Interpretation of results, outlook and new ideas

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Higgs, Top and Electroweak plenary session
ICHEP 2016
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Outline

Introduction: problems of the SM

Interpretation of results

Outlook: Higgs properties

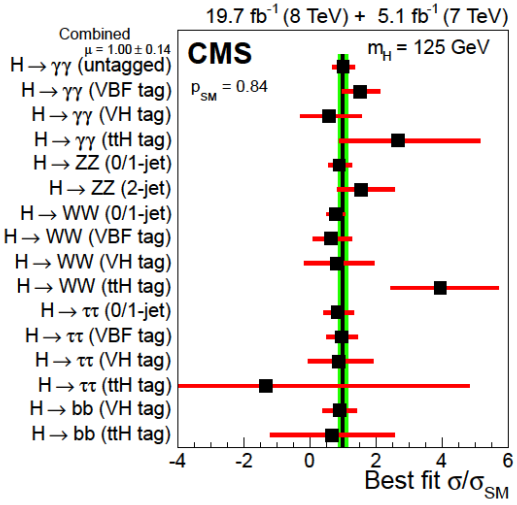
A few theory highlights

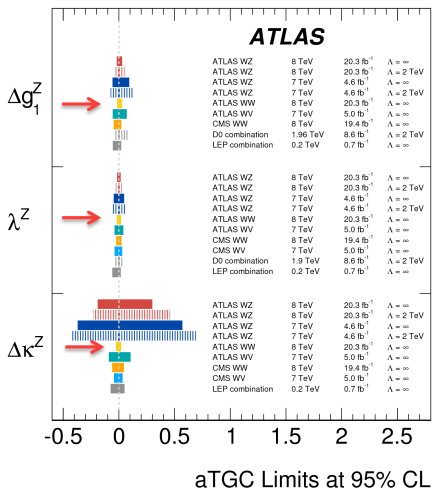
New ideas and things to watch

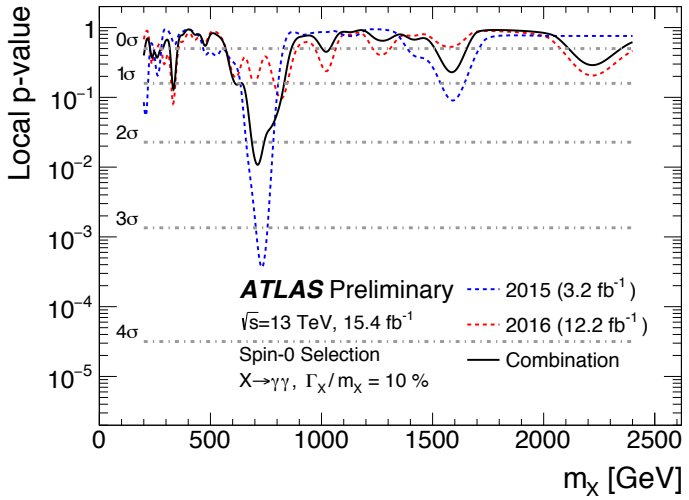
Summary

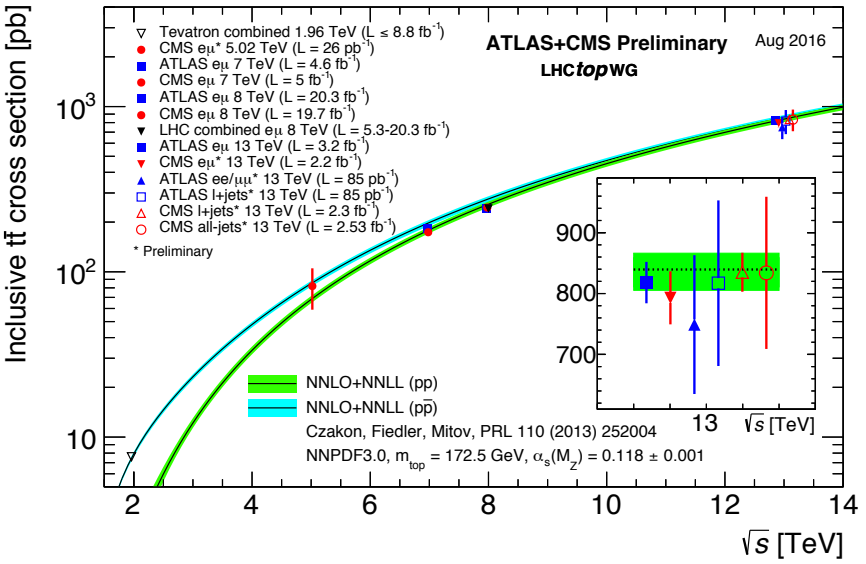
Introduction

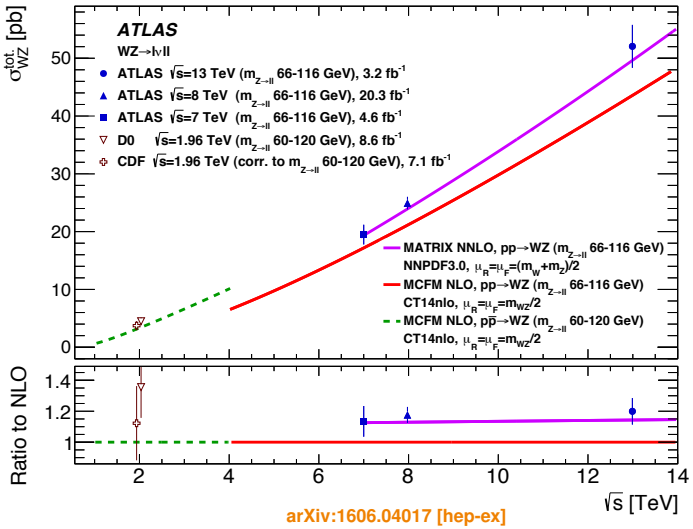
The Standard Model works very very well ...











Introduction

The Standard Model works very very well ... too well!

SM fails to explain many problems — and no hints of solutions!

