The beauty and the beast of the Higgs boson

Higgs and Di-Higgs measures from a Flavour Tagging perspective

Lorenzo Santi

l.santi@cern.ch

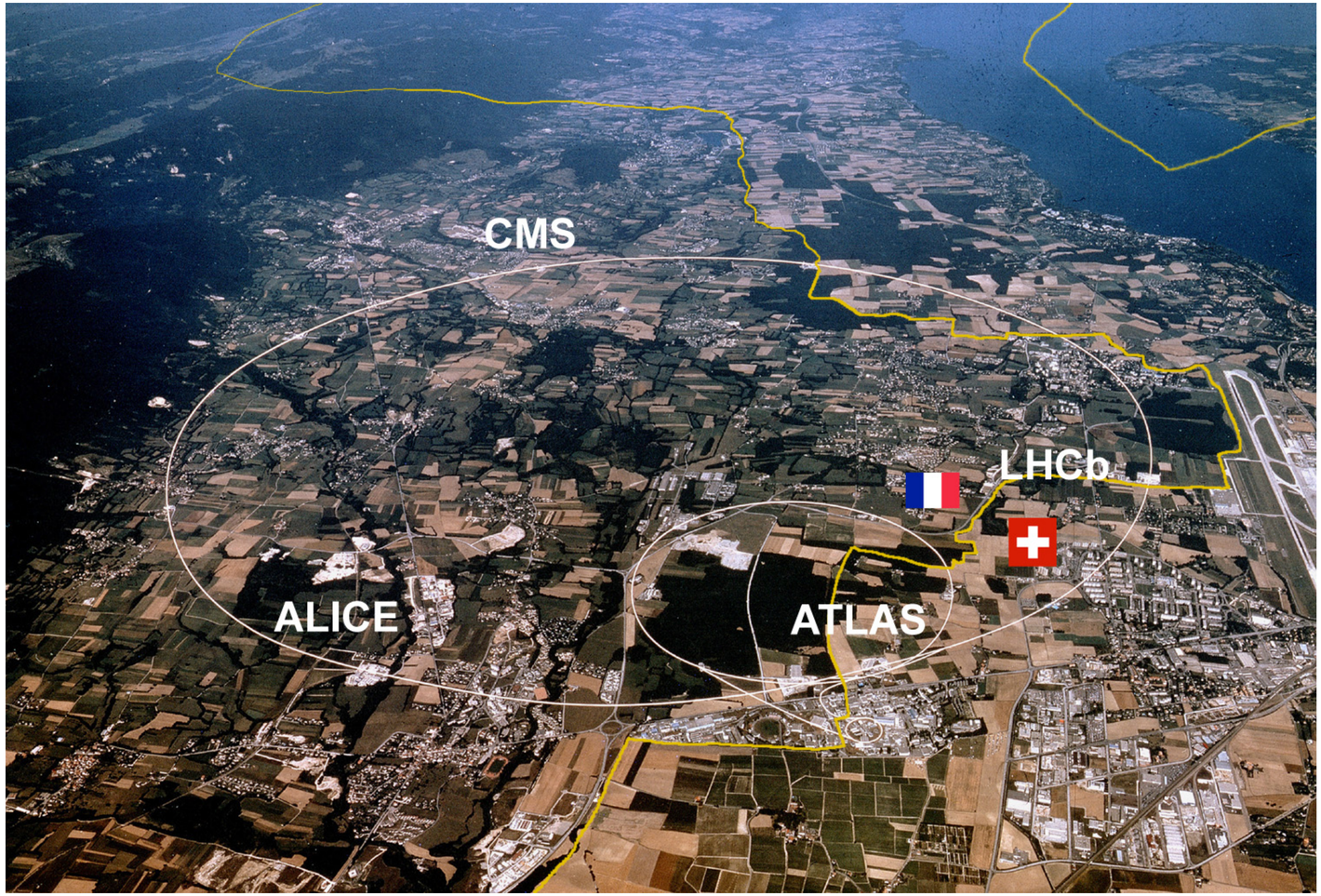
IJCLab Seminar

21/02/2026

Paris-Seclay

The ATLAS Experiment at LHC

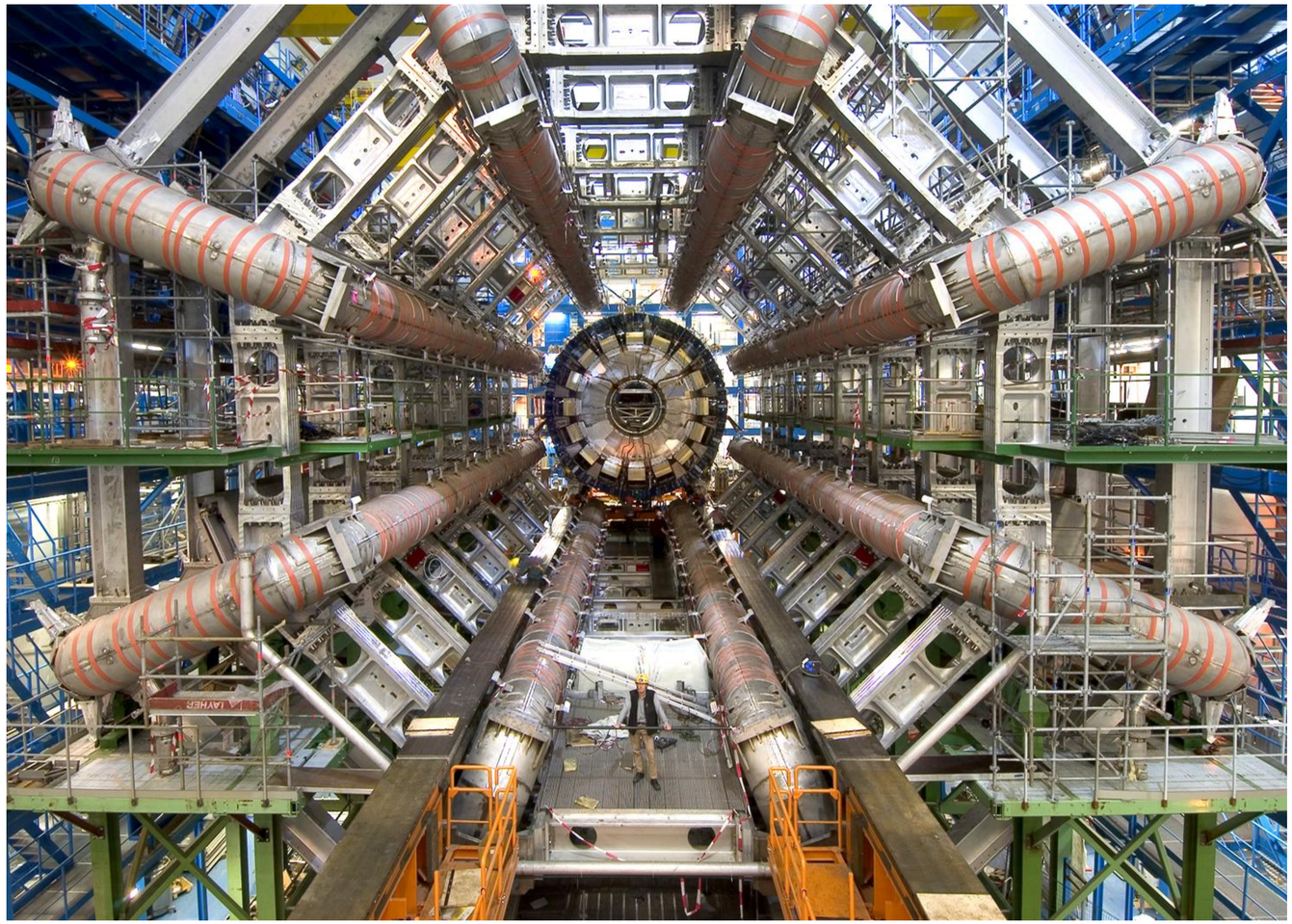
The **Large Hadron Collider** (LHC) is the largest *proton-proton* collider in the world with a 27km circumference placed ~100m underground **at CERN** near the Geneva Area.



The ATLAS Experiment at LHC

The **Large Hadron Collider** (LHC) is the largest *proton-proton* collider in the world with a 27km circumference placed ~100m underground **at CERN** near the Geneva Area.

ATLAS is ***the biggest*** of the four main experiments on the ring.
It is a **multi-purpose** experiment able to detect the final state **particles** produced from the collisions.



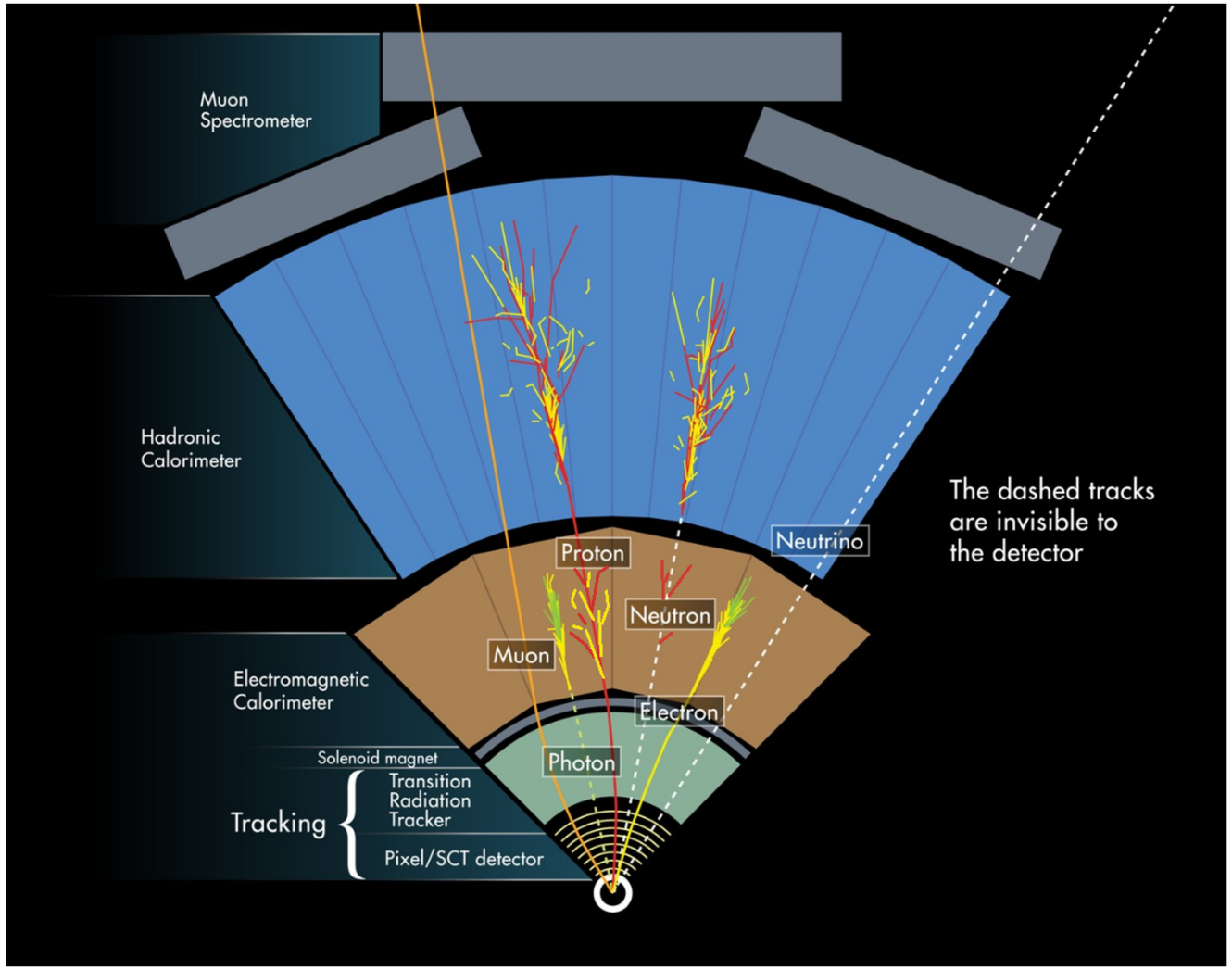
The ATLAS Experiment at LHC

The **Large Hadron Collider** (LHC) is the largest *proton-proton* collider in the world with a 27km circumference placed ~100m underground **at CERN** near the Geneva Area.

ATLAS is ***the biggest*** of the four main experiments on the ring.
It is a **multi-purpose** experiment able to detect the final state **particles** produced from the collisions.

It combines the information of several sub-detectors each designed to reveal a different kind of particles:

- **Inner Tracker**: charged particles
- **Electromagnetic Calorimeter**: photons and electrons
- **Hadronic Calorimeter**: neutral and charged hadrons
- **Muon Spectrometer**: muons



The ATLAS Experiment at LHC

The **Large Hadron Collider** (LHC) is the largest *proton-proton* collider in the world with a 27km circumference placed ~100m underground **at CERN** near the Geneva Area.

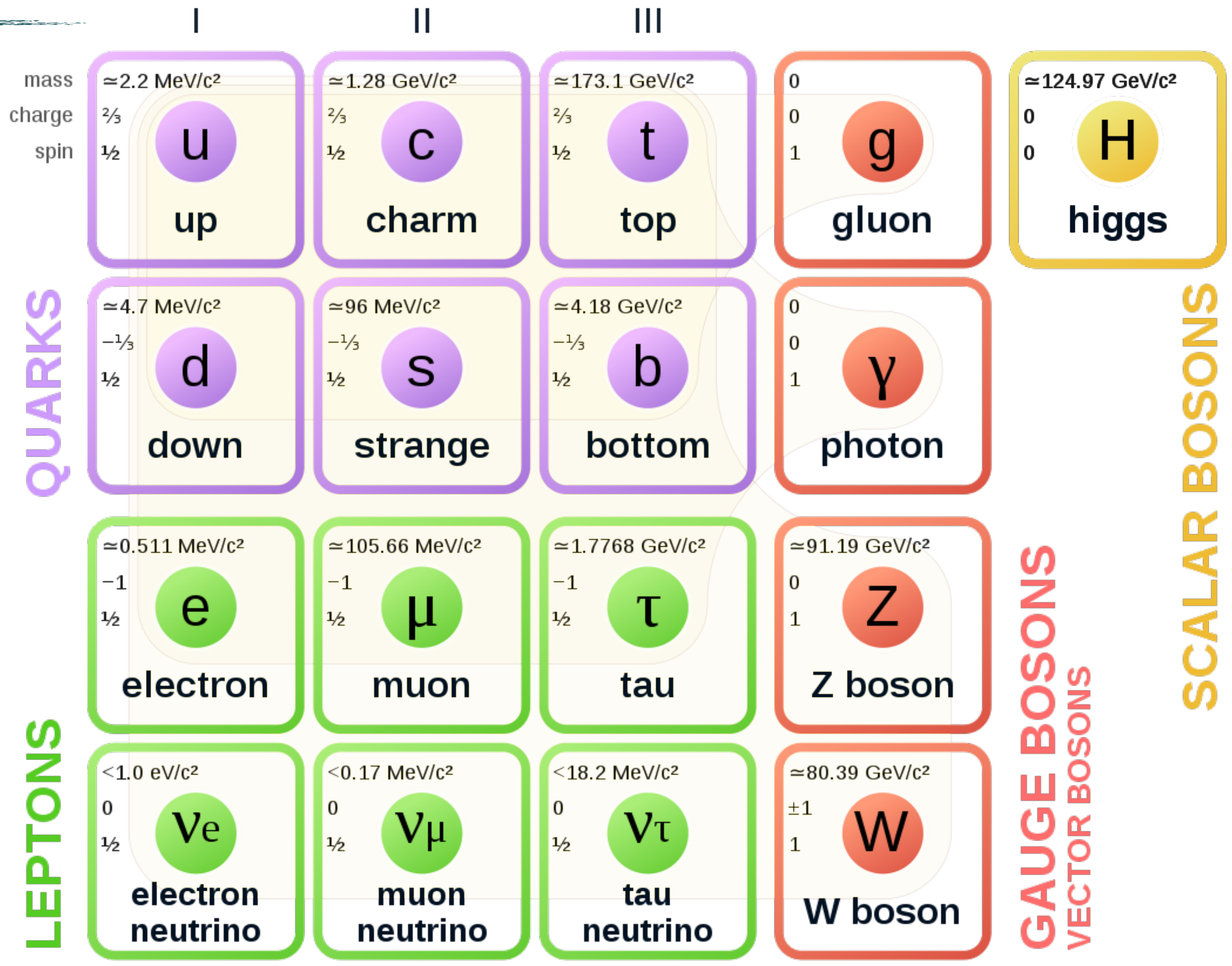
ATLAS is ***the biggest*** of the four main experiments on the ring.
It is a **multi-purpose** experiment able to detect the final state **particles** produced from the collisions.

It combines the information of several sub-detectors each designed to reveal a different kind of particles:

- **Inner Tracker**: charged particles
- **Electromagnetic Calorimeter**: photons and electrons
- **Hadronic Calorimeter**: neutral and charged hadrons
- **Muon Spectrometer**: muons

The Standard Model

Standard Model Elementary Particles



Why the Higgs Boson?

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

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

Why the Higgs Boson?

- In the Standard Model Lagrangian, mass terms for the $SU(2)_L \otimes U(1)_Y$ **gauge bosons** and **fermions** are **<u>not gauge invariant</u>**

$$\cancel{\frac{1}{2}m^2 A_\mu A^\mu}$$

$$\cancel{\frac{1}{2}m\bar{\psi}_L\psi_R} + h.c.$$

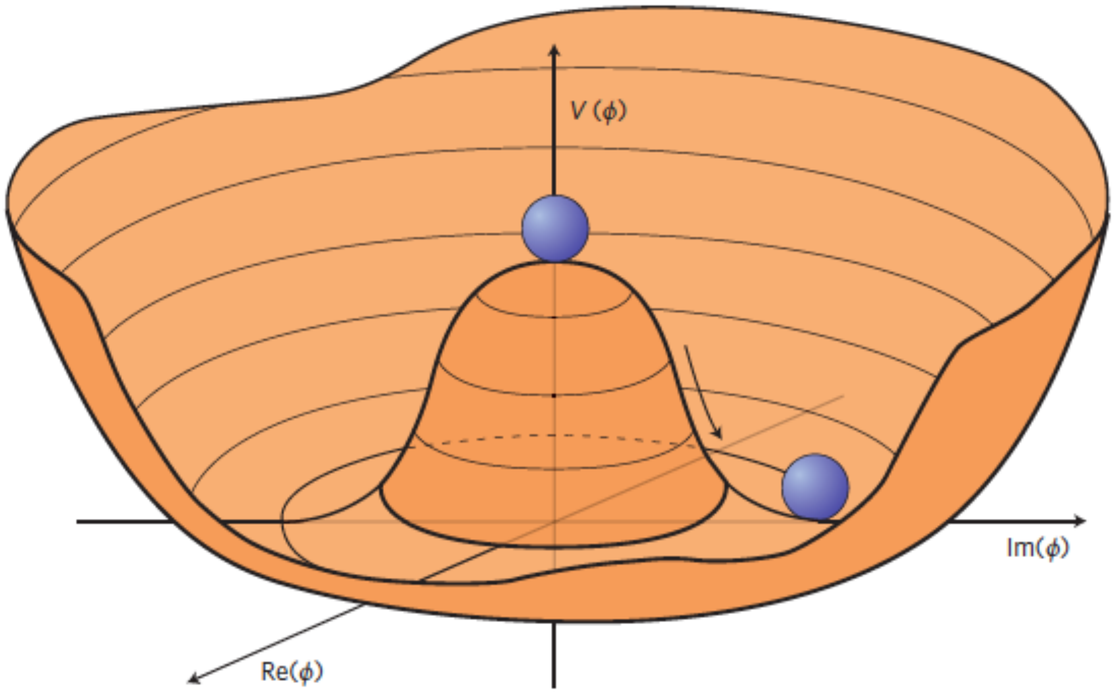
Broken gauge invariance has bad consequences on the SM:

- ultraviolet divergences in perturbation theory (non-renormalizable)
- unitarity violation in scattering amplitudes involving massive gauge bosons
- breaks Ward identity that makes the calculations finite order by order

Why the Higgs Boson?

[1] *a posteriori*

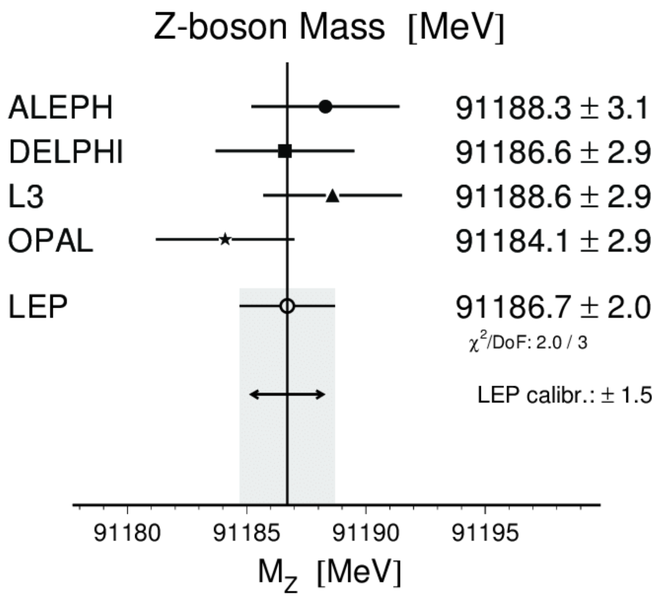
- In the Standard Model Lagrangian, mass terms for the $SU(2)_L \otimes U(1)_Y$ **gauge bosons** and **fermions** are **<u>not gauge invariant</u>**
- The Higgs mechanism is the **simplest**[1] **solution**: a complex scalar doublet acquires a non-zero vacuum expectation value (v), spontaneously breaking $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$

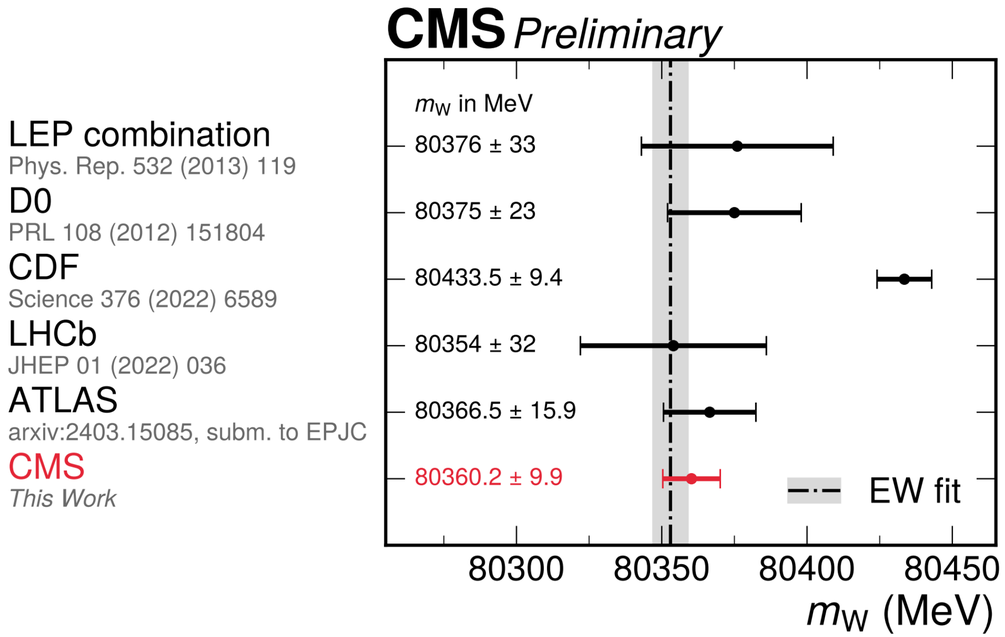


$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \xrightarrow{\text{SSB}} \langle \Phi \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v = 246 \text{ GeV}$$

Why the Higgs Boson?

- In the Standard Model Lagrangian, mass terms for the $SU(2)_L \otimes U(1)_Y$ **gauge bosons** and **fermions** are **<u>not gauge invariant</u>**
- The Higgs mechanism is the **simplest solution**: a complex scalar doublet acquires a non-zero vacuum expectation value (v), spontaneously breaking $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$
- Of the doublet's 4 real degrees of freedom, **3 are "eaten"** as the longitudinal polarizations of $W^{\pm}$, Z and the γ stays massless





A lesson (not) learned

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)

CERN -- Geneva

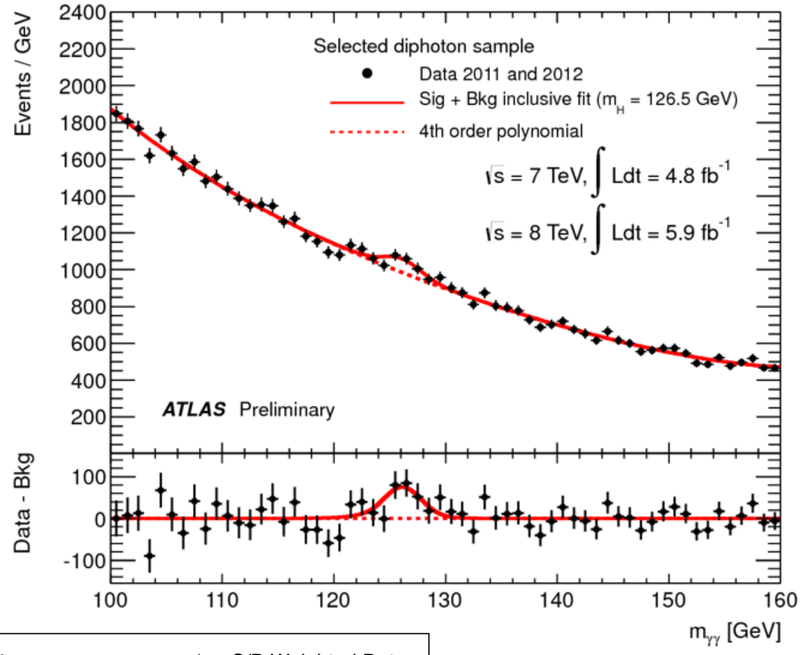
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

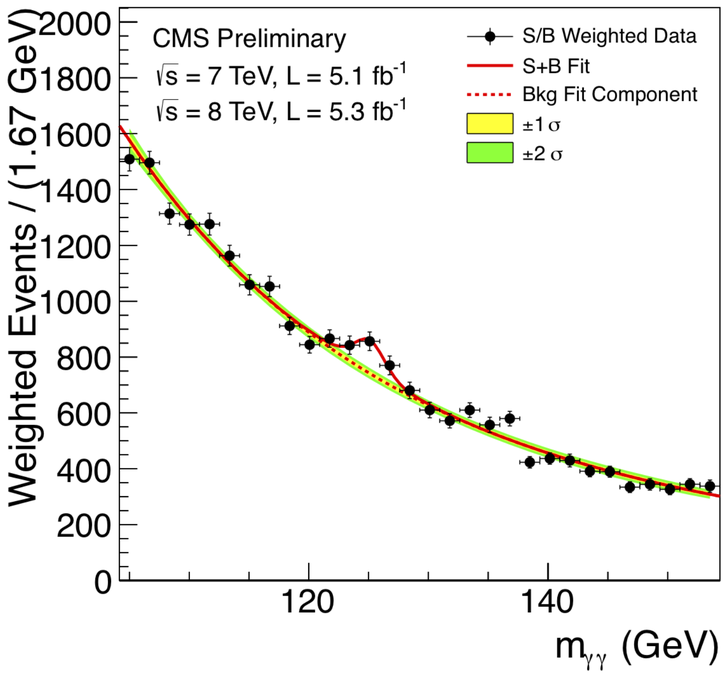
Ref.TH.2093-CERN

30 October 1975

Why the Higgs Boson?

- In the Standard Model Lagrangian, mass terms for the $SU(2)_L \otimes U(1)_Y$ **gauge bosons** and **fermions** are **<u>not gauge invariant</u>**
- The Higgs mechanism is the **simplest solution**: a complex scalar doublet acquires a non-zero vacuum expectation value (v), spontaneously breaking $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$
- Of the doublet's 4 real degrees of freedom, **3 are "eaten"** as the longitudinal polarizations of $W^{\pm}$, Z and the γ stays massless
- The **4th degree of freedom** survives as a physical particle: the **Higgs boson**





Why the Higgs Boson?

The **Higgs Mechanism** was incorporated in the SM by **Weinberg.**

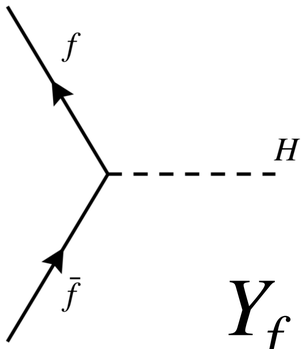
- **As for the gauge bosons** the leptons and quarks **acquire mass** dynamically

Why the Higgs Boson?

