Particle and Astroparticle Physics Colloquium Hamburg
June 28, 2022

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. Gouverned 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.

Four Jet Events in e+ e- A
M. Bengtsson (Aachen,
Mar, 1988

on Production by Neutrinos
hsch.), P.M. Zerwas (Aachen, Tech. Hochsch.)

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

Scaling Violations in Inclusive e+ e- Ann
C. Peterson (SLAC), D. Schlatter (SLAC), J. Schmitt (SLAC), Peter M. Zerwas
Apr, 1982

Apr, 1979

ton colliders: QCD corrections
pira (Aachen, Tech. Hochsch.), P.M. Zerwas (Aachen, Tech. Hochsch.)


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 cantine 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

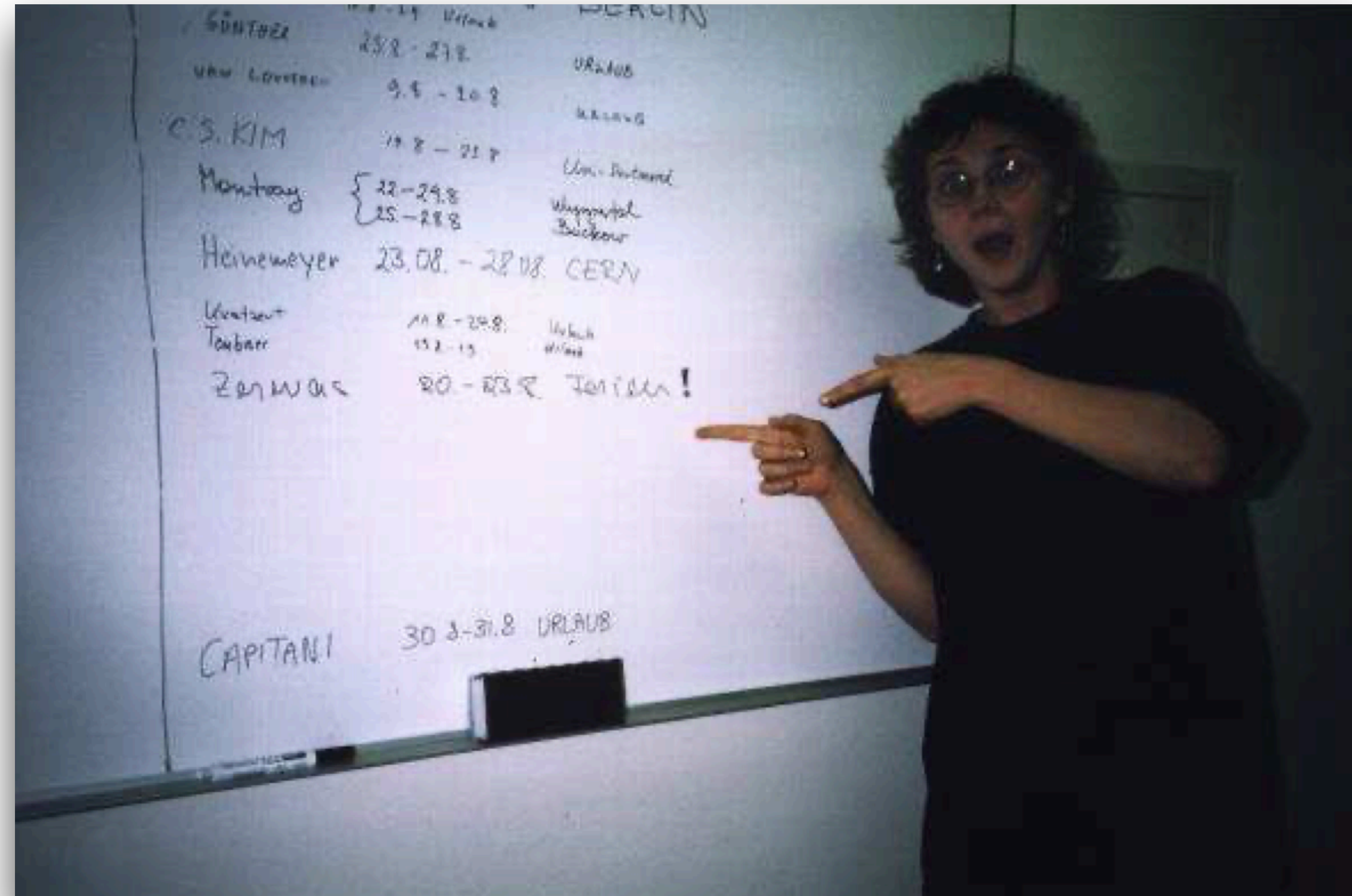
- Peter Zerwas followed this endeavor with enthusiasm and dedication

Facts

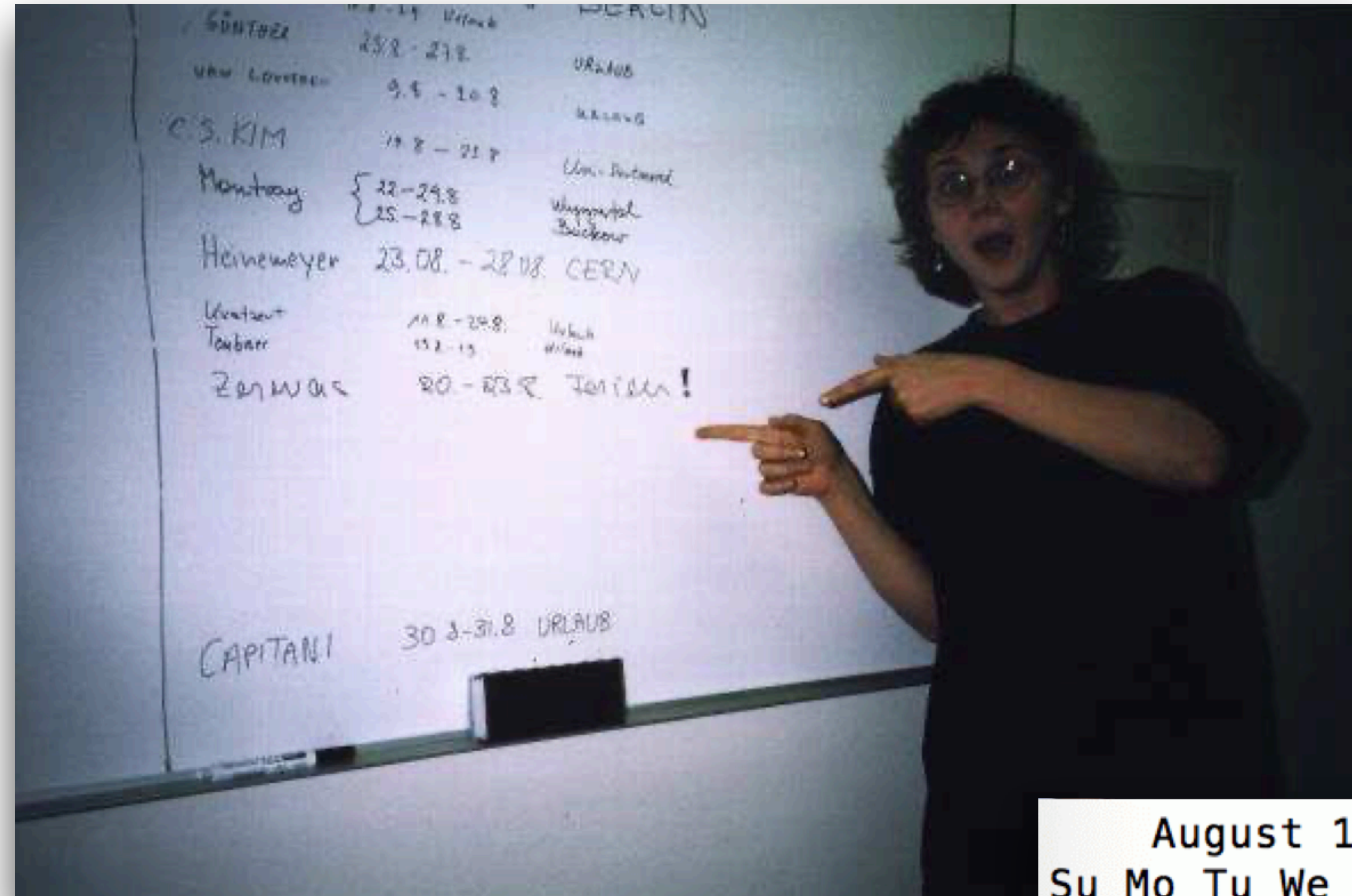
- Peter Zerwas followed this endeavor with enthusiasm and dedication

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

- Peter Zerwas followed this endeavor with enthusiasm and dedication



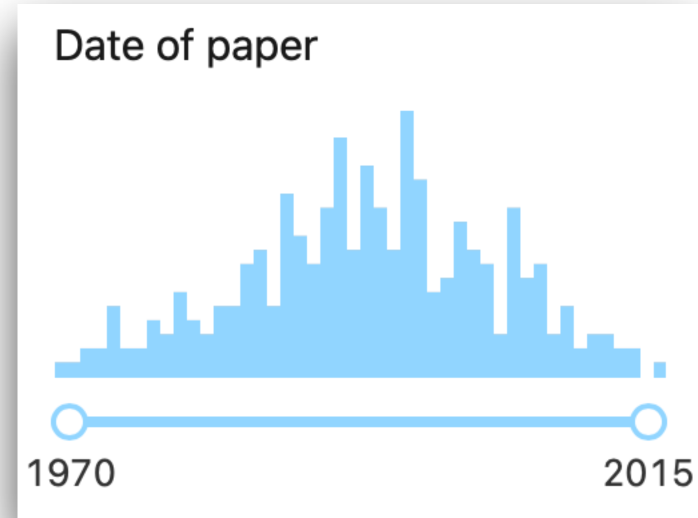
- Peter Zerwas followed this endeavor with enthusiasm and dedication



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				

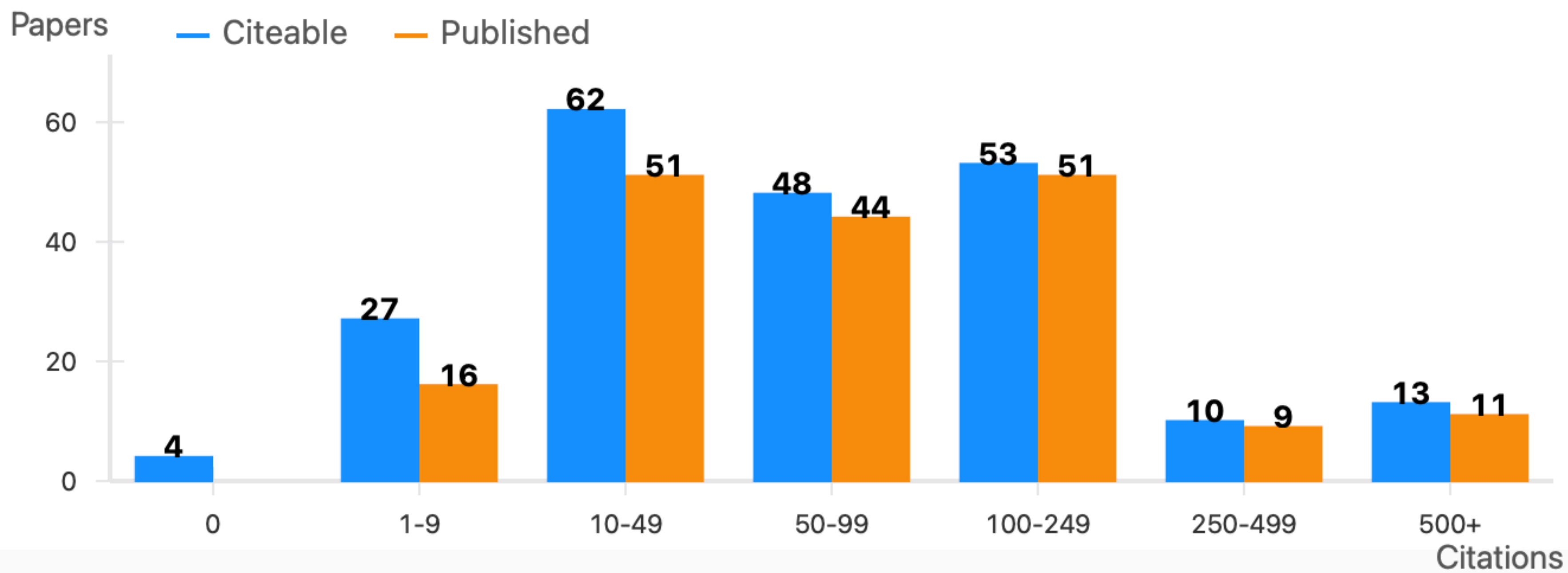
✦ Peter Zerwas followed this endeavor with enthusiasm and dedication



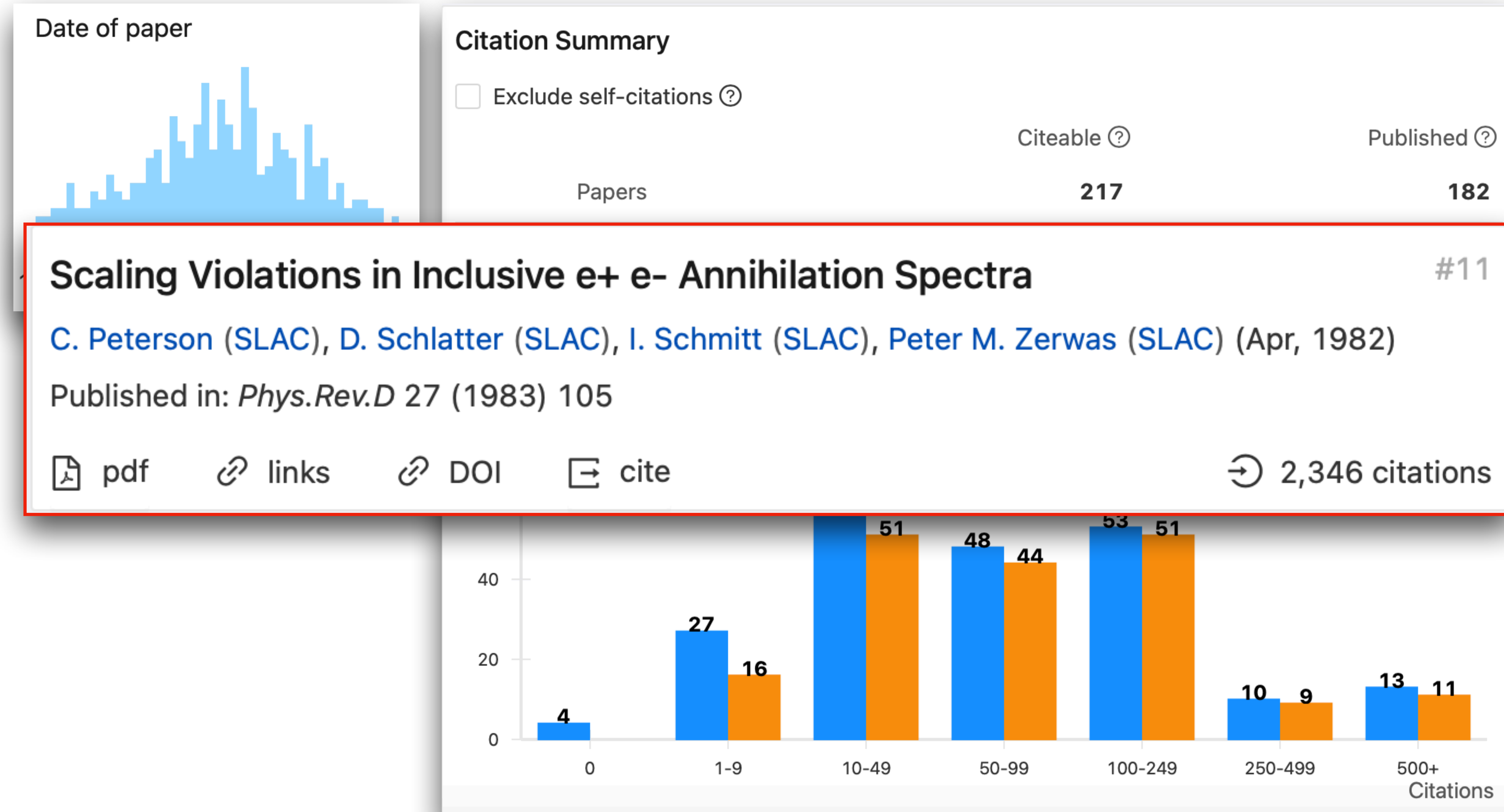
Citation Summary

☐ Exclude self-citations ⓘ

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



- Peter Zerwas followed this endeavor with enthusiasm and dedication



Facts

✦ Short Curriculum Vitae:

1970 Dissertation on Chiral Symmetry

Postdoc at DESY/Hamburg, SLAC Standford/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

- Early years: Main research field: Quantum Chromodynamics

- Early years: Main research field: Quantum Chromodynamics

  Determination of charm quark mass first time from neutrino data

VOLUME 36, NUMBER 8 PHYSICAL REVIEW LETTERS 23 FEBRUARY 1976

Model of Dimuon Production by Neutrinos*

L. M. Sehgal and P. M. Zerwas
III. Physikalisches Institut, Technische Hochschule, Aachen, West Germany
(Received 11 December 1975)

In an attempt to confirm the charm interpretation of dimuons, we have constructed an explicit quark-parton model for the production and decay of a new hadron in neutrino interactions. The model produces, among other results, a distribution for the muon energy ratio $E(\mu^+)/E(\mu^-)$, which is independent of the neutrino spectrum and in remarkable agreement with observations. The model encourages the hope that the study of dimuon characteristics could reveal the charge of the charmed quark and the chirality of the charmed current.

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

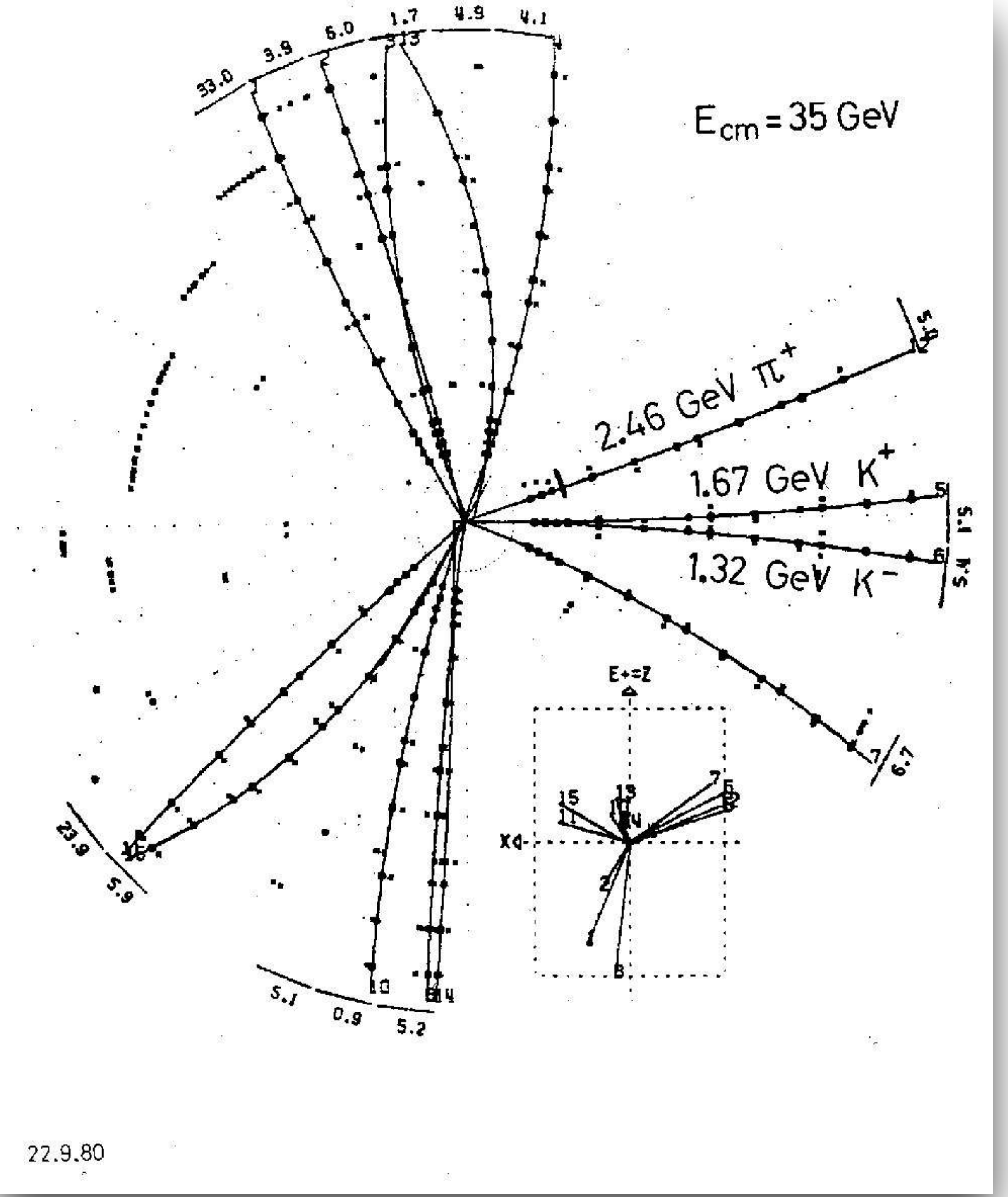
ELSEVIER

Nuclear Physics B
Volume 161, Issues 2–3, 17–24 December 1979, Pages 349-372

Quantum chromodynamics and jets in e^+e^-

P. Hoyer, P. Osland, H.G. Sander, T.F. Walsh, P.M. Zerwas [a, b]

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



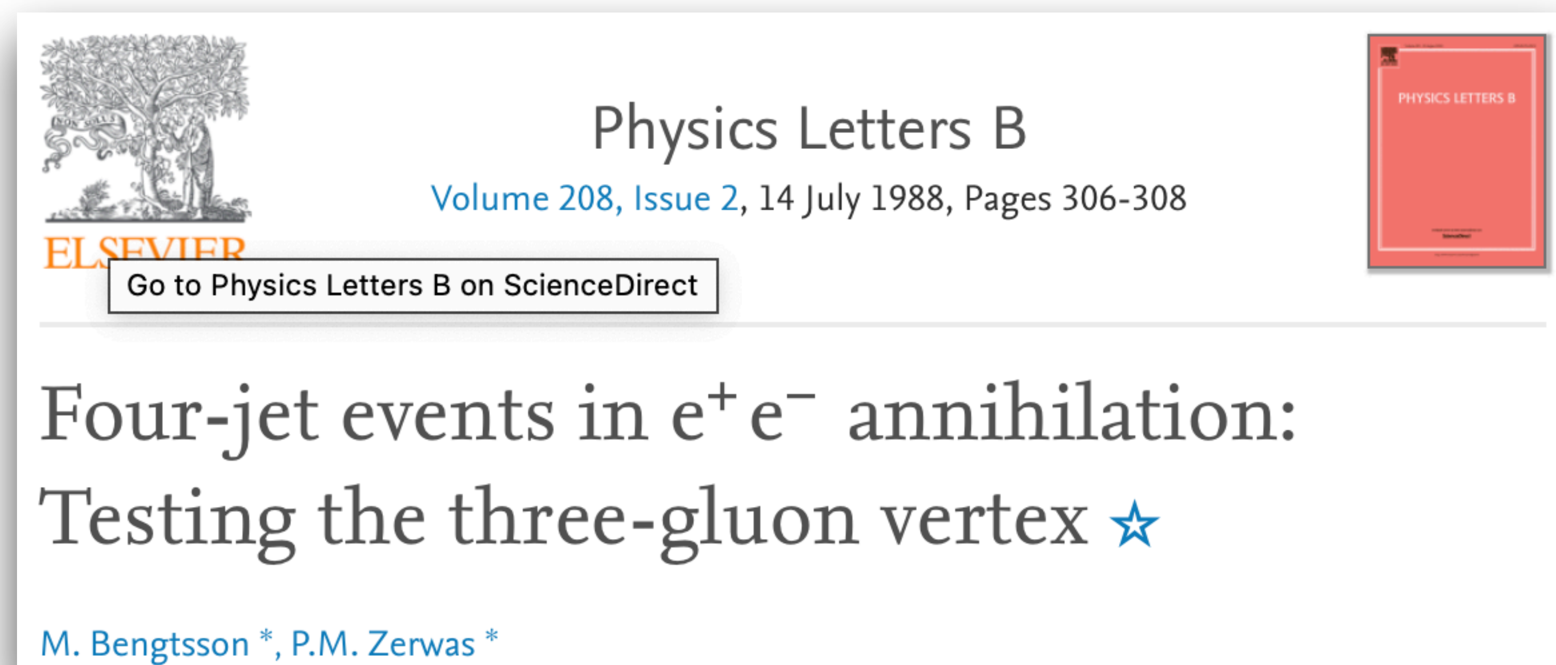
✦ Early years: Main research field: Quantum Chromodynamics

Determination of charm quark mass first time from neutrino data

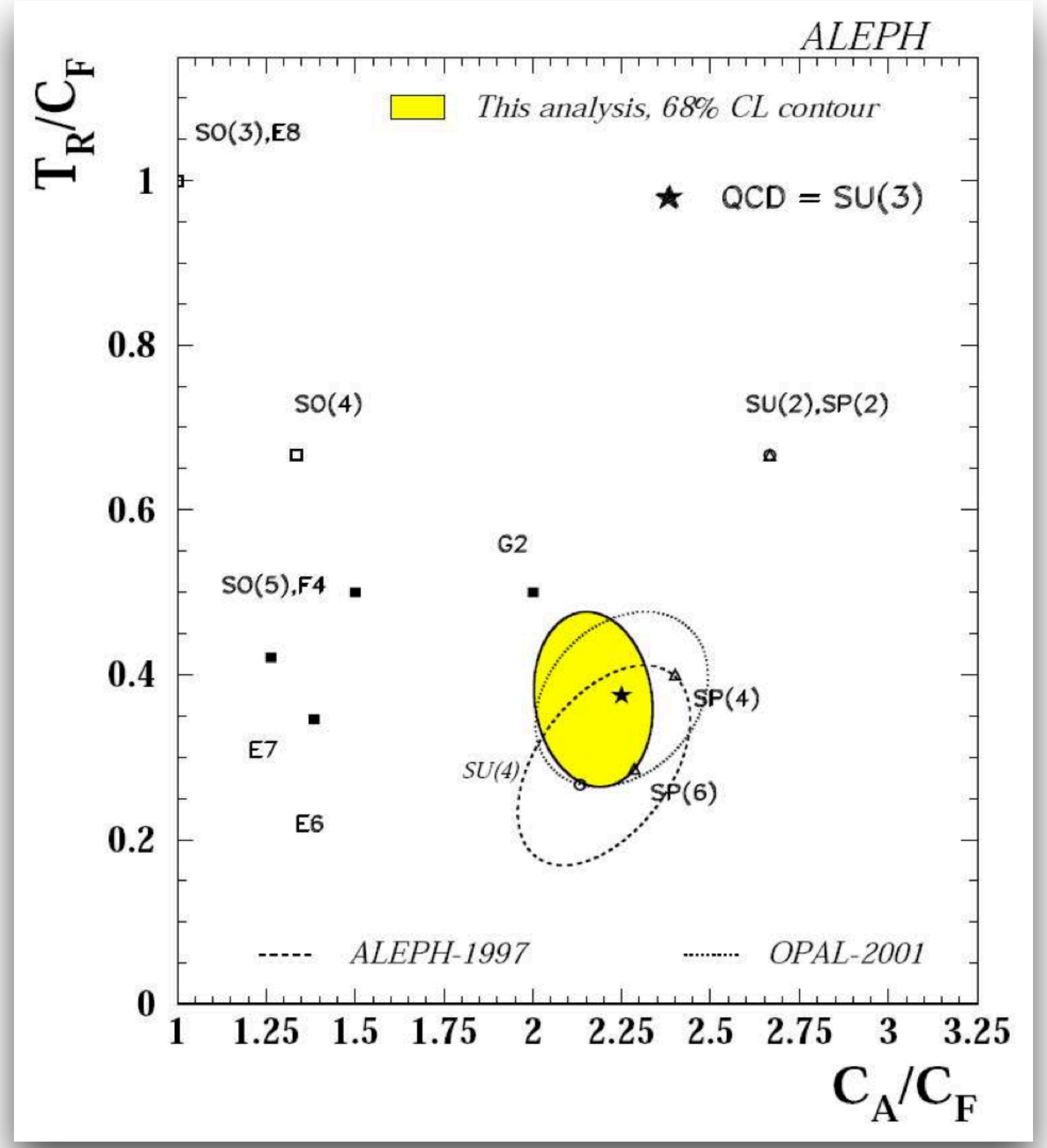
Peterson Fragmentation - transition of heavy quarks into jets

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



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

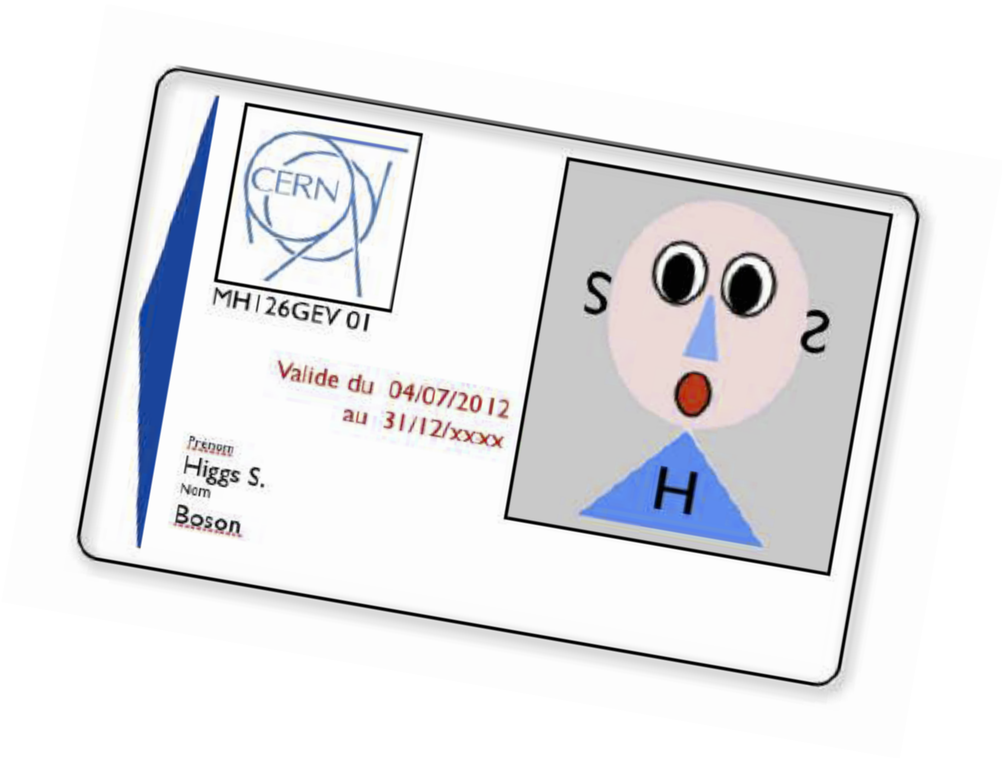
Bengtsson-Zerwas Winkel - signal of the self-interaction of the gluons -> asymptotic freedom of the QCD

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

✦ Later years:

- Later years:

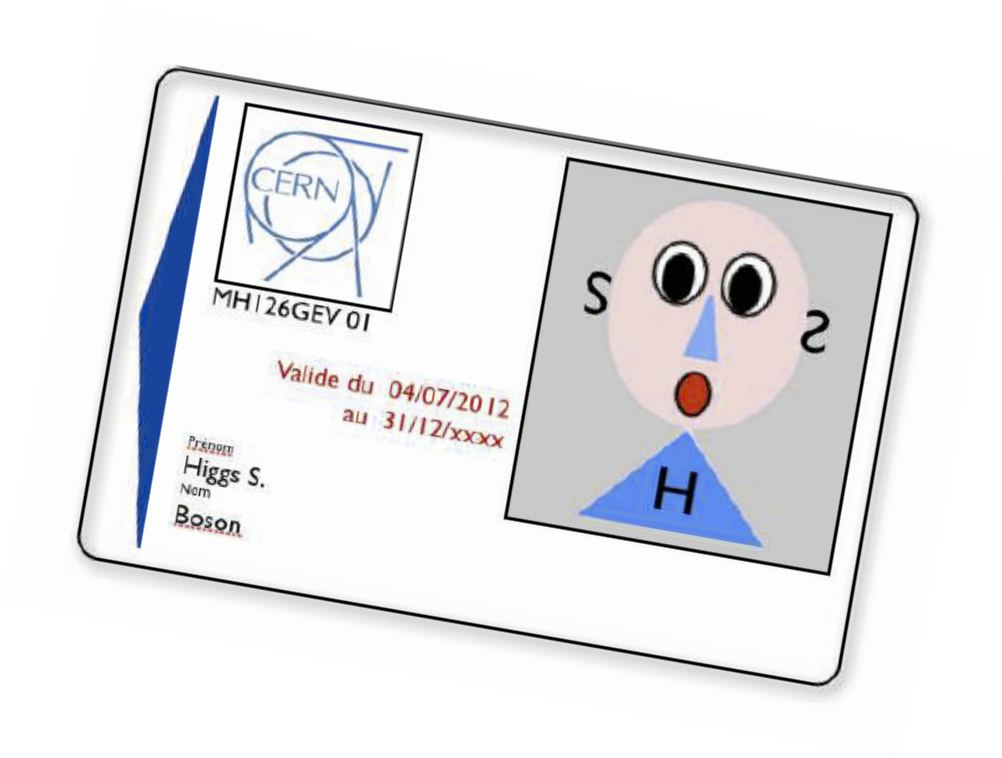
  Higgs Physics

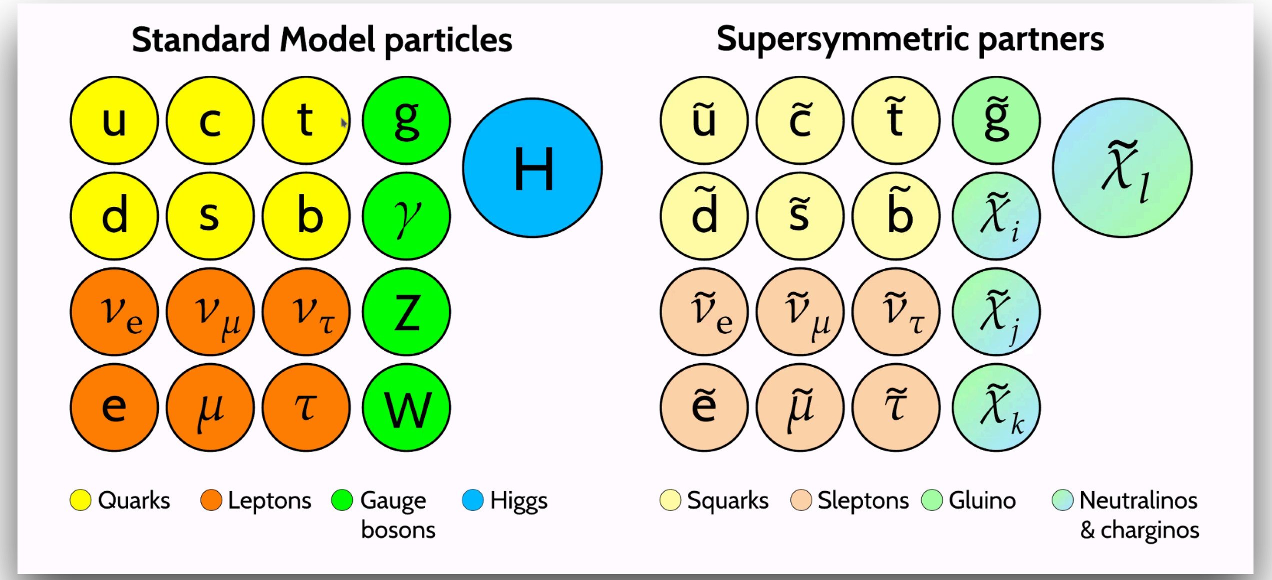


- Later years:

  Higgs Physics

  Supersymmetry



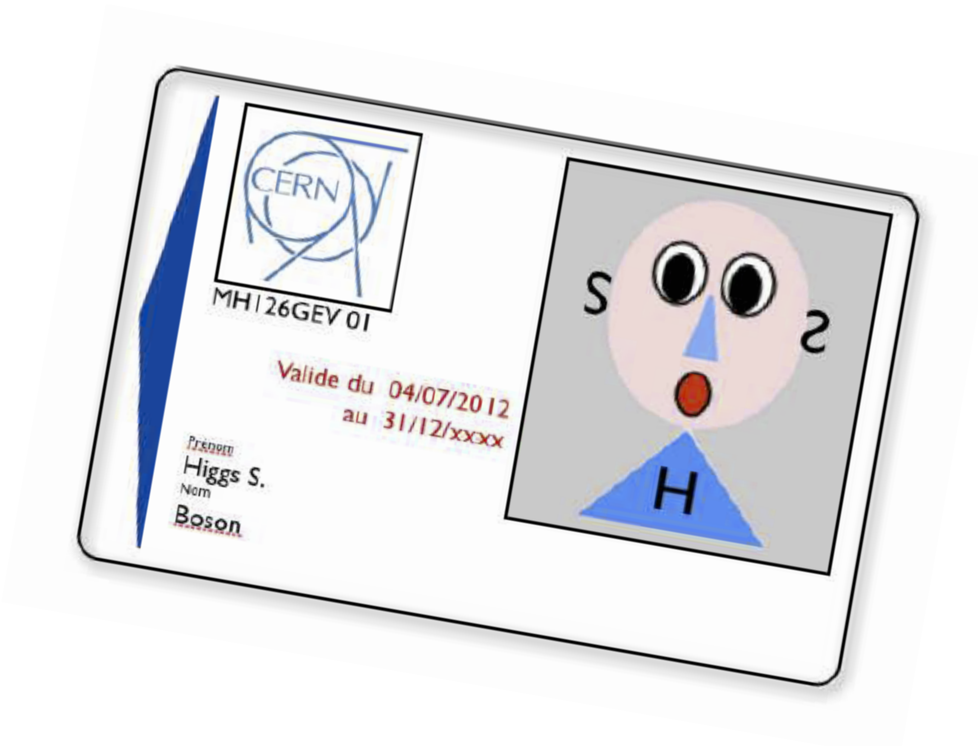


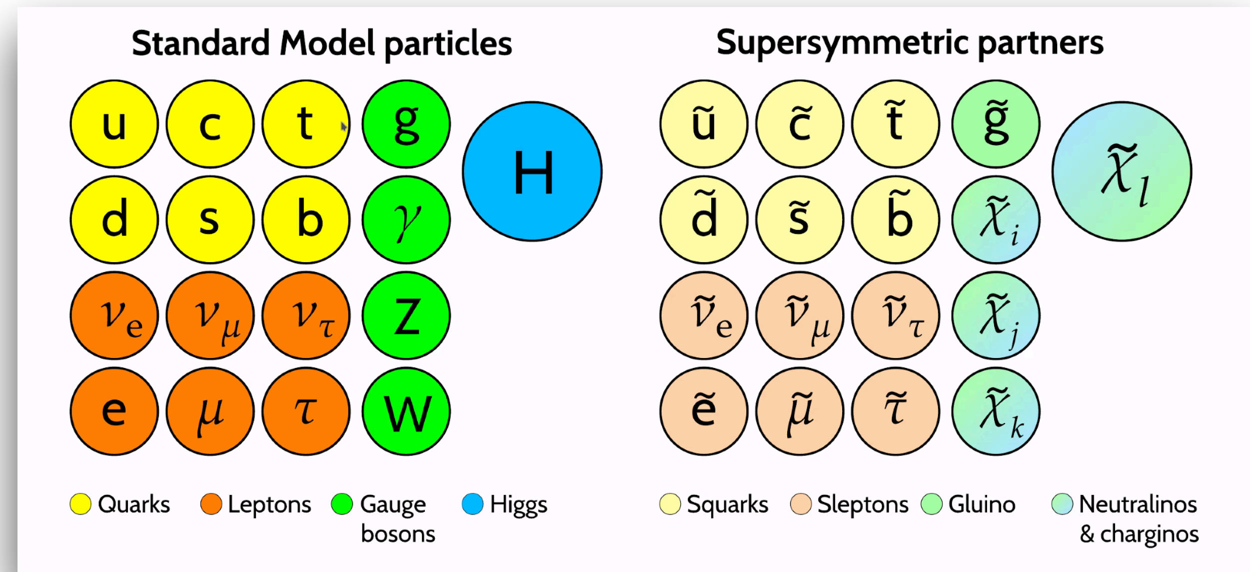
- Later years:

  Higgs Physics

  Supersymmetry

  Physics Potential of an e+e- collider





ECFA DESY
Linear Collider Workshop

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
  - 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 autho
  - Seventh Workshop, DESY, 22-25 September 2000.
    Speakers slides.
  - 5th International e+e- Linear Collider Workshop on Physics and Dete
- Meetings of working groups between main ECFA/DESY Workshops and oth

TESLA Technical Design Report

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

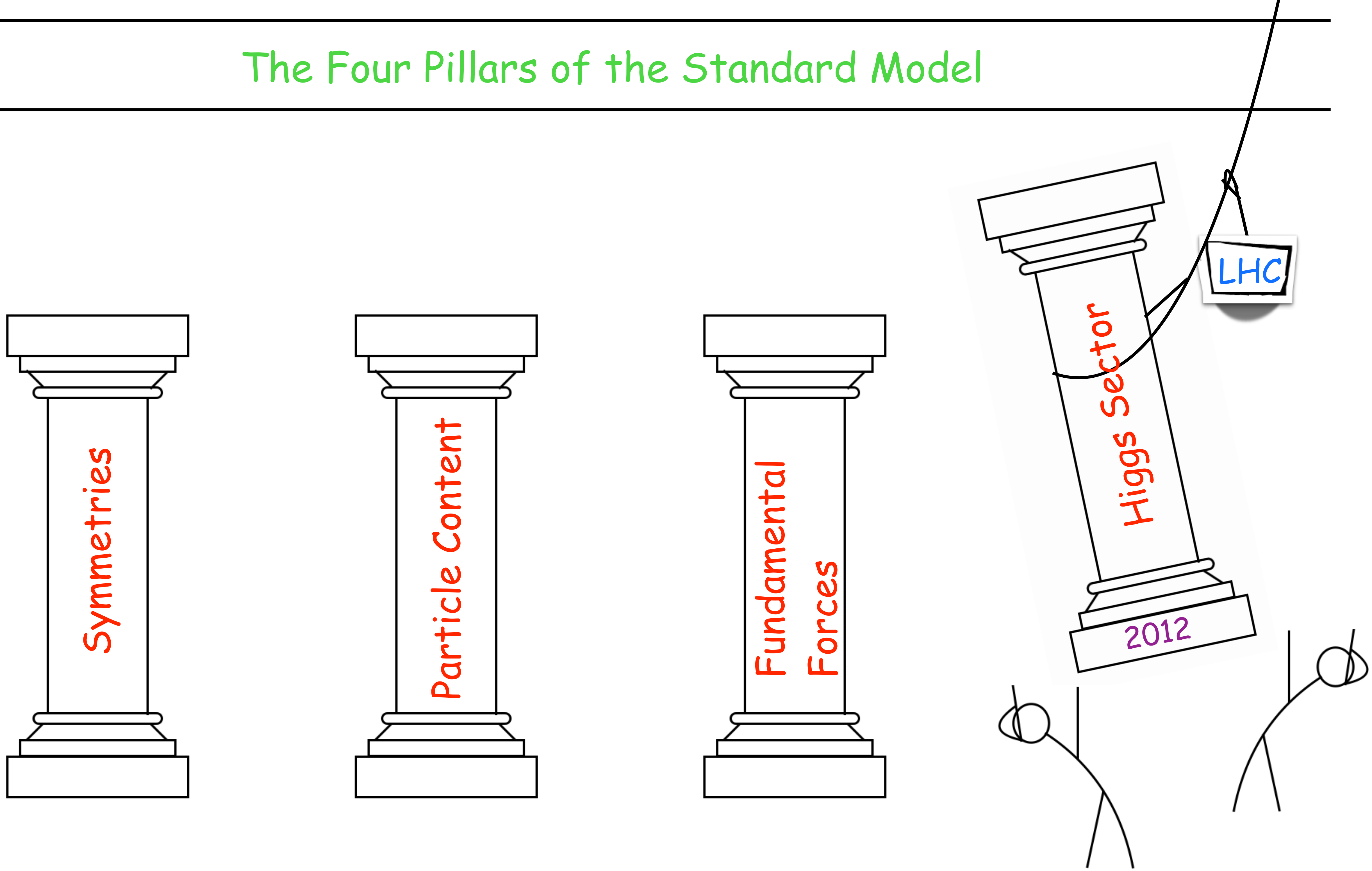
March 2001

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

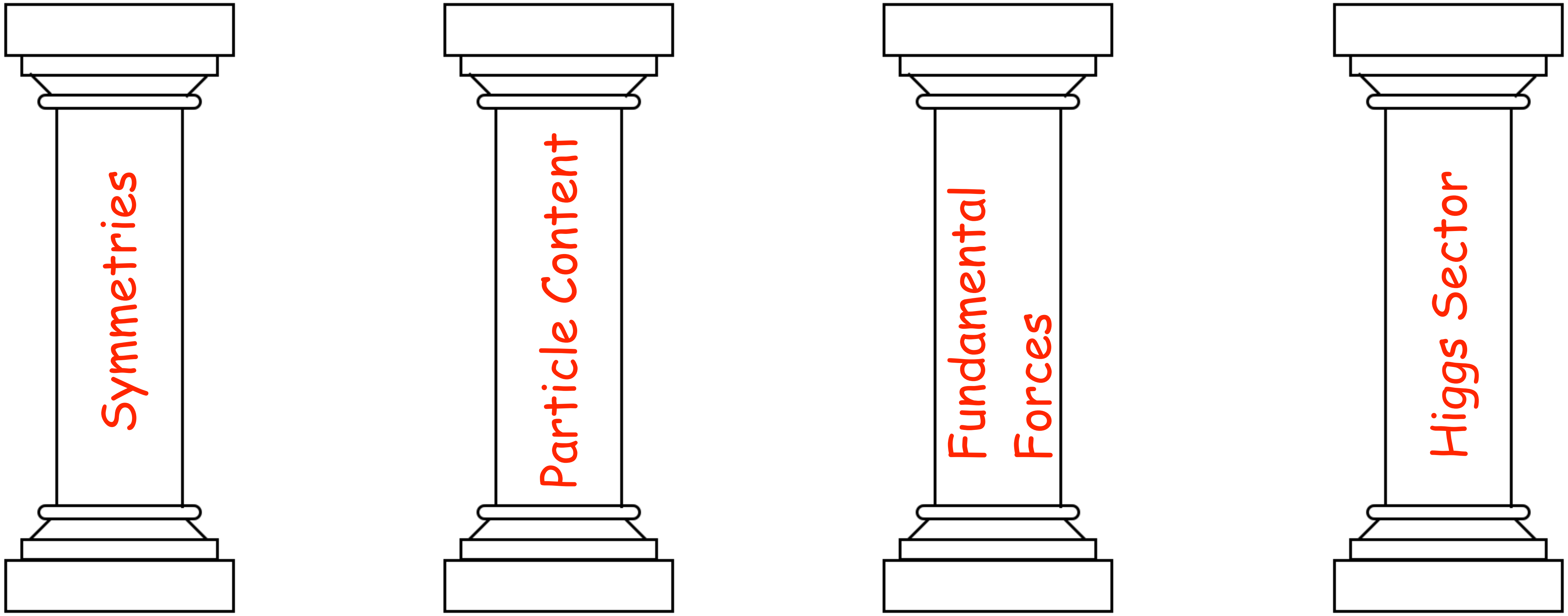
ECFA DESY
Linear Collider Workshop

The Legacy

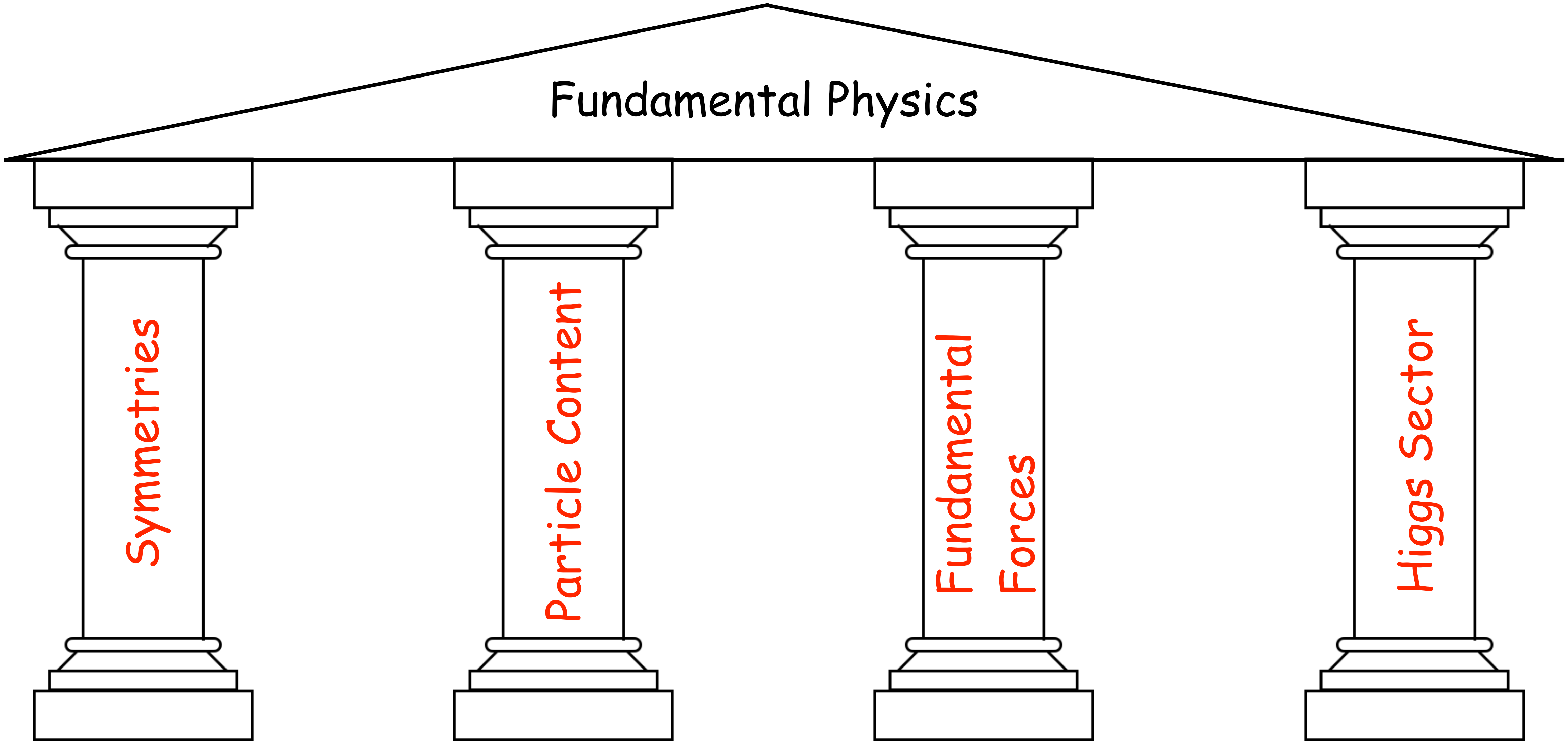
The Four Pillars of the Standard Model



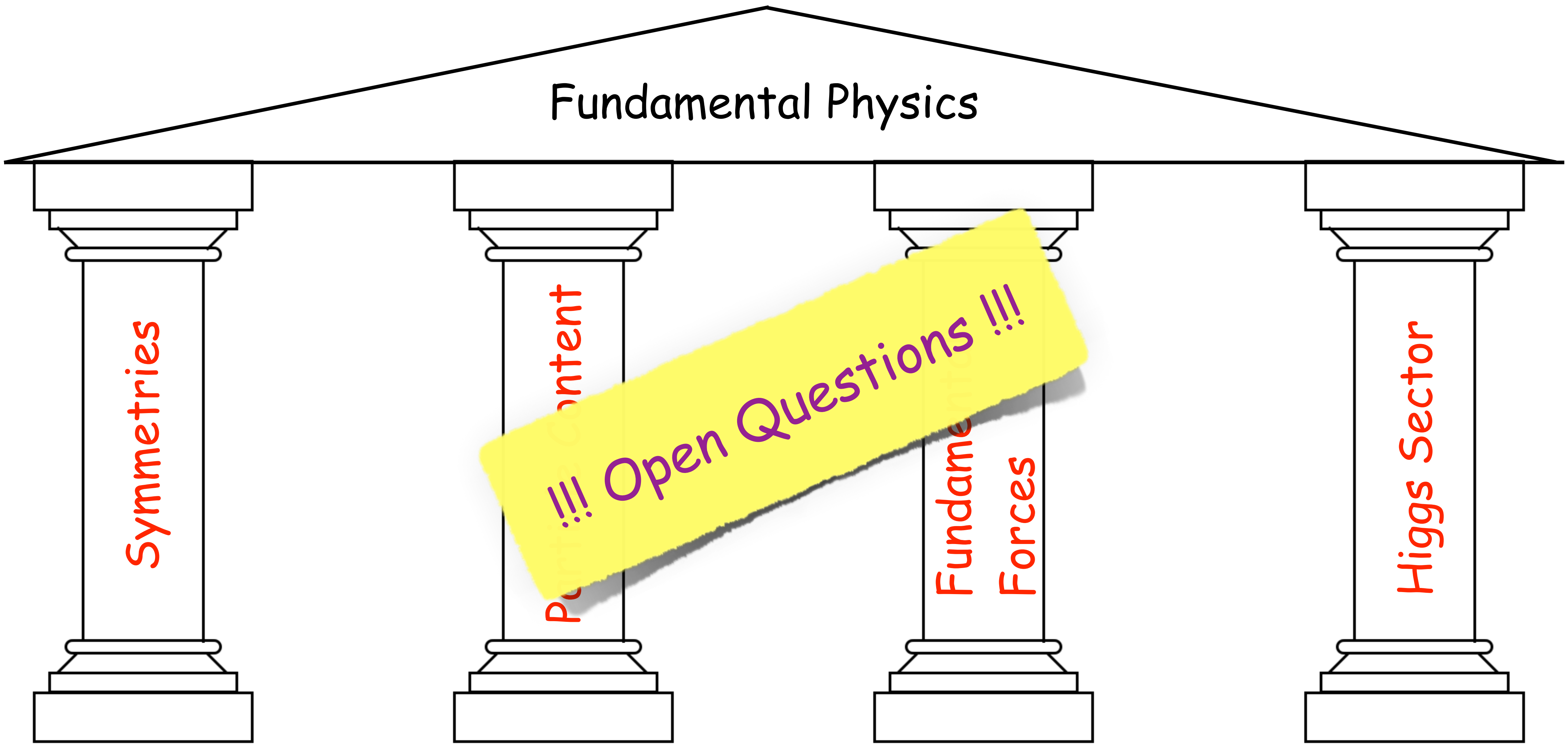
The Four Pillars of the Standard Model

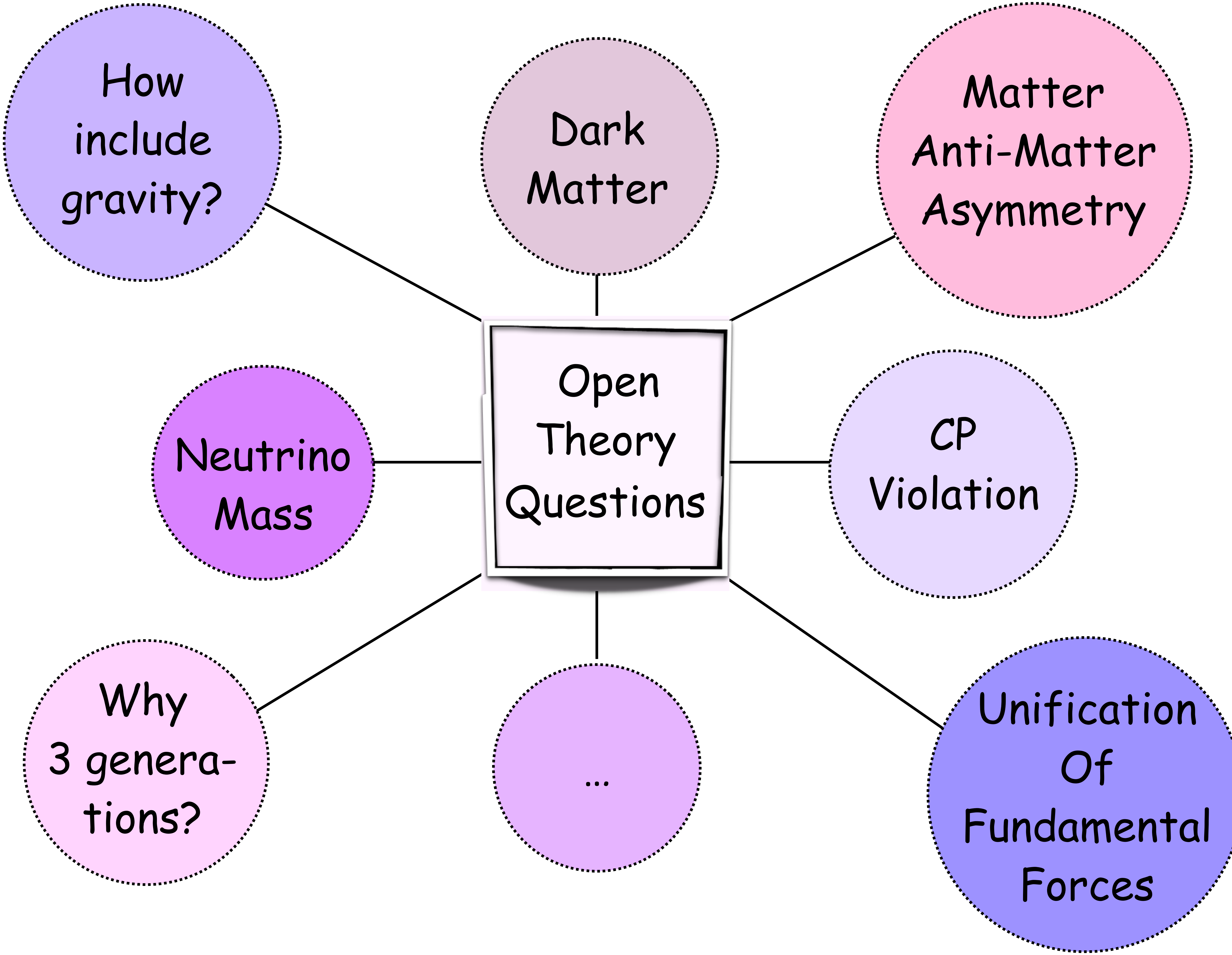


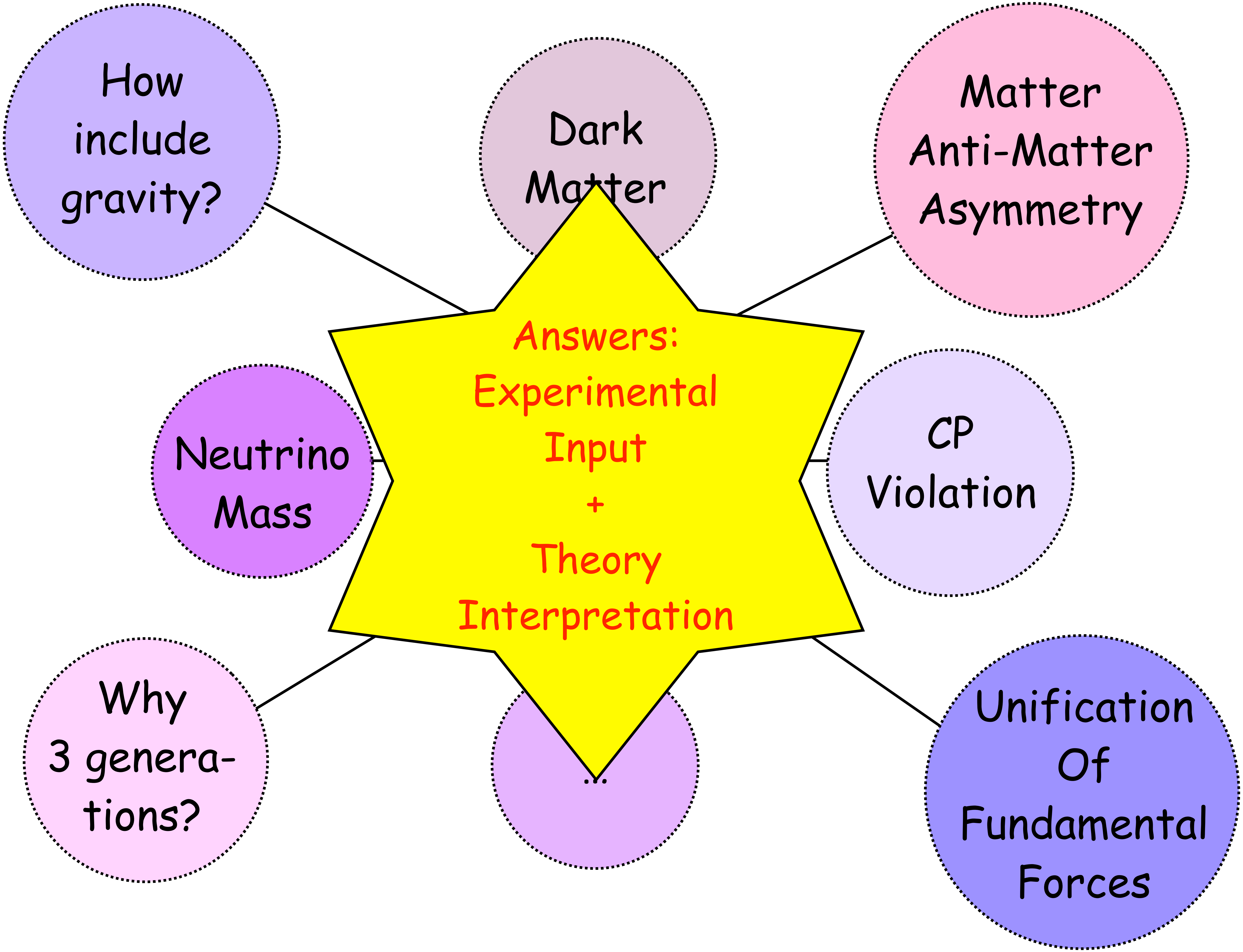
The Standard Model is Structurally Complete



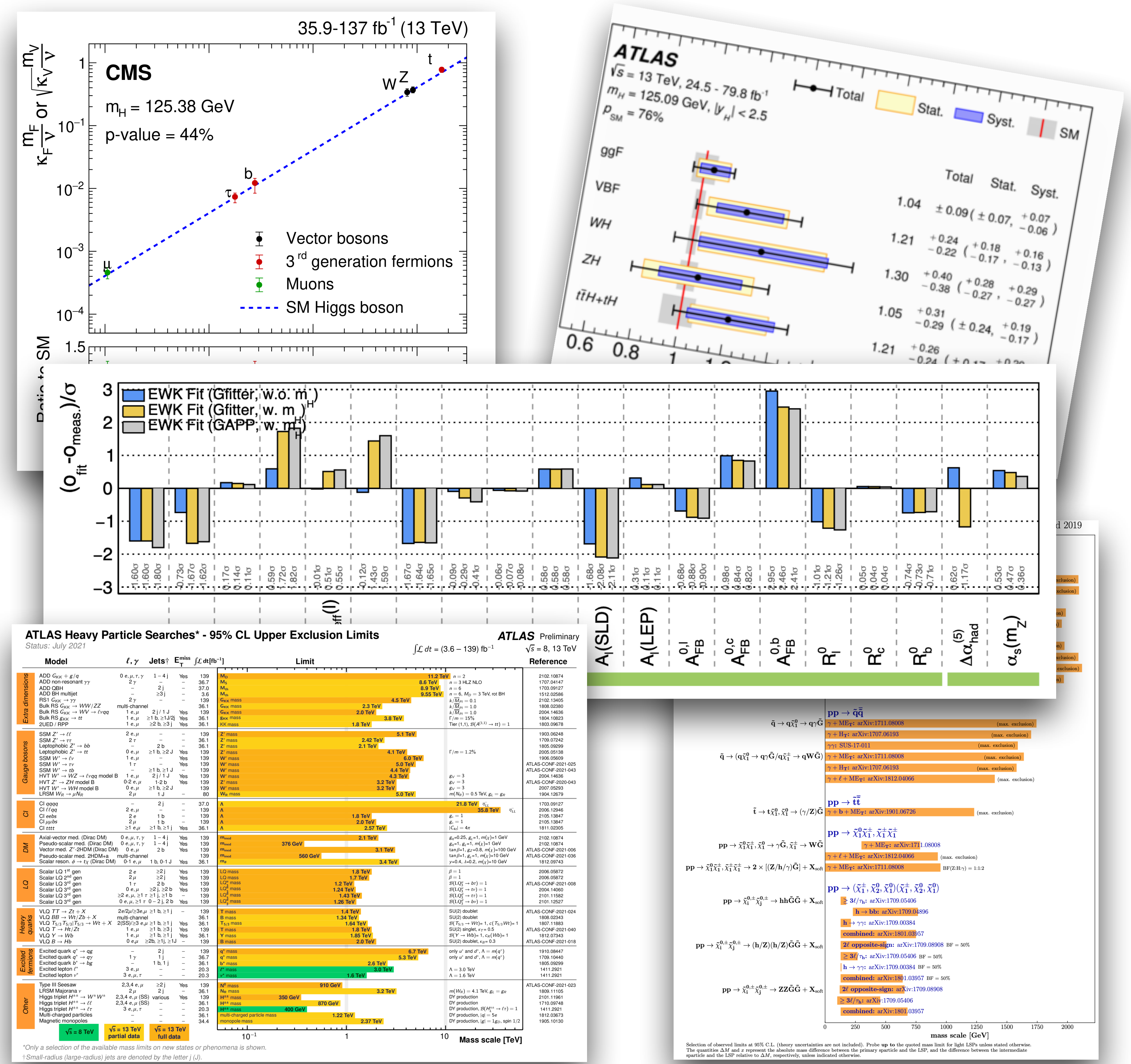
The Standard Model is Structurally Complete - But




How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
Open Theory Questions
CP Violation
Why 3 genera-tions?
...
Unification Of Fundamental Forces


How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
Answers: Experimental Input + Theory Interpretation
CP Violation
Why 3 genera-tions?
...
Unification Of Fundamental Forces

Status

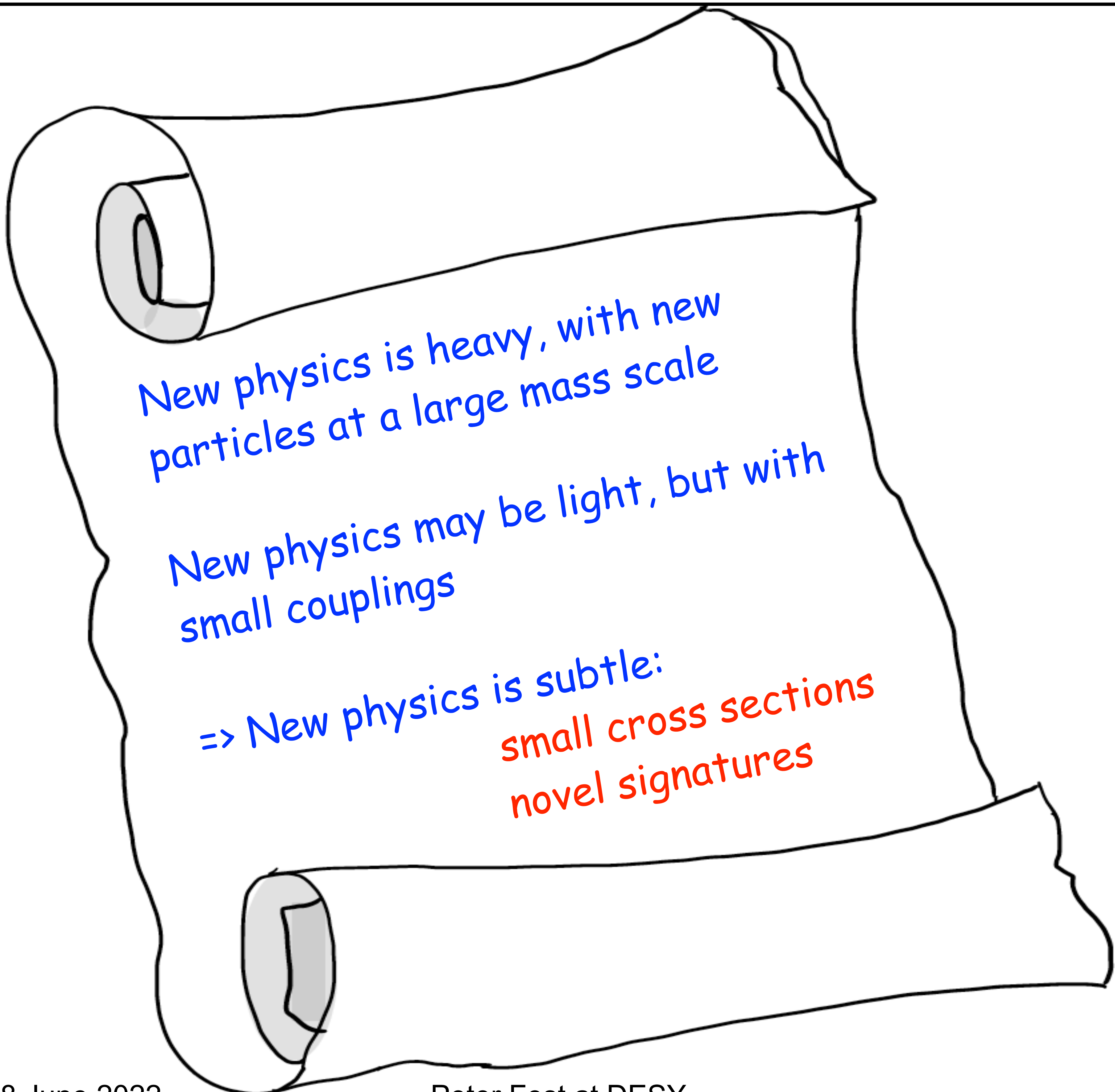


Discovered Higgs Boson behaves very SM-like

Consistency Test of the SM at the quantum level

No direct discovery of New Physics so far

Where is New Physics?




