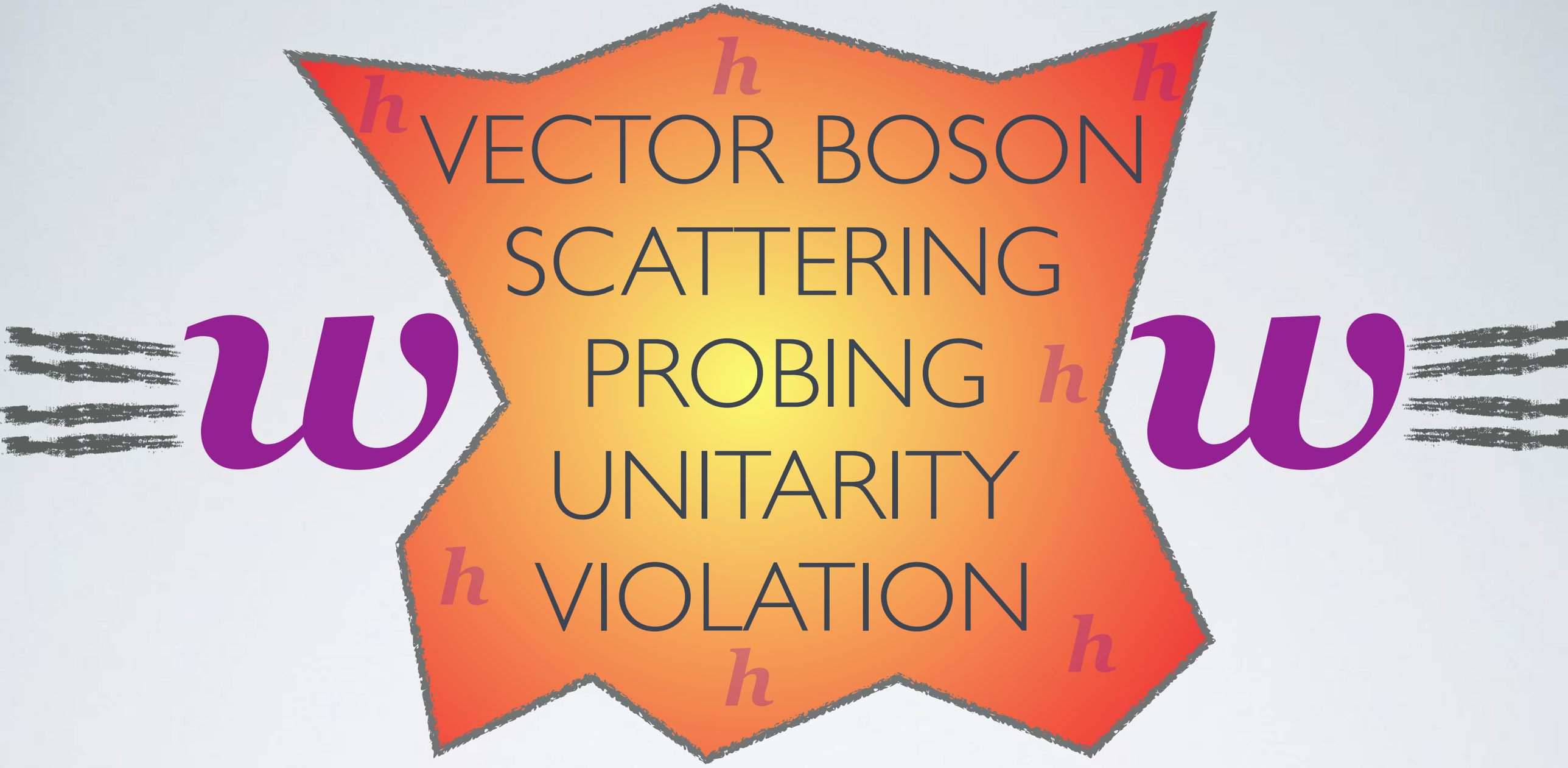


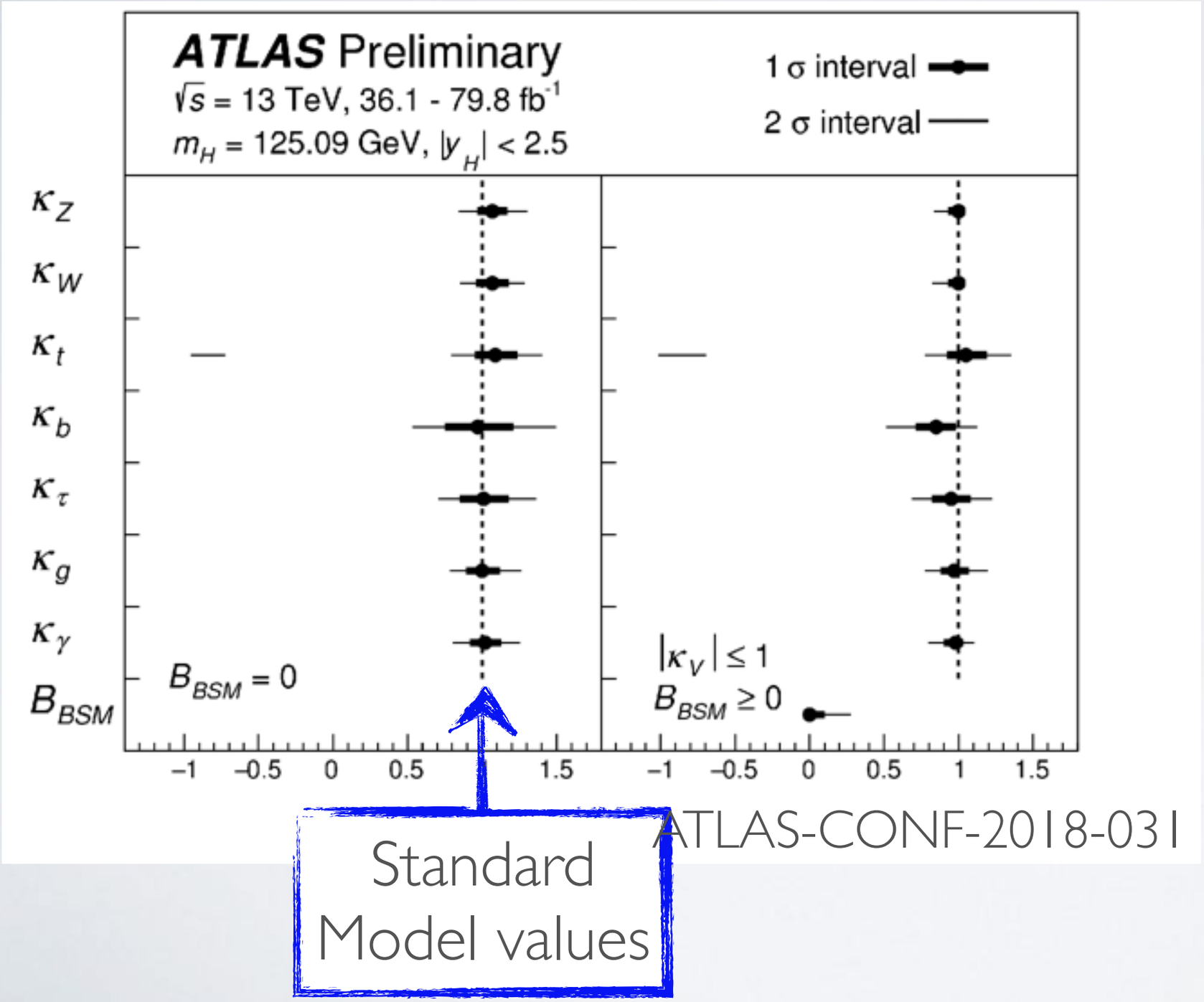
Spencer Chang 張勇龍 (U. Oregon/NTU)
w/ Markus Luty 1902.05556

NTU Flavor/Collider Workshop 2019

VECTOR BOSON SCATTERING & UNITARITY VIOLATION

- Nonstandard couplings (Higgs) and Unitarity violation
- Overview of collider probes
  - High energy scattering (model independent)
  - Resonances (model dependent)