The **Higgs Mechanism** was incorporated in the SM by **Weinberg.**

- **As for the gauge bosons** the leptons and quarks **acquire mass** dynamically
- The Higgs is coupled to fermions with an ad hoc gauge invariant **Yukawa term** in the Lagrangian.

$$\mathscr{L}_Y = Y[\bar{\psi}_L \phi \psi_R + h.c.]$$



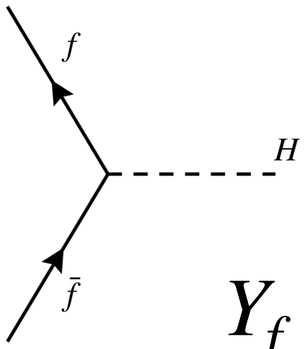
$$Y_f \propto m_f$$

Why the Higgs Boson?

The **Higgs Mechanism** was incorporated in the SM by **Weinberg.**

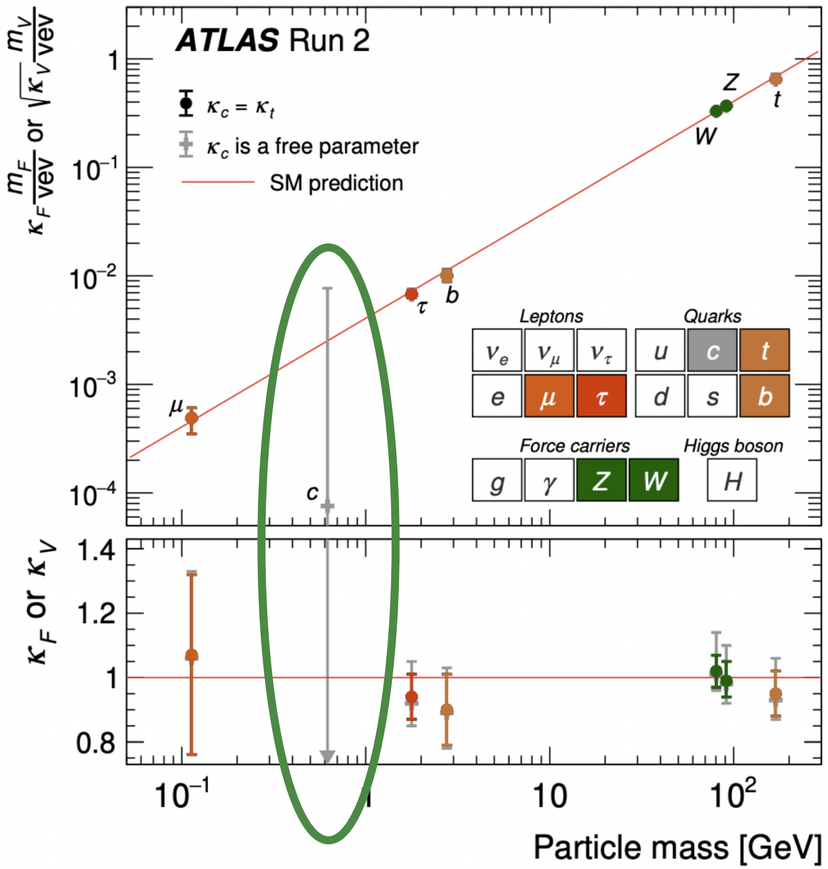
- **As for the gauge bosons** the leptons and quarks **acquire mass** dynamically
- The Higgs is coupled to fermions with an ad hoc gauge invariant **Yukawa term** in the Lagrangian.

$$\mathscr{L}_Y = Y[\bar{\psi}_L \phi \psi_R + h.c.]$$



$$Y_f \propto m_f$$

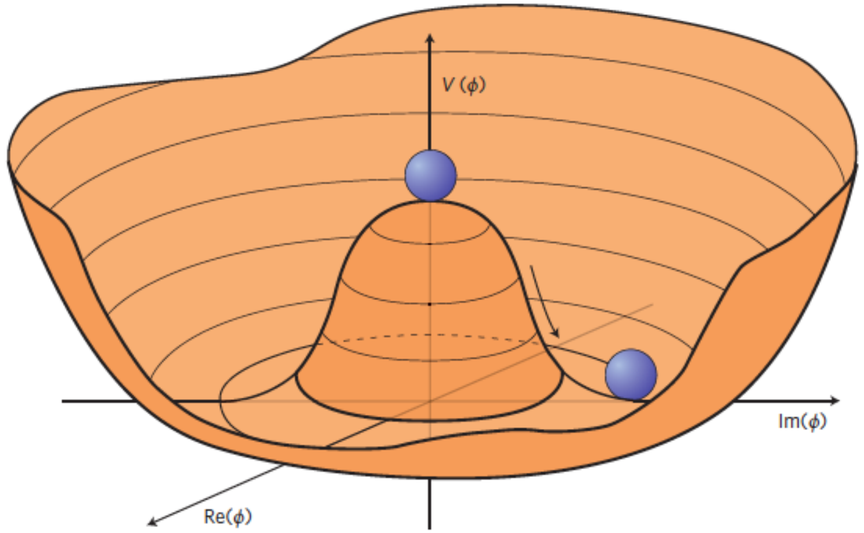
The **coupling** of **fermions** with the Higgs boson, also called **Yukawa coupling** (Y_f), and is proportional to the fermion mass m_f.



Why the Higgs Boson?

"The 4th degree of freedom survives as a physical particle: the Higgs boson"

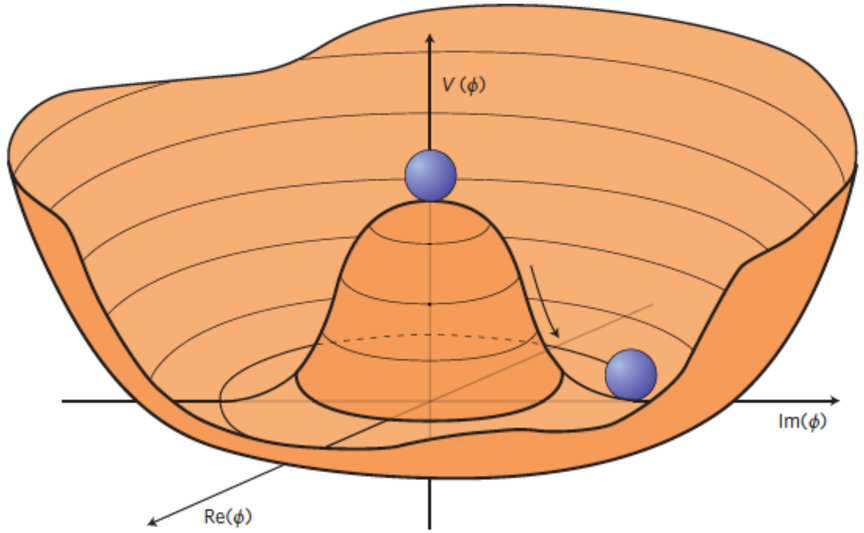
- For the Renormalizability only terms up to dimension 4 in H are allowed:
  $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$



Why the Higgs Boson?

"The 4th degree of freedom survives as a physical particle: the Higgs boson"

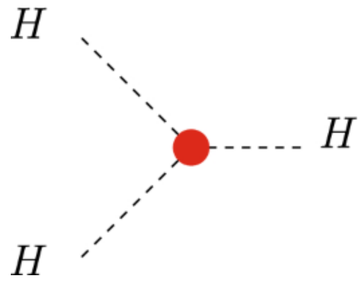
- For the Renormalizability only terms up to dimension 4 in H are allowed:
  $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$
- Expanding around the v.e.v. $\phi \to H(x) + v$ we obtain an **Higgs mass term** $m_H^2 = 2\lambda v^2$
  - depending on λ the **Higgs mass was non-predicted** by the SM

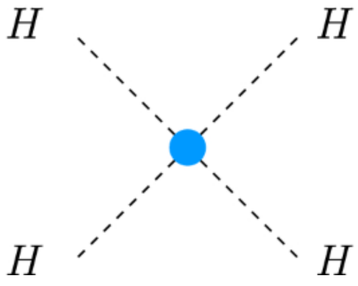


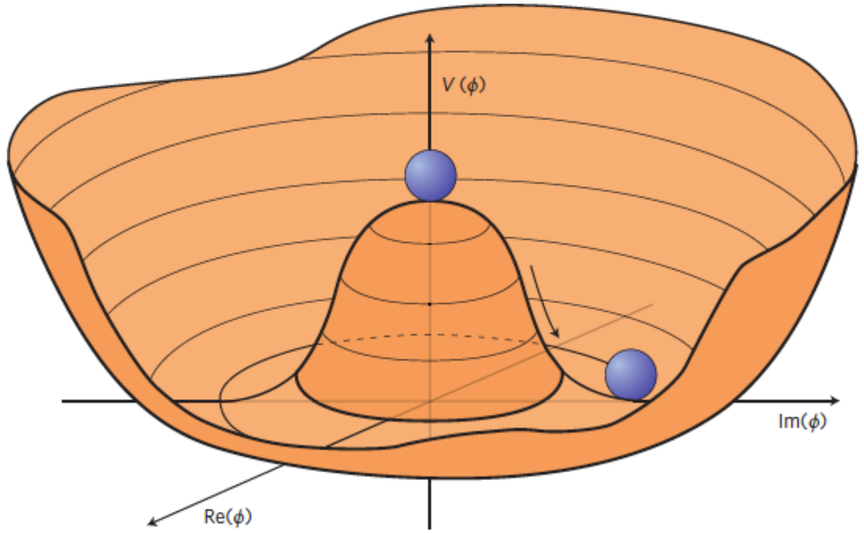
Why the Higgs Boson?

"The 4th degree of freedom survives as a physical particle: the Higgs boson"

- For the Renormalizability only terms up to dimension 4 in H are allowed:
  $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$
- Expanding around the v.e.v. $\phi \to H(x) + v$ we obtain an **Higgs mass term** $m_H^2 = 2\lambda v^2$
  - depending on λ the **Higgs mass was non-predicted** by the SM
- The expansion also generates **self-interaction terms** H^3, H^4



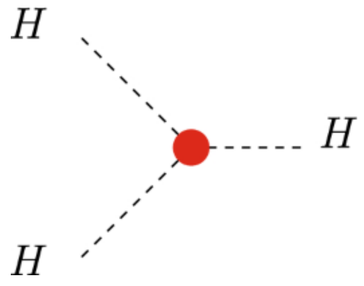


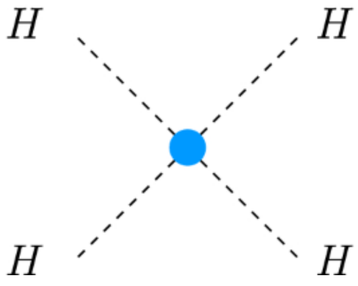


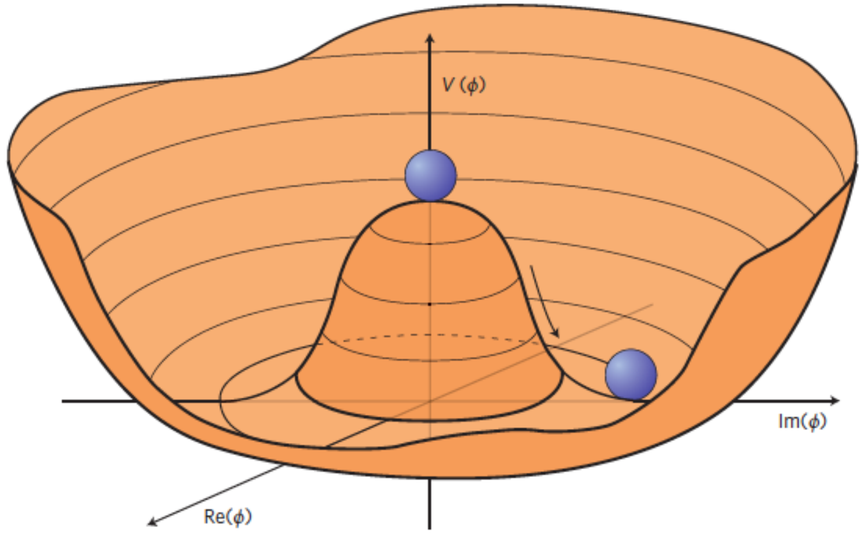
Why the Higgs Boson?

"The 4th degree of freedom survives as a physical particle: the Higgs boson"

- For the Renormalizability only terms up to dimension 4 in H are allowed:
  $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$
- Expanding around the v.e.v. $\phi \to H(x) + v$ we obtain an **Higgs mass term** $m_H^2 = 2\lambda v^2$
  - depending on λ the **Higgs mass was non-predicted** by the SM
- The expansion also generates **self-interaction terms** H^3, H^4





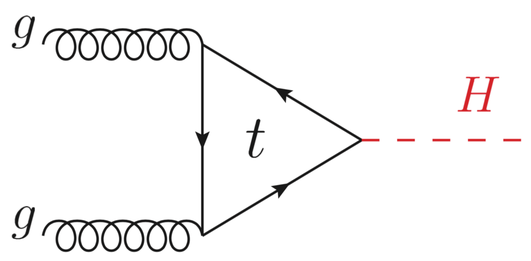


- Direct measurements of self coupling (otherwise inferred from m_H assuming the SM) is the only way to probe if the potential shape $V(\phi)$ may hidden any new-physics

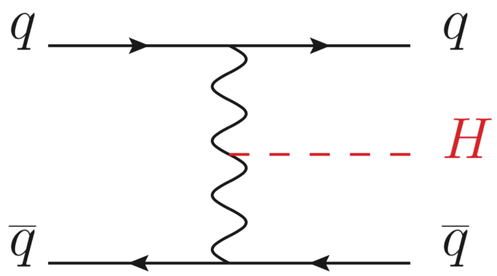
The Higgs production

The **Higgs boson** can be **produced** at LHC in **different modes** with different probabilities denominated **cross-sections** (σ).

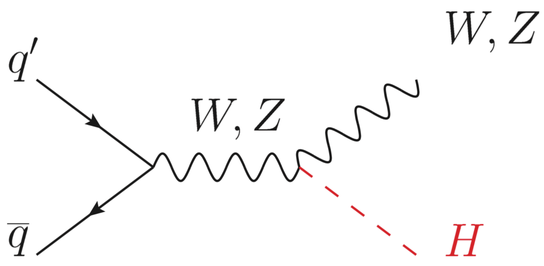
Due to non-Higgs processes generating similar final states (**backgrounds**) the most probable production is not automatically the most sensitive channel



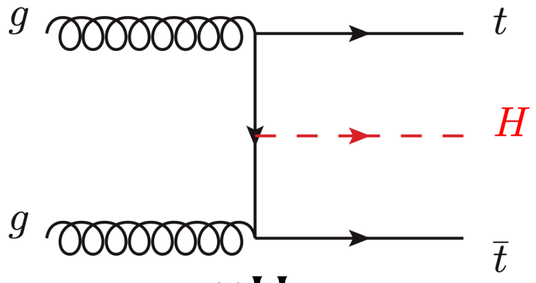
ggF H



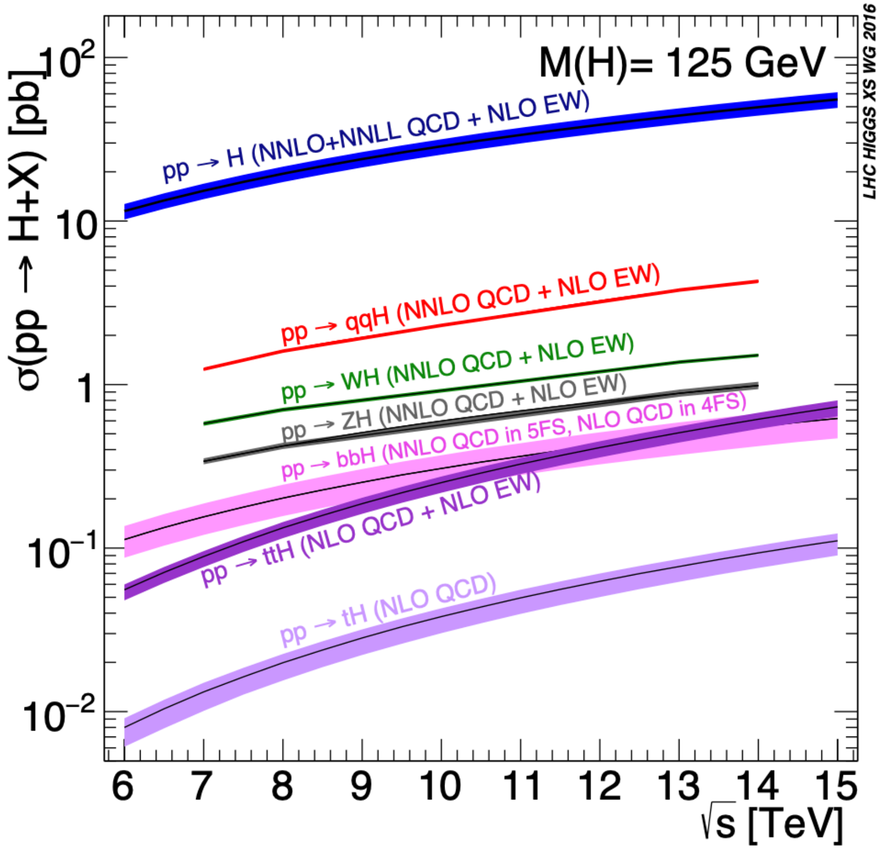
VBF H



VH

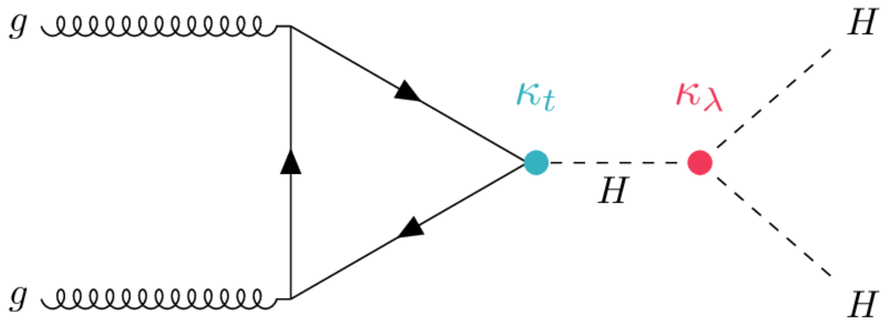


ttH

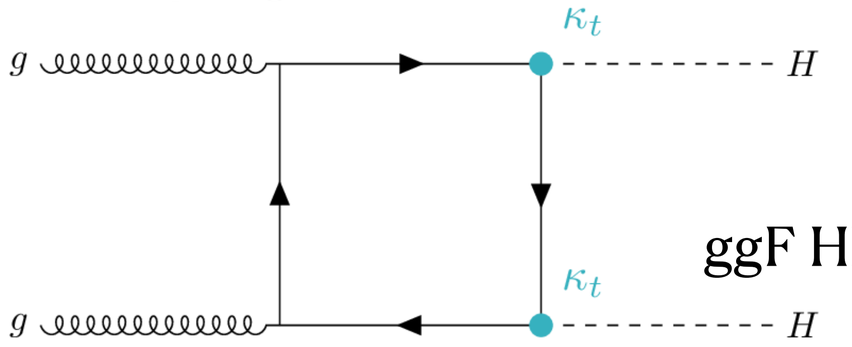


The Di-Higgs production

The **Di-Higgs** production is a way to probe the Higgs self-coupling

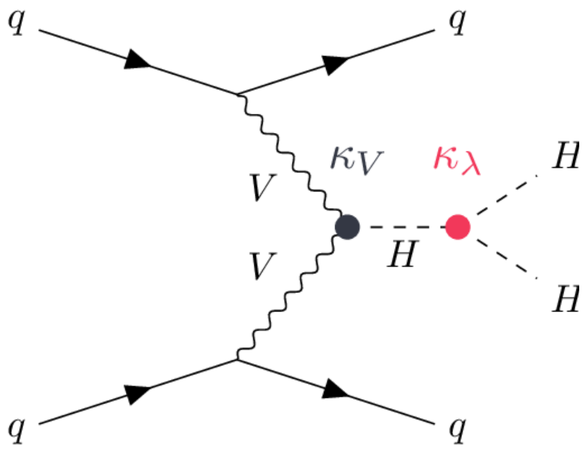


ggF HH triangle

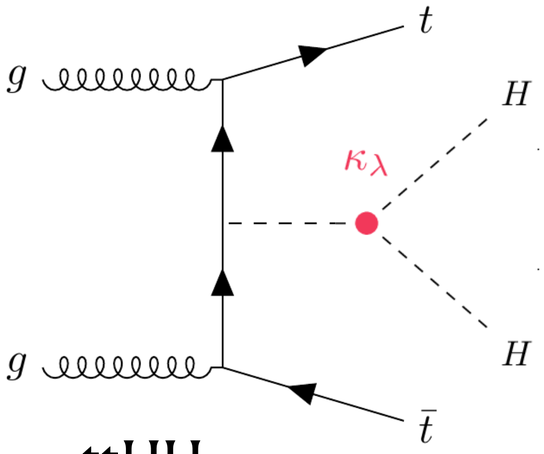


ggF HH box

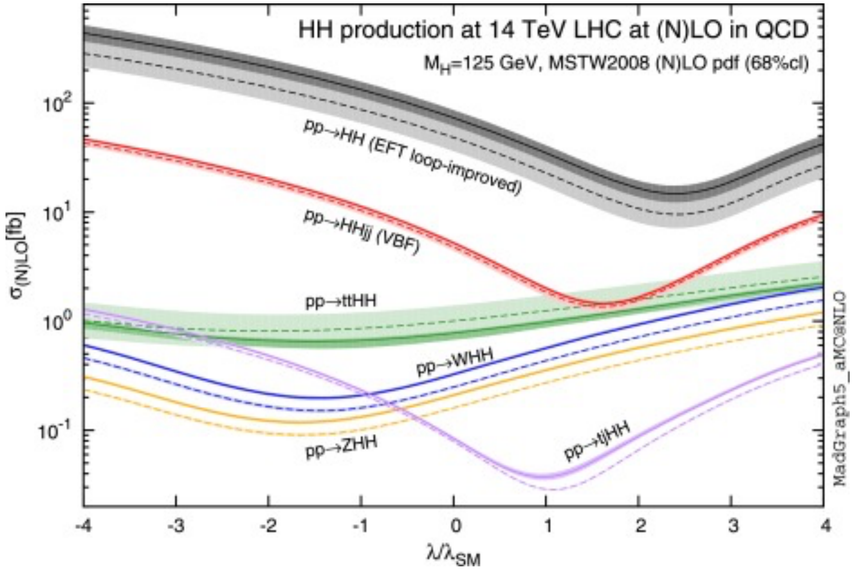
This diagram would exist independently from self coupling!



VBF HH



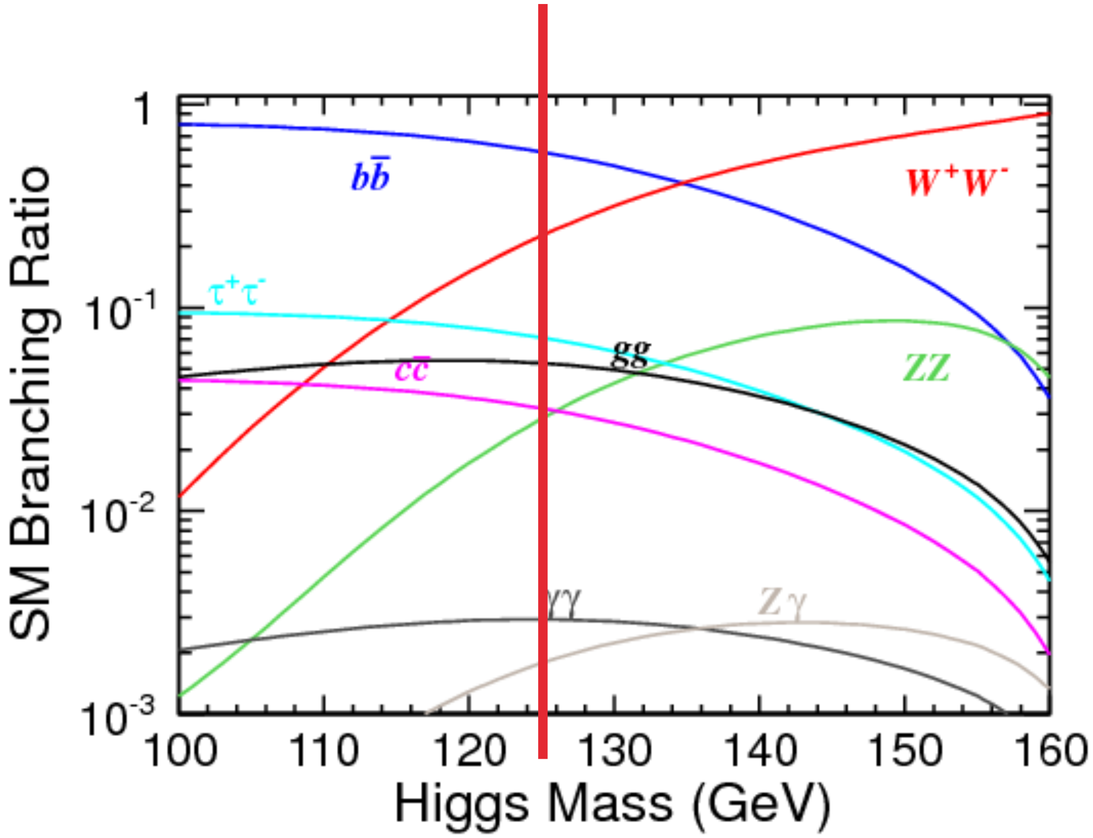
ttHH



Maximum interference at $k_\lambda = 2.4$

The Higgs decay

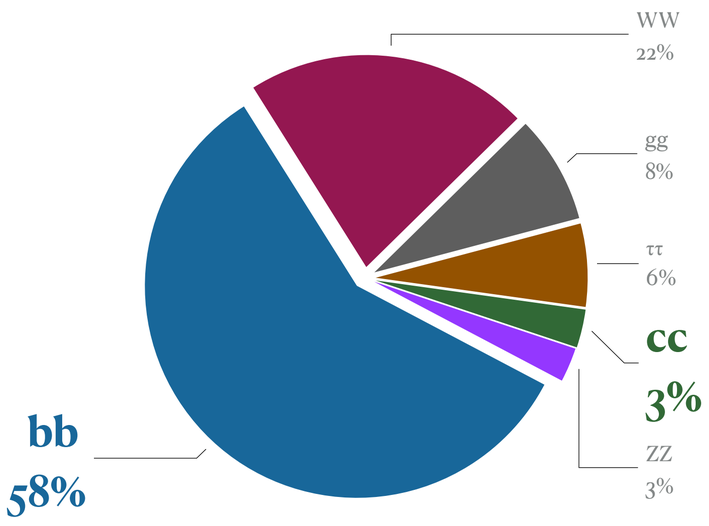
Since the Higgs **coupling** to gauge bosons and fermions is **proportional to mass**, the decay pattern directly reflects the mass spectrum of the SM.



The Higgs decay

Since the Higgs **coupling** to gauge bosons and fermions is **proportional to mass**, the decay pattern directly reflects the mass spectrum of the SM.

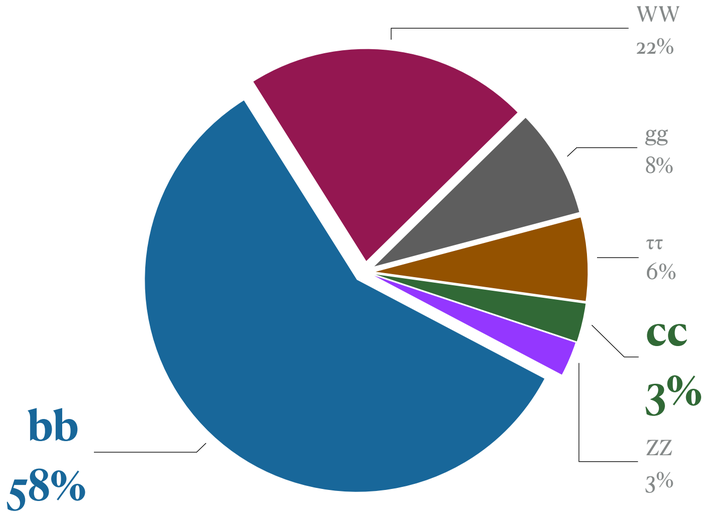
With the $m_H = 125$ GeV $< 2m_t = 346$ GeV, the $H \to t\bar{t}$ **channel is kinematically forbidden**, so among the accessible fermions, the heaviest (b-quark) dominates: $BR(H \to b\bar{b}) \sim 58\,\%$



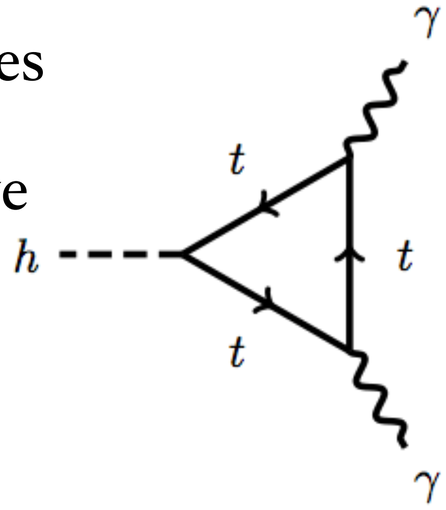
The Higgs decay

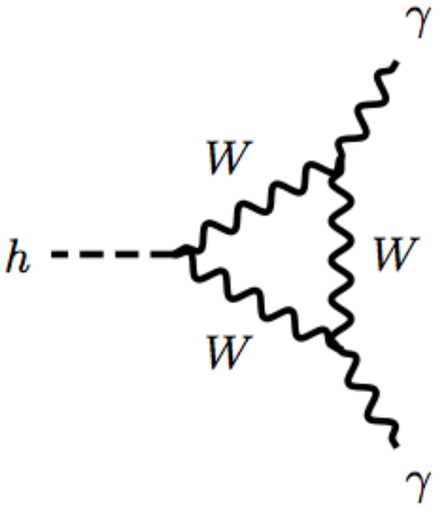
Since the Higgs **coupling** to gauge bosons and fermions is **proportional to mass**, the decay pattern directly reflects the mass spectrum of the SM.

