Working Group Summary
Electroweak Interactions (Theory)

Wolfgang Altmannshofer
altmanwg@ucmail.uc.edu

WIN 2017,
UC Irvine,
June 19 - 24, 2017

The Electroweak Working Group

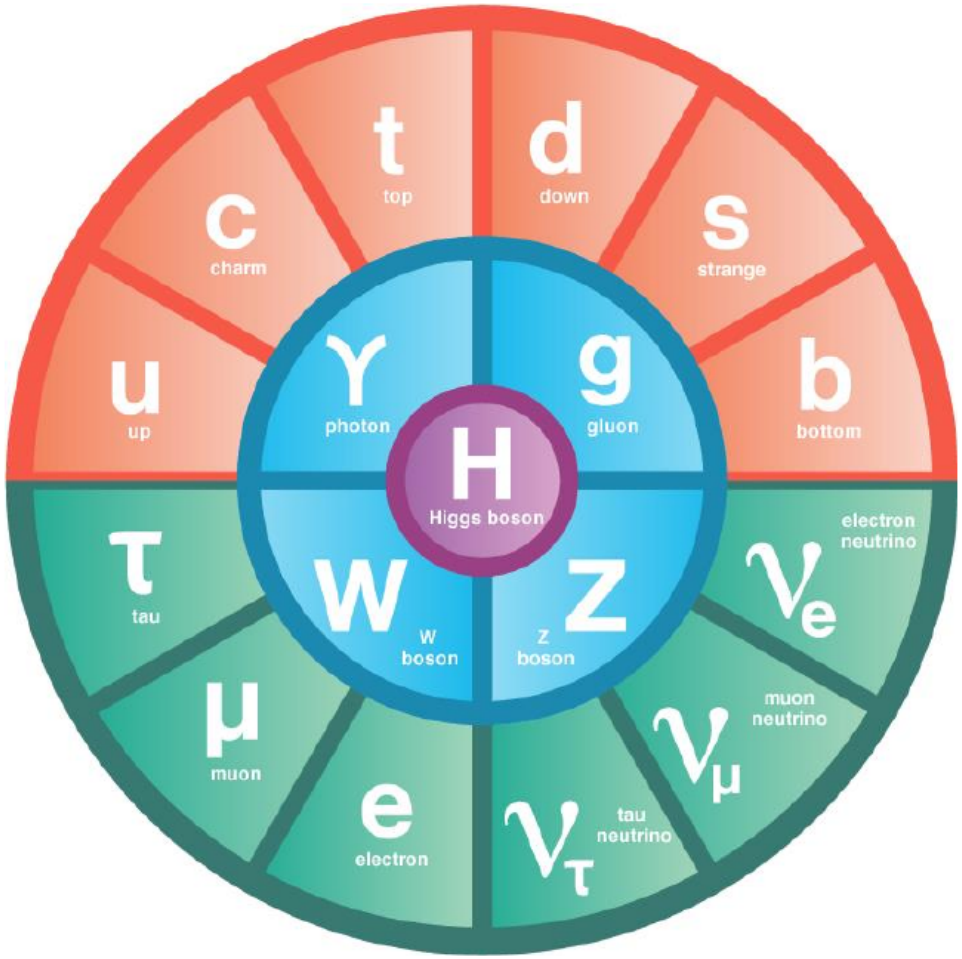
Woking Group Overview: New Physics at the EW Scale and Naturalness (Theory)	*Prof. JiJi FAN*	
Pacific Ballroom ABC, UC Irvine, Irvine, CA, USA		09:00 - 09:40
Working Group Overview: Electroweak Interactions (Experiment)	*Prof. Mayda VELASCO*	
Pacific Ballroom ABC, UC Irvine, Irvine, CA, USA		09:40 - 10:20
Developments in treating the SM as an EFT	*Dr. William SHEPHERD*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		11:20 - 11:50
Probing for anomalous Higgs-VV couplings in production and decay H→4l at CMS	*Jeffrey ROSKES*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		11:50 - 12:20
Heavy Neutrino Search from the Higgs decay	*Dr. Arindam DAS*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		12:20 - 12:50
QCD corrections to diboson processes	*Tobias NEUMANN*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		14:30 - 15:00
Precision Diboson Observables for the LHC	*Dr. Marat FREYTSIS*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		15:00 - 15:30
Multi-Boson production cross sections at CMS	*Mr. Daneng YANG*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		15:30 - 16:00
Cross section and coupling measurements with the ATLAS detector for the 125 GeV Higgs Boson	*Ms. Hannah HERDE*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		16:30 - 17:00
CMS Overview regarding Higgs Production Results	*Francesco FABOZZI*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		17:00 - 17:30
Measurements of the Higgs boson mass and its spin and CP properties with the ATLAS Detector	*Prof. Stephen SEKULA*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		17:30 - 18:00
Higgs Properties with the CMS detector	*Dr. roberto ROSSIN*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		18:00 - 18:30

Charged Higgs production in association with a W or a top	*Prof. Nikolaos KIDONAKIS*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		11:30 - 12:00
CMS Higgs and New Physics	*Dr. Pierluigi BORTIGNON*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		12:00 - 12:30
Search for rare or non-standard production and decay modes of the Higgs boson with the ATLAS detector	*Prof. Dhiman CHAKRABORTY*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		12:30 - 13:00
CMS Double Higgs Searches	*Michael KROHN*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		14:30 - 15:00
ATLAS Higgs physics prospects at the high luminosity LHC	*Dr. Tulin VAROL*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		15:00 - 15:30
CMS Upgrade (Phase-I and Phase-II) with future prospects in terms of Higgs/electroweak measurements	*Petar MAKSIMOVIC*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		15:30 - 16:00
Illuminating Electroweak States at Hadron Colliders	*Ahmed ISMAIL*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		16:30 - 17:00
Searches for electroweak production of supersymmetric gauginos and sleptons and R-parity violating and long-lived signatures with the ATLAS detector	*Mr. Ruo yu SHANG*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		17:00 - 17:30
Searches for squarks and gluinos with the ATLAS detector	*Dr. Vakhtang TSISKARIDZE*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		17:30 - 18:00
Charged-lepton decays from soft flavour violation in a two-Higgs doublet seesaw model	*Ms. Elke AEIKENS*	
Emerald Bay B, UC Irvine, Irvine, CA, USA		18:00 - 18:30
Electroweak Precision Physics	*Prof. Jens ERLER*	
Emerald Bay A, UC Irvine, Irvine, CA, USA		09:00 - 09:45
Constraining Higgs couplings using Bs -> mu mu	*Dr. Xing-Bo YUAN*	
Emerald Bay A, UC Irvine, Irvine, CA, USA		09:45 - 10:10

2 overview talks + 13 experimental talks + 9 theory talks

Thank you for all the fantastic contributions!