PINNING DOWN HIGGS COUPLINGS



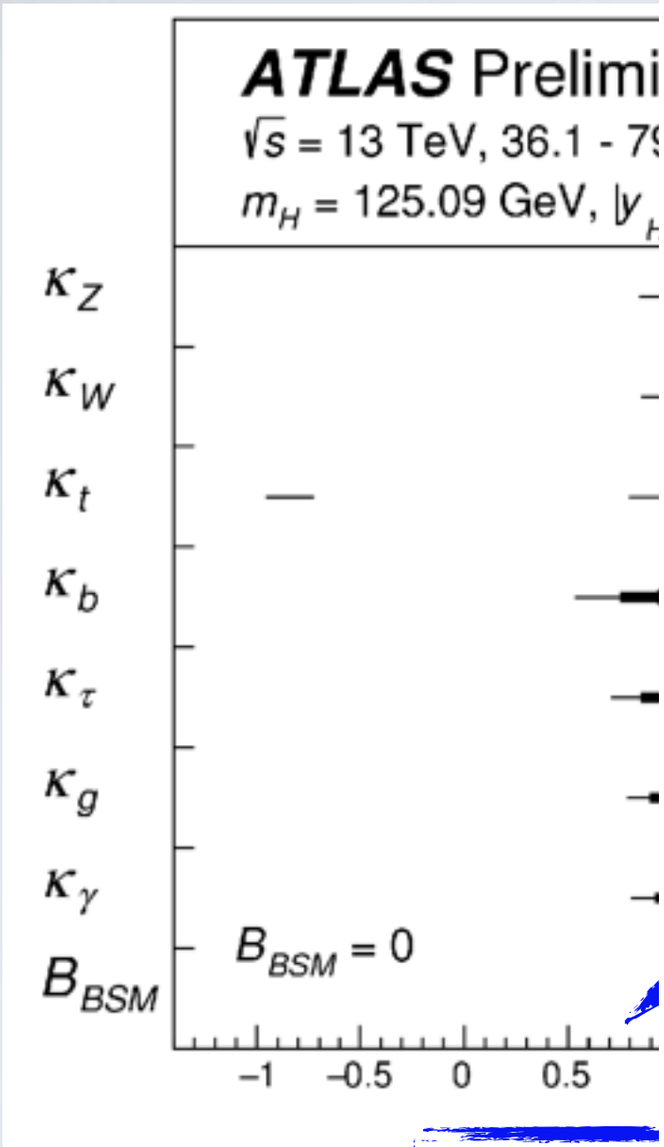
ATLAS-CONF-2018-031

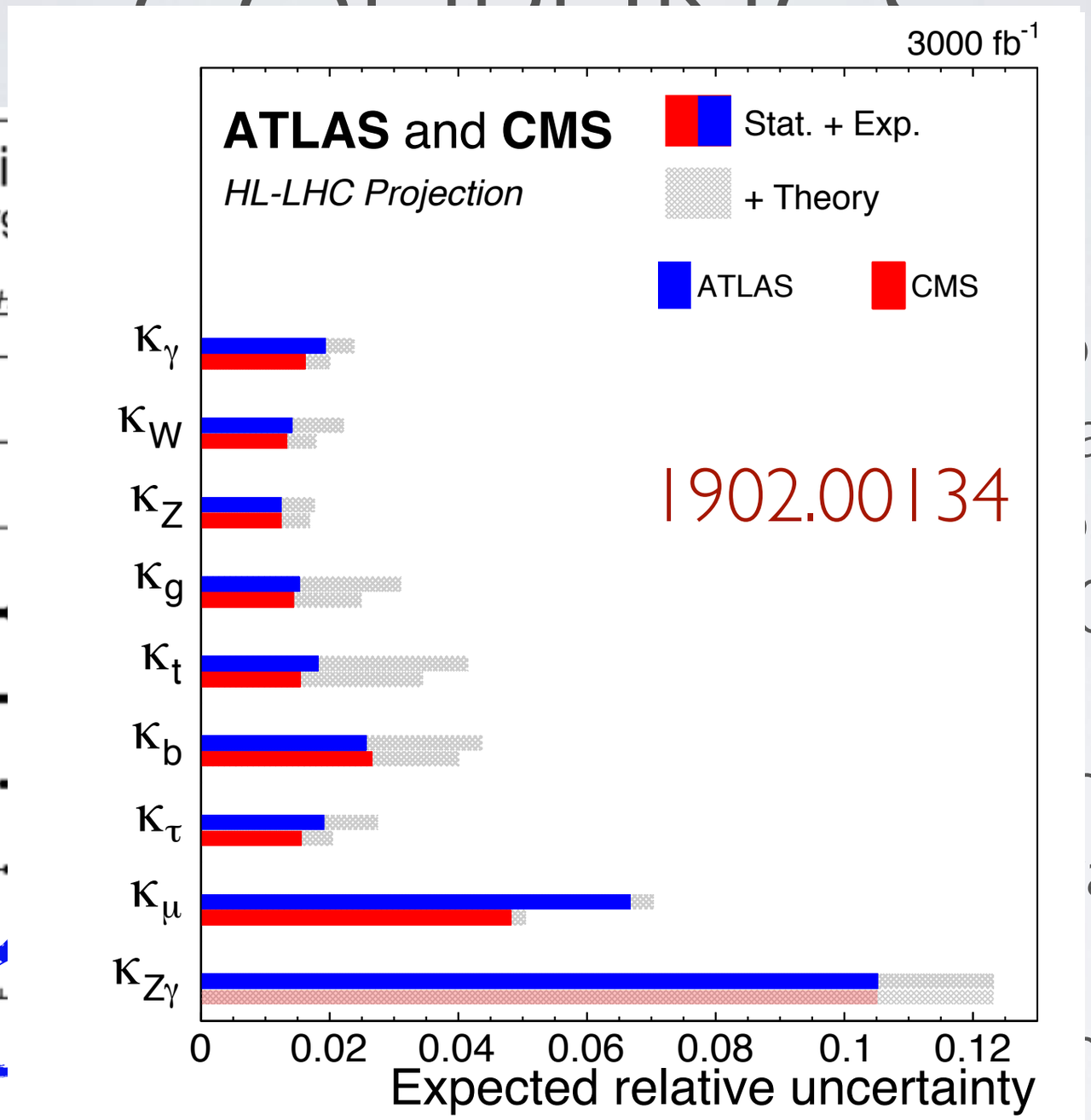
Standard Model values

Fits for Higgs couplings
Standard Model particles have 20-50% errors

One of the main motivation of HL-LHC and future colliders is measuring these better

PINNING DOWN HIGGS COUPLINGS





Standard Model values

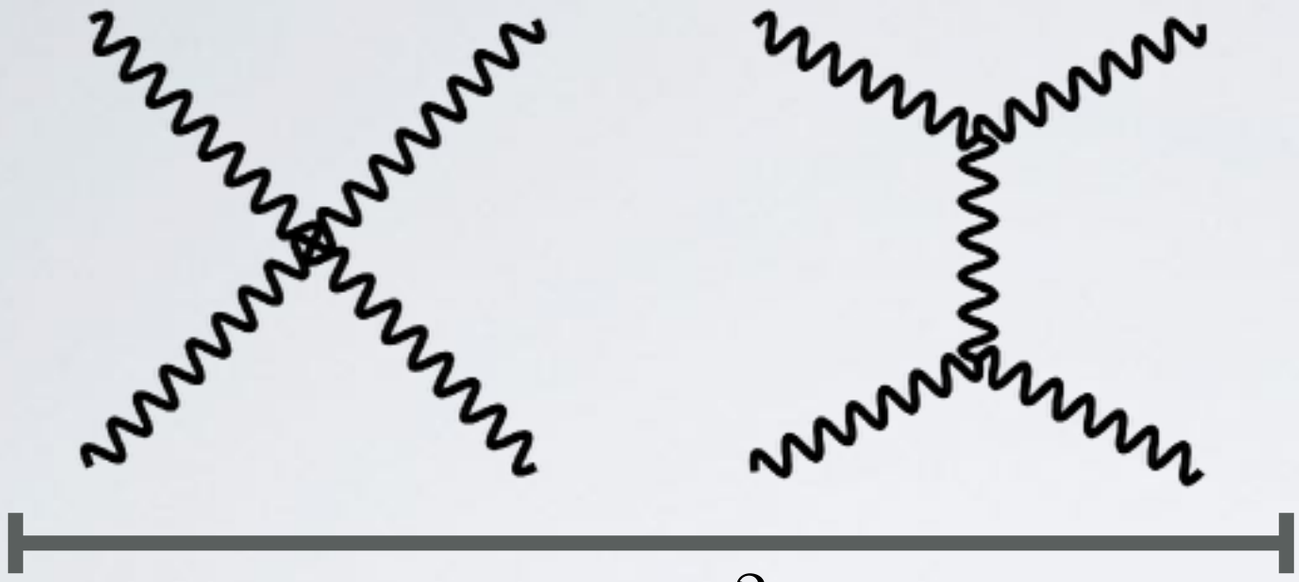
r Higgs couplings
andard Model
articles have
0-50% errors

ne of the main
ation of HL-LHC
future colliders
easuring these
better

UNITARITY VIOLATION

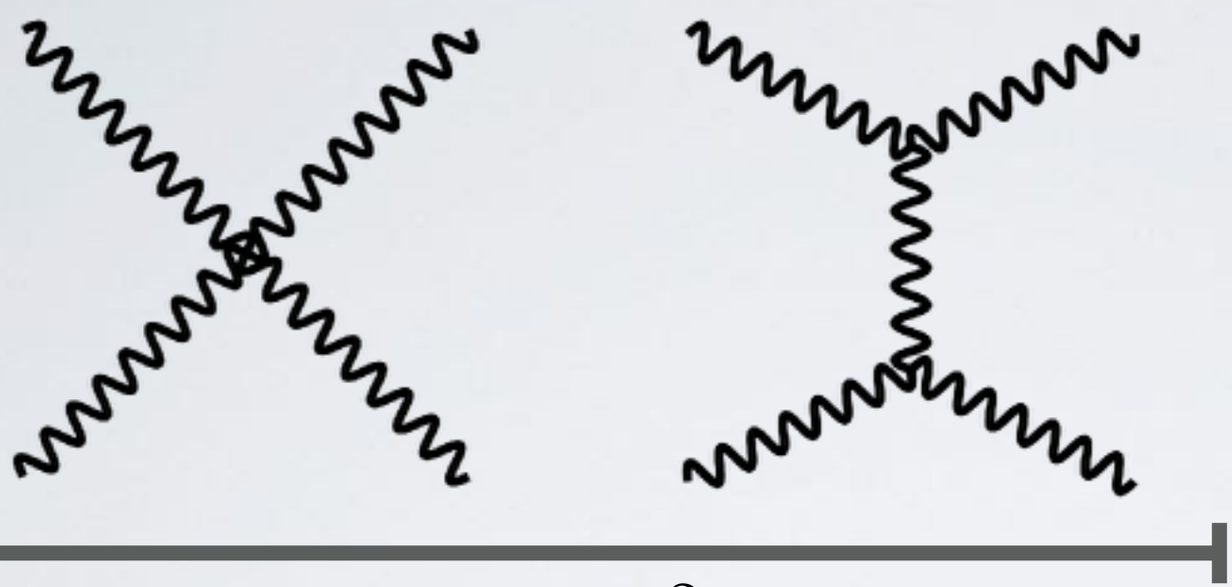
The Standard Model
is a precise deck of cards,
modifications of couplings
(Higgs, but also gauge bosons)
lead to scattering
amplitudes growing at
high energy