With the $m_H = 125$ GeV $< 2m_t = 346$ GeV, the $H \to t\bar{t}$ **channel is kinematically forbidden**, so among the accessible fermions, the heaviest (b-quark) dominates: $BR(H \to b\bar{b}) \sim 58\,\%$



The Higgs has **no direct coupling** to **massless** particles (photons, gluons), since there's no mass to generate a coupling. They only proceed **through loops** of massive particles

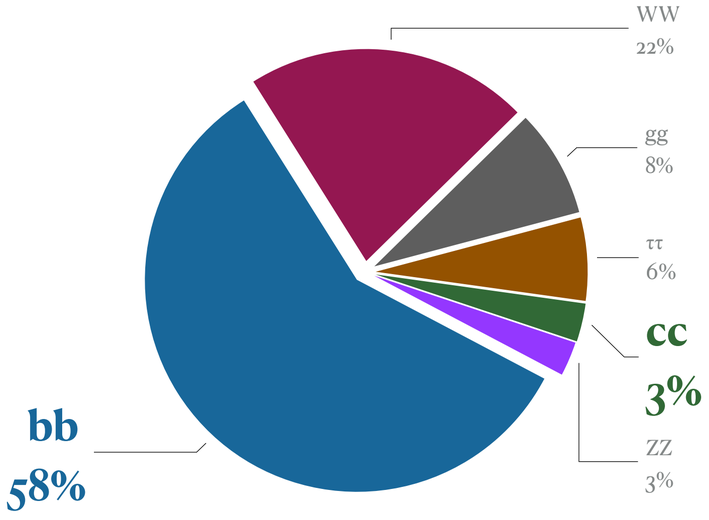




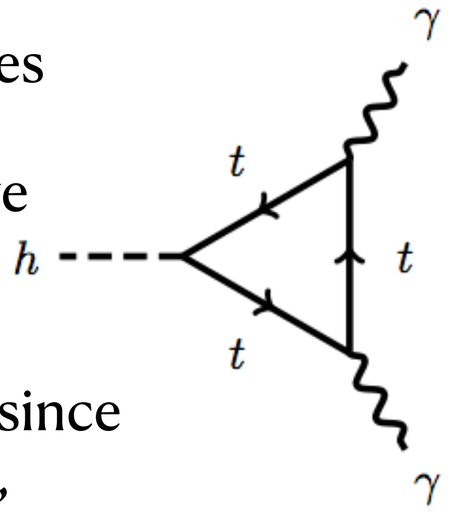
The Higgs decay

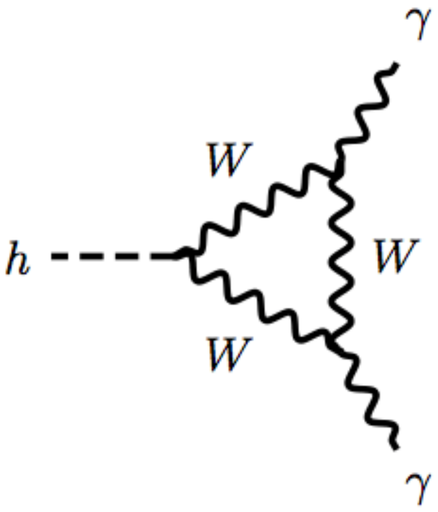
Since the Higgs **coupling** to gauge bosons and fermions is **proportional to mass**, the decay pattern directly reflects the mass spectrum of the SM.

With the $m_H = 125$ GeV $< 2m_t = 346$ GeV, the $H \to t\bar{t}$ **channel is kinematically forbidden**, so among the accessible fermions, the heaviest (b-quark) dominates: $BR(H \to b\bar{b}) \sim 58\,\%$



The Higgs has **no direct coupling** to **massless** particles (photons, gluons), since there's no mass to generate a coupling. They only proceed **through loops** of massive particles



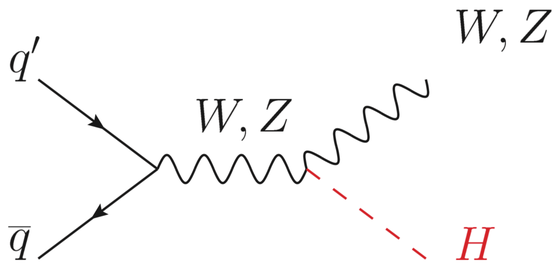


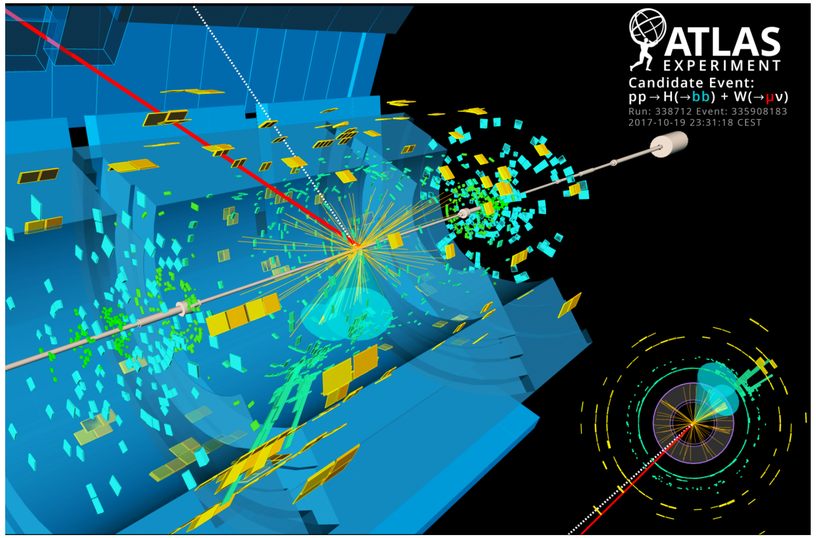
Despite the small BR (0.2%) the $H \to \gamma\gamma$ is a "*golden channel... one of the 2 discovery channels*" experimentally, since the **diphoton invariant mass resolution is excellent**, making it one of the two discovery channels in 2012

Higgs Boson analyses in Today's talk

Single Higgs:

$VH(b\bar{b}\,|\,c\bar{c}),\ V \to lep\,.$



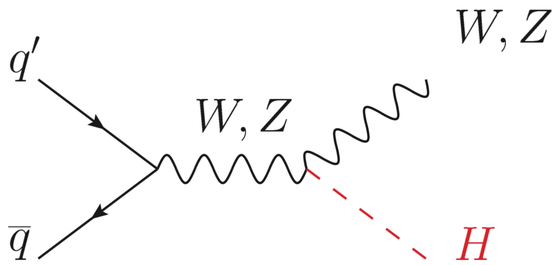


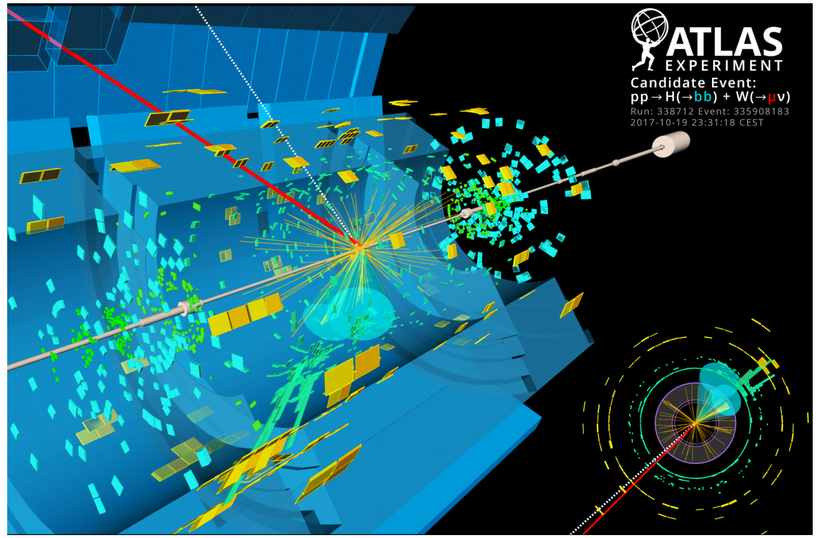
Run 2

Higgs Boson analyses in Today's talk

Single Higgs:

$VH(b\bar{b}\,|\,c\bar{c}),\ V \to lep\,.$

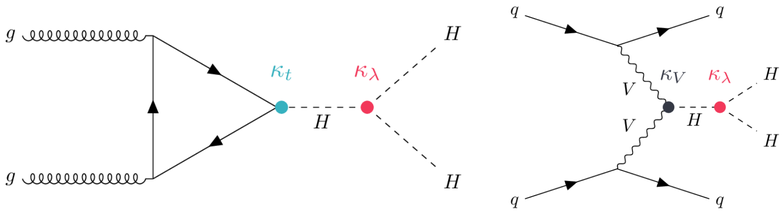


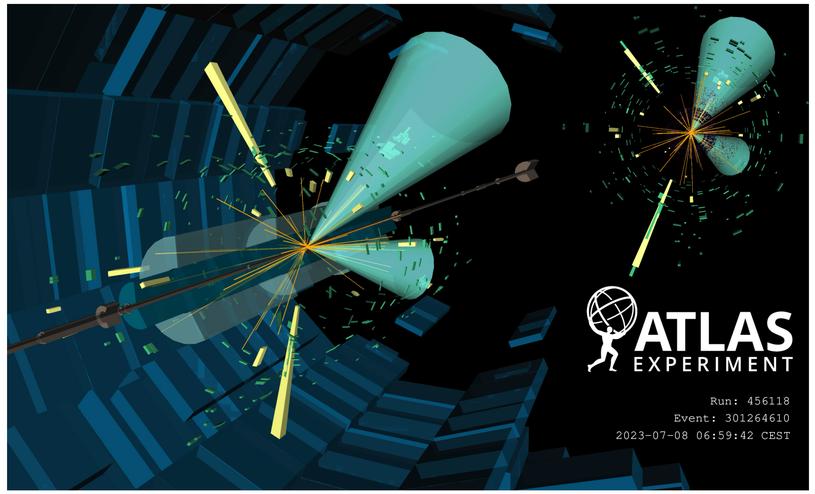


Run 2

Di Higgs:

$HH(b\bar{b}\gamma\gamma)$



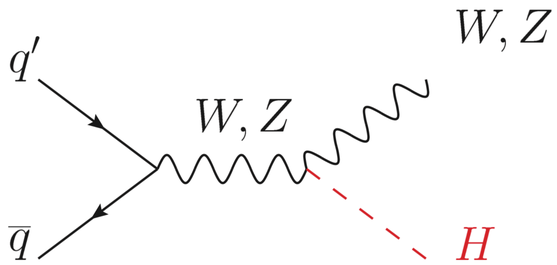


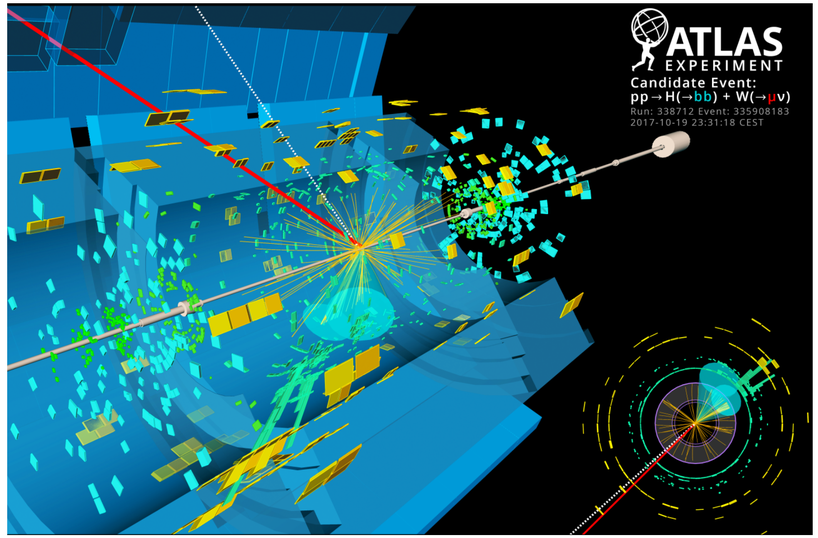
Run 2 + (22-24) Run 3

Higgs Boson analyses in Today's talk

Single Higgs:

$VH(b\bar{b}\,|\,c\bar{c}),\ V \to lep\,.$

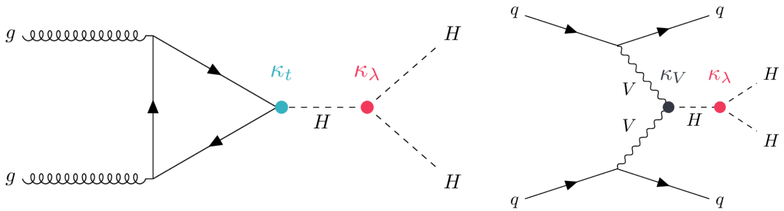


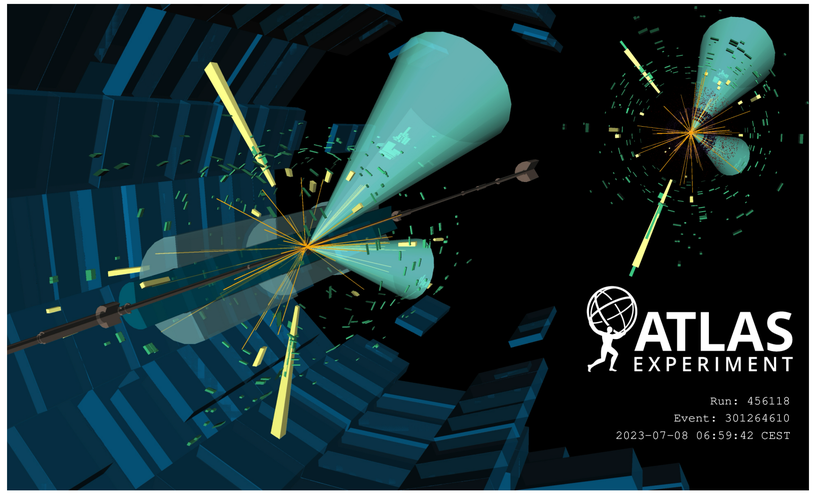


Run 2

Di Higgs:

$HH(b\bar{b}\gamma\gamma)$

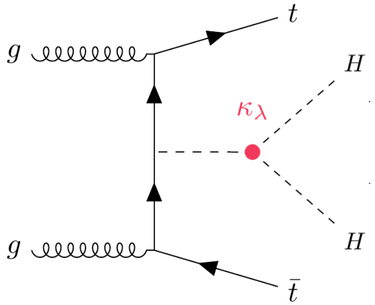


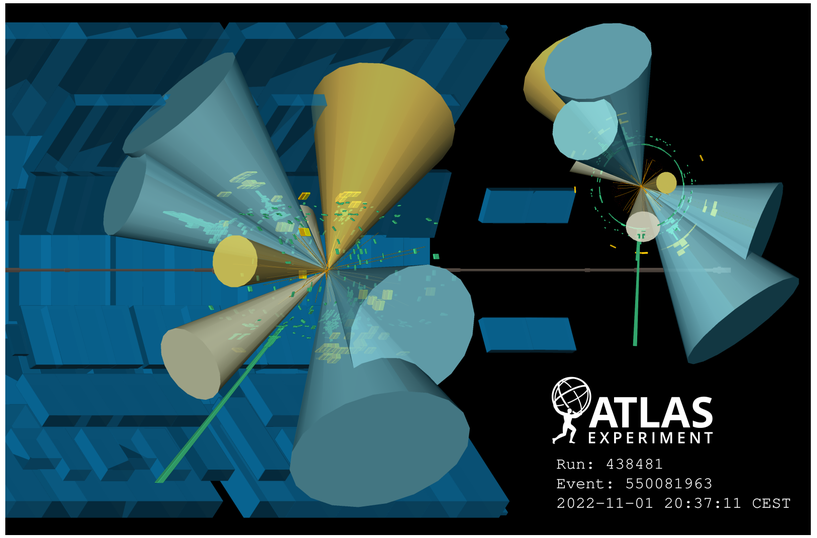


Run 2 + (22-24) Run 3

Di Higgs:

$ttHH,\ HH(b\bar{b}b\bar{b}),\ 1L$





Run 2 + (22-23) Run 3

The importance of identifying b-quarks

Identifying b-quarks, and discriminating from c-quarks, is therefore fundamental to most of these analyses.

The importance of identifying b-quarks

Identifying b-quarks, and discriminating from c-quarks, is therefore fundamental to most of these analyses.

This is what we call Flavour Tagging

Can we distinguish charm and beauty?

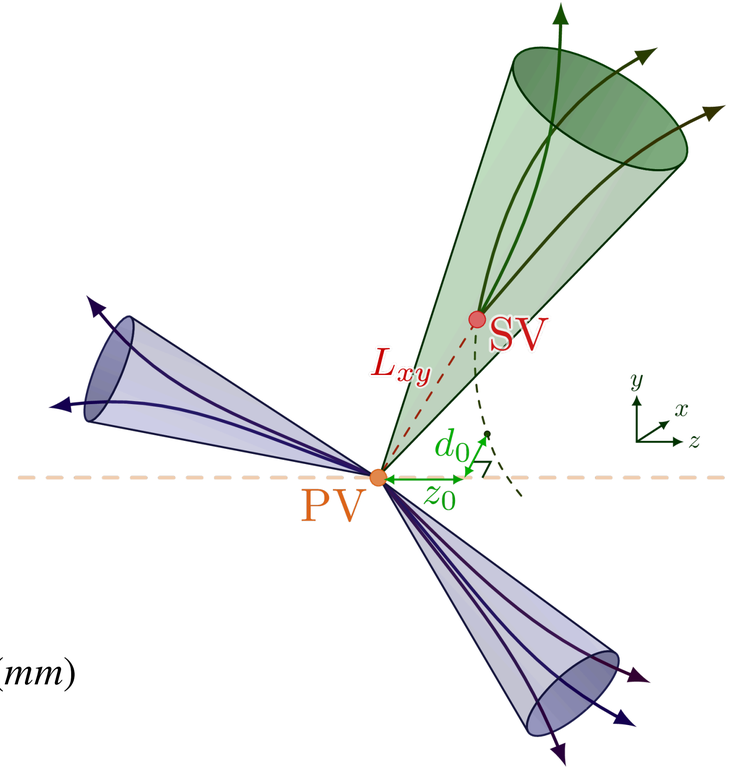
Searching for an Higgs decaying to **b-quarks** or **c-quarks** requires sophisticated algorithms able to identify them.

A quark produced in a LHC *pp* collision generate a shower of **partons** that **hadronize** shortly after production.

The set of particles produced by the original quark is called **Jet**

Jets originated by **different flavours** will have **different properties**

Final **Hadrons**, originated by a b(c)-quark have significant lifetimes* $\beta\gamma c\tau \sim \mathcal{O}(mm)$



*B-hadrons can also decay to D-hadrons providing a clear decay chain B→C→stable

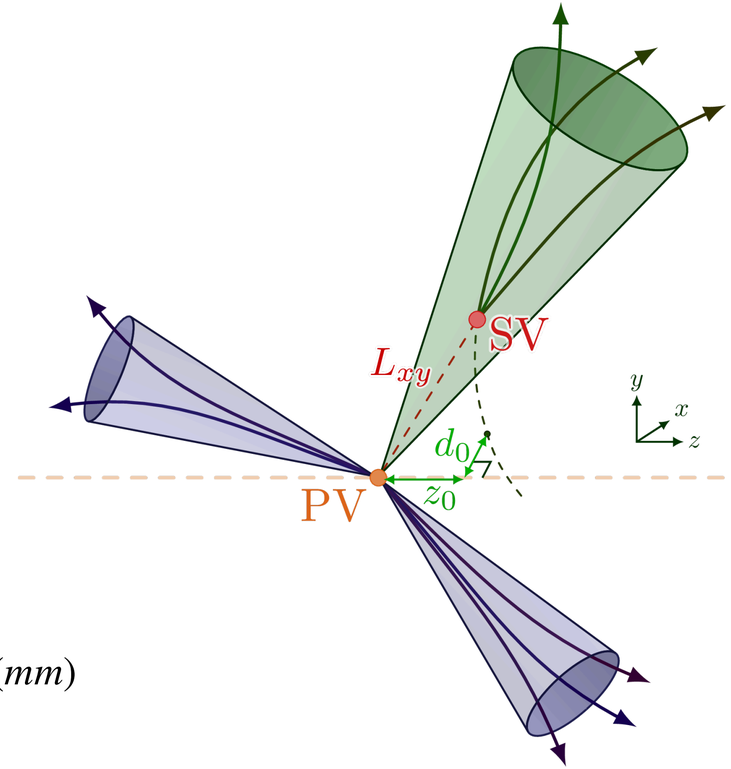
Can we distinguish charm and beauty?

Searching for an Higgs decaying to **b-quarks** or **c-quarks** requires sophisticated algorithms able to identify them

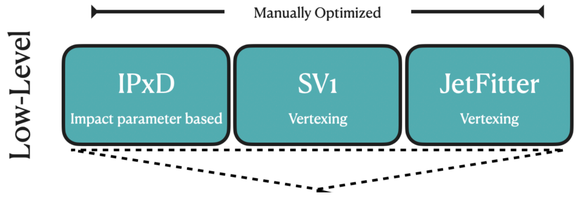
A quark produced in a LHC *pp* collision generate a shower of **partons** that **hadronize** shortly after production.

The set of particles produced by the original quark is called **Jet**

Jets originated by **different flavours** will have **different properties**



Final **Hadrons**, originated by a b(c)-quark have significant lifetimes* $\beta\gamma c\tau \sim \mathcal{O}(mm)$



The FTag beautiful story:

- Originally simple taggers based on the **track impact parameters** and **secondary vertices finding** were developed

*B-hadrons can also decay to D-hadrons providing a clear decay chain B→C→stable

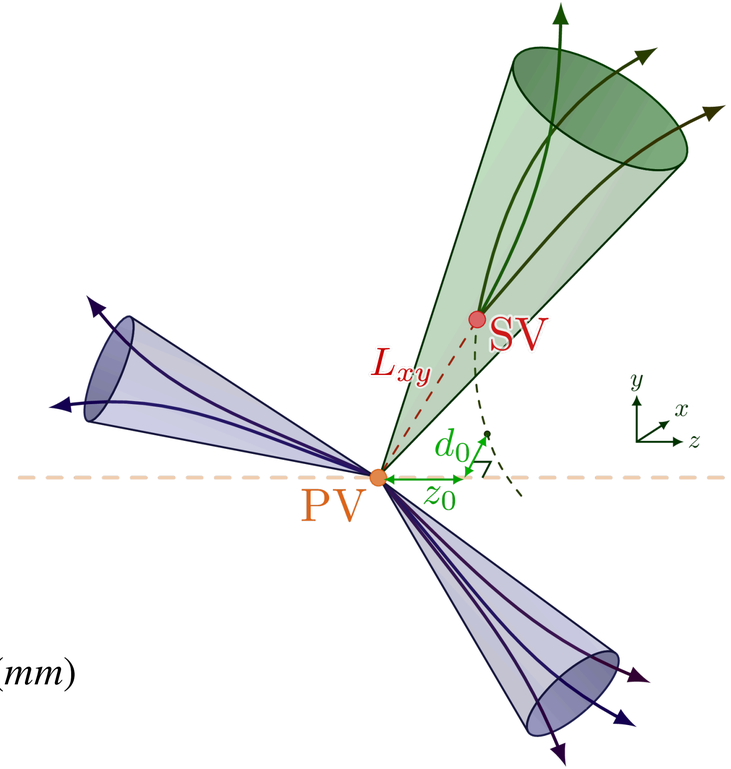
Can we distinguish charm and beauty?

Searching for an Higgs decaying to **b-quarks** or **c-quarks** requires sophisticated algorithms able to identify them

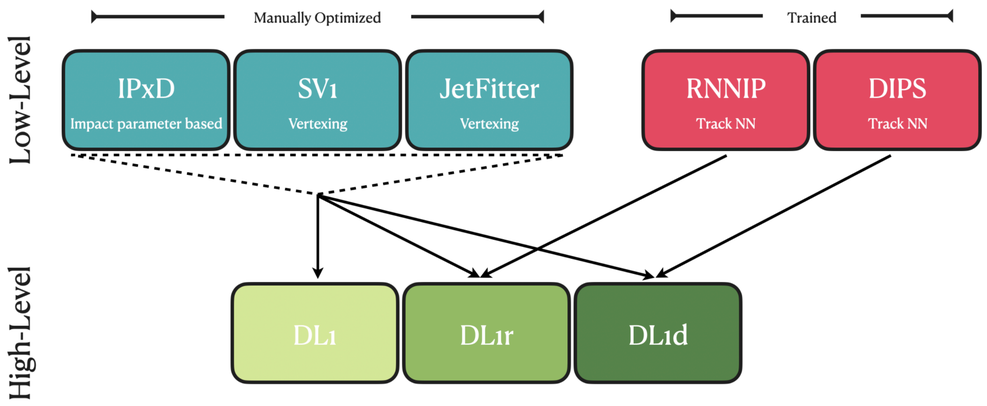
A quark produced in a LHC *pp* collision generate a shower of **partons** that **hadronize** shortly after production.

The set of particles produced by the original quark is called **Jet**

Jets originated by **different flavours** will have **different properties**



Final **Hadrons**, originated by a b(c)-quark have significant lifetimes* $\beta\gamma c\tau \sim \mathcal{O}(mm)$



FTag algorithm predicts the jet flavour as being originated by a light-quark** (p_l), a c-quark (p_c), a b-quark (p_b) or a hadronic τ (p_τ)

The FTag beautiful story:

- Originally simple taggers based on the **track impact parameters** and **secondary vertices finding** were developed
- With **Deep Learning** development new advanced algorithms have been developed **based directly on tracks 4-vectors**

*B-hadrons can also decay to D-hadrons providing a clear decay chain B→C→stable

** light = u/d/s/g

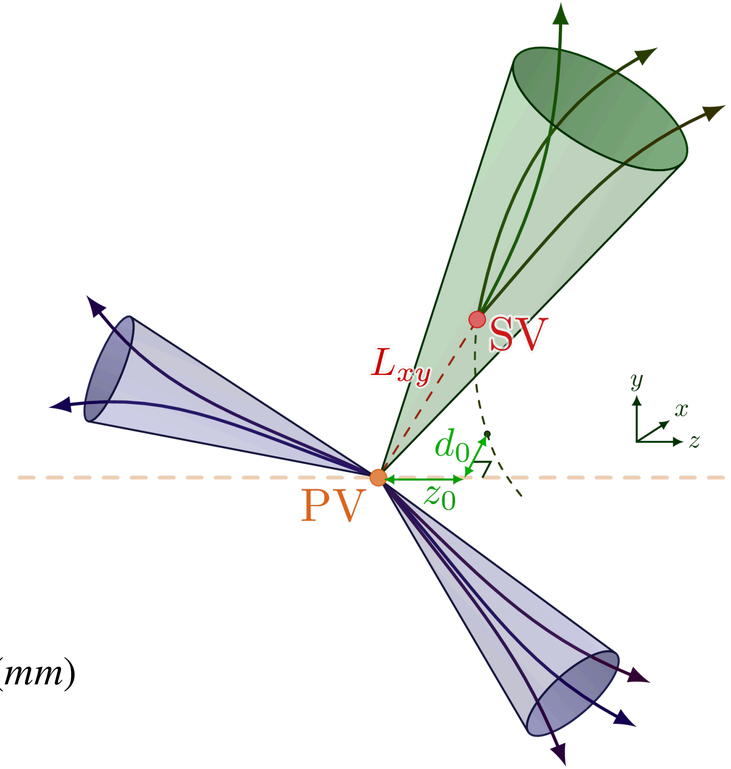
Can we distinguish charm and beauty?