The Standard Model of Particle Physics



The Hierarchy Problem

huge hierarchy between the electroweak scale and the Planck scale that is not stable under radiative corrections

$$v^2/M_{\text{Pl}}^2 \sim 10^{-34}$$

The Hierarchy Problem

huge hierarchy between the electroweak scale and the Planck scale that is not stable under radiative corrections

$$v^2/M_{\rm Pl}^2 \sim 10^{-34}$$

rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

The Hierarchy Problem

huge hierarchy between the electroweak scale and the Planck scale that is not stable under radiative corrections

$$v^2/M_{\rm Pl}^2 \sim 10^{-34}$$

rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

single event sensitivity of mu2e

The Hierarchy Problem

huge hierarchy between the electroweak scale and the Planck scale that is not stable under radiative corrections

$$v^2/M_{\mathrm{Pl}}^2 \sim 10^{-34}$$

rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17
. . .	. . .
Your house getting hit by a meteorite and you being struck by lightning twice, all by the end of this talk	10^{-34}

single event sensitivity of mu2e

Lessons from the LHC so far

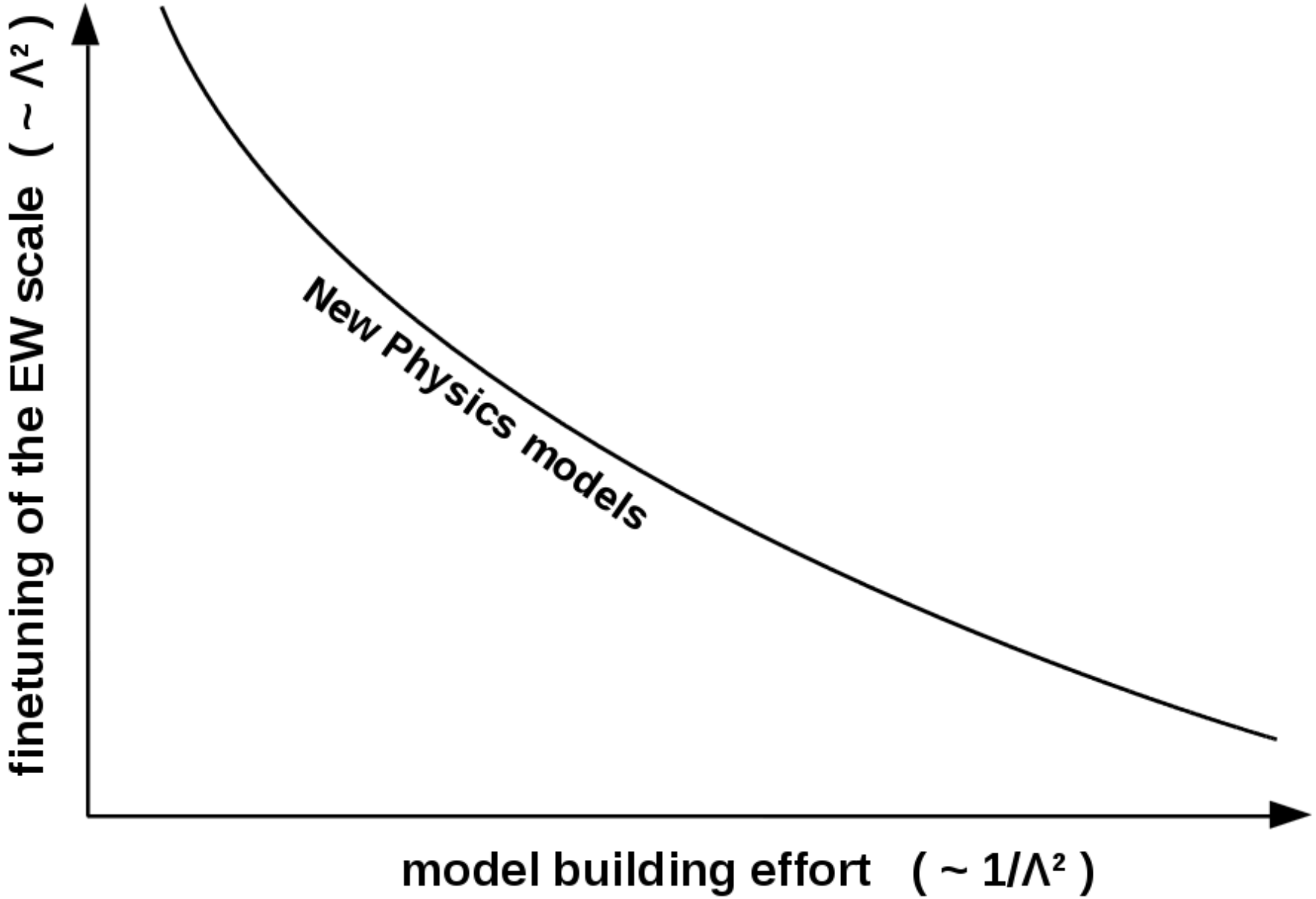
Null results teach us valuable lessons: traditional natural scenarios with electroweak fine-tuning no worse than 10% are very cornered.

Does it mean paradigm shifting?

