Higgs Adventure

A personal Journey

Kingman Cheung

IOP, Sinica, May 2026

Popularity of Higgs

- According to InSpires: a total of 19744 papers with "Higgs" in the title.
- The earliest one dated back to 1972, the most recent one is today.

Renormalizable Massive Vector Meson Theory: Perturbation Theory of the Higgs Phenomenon #3

Benjamin W. Lee (Fermilab and SUNY, Stony Brook) (Sep, 1971)

Published in: *Phys.Rev.D* 5 (1972) 823-835

- Peter Higgs's paper "Broken Symmetries and the Masses of Gauge Bosons" was published in 1964.
- The particle was named "Higgs" boson due to a mistake made by Steve Weinberg.

Where did the name come from?

In 1972: Ben Lee in the Rochester Conference at FNAL, attached my name to everything involving spontaneous symmetry breaking, including the "Higgs meson"

MY LIFE AS A BOSON: THE STORY OF "THE HIGGS"

Peter Higgs 2002 , IJMPA

The Crisis of Big Science

Steven Weinberg

May 10, 2012
Issue

As to my responsibility for the name "Higgs boson," because of a mistake in reading the dates on these three earlier papers, I thought that the earliest was the one by Higgs, so in my 1967 paper I cited Higgs first, and have done so since then. Other physicists apparently have followed my lead. But as Close points out, the earliest paper of the three I cited was actually the one by Robert Brout and François Englert. In extenuation of my mistake, I should note that Higgs and Brout and Englert did their work independently and at about the same time, as also did the third group (Gerald Guralnik, C.R. Hagen, and Tom Kibble). But the name "Higgs boson" seems to have stuck. ↩

My Personal Encounter

- I wrote a total > 250 papers, out of them >90 have "Higgs" in the title. The earliest one was during graduate school. Now still writing papers on Higgs.
- Thesis: "Search for heavy Higgs signals at hadronic supercolliders".
- Why working on the Higgs? Spin 0, very simple, yet the least known particle.
- Had been working on search strategies for the Higgs.
- It was found in 2012. Now doing precision studies, rare decays, pair production, … … on the Higgs physics.

First Encounter

- Learned in the particle physics class.
- Higgs boson is a by-product of the Higgs mechanism, which is essential to give masses to elementary particles — electroweak symmetry breaking (EWSB).
- The Higgs mechanism completes the picture of the SM.
- The existence of the Higgs boson is an evidence of EWSB.

A Historical Account of

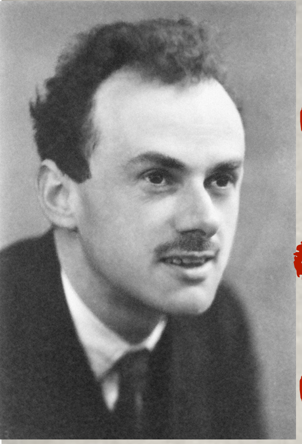
the Higgs Mechanism

A. Big Success with QED (local gauge theory)

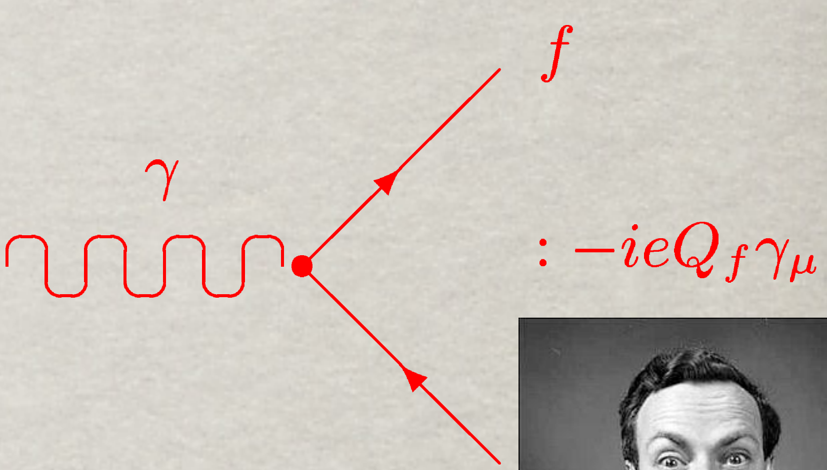
- Maxwell Equations --> Lorentz invariance
  --> U(1) invariance

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

- Lorentz, local invariance: manifest
- Introduction of a covariant $A_\mu(x,t)$ in place of E(x,t), B(x,t).



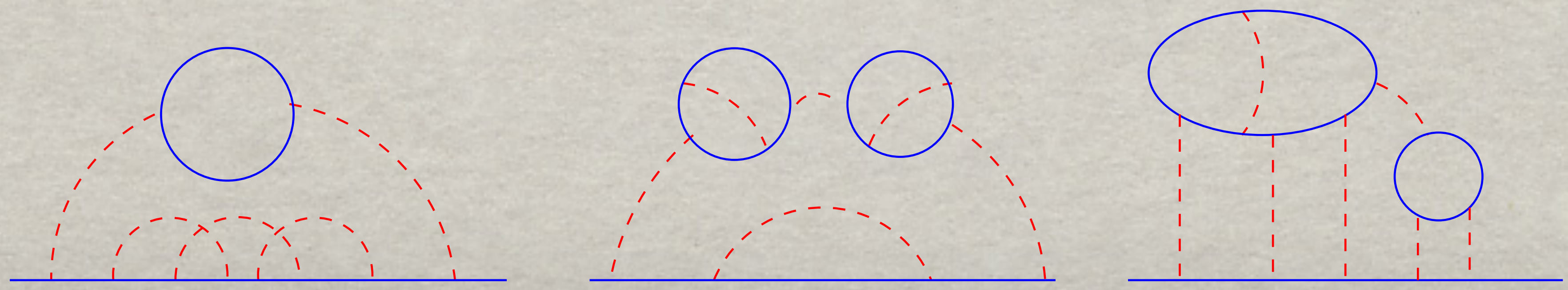
- Dirac relativistic theory -> existence of antiparticle e+
- To maintain local gauge invariance -> covariant derivative



$$D_\mu = \partial_\mu + ieQ_f A_\mu$$

$$\mathcal{L} = \bar{\psi}_f \left(i\gamma^\mu D_\mu - m\right) \psi_f - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

- Feynman diagram approach: can calculate to high accuracy: e.g. (g-2)
- QED became the most accurate theory.



B. Weak Interaction

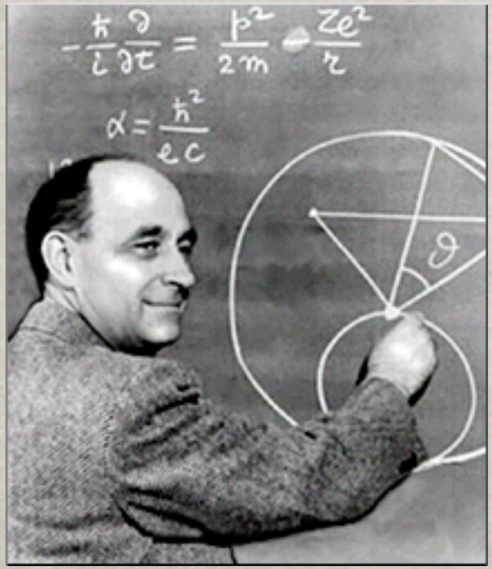
- Fermi formulated the beta decay in terms of 4-fermion interactions:

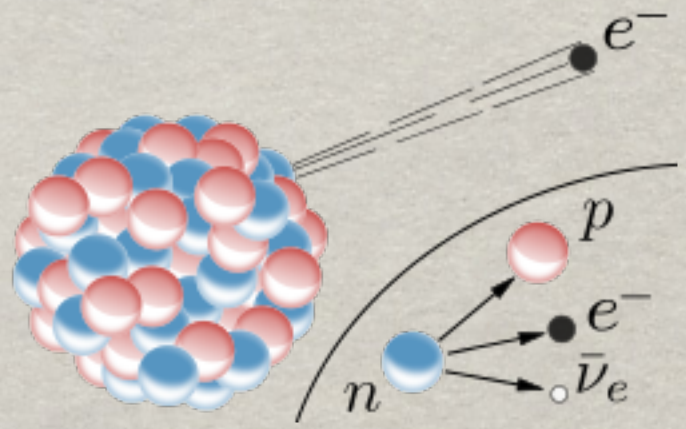
$$n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$$

- Current-current interaction, similar to QED currents, but with parity violation (V-A):

$$\mathcal{L} = -\frac{G_F}{\sqrt{2}} \left(\bar{\psi}_p \gamma^\mu (1-\gamma^5)\psi_n\right) \left(\bar{\psi}_e \gamma_\mu (1-\gamma^5)\psi_\nu\right)$$

- Predicted existence of neutrino
- $G_F \sim 1/(300\ \mathrm{GeV})^2$ -> new mass scale should appear at O(100) GeV





Idea of nonabelian gauge theory: SU(N)

- Yang-Mill extended the idea of abelian gauge theory to nonabelian ones. Used SU(N) to describe weak and strong interactions.

- Local gauge invariance prevents gauge bosons to have a mass:

$$\frac{1}{2}M_A^2 A_\mu A^\mu \longrightarrow \frac{1}{2}M_A^2 \left(A_\mu - \frac{1}{e}\partial_\mu \alpha\right)\left(A^\mu - \frac{1}{e}\partial^\mu \alpha\right) \neq \frac{1}{2}M_A^2 A_\mu A^\mu$$

- Even worse no mass terms for fermions, left- and right chiral fermions have different weak charges.

$$-m_f \bar{f} f = -m_f \left(\overline{f_R} f_L + \overline{f_L} f_R\right)$$

An Anecdote by C. N. Yang

The question of the gauge-field mass problem was raised by Pauli when Yang was invited to present the Yang-Mills results at the Princeton Institute in February 1954. As Yang relates:
Soon after my seminar began, when I had written on the blackboard,

$$(\partial_\mu - ieB_\mu)\psi$$

Pauli asked, "What is the mass of this field **B** ?" I said we did not know. Then I resumed my presentation but soon Pauli asked the same question again. I said something to the effect that it was a very complicated problem, we had worked on it and had come to no definite conclusions. I still remember his repartee: "That is not sufficient excuse". I was so taken aback that I decided, after a few moments' hesitation, to sit down. There was general embarrassment. Finally Oppenheimer, who was chairman of the seminar, said "We should let Frank proceed". I then resumed and Pauli did not ask any more questions during the seminar.

C. Ideas of Unification

Within a single framework of gauge theory to unify weak and EM interactions.

PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

SHELDON L. GLASHOW †

Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

Received 9 September 1960

Abstract: Weak and electromagnetic interactions of the leptons are examined under the hypothesis that the weak interactions are mediated by vector bosons. With only an isotopic triplet of leptons coupled to a triplet of vector bosons (two charged decay-intermediaries and the photon) the theory possesses no partial-symmetries. Such symmetries may be established if additional vector bosons or additional leptons are introduced. Since the latter possibility yields a theory disagreeing with experiment, the simplest partially-symmetric model reproducing the observed electromagnetic and weak interactions of leptons requires the of at least four vector-boson fields (including the photon). Corresponding partially- quantities suggest leptonic analogues to the conserved quantities associated with st actions: strangeness and isobaric spin.

SU(2)xU(1) Electroweak Unification

$$\psi_L = \frac{1}{2}(1-\gamma^5)\psi\,, \qquad \psi_R = \frac{1}{2}(1+\gamma^5)\psi\,, \qquad \psi = \psi_L + \psi_R$$

$$\mathcal{L} = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + \overline{\psi}i\gamma^\mu D_\mu\psi$$

$$\begin{aligned} W^a_{\mu\nu} &= \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g f^{abc}W^b_\mu W^c_\nu \\ B^a_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \\ D_\mu &= \partial_\mu + ig\frac{\tau^a}{2}W^a_\mu + ig'\frac{Y}{2}B_\mu \end{aligned}$$

$$\mathcal{L}_{\text{charged}} = -\frac{g}{\sqrt{2}}\left(\overline{\nu_L}\gamma^\mu e_L W^+_\mu + \overline{e_L}\gamma^\mu \nu_L W^-_\mu\right)$$

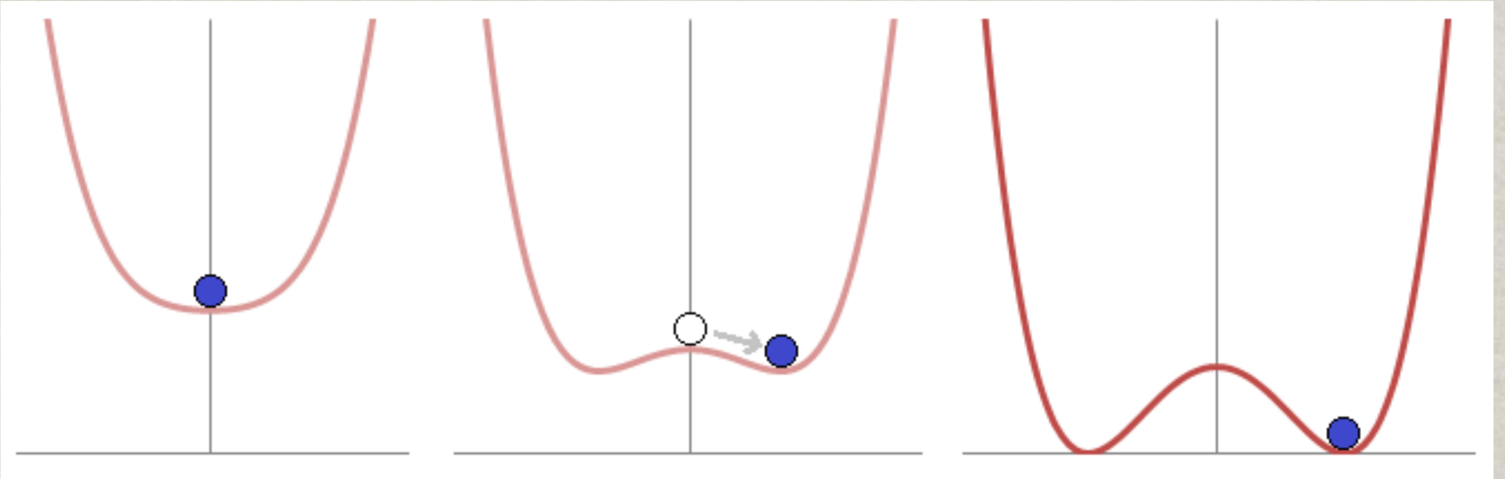
$$\mathcal{L}_{\text{neutral}} = -e\overline{\psi}\gamma^\mu Q\psi\, A_\mu - \frac{g}{\cos\theta_{\text{w}}}\overline{\psi}\gamma^\mu\left(\frac{\tau^3}{2} - \sin^2\theta_{\text{w}} Q\right)\psi\, Z_\mu$$

$$g = \frac{e}{\sin\theta_{\text{w}}}\,, \qquad g' = \frac{e}{\cos\theta_{\text{w}}}$$

D. Idea of Spontaneous Symmetry Breaking

-- Nature may not be symmetric

The Lagrangian of a system is invariant under a symmetry, but the ground state doesn't respect that symmetry.



Y. Nambu was the first to formulate SSB in relativistic quantum field theory (1960)

-- earned him 2008 Nobel Prize.

E. Goldstone Theorem

If a continuous symmetry is spontaneously broken, there will appear a massless dof called Nambu-Goldstone boson.

Symmetry: $[Q,H] = [H,Q] = 0$

Vacuum: $H|0\rangle = E_0\,|0\rangle$, but $Q|0\rangle = |0'\rangle \neq 0$

$$(Q\,H - H\,Q)\,|0\rangle = 0 = (E_0 - H)\,|0'\rangle$$

$$\Rightarrow \qquad H\,|0'\rangle = E_0\,|0'\rangle$$

There is a new nonsymmetric state $|0'\rangle$ that is degenerate with the vacuum $|0\rangle$. Thus it is massless called Nambu-Goldstone boson.

Goldstone Bosons or Pseudo-Nambu-Goldstone bosons does not help solving the problem of giving mass to the vector bosons that are responsible for weak and EM interactions.

Though Glashow's idea of unifying the EM and weak interactions of the leptons looked great, massless vector bosons are still BIG problems.

F. The Magical Higgs Mechanism (1964)

When a LOCAL gauge symmetry is spontaneously broken, the gauge boson will acquire a mass by absorbing the Goldstone mode.

massless gauge boson -> massive

dof : 2 -> 3

By absorbing the Goldstone boson.

The leftover is the massive radial field

-- the Higgs boson

1 massless gauge boson + 1 massless GB

--> 1 massive gauge boson + 0 GB

Problems solved

The local $U(1)$ symmetric Lagrangian:

$$\mathcal{L} = (D_\mu \phi)^* (D^\mu \phi) - \mu^2 \phi^* \phi - \lambda (\phi^* \phi)^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

where

$$D_\mu = \partial_\mu + ieA_\mu, \qquad \phi = \frac{1}{\sqrt{2}} \left(r(x) + \langle r \rangle \right) e^{2i\alpha(x)}$$

Substitute everything

$$\begin{aligned} \mathcal{L} &= \frac{1}{2} \partial_\mu r(x) \partial^\mu r(x) + \frac{1}{2} \left(1 + \frac{r(x)}{\langle r \rangle} \right)^2 e^2 \langle r \rangle^2 \left(A_\mu + \frac{1}{e\langle r \rangle} \partial_\mu \alpha(x) \right)^2 \\ &+ \frac{\lambda}{4} \langle r \rangle^4 - \lambda \langle r \rangle^2 r(x)^2 + \ldots \end{aligned}$$

The Goldstone field $\alpha(x)$ can be absorbed into A_μ by redefining

$$A_\mu(x) \to A'_\mu(x) = A_\mu + \frac{1}{e\langle r \rangle} \partial_\mu \alpha(x)$$

A(x) acquires a mass = e <r>

r(x) also has a mass = √(2 lambda <r>)

A MODEL OF LEPTONS*

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(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in

by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.

This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may

[3]P. W. Higgs, Phys. Letters 12, 132 (1964), Phys. Rev. Letters 13, 508 (1964), and Phys. Rev. 145, 1156 (1966); F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964); G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Phys. Rev. Letters 13, 585 (1964).

A MODEL OF LEPTONS*

Steven Weinberg†

$$L \equiv [\tfrac{1}{2}(1+\gamma_5)]\begin{pmatrix}\nu_e \\ e\end{pmatrix}$$

$$\varphi = \begin{pmatrix}\varphi^0 \\ \varphi^-\end{pmatrix}$$

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e.$$

$$\mathfrak{L} = -\tfrac{1}{4}(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu \times \vec{A}_\nu)^2 - \tfrac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu - i\tfrac{1}{2}g'B_\mu)L$$

$$-\tfrac{1}{2}|\partial_\mu\varphi - ig\vec{A}_\mu\cdot\vec{t}\varphi + i\tfrac{1}{2}g'B_\mu\varphi|^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^\dagger L) - M_1{}^2\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2.$$

$$\langle\varphi\rangle = \lambda\begin{pmatrix}1 \\ 0\end{pmatrix}.$$

$$-\tfrac{1}{8}\lambda^2 g^2[(A_\mu{}^1)^2 + (A_\mu{}^2)^2]$$

$$-\tfrac{1}{8}\lambda^2(gA_\mu{}^3 + g'B_\mu)^2 - \lambda G_e\bar{e}e.$$

$$W_\mu \equiv 2^{-1/2}(A_\mu{}^1 + iA_\mu{}^2)$$

$$M_W = \tfrac{1}{2}\lambda g.$$

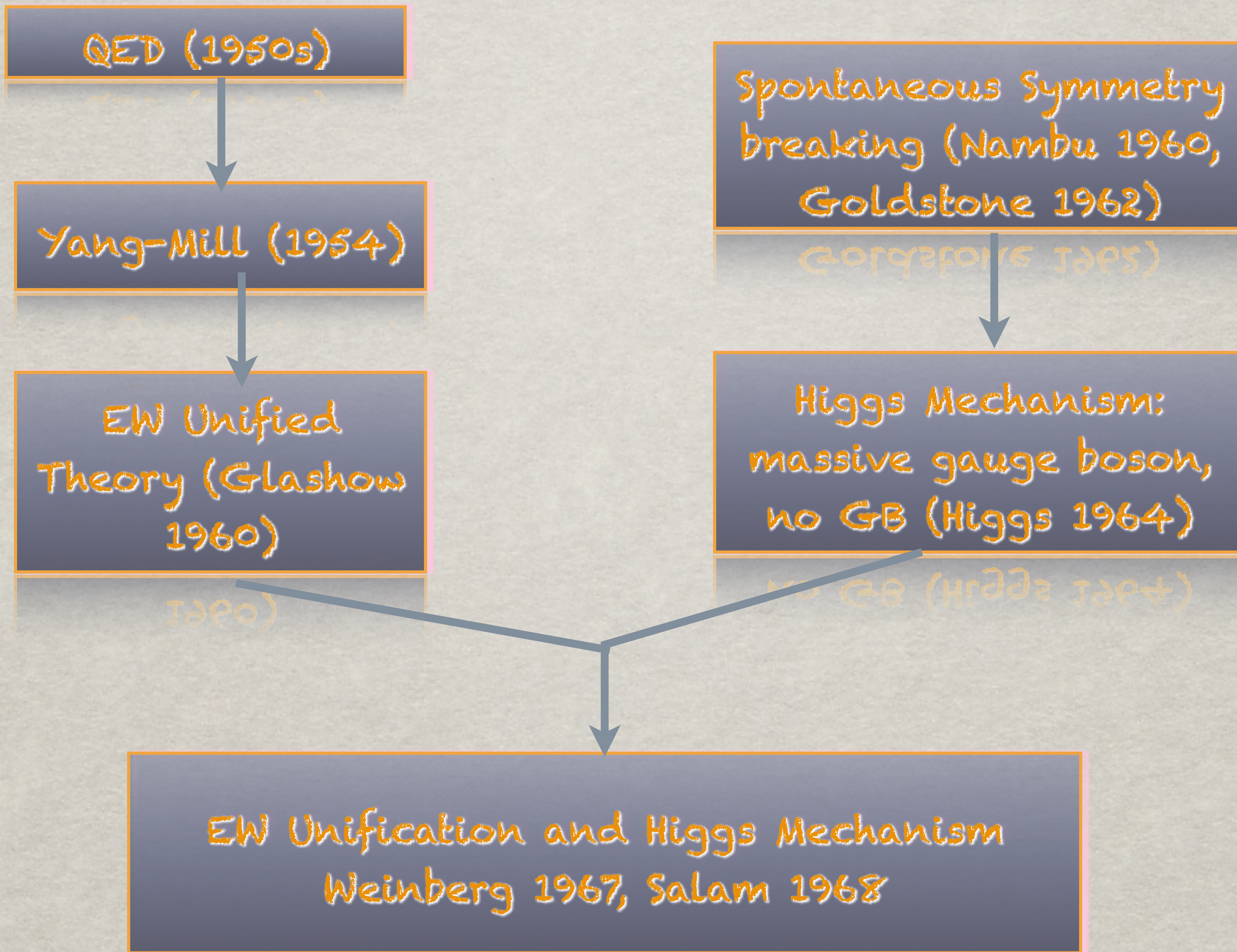
$$Z_\mu = (g^2 + g'^2)^{-1/2}(gA_\mu{}^3 + g'B_\mu),$$

$$A_\mu = (g^2 + g'^2)^{-1/2}(-g'A_\mu{}^3 + gB_\mu).$$

$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2},$$

$$M_A = 0,$$

Summary


QED (1950s)
Yang-Mill (1954)
EW Unified Theory (Glashow 1960)
Spontaneous Symmetry breaking (Nambu 1960, Goldstone 1962)
Higgs Mechanism: massive gauge boson, no GB (Higgs 1964)
EW Unification and Higgs Mechanism Weinberg 1967, Salam 1968

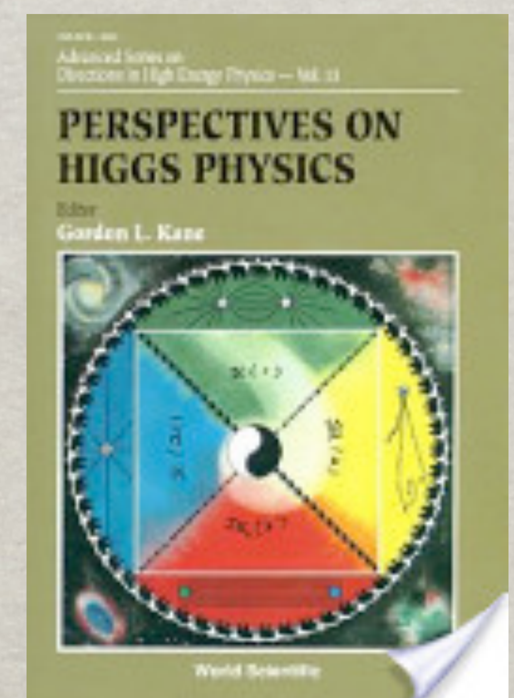
Experimental and phenomenological Efforts of Thousands of Peoples

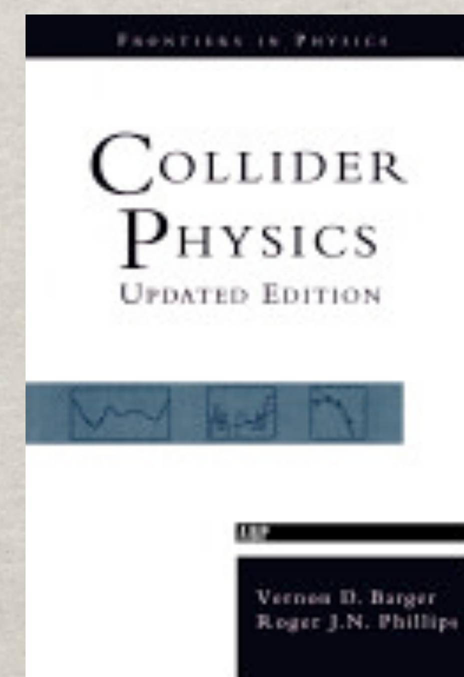
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

A number DPF/Snowmass studies on HEP:

- Snowmass '86 Summer Study On The Physics Of The Superconducting Supercollider
- 1988 DPF Summer Study On High-Energy Physics In The 1990s (Snowmass 88)
- 1996 DPF / DPB Summer Study On New Directions For High-Energy Physics (Snowmass 96)

Higgs was studied intensively





2017 J.J. Sakurai Prize

Second Encounter

- During graduate school, I studied collider signatures of heavy Higgs boson.
- The SM did not predict the mass of Higgs boson. It is a free parameter, can be MeV to TeV.
- There are a few theoretical arguments to restrict the mass range.
- But now the Higgs mass is light ~ 125 GeV.
- The techniques I found are still useful to present-day searches at the LHC.

$$\mathcal{L}_\Phi = |D_\mu \Phi|^2 - V(\Phi)$$

$$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

$$D_\mu = \partial_\mu + ieQA_\mu + i\frac{g}{\sqrt{2}}(\tau^+ W_\mu^+ + \tau^- W_\mu^-) + i\frac{g}{\cos\theta_\mathrm{w}}\left(\frac{\tau^3}{2} - \sin^2\theta_\mathrm{w}\right) Z_\mu$$

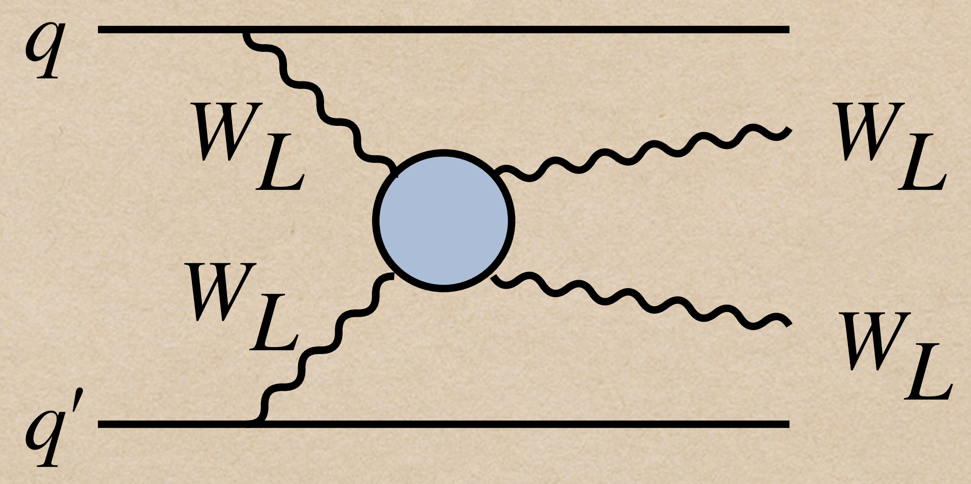
$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

$m_H = \sqrt{2\lambda} v$ after EWSB

Unitarity in Scattering requires the coupling not too large

$$m_H < \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} \approx 1 \text{ TeV}$$

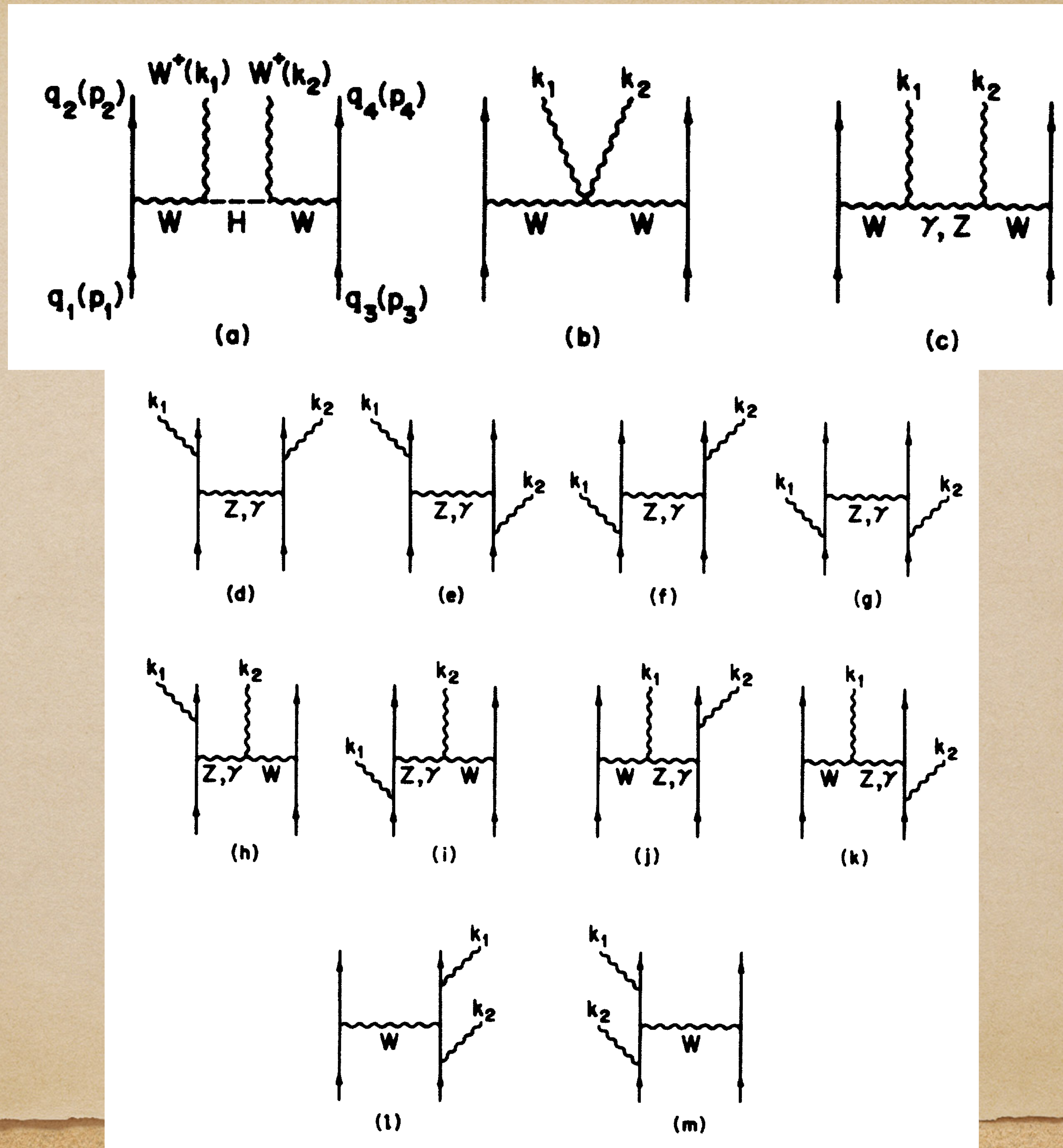
Vector Boson Fusion (VBF)



At high energy, the longitudinal W recalls themselves as parts of EWSB. Their scattering can reveal the structure of the EWSB sector. It can a Higgs or something more complicated. We can study the W W and 2 jets in final state to the signal from background.