Searching for an Higgs decaying to **b-quarks** or **c-quarks** requires sophisticated algorithms able to identify them

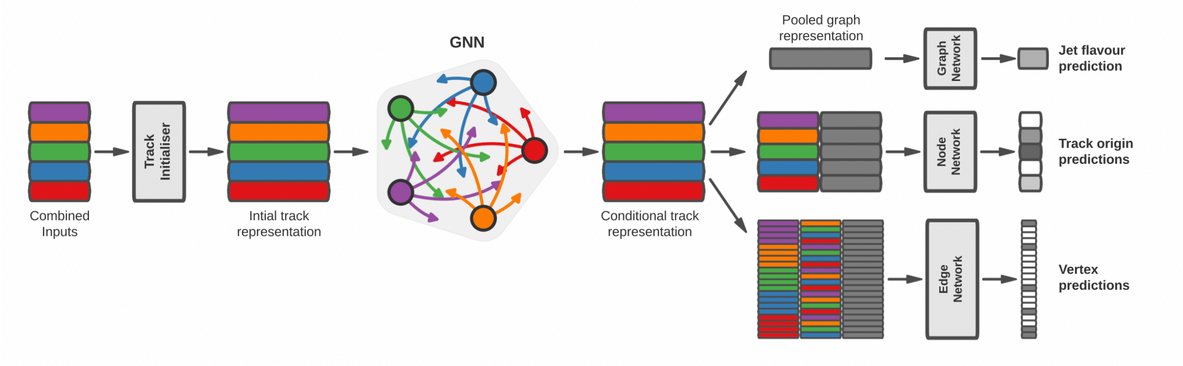
A quark produced in a LHC *pp* collision generate a shower of **partons** that **hadronize** shortly after production.

The set of particles produced by the original quark is called **Jet**

Jets originated by **different flavours** will have **different properties**



Final **Hadrons**, originated by a b(c)-quark have significant lifetimes* $\beta\gamma c\tau \sim \mathcal{O}(mm)$



FTag algorithm predicts the jet flavour as being originated by a light-quark** (p_l), a c-quark (p_c), a b-quark (p_b) or a hadronic τ (p_τ)

With the advent of **Graph Neural Networks**

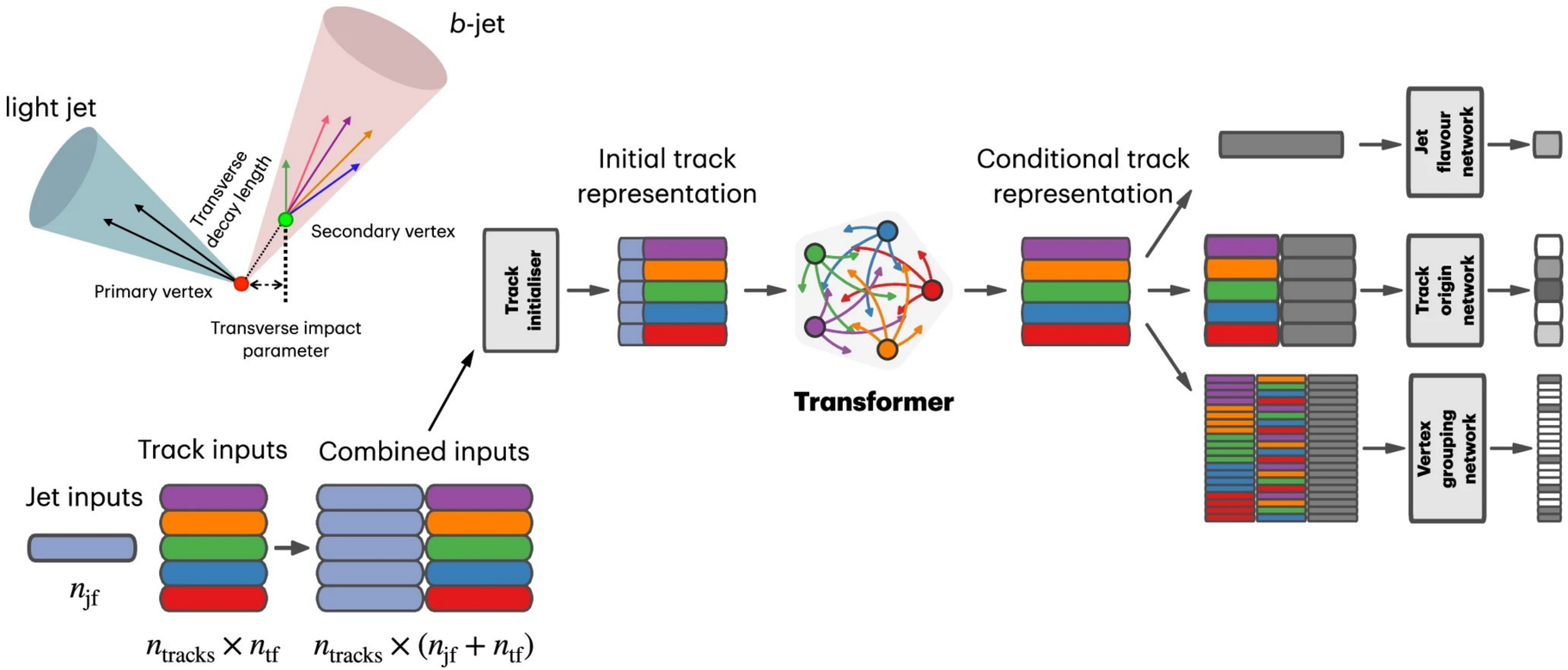
FTag performances have been pushed to **unimaginable limits** nowadays

This is opening access to new horizons considered hopeless in the past

*B-hadrons can also decay to D-hadrons providing a clear decay chain B→C→stable

** light = u/d/s/g

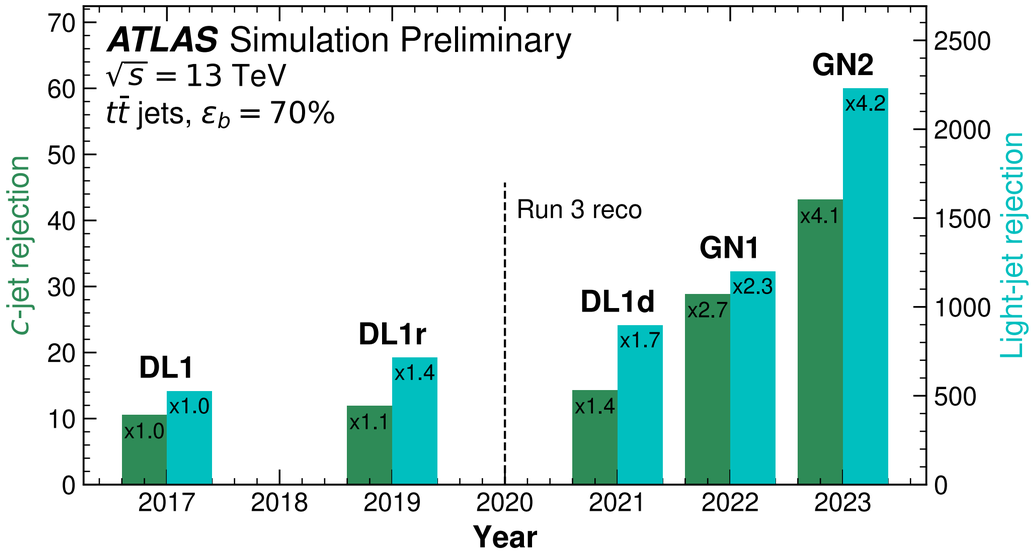
State-of-the art: GN2



Transforming jet flavour tagging at ATLAS now Published on Nature!

The algorithm evolution

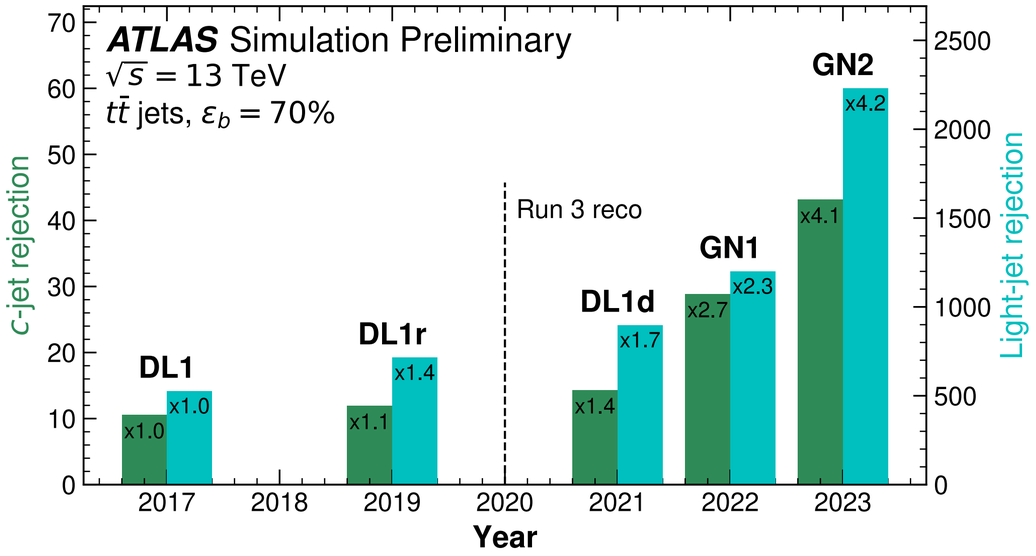
The improvement of GN2 over the past taggers is impressive

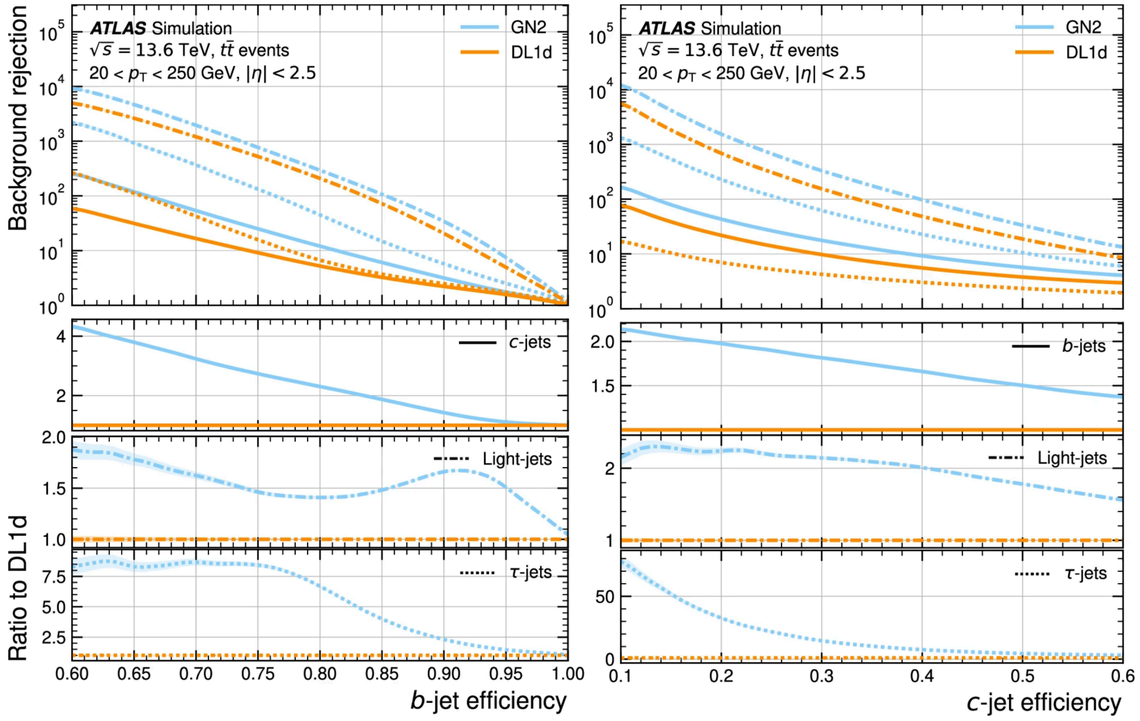


ROC curve showing how the improvement is significant in mis-tag rejection as a function of b-/c-tagging!

The algorithm evolution

The improvement of GN2 over the past taggers is impressive





ROC curve showing how the improvement is significant in mis-tag rejection as a function of b-/c-tagging!

b-tagging @ 70%

(w.r.t. DL1d)

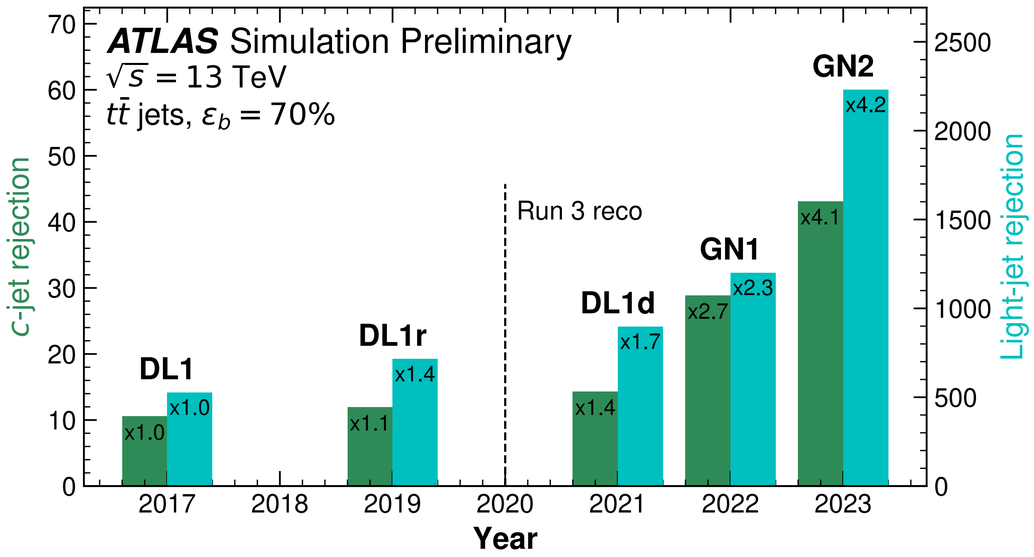
- × 3.5 c-rej
- × 1.6 light-rej
- × 8 τ-rej

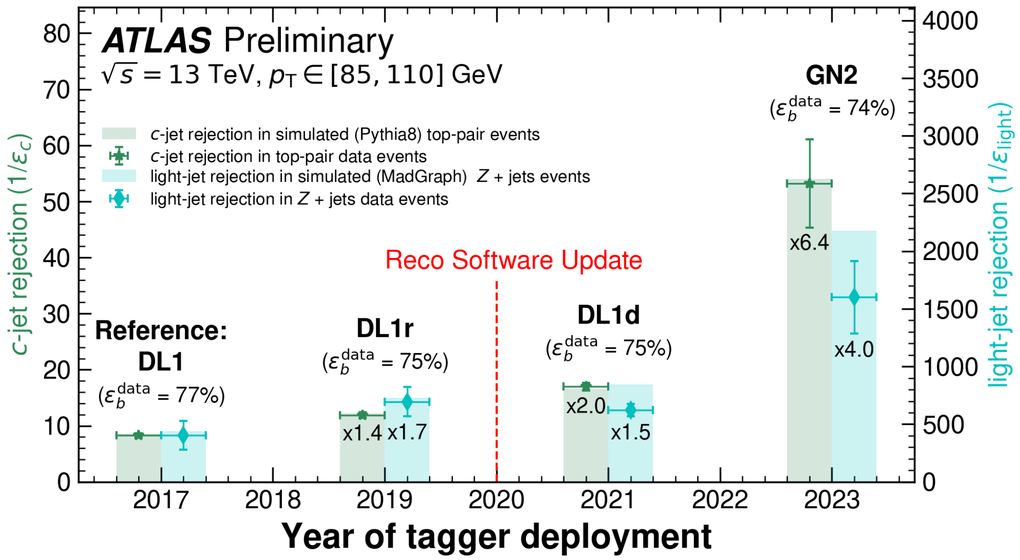
c-tagging @ 30%

(w.r.t. DL1d)

- × 1.7 b-rej
- × 2.2 light-rej
- × 12 τ-rej

Facing reality with calibration

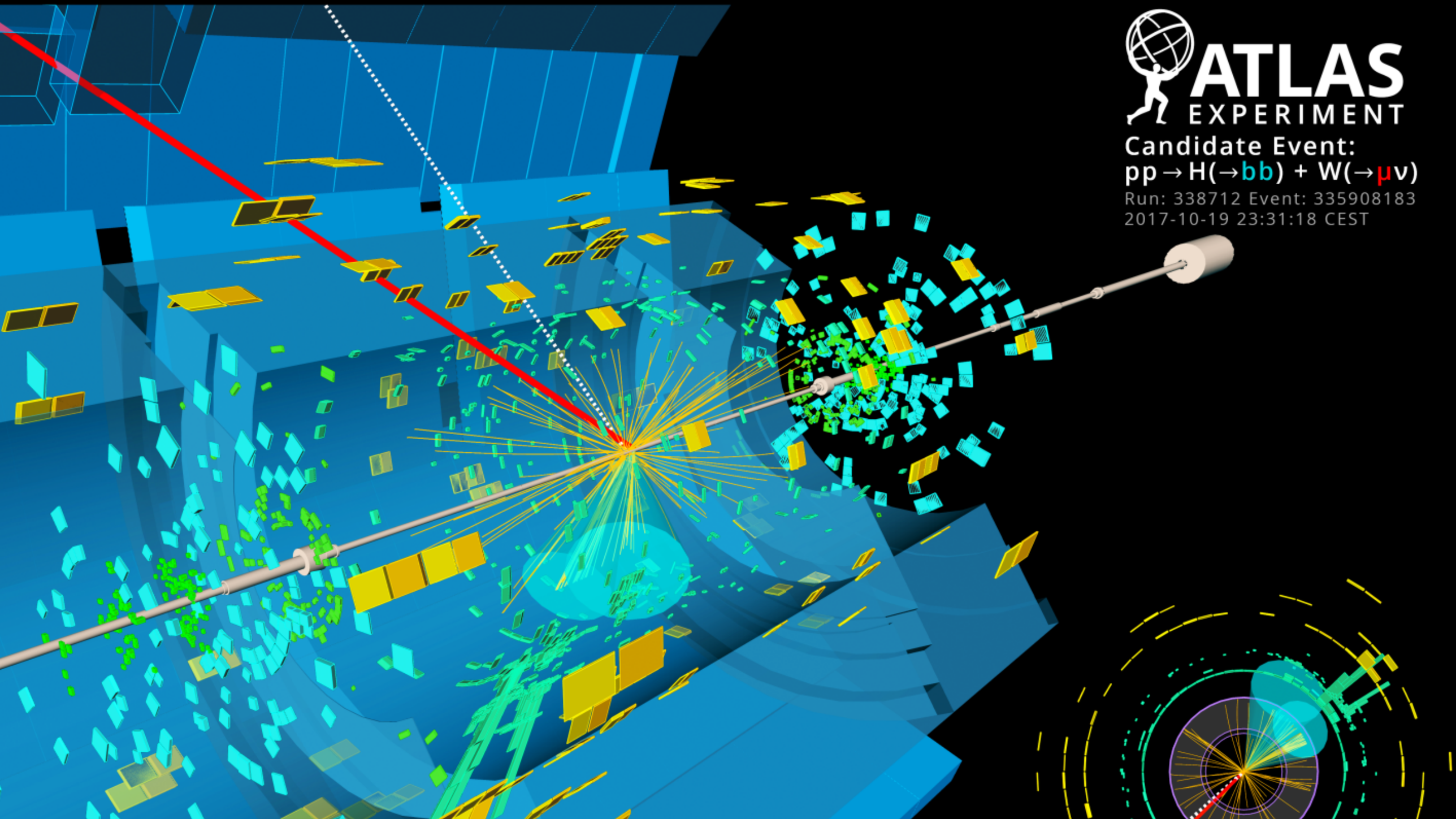




Algorithms are trained and evaluated on MC but the final result for the collaboration is the actual efficiency of the algorithm on Data.

For this reason we perform calibrations providing data/MC correcting factors to analyses using b- or c-tagging.

As of now we performed the calibration of GN2 algorithm up to 2024 dataset

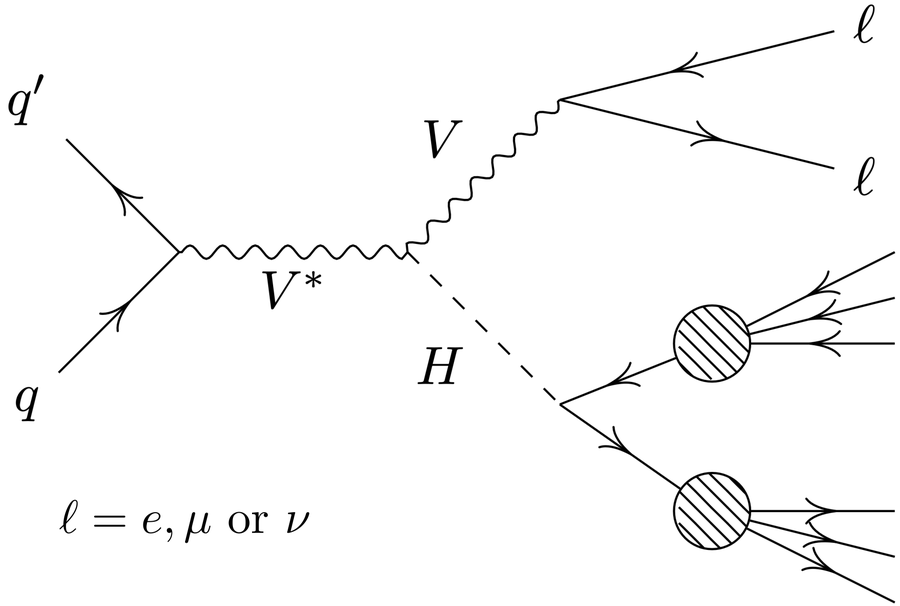

ATLAS
EXPERIMENT
Candidate Event:
pp→H(→bb) + W(→μν)
Run: 338712 Event: 335908183
2017-10-19 23:31:18 CEST

The beauty and the charm of the Higgs: VH(bb|cc)

The VH analysis targets $H \to b\bar{b}$ and $H \to c\bar{c}$ **simultaneously**

Using Run 2 140 fb^{-1} data!

$$\sigma_{VH}^{\mathrm{SM}}(m_H) = 2.26\,^{+2.5\%}_{-2.4\%}\ \mathrm{pb}\ @\ 13\ \mathrm{TeV}$$



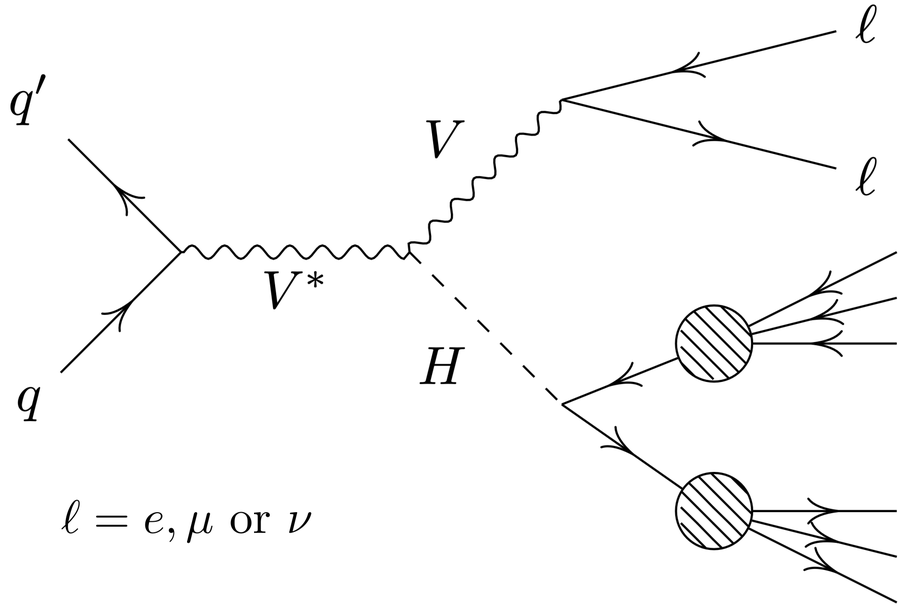
The beauty and the charm of the Higgs: VH(bb|cc)

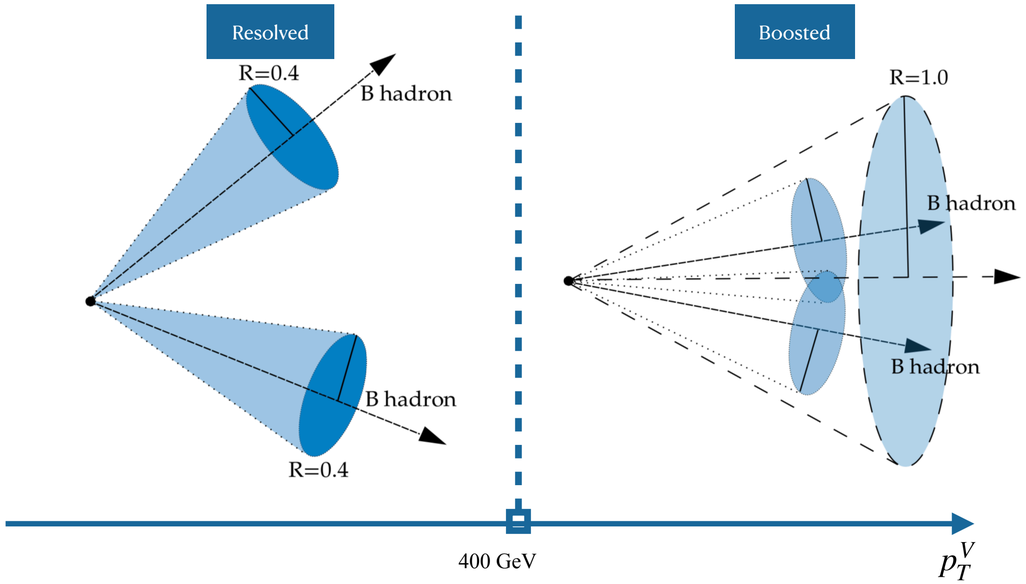
The VH analysis targets $H \to b\bar{b}$ and $H \to c\bar{c}$ **simultaneously**

Using Run 2 140 fb^{-1} events!

Three channels are defined depending on the leptonic decay of the Vector boson where at LO $p_T^V \propto p_T^H$:

- $Z \to \nu\nu$: 0-Lepton Channel – $p_T^V = MET$
- $W \to l\nu$: 1-Lepton Channel – $p_T^V = p_T^l + MET$
- $Z \to l^+l^-$: 2-Lepton Channel – $p_T^V = p_T^{l^+} + p_T^{l^-}$





The Higgs Boson Candidate (H):

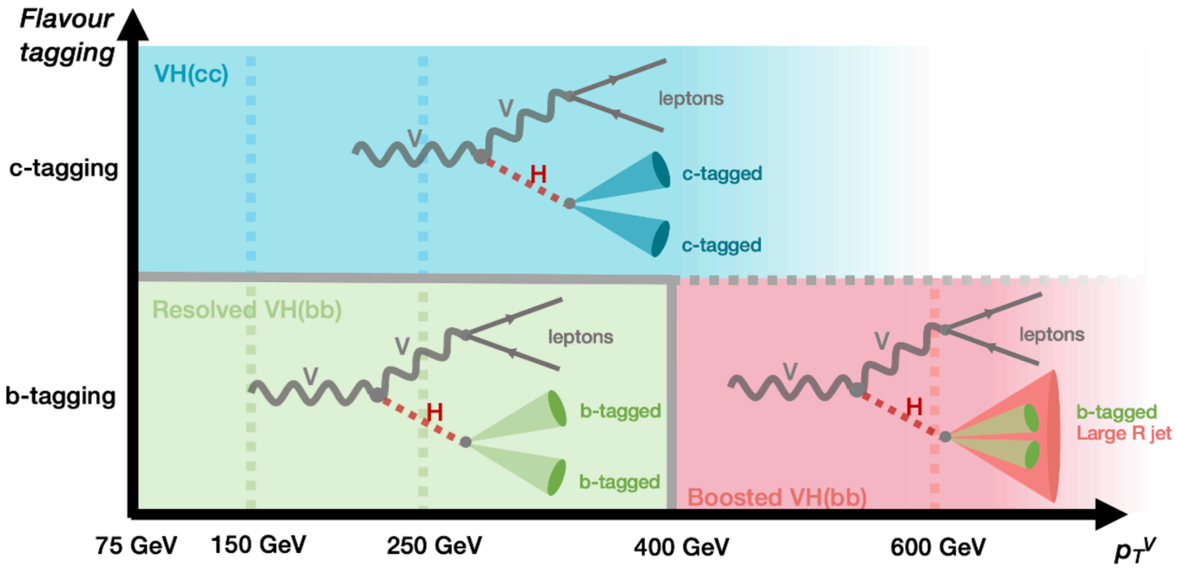
- The H is reconstruction depends on the p_T^V as the angular distance between the two quarks is proportional to the inverse of the p_T^H
  - **Resolved**: 2 small-R jets (R=0.4)
  - **Boosted**: 1 large-R jet (R=1.0)

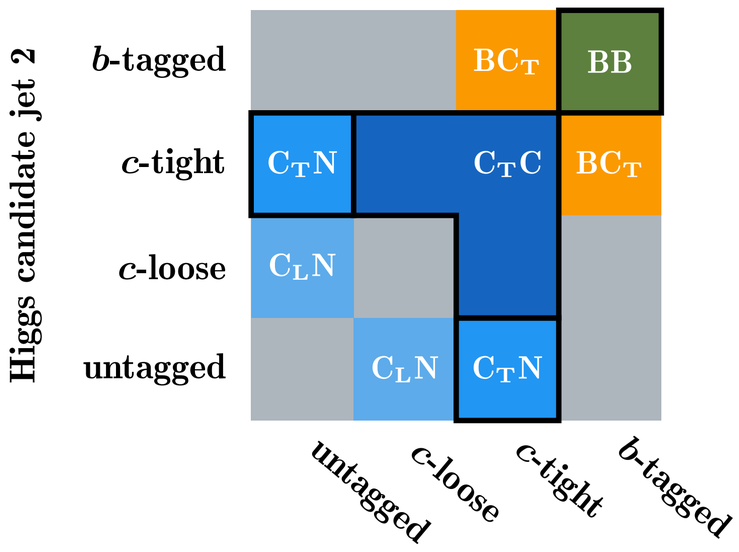
VH(bb|cc) Categories

Resolved: It is possible to build **orthogonal regions** for H(bb) and H(cc) exploiting ad hoc **b-tagging** and **c-tagging** of the jets

Run 2 analysis, still based on DL1r; the GN2-based Run 3 version is in progress.