The Higgs
Discovery

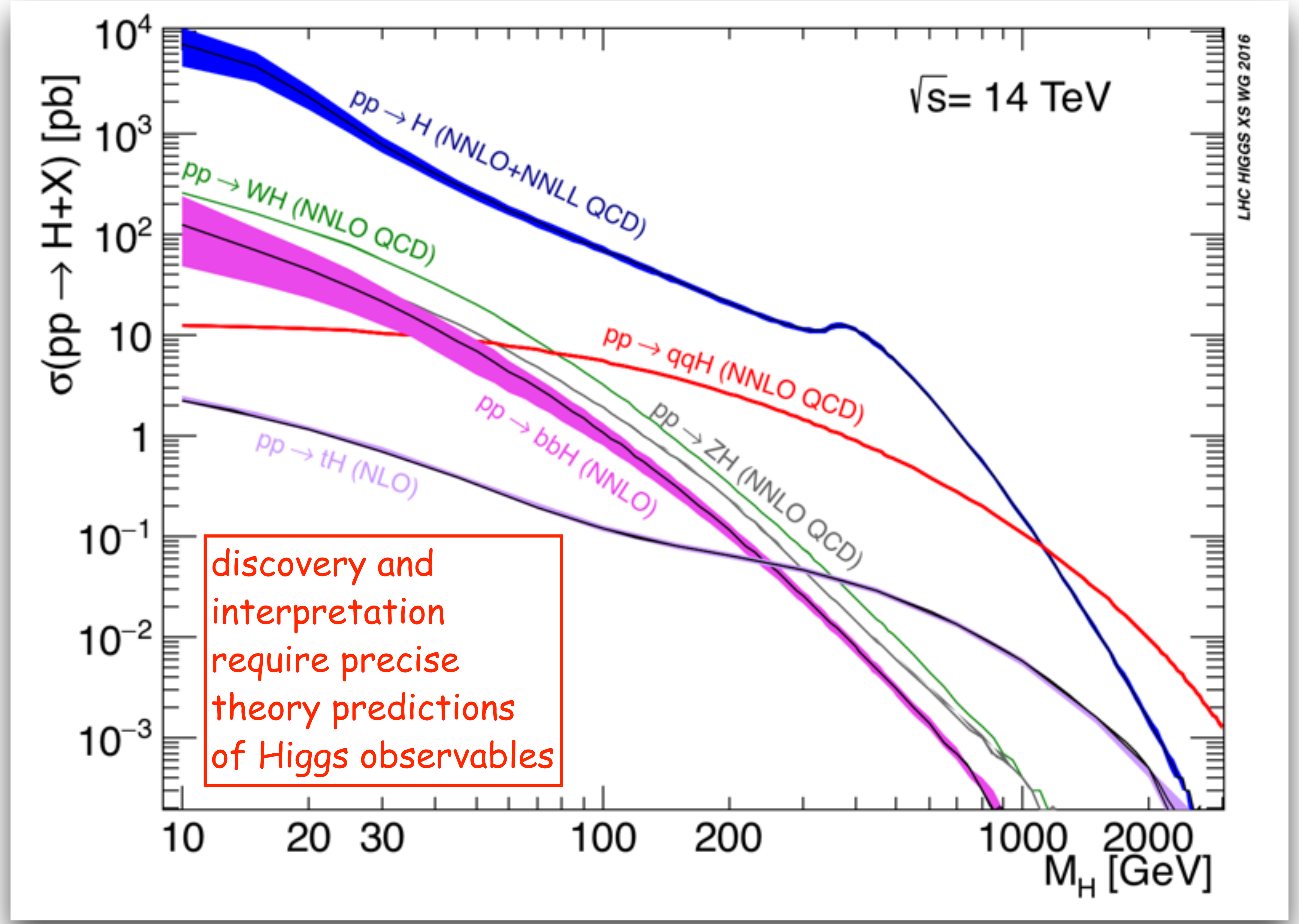
The Higgs Discovery 4th July 2012

The Higgs Discovery 4th July 2012

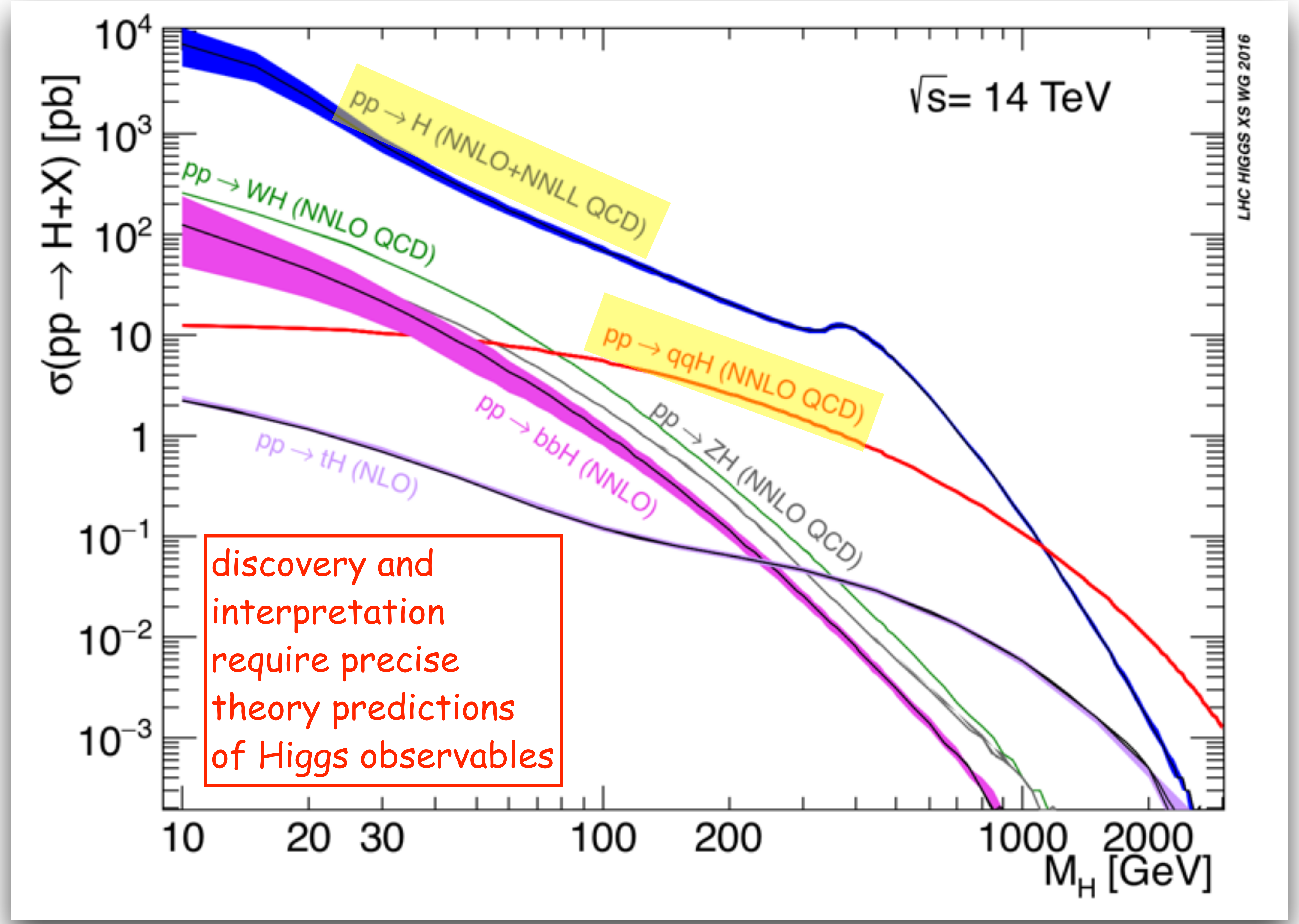
The Higgs Discovery 4th July 2012

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

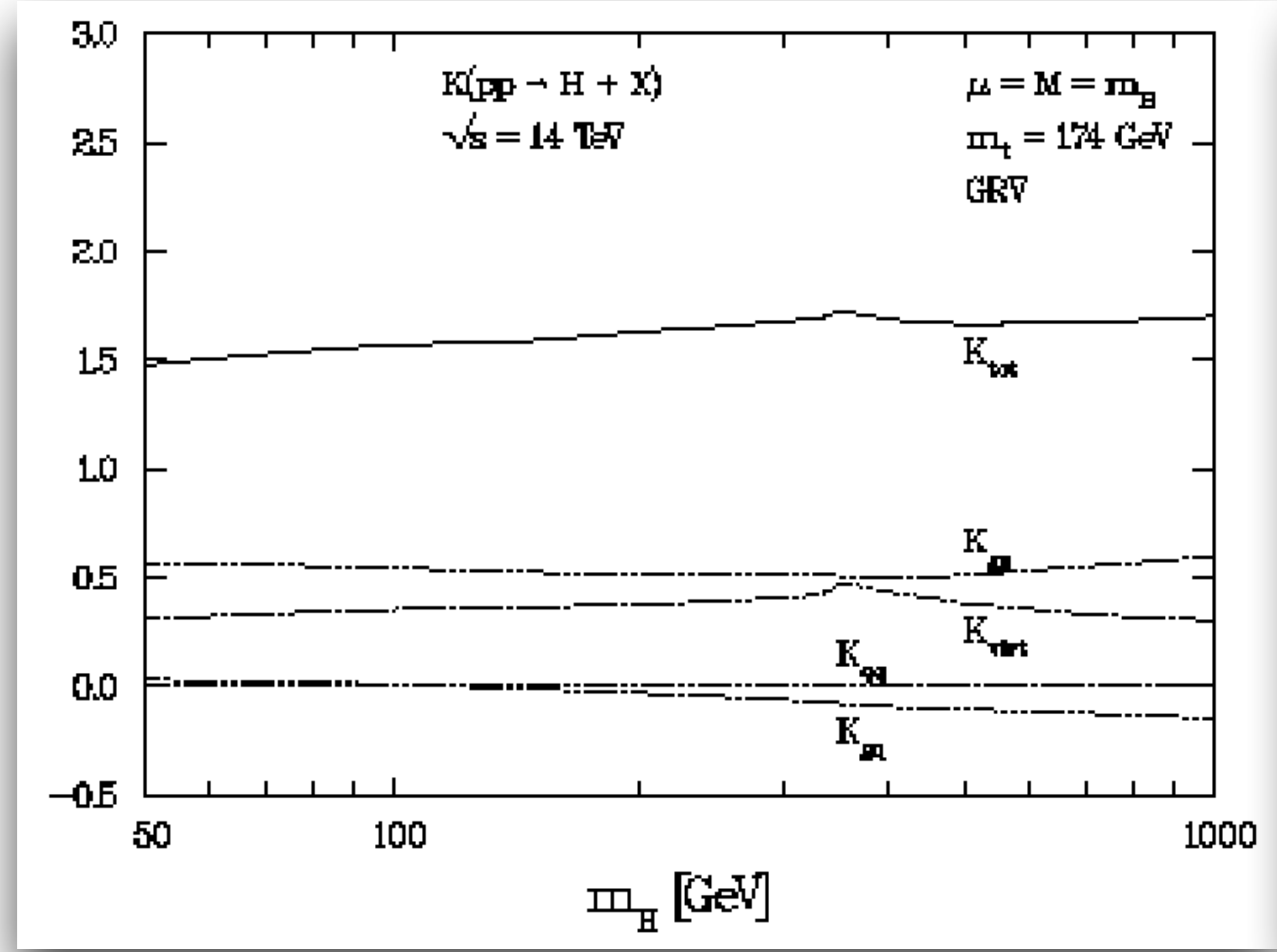
M. Spira (Hamburg U.), A. Djouadi (Montreal U. and DESY), D. Graudenz (CERN), P.M. Zerwas (DESY) (Feb, 1995)

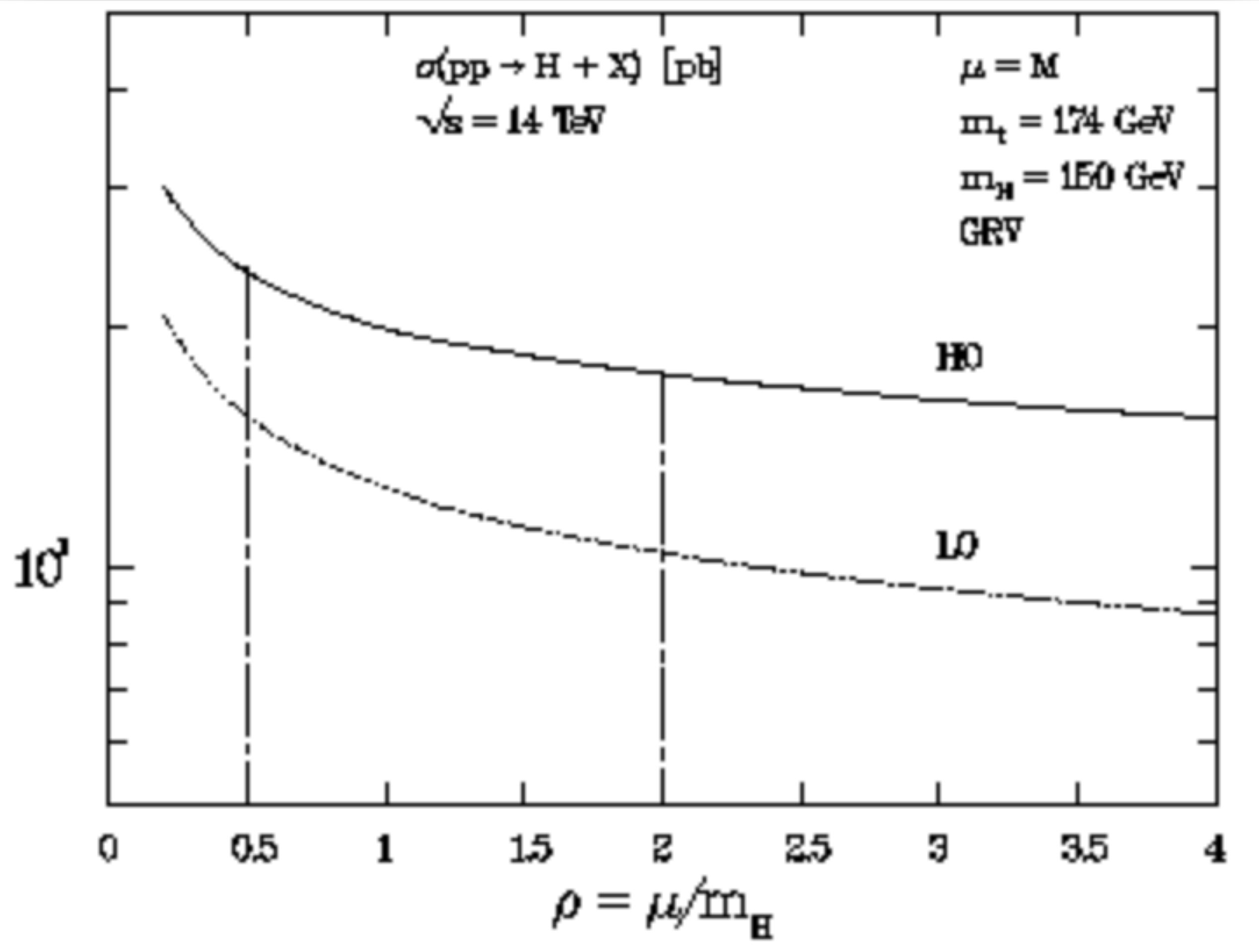
Published in: *Nucl.Phys.B* 453 (1995) 17-82 • e-Print: hep-ph/9504378 [hep-ph]

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

NLO QCD corrections to t anti-t H production in hadron collisions #1

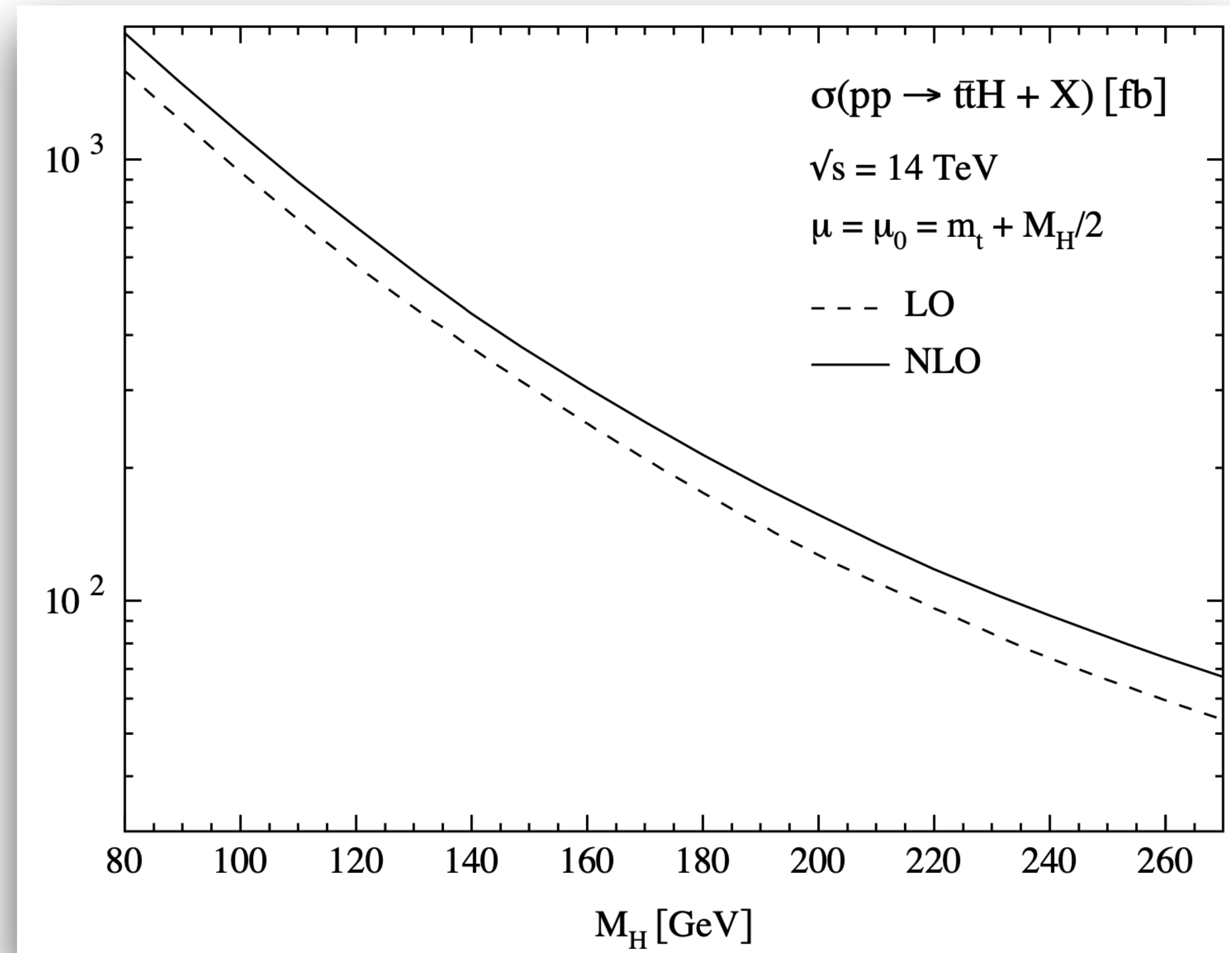
W. Beenakker (Nijmegen U., IMAPP), S. Dittmaier (DESY and Munich, Max Planck Inst.), M. Kramer (Edinburgh U.), B. Plumper (DESY), M. Spira (PSI, Villigen) et al. (Nov, 2002)

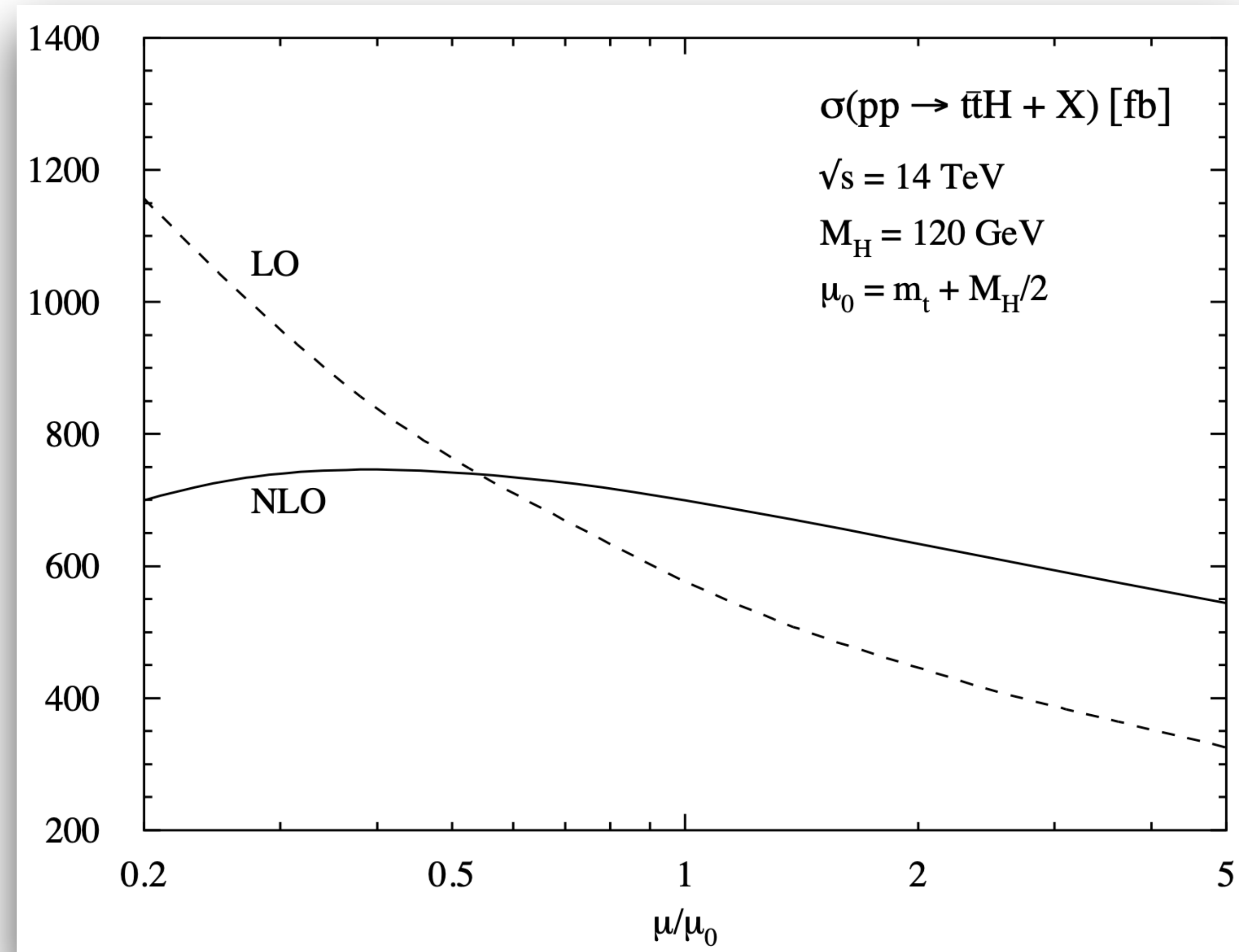
Published in: *Nucl.Phys.B* 653 (2003) 151-203 • e-Print: hep-ph/0211352 [hep-ph]

pdf DOI cite

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

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



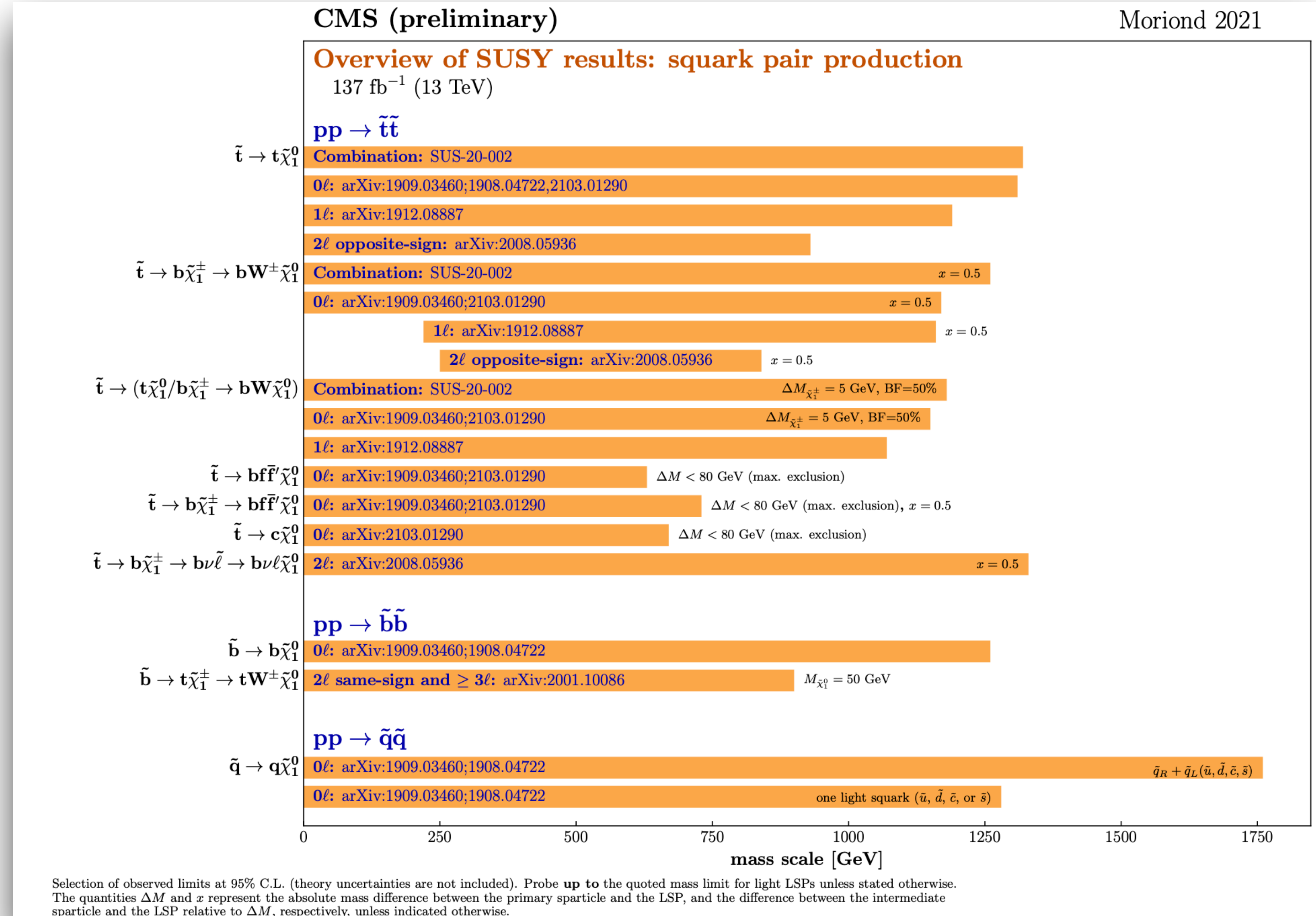


- ✦ NLO QCD corrections increase cross section @LHC by 20%
- ✦ renormalization scale dependence: reduction of theoretical uncertainty

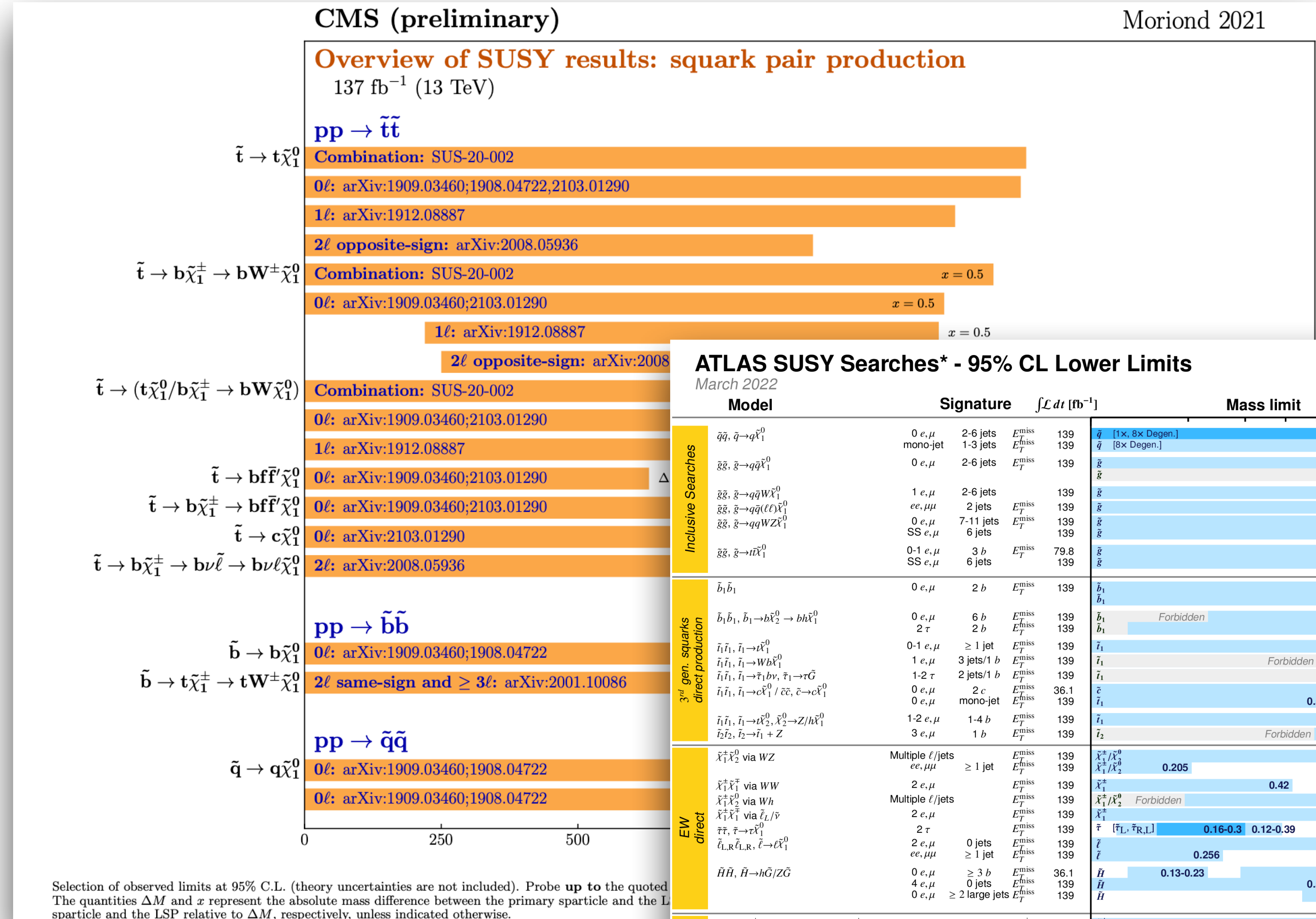
Where we are

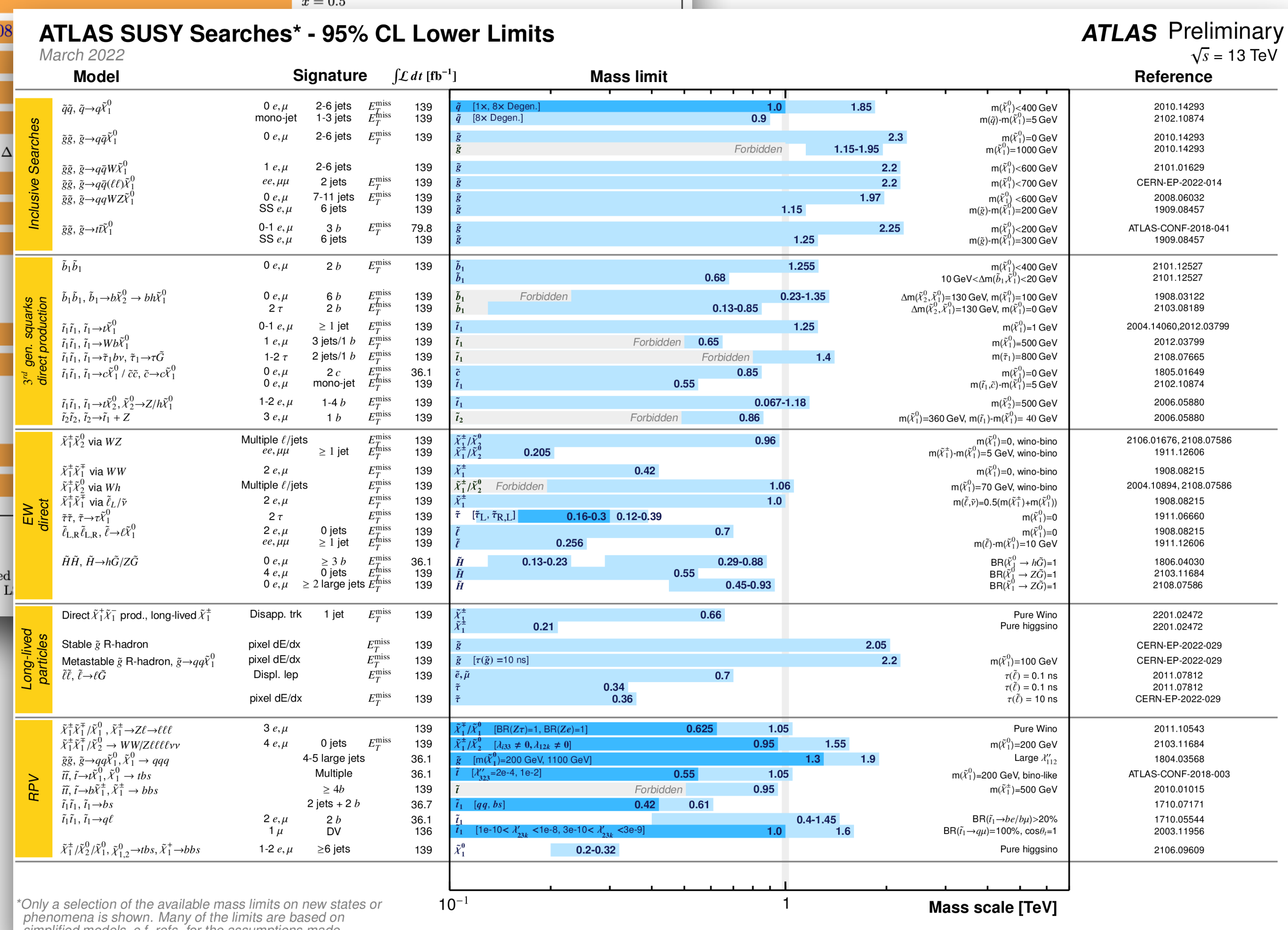
- Experimental reality: No Beyond the Standard Model Physics discovered so far!