- Hierarchy problem

- Baryogenesis

- Dark matter

- Flavour (Yukawa matrices) & neutrino masses – patterns?

- SM gauge & matter content; hypercharge quantization (GUT?)

- Inflation; dark energy

- Quantum mechanics $\leftarrow ? \rightarrow$ general relativity

Introduction

Many of these problems are connected to electroweak symmetry breaking:

- Hierarchy problem – scalar mass^2 radiative corrections $\sim \Lambda^2$

- Baryogenesis – electroweak phase transition?

- Dark matter – maybe Higgs portal?

- Flavour (Yukawa matrices) & neutrino masses – patterns?

- SM gauge & matter content; hypercharge quantization (GUT?)

- Inflation; dark energy – maybe connected to hierarchy problem?

- Quantum mechanics $\leftarrow ? \rightarrow$ general relativity – ????

Introduction

To learn about electroweak symmetry breaking, study the things most strongly coupled to the electroweak-breaking vacuum:

Higgs, top, & electroweak gauge bosons

Higgs couplings – search for evidence of Higgs compositeness, mixing with extra scalars (EW phase transition?), flavour-violating decays, exotic/invisible decays

Top quark – search for partial compositeness (anomalous couplings), top-partners, $t\bar{t}$ resonances

Electroweak gauge bosons – EW precision tests for new physics, vector boson scattering (anomalous couplings), additional Higgs bosons (VBF $\to H' \to VV$)

Interpretation of results: ~ 13 fb^{-1} at 13 TeV

SM cross section measurements:
- new collision energy $\rightarrow$ check for new kinematic thresholds
- new collision energy $\rightarrow$ sensitivity to BSM tails $\sim (Q/\Lambda)^2$
- theory predictions continuously improving $\rightarrow$ more distributions
- higher signal cross sections, e.g. $t\bar{t}h$, $t\bar{t}Z$, VBF $\rightarrow VV$

New limits from searches:
- new collision energy $\rightarrow$ improved reach at high mass
- BSM Higgs bosons
- new resonances
- top partners
- SUSY particles

Themes for the next few years:
1) More luminosity!!
2) Theory improvements

Higgs properties: outlook

Higgs is now part of the Intensity Frontier. - A. Petrov

Snowmass 2013 projections:

Luminosity	300 fb^{-1}	3000 fb^{-1}
Coupling parameter	7-parameter fit	
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_u	$14-15\%$	$7-10\%$
κ_d	$10-13\%$	$4-7\%$
κ_ℓ	$6-8\%$	$2-5\%$
Γ_H	$12-15\%$	$5-8\%$
	additional parameters (see text)	
$\kappa_{Z\gamma}$	$41-41\%$	$10-12\%$
κ_μ	$23-23\%$	$8-8\%$
$\mathrm{BR}_{\mathrm{BSM}}$	$<14-18\%$	$<7-11\%$

Ranges represent assumptions on systematics: low end is theory uncerts $\times 1/2$, expt systematics $\times 1/\sqrt{\mathcal{L}}$.

Expectations in various models:

- All new particles at $M \sim 1$ TeV
- Electroweak precision fits satisfied

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Snowmass 2013, 1310.8361

- Decoupling MSSM: κ_γ assumes 1 TeV stop with $\tan\beta = 3.2$, $X_t = 0$.

Projections based on scaling 2012–13 expt analyses to higher lumi: probably better already. Thy uncert reductions ≈already achieved! Franz Herzog's talk

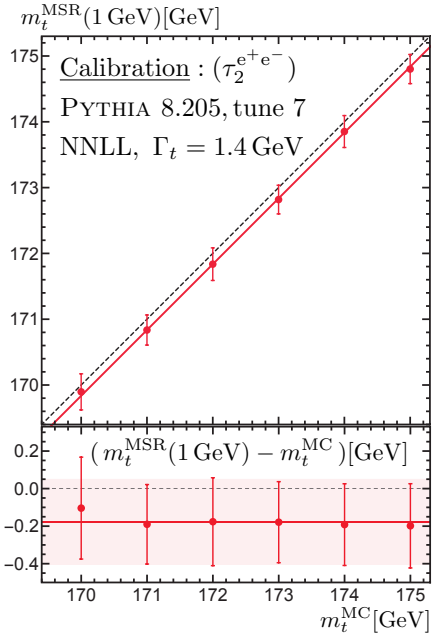
A few theory highlights

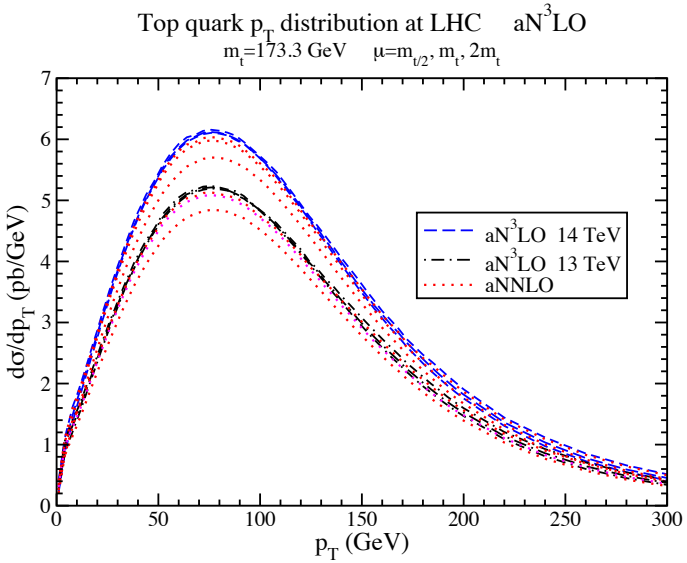
Top mass measurement from kinematic templates: measures "Pythia's m_t"

$\rightarrow$ Translate to more physical mass?

