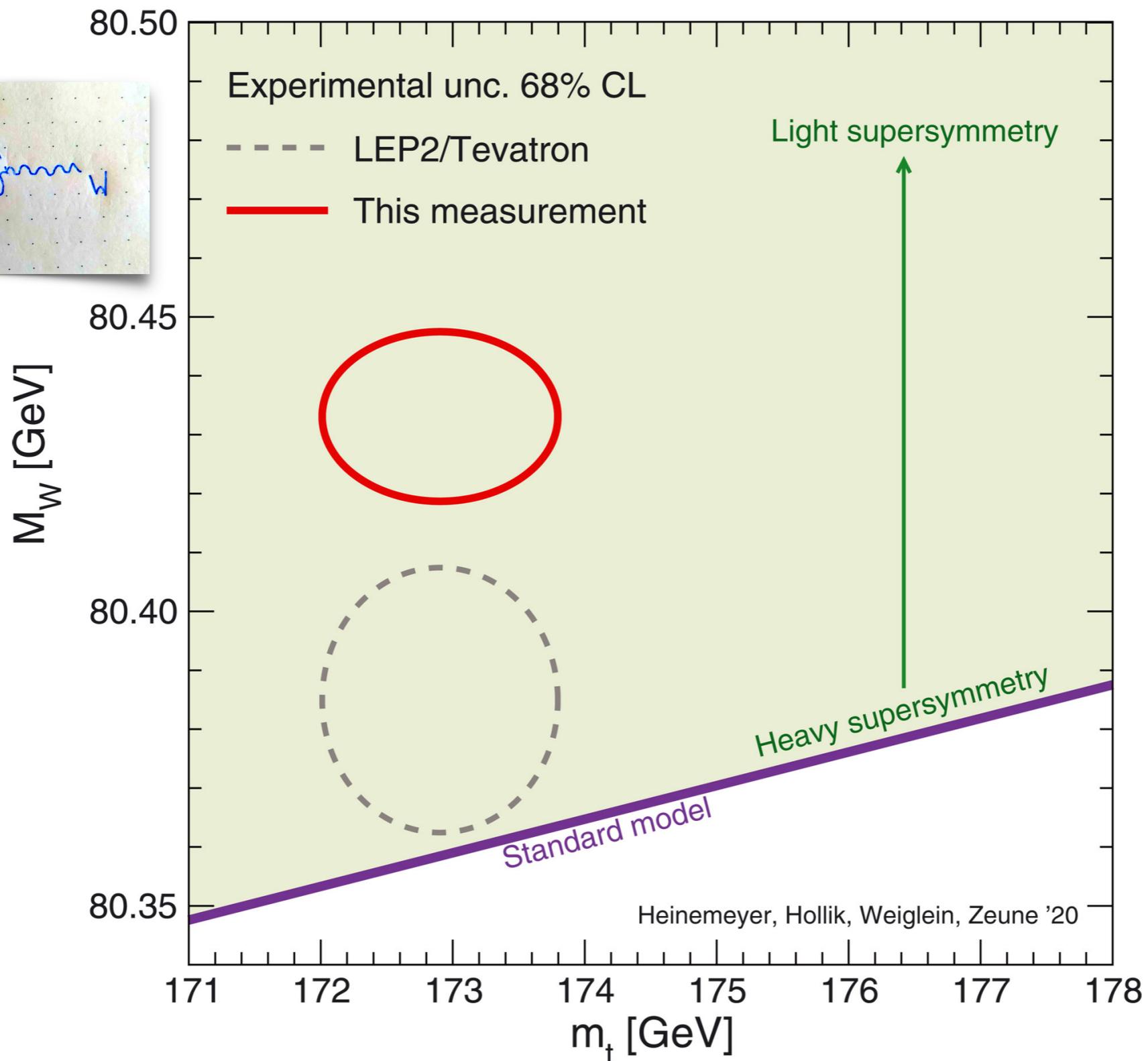
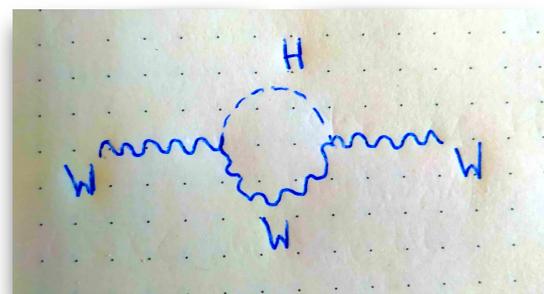
$$M_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)} \text{ GeV}$$

♦ Why precision? What can we learn?

- 
- \* Self-consistency test of SM at quantum level (e.g.: Higgs loop corrections to **W boson mass**)
  - \*  $M_H \leftrightarrow$  **stability of the electroweak vacuum** [Degrassi eal;Bednyakov eal]
  - \* Higgs mass uncertainty feeds back in uncertainty on **Higgs observables**
  - \* **Test parameter relations** in beyond-SM theories  
 $\Rightarrow$  **indirect constraint of viable BSM parameter space!**

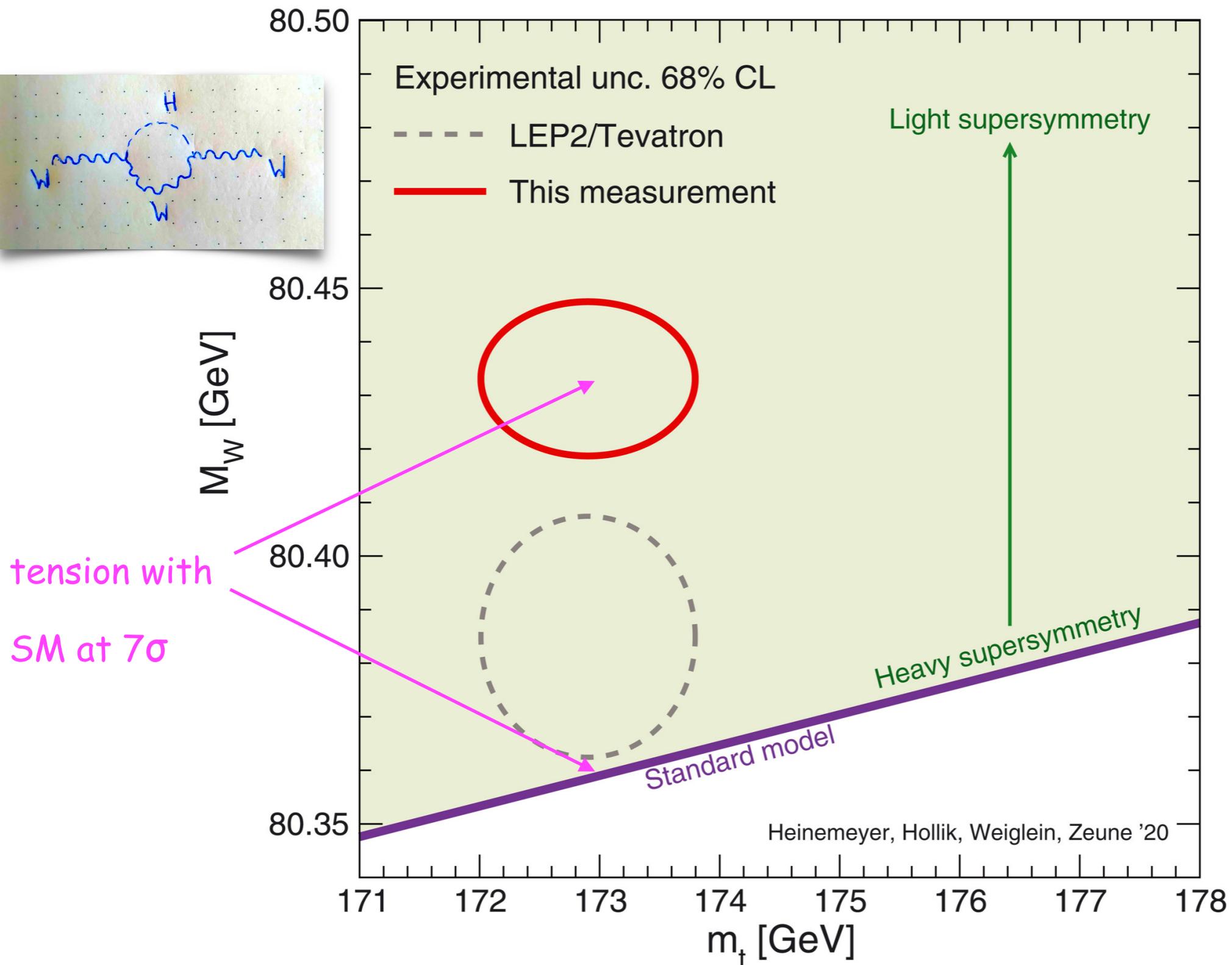
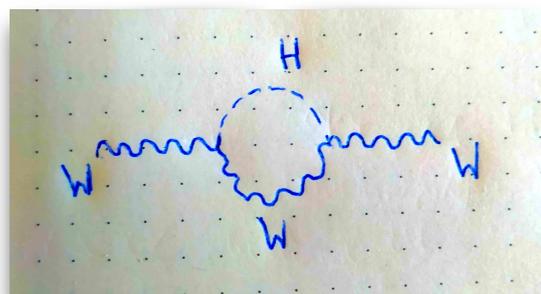
# The W Boson Mass

[CDF,2022]



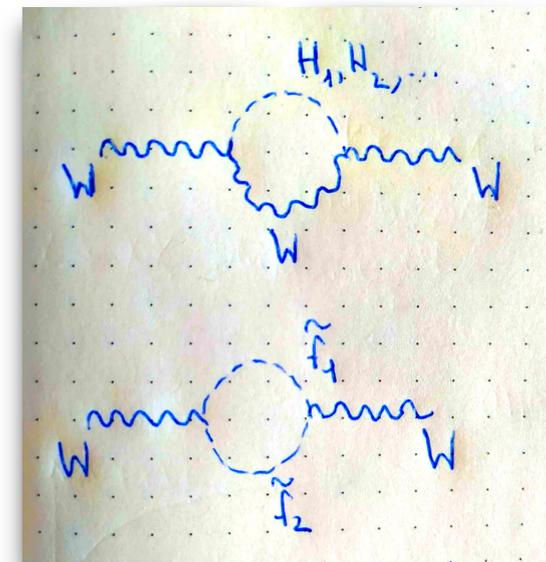
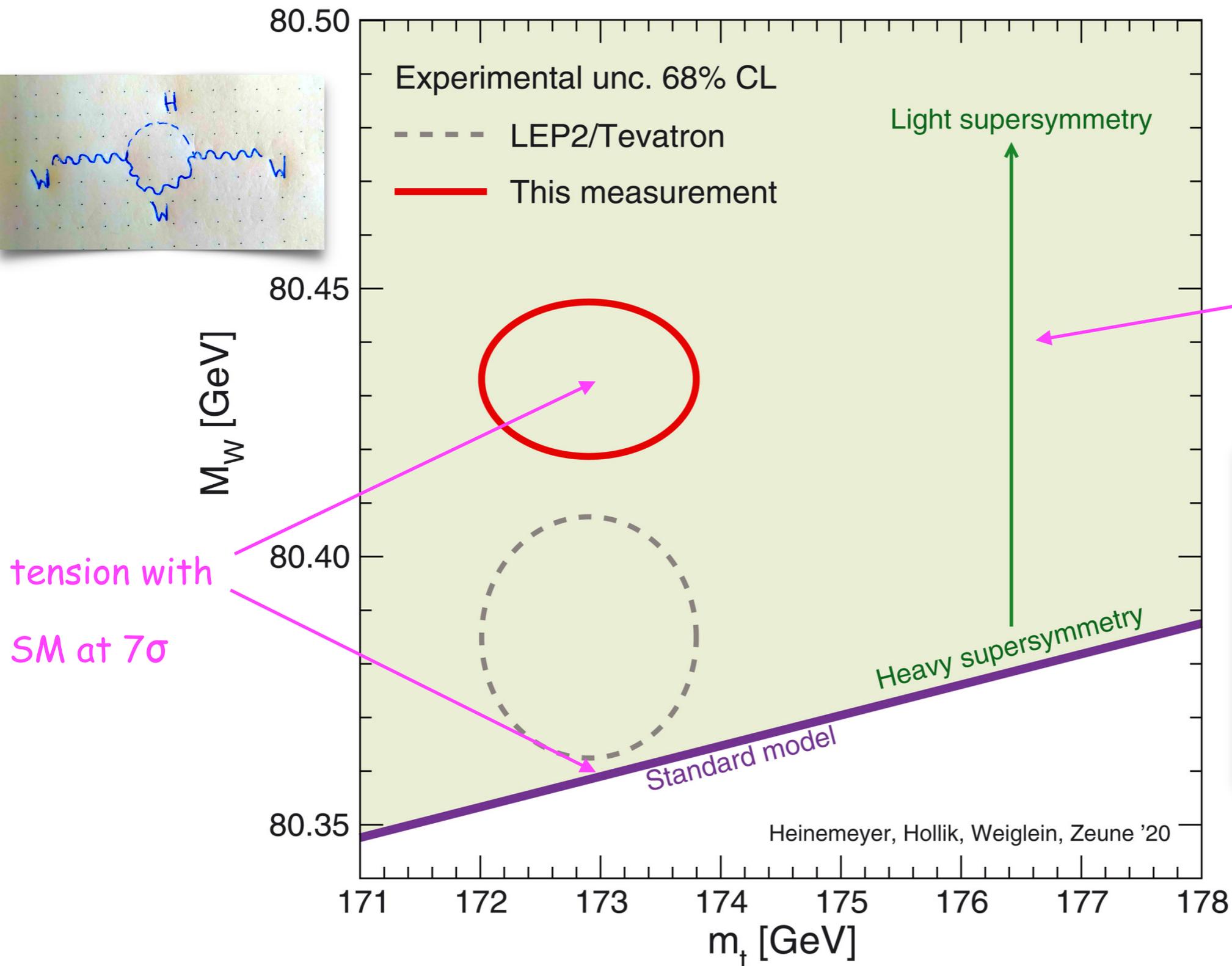
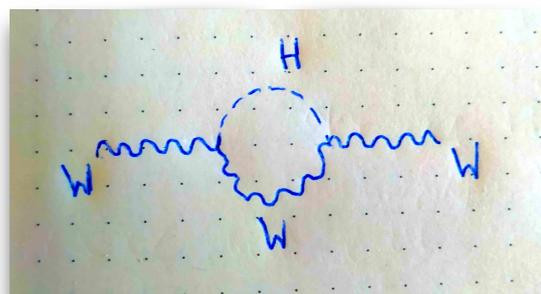
# The W Boson Mass

[CDF,2022]



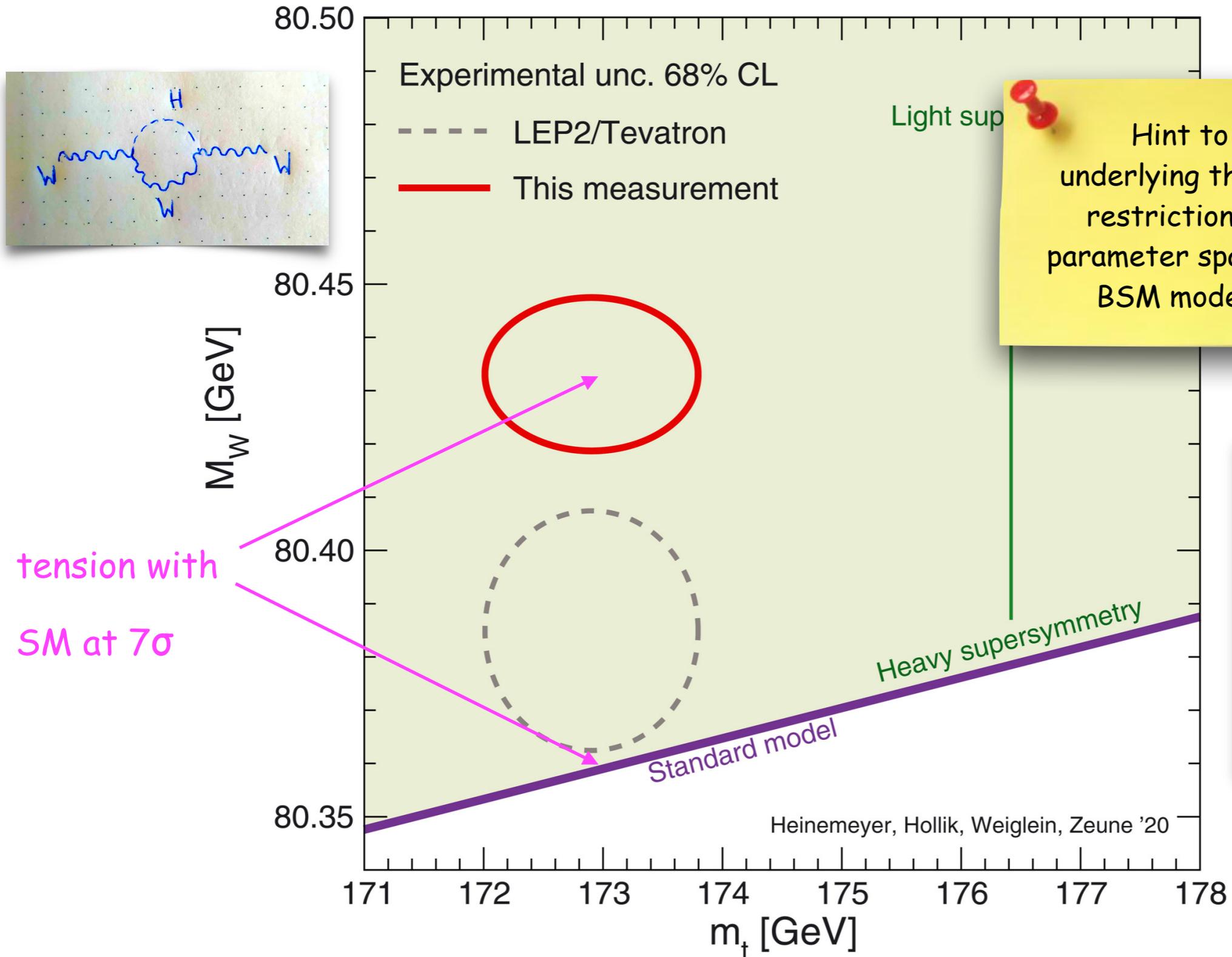
# The W Boson Mass

[CDF, 2022]



# The W Boson Mass

[CDF, 2022]



# Higgs Mass in New Physics Extensions

## Higgs boson mass:

- \* SM: fundamental parameter, not predicted by the theory
- \* Supersymmetry: calculable from input parameters; quantum corrections  $\Delta m^2_h$  are important!

$$\text{MSSM: } m_H^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_H^2 \leftarrow (85 \text{ GeV})^2!$$

$$\text{NMSSM: } m_H^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_H^2 \leftarrow (55 \text{ GeV})^2$$

## NMSSM:

- \* less important loop corrections compared to the MSSM
- \* solves little hierarchy problem

[Kim, Nilles, '84]

# Higgs Mass in New Physics Extensions

## Higgs boson mass:

- \* SM: fundamental parameter, not predicted
- \* Supersymmetry: calculable from input parameters, quantum corrections  $\Delta m^2_h$  are important!

