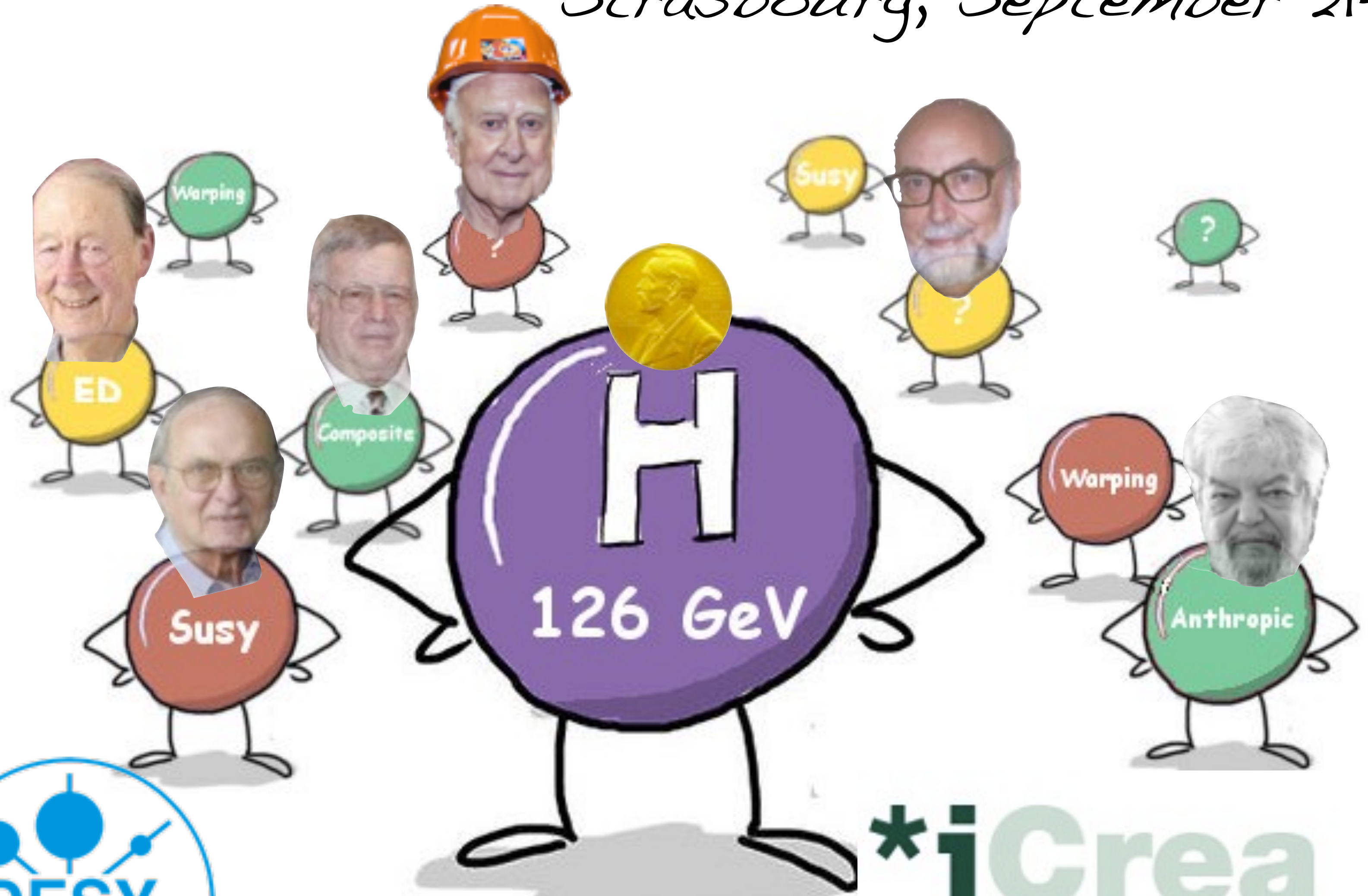
Future Colliders

47e Ecole de Gif
"Quel futur pour le modèle standard après la découverte du Higgs?"
Strasbourg, September 21-25, 2015



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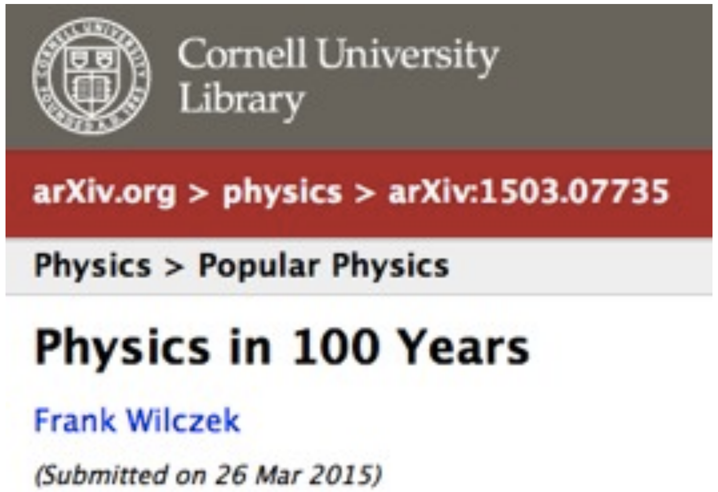
DESY

*iCrea
INSTITUCIÓ CATALANA DE
RECERCA I ESTUDIS AVANÇATS

A unique moment in the history of physics

The Higgs discovery is the triumph of XX$^{\text{th}}$ century physics
combination of Quantum Mechanism + Special Relativity

For the first time in the history of physics,
we have a *consistent* description of the fundamental constituents of matter and their interactions and this description can be extrapolated to very high energy (up M_{Planck}?)



Cornell University Library

arXiv.org > physics > arXiv:1503.07735

Physics > Popular Physics

Physics in 100 Years

Frank Wilczek

(Submitted on 26 Mar 2015)

The equations of the [SM] have been tested with far greater accuracy, and under far more extreme conditions, than are required for applications in chemistry, biology, engineering, or astrophysics. While there certainly are many things we don't understand, we do understand the Matter we're made from, and that we encounter in normal life - even if we're chemists, engineers, or astrophysicists (sic: DM!)

The SM is not free of inadequacies: (without forgetting flavor and neutrinos)

1) Only a description of EW symmetry breaking, not an explanation
   ➠ What separates the EW scale from the Planck scale?
2) No place for the particle(s) that make up the cosmic DM
   ➠ What are the DM particles?
3) Does not explain the asymmetry matter-antimatter
   ➠ Are the conditions realized to allow for EW baryogenesis?

we do not understand the Matter the Universe is made from

A unique moment in the history of physics

The Higgs discovery is the triumph of XXth century physics
combination of Quantum Mechanism + Special Relativity

For the first time in the history of physics,
we have a *consistent* description of the fundamental constituents of matter and their interactions and this description can be extrapolated to very high energy (up M_{Planck}?)

Where and how does the SM break down?
Which machine(s) will reveal (best) this breakdown?

The SM is not free of inadequacies: (without forgetting flavor and neutrinos)

1) Only a description of EW symmetry breaking, not an explanation
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we do not understand the Matter the Universe is made from

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- ⇛ couplings to quarks and gluons

Leptons

- S/B ~ 1
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇛ EW couplings

Circular

- $\sqrt{s}$ limited by synchroton radiation
- higher luminosity
- several interaction points
- precise E-beam measurement
- but only pdf access to $\sqrt{\hat{s}}$

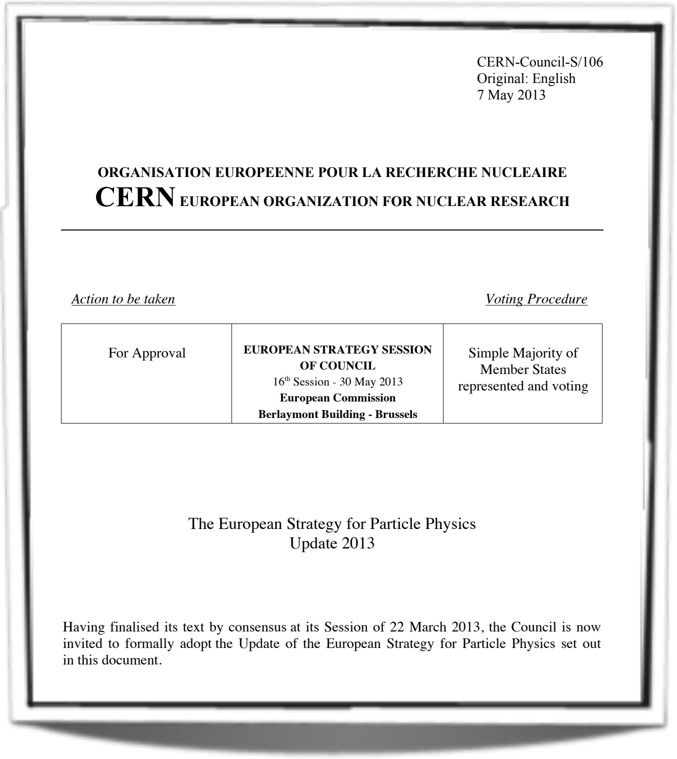
Linear

- larger $\sqrt{s}$, energy scanning
- easier to upgrade in energy
- greener: less power consumption
- easier polarized beams
- large beamsthralung

Which Strategy(ies)?

European Strategy

approved by CERN Council, June 2013



CERN-Council-S/106
Original: English
7 May 2013

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken *Voting Procedure*

For Approval	**EUROPEAN STRATEGY SESSION OF COUNCIL** 16th Session - 30 May 2013 **European Commission** **Berlaymont Building - Brussels**	Simple Majority of Member States represented and voting

The European Strategy for Particle Physics
Update 2013

Having finalised its text by consensus at its Session of 22 March 2013, the Council is now invited to formally adopt the Update of the European Strategy for Particle Physics set out in this document.

In the meantime:

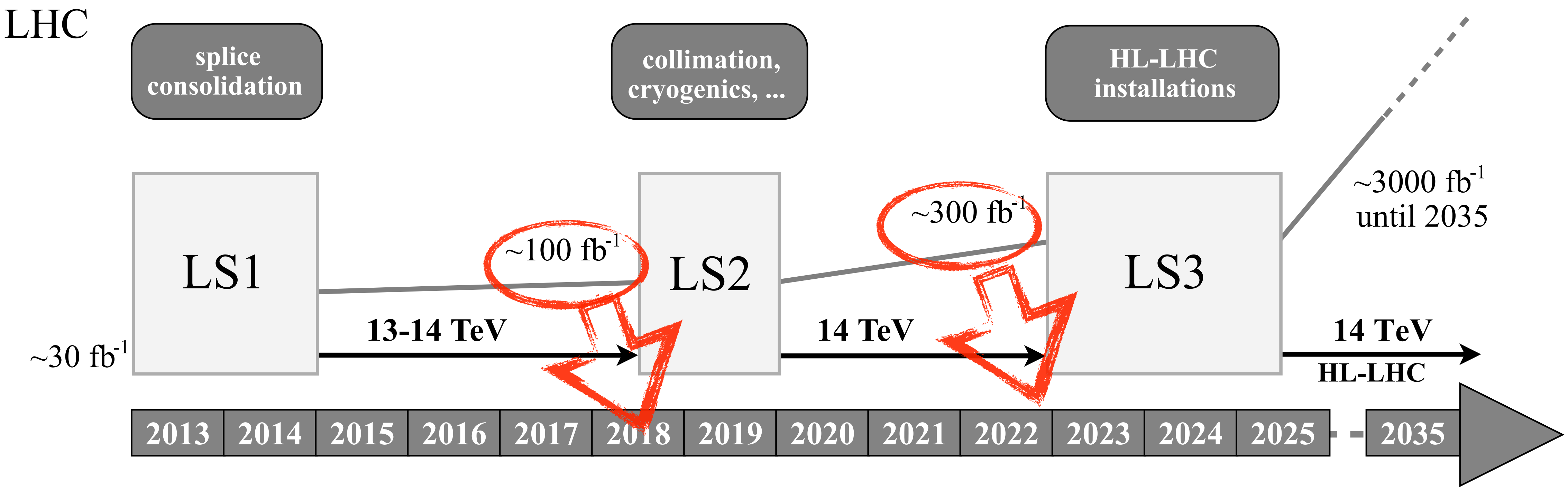
➠ confirmation of a very SM-like Higgs boson

➠ more and more stringent bounds on New Physics

➠ **where is everybody else?**

1. Should we wait for the results of LHC-run 2 to decide?
    ➠ no model independent answer!
2. If LHC sees new physics @ 1 TeV, does it still make sense to go for a Higgs factory?
    ➠ the LHC is unlikely to discover the full set of new particles
    ➠ indirect sensitivity via precision measurements
    ➠ study the correlations
    ➠ fill the time gap till the next machine is ready
3. If the LHC doesn't see new physics, does it still make sense to go for a Higgs factory?
    ➠ legacy measurements + stress test of the SM structure
    ➠ indirect search for NP (more robust that flavor)
4. Which energy? Which luminosity?
5. In any case, our priority should be to continue exploring the unknown and to push the frontiers of knowledge

The world according to LHC



LHC

splice consolidation

collimation, cryogenics, ...

HL-LHC installations

LS1

LS2

LS3

~30 fb^{-1}

~100 fb^{-1}

~300 fb^{-1}

~3000 fb^{-1} until 2035

13-14 TeV

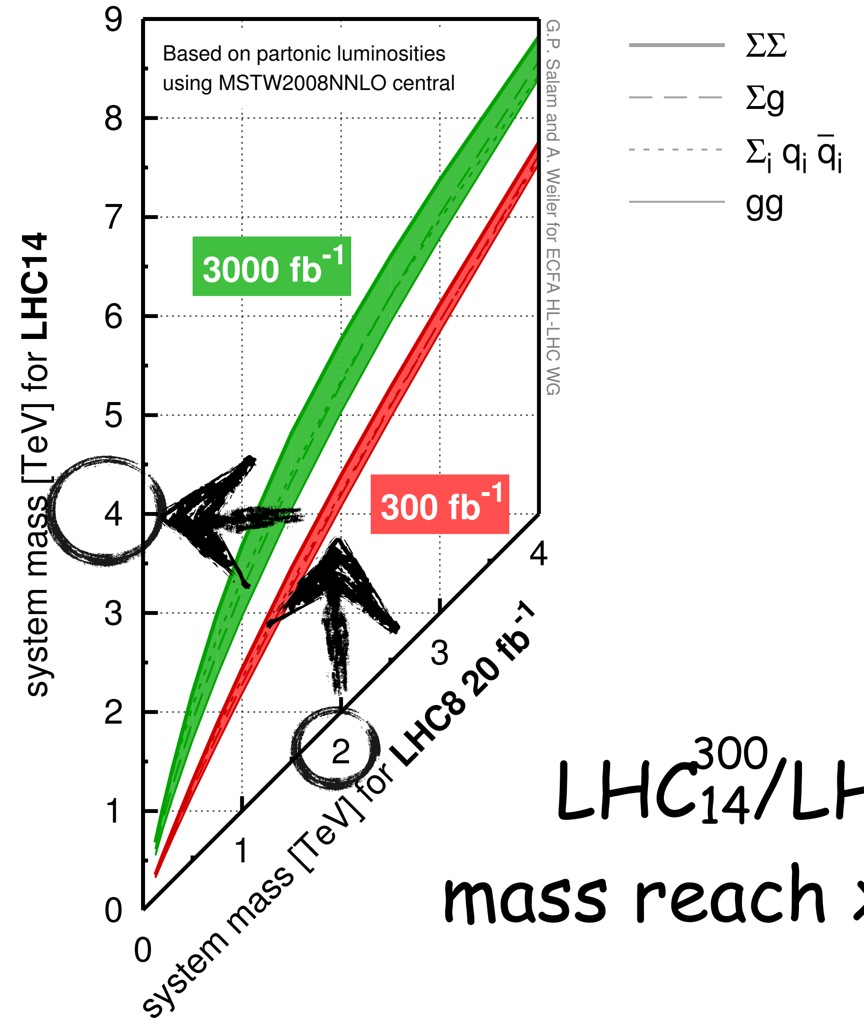
14 TeV

14 TeV

HL-LHC

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2035

Salam & Weiler "cern.ch/collider-reach" '14



Direct exploration of an uncharted territory

A significative energy step

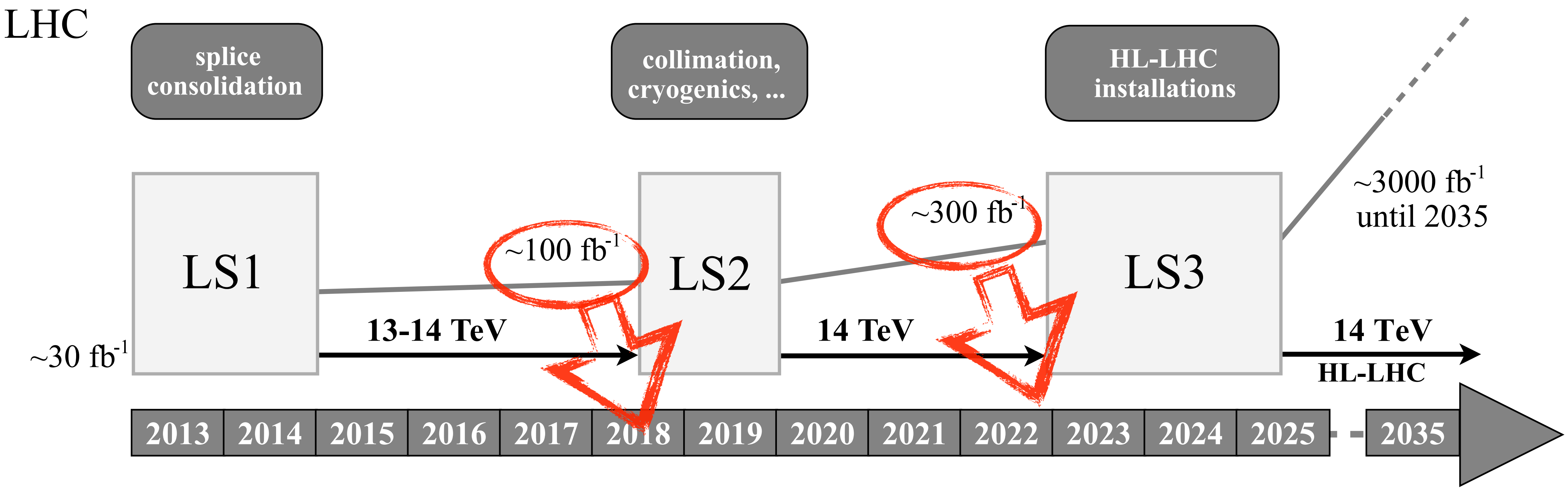
(maybe the last one before a long time)

$LHC_{14}^{300}/LHC_8^{20}$

mass reach x O(2)

What can be discovered @ 100/fb-14TeV knowing what is excluded @ 20/fb-8TeV?

The world according to LHC



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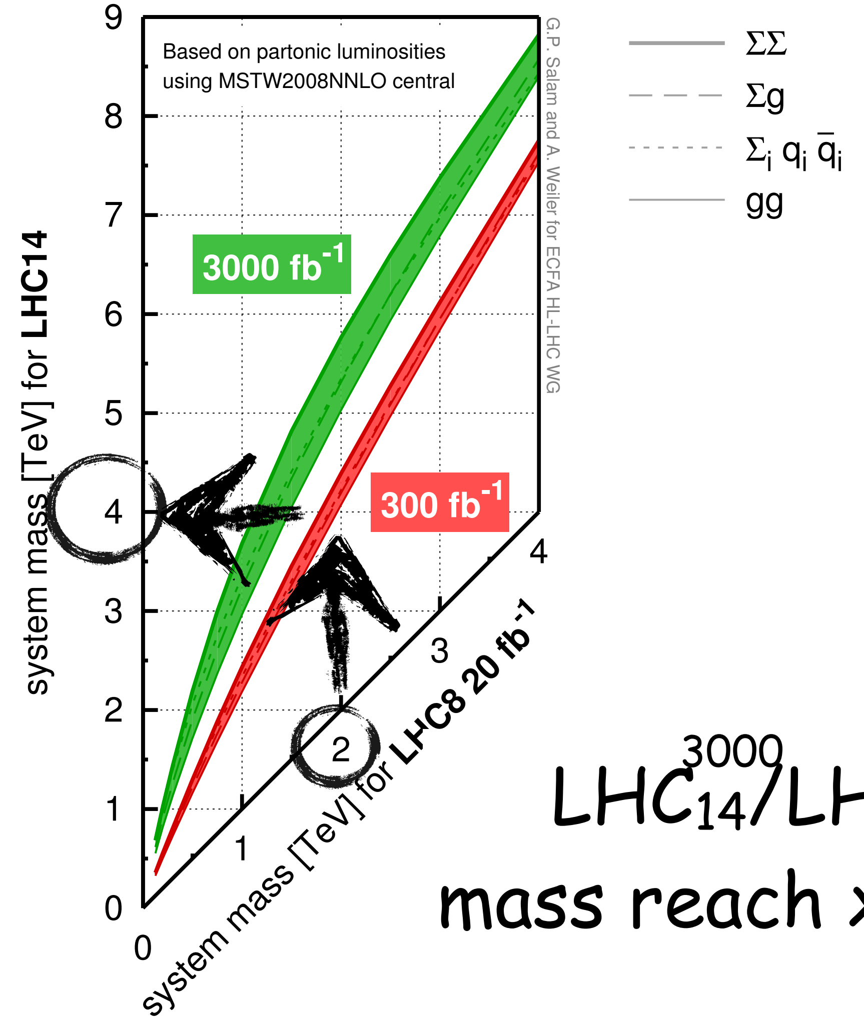


Salam & Weiler "cern.ch/collider-reach" '14

$\mathrm{LHC}_{14}^{3000}/\mathrm{LHC}_{8}^{20}$

mass reach x O(3)

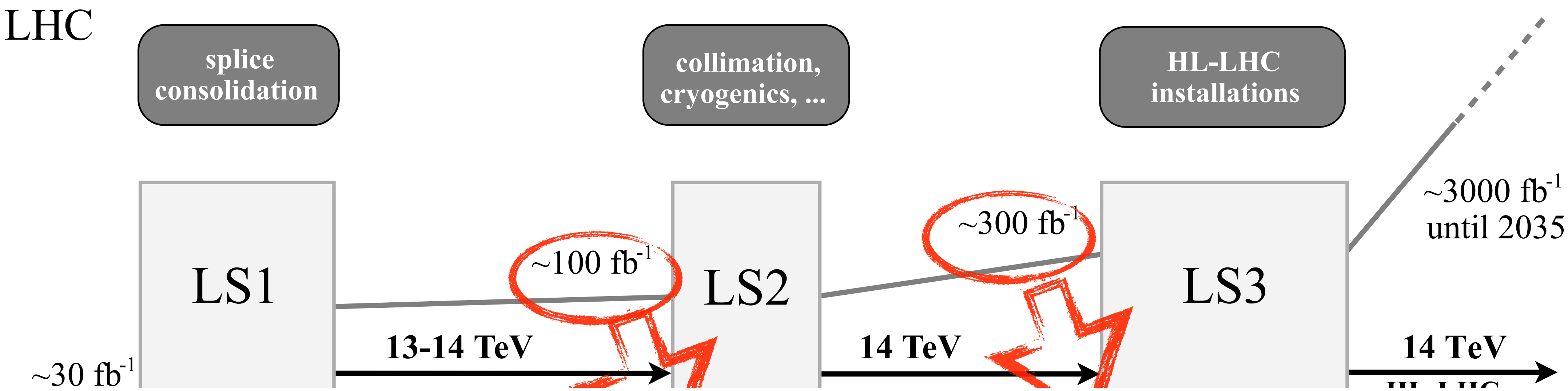
Direct exploration
of an
uncharted territory

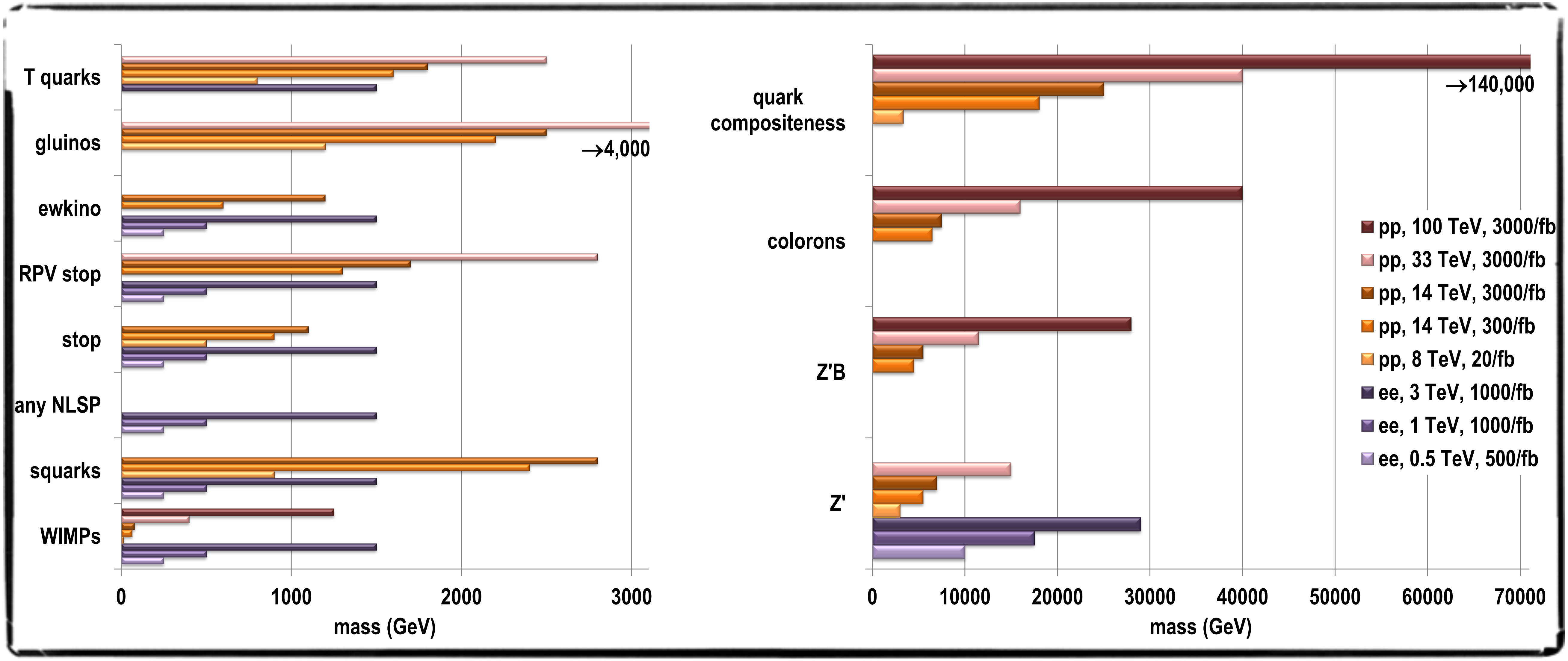
A significative energy step

(maybe the last one before a long time)

What can be discovered @ 3/ab-14TeV
knowing what is excluded @ 100/fb-14TeV?

The world according to LHC





Energy Frontier Snowmass Study '13

0

The future collider landscape

1) to which extent the various concepts are competitive, complementary, realistic or redundant, in terms of both physics and technology?

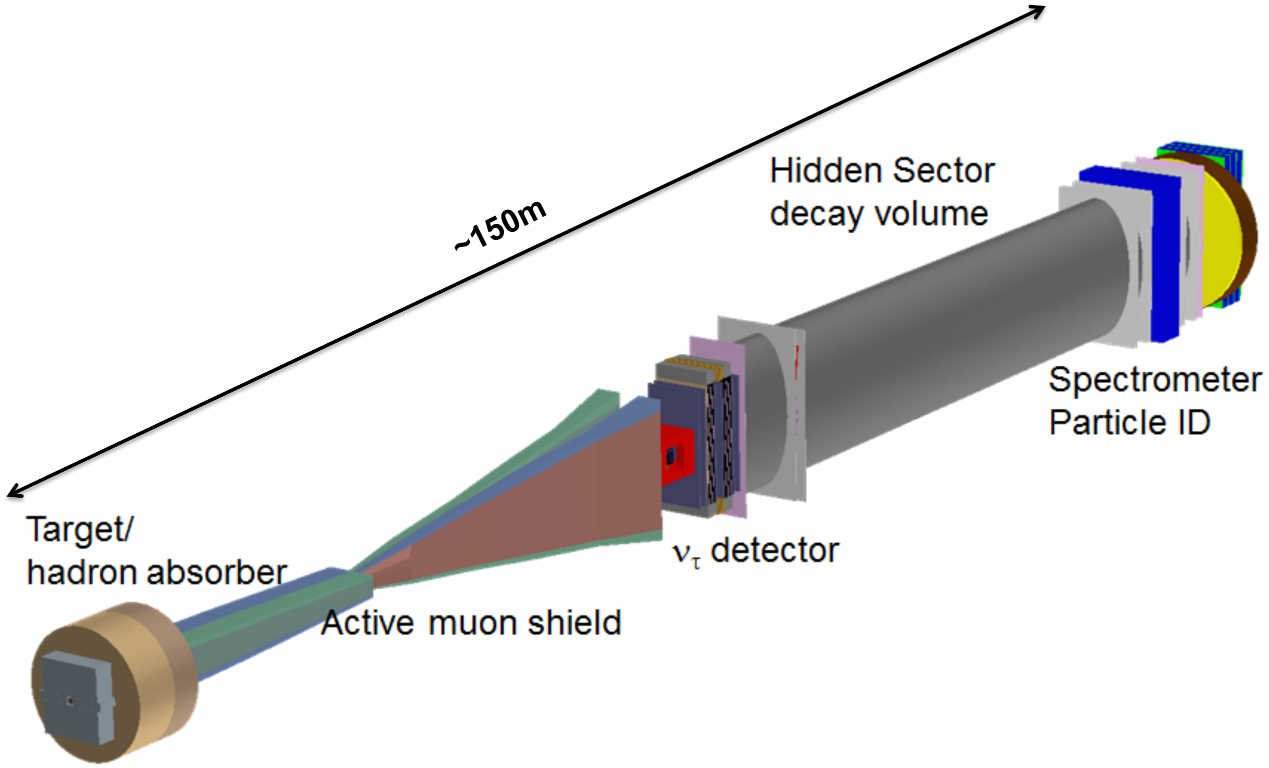
2) should the community continue with its current R&D efforts or consider adopting other programmes?

3) what should be the priorities in view of what we know today and the physics cases?

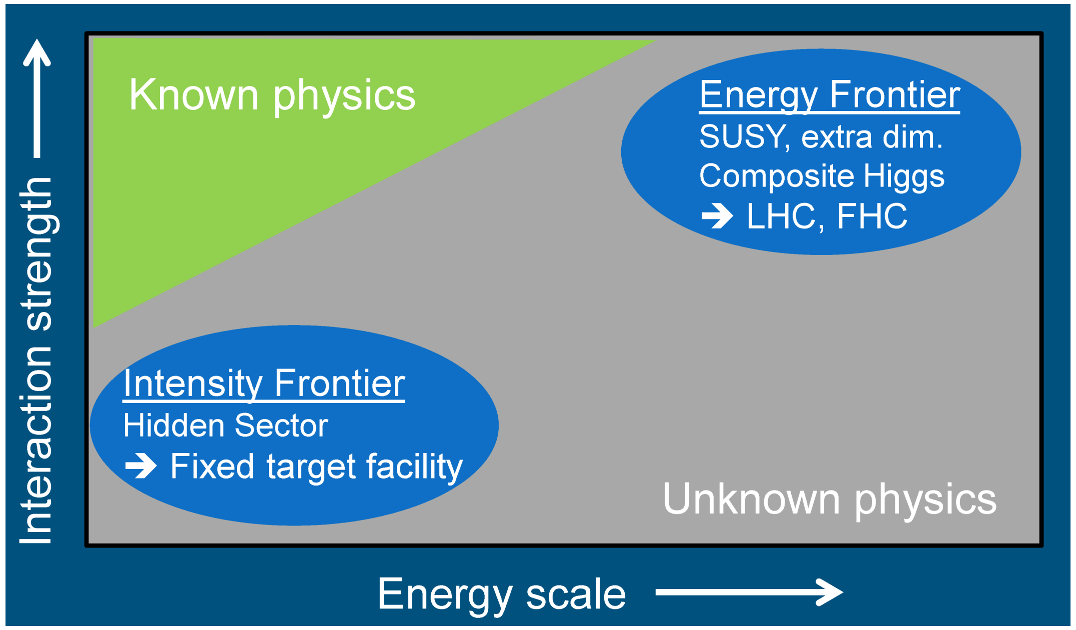
SHiP(TBA: 2018-2030)

beam dump experiment: 400 GeV SPS protons on fixed target

√s~28 GeV 10^{20} protons over 10 years, i.e. $\mathcal{L} = 10^{39}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$



intensity frontier

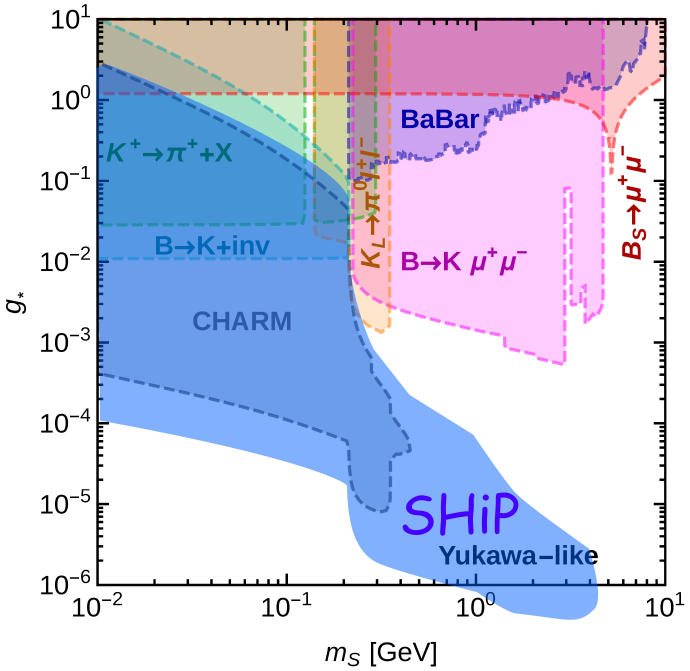


Known physics

Energy Frontier
SUSY, extra dim.
Composite Higgs
➔ LHC, FHC

Intensity Frontier
Hidden Sector
➔ Fixed target facility

Unknown physics



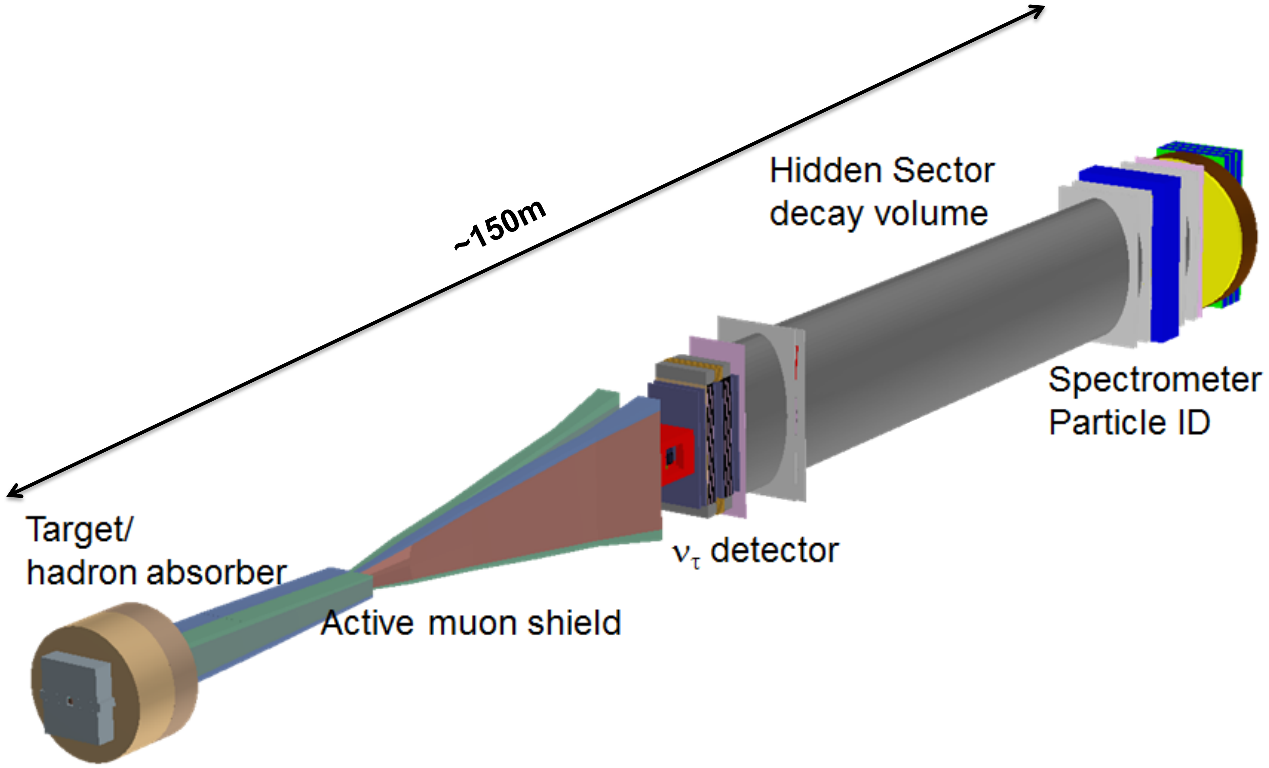
Higgs portal

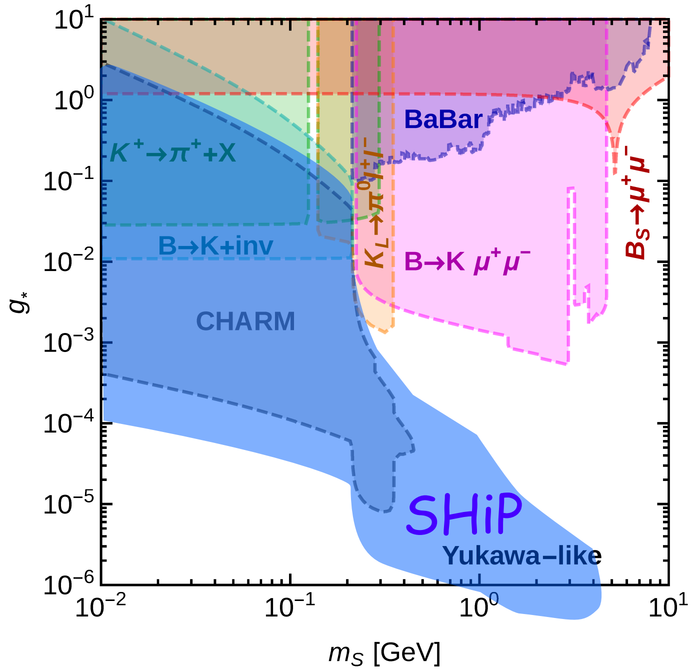
$$(\alpha_1 S + \alpha S^2) H^\dagger H + L_{SM} + L_{hidden}$$

SHiP (TBA: 2018-2030)

beam dump experiment: 400 GeV SPS protons on fixed target

$\sqrt{s}\sim 28$ GeV 10^{20} protons over 10 years, i.e. $\mathcal{L} = 10^{39}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$





Higgs portal

$$(\alpha_1 S + \alpha S^2) H^\dagger H + L_{SM} + L_{hidden}$$

Physics case

CERN-SPSC-2015-017 (SPSC-P-350-ADD-1)

A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case

Sergey Alekhin,[1,2] Wolfgang Altmannshofer,[3] Takehiko Asaka,[4] Brian Batell,[5] Fedor Bezrukov,[6,7] Kyrylo Bondarenko,[8] Alexey Boyarsky⋆,[8] Nathaniel Craig,[9] Ki-Young Choi,[10] Cristóbal Corral,[11] David Curtin,[12] Sacha Davidson,[13,14] André de Gouvêa,[15] Stefano Dell'Oro,[16] Patrick deNiverville,[17] P. S. Bhupal Dev,[18] Herbi Dreiner,[19] Marco Drewes,[20] Shintaro Eijima,[21] Rouven Essig,[22] Anthony Fradette,[17] Björn Garbrecht,[20] Belen Gavela,[23] Gian F. Giudice,[5] Dmitry Gorbunov,[24,25] Stefania Gori,[3] Christophe Grojean§,[26,27] Mark D. Goodsell,[28,29] Alberto Guffanti,[30] Thomas Hambye,[31] Steen H. Hansen,[32] Juan Carlos Helo,[11] Pilar Hernandez,[33] Alejandro Ibarra,[20] Artem Ivashko,[8,34] Eder Izaguirre,[3] Joerg Jaeckel§,[35] Yu Seon Jeong,[36] Felix Kahlhoefer,[27] Yonatan Kahn,[37] Andrey Katz,[5,38,39] Choong Sun Kim,[36] Sergey Kovalenko,[11] Gordan Krnjaic,[3] Valery E. Lyubovitskij,[40,41,42] Simone Marcocci,[16] Matthew Mccullough,[5] David McKeen,[43] Guenakh Mitselmakher ,[44] Sven-Olaf Moch,[45] Rabindra N. Mohapatra,[46] David E. Morrissey,[47] Maksym Ovchynnikov,[34] Emmanuel Paschos,[48] Apostolos Pilaftsis,[18] Maxim Pospelov§,[3,17] Mary Hall Reno,[49] Andreas Ringwald,[27] Adam Ritz,[17] Leszek Roszkowski,[50] Valery Rubakov,[24] Oleg Ruchayskiy⋆,[21] Jessie Shelton,[51] Ingo Schienbein,[52] Daniel Schmeier,[19] Kai Schmidt-Hoberg,[27] Pedro Schwaller,[5] Goran Senjanovic,[53,54] Osamu Seto,[55] Mikhail Shaposhnikov⋆,§,[21] Brian Shuve,[3] Robert Shrock,[56] Lesya Shchutska§,[44] Michael Spannowsky,[57] Andy Spray,[58] Florian Staub,[5] Daniel Stolarski,[5] Matt Strassler,[39] Vladimir Tello,[53] Francesco Tramontano§,[59,60] Anurag Tripathi,[59] Sean Tulin,[61] Francesco Vissani,[16,62] Martin W. Winkler,[63] Kathryn M. Zurek[64,65]

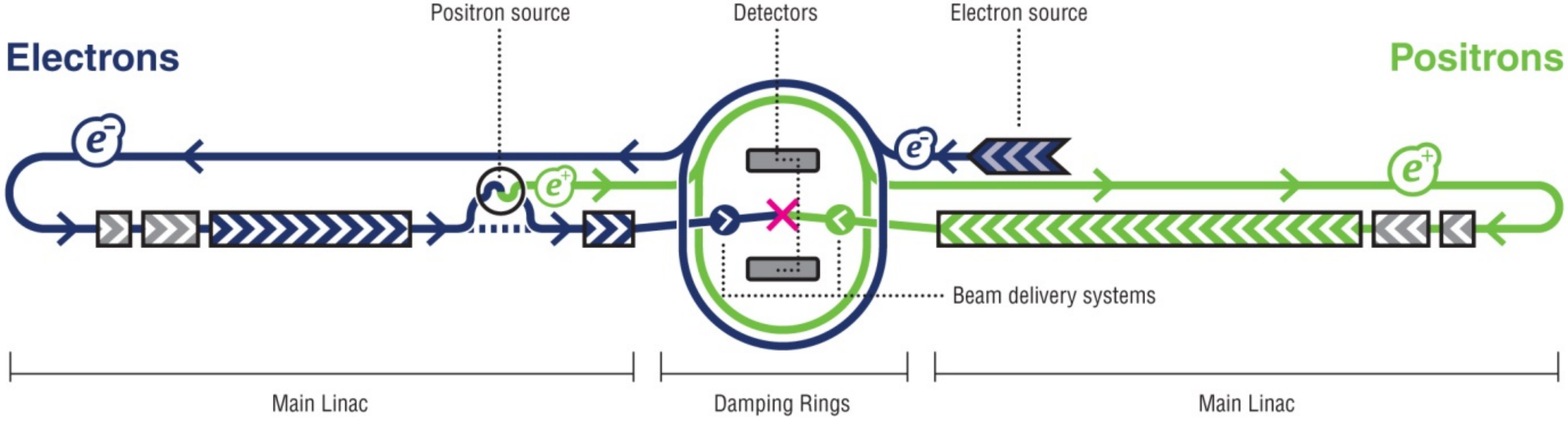
arXiv:1504.04855v1 [hep-ph] 19 Apr 2015

Abstract: This paper describes the physics case for a new fixed target facility at CERN SPS. The SHiP (*Search for Hidden Particles*) experiment is intended to hunt for new physics in the largely unexplored domain of very weakly interacting particles with masses below the Fermi scale, inaccessible to the LHC experiments, and to study tau neutrino physics. The same proton beam setup can be used later to look for decays of tau-leptons with lepton flavour number non-conservation, $\tau\to 3\mu$ and to search for weakly-interacting sub-GeV dark matter candidates. We discuss the evidence for physics beyond the Standard Model and describe interactions between new particles and four different *portals* — scalars, vectors, fermions or axion-like particles. We discuss motivations for different models, manifesting themselves via these interactions, and how they can be probed with the SHiP experiment and present several case studies. The prospects to search for relatively light SUSY and composite particles at SHiP are also discussed. We demonstrate that the SHiP experiment has a unique potential to discover new physics and can directly probe a number of solutions of beyond the Standard Model puzzles, such as neutrino masses, baryon asymmetry of the Universe, dark matter, and inflation.