$e^+e^- \rightarrow t\bar{t}$ NNLL+NLO, match "2-jettiness" templates to Pythia, calibrate to (evolved) $\overline{\text{MS}}$ mass

Moritz Preisser's talk





New approximate N^{3}LO calculation of $t\bar{t}$ production

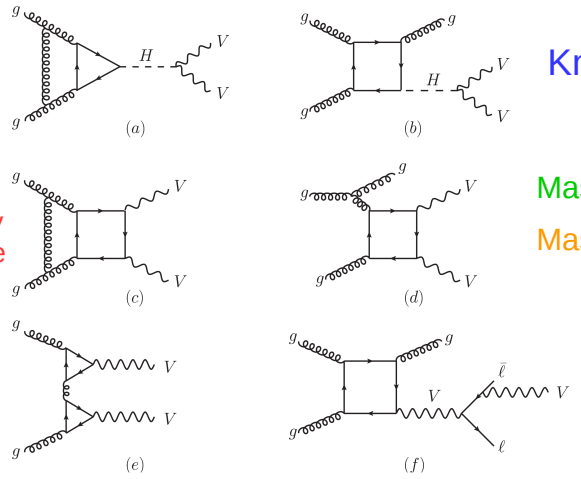
Needed to match coming experimental precision!

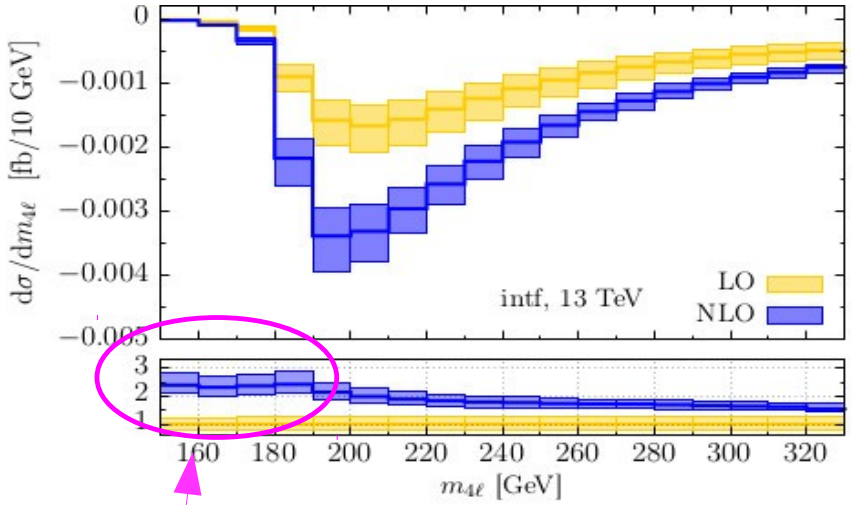
(not yet in expt/thy comparison plots)

Nikolaos Kidonakis' talk

A few theory highlights

Offshell $gg \to H \to VV$ interference with continuum $gg \to VV$
First calculation of (partial) NLO QCD corrections to $gg \to VV$ and interference term





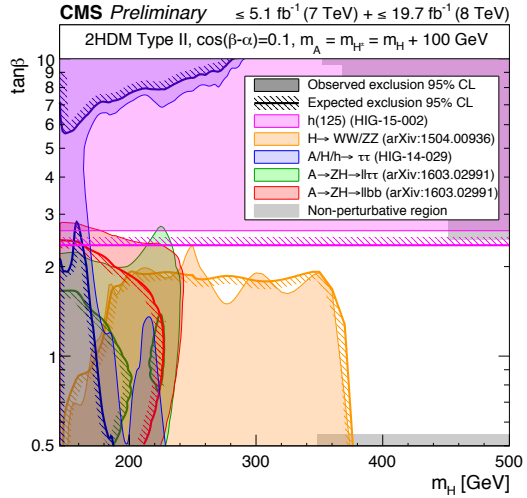
Raoul Röntsch's talk

New ideas 1 – extended scalar sectors

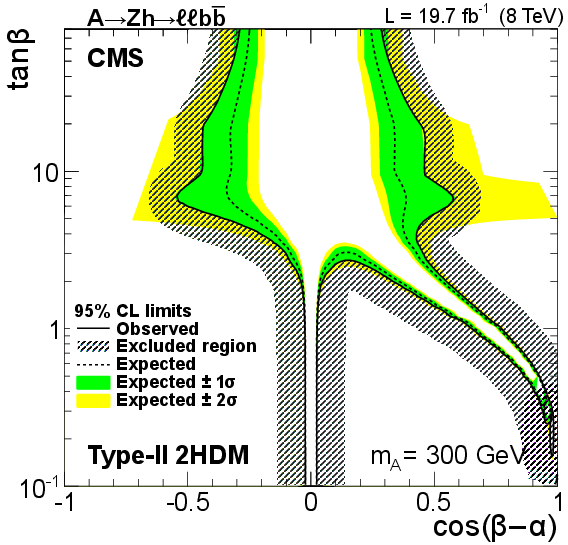
This is not a new idea, but there are some new developments.