*spectrum*:  $R^0$   
 $H^0, A^0, H^\pm, \dots$   $\leq 135/180$  GeV  
 $\sim \Theta(v) - \Theta(\text{TeV})$

$$\text{MSSM: } m_H^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_H^2 \leftarrow (85 \text{ GeV})^2!$$

$$\text{NMSSM: } m_H^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_H^2 \leftarrow (55 \text{ GeV})^2$$

## NMSSM:

- \* less important loop corrections compared to the MSSM
- \* solves little hierarchy problem

[Kim, Nilles, '84]

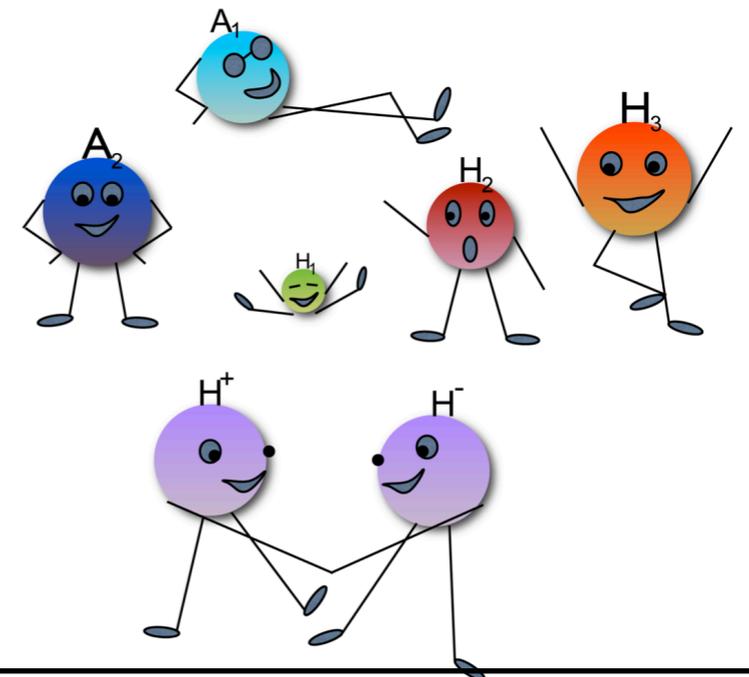
# SUSY Higgs Masses

SUSY HIGGS BOSONS

- ♦ **Supersymmetry:** requires at least 2 complex Higgs doublets
- ♦ **Next-to-MSSM (NMSSM):** 2 complex Higgs doublets plus complex singlet field
- ♦ **Enlarged Higgs and neutralino sector:**

7 Higgs bosons:  $H_1, H_2, H_3, A_1, A_2, H^+, H^-$

5 neutralinos:  $\tilde{\chi}_i^0$  ( $i = 1, \dots, 5$ )



## The Higgs Sector of the Next-to-Minimal Supersymmetric Standard Model

D.J. Miller<sup>1</sup>, R. Nevzorov<sup>2</sup>  
and P.M. Zerwas<sup>3</sup>

<sup>1</sup> *Theory Division, CERN, CH-1211 Geneva 23, Switzerland*

<sup>2</sup> *ITEP, Moscow, Russia*

<sup>3</sup> *Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany*

### Abstract

The Higgs boson spectrum of the Next-to-Minimal Supersymmetric Standard Model is examined. The model includes a singlet Higgs field  $S$  in addition to the two Higgs doublets of the minimal extension. ‘Natural’ values of the parameters of the model are motivated by their renormalization group running and the vacuum stability. The qualitative features of the Higgs boson masses are dependent on how strongly the Peccei-Quinn  $U(1)$  symmetry of the model is broken, measured by the self-coupling of the singlet field in the superpotential. We explore the Higgs boson masses and their couplings to gauge bosons for various representative scenarios.

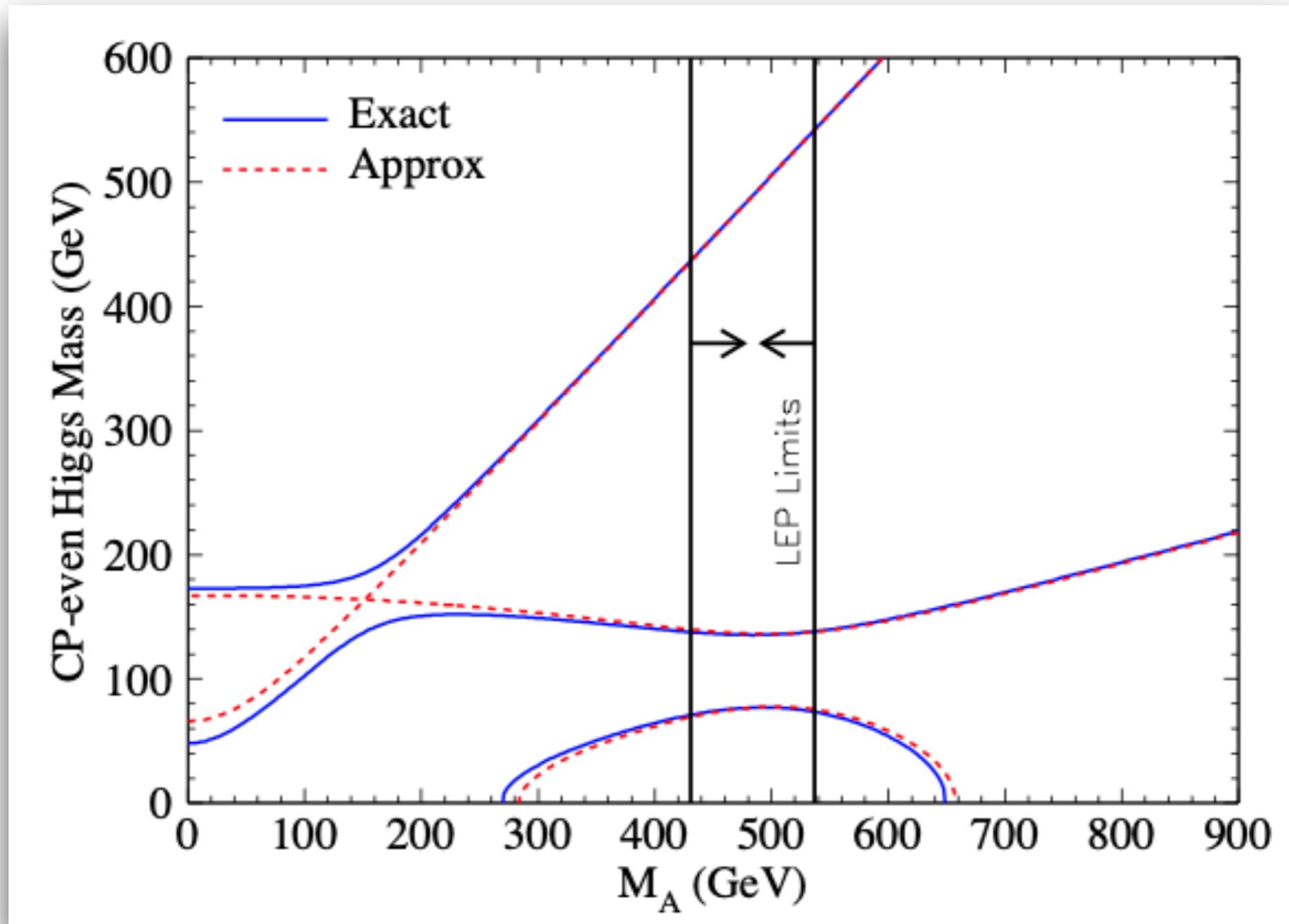
# NMSSM Mass Spectrum

[Miller, Nevezorov, Zerwas, '03]

$$M_{H_3}^2 = M_{11}^2 + \frac{M_{13}^4}{M_{11}^2},$$
$$M_{H_{2/1}}^2 = \frac{1}{2} \left( M_{22}^2 + M_{33}^2 - \frac{M_{13}^4}{M_{11}^2} \pm \sqrt{\left( M_{22}^2 - M_{33}^2 + \frac{M_{13}^4}{M_{11}^2} \right)^2 + 4 \left( M_{23}^2 - \frac{M_{13}^2 M_{12}^2}{M_{11}^2} \right)^2} \right)$$

# NMSSM Mass Spectrum

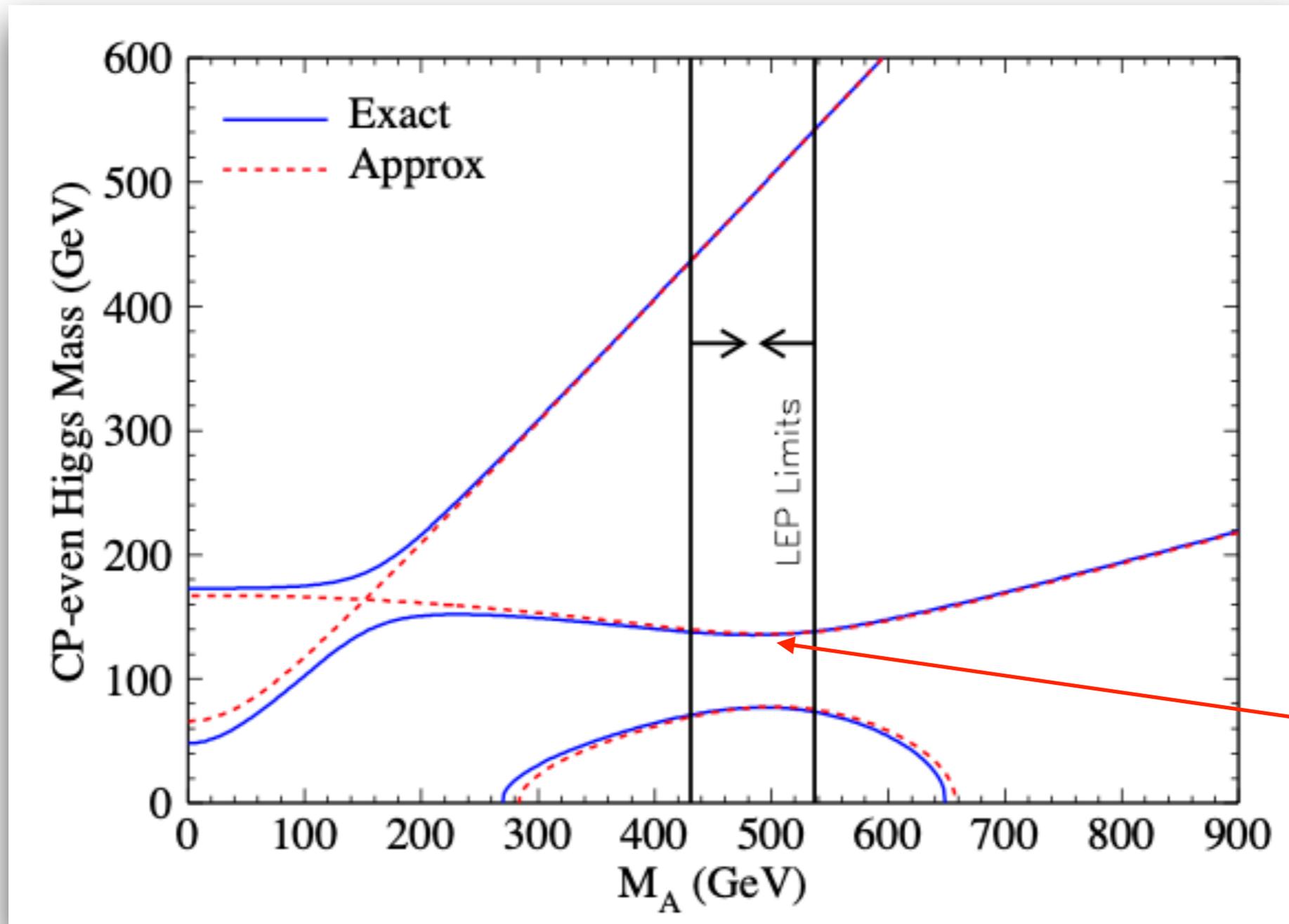
[Miller, Nevzorov, Zerwas, '03]



NMSSM with a slightly broken Peccei-Quinn Symmetry

# NMSSM Mass Spectrum

[Miller, Nevzorov, Zerwas, '03]



SM-like CP-even  
Higgs boson w/  
138 GeV

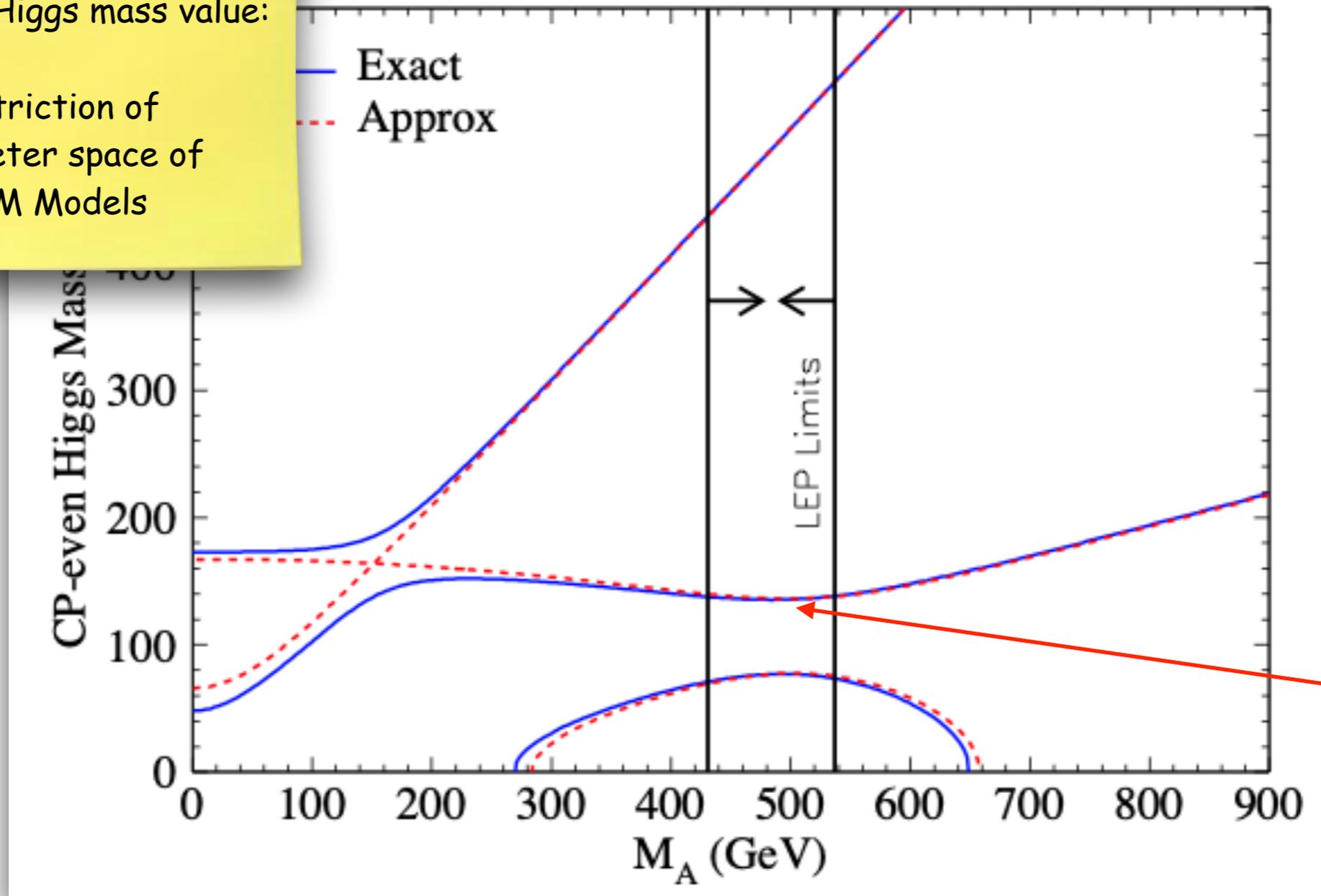
NMSSM with a slightly broken Peccei-Quinn Symmetry

# NMSSM Mass Spectrum

[Miller, Nevzorov, Zerwas, '03]

Comparison with  
measured Higgs mass value:

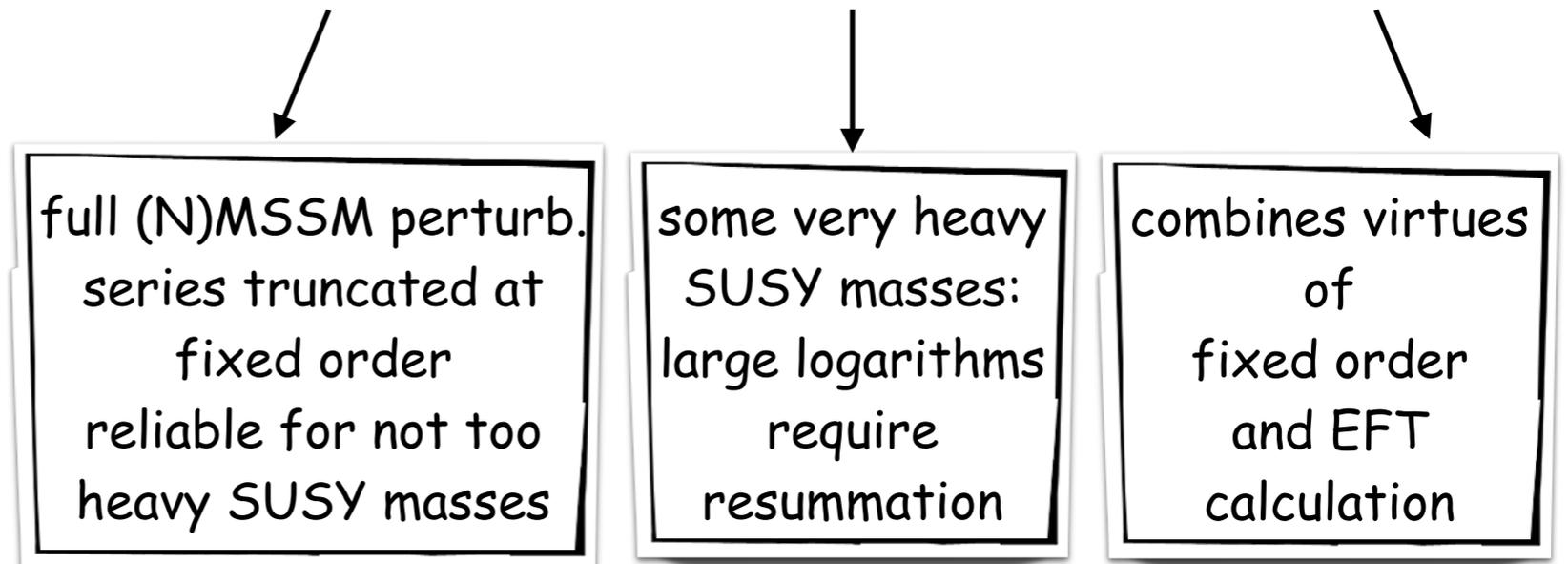
Restriction of  
parameter space of  
BSM Models



NMSSM with a slightly broken Peccei-Quinn Symmetry

# Spectrum Calculations 2022

❖ Methods for Higgs mass calculations: fixed-order (FO) - effective field theory (EFT) - hybrid



❖ Status MSSM spectrum calculations:

FO: up to 2-loop in on-shell (OS) and DR scheme, partial 3-loop in DR scheme

EFT: up to  $N^2LL$  (included in calculators),  $N^3LL$

❖ Status NMSSM spectrum calculations:

FO: up to 2-loop in mixed OS-DR scheme and in DR-scheme

EFT: matching to quartic coupling in NMSSM w/ all BSM particles at TeV scale

hybrid

# Spectrum Calculations 2022

## ❖ Methods for Higgs

## ❖ Status MSSM spec

FO: up to 2-loop in  
EFT: up to N<sup>2</sup>LL (in

## ❖ Status NMSSM spec

FO: up to 2-loop in  
EFT: matching to q  
hybrid

arXiv:2012.15629v3 [hep-ph] 17 May 2021

DESY 20-229, IFT-UAM/CSIC-20-184, FR-PHENO-2020-021,  
KA-TP-23-2020, MPP-2020-235, P3H-20-086, TTK-20-53

## Higgs-mass predictions in the MSSM and beyond

P. Slavich<sup>a</sup> and S. Heinemeyer<sup>b,c,d</sup> (eds.),

E. Bagnaschi<sup>e</sup>, H. Bahl<sup>f</sup>, M. Goodsell<sup>a</sup>, H.E. Haber<sup>g</sup>, T. Hahn<sup>h</sup>, R. Harlander<sup>i</sup>,  
W. Hollik<sup>h</sup>, G. Lee<sup>j,k,l</sup>, M. Mühlleitner<sup>m</sup>, S. Paßehr<sup>i</sup>, H. Rzehak<sup>n</sup>, D. Stöckinger<sup>o</sup>,  
A. Voigt<sup>p</sup>, C.E.M. Wagner<sup>q,r,s</sup> and G. Weiglein<sup>f</sup>,

B.C. Allanach<sup>t</sup>, T. Biekötter<sup>f</sup>, S. Borowka<sup>u†</sup>, J. Braathen<sup>f</sup>, M. Carena<sup>r,s,v</sup>,  
T.N. Dao<sup>w</sup>, G. Degrandi<sup>x</sup>, F. Domingo<sup>y</sup>, P. Drechsel<sup>f†</sup>, U. Ellwanger<sup>z</sup>, M. Gabelmann<sup>m</sup>,  
R. Gröber<sup>aa</sup>, J. Klappert<sup>i</sup>, T. Kwasnitza<sup>o</sup>, D. Meuser<sup>f</sup>, L. Mihaila<sup>bb†</sup>, N. Murphy<sup>cc†</sup>,  
K. Nickel<sup>y†</sup>, W. Porod<sup>dd</sup>, E.A. Reyes Rojas<sup>ee</sup>, I. Sobolev<sup>f</sup> and F. Staub<sup>m†</sup>

Predictions for the Higgs masses are a distinctive feature of supersymmetric extensions of the Standard Model, where they play a crucial role in constraining the parameter space. The discovery of a Higgs boson and the remarkably precise measurement of its mass at the LHC have spurred new efforts aimed at improving the accuracy of the theoretical predictions for the Higgs masses in supersymmetric models. The “*Precision SUSY Higgs Mass Calculation Initiative*” (KUTS) was launched in 2014 to provide a forum for discussions between the different groups involved in these efforts. This report aims to present a comprehensive overview of the current status of Higgs-mass calculations in supersymmetric models, to document the many advances that were achieved in recent years and were discussed during the KUTS meetings, and to outline the prospects for future improvements in these calculations.