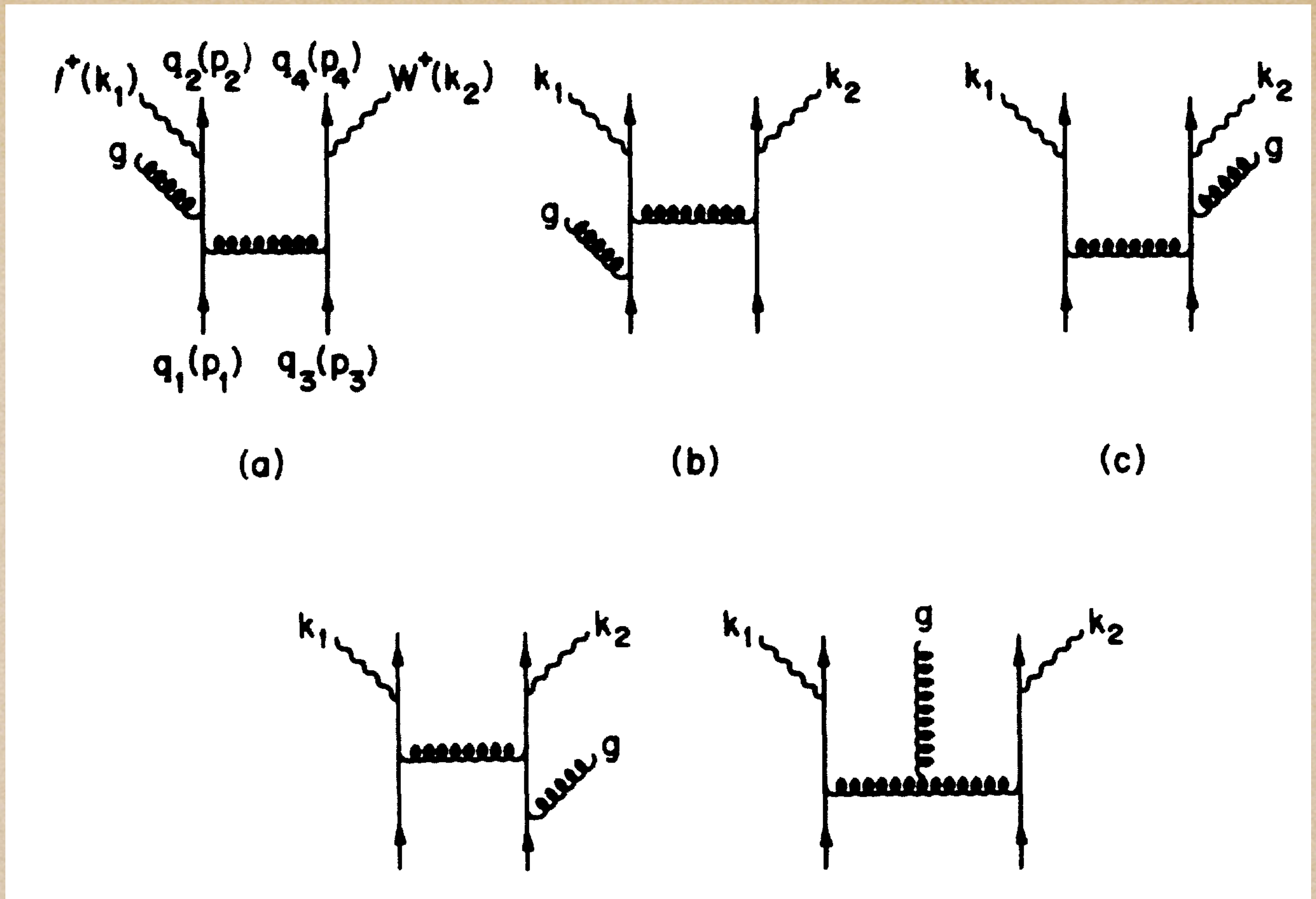
VBF

EW Bkgd

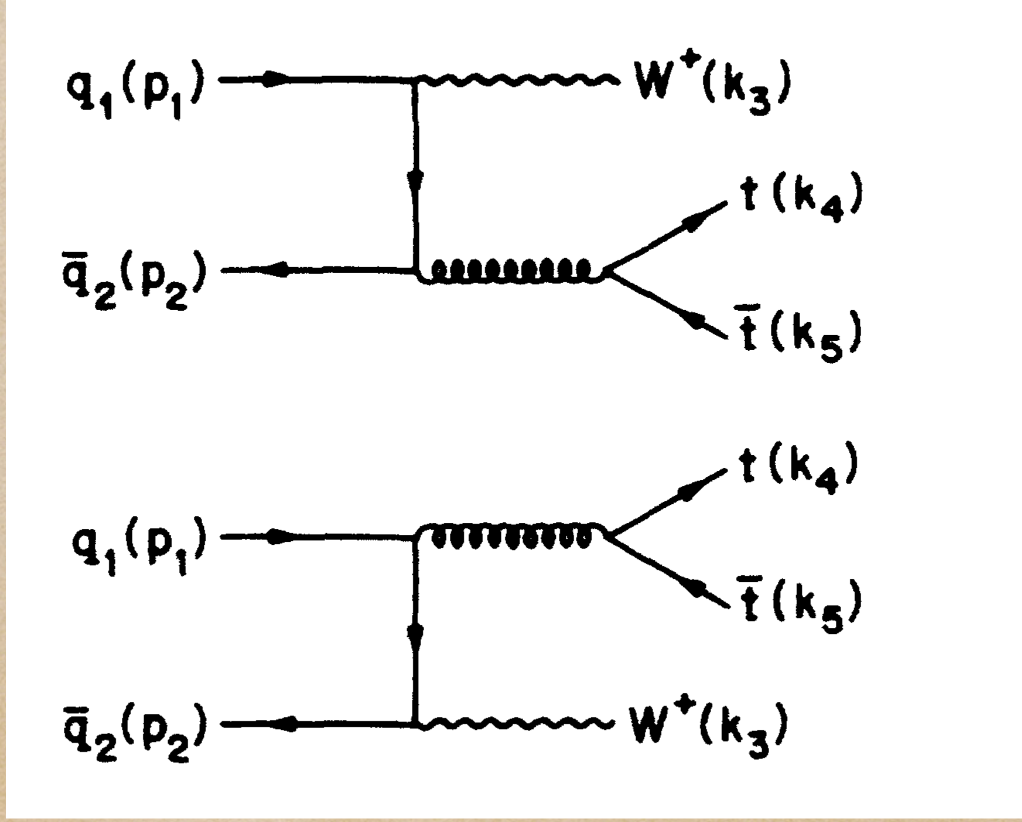


$q_2(p_2)$
$W^+(k_1)$
$W^+(k_2)$
$q_4(p_4)$
W
H
W
$q_1(p_1)$
$q_3(p_3)$
(a)
k_1
k_2
W
W
(b)
k_1
k_2
W
γ, Z
W
(c)
k_1
k_2
Z, γ
(d)
(e)
(f)
(g)
Z, γ
W
(h)
(i)
W
Z, γ
(j)
(k)
W
(l)
(m)

QCD Bkgd



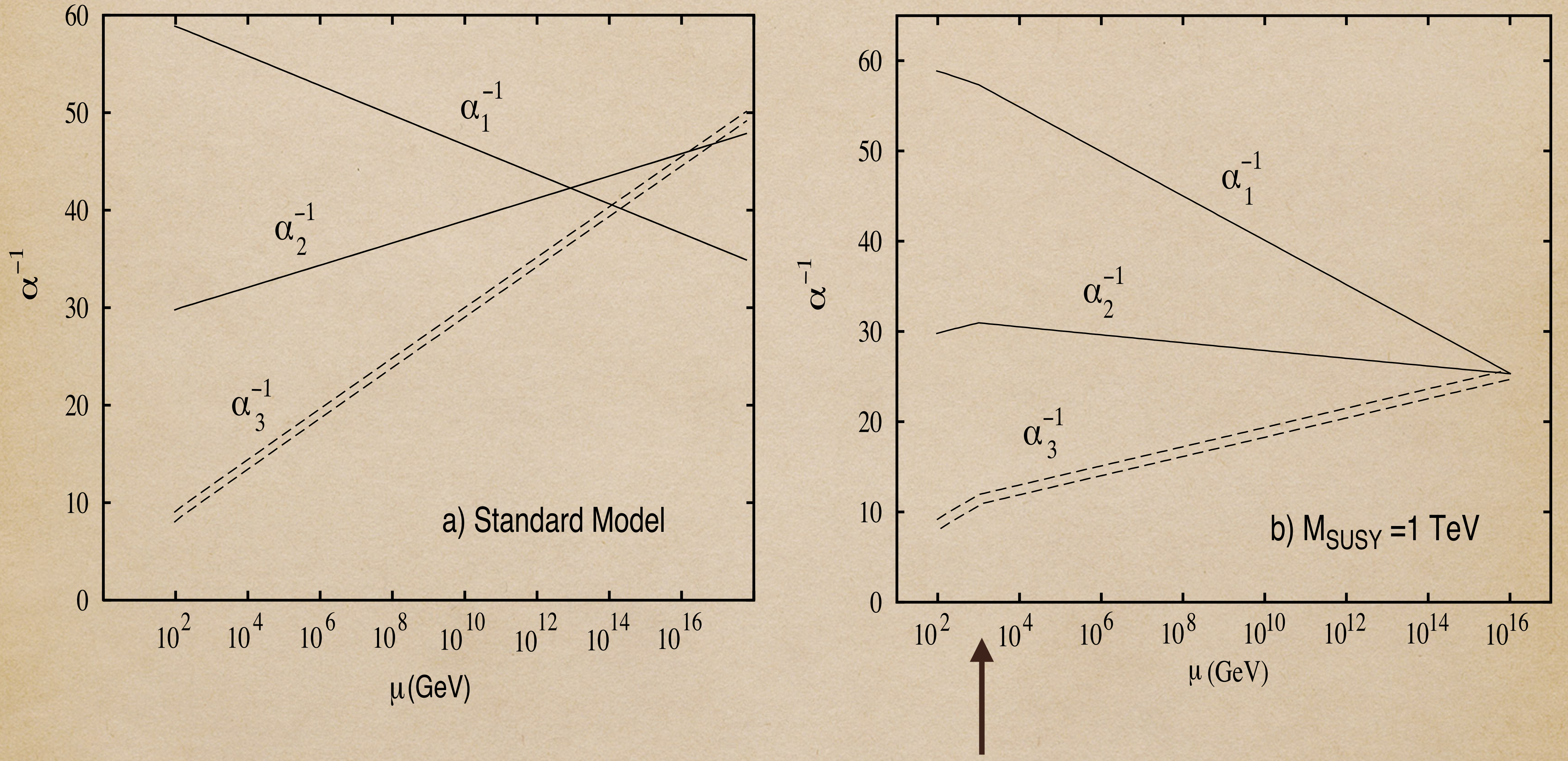
Wtt Bkgd



- Discovered the rapidity gap, central jet veto techniques.
- Also developed the forward-jet tagging technique to separate VBF signals from QCD backgrounds.
- Still useful for the present day Higgs searches.

Journey from graduation to Discovery of Higgs

- Continued to study strong EWSB at e+ e-, photon colliders, more channels etc.
- Until the point that most peoples think the Higgs should be light, as Supersymmetry was gaining a lot of momentum.
- Measurement of QCD coupling constant at LEP in 1991 gave a strong motivation for SUSY.
- At some point, weak scale SUSY was regarded as "standard model" in Europe.



SUSY particles at TeV

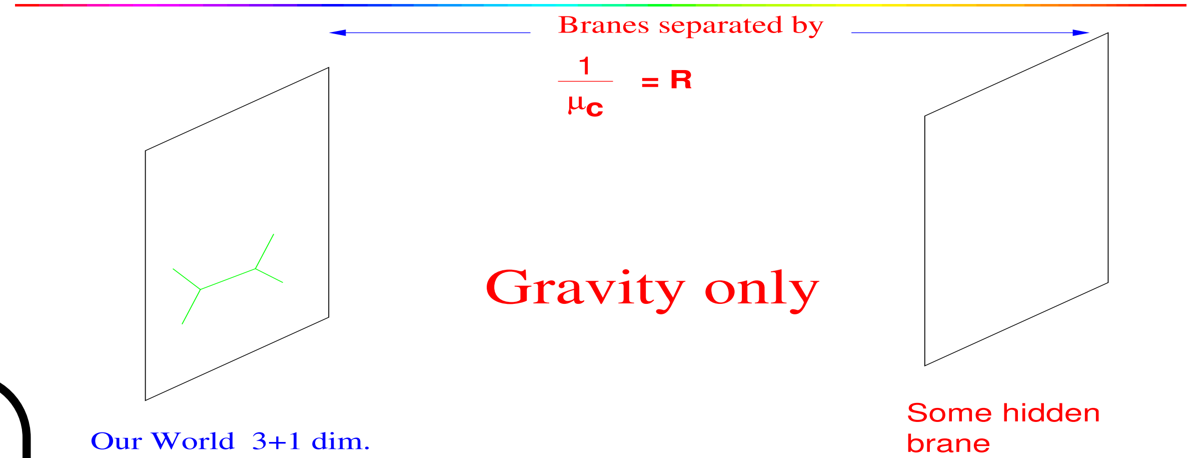
Motivations for Supersymmetry

- Provide an elegant solution to hierarchy problem
- Gauge coupling unification
- Dynamical electroweak symmetry breaking
- Provide a natural dark matter candidate

Extra Dimension Models

- Developed around the turn of millennium.
- ADD model:
- Randall-Sundrum model

ADD model

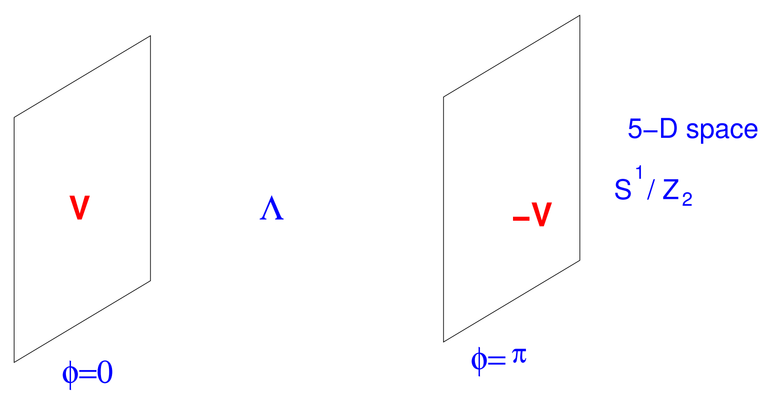


oposed by Arkani et al. the size of the extra dimensions can be as large $R \lesssim 1$ mm.

$$\mu_c \equiv R^{-1} \gtrsim 10^{-4}\ \text{eV} \ll M_{\text{EW}}$$

$$M_{\text{Pl}}^2 \sim M_D^{n+2}\ R^n \qquad \text{(Gauss)}$$

Randall-Sundrum model



With a nonfactorizable metric

$$ds^2 = e^{-2kr_c|\phi|}\ \eta_{\mu\nu} dx^\mu\ dx^\nu - r_c^2 d\phi^2$$

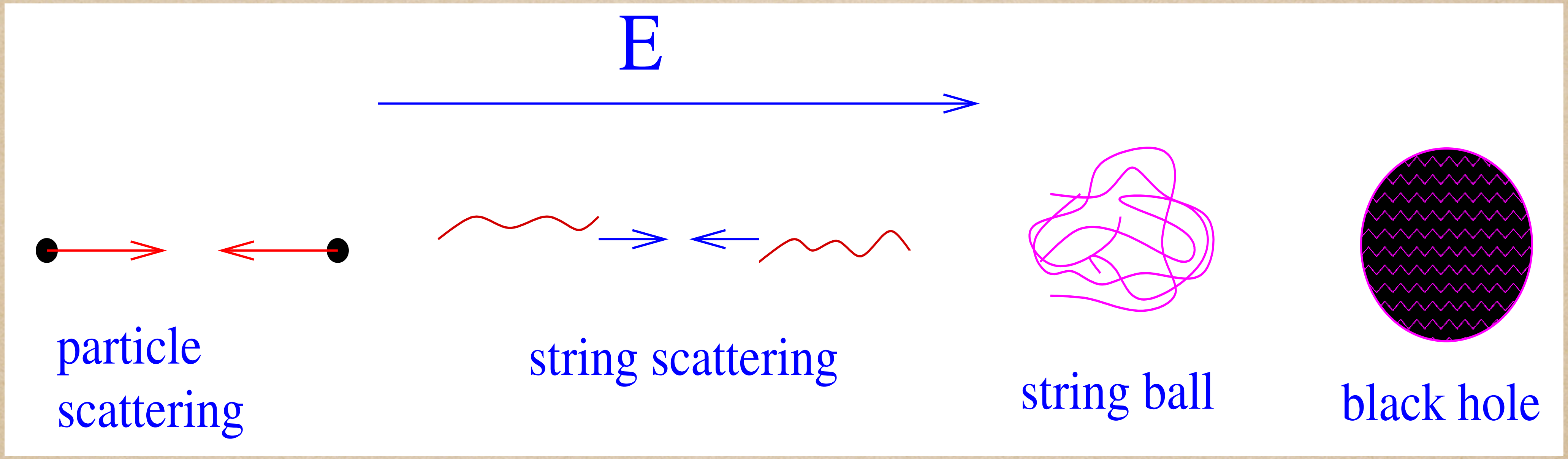
$\overline{M_5}$ is the 5D fundamental Planck scale, k: curvature of the AdS space.

$$\overline{M_{\text{Pl}}}^2 = \overline{M_5}/k$$

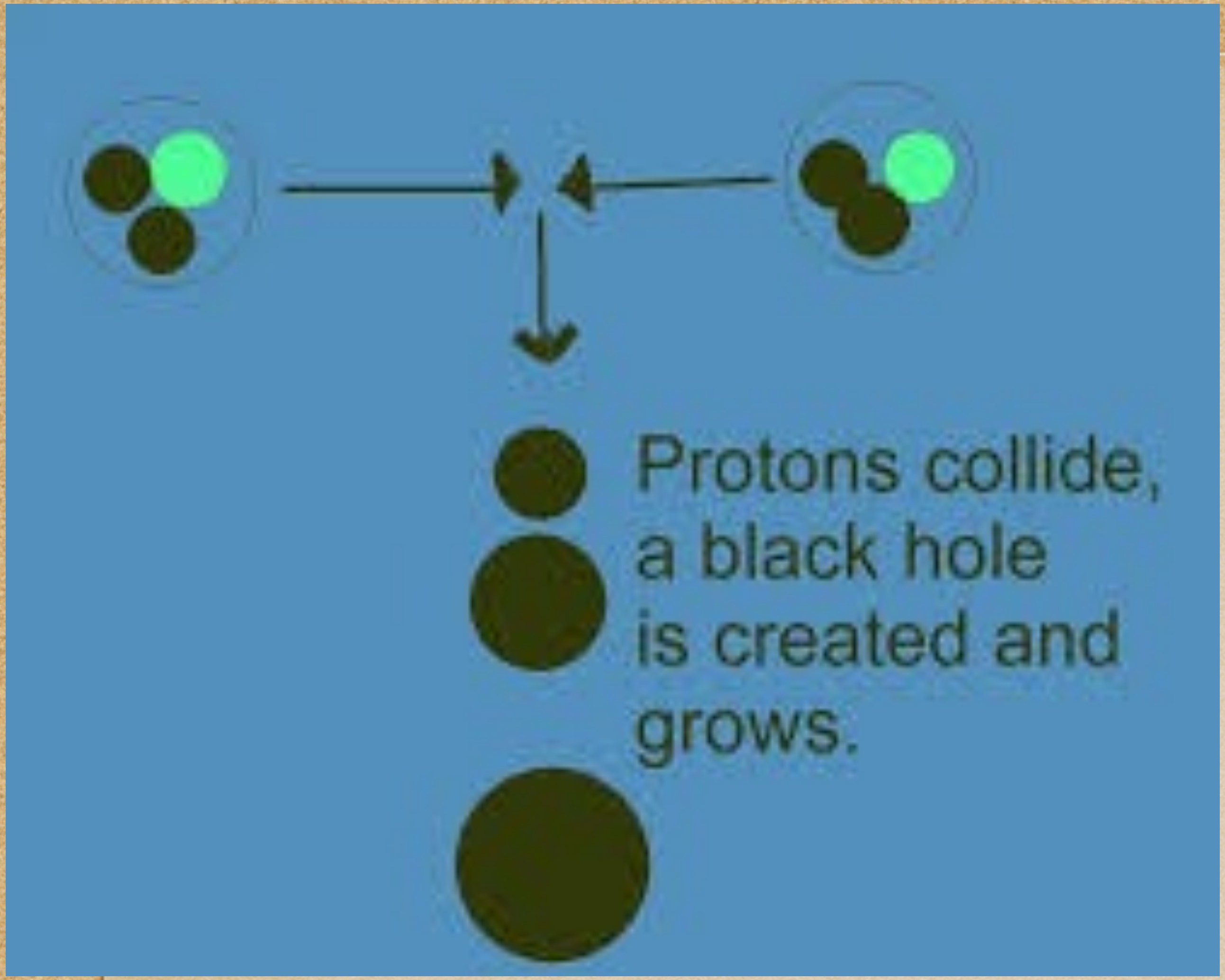
The scale $\Lambda_\pi \equiv \overline{M_{\text{Pl}}}\, e^{-kr_c\pi}$ describes the scale of physical processes on the TeV brane.

The weak scale can be generated from the Planck scale for kr_c around 12.

Production of Black Holes



- When E is above the Planck scale (now at TeV), quantum gravity becomes very strong ==> creation of BH.
- Fear of LHC turn on.

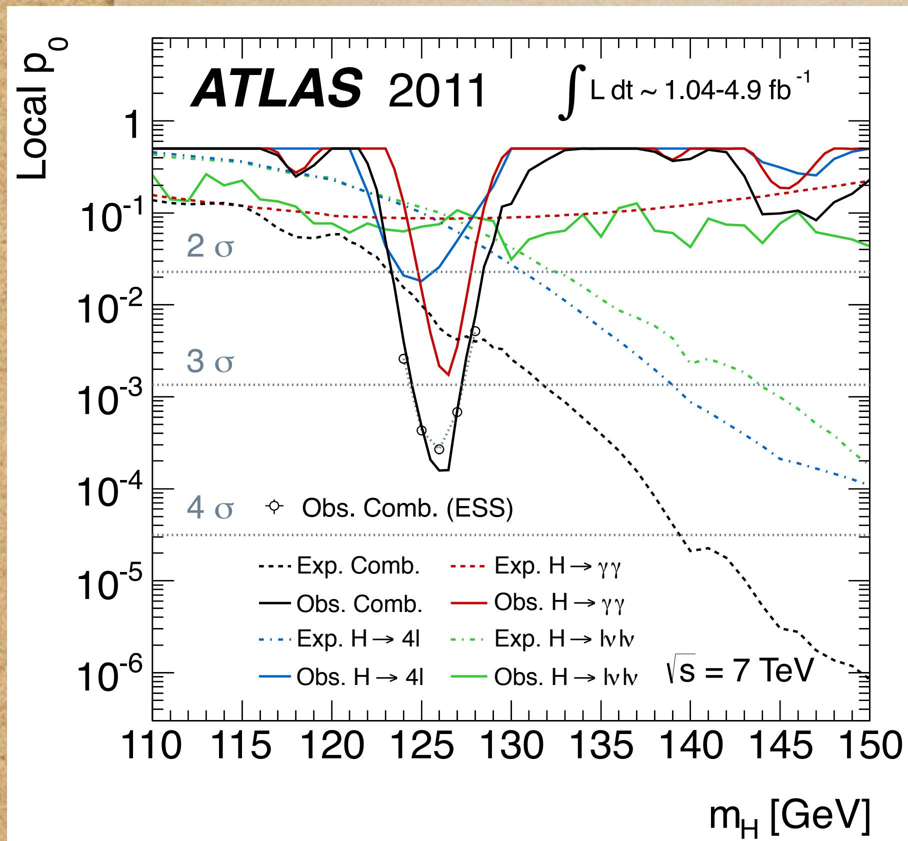

Protons collide,
a black hole
is created and
grows.

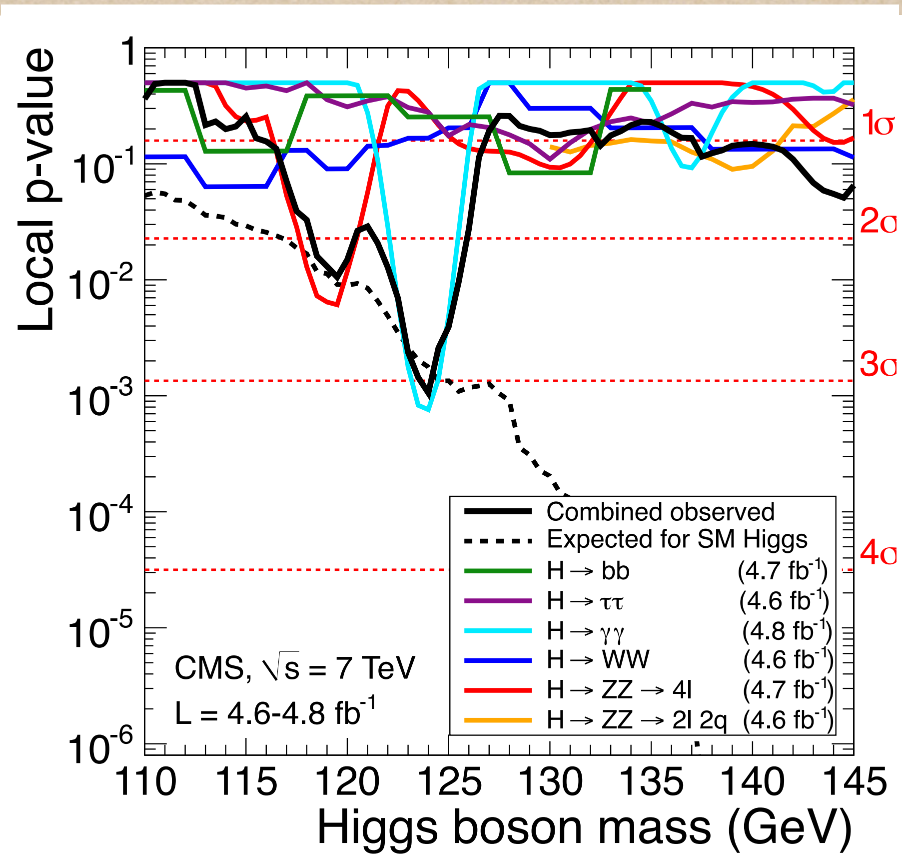
Development of Higgs models in last decade

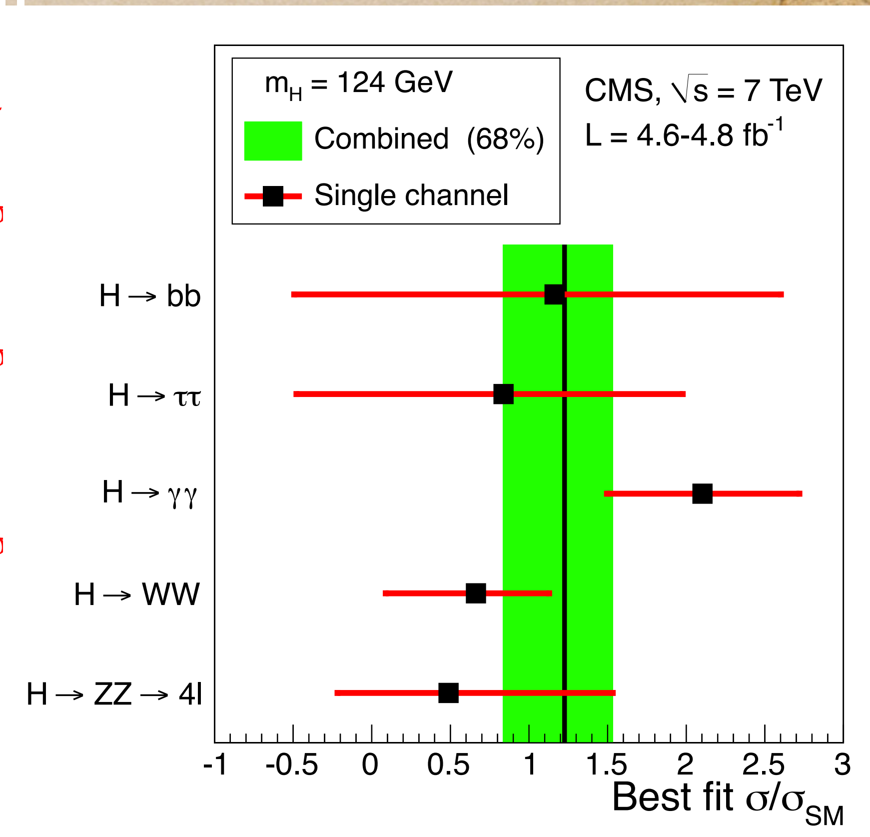
- Extra dimension ideas have motivated new Higgs models.
- Little Higgs models: littlest Higgs model, simplest little Higgs models, minimal little Higgs model, ...
- Twin Higgs model, private Higgs model, (you can name one whatever you like), ...
- Higgs boson arises as pseudo-Goldstone boson.
- Higgsless models

Hints before its Discovery

- Around the end of 2011, LHC announced that they saw something.
- Most channels are consistent with the SM, except for diphoton.
- It stimulated a lot of speculations.







Could the Excess Seen at 124–126 GeV Be due to the Randall-Sundrum Radion?