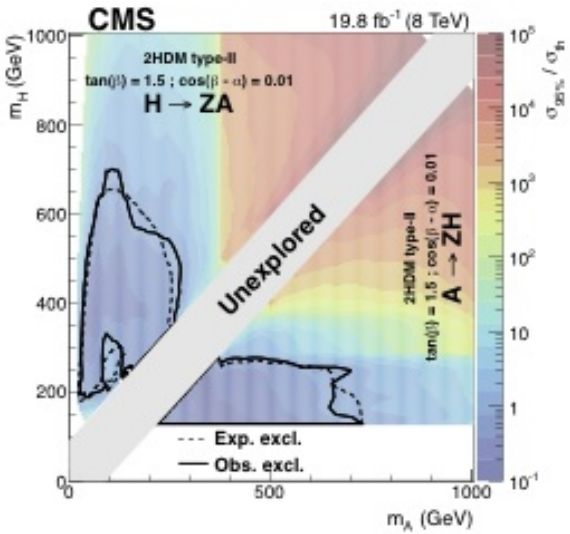
1) "Higgs to Higgs" decays

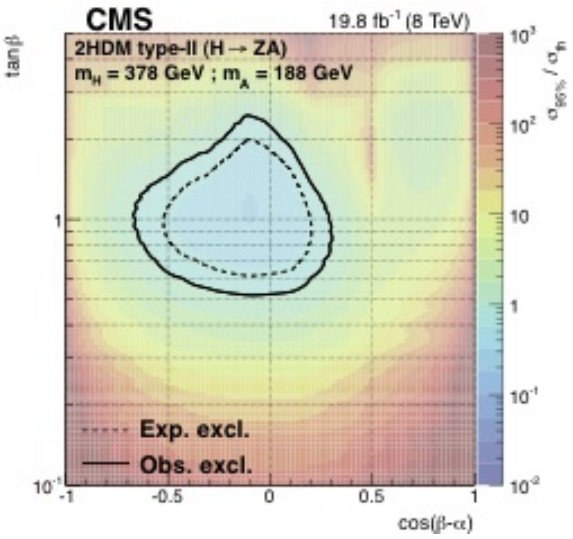
$A \to Zh$ and $A \to ZH$, $H \to ZA$



CMS-PAS-HIG-16-007







Alexandre Mertens' talk

Constrains alignment limit!

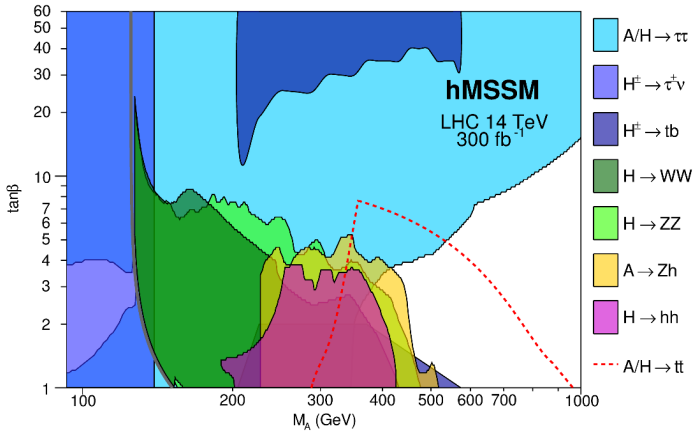
New ideas 1 – extended scalar sectors

2) $H/A \to t\bar{t}$ at low $\tan\beta$

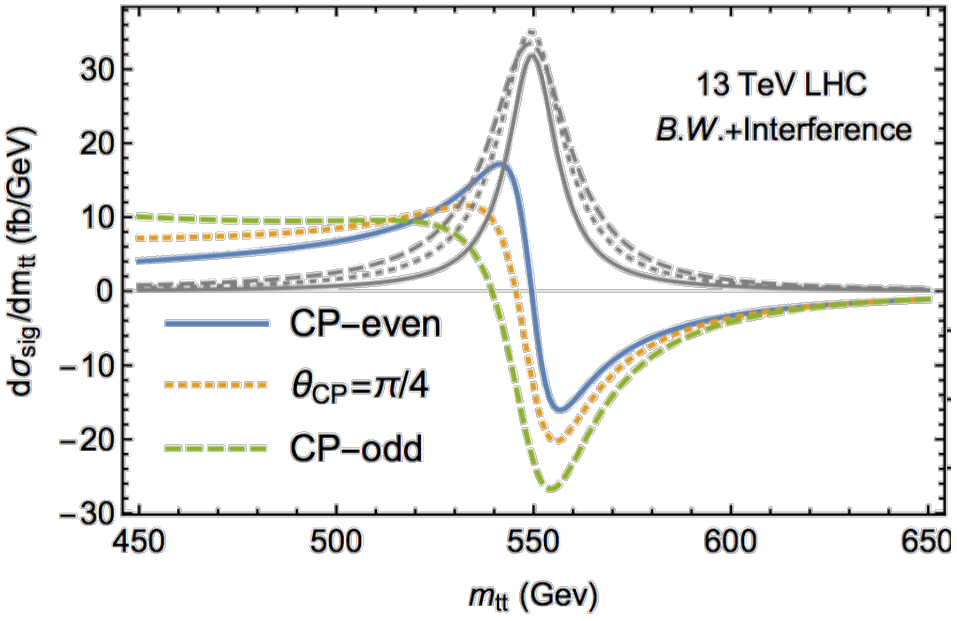
Important for closing "wedge"

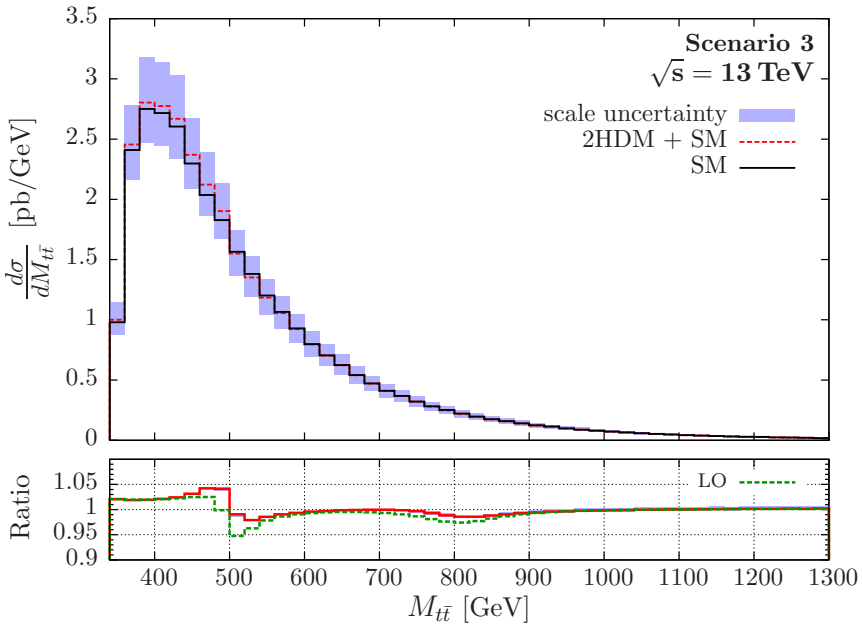
(plot: naive scaling of $t\bar{t}$ resonance search)

Djouadi et al, 1502.05653



Need to include interference with QCD $gg \to t\bar{t}$ background: dip strucutre!