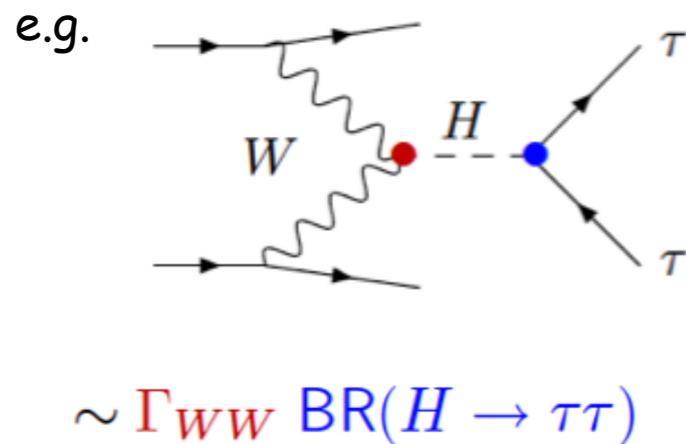
EFT) - hybrid

combines virtues  
of  
fixed order  
and EFT  
calculation

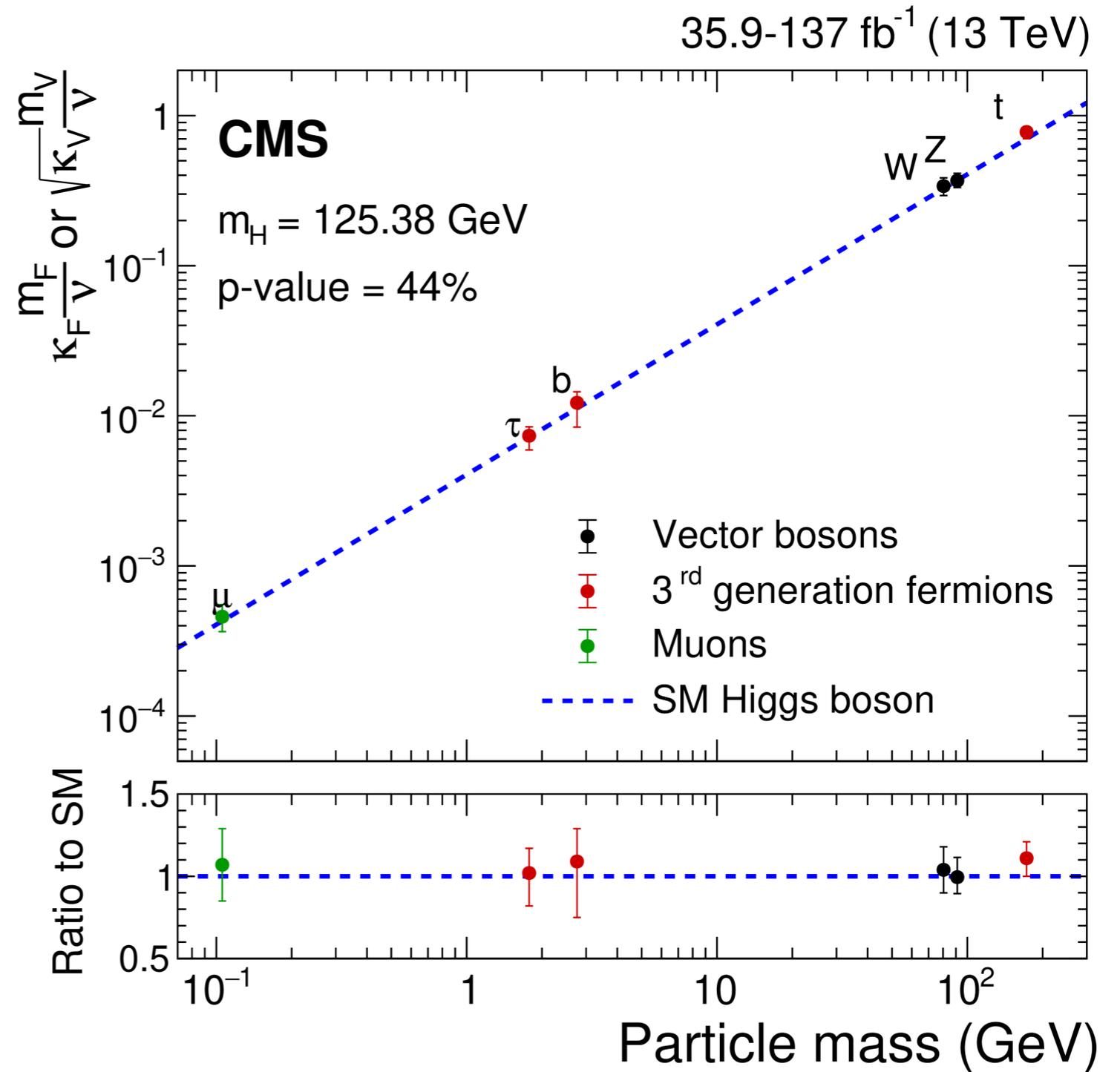
A lush green forest scene with a stream in the foreground. A large tree trunk is visible on the right side, and its branches arch over the stream. The water reflects the surrounding greenery. The text is centered in a white-bordered box with a green background.

*Higgs Boson Properties -  
Couplings*

Combination of production & decay  
 => Higgs couplings  
 => test if  $g_{HXX} \sim m_X$   
 insight in mechanism of mass generation



$$\sim \Gamma_{WW} \text{BR}(H \rightarrow \tau\tau)$$



## Heavy SUSY Higgs bosons at $e^+e^-$ linear colliders

#15

A. Djouadi (DESY and Karlsruhe U.), J. Kalinowski (Warsaw U.), P. Ohmann (DESY and Oxford U.), P.M. Zerwas (DESY) (May, 1996)

Published in: *Z.Phys.C* 74 (1997) 93-111 • e-Print: [hep-ph/9605339](https://arxiv.org/abs/hep-ph/9605339) [hep-ph]

 pdf  DOI  cite

 148 citations

## SUSY decays of Higgs particles

#19

A. Djouadi (DESY and Karlsruhe U.), P. Janot (CERN), J. Kalinowski (Warsaw U.), P.M. Zerwas (DESY) (Mar, 1996)

Published in: *Phys.Lett.B* 376 (1996) 220-226 • e-Print: [hep-ph/9603368](https://arxiv.org/abs/hep-ph/9603368) [hep-ph]

 pdf  DOI  cite

 130 citations

## Two and three-body decay modes of SUSY Higgs particles

#24

A. Djouadi (Karlsruhe U. and DESY), J. Kalinowski (Warsaw U.), P.M. Zerwas (DESY) (Nov, 1995)

Published in: *Z.Phys.C* 70 (1996) 435-448 • e-Print: [hep-ph/9511342](https://arxiv.org/abs/hep-ph/9511342) [hep-ph]

 pdf  links  DOI  cite

 216 citations

## SUSY Higgs production at proton colliders

#7

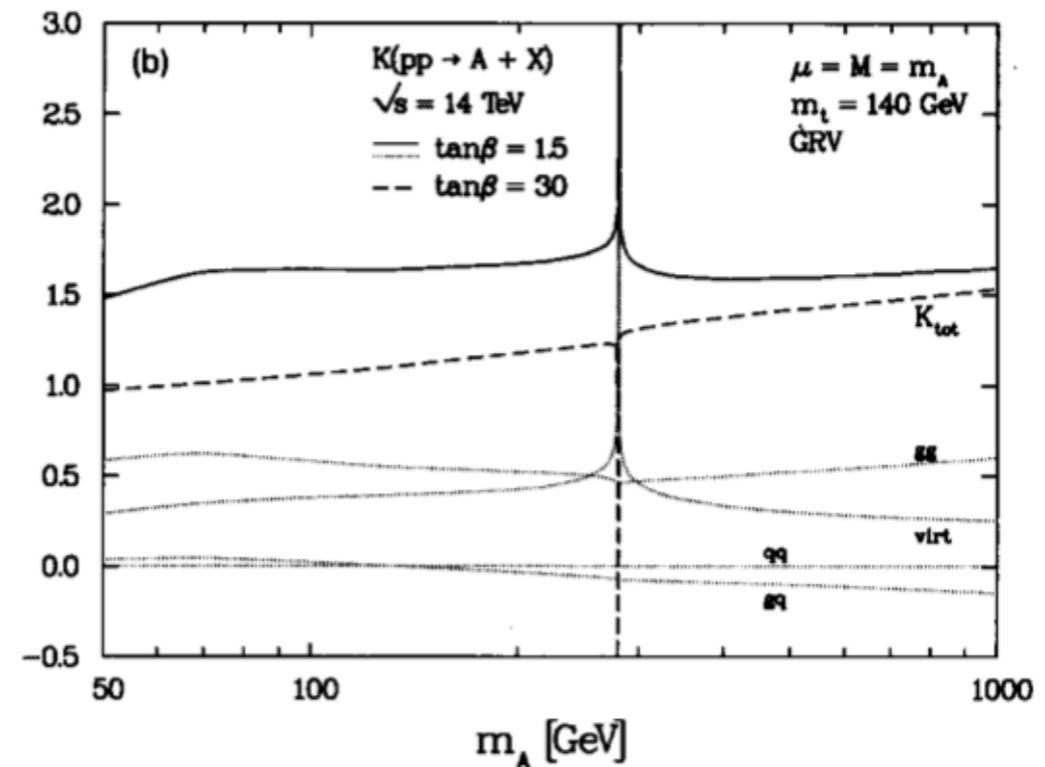
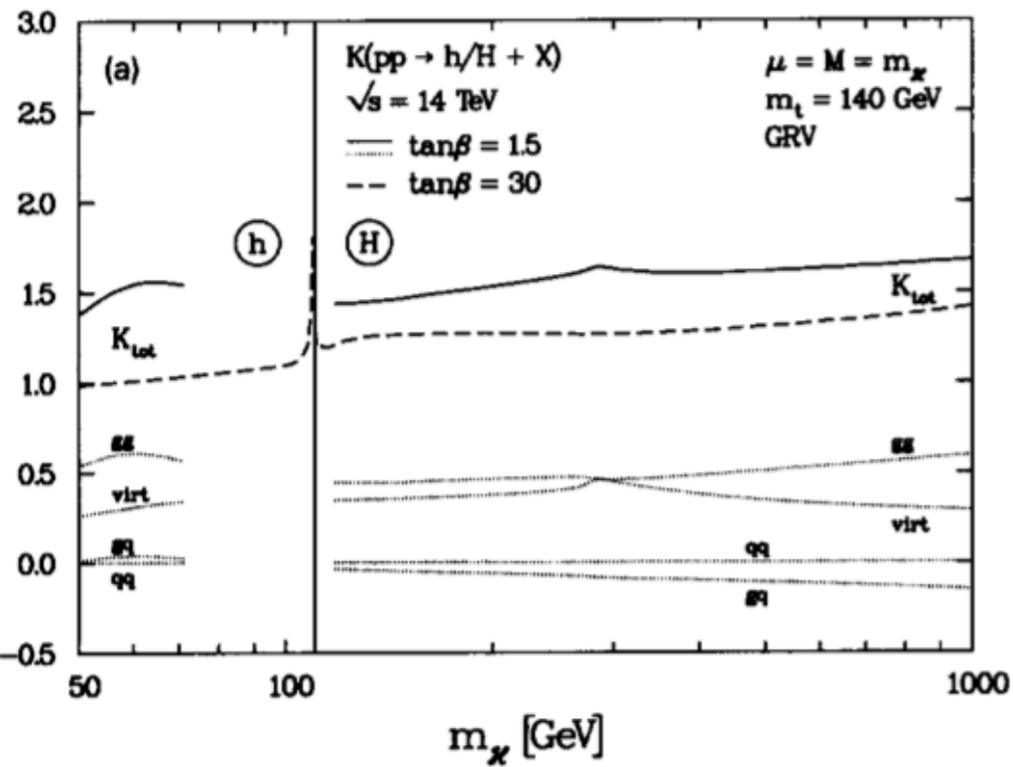
M. Spira (DESY), A. Djouadi (Montreal U.), D. Graudenz (LBL, Berkeley), P.M. Zerwas (DESY) (Sep, 1993)

Published in: *Phys.Lett.B* 318 (1993) 347-353

 pdf  links  DOI  cite

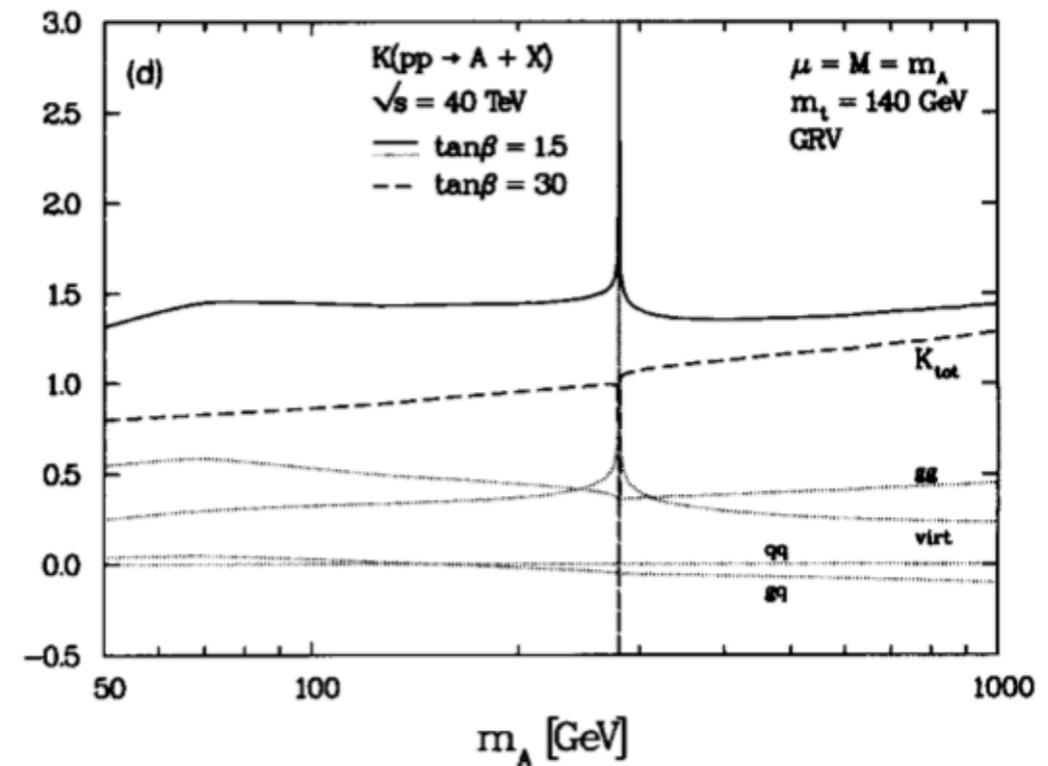
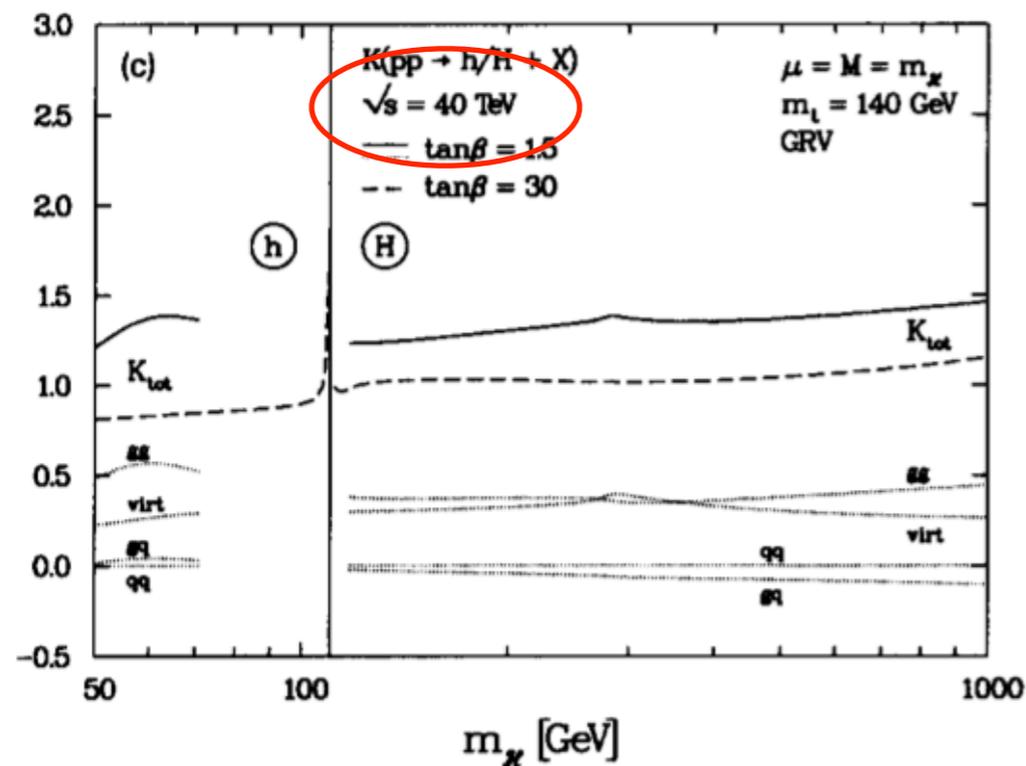
 174 citations