Kingman Cheung[1,2] and Tzu-Chiang Yuan[3]

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Give us a clue

Phys. Rev. Lett. **108,** 141602 (2012)

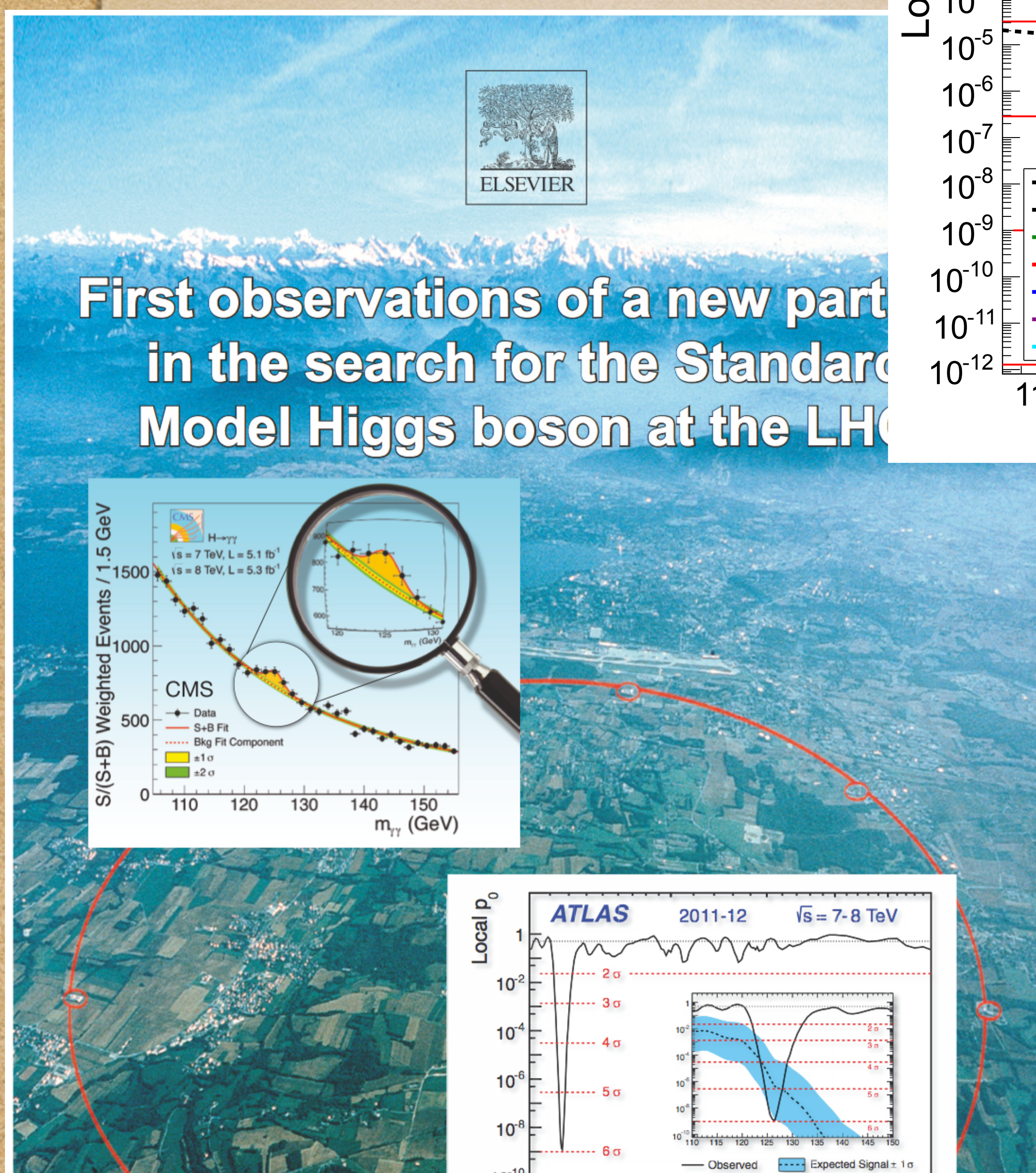
At the end of 2011, the ATLAS and CMS collaborations at CERN's Large Hadron Collider reported tentative signs of an excess in their data, around a mass value of 125 GeV — possibly the first evidence of the existence of the Higgs boson. Theorists have raced to interpret the signal, even though, statistically, it's hovering below the all-important three-sigma mark that constitutes 'evidence'. The trouble is, going on what is known so far about this object's preferences for decay channels — how often it decays, for example, to two photons or to a bottom quark–antiquark pair — this would-be Higgs doesn't look quite like a Higgs, at least not as expected in various supersymmetric extensions of the standard model.

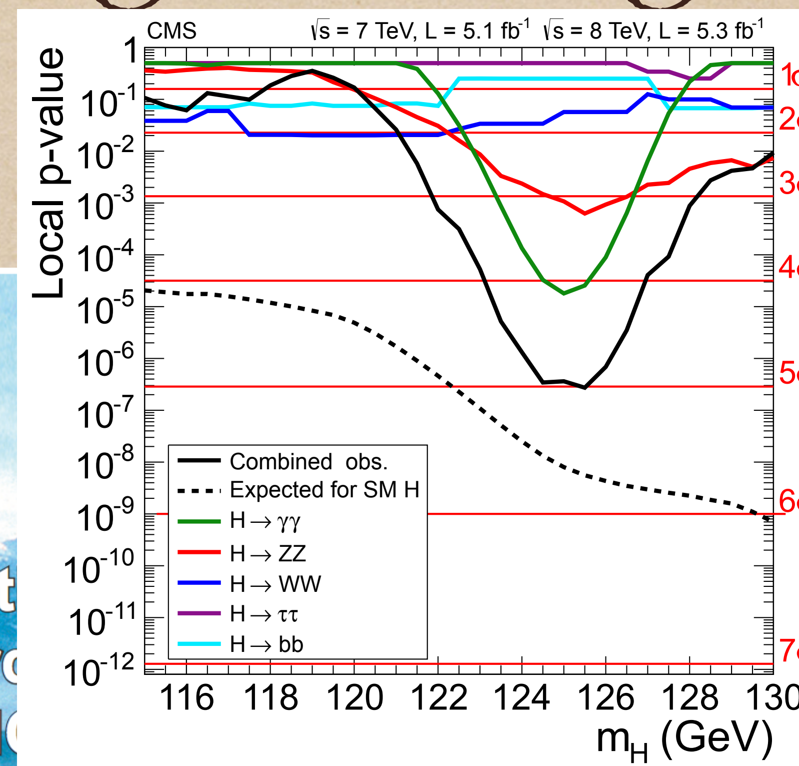
Kingman Cheung and Tzu-Chiang Yuan suggest instead that it could be the Randall–

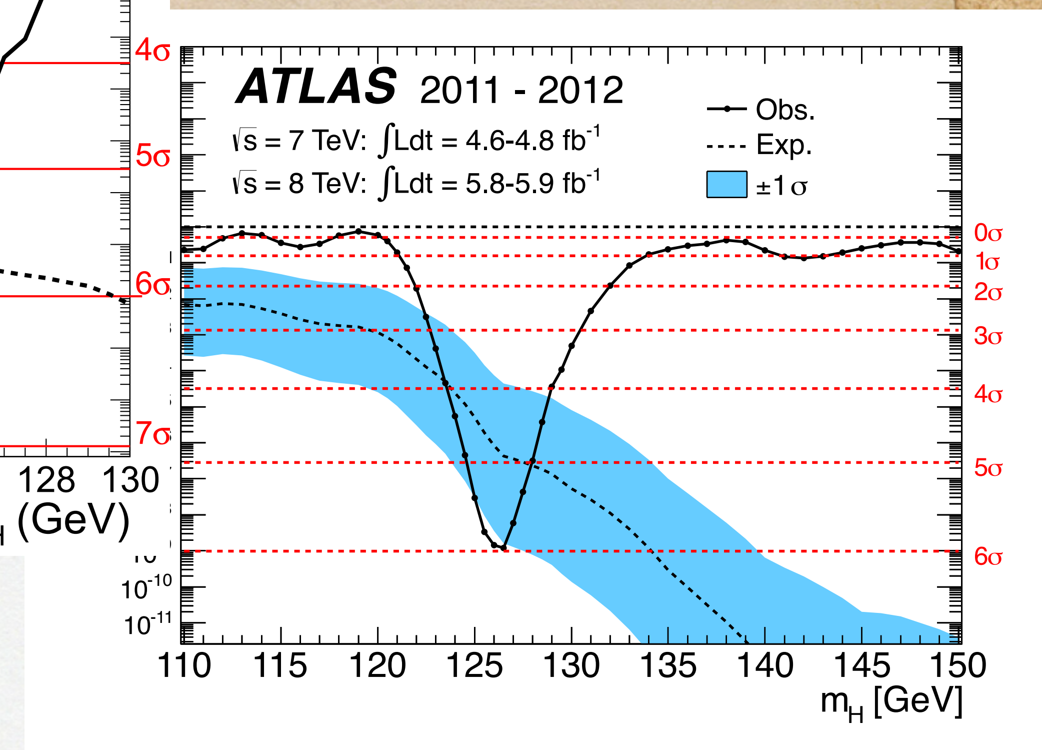
TABLE III. The ratio $\frac{\sigma(\phi)B(\phi\to X)}{\sigma(H)B(H\to X)}$ for $m_{\phi\ \mathrm{or}\ H} = 123$–126 GeV.

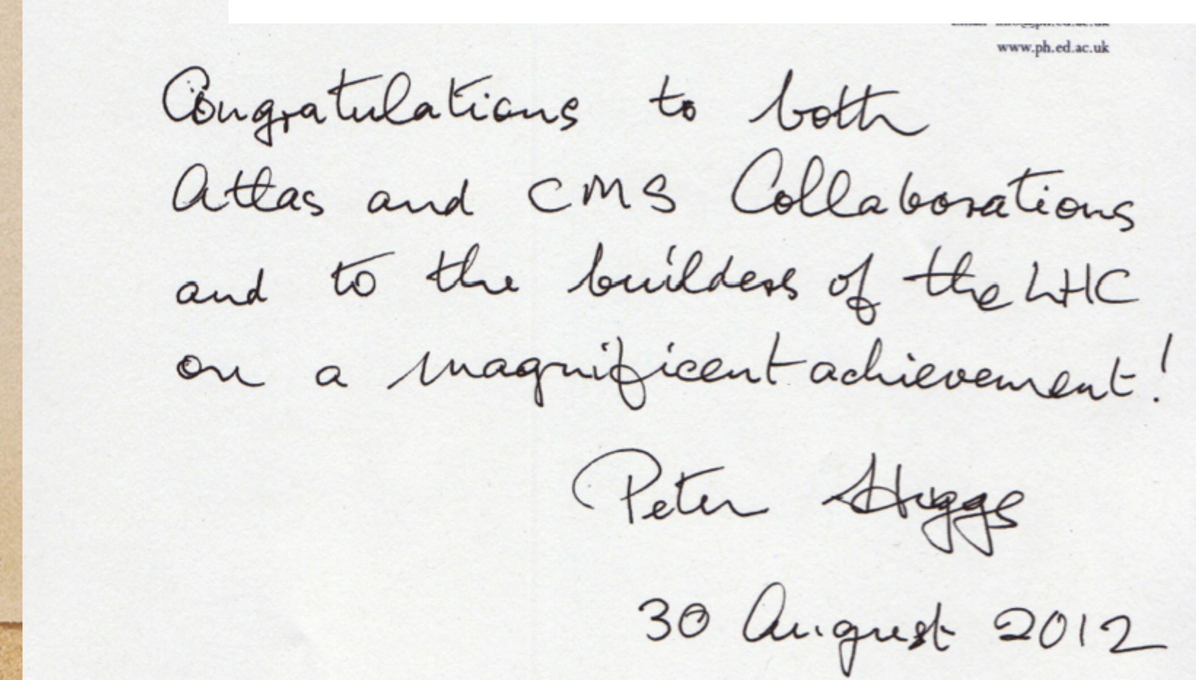
$m_{\phi\ \mathrm{or}\ H}$ (GeV)	$\frac{\sigma(\phi)B(\phi\to X)}{\sigma(H)B(H\to X)}$ $\gamma\gamma$	$b\bar{b}$	$\tau\tau$	WW^*	ZZ^*
123	2.1	0.53	0.74	0.70	0.70
124	2.1	0.53	0.75	0.70	0.70
125	2.1	0.53	0.75	0.70	0.70
126	2.1	0.53	0.75	0.70	0.71

Discovery in July 2012





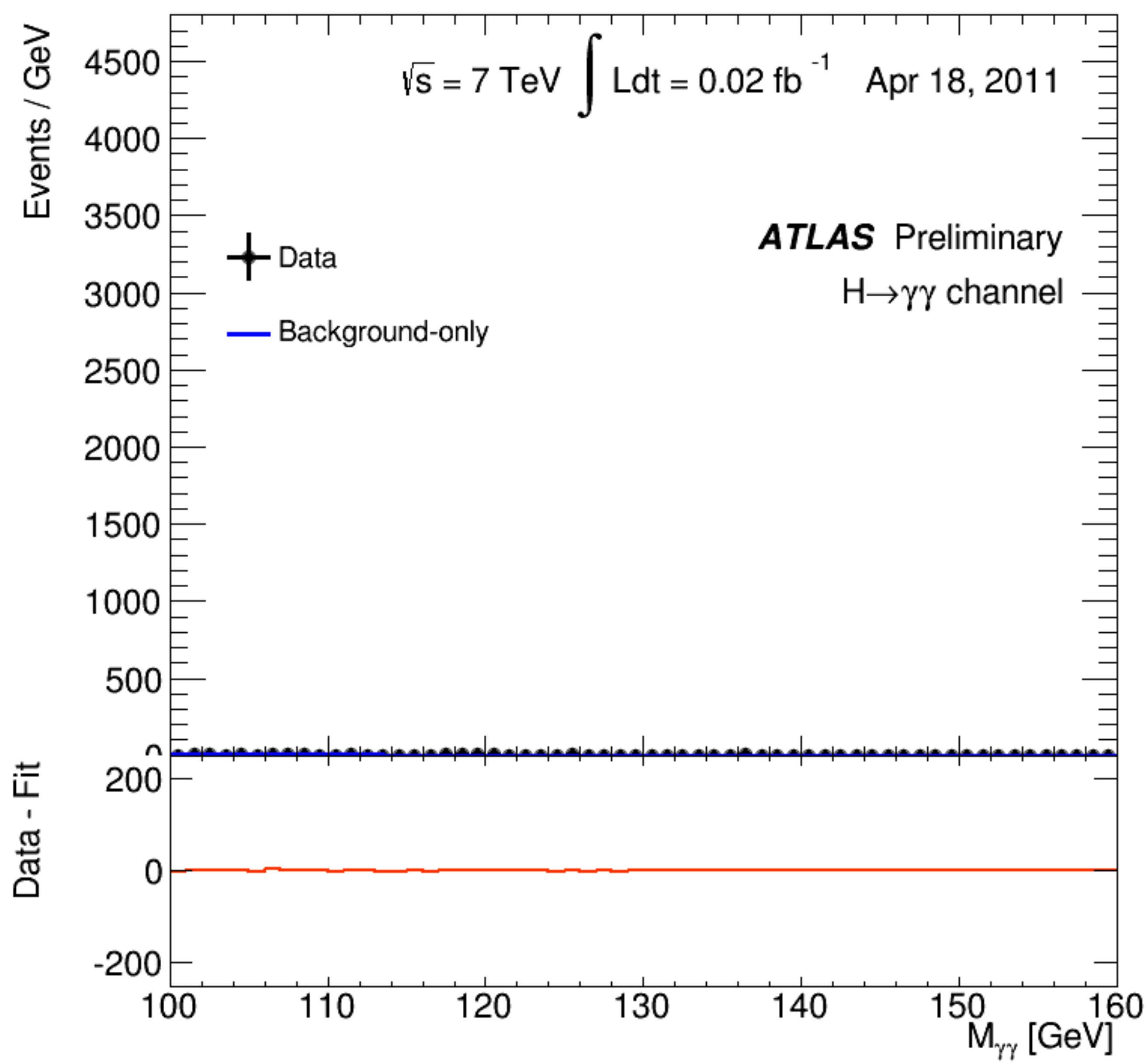



www.ph.ed.ac.uk

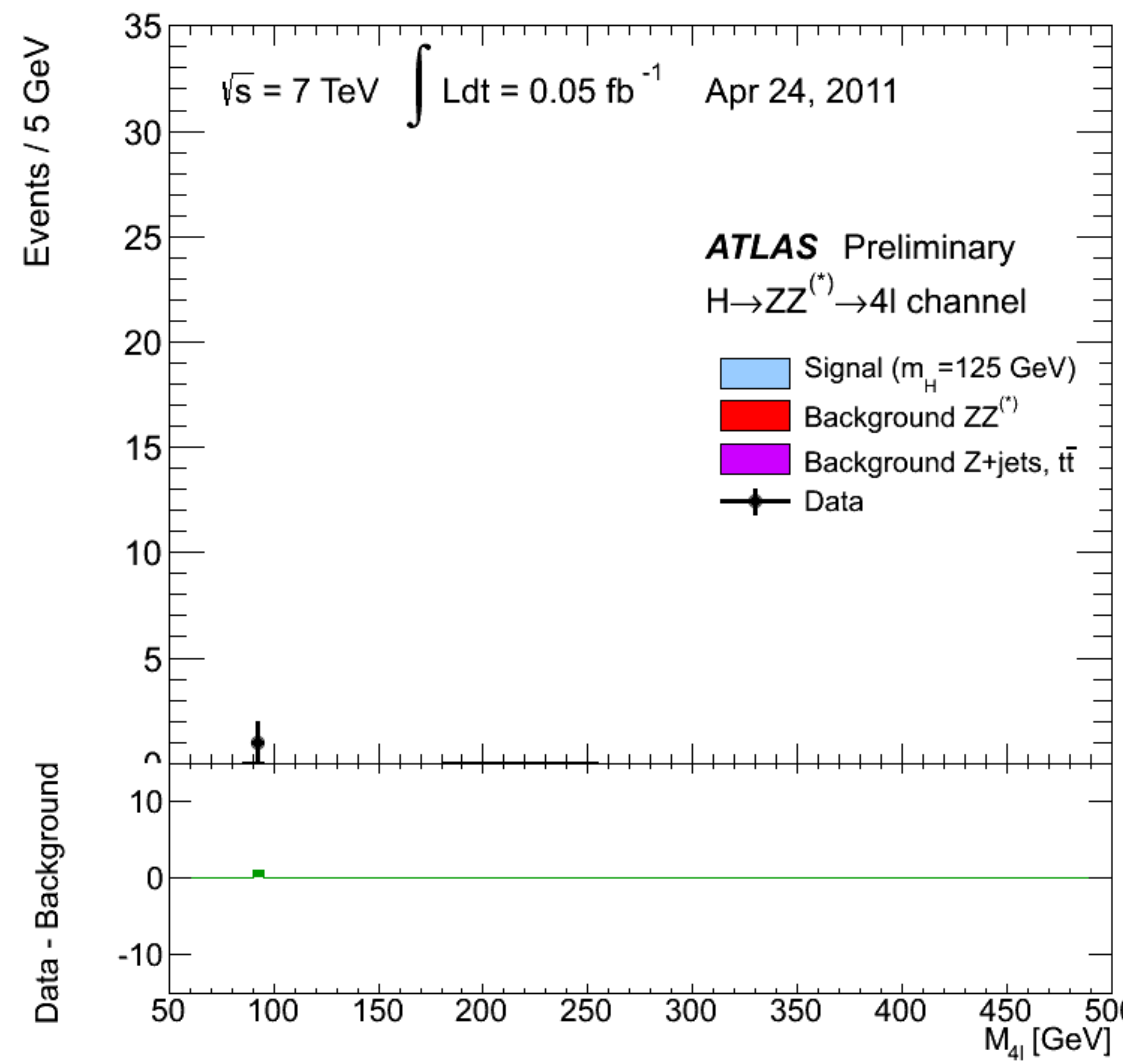
Congratulations to both
Atlas and CMS Collaborations
and to the builders of the LHC
on a magnificent achievement!

Peter Higgs

30 August 2012

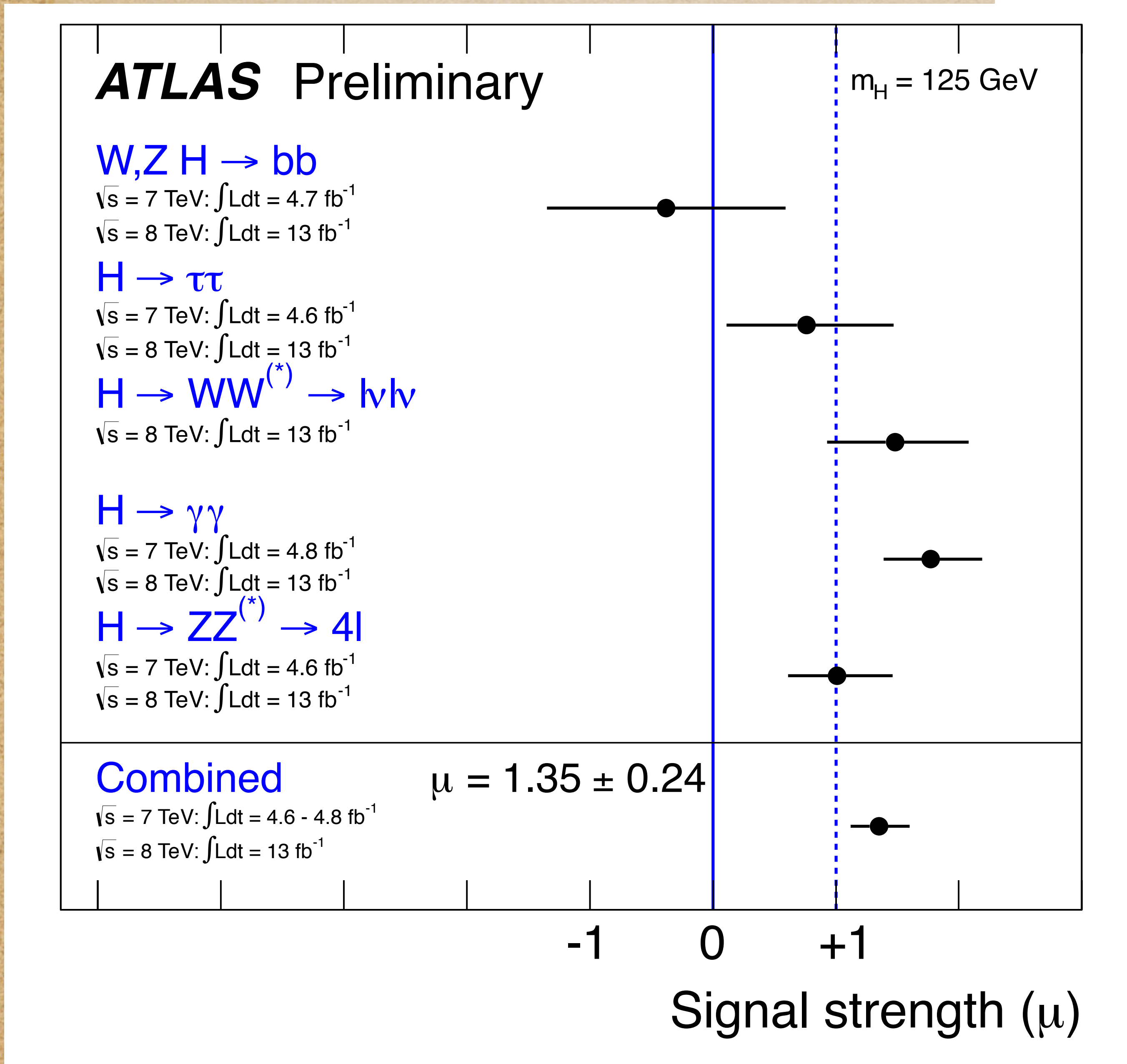


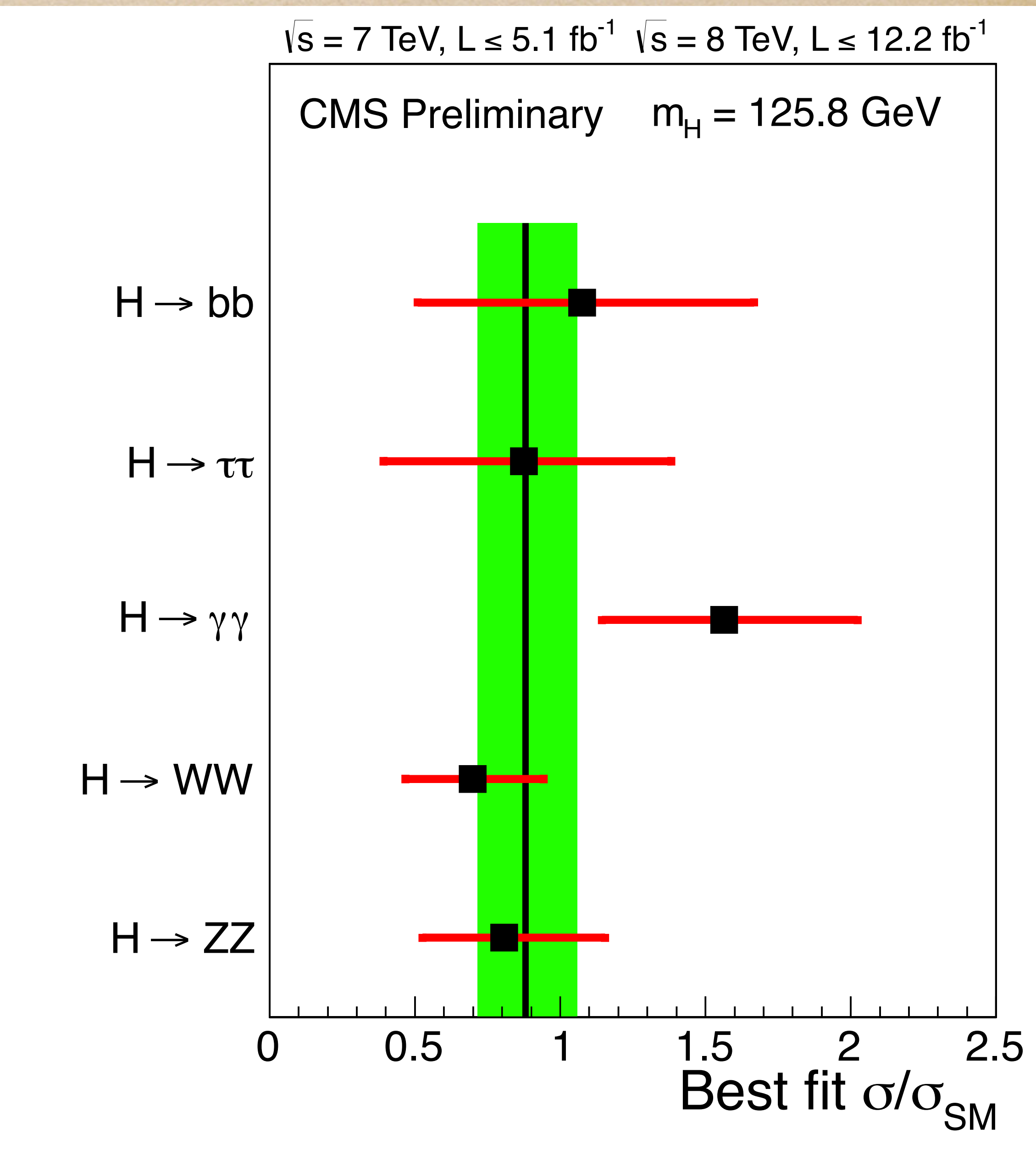
√s = 7 TeV ∫ Ldt = 0.02 fb -1 Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
Data - Fit
M γγ [GeV]



√s = 7 TeV ∫ Ldt = 0.05 fb -1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M 4l [GeV]

Around the end of 2012





Higgcision Era

- At the beginning of 2013, we started a project of constraining Higgs couplings by Higgs data — Higgcision.
- It involves gauge, Yukawa couplings and loop vertices of gg and diphoton.
- We have constrained the Higgs couplings in model-independent framework, 2HDM, MSSM, Higgs-portal models.

KC, Jae-Sik Lee, Po-Yan Tseng

Understand Higgs Interactions

- Basically the Higgs boson couples to massive particles, proportional to the mass.
- So the Higgs boson mainly interacts with W, Z bosons, top quark. Because they are heavy.