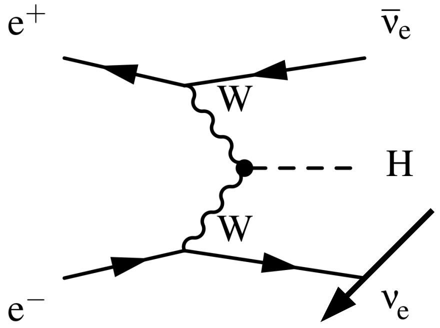
⋆Editor of the paper
§Convener of the Chapter

ILC (TBA: 2025-2045*)

*ready for construction once approved



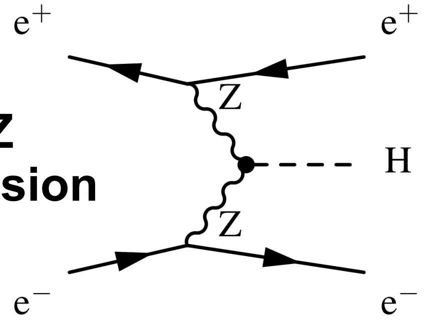
(350)/500/1000 GeV - 5/ab

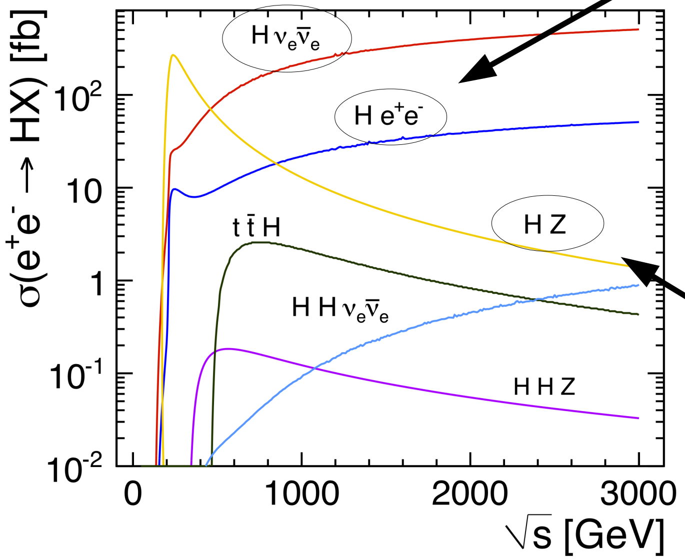


σ ~ log(s)

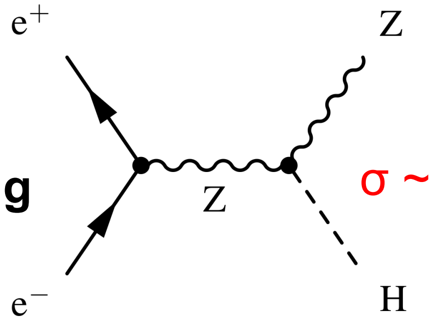
WW fusion

ZZ fusion





Higgs-strahlung

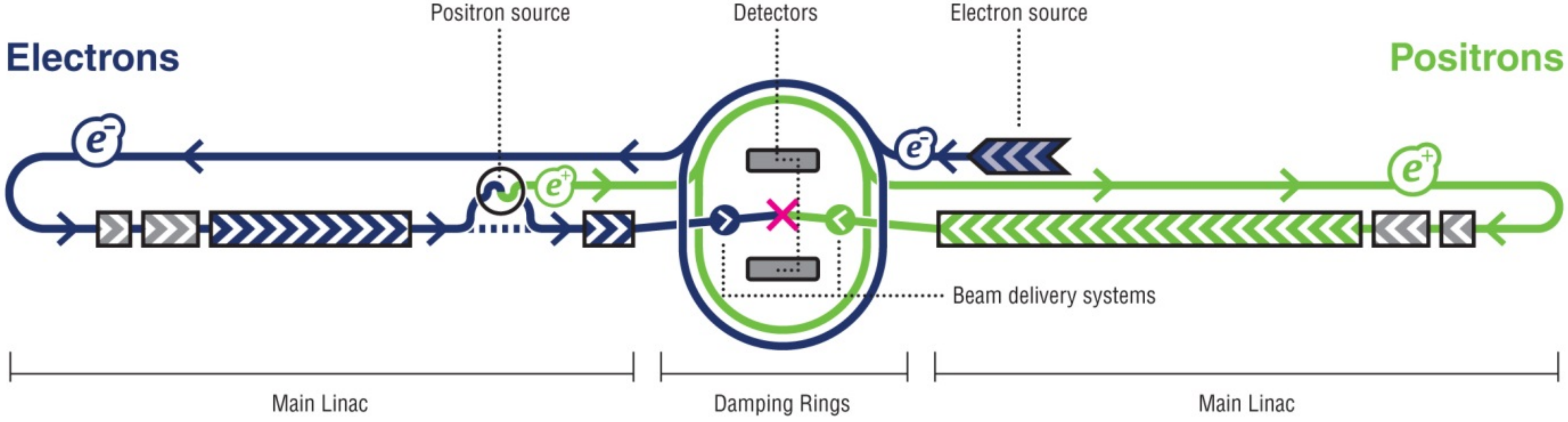


σ ~ 1/s

O(10^6) Higgs produced and reconstructed

ILC (TBA: 2025-2045*)

*ready for construction once approved



(350)/500/1000 GeV - 5/ab

Center of Mass Energy

~250 GeV: Zh

~350 GeV: $t\bar{t}$

~ 500 GeV: Zhh(DHS)

HHH opens up!

Top Yukawa via $t\bar{t}h$

~ 1 TeV: VBF at 1 TeV improves HHH coupling by combining with Zhh

m_h
Γ_h
higgs couplings

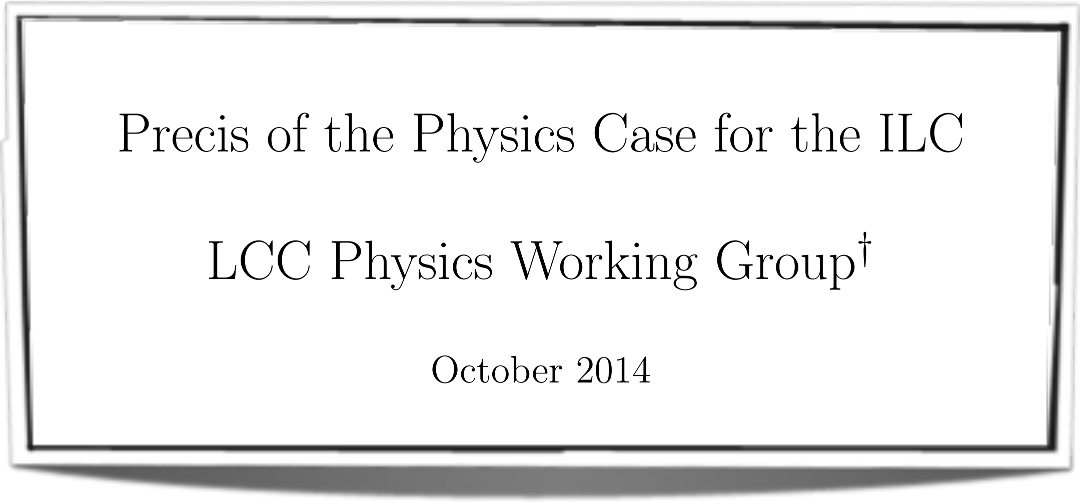
m_t
top Yuk.

ZZhh coupling
h^3 coupling
direct top Yuk

h^3 coupling

O(10^6) Higgs produced and reconstructed

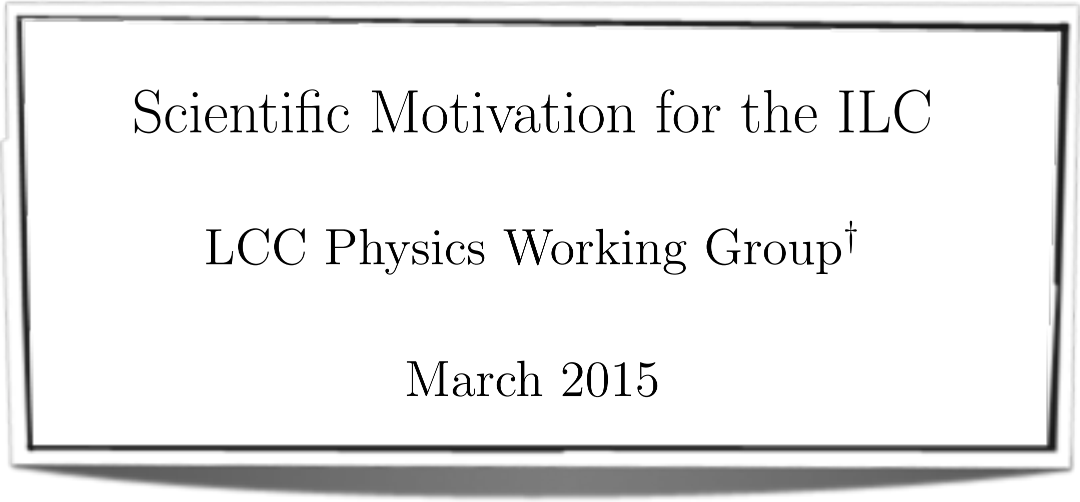
ILC (TBA: 2025-2045*)



Precis of the Physics Case for the ILC

LCC Physics Working Group[†]

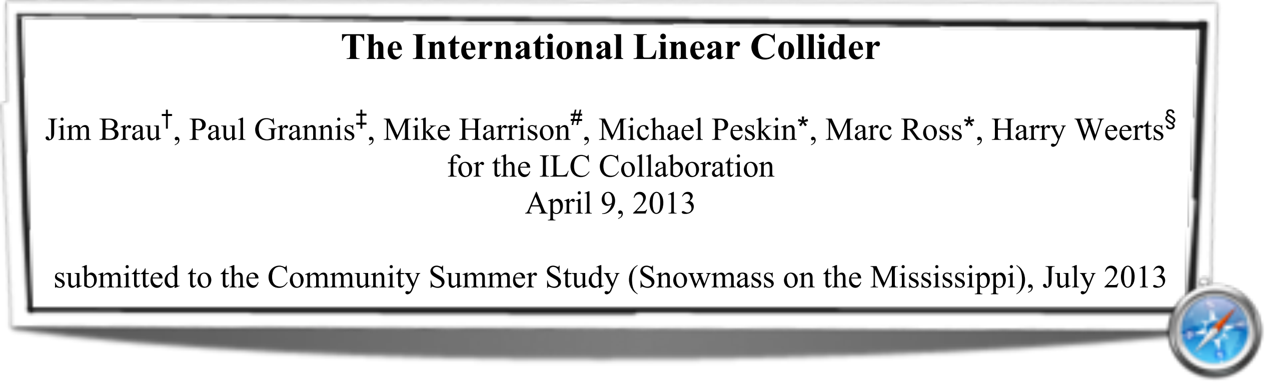
October 2014



Scientific Motivation for the ILC

LCC Physics Working Group[†]

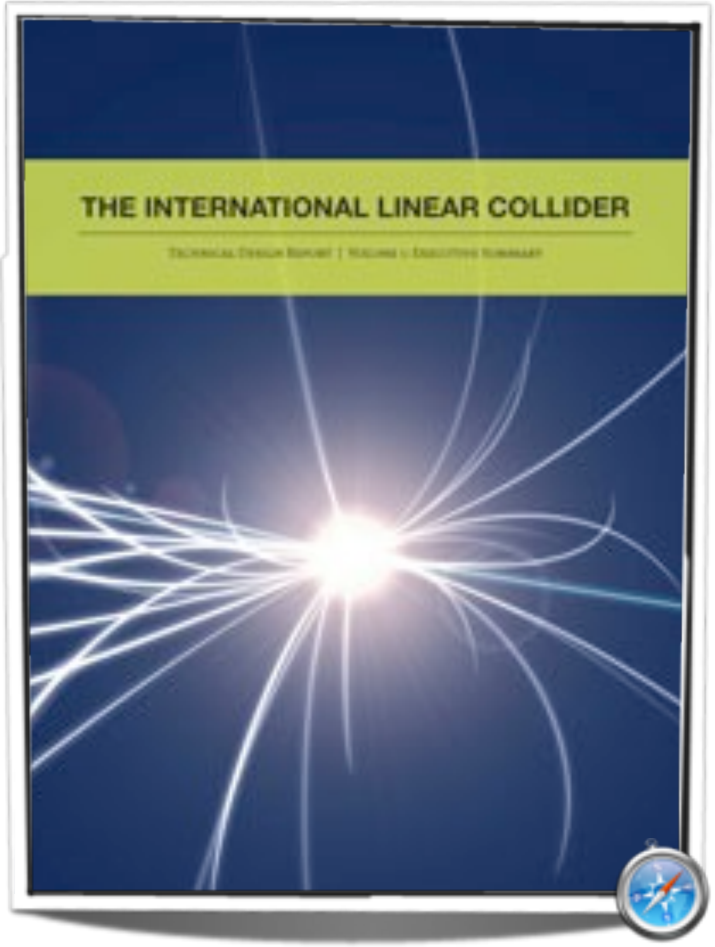
March 2015



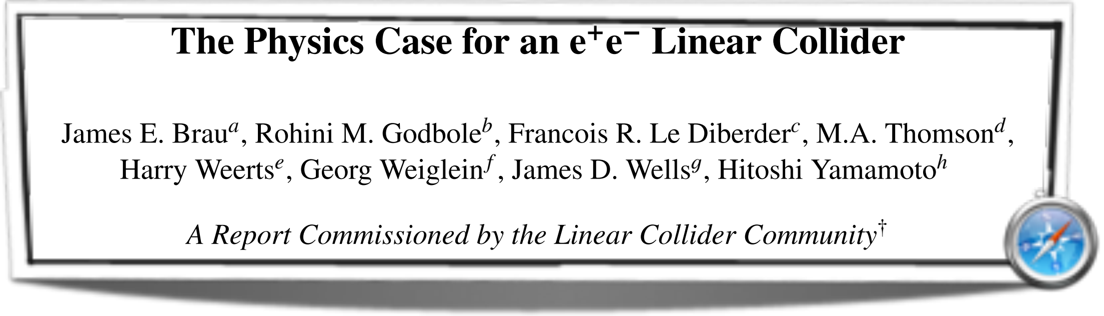
The International Linear Collider

Jim Brau[†], Paul Grannis[‡], Mike Harrison[#], Michael Peskin[*], Marc Ross[*], Harry Weerts[§]
for the ILC Collaboration
April 9, 2013

submitted to the Community Summer Study (Snowmass on the Mississippi), July 2013



THE INTERNATIONAL LINEAR COLLIDER



The Physics Case for an e^+e^- Linear Collider

James E. Brau[a], Rohini M. Godbole[b], Francois R. Le Diberder[c], M.A. Thomson[d], Harry Weerts[e], Georg Weiglein[f], James D. Wells[g], Hitoshi Yamamoto[h]

A Report Commissioned by the Linear Collider Community[†]

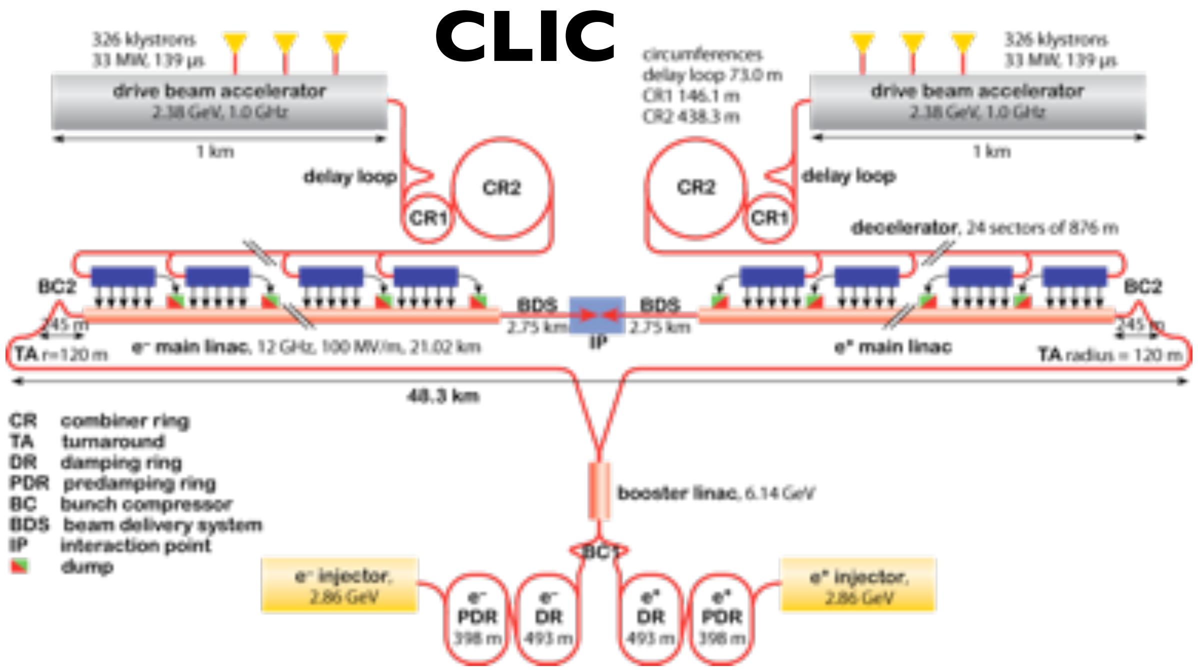
Physics Case for the ILC Project:
Perspective from Beyond the Standard Model

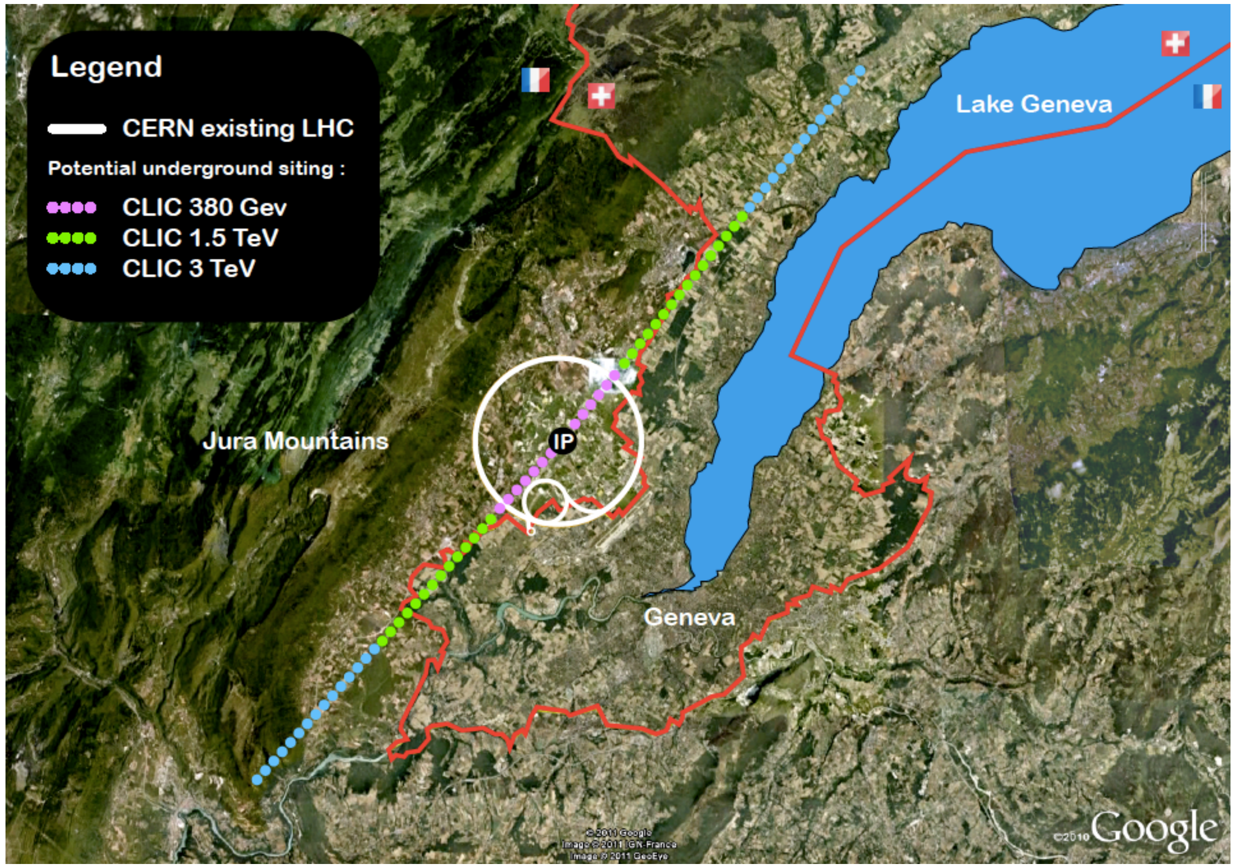
Howard Baer[1], Mikael Berggren[2], Jenny List[2], Mihoko M. Nojiri[3,4], Maxim Perelstein[5], Aaron Pierce[6], Werner Porod[7], Tomohiko Tanabe[8]

Physics at the e^+e^- Linear Collider

CLIC (TBA: 2025-?)

(350)/1000/3000 GeV - 5/ab





Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	10^{34}cm^{-2}s^{-1}	1.5	5.9
Luminosity above 99% of √s	10^{34}cm^{-2}s^{-1}	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100
Site length	km	11	50

- sub-percent Higgs coupling measurements
- few percents Higgs width
- top mass, top EW couplings
- direct BSM sensitivity in the multi-TeV region (direct and indirectly via precision)

CLIC (TBA: 2025-?)

(350)/1000/3000 GeV - 5/ab

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CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TEV LINEAR COLLIDER BASED ON CLIC TECHNOLOGY
CLIC CONCEPTUAL DESIGN REPORT

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AND DETECTORS AT CLIC
CLIC CONCEPTUAL DESIGN REPORT

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE CLIC PROGRAMME: TOWARDS A STAGED e^+e^- LINEAR COLLIDER EXPLORING THE TERASCALE
CLIC CONCEPTUAL DESIGN REPORT

		380	
		0.38	
	$^{-2}s^{-1}$	1.5	
	$^{-2}s^{-1}$	0.9	
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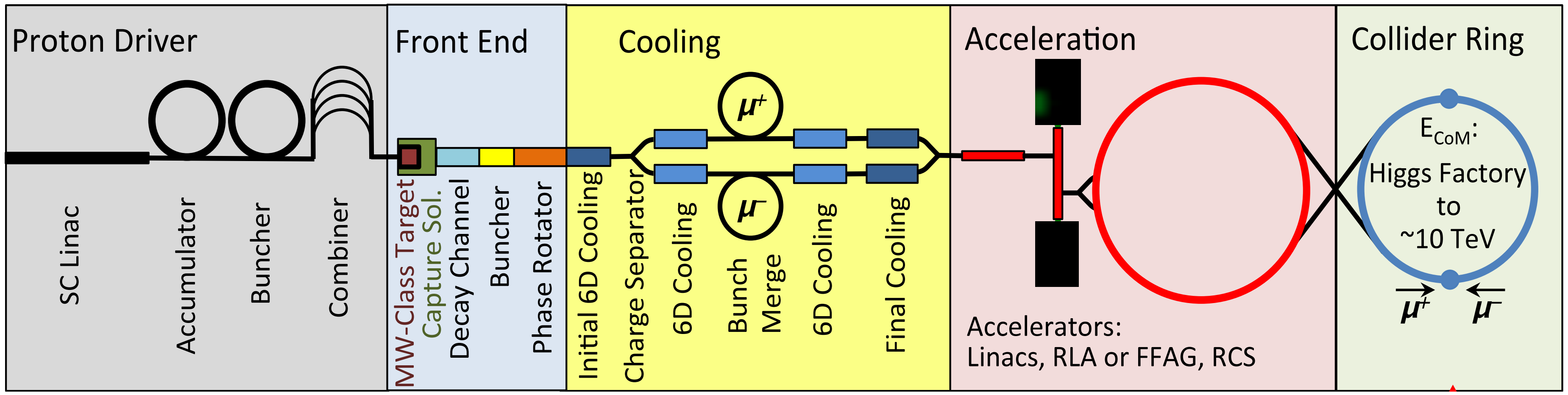
Higgs

Higg

- top mass, top EW couplings
- direct BSM sensitivity in the multi-TeV region (direct and indirectly via precision)

μ collider aka project X (TBD: ?-?)

126/1'000/10'000 GeV - O(1)/ab



M. Palmer, CERN '15

Physics Frontiers

- **Intense and cold muon beams ➩ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\,MeV/c^2$$

$$\tau_\mu = 2.2\,\mu s$$

Colliders

- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs
  - Reduced synchrotron radiation ➩ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT* accelerator complex/detector must be able to handle the impacts of μ decay**

$$\triangleleft\left(\frac{m_\mu^2}{m_e^2}\right) \cong 4\times10^4$$

Collider Synergies

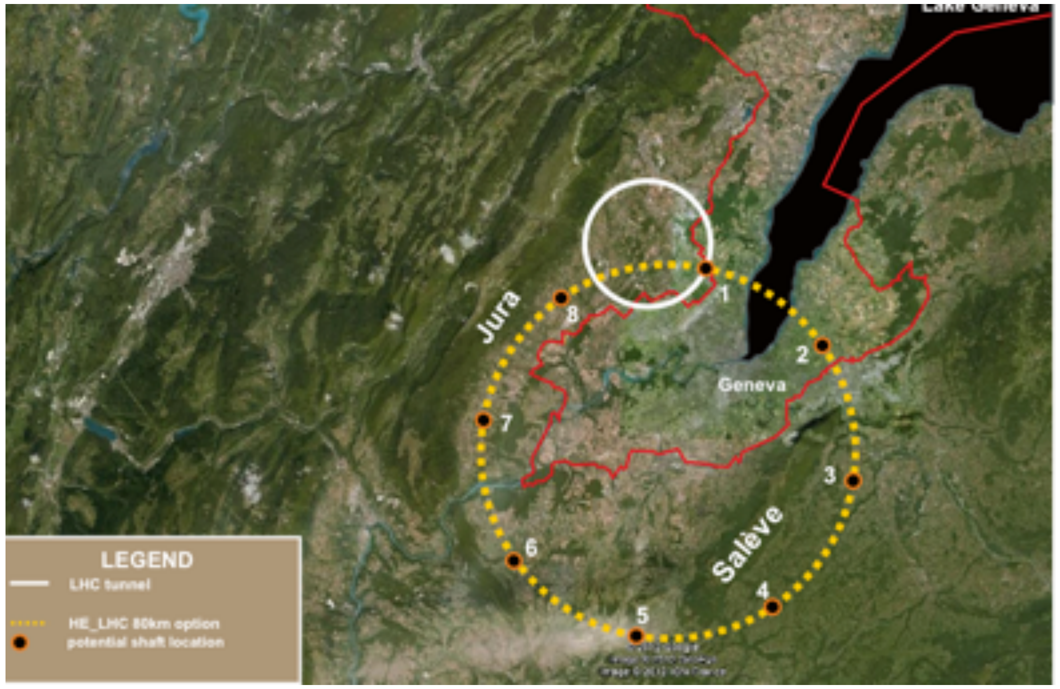
- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

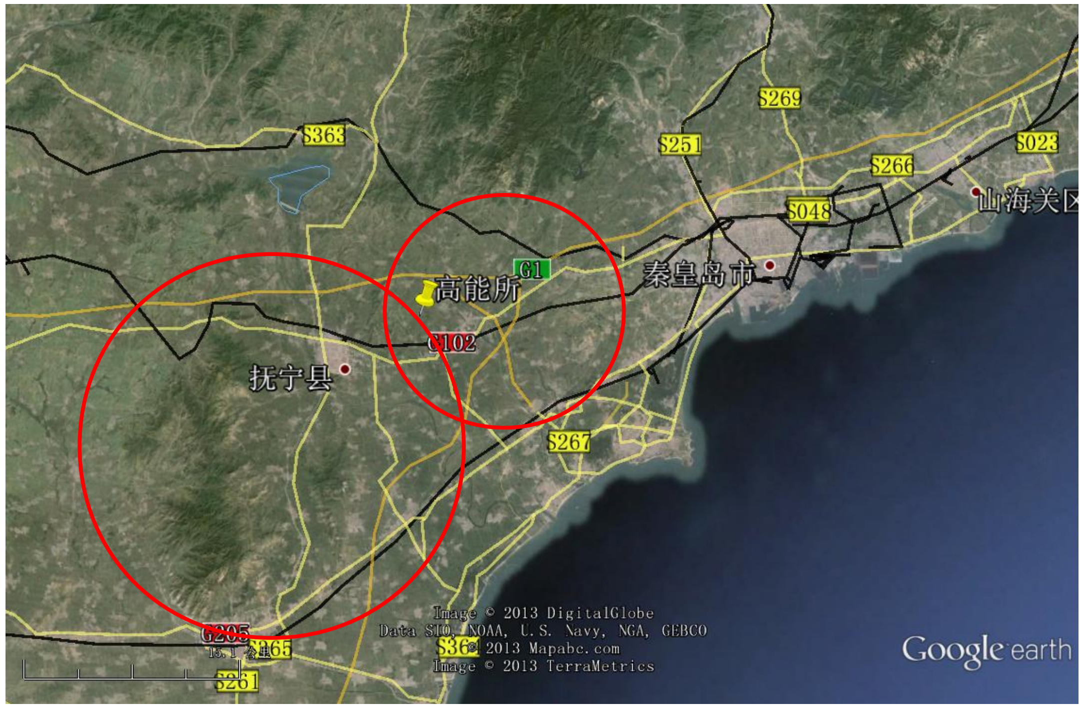
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

FCC-ee/CepC (TBA: maybe soon?-?)

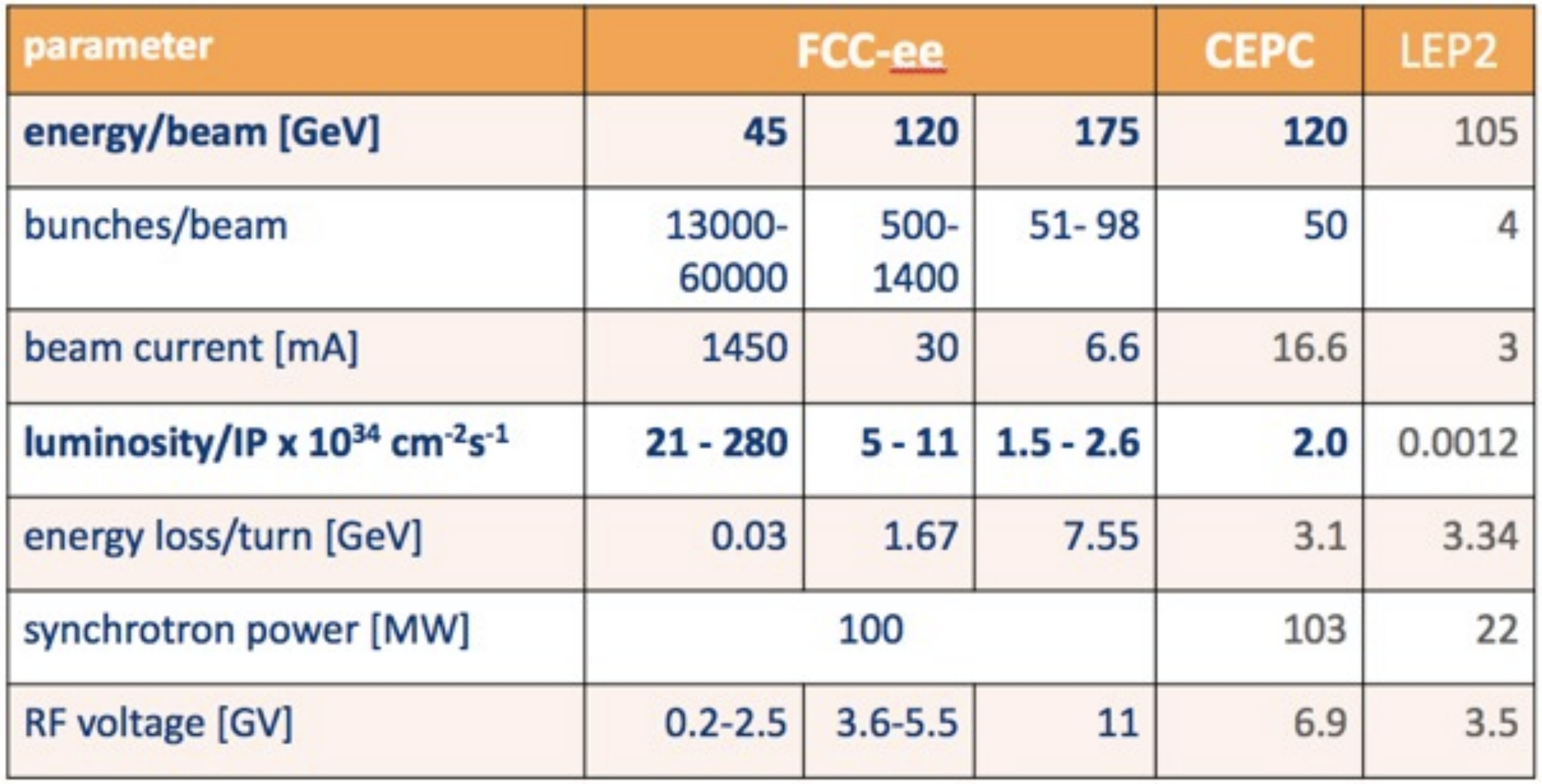
240/350/(500) - 10/ab



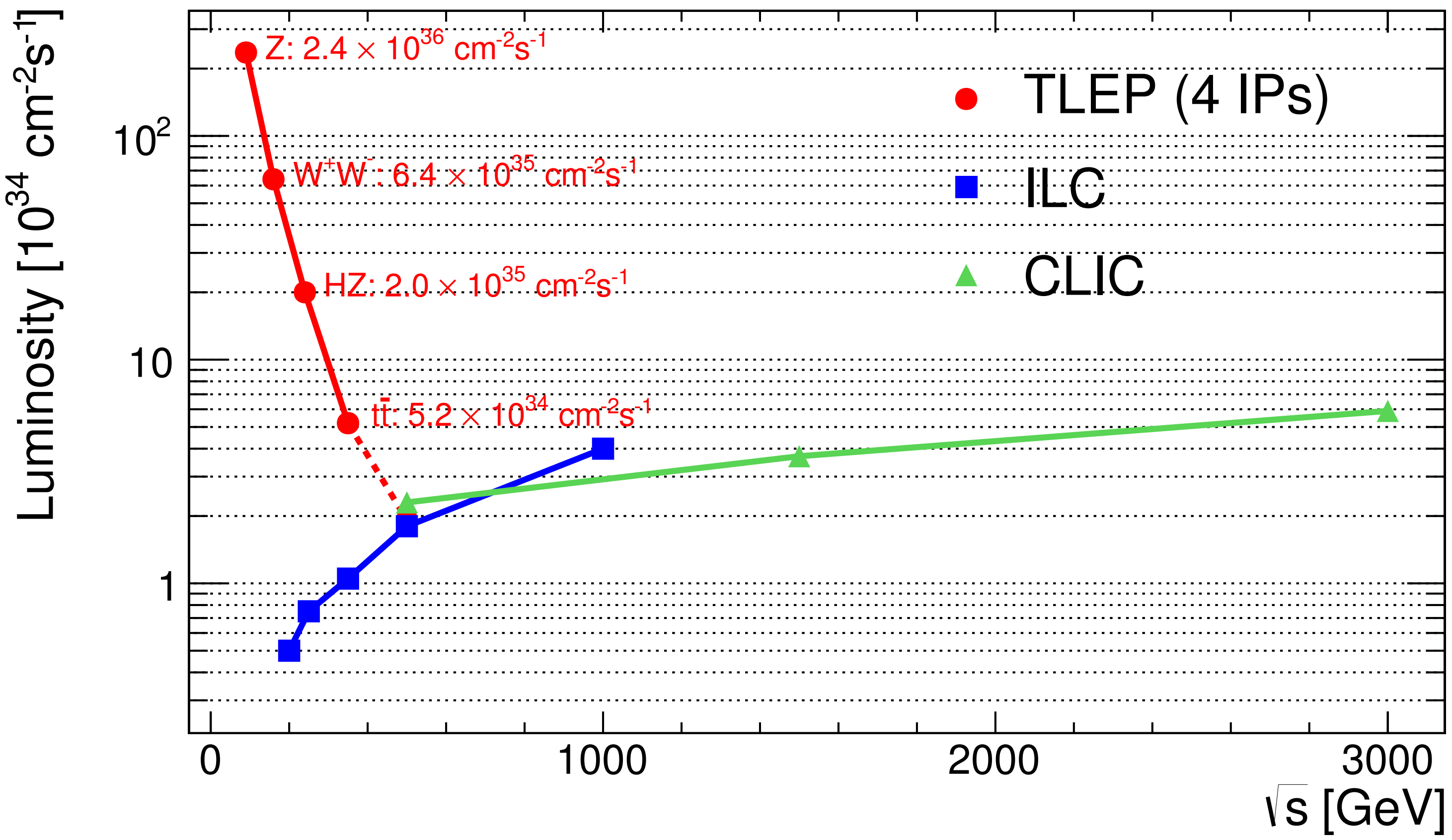


FCC-ee/CepC (TBA: maybe soon?-?)

240/350/(500) - 10/ab

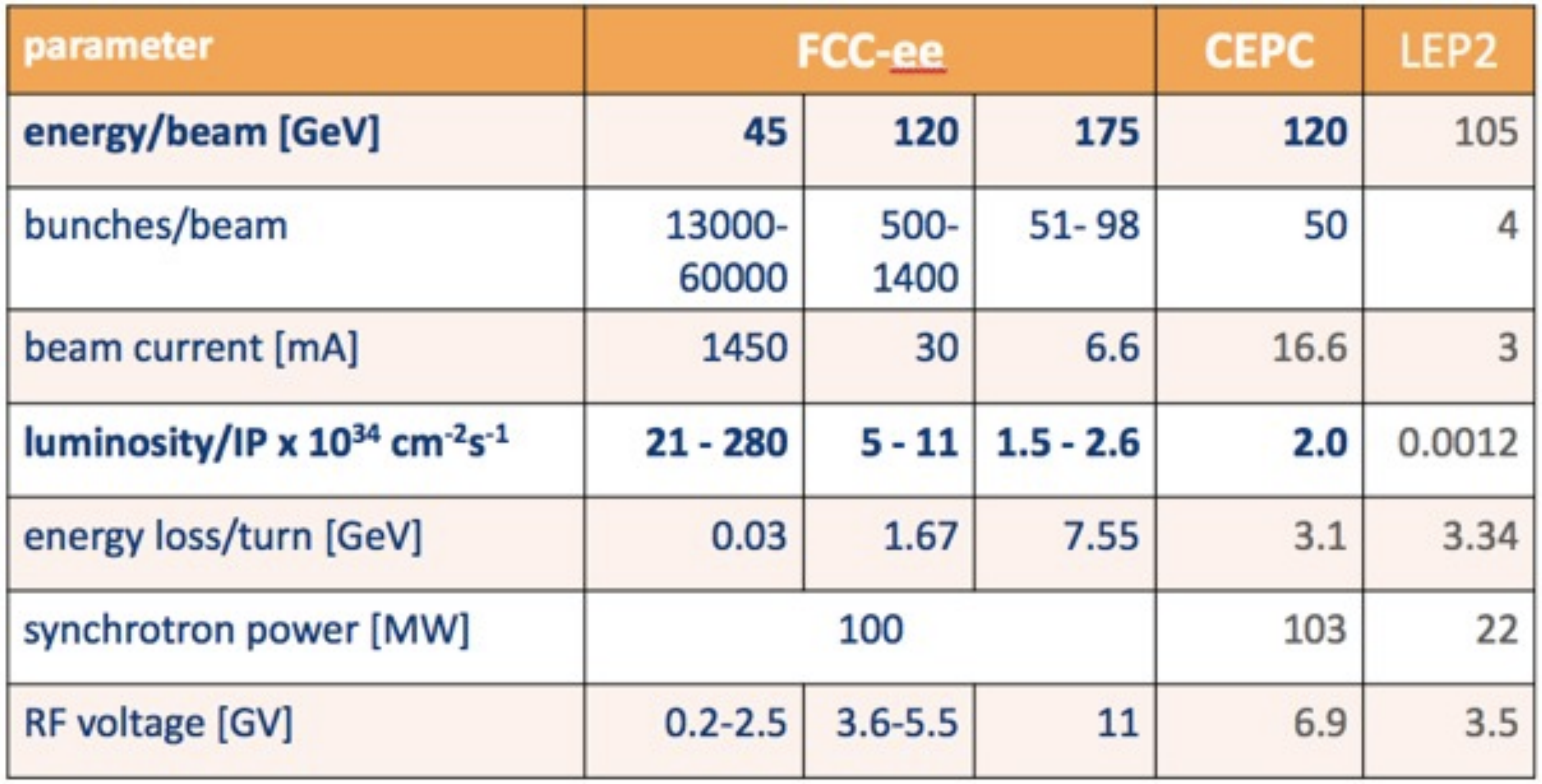


parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	13000-60000	500-1400	51- 98	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} cm^{-2}s^{-1}	**21 - 280**	**5 - 11**	**1.5 - 2.6**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.2-2.5	3.6-5.5	11	6.9	3.5



FCC-ee/CepC (TBA: maybe soon?-?)

240/350/(500) - 10/ab



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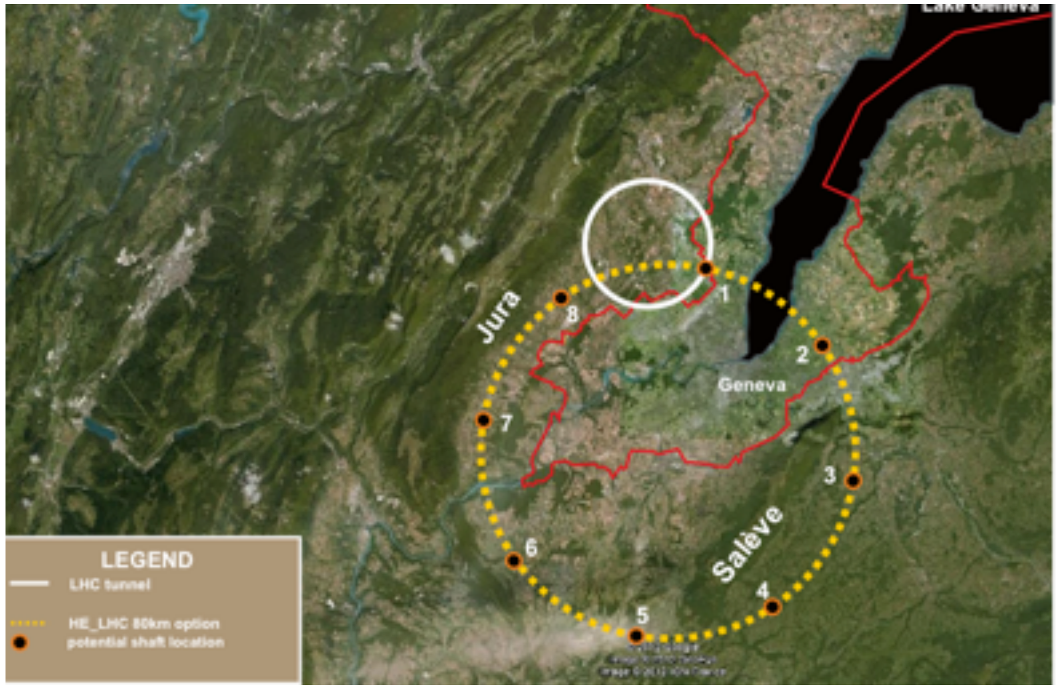
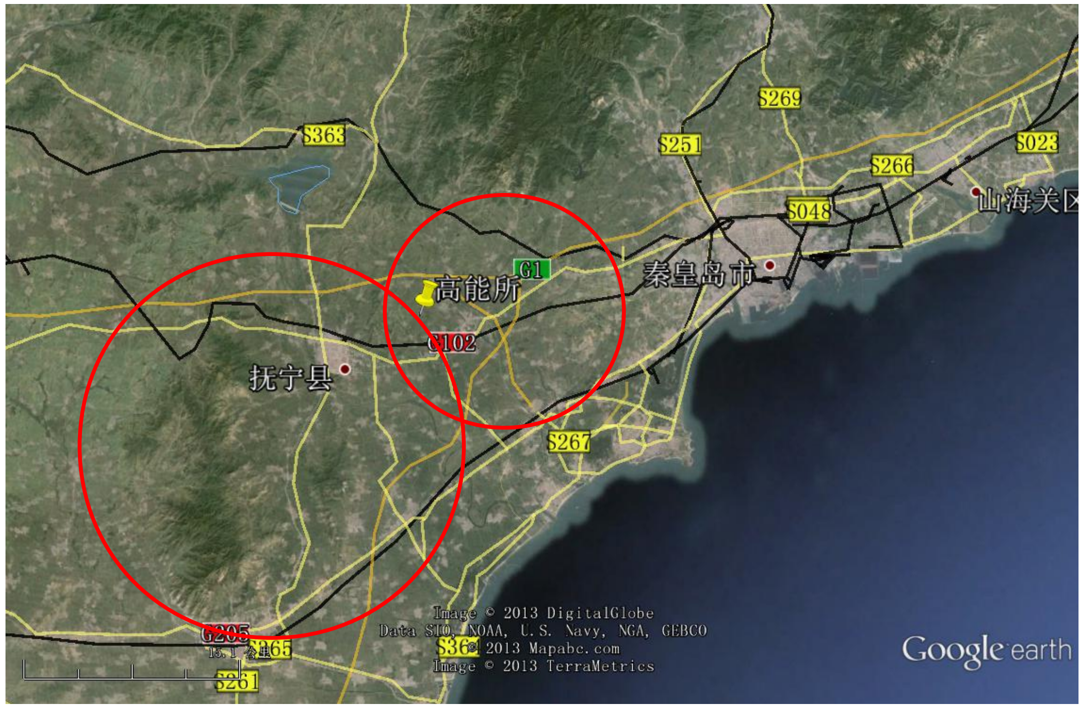
- 10^6 H
- 10^{12} Z (line-shape, mass & width, probe rare (FCNC) decays)
- 10^8 W (mass)
- 3×10^{10} tau/muon pairs
- 2×10^{11} b/c quarks ⇒ >20'000 $B_s\to\tau^+\tau^-$
- TLEP@340/500: 10^6 top pairs (pole mass, probe FCNC decays, top Yukawa)

FCC-ee/CepC (TBA: maybe soon?-?)