Where we are - Example SUSY Search Limits



Where we are - Example SUSY Search Limits





Let's talk about Supersymmetry

Two SUSY-Gurus

✦ 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

Supersymmetry

Two SUSY-Gurus

✦ Motivation:

* maximal possible symmetry compatible with Poincaré group (space-time symmetry)

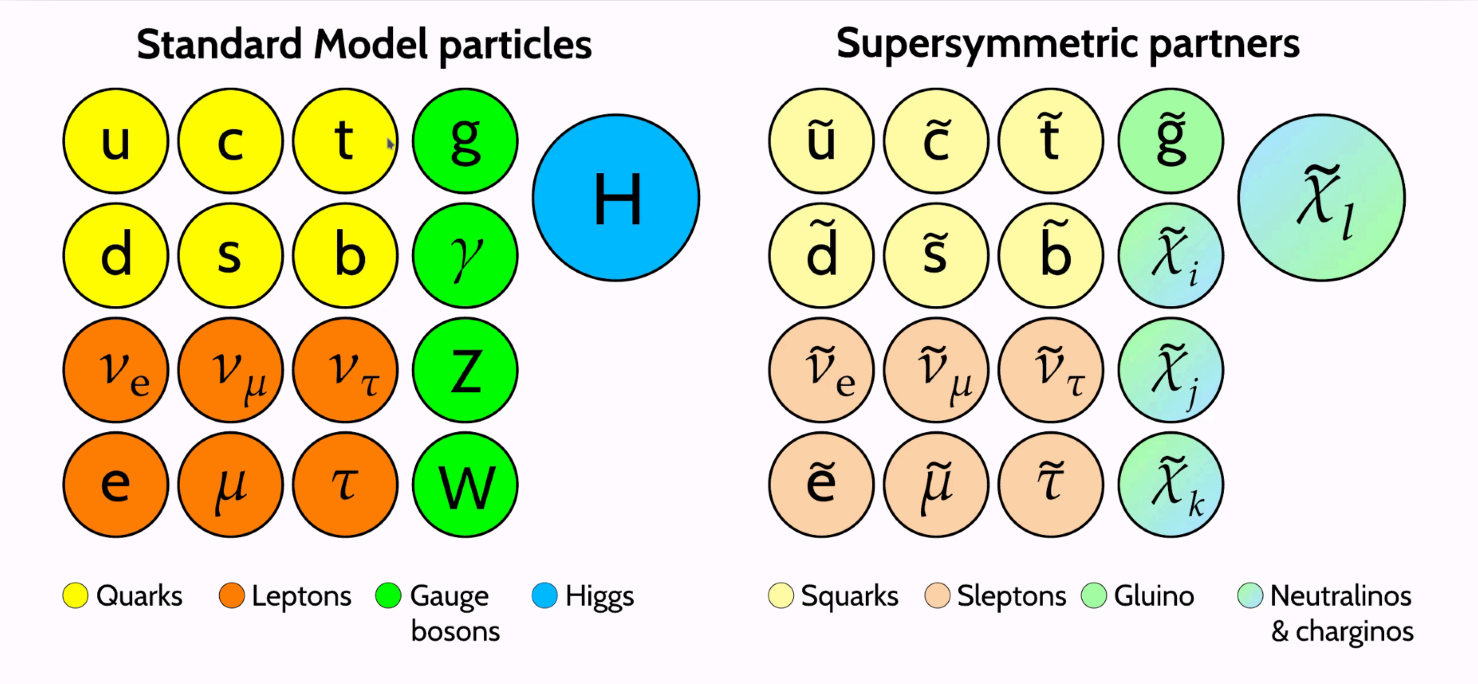
* solves some of the open problems of the SM:

  - candidate for Dark Matter
  - inclusion of gravity
  - unification of fundamental forces

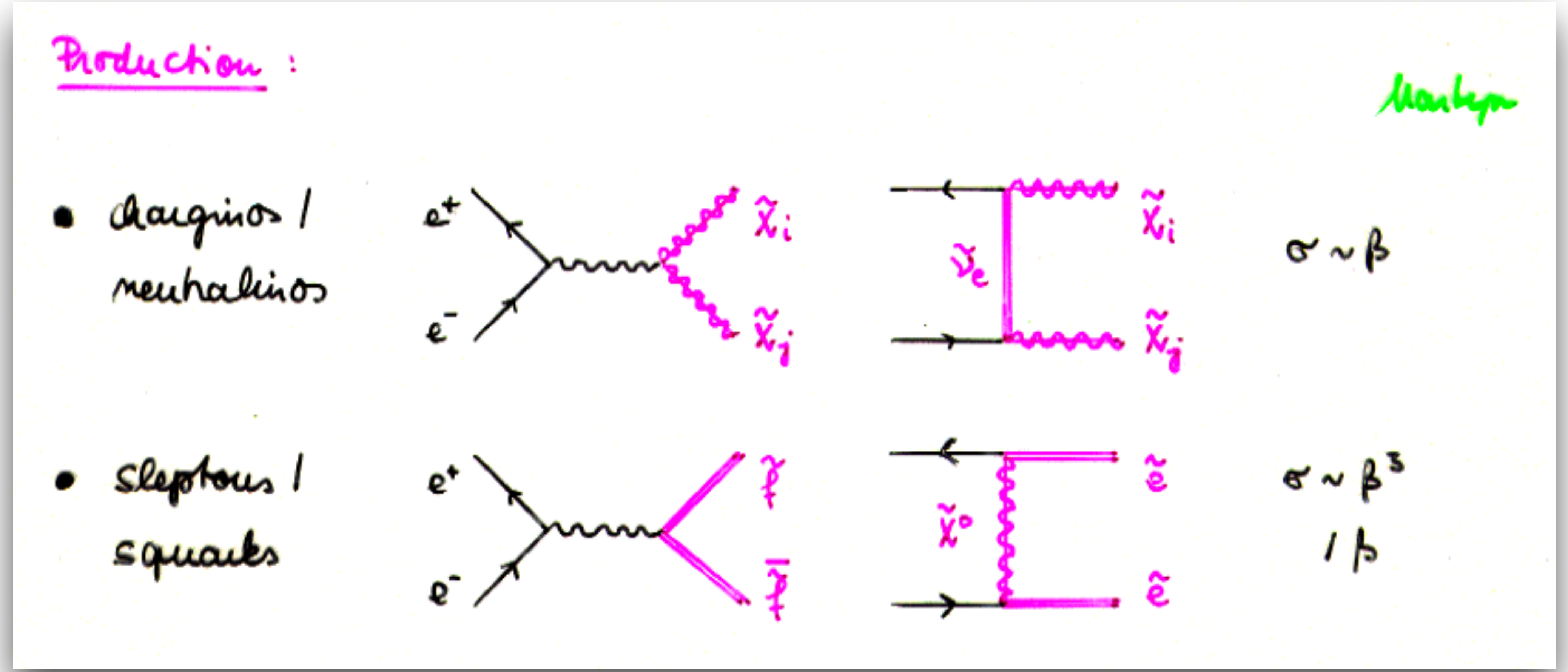
✦ Implications:

* enlarged particle spectrum: each SM particle has supersymmetric partner particle

* enlarged Higgs sector



Discovery Requires Precise Theory Predictions

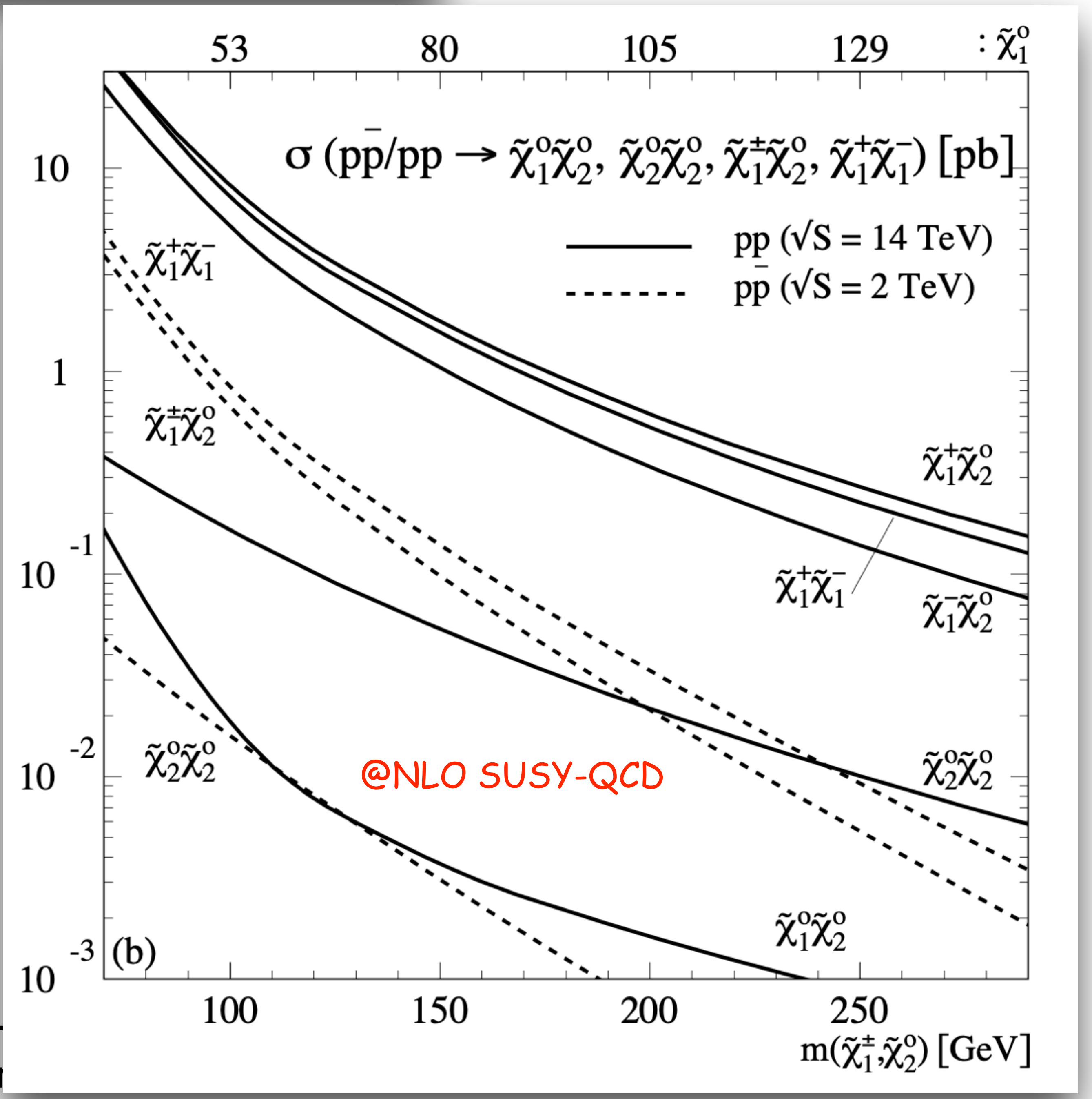


Discovery Requires Precise Theory Predictions

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 [hep-ph]



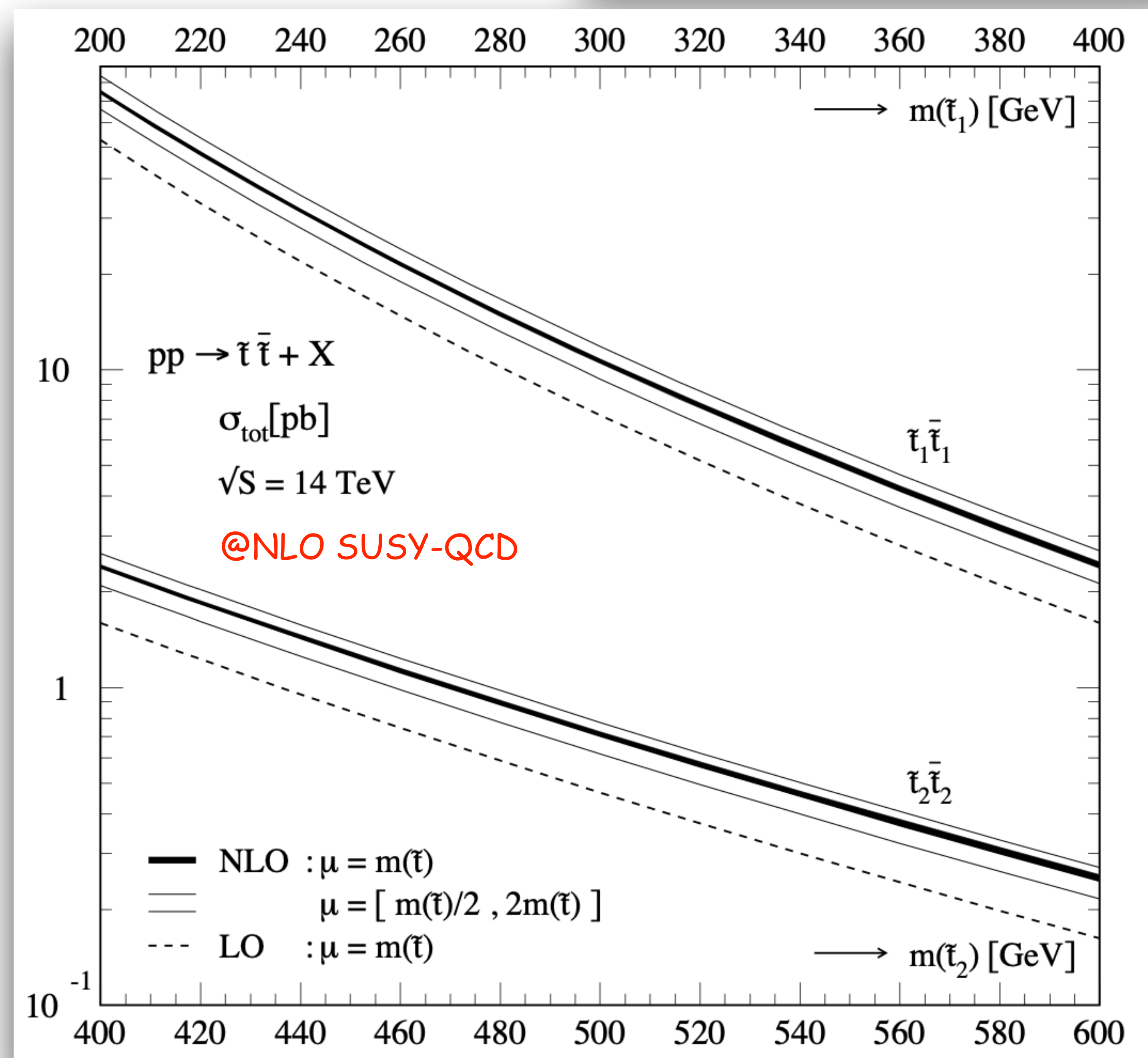
Discovery Requires Precise Theory Predictions

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 [hep-ph]

pdf DOI cite 646 citations



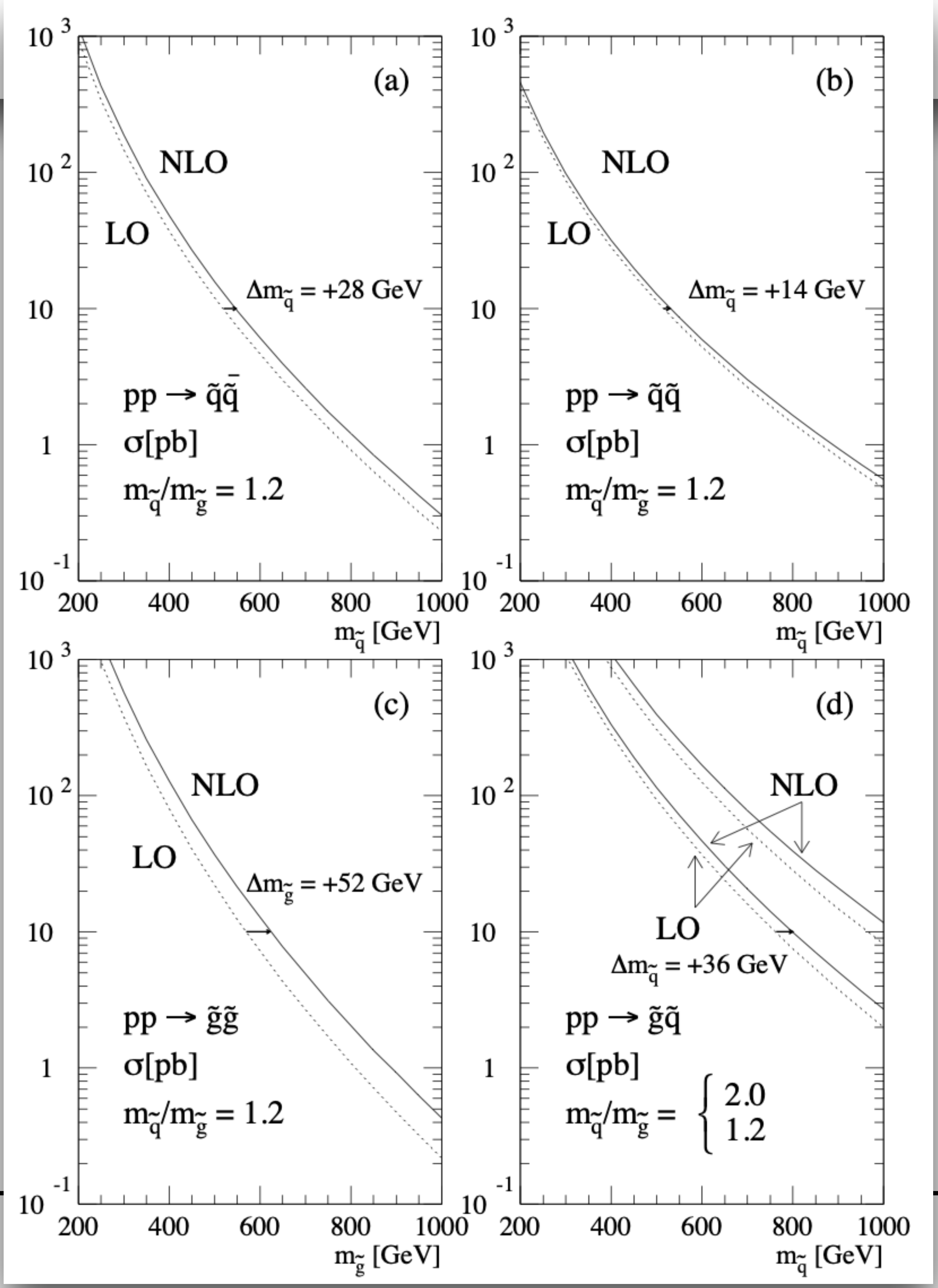
Discovery Requires Precise Theory Predictions

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 [hep-ph]

pdf DOI 1,224 citations



Discovery Requires Precise Theory Predictions

DECAYS :

$$\tilde{\chi}_i \to W + \tilde{\chi}^0_1 \qquad \oplus \quad \text{n cascade}$$

$$\tilde{\ell} \to \ell + \tilde{\chi}^0_1$$

$$\tilde{q} \to q + \tilde{\chi}^0_1$$

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 [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 [hep-ph]

pdf DOI cite 95 citations

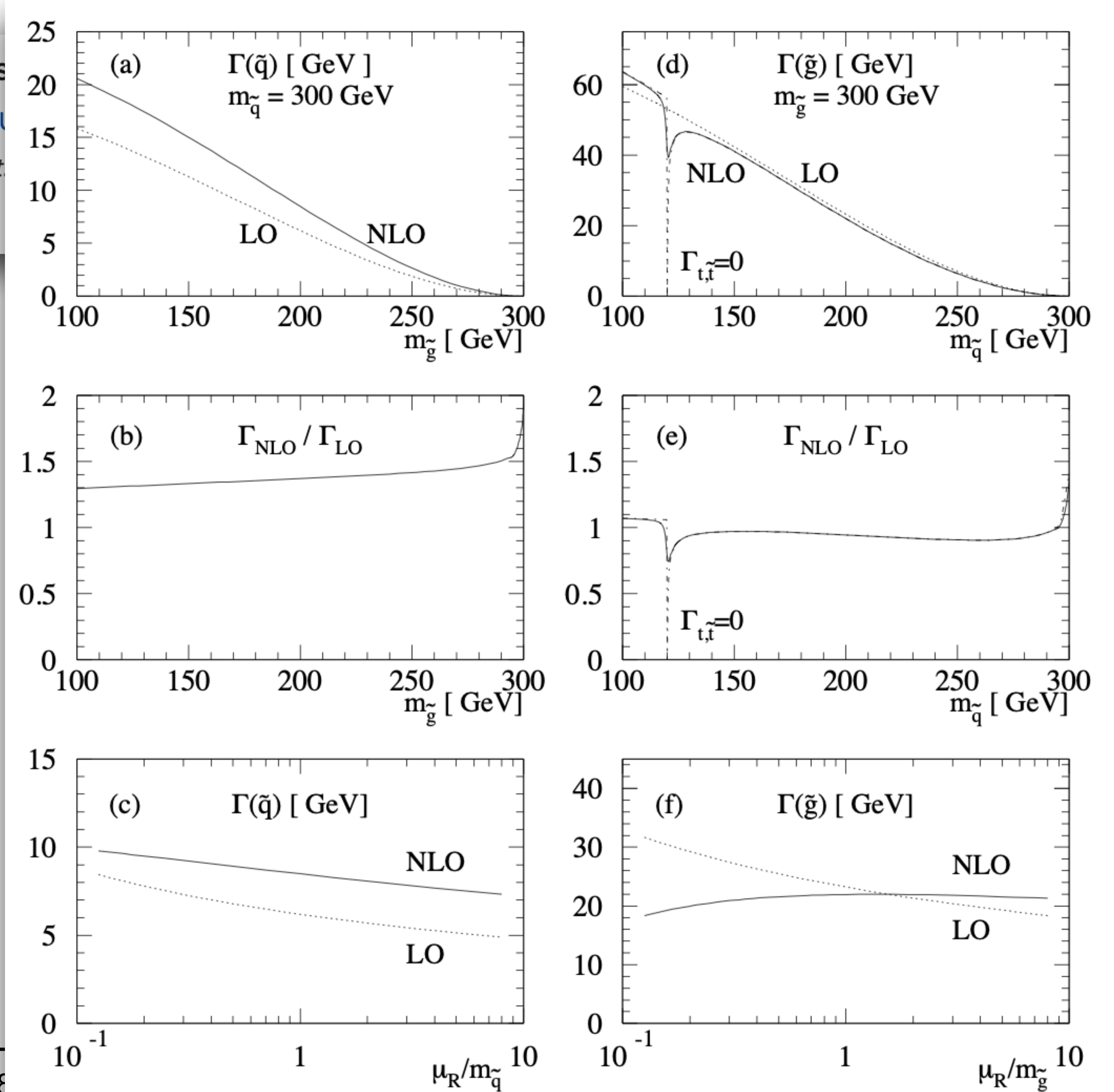
Discovery Requires Precise Theory Predictions

SUSY QCD decays

W. Beenakker (Leiden

Published in: *Phys.Lett.*

pdf DOI

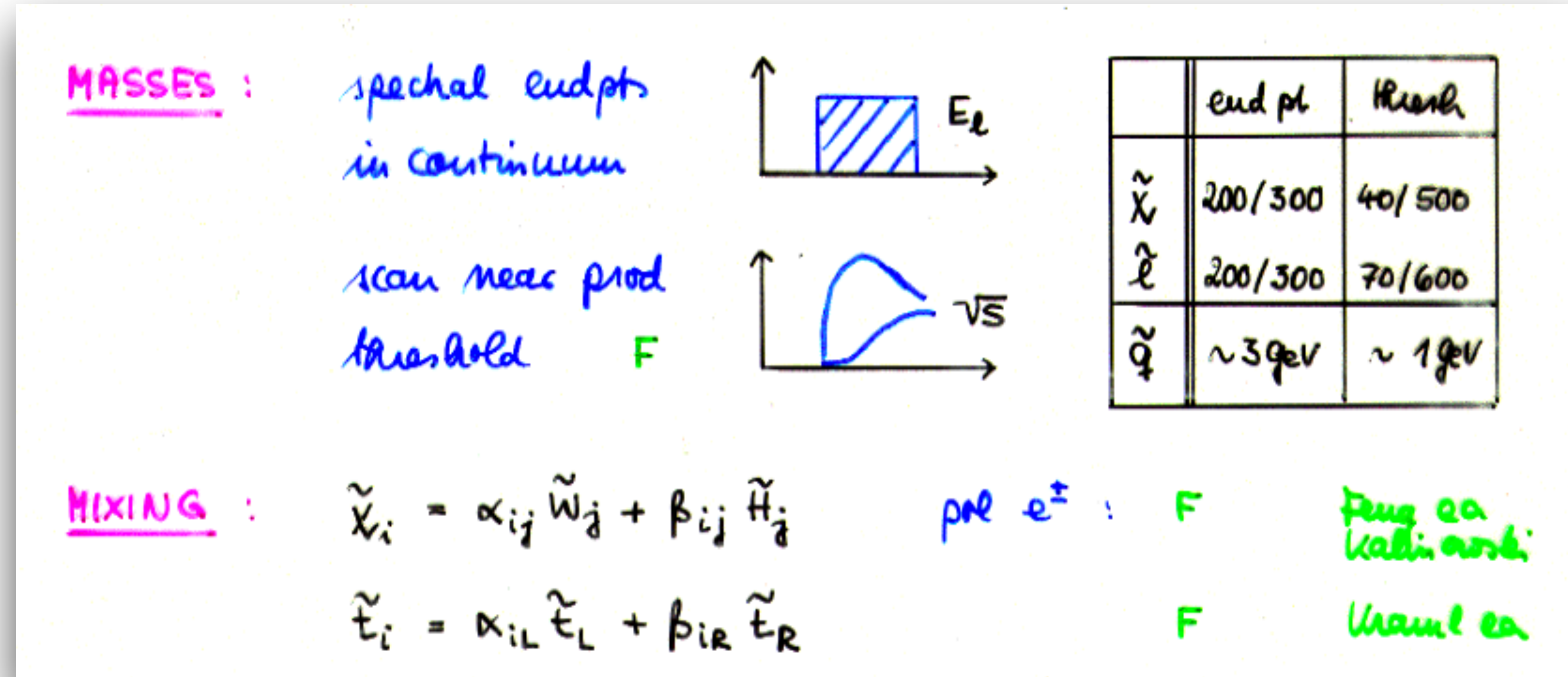


#9

96)

95 citations

Underlying Theory: Determination of SUSY Properties



MASSES :

spectral endpts in continuum

E_ℓ

scan near prod threshold F

$\sqrt{s}$

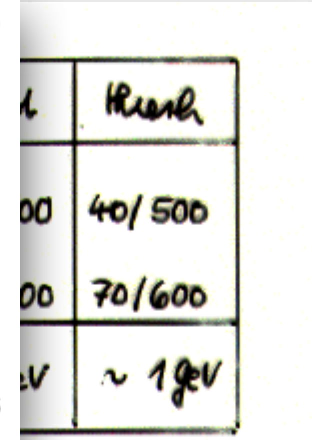
	end pt	thresh
$\tilde{\chi}$	200/300	40/500
$\tilde{\ell}$	200/300	70/600
$\tilde{q}$	~3 GeV	~1 GeV

MIXING :

$\tilde{\chi}_i = \alpha_{ij} \tilde{W}_j + \beta_{ij} \tilde{H}_j$ pol $e^\pm$: F Feng ea Kalinowski

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

Gluino 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

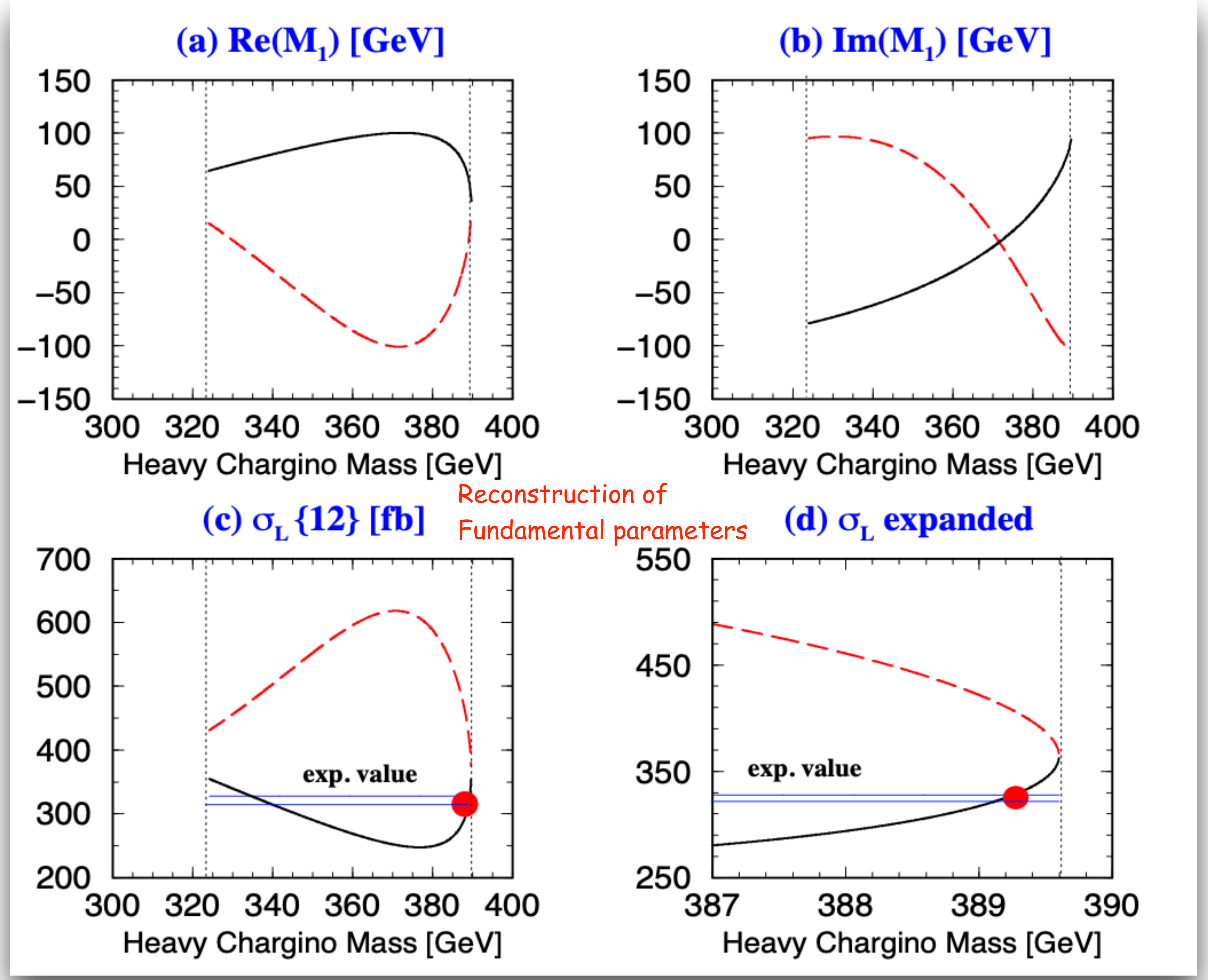
Analysis of the neutralino system in supersymmetric theories #11

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



(iv) reconstruction of fund. SUSY theory:

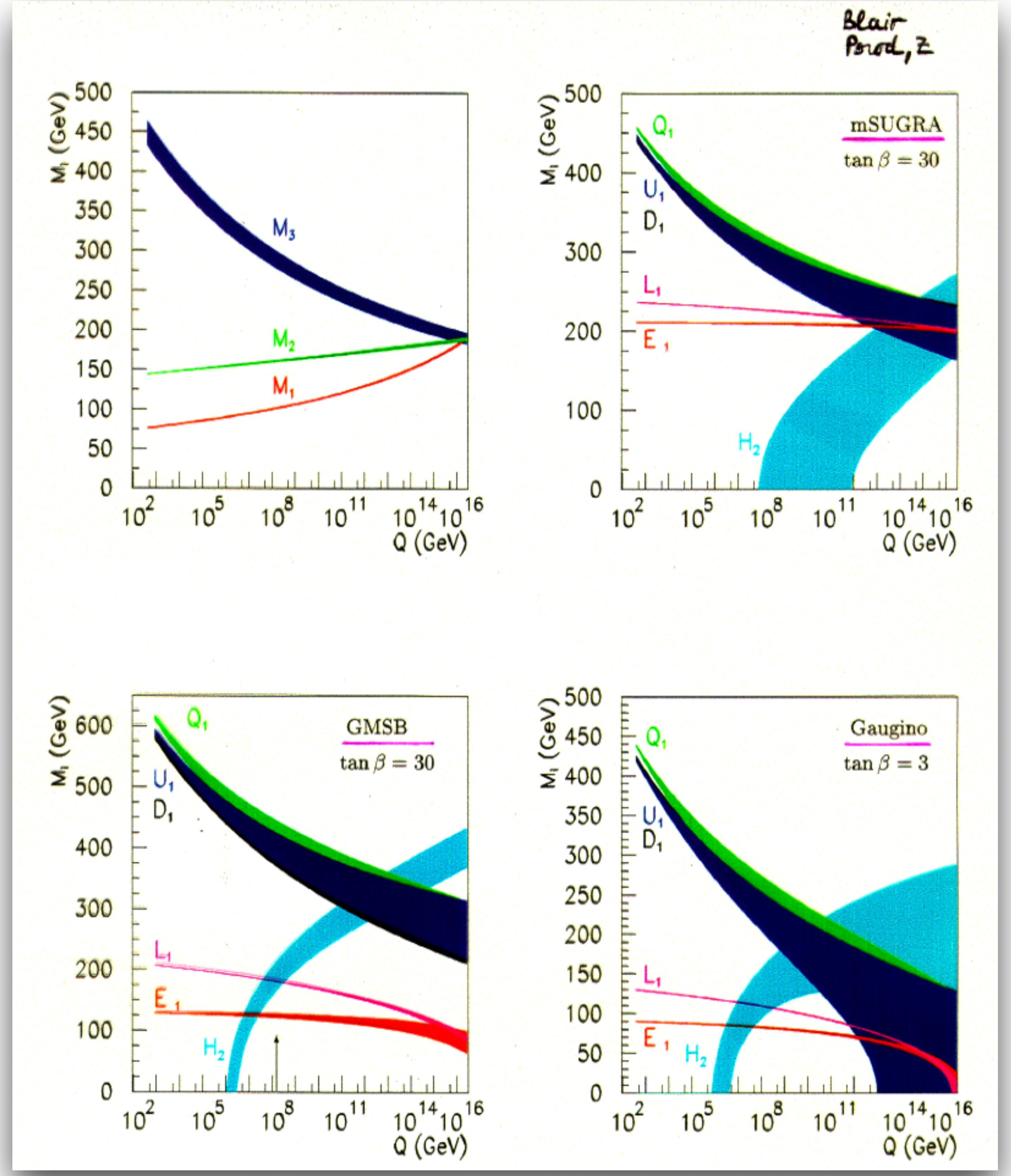
The Reconstruction of supersymmetric theories at high-energy scales #10