Heavy  
A. Djouadi  
Zerwas  
Published  
pdf



[Djouadi, Graudenz, Spira, Zerwas, '93]

Two an  
A. Djouadi  
Published  
pdf



#19

ESY)

tations

#7

p,

tations

*Higgs Boson Quantum Numbers*



---

# Higgs Boson Quantum Numbers

---

- **Quantum numbers of the Higgs boson:**
  - $J$  spin
  - $J^{PC}$   $P$  parity
  - $C$  charge conjugation
- **Observation in  $\gamma\gamma$ :** No spin 1 [Landau-Yang];  $C=+1$  [assuming charge invariance]
- **Theoretical Tools:**
  - \* helicity analyses
  - \* operator expansions
- **Systematic analysis of production and decay processes**
  - \* angular distributions, threshold analyses

# Higgs Boson Quantum Numbers

## Prospects of measuring the parity of Higgs particles

#5

M. Kramer (Mainz U., Inst. Phys.), Johann H. Kuhn (Karlsruhe U., TTP), M.L. Stong (Karlsruhe U., TTP), P.M. Zerwas (DESY) (Dec, 1993)

Published in: *Z.Phys.C* 64 (1994) 21-30 • e-Print: [hep-ph/9404280](https://arxiv.org/abs/hep-ph/9404280) [hep-ph]

 pdf  links  DOI  cite

 196 citations

## Workshop on CP Studies and Non-Standard Higgs Physics

#1

E. Accomando, A.G. Akeroyd, E. Akhmetzyanova, J. Albert, A. Alves et al. (Jul, 2006)

Published in: CERN Yellow Reports: Conference Proceedings • e-Print: [hep-ph/0608079](https://arxiv.org/abs/hep-ph/0608079) [hep-ph]

 pdf  links  DOI  cite

 410 citations

## Measuring the spin of the Higgs boson

#12

D.J. Miller (DESY), S.Y. Choi (DESY and Chonbuk Natl. U.), B. Eberle (DESY), M.M. Muhlleitner (DESY and Montpellier U.), P.M. Zerwas (DESY) (Feb, 2001)

Published in: *Phys.Lett.B* 505 (2001) 149-154 • Contribution to: [2nd Workshop of the 2nd Joint ECFA / DESY Study on Physics and Detectors for a Linear Electron Positron Collider](#), 1825-1834 • e-Print: [hep-ph/0102023](https://arxiv.org/abs/hep-ph/0102023) [hep-ph]

 pdf  links  DOI  cite

 116 citations

## Identifying the Higgs spin and parity in decays to Z pairs

#9

S.Y. Choi (Chonbuk Natl. U.), D.J. Miller (CERN), M.M. Muhlleitner (Montpellier U.), P.M. Zerwas (DESY) (Oct, 2002)

Published in: *Phys.Lett.B* 553 (2003) 61-71 • e-Print: [hep-ph/0210077](https://arxiv.org/abs/hep-ph/0210077) [hep-ph]

 pdf  links  DOI  cite

 265 citations

## Theoretical Basis of Higgs-Spin Analysis in $H \rightarrow \gamma\gamma$ and $Z\gamma$ Decays

#3

S.Y. Choi (Chonbuk Natl. U.), M.M. Muhlleitner (KIT, Karlsruhe, TP), P.M. Zerwas (DESY) (Sep, 2012)

Published in: *Phys.Lett.B* 718 (2013) 1031-1035 • e-Print: [1209.5268](https://arxiv.org/abs/1209.5268) [hep-ph]

M. Muhlleitner, KIT, 28 June 2022

Peter Fest at DESY

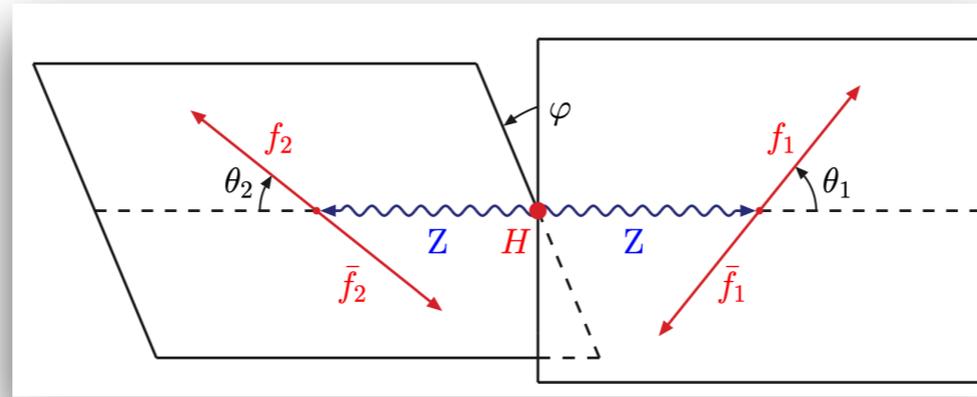
 pdf  DOI  cite

 55 citations

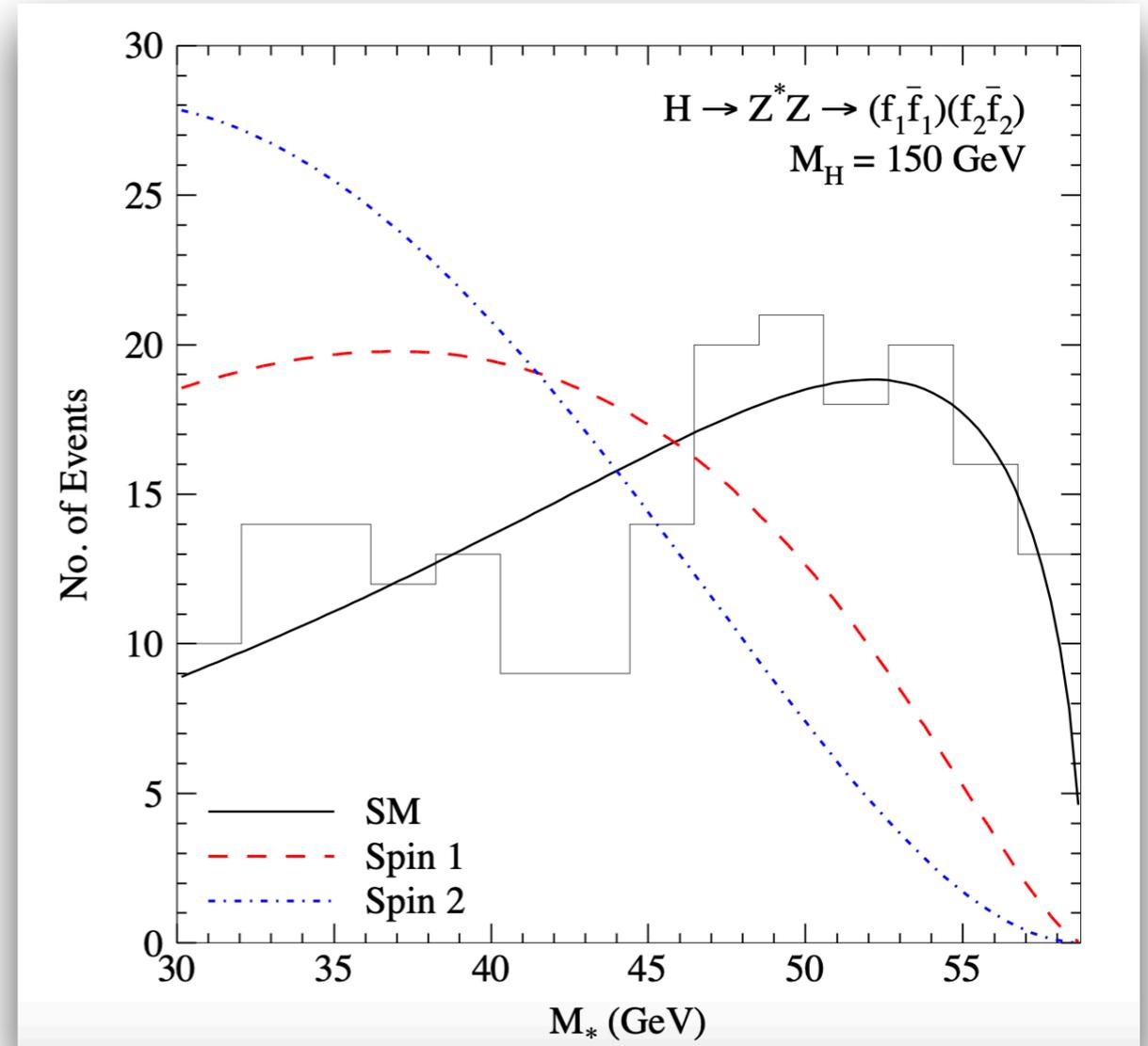
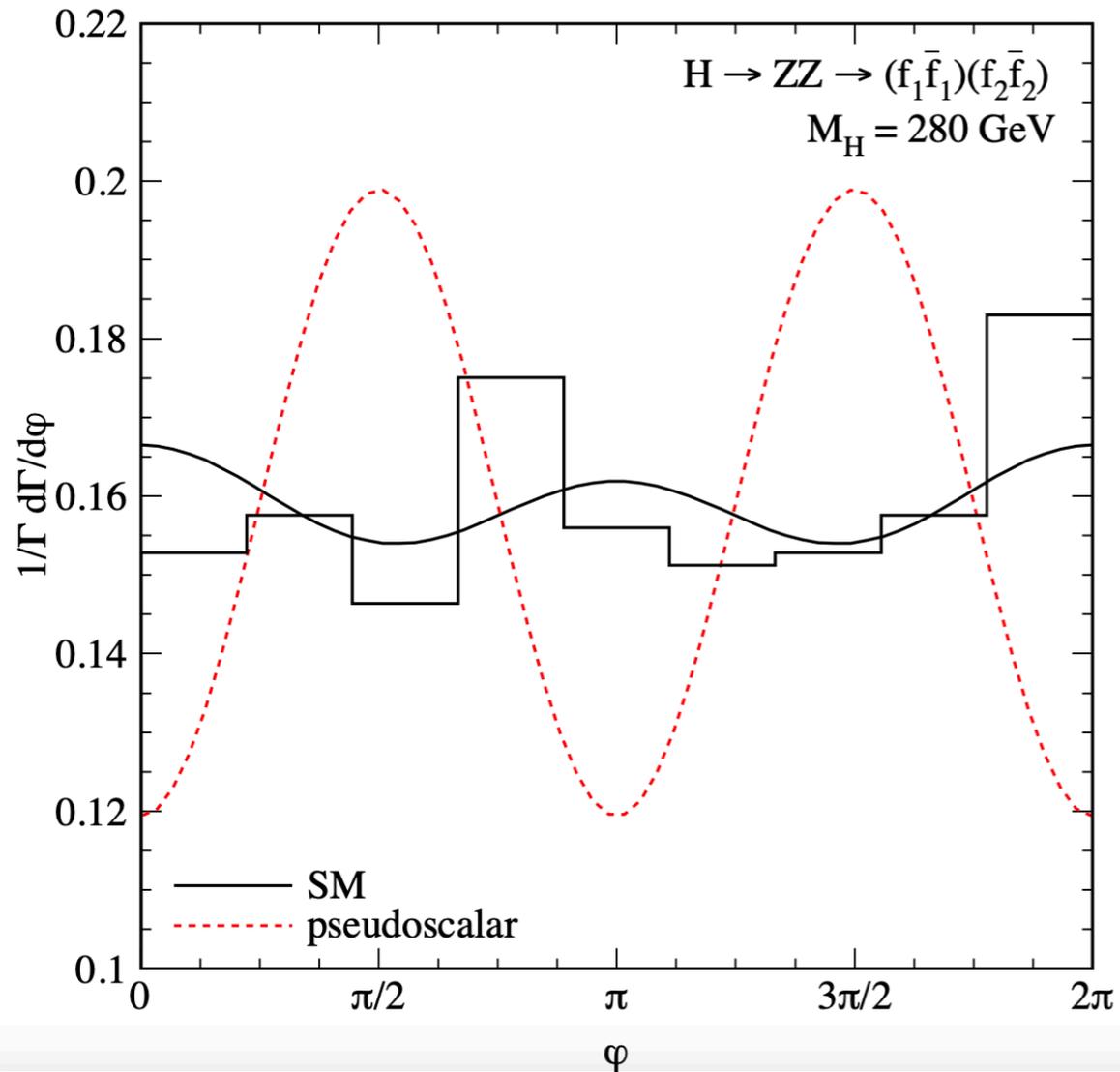
# Higgs Boson Quantum Numbers

[Choi, Miller, MM, Zerwas, '02]

parity



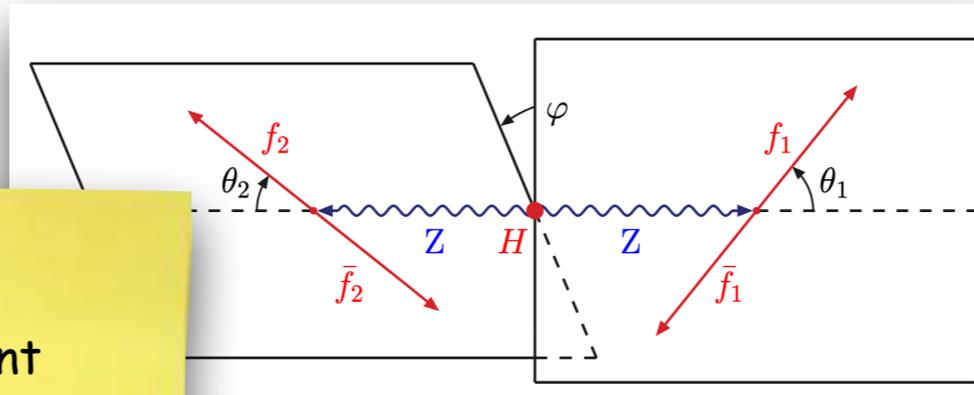
spin



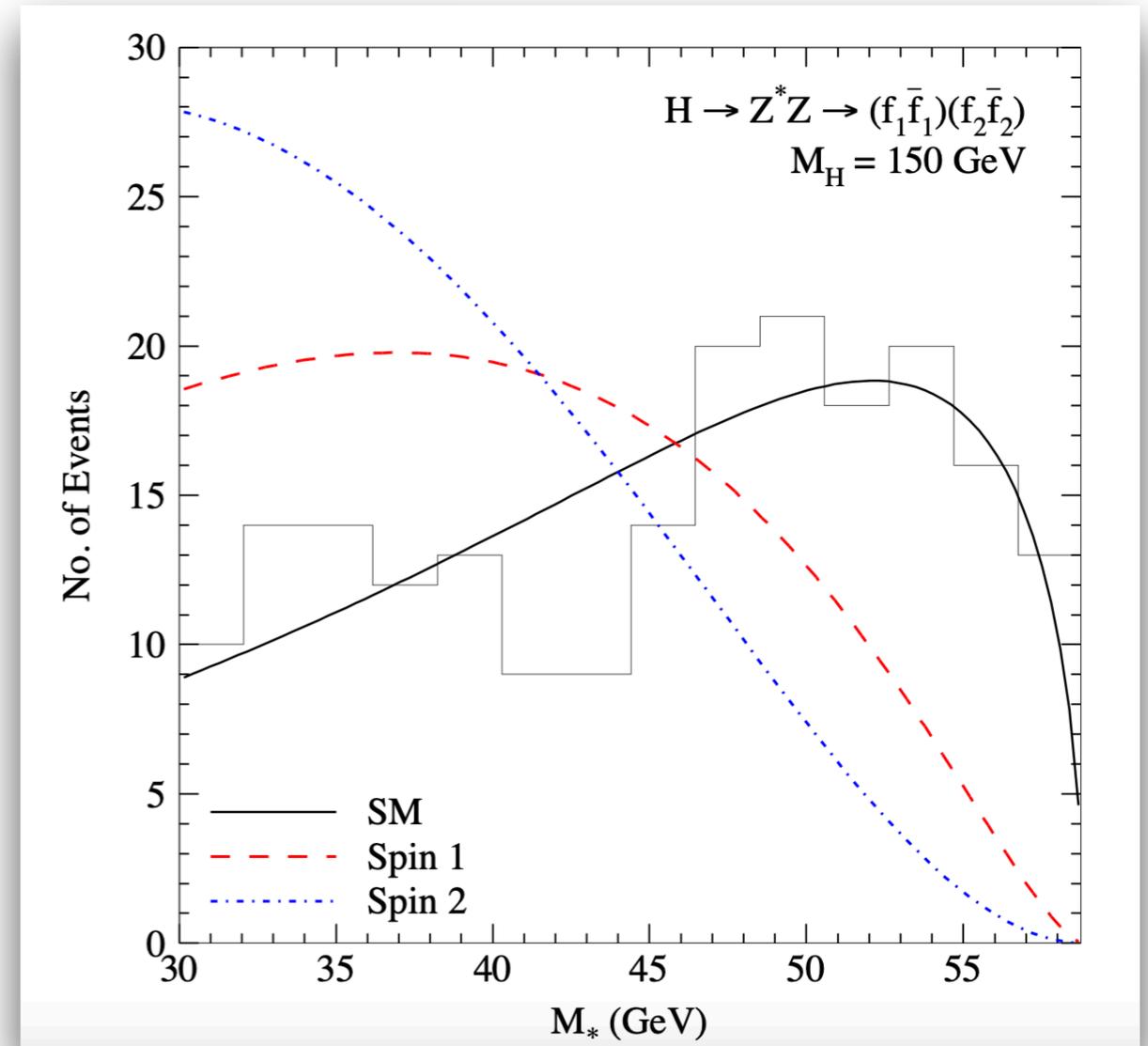
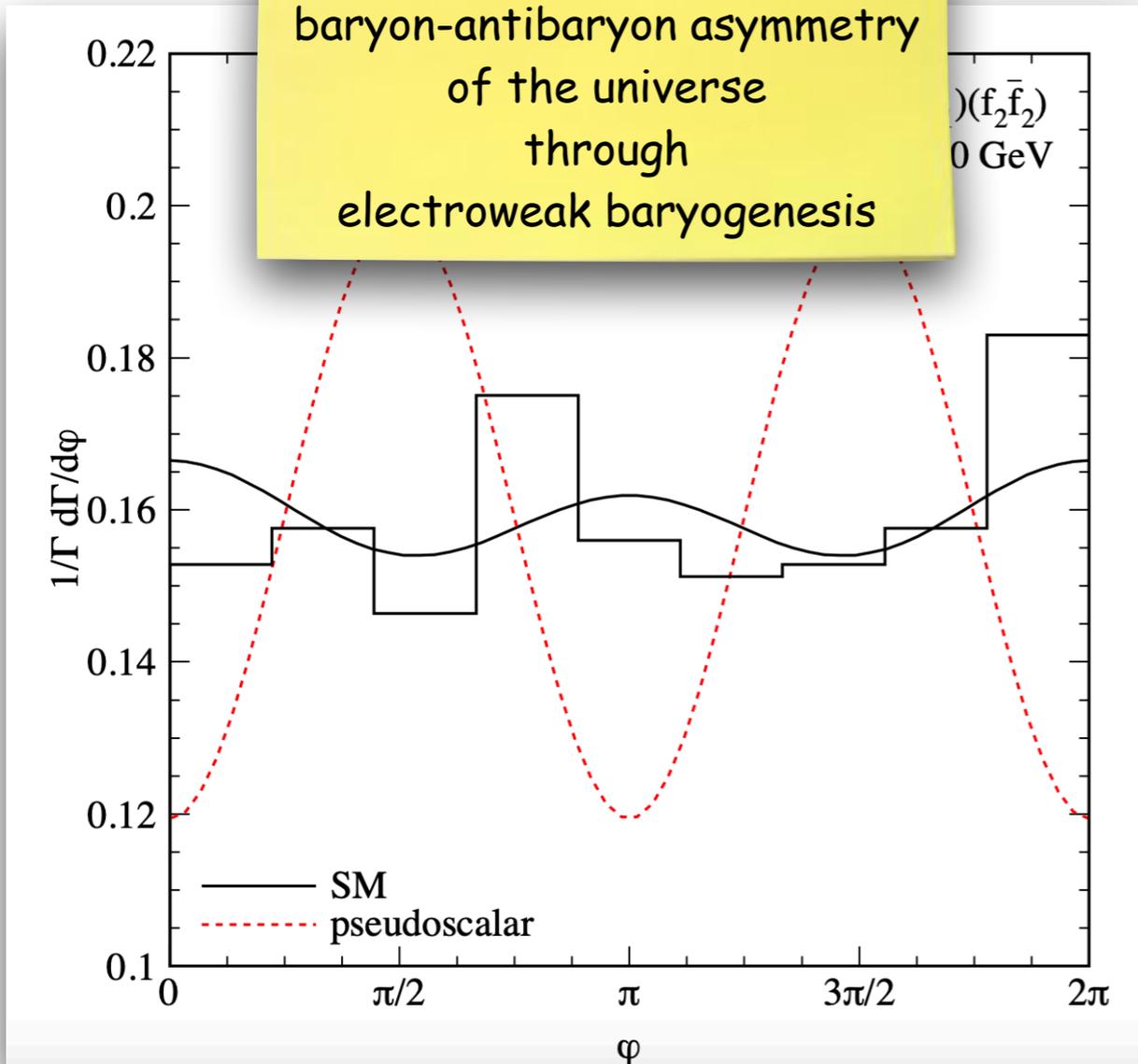
# Higgs Boson Quantum Numbers