Boosted: In boosted only **b-tagging** is considered and different tagging strategy is applied based on subtructure



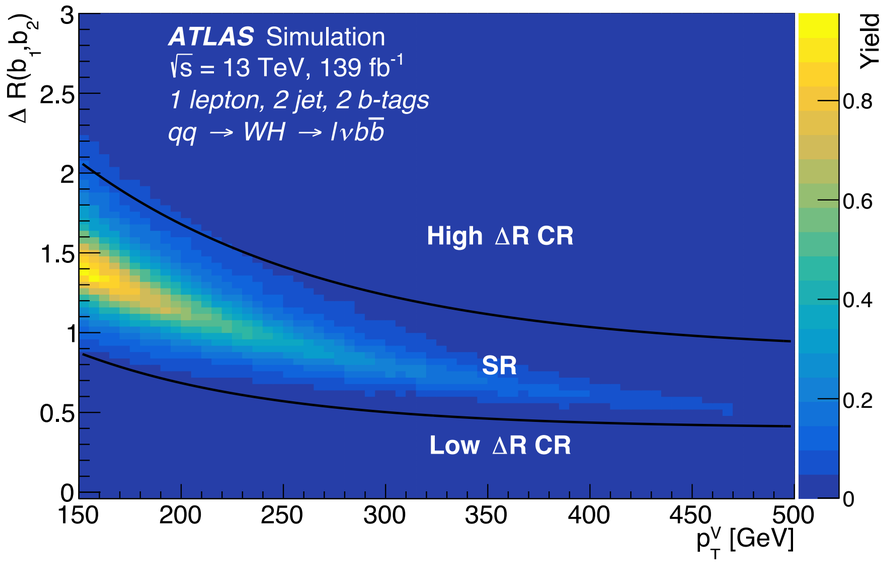


VH(bb|cc): Backgrounds

The **main quantities** in the analysis are p_T^V and m_H , related by the angular distance between the two quarks $\Delta R(j_1, j_2)$.

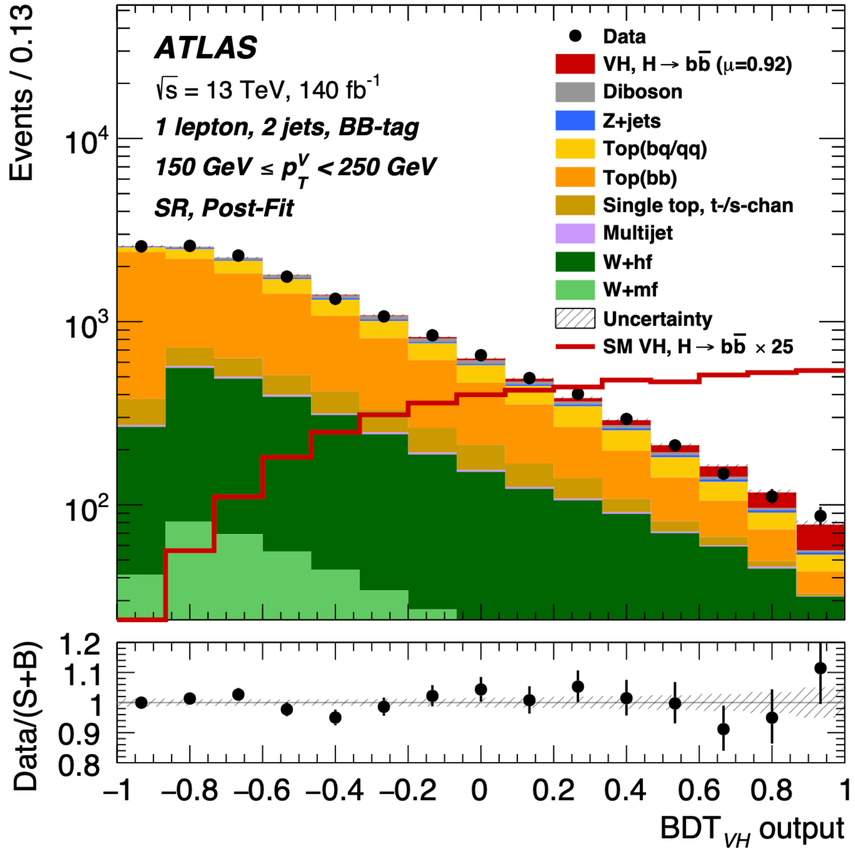
This can be exploit to control the **main backgrounds** of the analysis:

- **W+jets**: contaminating mostly 1L Channel
- **Z+jets**: contaminating mostly the 0 and 2L Channels
- **$t\bar{t}$ and single-top**: dominant at large $\Delta R(j_1, j_2)$
- **diboson**: irreducible background where a Z is produced in place of the Higgs boson
- **multijet**: minor background mainly impacting 1L



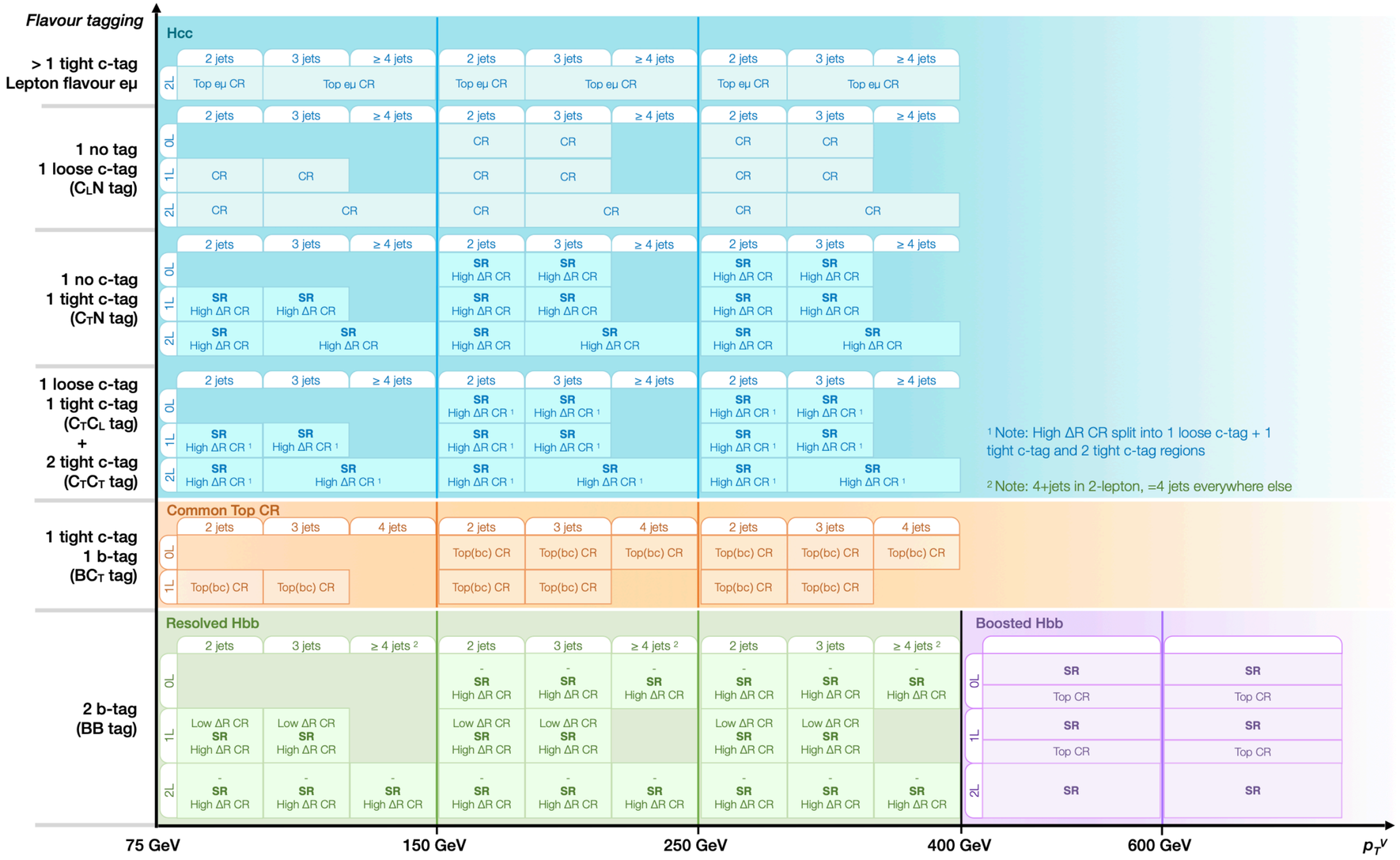
VH(bb|cc): Multi Variate Analysis

A **BDT** is trained in each category and region to discriminate signal from background and maximise the analysis sensitivity



	Resolved VH, $H \to b\bar{b}, c\bar{c}$			Boosted VH, $H \to b\bar{b}$		
Variable	0-lepton	1-lepton	2-lepton	0-lepton	1-lepton	2-lepton
m_H	✓	✓	✓	✓	✓	✓
$m_{j_1 j_2 j_3}$	✓	✓	✓			
$p_T^{j_1}$	✓	✓	✓	✓	✓	✓
$p_T^{j_2}$	✓	✓	✓	✓	✓	✓
$p_T^{j_3}$				✓	✓	✓
$\sum p_T^{j_i}, i > 2$	✓	✓	✓			
$\mathrm{bin}_{D_{\mathrm{DL1r}}}(j_1)$	✓	✓	✓	✓	✓	✓
$\mathrm{bin}_{D_{\mathrm{DL1r}}}(j_2)$	✓	✓	✓	✓	✓	✓
p_T^V	$\equiv E_T^{\mathrm{miss}}$	✓	✓	$\equiv E_T^{\mathrm{miss}}$	✓	✓
E_T^{miss}	✓	✓		✓	✓	
$E_T^{\mathrm{miss}}/\sqrt{S_T}$			✓			
$\lvert\Delta\phi(\boldsymbol{V},\boldsymbol{H})\rvert$	✓	✓	✓	✓	✓	✓
$\lvert\Delta y(\boldsymbol{V},\boldsymbol{H})\rvert$		✓	✓		✓	✓
$\Delta R(\boldsymbol{j_1},\boldsymbol{j_2})$	✓	✓	✓	✓	✓	✓
$\min[\Delta R(\boldsymbol{j_i},\boldsymbol{j_1}\text{ or }\boldsymbol{j_2})], i > 2$	✓	✓				
N(track-jets in J)				✓	✓	✓
N(add. small-R jets)				✓	✓	✓
colour ring				✓	✓	✓
$\lvert\Delta\eta(\boldsymbol{j_1},\boldsymbol{j_2})\rvert$	✓					
$H_T + E_T^{\mathrm{miss}}$	✓					
m_T^W		✓				
m_{top}		✓				
$\min[\Delta\phi(\boldsymbol{\ell},\boldsymbol{j_1}\text{ or }\boldsymbol{j_2})]$		✓				
p_T^ℓ					✓	
$(p_T^\ell - E_T^{\mathrm{miss}})/p_T^V$					✓	
$m_{\ell\ell}$			✓			
$\cos\theta^*(\boldsymbol{\ell^-},\boldsymbol{V})$			✓			✓

A complicated analysis

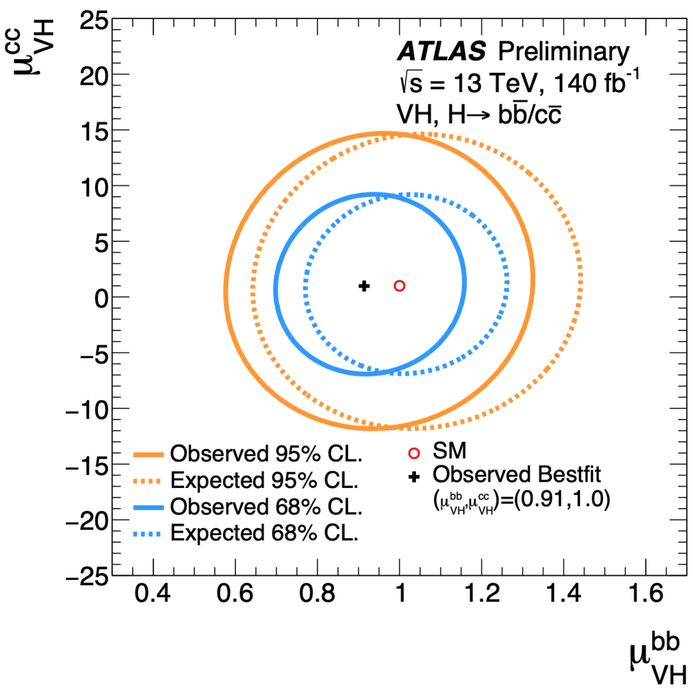


VH(bb|cc): signal-strength

Results on the **2POI:** with ~15% precision on VH(bb):

$$\hat{\mu}^{bb}_{VH} = 0.91^{+0.16}_{-0.14} = 0.91^{+0.10}_{-0.10}(\text{stat.})^{+0.12}_{-0.11}(\text{syst.})$$
$$\hat{\mu}^{cc}_{VH} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}(\text{stat.})^{+3.6}_{-3.5}(\text{syst.}).$$

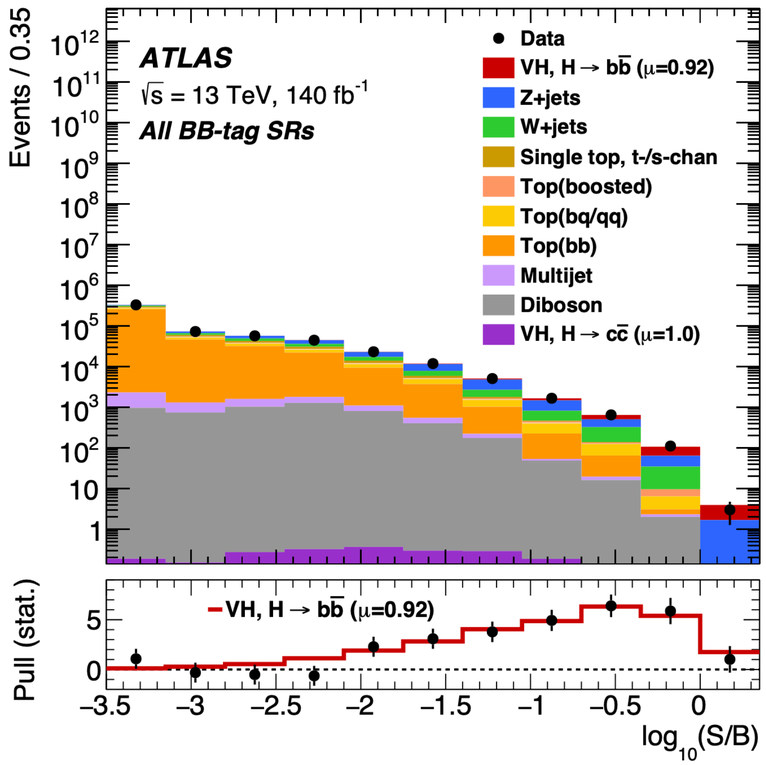
Small correlation (5%) between VH(bb) and VH(cc)

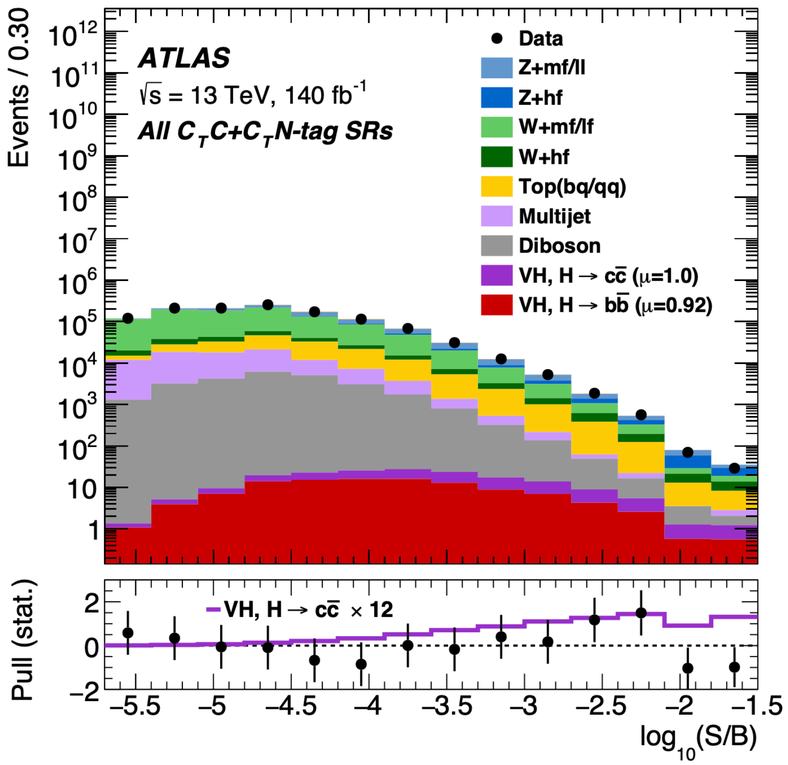


VH(bb|cc) results: VH(bb)

Results on the **2POI:** with ~15% precision on VH(bb):

$$\hat{\mu}^{bb}_{VH} = 0.91^{+0.16}_{-0.14} = 0.91^{+0.10}_{-0.10}(\text{stat.})^{+0.12}_{-0.11}(\text{syst.})$$
$$\hat{\mu}^{cc}_{VH} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}(\text{stat.})^{+3.6}_{-3.5}(\text{syst.}).$$





VH(bb|cc) results: VH(bb)

Results on the **2POI:** with ~15% precision on VH(bb):

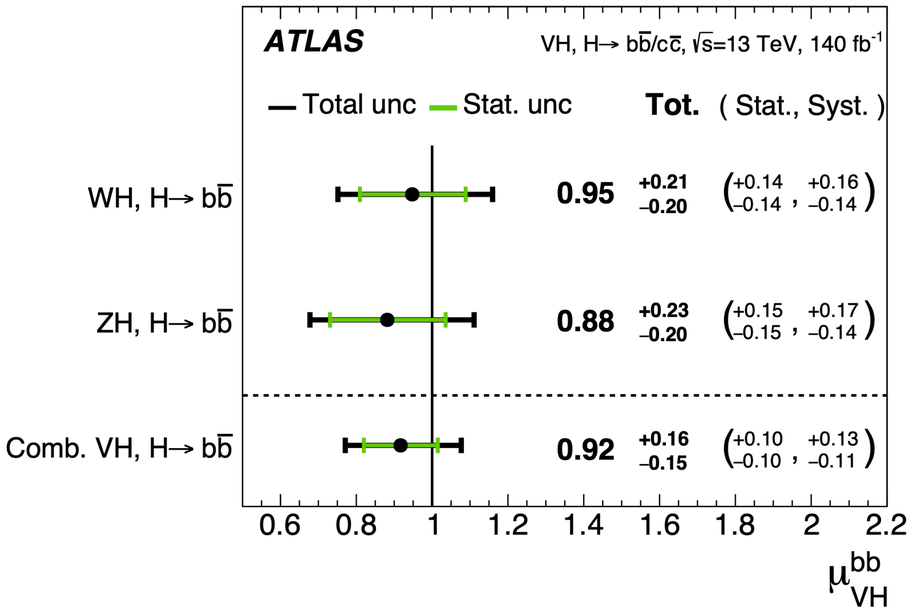
$$\hat{\mu}^{bb}_{VH} = 0.91^{+0.16}_{-0.14} = 0.91^{+0.10}_{-0.10}(\text{stat.})^{+0.12}_{-0.11}(\text{syst.})$$
$$\hat{\mu}^{cc}_{VH} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}(\text{stat.})^{+3.6}_{-3.5}(\text{syst.}).$$

Small correlation (5%) between VH(bb) and VH(cc)

Significance	Expected	Observed
WH(bb)	5,5	5,3
ZH(bb)	5,7	4,9
VH(bb)	8,0	7,4
VH(cc) Limits	10	11

Results

First Observation of WH(bb) process!



VH(bb|cc) results: VH(cc)

Results on the **2POI:** with ~15% precision on VH(bb):

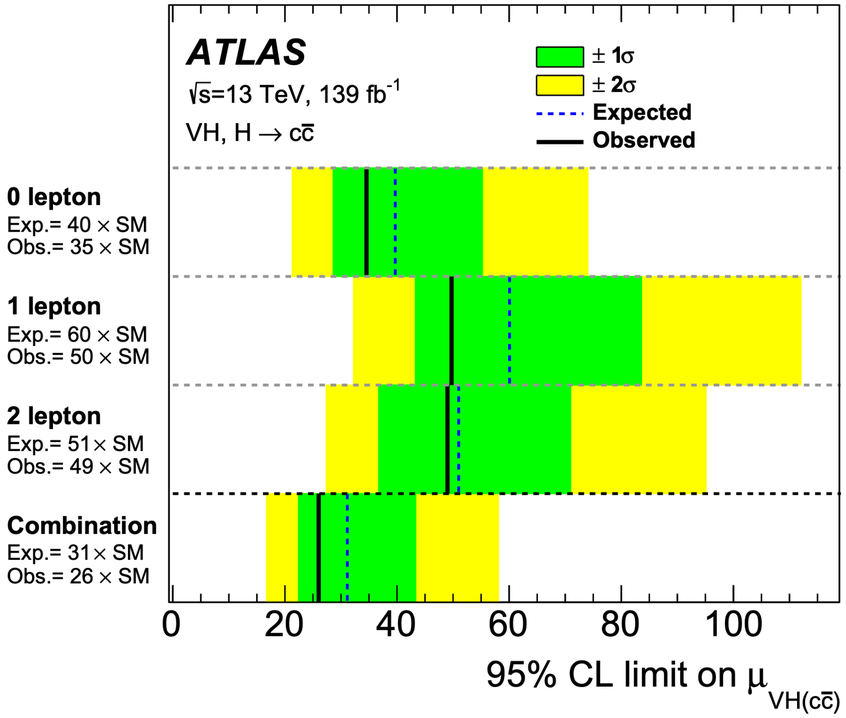
$$\hat{\mu}^{bb}_{VH} = 0.91^{+0.16}_{-0.14} = 0.91^{+0.10}_{-0.10}(\text{stat.})^{+0.12}_{-0.11}(\text{syst.})$$
$$\hat{\mu}^{cc}_{VH} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}(\text{stat.})^{+3.6}_{-3.5}(\text{syst.}).$$

Small correlation (5%) between VH(bb) and VH(cc)

Significance	Expected	Observed
WH(bb)	5,5	5,3
ZH(bb)	5,7	4,9
VH(bb)	8,0	7,4
VH(cc) Limits	10	11

Results

95% CL Limits on VH(cc) improved by ~3



VH(bb|cc) results: VH(cc)

Results on the **2POI:** with ~15% precision on VH(bb):

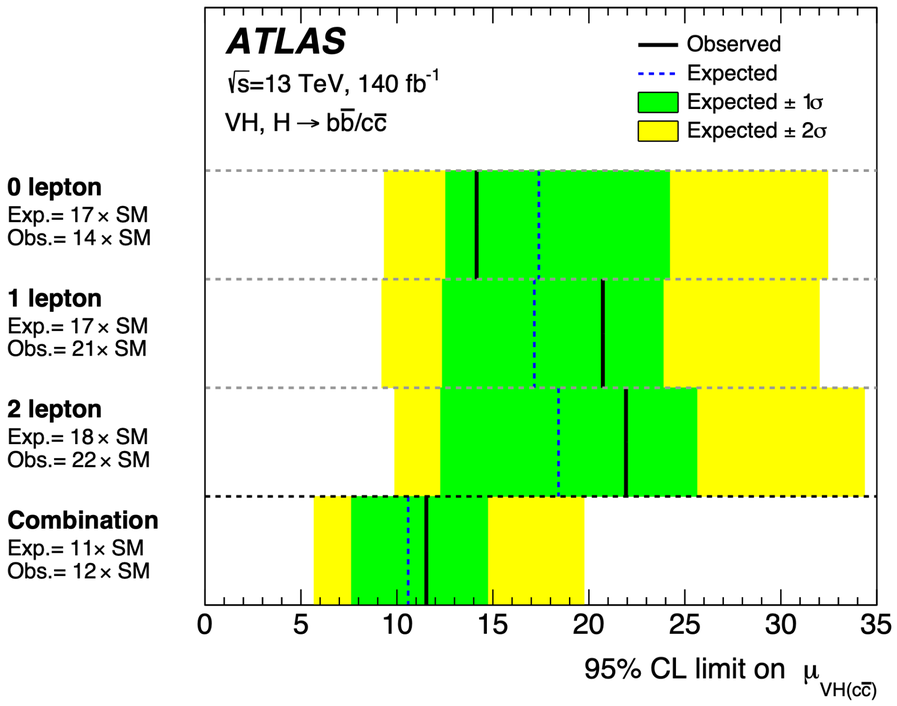
$$\hat{\mu}^{bb}_{VH} = 0.91^{+0.16}_{-0.14} = 0.91^{+0.10}_{-0.10}(\text{stat.})^{+0.12}_{-0.11}(\text{syst.})$$
$$\hat{\mu}^{cc}_{VH} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}(\text{stat.})^{+3.6}_{-3.5}(\text{syst.}).$$

Significance	Expected	Observed
WH(bb)	5,5	5,3
ZH(bb)	5,7	4,9
VH(bb)	8,0	7,4
VH(cc) Limits	10	11

Small correlation (5%) between VH(bb) and VH(cc)

Results

95% CL Limits on VH(cc) improved by ~3



VH(bb|cc) results: k-framework

Results on the **2POI:** with ~15% precision on VH(bb):

$$\hat{\mu}^{bb}_{VH} = 0.91^{+0.16}_{-0.14} = 0.91^{+0.10}_{-0.10}(\text{stat.})^{+0.12}_{-0.11}(\text{syst.})$$
$$\hat{\mu}^{cc}_{VH} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}(\text{stat.})^{+3.6}_{-3.5}(\text{syst.}).$$

Small correlation (5%) between VH(bb) and VH(cc)

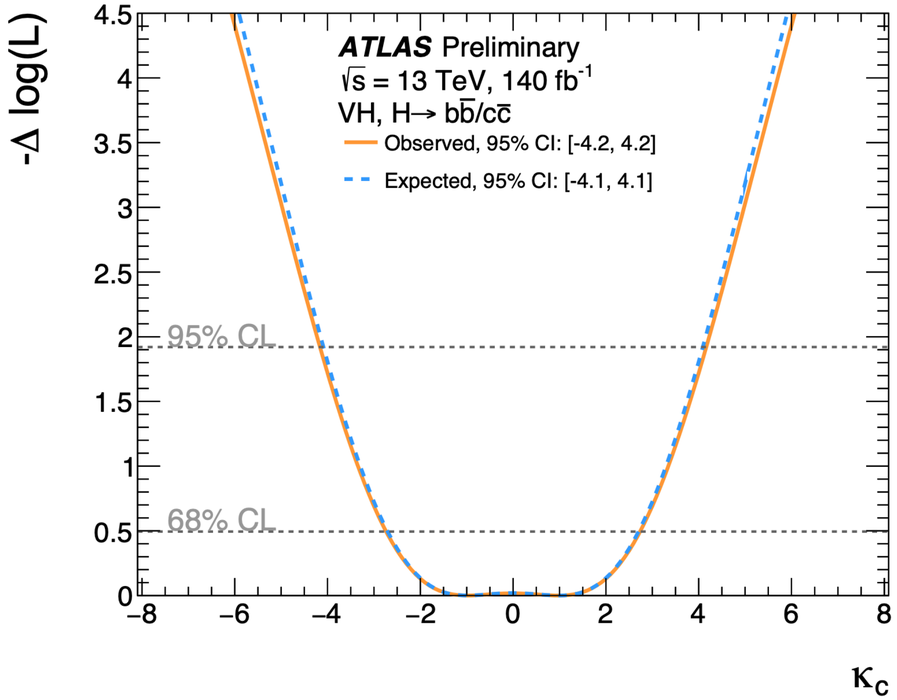
Significance	Expected	Observed
WH(bb)	5,5	5,3
ZH(bb)	5,7	4,9
VH(bb)	8,0	7,4
VH(cc) Limits	10	11

Results

Within the **k-framework** the signal strengths can be parametrized as a function of **multiplicative Yukawa coupling modifiers***: $k_{b(c)}$

$$\mu^{bb(cc)}_{VH} = \frac{k^2_{b(c)}}{1 + BR^{SM}_{Hbb}(k_b^2 - 1) + BR^{SM}_{Hcc}(k_c^2 - 1)}$$

Constraint at **95% CL** of $|k_c| < 4.2$!