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 [hep-ph]

pdf DOI cite 130 citations

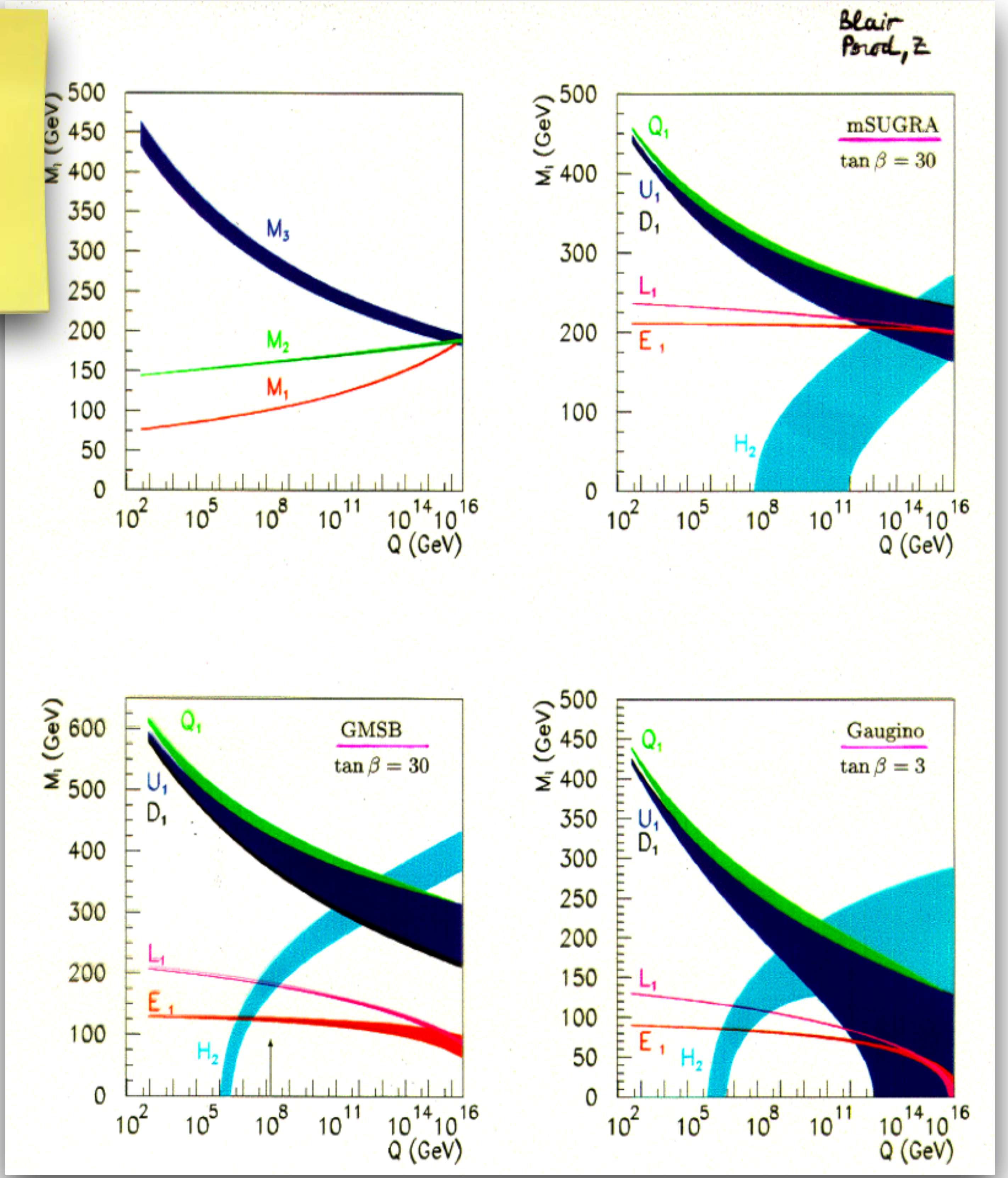
Reconstructing SUSY



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 cite 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

- 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 ≡ 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

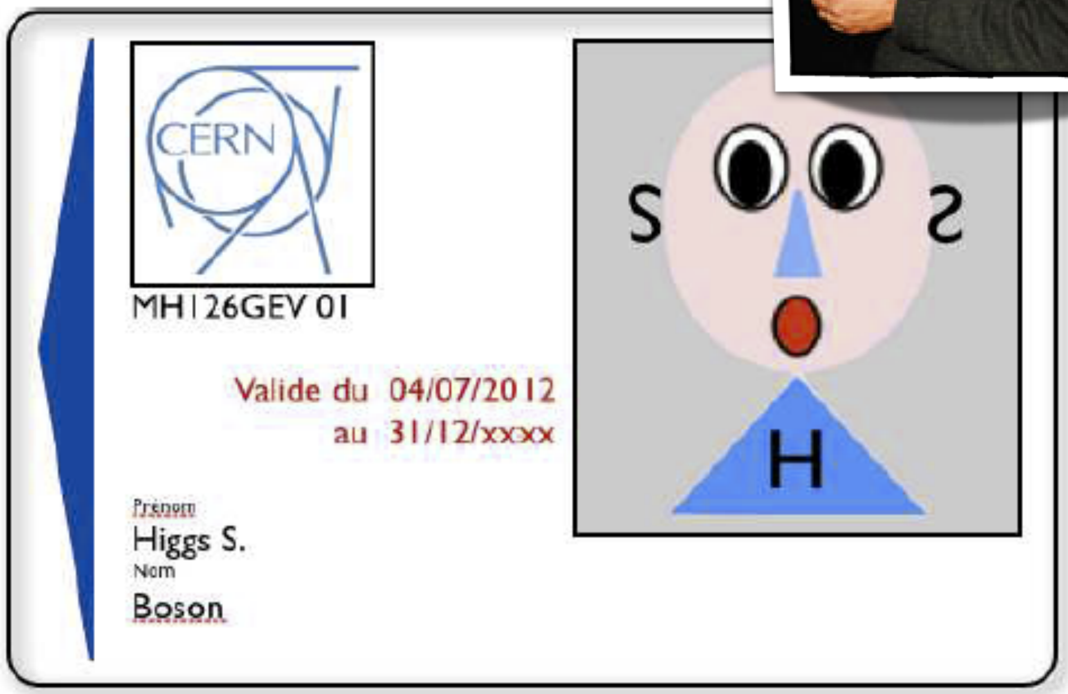
What we have

- 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]

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

- Why precision? What can we learn?

The Role of the Higgs Boson Mass

- Combined Higgs mass value: [ATLAS,CMS]

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

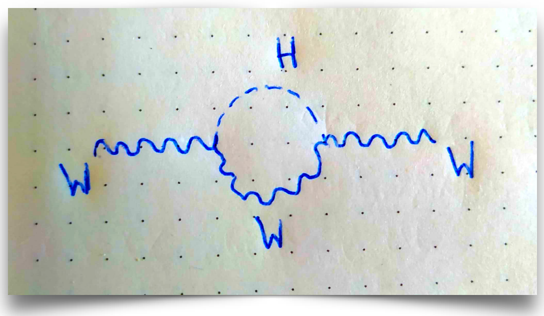
- Why precision? What can we learn?

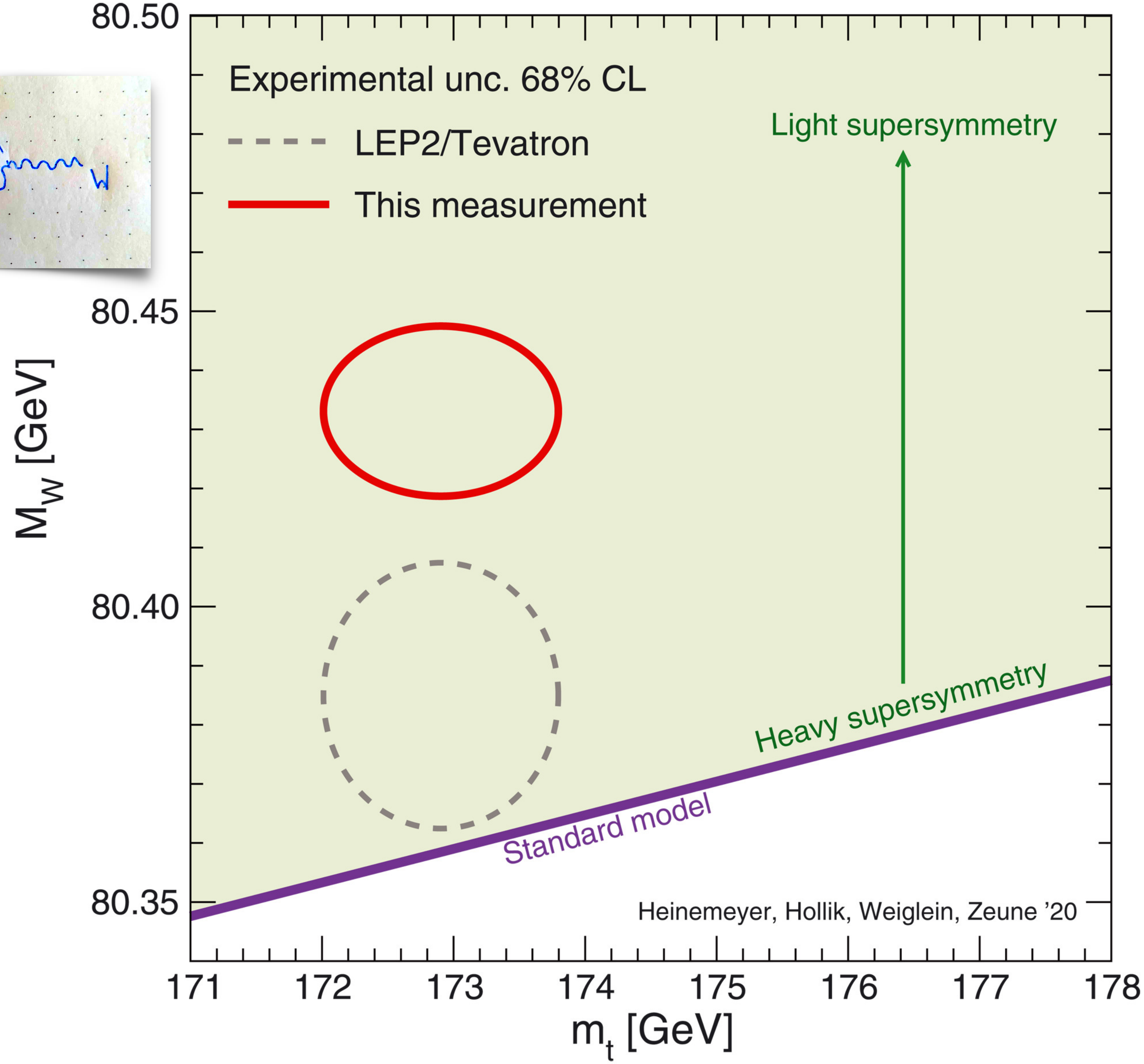
  * Self-consistency test of SM at quantum level (e.g.: Higgs loop corrections to W boson mass)
  * $M_H \leftrightarrow$ stability of the electroweak vacuum [Degrassi eal;Bednyakov eal]
  * Higgs mass uncertainty feeds back in uncertainty on Higgs observables
  * Test parameter relations in beyond-SM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

    $\Rightarrow$ indirect constraint of viable BSM parameter space!

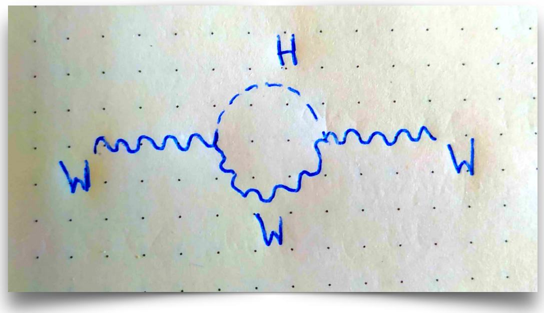
The W Boson Mass

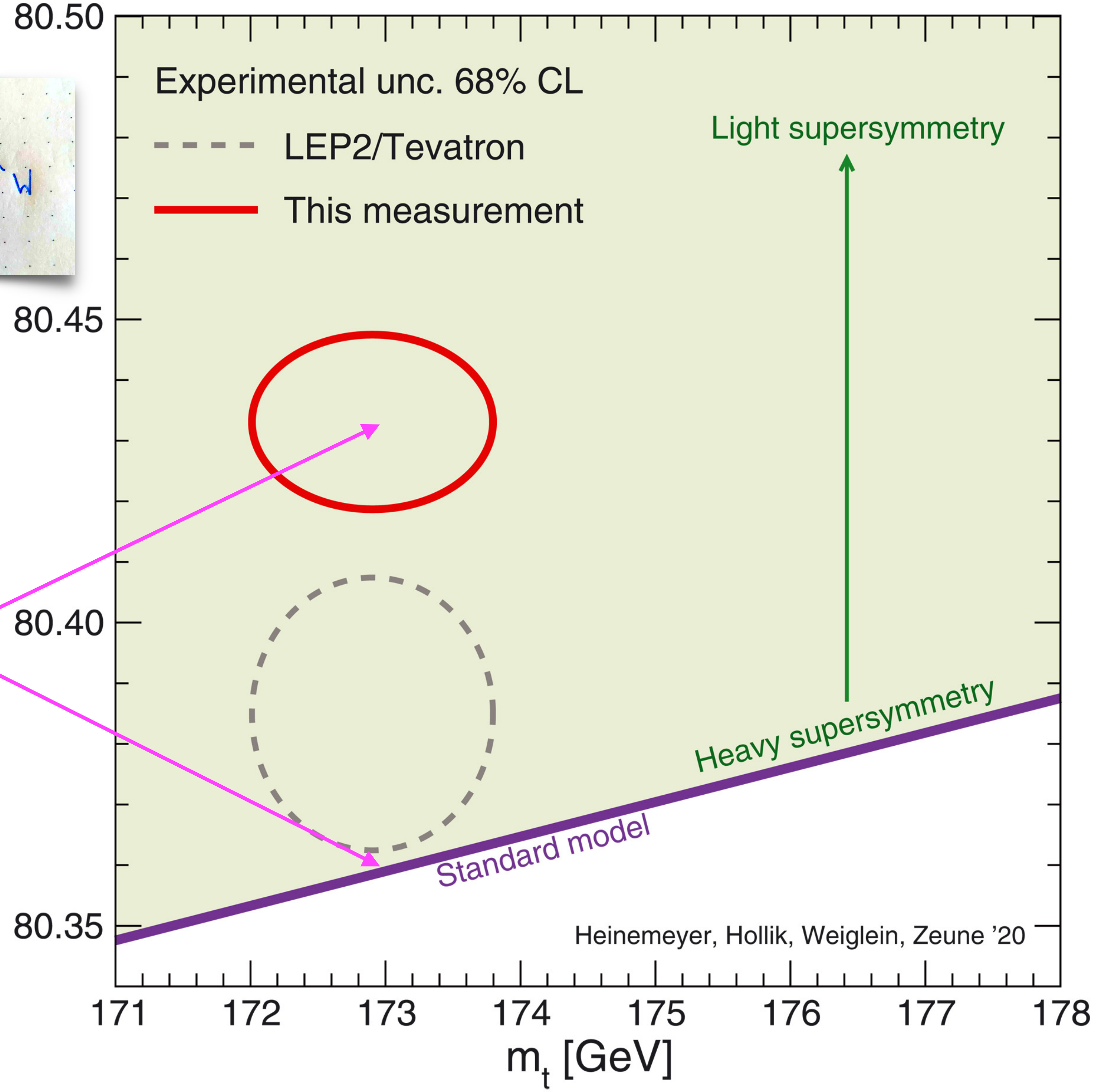
[CDF,2022]





[CDF,2022]

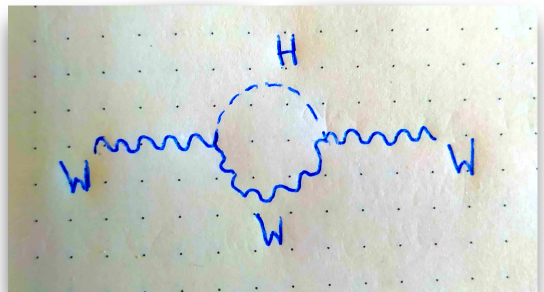


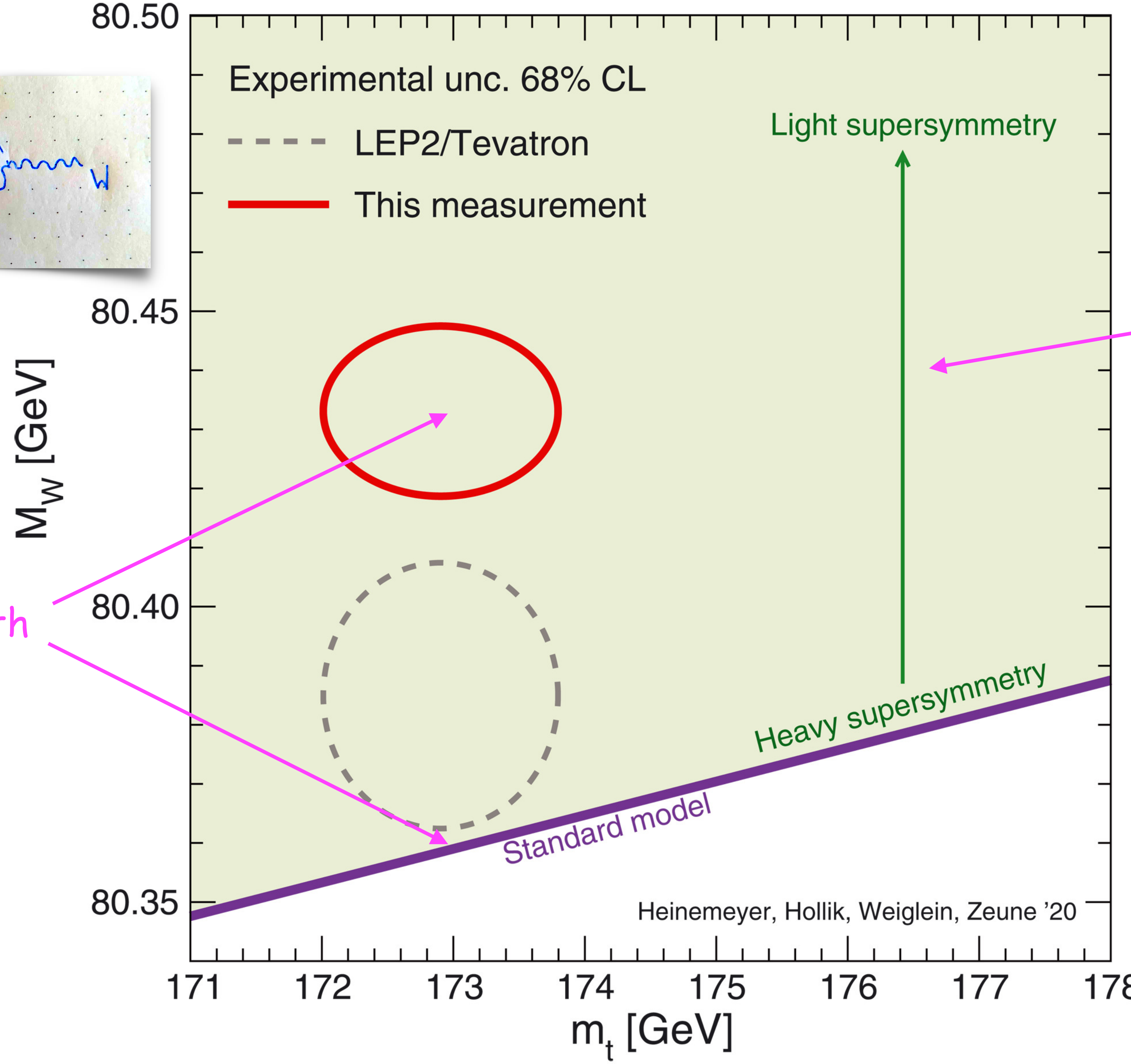


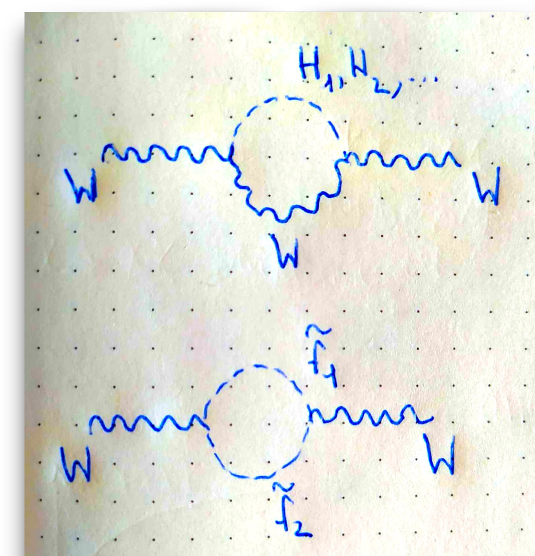
tension with SM at 7σ

The W Boson Mass

[CDF,2022]





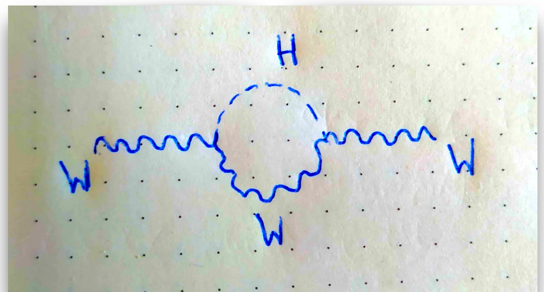


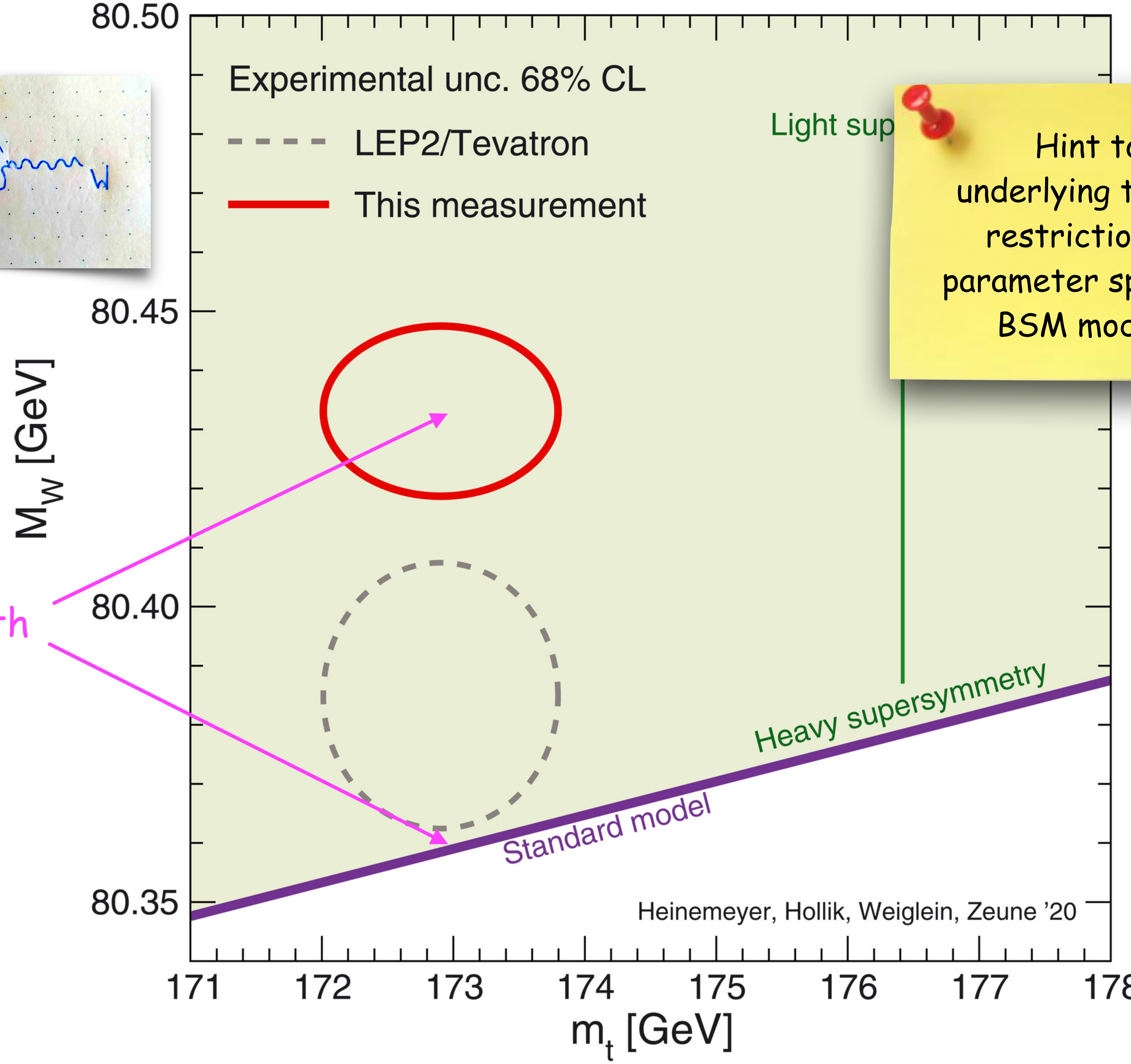
tension with SM at 7σ

new physics -> compatibility

The W Boson Mass

[CDF,2022]



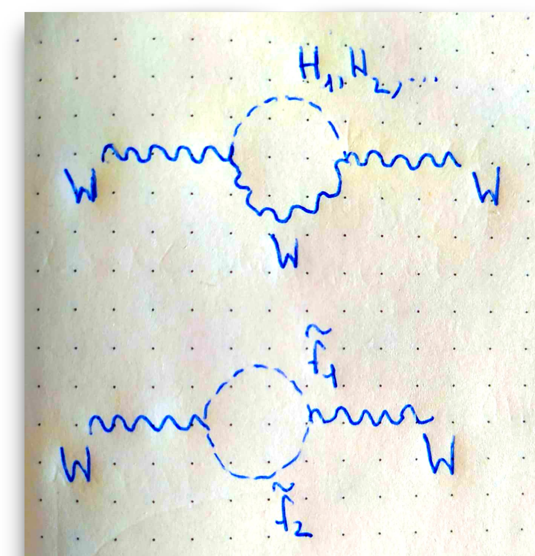


Hint to underlying theory restriction of parameter space of BSM models

tension with SM at 7σ

…ysics ->

compatibility



Higgs Mass in New Physics Extensions

Higgs boson mass:

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

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

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

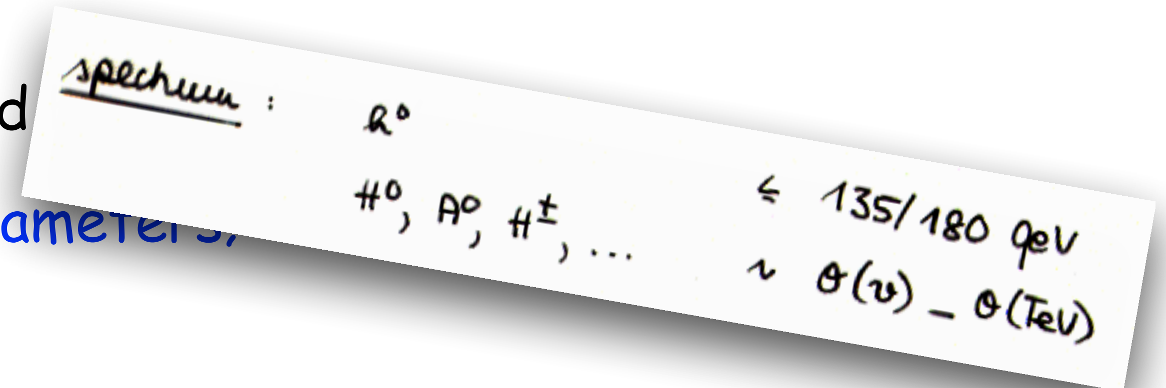
NMSSM:

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

[Kim, Nilles, '84]

Higgs boson mass:

* SM: fundamental parameter, not predicted
* Supersymmetry: calculable from input parameters,
  quantum corrections Δm^2_h are important!