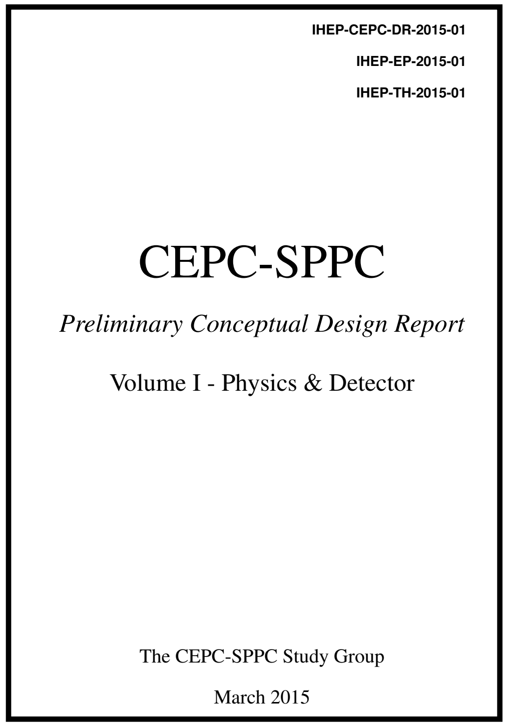
240/350/(500) - 10/ab





pre-CDR:

- physics case: arXiv:1308.6176
- CDR and cost review due in 2018



IHEP-CEPC-DR-2015-01
IHEP-EP-2015-01
IHEP-TH-2015-01

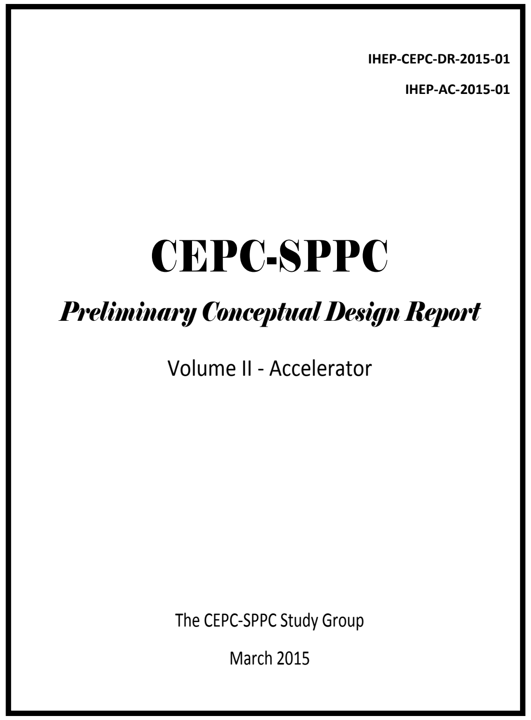
CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

The CEPC-SPPC Study Group

March 2015



IHEP-CEPC-DR-2015-01
IHEP-AC-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume II - Accelerator

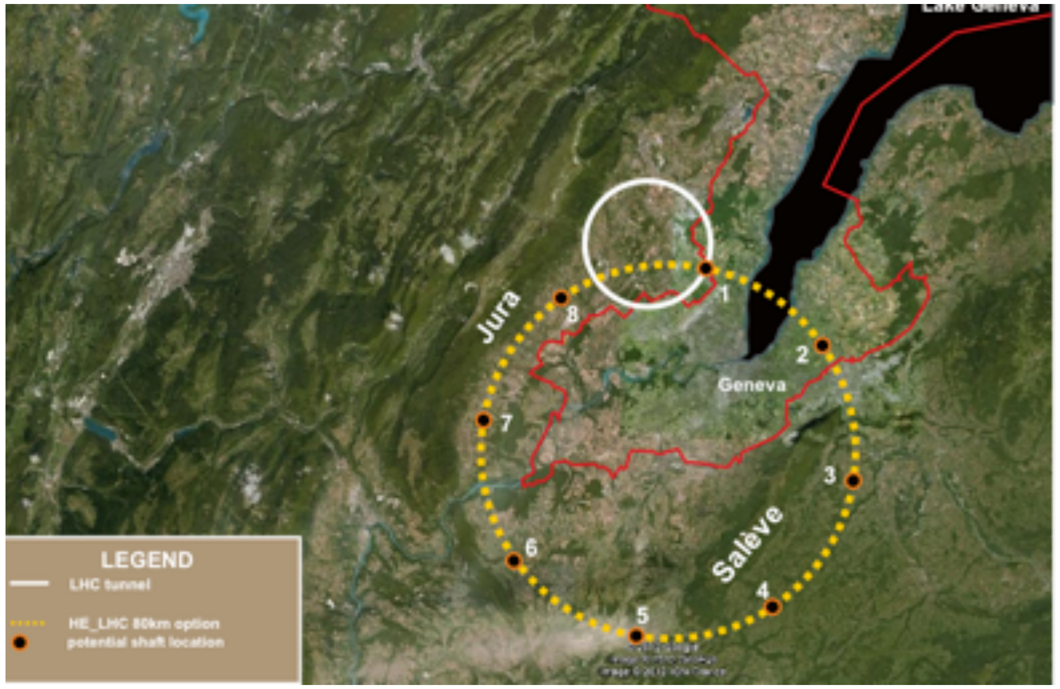
The CEPC-SPPC Study Group

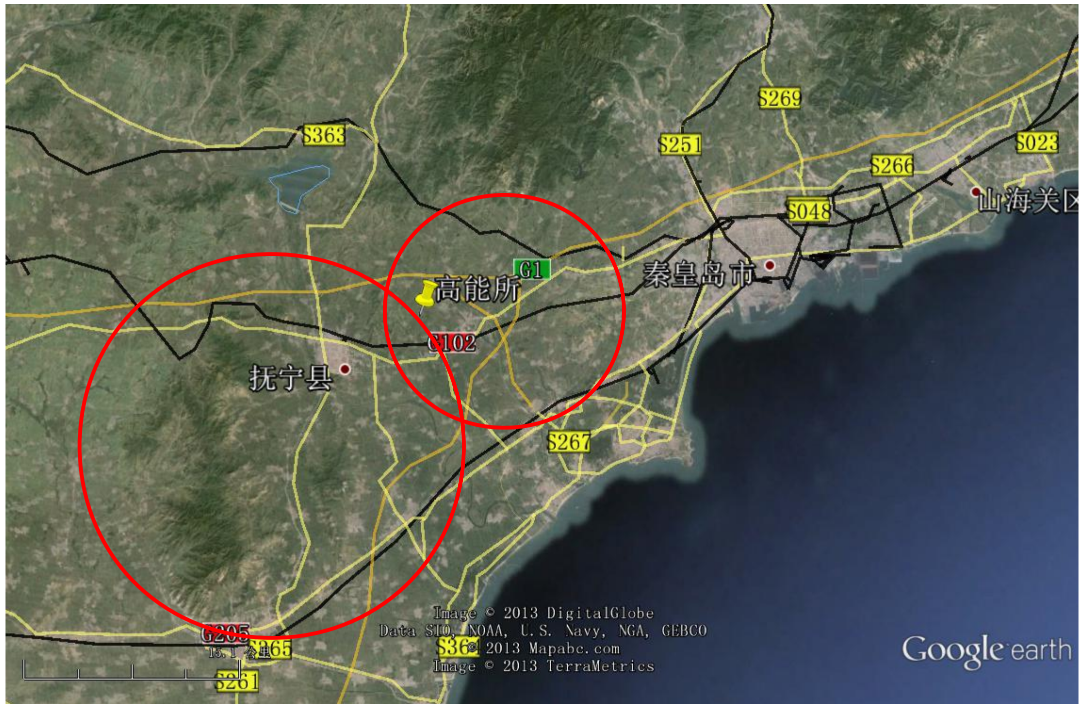
March 2015

The FCC and CepC are essentially equivalent proposals with different emphasis; FCC – hadrons via e+e-, CepC – e+e- then hadrons

FCC-hh/SppC (TBA: 2035-2060)

80/100 TeV - 30/ab





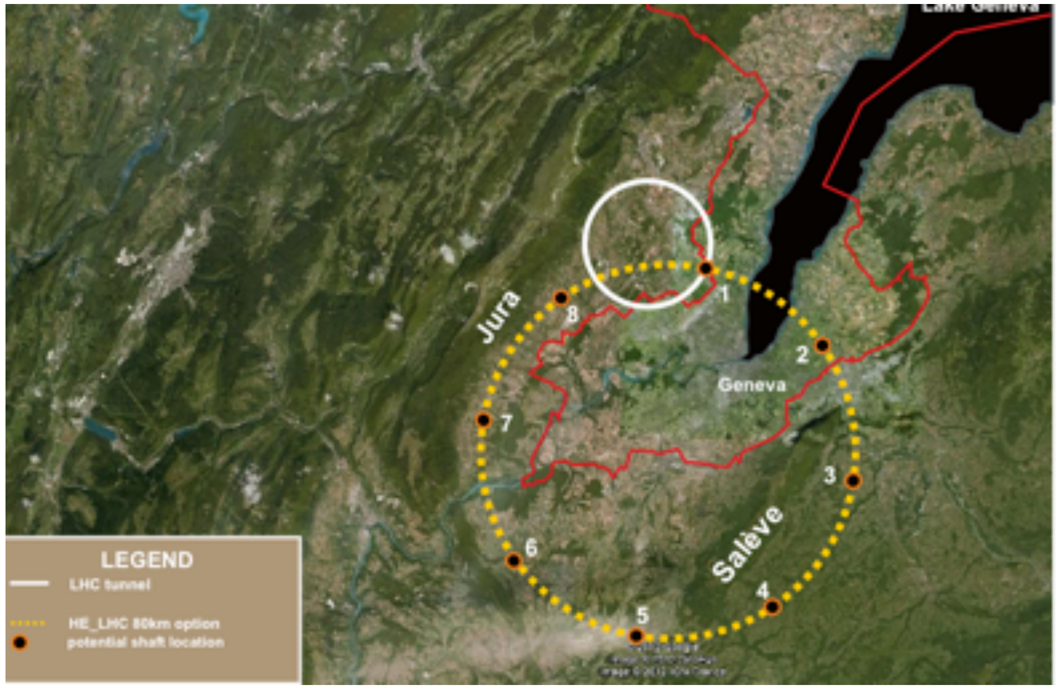
SppC

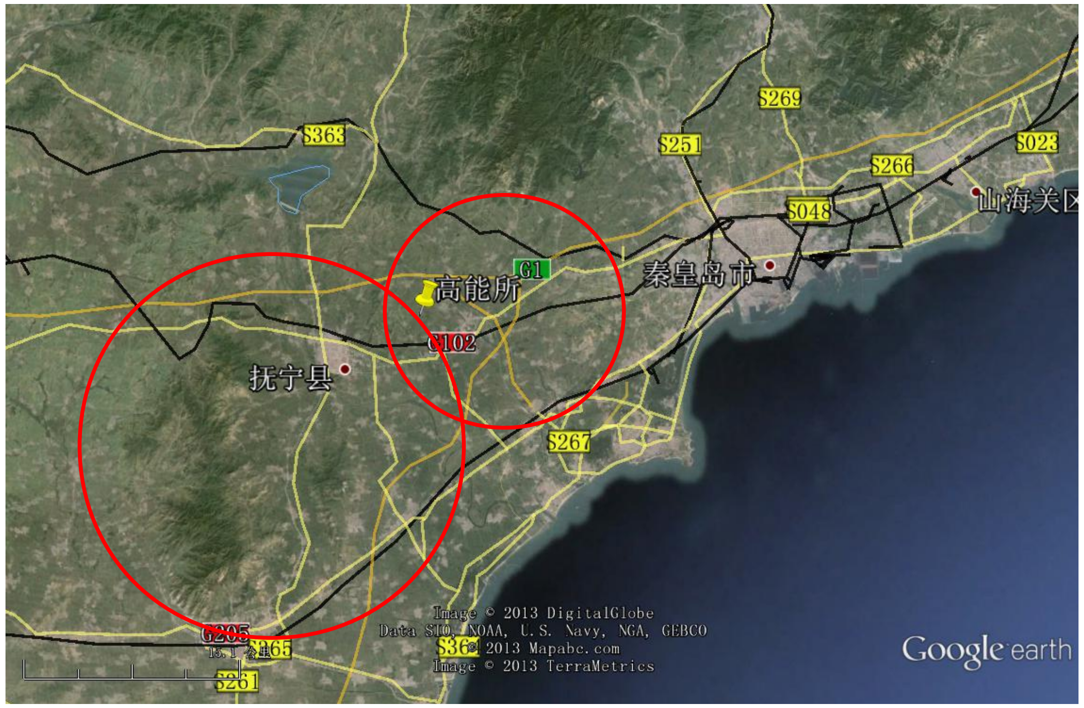
2020 — 2030 — 2040

R&D (2014-2030)	Engineering Design (2030-2035)	Construction (3035-2042)	Data taking (2042-2055)

FCC-hh/SppC (TBA: 2035-2060)

80/100 TeV - 30/ab

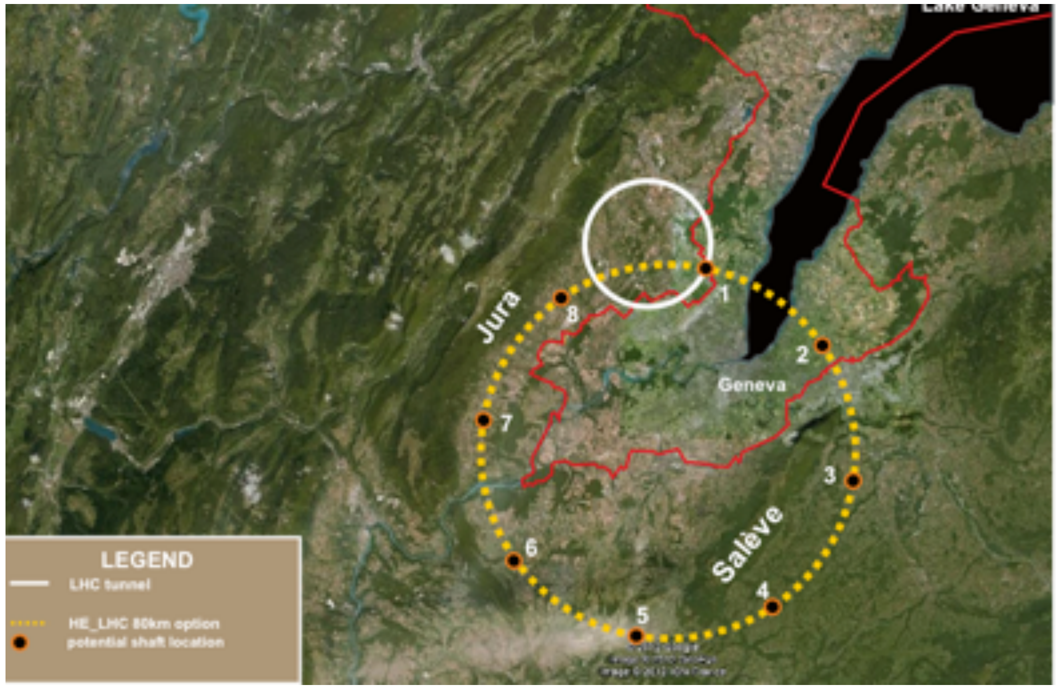


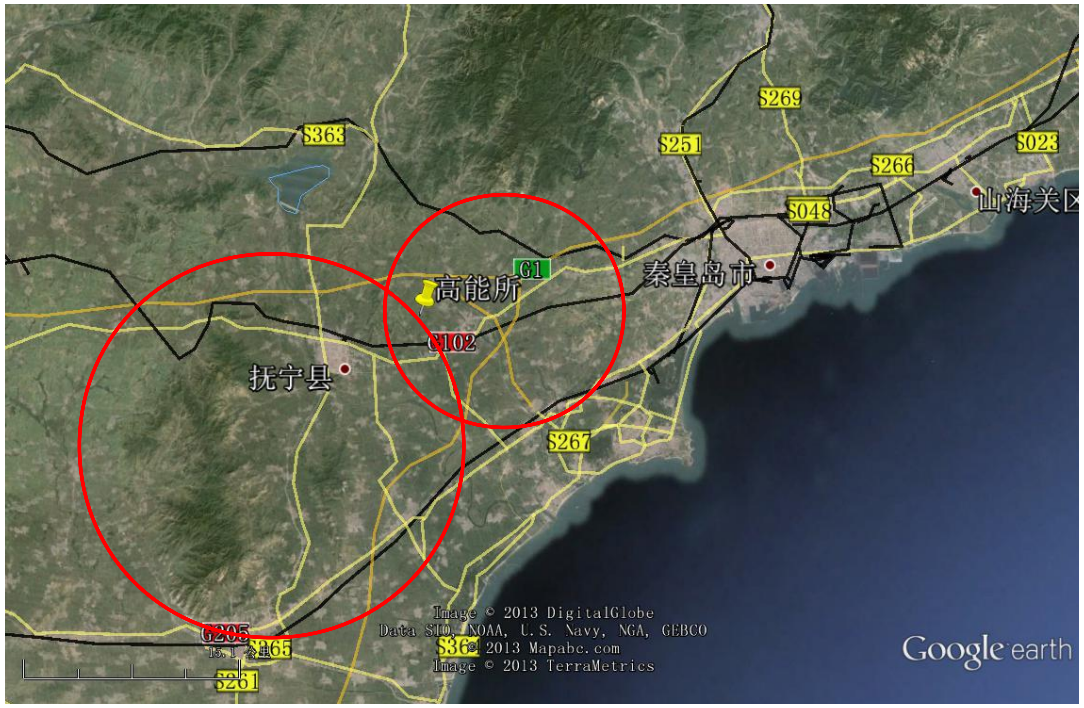


Parameter	**FCC-hh**		**SPPC**	**LHC**	**HL LHC**
collision energy cms [TeV]	**100**		**71.2**	14	
dipole field [T]	**16**		**20**	8.3	
# IP	**2 main & 2**		**2**	2 main & 2	
bunch intensity [10^{11}]	**1**	**1 (0.2)**	**2**	1.1	2.2
bunch spacing [ns]	**25**	**25 (5)**	**25**	25	25
luminosity/Ip [10^{34} cm^{-2}s^{-1}]	**5**	**25**	**12**	1	5
events/bx	**170**	**850 (170)**	**400**	27	135
stored energy/beam [GJ]	**8.4**		**6.6**	0.36	0.7
synchr. rad. [W/m/apert.]	**30**		**58**	0.2	0.35

FCC-hh/SppC (TBA: 2035-2060)

80/100 TeV - 30/ab






SppC

R&D (2014-2030)	Engineering Design (2030-2035)	Construction (3035-2042)	Data taking (2042-2055)

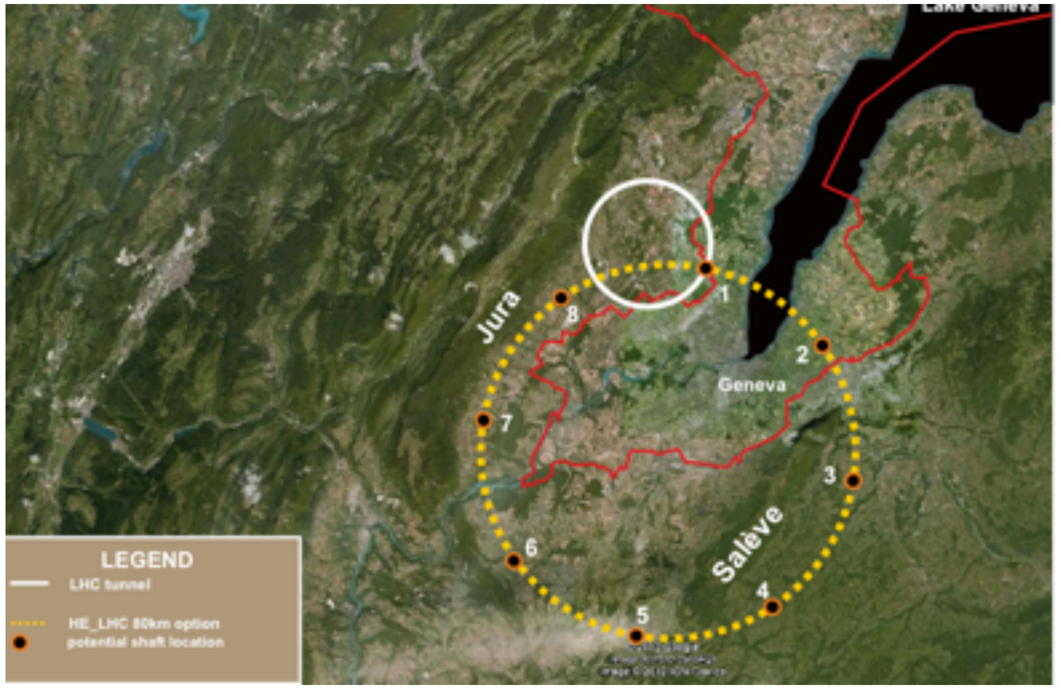
	σ	N / 10ab^{-1}
gg→H	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
gg→HH	1.4 pb	14 M

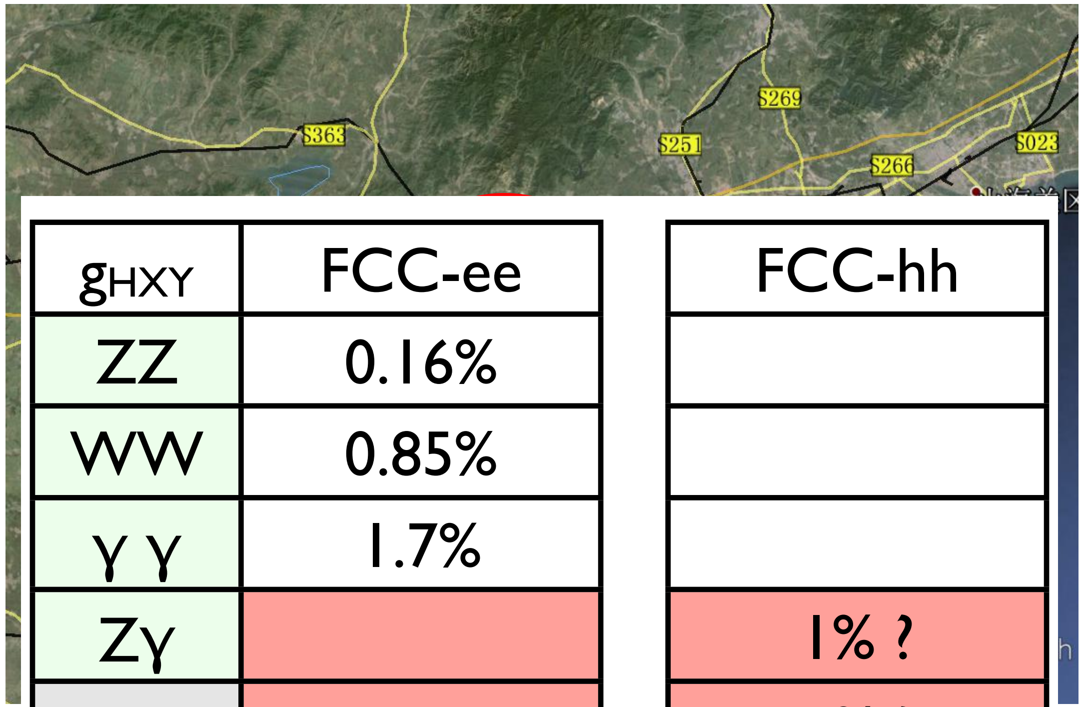
10^{10} Higgs bosons => 10^4 x today

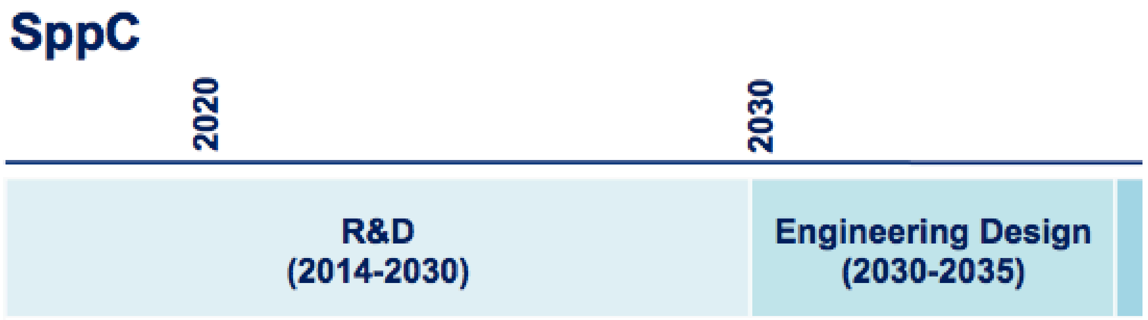
10^{12} top quarks => 5 10^4 x today

FCC-hh/SppC (TBA: 2035-2060)

80/100 TeV - 30/ab







R&D (2014-2030)

Engineering Design (2030-2035)

	σ	N / 10ab^{-1}
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WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
gg→HH	1.4 pb	14 M

10^{10} Hig

10^{12} top

g_{HXY}	FCC-ee	FCC-hh
ZZ	0.16%	
WW	0.85%	
γ γ	1.7%	
Zγ		1% ?
tt		1% ?
bb	0.88%	
τ τ	0.94%	
cc	1.0%	
ss	H→Vγ, in progr.	
μμ	6.4%	2% ?
uu,dd	H→Vγ, in progr.	
ee	e^+e^-→H, in progr.	
HH		5% ?
BR_{exo}	0.48%	$< 10^{-6}$?

1

Higgs physics

HEP with a Higgs boson

The successes have been breathtaking

- in O(2) years, the Higgs mass has been measured to 0.2% (vs 0.5% for the 20-year old top)
- some of its couplings, e.g. κ_γ, have been measured with LEP accuracy (10^{-3})

The meaning of the Higgs

Particle physics is not so much about particles but more about fundamental principles

- About 10^{-10}s after the Big Bang, the Universe filled with the Higgs substance because it saved energy by doing so: the vacuum is not empty (even when $\to 0$, not a Casimir effect)!

- The masses are emergent quantities due to a non-trivial vacuum structure

HEP with a Higgs boson

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Higgs agenda for the LHC-II, HL-LHC, ILC/CLIC, FCC, CepC, SppC, SHiP

multiple independent, synergetic and complementary approaches to achieve **precision** (couplings), **sensitivity** (rare and forbidden decays) and **perspective** (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, inflation, naturalness, etc)

M.L. Mangano, Washington '15

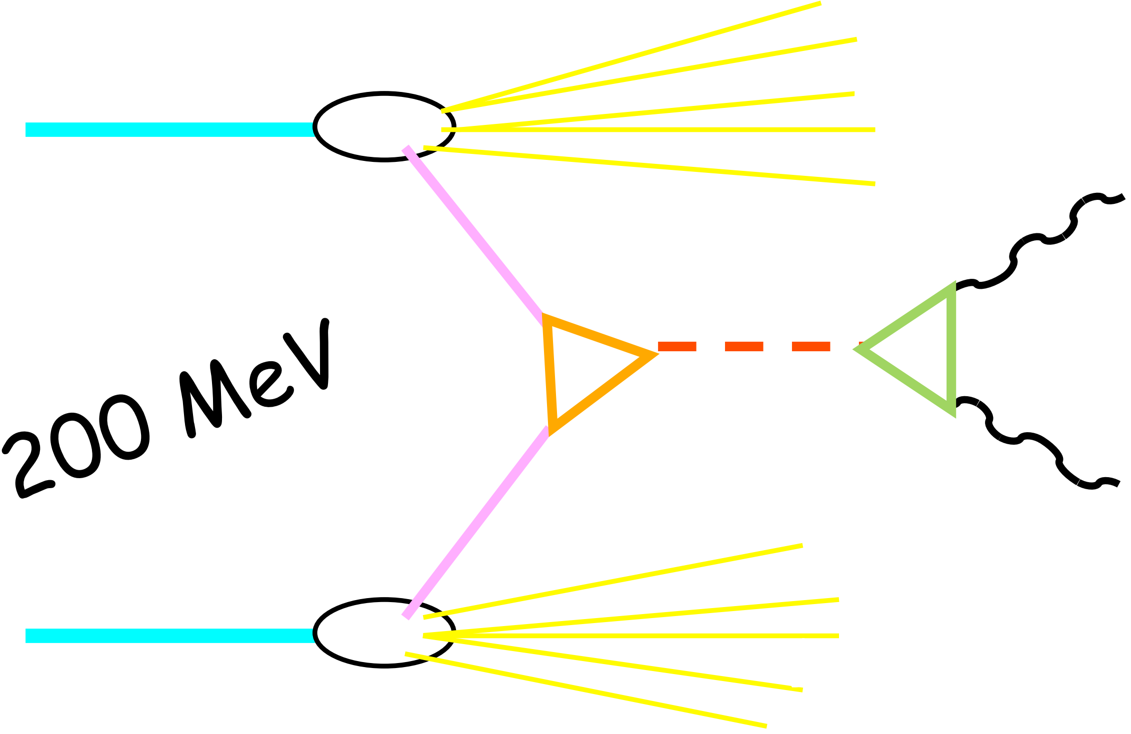
- rare Higgs decays: h→$\mu\mu$, h→γZ
- Higgs flavor violating couplings: h→$\mu\tau$ and t→hc
- Higgs CP violating couplings
- exclusive Higgs decays (e.g. h→$J/\Psi+\gamma$) and measurement of couplings to light quarks
- exotic Higgs decay channels:

  h→ $\not\!E_T$, h→4b, h→2b2μ, h→4τ,2τ2μ, h→4j, h →2γ2j, h→4γ, h→γ/2γ+ $\not\!E_T$,

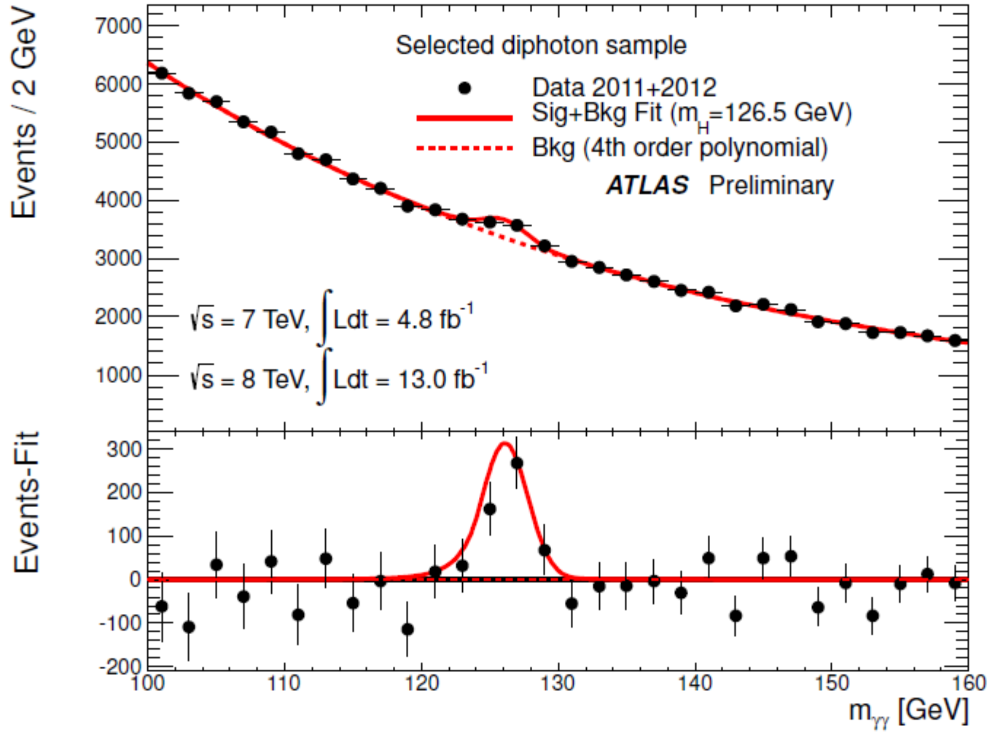
  h→isolated leptons+ $\not\!E_T$, h→2l+ $\not\!E_T$, h→one/two lepton-jet(s)+X, h→bb+ $\not\!E_T$, h→$\tau\tau$+ $\not\!E_T$ ...
- searches for extended Higgs sectors (H, A, $H^\pm$,$H^{\pm\pm}$...)
- Higgs self-coupling(s)
- Higgs width
- Higgs/axion coupling?
- ...

Higgs mass

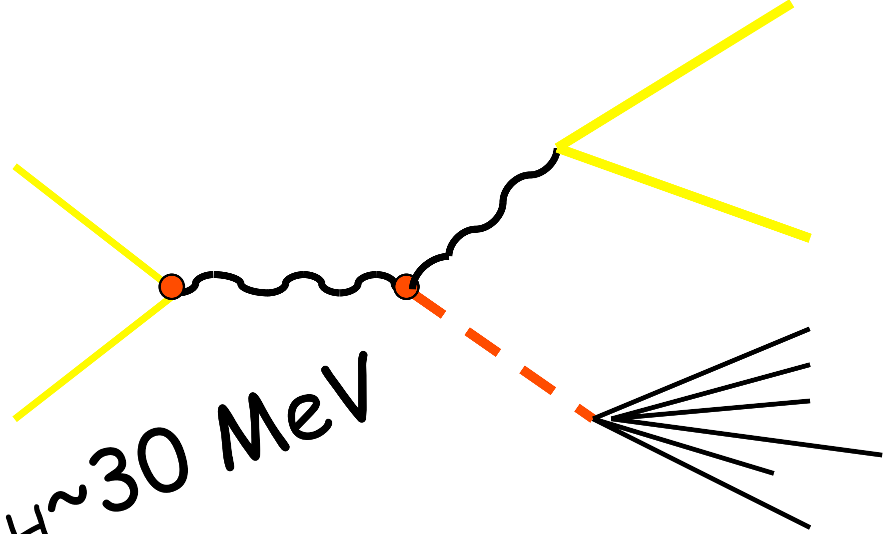
LHC H→γγ Invariant mass of γγ



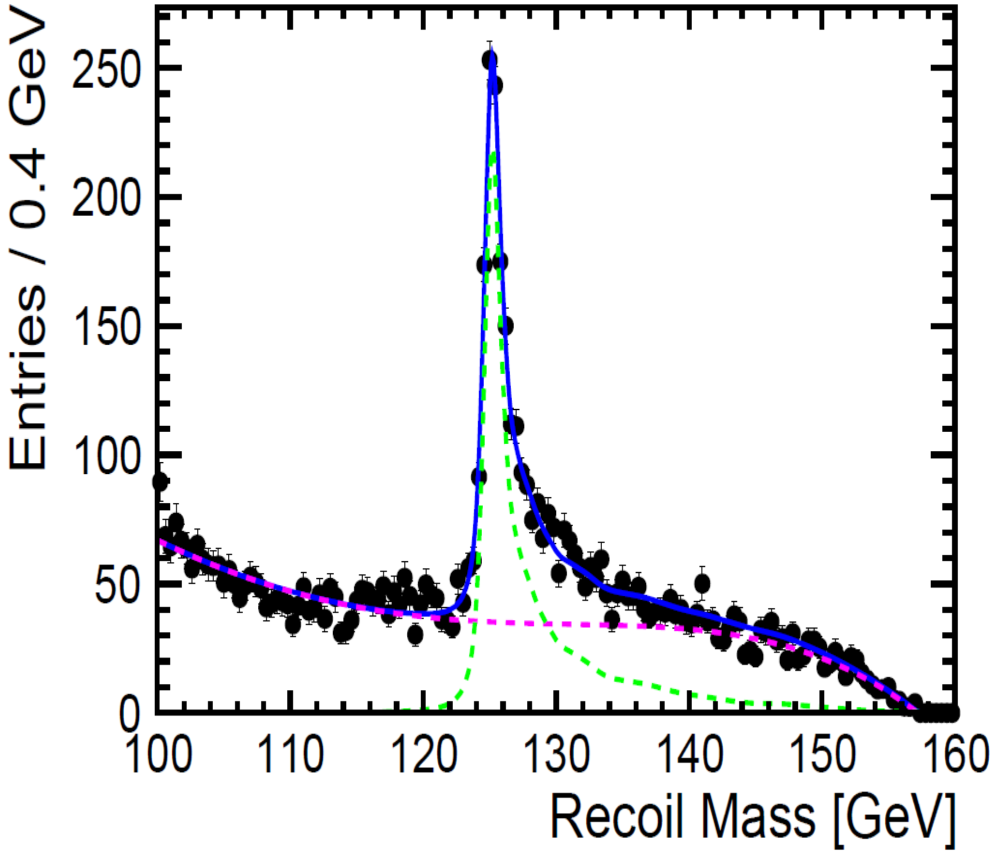
Δm_H~200 MeV



ILC Recoil mass of Z($\mu^+\mu^-$)

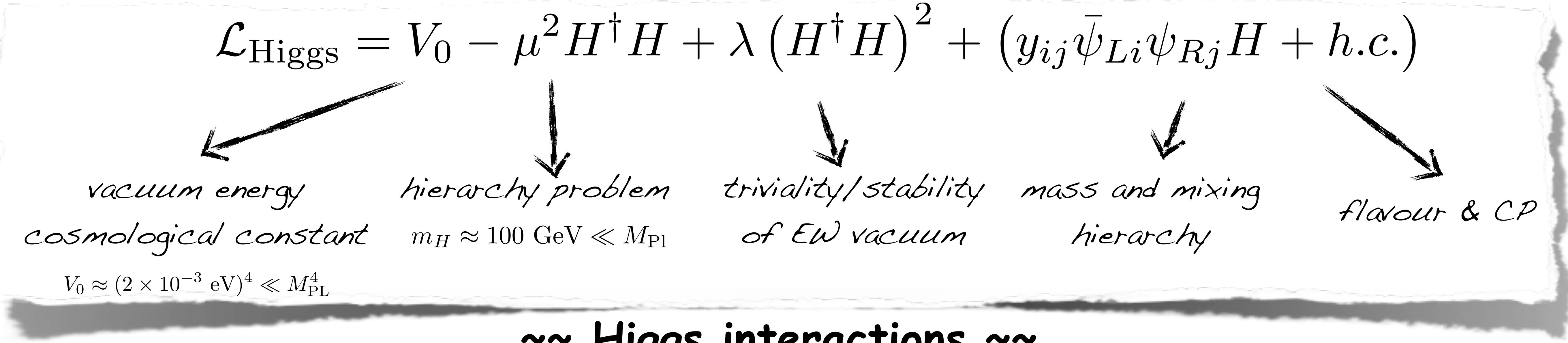


Δm_H~30 MeV



Higgs boson & New Physics

The Higgs is related to some of the deepest problems of HEP



$$\mathcal{L}_{\text{Higgs}} = V_0 - \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \left(y_{ij}\bar{\psi}_{Li}\psi_{Rj}H + h.c.\right)$$

vacuum energy
cosmological constant
$V_0 \approx (2\times 10^{-3}\ \text{eV})^4 \ll M_{\text{PL}}^4$

hierarchy problem
$m_H \approx 100\ \text{GeV} \ll M_{\text{Pl}}$

triviality/stability
of EW vacuum

mass and mixing
hierarchy

flavour & CP

~~ Higgs interactions ~~

many different couplings not set by any gauge symmetry

(are fundamental interactions all linked to gauge symmetry?)

but they obey 3 basic structures

1) proportionality: $g_{hff} \propto m_f$ $g_{hVV} \propto m_V^2$

➠ test for extended Higgs sectors

2) factor of proportionality: $g_{hff}/m_f = \sqrt{2}/v$

➠ test for extended Higgs sectors

➠ test for Higgs compositeness

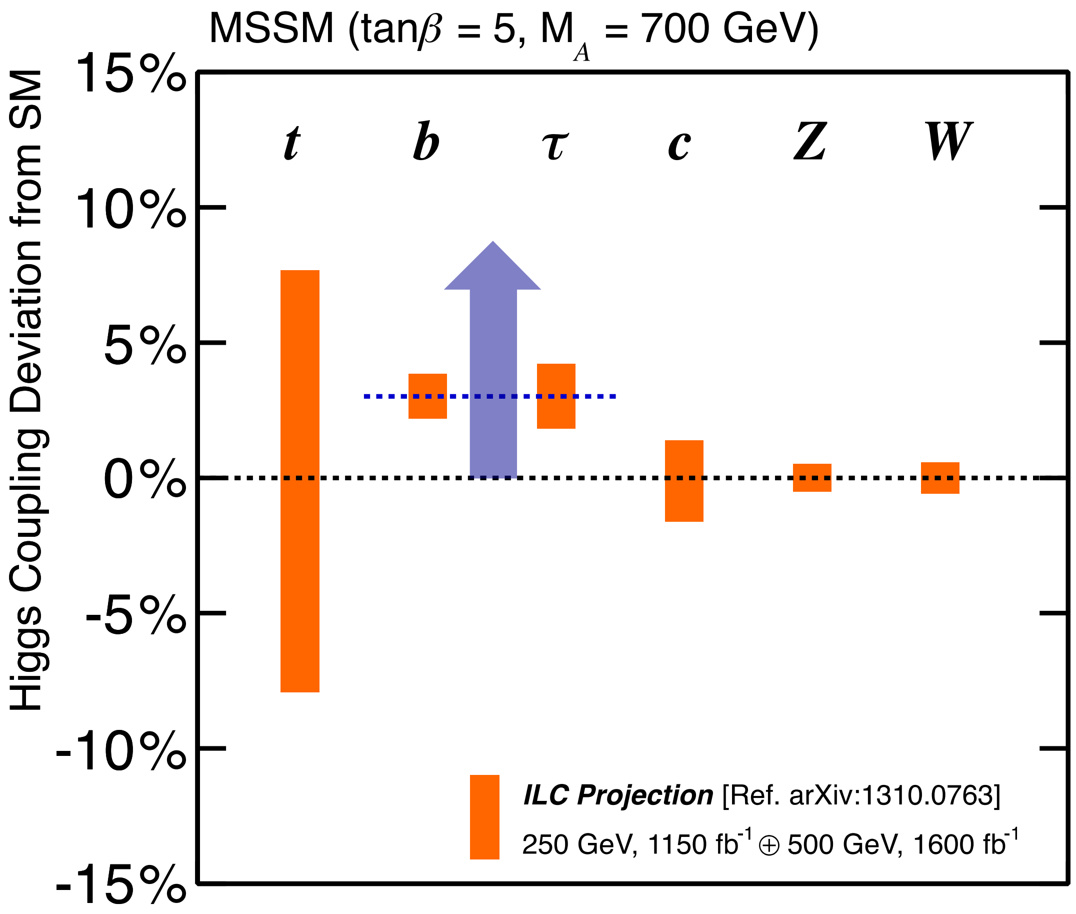
3) flavor alignment: $g_{hf_if_j} \propto \delta_{ij}$

➠ test for flavor models, origin of fermion masses

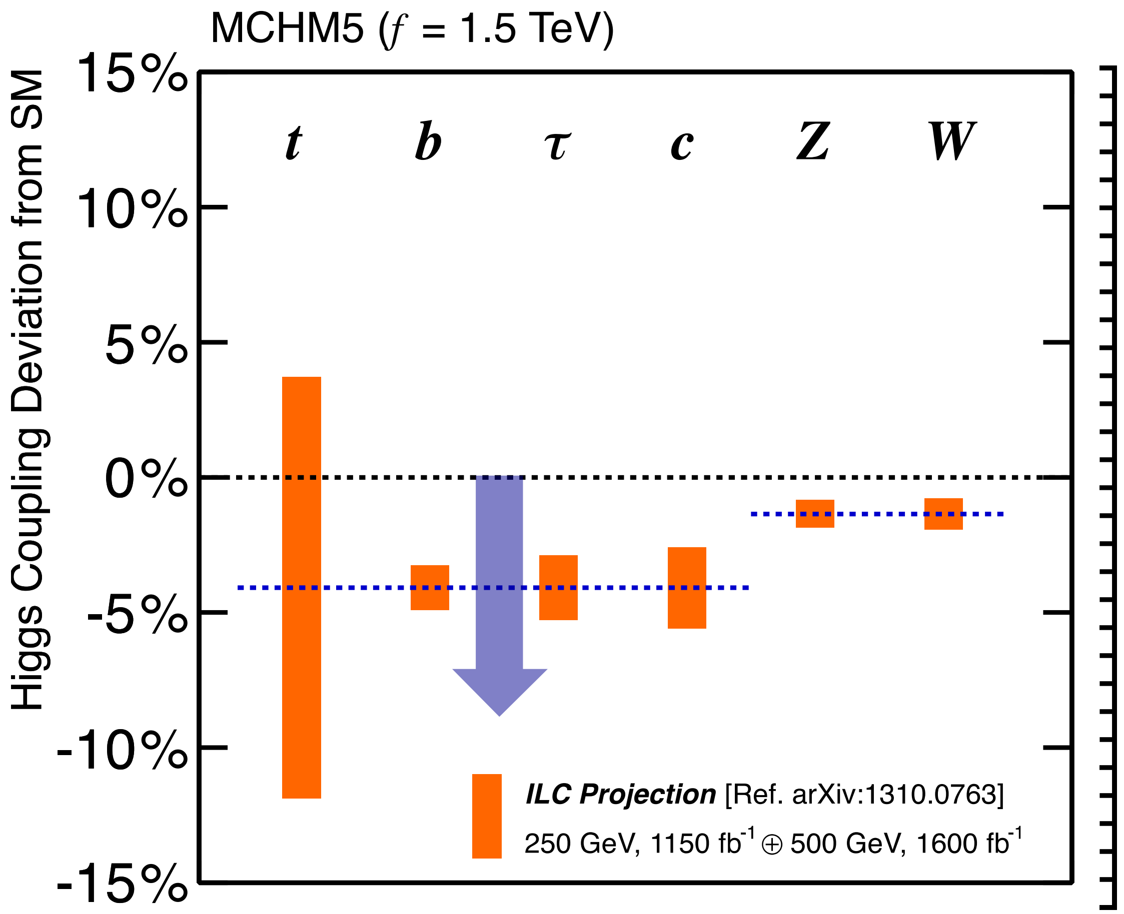
Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