- $H \to WW, ZZ$: The couplings of H to WW and ZZ are

$$\mathcal{L} = g m_W \, H \, W^{+\,\mu} \, W^{-}_{\mu} + \frac{1}{2} g_z m_Z H \, Z \, Z$$

- $H \to f\bar{f}$: The decay into a fermion pair is given by

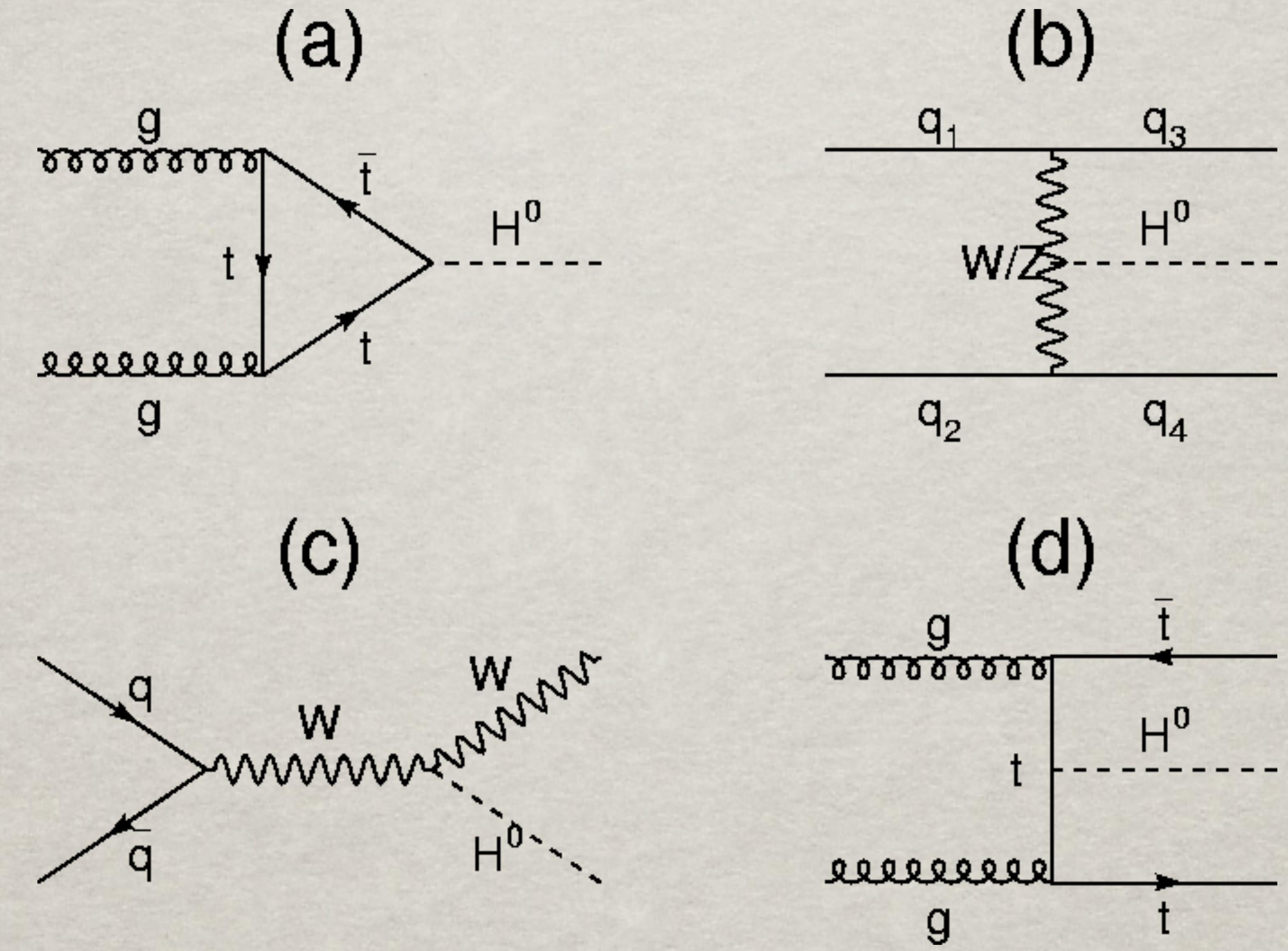
$$\mathcal{L} = -\frac{g m_f}{2 m_W} H \, \bar{f} \, f$$

- $H \to gg$: Higgs decays into a pair of gluons via a triangular loop described by an effective Lagrangian

$$\mathcal{L} = -\frac{g^2}{2 m_W} \frac{\alpha_s(m_H)}{12\pi} \, I \, G^a_{\mu\nu} \, G^{a\,\mu\nu} \, H$$

- $H \to \gamma\gamma, Z\gamma$:

Higgs Production Mechanisms

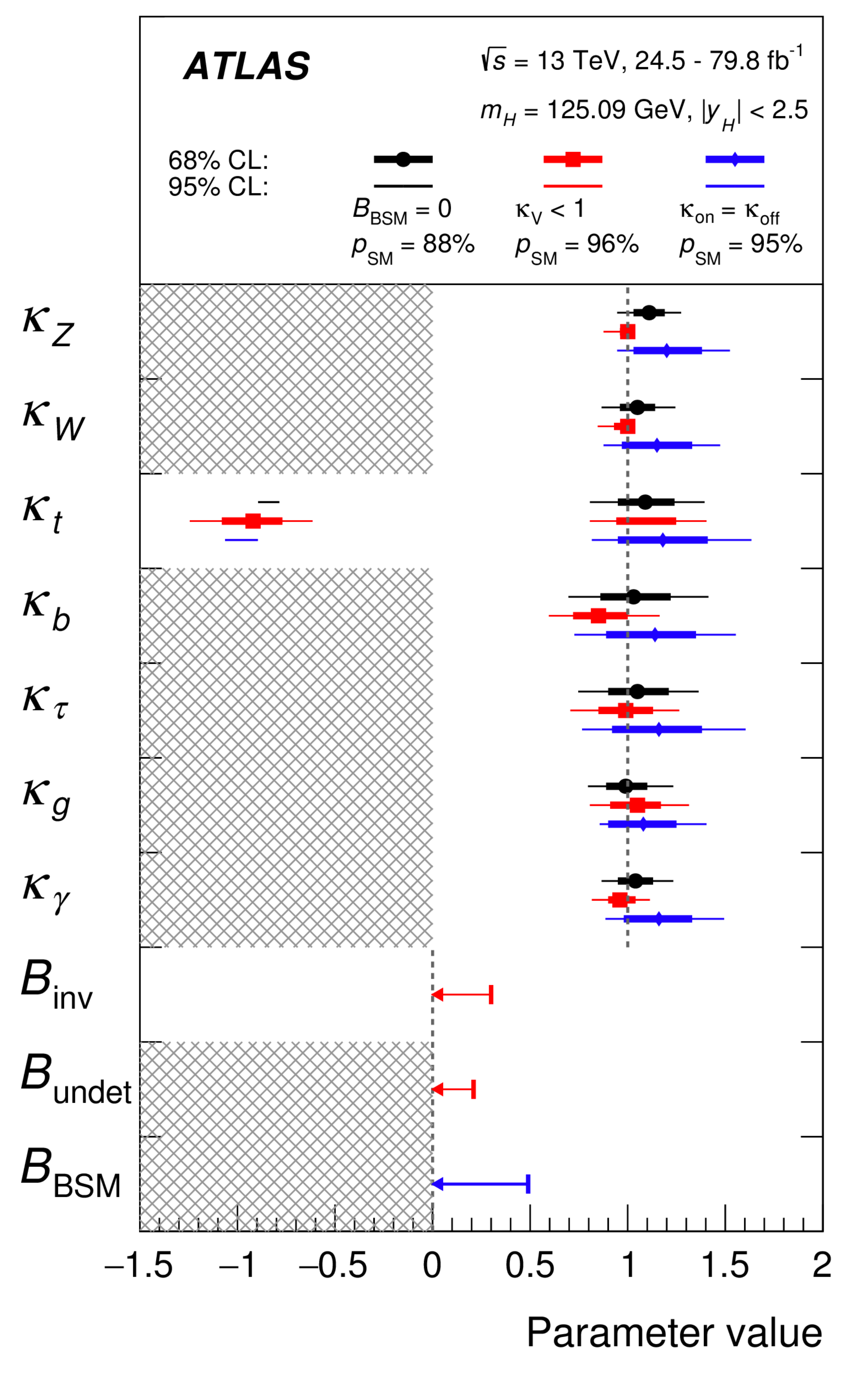


Summary by ATLAS

$B_{inv}=B_{undet}=0$ (black);

B_{inv} and B_{undet} included as free parameters, the conditions $\kappa_{W,Z} \leq 1$ (RED)

$B_{BSM}=B_{inv}+B_{undet}$ included as a free parameter (BLUE)

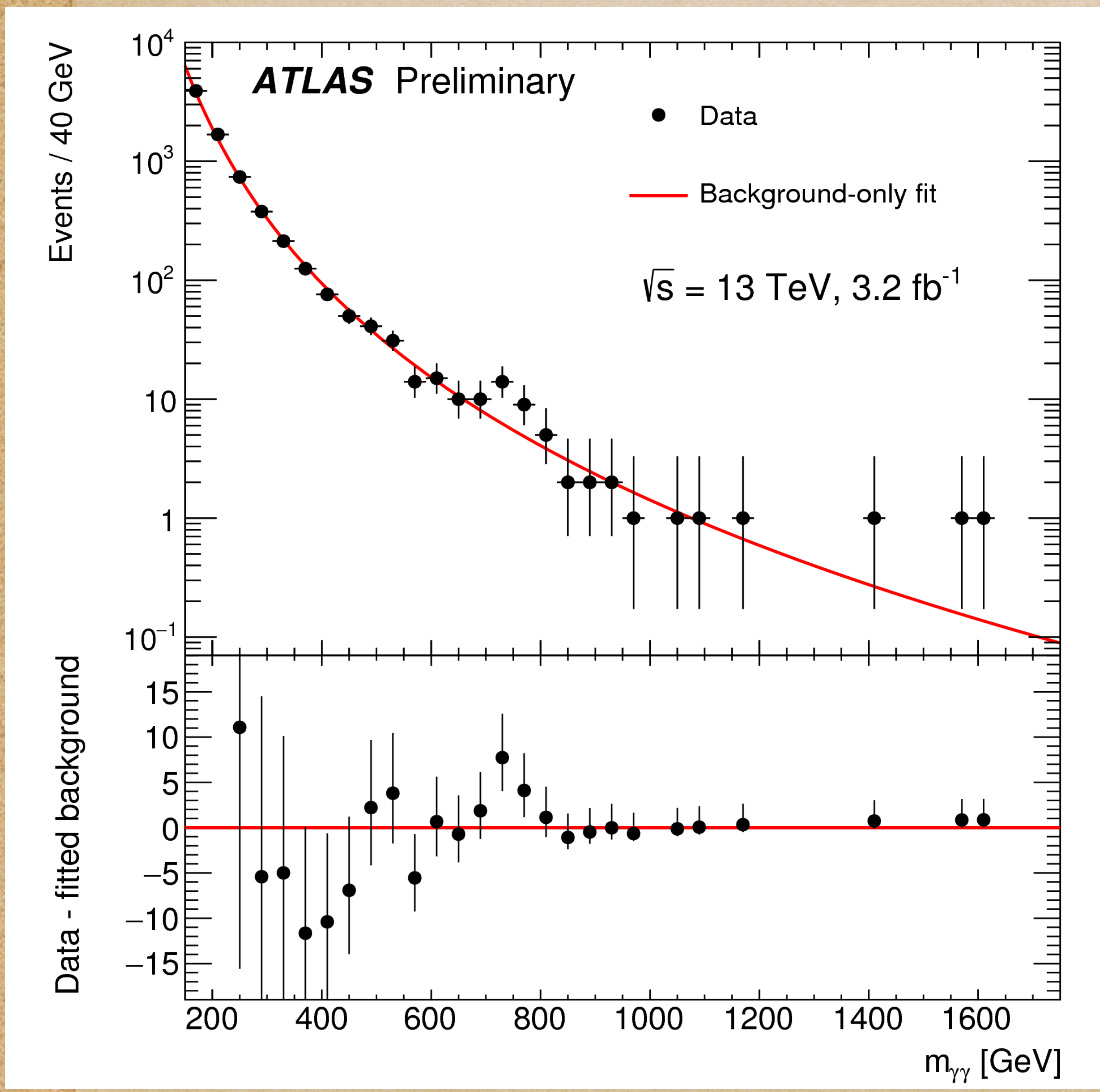


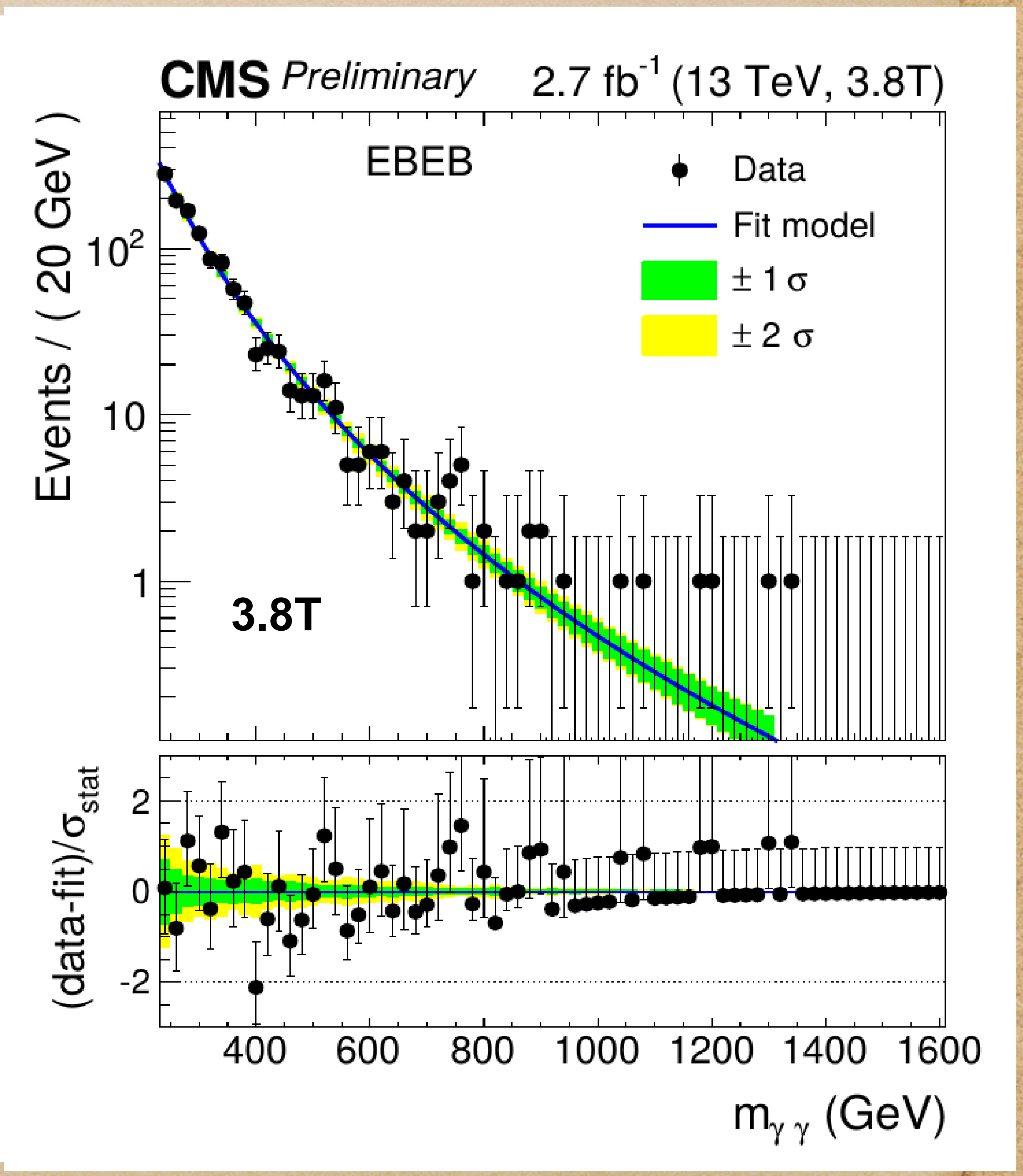
Further Investigations of the Higgs

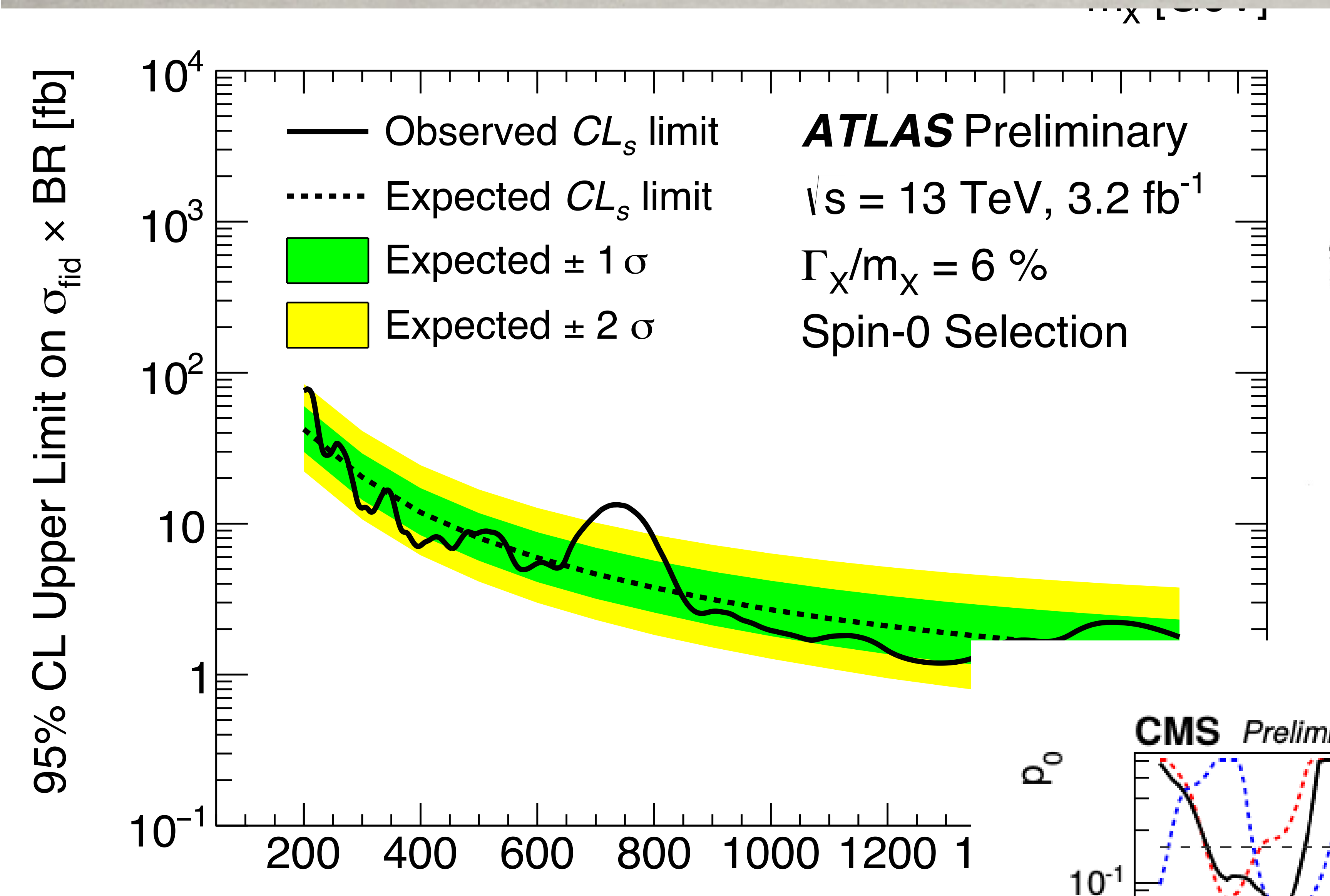
- Use EDMs to constrain the pseudoscalar Higgs couplings, such as C_u^P and ΔP^γ.
- Search for non-standard decays of the Higgs boson, e.g. dark matter, Goldstone bosons, etc.
- Investigate the WW scattering.
- The associated production of Higgs with W, Z, $t\bar{t}$, or a single top. Probe the Yukawa couplings.
- Use the single top + Higgs production to determine the sign and the size of top-Yukawa coupling.
- Higgs boson pair production: (Chang, Cheung, Lee, Lu, 1505.00957)

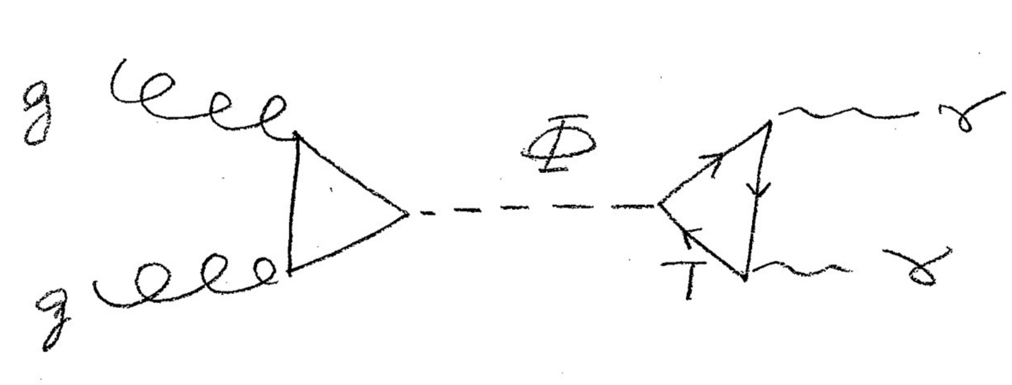
Search for other scalars

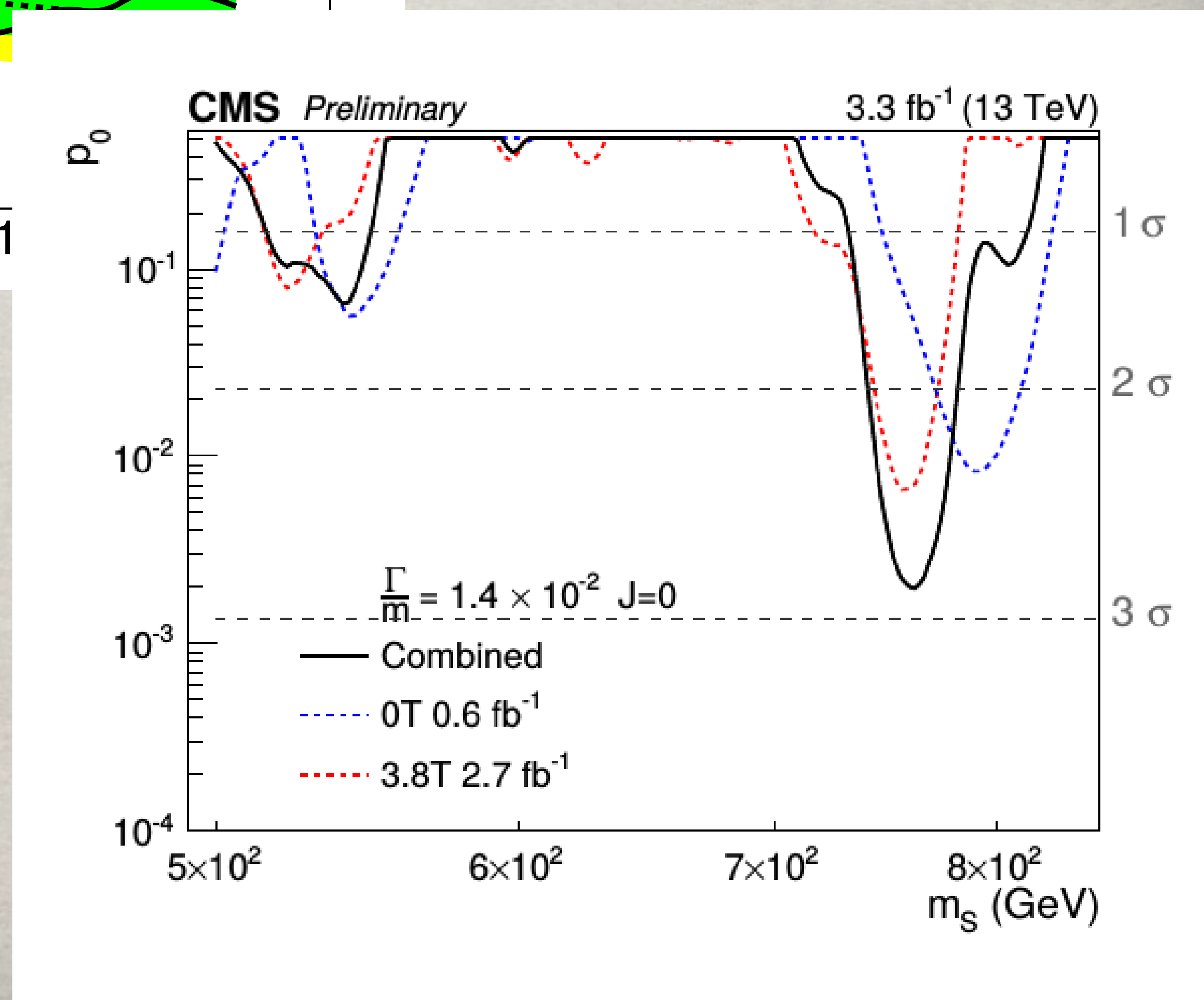
Surprise in 2015





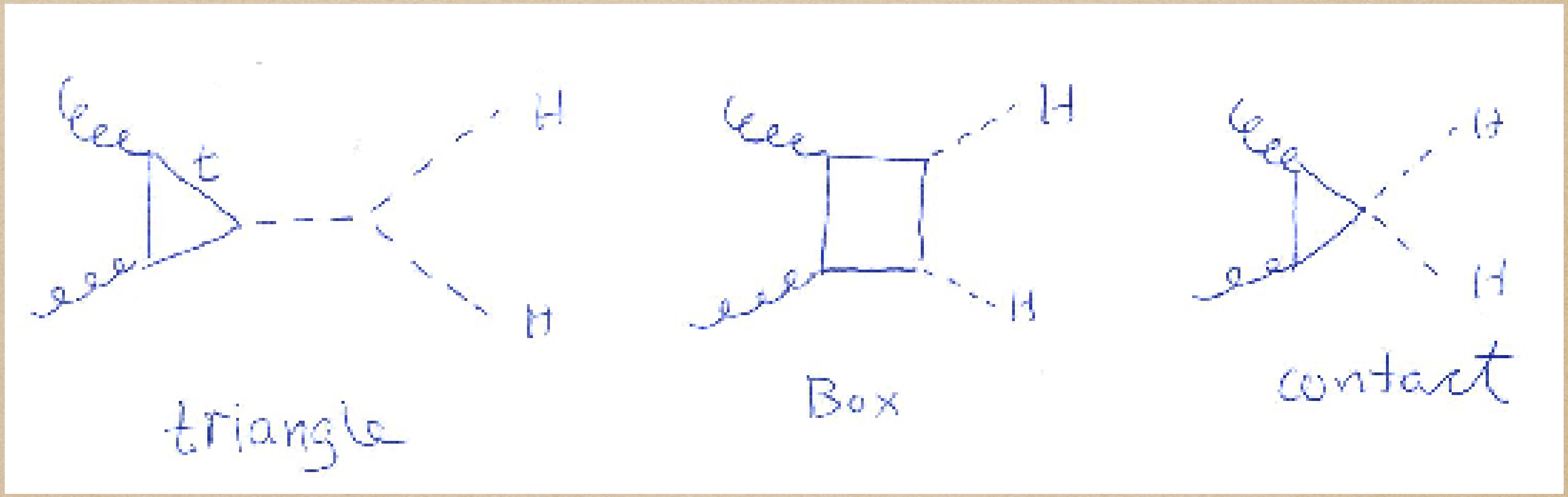






It has motivated more than X00 papers interpreting the bump.

Higgs Pair Production



Higgs Sector Itself

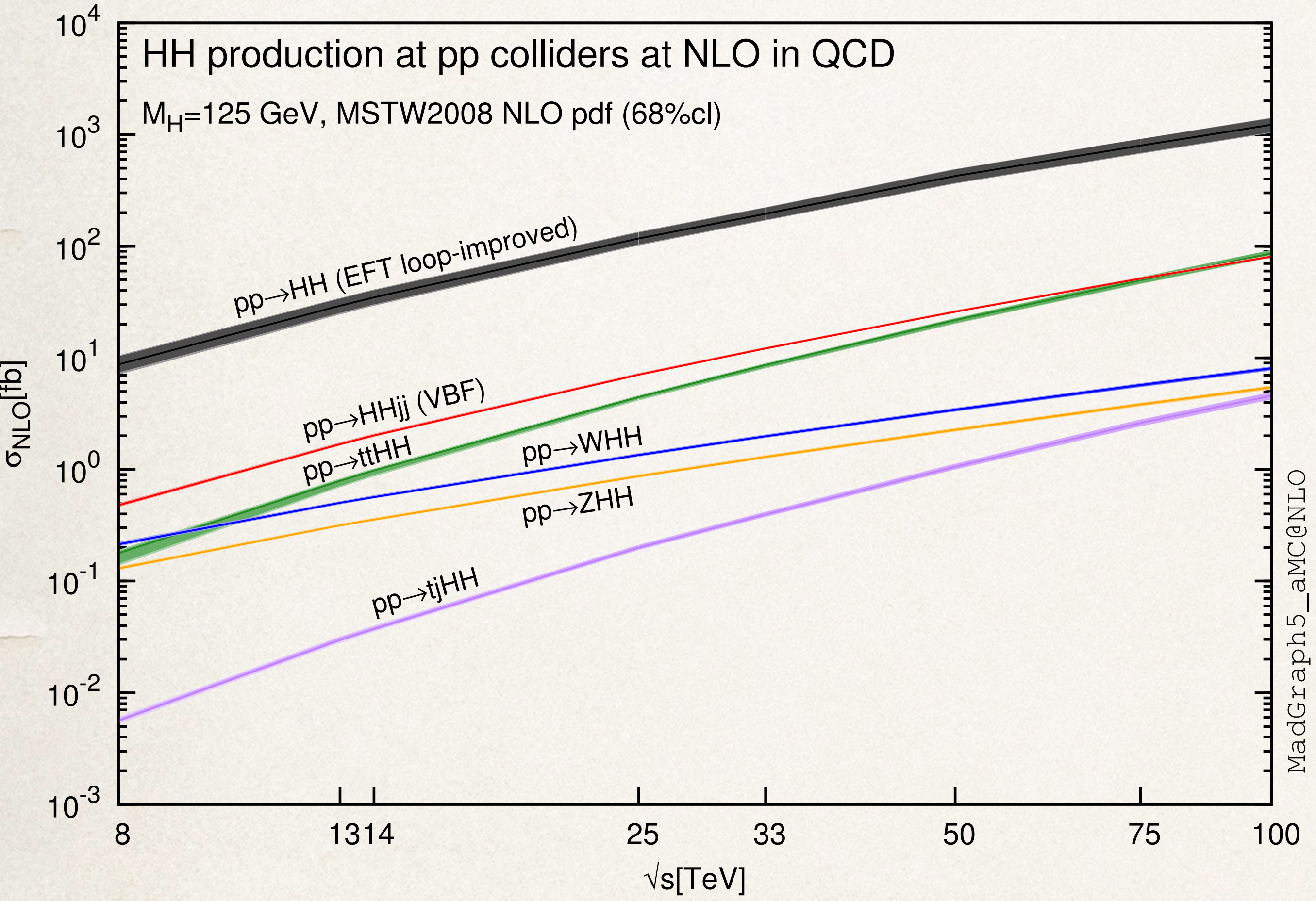
We have no information about $V(\Phi)$ except that it gives a nontrivial VEV. In the SM,

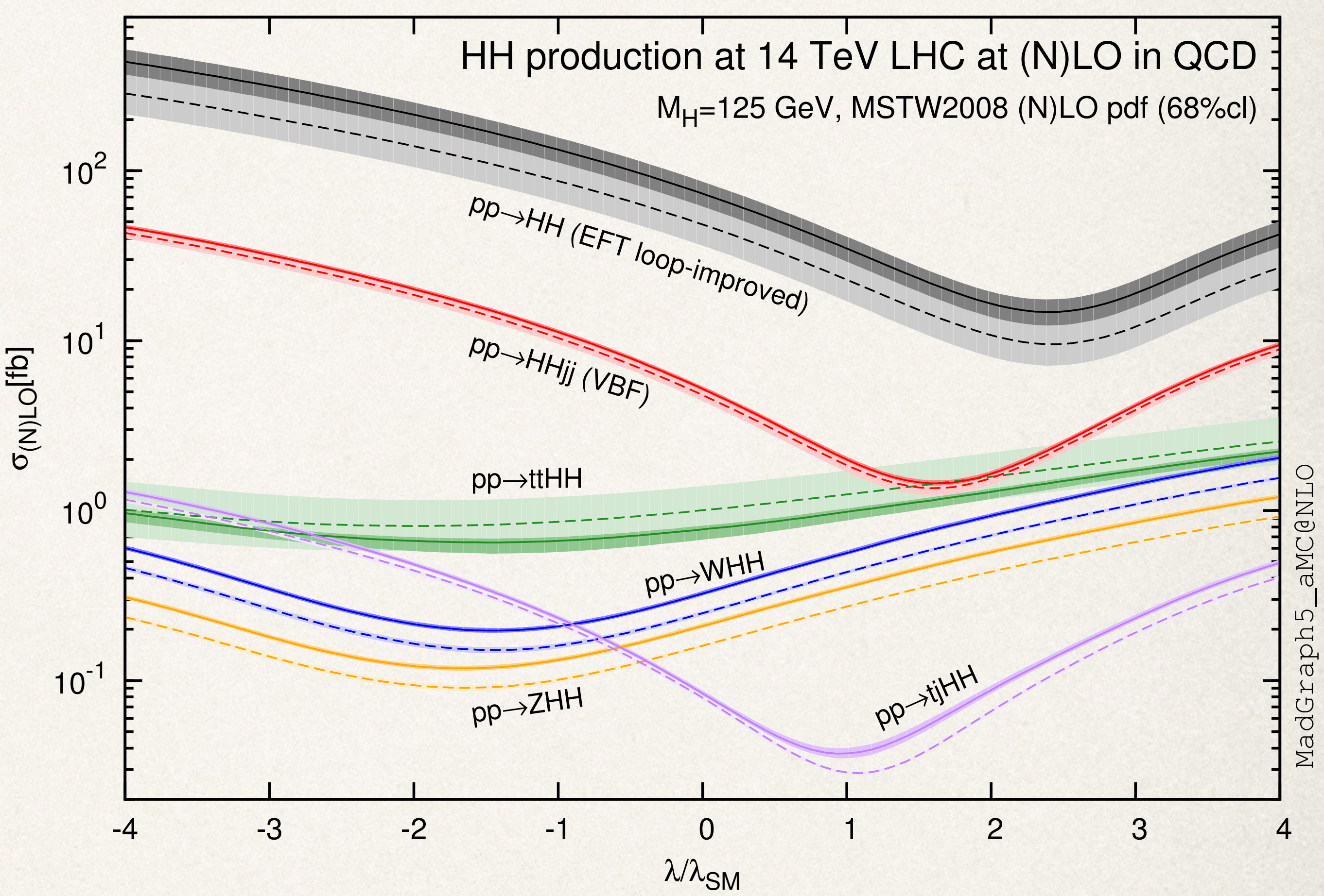
$$V(\phi) = -\frac{\lambda}{4}v^4 + \frac{1}{2}m_H^2 H^2 + \frac{m_H^2}{2v}H^3 + \frac{\lambda}{4}H^4$$

This is the simplest structure. The self couplings are fixed. But for extended Higgs sector it is not the case.

Probing self interactions of the Higgs boson becomes an important avenue to understand the Higgs sector.