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

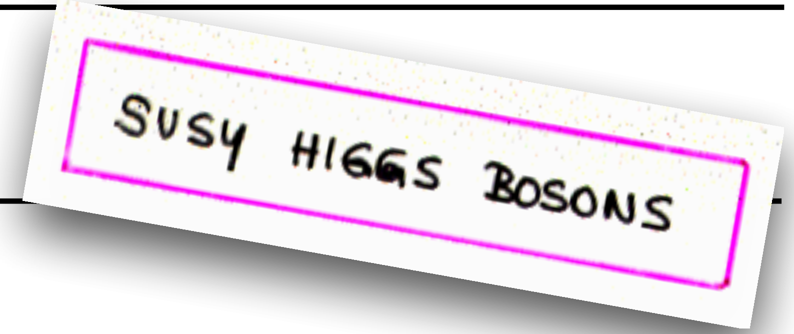
$$\text{NMSSM:} \quad m_H^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \quad + \Delta m_H^2 \leftarrow (55\ \text{GeV})^2$$

NMSSM:

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

[Kim, Nilles, '84]

SUSY Higgs Masses

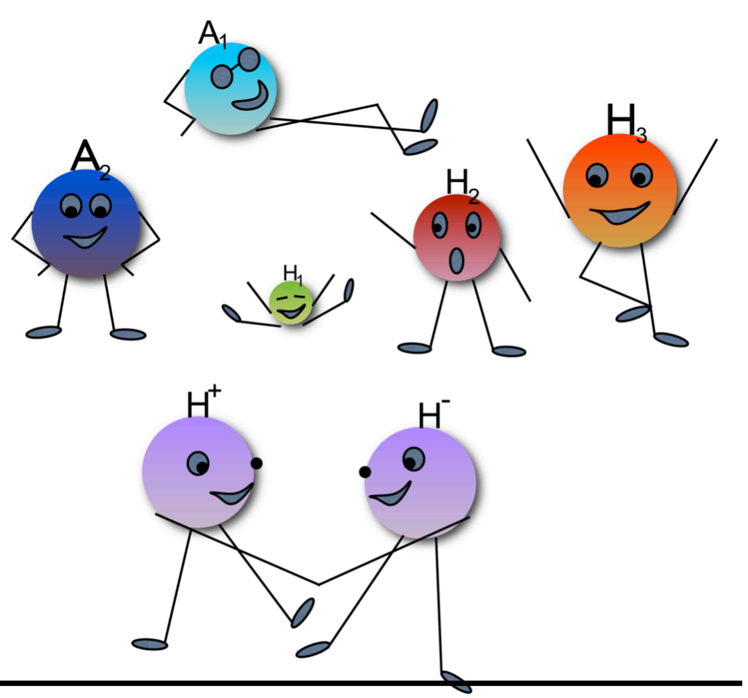


- **Supersymmetry:** requires at least 2 complex Higgs doublets

- **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:	$\tilde{\chi}_i^0 \ (i = 1, ..., 5)$



NMSSM Mass Spectrum

CERN-TH/2003-077
DESY 03-066
ITEP-03-05

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

D.J. Miller[1], R. Nevzorov[2]
and P.M. Zerwas[3]

[1] *Theory Division, CERN, CH-1211 Geneva 23, Switzerland*
[2] *ITEP, Moscow, Russia*
[3] *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

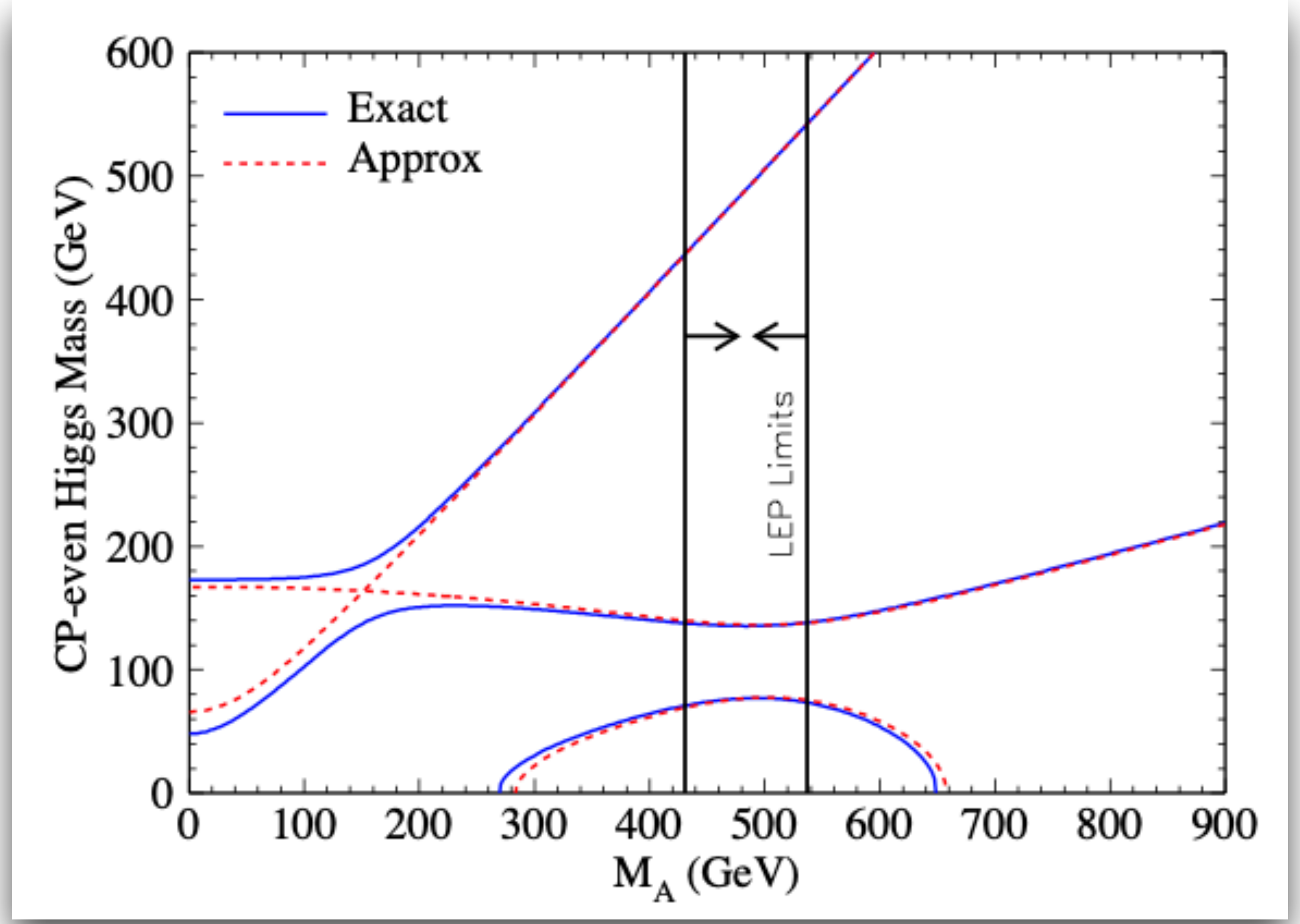
[Miller,Nevzorov,Zerwas,'03]

$$M_{H_3}^2 = M_{11}^2 + \frac{M_{13}^4}{M_{11}^2},$$

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

NMSSM Mass Spectrum

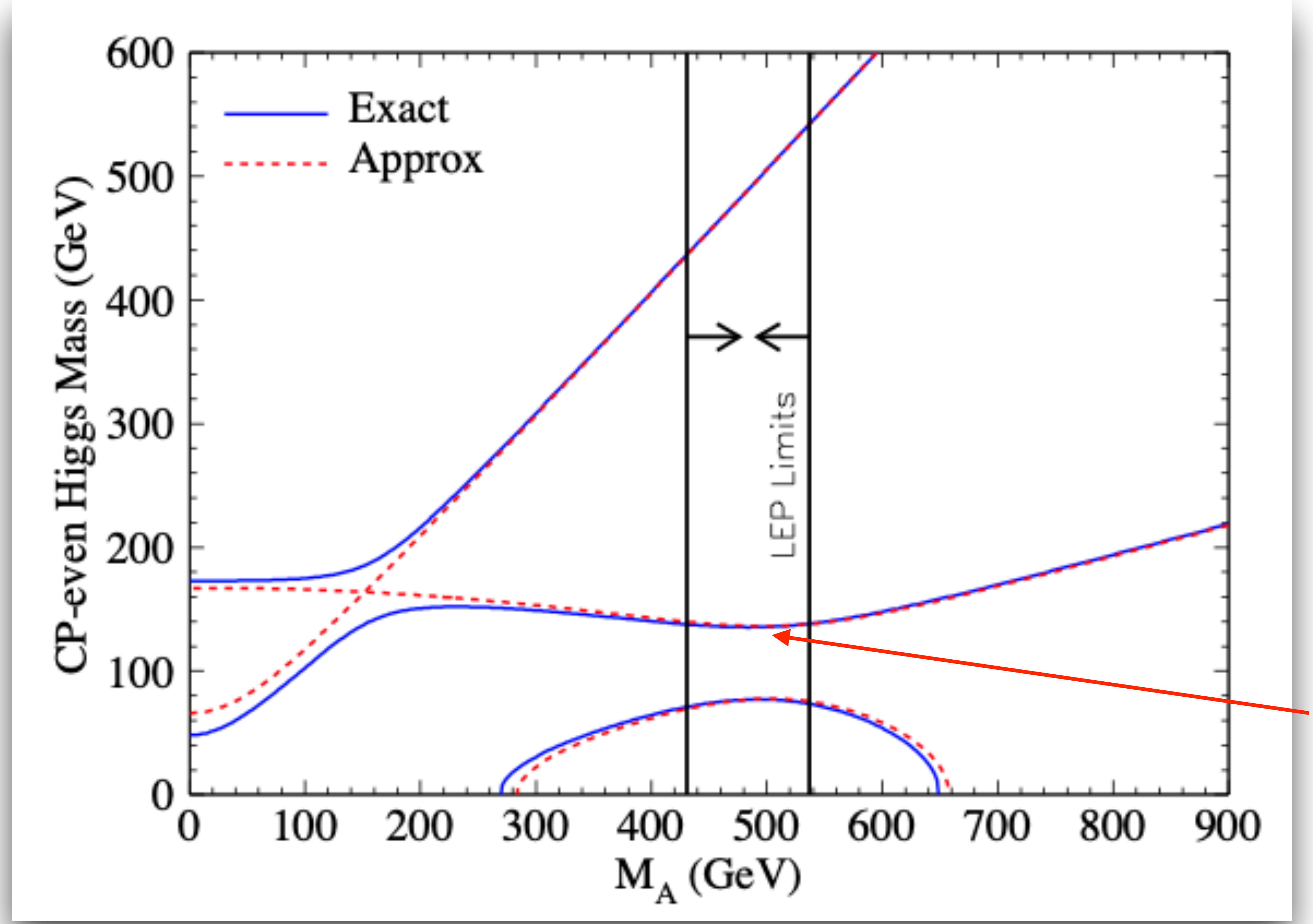
[Miller,Nevzorov,Zerwas,'03]



NMSSM with a slightly broken Peccei-Quinn Symmetry

NMSSM Mass Spectrum

[Miller,Nevzorov,Zerwas,'03]



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

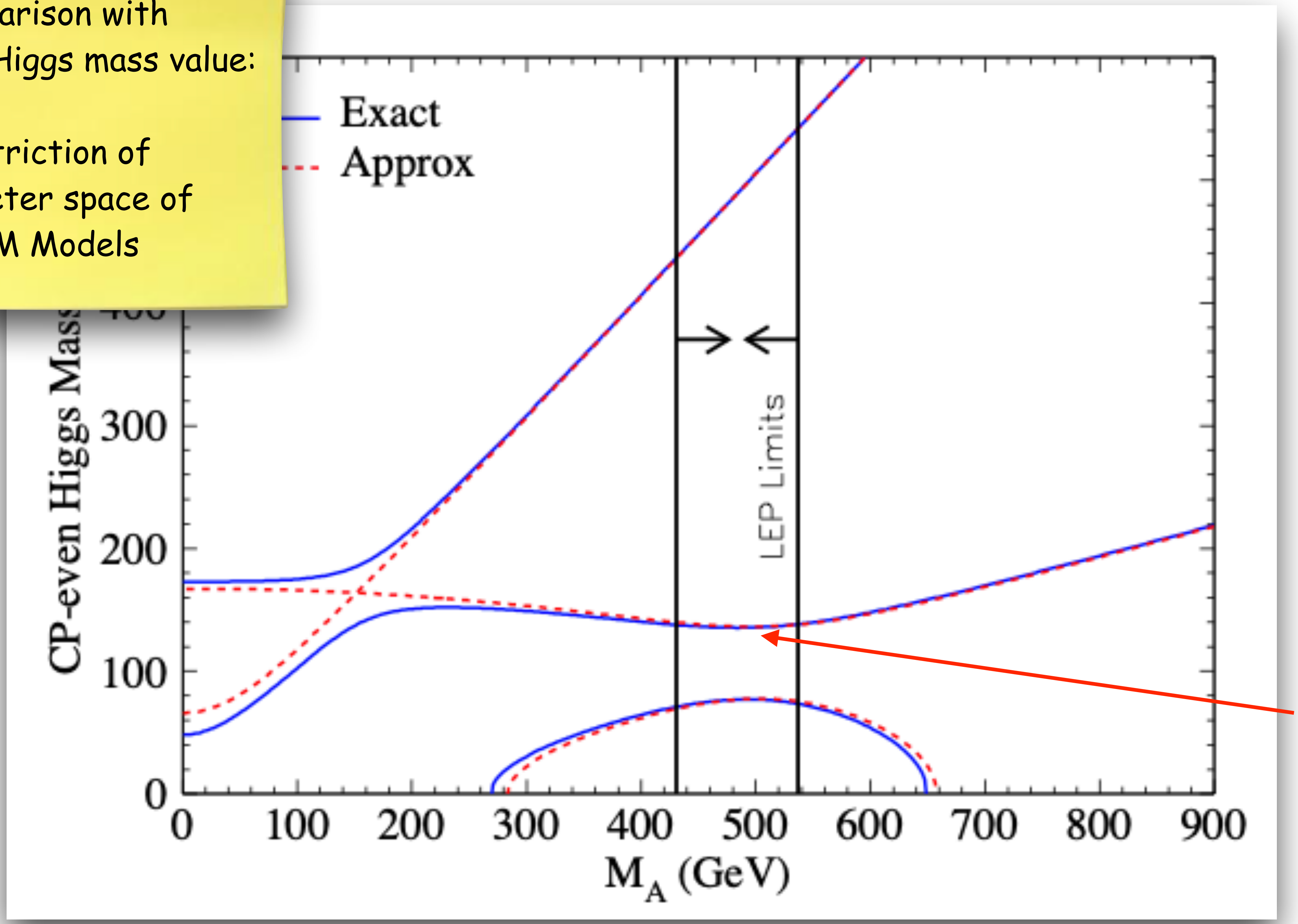
NMSSM with a slightly broken Peccei-Quinn Symmetry

NMSSM Mass Spectrum

[Miller,Nevzorov,Zerwas,'03]

Comparison with measured Higgs mass value:

Restriction of parameter space of BSM Models



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

NMSSM with a slightly broken Peccei-Quinn Symmetry

Spectrum Calculations 2022

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

- full (N)MSSM perturb. series truncated at fixed order reliable for not too heavy SUSY masses
- some very heavy SUSY masses: large logarithms require resummation
- combines virtues of fixed order and EFT calculation

❖ 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^{2}LL (included in calculators), N^{3}LL

❖ 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 [...] EFT) - hybrid

ombines virtues of fixed order and EFT calculation

❖ Status MSSM spec[...]

FO: up to 2-loop in [...]

EFT: up to N^{2}LL (in[...]

❖ Status NMSSM spe[...]

FO: up to 2-loop in [...]

EFT: matching to q[...]

hybrid

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[a] and S. Heinemeyer[b,c,d] (eds.),

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

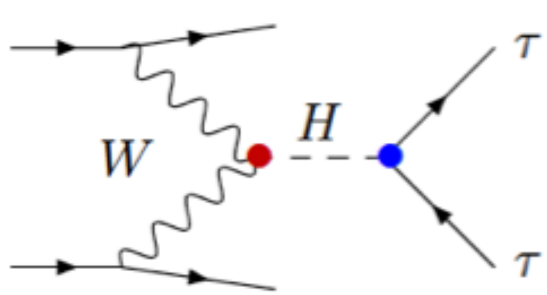
B.C. Allanach[t], T. Biekötter[f], S. Borowka[u ‡], J. Braathen[f], M. Carena[r,s,v], T.N. Dao[w], G. Degrassi[x], F. Domingo[y], P. Drechsel[f ‡], U. Ellwanger[z], M. Gabelmann[m], R. Gröber[aa], J. Klappert[i], T. Kwasnitza[o], D. Meuser[f], L. Mihaila[bb ‡], N. Murphy[cc ‡], K. Nickel[y ‡], W. Porod[dd],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

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.

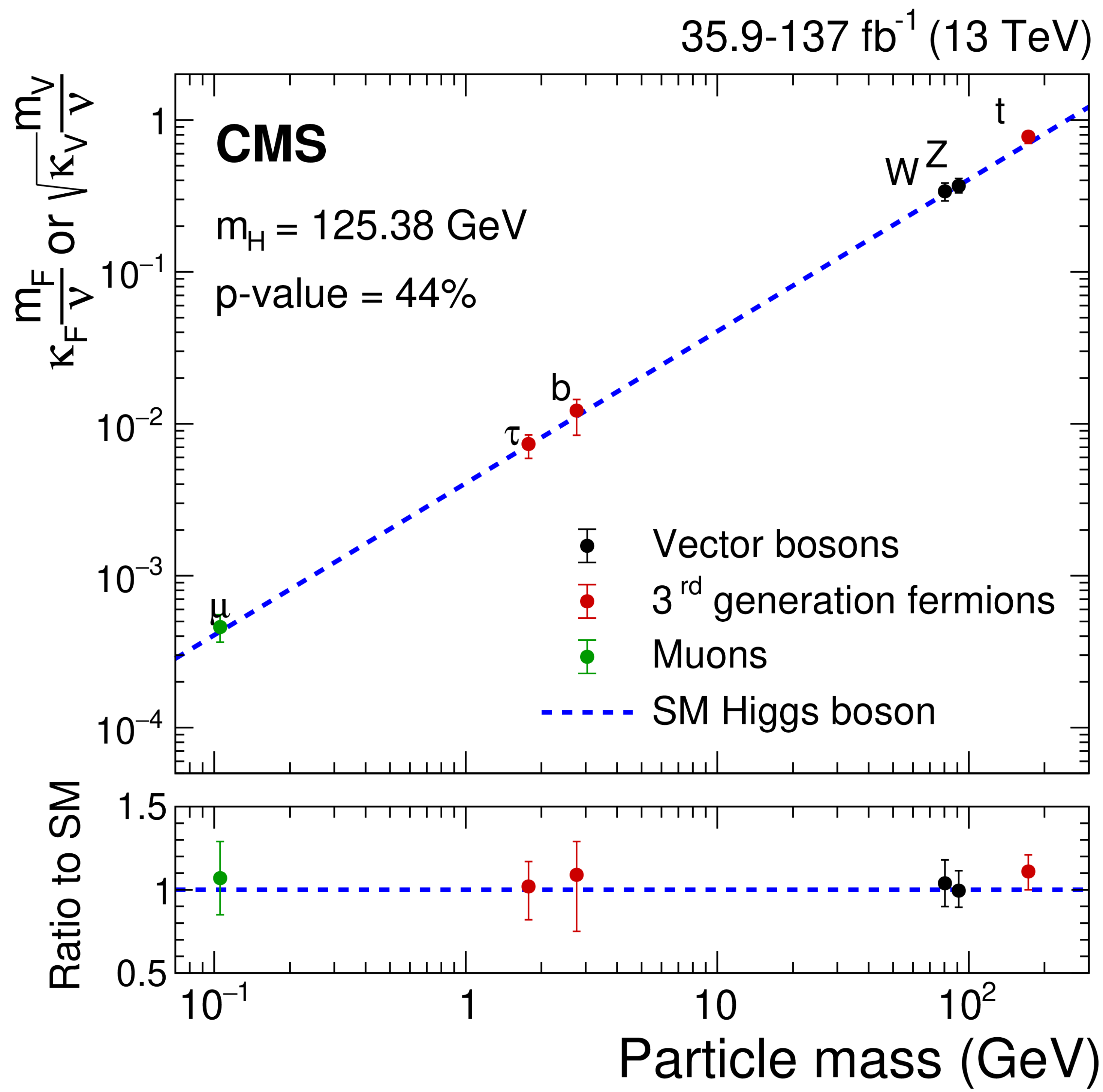

Higgs Boson Properties -
Couplings

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

e.g.



$$\sim \Gamma_{WW}\, \mathrm{BR}(H \to \tau\tau)$$



SM and also MSSM Higgs Production and Decay

SUSY HIGGS BOSONS

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 [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 [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 [hep-ph]

pdf links DOI cite 216 citations

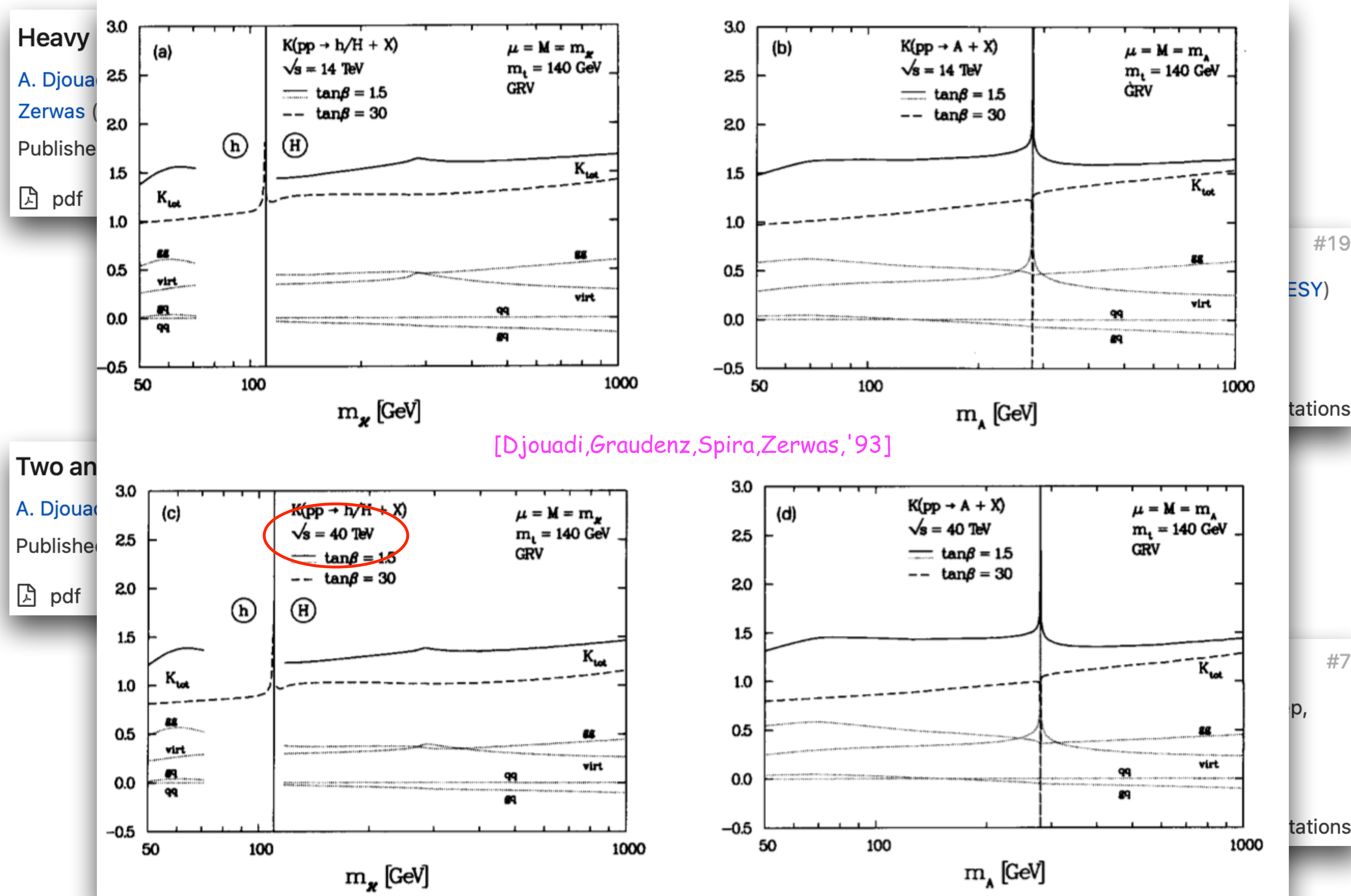
SUSY Higgs production at proton colliders
#7

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

SUSY HIGGS BOSONS



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

Higgs Boson Quantum Numbers

Higgs Boson Quantum Numbers

- **Quantum numbers of the Higgs boson:** J^{PC}
  - J spin
  - 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 [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 [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 [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 [hep-ph]

pdf links DOI cite 265 citations

Theoretical Basis of Higgs-Spin Analysis in $H \to \gamma\gamma$ and $Z\gamma$ Decays #3

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

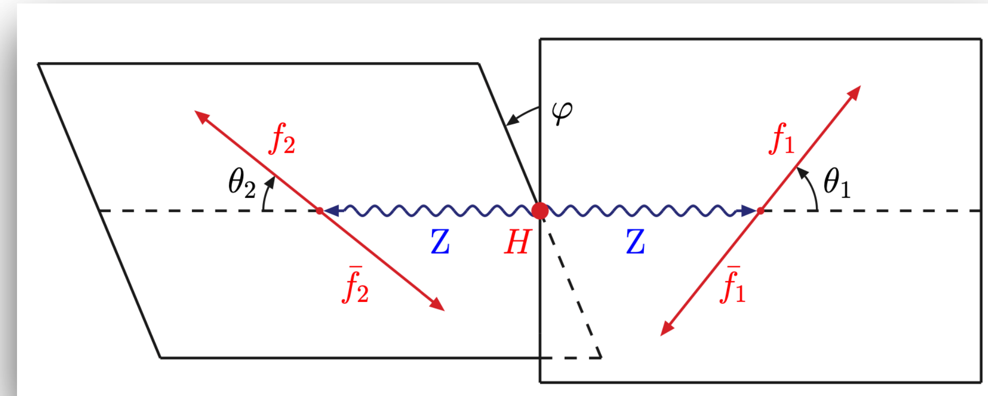
Published in: *Phys.Lett.B* 718 (2013) 1031-1035 • e-Print: 1209.5268 [hep-ph]

pdf DOI cite 55 citations

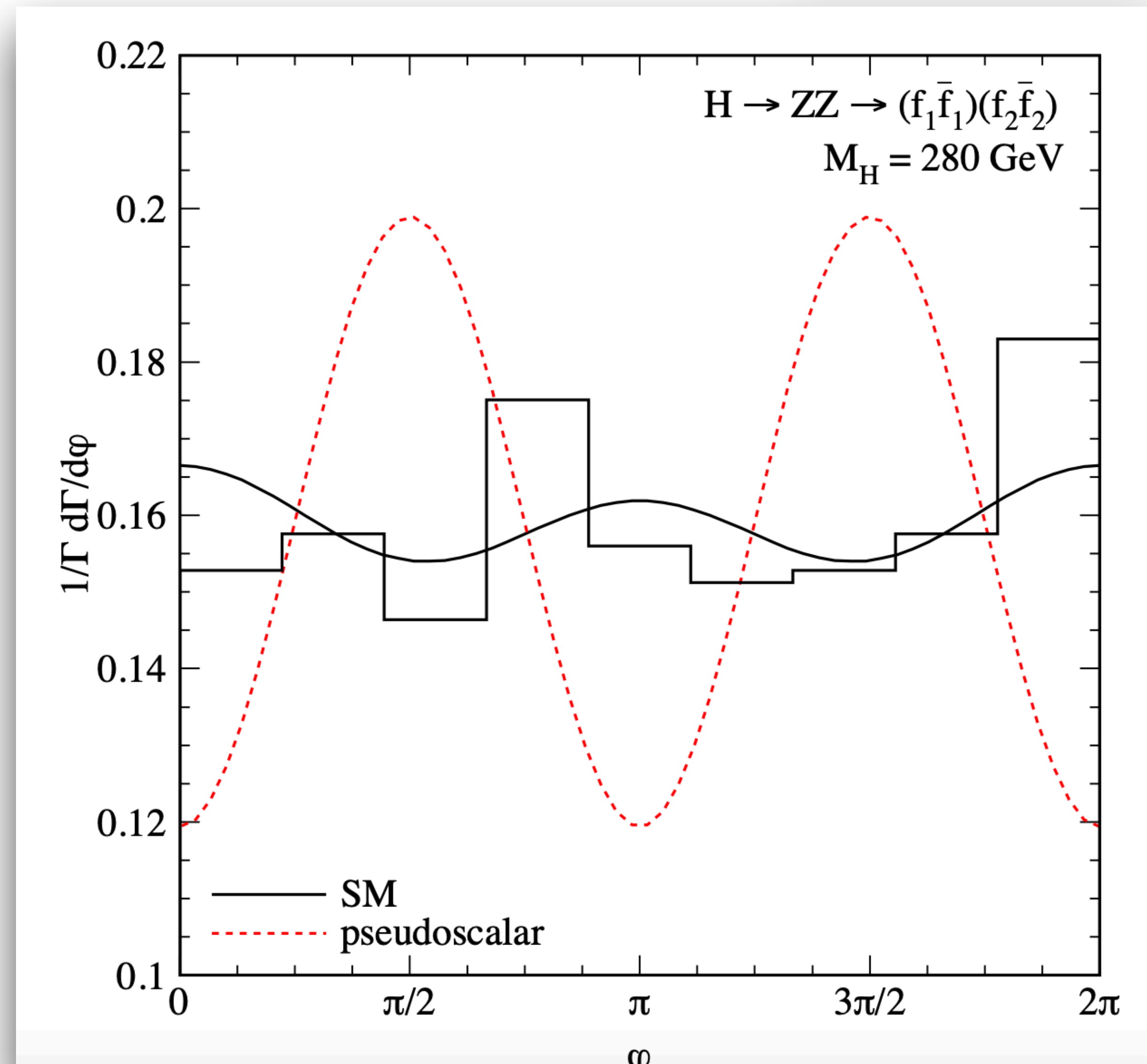
Higgs Boson Quantum Numbers

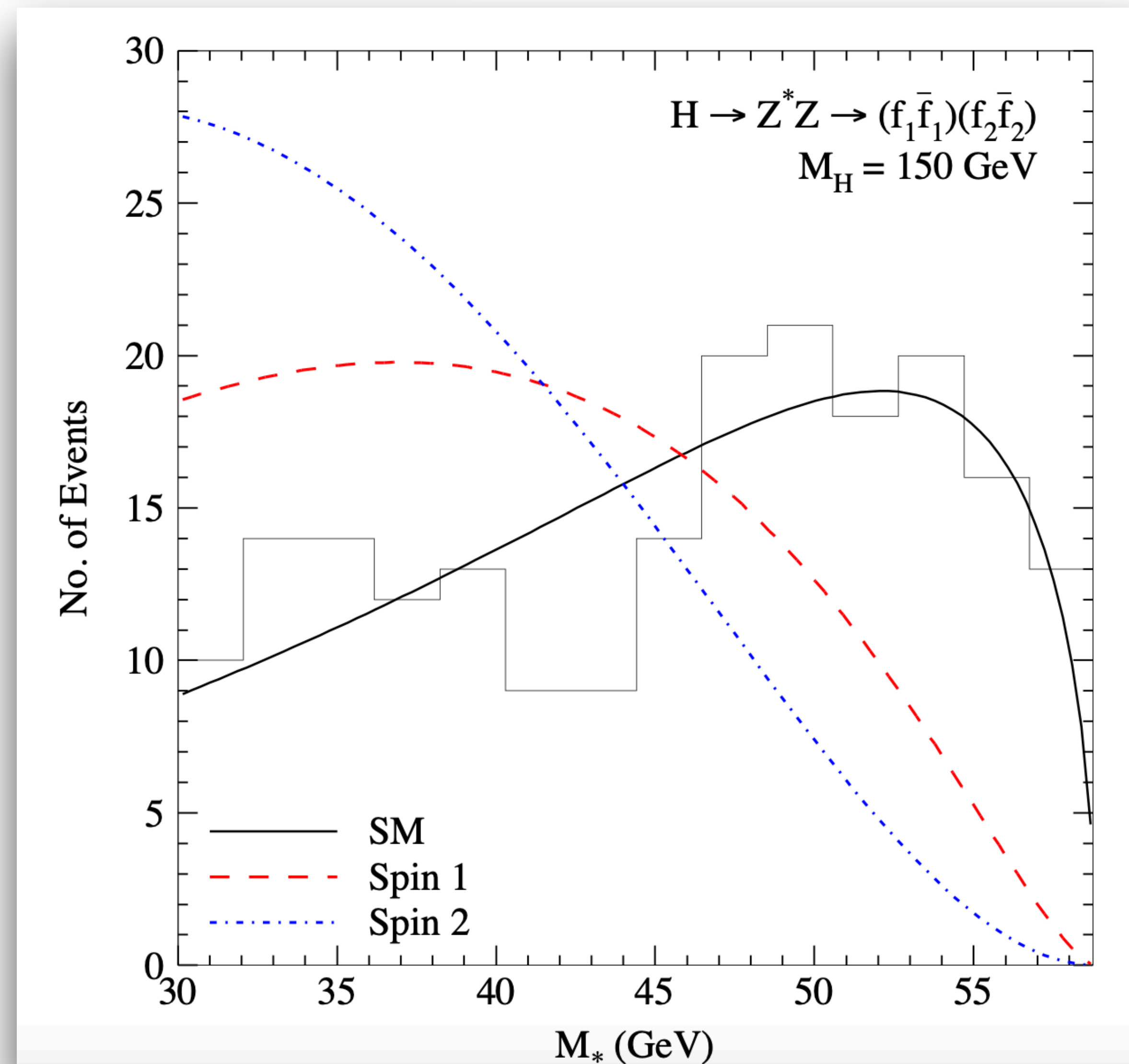
[Choi,Miller,MM,Zerwas,'02]

parity



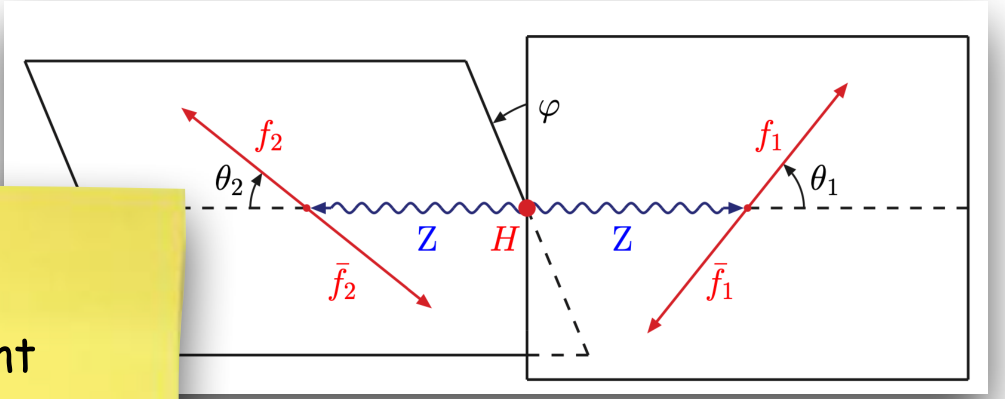
spin





Higgs Boson Quantum Numbers

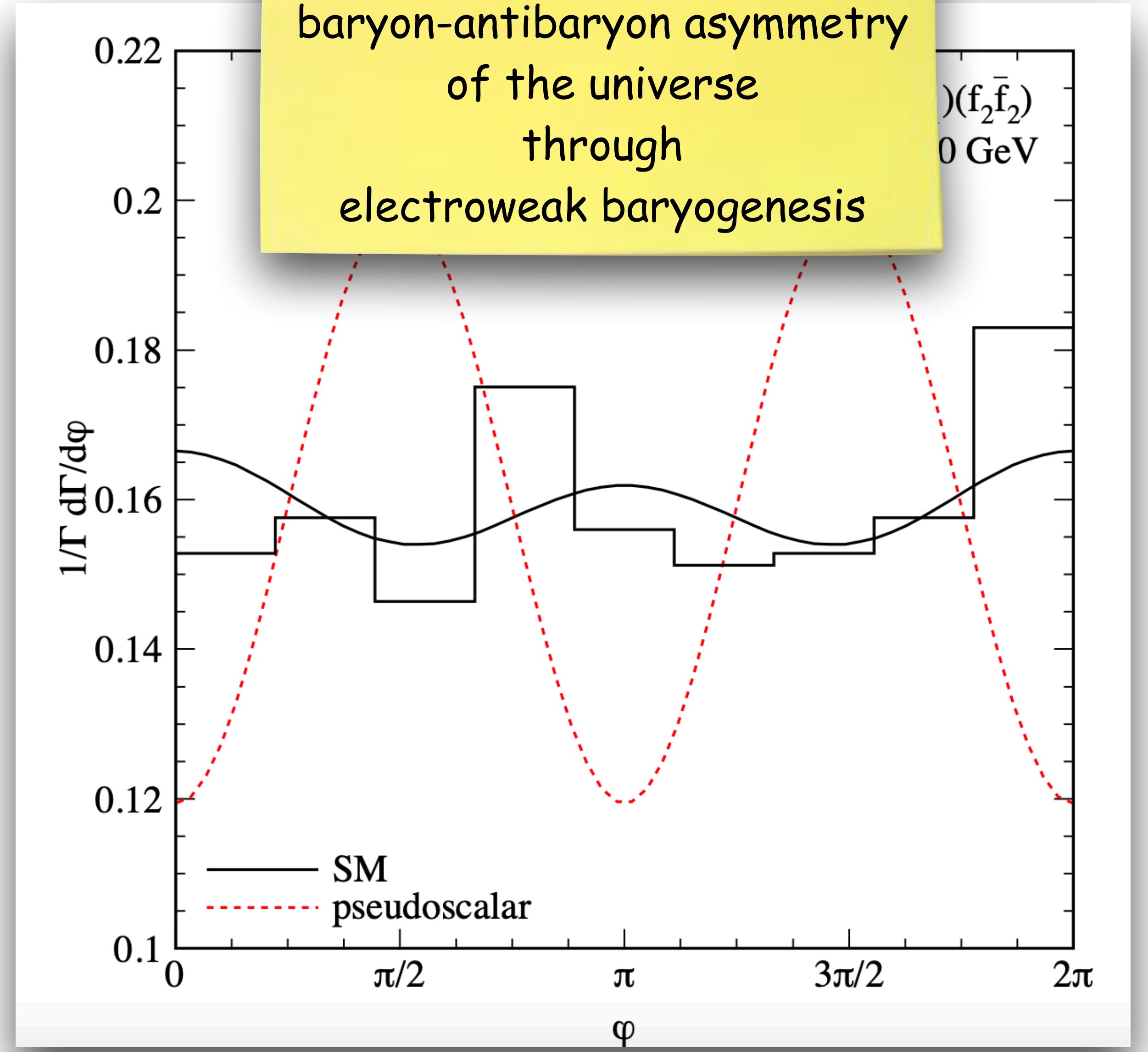
[Choi,Miller,MM,Zerwas,'02]