ILC Physics WG, '15

Higgs couplings and model discriminations

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Supersymmetry
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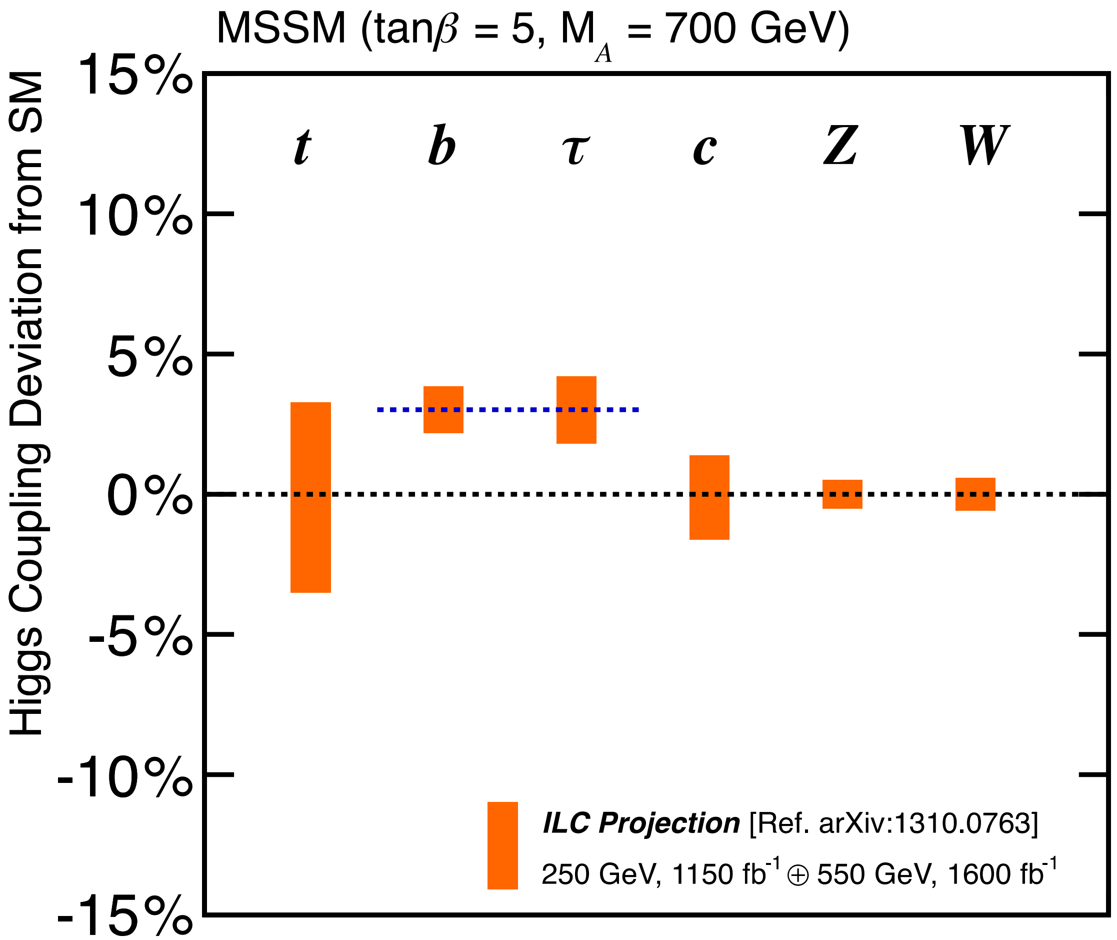

Composite Higgs
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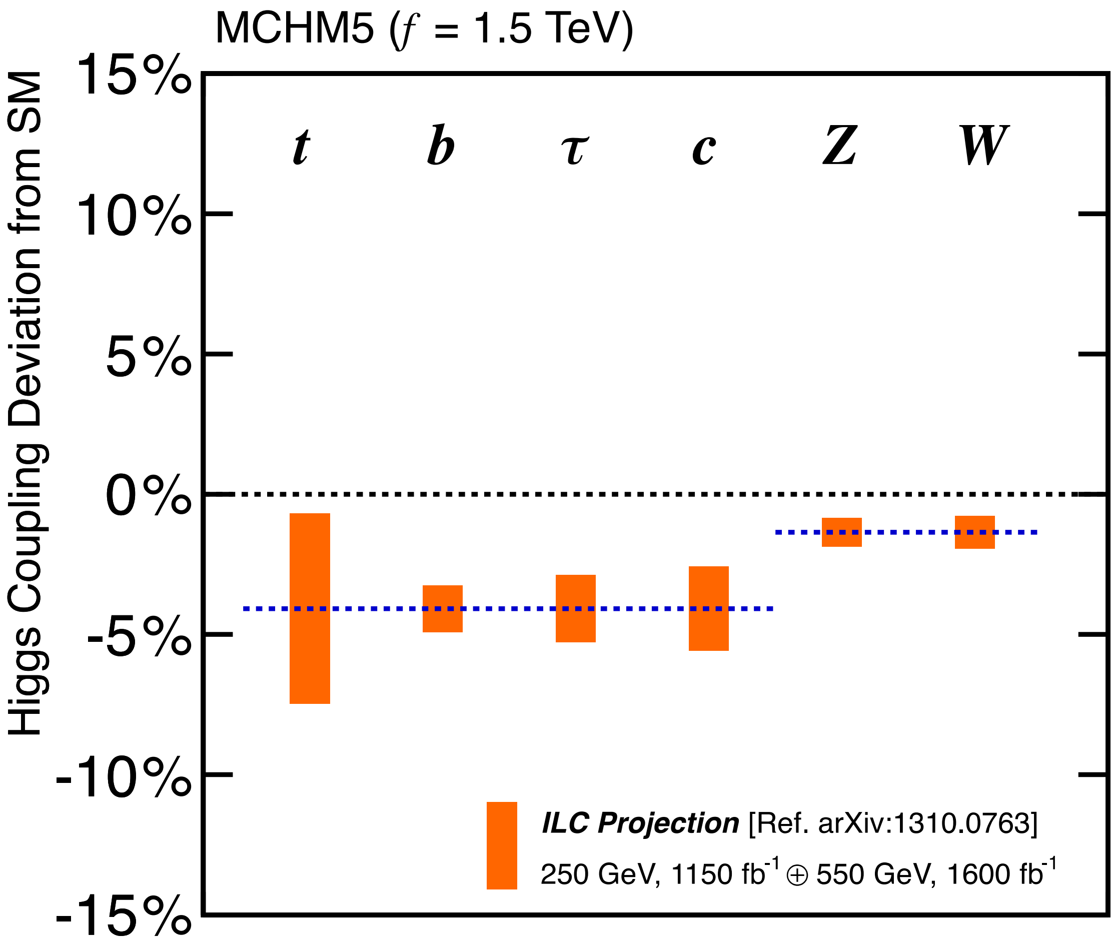


ILC Physics WG, '15

ILC 250+550 LumiUp

Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

~~ expected largest relative deviations ~~

	hff	hVV	hγγ	hγZ	hGG	h^3
MSSM	√		√	√	√	
NMSSM	√	√	√	√	√	
PGB Composite	√	√		√		√
SUSY Composite	√	√	√	√	√	√
SUSY partly-composite			√	√	√	√
“Bosonic TC”						√
Higgs as a dilaton			√	√	√	√

]

A. Pomarol, Naturalness ’15

Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

~~ expected largest relative deviations ~~

	hff	hVV	hγγ	hγZ	hGG	h^3
MSSM	√		√	√	√	
NMSSM	√	√	√	[illegible]	√	
PGB Composite	[illegible]	[illegible]	[illegible]	[illegible]		√
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	√	√
SUS	[illegible]	[illegible]	√	√	√	√
[illegible]	[illegible]					√
Higgs as a dilaton			√	√	√	√

There exist some physics scenarios where high energy thresholds are important and complementary to physics near Higgs threshold

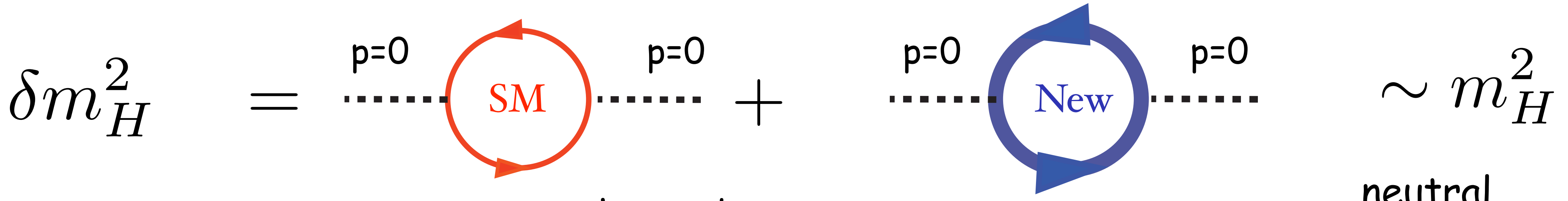
(HH & ttH productions)

]

A. Pomarol, Naturalness '15

Higgs couplings as a test of naturalness

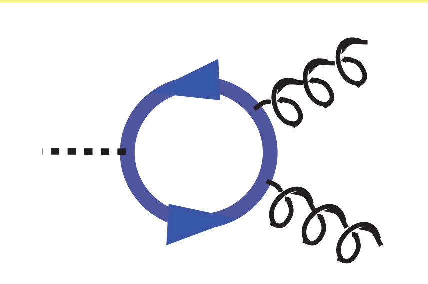
$$-(125\ \text{GeV})^2\left(\frac{\Lambda}{600\ \text{GeV}}\right)^2 \qquad\qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$



charged particles

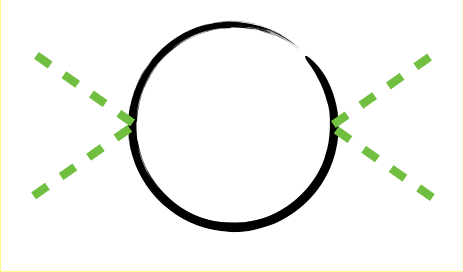
generically

neutral particles



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$



$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$BR(h\to ii) = BR_{\text{SM}} \qquad \Gamma = \left(1-\frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

$$\delta\sigma_{Zh} = -\frac{g_\star^2}{8\pi^2}\frac{v^2}{m_\star^2}$$

nice to be able to measure Zh & Γ

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

Higgs couplings measurement projections

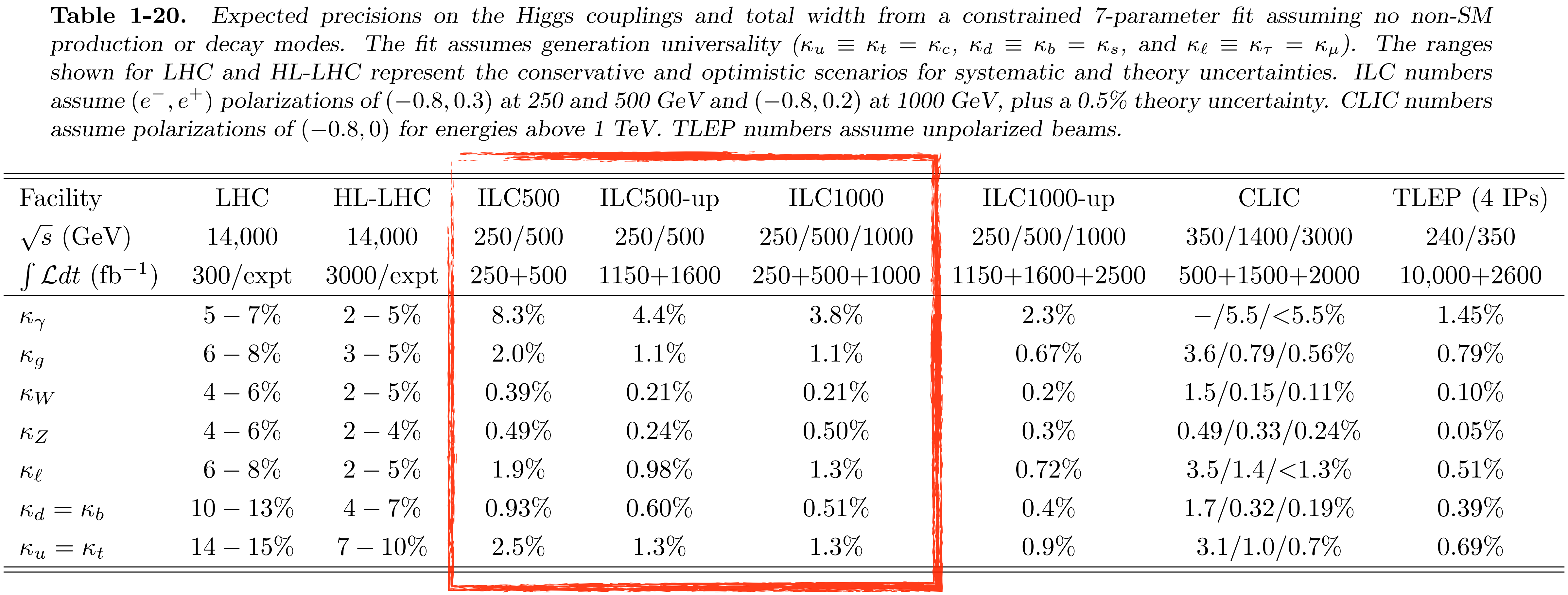


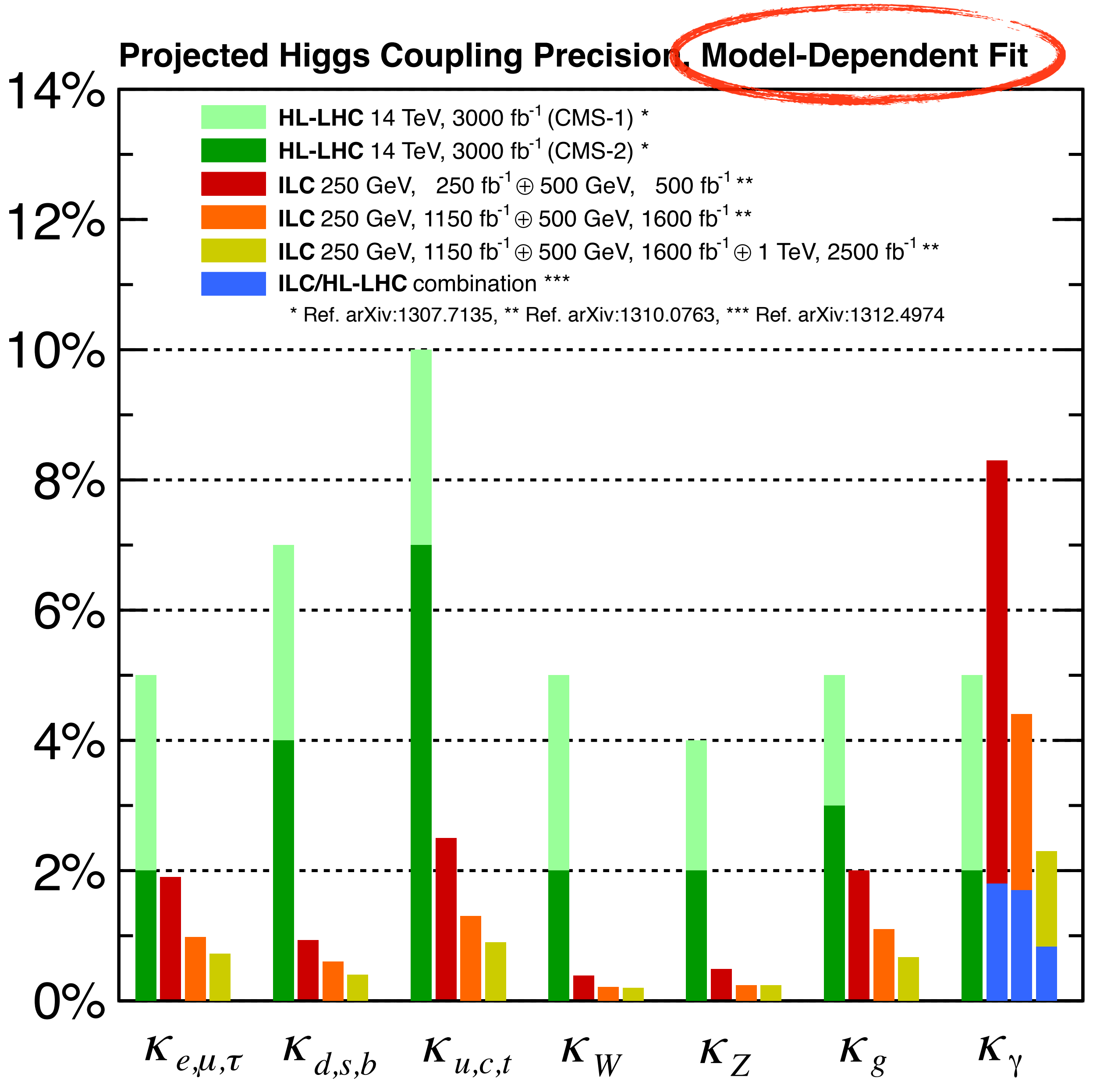
Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

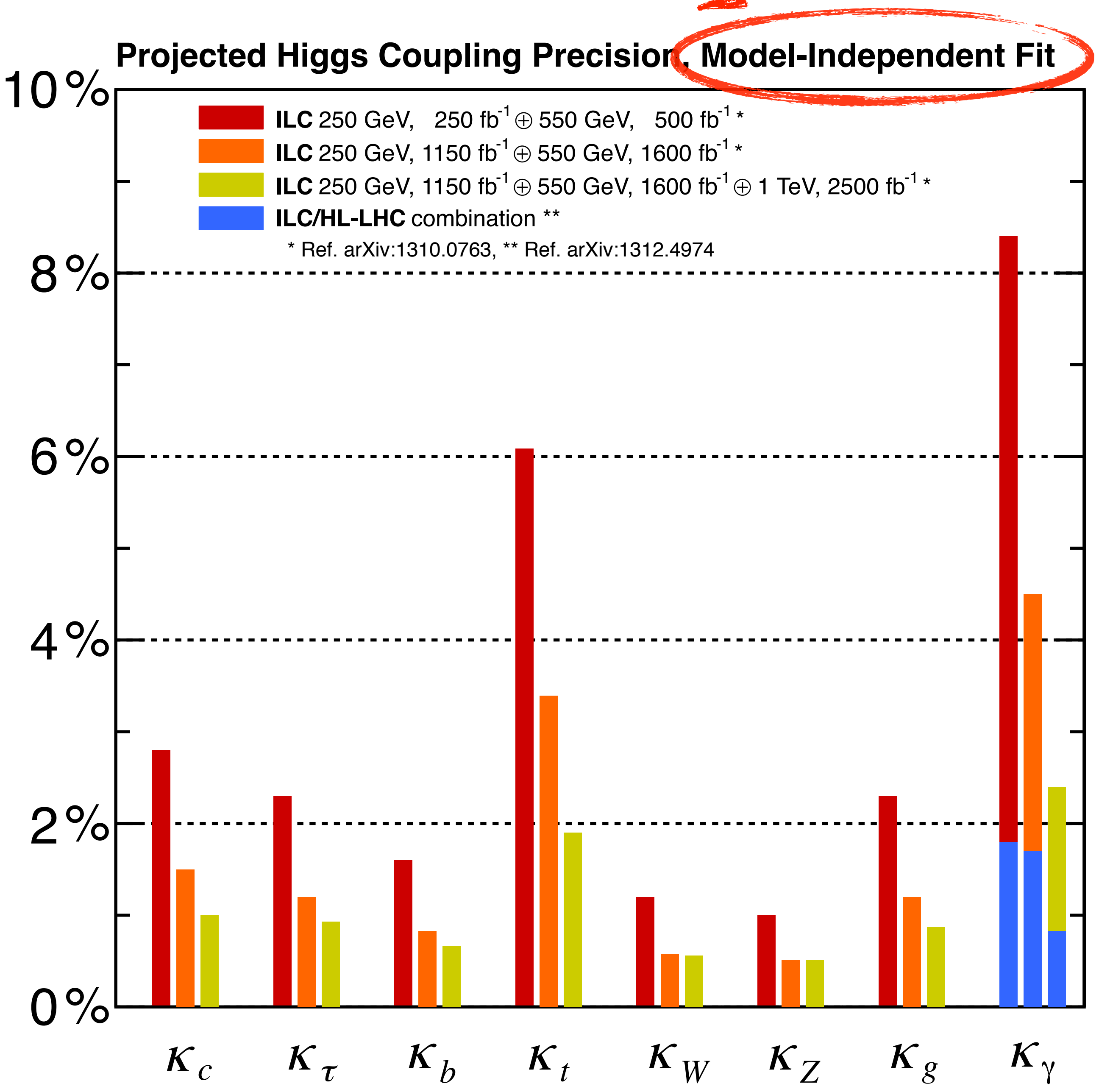
Rich experimental program of (sub)percent precision

Higgs couplings measurement projections

assumption about Higgs width



no assumption about Higgs width



Rich experimental program of (sub)percent precision

Nice synergy/complementarity LHC-ILC ($h\gamma\gamma$)

use BR ratios from hh with absolute precise BR from ee

to export ee precision to Higgs decays that are limited by statistics in ee

Higgs couplings measurement projections

g_{HXY}	FCC-ee	FCC-hh
ZZ	0.16%	
WW	0.85%	
$\gamma\gamma$	1.7%	<1% ?
$Z\gamma$		1% ?
tt		1% ?
bb	0.88%	
$\tau\tau$	0.94%	
cc	1.0%	
ss	$H \to V\gamma$, in progr.	
$\mu\mu$	6.4%	2% ?
uu,dd	$H \to V\gamma$, in progr.	
ee	$e^+e^- \to H$, in progr.	
HH		5% ?
BR_{exo}	0.48%	$< 10^{-6}$?

# of Higgses in 3 ab^{-1}

100 TeV > 2 billion

33 TeV > 500 million

14 TeV > 150 million

In comparison, O(million) Higgs at Higgs factories

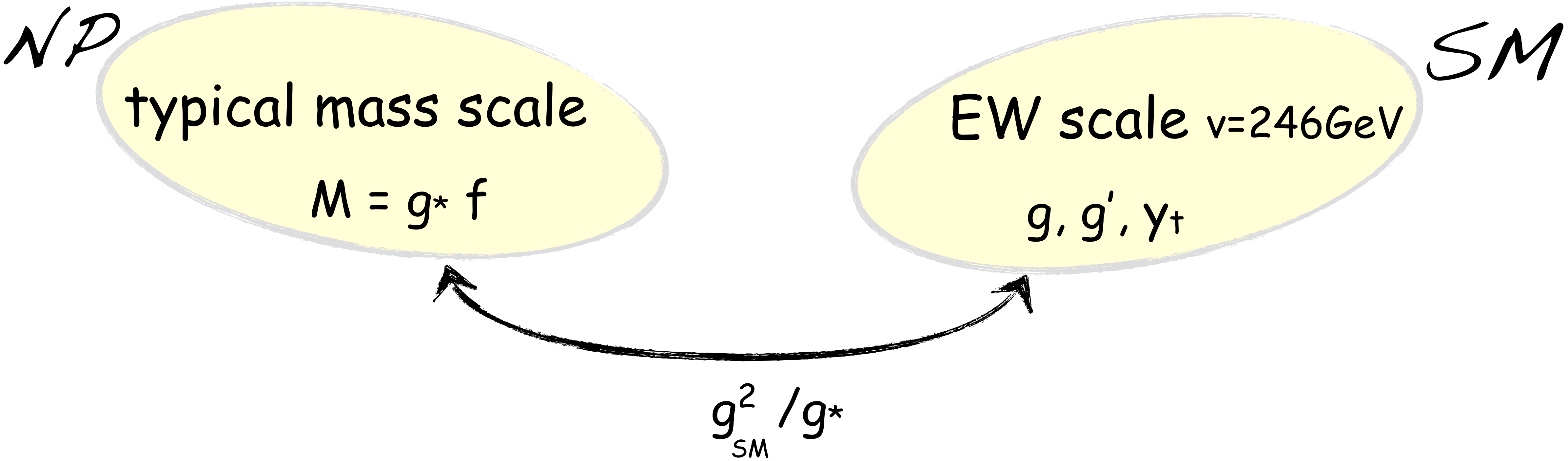
@ 100 TeV	σ	N / $10ab^{-1}$
$gg \to H$	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
$gg \to HH$	1.4 pb	14 M

M. Mangano, HXSWG '15

the Higgses produced are not the Higgses reconstructed but fantastic playground for rare/exotic decays

Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)



NP

typical mass scale

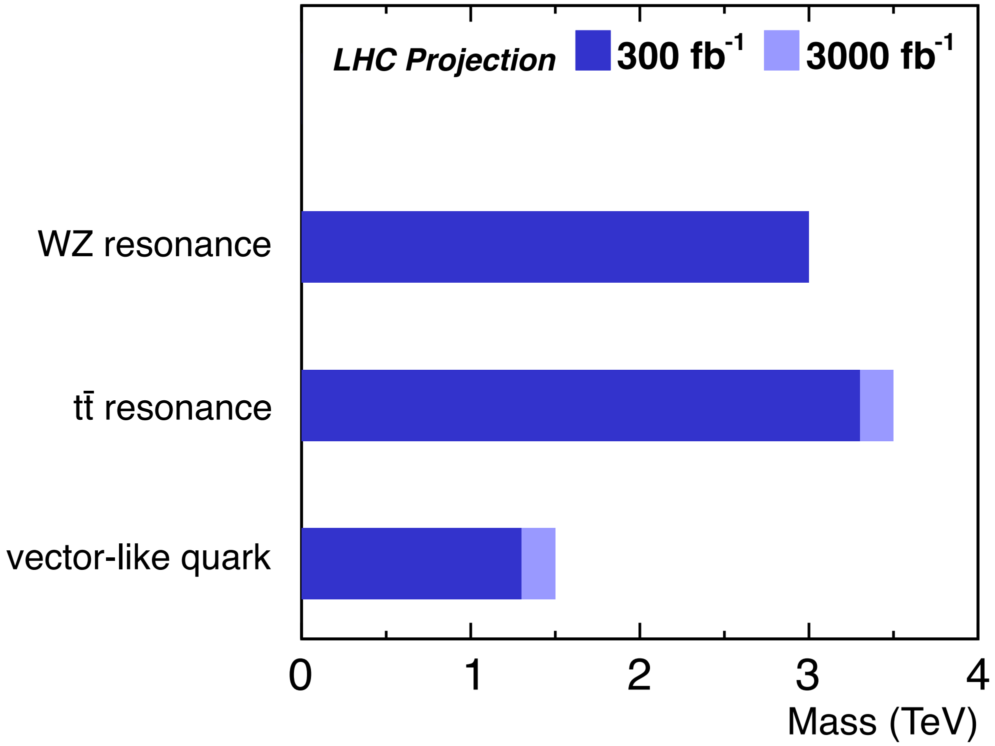
$M = g_* f$

SM

EW scale v=246GeV

g, g', y_t

g_{SM}^2 / g_*



LHC direct search

- ○ Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- ○ Direct searches for resonances: $m_\rho \approx g_* f$

Which one is doing best?
it depends on value of g_*

Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

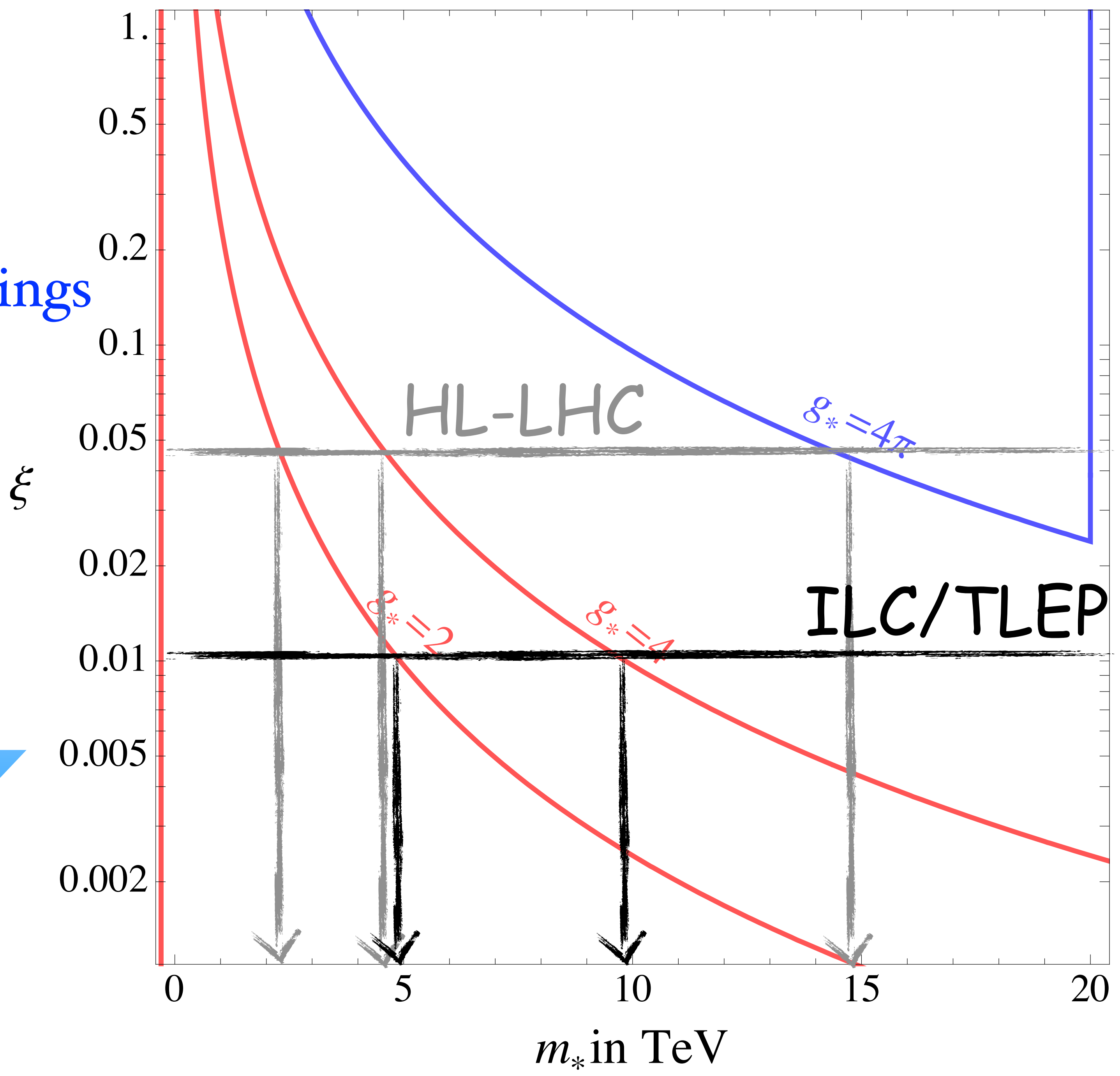
Mass reach:

a deviation in Higgs couplings also teaches us on the maximum mass scale to search for!

e.g. 10% deviation ⇛ m_V < 10TeV

i.e. resonance within the reach of FCC-hh

Higgs couplings



Rattazzi, BSM@100TeV, CERN '14

direct searches

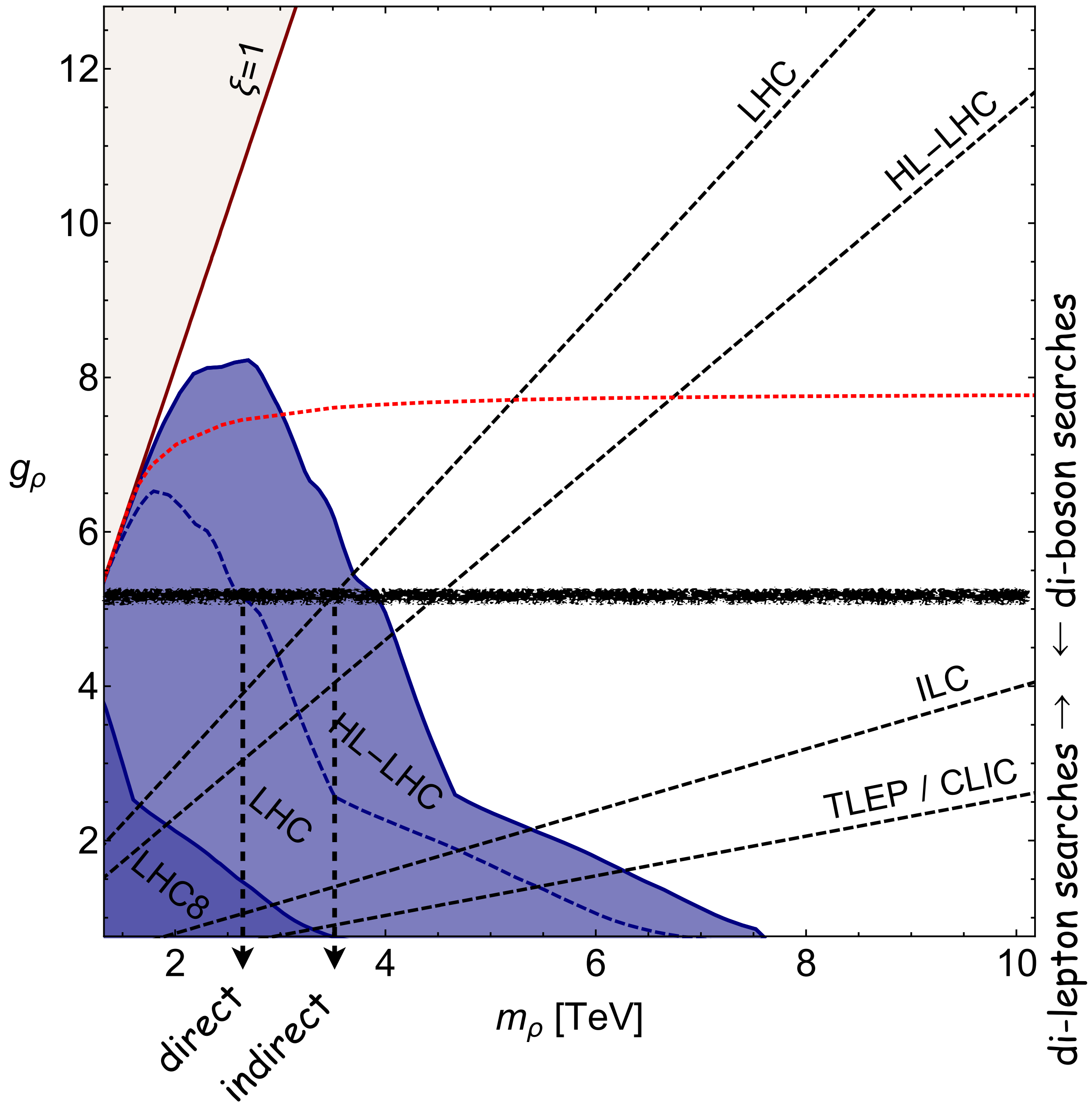
Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Torre, Thamm, Wulzer '15

Collider	Energy	Luminosity	ξ $[1\sigma]$
LHC	14 TeV	$300\,\mathrm{fb}^{-1}$	$6.6-11.4\times10^{-2}$
LHC	14 TeV	$3\,\mathrm{ab}^{-1}$	$4-10\times10^{-2}$
ILC	250 GeV + 500 GeV	$250\,\mathrm{fb}^{-1}$ $500\,\mathrm{fb}^{-1}$	4.8-7.8 $\times10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	$500\,\mathrm{fb}^{-1}$ $1.5\,\mathrm{ab}^{-1}$ $2\,\mathrm{ab}^{-1}$	2.2 $\times10^{-3}$
TLEP	240 GeV + 350 GeV	$10\,\mathrm{ab}^{-1}$ $2.6\,\mathrm{ab}^{-1}$	2×10^{-3}

DY production xs of resonances decreases as $1/g_\rho^2$



- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

e.g.

indirect searches at LHC over-perform direct searches for g > 4.5

indirect searches at ILC over-perform direct searches at HL-LHC for g > 2

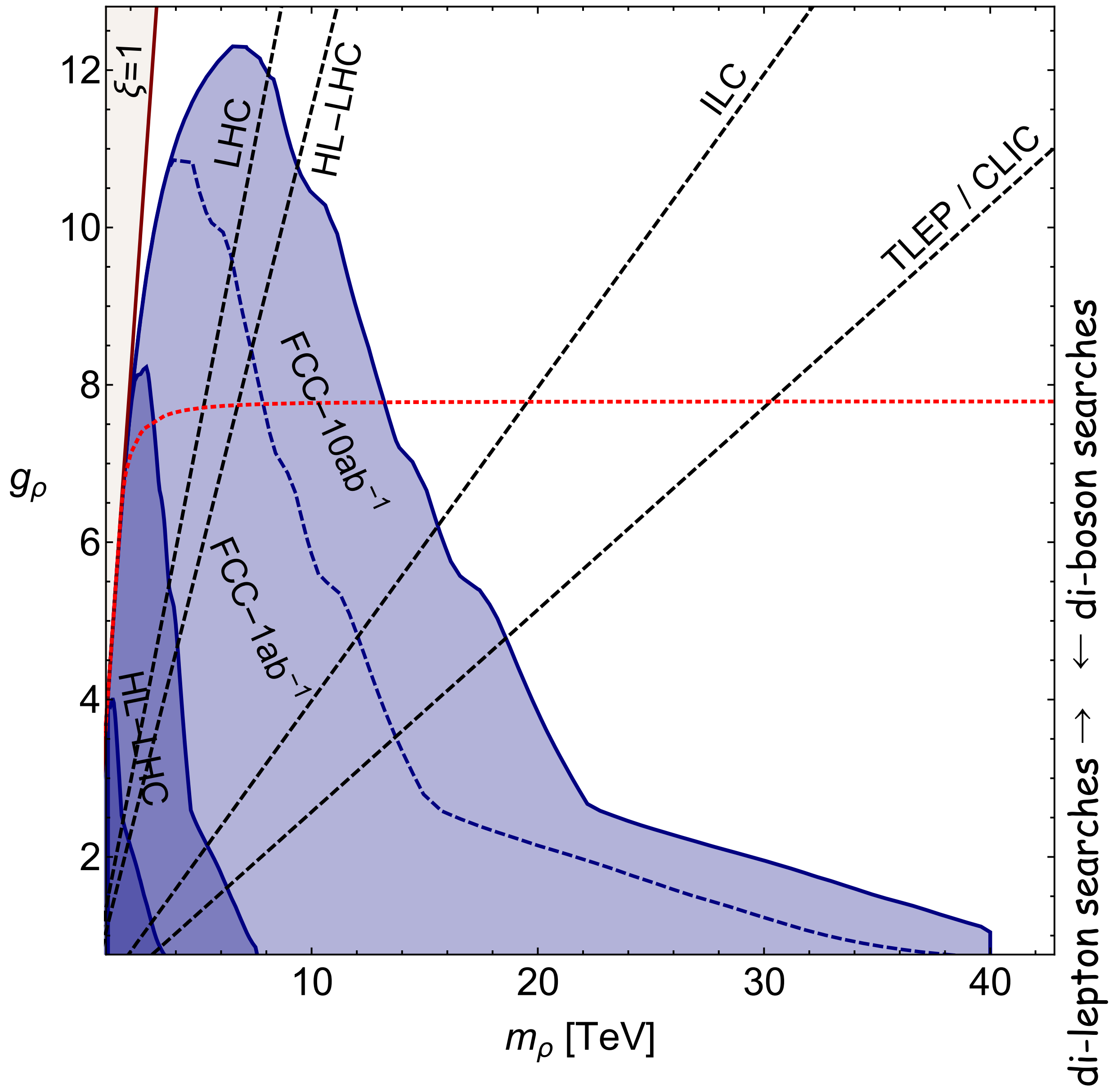
Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Torre, Thamm, Wulzer '15

Collider	Energy	Luminosity	ξ [1σ]
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	250 fb^{-1} 500 fb^{-1}	4.8-7.8 $\times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb^{-1} 1.5 ab^{-1} 2 ab^{-1}	2.2 $\times 10^{-3}$
TLEP	240 GeV + 350 GeV	10 ab^{-1} 2.6 ab^{-1}	2×10^{-3}

DY production xs of resonances decreases as $1/g_\rho^2$



- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

e.g.
indirect searches at LHC over-perform direct searches for g > 4.5
indirect searches at ILC over-perform direct searches at HL-FCChh for g > 6

Flavor alignment

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \bar{f}_{L_i} f_{R_j} + \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

mass

higgs-fermion interactions

both matrices are simultaneously diagonalizable

no tree-level Flavor Changing Current induced by the Higgs

Not true anymore if the SM fermions mix with vector-like partners$^{(*)}$ or for non-SM Yukawa

$$y_{ij}\left(1+c_{ij}\frac{|H|^2}{f^2}\right)\bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}}\left(1+c_{ij}\frac{v^2}{2f^2}\right)\bar{f}_{L_i} f_{R_j} + \left(1+3c_{ij}\frac{v^2}{2f^2}\right)\frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

Look for SM forbidden Flavor Violating decays h → μτ and t→hc

- weak indirect constrained by flavor data (e.g. μ→ eγ): BR<10%
- ATLAS and CMS have the sensitivity to set bounds O(1%)
- ILC/CLIC/FCC-ee can certainly do much better

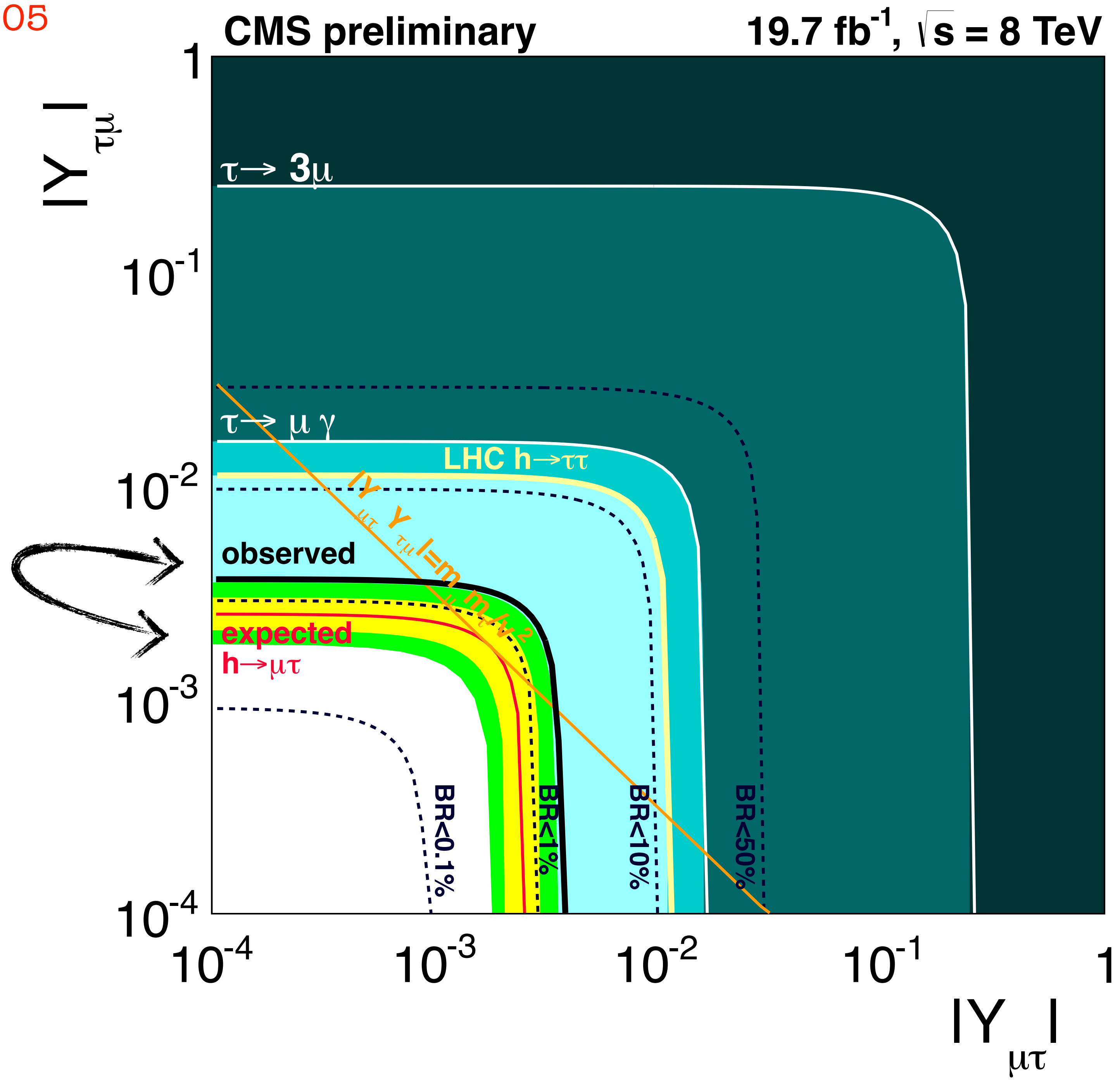
Blankenburg, Ellis, Isidori '12

Harnik et al '12
Davidson, Verdier '12
CMS-PAS-HIG-2014-005

(*) e.g. Buras, Grojean, Pokorski, Ziegler '11

Flavor alignment

CMS-PAS-HIG-2014-005



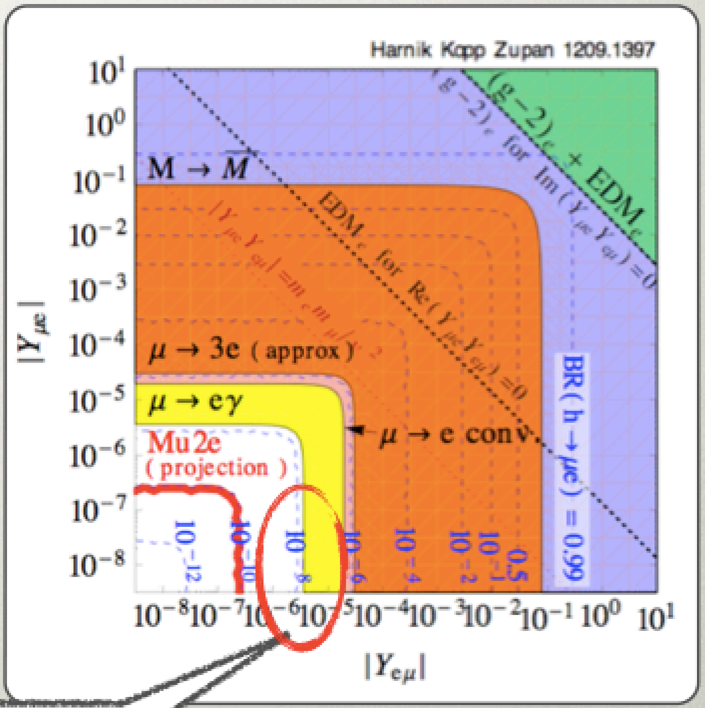
by the way:
2.3σ excess!

Off-diagonal Higgs couplings can reveal the origin of flavor

Importance of efficient flavor tagging!