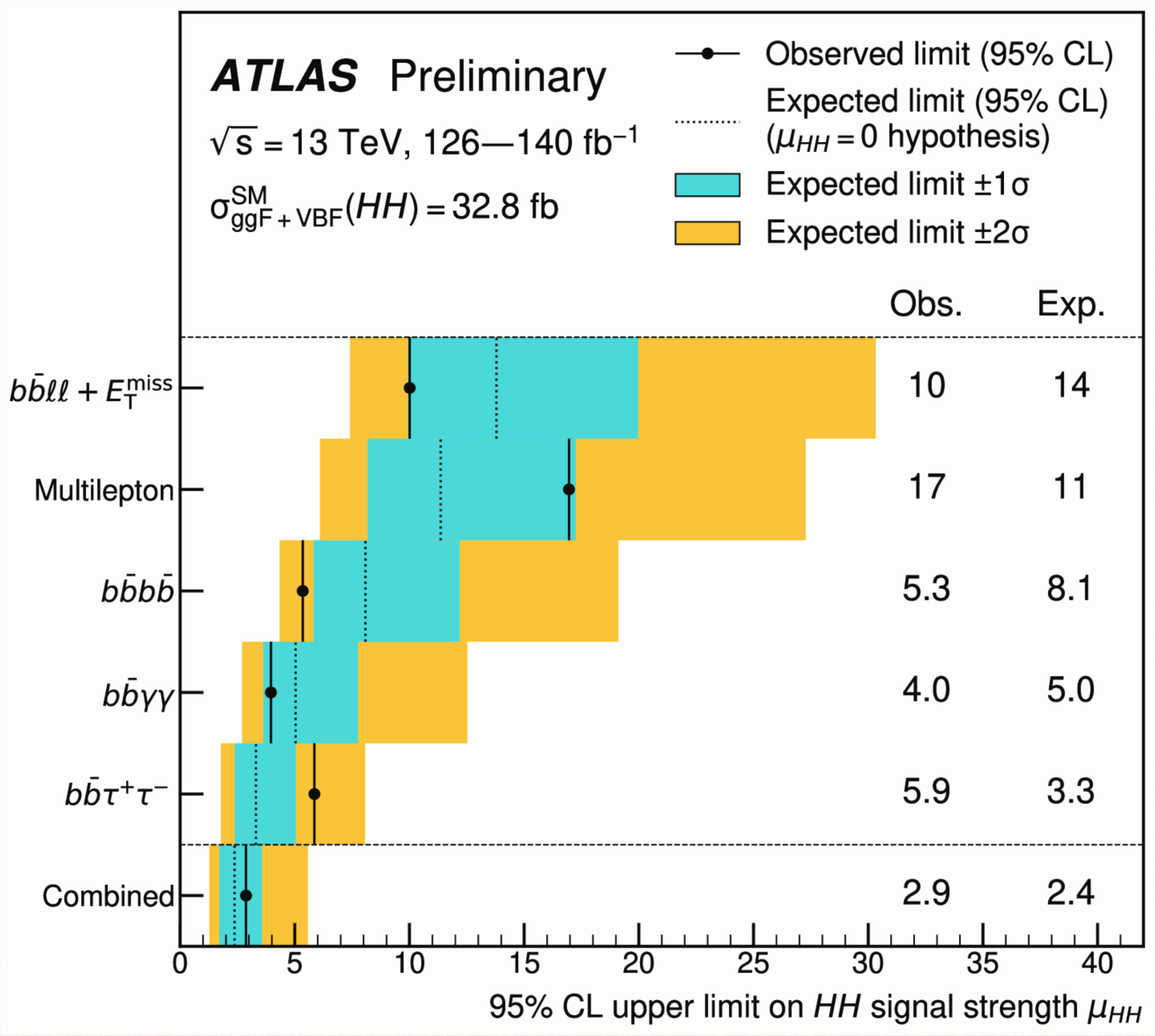
Channels for testing HHH coupling



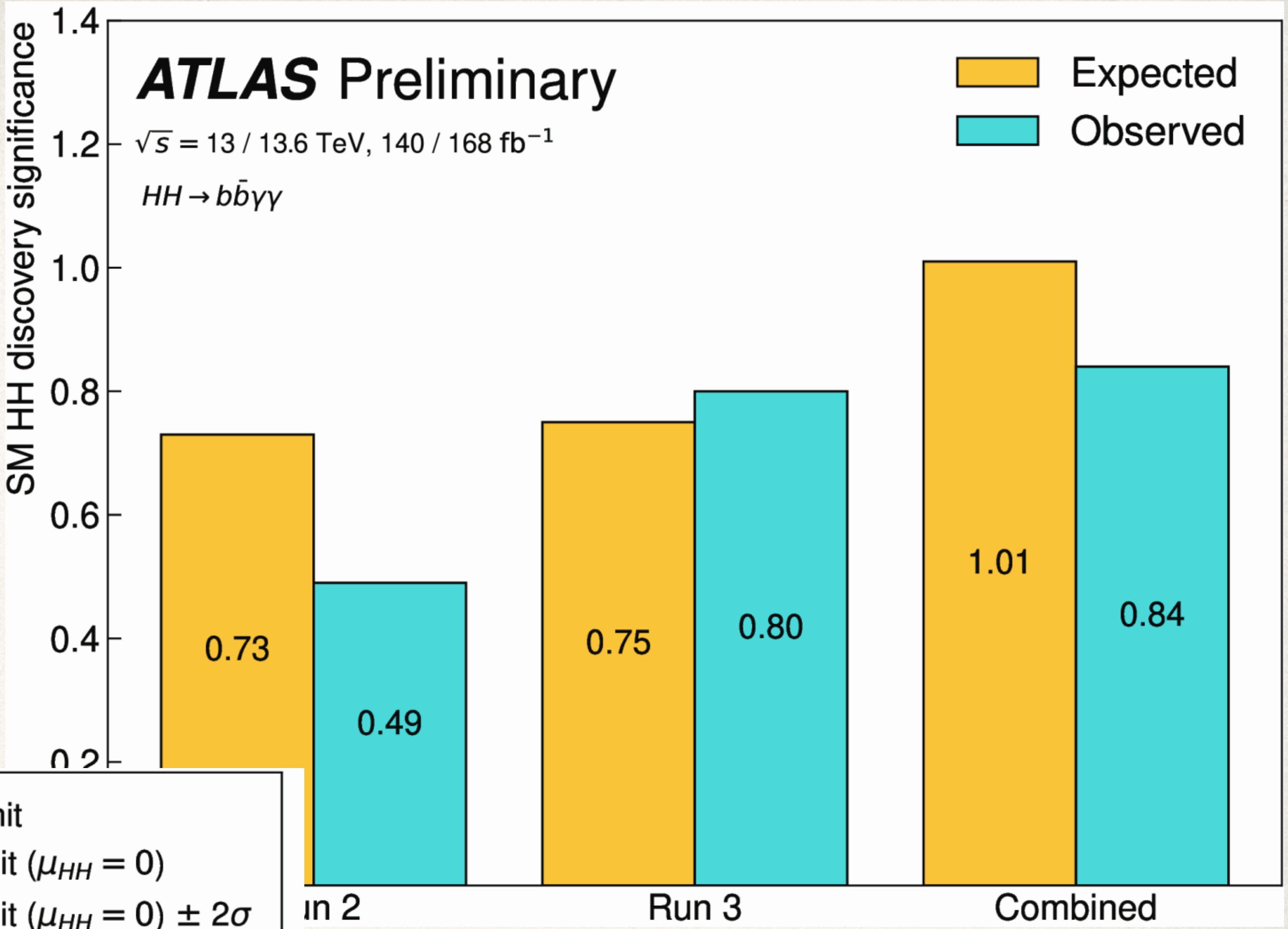


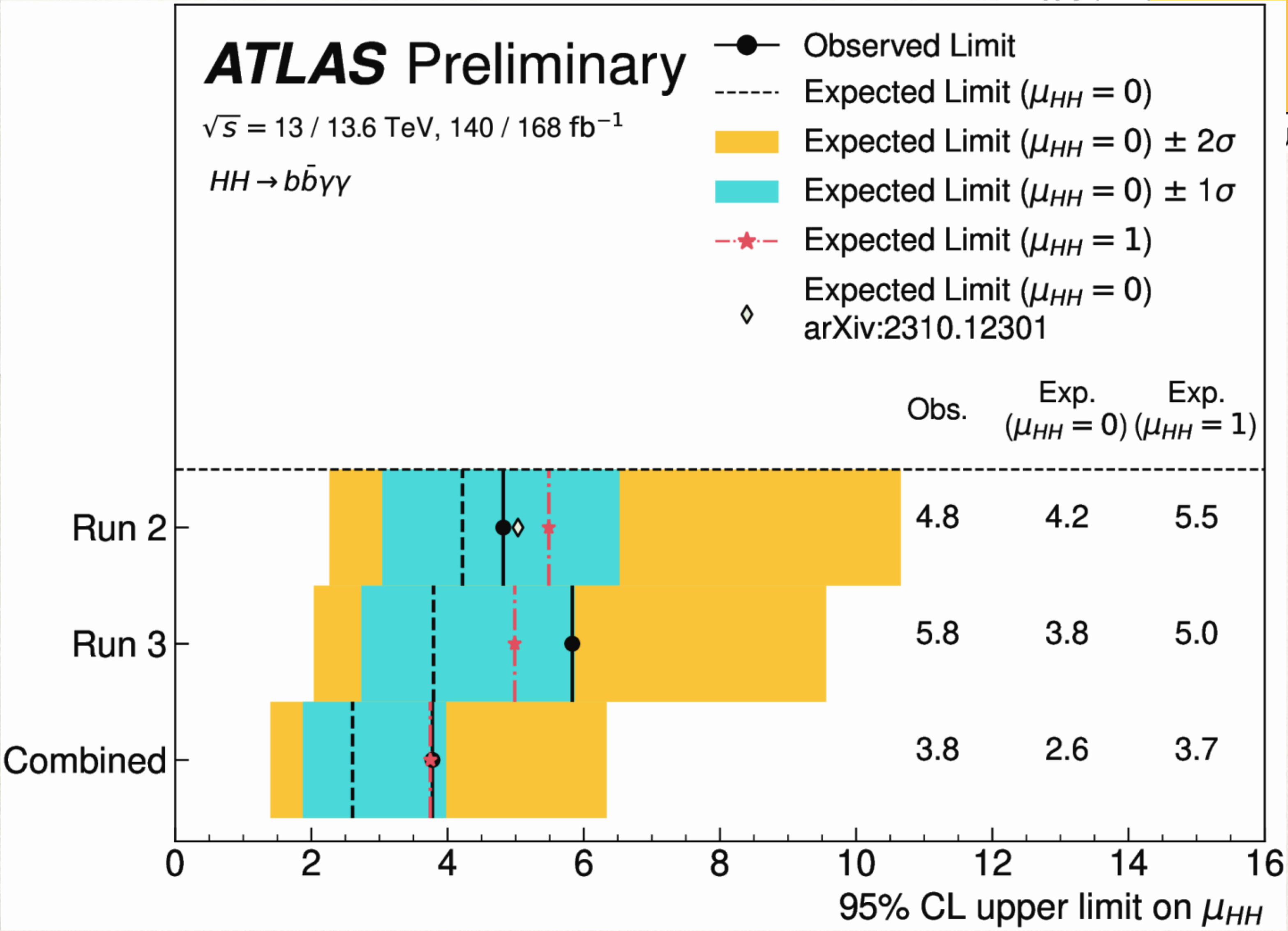
Frederix et al. 1401.7340

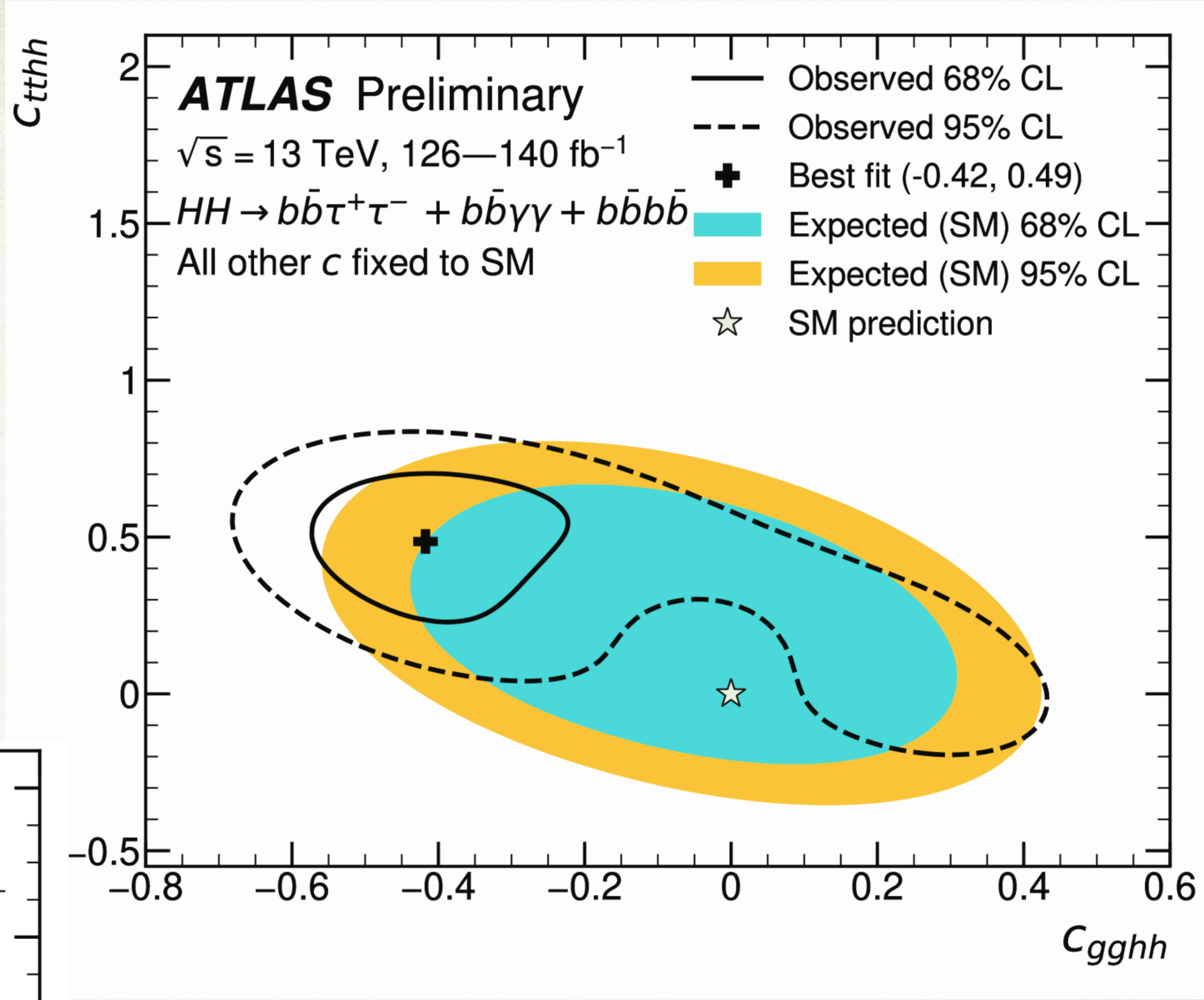
A summary of HH production by ATLAS



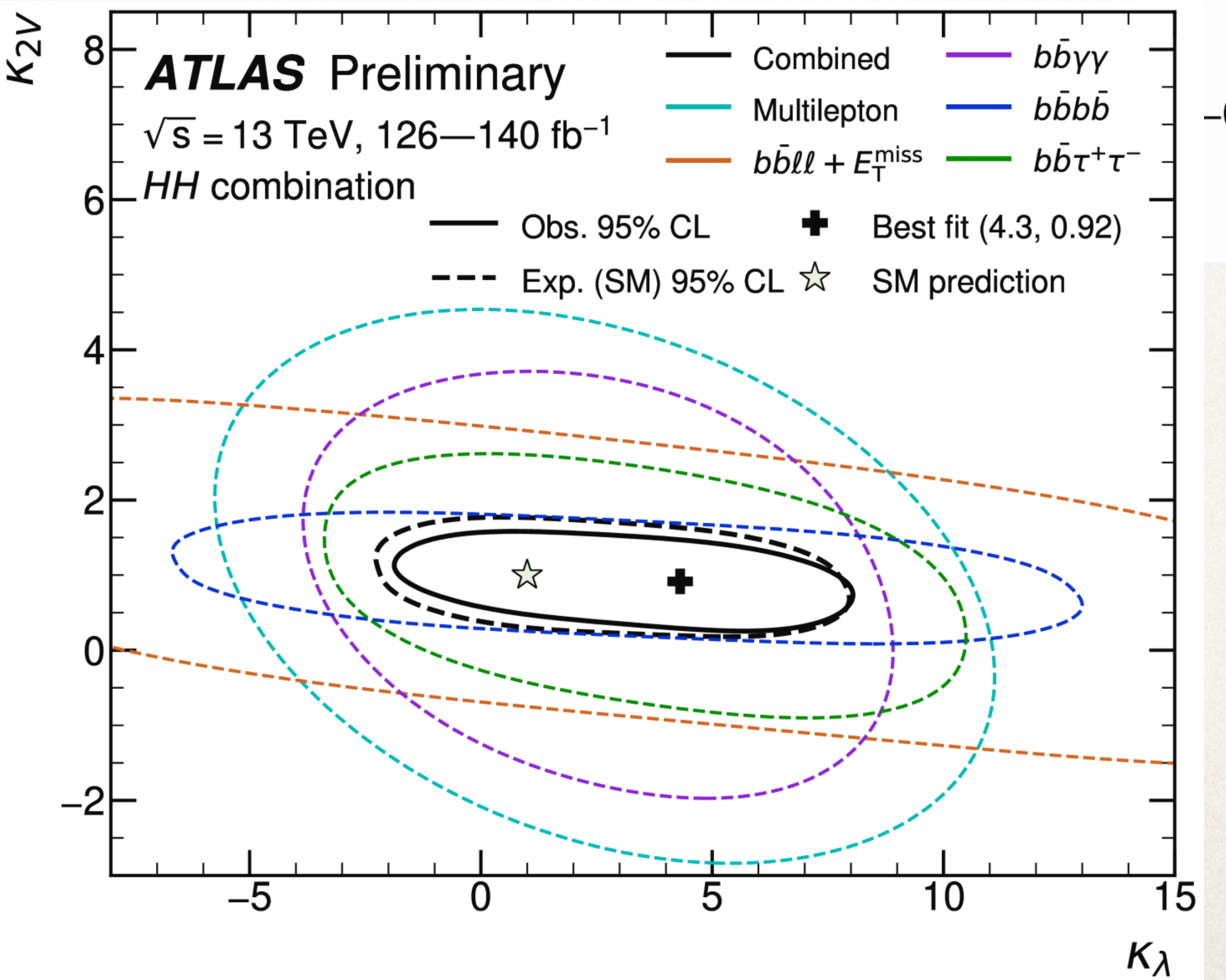
Non-resonant HH Production


ATLAS Preliminary
$\sqrt{s}$ = 13 / 13.6 TeV, 140 / 168 fb^{-1}
$HH \rightarrow b\bar{b}\gamma\gamma$
Expected
Observed
SM HH discovery significance
0.73
0.49
0.75
0.80
1.01
0.84
Run 3
Combined
0.2
0.4
0.6
0.8
1.0
1.2
1.4


ATLAS Preliminary
$\sqrt{s}$ = 13 / 13.6 TeV, 140 / 168 fb^{-1}
$HH \rightarrow b\bar{b}\gamma\gamma$
Observed Limit
Expected Limit ($\mu_{HH} = 0$)
Expected Limit ($\mu_{HH} = 0$) ± 2σ
Expected Limit ($\mu_{HH} = 0$) ± 1σ
Expected Limit ($\mu_{HH} = 1$)
Expected Limit ($\mu_{HH} = 0$)
arXiv:2310.12301
Obs.
Exp. ($\mu_{HH} = 0$)
Exp. ($\mu_{HH} = 1$)
Run 2
4.8
4.2
5.5
Run 3
5.8
3.8
5.0
Combined
3.8
2.6
3.7
0
2
4
6
8
10
12
14
16
95% CL upper limit on μ_{HH}

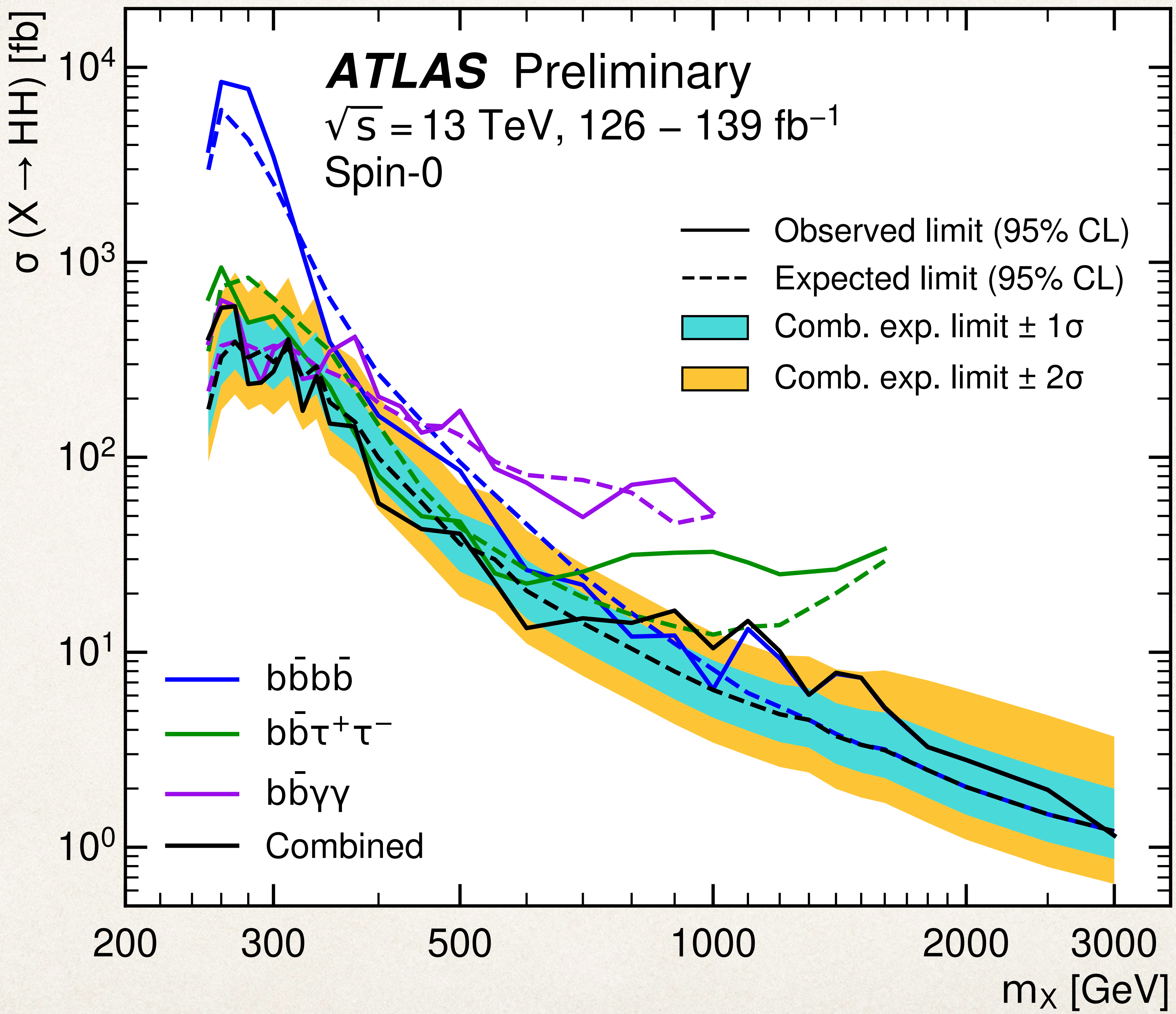


ATLAS Preliminary
√s = 13 TeV, 126—140 fb⁻¹
HH → bb̄τ⁺τ⁻ + bb̄γγ + bb̄bb̄
All other c fixed to SM
Observed 68% CL
Observed 95% CL
Best fit (-0.42, 0.49)
Expected (SM) 68% CL
Expected (SM) 95% CL
SM prediction
c_tthh
c_gghh



ATLAS Preliminary
√s = 13 TeV, 126—140 fb⁻¹
HH combination
Combined
Multilepton
bb̄ℓℓ + E_T^miss
bb̄γγ
bb̄bb̄
bb̄τ⁺τ⁻
Obs. 95% CL
Exp. (SM) 95% CL
Best fit (4.3, 0.92)
SM prediction
κ_2V
κ_λ

95% confidence level upper limits on $\sigma(X \rightarrow HH)$ for a spin-0 resonance



Resonant HH Production

Instead of investigating modified λ_{hhh}, we turn the focus to

resonance effects in Higgs pair production

Motivation

1. The SM Higgs boson cannot fix the gauge hierarchy problem. It requires unnatural cancellation for the bare and loop-corrected Higgs boson mass.

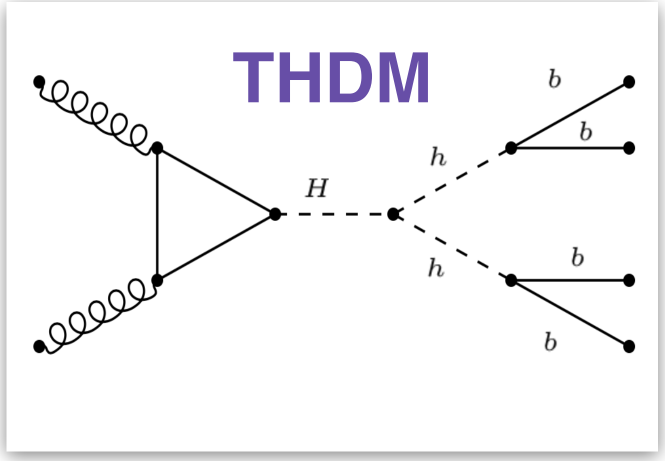
2. Many extensions of the EWSB sector consist of more Higgs fields
   - **Two-Higgs doublet models (2HDMs)**, MSSM, and any composite Higgs models

3. Probe the Higgs self-couplings is to probe the structure of the Higgs sector
   - Higgs-pair production via gluon-gluon fusion at the LHC

4. Study the signal process $pp \to hh \to b\bar{b}b\bar{b}$ via gluon fusion against the SM backgrounds at the High-Luminosity LHC via machine learning approach.

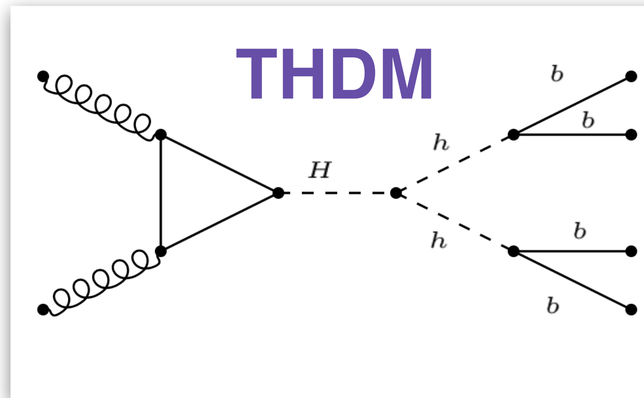
5. The boosted hadronic Higgs jet can help to against the background

hadronic jet tagger

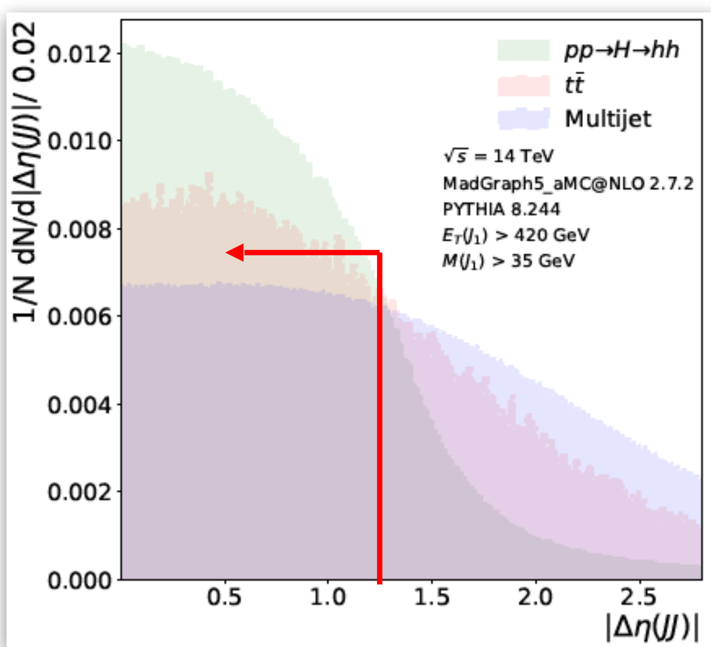


$pp \to hh \to b\bar{b}b\bar{b}$ via gluon-gluon fusion in THDMs at the High-Luminosity LHC

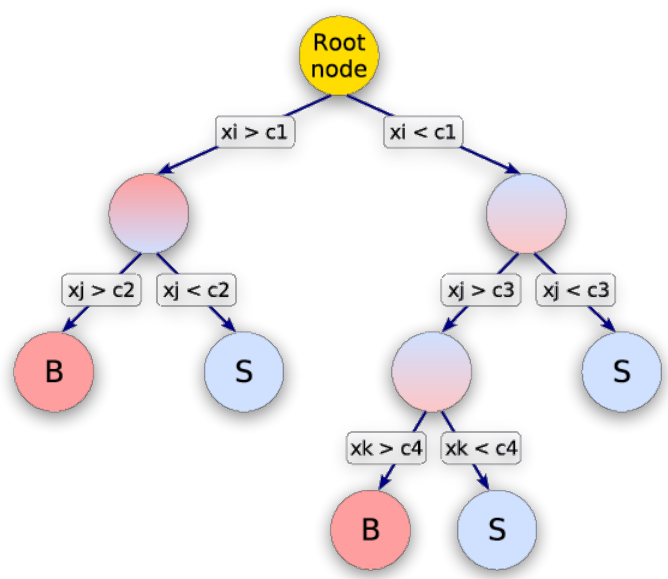
- Three approaches to study Higgs-pair production



the conventional
cut-based approach

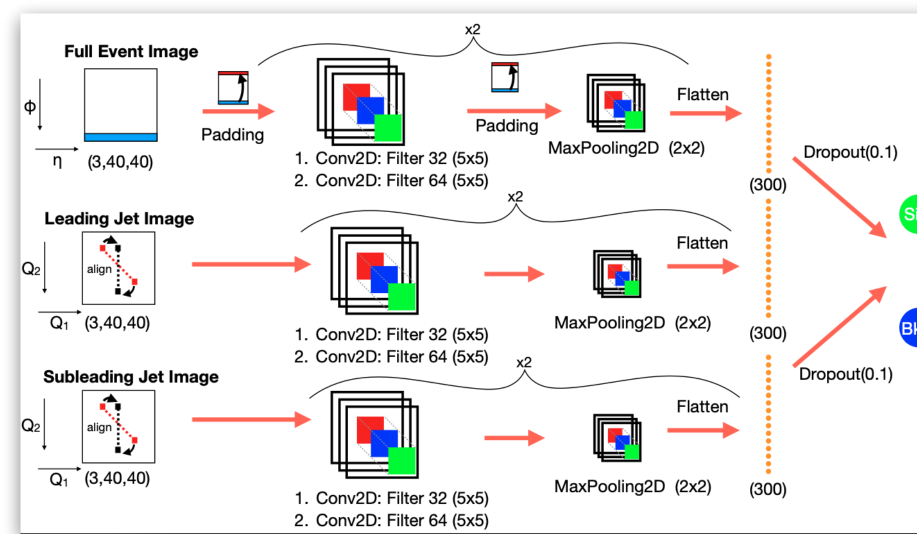


boosted decision tree
BDT



[A. Hoecker et al, arXiv:physics/0703039](https://arxiv.org/abs/physics/0703039)

three-stream
convolutional neural network



Two-Higgs Doublet Models

General Higgs potential:

$$V^{\rm THDM} = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - m_3^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$$