[Choi, Miller, MM, Zerwas, '02]

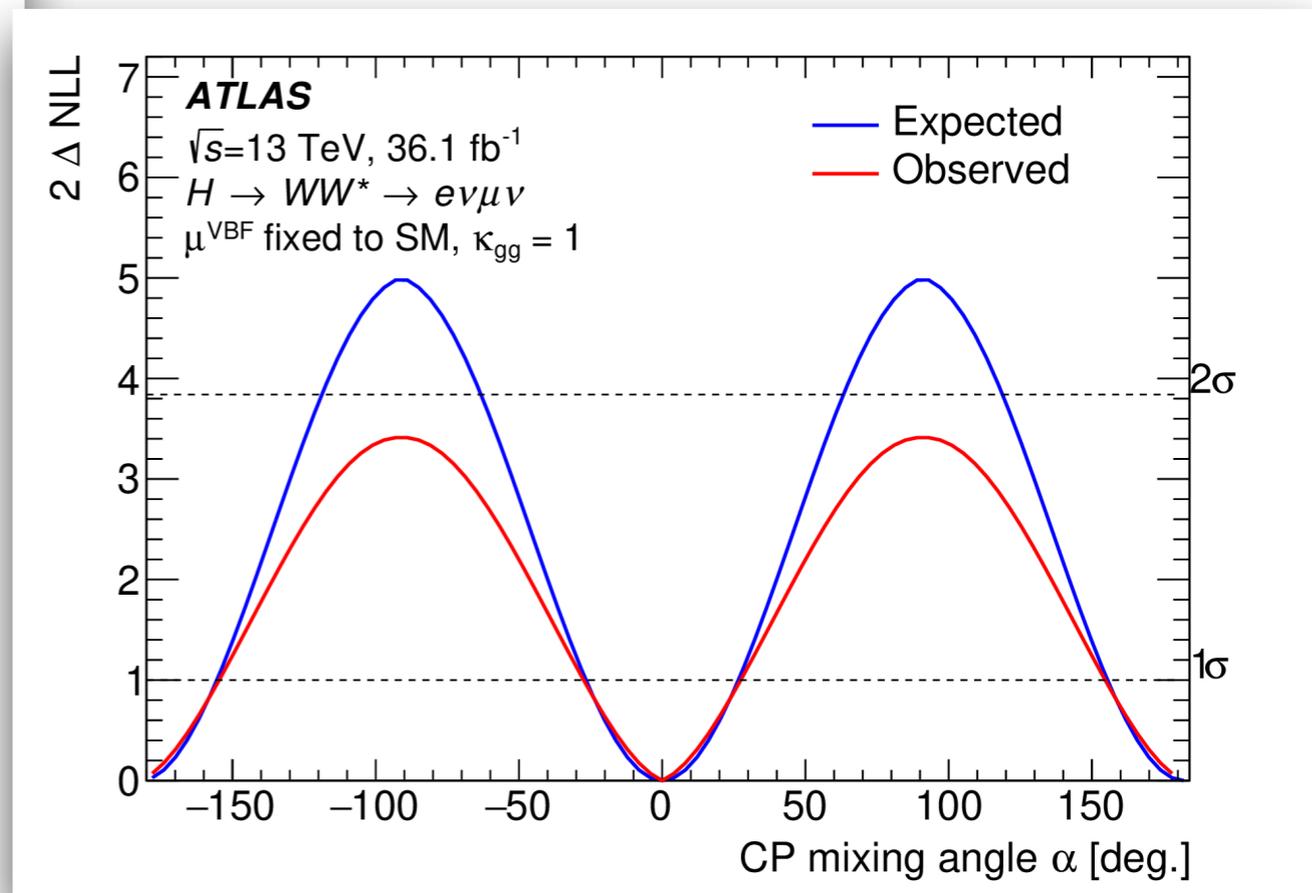
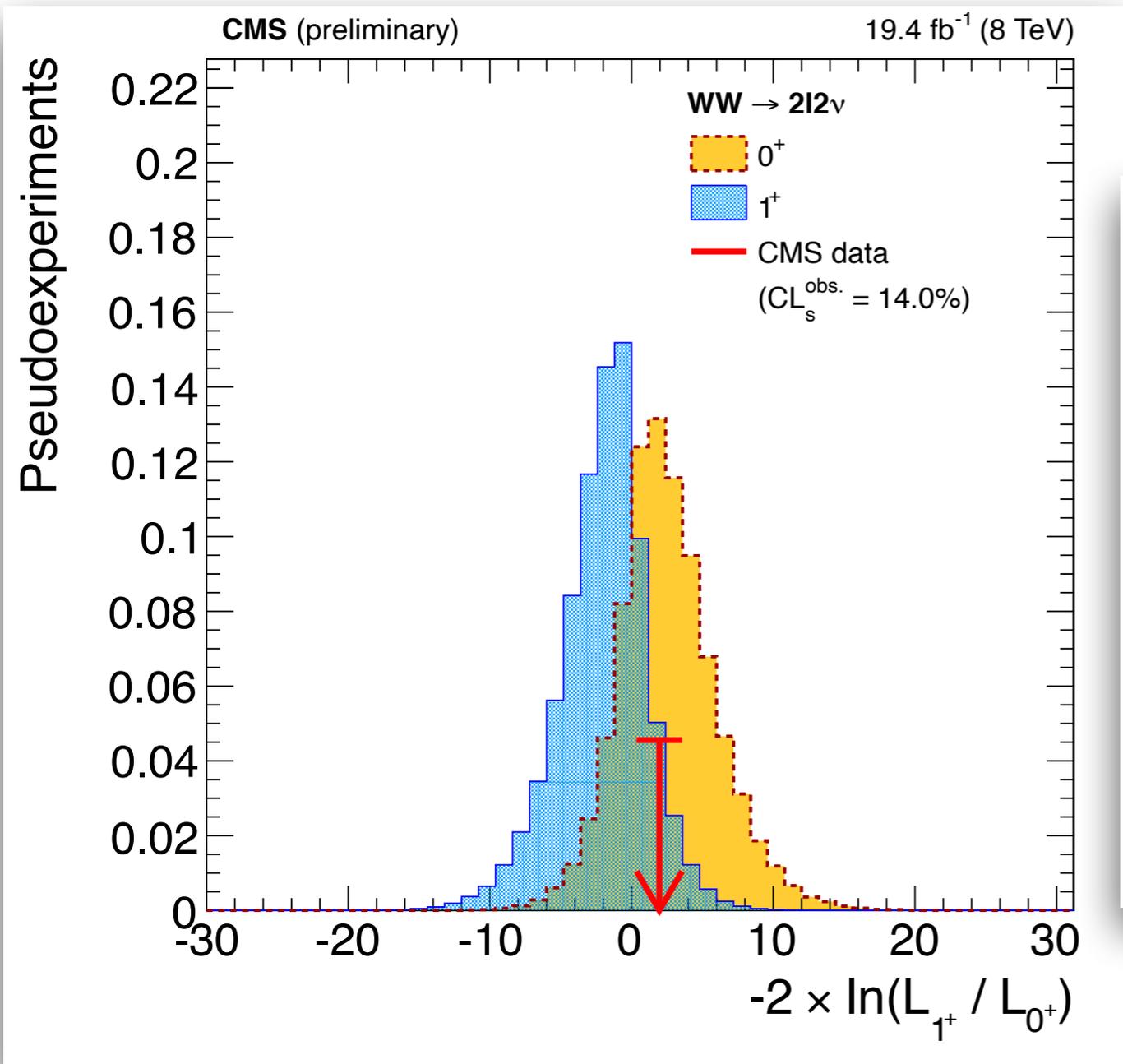
CP violation  
 Required ingredient  
 for generation of  
 baryon-antibaryon asymmetry  
 of the universe  
 through  
 electroweak baryogenesis



spin



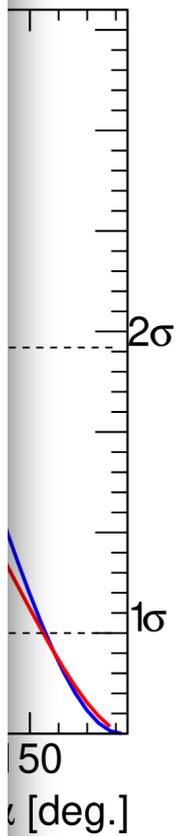
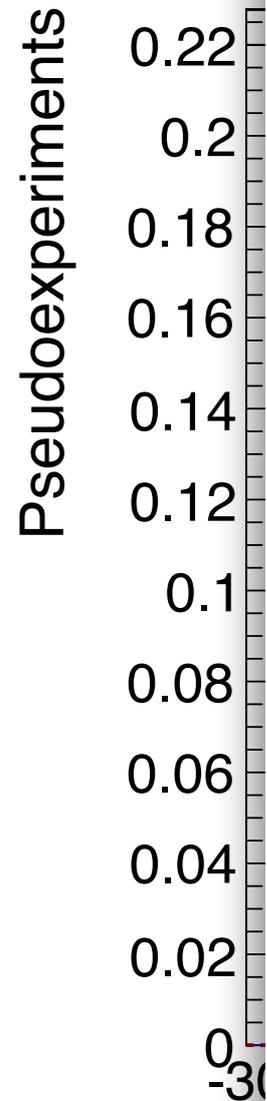
# CMS, ATLAS: Testing Spin-Parity Hypotheses



# CMS, ATLAS: Testing Spin-Parity Hypotheses



DESY Theory Workshop 2000 – Peter Zerwas (DESY) (right) tells Martin Holder (Siegen) to measure CP violation more precisely.

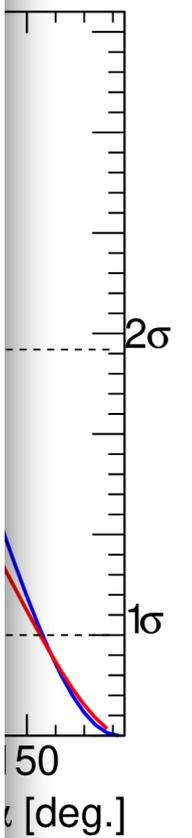


# CMS, ATLAS: Testing Spin-Parity Hypotheses



DESY Theory Workshop 2000 – Peter Zerwas (DESY) (right) tells Martin Holder (Siegen) to measure CP violation more precisely.

Pseudoexperiments  
0.22  
0.2  
0.18  
0.16  
0.14  
0.12  
0.1  
0.08  
0.06  
0.04  
0.02  
0  
-30



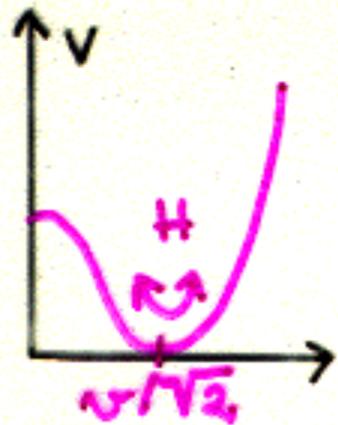
A lush green forest scene with a pond in the foreground. The pond is covered in a dense layer of bright green duckweed. A wooden bridge with a railing crosses the pond on the left side. The background is filled with tall, leafy trees, and a large weeping tree is prominent in the center. The sky is visible through the canopy, showing a clear blue color with some light clouds. The overall atmosphere is peaceful and natural.

*Higgs Pair  
Production*

# Establish the Higgs Mechanism

## SM HIGGS MECHANISM

task: establish Higgs mechanism *sui generis* 😊 for generating masses of fundamental particles



(1) Higgs excitation  $\equiv$  Higgs boson  
must be discovered

LEP2  
TeVatron  
LHC

(2) generating masses by interaction  
with Higgs field: coupling  $\sim$  mass

[LHC]  
LC

(3) Higgs field  $v/\sqrt{2}$  generated by Spont. Sym. Break :  
reconstruction of Higgs potential

LC

# Ultimate Test of the Higgs Mechanism

$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

- Higgs mass :  $M_H = \sqrt{2\lambda} v$
- trilinear Higgs self-coupling :  $\lambda_{HHH} = 3M_H^2/M_Z^2$  
- quadrilinear Higgs self-coupling :  $\lambda_{HHHH} = 3M_H^2/M_Z^4$  
- (units  $\lambda_0 = 33.8 \text{ GeV}/\lambda^2$ )

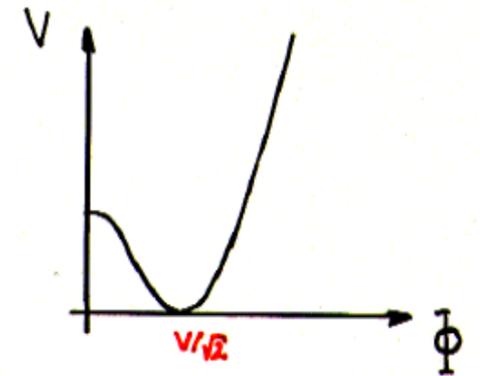
- (a) trilinear coupling: via Higgs pair production
- (b) quadrilinear coupling: via triple Higgs production

measurement of the Higgs self-couplings and reconstruction of the Higgs potential }  $\Rightarrow$  establish the scalar sector of the Higgs mechanism experimentally

$$V(\Phi) = \lambda \left( \Phi^\dagger \Phi - \frac{v}{2} \right)^2$$

$$v = 246 \text{ GeV}$$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H \end{pmatrix} \sim$$



@LC Workshop  
Fermilab 2000

# Ultimate Test of the Higgs Mechanism

$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

Higgs mass :  $M_H = \sqrt{2\lambda} v$

trilinear Higgs self-coupling :  $\lambda_{HHH} = 3M_H^2/M_Z^2$  

quadrilinear Higgs self-coupling :  $\lambda_{HHHH} = 3M_H^2/M_Z^4$  

(units  $\lambda_0 = 33.8 \text{ GeV}/\lambda^2$ )

(a) trilinear coupling : via Higgs pair production

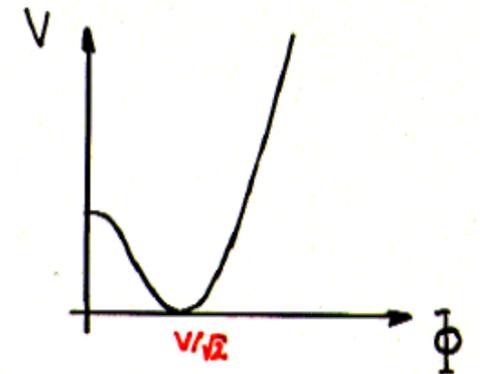
(b) quadrilinear coupling : via triple Higgs production

measurement of the Higgs self-couplings and reconstruction of the Higgs potential }  $\Rightarrow$  establish the scalar sector of the Higgs mechanism experimentally

$$V(\Phi) = \lambda \left( \Phi^\dagger \Phi - \frac{v}{2} \right)^2$$

$v = 246 \text{ GeV}$

$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H \end{pmatrix} \sim$



Ultimate understanding of mechanism of mass generation

# Higgs Pair Production and Beyond

## Multiple production of MSSM neutral Higgs bosons at high-energy $e^+ e^-$ colliders

#2

A. Djouadi (Karlsruhe U. and DESY), H.E. Haber (UC, Santa Cruz), P.M. Zerwas (DESY) (Feb, 1996)

Published in: *Phys.Lett.B* 375 (1996) 203-212 • e-Print: [hep-ph/9602234](https://arxiv.org/abs/hep-ph/9602234) [hep-ph]

 pdf  DOI  cite

 112 citations

## Pair production of neutral Higgs particles in gluon-gluon collisions

#13

T. Plehn (DESY), M. Spira (Hamburg U.), P.M. Zerwas (DESY) (Mar, 1996)

Published in: *Nucl.Phys.B* 479 (1996) 46-64, *Nucl.Phys.B* 531 (1998) 655-655 (erratum) • e-Print: [hep-ph/9603205](https://arxiv.org/abs/hep-ph/9603205) [hep-ph]

 pdf  DOI  cite

 416 citations

## Production of neutral Higgs boson pairs at LHC

#16

A. Djouadi (Montpellier U.), W. Kilian (Karlsruhe U., TTP), M. Muhlleitner (DESY), P.M. Zerwas (DESY) (Apr, 1999)

Published in: *Eur.Phys.J.C* 10 (1999) 45-49 • e-Print: [hep-ph/9904287](https://arxiv.org/abs/hep-ph/9904287) [hep-ph]

 pdf  DOI  cite

 271 citations

## Testing Higgs selfcouplings at $e^+ e^-$ linear colliders

#17

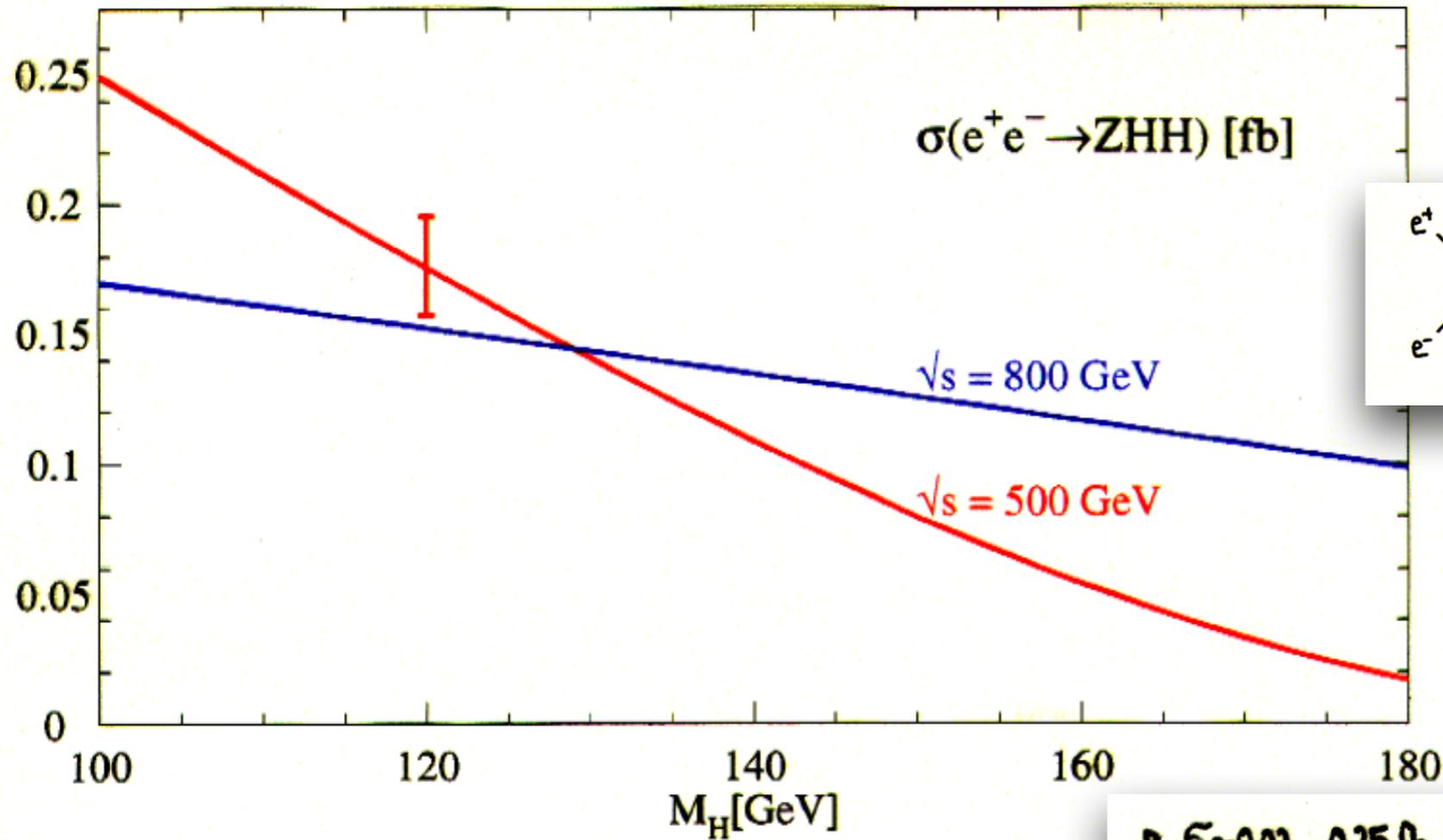
A. Djouadi (Montpellier U.), W. Kilian (Karlsruhe U., TTP), M. Muhlleitner (DESY), P.M. Zerwas (DESY) (Mar, 1999)