$h\to\mu e$

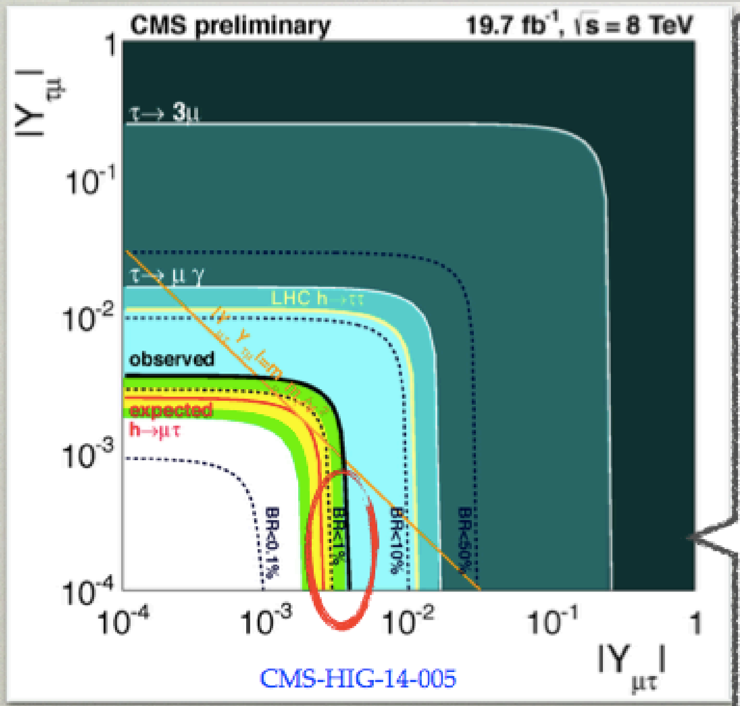
- indirect bounds better than LHC
- *$h\to\mu e$* very clean channel



- what can one do with 10^9 Higgses @100TeV?

FCC week, Mar 26 2015, Washington DC

$h\to\tau\mu$



CMS-HIG-14-005

- right now: 2j channel statistics limited, 0j+1j not
- how about with *~10^9 h?* ***LHC8 ⇒ 100 TeV 3 ab^{-1}***
- assume same scaling for signal and bckg
  - *$Br\sim10^{-2} \Rightarrow Br\sim10^{-4}$*
  - *$\Lambda\sim0.2$ TeV ⇒ $\Lambda\sim2$TeV*
- if bckg free
  - *$Br\sim10^{-2} \Rightarrow Br\sim10^{-6}$*
  - *$\Lambda\sim0.2$ TeV ⇒ $\Lambda\sim20$TeV*

    $(Y_{\mu\tau}\,Y_{\tau\mu}=m_\mu m_\tau/\Lambda^2)$

J. Zupan BSM discovery… 11 FCC week, Mar 26 2015, Washington DC

Flavor changing Higgs couplings @ LHC

		ATLAS	CMS
h→$\mu\tau$		✔	✔
t→hq w/	h→$\gamma\gamma$	✔	✔
	h→multilepton		✔
	h→bb	✔	

Assuming a simple universal scaling: $Y_{ij} \sim \sqrt{(m_i m_j/v^2)}$,

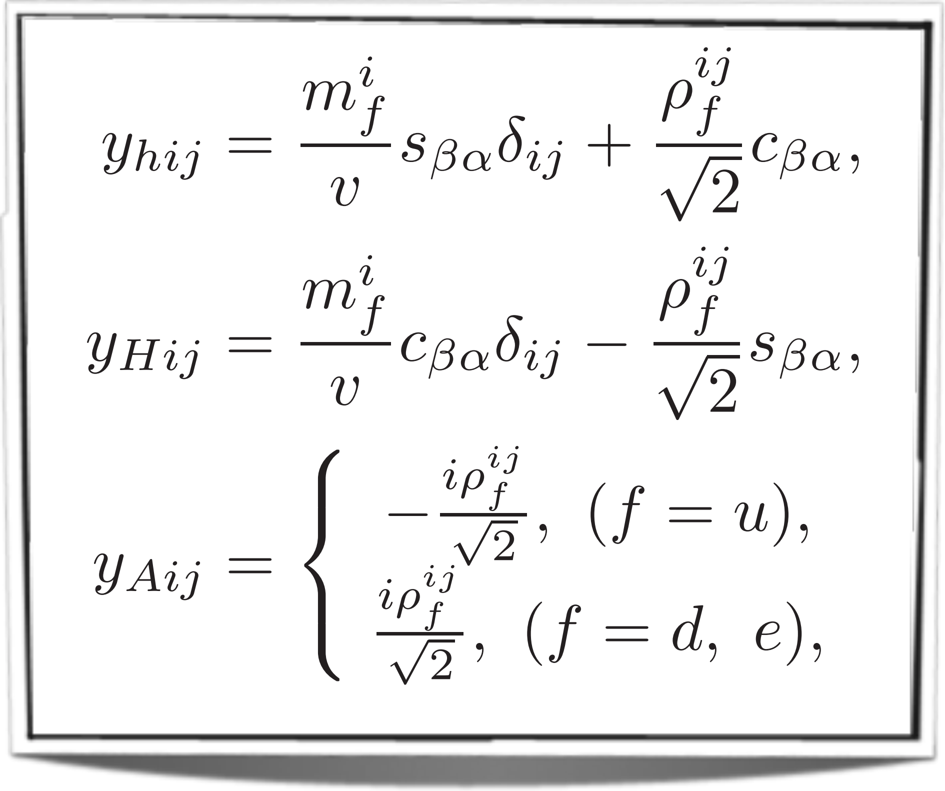
BR(h→$\mu\tau$)=(0.89±0.40)% implies BR(t→hc)~0.25%

while direct constraint is currently ~0.5%, but can improve by combining various channels

Flavor changing Higgs couplings @ LHC

In SM, the Yukawa interactions are the only source of the fermion masses
Not the case in e.g. generic 2HDM

Omura, Senaha and Tobe ’15
Botella and Branco ‘in progress



$$y_{hij} = \frac{m_f^i}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho_f^{ij}}{\sqrt{2}} c_{\beta\alpha},$$

$$y_{Hij} = \frac{m_f^i}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho_f^{ij}}{\sqrt{2}} s_{\beta\alpha},$$

$$y_{Aij} = \begin{cases} -\frac{i\rho_f^{ij}}{\sqrt{2}}, & (f = u), \\ \frac{i\rho_f^{ij}}{\sqrt{2}}, & (f = d,\ e), \end{cases}$$

even small mixing ($c_{\beta\alpha}$~0.1)
and moderate FCYC (ρ~0.3)
can explain
BR(h→$\mu\tau$)=(0.89±0.40)%

consequences:

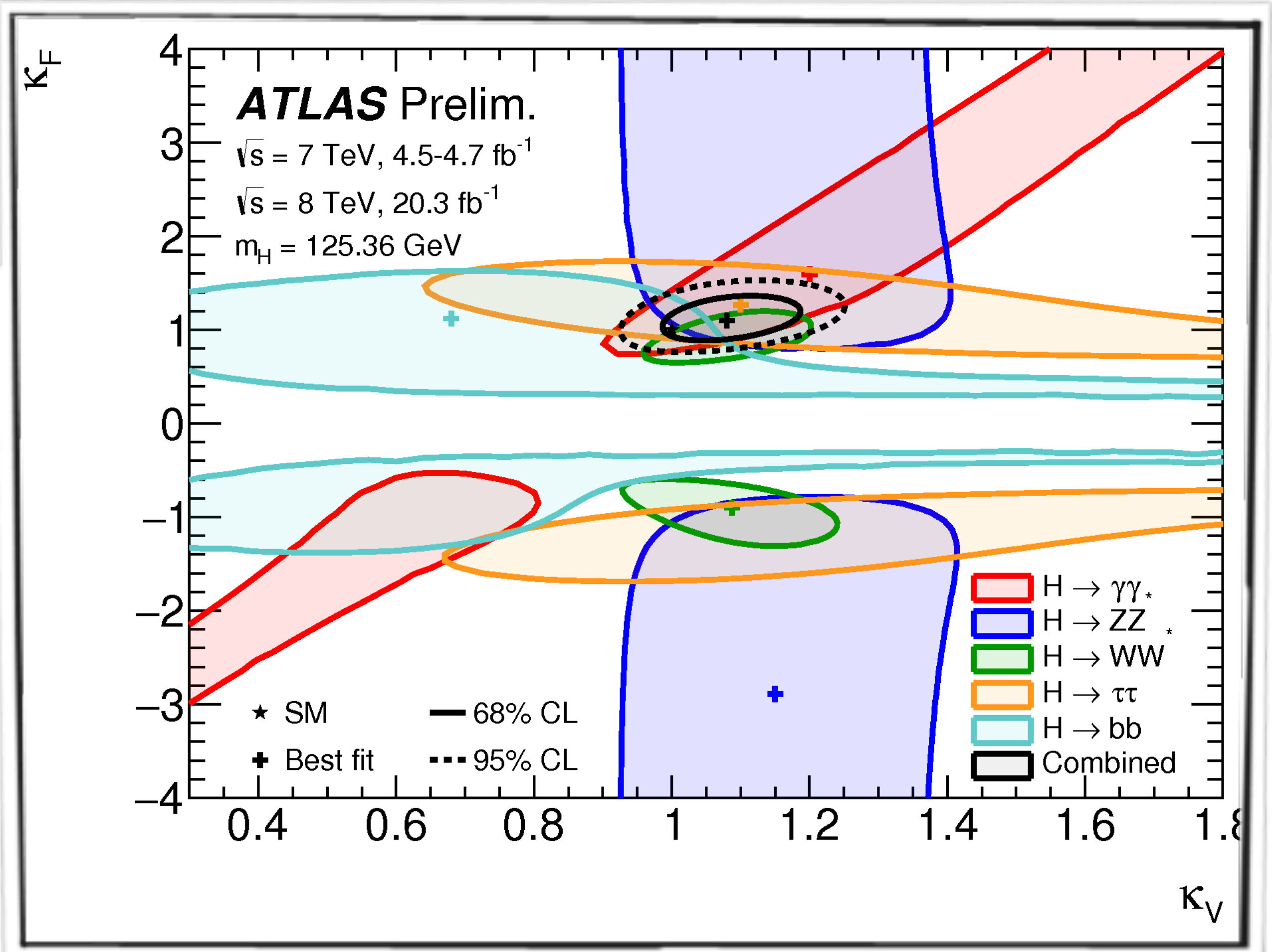
- $(g-2)_\mu$
- $\tau\to\mu\gamma$

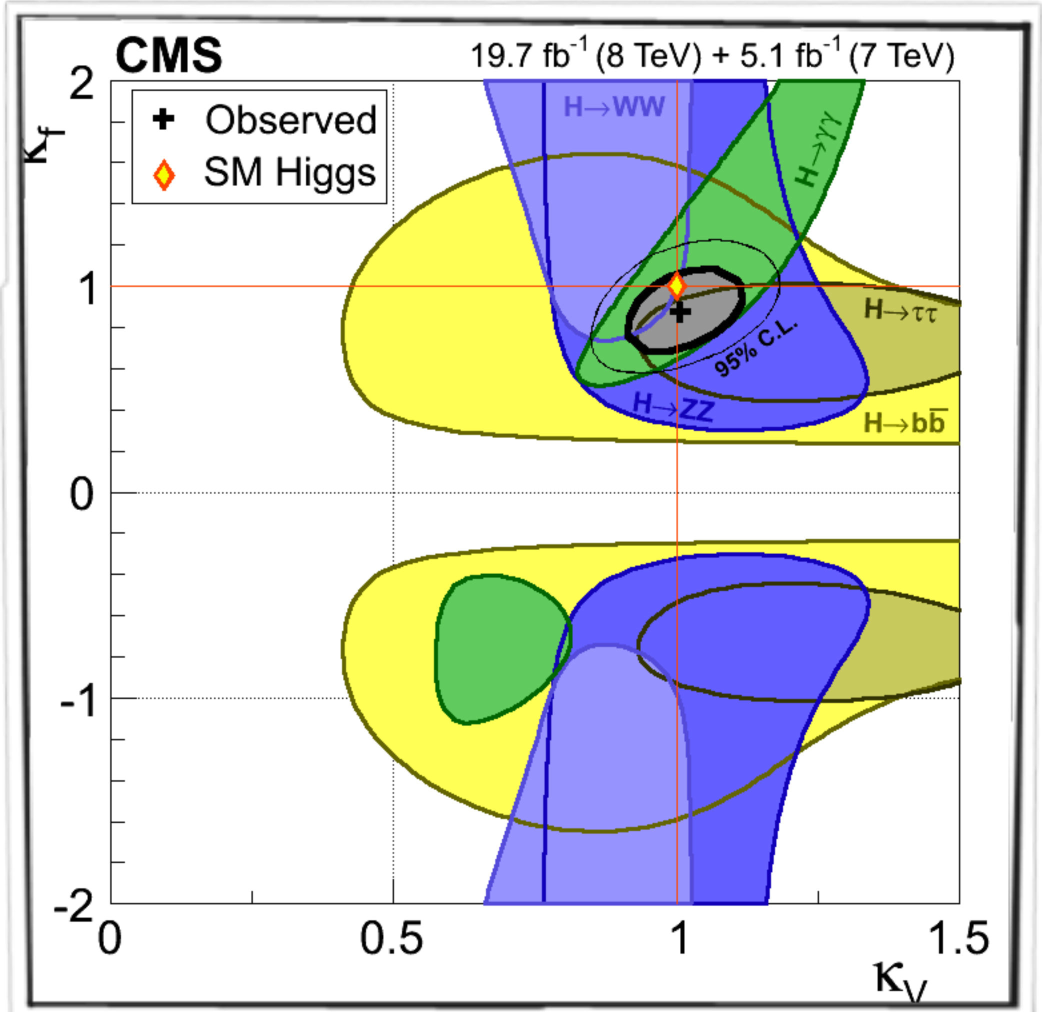
NB: Flavor Changing decays of H and A can easily dominate
would explain why even light H/A hasn’t been found at LHC directly

Why going beyond inclusive Higgs processes?

So far the LHC has mostly produced Higgses on-shell
in processes with a characteristic scale μ ≈ m_H

access to Higgs couplings @ m_H





Why going beyond inclusive Higgs processes?

So far the LHC has mostly produced Higgses on-shell
in processes with a characteristic scale $\mu \approx m_H$

⇩ ⇩

access to Higgs couplings @ m_H

Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

Probing new corrections to the SM Lagrangian?

on-shell Z @ LEP1

constraints on
S and T oblique corrections

off-shell Z @ LEP2
constraints on
W and Y oblique corrections
(same order as S and T but cannot be probed @ LEP1)

But... off-shell Higgs data do not probe new corrections
that cannot be constrained by on-shell data

Boosted Higgs

inability to resolve the top loops

- the bearable lightness of the Higgs: rich spectroscopy w/ multiple decays channels
- the unbearable lightness: loops saturate and don't reveal the physics @ energy physics (*)

$m_H(\text{GeV})$	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. Grazzini, Sargsyan '13

(*) unless it doesn't decouple
(e.g. 4th generation)

the inclusive rate
doesn't "see" the finite mass of the top

⇛ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop)

⇚

$$\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$$

$$\frac{\sigma(gg\to h)}{\text{SM}} = (1+(c_g-c_t)v^2)^2 \qquad \frac{\Gamma(h\to\gamma\gamma)}{\text{SM}} = (1+(c_\gamma-4c_t/9)v^2)^2$$

fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

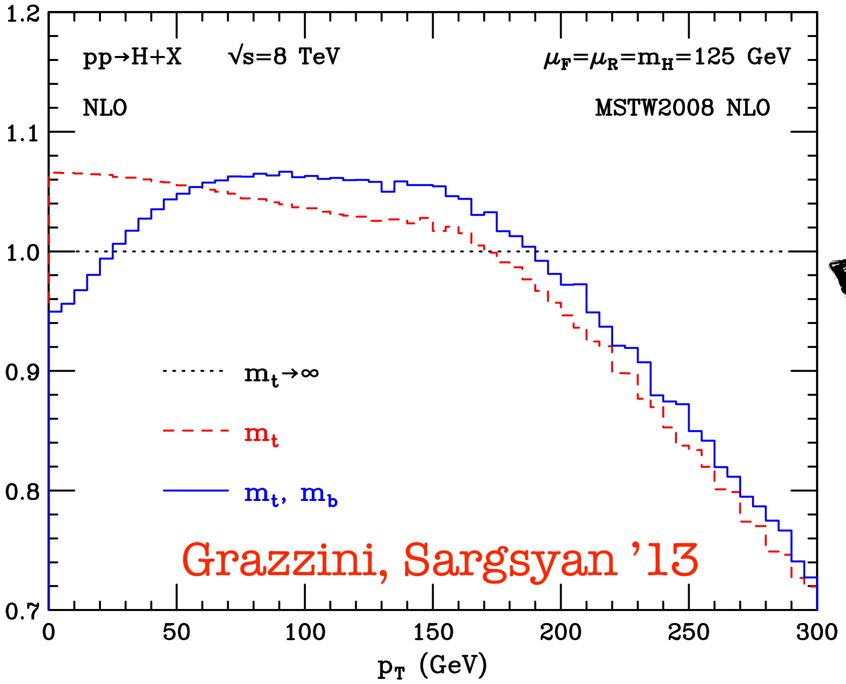
having access to ht$\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC$^{14}_{300}$-LHC$^{14}_{3000}$ vs 10%-4% @ ILC$^{500}_{500}$-ILC$^{1000}_{1000}$

Resolving top loop: Boosted Higgs

cut open the top loops

high p_T ≈ Higgs off-shell
we “see” the details of the particles
running inside the top loops

Baur, Glover ’90
Langenegger, Spira, Starodumov, Trueb ’06



Grazzini, Sargsyan ’13

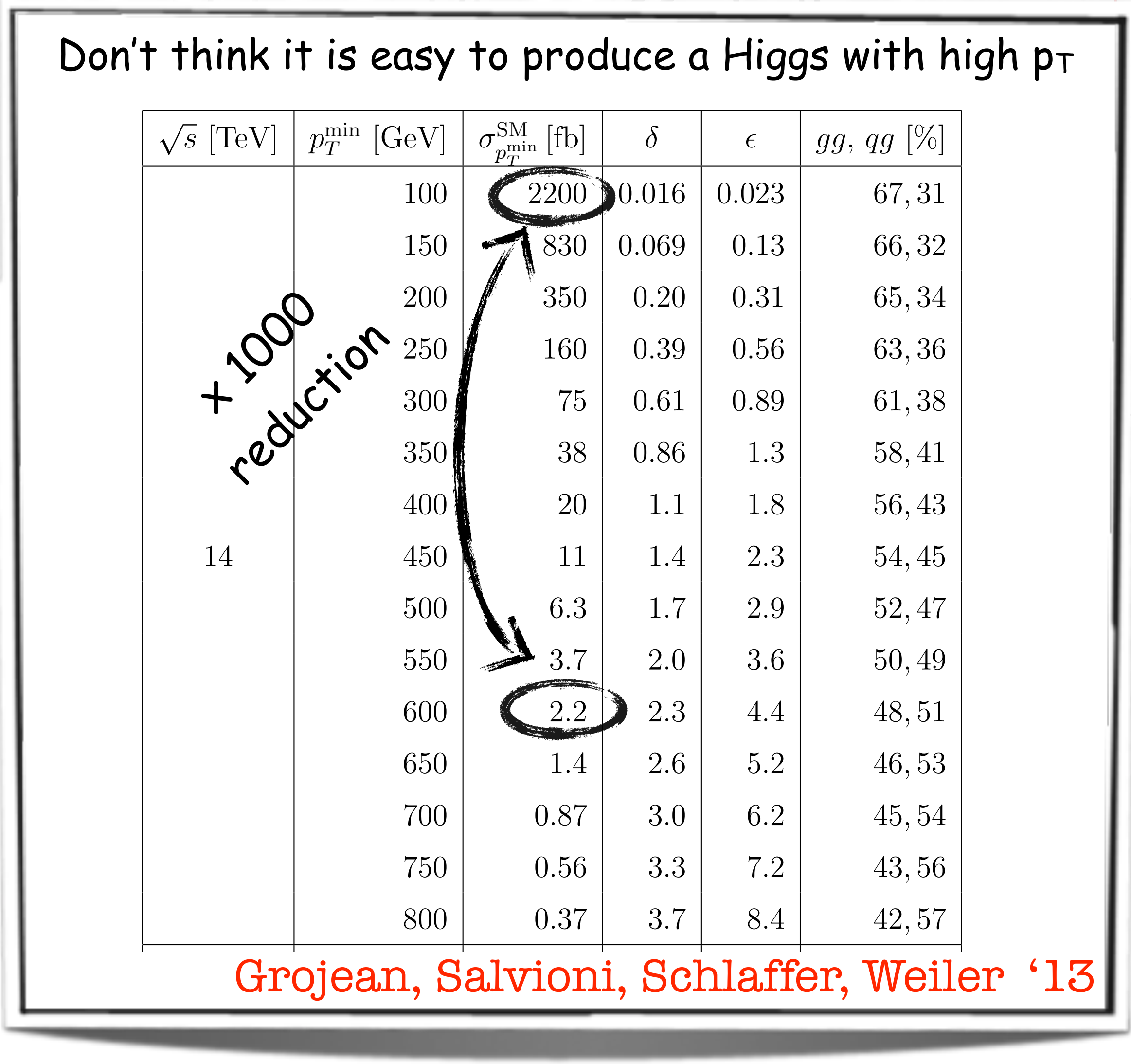
Note: LO only
NLO_{m_t} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al ’12

the high p_T tail
is tens’ % sensitive
to the mass of top

Resolving top loop: Boosted Higgs

cut open the top loops

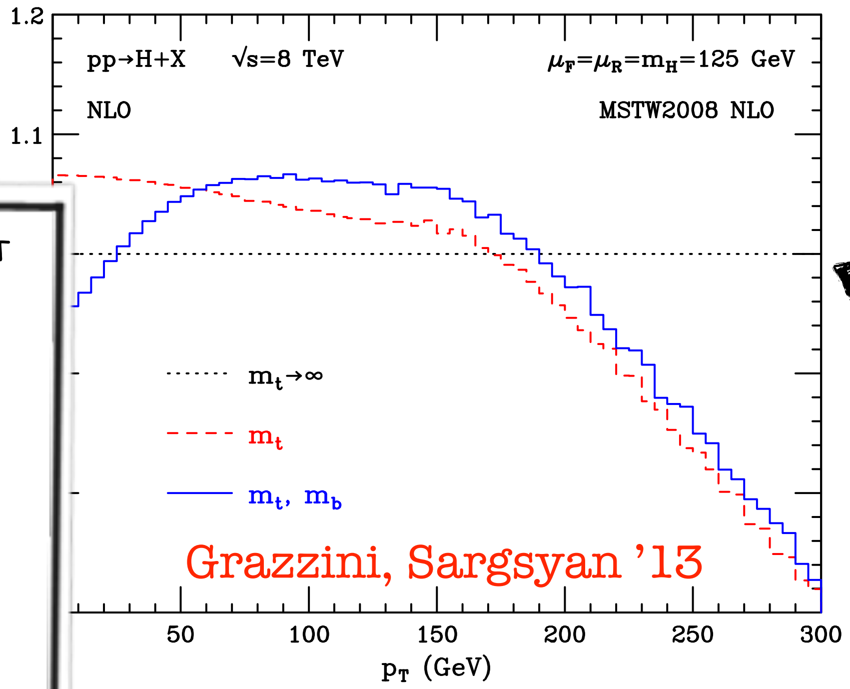


Don't think it is easy to produce a Higgs with high p_T

$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma_{p_T^{\min}}^{\rm SM}$ [fb]	δ	ϵ	gg, qg [%]
14	100	2200	0.016	0.023	67, 31
	150	830	0.069	0.13	66, 32
	200	350	0.20	0.31	65, 34
	250	160	0.39	0.56	63, 36
	300	75	0.61	0.89	61, 38
	350	38	0.86	1.3	58, 41
	400	20	1.1	1.8	56, 43
	450	11	1.4	2.3	54, 45
	500	6.3	1.7	2.9	52, 47
	550	3.7	2.0	3.6	50, 49
	600	2.2	2.3	4.4	48, 51
	650	1.4	2.6	5.2	46, 53
	700	0.87	3.0	6.2	45, 54
	750	0.56	3.3	7.2	43, 56
	800	0.37	3.7	8.4	42, 57

× 1000 reduction

Grojean, Salvioni, Schlaffer, Weiler '13



Grazzini, Sargsyan '13

Note: LO only

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few % up to p_T~150 GeV

Harlander et al '12

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to the mass of top

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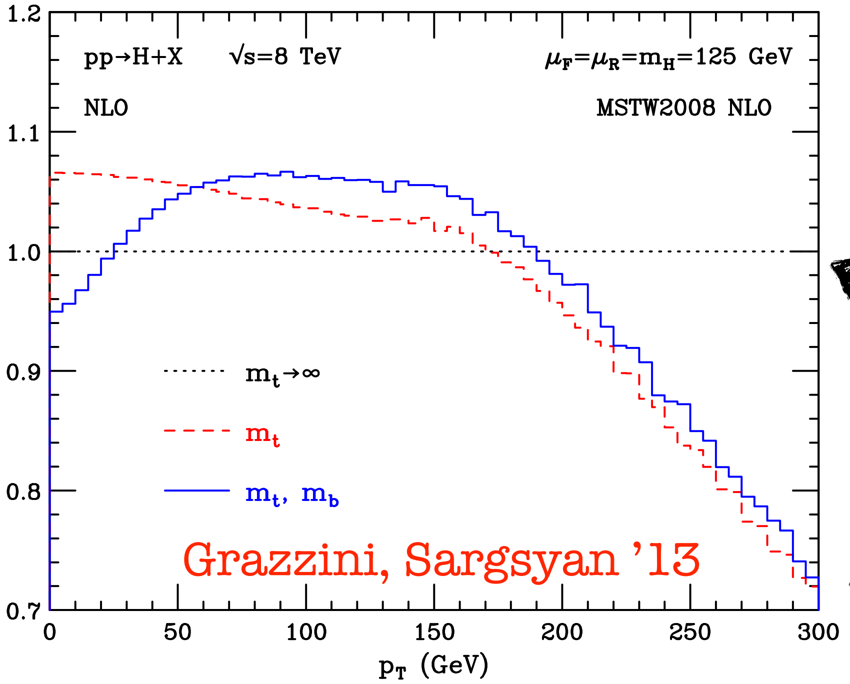

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Harlander et al '12

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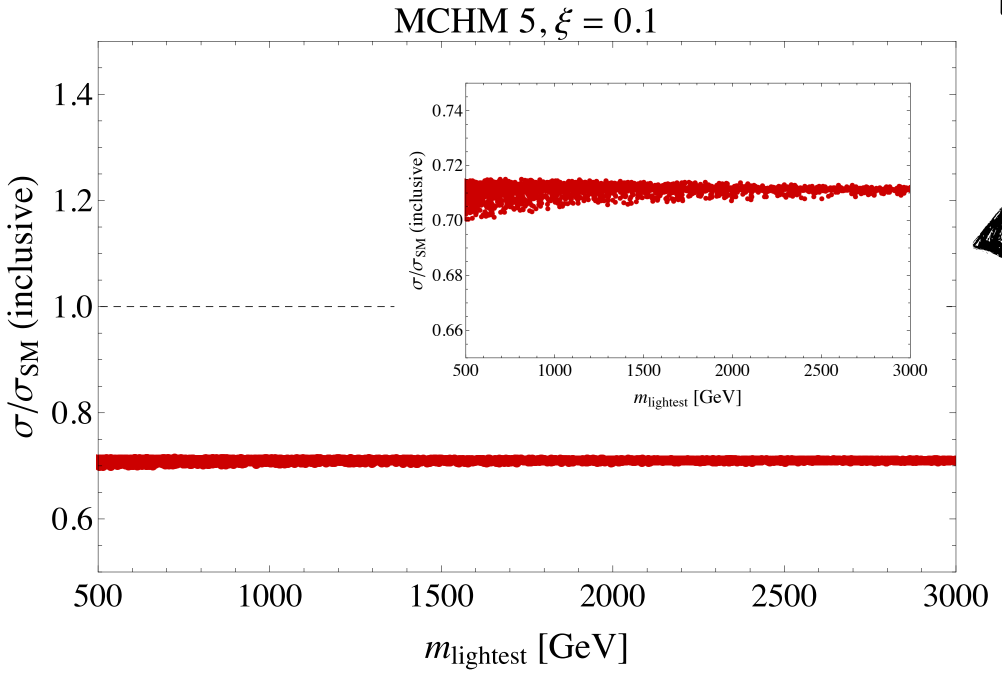
Composite Higgs Model

top partners contributions

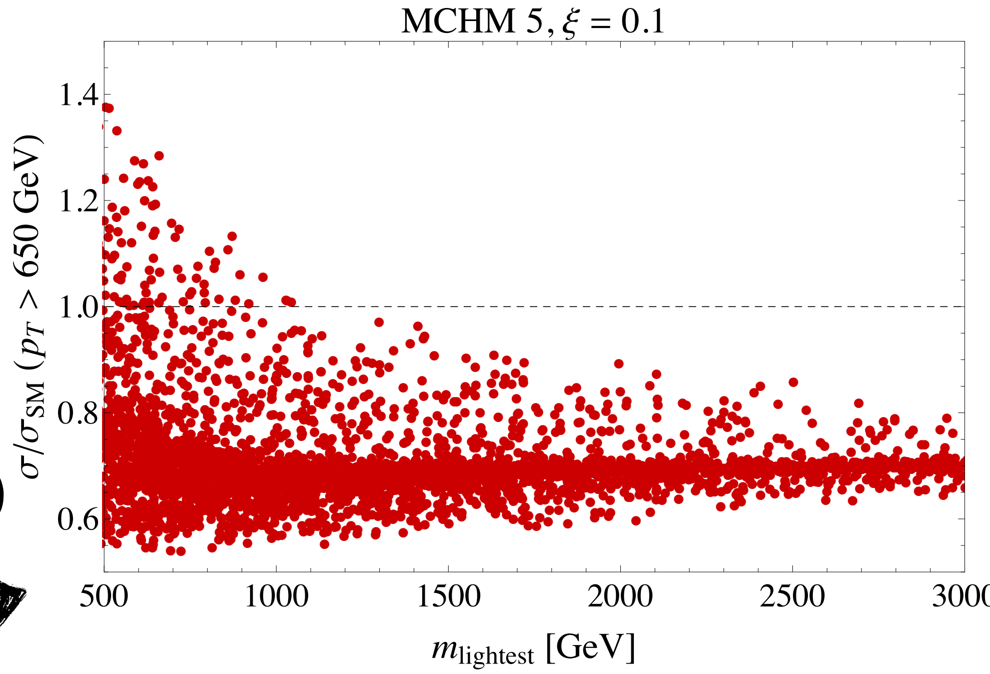
see also Banfi, Martin, Sanz '13
see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13



inclusive rate: O(%)

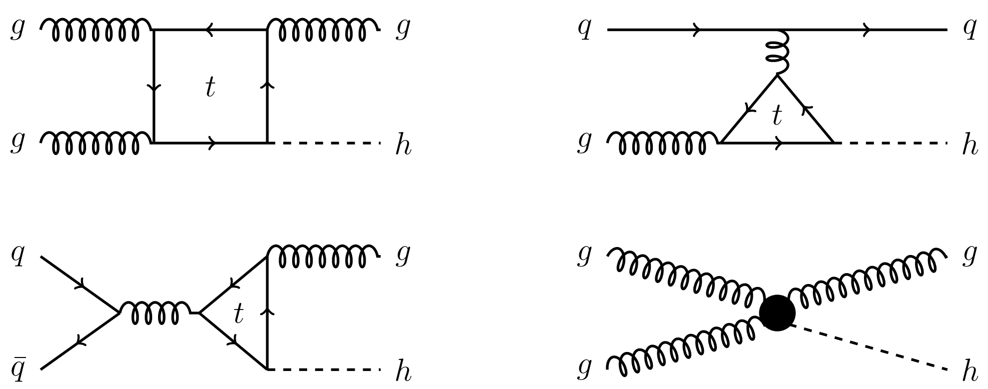
with high-p_T cut: O(x10'%)



high-p_T tail "sees" the top partners that are missed by the inclusive rate

Boosted Higgs

Grojean, Salvioni, Schlaffer, Weiler '13



$$\frac{\sigma_{p_T^{\min}}(\kappa_t,\kappa_g)}{\sigma^{\rm SM}_{p_T^{\min}}} = (\kappa_t+\kappa_g)^2 + \delta\,\kappa_t\,\kappa_g + \epsilon\,\kappa_g^2$$

large pT, small rates

need to focus on dominant decay modes

$$h \to b\bar{b}, WW, \tau\tau$$

non-isolated "ditau-jets"

(separation between the 2 tau's: $\Delta R \sim 2m_h/p_T \lesssim 0.5$)

$$\epsilon_{\rm tot} = {\rm BR}(h\to\tau\tau)\left(\sum_{i=\tau_\ell\tau_\ell,\,\tau_\ell\tau_h,\,\tau_h\tau_h} {\rm BR}(\tau\tau\to i)\,\epsilon_i\right) \simeq 2\times10^{-2}$$

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	800	0.37	3.7	8.4	42, 57
100	500	970	1.8	3.1	72, 28
	2000	1.0	14	78	56, 43

x 150 enhancement

VHE-LHC is the machine
to decipher the gg→h process

Boosted Higgs

see also Azatov, Paul '13

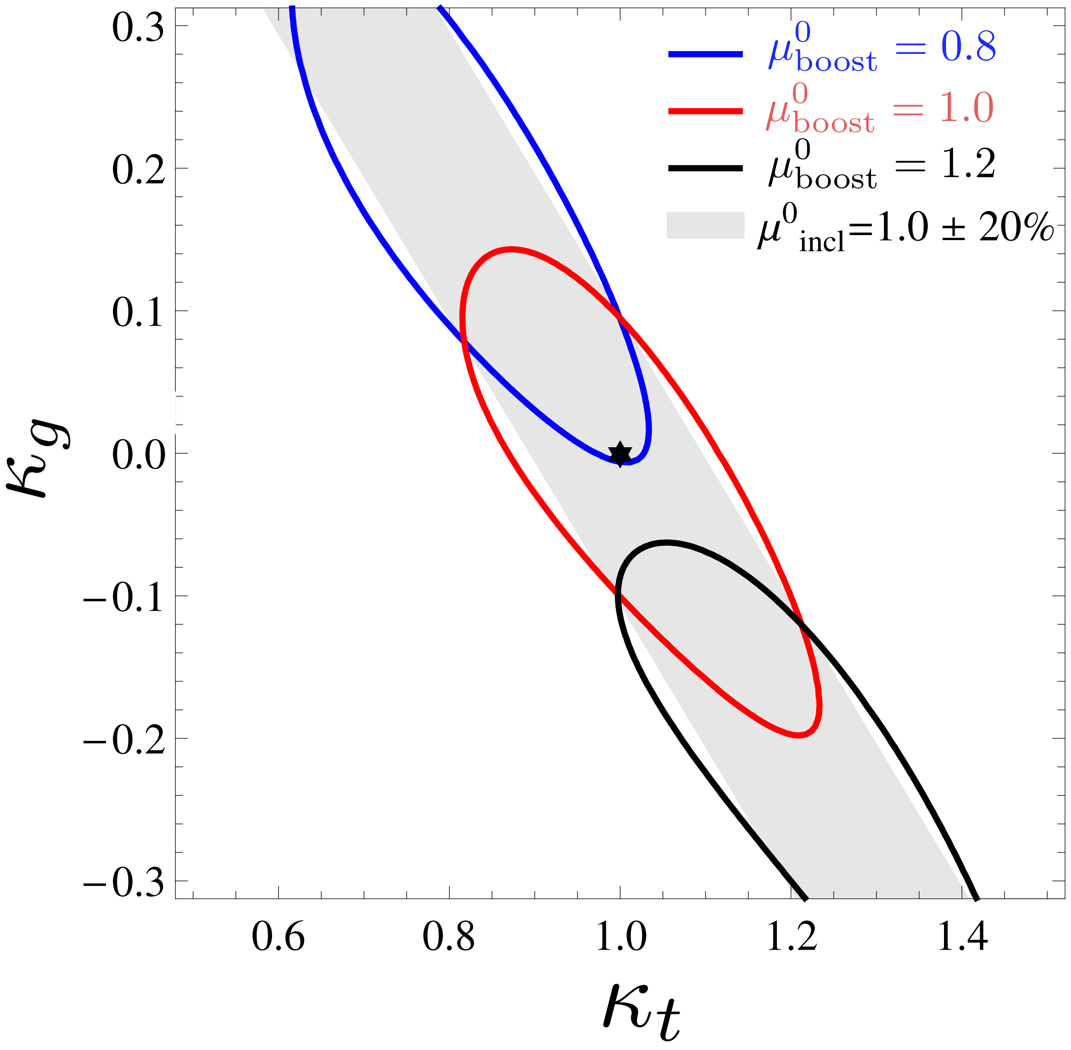
Grojean, Salvioni, Schlaffer, Weiler '13

high p_T tail discriminates short and long distance physics contribution to gg → h

$$\sqrt{s} = 14 \text{ TeV}, \int dt\, \mathcal{L} = 3\text{ab}^{-1}, p_T > 650 \text{ GeV}$$

(partonic analysis in the boosted "ditau-jets" channel)

see Schlaffer et al '14 for a more complete analysis including WW channel



10-20% precision on κ_t

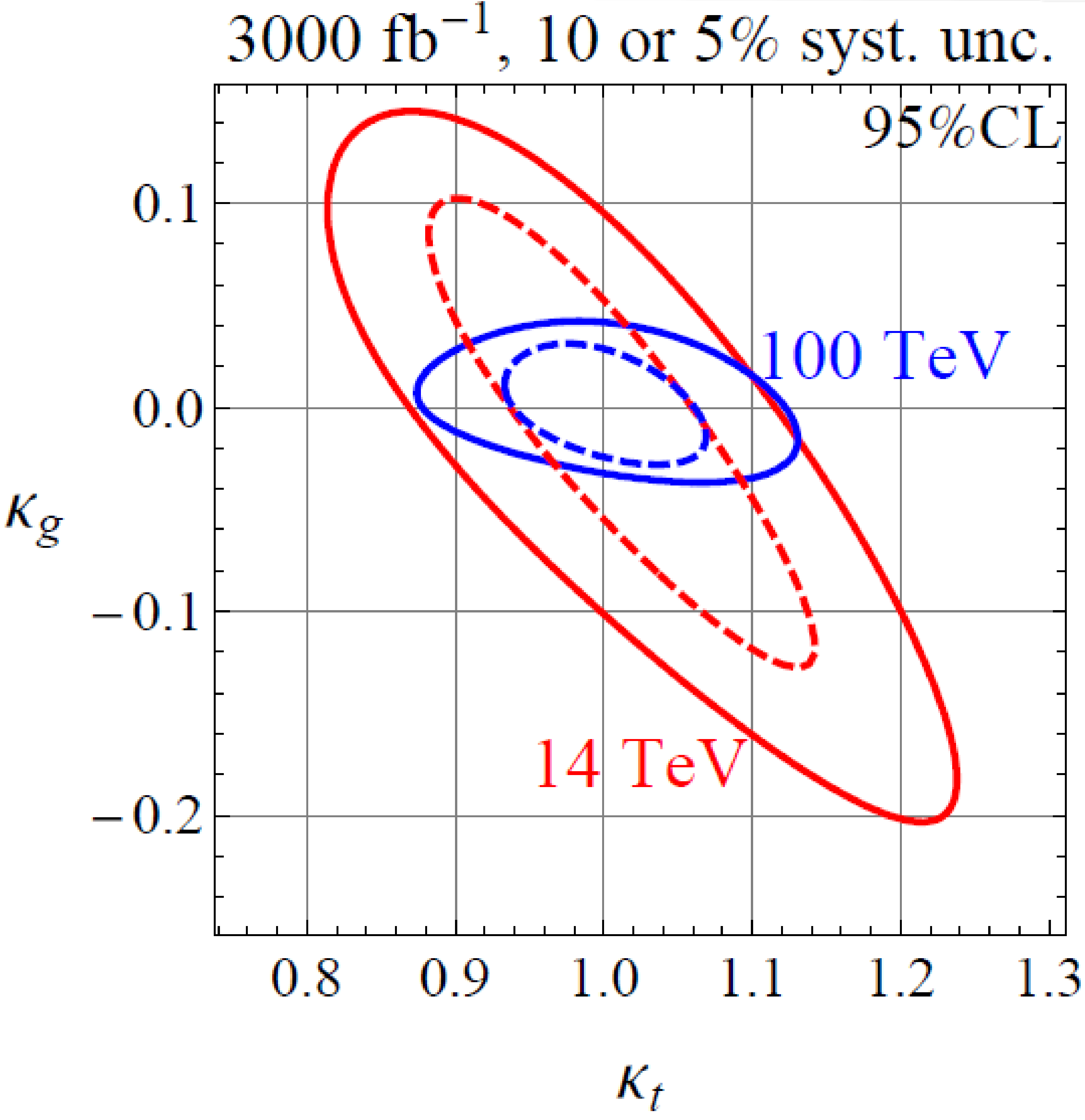
⇓ ⇓

competitive/complementary to htt channel for the measure the top-Higgs coupling

Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: $\text{N}^3\text{LO}_\infty$ for inclusive xs or NLO_{mt} for pT spectrum?

Boosted Higgs

high p_T tail discriminates short and long distance physics contribution to gg → h



see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13

A perfect case for a very energetic machine

tth increases by 10 from 14 to 100TeV

h+j$_{p_T>600\text{GeV}}$ increases by 210

$$\mathcal{R}_{14} = \frac{\sigma(p_T > 650\ \text{GeV})}{\sigma(p_T > 150\ \text{GeV})}$$

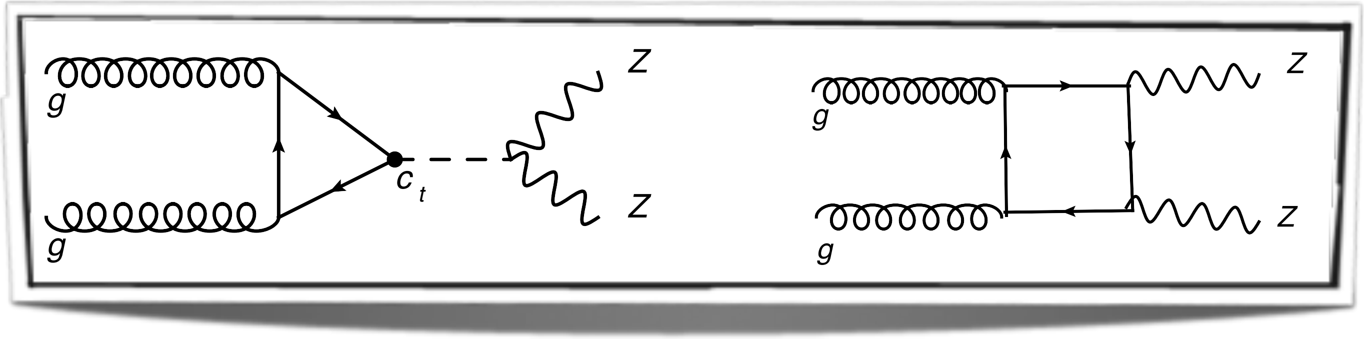
$$\mathcal{R}_{100} = \frac{\sigma(p_T > 2000\ \text{GeV})}{\sigma(p_T > 500\ \text{GeV})}$$

Frontier priority: N^{3}LO$_\infty$ for inclusive xs or NLO$_{mt}$ for pT spectrum?