Mayumi Aoki et al, Phys.Rev.D, arXiv:0902.4665

	up-type	down-type	charged leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton Specific(Type III)	Φ_2	Φ_2	Φ_1
Flipped(Type IV)	Φ_2	Φ_1	Φ_2

The Yukawa interactions:

$$\mathcal{L}_{\rm yukawa}^{\rm THDM} = -\sum_{f=u,d,\ell}\left(\frac{m_f}{v}\xi_h^f\overline{f}fh + \frac{m_f}{v}\xi_H^f\overline{f}fH - i\frac{m_f}{v}\xi_A^f\overline{f}\gamma_5 fA\right) - \left\{\frac{\sqrt{2}V_{ud}}{v}\overline{u}\left(m_u\xi_A^u \mathrm{P}_L + m_d\xi_A^d \mathrm{P}_R\right)d\,H^+ + \frac{\sqrt{2}m_\ell\xi_A^\ell}{v}\overline{\nu_L}\ell_R H^+ + \mathrm{H.c.}\right\}$$

The modifier in Yukawa interactions:

	ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

*$\tan(\beta) = v_2 / v_1$

Calculation of Current Constraints

- Combine 3CNN analysis with the current constraints
- Calculate from the public code
  - HiggsBounds-v5.10.2 arxiv:2006.06007 HiggsBounds GitLab
    - direct searches at high energy colliders
    - include all processes at LEP, Tevatron, and LHC
    - provide most sensitive channel and whether the point is still allowed or not at the 95% CL
  - HiggsSignals-v2.6.2 arxiv:2012.0917 HiggsSignals GitLab
    - the Higgs-signal strengths obtained at the LHC
    - gives the χ^2 output for 111 Higgs observables
    - require that the p-value is larger than 0.05, corresponding to 2σ level
- Regard the overlapping regions as the currently allowed parameter space

Currently Allowed Region

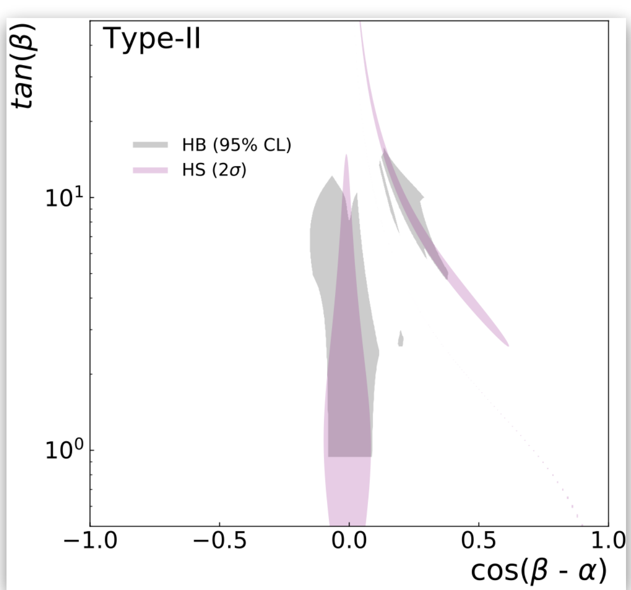
- Gray area is the currently allowed region from **HiggsBounds at the 95% CL**
  - direct searches at high energy colliders
  - include all processes at LEP, Tevatron, and LHC

  Philip Bechtle et al, Eur.Phys.J.C, arxiv:2006.06007 — HiggsBounds GitLab

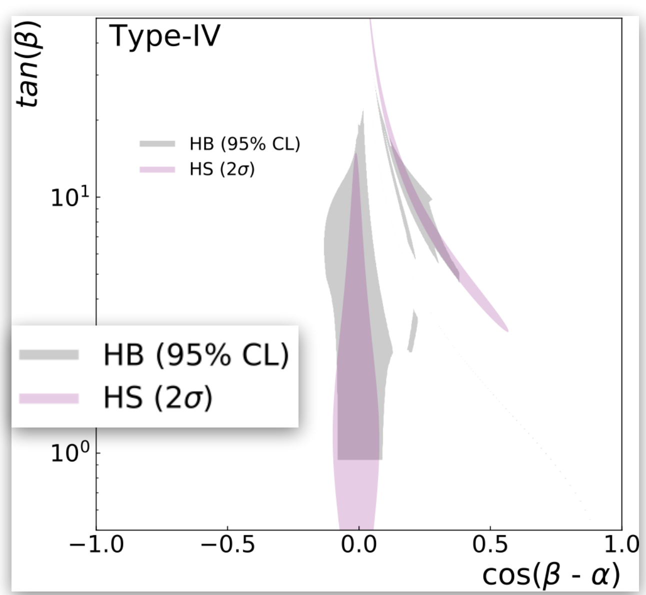
- **Purple area** is the allowed region from **HiggsSignals at 2 σ level**
  - the Higgs-signal strengths obtained at the LHCs
  - gives the χ^2 output for 111 Higgs observables
  - require that the p-value is larger than 0.05, corresponding to 2σ level

  Philip Bechtle et al, Eur.Phys.J.C, arxiv:2012.0917 — HiggsSignals GitLab

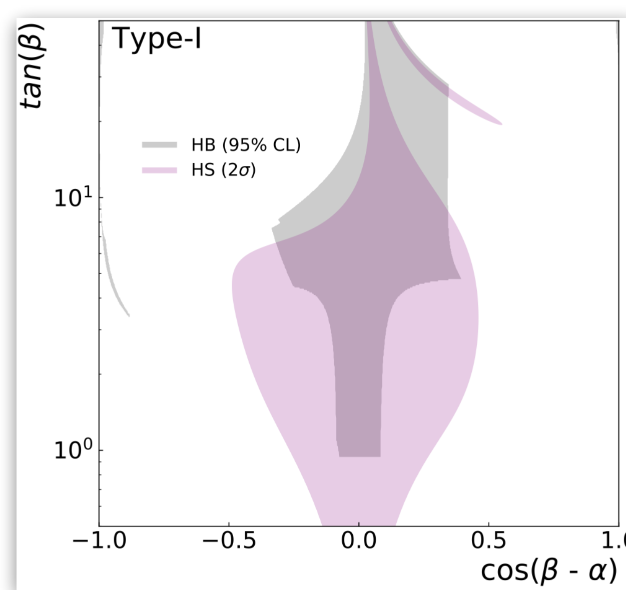
Type II



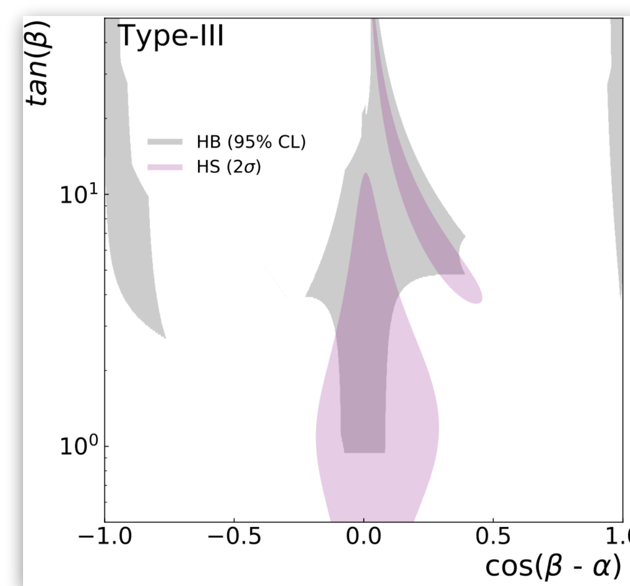
Type IV



Type I



Type III



* at m_{12}^2 = 400000 GeV^2, cos(β-α) = 0.08 and $m_A = m_H = m_{H\pm}$ = 1000 GeV

Higgs-pair Production in THDMs

Triple Higgs self–interaction:

Parametrized as a shift from the SM:

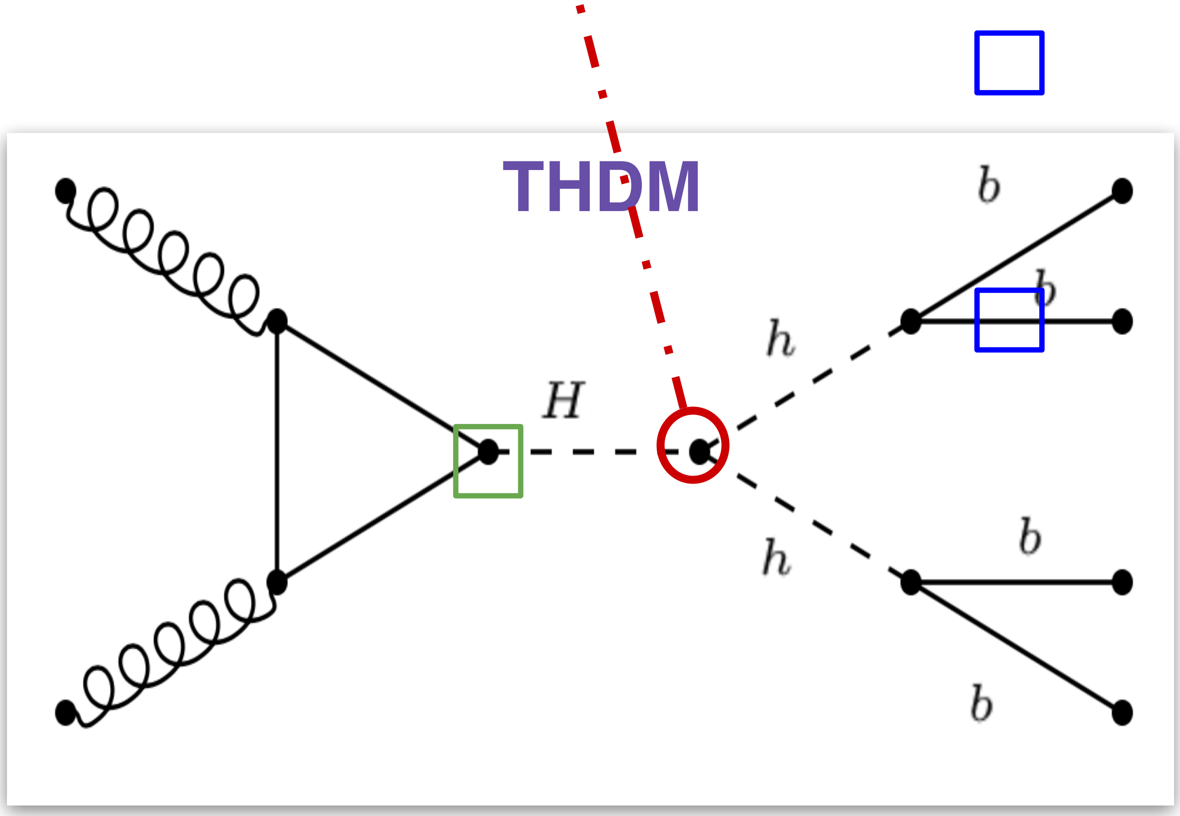
$$\lambda_{h^0h^0H^0}: \frac{\cos(\beta-\alpha)}{\sin 2\beta}\left[\sin 2\alpha\,(2m^2_{h^0}+m^2_{H^0}) - \frac{2m^2_{12}}{\sin 2\beta}(3\sin 2\alpha - \sin 2\beta)\right]$$

	Type II
$1+\Delta_t^{h^0}$	$\frac{\cos\alpha}{\sin\beta} = 1+\xi/\tan\beta - \xi^2/2 + \mathcal{O}(\xi^3)$
$1+\Delta_b^{h^0}$	$-\frac{\sin\alpha}{\cos\beta} = 1-\xi\,\tan\beta - \xi^2/2 + \mathcal{O}(\xi^3)$
$1+\Delta_t^{H^0}$	$\frac{\sin\alpha}{\sin\beta} = -1/\tan\beta + \xi + \xi^2/(2\tan\beta) + \mathcal{O}(\xi^3)$
$1+\Delta_b^{H^0}$	$\frac{\cos\alpha}{\cos\beta} = \tan\beta + \xi - \xi^2/2\,\tan\beta + \mathcal{O}(\xi^3)$

*ξ = cos(β-α)

Benoit Hespel et al, JHEP, arxiv:1407.0281

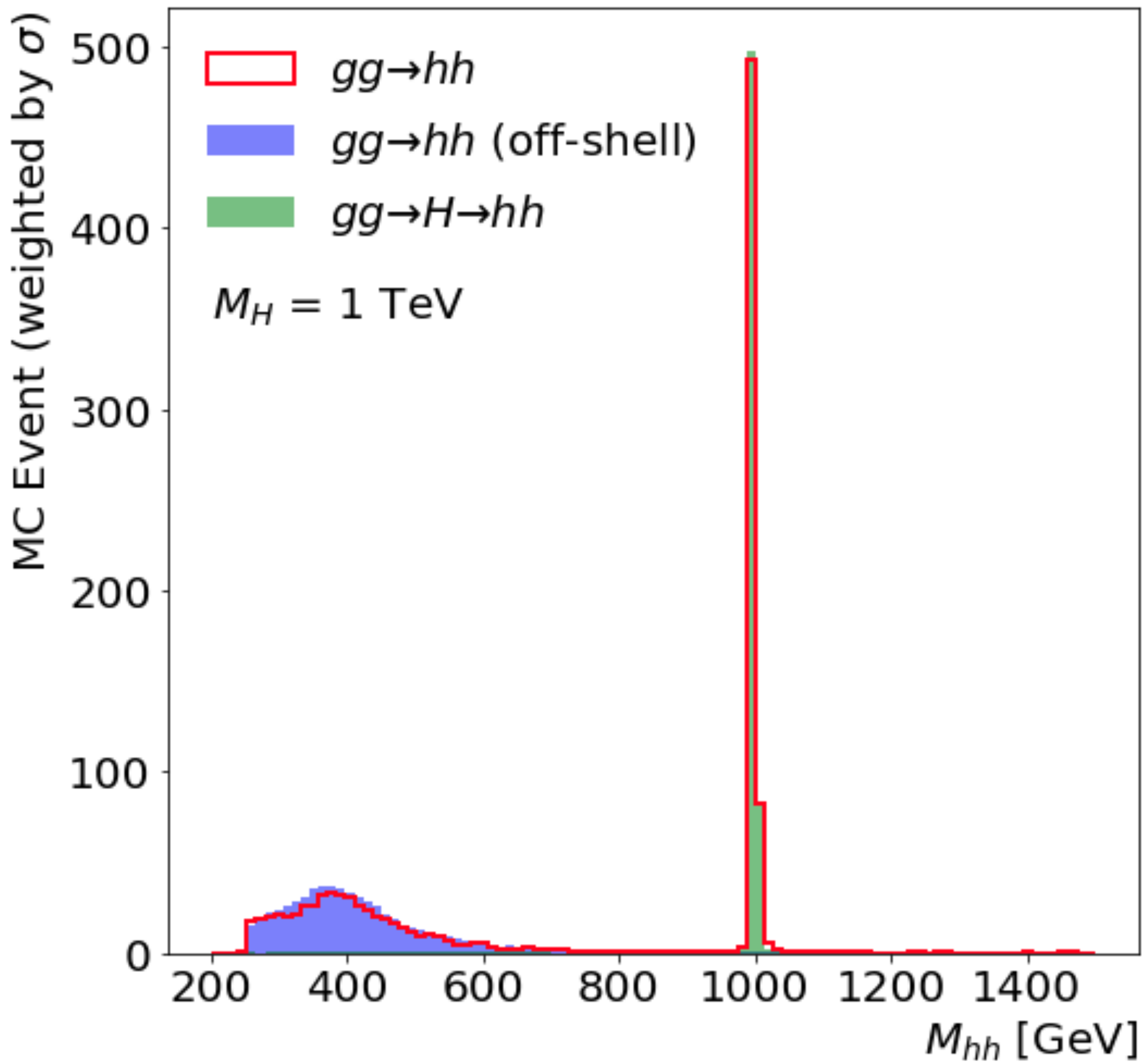
Benoit Hespel et al, JHEP, arxiv:1407.0281



- **Fix m^2_{12}, m_h, m_H, scan (cos(β-α), tan(β)) plane**
- **Fix tan(β), m_h, m_H, scan (cos(β-α), m^2_{12}) plane**

Resonance Against the Continuum

- Resonance is dominate around M_{hh} = 1 TeV



*tan(β)=5, m_{12}^2 = 400000 GeV^2, cos(β-α) = 0.01 and m_H=1000 GeV, m_A= $m_{H\pm}$= 1001 GeV in Type II

Higgs-Jet-Tagging Method

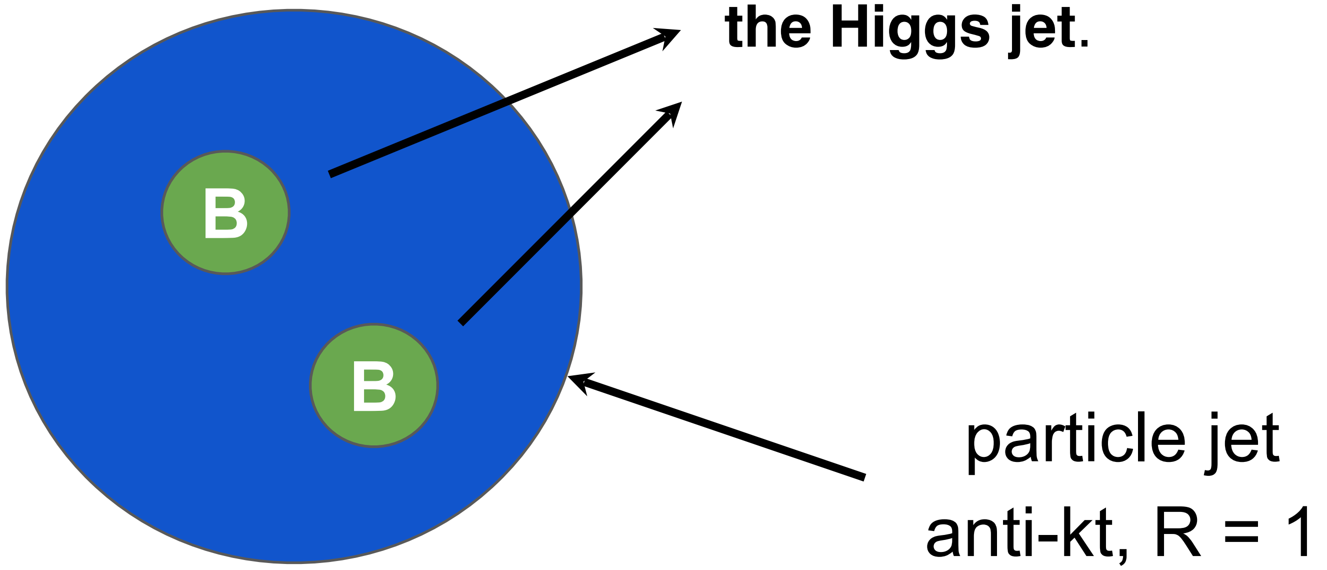
Higgs jet is recognized by double b-tagging due to the hadronic Higgs decay.

arXiv:1507.00508

arXiv:1507.00508

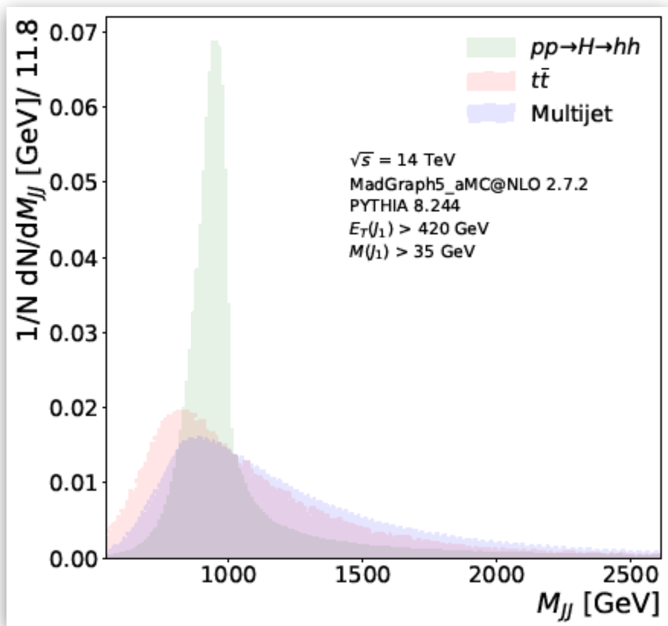
Double-B Hadrons-tagging via **ghost-association** method is used to do double b-tagging in this study.

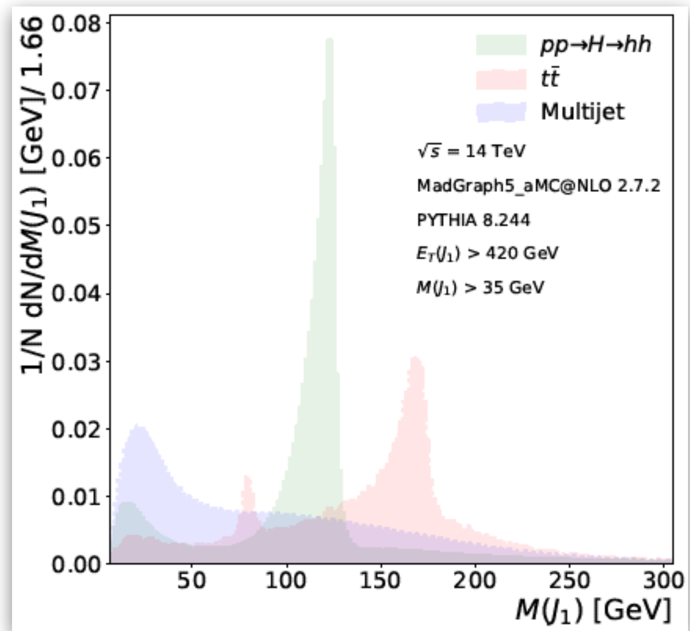
1. Multiply infinitesimal value to B hadrons, it is **ghosted B hadrons**.
2. Adding this ghosted B hadrons into the final state list and cluster the jets
3. **If large R(=1) jet contains two ghost-associated B hadrons, it will be tagged to the Higgs jet**.

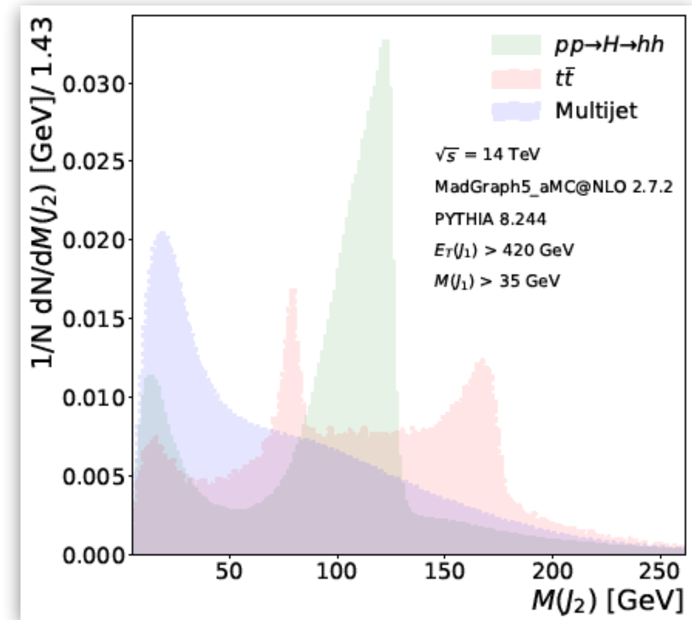


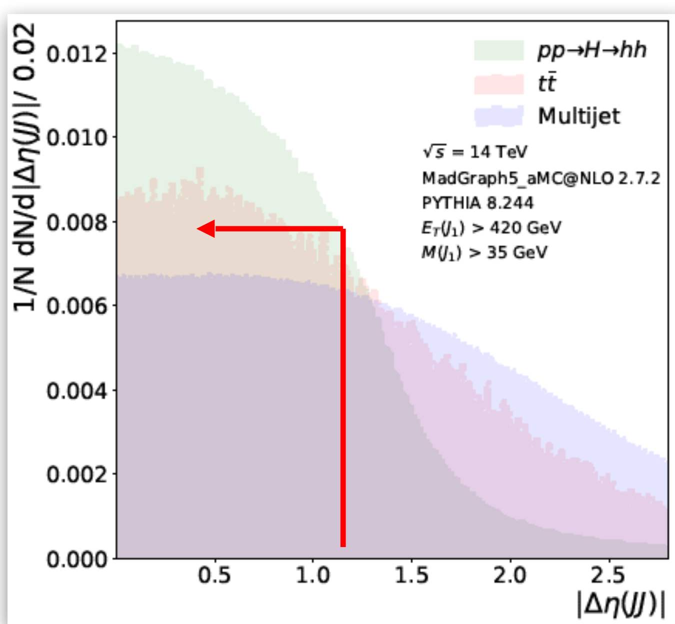
$$X_{HH} = \sqrt{\left(\frac{m(H_1) - 124\ \text{GeV}}{0.1 \times m(H_1)}\right)^2 + \left(\frac{m(H_2) - 115\ \text{GeV}}{0.1 \times m(H_2)}\right)^2}$$

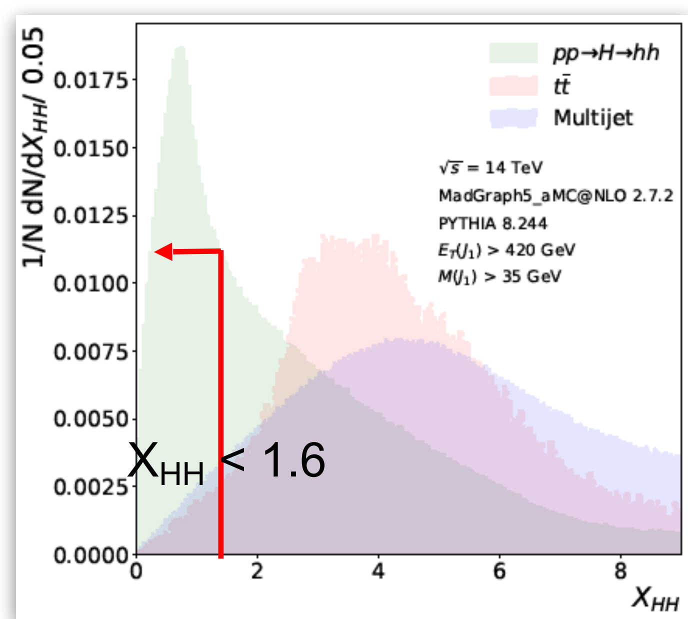
High-Level Features - Kinematic Features