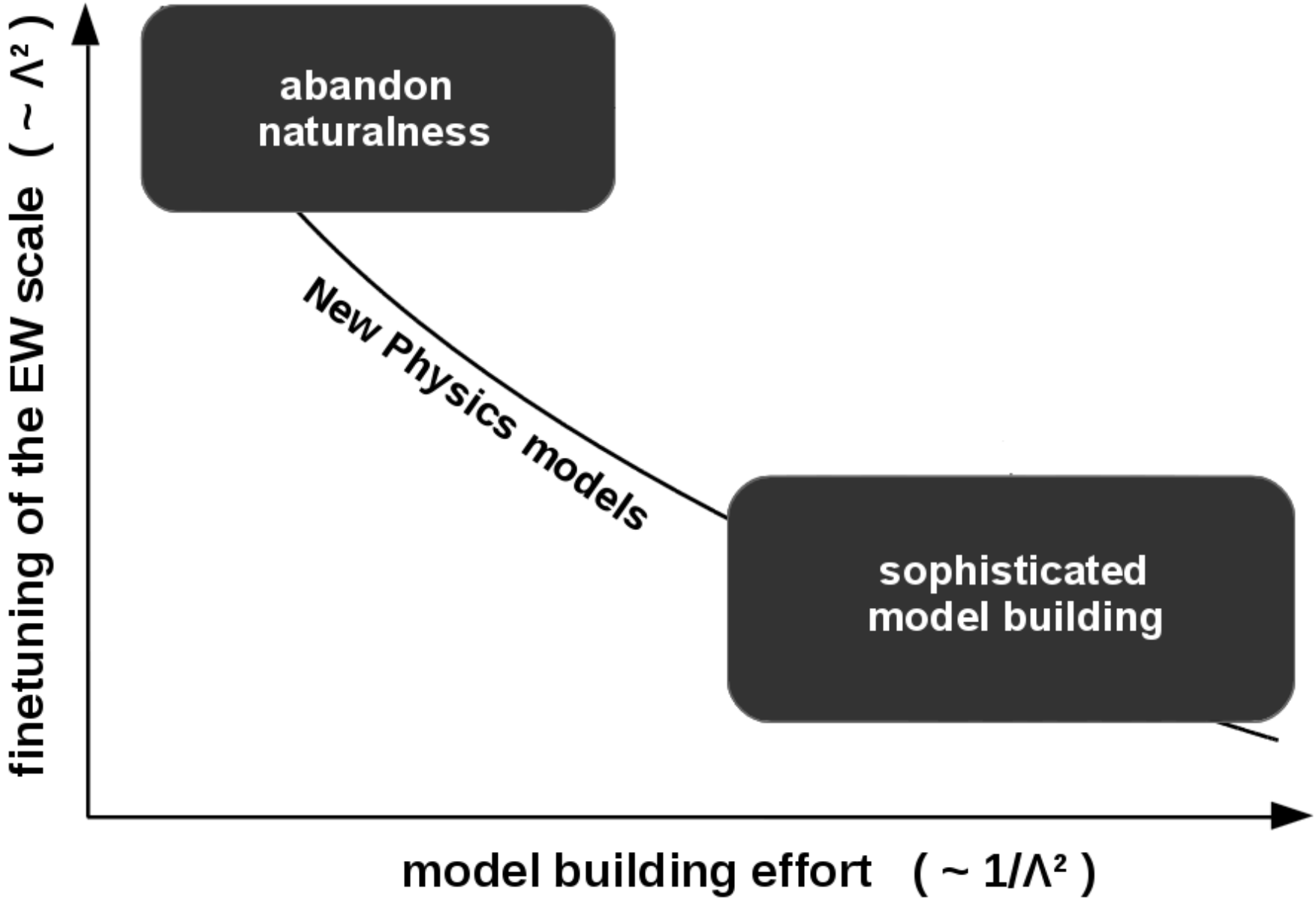
Could be. It could be a dramatically new paradigm or a mild paradigm shift: meso-tuning scenario such as heavy SUSY scenario with susy scalars ~ (10 - 100) TeV (sufficient to explain the Higgs mass). Yet the bottom of the spectrum including the gluino and the electroweak sector could still be light and be searched for at the LHC.

[JiJi Fan]

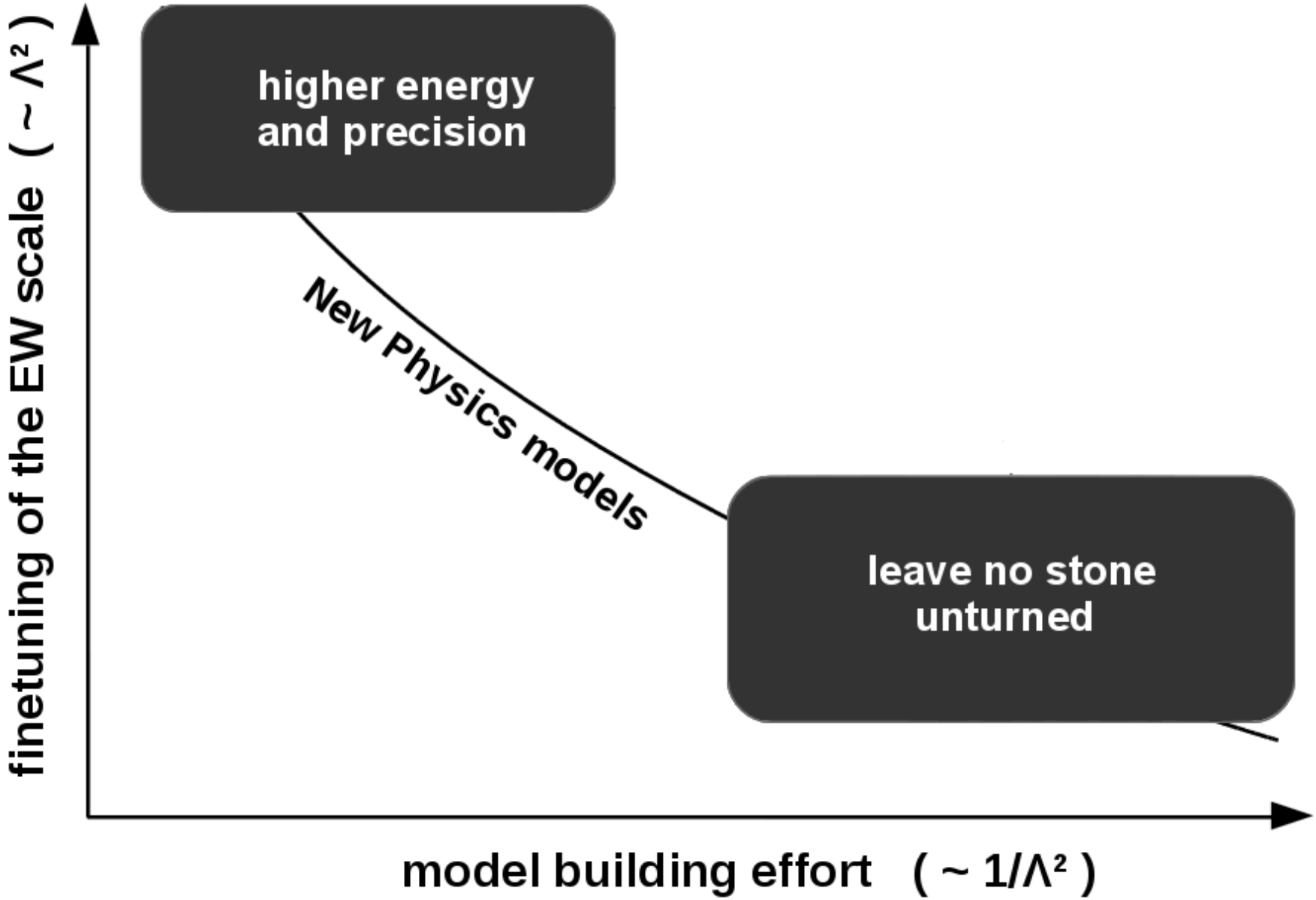
New Physics Parameter Space



New Physics Parameter Space



New Physics Parameter Space



Two Candidate Theories

Higgs EFT

- That's some "Higgs-like scalar"
- If that's not THE Higgs then something else breaks EWS
- Expand EW sector a la χPT
- Scalar contributions may be suppressed by a lower scale, include them to higher orders