Off-shell Higgs: gg → h* → ZZ → 4l

off-shell effects enhanced by the particular couplings of H to V_L

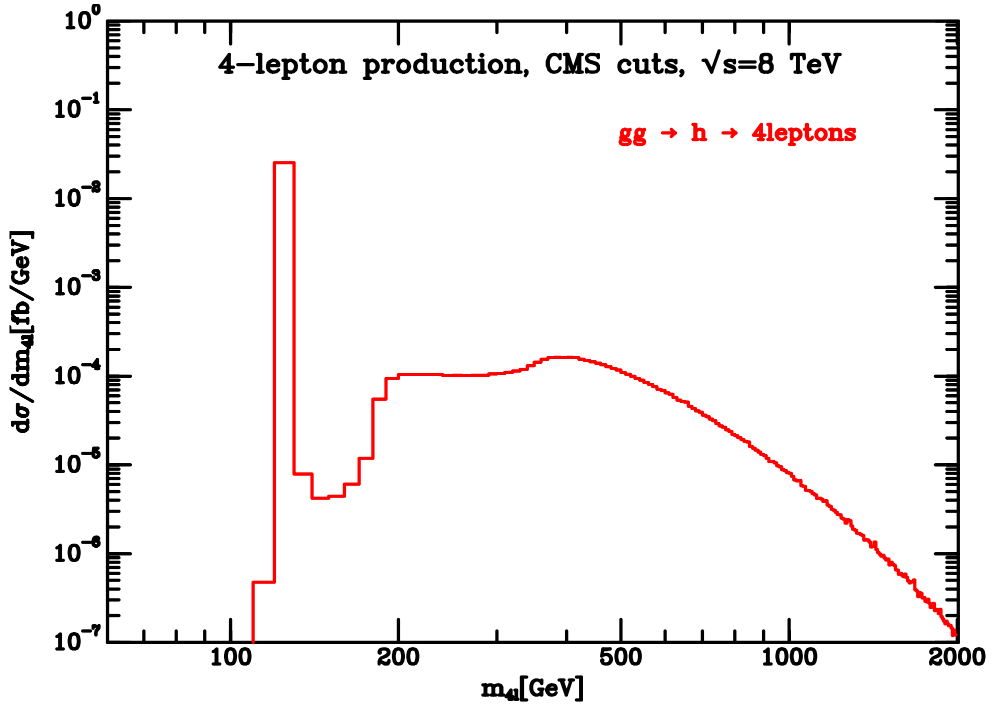
Glover, van der Bij '89



$$\mathcal{M}^{++00}_{\rm Higgs} \sim \log^2 \frac{\hat{s}}{m_t^2} \qquad \mathcal{M}^{++00}_{\rm box} \sim -\log^2 \frac{\hat{s}}{m_t^2}$$

SM: cancelation forced by unitarity

BSM: deviations of Higgs couplings at large s will be amplified



Azatov, Grojean, Paul, Salvioni '14

Off-shell Higgs: gg → h* → ZZ → 4l

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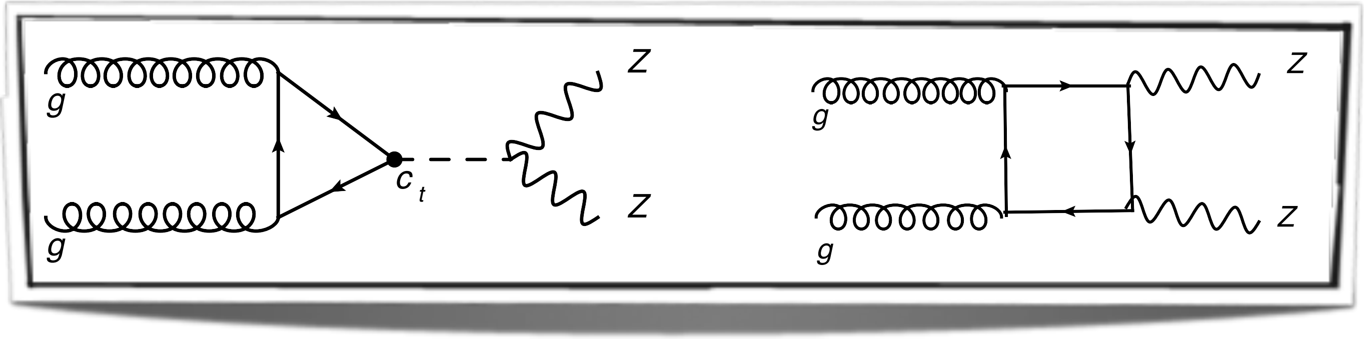
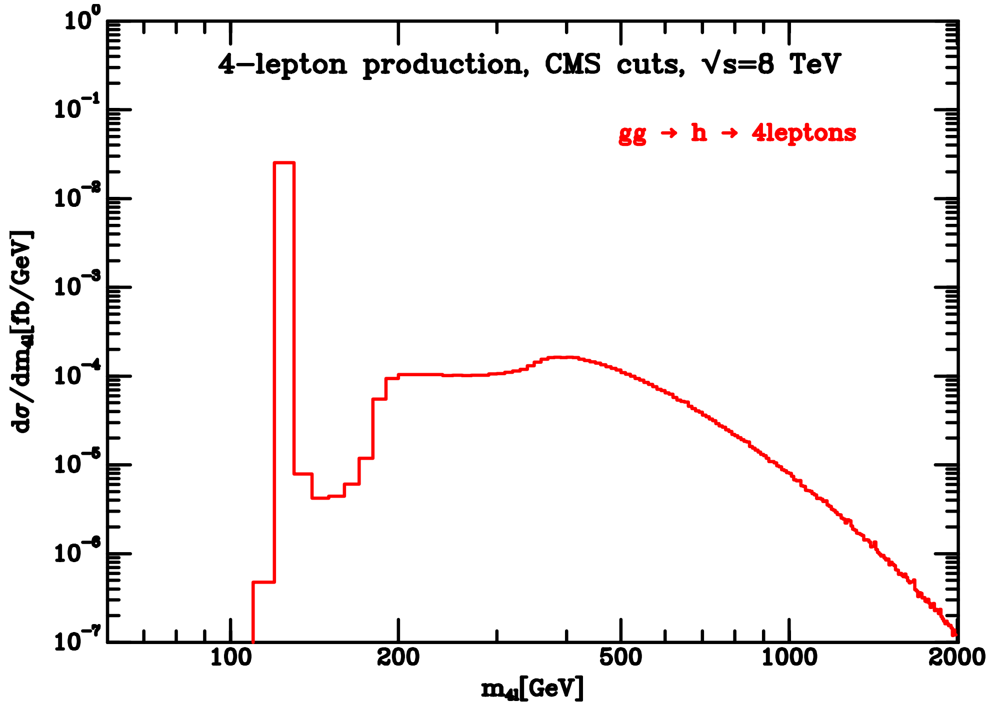


$$\mathcal{M}^{++00}_{\text{Higgs}} \sim \log^2 \frac{\hat{s}}{m_t^2} \qquad \mathcal{M}^{++00}_{\text{box}} \sim -\log^2 \frac{\hat{s}}{m_t^2}$$



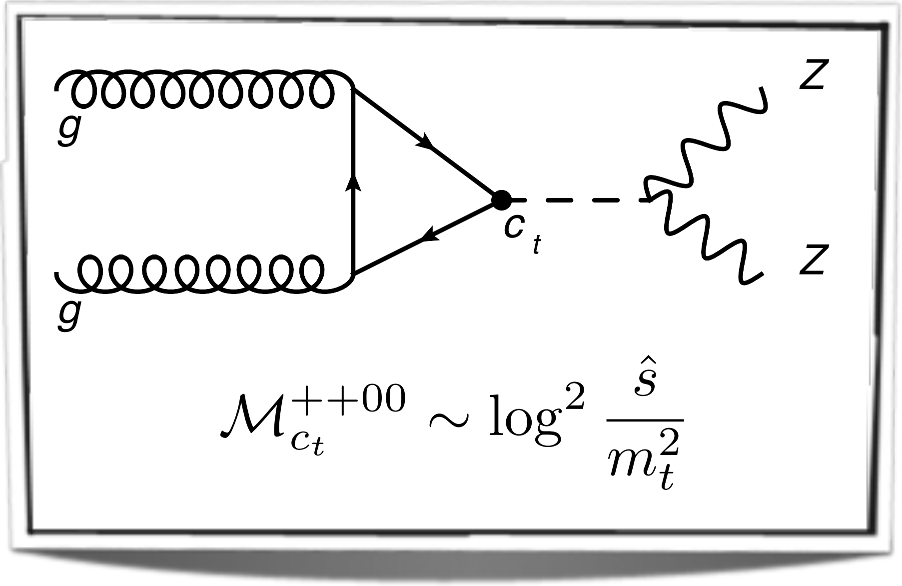
SM: cancelation forced by unitarity

BSM: deviations of Higgs couplings at large s will be amplified

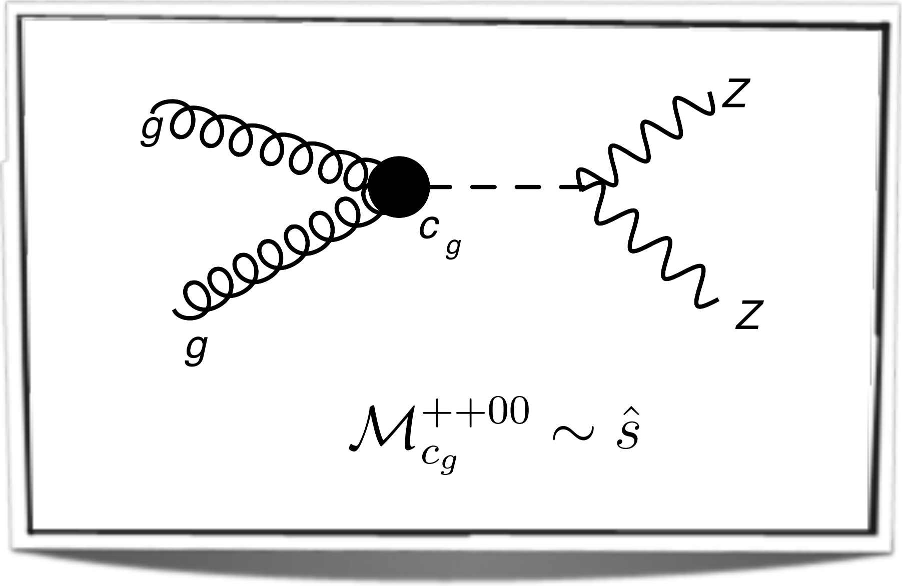
Azatov, Grojean, Paul, Salvioni ’14

interpretations in terms of bounds of the Higgs width are limited/model-dependent

but data can be better used to measure the structure of the couplings at high √s



$$\mathcal{M}^{++00}_{c_t} \sim \log^2 \frac{\hat{s}}{m_t^2}$$

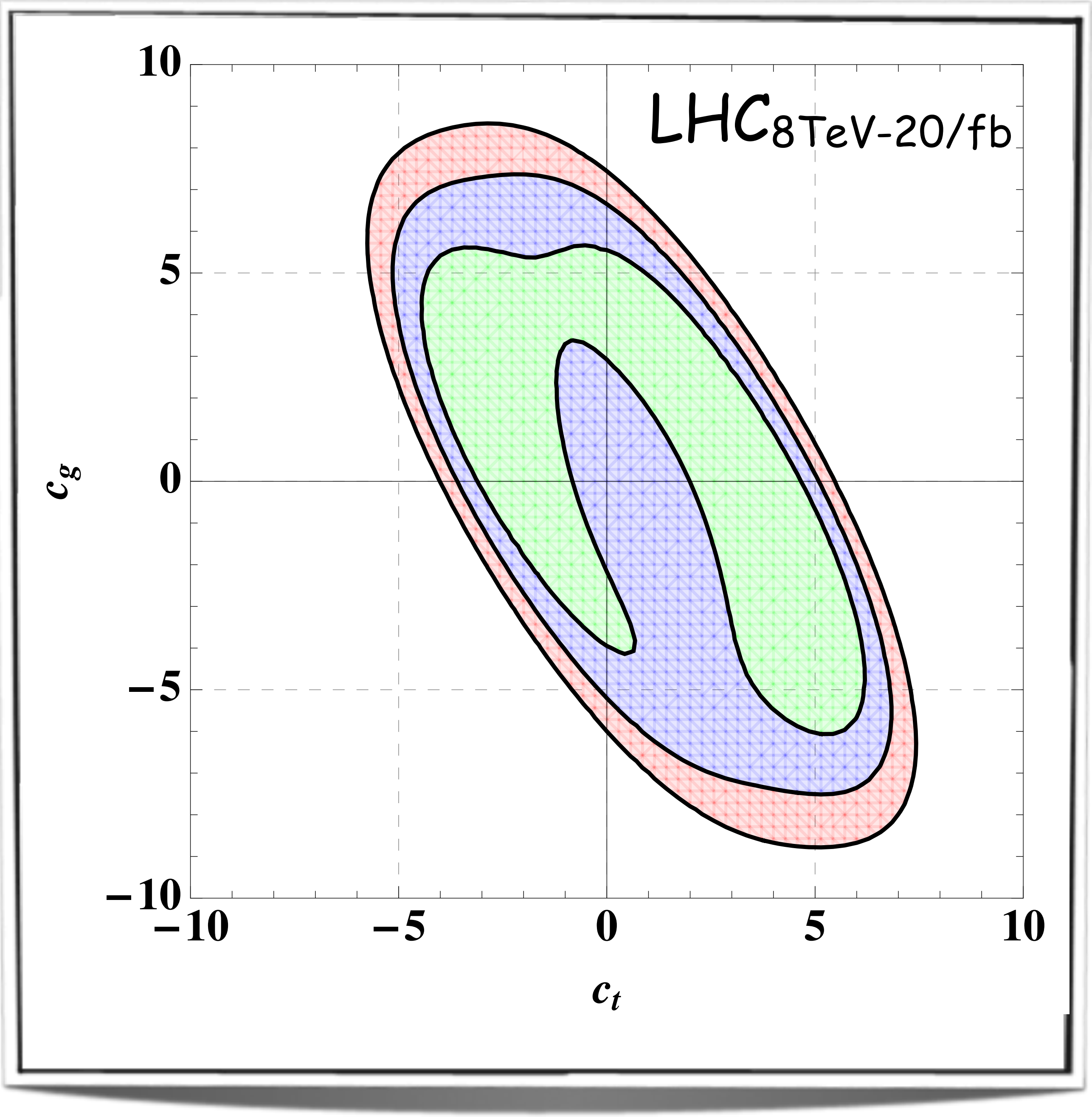


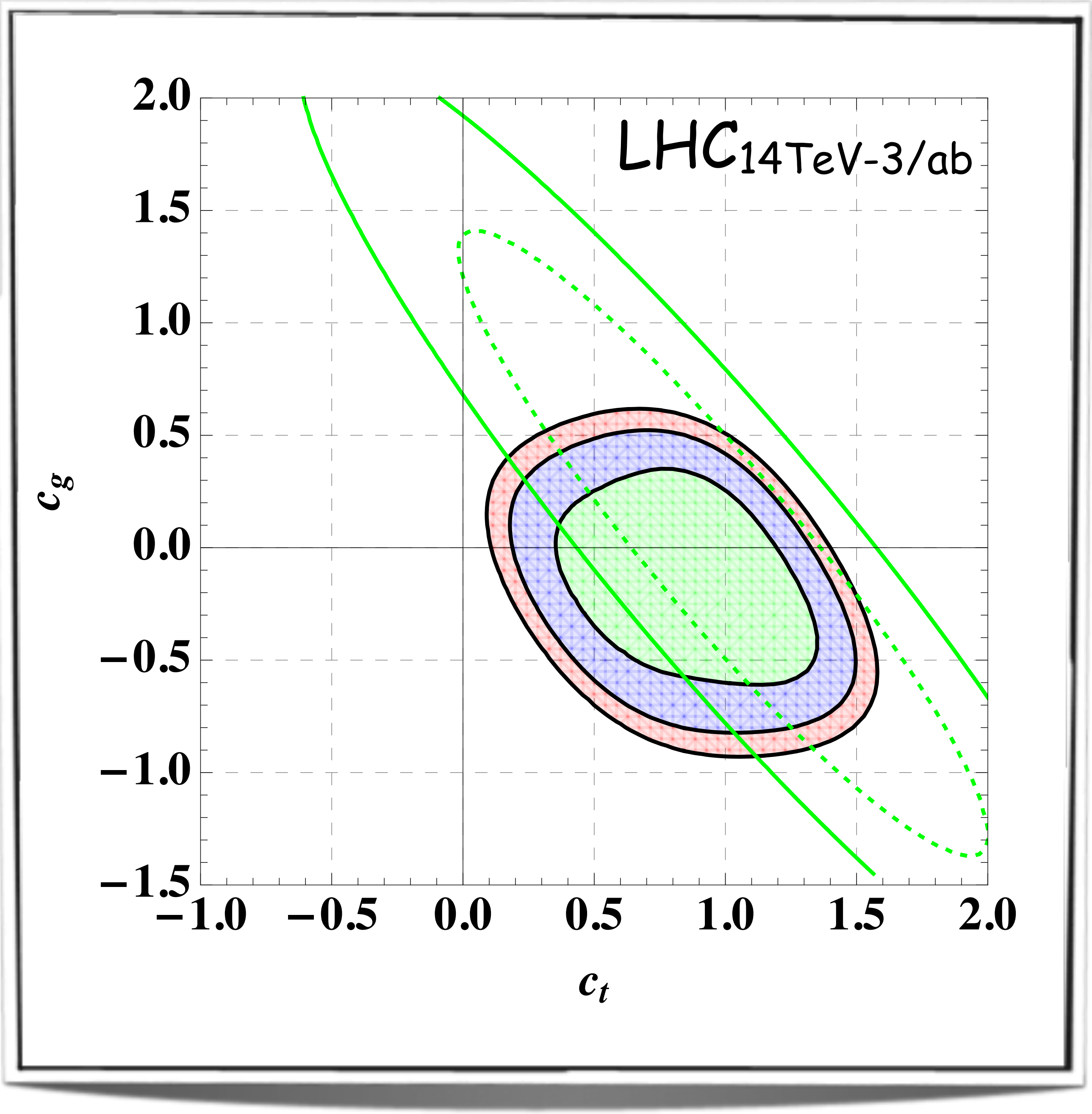
$$\mathcal{M}^{++00}_{c_g} \sim \hat{s}$$

Off-shell Higgs: gg → h* → ZZ → 4l

off-shell effects enhanced by the particular couplings of H to V_L

Azatov, Grojean, Paul, Salvioni '14





Beyond single Higgs processes

Producing one Higgs is good. Producing H+X is better

@ 14 TeV

Higgs multiplicty →

Jet multiplicty ↓

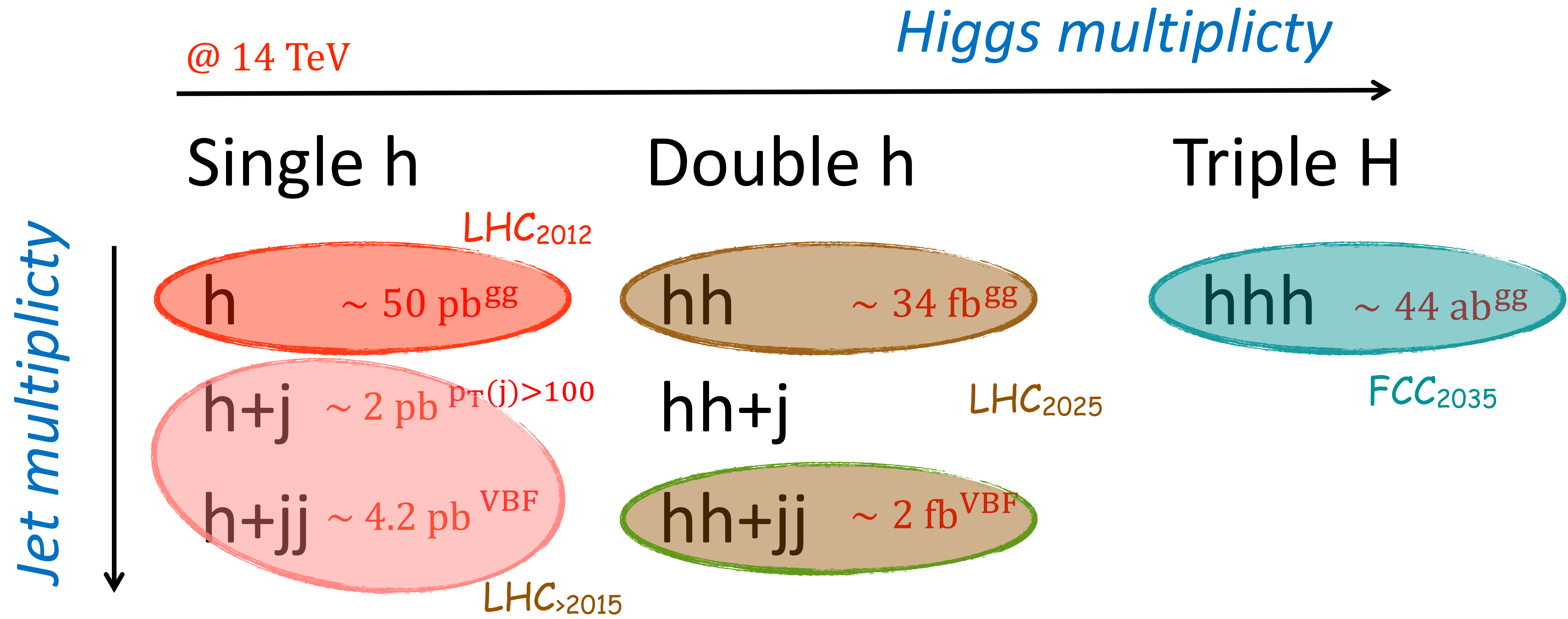
Single h	Double h	Triple H
h $\sim 50\ \text{pb}^{gg}$	hh $\sim 34\ \text{fb}^{gg}$	hhh $\sim 44\ \text{ab}^{gg}$
h+j $\sim 2\ \text{pb}^{\ p_T(j)>100}$	hh+j	
h+jj $\sim 4.2\ \text{pb}^{\ VBF}$	hh+jj $\sim 2\ \text{fb}^{VBF}$	

- also roughly indicates possible initial states/related kinematics
- Jet multiplicity might be replaced with V=W,Z, top, etc…

(adapted from M. Son@Planck2014)

Beyond single Higgs processes

Producing one Higgs is good. Producing H+X is better



@ 14 TeV

Higgs multiplicty

Jet multiplicty

Single h

Double h

Triple H

LHC$_{2012}$

h $\sim$ 50 pb^{gg}

h+j $\sim$ 2 pb $p_T(j)>100$

h+jj $\sim$ 4.2 pb ^{VBF}

LHC$_{>2015}$

hh $\sim$ 34 fb^{gg}

hh+j

LHC$_{2025}$

hh+jj $\sim$ 2 fb^{VBF}

hhh $\sim$ 44 ab^{gg}

FCC$_{2035}$

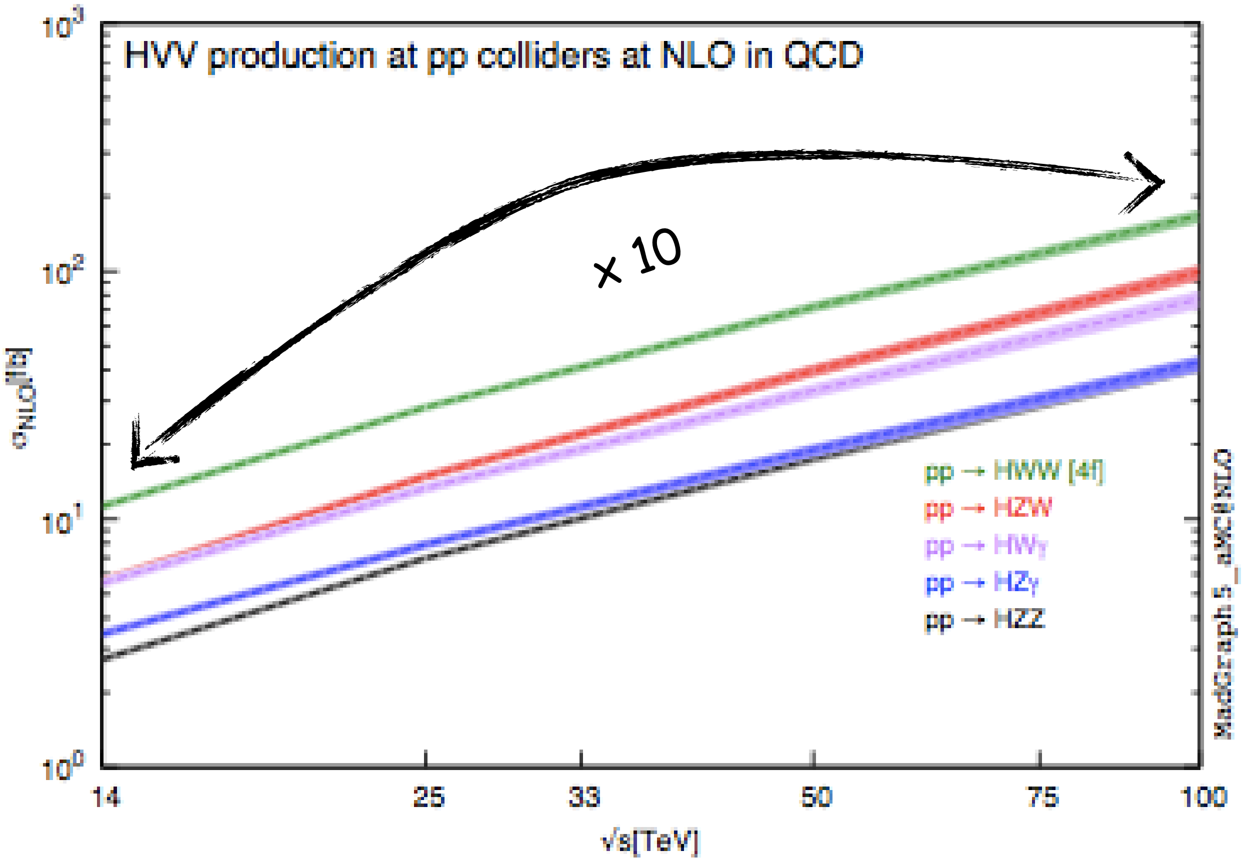
- also roughly indicates possible initial states/related kinematics
- Jet multiplicity might be replaced with V=W,Z, top, etc…

(adapted from M. Son@Planck2014)

Beyond single Higgs processes

Producing one Higgs is good. Producing H+X is better
A long term plan?

Higgs-diboson associated production

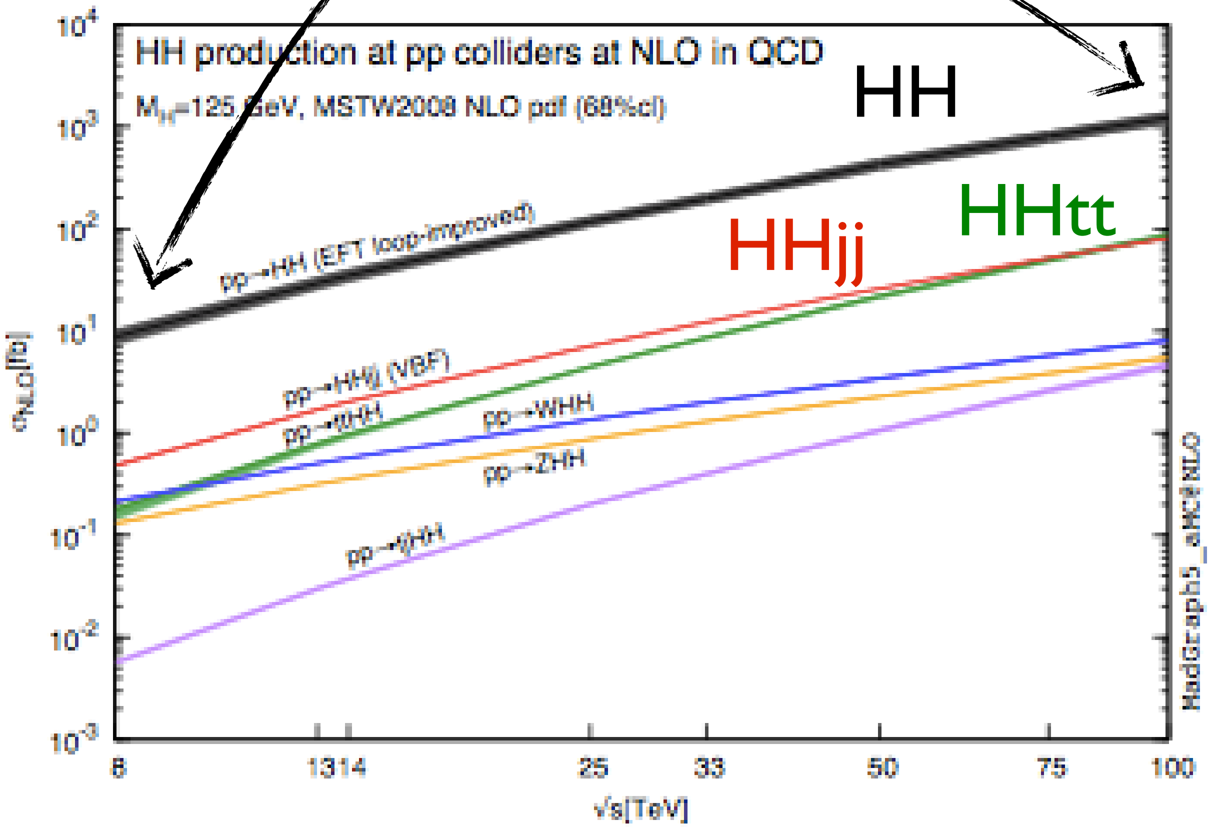


100 fb

FCC = H+X factory

× 100-1000

Higgs-pair associated production



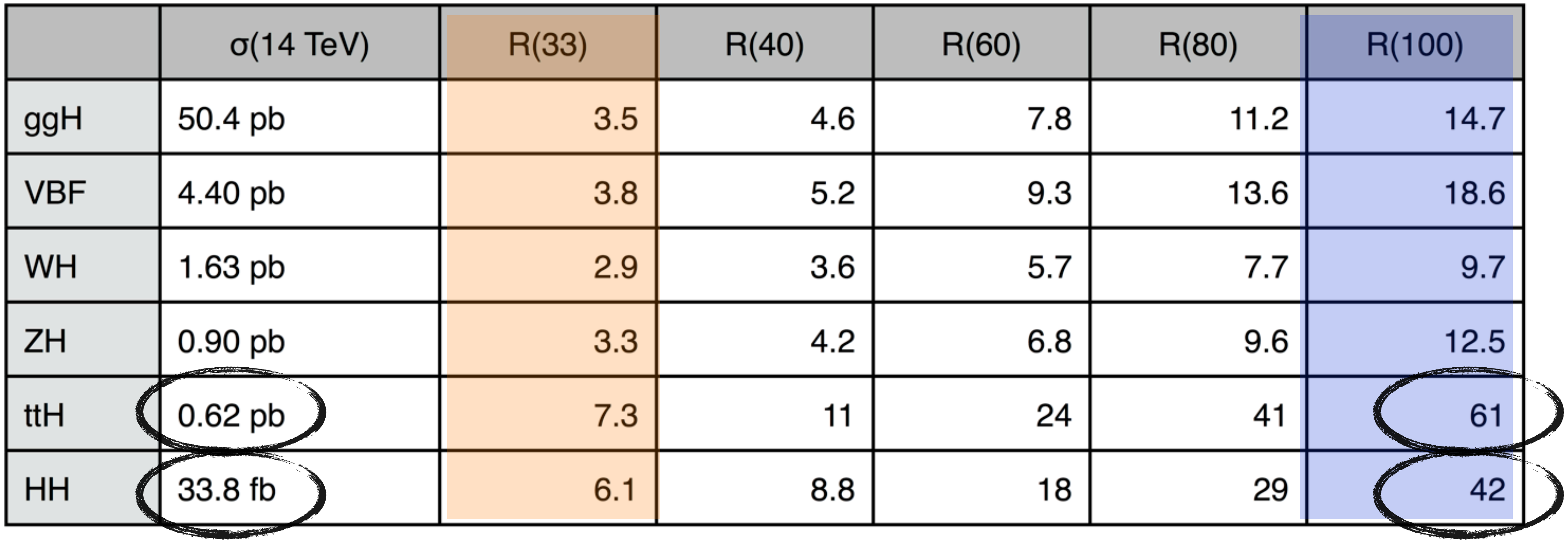
1000 fb

100 fb

(Plots from P. Torrielli and MLM, CERN'14)

Multi Higgs processes

Producing one Higgs is good. Producing more Higgses is better



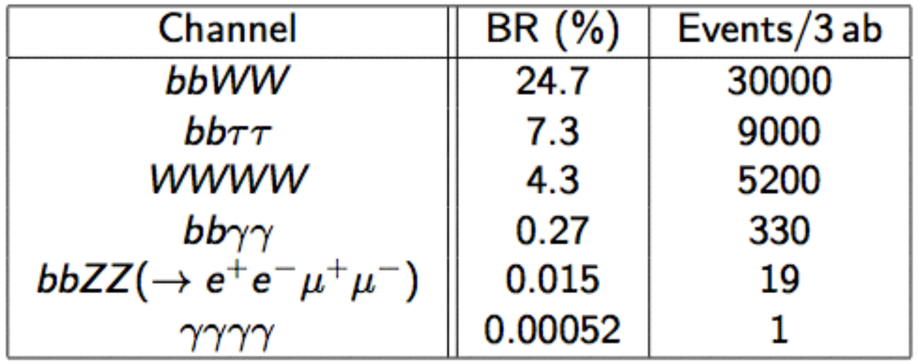
	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

The two difficult processes @ LHC (tth and hh) are the real winners of the energy boost
(these 2 processes have to do with the top Yukawa coupling
one of the most promising probes of new physics)

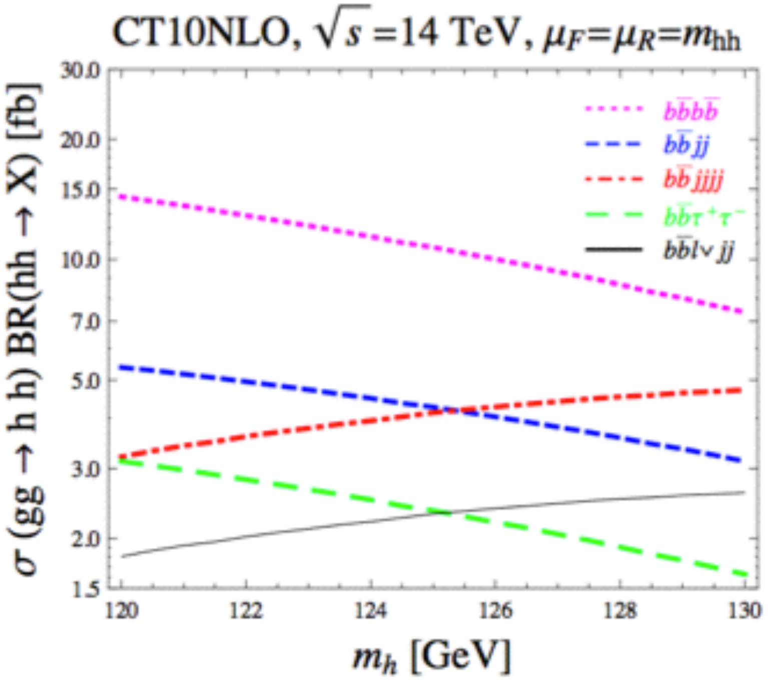
HH@LHC

Measuring this small cross section in an inclusive search is very challenging at the HL-LHC: compromise between branching ratio and cleanliness of the signal

M. Spannowsky, Mainz '15

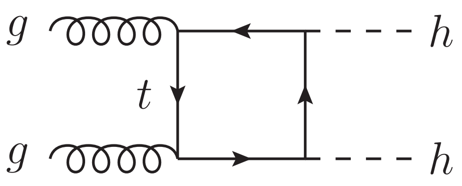


Channel	BR (%)	Events/3 ab
$bbWW$	24.7	30000
$bb\tau\tau$	7.3	9000
$WWWW$	4.3	5200
$bb\gamma\gamma$	0.27	330
$bbZZ(\to e^+e^-\mu^+\mu^-)$	0.015	19
$\gamma\gamma\gamma\gamma$	0.00052	1

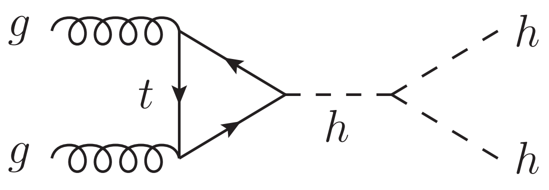


Decay	Issues	Expectation 3000 ifb	References
$b\bar{b}\gamma\gamma$	• Signal small • BKG large & difficult to asses • Simple reconst.	$S/B \simeq 1/3$ $S/\sqrt{B} \simeq 2.5$	[Baur, Plehn, Rainwater] [Yao 1308.6302] [Baglio et al. JHEP 1304]
$b\bar{b}\tau^+\tau^-$	• tau rec tough • largest bkg tt • Boost+MT2 might help	**differ a lot** $S/B \simeq 1/5$ $S/\sqrt{B} \simeq 5$	[Dolan, Englert, MS] [Barr, Dolan, Englert, MS] [Baglio et al. JHEP 1304]
$b\bar{b}W^+W^-$	• looks like tt • Need semilep. W to rec. two H • Boost + BDT proposed	**differ a lot** best case: $S/B \simeq 1.5$ $S/\sqrt{B} \simeq 8.2$	[Dolan, Englert, MS] [Baglio et al. JHEP 1304] [Papaefstathiou, Yang, Zurita 1209.1489]
$b\bar{b}b\bar{b}$	• Trigger issue (high pT kill signal) • 4b background large difficult with MC • Subjets might help	$S/B \simeq 0.02$ $S/\sqrt{B} \leq 2.0$	[Dolan, Englert, MS] [Ferreira de Lima, Papaefstathiou, MS] [Wardrope et al, 1410.2794]
others	• Many taus/W not clear if 2 Higgs • Zs, photons no rate		

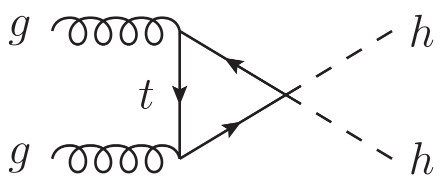
HH production as a probe of HE couplings



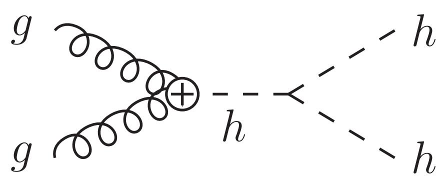
$\sim c_t^2 \times const.$



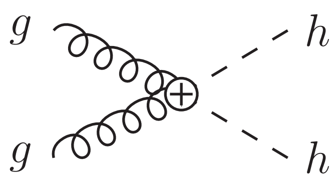
$\sim c_t c_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



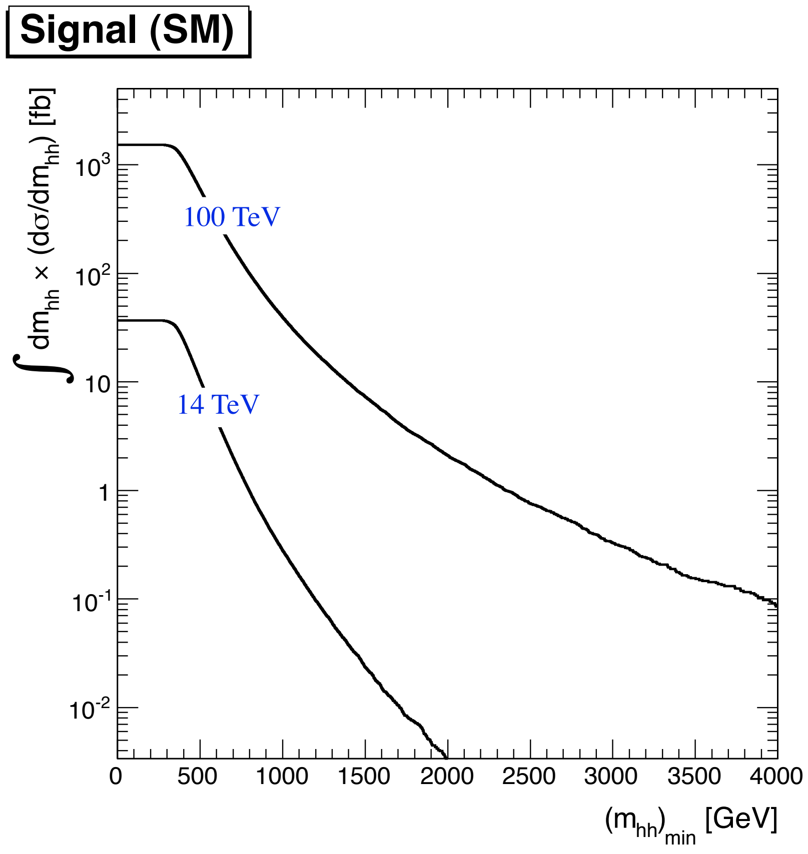
$\sim c_{2t} \times \log^2\left(\frac{m_t^2}{\hat{s}}\right)$

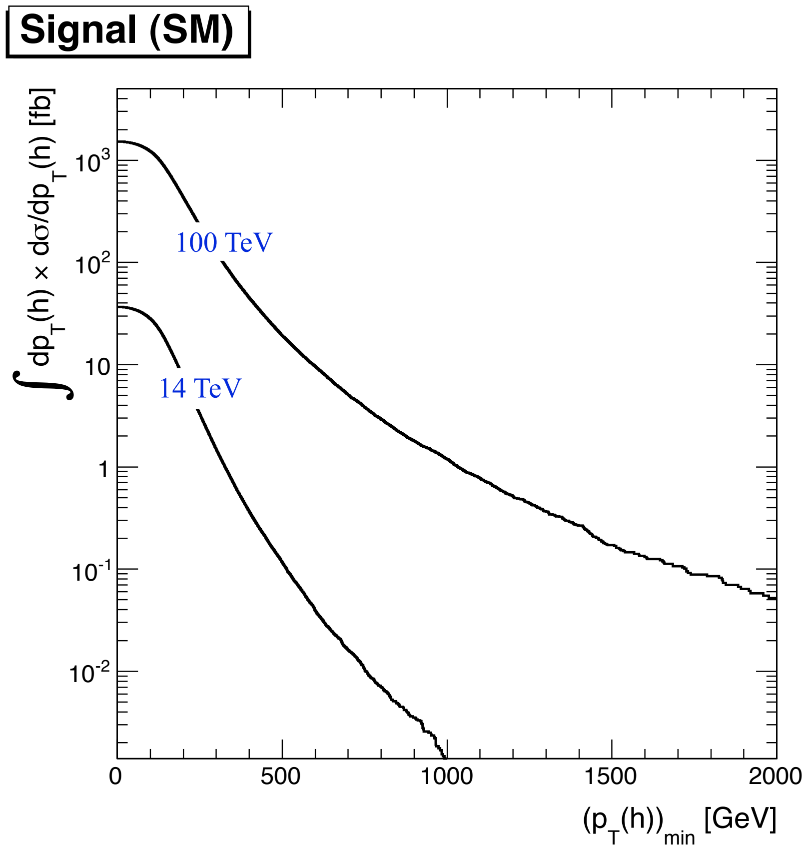


$\sim c_g c_3 \frac{\alpha_s}{4\pi} \times const.$



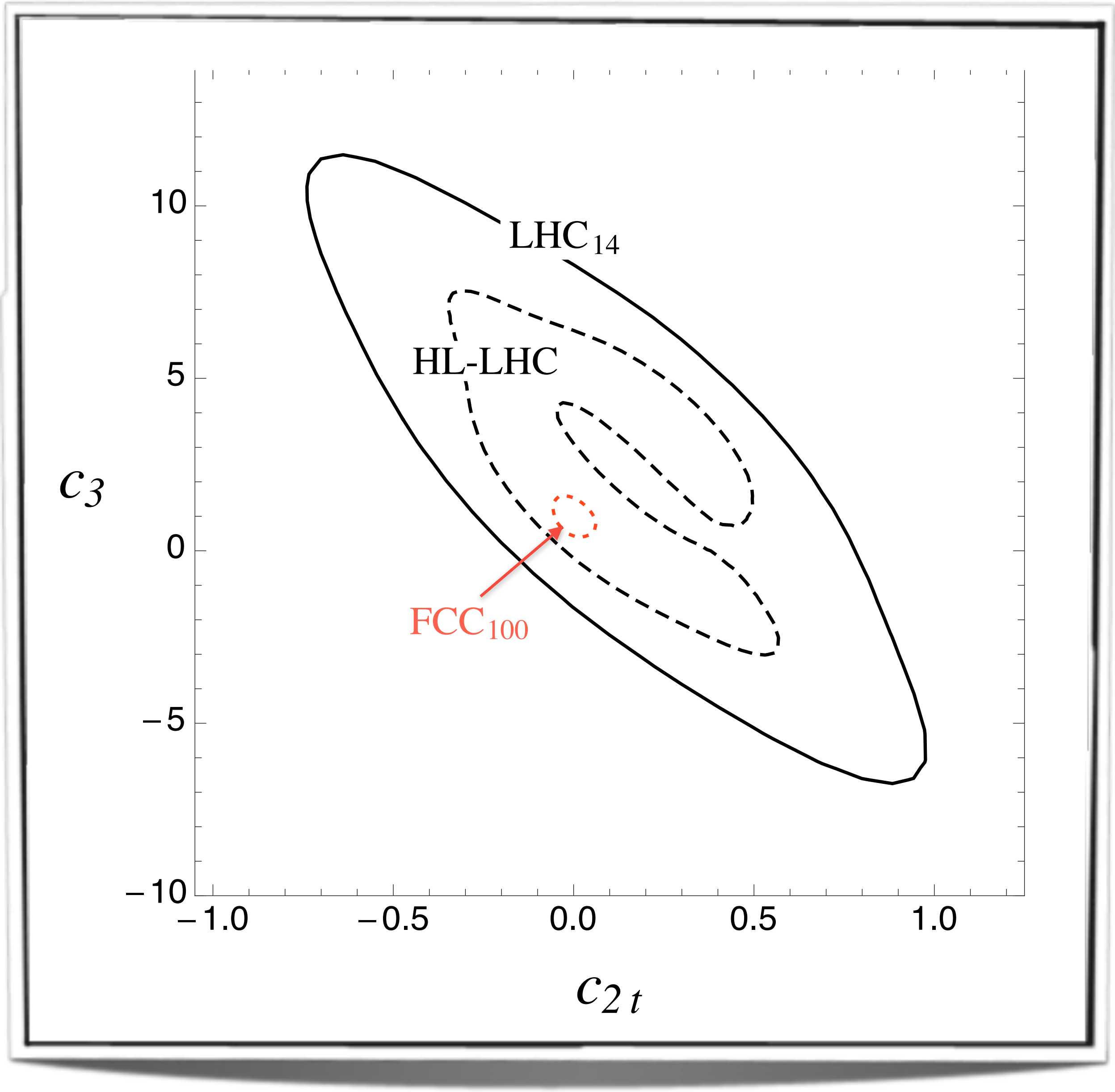
$\sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2}$

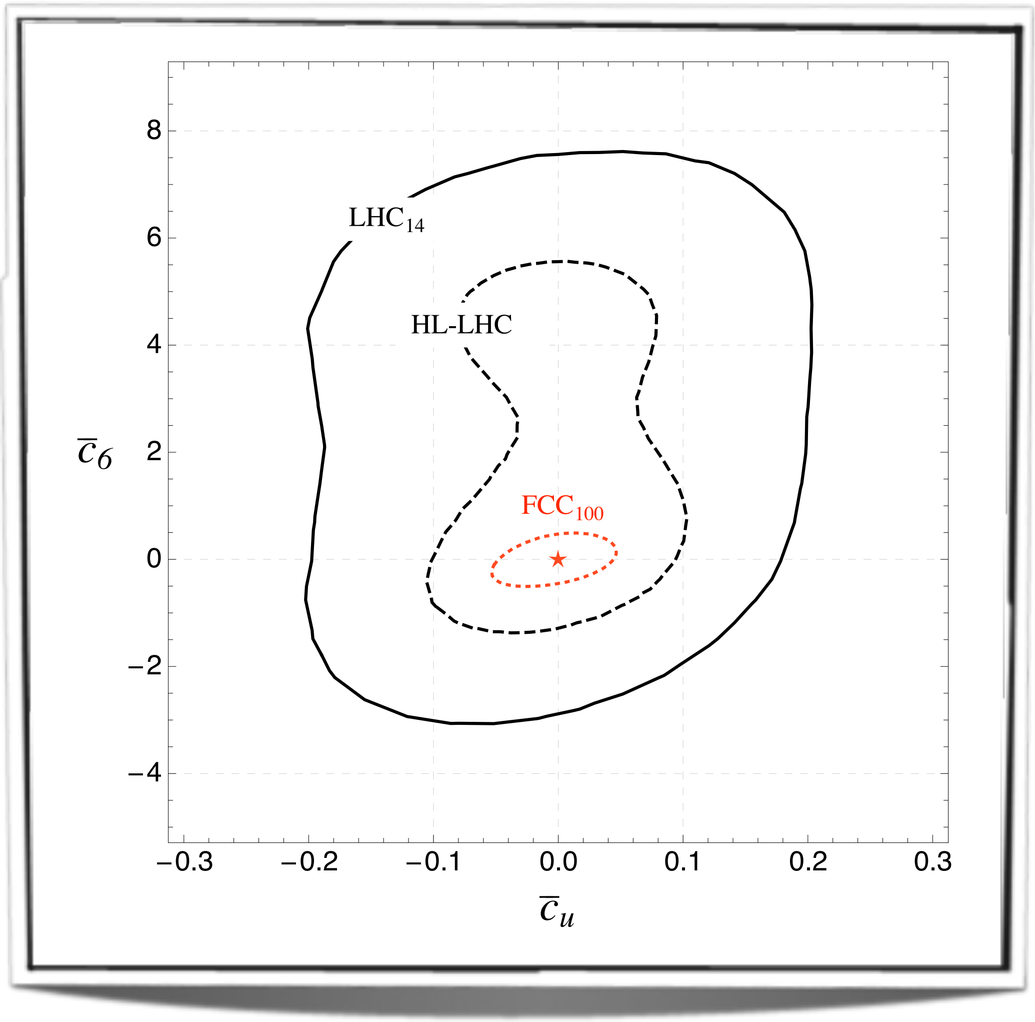




Azatov, Contino, Panico, Son ’15

HH production as a probe of HE couplings





Azatov, Contino, Panico, Son ’15
see also Goertz, Papaefstathiou, Yang, Zurita ’14

Remarks:

- unique access to c_3 but sensitivity is limited (within the validity of EFT?).
- statistically limited, with more luminosity

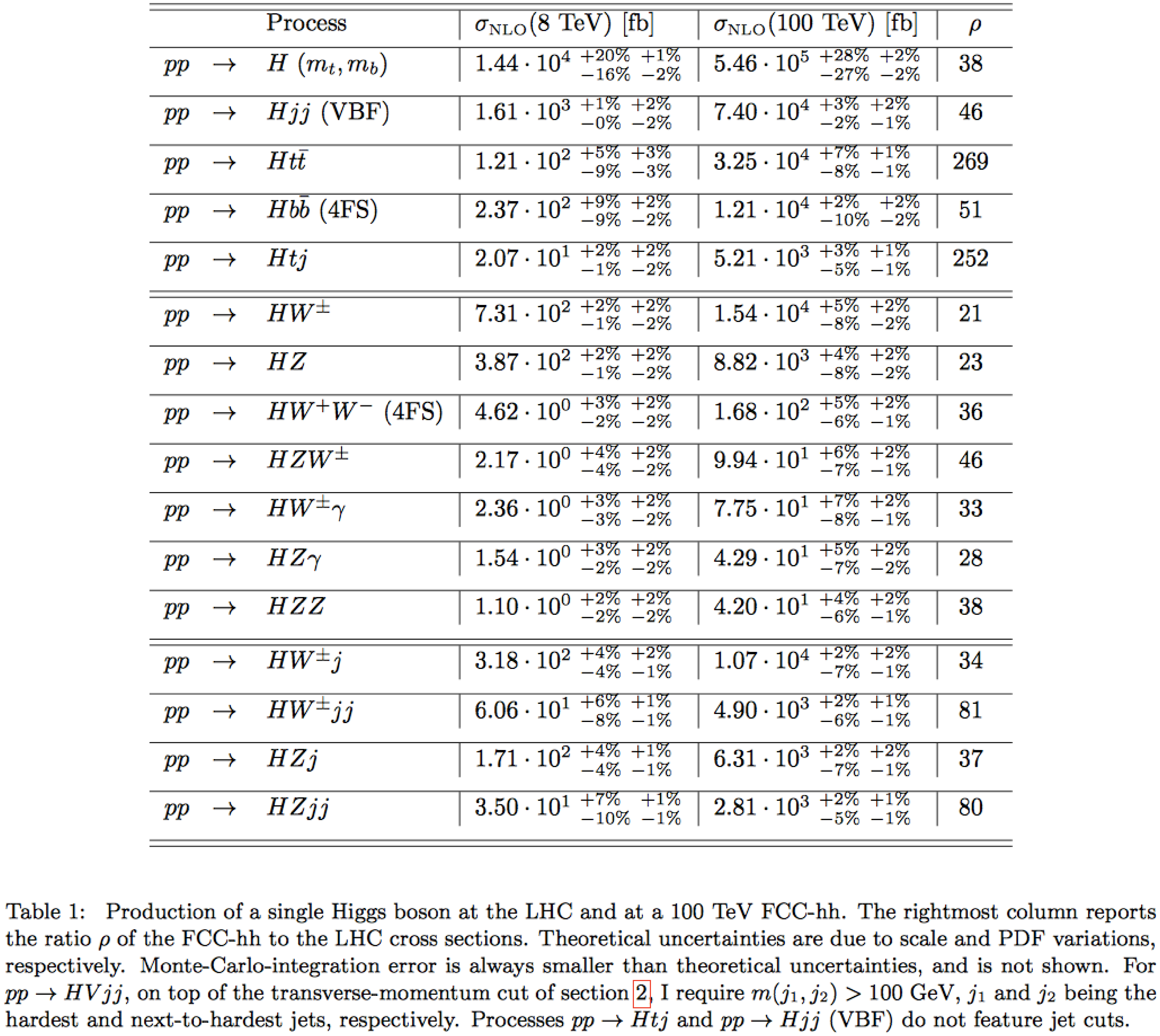
⇛ access to distribution

⇛ discriminating power c_3 vs. c_{2t} vs c_g

Rare Higgs decays

Rare associated-production processes

Are they good for something? Reduced systematics? Complementary information?