EXAMPLE: $Z_L\ Z_L \Leftrightarrow W^+_L\ W^-_L$

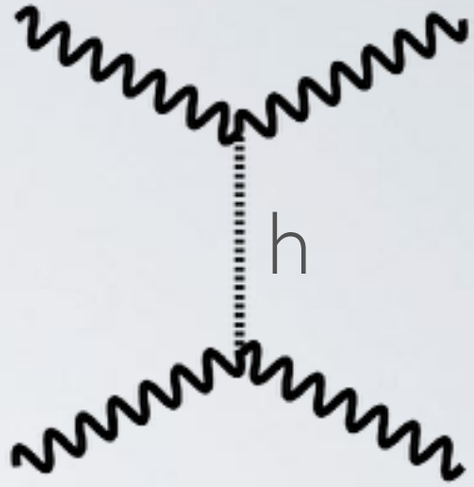


$$M = \frac{E^2_{com}}{v^2}$$

EXAMPLE: $Z_L\ Z_L \Leftrightarrow W^+_L\ W^-_L$

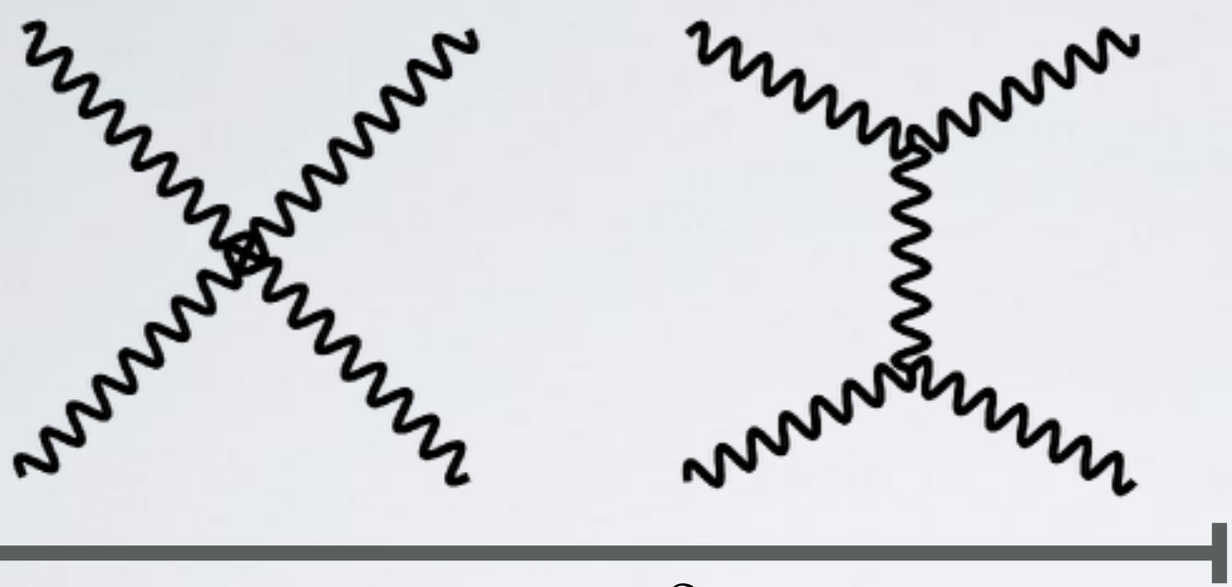


$$M = \frac{E^2_{com}}{v^2}$$

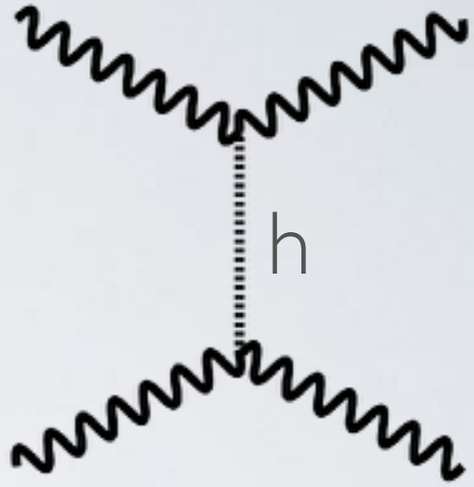


$$M = -\kappa^2_Z \frac{E^2_{com}}{v^2}$$

EXAMPLE: $Z_L\ Z_L \Leftrightarrow W^+_L\ W^-_L$



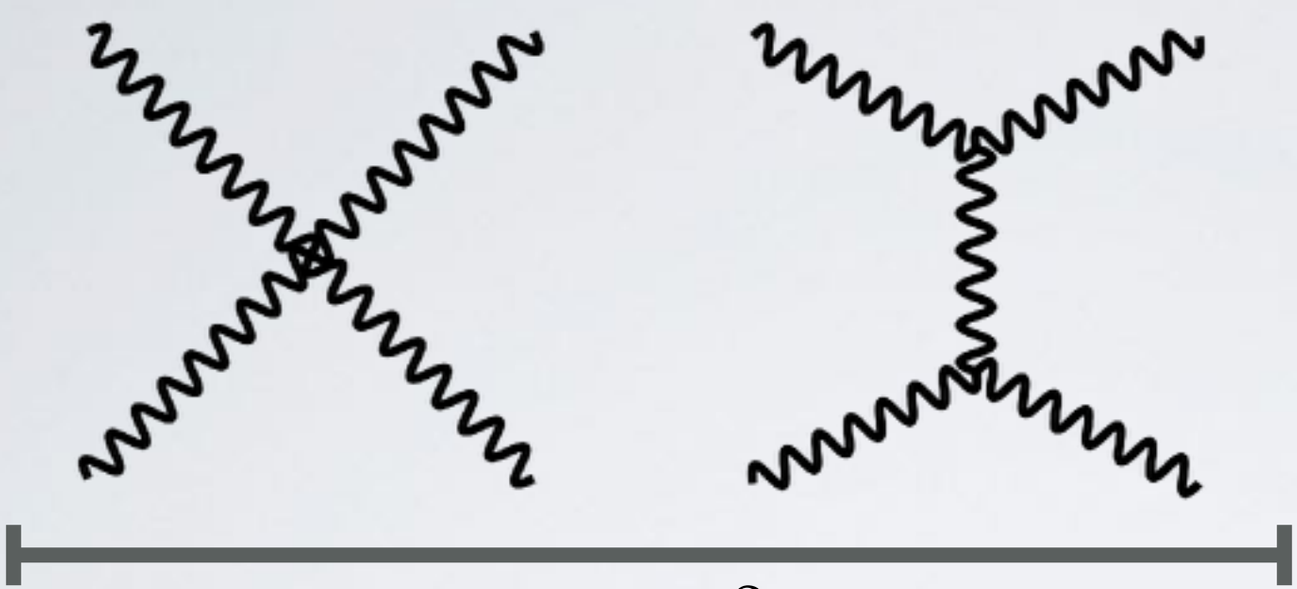
$$M = \frac{E^2_{com}}{v^2}$$



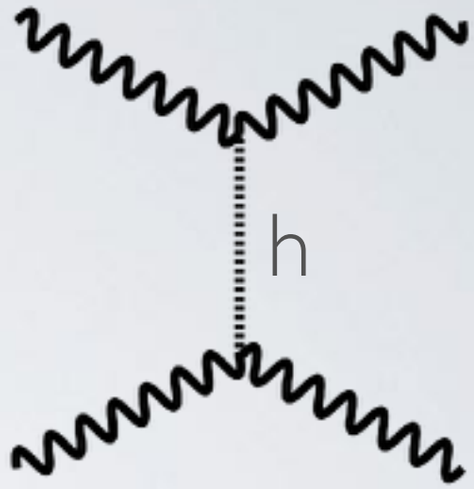
$$M = -\kappa^2_Z \frac{E^2_{com}}{v^2}$$

Higgs exchange cancels high energy growth if its couplings are SM-like and $m_H \lesssim$ 1 TeV (Lee, Quigg, Thacker)

EXAMPLE: $Z_L\ Z_L \Leftrightarrow W^+_L\, W^-_L$



$$M = \frac{E^2_{com}}{v^2}$$



$$M = -\kappa_Z^2 \frac{E^2_{com}}{v^2}$$

Higgs exchange cancels high energy growth if its couplings are SM-like and $m_H \lesssim 1$ TeV (Lee, Quigg, Thacker)

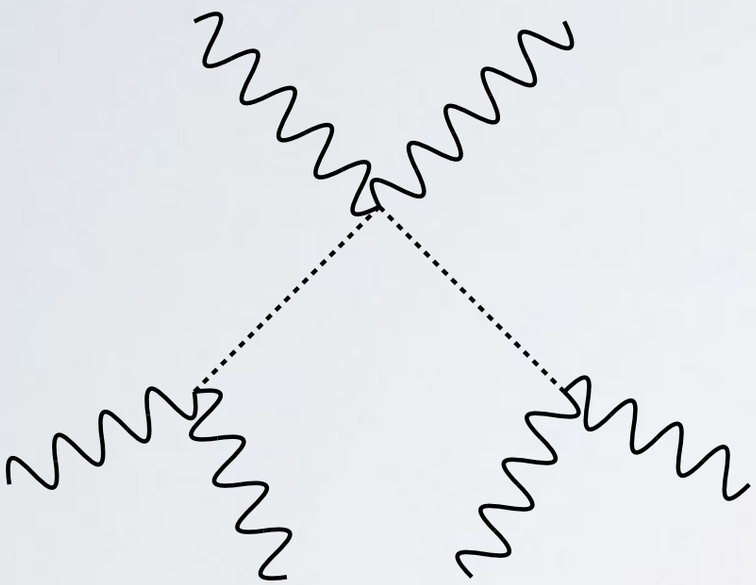
Unitarity Bound $$E_{com} \lesssim \frac{1\ \mathrm{TeV}}{\sqrt{|\kappa_Z - 1|}}$$

TRILINEAR UNITARITY VIOLATION

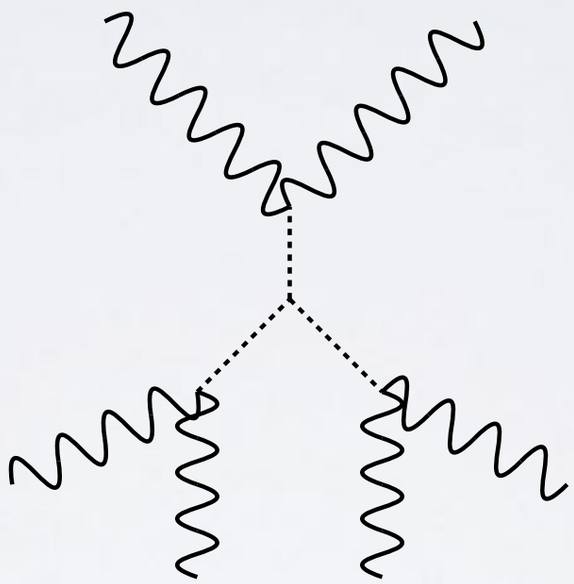
Modifying trilinear from SM value automatically leads to Unitarity violation at high energies (SC & Luty, Falkowski & Rattazzi)

TRILINEAR UNITARITY VIOLATION

Modifying trilinear from SM value automatically leads to Unitarity violation at high energies (SC & Luty, Falkowski & Rattazzi)



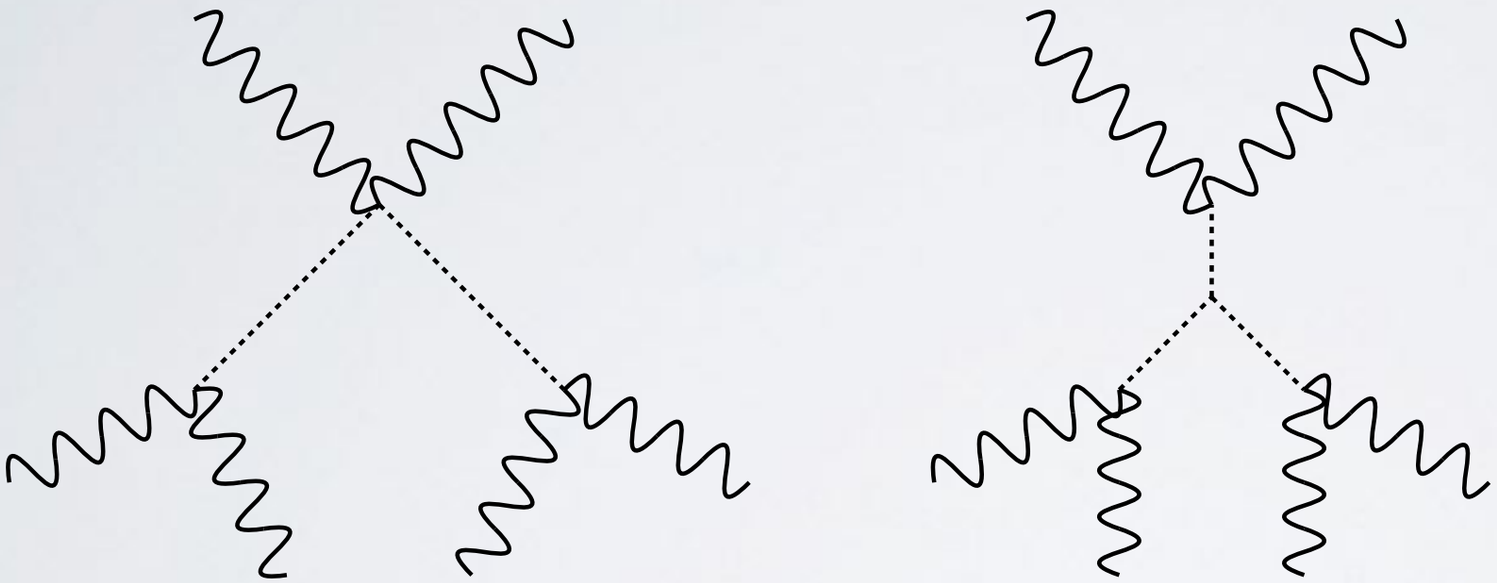
$Z_L\, Z_L\, Z_L \Leftrightarrow Z_L\, Z_L\, Z_L$



$$E_{com} \lesssim \frac{13\ \text{TeV}}{\sqrt{|\kappa_{hhh} - 1|}}$$

TRILINEAR UNITARITY VIOLATION

Modifying trilinear from SM value automatically leads to Unitarity violation at high energies (SC & Luty, Falkowski & Rattazzi)