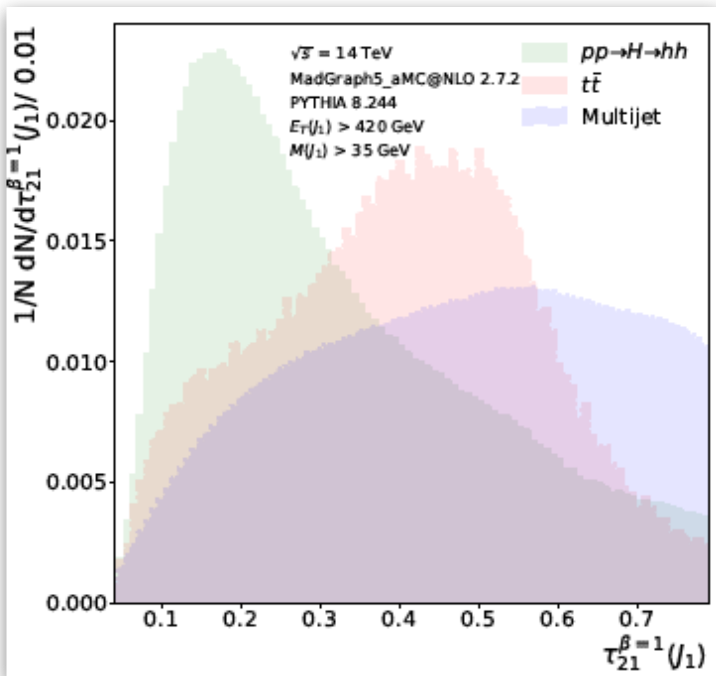


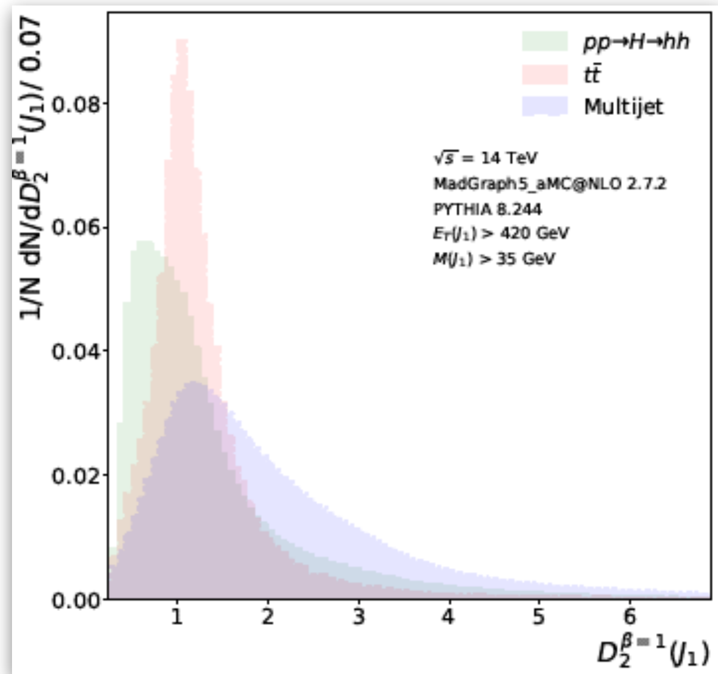


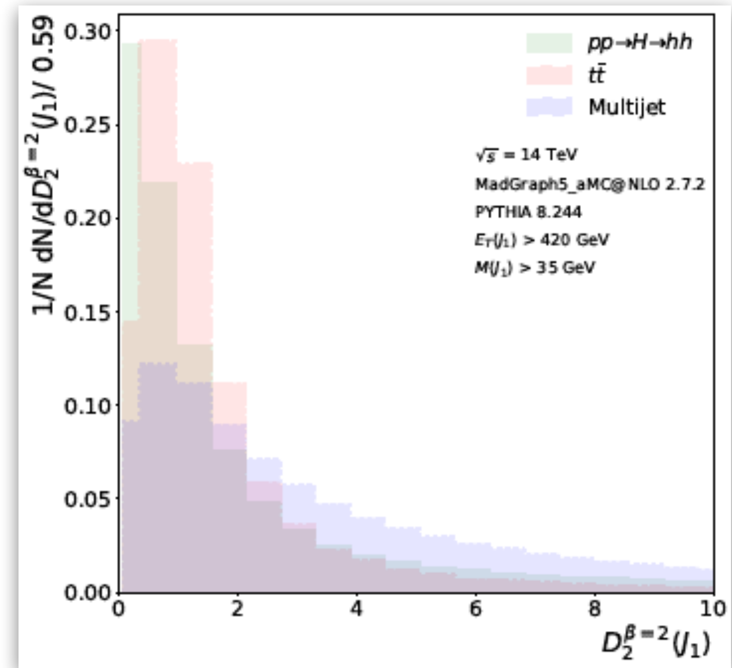


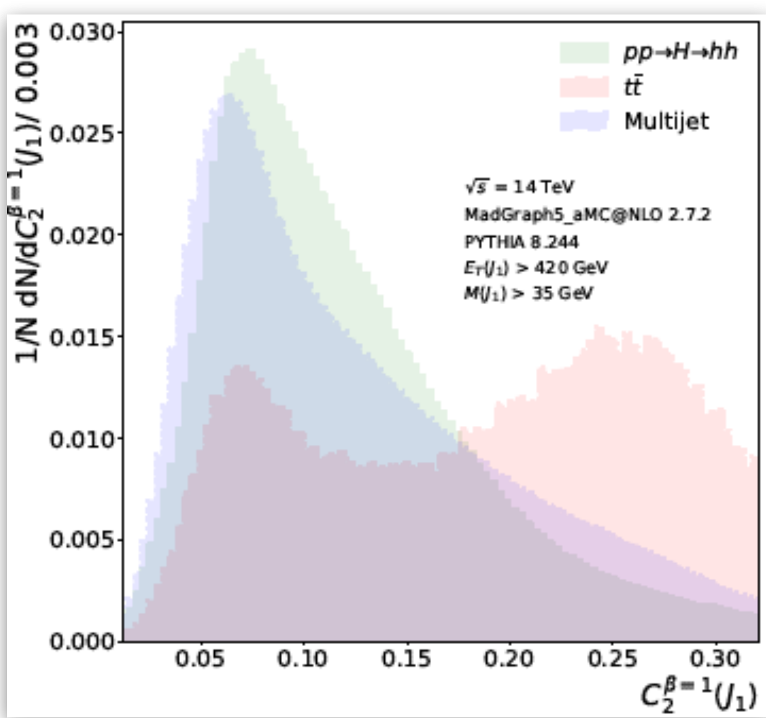
$|\Delta[\eta(J1), \eta(J2)]| < 1.3$

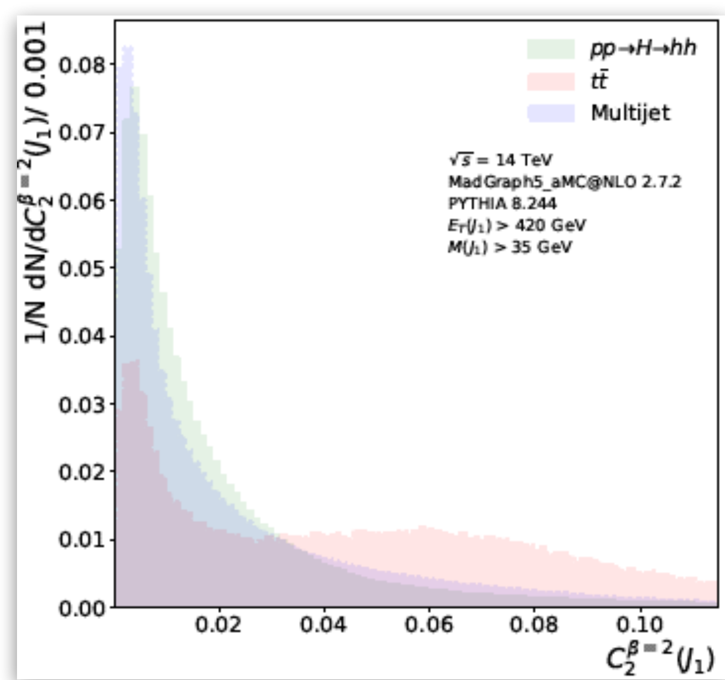
High-Level Features - Jet Substructures





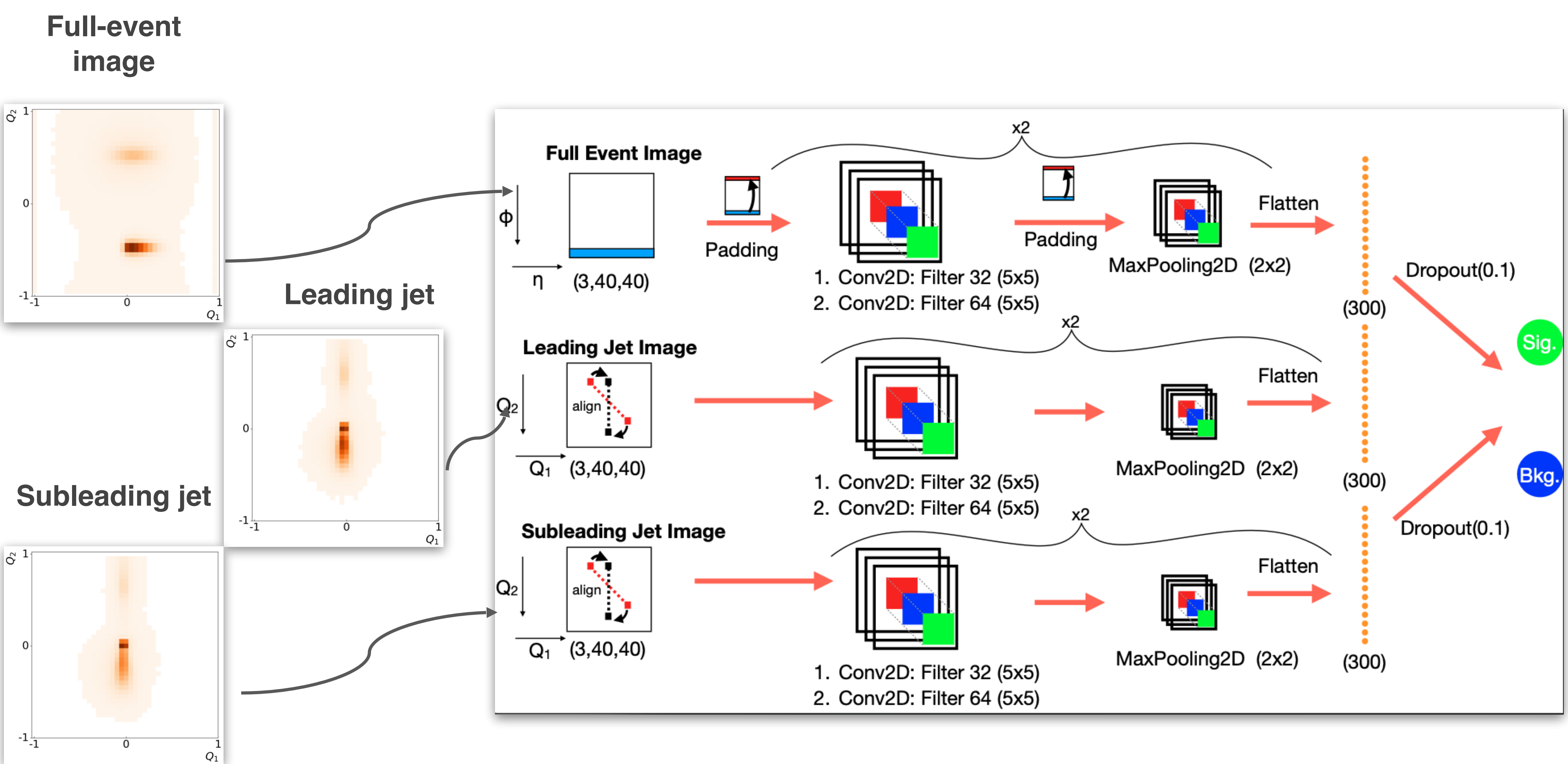






3CNN Architecture

- Inspired by works [Joshua Lin et al, JHEP, arxiv:1807.10768]
  [Yi-Lun Chung et al, JINST, arxiv:2009.05930]



Low-Level Features

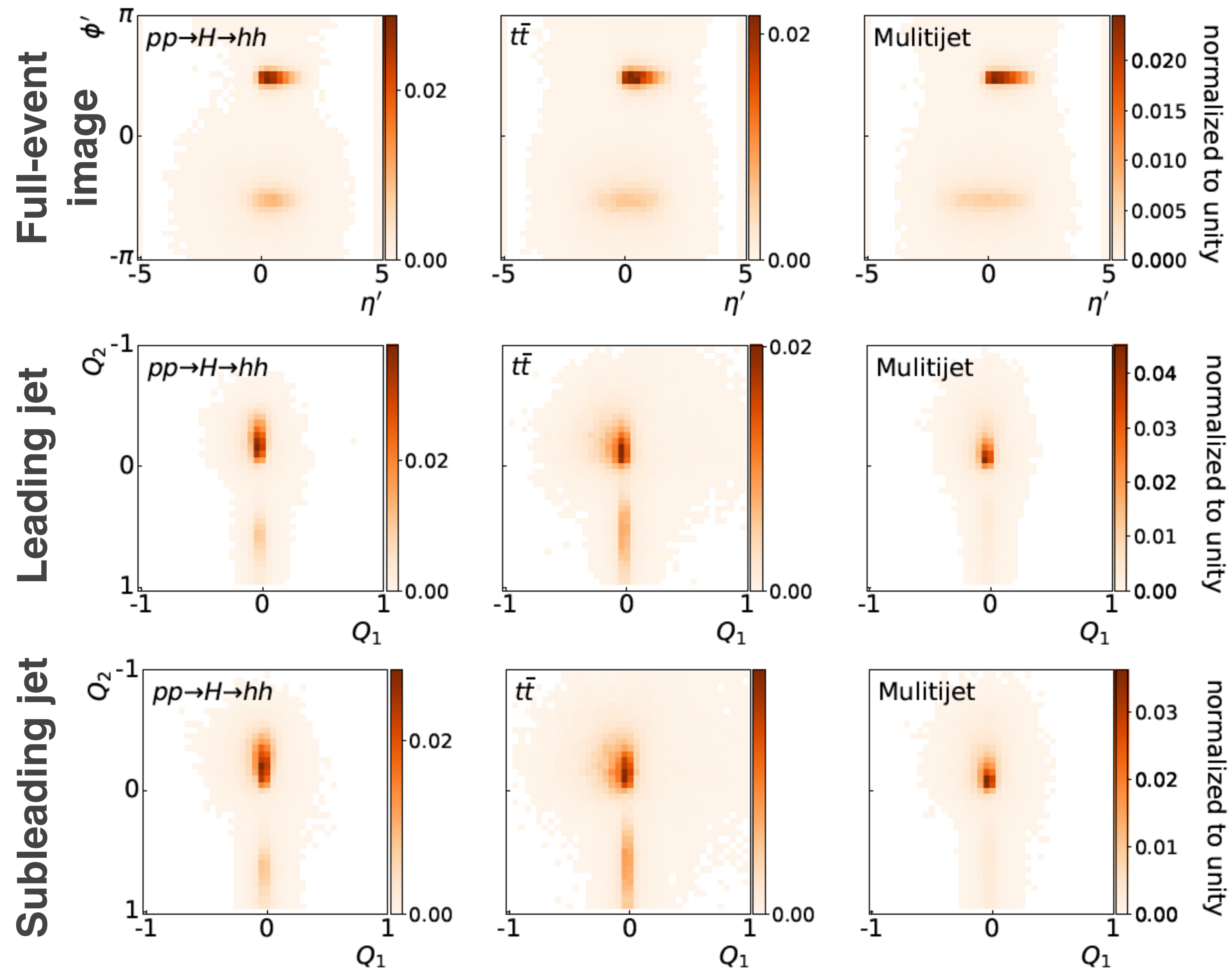
1. The leading and subleading trimmed jet
2. Rotated full-event images
3. Deposit intensities into 40X40 pixels
   (1RX1R -> 40X40 pixels)

- charged pt
- neutral pt
- charged multiplicity (analogy RGB)

4. Rotation and Reflection:
   - put the leading subjet at the origin
   - subleading subjet directly below the leading subjet
   - put the third-leading subjet on the right-hand side

1. Normalized: sum of intensity is unity
2. Standardization: mean zero and unit variance

The average of 10000 images



* Q_1 and Q_2 are new axes for the jet's axis

Comparisons for 4-Types of 2HDM

- Significance of 4 types in 3 analyses

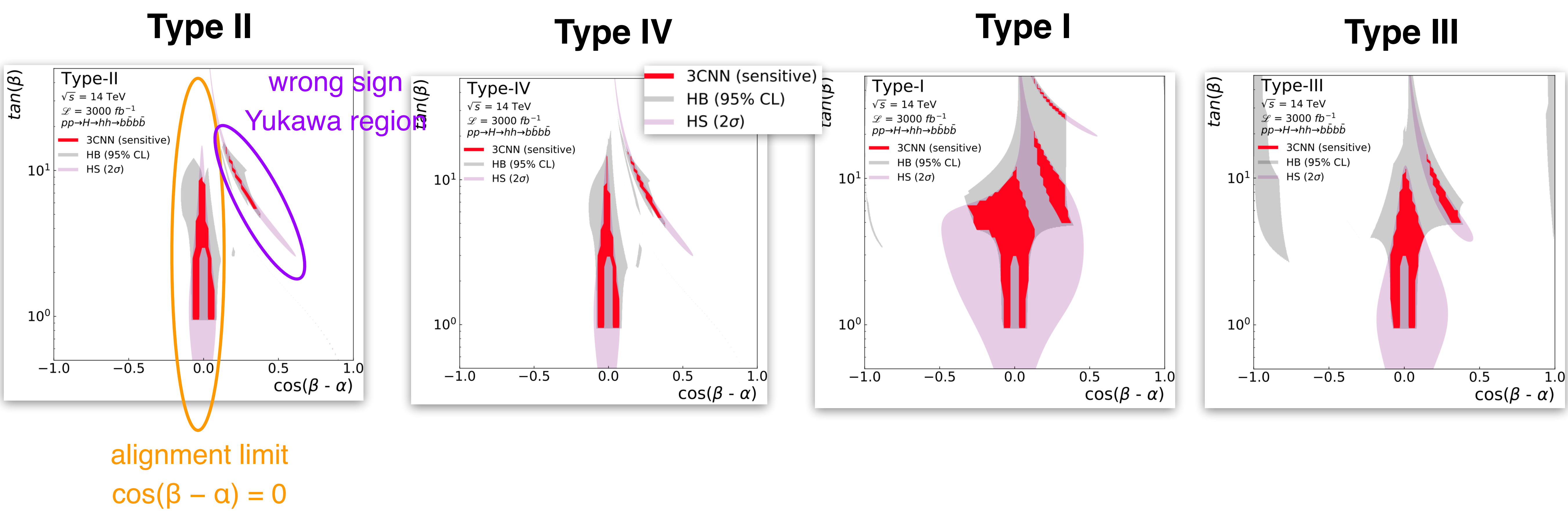
$\mathcal{L}$ = 3000 fb^{-1}	Type I	Type II	Type III	Type IV
σ(pp->H) (fb)	0.9864	0.81186	0.98173	0.83234
Br(H->hh)	0.88221	0.87147	0.88087	0.87279
Br(h->bb)	0.62102	0.35596	0.64835	0.32968
Cut-based Method (sig. eff. = 0.1059, # of bkg = 1392.67)				
Survival Events	37.48	10.01	40.60	8.82
S/√B	1.00	0.27	1.09	0.24
BDT Method (sig. eff. =, # of bkg = 142.46)				
Survival Events	33.98	9.08	36.80	7.99
S/√B	2.85	0.76	3.08	0.67
3CNN Method (sig. eff. = 0.0961, # of bkg = 56.73)				
Survival Events	33.98	9.08	36.81	7.99
S/√B	4.51	1.21	4.89	1.06

* include B-hadron tagging eff. = 0.77

* For signal: tan(β)=5, m_{12}^2 = 400000 GeV^2, cos(β-α) = 0.08 and m_A=m_H=$m_{H\pm}$= 1000 GeV

Allowed Sensitivity Region Under Current Constraints at 14 TeV HL-LHC

- **Red area** is the **sensitive region at 95% CL** (where the significance > 2)
- **Gray area** is the currently allowed region from **HiggsBounds at the 95% CL**
- **Purple area** is the allowed region from **HiggsSignals at 2 σ level**
- The 3CNN can cover a large area of the overlapping region in all 4 types of 2HDMs



* m_{12}^2 = 400000 GeV^2 and m_A=m_H=$m_{H\pm}$= 1000 GeV

* significance $Z = \sqrt{2*((s+b)\times\ln(1+s/b)-s)}$, where s is number of signal and b is number of total background

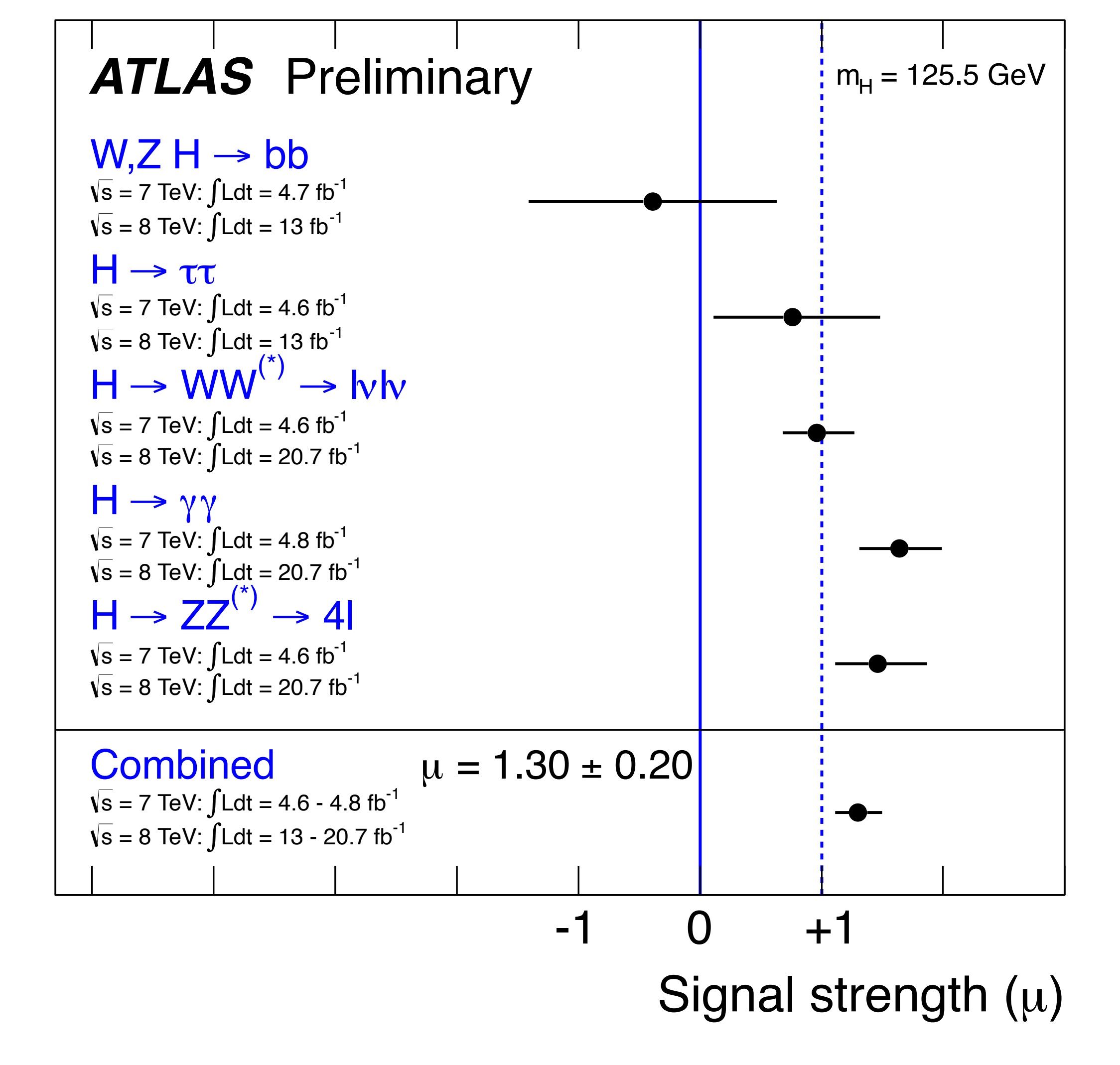
Outlooks

- Higgs physics enters an exciting era in LHC Run-3.
- Higgs pair production is one of the most important tasks at the LHC to unlock the Higgs mechanism.
- Not to mention there are continuous efforts to search for other scalar bosons.
- With $v \simeq 2m_H \simeq \sqrt{2}m_t$ the top quark and the Higgs boson are gateway to EWSB or new physics.

Backup

Around March 2013 (Moriond)

The bb and tau tau modes appeared. But the surprise is the diphoton mode by CMS. It gets 0.78 +- 0.27.



Signal Strengths (CMS)

Higgs Boson Decay	μ (Before Moriond)	μ (After Moriond)
$VH \to Vb\bar{b}$	$1.31^{+0.65}_{-0.60}$	Same
$H \to \tau^+\tau^-$ (0/1 j)	$0.85^{+0.68}_{-0.66}$	$0.76^{+0.50}_{-0.52}$
$H \to WW^*$ (0/1 j)	$0.77^{+0.27}_{-0.25}$	0.76 ± 0.21
$H \to \gamma\gamma$ (untagged)	$1.42^{+0.55}_{-0.49}$	$0.78^{+0.28}_{-0.26}$
$H \to ZZ^*$	$0.80^{+0.35}_{-0.28}$	$0.91^{+0.30}_{-0.24}$
Combined	0.88 ± 0.21	

Fitting analysis

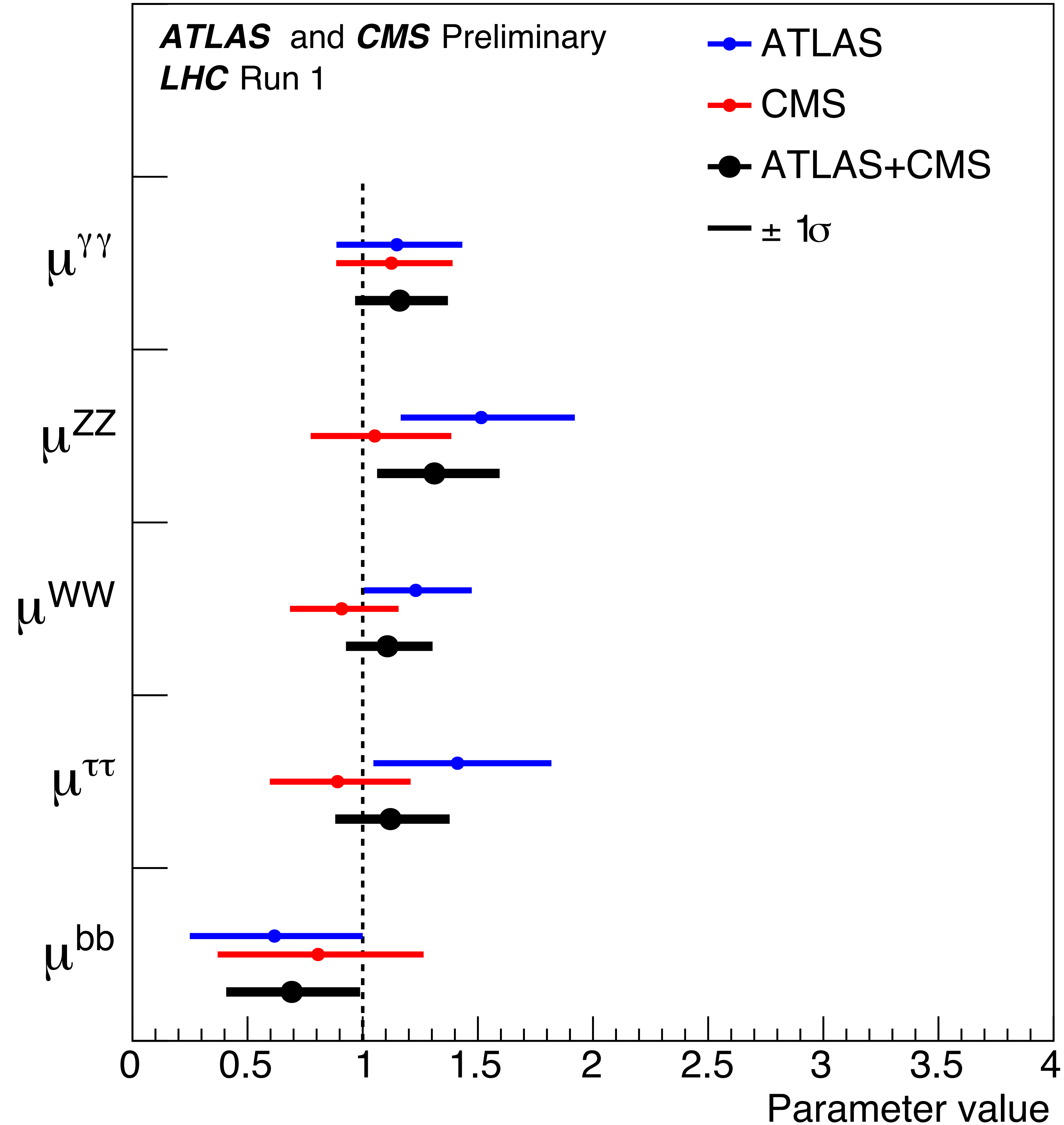
- Ratios of Yukawa and gauge couplings

$$C_u^S = g^S_{H\bar{u}u}\,, \quad C_d^S = g^S_{H\bar{d}d}\,, \quad C_\ell^S = g^S_{H\bar{l}l}\,; \quad C_v = g_{HVV}\,;$$
$$C_u^P = g^P_{H\bar{u}u}\,, \quad C_d^P = g^P_{H\bar{d}d}\,, \quad C_\ell^P = g^P_{H\bar{l}l}\,.$$

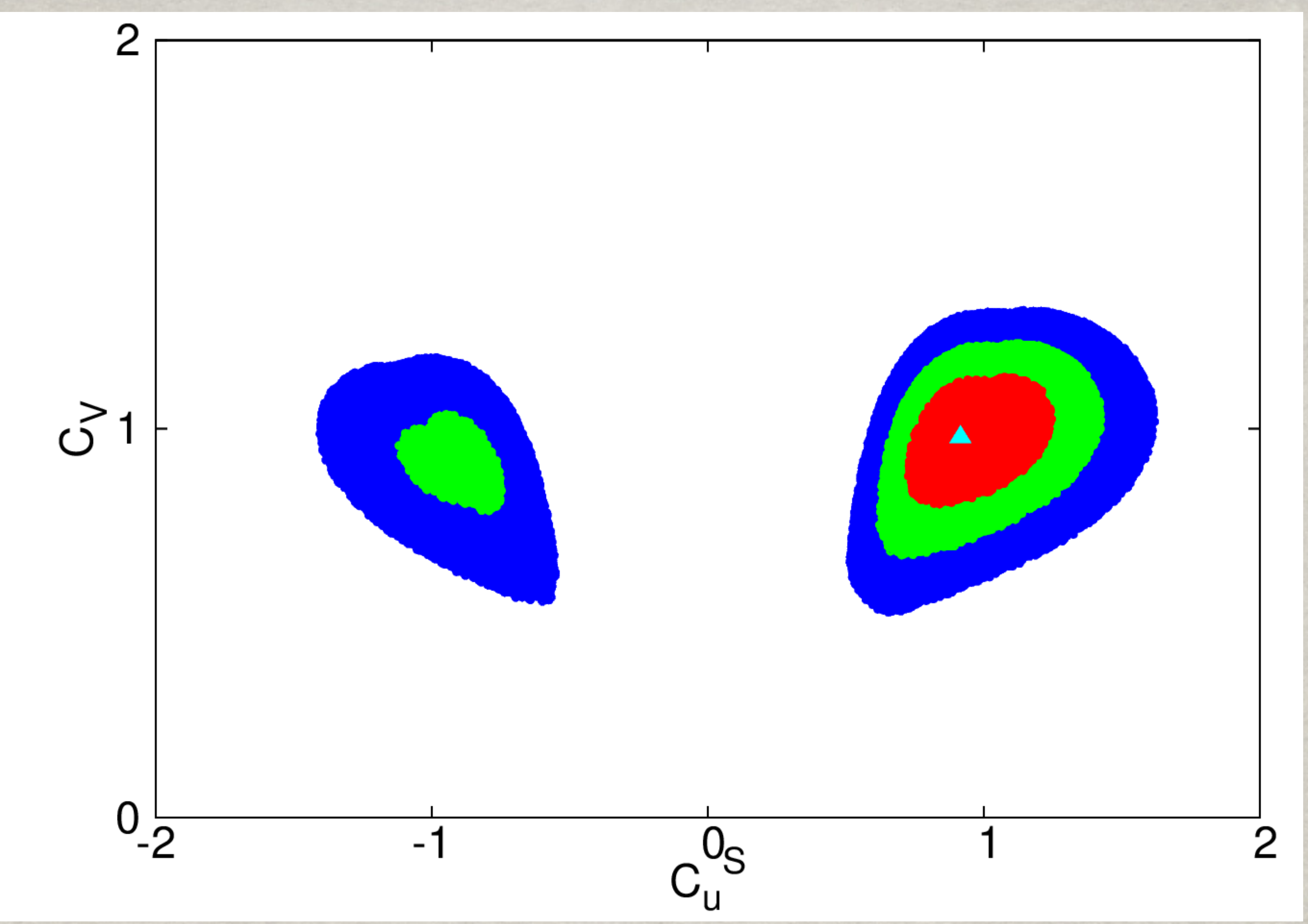
- Extra loop contributions other than the Yukawa and gauge couplings:

$$\Delta S^g\,, \quad \Delta S^\gamma\,; \quad \Delta P^g\,, \quad \Delta P^\gamma$$

- $\Delta\Gamma_{\rm tot}$



ATLAS and CMS Preliminary
LHC Run 1
ATLAS
CMS
ATLAS+CMS
± 1σ
μ^γγ
μ^ZZ
μ^WW
μ^ττ
μ^bb
0
0.5
1
1.5
2
2.5
3
3.5
4
Parameter value



$C_u^S > 0$ is preferred but $C_u^S < 0$ is still allowed at 95% CL;

$$C_v = 0.98^{+0.10}_{-0.11}$$

Remarks

- The HVV coupling is the most restrictive:

$$C_v = 0.93 - 1.0$$

with $7 - 12\%$ uncertainty.

- The CPC top-Yukawa coupling C_u^S is preferred to be positive in those fits with ΔS^γ and ΔS^g fixed at zero. $C_u^S < 0$ is ruled out at 68.3% CL, but allowed at 95%CL.
- The nonstandard Higgs decay is limited to be below 19%.
- The Higgs signal strengths cannot rule out the pseudoscalar couplings, and only a combination of C_u^S and C_u^P is constrained in the form of an elliptical equation.

- Fermionic couplings

$$\mathcal{L}_{H\bar{f}f} = -\sum_{f=u,d,l} \frac{g m_f}{2M_W} \sum_{i=1}^{3} H\,\bar{f}\left(g^S_{H\bar{f}f} + i g^P_{H\bar{f}f}\gamma_5\right) f\ .$$

For the SM $g^S_{H\bar{f}f} = 1$ and $g^P_{H\bar{f}f} = 0$.

- gauge boson couplings:

$$\mathcal{L}_{HVV} = g\,M_W \left(g_{HWW} W^+_\mu W^{-\mu} + g_{HZZ} \frac{1}{2c_W^2} Z_\mu Z^\mu \right) H\ .$$

- two photons:

$$\mathcal{M}_{\gamma\gamma H} = -\frac{\alpha M_H^2}{4\pi\, v}\left\{ S^\gamma(M_H)\ \left(\epsilon^*_{1\perp}\cdot\epsilon^*_{2\perp}\right) - P^\gamma(M_H)\frac{2}{M_H^2}\langle\epsilon_1^*\epsilon_2^* k_1 k_2\rangle \right\},$$

$$\begin{aligned} S^\gamma \quad &\simeq \quad -8.35\, g_{HWW} + 1.76\, g^S_{H\bar{t}t} + (-0.015 + 0.017\, i)\, g^S_{H\bar{b}b} \\ &\quad +(-0.024 + 0.021\, i)\, g^S_{H\bar{\tau}\tau} + (-0.007 + 0.005\, i)\, g^S_{H\bar{c}c} + \Delta S^\gamma \end{aligned}$$

- two gluons

$$\mathcal{M}_{ggH} = -\frac{\alpha_s\, M_H^2\,\delta^{ab}}{4\pi\, v}\left\{ S^g(M_H)\left(\epsilon^*_{1\perp}\cdot\epsilon^*_{2\perp}\right) - P^g(M_H)\frac{2}{M_H^2}\langle\epsilon_1^*\epsilon_2^* k_1 k_2\rangle \right\},$$

Signal Strengths:

- The signal strength can be written as the product of

$$\widehat{\mu}(\mathcal{P},\mathcal{D}) \simeq \widehat{\mu}(\mathcal{P})\ \widehat{\mu}(\mathcal{D})$$

  where $\mathcal{P} = \mathrm{ggF}, \mathrm{VBF}, \mathrm{VH}, \mathrm{ttH}$ denote the production mechanisms and $\mathcal{D} = \gamma\gamma, ZZ, WW, b\bar{b}, \tau\bar{\tau}$ the decay channels.