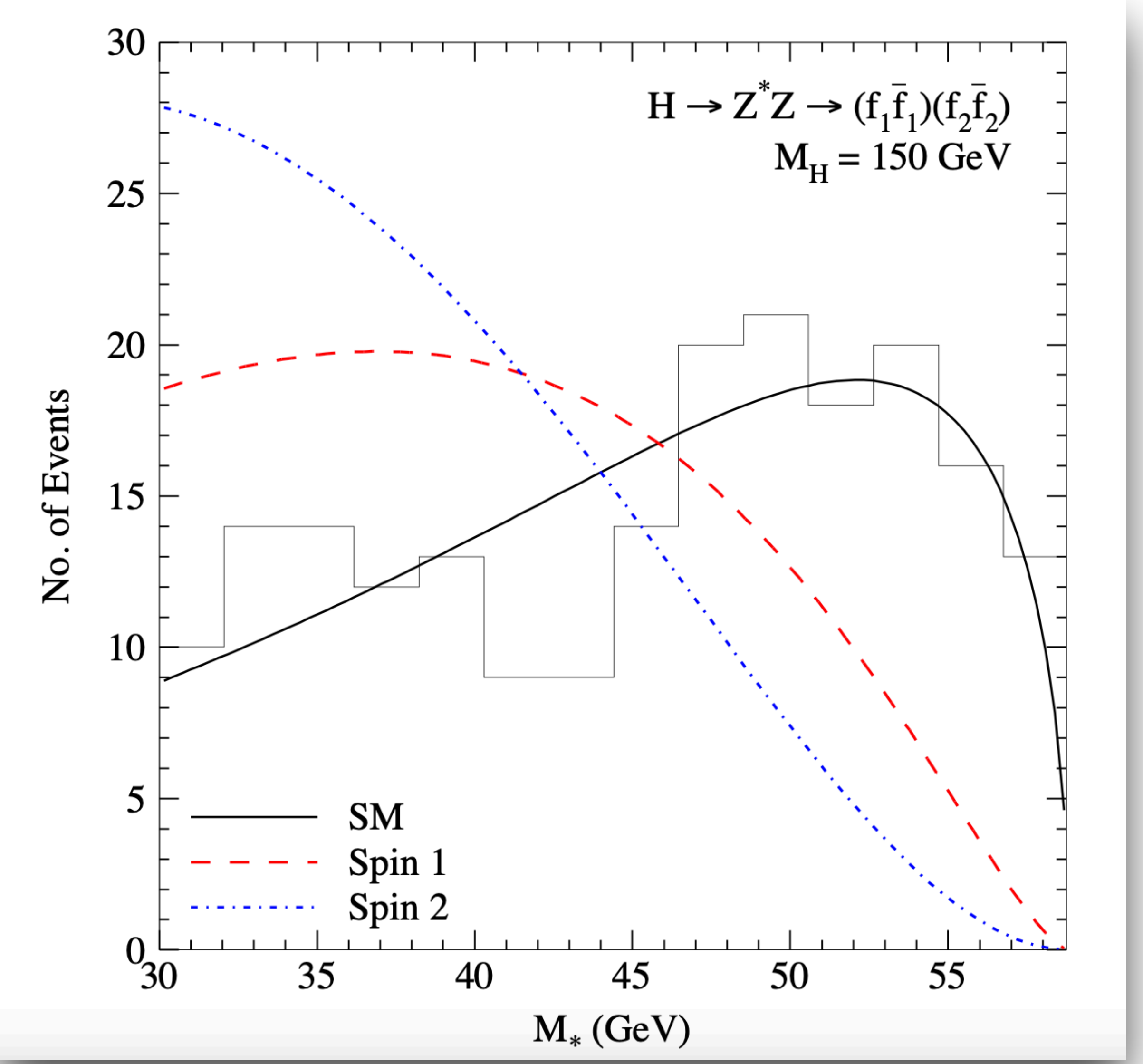


spin

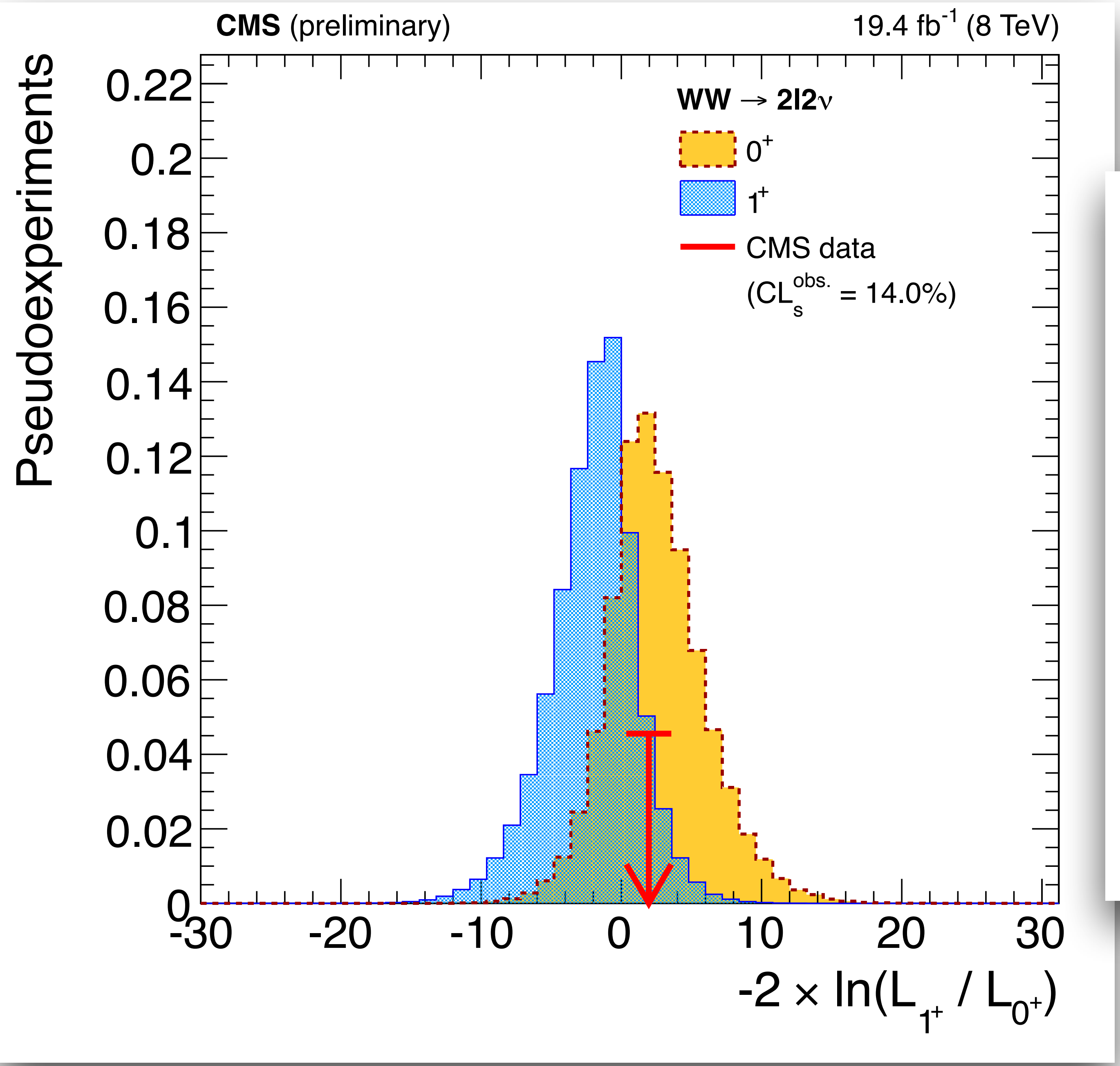
CP violation

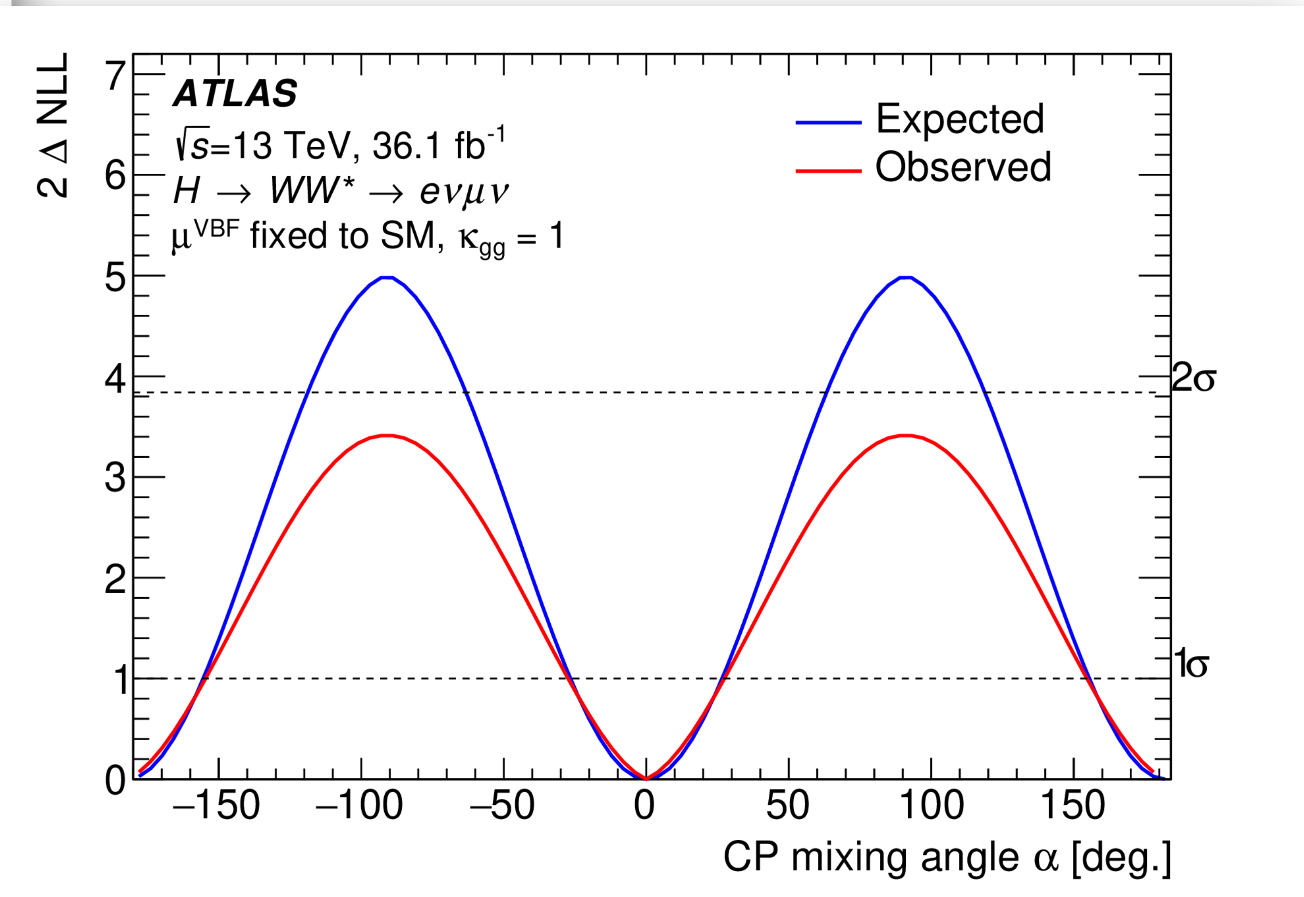
Required ingredient
for generation of
baryon-antibaryon asymmetry
of the universe
through
electroweak baryogenesis

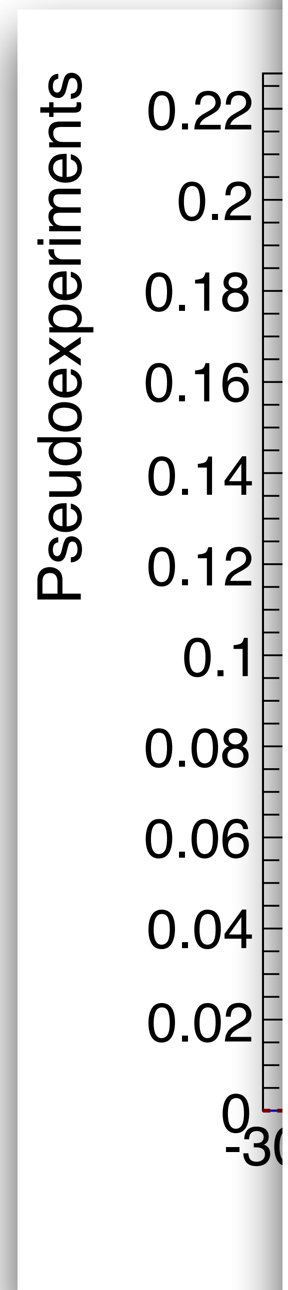


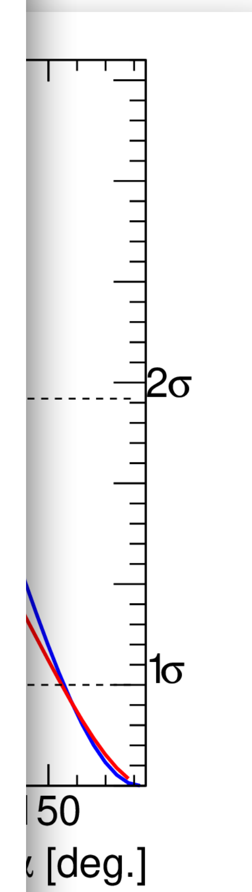


CMS, ATLAS: Testing Spin-Parity Hypotheses



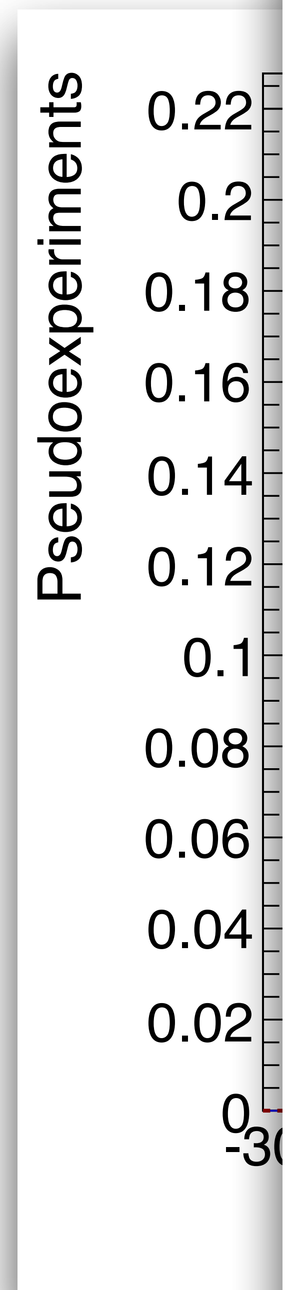




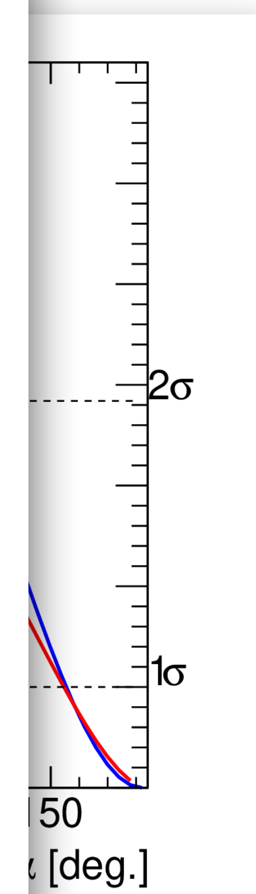


DESY Theory Workshop 2000 – Peter Zerwas (DESY) (right) tells Martin Holder (Siegen) to measure CP violation more precisely.

CMS, ATLAS: Testing Spin-Parity Hypotheses



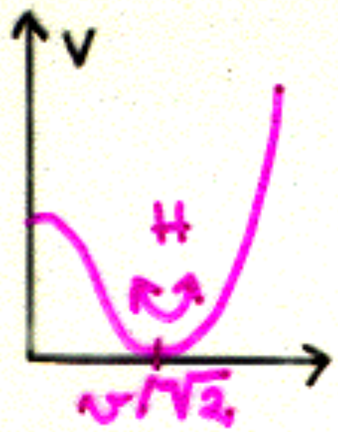
DESY Theory Workshop 2000 – Peter Zerwas (DESY) (right) tells Martin Holder (Siegen) to measure CP violation more precisely.




Higgs Pair Production

SM HIGGS MECHANISM

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



(1) Higgs excitation ≡ Higgs boson must be discovered — LEP2, Tevatron, LHC

(2) generating masses by interaction with Higgs field: coupl'g ~ mass — [LHC], LC

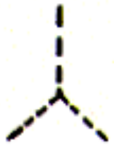
(3) Higgs field $v/\sqrt{2}$ generated by spont. sym. break'g: reconstruction of Higgs potential — LC

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 : $\lambda_{HHH} = 3 M_H^2 / M_Z^2$



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

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

(a) trilinear coupling : via Higgs pair production

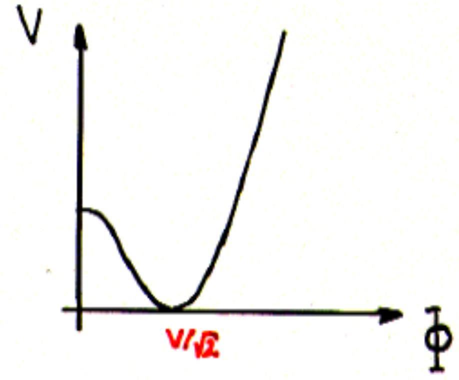
(b) quadrilinear coupling : via triple Higgs production

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

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

$v = 246$ GeV

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



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

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

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

(a) trilinear coupling : via Higgs pair production

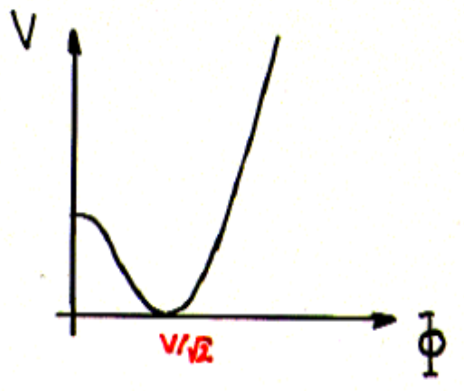
(b) quadrilinear coupling : via triple Higgs production

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

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

v = 246 GeV

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



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 [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 [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 [hep-ph]

pdf DOI cite 271 citations

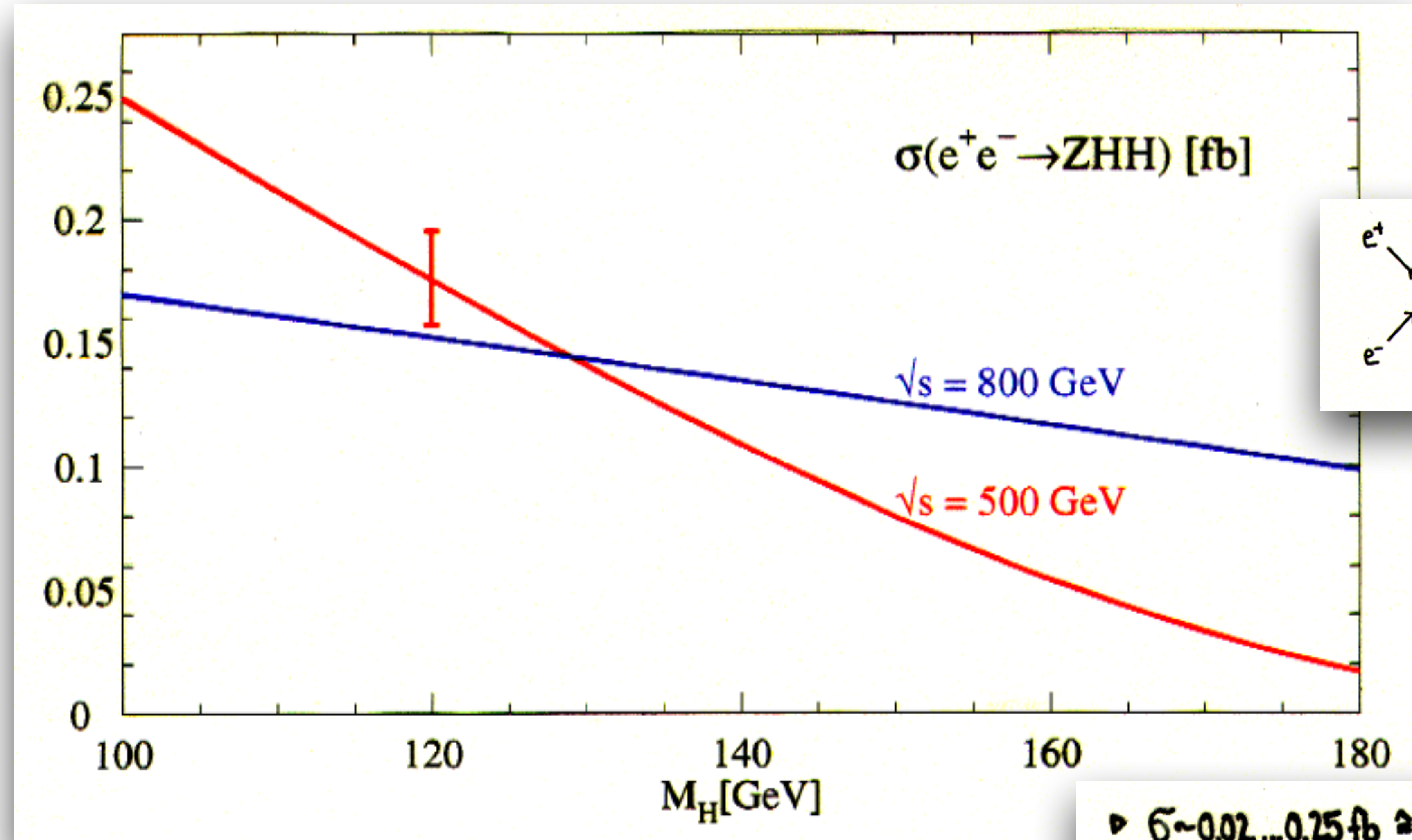
Testing Higgs selfcouplings at e+ e- linear colliders #17

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

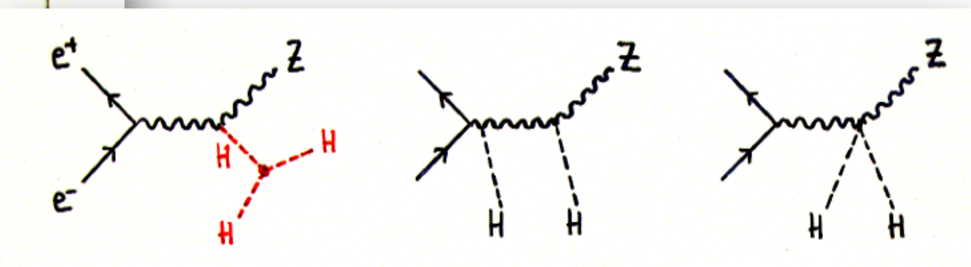
Published in: *Eur.Phys.J.C* 10 (1999) 27-43 • e-Print: hep-ph/9903229 [hep-ph]

pdf DOI cite 249 citations

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



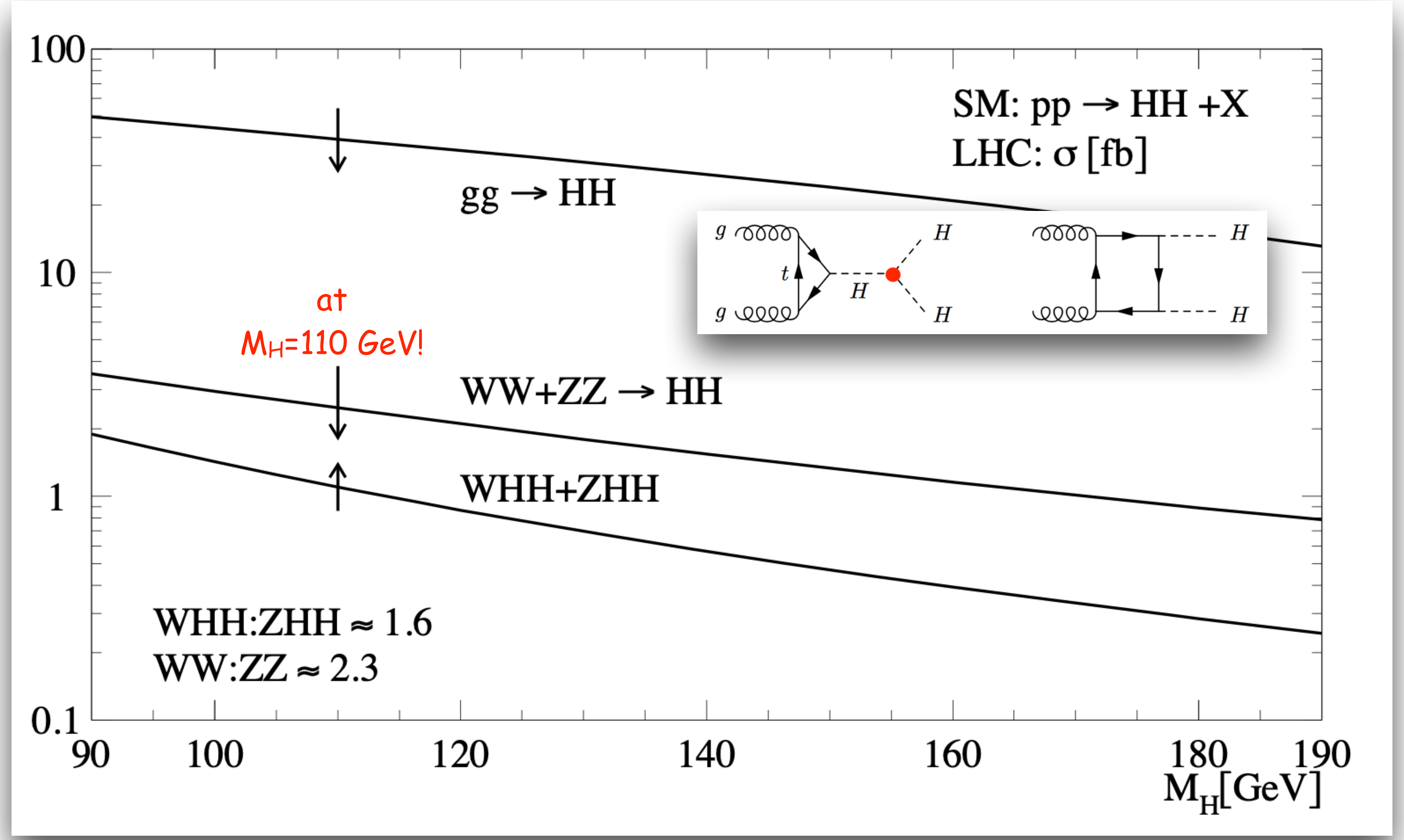
[Djouadi,Kilian,MM,Zerwas,'99]



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

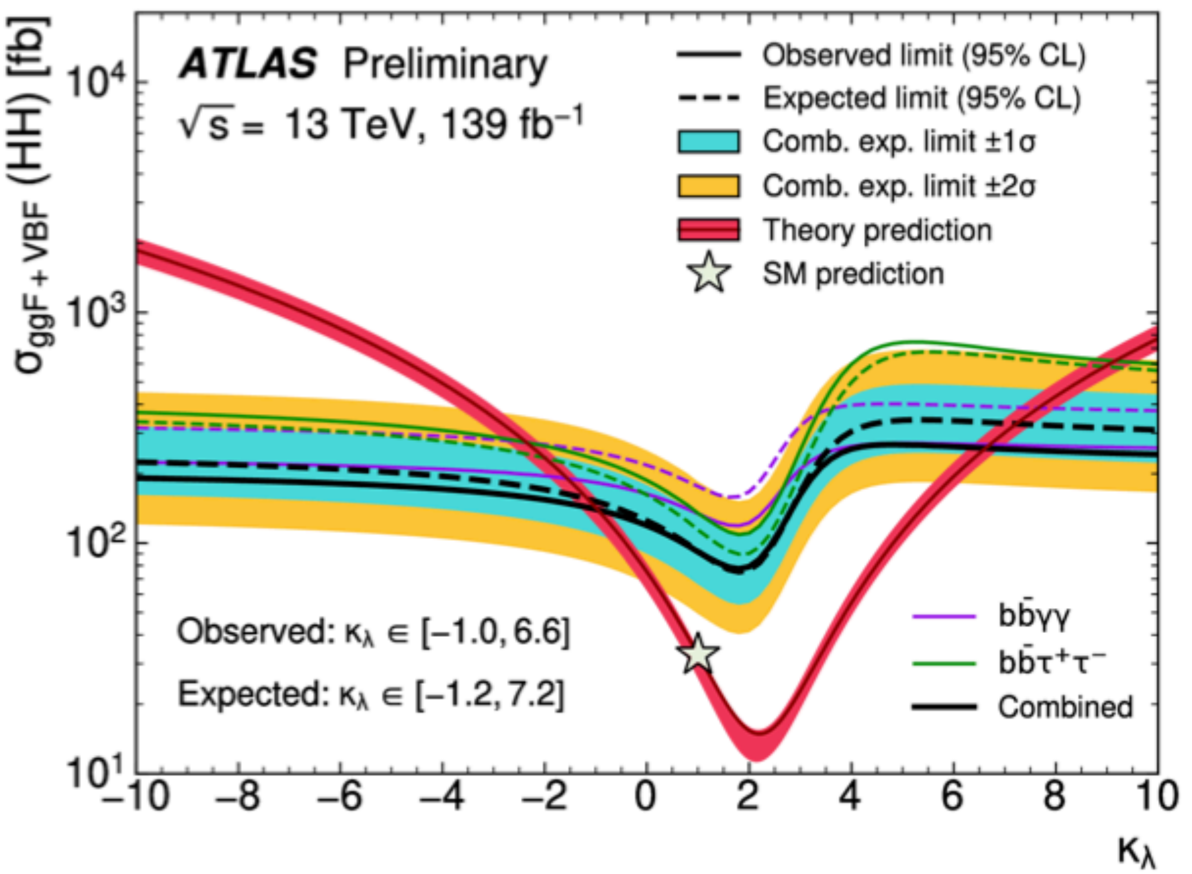
SM Higgs Pair Production at the LHC

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



✦ Challenge: small cross sections and large QCD backgrounds

Experimental Results - Limits on Trilinear Higgs Self-Coupling

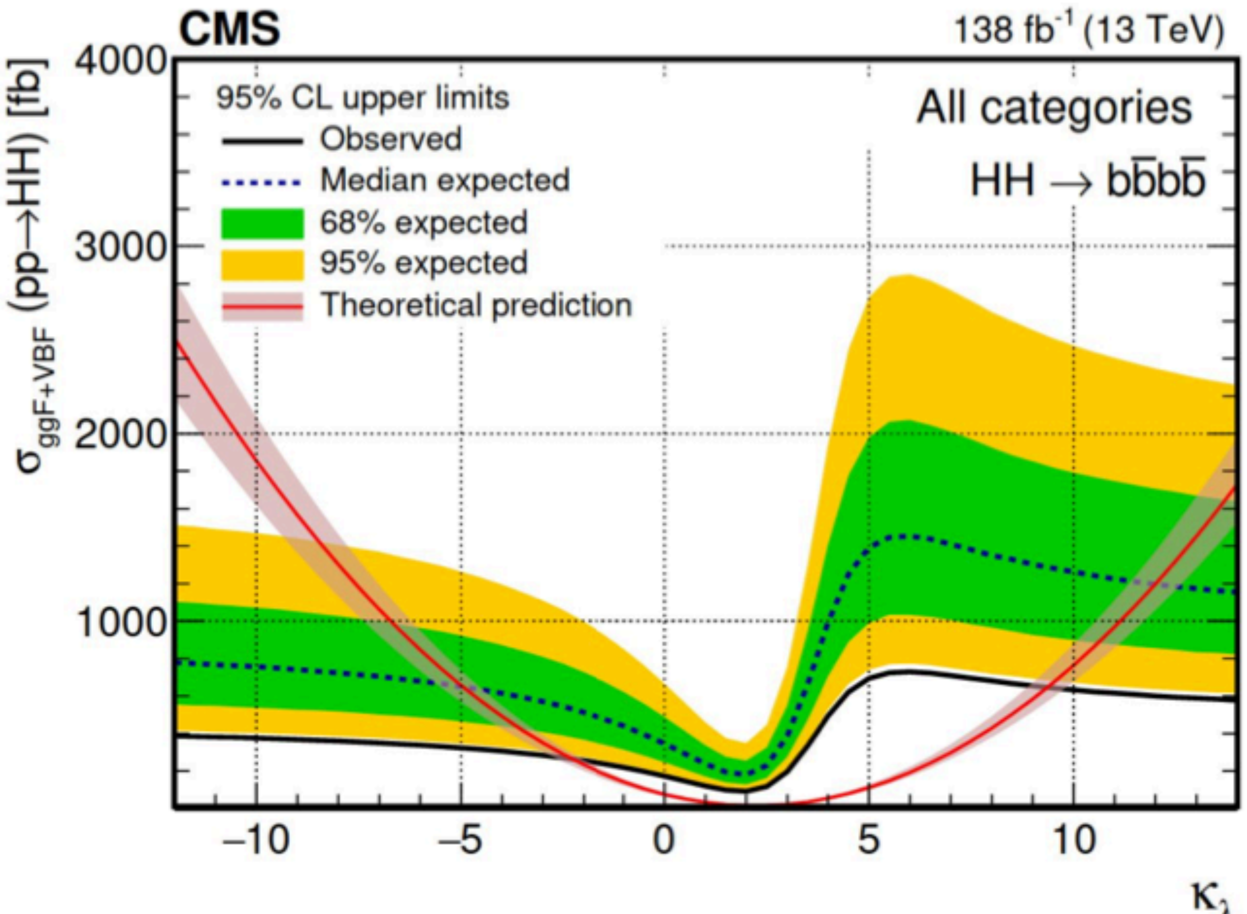


[Rui Zhang, ATLAS, HH Workshop´22]

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

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

[Fabio Monti, CMS, HH Workshop´22]