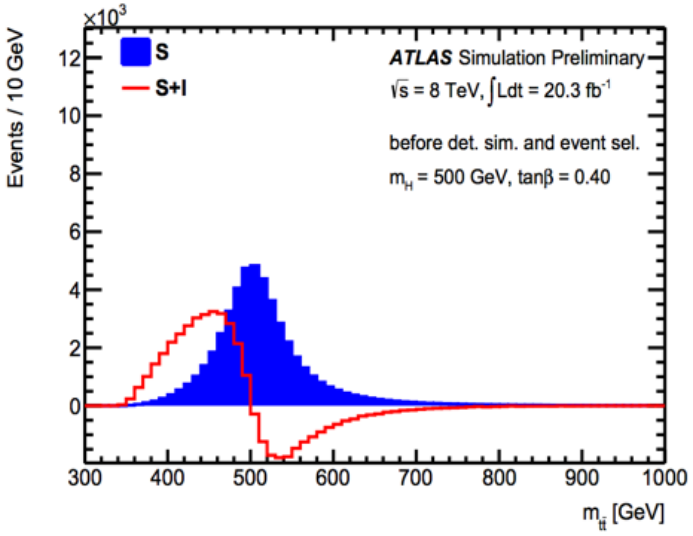
Zhen Liu's talk

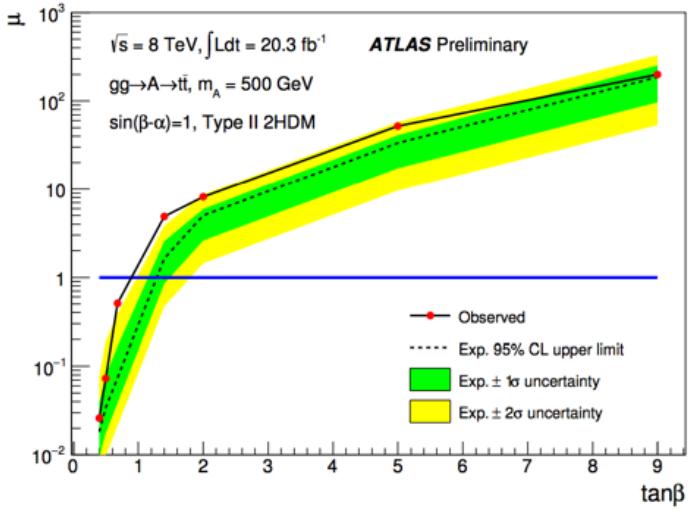
Peter Galler's talk

New ideas 1 – extended scalar sectors

2) $H/A \to t\bar{t}$ at low $\tan\beta$

First ATLAS analysis (8 TeV, LO signal MC) Trevor Vickey's talk

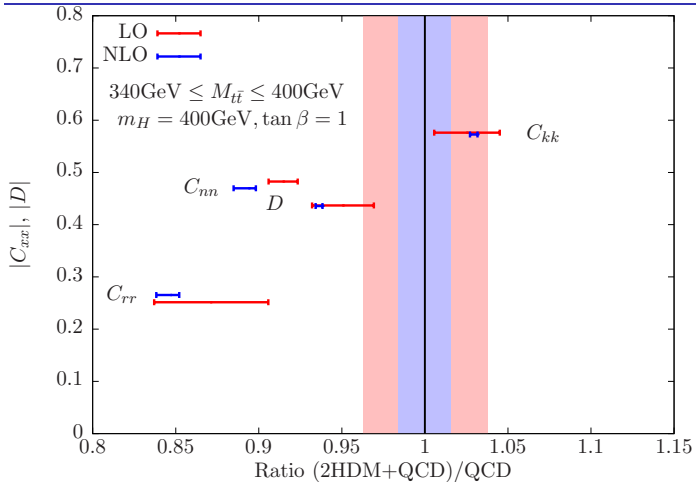




NEW approx. NLO calculation, including interference

Studies of angular & spin-dependent observables to improve discrimination

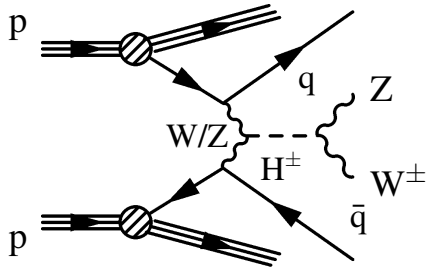
Peter Galler's talk



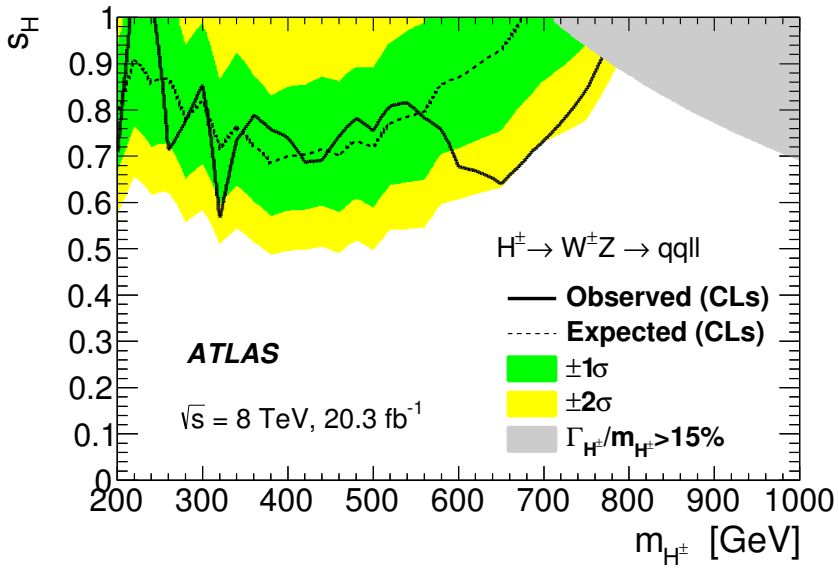
New ideas 1 – extended scalar sectors