$Z_L\, Z_L\, Z_L \Leftrightarrow Z_L\, Z_L\, Z_L$

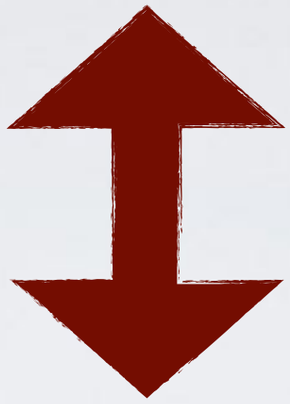
$$E_{com} \lesssim \frac{13\ \text{TeV}}{\sqrt{|\kappa_{hhh} - 1|}}$$

Another process

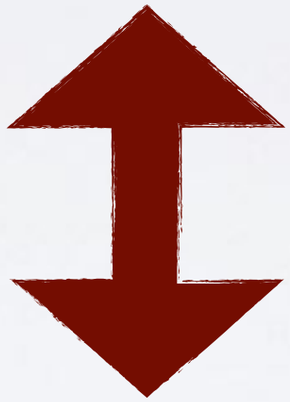
$W^+_L\, W^-_L \Leftrightarrow h\ \ W^+_L\, W^-_L$

$$E_{com} \lesssim \frac{57\ \text{TeV}}{|\kappa_{hhh} - 1|}$$

HIGGS SEARCHES



NONSTANDARD COUPLINGS



HIGH ENERGY SCATTERING

COLLIDER PROBES

Probing high energy processes can test energy growth, confirming nonstandard couplings as well as finding new particles that Unitarize process

COLLIDER PROBES

Probing high energy processes can test energy growth, confirming nonstandard couplings as well as finding new particles that Unitarize process

COLLIDER PROBES

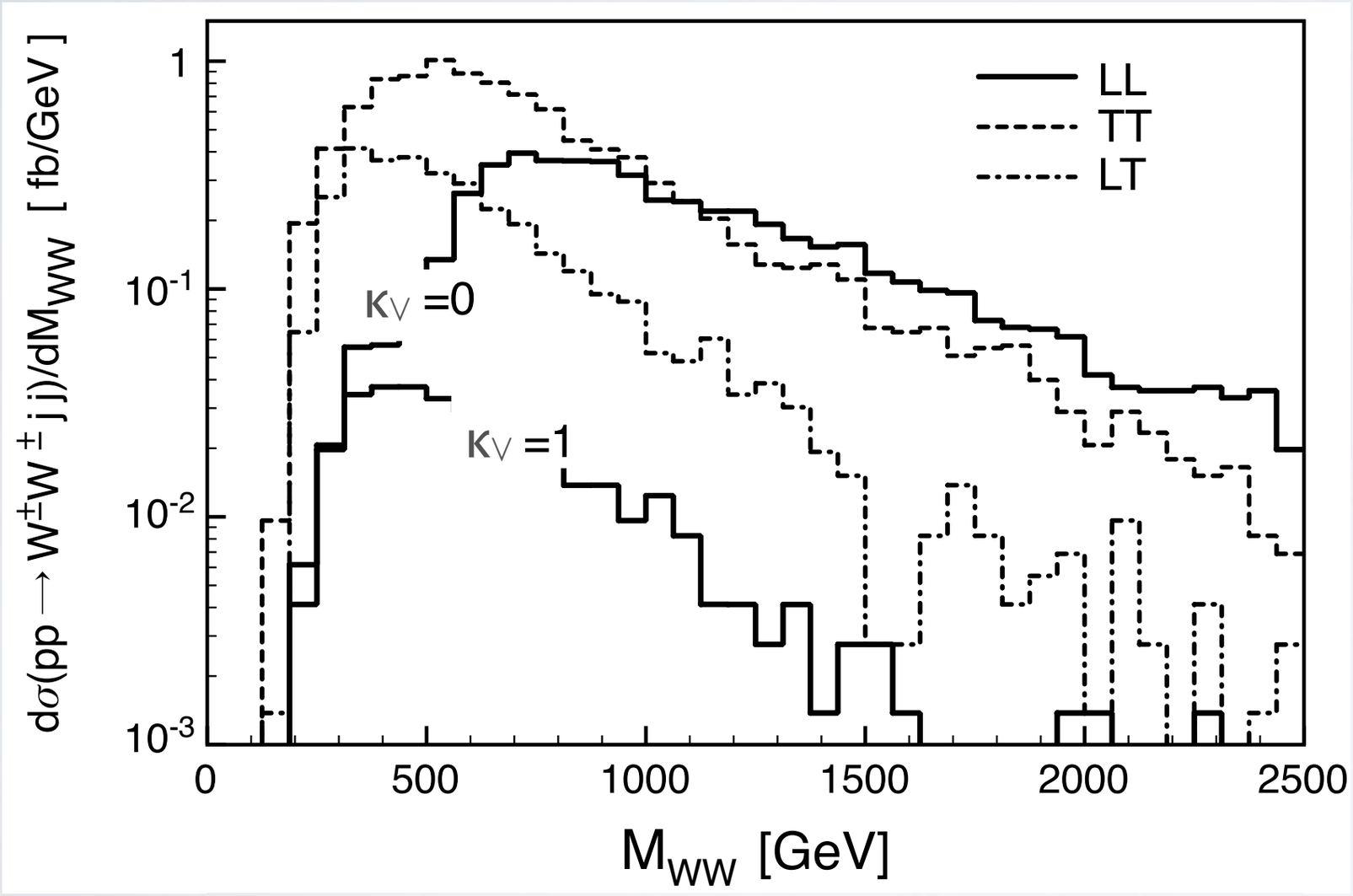
Probing high energy processes can test energy growth, confirming nonstandard couplings as well as finding new particles that Unitarize process

VECTOR BOSON SCATTERING

Naive expectation that longitudinal VBS is
large is not borne out by calculation
(e.g. Contino et.al. 1002.1011, also see CW Chiang's talk)

VECTOR BOSON SCATTERING

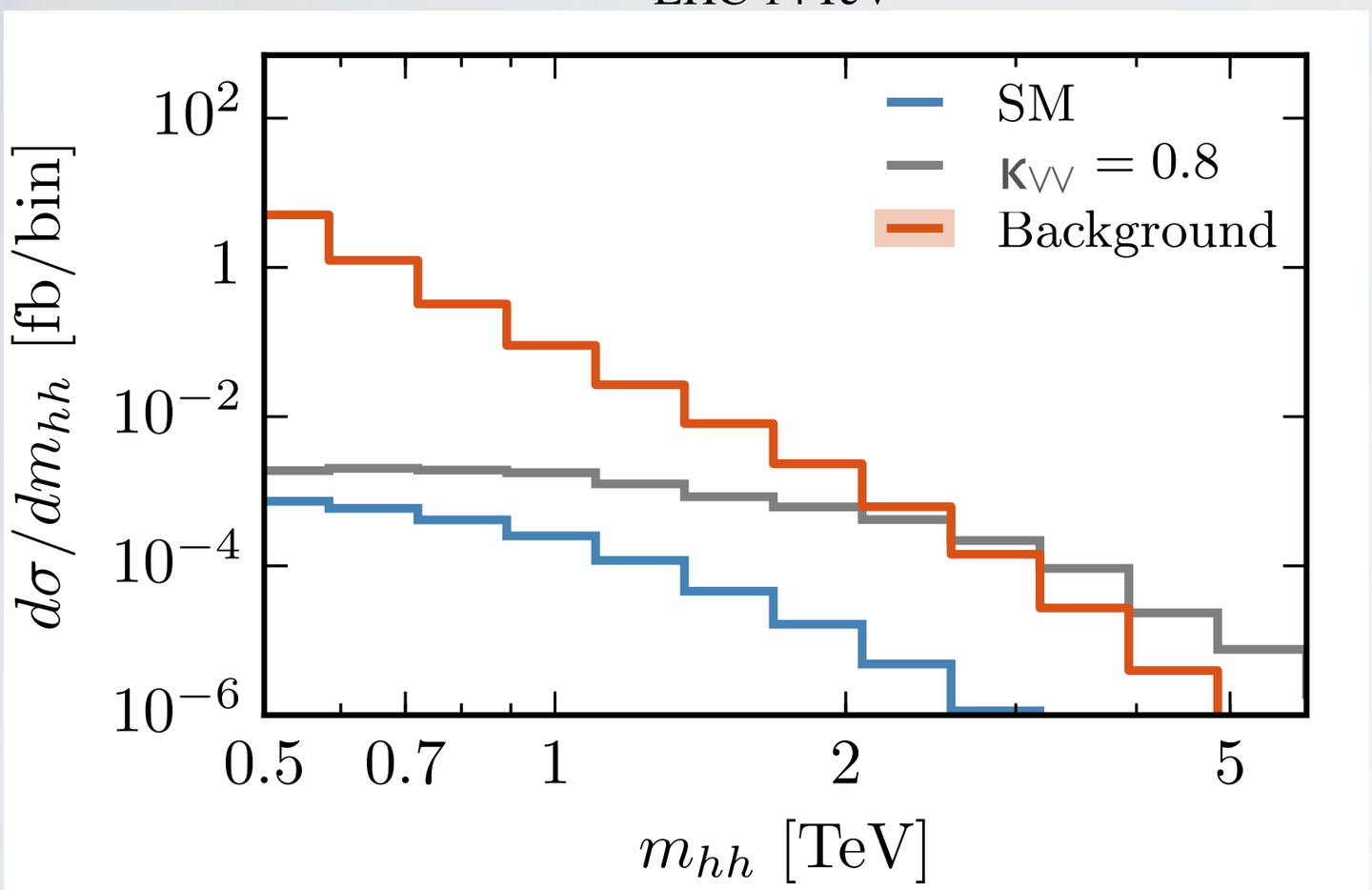
Naive expectation that longitudinal VBS is large is not borne out by calculation (e.g. Contino et.al. 1002.1011, also see CW Chiang's talk)



Due to many suppression factors, longitudinal scattering doesn't dominate until several TeV.
Easier to search for anomalous quartic gauge couplings.