Standard Model EFT

- That's the Higgs
- We can insist on full EW symmetry at the weak scale
- Any new physics appears suppressed by a large scale
- Expand straightforwardly in operator dimension

[Will Shepherd]

SMEFT Developments

- Fits to LEP and Higgs data
- Development of multiple bases and translation tools
- Revitalization of matching techniques
  - Automating Feynman 1-loop matching
  - CDE techniques in functional matching
- Loop corrections to precise observables

[Will Shepherd]

New Search Strategies for Elusive Light New Physics

light electroweak states with small mass splitting

$$pp \to \chi^0 \chi^\pm \to \chi^0 \chi^0 W^*$$

For mass differences between ~0.2-5 GeV, leptons from χ^+ decay are too soft to see in detector

But decay is prompt enough to avoid disappearing tracks!

(unless disappearing track search is improved)

Mahbubani et al., 1703.05327
Fukuda et al., 1703.09675

canonical example: Higgsinos (doublets)

8 TeV monojet limits

$$\text{ATLAS} : m_\chi > 103\,\text{GeV}\ (\text{SR4})$$
$$\text{CMS} : m_\chi > 73\,\text{GeV}\ (\text{SR5}),$$

Han et al., 1401.1235

→ alternative: go back to mono-X searches

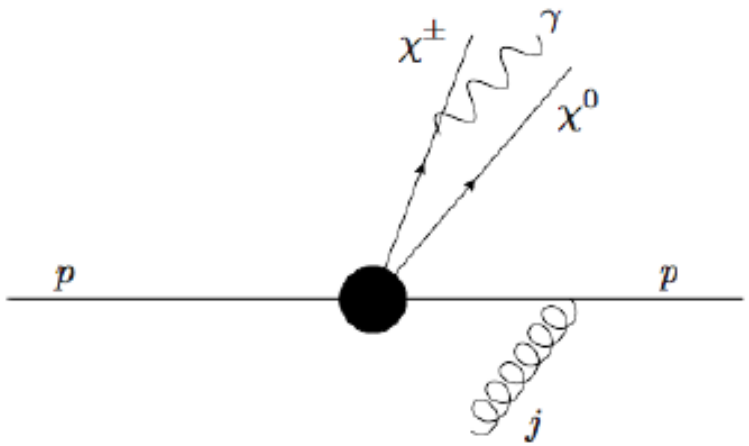
Current limits comparable to LEP

[Ahmed Ismail]

Photon final-state radiation

Take advantage of photon radiation by boosting

In monojet events with $p_T(j) > m_\chi$, jet recoils against missing energy + any radiation

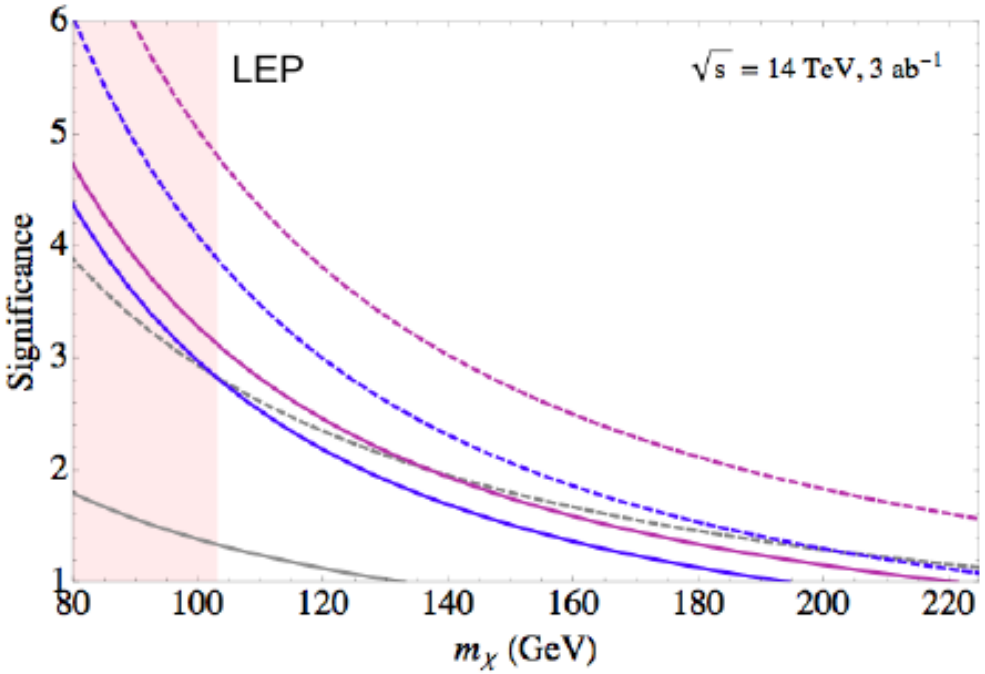


Pay statistical price of α for radiation, but benefit from low backgrounds and extra kinematic handle in γ + j + MET

[Ahmed Ismail]

Results - Higgsino

Adding photon to monojet final state helps, except in the case of low statistics (high mass) with significantly improved systematic uncertainties



Photon + jet + MET

Monojet

Combination

Solid: 5% systematics
Dashed: 2% systematics

[Ahmed Ismail]

Still Many Questions about the Higgs

Does the Higgs give mass to all SM fermions?

Is the Higgs vacuum stable?

Is the Higgs a portal to Dark Matter?

Is the Higgs related to Baryogenesis?