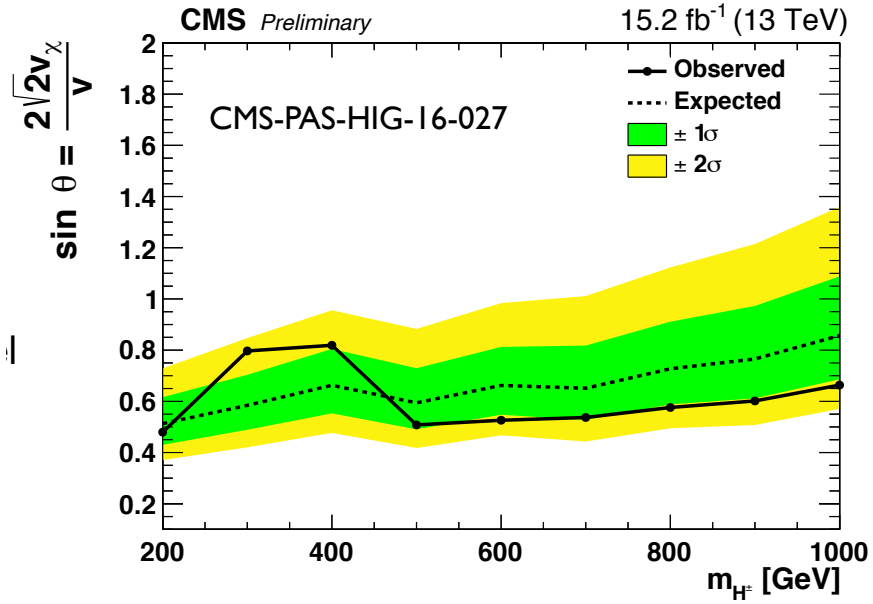
3) Portion of $M_{W,Z}$ from isospin-triplet (or higher) scalars?

Generic feature: $H_5^{\pm\pm}, H_5^{\pm}, H_5^0$
5-plet under custodial symmetry,
fermiophobic, couple to $VV \propto v_\chi$.



13 TeV CMS result ($WZ \to \ell\nu\ell\ell$)





ATLAS 1503.04233 Andrea Marini's talk

$\sin^2\theta_H$ = fraction of $M^2_{W,Z}$ generated by isospin-triplet vev.

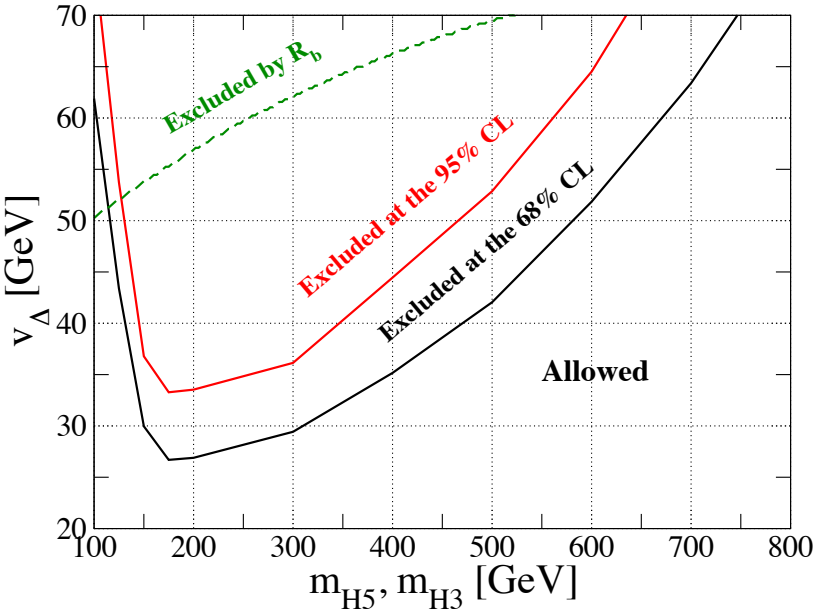
New ideas 1 – extended scalar sectors

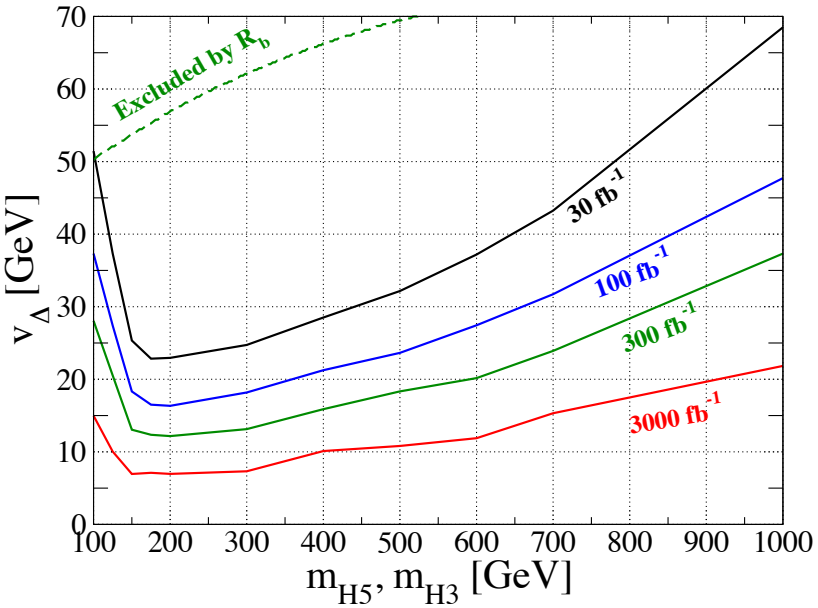
3) Portion of $M_{W,Z}$ from isospin-triplet (or larger) scalars?