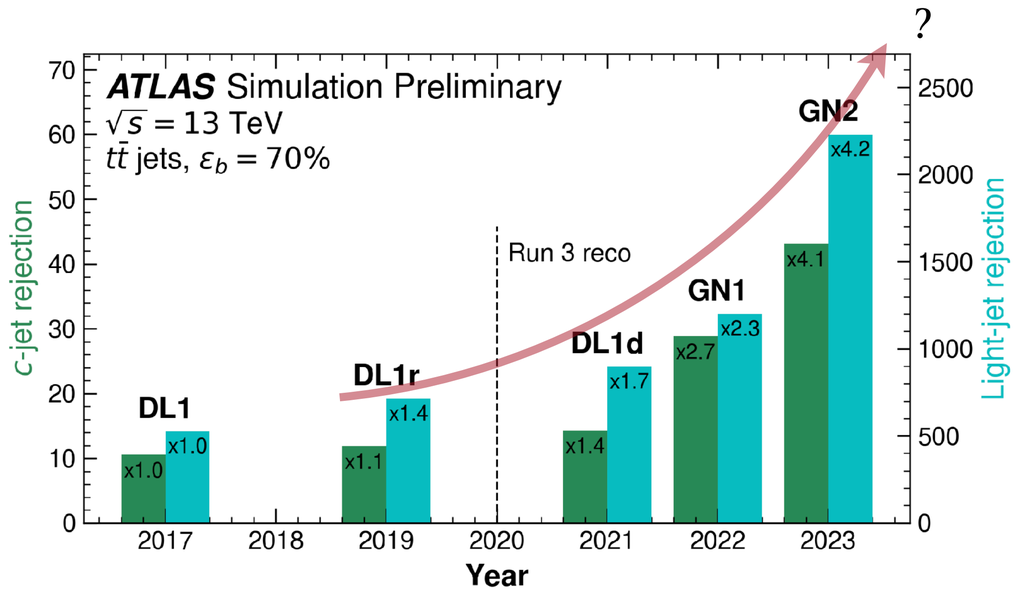


*Assuming all the other SM decays of the Higgs

VH(bb|cc) outlook

It is **now** becoming plausible to reach **evidence (3σ)** for $H \to c\bar{c}$ by the end of HL-LHC

New **improvements in detector technology** and **techniques**, could be crucial in achieving results that were once thought improbable.

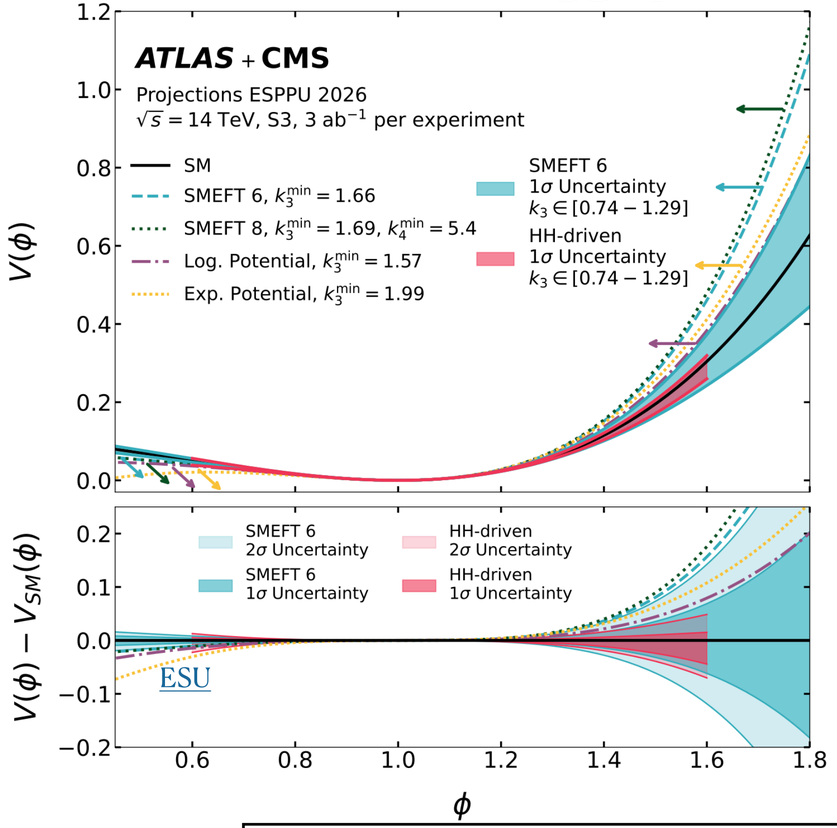


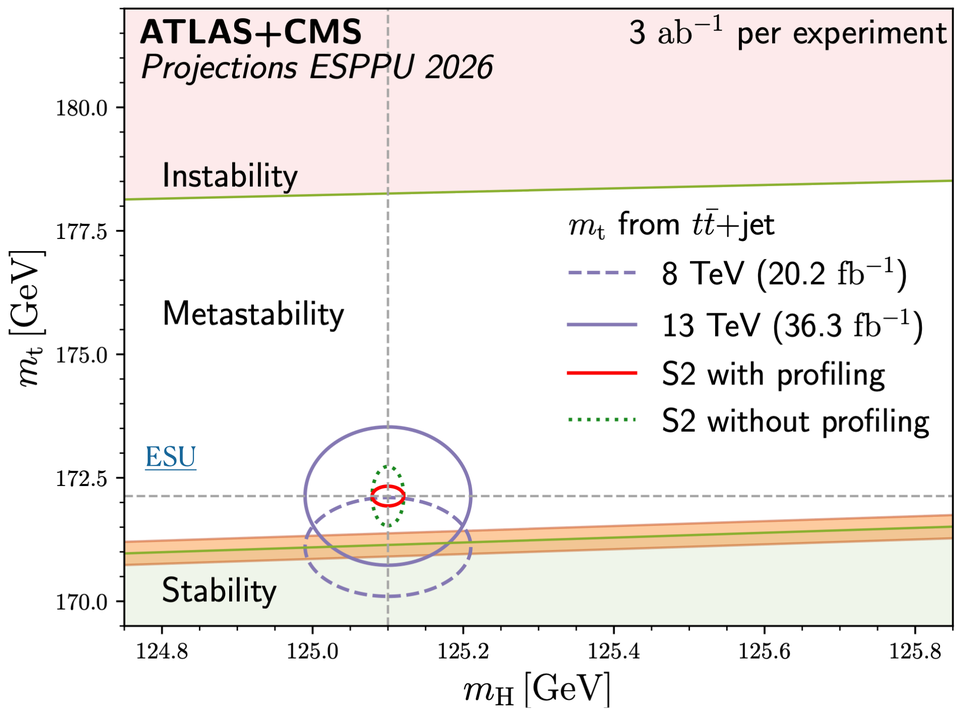
Twice the Higgs
Twice the fun

The Di-Higgs potential

Direct evidence of Higgs self-coupling (λ) remains one of the major **missing pieces** of Standard Model

Huge implications on the **Higgs potential shape**: EW stability, Phase Transition, Baryogenesis etc.





$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \xrightarrow[\phi \to H + v]{\text{SSB}} V(H) = \frac{m_H^2}{2}H^2 + \lambda v H^3 + \frac{\lambda H^4}{4}$$

HH Decay Channels

Several decay channels are combined together to maximize the sensitivity!

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

HH Decay Channels

Several decay channels are combined together to maximize the sensitivity!

Main channels:

- $HH(b\bar{b}b\bar{b})$

Pros: Very large Branching Ratio (34%)

Cons: overwhelming QCD background

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

HH Decay Channels

Several decay channels are combined together to maximize the sensitivity!

Main channels:

- $HH(b\bar{b}b\bar{b})$
- $HH(b\bar{b}\tau^{+}\tau^{-})$

Pros: Good compromise between Branching Ratio (7.3%) and background

Cons: Complex object reconstruction and modelling

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

HH Decay Channels

Several decay channels are combined together to maximize the sensitivity!

Main channels:

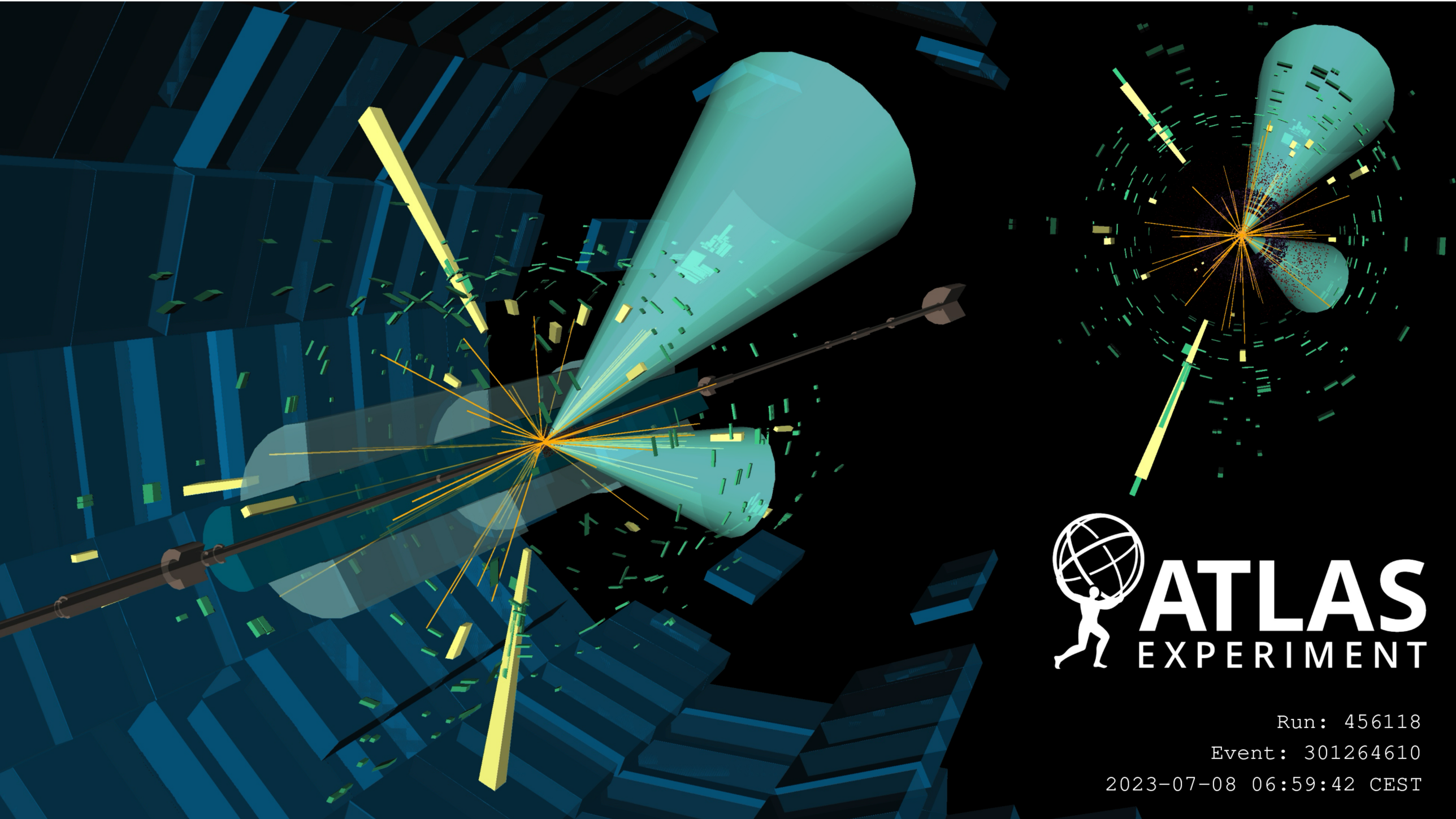
- $HH(b\bar{b}b\bar{b})$
- $HH(b\bar{b}\tau^+\tau^-)$
- $HH(b\bar{b}\gamma\gamma)$ **[Today!]**

Pros: Very clean signature to trigger

Cons: Extremely small BR (0.26%)

- statistically limited

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%


ATLAS
EXPERIMENT
Run: 456118
Event: 301264610
2023-07-08 06:59:42 CEST

Run 2 + partial Run 3 $HH(b\bar{b}\gamma\gamma)$

Using Run 2 140 fb^{-1} and Run 3 168 fb^{-1} data!

Several improvements performed to enhance the sensitivity!

$$\sigma_{ggF}^{SM}(m_H) = 34.1^{+2.2}_{-7.9}\ fb \text{ @ 13.6 TeV (+10\% wrt 13 TeV)}$$

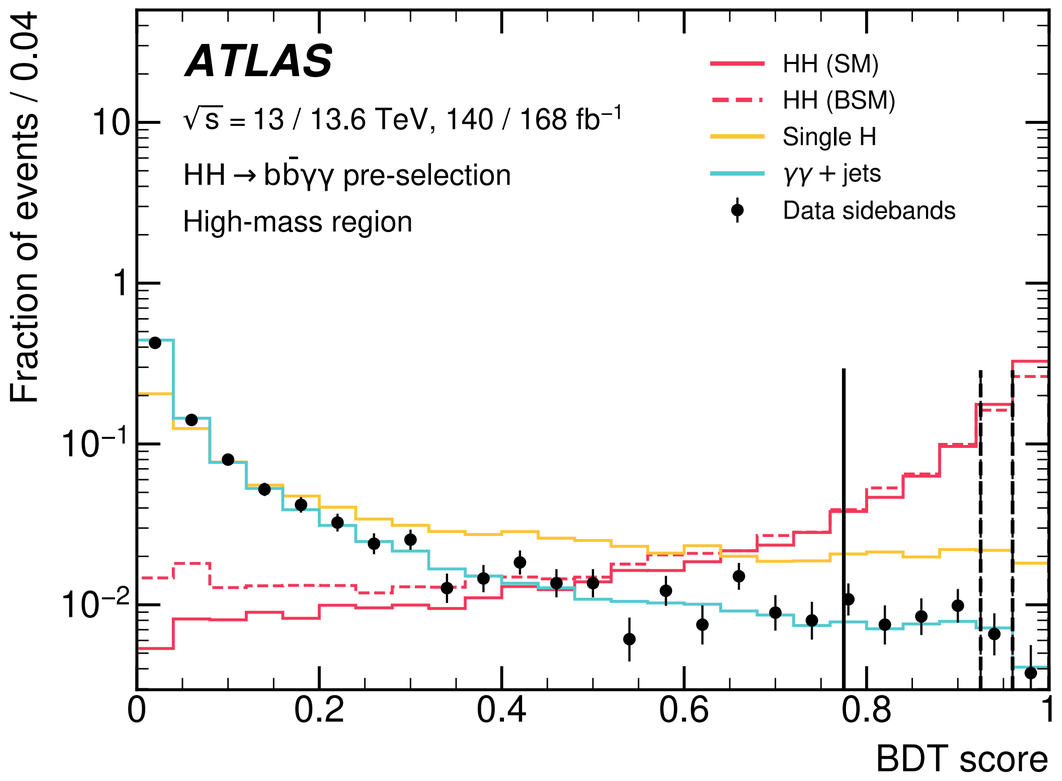
- Selection improved requiring ≥2 b-jets with GN2 $\epsilon_b = 85\ \%$

Run 2 + partial Run 3 $HH(b\bar{b}\gamma\gamma)$

Several improvements performed to enhance the sensitivity!

$$\sigma_{ggF}^{SM}(m_H) = 34.1^{+2.2}_{-7.9}\ fb \text{ @ } 13.6 \text{ TeV } (+10\% \text{ wrt } 13 \text{ TeV})$$

- Selection improved requiring ≥2 b-jets with GN2 $\epsilon_b = 85\ \%$
- Training simultaneous in Run 2 and Run 3 exploiting the correlation to categorize tighter

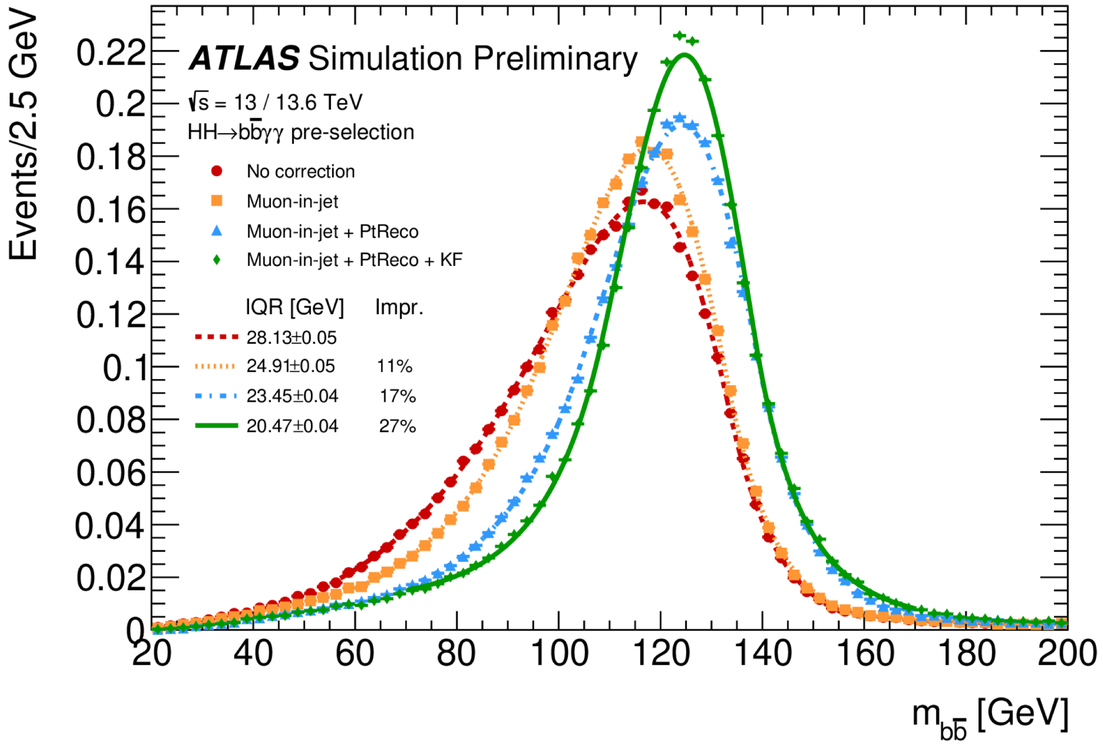


Run 2 + partial Run 3 $HH(b\bar{b}\gamma\gamma)$

Several improvements performed to enhance the sensitivity!

$$\sigma^{SM}_{ggF}(m_H) = 34.1^{+2.2}_{-7.9}\ fb \text{ @ 13.6 TeV (+10\% wrt 13 TeV)}$$

- Selection improved requiring ≥2 b-jets with GN2 $\epsilon_b = 85\ \%$
- Training simultaneous in Run 2 and Run 3 exploiting the correlation to categorize tighter
- Kinematic fit improving the m_{bb} resolution



Run 2 + partial Run 3 $HH(b\bar{b}\gamma\gamma)$

Several improvements performed to enhance the sensitivity!

$$\sigma_{ggF}^{SM}(m_H) = 34.1^{+2.2}_{-7.9}\ fb \text{ @ } 13.6 \text{ TeV } (+10\% \text{ wrt } 13 \text{ TeV})$$

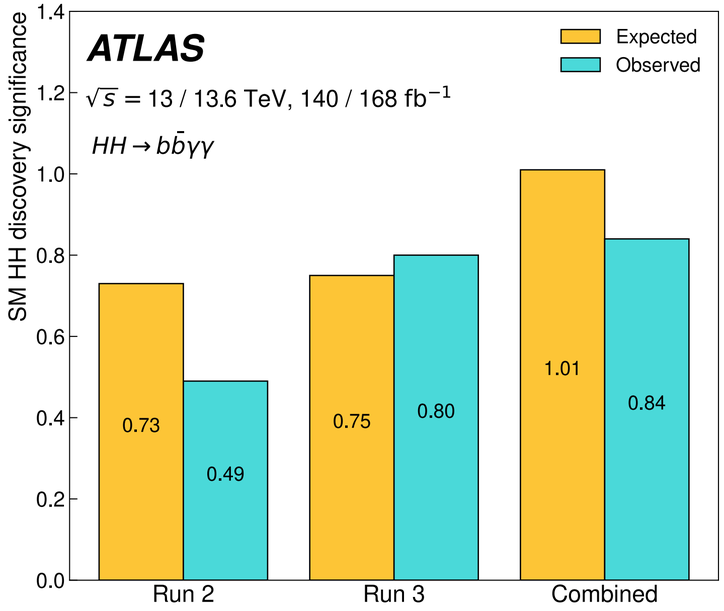
- Selection improved requiring ≥2 b-jets with GN2 $\epsilon_b = 85\ \%$
- Training simultaneous in Run 2 and Run 3 exploiting the correlation to categorize tighter
- Kinematic fit improving the m_{bb} resolution
- And of course $\times 2.2$ **more data !**

Run 2 + partial Run 3 $HH(b\bar{b}\gamma\gamma)$

Simultaneous fit in the 14 categories

Observed HH SM Significance: 0.8 σ

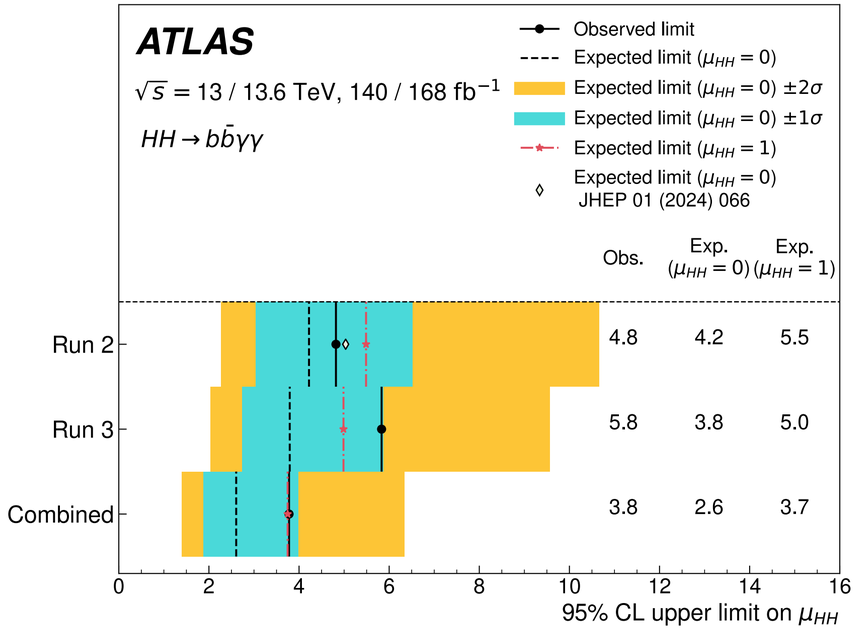
Expected HH SM Significance: 1.0 σ



Observed (Expected) upper limits @ 95% CL

on μ_{HH}: $3.8(2.6) \times SM$

! Comparable with Full Run 2 HH Combination

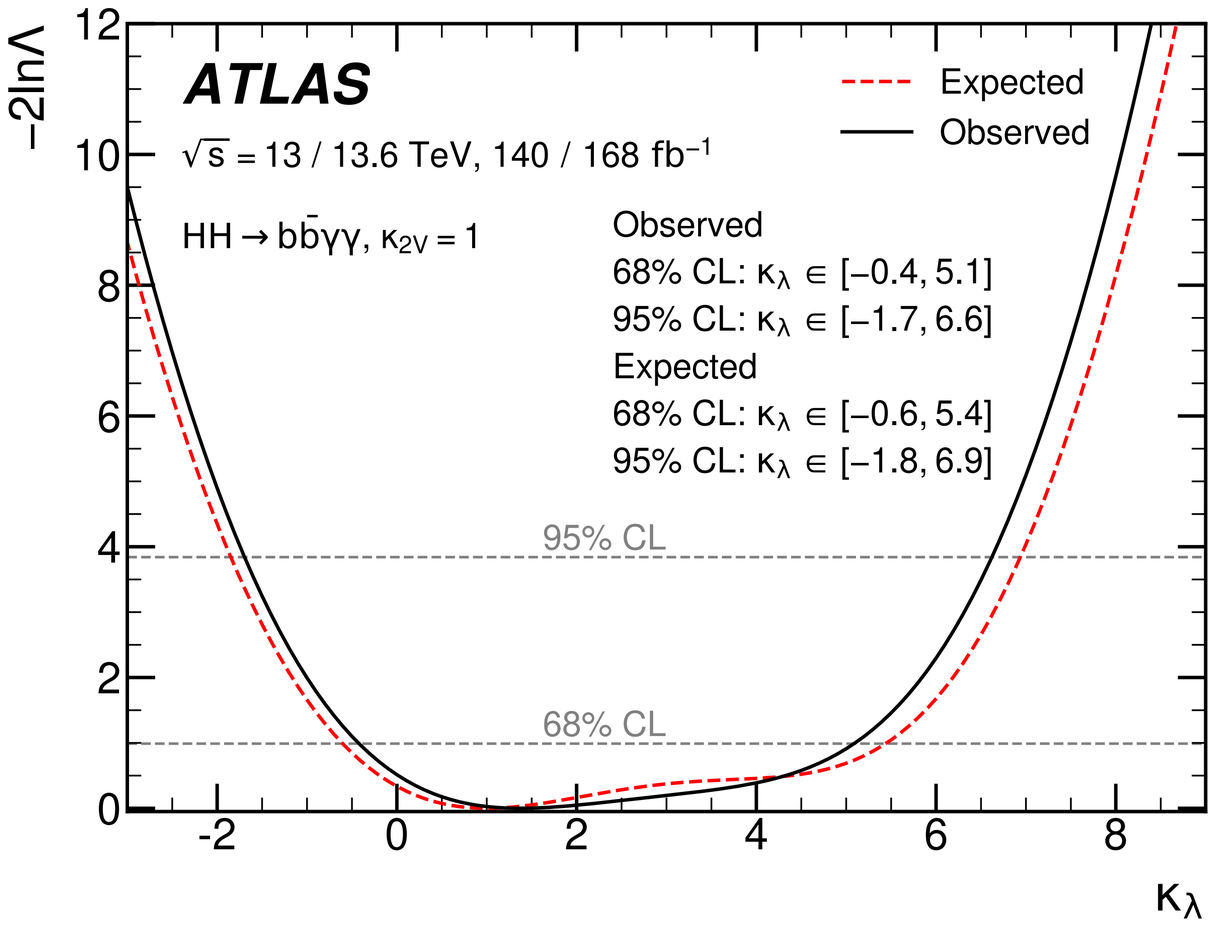


Run 2 + partial Run 3 $HH(b\bar{b}\gamma\gamma)$

Simultaneous fit in the 14 categories

Observed HH SM Significance: 0.8 σ

Expected HH SM Significance: 1.0 σ



Observed (Expected) upper limits @ 95% CL

on μ_{HH}: $3.8(2.6) \times SM$

! Comparable with Full Run 2 HH Combination

Observed (Expected) limits @ 68% CL:

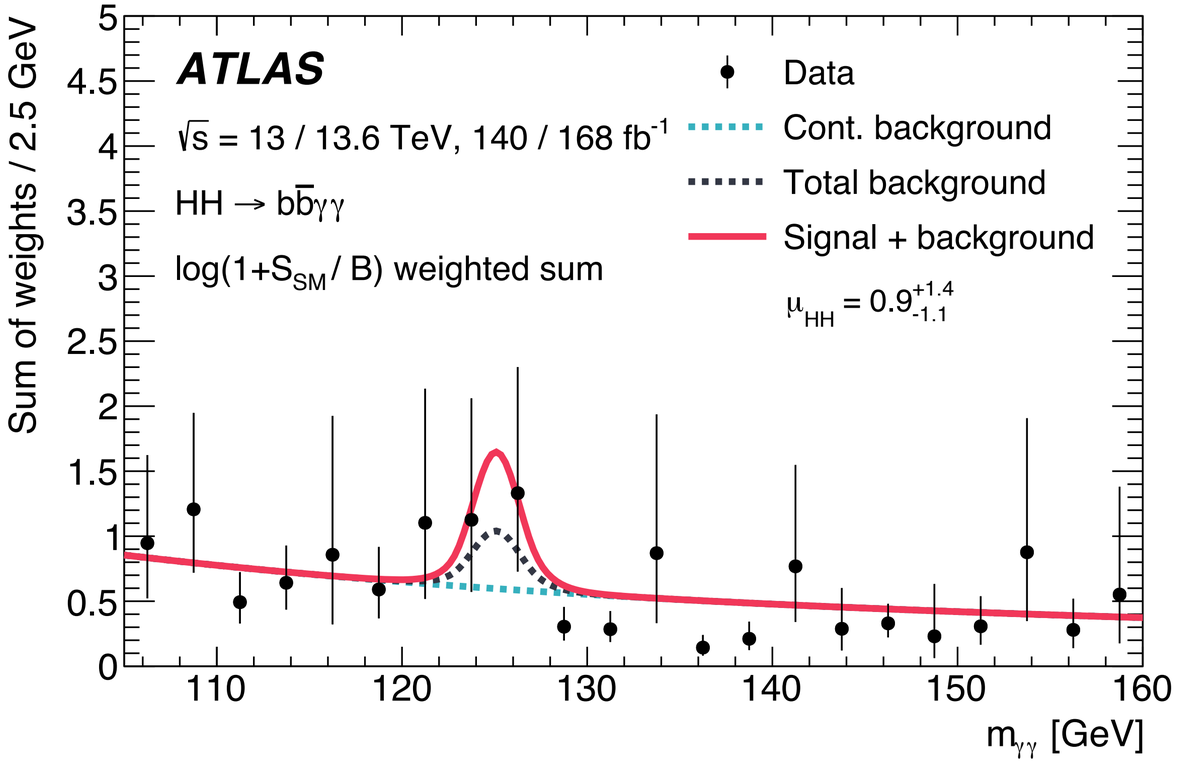
$\kappa_\lambda \in [-0.4,\ 5.1]([-0.6,\ 6.9])$

Run 2 + partial Run 3 $HH(b\bar{b}\gamma\gamma)$

Simultaneous fit in the 14 categories

Observed HH SM Significance: 0.8 σ

Expected HH SM Significance: 1.0 σ



Observed (Expected) upper limits @ 95% CL on μ_{HH}: $3.8(2.6) \times SM$

! Comparable with Full Run 2 HH Combination

Observed (Expected) limits @ 68% CL:

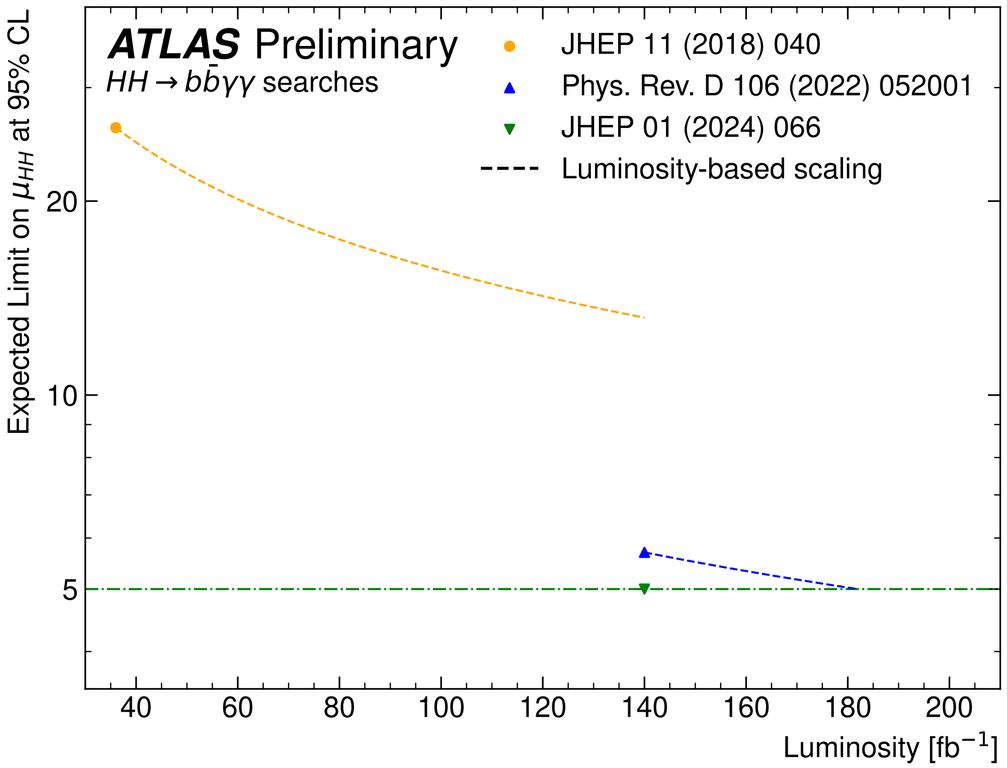
$\kappa_\lambda \in [-0.4,\ 5.1]([-0.6,\ 6.9])$

Better than the extrapolations

To have a feeling on what is the impact of all the analysis improvements let's look at lumi extrapolations

The Legacy Run 2 results was extrapolated to HL-LHC expected sensitivity in several scenarios!