VBS PRODUCTION OF HH

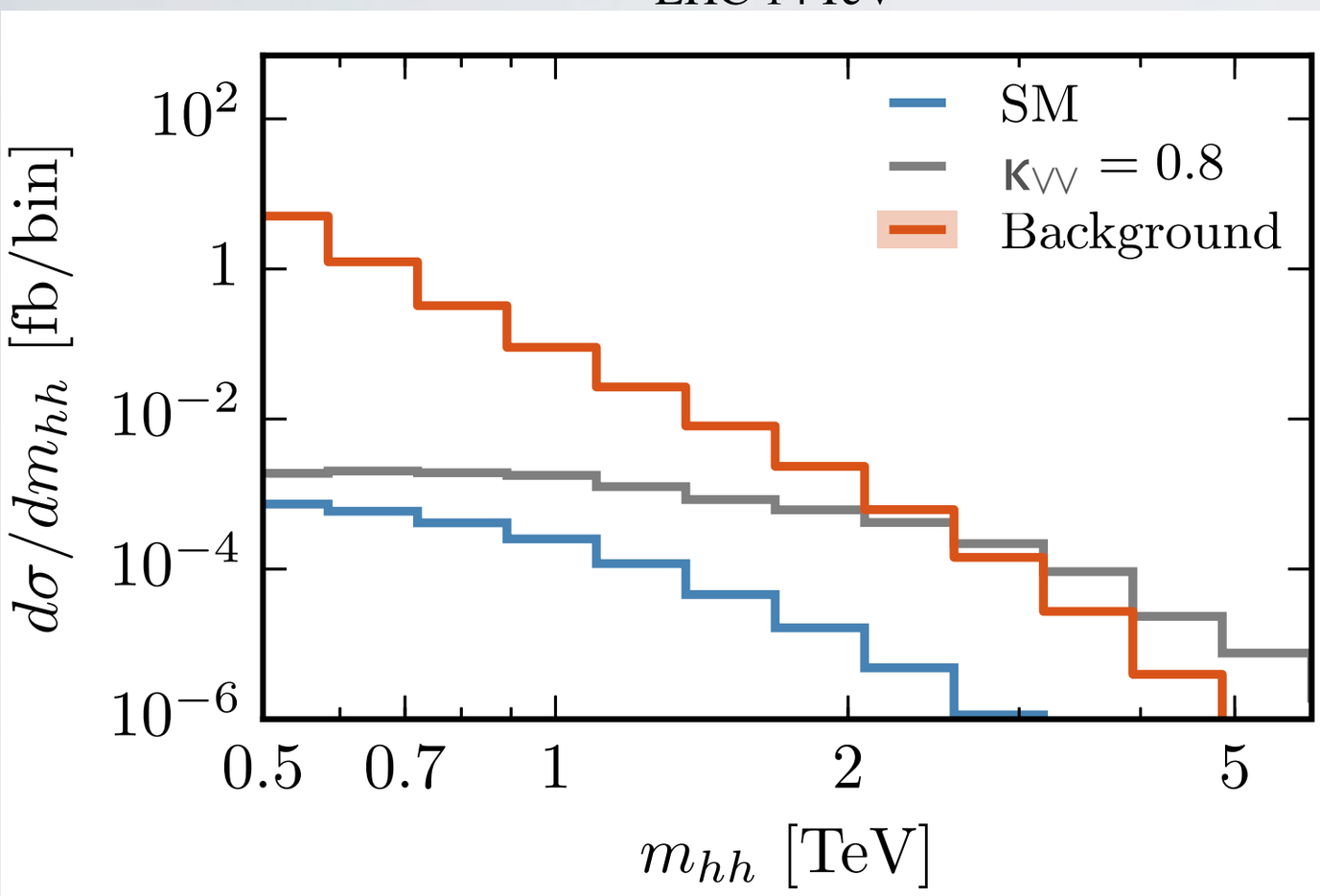
(BISHARA ET.AL. 1611.03860)



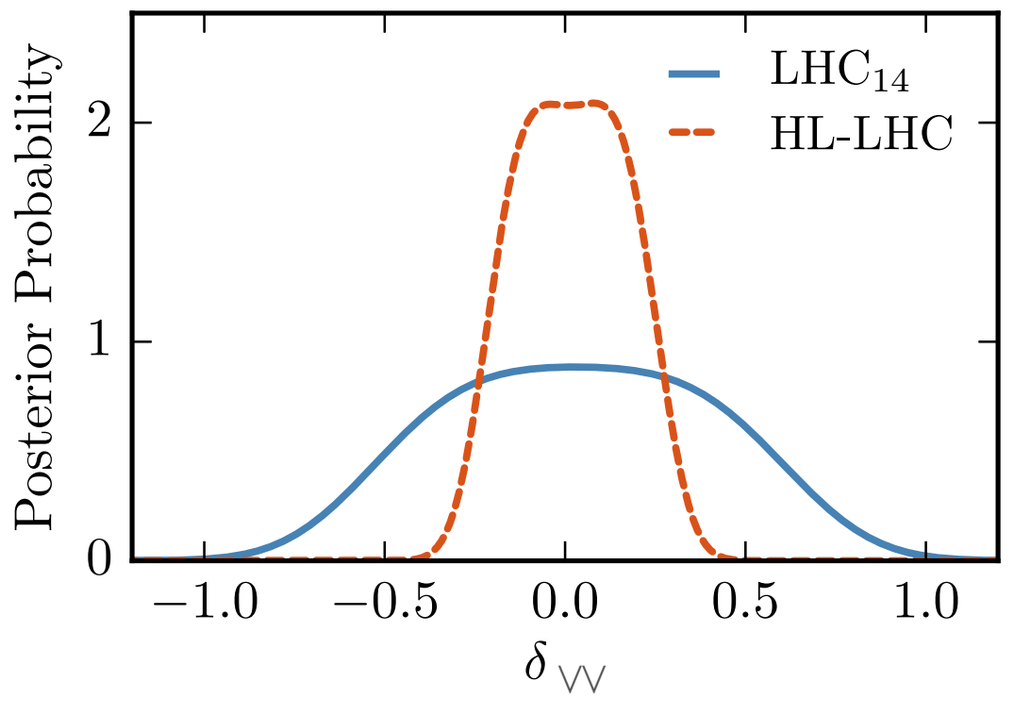
VBS to a Higgs pair is not as suppressed (and is also sensitive to hhVV coupling)

VBS PRODUCTION OF HH

(BISHARA ET.AL. 1611.03860)



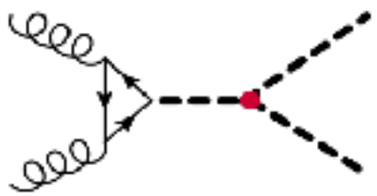
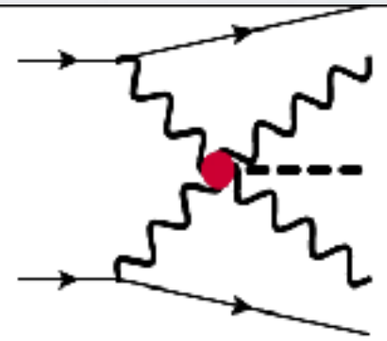
VBS to a Higgs pair is not as suppressed (and is also sensitive to hhVV coupling)



Search for jjbbbb 300 fb^{-1} can give a rough bound on hhVV coupling

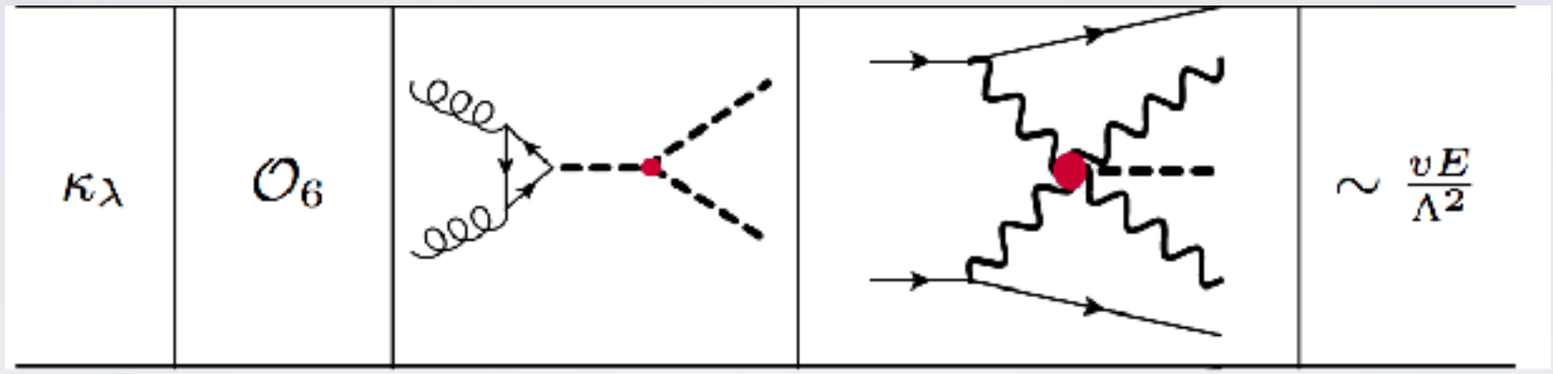
TRILINEAR PROCESS Henning et.al.1812.09299