Published in: *Eur.Phys.J.C* 10 (1999) 27-43 • e-Print: [hep-ph/9903229](https://arxiv.org/abs/hep-ph/9903229) [hep-ph]

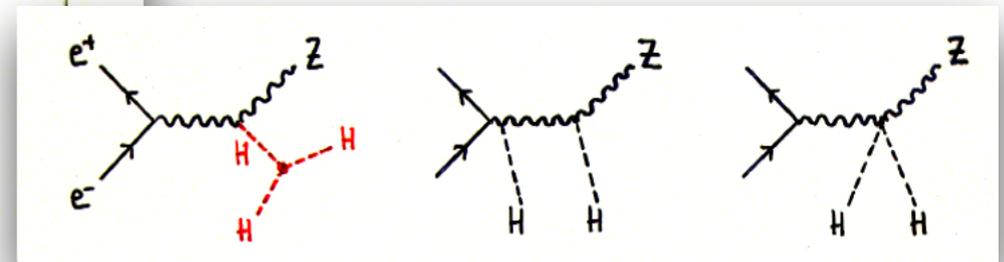
 pdf  DOI  cite

 249 citations

SM double Higgs-strahlung:  $\sqrt{s} = 500 \text{ GeV}, 800 \text{ GeV}$



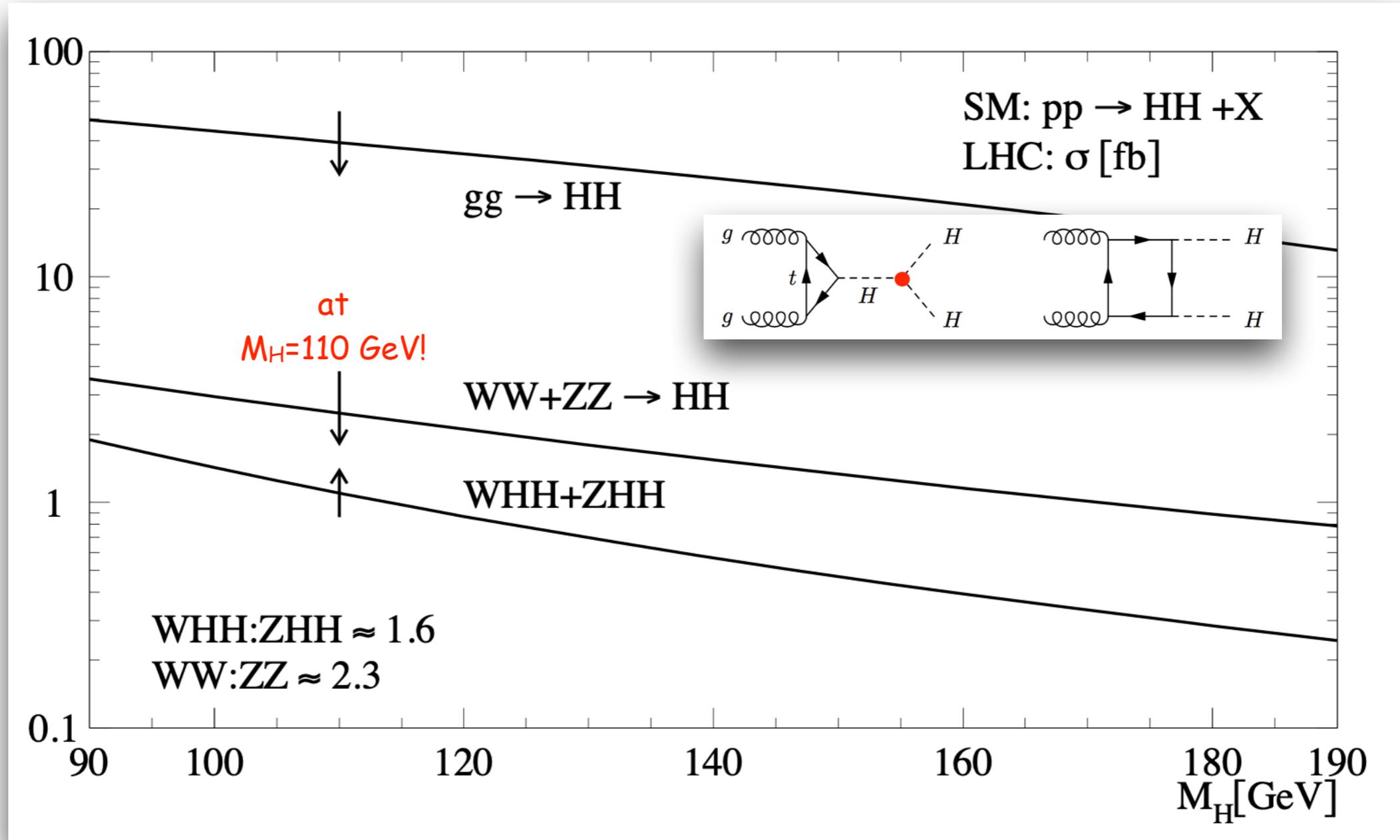
[Djouadi, Kilian, MM, Zerwas, '99]



- ▶  $\sigma \sim 0.02 \dots 0.25 \text{ fb} \approx 40 \dots 500 \text{ events for } \int \mathcal{L} = 2000 \text{ fb}^{-1}$
- ▶ polarized  $e^+, e^-$  beams  $\sim \sigma^{\text{pol}} = 2\sigma^{\text{unpol}}$
- ▶  $\sigma$  shows scaling behaviour
- ▶ I variation of  $\sigma(ZHH)$  for  $\Delta\lambda/\lambda = 0.2$
- ▶  $\sqrt{s} = 500 \text{ GeV}$  good choice for  $M_H = 120 \text{ GeV}$ :  $\sigma$  large  
sensitivity to  $\lambda_{HHH}$  large

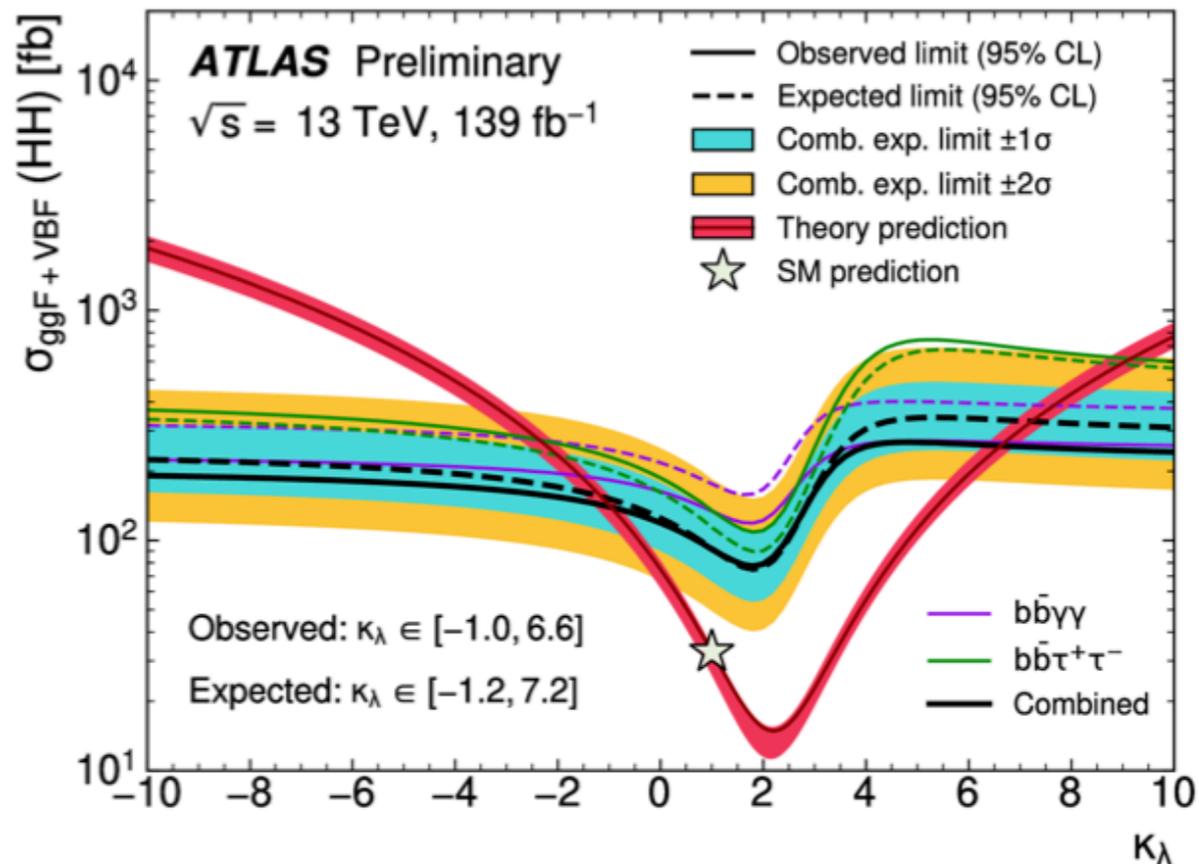
# SM Higgs Pair Production at the LHC

[Djouadi, Kilian, MM, Zerwas, '99]



♦ Challenge: small cross sections and large QCD backgrounds

# Experimental Results - Limits on Trilinear Higgs Self-Coupling



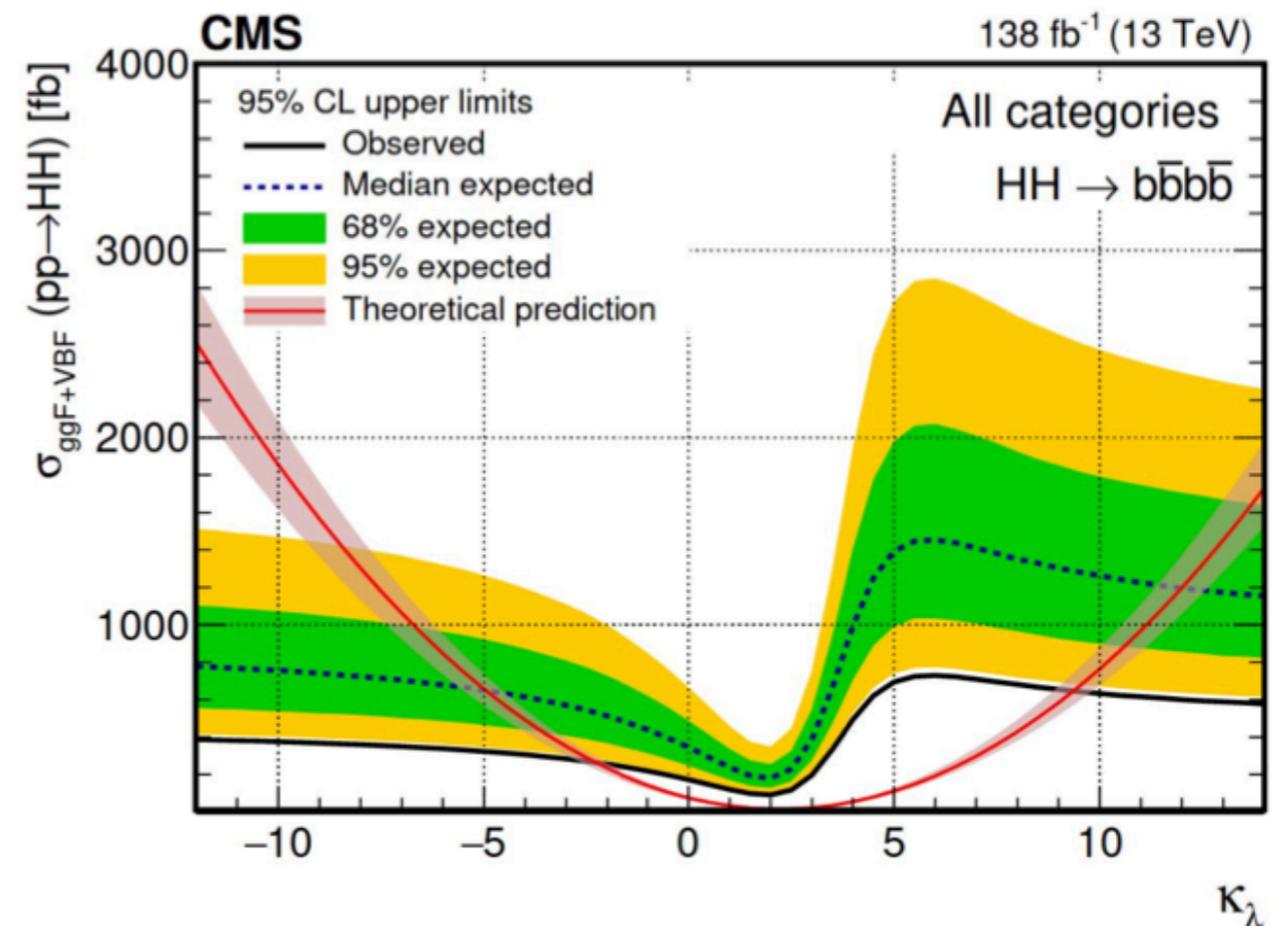
[Rui Zhang, ATLAS, HH Workshop' 22]

Observed:  $\kappa_\lambda \in [-1.0, 6.6]$

Expected:  $\kappa_\lambda \in [-1.2, 7.2]$

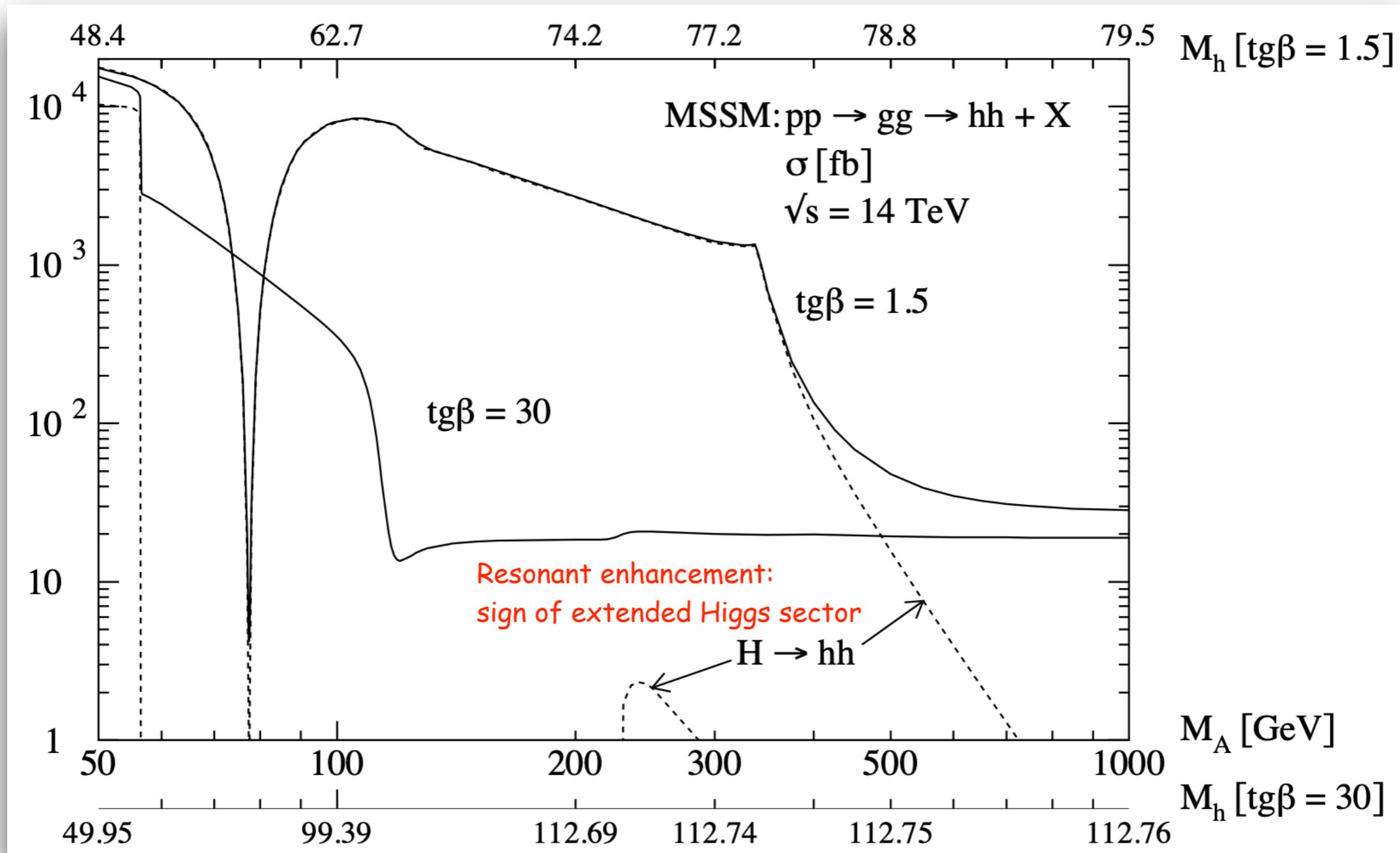
Obs.  $\kappa_\lambda \in [-2.3, 9.4]$   
 Exp.  $\kappa_\lambda \in [-5.0, 12.0]$