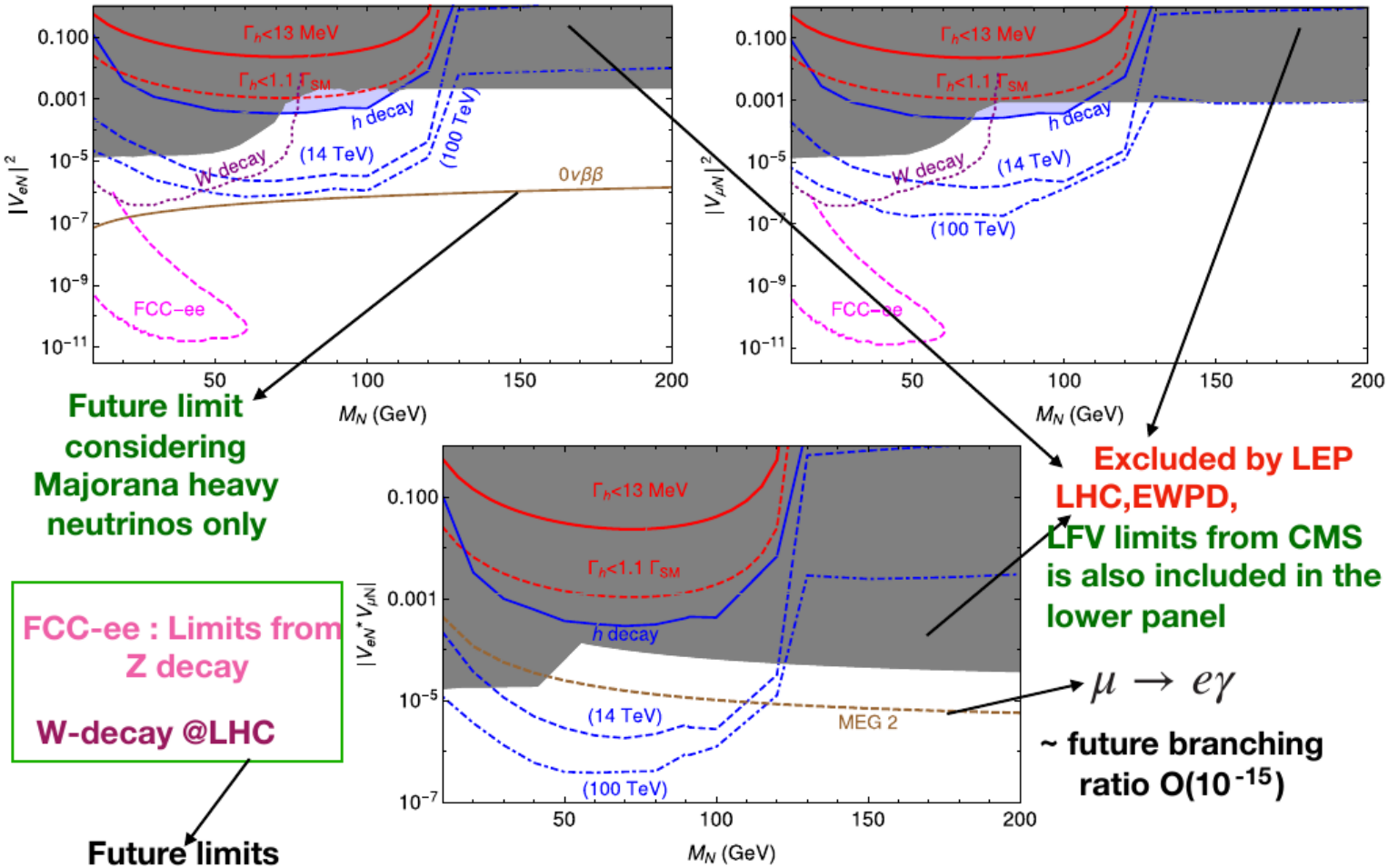
Is the Higgs connected to Dark Energy?

Is there something that stabilizes the Higgs mass against Quantum corrections?

Are there more Higgs bosons?

Probing Sterile Neutrinos with Higgs Decays

$$h \to \nu N \to 2\nu 2\ell$$



Future limit considering Majorana heavy neutrinos only

FCC-ee : Limits from Z decay

W-decay @LHC

Future limits

Excluded by LEP LHC,EWPD,

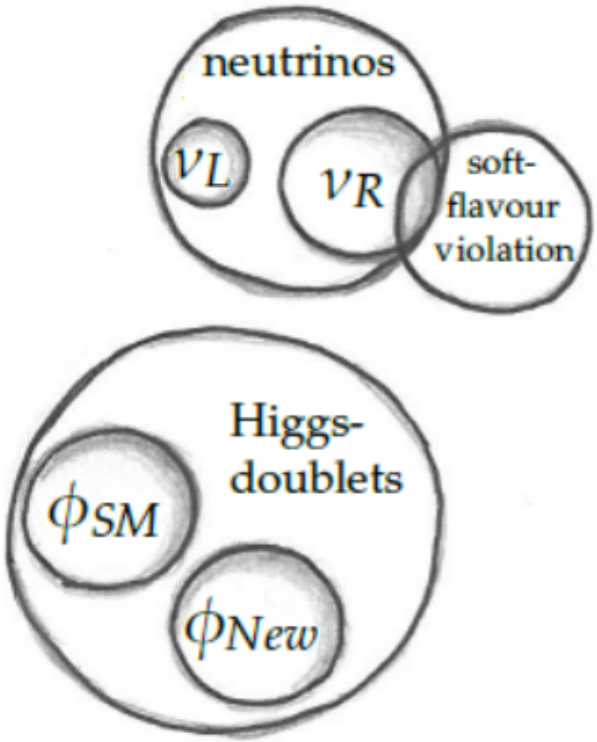
LFV limits from CMS is also included in the lower panel

$\mu \to e\gamma$

~ future branching ratio O(10^{-15})

[Arindam Das]

An Extended Higgs Sector for Neutrinos



- explain tiny ν–masses
- additional particles: φ_3, φ_4, ν_R
- elegant symmetry:
  - no FCNI at tree-level
  - one-loop contributions are finite
  - explains U_{PMNS} & V_{CKM} different

open questions:

- model experimental testable in FCNIs
- solves the exp.-theor. discrepancy of μ–MDM?

Yes!