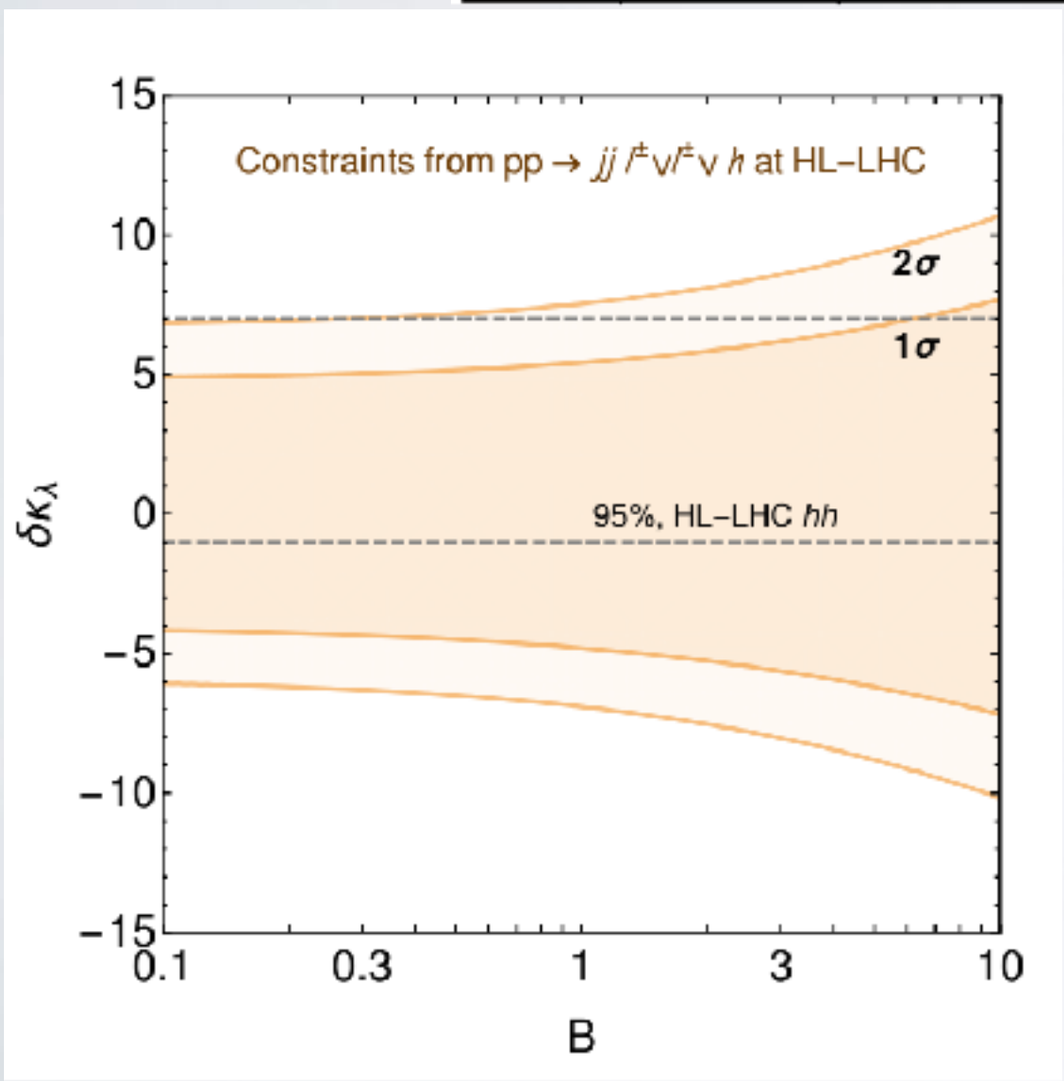
Similarly can look for growth in processes related to trilinear

κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$

TRILINEAR PROCESS Henning et.al.1812.09299

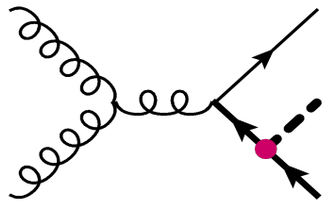
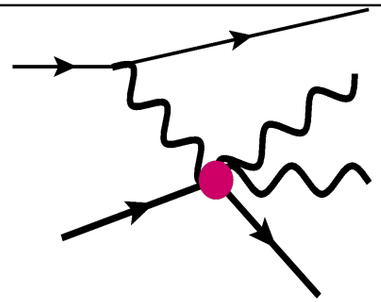
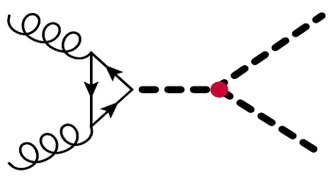
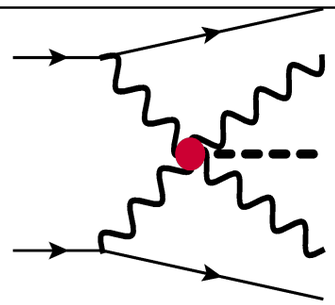
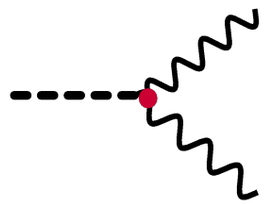
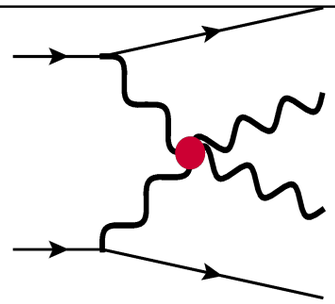
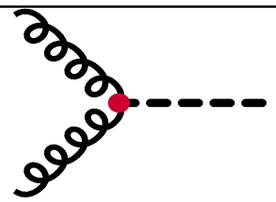
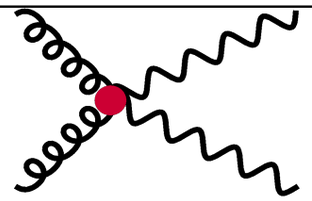
Similarly can look for growth in processes related to trilinear

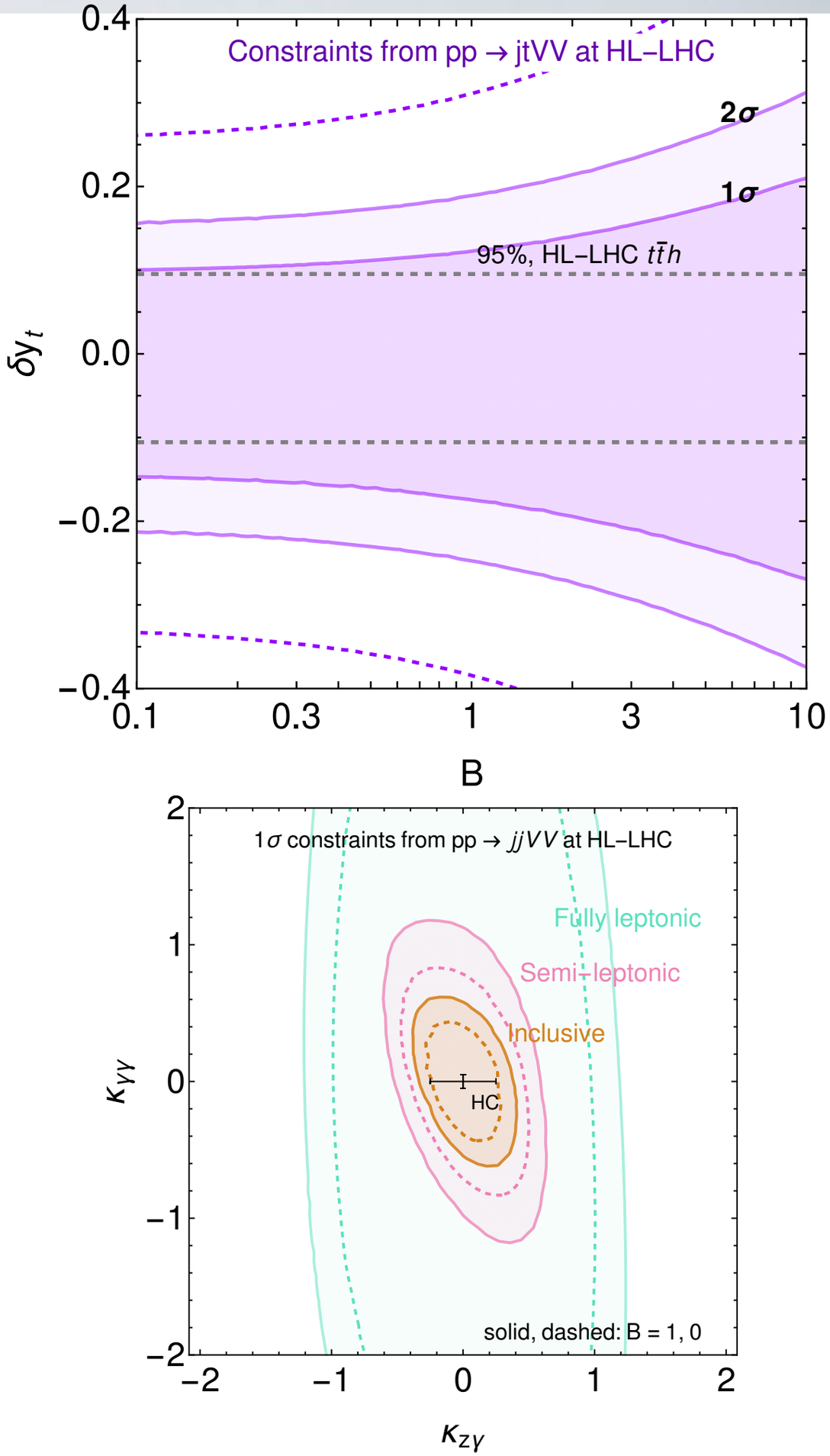




Searching for jj W^+W^+ h is competitive with di-Higgs sensitivity to Higgs trilinear coupling

HENNING ET.AL.