Usually the extrapolations are conservative given many improvements happens along the way

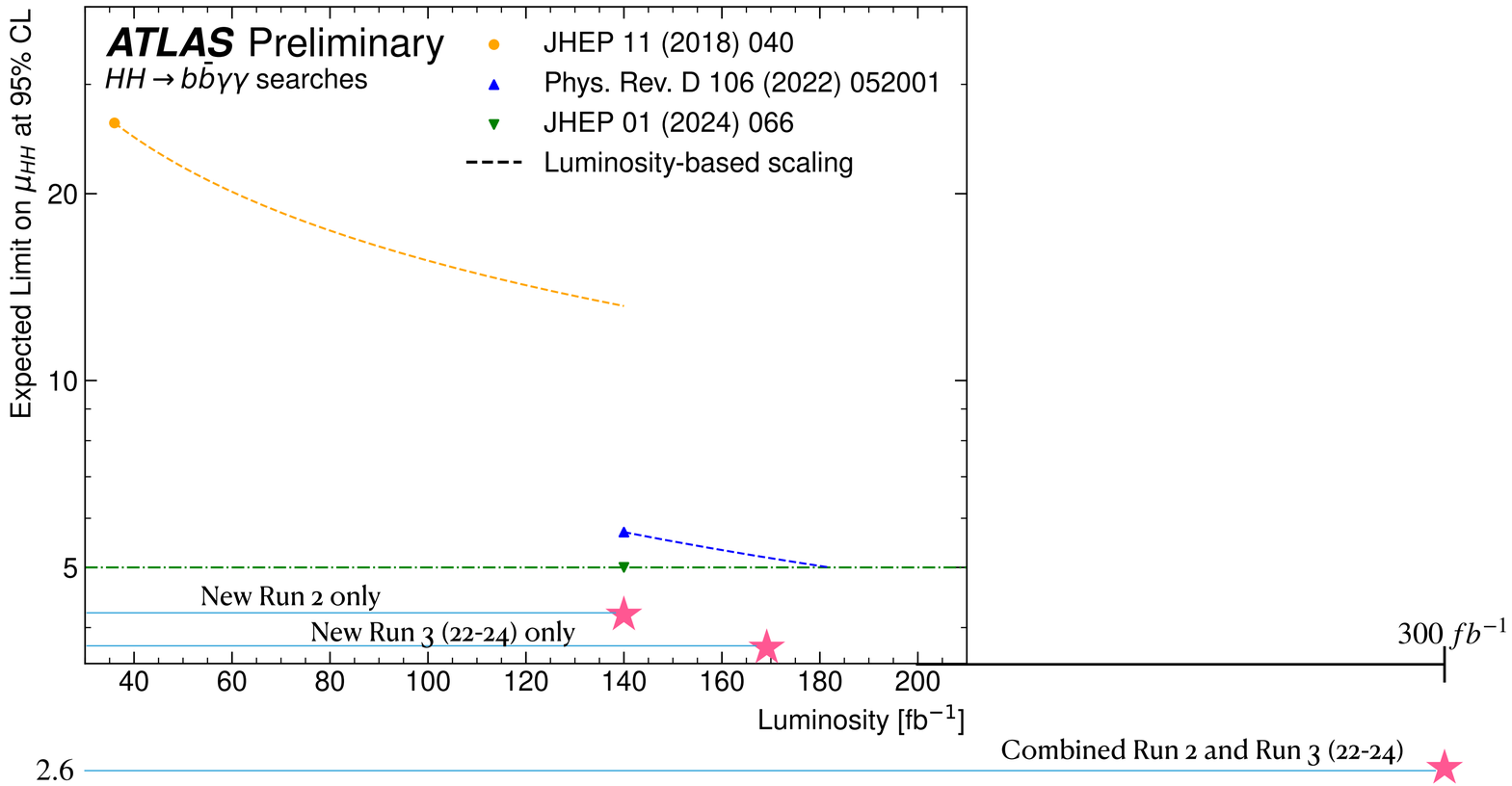


Better than the extrapolations

To have a feeling on what is the impact of all the analysis improvements let's look at lumi extrapolations

The Legacy Run 2 results was extrapolated to HL-LHC expected sensitivity in several scenarios!

Usually the extrapolations are conservative given many improvements happens along the way

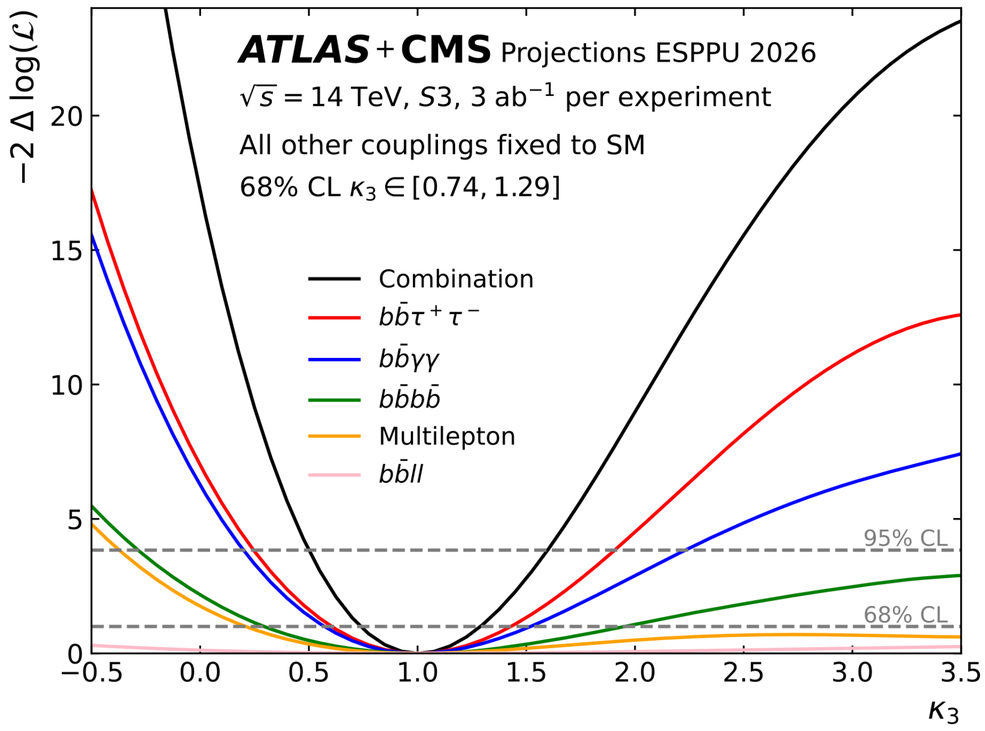


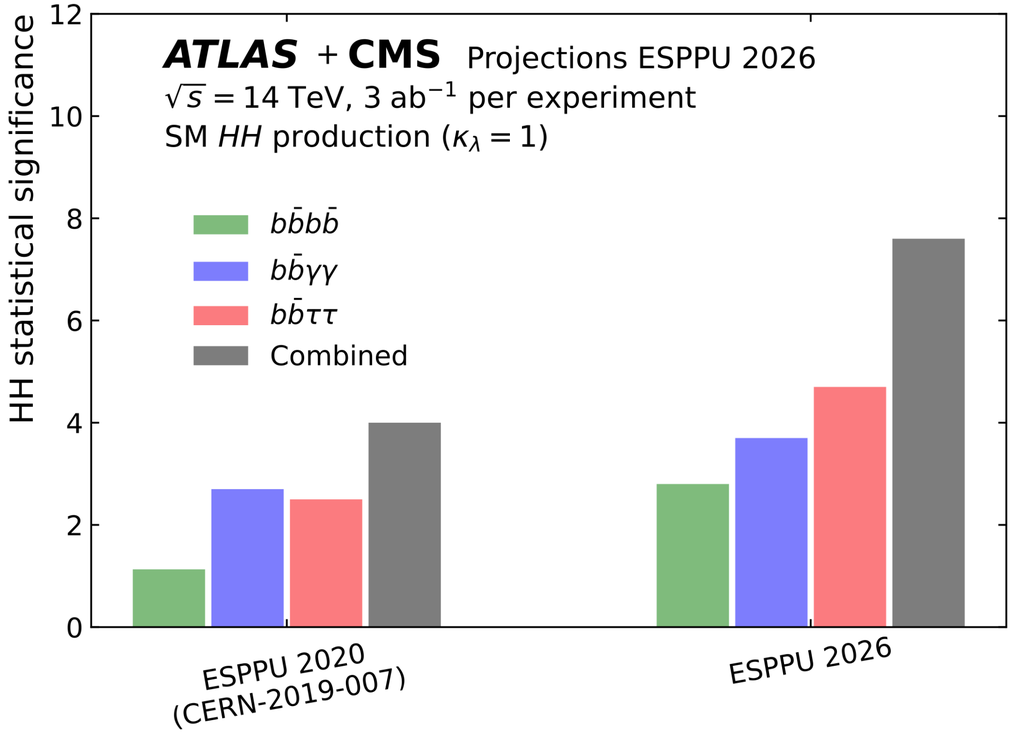
European Strategy Update

The Higgs pairs program plays a crucial role for HL-LHC program

All the HH analyses have been input to the European Strategy Update:

Highlights of the HL-LHC physics projections by ATLAS and CMS

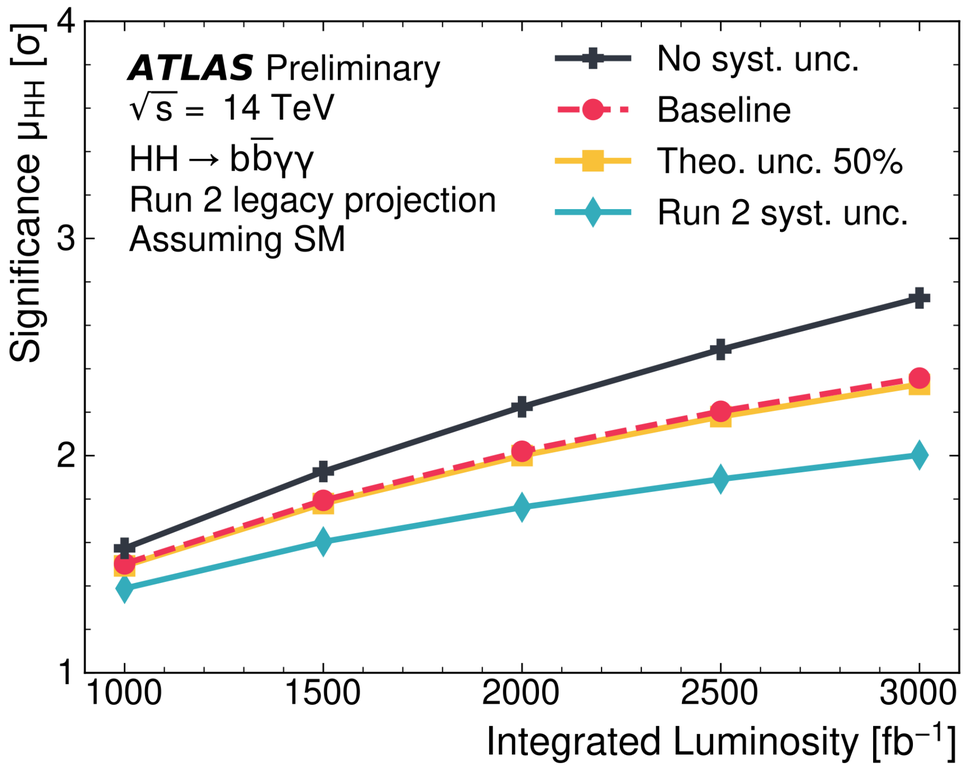




ATLAS HL-LHC Extrapolations

Assuming no improvements with respect to Run 2 legacy analyses!

$HH(b\bar{b}\gamma\gamma)$

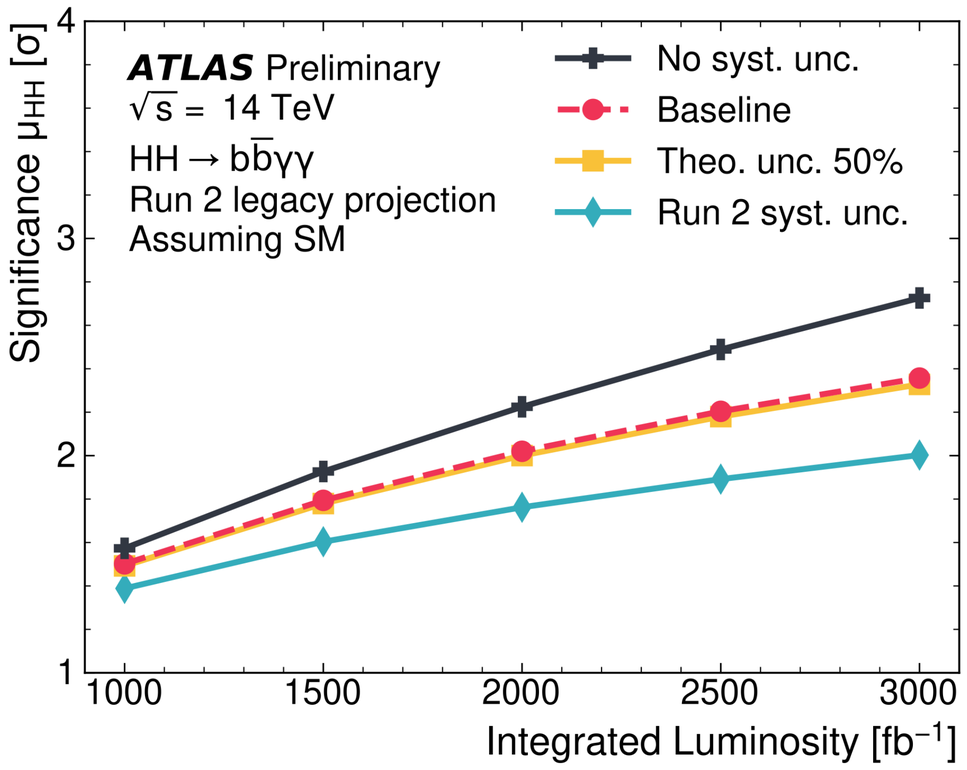


Expected $HH(b\bar{b}\gamma\gamma)$ SM Significance: 2.4 σ

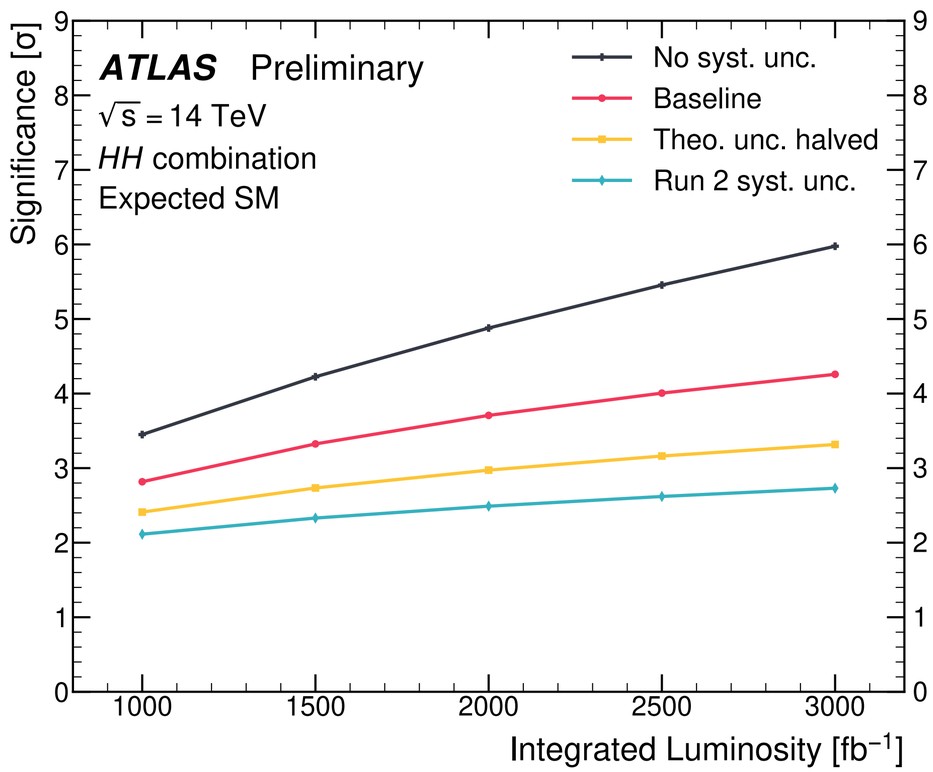
ATLAS HL-LHC Extrapolations

Assuming no improvements with respect to Run 2 legacy analyses!

$HH(b\bar{b}\gamma\gamma)$



HH

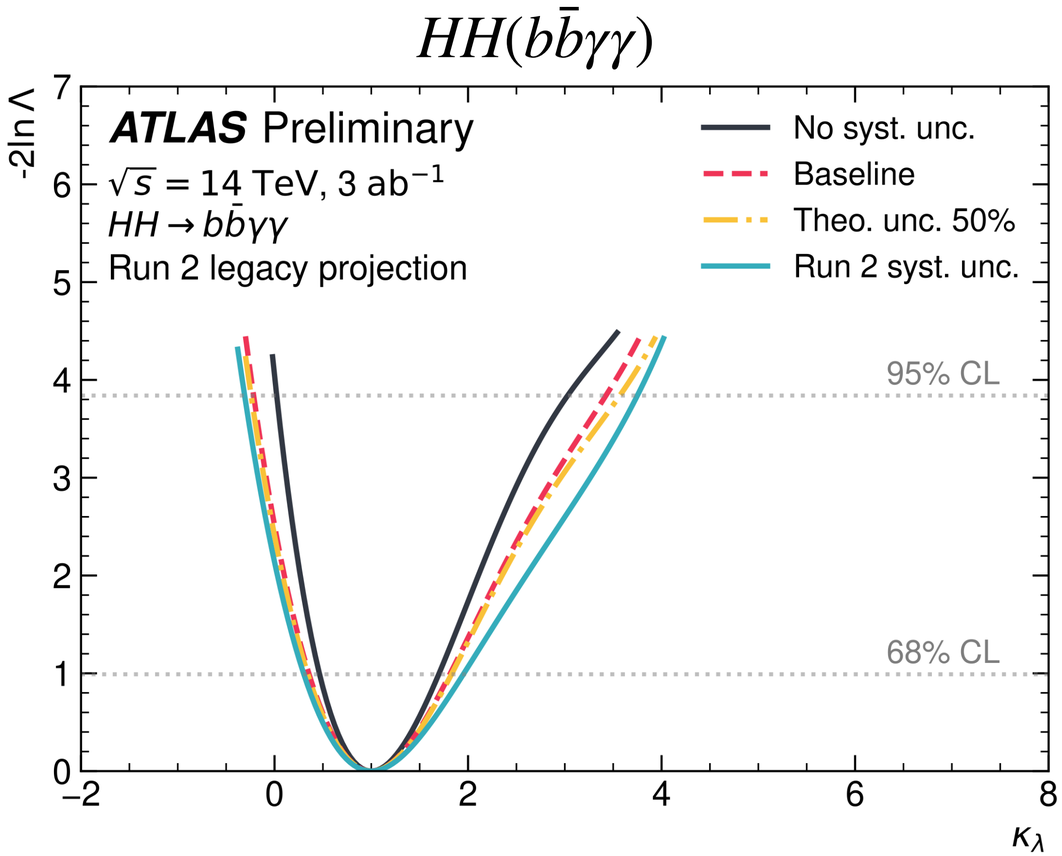


Expected $HH(b\bar{b}\gamma\gamma)$ SM Significance: 2.4 σ

Expected HH SM Significance: 4.1 σ

ATLAS HL-LHC Extrapolations

Assuming no improvements with respect to Run 2 legacy analyses!

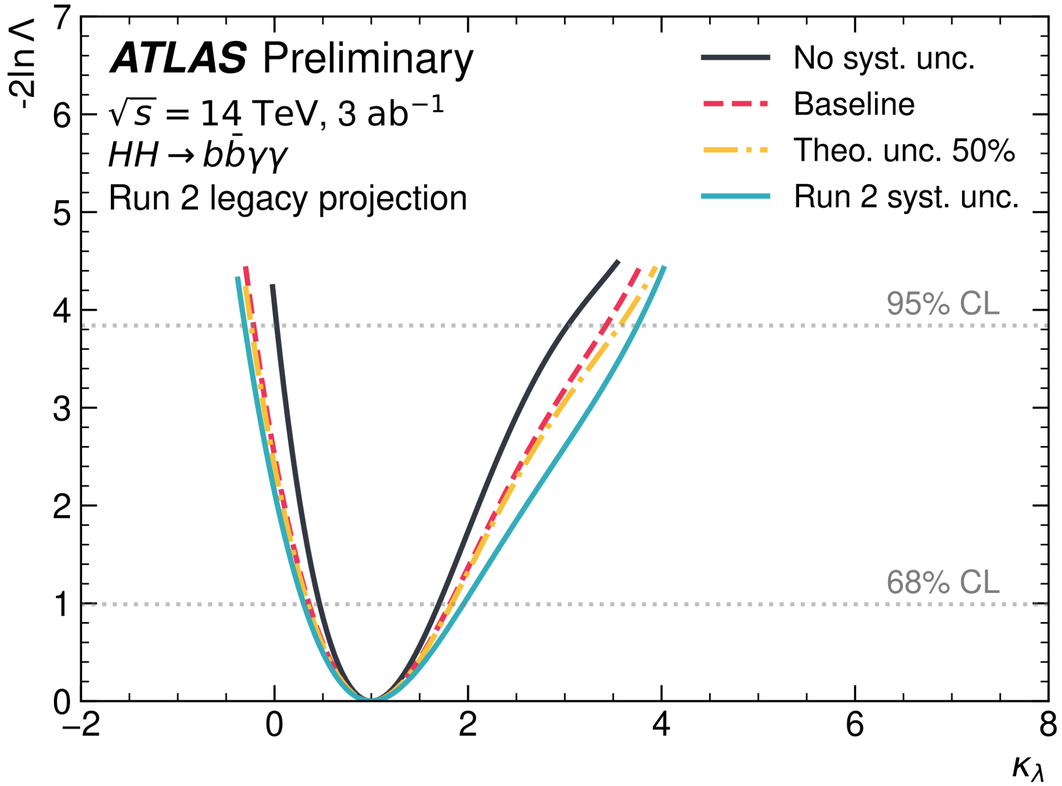


Expected limits at 68% CL: $\kappa_\lambda \in [0.4,\ 1.8]$

ATLAS HL-LHC Extrapolations

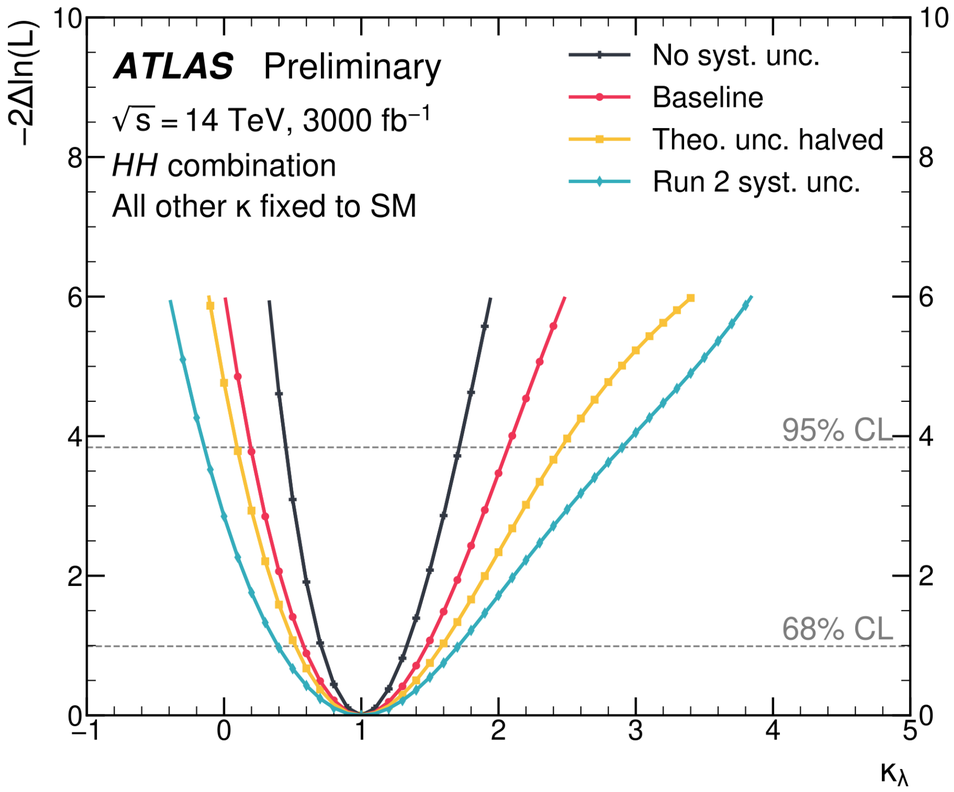
Assuming no improvements with respect to Run 2 legacy analyses!