	Process	σ_{NLO}(8 TeV) [fb]	σ_{NLO}(100 TeV) [fb]	ρ
$pp \to$	$H\ (m_t, m_b)$	$1.44 \cdot 10^4\ ^{+20\%}_{-16\%}\ ^{+1\%}_{-2\%}$	$5.46 \cdot 10^5\ ^{+28\%}_{-27\%}\ ^{+2\%}_{-2\%}$	38
$pp \to$	Hjj (VBF)	$1.61 \cdot 10^3\ ^{+1\%}_{-0\%}\ ^{+2\%}_{-2\%}$	$7.40 \cdot 10^4\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-1\%}$	46
$pp \to$	$Ht\bar{t}$	$1.21 \cdot 10^2\ ^{+5\%}_{-9\%}\ ^{+3\%}_{-3\%}$	$3.25 \cdot 10^4\ ^{+7\%}_{-8\%}\ ^{+1\%}_{-1\%}$	269
$pp \to$	$Hb\bar{b}$ (4FS)	$2.37 \cdot 10^2\ ^{+9\%}_{-9\%}\ ^{+2\%}_{-2\%}$	$1.21 \cdot 10^4\ ^{+2\%}_{-10\%}\ ^{+2\%}_{-2\%}$	51
$pp \to$	Htj	$2.07 \cdot 10^1\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$5.21 \cdot 10^3\ ^{+3\%}_{-5\%}\ ^{+1\%}_{-1\%}$	252
$pp \to$	$HW^\pm$	$7.31 \cdot 10^2\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$1.54 \cdot 10^4\ ^{+5\%}_{-8\%}\ ^{+2\%}_{-2\%}$	21
$pp \to$	HZ	$3.87 \cdot 10^2\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$8.82 \cdot 10^3\ ^{+4\%}_{-8\%}\ ^{+2\%}_{-2\%}$	23
$pp \to$	HW^+W^- (4FS)	$4.62 \cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$1.68 \cdot 10^2\ ^{+5\%}_{-6\%}\ ^{+2\%}_{-1\%}$	36
$pp \to$	$HZW^\pm$	$2.17 \cdot 10^0\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-2\%}$	$9.94 \cdot 10^1\ ^{+6\%}_{-7\%}\ ^{+2\%}_{-1\%}$	46
$pp \to$	$HW^\pm\gamma$	$2.36 \cdot 10^0\ ^{+3\%}_{-3\%}\ ^{+2\%}_{-2\%}$	$7.75 \cdot 10^1\ ^{+7\%}_{-8\%}\ ^{+2\%}_{-1\%}$	33
$pp \to$	$HZ\gamma$	$1.54 \cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.29 \cdot 10^1\ ^{+5\%}_{-7\%}\ ^{+2\%}_{-2\%}$	28
$pp \to$	HZZ	$1.10 \cdot 10^0\ ^{+2\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.20 \cdot 10^1\ ^{+4\%}_{-6\%}\ ^{+2\%}_{-1\%}$	38
$pp \to$	$HW^\pm j$	$3.18 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-1\%}$	$1.07 \cdot 10^4\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	34
$pp \to$	$HW^\pm jj$	$6.06 \cdot 10^1\ ^{+6\%}_{-8\%}\ ^{+1\%}_{-1\%}$	$4.90 \cdot 10^3\ ^{+2\%}_{-6\%}\ ^{+1\%}_{-1\%}$	81
$pp \to$	HZj	$1.71 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+1\%}_{-1\%}$	$6.31 \cdot 10^3\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	37
$pp \to$	$HZjj$	$3.50 \cdot 10^1\ ^{+7\%}_{-10\%}\ ^{+1\%}_{-1\%}$	$2.81 \cdot 10^3\ ^{+2\%}_{-5\%}\ ^{+1\%}_{-1\%}$	80

Table 1: Production of a single Higgs boson at the LHC and at a 100 TeV FCC-hh. The rightmost column reports the ratio ρ of the FCC-hh to the LHC cross sections. Theoretical uncertainties are due to scale and PDF variations, respectively. Monte-Carlo-integration error is always smaller than theoretical uncertainties, and is not shown. For $pp \to HVjj$, on top of the transverse-momentum cut of section 2, I require $m(j_1, j_2) > 100$ GeV, j_1 and j_2 being the hardest and next-to-hardest jets, respectively. Processes $pp \to Htj$ and $pp \to Hjj$ (VBF) do not feature jet cuts.

P.Torrielli, arXiv:1407.1623

2

Top quark physics

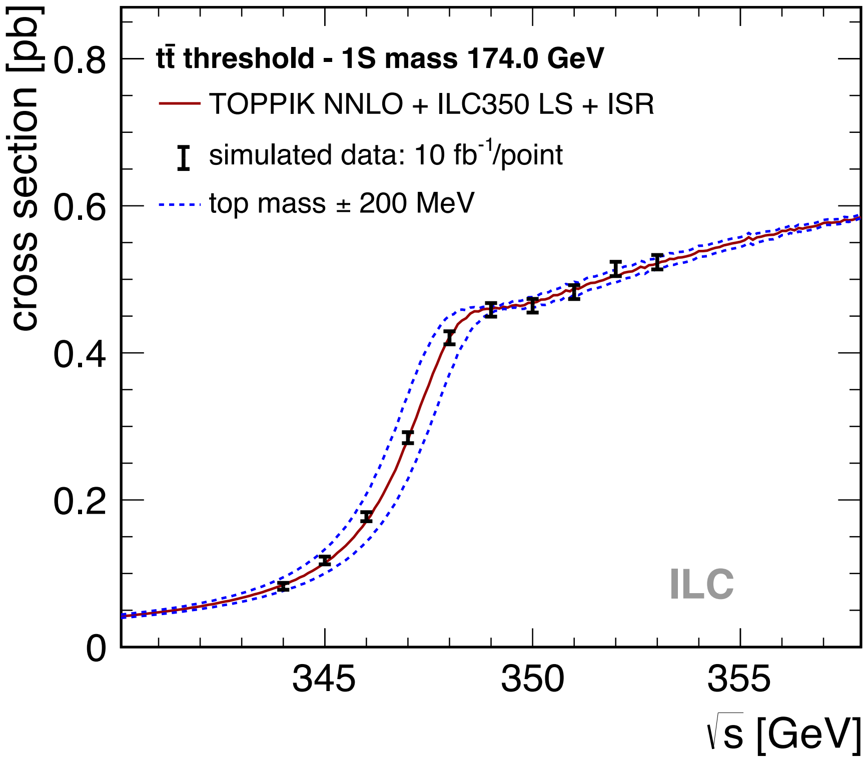
Top programme @ ILC

The top programme at ILC is three-fold

1) study of the threshold for $t\bar{t}$ production around 350 GeV = “hydrogen atom for strong interactions”, ie bound state free of nonperturbative quark confining interactions

2) measure the top-Higgs coupling

3) study of top quark production and decay at 500 GeV



$$\delta m_t \sim 30 \text{ MeV}$$

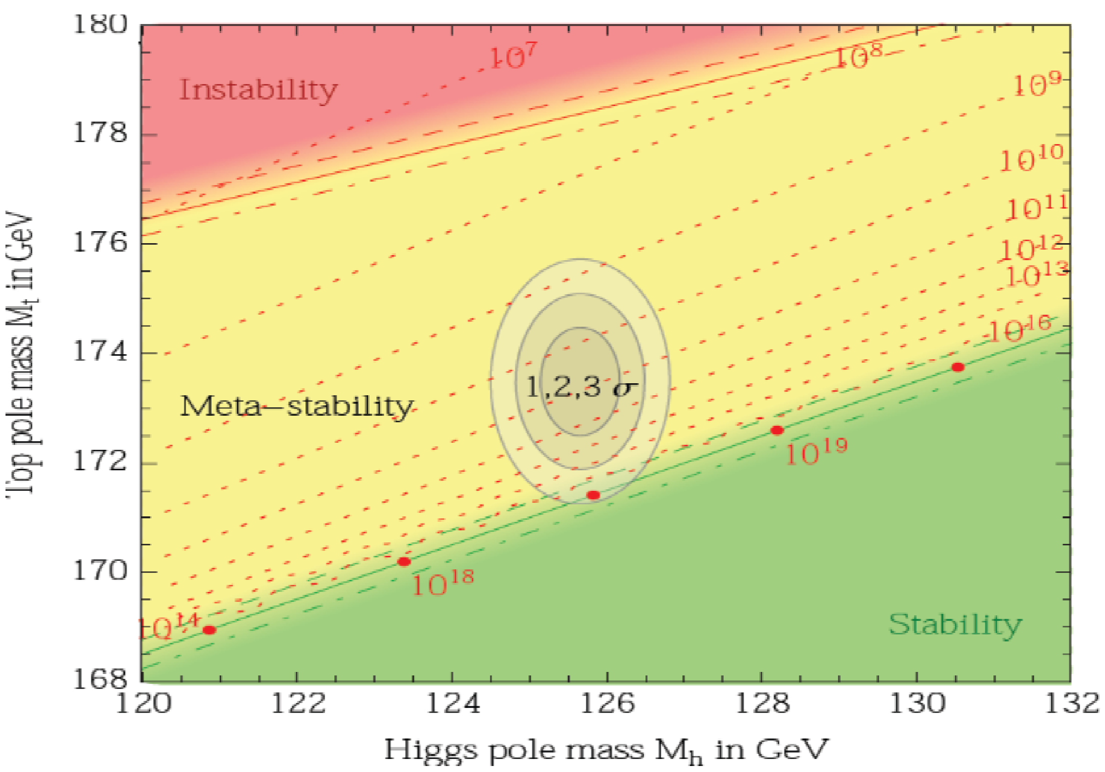
to be compared to HL-LHC prospect

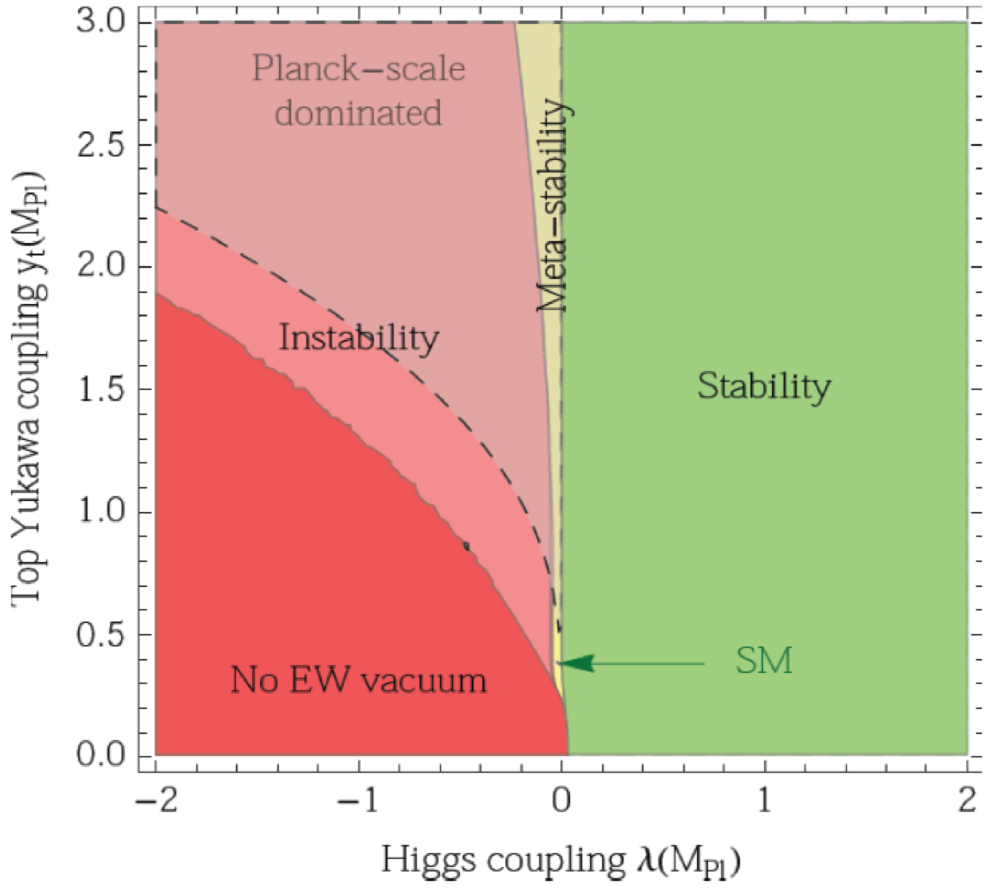
$$\delta m_t \sim 500 \text{ MeV}$$

Top-Higgs coupling

The top-Higgs controls the fate of the EW vacuum

Buttazzo et al '13 Bezrukov et al '12 Degrassi et al '12





Access ttH @ ILC

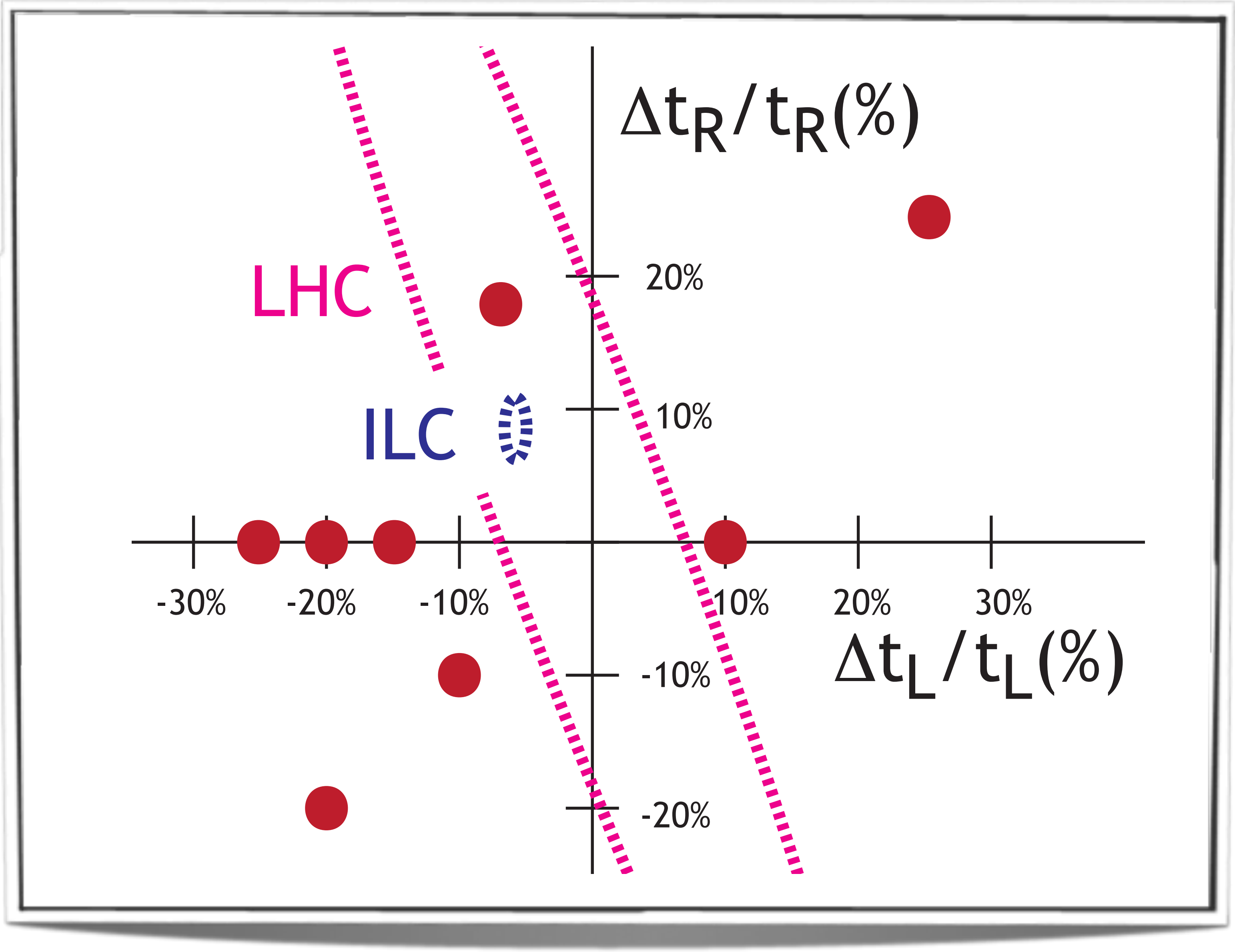
see talk by J. Brau yesterday

Top EW couplings

important to access the EW top couplings

chiral gauge symmetries are the only one to be spontaneously broken?

probe various scenarios of physcs beyond the SM



adapted from Richard '14

see also Agashe et al '13

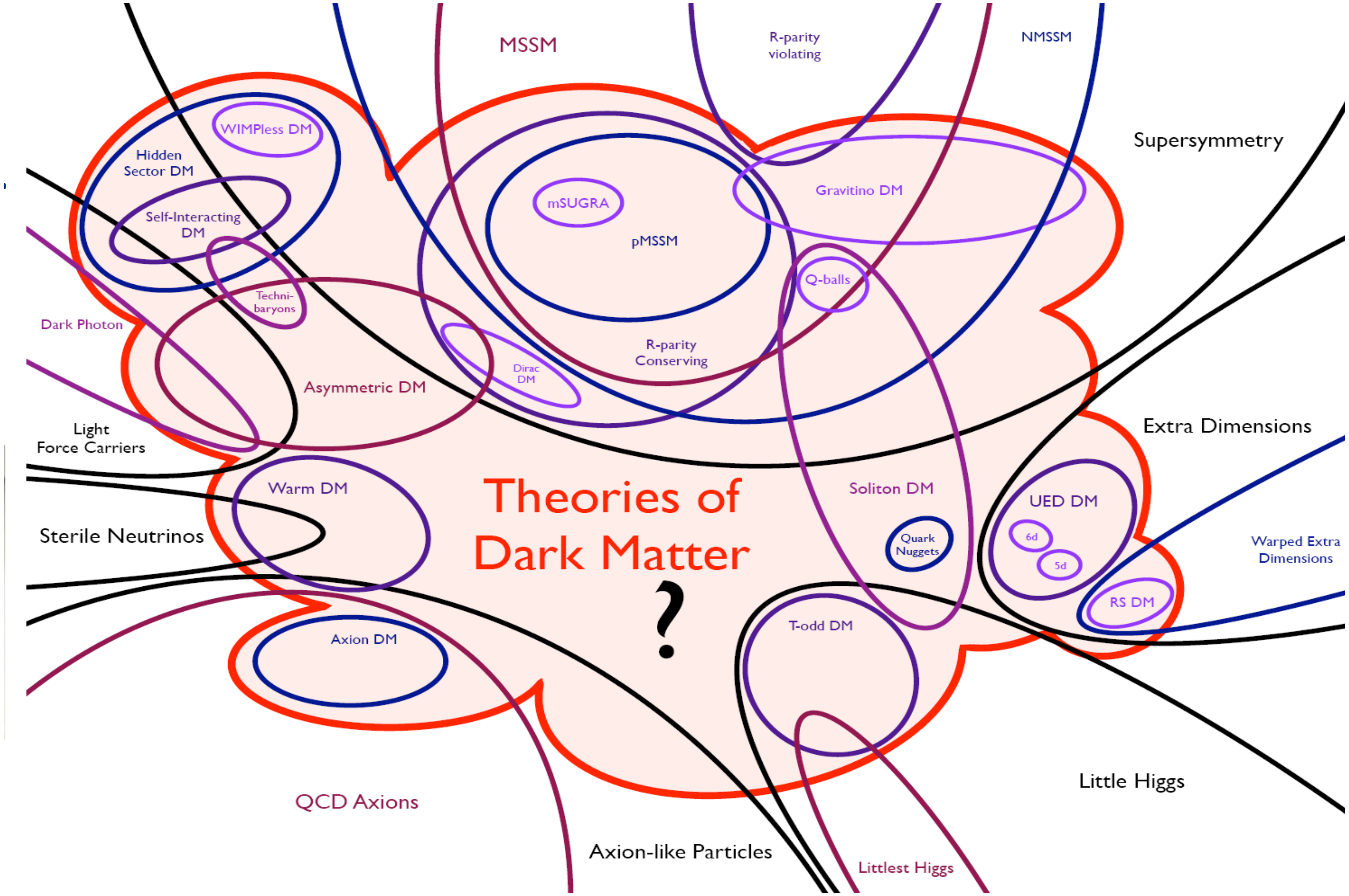
ILC sensitivity down to 0.5% (factor 10 improvement over TESLA estimates)

⇒ probe New Physics resonances up to 15-20 TeV, way above direct LHC access

3

Dark Matter

The energy scale(s) of new physics



T. Tait, DM@LHC '14

The prediction about the mass scale of DM comes with large error bars:

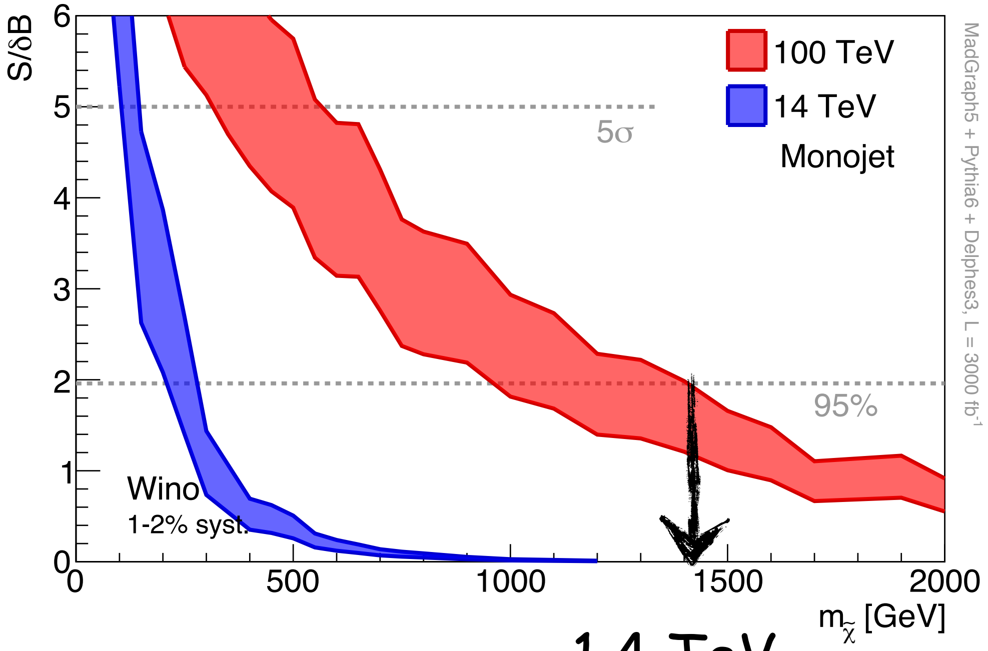
$$10^{-22}\,\mathrm{eV} < m_{DM} < 10^{20}\,\mathrm{GeV}$$

(ALPs) (Wimpzillas, Q-balls)

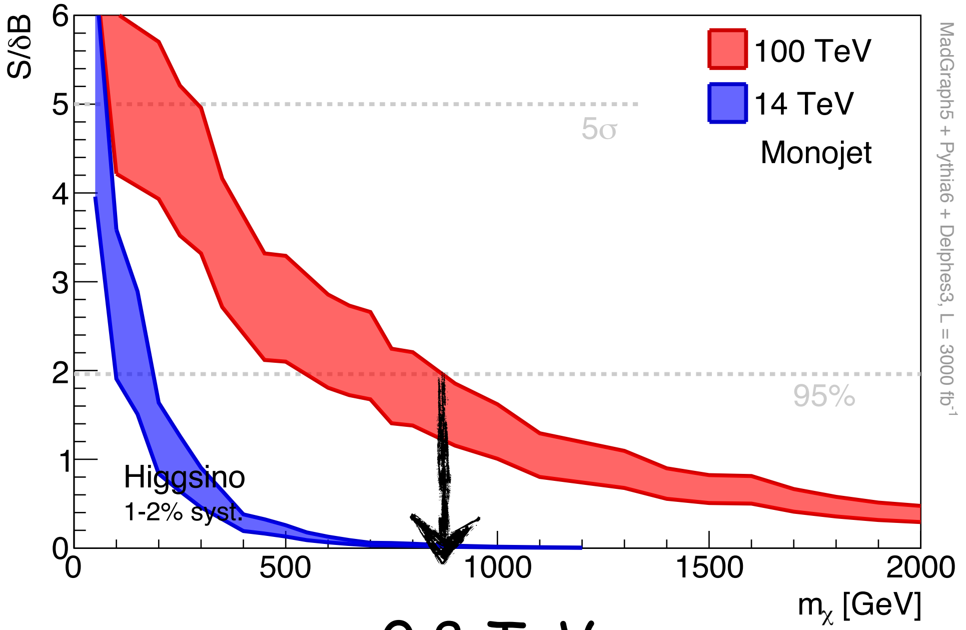
Exploring TeV-scale DM

- monojet searches
- soft lepton searches (compressed spectra)
- disappearing track searches (long chargino lifetime)

Low, Wang '14



1.4 TeV



0.8 TeV

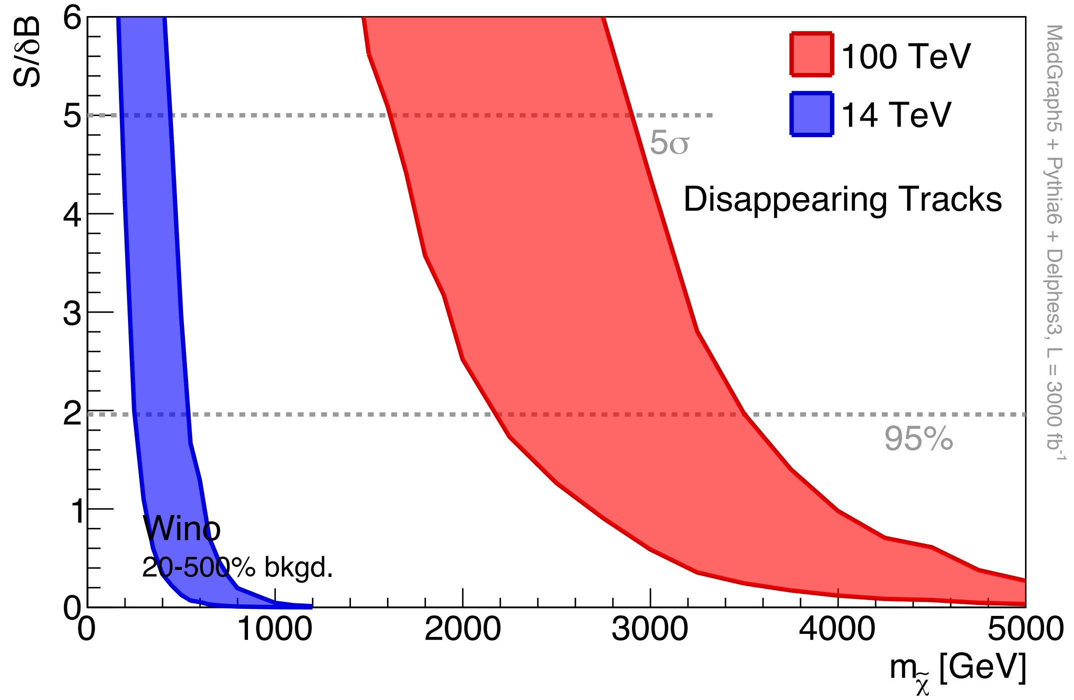
$$M_{\text{WIMP}} \leq 1.8\ \text{TeV} \left(\frac{g^2}{0.3}\right)$$ to avoid overclosing the Universe

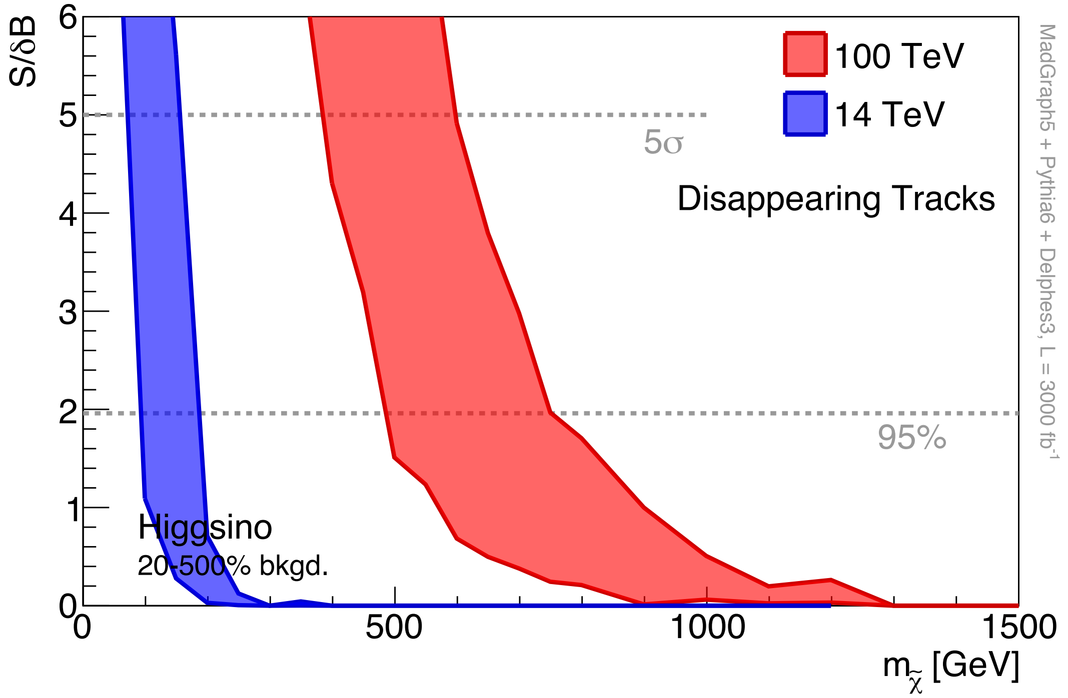
- LHC only coverage very limited. Rate, systematics...
- 100 TeV pp collider can probe the "bulk" of WIMP parameter space.

Exploring TeV-scale DM

- monojet searches
- soft lepton searches (compressed spectra)
- disappearing track searches (long chargino lifetime)

Low, Wang '14





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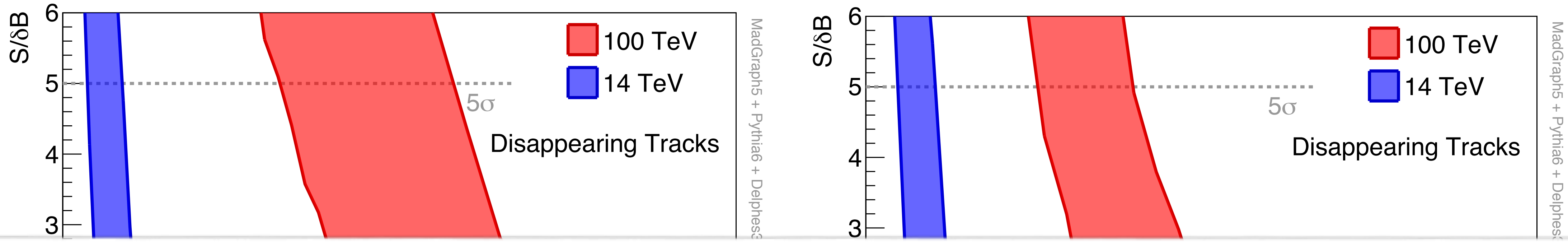
Exploring TeV-scale DM

- monojet searches
- soft lepton searches (compressed spectra)
- disappearing track searches (long chargino lifetime)

Low, Wang '14



Once a DM particle is discovered
it remains to be seen if its relic abundance
can match the cosmological data
➠ needs to precisely "weight" DM

– 100 TeV pp collider can probe the "bulk" of WIMP parameter space.

4

Baryogenesis

Higgs self-couplings

The Higgs self-couplings plays important roles

1) controls the stability of the EW vacuum

2) dictates the dynamics of EW phase transition and potentially conditions the generation of a matter-antimatter asymmetry via EW baryogenesis

Does it need to be measured with high accuracy?

difficult to design new physics scenarios that dominantly affect the Higgs self-couplings and leave the other Higgs coupling deviations undetectable

Higgs self-coupling prospects

	HL LHC 3/ab	ILC/CLIC	FCC 100TeV
Precision on λ_{HHH}	$b\bar{b}\gamma\gamma$: poor, only $\sim O(1)$ determination Other channels: needs more detailed studies	ILC • DHS alone at 500 GeV and 1TeV gives only $\sim O(1)$ determination • ~28% via VBF at 1TeV, 1/ab CLIC at 3TeV, 2/ab • ~12% via VBF	$b\bar{b}\gamma\gamma$: golden channel. 5-10% determination might be possible with 30/ab. ~3x less sensitivity with 3/ab
Comments	Combining various channels might be important	The role of VBF is important High CM energy and high luminosity are crucial	Improvements on heavy flavor tagging, fakes, mass resolution etc are crucial to achieve our goal

ILC current studies:
(4b and 2b2W modes)
29%@4/ab, 500GeV
16%@2/ab, 1TeV
10%@5/ab, 1TeV

M. Son, Washington '15

Higgs self-couplings and Naturalness

In the SM, $|H|^2$ is the only relevant operator
and it is the source of the hierarchy/naturalness/fine-tuning problem
It presence has never been tested!

Reconstructing the Higgs potential before EW symmetry breaking
from measurements around the vacuum is difficult in general
but we can easily test gross features, like the presence of the relevant operator

SM

$$V = -\mu^2|H|^2 + \lambda|H|^4 \quad\Longrightarrow\quad V(h) = \frac{1}{2}m_h^2 h^2 + \frac{1}{6}\frac{3m_h^2}{v}h^3 + \dots$$

EWSB W/O H^2

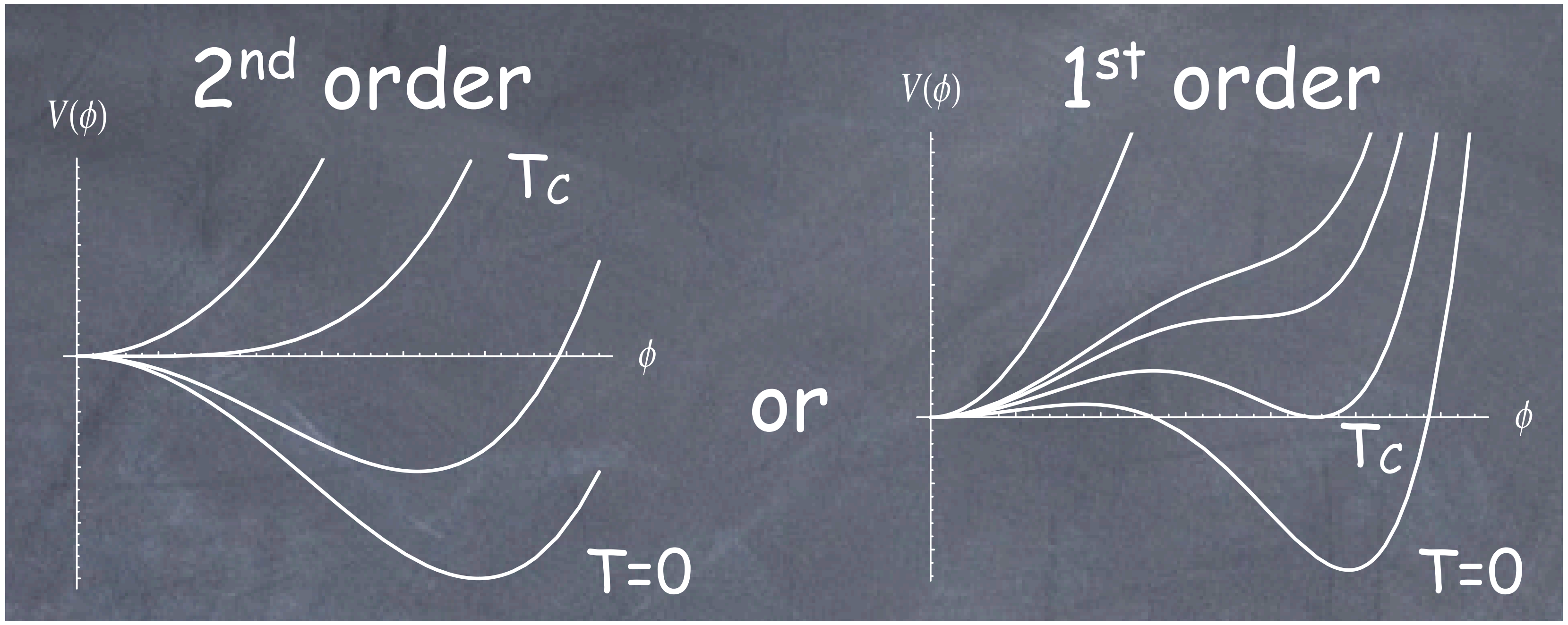
$$V = -\lambda|H|^4 + \frac{1}{\Lambda^2}|H|^6 \quad\Longrightarrow\quad V(h) = \frac{1}{2}m_h^2 h^2 + \frac{1}{6}\frac{7m_h^2}{v}h^3 + \dots$$

200% correction
to SM prediction
+
allows 1st phase transition

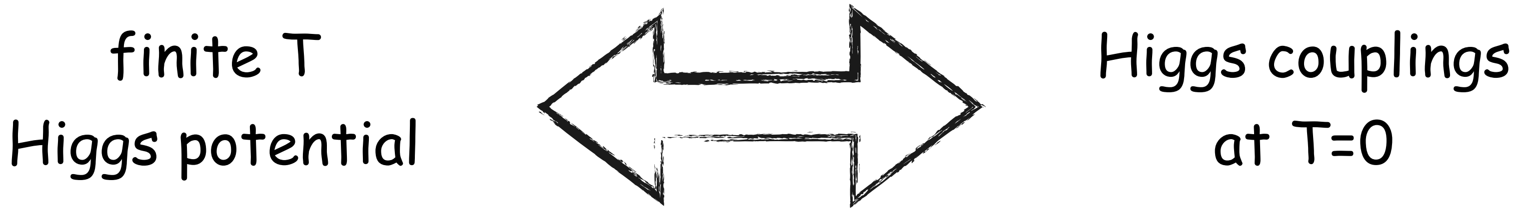
Dynamics of EW phase transition

The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

An appealing idea is EW baryogenesis associated to a first order EW phase transition
(not the only option but the only one that can be tested at colliders)



the dynamics of the phase transition is determined by Higgs effective potential at finite T
which we have no direct access at in colliders (LHC≠Big Bang machine)


finite T
Higgs potential

Higgs couplings
at T=0

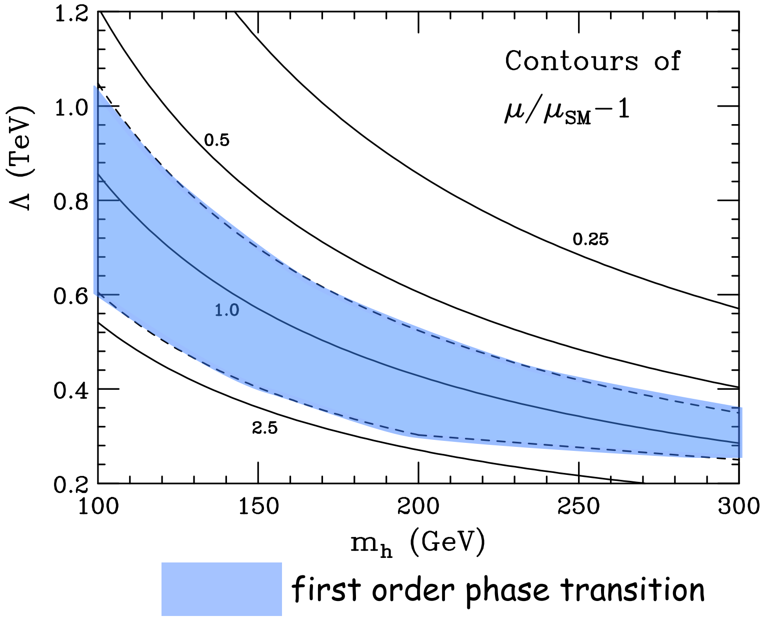
SM: first order phase transition iff mH < 47 GeV
BSM: first order phase transition needs some sizeable deviations in Higgs couplings

Higgs couplings for 1st order EW phase transition

New physics @ tree-level

Grojean, Servant, Wells ’04
Noble, Perelstein ’07

mixing with other scalars modify the tree-level Higgs potential



$$V(\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 + \frac{1}{\Lambda^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3$$