[Fabio Monti, CMS, HH Workshop' 22]



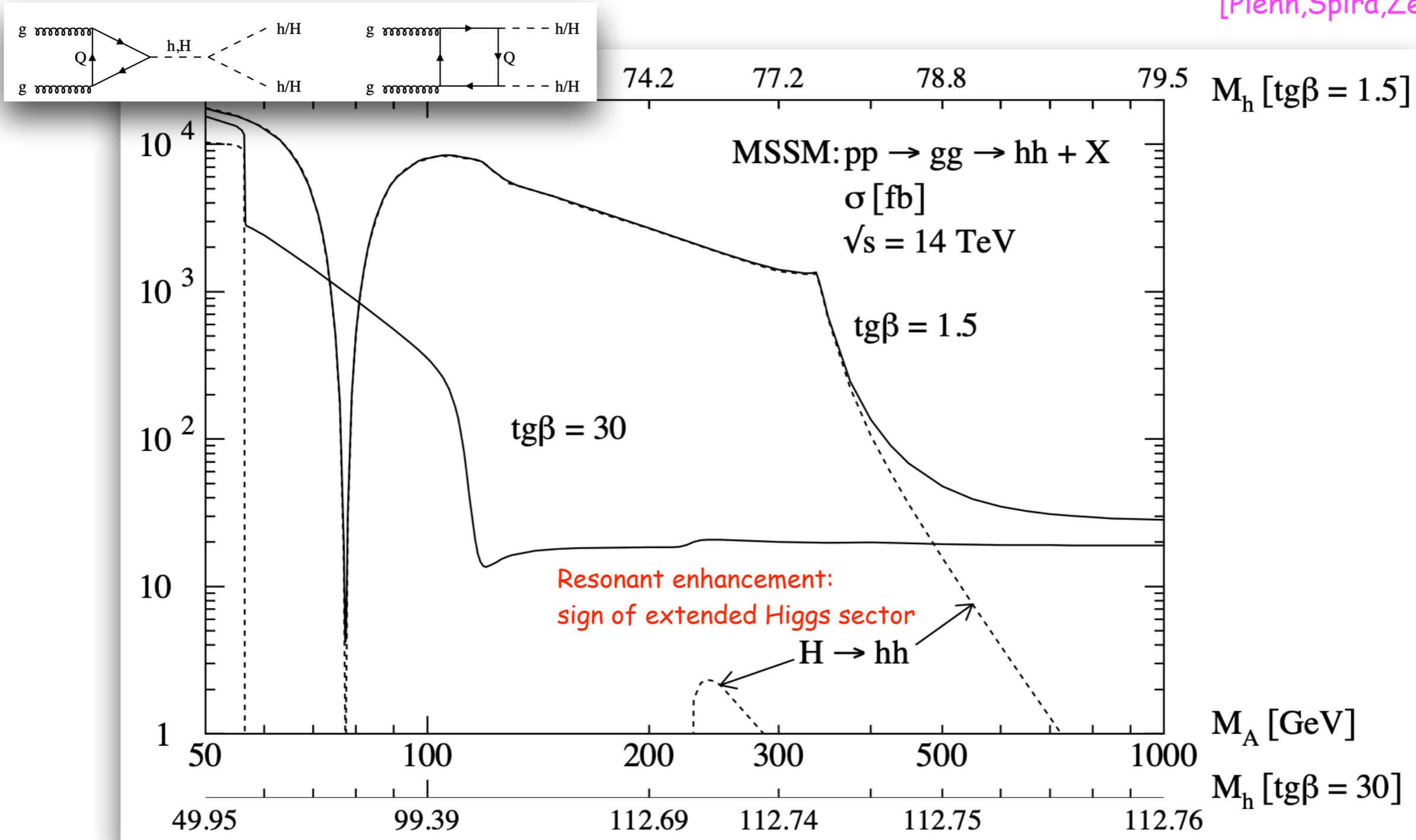
# MSSM Higgs Pair Production at the LHC

[Plehn, Spira, Zerwas, '96]

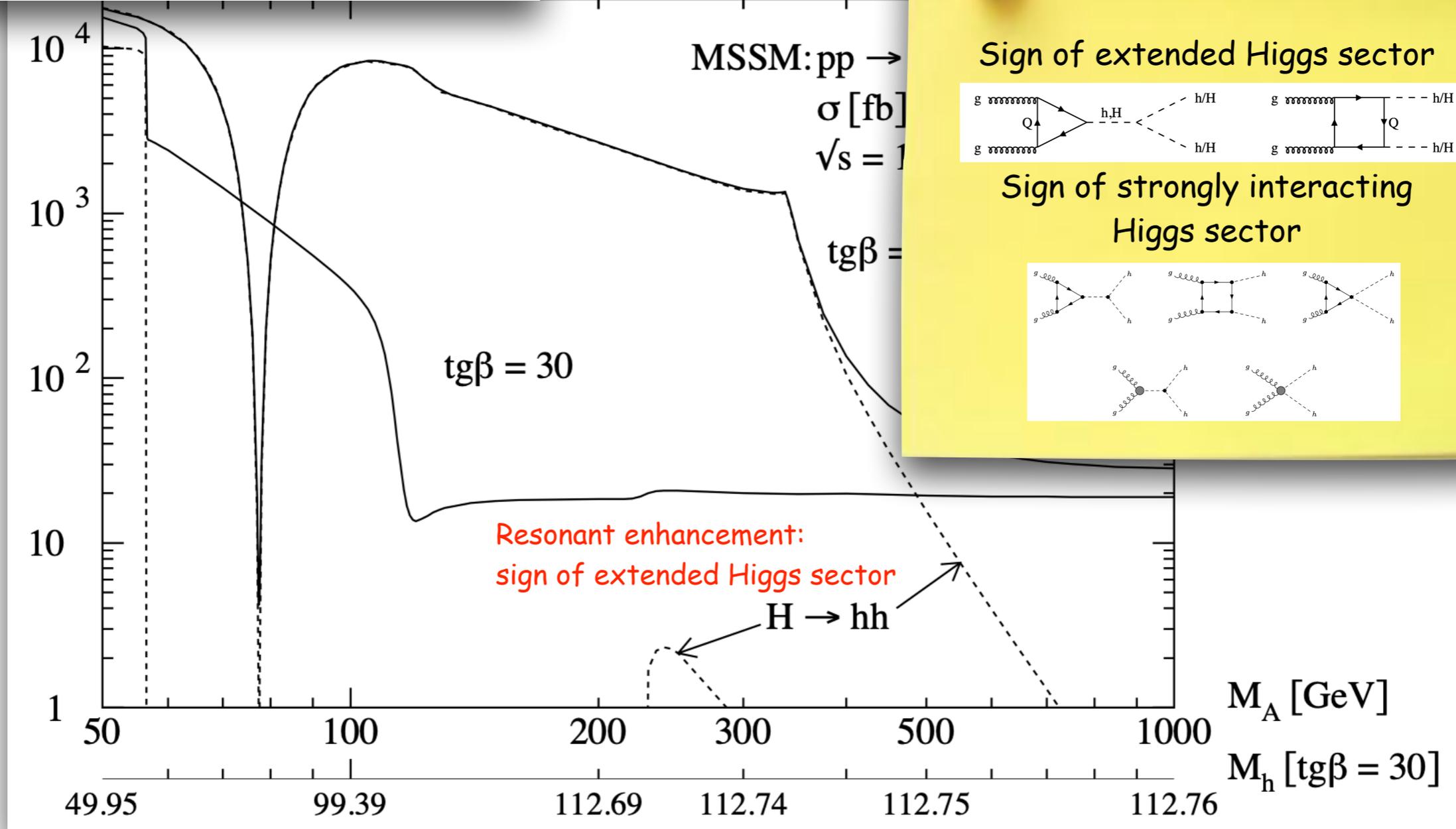
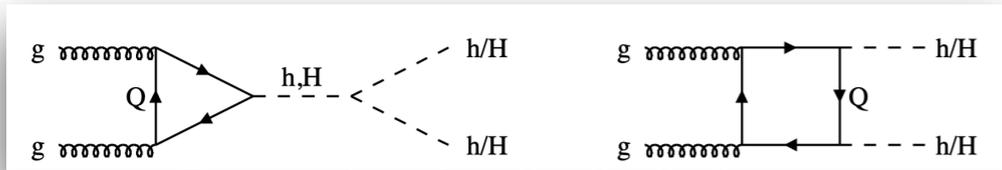


# MSSM Higgs Pair Production at the LHC

[Plehn, Spira, Zerwas, '96]



# MSSM Higgs Pair Production at the LHC



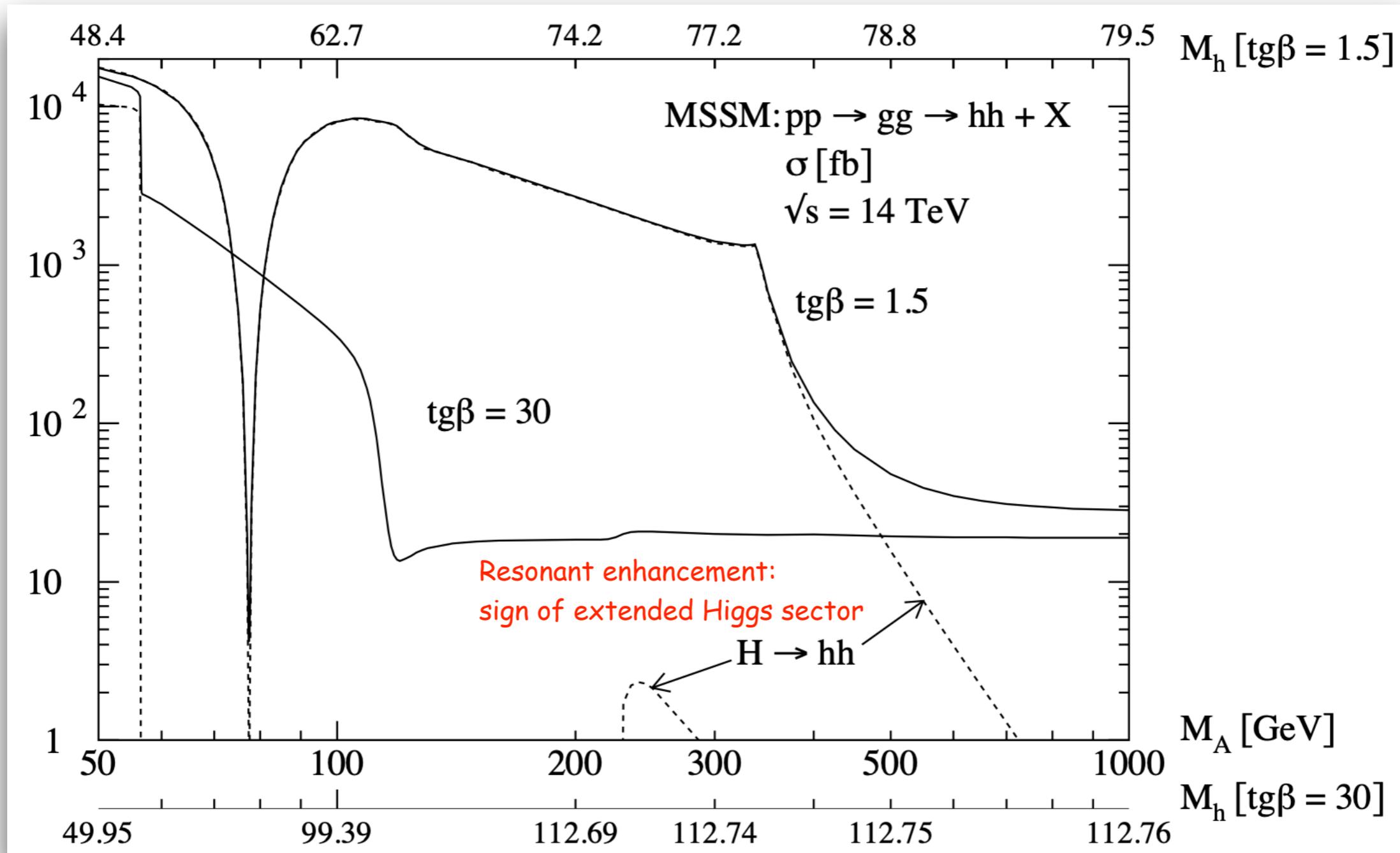
Deviation from SM di-Higgs cross section value:

Sign of extended Higgs sector

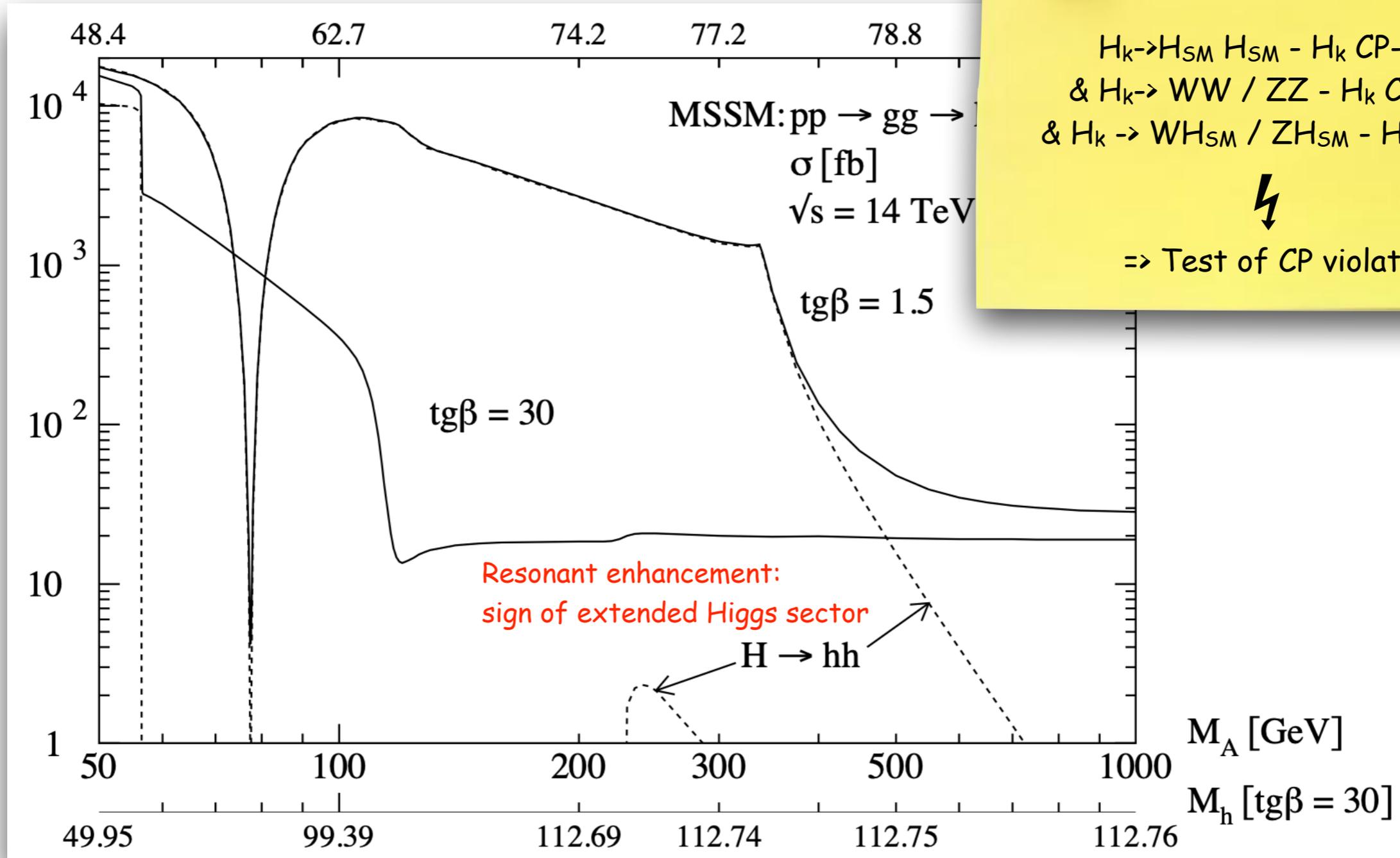
Sign of strongly interacting Higgs sector

# MSSM Higgs Pair Production at the LHC

[Plehn, Spira, Zerwas, '96]



# MSSM Higgs Pair Production at the LHC



Combination of Higgs decays:

$H_k \rightarrow H_{SM} H_{SM} - H_k$  CP-even  
 &  $H_k \rightarrow WW / ZZ - H_k$  CP-even  
 &  $H_k \rightarrow WH_{SM} / ZH_{SM} - H_k$  CP-odd



=> Test of CP violation

*Dark  
Matter*



---

# The Higgs Portal to a Hidden Sector

---

---

# The Higgs Portal to a Hidden Sector

---

## Exploring the Higgs portal

#3

[Christoph Englert](#) (Heidelberg U.), [Tilman Plehn](#) (Heidelberg U.), [Dirk Zerwas](#) (Orsay, LAL), [Peter M. Zerwas](#) (DESY and RWTH Aachen U.) (Jun, 2011)

Published in: *Phys.Lett.B* 703 (2011) 298-305 • e-Print: [1106.3097](#) [hep-ph]