VBF $\to H_5^{\pm\pm} \to W^\pm W^\pm$ feeds into LHC measurement of VBF $\to W^\pm W^\pm$ cross section

(3.6σ significance in Run 1, ATLAS 1405.6241 PRL)

Theory projection based solely on extrapolation of 7+8 TeV xsec measurement (dedicated expt selection could improve this)





current $H^{\pm\pm}$ limit: 7+8 TeV dataset

Chiang, Kanemura & Yagyu, 1407.5053

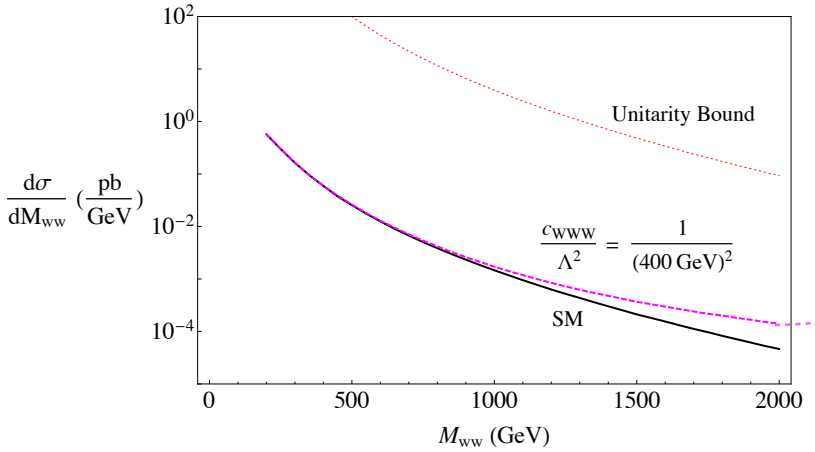
New ideas 2 – Effective Field Theory approach

A theme of Run-2: being used in Higgs, top, and EW (esp. VBS)

New Physics at a scale Λ, pure SM below $\rightarrow$ EFT cut off by Λ
$\rightarrow$ NP encoded in coefficients of higher-dimension operators

Just like measuring Wilson coefficients in B physics: agnostic!

- A real theory: can calculate systematically to higher orders, incorporate scale-dependent constraints (e.g. LEP EW)
- Allows to take advantage of kinematic distributions: TGCs/QGCs



F. Riva, C. Degrande et al arxiv:1205.4231

Validity of EFT requires event energies $< \Lambda$:

- $E > \Lambda$: see NP resonances!
- $E \sim \Lambda$: expansion in powers of Λ no longer reliable.

Josh Kunkle's talk

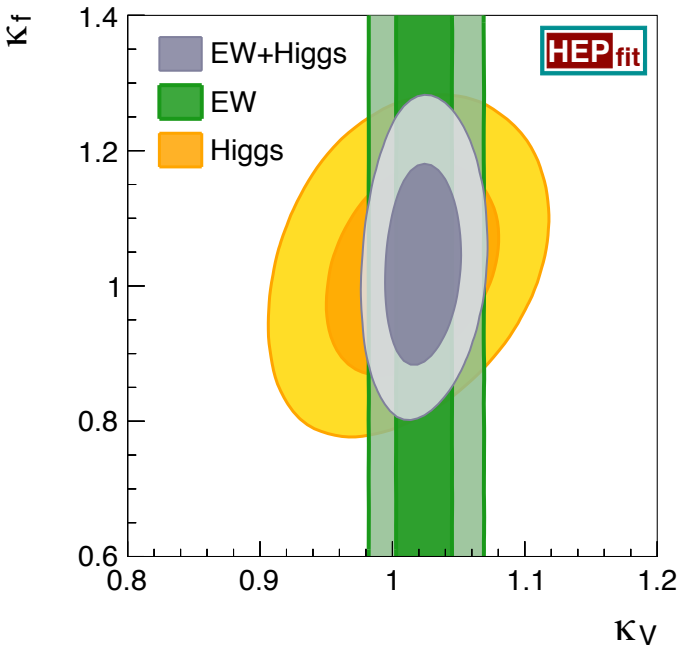
New ideas 2 – Effective Field Theory approach

Tools coming onto the market:

1) NLO SMEFT model in MadGraph5_aMC@NLO Cen Zhang's talk
$tbW/ttZ/tt\gamma$, top-Higgs, FCNC top operators
Captures important QCD corrections to operator mixing, kinematic distributions

2) HEPfit: code to test your favourite models against indirect (and direct) measurements

Jorge de Blas' talk



New ideas 3 – Neutral Naturalness

Top quark gives the largest contribution to the Higgs mass radiative correction: its cancellation is most important for naturalness

But searches for coloured top partners (top squark, fermionic top-partners) continue to push up their mass limits

$\Rightarrow$ Could the top-partners be uncharged (neutral) under QCD?
- Much smaller production cross sections at LHC
- Could be quite light, weak scale: excellent for naturalness!

Not a new idea: original model papers 2005-06
- "Twin Higgs" Chacko, Goh & Harnik, hep-ph/0506256
- "Folded supersymmetry" Burdman, Chacko, Goh & Harnik, hep-ph/0609152

Stabilize the "little hierarchy" up to ~ 10 TeV scale: same spirit as little Higgs models (but with top partners neutral under QCD).

Idea has become very popular in past couple of years as limits on coloured top-partners make SUSY, little Higgs, etc. less natural.

New ideas 3 – Neutral Naturalness

Need (approximate) symmetry that protects Higgs mass.