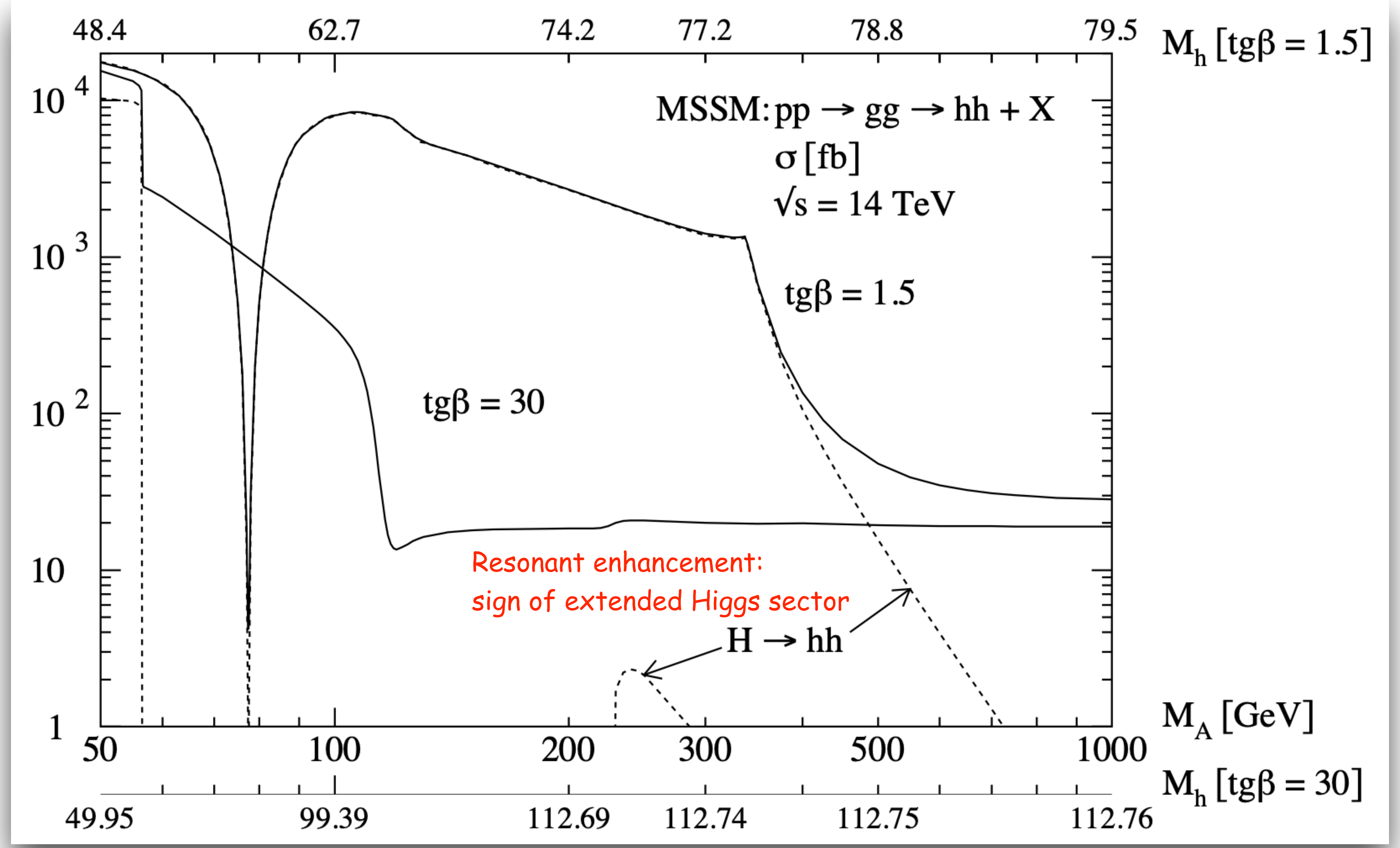


Obs. $k_\lambda \in [-2.3, 9.4]$

Exp. $k_\lambda \in [-5.0, 12.0]$

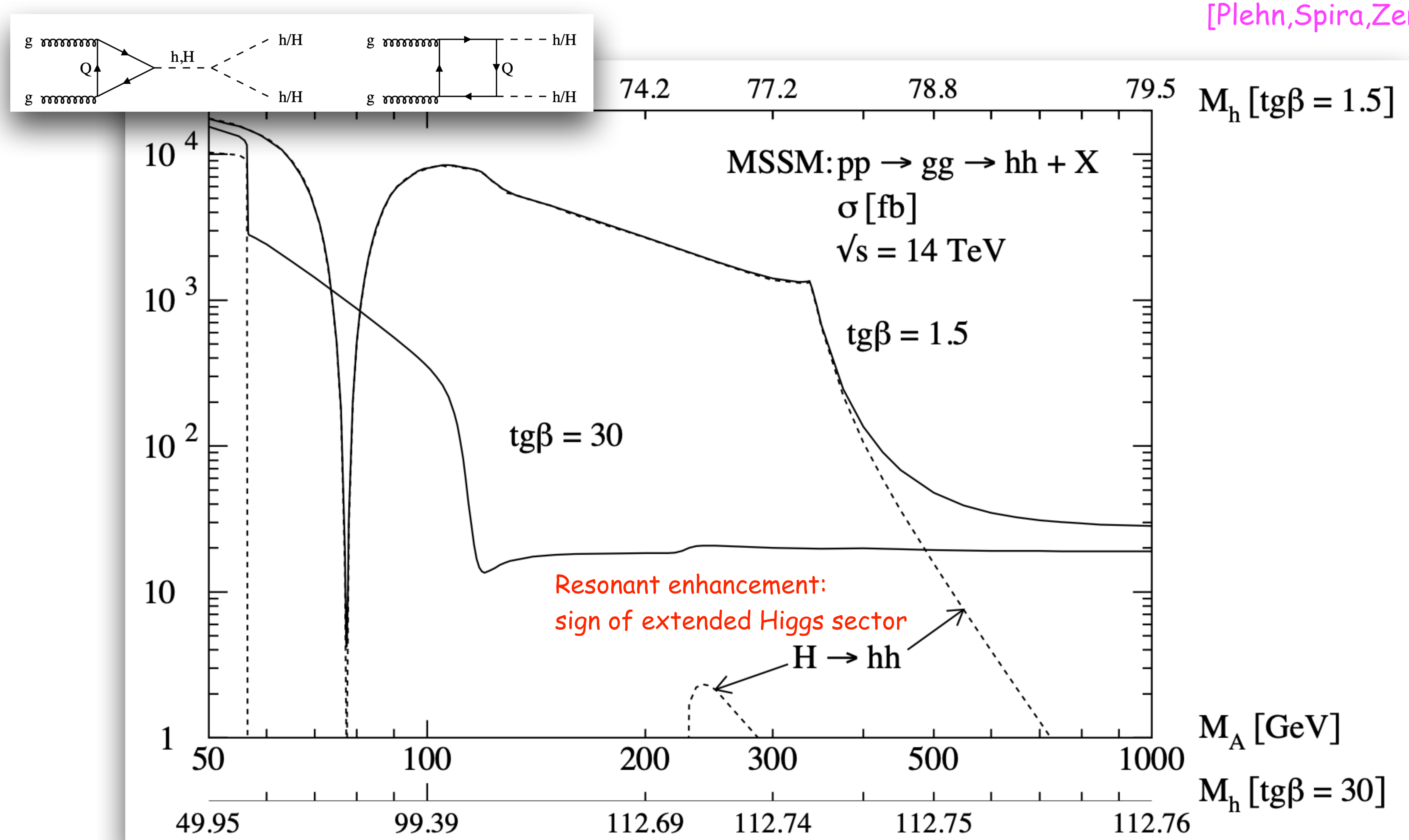
MSSM Higgs Pair Production at the LHC

[Plehn,Spira,Zerwas,'96]

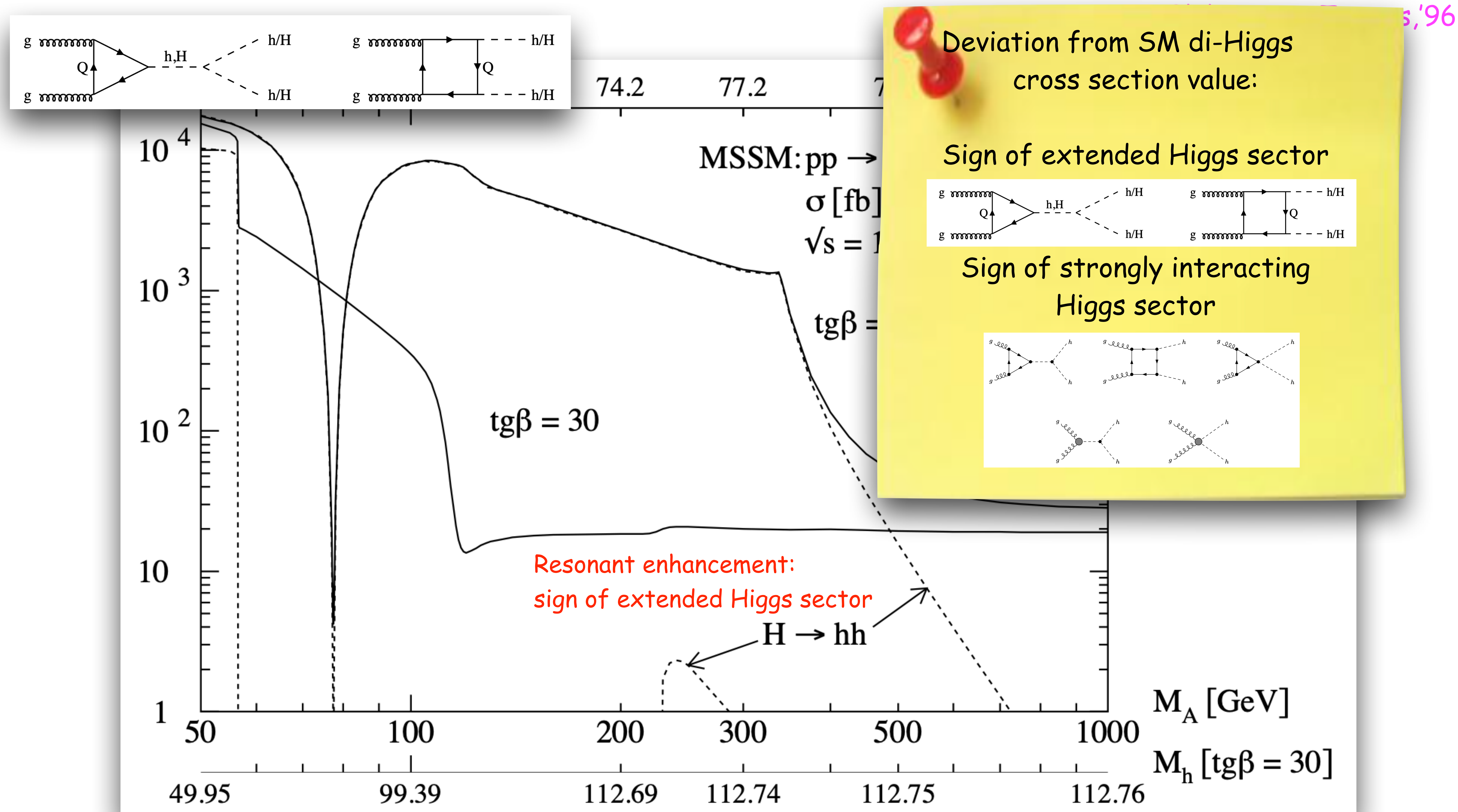


MSSM Higgs Pair Production at the LHC

[Plehn,Spira,Zerwas,'96]

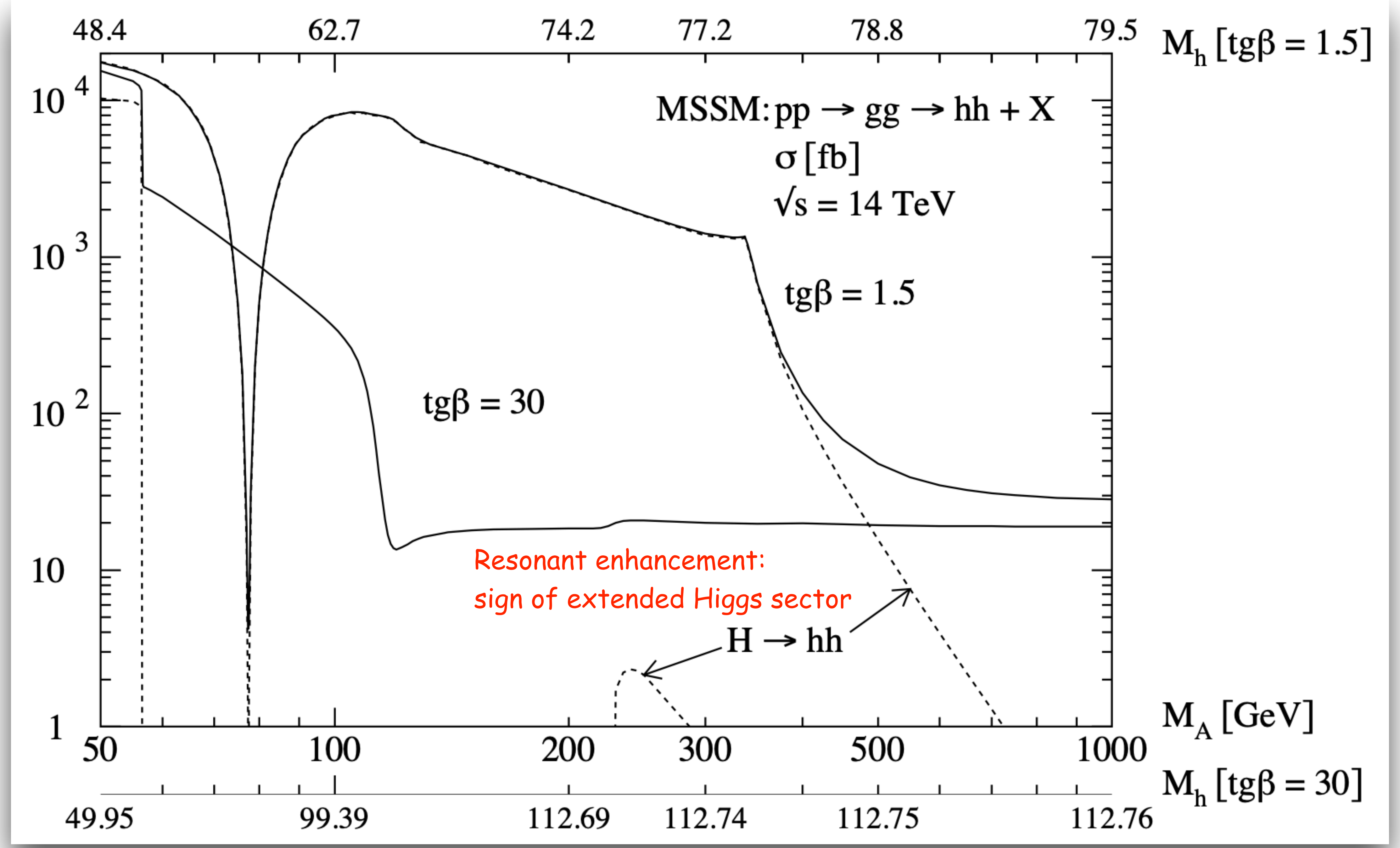


MSSM Higgs Pair Production at the LHC

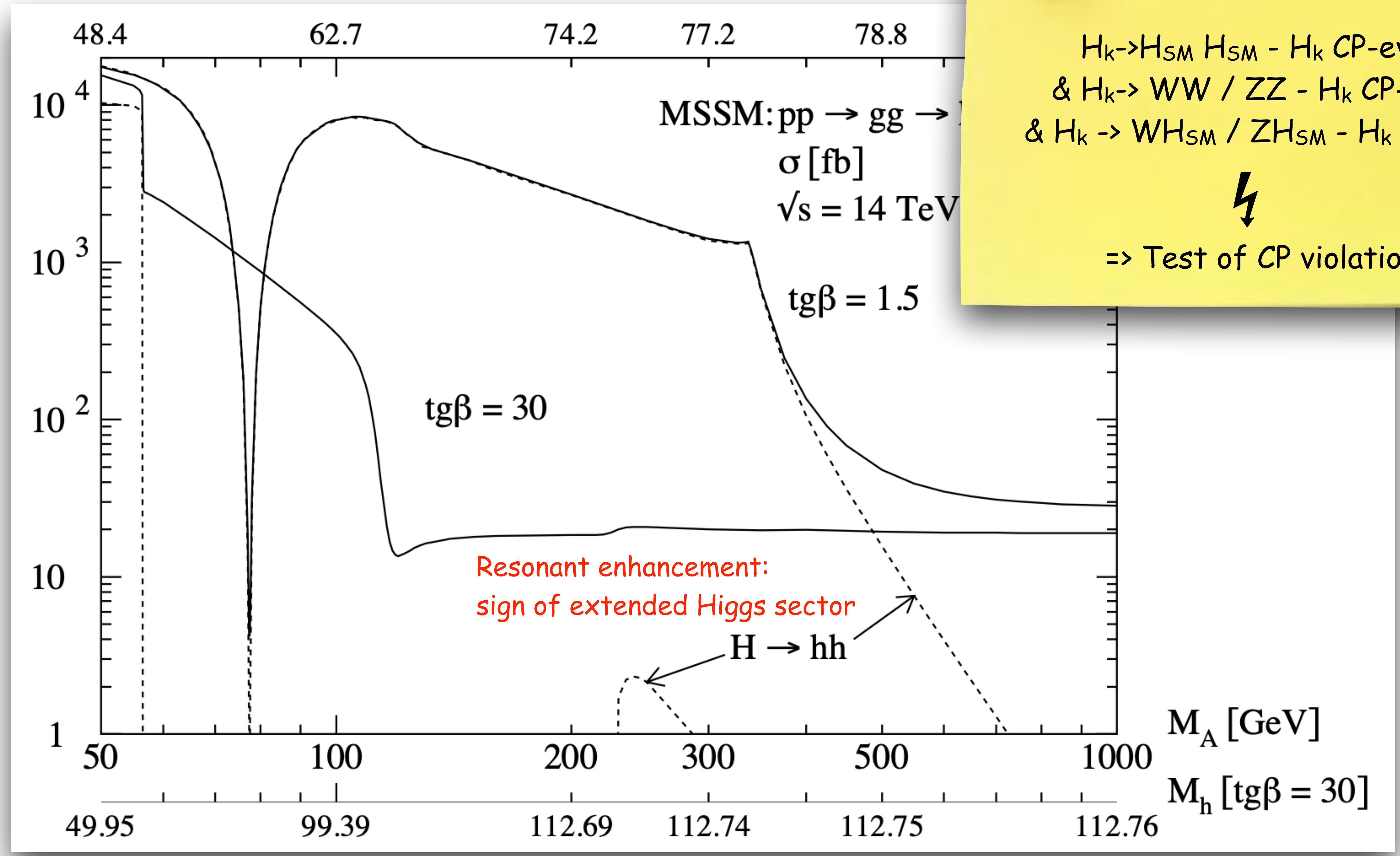


MSSM Higgs Pair Production at the LHC

[Plehn,Spira,Zerwas,'96]



MSSM Higgs Pair Production at the LHC



Combination of Higgs decays:

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

=> Test of CP violation


Dark
Matter

The Higgs Portal to a Hidden Sector

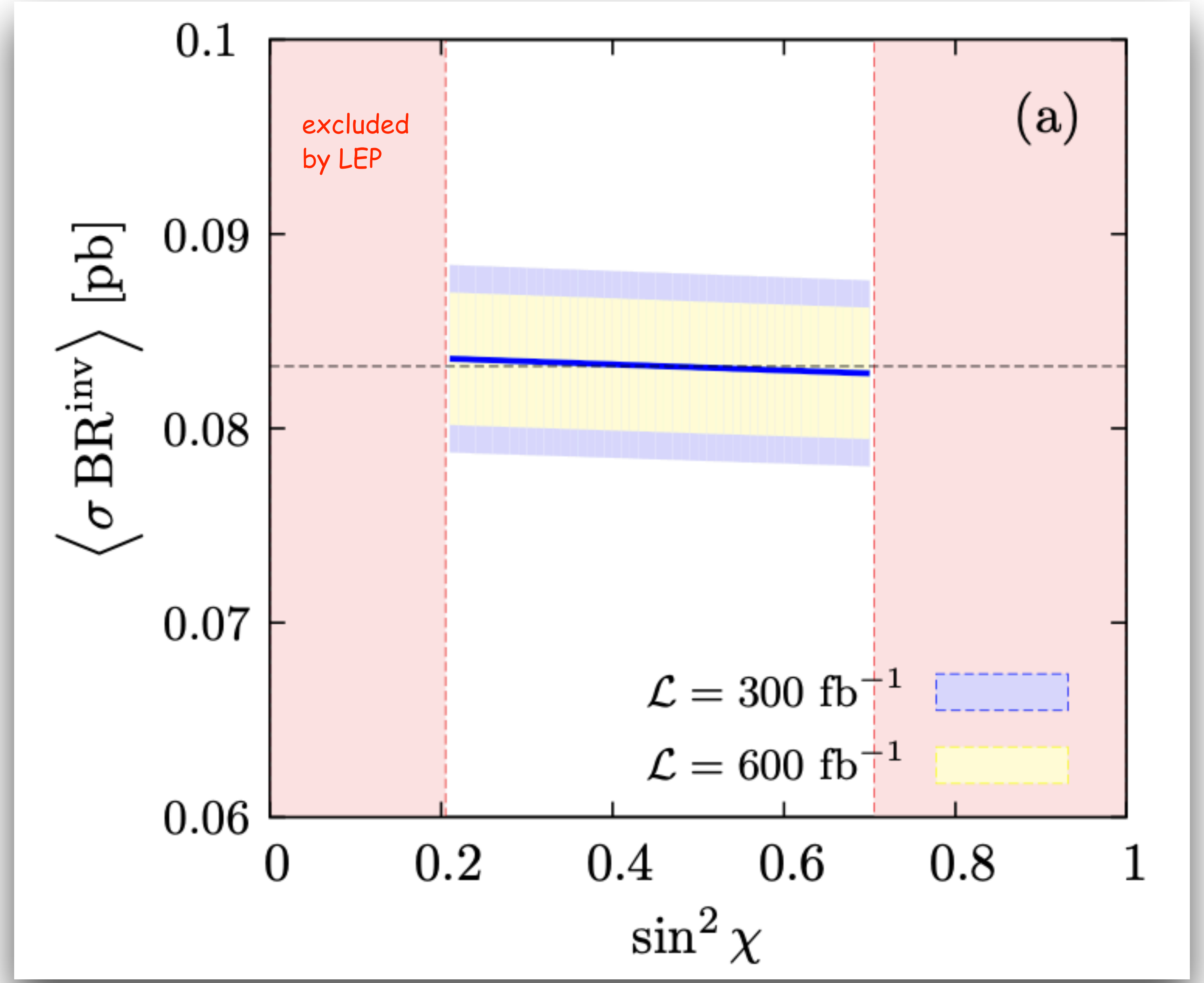
Exploring the Higgs portal #3

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]

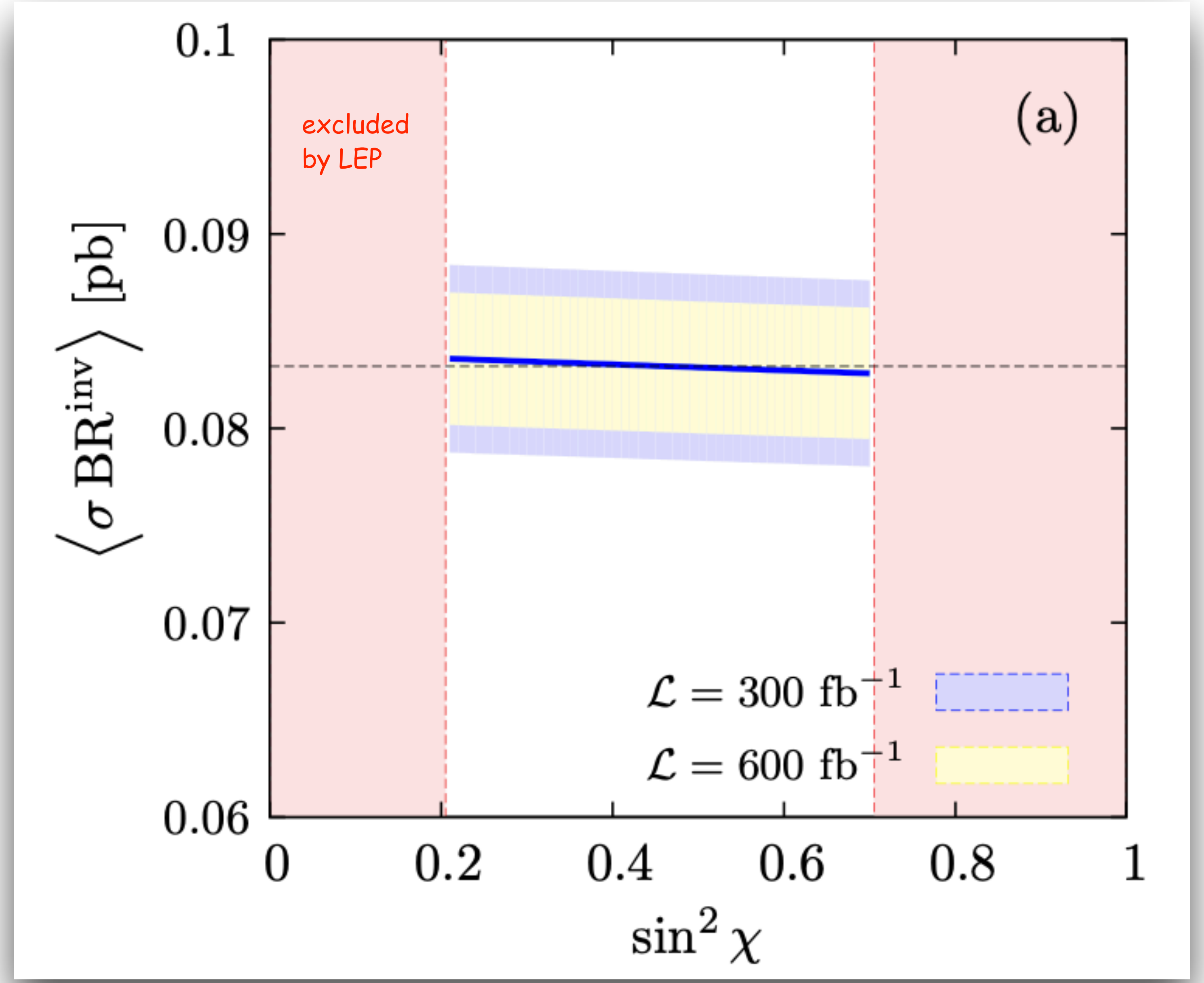
pdf DOI cite 216 citations

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]

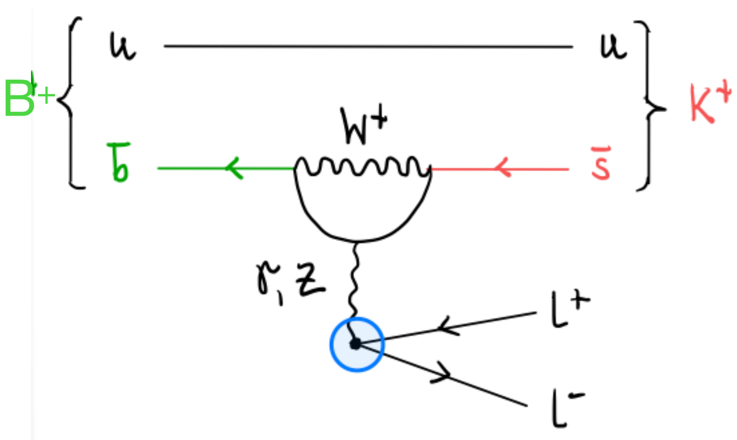


Incorporation of discrete symmetries => Higgs portal to DM

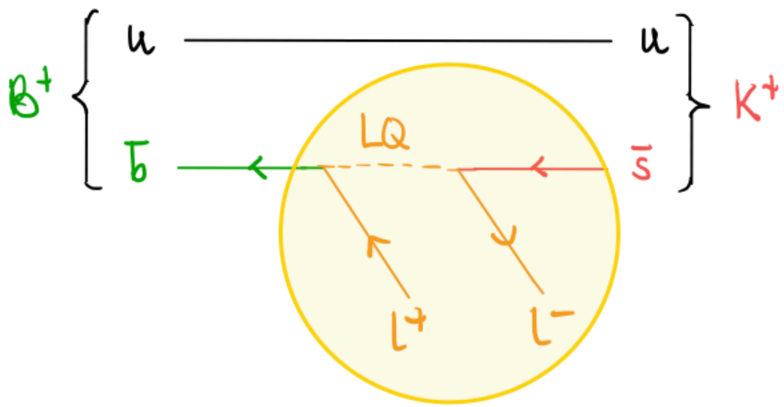
Insights in nature of Dark Matter

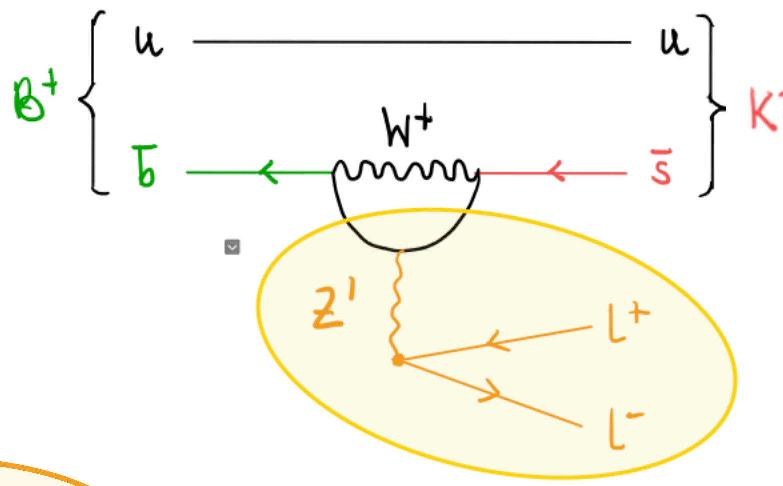

Varia

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



measurement in disagreement w/ SM
γ,Z interact w/ same strength w/ all leptons
=> 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

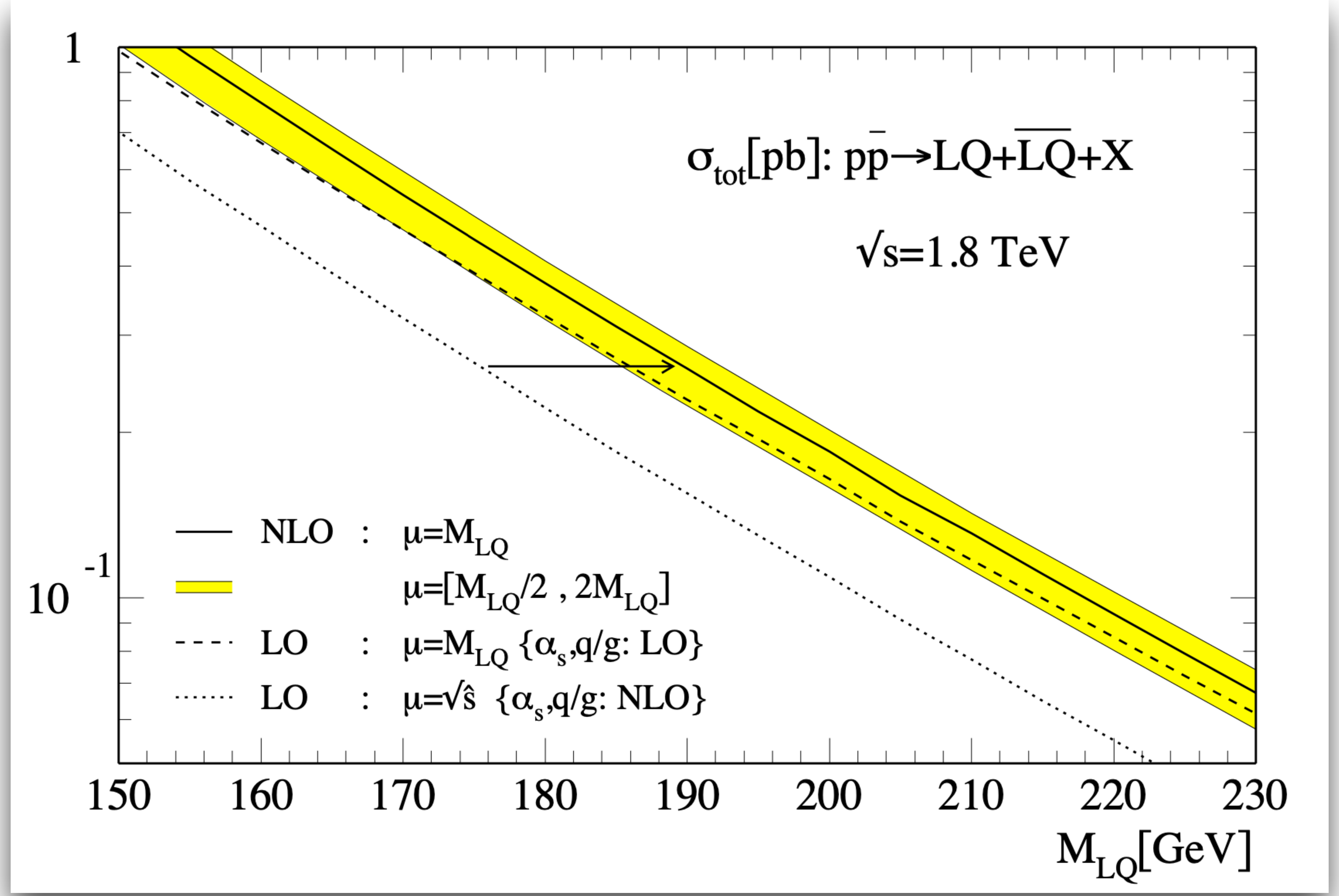
M. Kramer (Edinburgh U.), T. Plehn (CERN and Munich, Max Planck Inst.), M. Spira (PSI, Villigen), P.M. Zerwas (DESY and Fermilab) (Nov, 2004)

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:
$H_k \to H_{SM} H_{SM}$ - H_k CP-even
& $H_k \to WW / ZZ$ - H_k CP-even
& $H_k \to WH_{SM} / ZH_{SM}$ - H_k CP-odd
=> Test of CP violation

Insights in nature of Dark Matter

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

Combination of production & decay
=> Higgs couplings
=> 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 ⇒ 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
=> 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

in
of
ter

nding
ion

* Self-consistency test of SM at the quantum level
* stability of the electroweak vacuum
* Test BSM parameter relations ⇒

  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:
$H_k \to H_{SM} H_{SM}$ - H_k CP-even
& $H_k \to WW / ZZ$ - H_k CP-even
& $H_k \to WH_{SM} / ZH_{SM}$ - H_k CP-odd
=> Test of CP violation

Insights in nature of Dark Matter

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

Combination of production & decay
=> Higgs couplings
=> 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 ⇒

  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->H_{SM} H_{SM} - H_k CP-even

H_k-> WW / ZZ - H_k CP-even

-> WH_{SM} / ZH_{SM} - H_k CP-odd

of CP violation

Insights in nature of Dark Matter

Deviation from SM

cross section

Sign of extended H

Sign of strongly in

Higgs sect

bination of

tion & decay

gs couplings

t if g_{HXX}~m_X

in mechanism

s generation

* Self-consistency test

  quantum level

* stability of the electr

* Test BSM parameter relations ⇒

  indirect constraint of BSM parameters

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 ☺**