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$



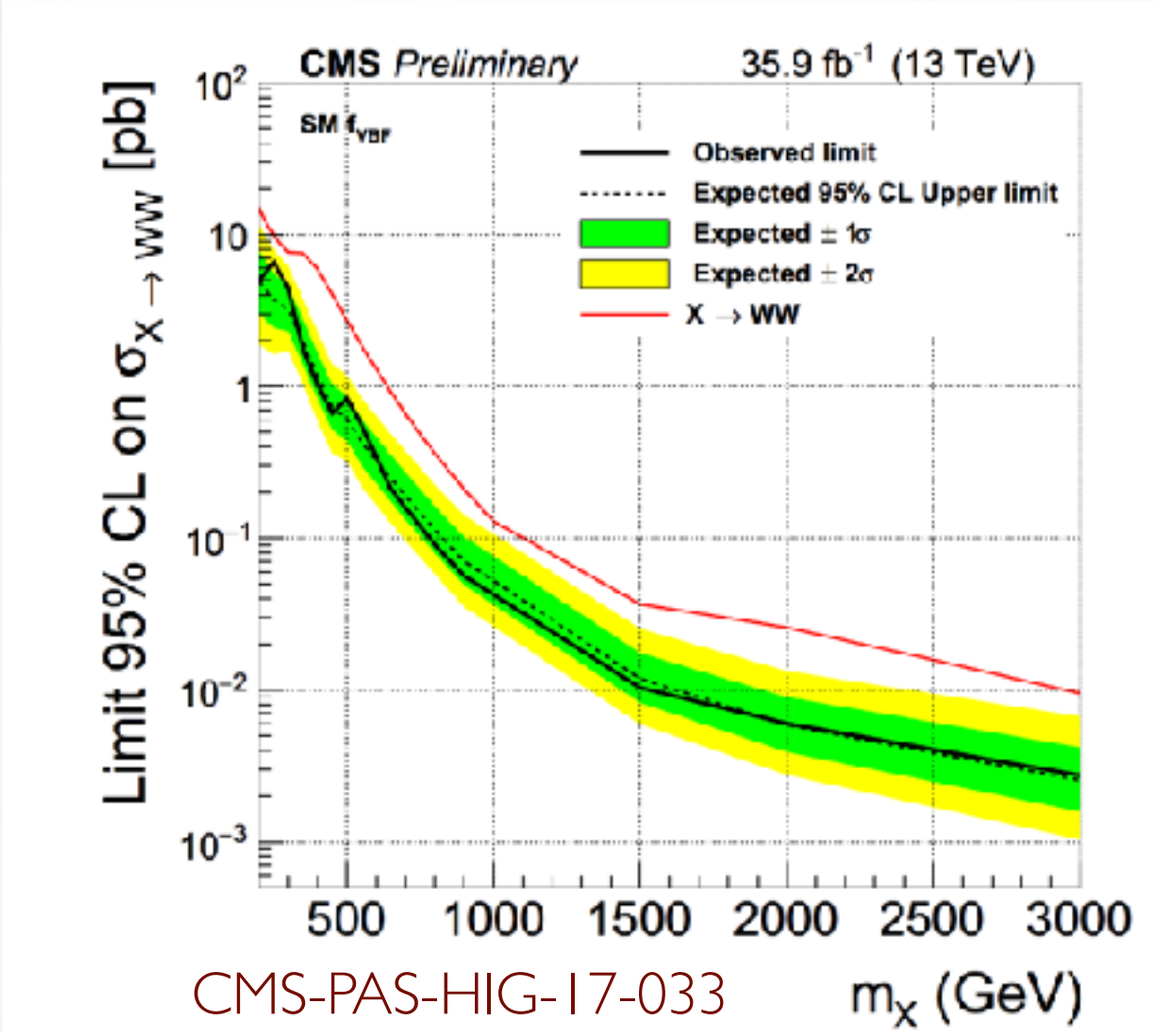
RESONANCES

Lesson from Higgs
New states can appear much
below Unitarity bound (1 TeV)
and in other channels
(GGF to **γγ**, ZZ*)

RESONANCES

Lesson from Higgs
New states can appear much below Unitarity bound (1 TeV) and in other channels (GGF to **γγ**, ZZ*)

Many particles can Unitarize including
New Higgs bosons
(e.g. talk by C.W. Chiang)
Heavy singlets
Techni-rhos

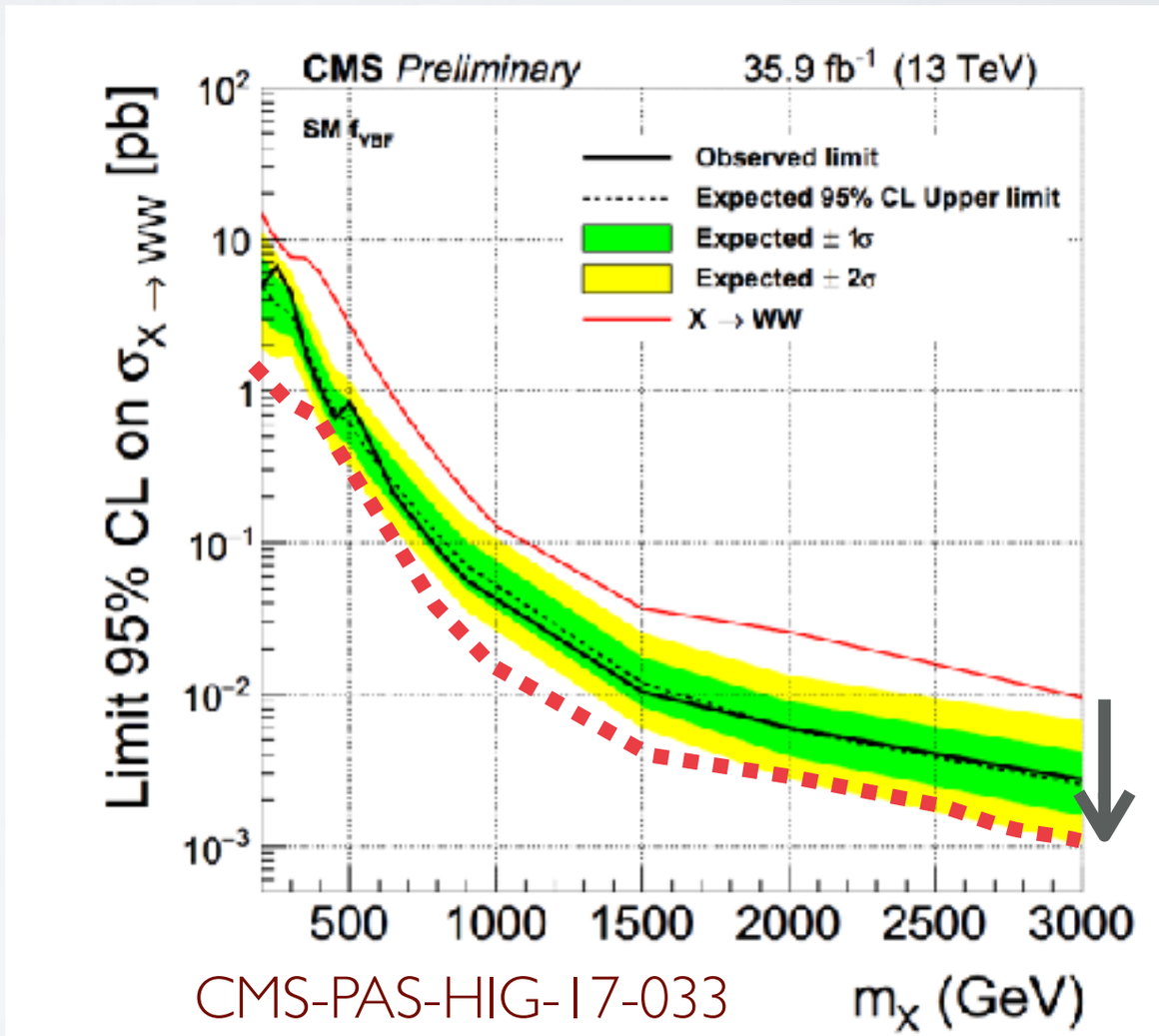


CMS-PAS-HIG-17-033

RESONANCES

Lesson from Higgs
New states can appear much below Unitarity bound (1 TeV) and in other channels (GGF to **γγ**, ZZ*)

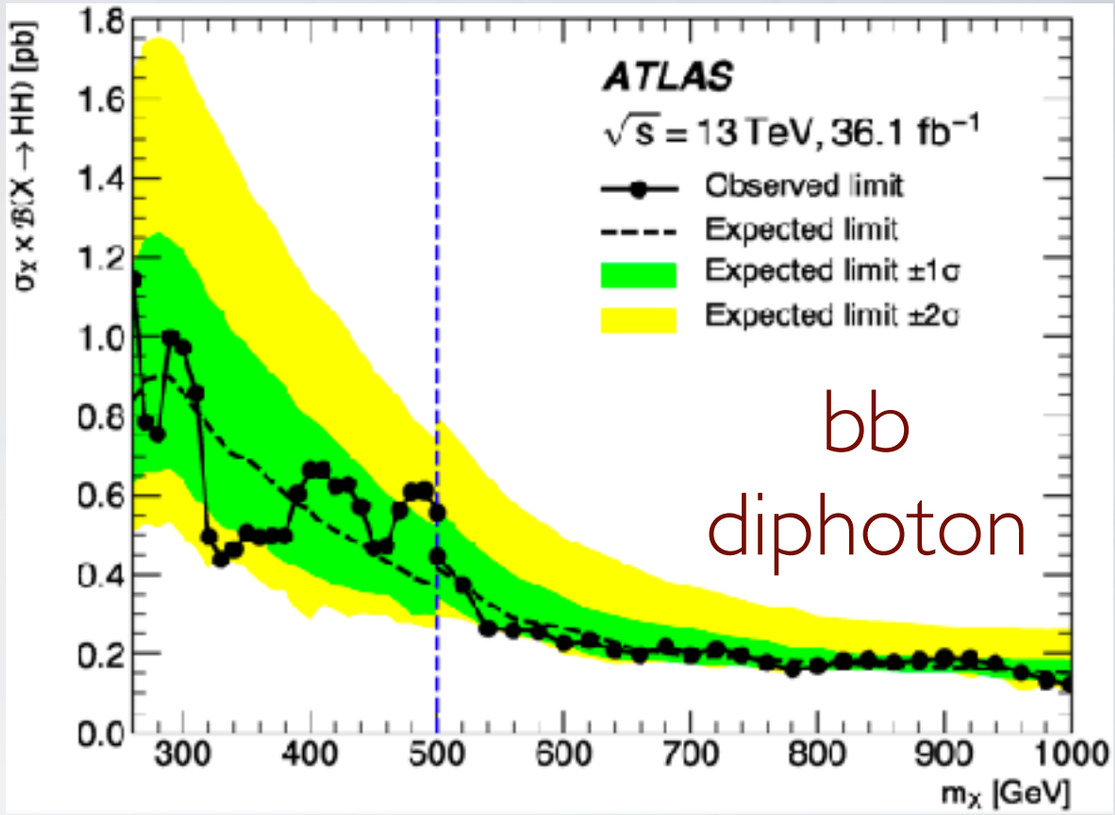
Many particles can Unitarize including
New Higgs bosons
(e.g. talk by C.W. Chiang)
Heavy singlets
Techni-rhos