SM is "twinned" with a mirror sector:
- mirror top charged under mirror QCD (not our QCD): neutral!
- discovered Higgs is linear combination of the two sectors
- mirroring of entire SM $\rightarrow$ cosmological problems: model-building
- "folded SUSY": mirror stops color-neutral but weak-charged

Signatures: highly model dependent
- top-partners could be electroweak-charged: like chargino searches
- exotic Higgs decays into mirror sector (depends on spectrum)
- mirror QCD glueballs could decay back to SM: "emerging jets"
- folded SUSY: colored SUSY partners still can't be too heavy

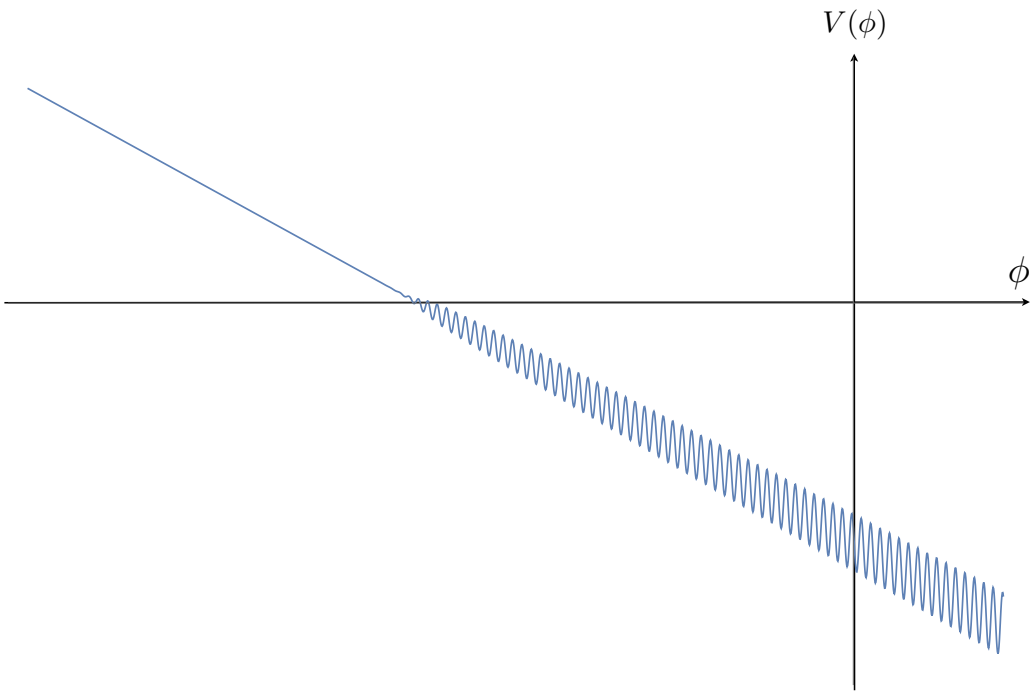
Only generic signature:
Higgs must be linear combination of our sector & mirror sector.
$\rightarrow$ Universal suppression of Higgs couplings by mixing angle $\cos\theta$.
Probe with signal strengths: LHC Run 1, $\mu = 1.09^{+0.11}_{-0.10}$ 1606.02266
$\rightarrow \cos^2\theta = (1 - v^2/f^2) > 0.89 \Rightarrow v/f < 0.33$, $\sim 30\%$ tuning.

New ideas 4 – Naturalness from cosmological relaxation

Radically different idea to solve the hierarchy problem using self-organized criticality

Graham, Kaplan & Rajendran, 1504.07551

- Couple Higgs to axion-like field: $\mathcal{L} \supset (-M^2 + g\phi)|H|^2 + \cdots$
- ϕ slow-rolls down its potential during inflation (need inflaton too)
- When $-(-M^2 + g\phi)$ goes negative, Higgs gets a vev
- Turns on periodic axion-potential barriers, stops rolling of ϕ



Predictions:

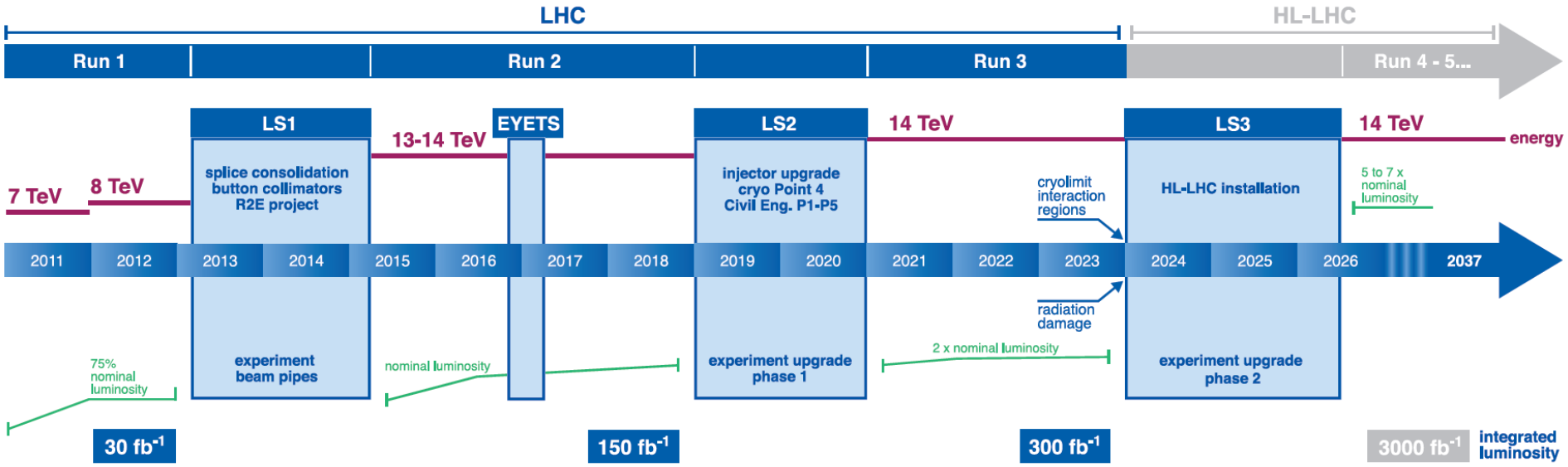
- axion-like dark matter
- maybe nothing at colliders :(
- intimately connected to inflation model: cosmo signatures?
- higher-scale UV completion, e.g. SUSY at 10^7 GeV

Very new idea; modelbuilding ongoing

Jason Evans' & Michael Fedderke's talks

Summary

The first analyses of 13–15 fb^{-1} of data at $\sqrt{s} = 13$ TeV have revealed no surprises, but 10x more data to come by end of 2018.



- Precision measurements of Higgs, electroweak, and top physics

- Probe high-scale New Physics through effective operators

- Dig deep for new weakly-interacting physics below TeV scale