- On the production side:

$$\begin{aligned}
\widehat{\mu}(\mathrm{ggF}) &= \frac{|S^g(M_H)|^2 + |P^g(M_H)|^2}{\left|S^g_{\mathrm{SM}}(M_H)\right|^2} \\
\widehat{\mu}(\mathrm{VBF}) &= g^2_{HWW,HZZ} \\
\widehat{\mu}(\mathrm{VH}) &= g^2_{HWW,HZZ} \\
\widehat{\mu}(\mathrm{ttH}) &= \left(g^S_{H\bar{t}t}\right)^2 + \left(g^P_{H\bar{t}t}\right)^2
\end{aligned}$$

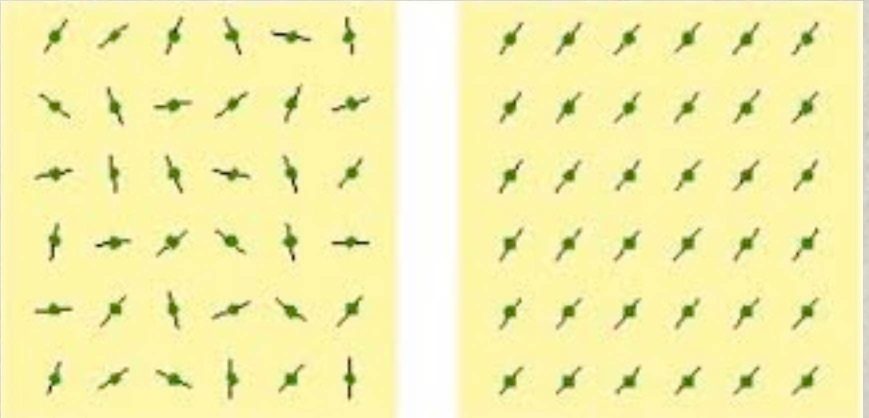
- On the decay side

$$\widehat{\mu}(\mathcal{D}) = \frac{B(H \to \mathcal{D})}{B(H_{\mathrm{SM}} \to \mathcal{D})}$$

$$B(H \to \mathcal{D}) = \frac{\Gamma(H \to \mathcal{D})}{\Gamma_{\mathrm{tot}}(H) + \Delta\Gamma_{\mathrm{tot}}}$$

Well known example of Spontaneous symmetry breaking

Ferromagnetism



- Above the critical temperature, the system is symmetric under SO(3) rotation -- dipoles are randomly oriented.
- Below the critical temperature the dipoles are completely ordered in some arbitrary direction:

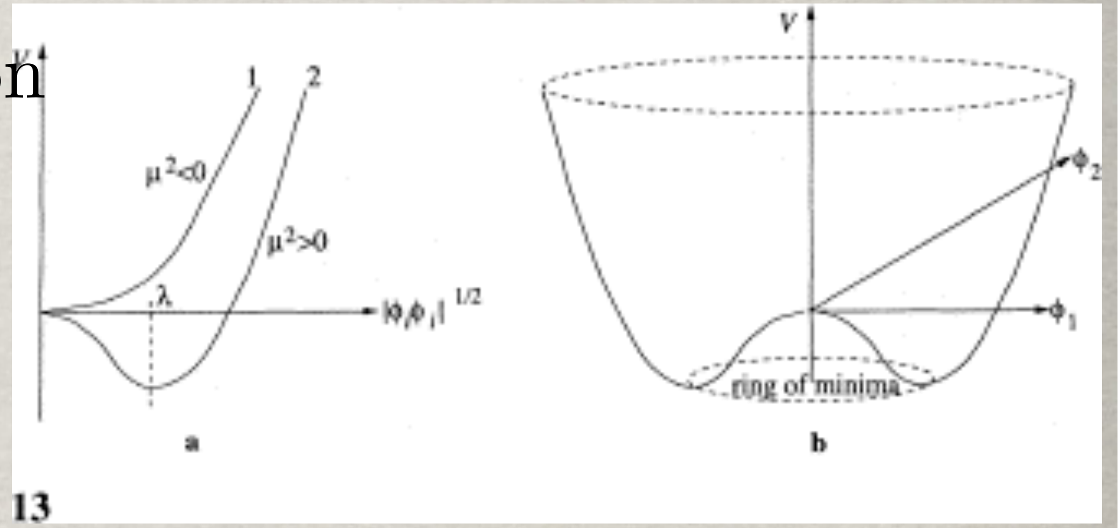
SO(3) --> SO(2)

Goldstone Model

$$\mathcal{L} = \partial_\mu \phi \partial^\mu \phi - V(\phi^* \phi) \qquad V = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2$$

Invariant under a global $U(1)$ transformation

$$\phi \to e^{i\alpha} \phi$$

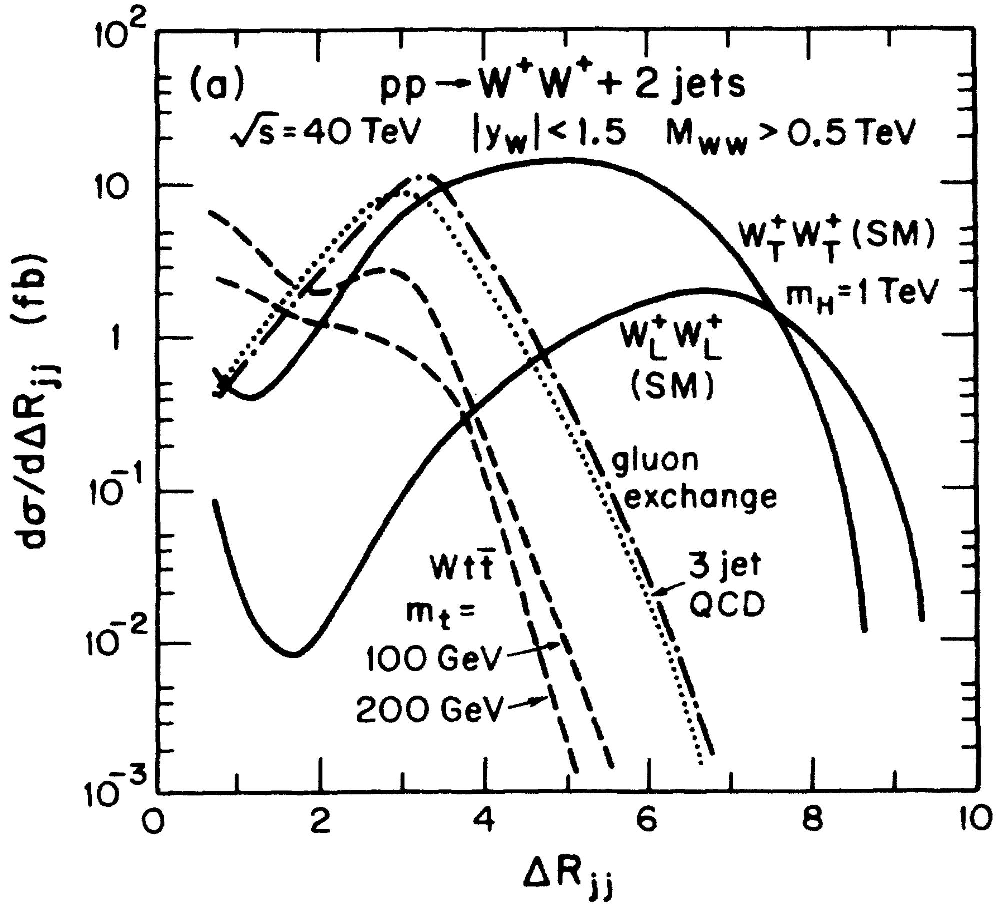


At $\phi = 0$, $V = 0$.

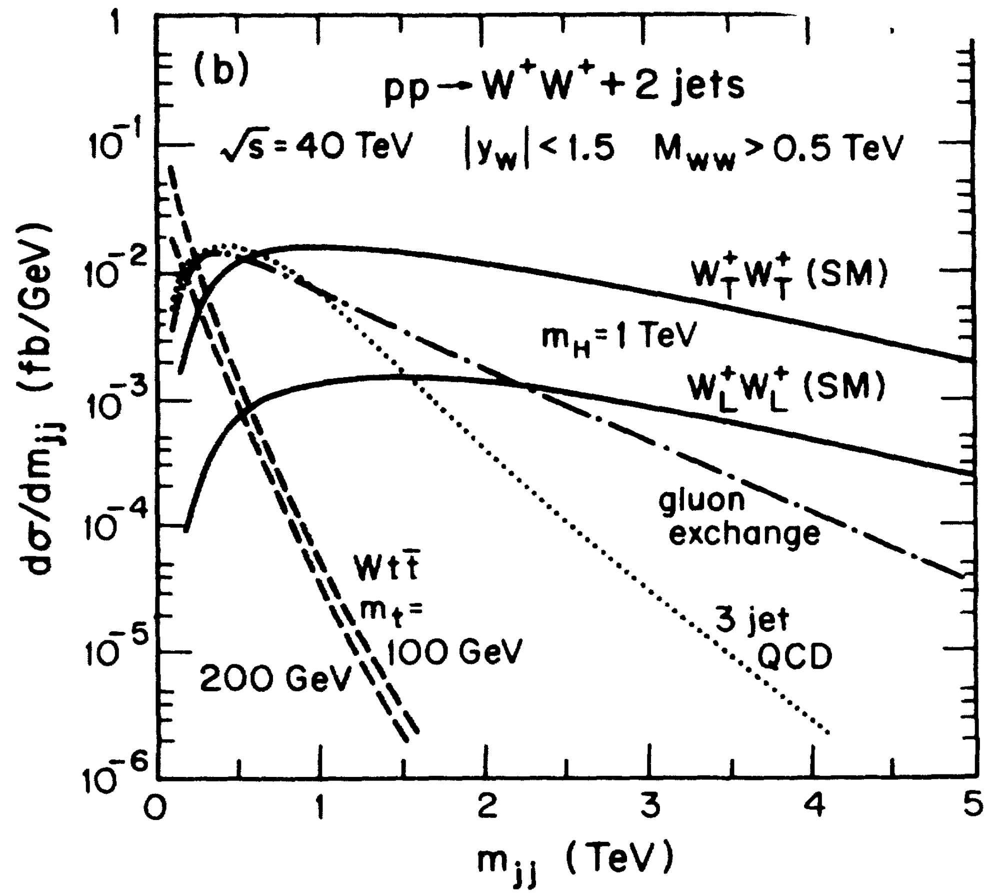
For $\mu^2 < 0$, min V occurs at

$$\langle \phi \rangle = \sqrt{\frac{-\mu^2}{2\lambda}} \qquad V_{\min} = -\frac{\mu^4}{4\lambda}$$

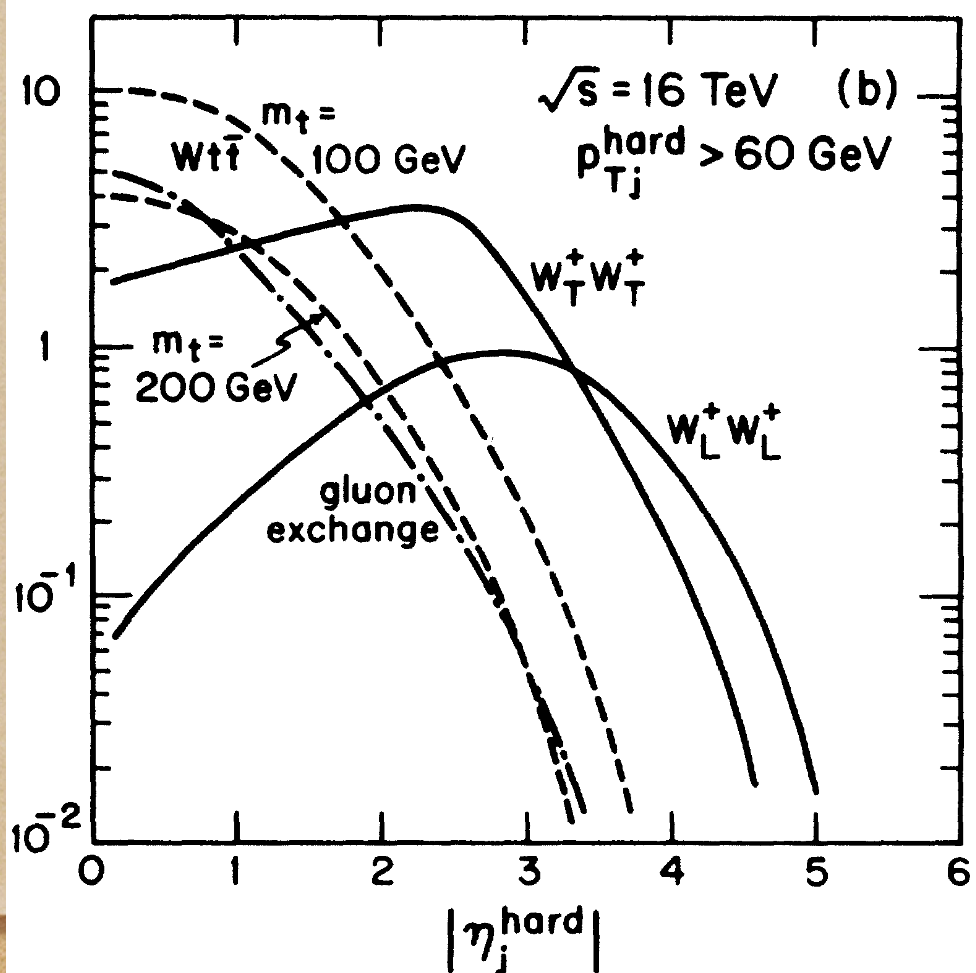
At the new minimum, V is lower. The vacuum shifts to <φ>.



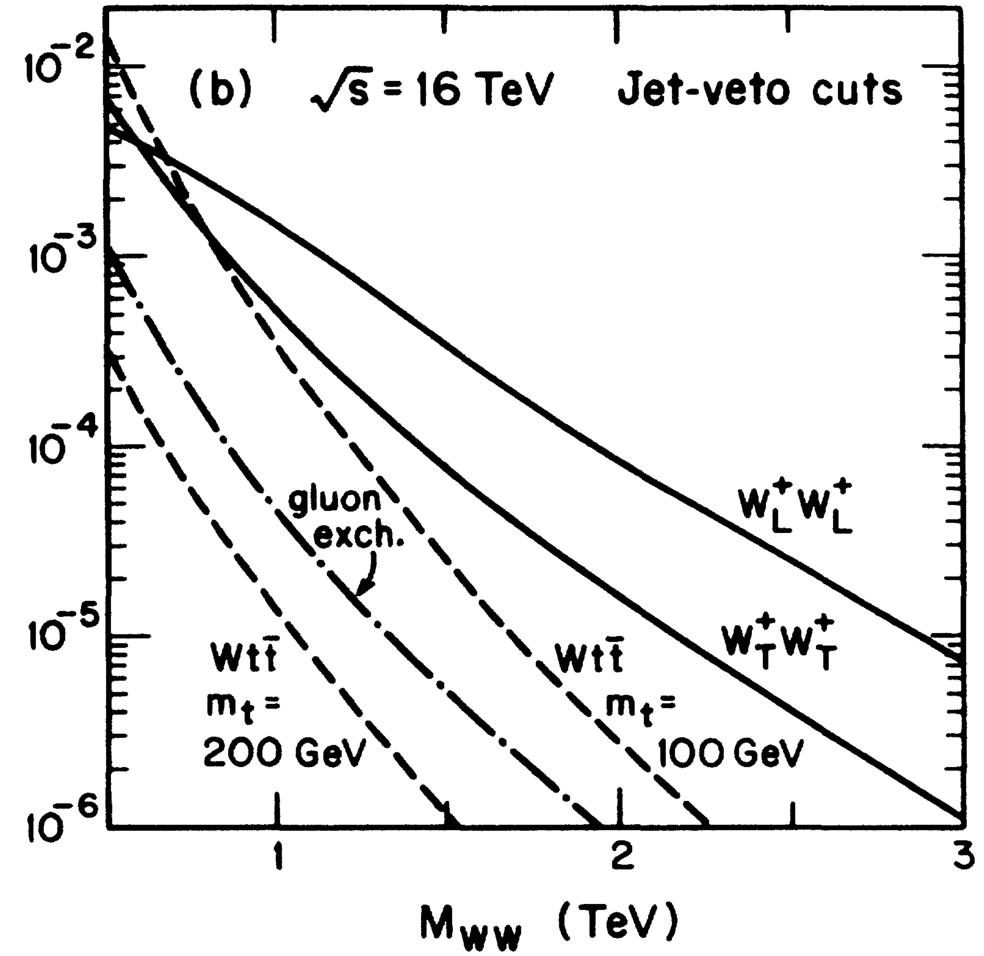
(a)
pp → W⁺W⁺ + 2 jets
√s = 40 TeV |y_W| < 1.5 M_WW > 0.5 TeV
W_T⁺W_T⁺ (SM)
m_H = 1 TeV
W_L⁺W_L⁺ (SM)
gluon exchange
3 jet QCD
Wtt̄
m_t =
100 GeV
200 GeV
dσ/dΔR_jj (fb)
ΔR_jj



(b)
pp → W⁺W⁺ + 2 jets
√s = 40 TeV |y_W| < 1.5 M_WW > 0.5 TeV
W_T⁺W_T⁺ (SM)
m_H = 1 TeV
W_L⁺W_L⁺ (SM)
gluon exchange
3 jet QCD
Wtt̄
m_t =
100 GeV
200 GeV
dσ/dm_jj (fb/GeV)
m_jj (TeV)



√s = 16 TeV (b)
p_Tj^hard > 60 GeV
Wtt̄
m_t =
100 GeV
m_t =
200 GeV
W_T⁺W_T⁺
W_L⁺W_L⁺
gluon exchange
|η_j^hard|



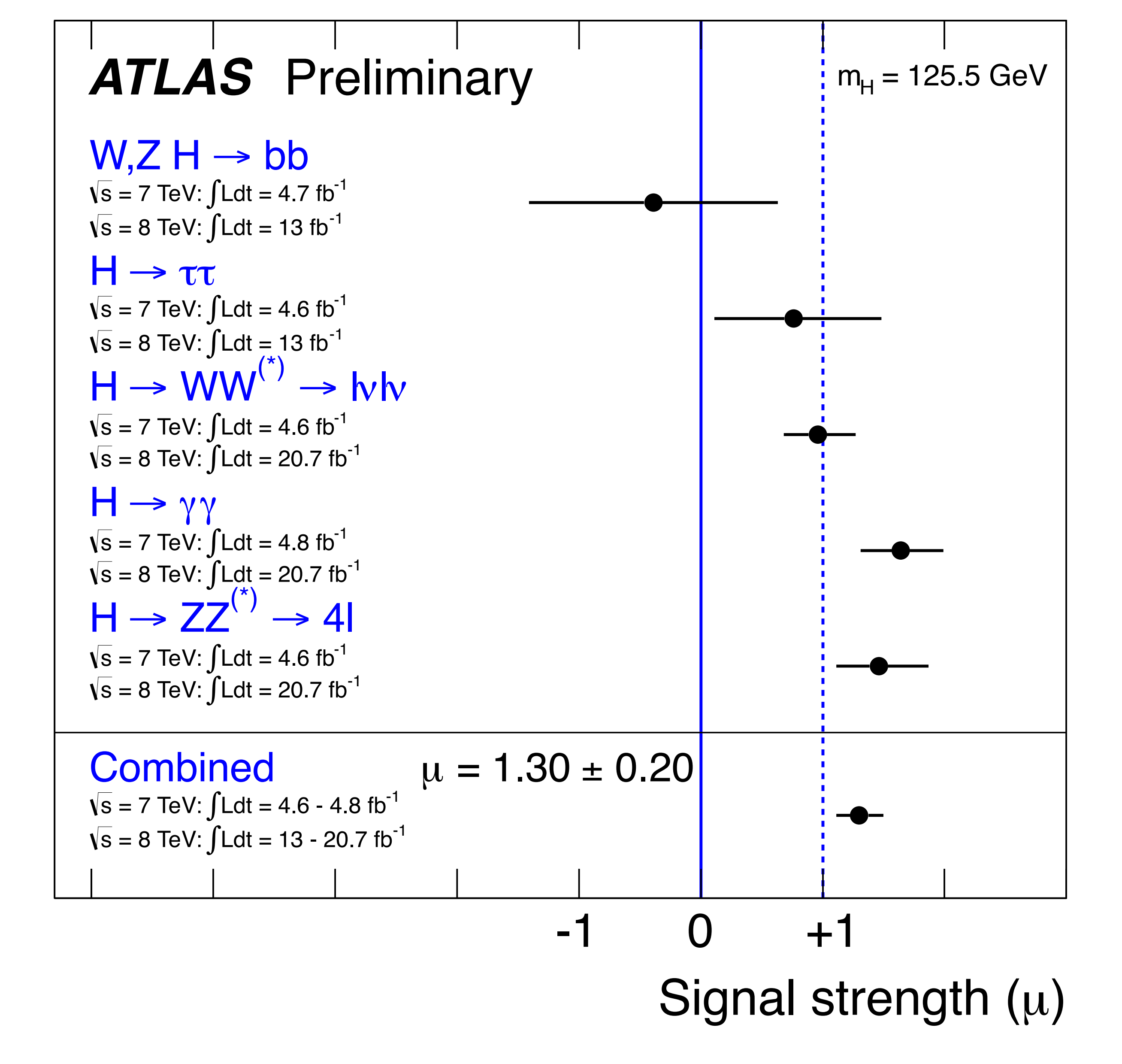
(b) √s = 16 TeV Jet-veto cuts
gluon exch.
W_L⁺W_L⁺
W_T⁺W_T⁺
Wtt̄
m_t =
200 GeV
Wtt̄
m_t =
100 GeV
M_WW (TeV)

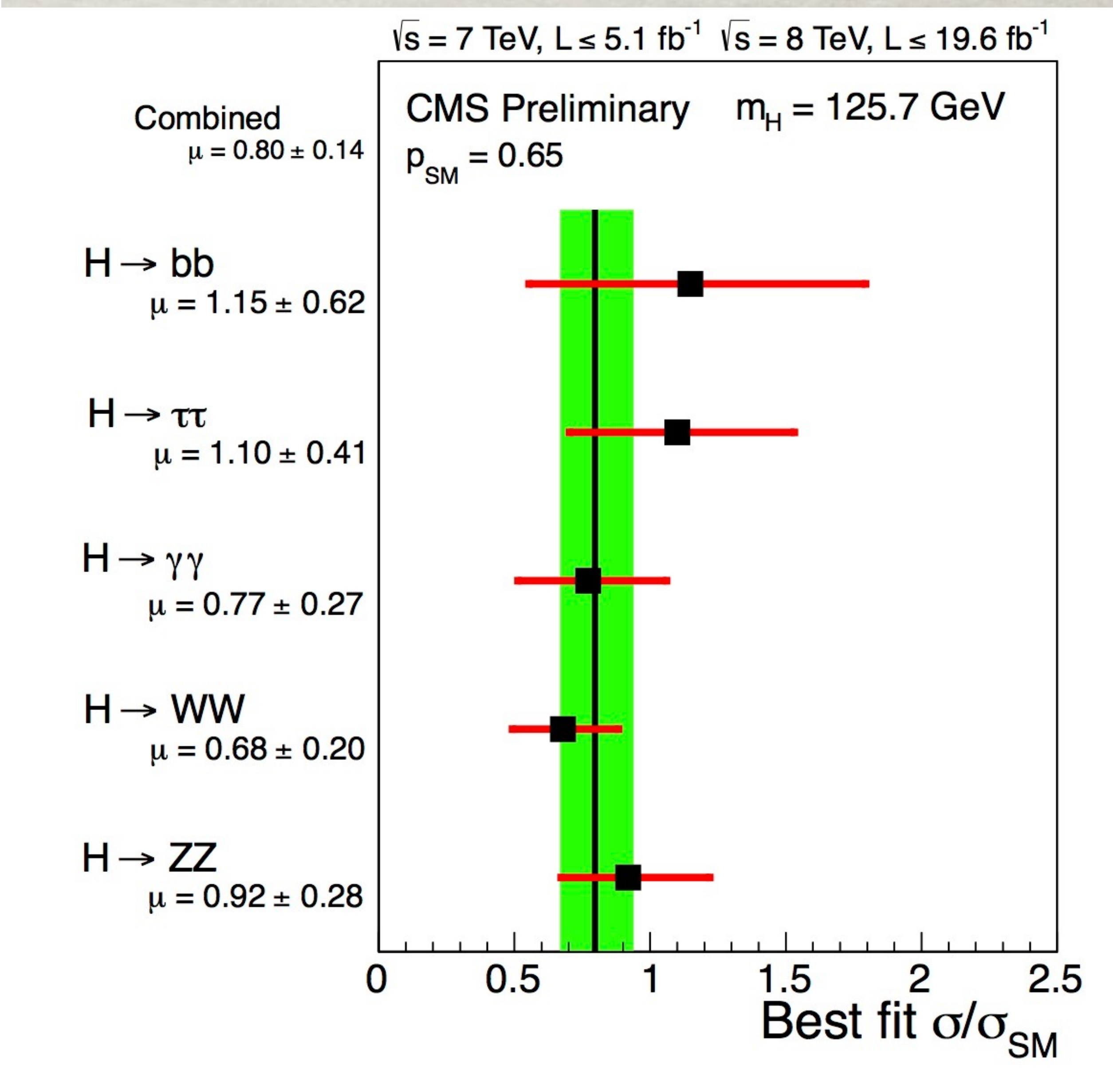
Developments

- Refinements in RGE running, spectrum predictions, Higgs boson mass calculations, …
- More SUSY breaking mediations: gravity, gauge-mediated, anomaly-mediated.
- Developments in connection with cosmology — dark matter, DM detections, …
- Searches for SUSY particles at LEP, Tevatron, HERA, …
- Many limits on SUSY particles, DM allowed regions, LHC predictions.

Full datasets for 7 + 8 TeV

The SM Higgs boson provides the best fit to both CMS and ATLAS datasets.

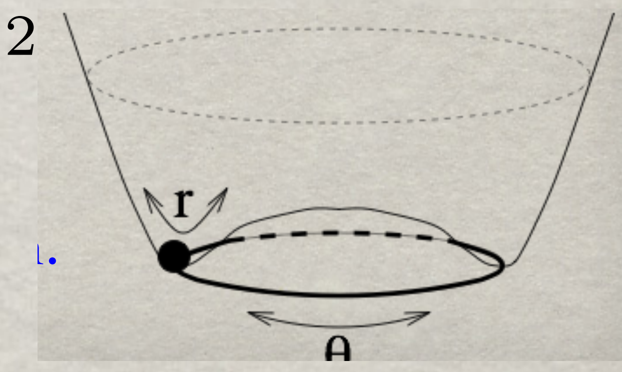




Where is the Goldstone Boson?

Weinberg's 3rd law of Progress in Theoretical Physics:
You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you'll be sorry!

$$\mathcal{L} = \partial_\mu \phi \partial^\mu \phi - \mu^2 \phi^* \phi - \lambda (\phi^* \phi)^2$$



Write

$$\phi = \frac{1}{\sqrt{2}} \left(r(x) + \langle r \rangle \right) e^{i2\alpha(x)}$$

Massless Goldstone boson

Field redefinition $\alpha(x) \to \alpha(x)/2\langle r \rangle$:

$$\mathcal{L} = \frac{1}{2}\partial_\mu r(x) \partial^\mu r(x) + \frac{1}{2}\left[1 + 2\frac{r}{\langle r \rangle} + \frac{r^2}{\langle r \rangle^2}\right] \partial_\mu \alpha(x) \partial^\mu \alpha(x)$$

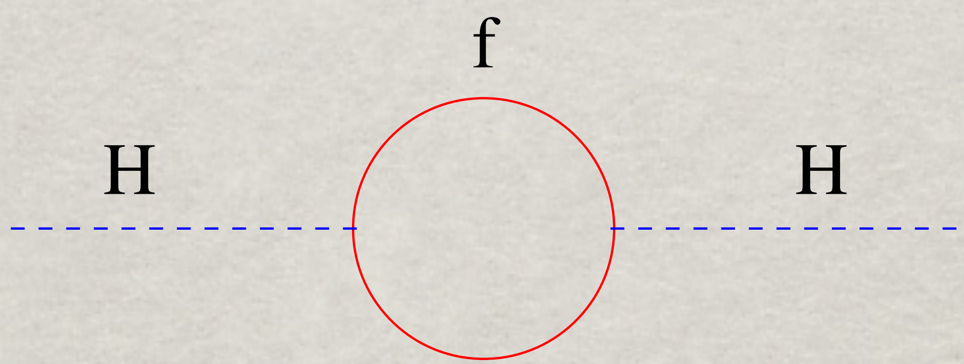
$$-\frac{\mu^2}{2}\left(r(x) + \langle r \rangle\right)^2 - \frac{\lambda}{4}\left(r(x) + \langle r \rangle\right)^4$$

derivative coupling only, decouples at low energy

r(x) is the massive radial excitation

Mass Protection

- Fermion mass protected by chiral symmetry.
- Gauge boson mass protected by gauge symmetry.
- Scalar boson mass?

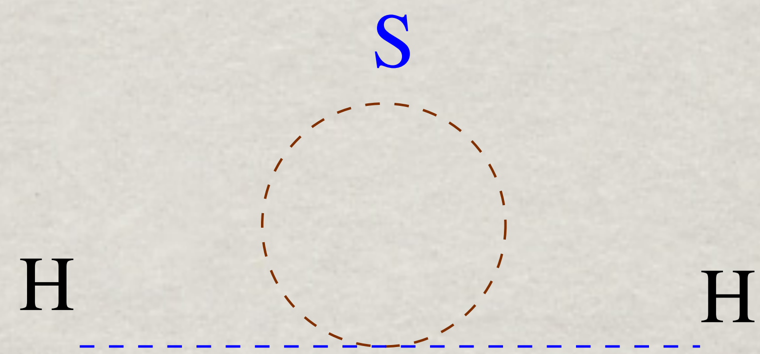


$$\Delta M_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln\left(\frac{\Lambda_{UV}}{m_f}\right) + ...\right]$$

Two choices:

1. Make Λ_{UV} not too large, where some new physics appears.
2. Find some cancellation mechanism to remove Λ_{UV}^2 divergence

Suppose there exists a new scalar



$$\Delta M_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_S^2 \ln\left(\frac{\Lambda_{UV}}{m_S}\right) + \ldots\right]$$

The leading term in Λ_{UV} will cancel if

$\lambda_S = |\lambda_f|^2$ and if there are 2 such scalars

Such systematic cancellation requires a new symmetry

$\Rightarrow$ Supersymmetry.

$$Q|\text{boson}\rangle = |\text{fermion}\rangle \quad Q|\text{fermion}\rangle = |\text{boson}\rangle$$

Cancellation OK if SUSY partner mass splitting $\sim M_W$