[Elke Aeikens]

Higgs FCNC: exp

e	μ	τ	
e^+e^- collider	$\mathcal{B} < 0.035\%$	$\mathcal{B} < 0.61\%$	e
	$\mu < 2.8$	$\mathcal{B} < 0.25\%$	μ
		$\mu = 1.1 \pm 0.2$	τ

u	c	t	
		$\mathcal{B} < 0.55\%$	u
		$\mathcal{B} < 0.40\%$	c
		$\mu_{tth} = 2.3^{+0.7}_{-0.6}$	t

d	s	b	
			d
			s
		$\mu = 0.70^{+0.29}_{-0.27}$	b

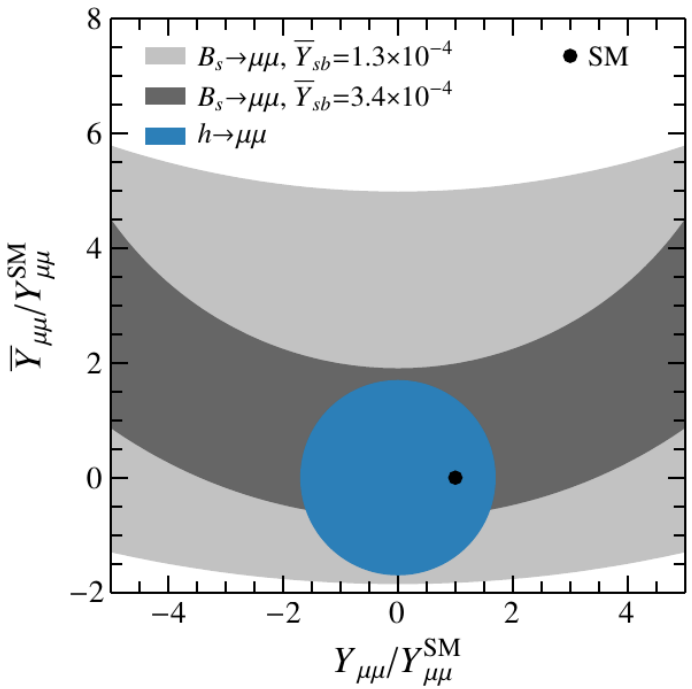
◀ direct search

▼ indirect study

McWilliams, Li 1981
Shanker 1982
Barr, Zee 1990
Kanemura, Ota, Tsumura 2006
Davidson, Grenier 2010
Golowich et al 2011
Buras, Girrbach 2012
Blankenburg, Ellis, Isidori 2012
Harnik, Kopp, Zupan 2013
Gorbahn, Haisch 2014
Celis, Cirigliano, Passemar 2014
... ...

[Xing-Bo Yuan]

Complementarity of Direct and Indirect Searches



- light gray: 95% CL allowed with $\bar{Y}_{sb} = 1.4 \times 10^{-4}$
- dark gray: 95% CL allowed with $\bar{Y}_{sb} = 3.4 \times 10^{-4}$
- blue: $\mu_{\mu\mu} < 2.8$ at 95% CL ATLAS Run I + II
- $|\bar{Y}_{sb}| = 3.4 \times 10^{-4}$: maximal value allowed by $B_s - \bar{B}_s$

[Xing-Bo Yuan]

The Need for Precision

Searches for New Physics and precision measurements at the LHC rely on detailed quantitative descriptions of QCD and EW processes

- Precision knowledge of PDFs
- Sophisticated Monte Carlo tools
- Higher order corrections:
  NLO, NNLO, N^3LO in QCD,
  NLO electroweak,
  resummation, ...

  (both for SM processes and for new physics processes!)
- ...

Precise SM Predictions for Diboson Production

LHC diboson production: theory perspective

Diboson processes are DY-like $q\bar{q}$ initiated at LO.
New channels gq at NLO, and gg, qq' at NNLO.

NNLO QCD is absolutely mandatory for

- .. a somewhat reliable uncertainty estimation by scale var.
- .. competing with %-level experimental precision

Let's not forget: numerically $\alpha_s^2 \simeq \alpha$
NLO (QCD + EW) effects for most processes: '15 '16

(Biedermann, Denner, Dittmaier, Hofer, Jaeger, '16); (Biedermann, Billoni, Denner, Dittmaier, Hofer, Jaeger, Salfelder '16)

(Denner, Dittmaier, Hecht, Pasold '15, '16); ...

Let's also not forget: Resummation (p_T, jettiness, jet-veto, ..), PS

(Dawson, Jaiswal, Li, Ramani, Zeng '16); (Wang, Li, Liu, Shao, Li '13); (Grazzini, Kallweit, Rathlev, Wiesemann '15); (Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '14); ...

[Tobias Neumann]

Sophisticated Methods are Used

NNLO is still highly difficult!

Despite enormous progress in..

- Loop calculation techniques: calculate master integrals
  - Revival of differential equations: "canonical form" *(Henn '13)*
  - Numerical techniques (MB, Sector Decomposition)
    e.g. NLO HH *(Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke '16)*
- Availability of 2-loop VV amplitudes *(Gehrmann, Tancredi '12); (Caola, Henn, Melnikov, Smirnov, Smirnov '14); (Gehrmann, Manteuffel, Tancredi '15)*
- Subtraction techniques to combine IR singular pieces
  - Local: Sector Decomposition based *(Czakon '10, '11); (Boughezal, Melnikov, Petriello '12)* , Antennae *(Gehrmann-De Ridder, Gehrmann, Glover '05); (Currie, Glover, Wells '13)*, ColorFull *(Del Duca, Somogyi, Tramontano, Troscanyi '15)*
  - Global (slicing): q_t *(Catani, Grazzini '07)*, N-jettiness *(Gaunt, Stahlhofen, Tackmann, Walsh '15); (Boughezal, Liu, Petriello '15)*
- Computational advancements
- ...

[Tobias Neumann]

Independent Cross Checks are Crucial

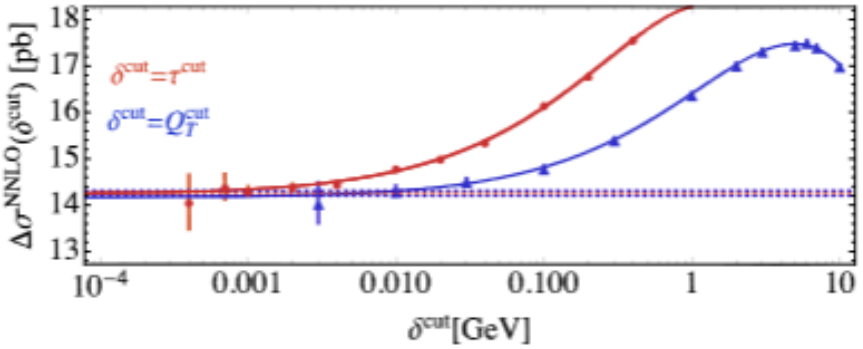
Slicing example: $\gamma\gamma$ at NNLO

σ[fb]	LO	NLO	NNLO
$\mu_F = \mu_R = m_{\gamma\gamma}/2$	5045 ± 1	26581 ± 23	45588 ± 97
$\mu_F = \mu_R = m_{\gamma\gamma}$	5712 ± 2	26402 ± 25	43315 ± 54
$\mu_F = \mu_R = 2m_{\gamma\gamma}$	6319 ± 2	26045 ± 24	41794 ± 77

(Catani, Cieri, de Florian, Ferrera, Grazzini '11)