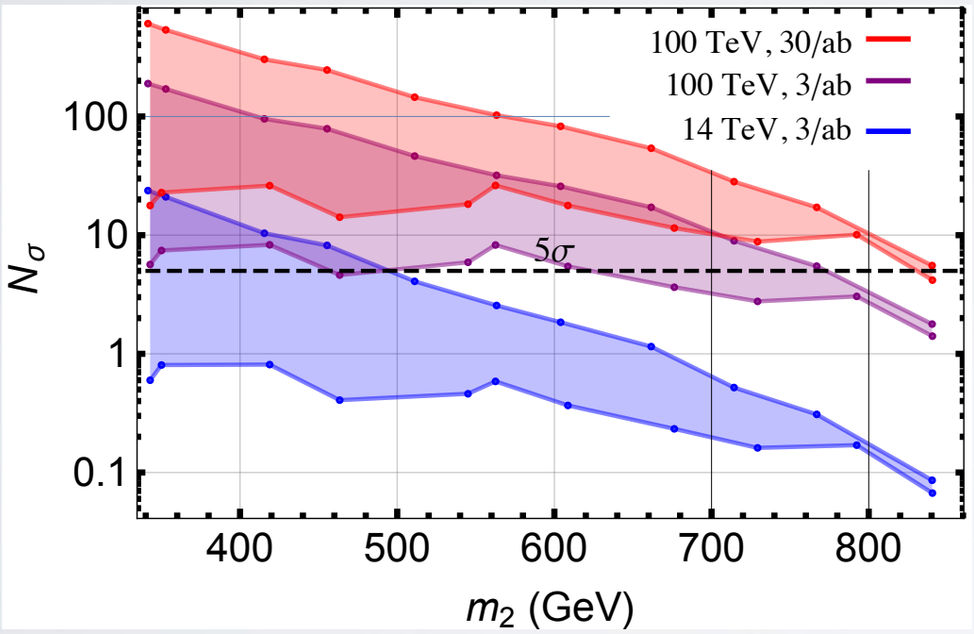


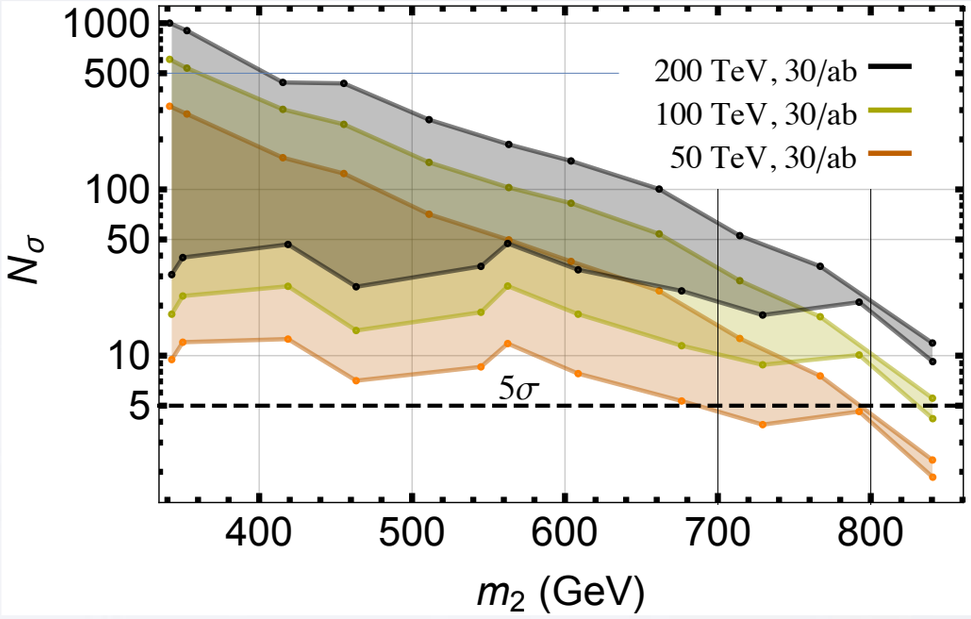
CMS-PAS-HIG-17-033

Heavy Singlet
δκ ~ 0.2

S → HH







EWBG motivated parameter space 1902.00134

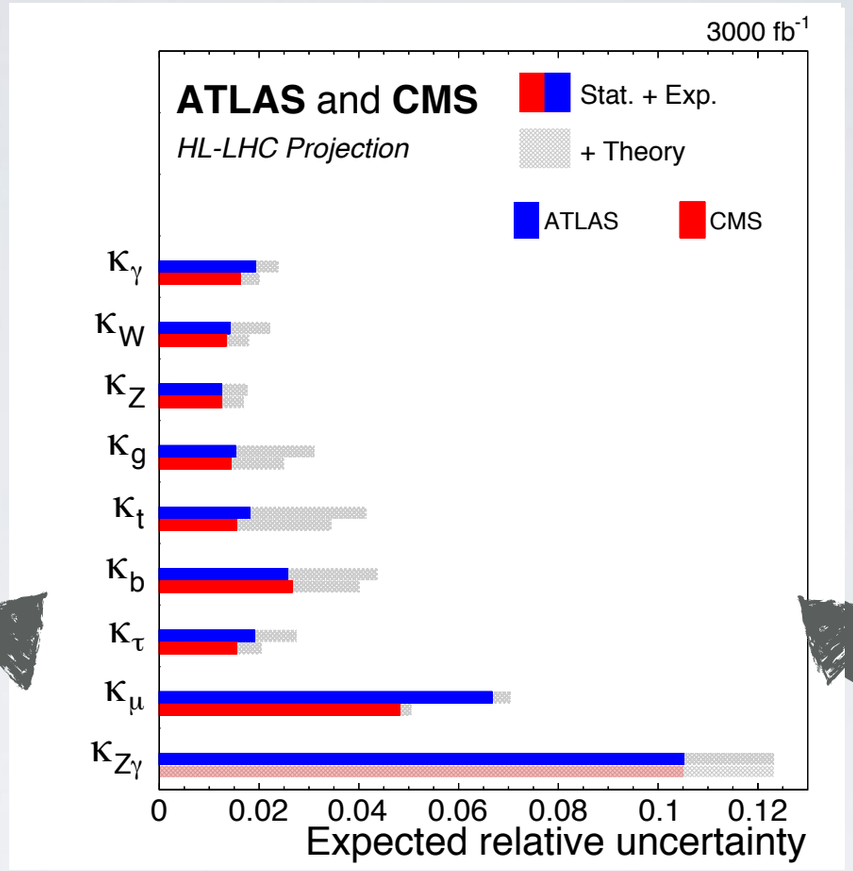
Fig. 86: Discovery potential for the singlet-induced strong first order EWPT using resonant di-Higgs production combining 4τ and $b\bar{b}\gamma\gamma$ final states [403]. Vertical axis gives significance as a function of the singlet-like scalar mass m_2. Left panel gives comparison of the reach for the HL-LHC (blue band) and the FCC-hh with 3 ab^{-1} and 30 ab^{-1} (purple and red bands, respectively). Right panel shows the prospective reach for different centre of mass energies, assuming 30 ab^{-1}.

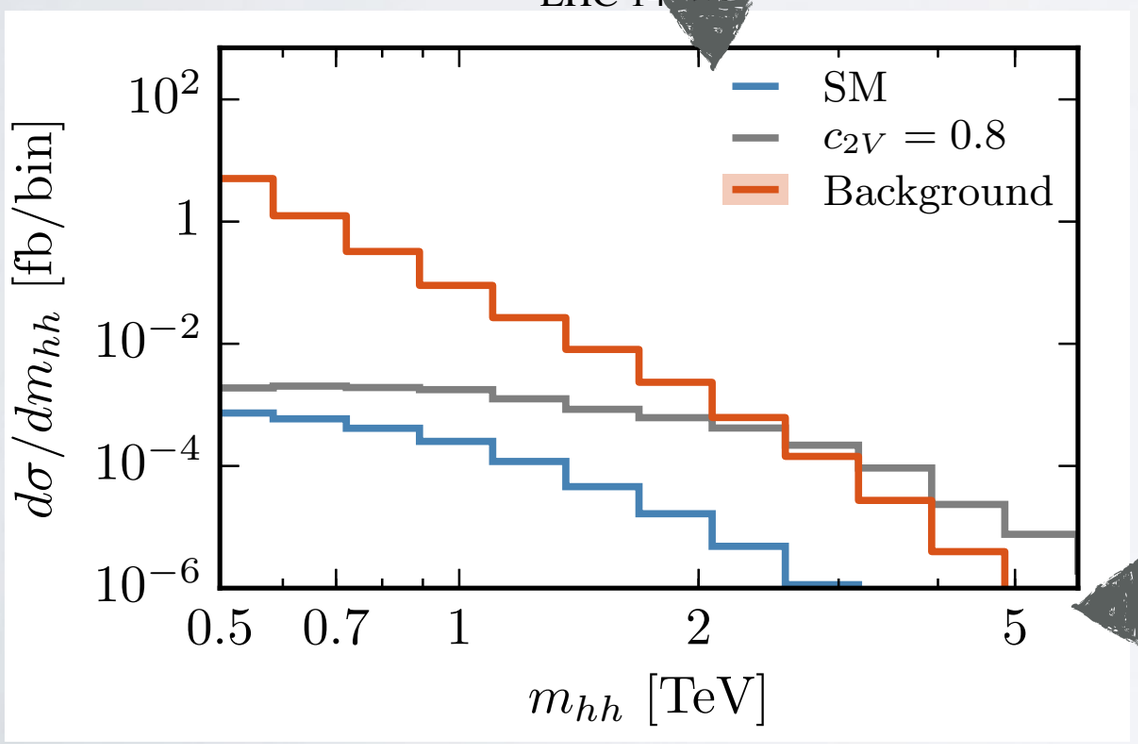
CONCLUSIONS

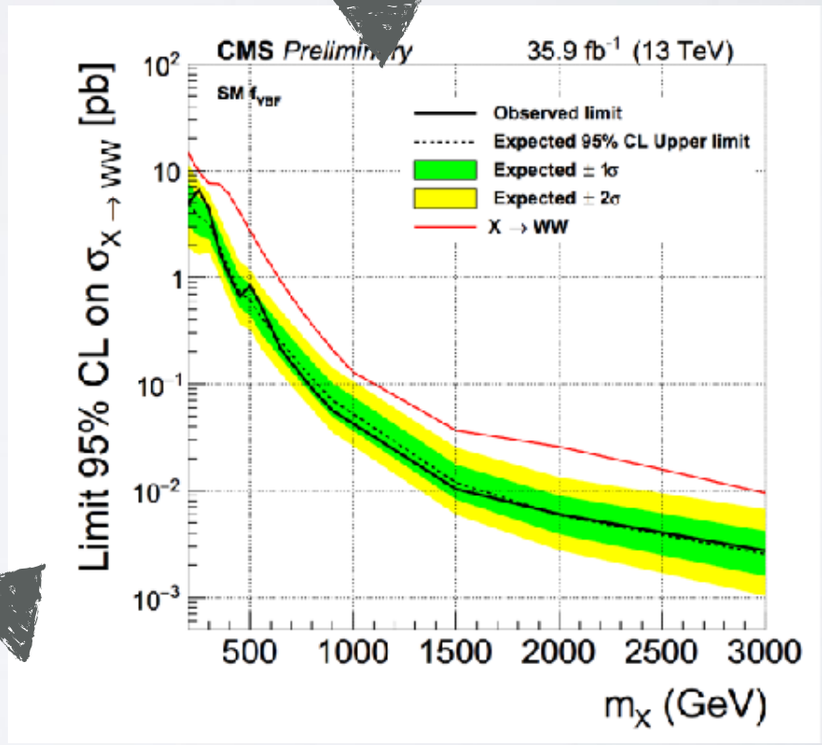
- Near term LHC and future colliders will aim to measure Higgs couplings

- Complementary approach, look for energy growth or resonances in Unitarity violating processes

THANK YOU!


3000 fb-1
ATLAS and CMS
HL-LHC Projection
Stat. + Exp.
+ Theory
ATLAS
CMS
κγ
κW
κZ
κg
κt
κb
κτ
κμ
κZγ
0
0.02
0.04
0.06
0.08
0.1
0.12
Expected relative uncertainty


LHC 14 TeV
SM
$c_{2V} = 0.8$
Background
$d\sigma/dm_{hh}$ [fb/bin]
m_{hh} [TeV]


CMS Preliminary
35.9 fb-1 (13 TeV)
SM fVBF
Observed limit
Expected 95% CL Upper limit
Expected ± 1σ
Expected ± 2σ
X → WW
Limit 95% CL on σX→WW [pb]
mX (GeV)

EXTRA SLIDES