1st order phase transition

comes with 80-200% deviations in Higgs self-interaction

$\Downarrow$ $\Downarrow$

visible @ ILC/TLEP

New physics in loops

Katz, Perelstein ’14

new particles, e.g. scalars, coupled to the Higgs without affecting its tree-level potential

$$V \propto \kappa|\Phi|^2|H|^2$$

Higgs couplings for 1st order EW phase transition

New physics @ tree-level

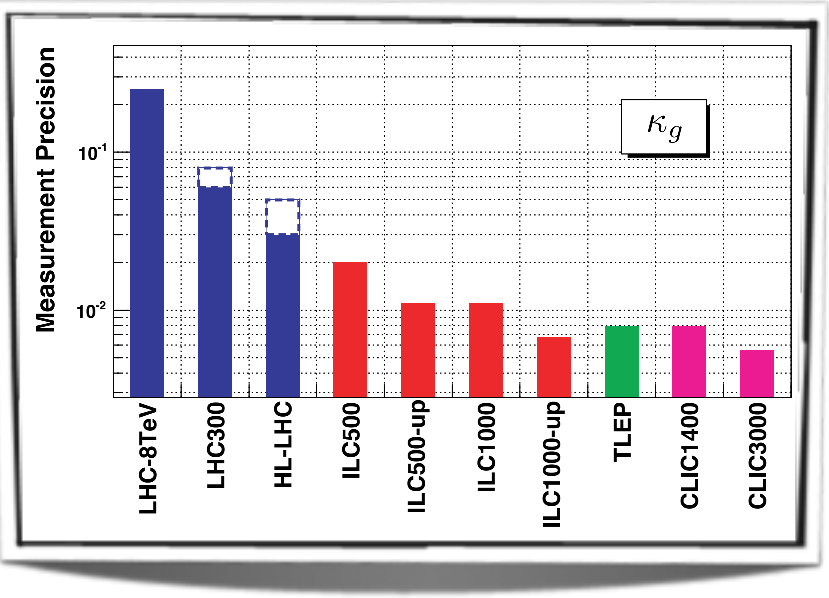
Grojean, Servant, Wells '04
Noble, Perelstein '07

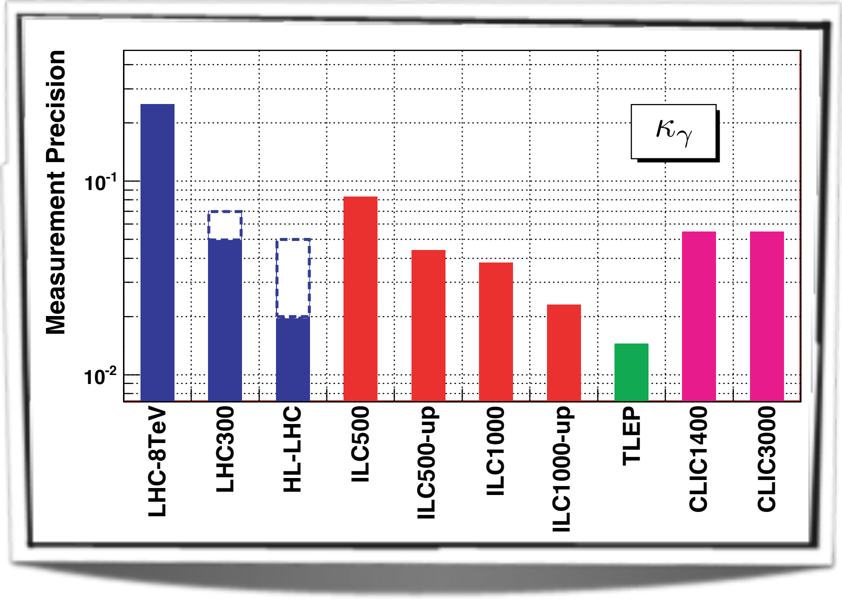
New physics in loops

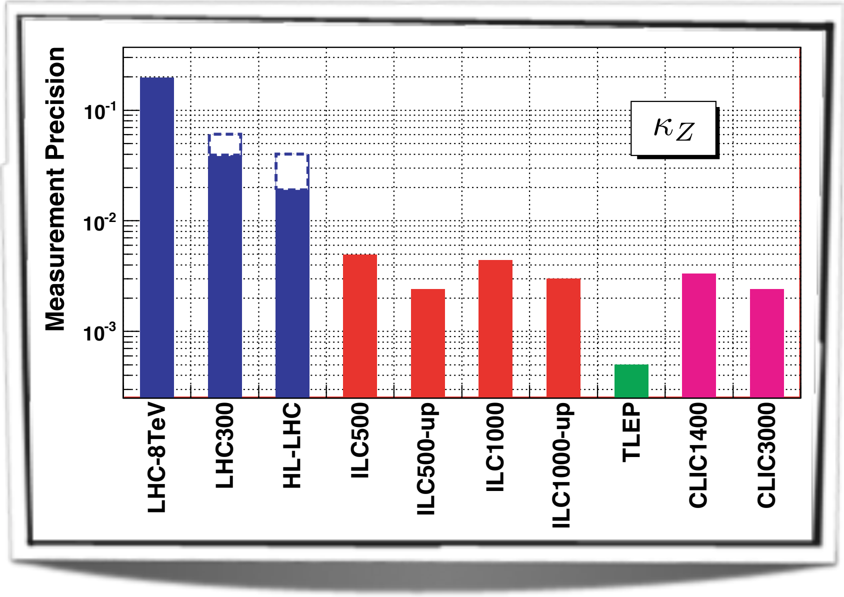
Katz, Perelstein '14

new particles, e.g. scalars, coupled to the Higgs without affecting its tree-level potential

$$V \propto \kappa |\Phi|^2 |H|^2$$







colored scalars
⇓
O(20%) deviation in h→gg

(8%LHC$_{14}$, 5%HL-LHC,1%ILC,<1%TLEP)

electrically charged scalars
⇓
O(5%) deviation in h→$\gamma\gamma$

(5%LHC$_{14}$, 2%HL-LHC,2%ILC,1%TLEP)

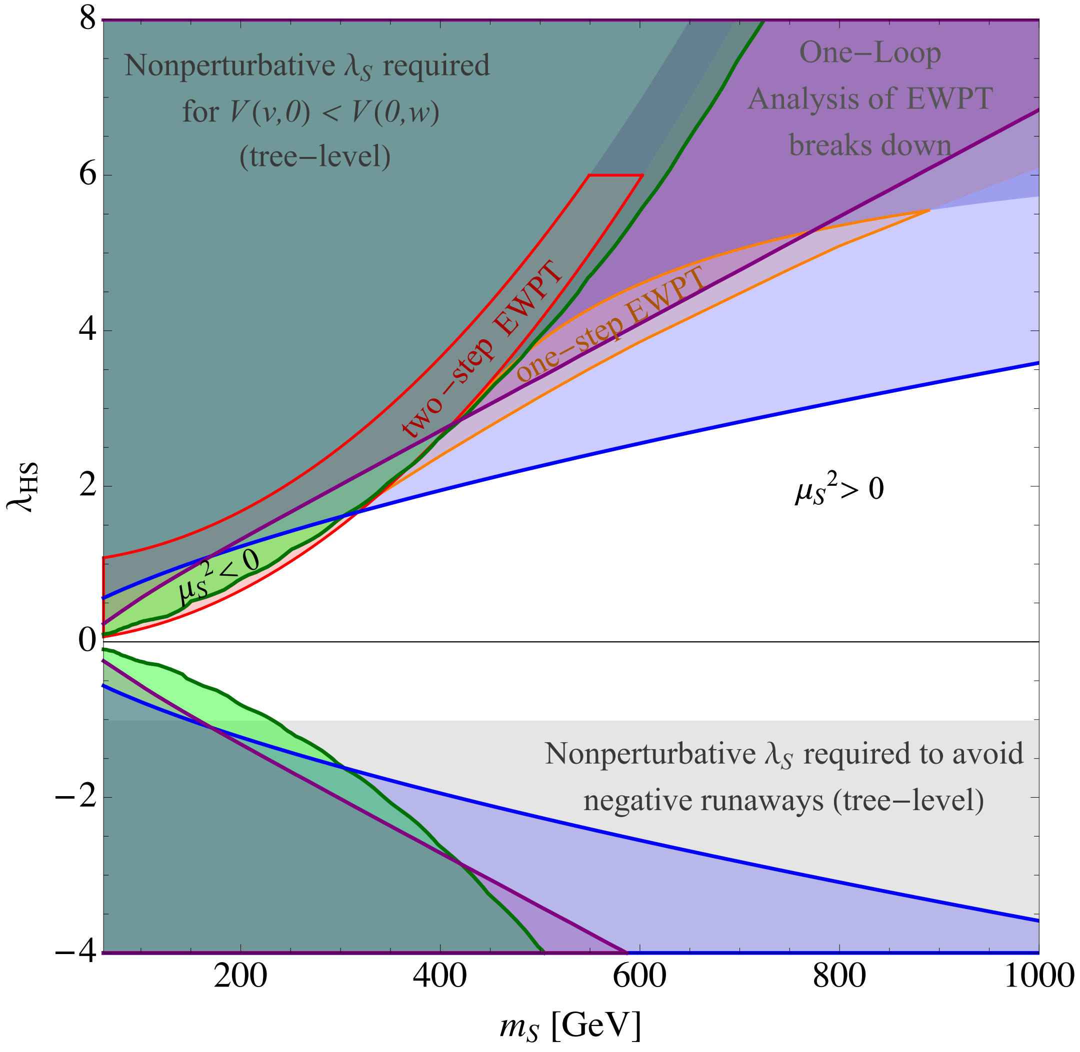
SM neutral scalars
⇓
O(1%) deviation in σ(ee→Zh)

(10%LHC$_{14}$, 2%HL-LHC,0.25%ILC,0.05%TLEP)

Minimal stealthy model for a strong EWPT

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

Unmixed SM+S. No exotic higgs decays, no higgs-singlet mixing, no EWPO, ...



Two regions with strong EWPT

Only Higgs Portal signatures:

h*→SS direct production

Higgs cubic coupling

σ(Zh) deviation (> 0.6% @ TLEP)

100 TeV collider could cover *entire* parameter space.

TLEP (super ILC) can cover *some* of parameter space.

Potential complimentarily!

1409.0005 DC, Patrick Meade, Tien-Tien Yu

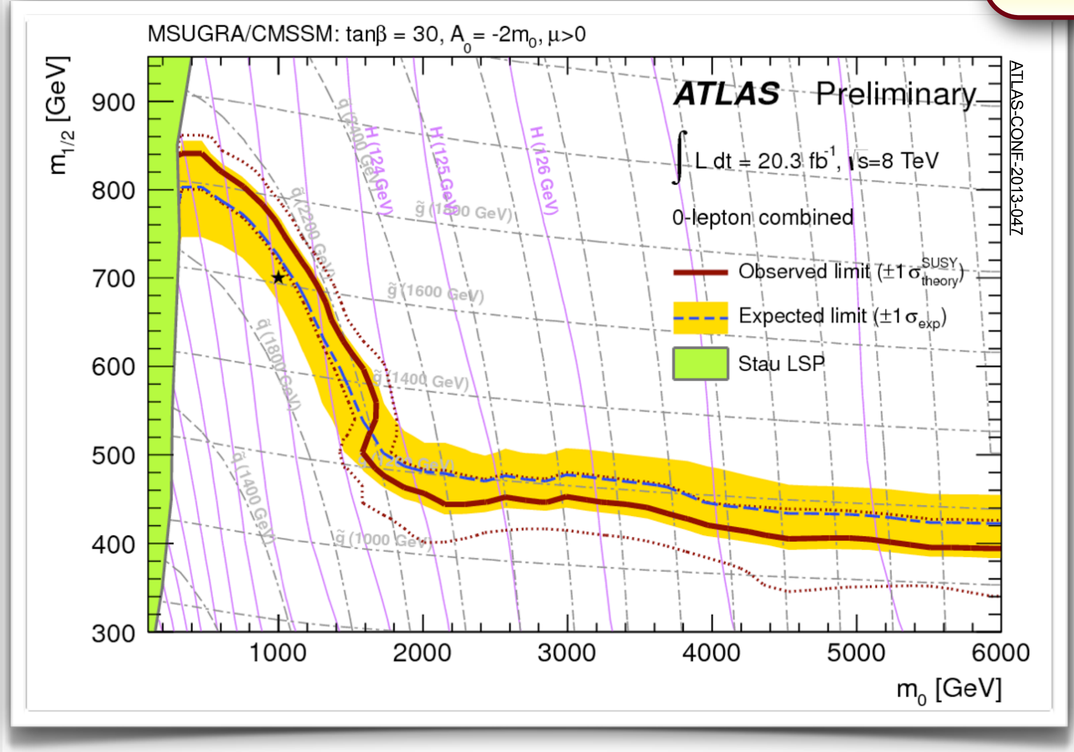
5

Searching for New Physics directly

Cornering SUSY parameter space

Dissertori @ ECFA-LC ‘14

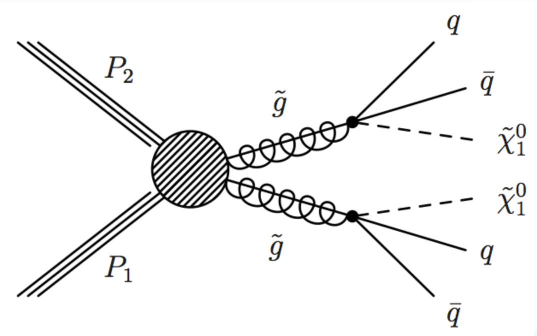
in the context of a concrete model, here MSUGRA/cMSSM

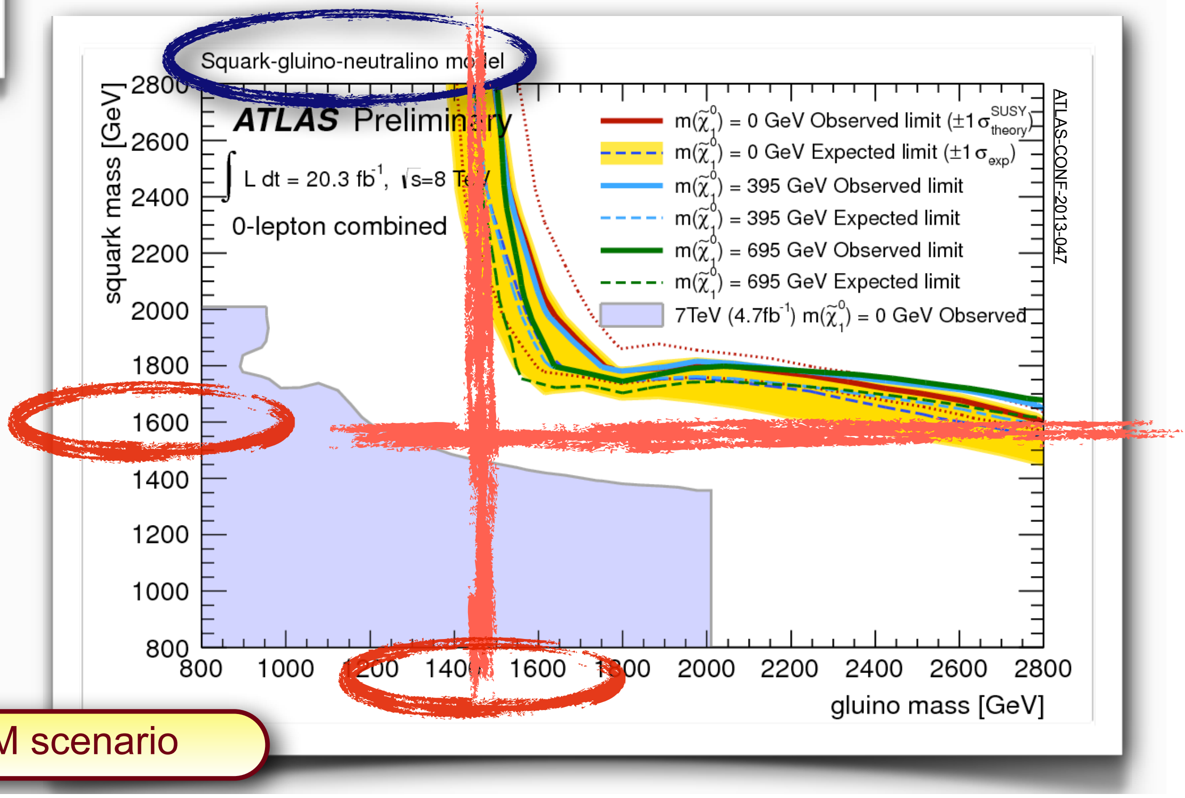


here: example of scenario compatible with a low-mass Higgs as recently discovered

- **eg. for m(squark) = m(gluino), exclude below ~1800 GeV**
- these searches typically target large M_{eff} and large difference m(SUSY) - m(LSP)
- the very inclusive searches keep sensitivity even for m(LSP) up to several hundreds of GeV (at some stage trigger-constrained)

- recently also targeting more compressed spectra and higher jet multiplicities

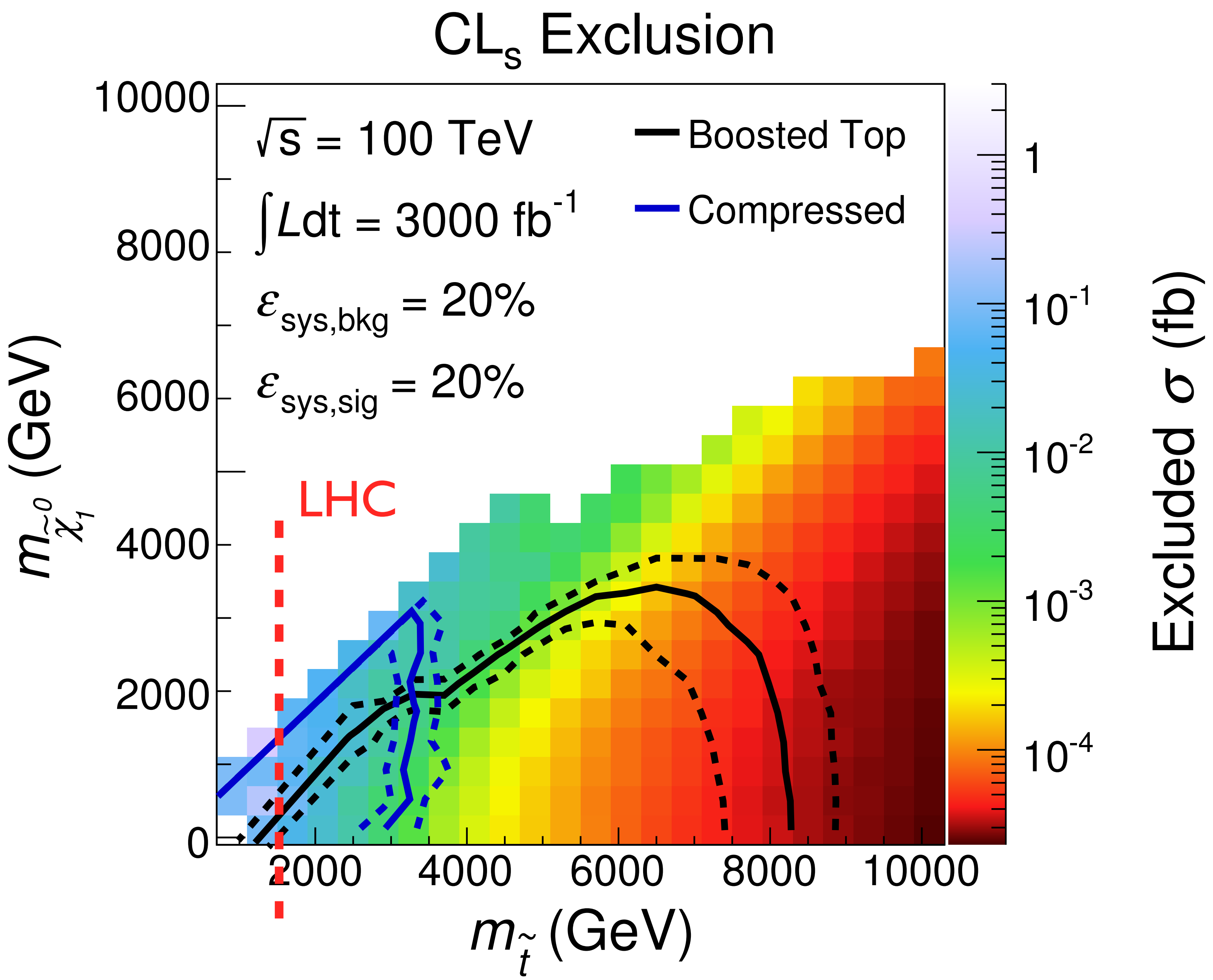




in the context of a simplified MSSM scenario

These bounds are not “robust” and don’t exclude weak scale SUSY but call for non-minimal models

Pushing the boundaries



Cohen, d'Agnolo, Hance, Lou, Wacker '14

Saving SUSY

Should be priority #1

SUSY is Natural
but not plain vanilla

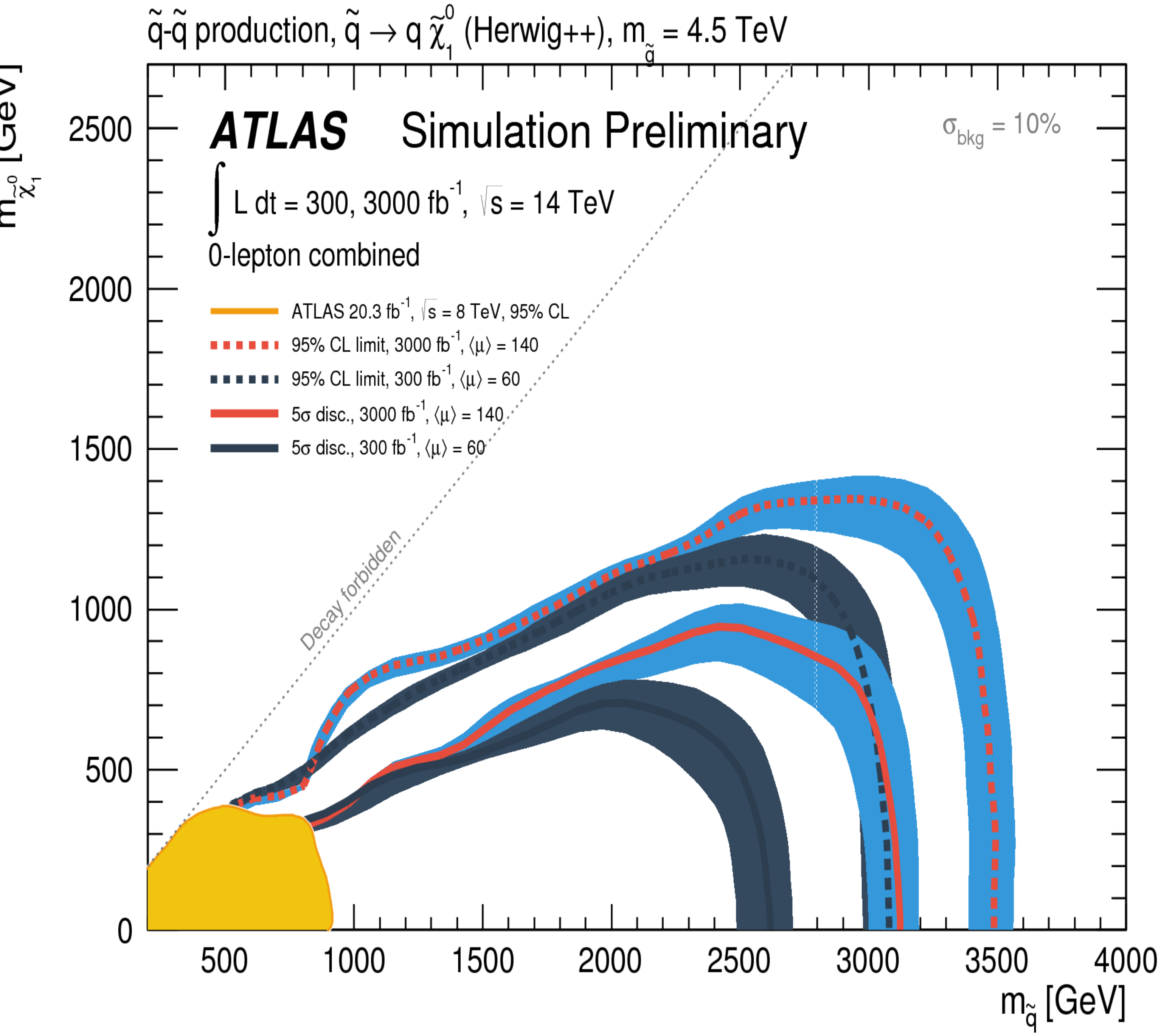
- ~~CMSSM~~
- pMSSM
- NMSSM
- Hide SUSY, e.g. smaller phase space
  - reduce production (eg. split families)
    Mahbubani et al
  - reduce MET (e.g. ~~R-parity~~, compressed spectrum)
    Csaki et al
  - dilute MET (decay to invisible particles with more invisible particles)
  - soften MET (stealth susy, stop -top degeneracy)
    Fan et al

Good coverage of

hidden natural susy

- mono-top searches (DM, flavored naturalness - mixing among different squark flavors-, stop-higgsino mixings)
- mono-jet searches with ISR recoil (compressed spectra)
- precise tt inclusive measurement+ spin correlations

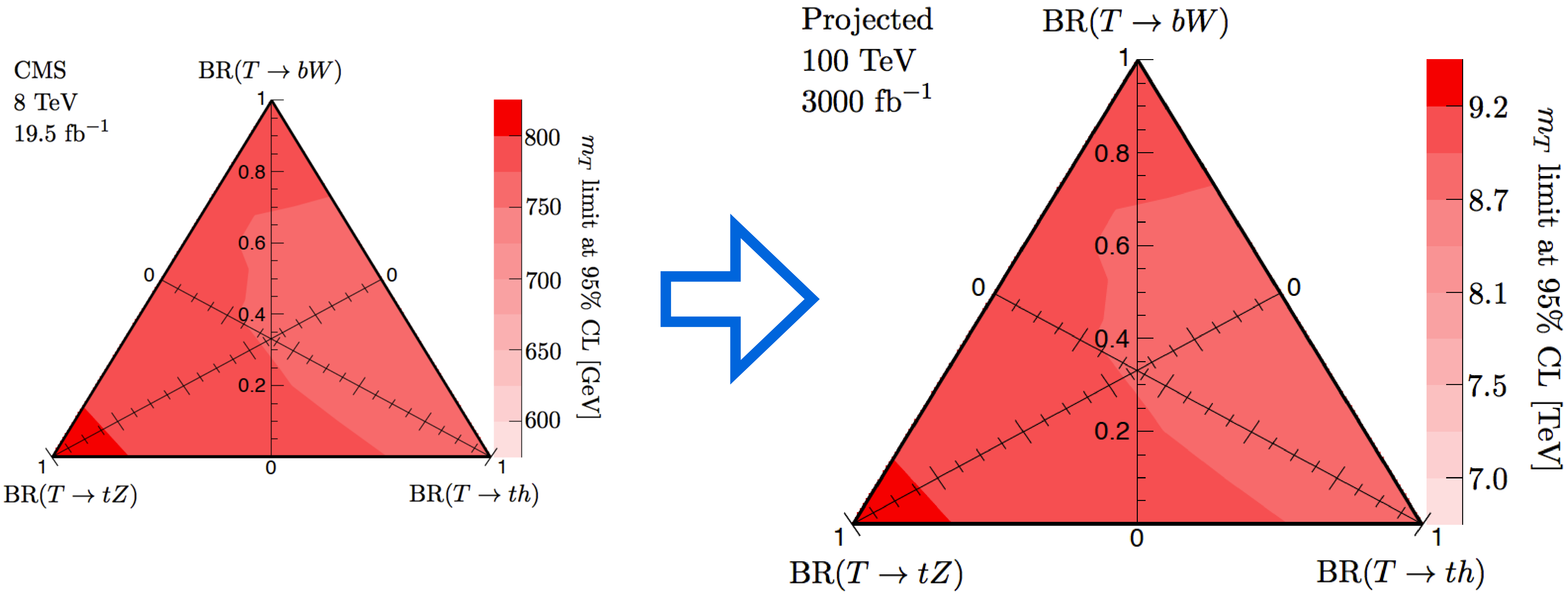
Fully exclude SUSY @ weak scale



HL-LHC can exclude squark up to 3.5 TeV but there are holes in particular for compressed spectra that are particularly relevant for DM.

ILC can complement and close these holes

Looking for fermionic top partners



- Room for improvement by using single production, boosted technique, etc.

LT Wang @ SUSY'15

6

Is there a loophole for TeV-scale new physics?

Naturalness & TeV scale new physics

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections
(others are not necessarily theoretically inconsistent
but they require some conspiracy at different scales)

Field	Symmetry as $m \to 0$	Implication
Spin-1/2 $m\Psi\bar{\Psi}$	$\Psi \to e^{i\theta}\Psi$ $\bar{\Psi} \to e^{-i\theta}\bar{\Psi}$ (chiral symmetry)	$\delta m \propto m$ **Natural!**
Spin-1 $m^2 A_\mu A^\mu$	$A_\mu \to A_\mu + \partial_\mu \alpha$ (gauge invariance)	$\delta m \propto m$ **Natural!**

courtesy to N. Craig @ Blois '15

The Higgs mass in the SM doesn't break any (quantum*) symmetry

* it does break classical scale invariance, as the running of the gauge couplings does too!

Naturalness principle @ work

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections
(others are not necessarily theoretically inconsistent
but they require some conspiracy at different scales)

Beautiful examples of naturalness to understand the need of "new" physics

see for instance Giudice '13 (and refs. therein) for a recent account

- the need of the positron to screen the electron self-energy: $\Lambda < m_e/\alpha_{\rm em}$
- the rho meson to cutoff the EM contribution to the charged pion mass: $\Lambda^2 < \delta m_\pi^2/\alpha_{\rm em}$
- the kaon mass difference regulated by the charm quark: $\Lambda^2 < \frac{\delta m_K}{m_K}\frac{6\pi^2}{G_F^2 f_K^2 \sin^2\theta_C}$
- the light Higgs boson to screen the EW corrections to gauge bosons self-energies
- ...
- new physics at the weak scale to cancel the UV sensitivity of the Higgs mass?

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by the time evolution/the age of the Universe

Graham, Kaplan, Rajendran '15

- Higgs mass-squared promoted to a field
- The field evolves in time in the early universe
- The mass-squared relaxes to a small negative value
- The electroweak symmetry breaking stops the time-dependence

Self-organized criticality

when the Higgs mass becomes negative, it
back-reacts and generates a potential barrier
that stops the evolution of the scanning field

Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics

see also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

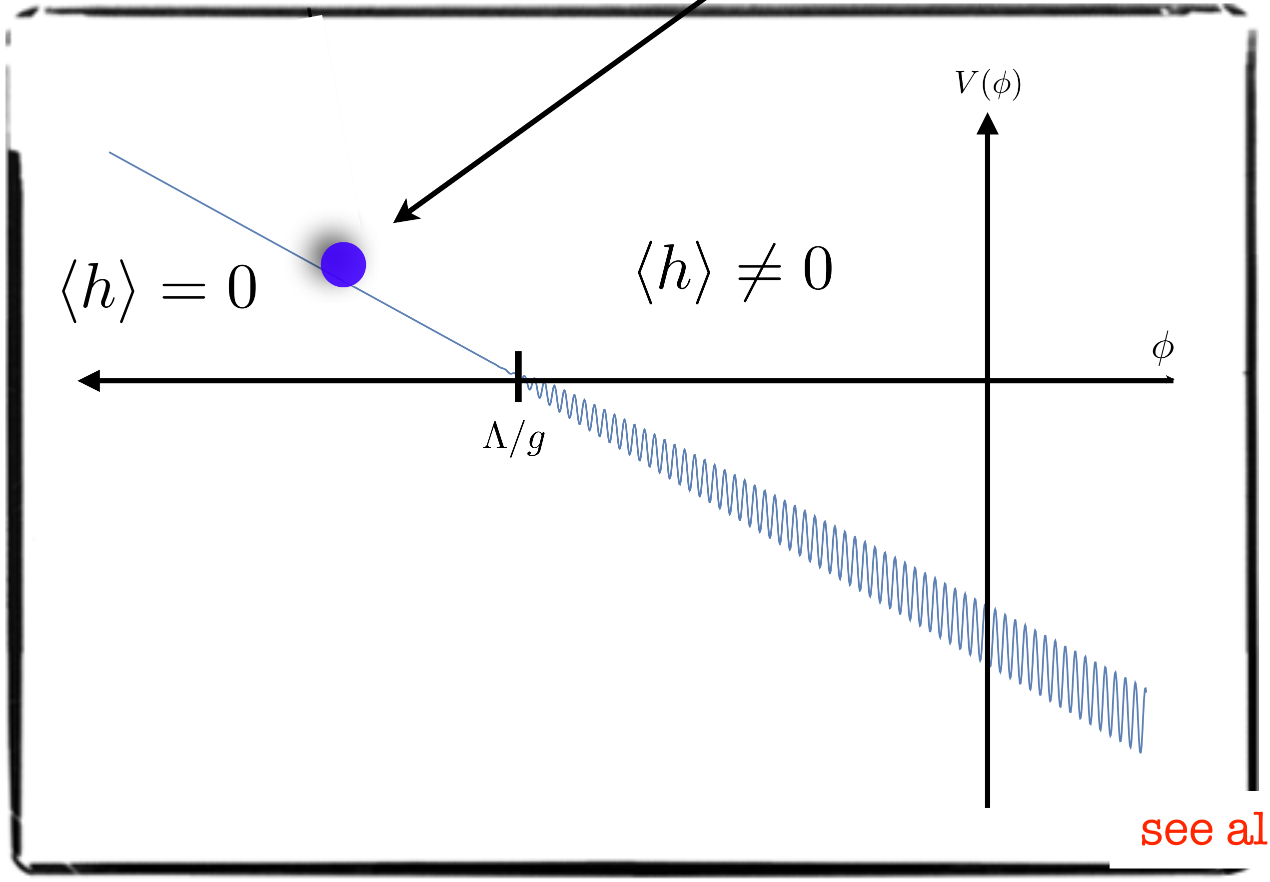
$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev

$$\Lambda^3_{\rm QCD}\, h\, \cos\frac{\phi}{f}$$



see also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

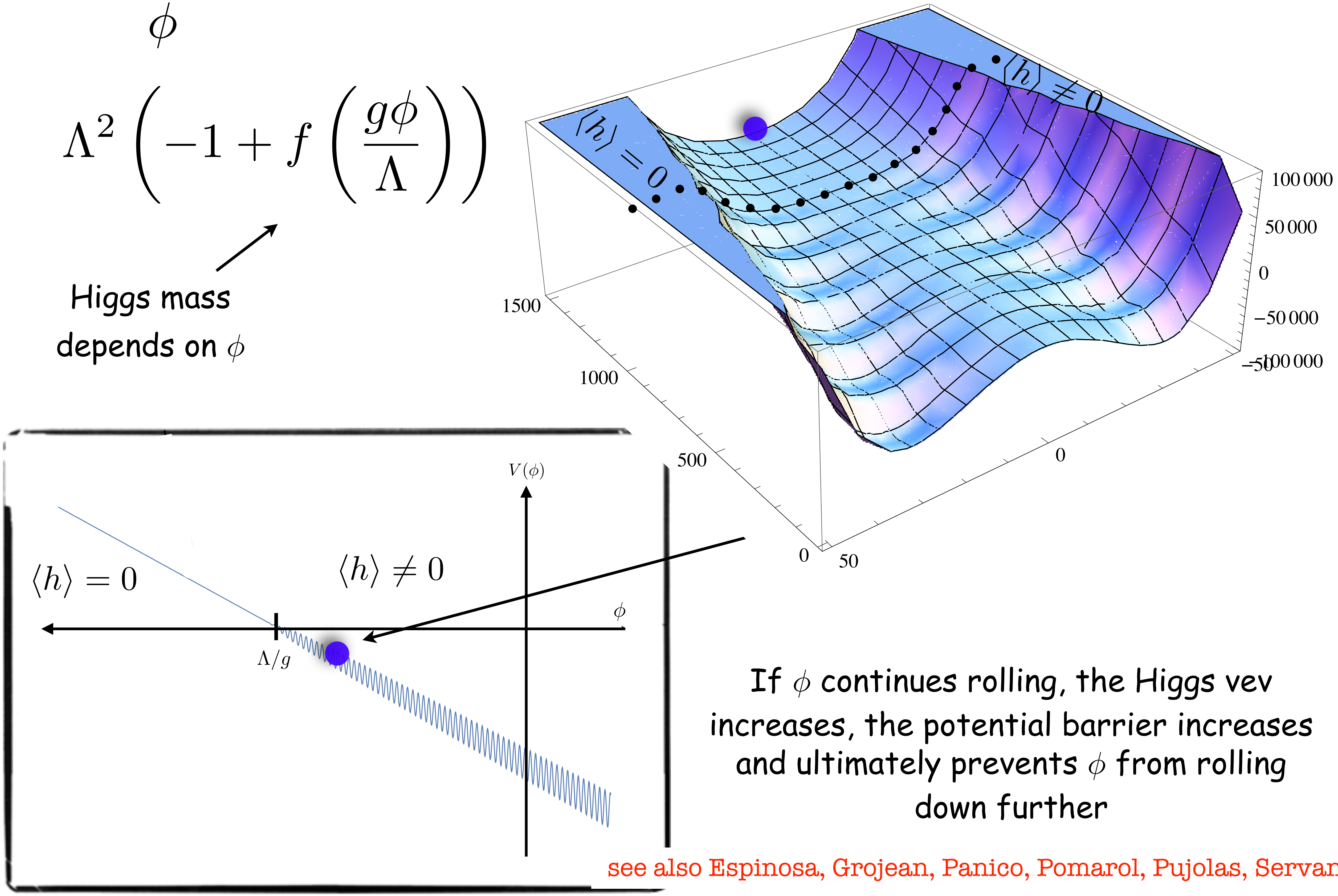
Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ

$$\Lambda^2 \left(-1 + f\left(\frac{g\phi}{\Lambda} \right) \right)$$

Higgs mass depends on ϕ



If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents ϕ from rolling down further

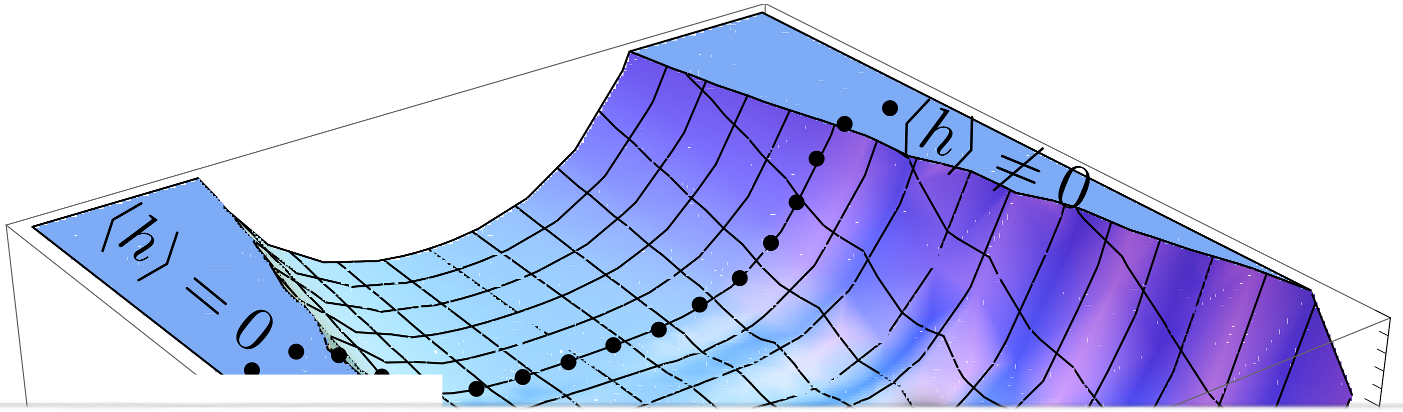
see also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran ’15

$$\phi$$

$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)$$



Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics

~interesting cosmology signatures~

◎ BBN constraints

◎ decaying DM signs in γ-rays background

◎ ALPs

◎ superradiance

~interesting signatures @ SHiP~

◎ production of light scalars
by B and K decays

see also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant ’15

Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

only BSM physics below Λ

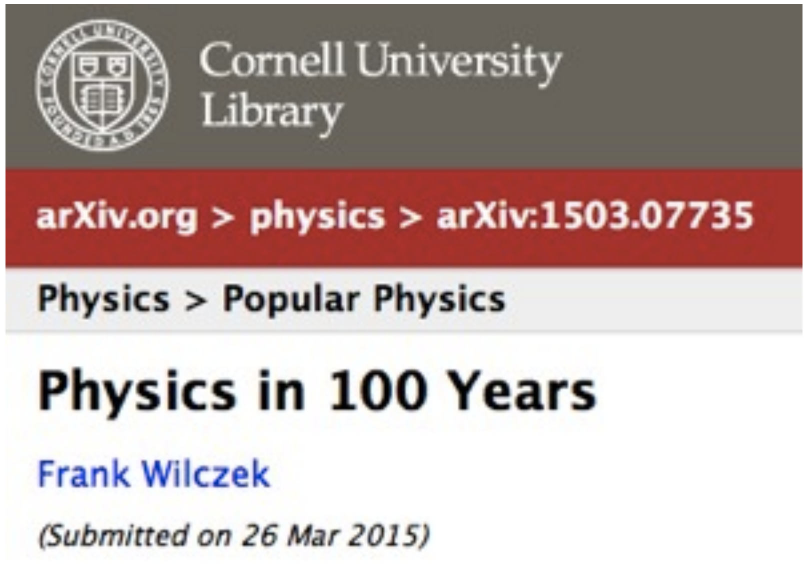
two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim (10^{-20} - 10^{2})\,\mathrm{GeV}$$

$$m_\sigma \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

interesting signatures in cosmology

Conclusions



Cornell University Library

arXiv.org > physics > arXiv:1503.07735

Physics > Popular Physics

Physics in 100 Years

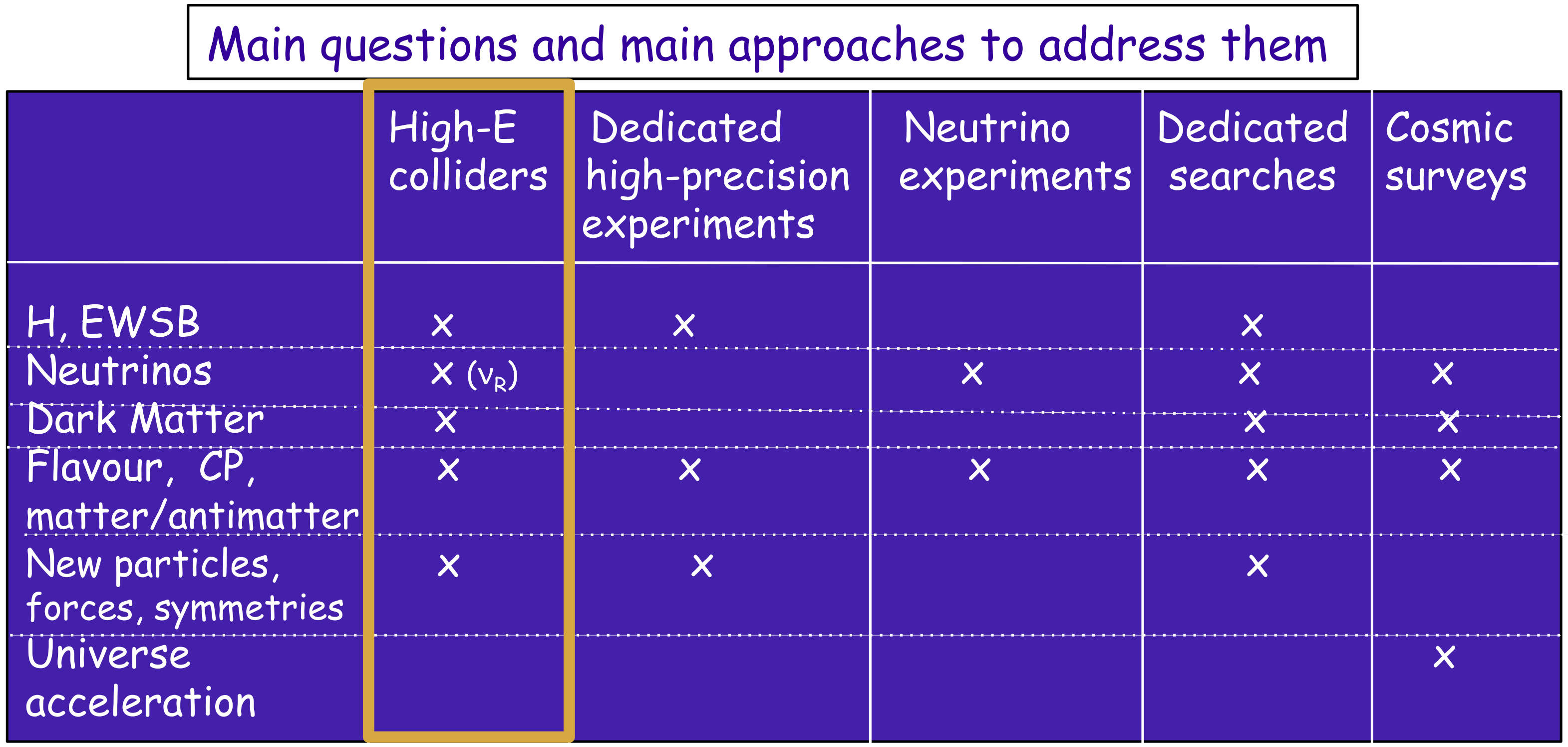
Frank Wilczek

(Submitted on 26 Mar 2015)

- *What are the weak points in our current understanding and practices?*
- *What are the growth areas in technique and capability?*
- *Where are the sweet spots where those two meet?*

F. Gianoti EPS '15

More than ever: importance of the synergy and complementarity of the experimental programme ⇚



Main questions and main approaches to address them

	High-E colliders	Dedicated high-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
H, EWSB	x	x		x	
Neutrinos	x (ν_R)		x	x	x
Dark Matter	x			x	x
Flavour, CP, matter/antimatter	x	x	x	x	x
New particles, forces, symmetries	x	x		x	
Universe acceleration					x

Combination of these complementary approaches is crucial to explore the largest range of E scales (directly and indirectly) and couplings, and properly interpret signs of new physics → hopefully build a coherent picture of the underlying theory.