σ[fb]	LO	NLO	NNLO
$\mu_F = \mu_R = m_{\gamma\gamma}/2$	5043 ± 1	26578 ± 13	42685 ± 35
$\mu_F = \mu_R = m_{\gamma\gamma}$	5710 ± 1	26444 ± 12	40453 ± 30
$\mu_F = \mu_R = 2m_{\gamma\gamma}$	6315 ± 2	26110 ± 13	38842 ± 27

MCFM: (Campbell, Ellis, Li, Williams '16)



σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = M_{\gamma\gamma}/2$	5045 ± 1	26581 ± 23	42238 ± 330
$\mu_F = \mu_R = M_{\gamma\gamma}$	5712 ± 2	26402 ± 25	40269 ± 250
$\mu_F = \mu_R = 2M_{\gamma\gamma}$	6319 ± 2	26045 ± 24	38901 ± 310

Erratum (Catani, Cieri, de Florian, Ferrera, Grazzini '16)

[Tobias Neumann]

New High Precision Diboson Observables (1)

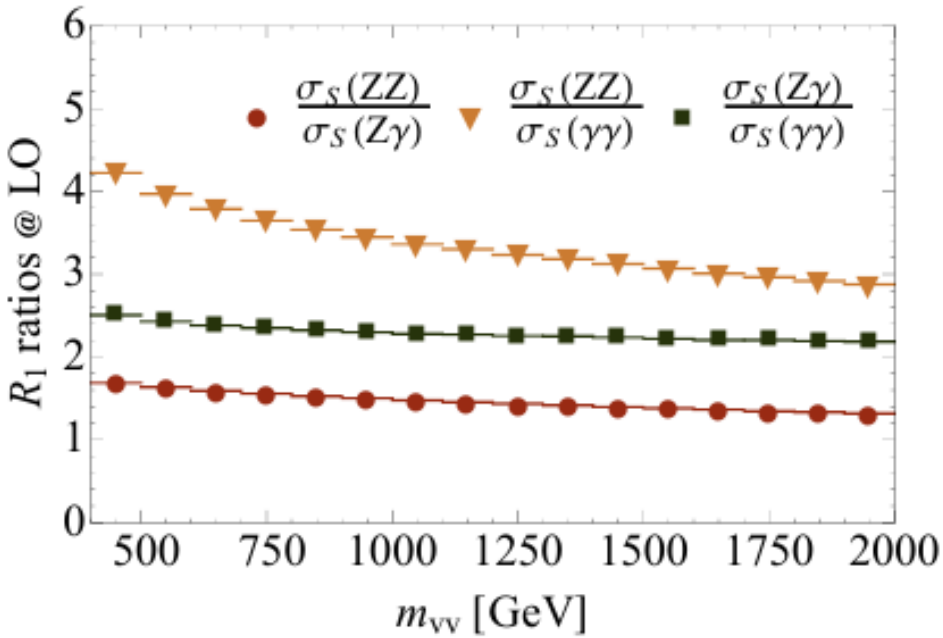
use the fact that electro-weak symmetry is approximately restored at high energy to define precision observables in di-boson production

$\gamma\gamma, Z\gamma, ZZ$

Ratio observables

$V_1^0 V_2^0$	$C_{12}^u \cdot 10^5$	$C_{12}^d \cdot 10^5$
$\gamma\gamma$	1.2	0.07
$Z\gamma$	2.2	0.7
ZZ	1.6	3.3

$u\bar{u}$ dominates – PDFs mostly cancel

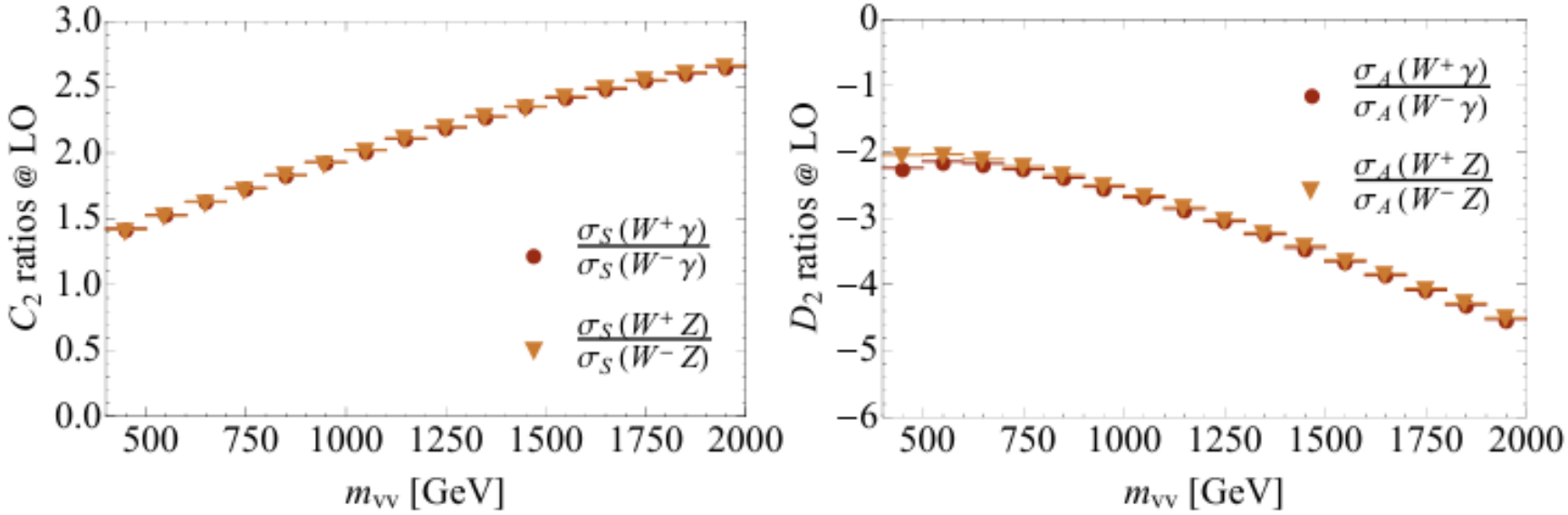


[Marat Freytsis]

New High Precision Diboson Observables (2)