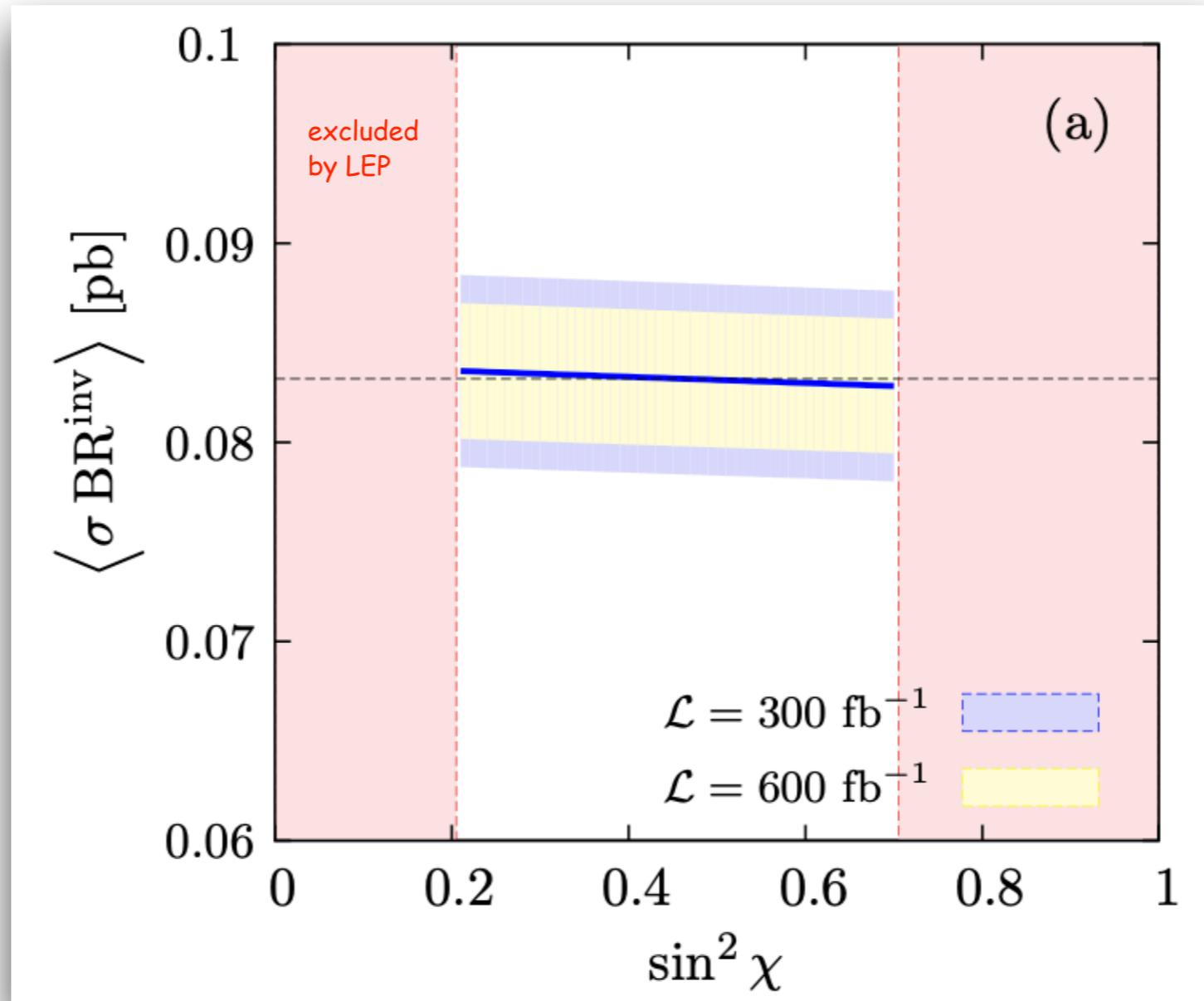
 pdf    DOI    cite

 216 citations

# The Higgs Portal to a Hidden Sector

SM Higgs sector extended by singlet field

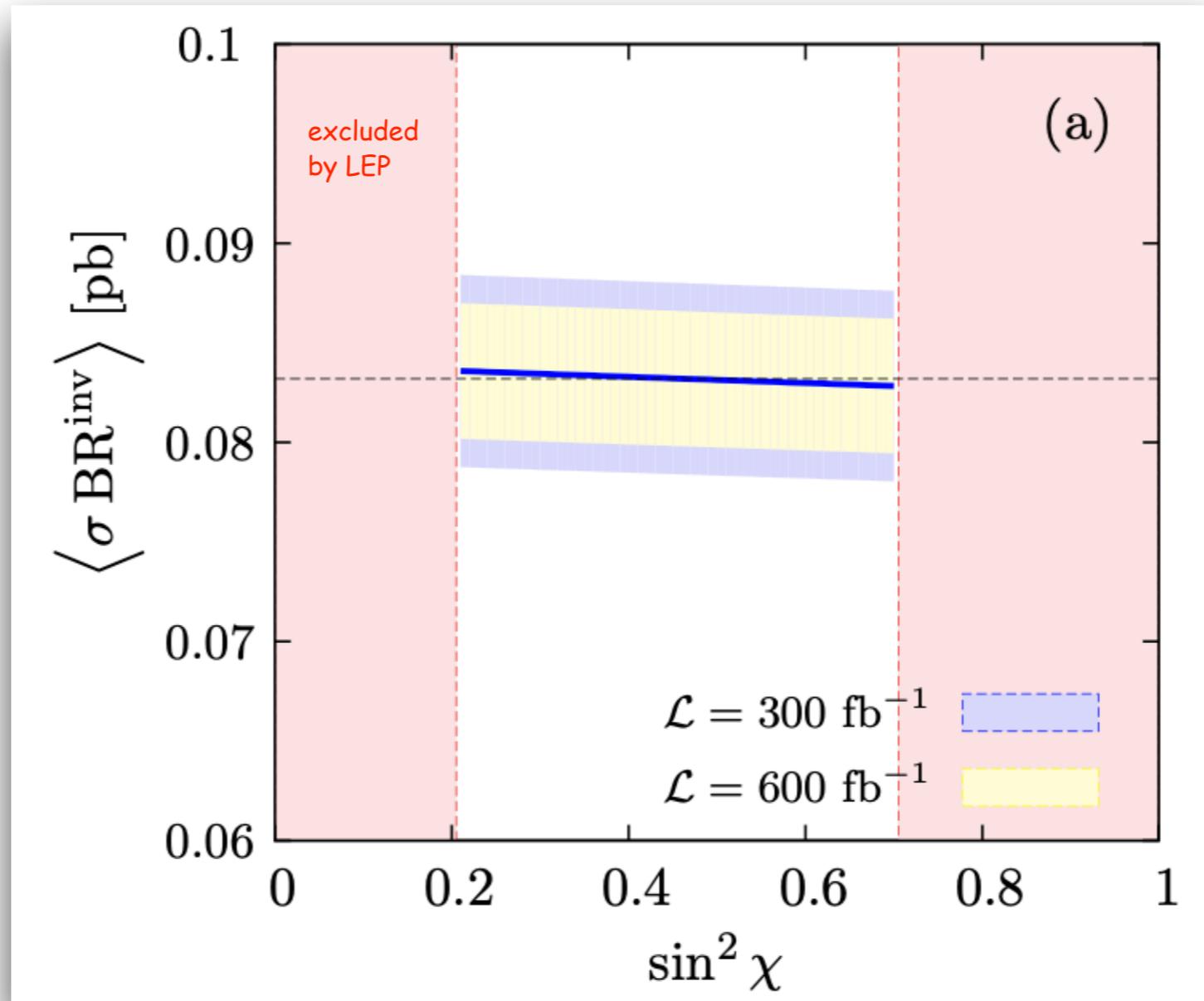
[Englert,Plehn,Zerwas,Zerwas,'11]



# The Higgs Portal to a Hidden Sector

SM Higgs sector extended by singlet field

[Englert, Plehn, Zerwas, Zerwas, '11]



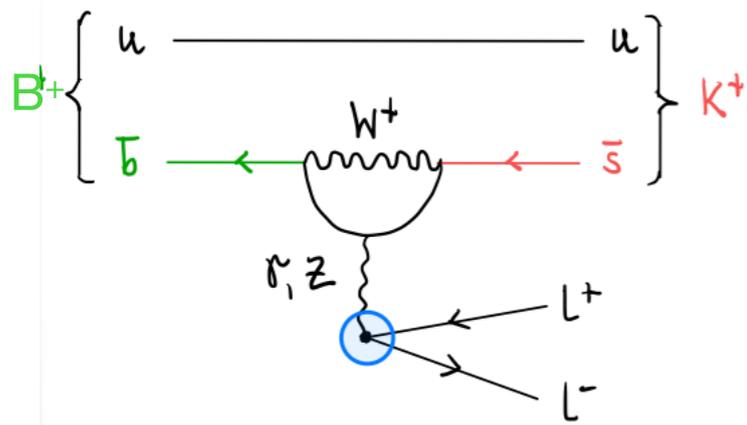
Incorporation of discrete symmetries => Higgs portal to DM

Insights in  
nature of  
Dark Matter

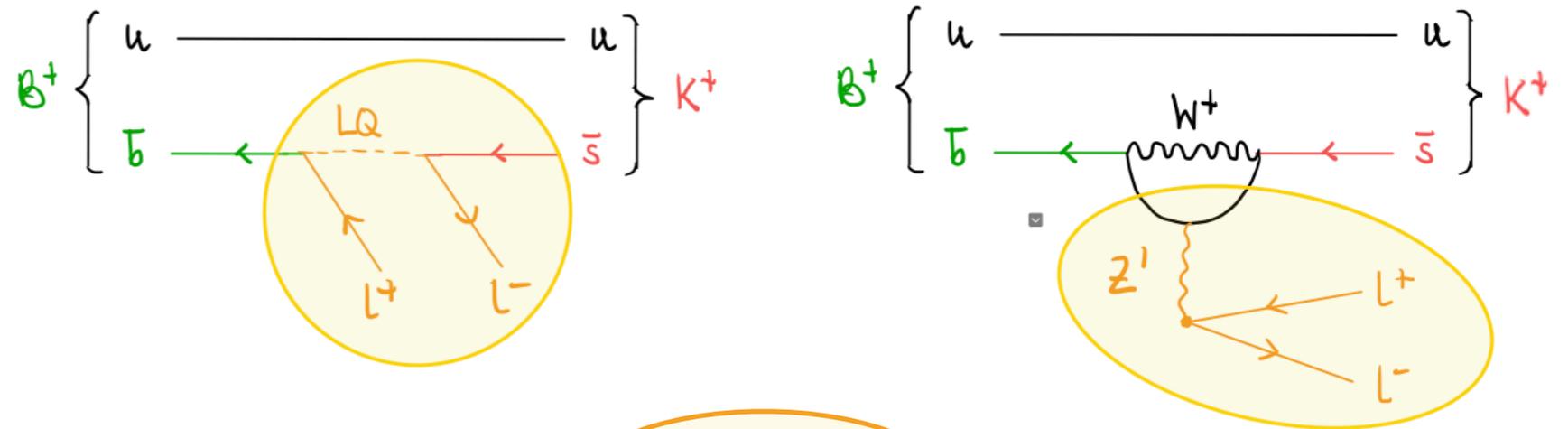
Varia 😊



# New Physics in $B^+ \rightarrow K^+ \mu^+ \mu^-$ ?



measurement in disagreement w/ SM  
 $\gamma, Z$  interact w/ same strength w/ all leptons  
 $\Rightarrow$  equal number of  $\mu^\pm, e^\pm$  in final state



New Physics

Leptoquarks

Z' bosons

can couple w/ different strength to  $\mu^\pm, e^\pm$

w/ mass somewhere between 1TeV and 40TeV

high-lumi LHC

physics case for 100 TeV collider

# Leptoquark Pair Production

## Pair production of scalar leptoquarks at the Tevatron

#6

[M. Kramer](#) (Rutherford), [T. Plehn](#) (DESY), [M. Spira](#) (CERN), [P.M. Zerwas](#) (DESY) (Apr, 1997)

Published in: *Phys.Rev.Lett.* 79 (1997) 341-344 • e-Print: [hep-ph/9704322](#) [hep-ph]

 pdf  DOI  cite

 195 citations

## Pair production of scalar leptoquarks at the CERN LHC

#2

[M. Kramer](#) (Edinburgh U.), [T. Plehn](#) (CERN and Munich, Max Planck Inst.), [M. Spira](#) (PSI, Villigen), [P.M. Zerwas](#) (DESY and Fermilab) (Nov, 2004)

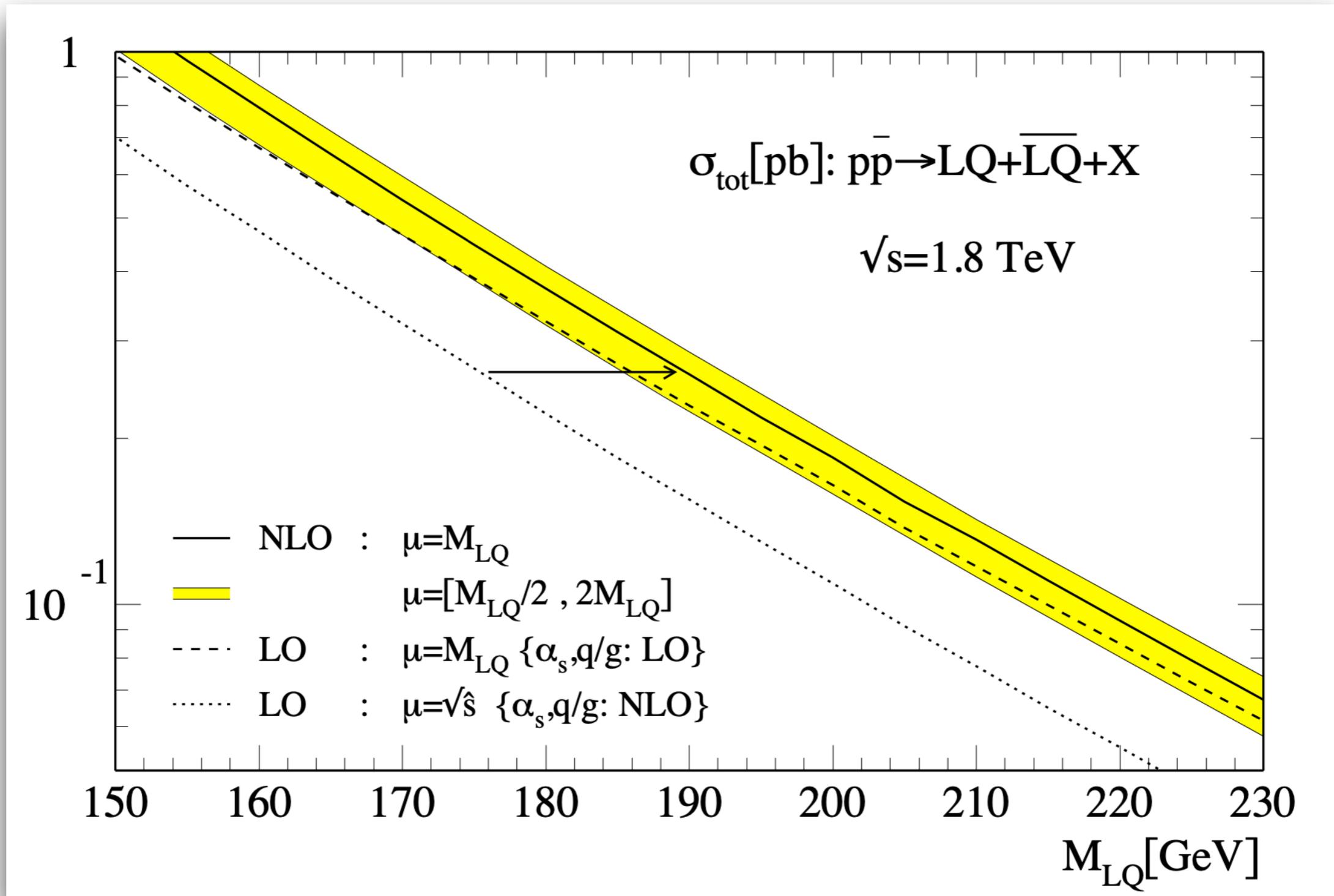
Published in: *Phys.Rev.D* 71 (2005) 057503 • e-Print: [hep-ph/0411038](#) [hep-ph]

 pdf  links  DOI  cite

 164 citations

# Leptoquark Pair Production at Tevatron

[Krämer, Plehn, Spira, Zerwas, '97]



# Conclusions - What we learn from what we have already!

Gain insight in the underlying theory

glimpse at the early universe

Comparison with measured Higgs mass value:

Restriction of parameter space of BSM Models

Combination of Higgs decays:  
 $H_k \rightarrow H_{SM} H_{SM} - H_k$  CP-even  
&  $H_k \rightarrow WW / ZZ - H_k$  CP-even  
&  $H_k \rightarrow WH_{SM} / ZH_{SM} - H_k$  CP-odd  
 $\Rightarrow$  Test of CP violation

Deviation from SM di-Higgs cross section value:  
Sign of extended Higgs sector  
Sign of strongly interacting Higgs sector

CP violation  
Required ingredient for generation of baryon-antibaryon asymmetry of the universe through electroweak baryogenesis

Insights in nature of Dark Matter

Combination of production & decay  
 $\Rightarrow$  Higgs couplings  
 $\Rightarrow$  test if  $g_{HXX} \sim m_X$   
insight in mechanism of mass generation

- \* Self-consistency test of SM at the quantum level
- \* stability of the electroweak vacuum
- \* Test BSM parameter relations  $\Rightarrow$  indirect constraint of BSM parameters

Hint on underlying theory  
restriction of parameter space of BSM models

Ultimate understanding of mechanism of mass generation

# Conclusions - What we learn from what we have already!

Gain insight in the underlying theory

glimpse at the early universe

Comparison with measured Higgs mass value:

Restriction of parameter space of BSM Models

Combination of Higgs decays:  
 $H_k \rightarrow H_{SM} H_{SM} - H_k$  CP-even  
&  $H_k \rightarrow WW / ZZ - H_k$  CP-even  
&  $H_k \rightarrow WH_{SM} / ZH_{SM} - H_k$  CP-odd  
 $\Rightarrow$  Test of CP violation

Deviation from SM di-Higgs cross section value:  
Sign of extended Higgs sector  
Sign of strongly interacting Higgs sector

CP violation  
Required ingredient for generation of baryon-antibaryon asymmetry of the universe through electroweak baryogenesis

- \* Self-consistency test of SM at the quantum level
- \* stability of the electroweak vacuum
- \* Test BSM parameter relations  $\Rightarrow$  indirect constraint of BSM parameters

Hint on underlying theory restriction of parameter space of BSM models



# Conclusions - What we learn from what we have already!

Gain insight in the underlying theory

glimpse at the early universe

Comparison with measured Higgs mass value:

Restriction of parameter space of BSM Models

Combination of Higgs decays:  
 $H_k \rightarrow H_{SM} H_{SM} - H_k$  CP-even  
&  $H_k \rightarrow WW / ZZ - H_k$  CP-even  
&  $H_k \rightarrow WH_{SM} / ZH_{SM} - H_k$  CP-odd  
 $\Rightarrow$  Test of CP violation

Deviation from SM di-Higgs cross section value:  
Sign of extended Higgs sector  
Sign of strongly interacting Higgs sector

CP violation  
Required ingredient for generation of baryon-antibaryon asymmetry of the universe through electroweak baryogenesis

Insights in nature of Dark Matter

Combination of production & decay  
 $\Rightarrow$  Higgs couplings  
 $\Rightarrow$  test if  $g_{HXX} \sim m_X$   
insight in mechanism of mass generation

- \* Self-consistency test of SM at the quantum level
- \* stability of the electroweak vacuum
- \* Test BSM parameter relations  $\Rightarrow$  indirect constraint of BSM parameters

Hint on underlying theory  
restriction of parameter space of BSM models

Ultimate understanding of mechanism of mass generation

# Conclusions - What we learn from what we have already!

Gain insight in the underlying theory

glimpse at the early universe

Comparison with

Exciting times ahead!

Combination of Higgs decays:

$H_k \rightarrow H_{SM} H_{SM} - H_k$  CP-even

$H_k \rightarrow WW / ZZ - H_k$  CP-even

$H_k \rightarrow WH_{SM} / ZH_{SM} - H_k$  CP-odd

of CP violation

Deviation from SM cross section

Sign of extended H

Sign of strongly in Higgs sect

Insights in nature of Dark Matter

\* Self-consistency test quantum level

\* stability of the elect

\* Test BSM parameter relations  $\Rightarrow$

indirect constraint of BSM parameters

Combination of production & decay

Higgs couplings

if  $g_{HXX} \sim m_X$

in mechanism

mass generation

restriction of parameter space of BSM models

Ultimate understanding of mechanism of mass generation





*Thank you for  
your attention!*



# Particle and Astroparticle Physics Colloquium Hamburg June 28, 2022

Dear friends,

Many thanks for the competent discussion of open questions in particles physics. We hope – as shown by Margarete – answers will be found soon, and we look forward to exciting developments of particle physics in the near future!

Finally thank you to:

- Margarete Mühlleitner for the excellent talk
- Wilfried Buchmüller for the idea
- DESY Theory Department for the organization of the event
- Your attendance 😊

Four Jet Events in  $e^+ e^-$  A

M. Bengtsson (Aachen, Tech. Hochsch.), P.  
Mar, 1988

Scaling Violations in

C. Peterson (SLAC), D. Schlatter (SLAC),  
Apr, 1982

Production by Neutrinos

(Aachen, Tech. Hochsch.), P.M. Zerwas (Aachen, Tech. Hochsch.)

(DESY), T.F. Walsh (DESY), P.M.  
Hochsch.)

Colliders: QCD corrections

(Aachen, Tech. Hochsch.), P.M. Zerwas (Aachen, Tech. Hochsch.)