$W^{\pm}\gamma$, $W^{\pm}Z$

ratio observables

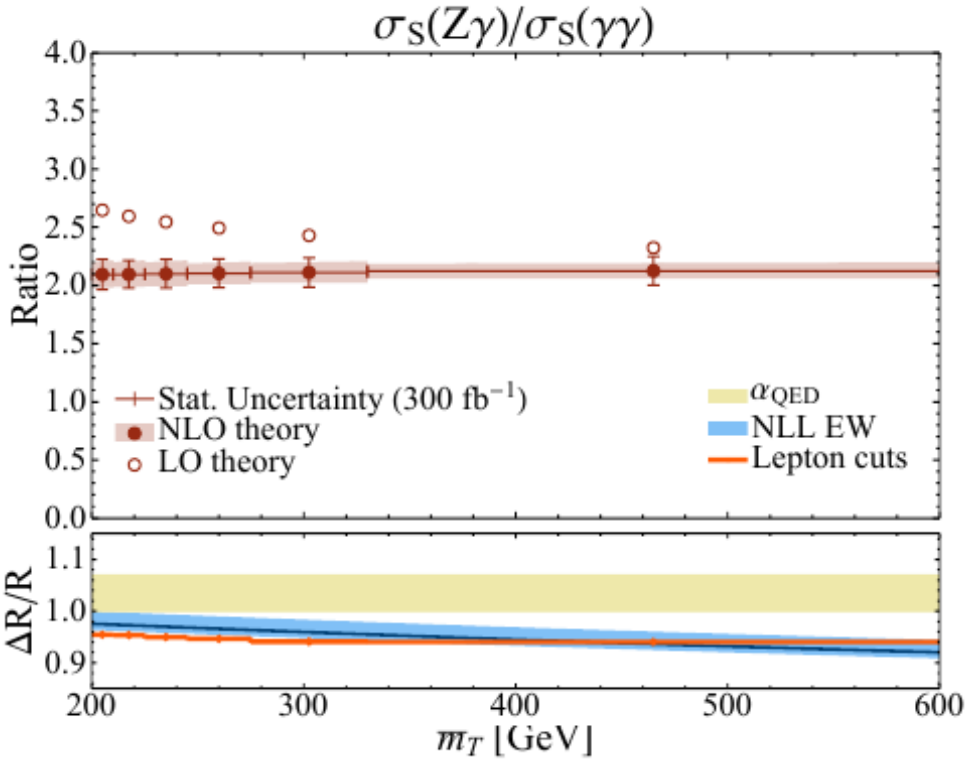


ratios roughly $\sim f_u/f_d$

[Marat Freytsis]

Higher Order Corrections Seem Under Control

low uncertainties, small QCD corrections
candidates for (even) high(er)-precision calculation



[Marat Freytsis]

Precise Predictions for Charged Higgs Production

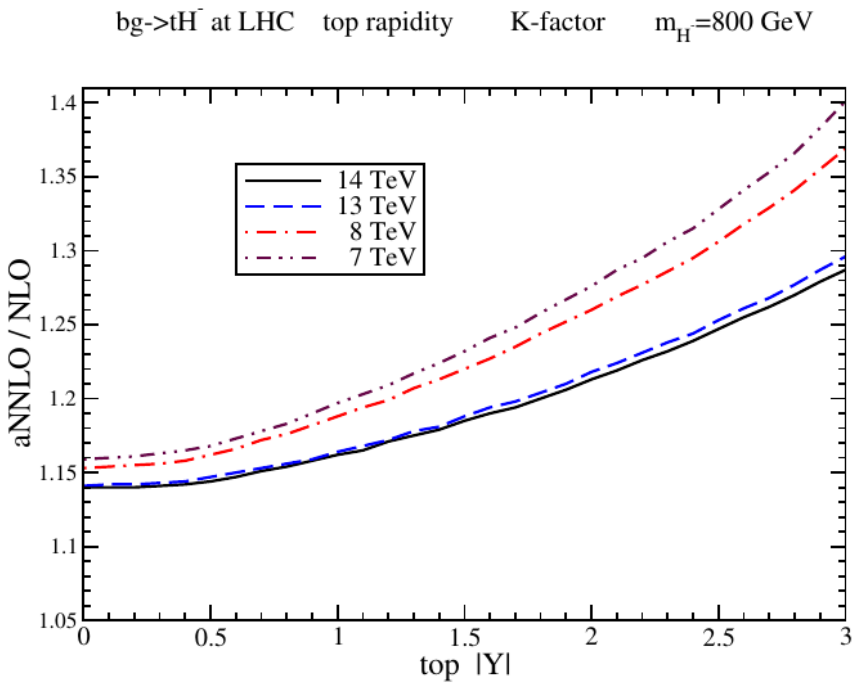
- many new results in charged Higgs production
- total cross sections for tH^- production
- top-quark p_T and rapidity distributions in tH^- production
- total cross sections for H^-W^+ production
- charged-Higgs p_T and rapidity distributions in H^-W^+ production
- higher-order corrections are very significant

[Nikolaos Kidonakis]

Two Examples

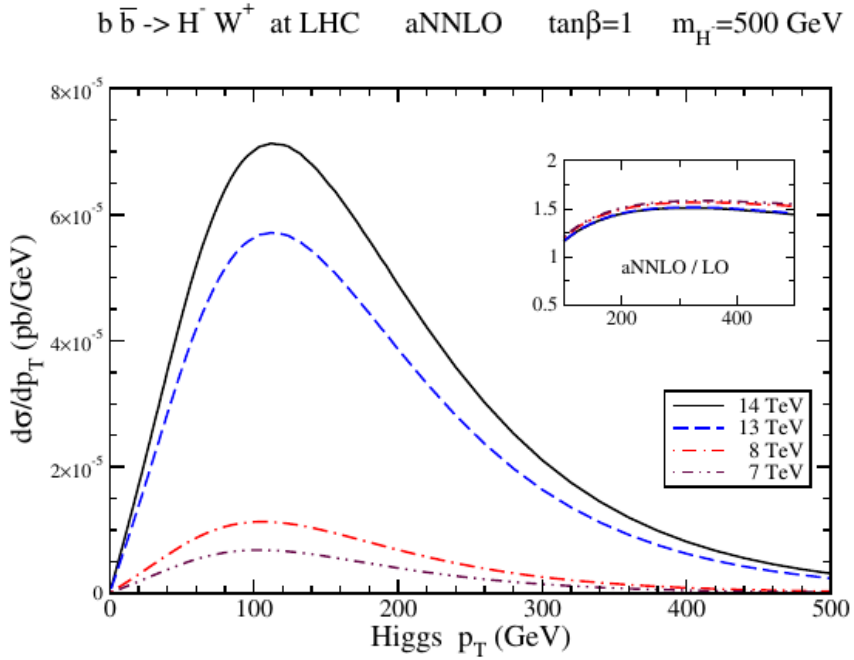
$bg \to tH^-$

top rapidity distribution



$b\bar{b} \to H^\pm W^\mp$

charged Higgs p_T distribution



[Nikolaos Kidonakis]

No conclusion, keep exploring!

[JiJi Fan]