$HH(b\bar{b}\gamma\gamma)$



Expected limits at 68% CL: $\kappa_\lambda \in [0.4,\ 1.8]$

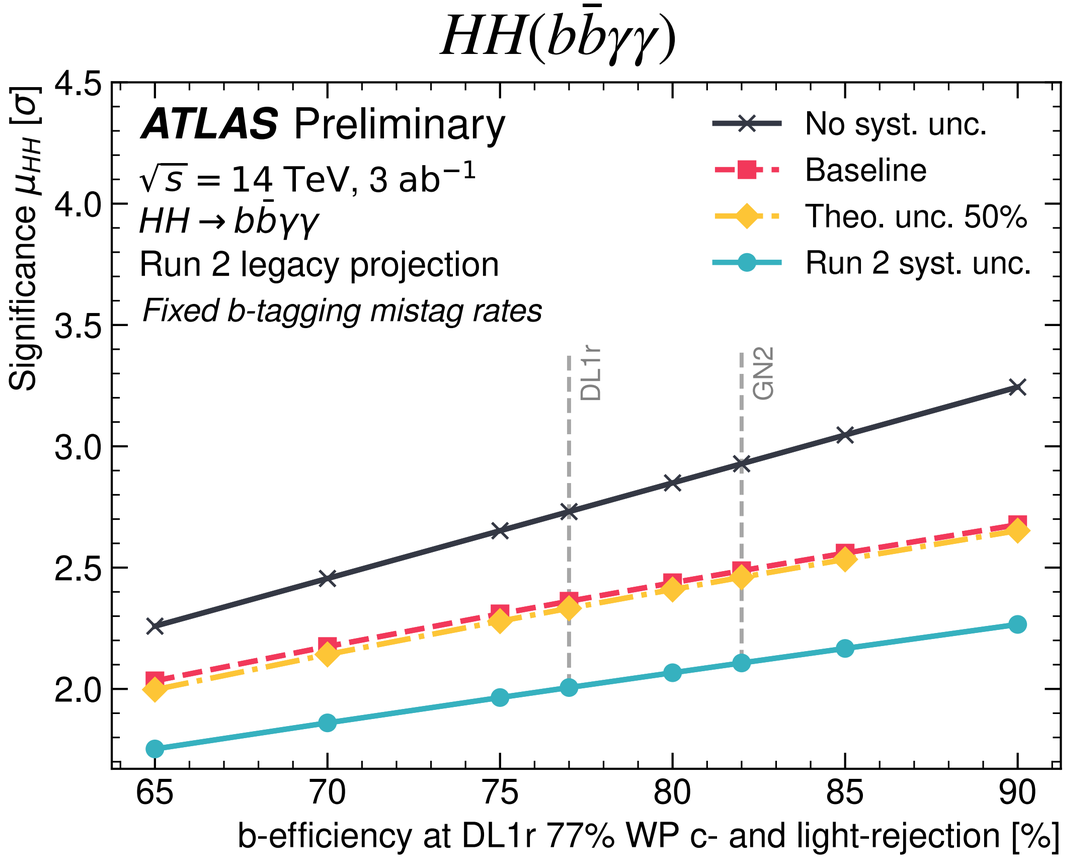
HH



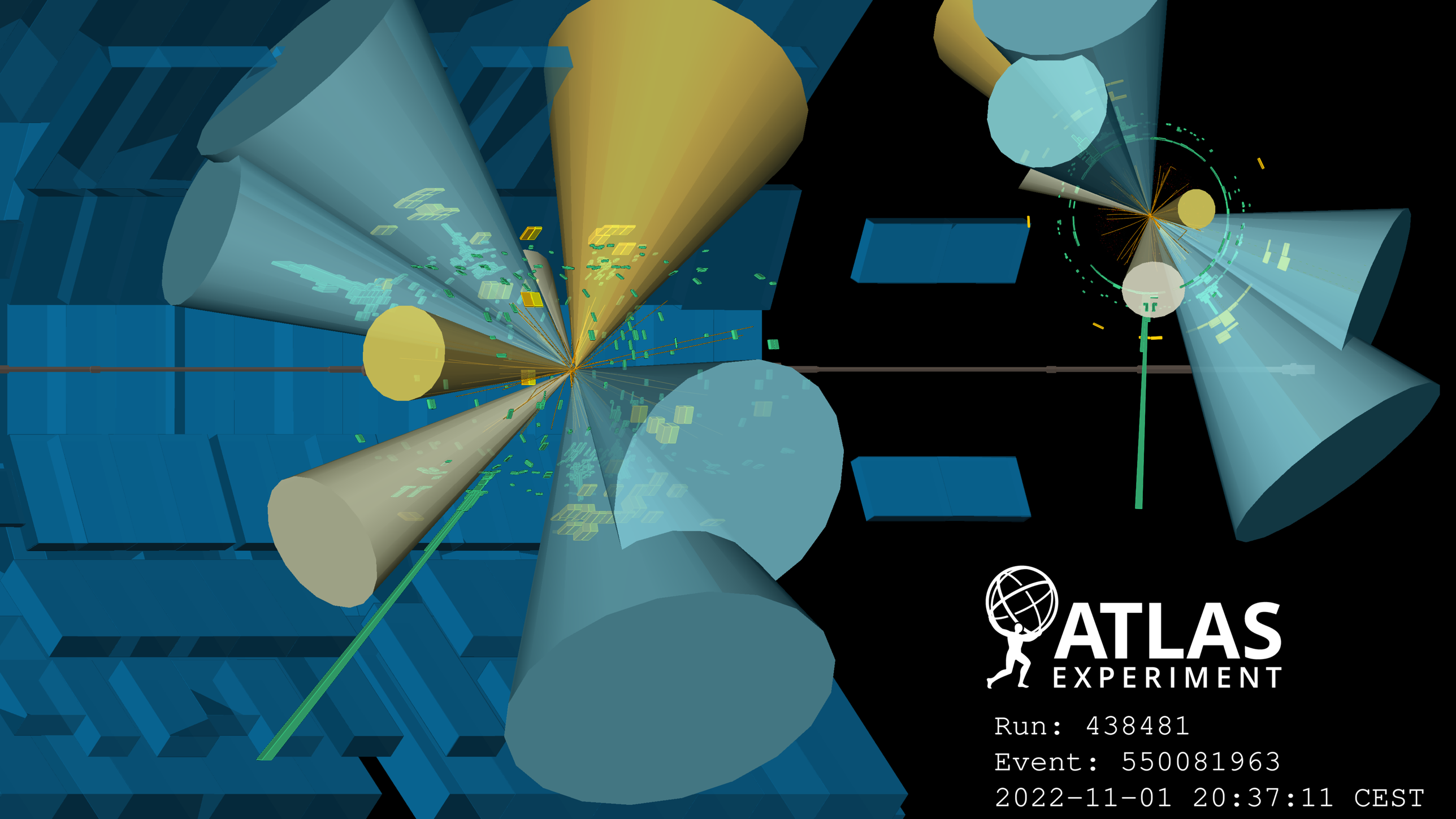
Expected limits at 68% CL: $\kappa_\lambda \in [0.71,\ 1.48]$

Impact from performance improvements

Improvements in combined performances *directly* reflect into sensitivity improvements



+5% improvement assuming no optimization

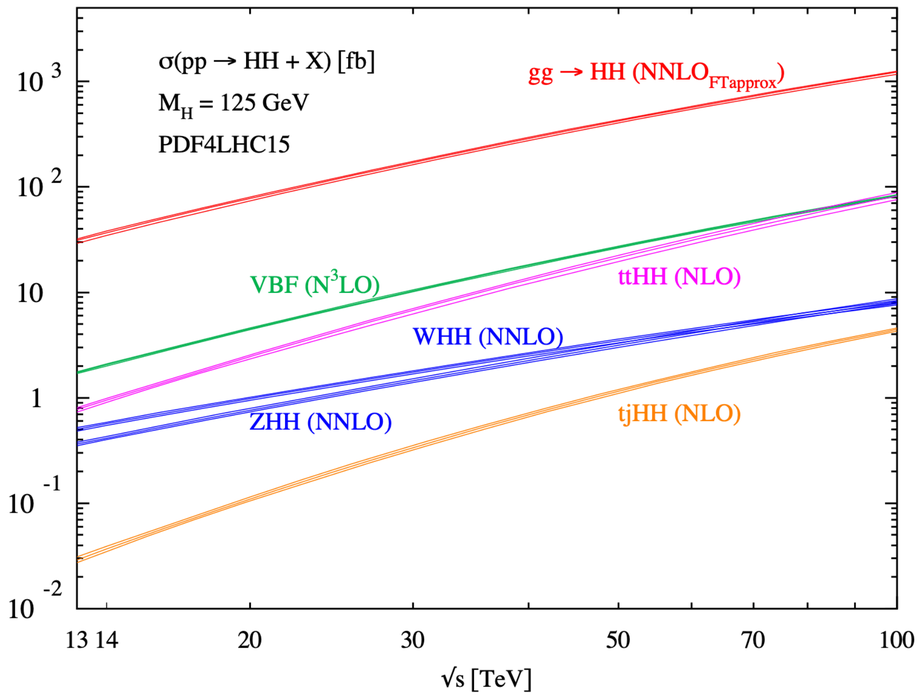

ATLAS
EXPERIMENT
Run: 438481
Event: 550081963
2022-11-01 20:37:11 CEST

The first ttHH search

- **ttHH production** is the **3rd leading HH production**
- the **x-sec increases faster** with $\sqrt{s}$ than VBF

$$\sigma_{ttHH}(13TeV) = 0.756\ fb$$

$$\sigma_{ttHH}(13.6TeV) = 0.860\ fb$$



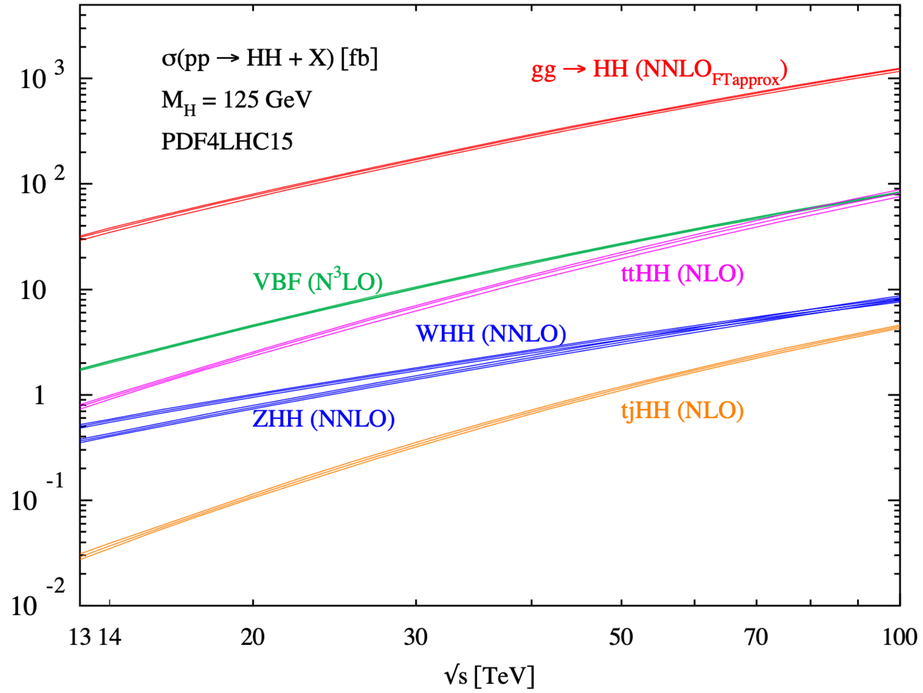
The first ttHH search

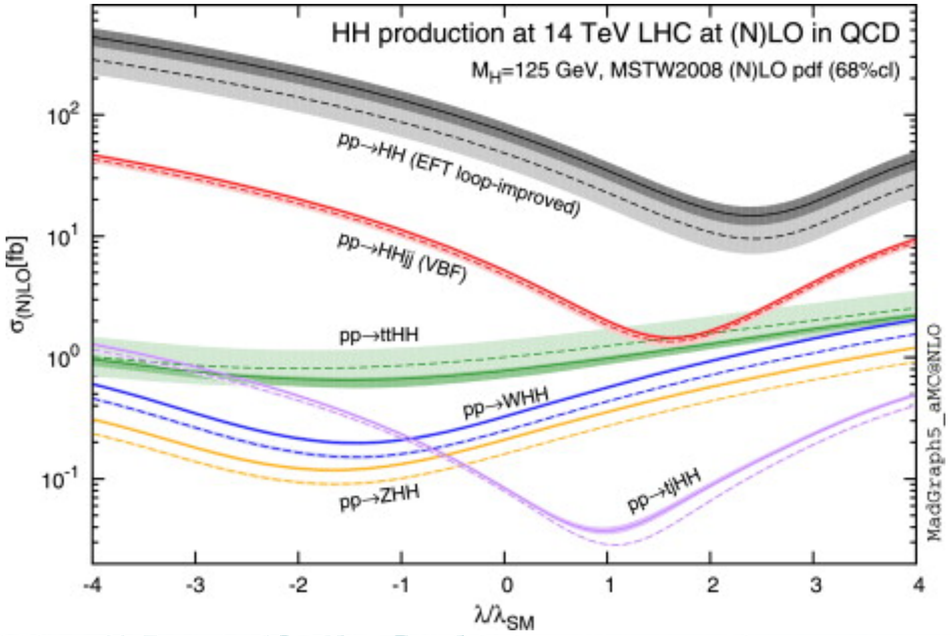
- **ttHH production** is the **3rd leading HH production**
- the **x-sec increases faster** with $\sqrt{s}$ than VBF

$$\sigma_{ttHH}(13TeV) = 0.756\ fb$$

$$\sigma_{ttHH}(13.6TeV) = 0.860\ fb$$

- no destructive interference



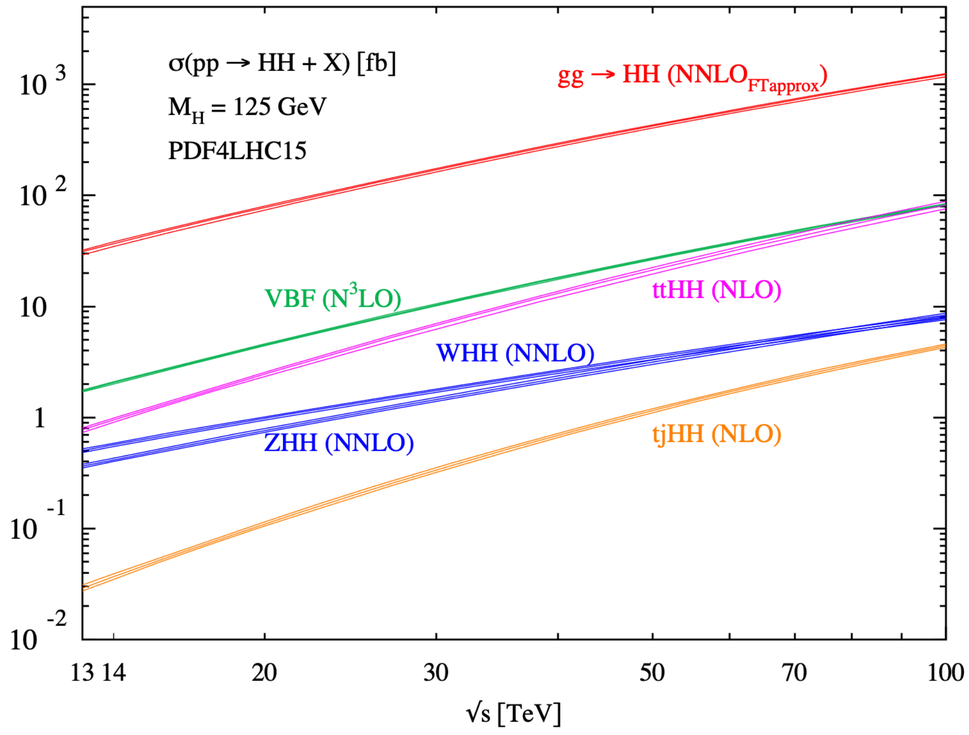


The first ttHH search

- **ttHH production** is the **3rd leading HH production**
- the **x-sec increases faster** with $\sqrt{s}$ than VBF

  $\sigma_{ttHH}(13TeV) = 0.756\ fb$

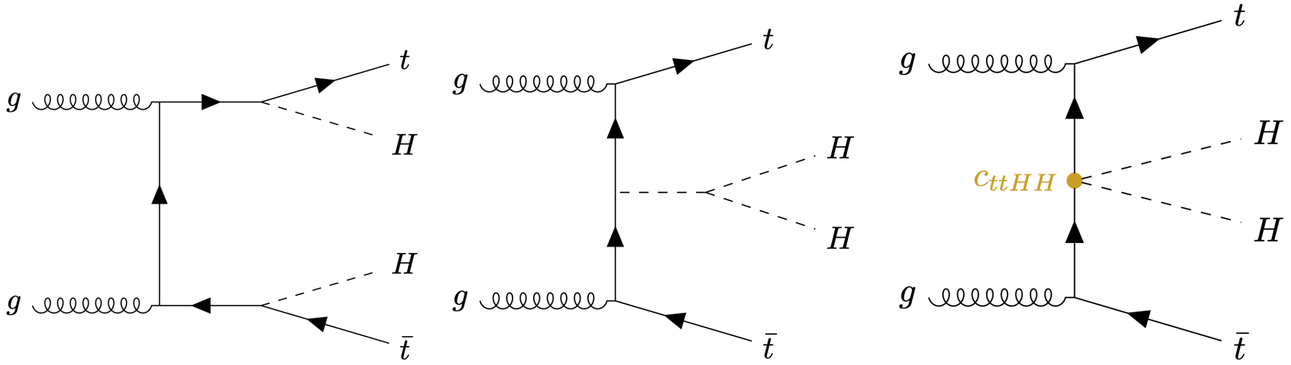
  $\sigma_{ttHH}(13.6TeV) = 0.860\ fb$
- no destructive interference



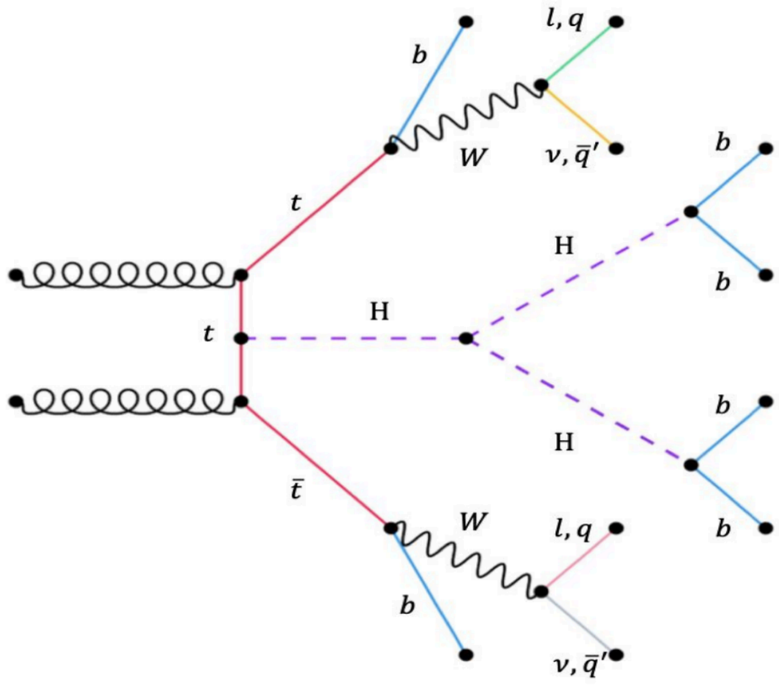
Direct access to anomalous ttHH quartic interaction

- quadratic dependence $\sigma(ttHH) \propto c_{ttHH}^2$
- constraints from ggF and VBF comb. paper

  $c_{ttHH} \in [-0.19,\ 0.70]$ @ 95% CL



The final states



- Very complex final state with 2 H and 2 Tops
- **high b-jet multiplicity to increase the BR**

	HH	bb	WW	ττ	ZZ	γγ
1L	bb	34%				
ML	WW	25%	4.6%			
ML	ττ	7.3%	2.7%	0.39%		
ML	ZZ	3.1%	1.1%	0.33%	0.069%	
$b\bar{b}\gamma\gamma$	γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

This is the first ttHH analysis published!

The final states

First ATLAS ttHH search using Run 2 + Partial (22+23) Run 3

Targeting 3 Final States:

- **1L**: HH $\rightarrow 4b$
- **ML**: non all -hadronic decay modes
- $b\bar{b}\gamma\gamma$: clean and nearly background free signature

	HH	bb	WW	ττ	ZZ	γγ
1L	bb	34%				
ML	WW	25%	4.6%			
ML	ττ	7.3%	2.7%	0.39%		
ML	ZZ	3.1%	1.1%	0.33%	0.069%	
$b\bar{b}\gamma\gamma$	γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Focus on **1L** channel, capturing 20% of all the produced ttHH events!

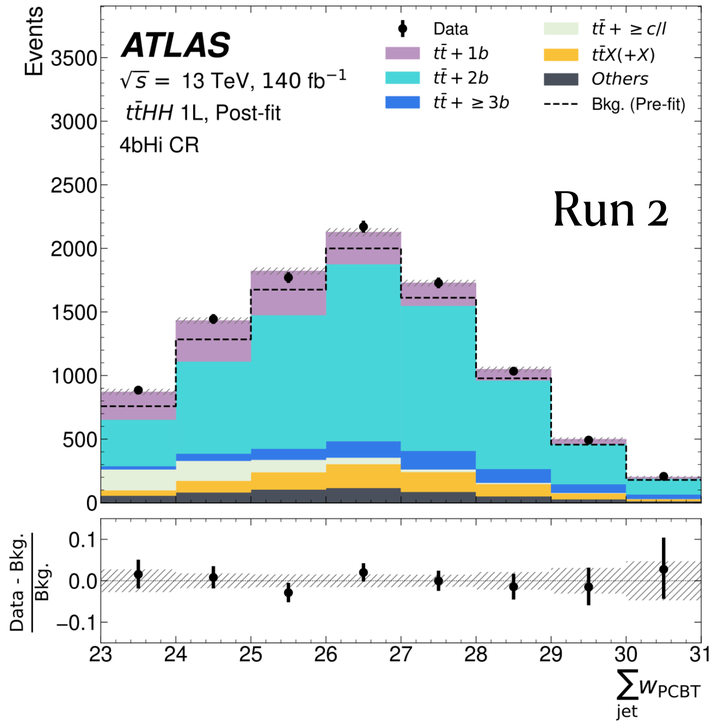
Analysis categories

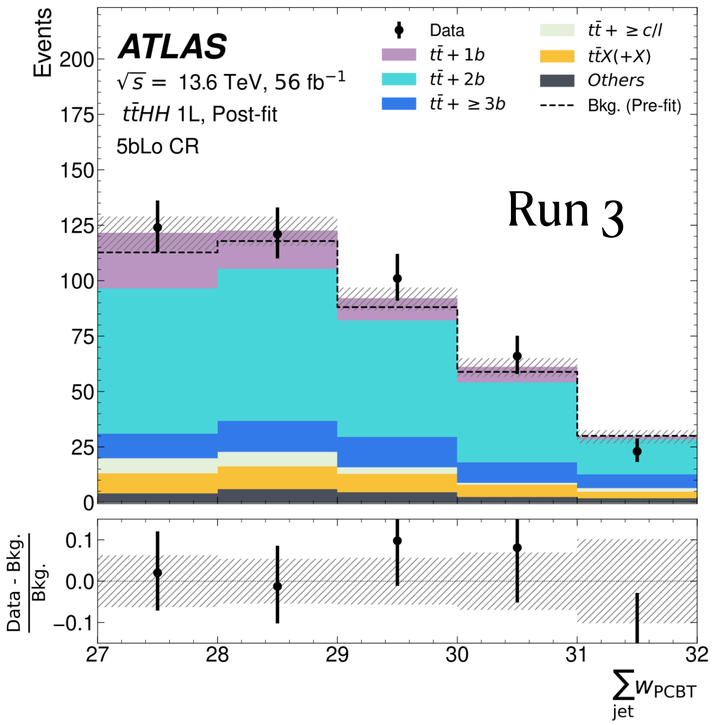
The regions are defined by the number of b-tagged jets (N_b)

The main background is $t\bar{t}$+jets

Very complicated the modelling at high jet multiplicity

Region	Type	$N_b^{85\%}$	$N_b^{77\%}$	Fit variable
$4b_{\mathrm{Hi}}$	CR	4	4	$\sum_{\mathrm{jet}} w_{\mathrm{PCBT}}$
$5b_{\mathrm{Lo}}$	CR	5	≤ 4	$\sum_{\mathrm{jet}} w_{\mathrm{PCBT}}$
$5b_{\mathrm{Hi}}$	SR	5	5	Transformer output
$6b$	SR	≥ 6	–	Transformer output





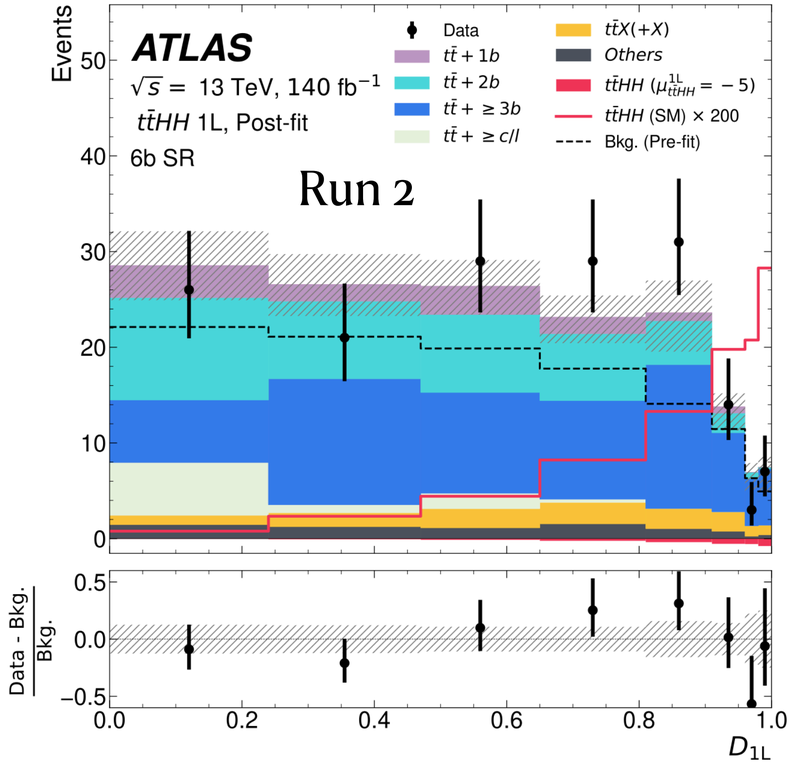
Transforming the analysis

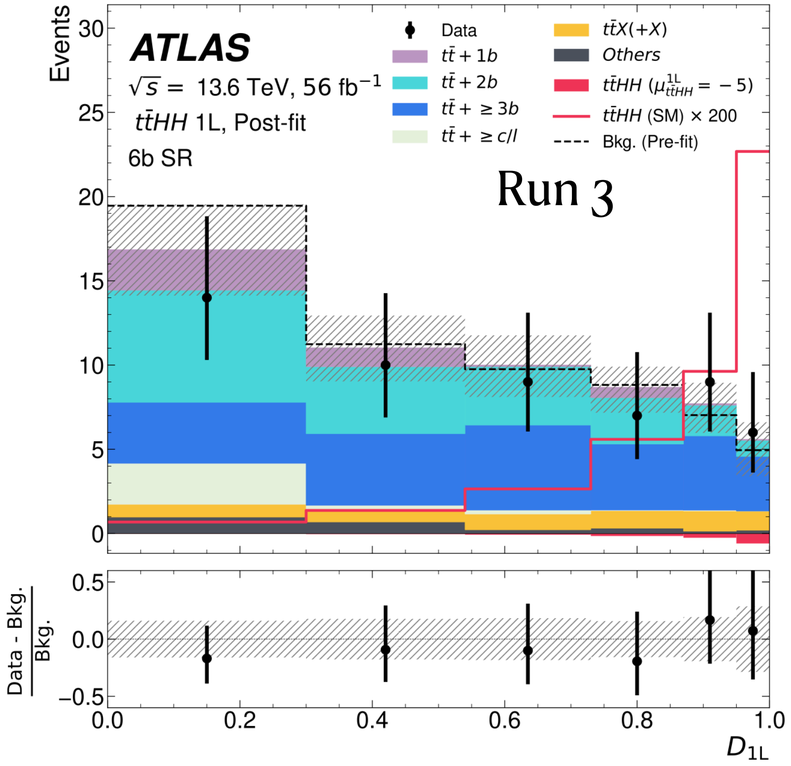
A transformer model is trained to separate signal from background in signal region:

Pros: benefit from high jet multiplicity exploiting multidimensional correlations!

Cons: learning strongly depending on the MC modelling of input samples

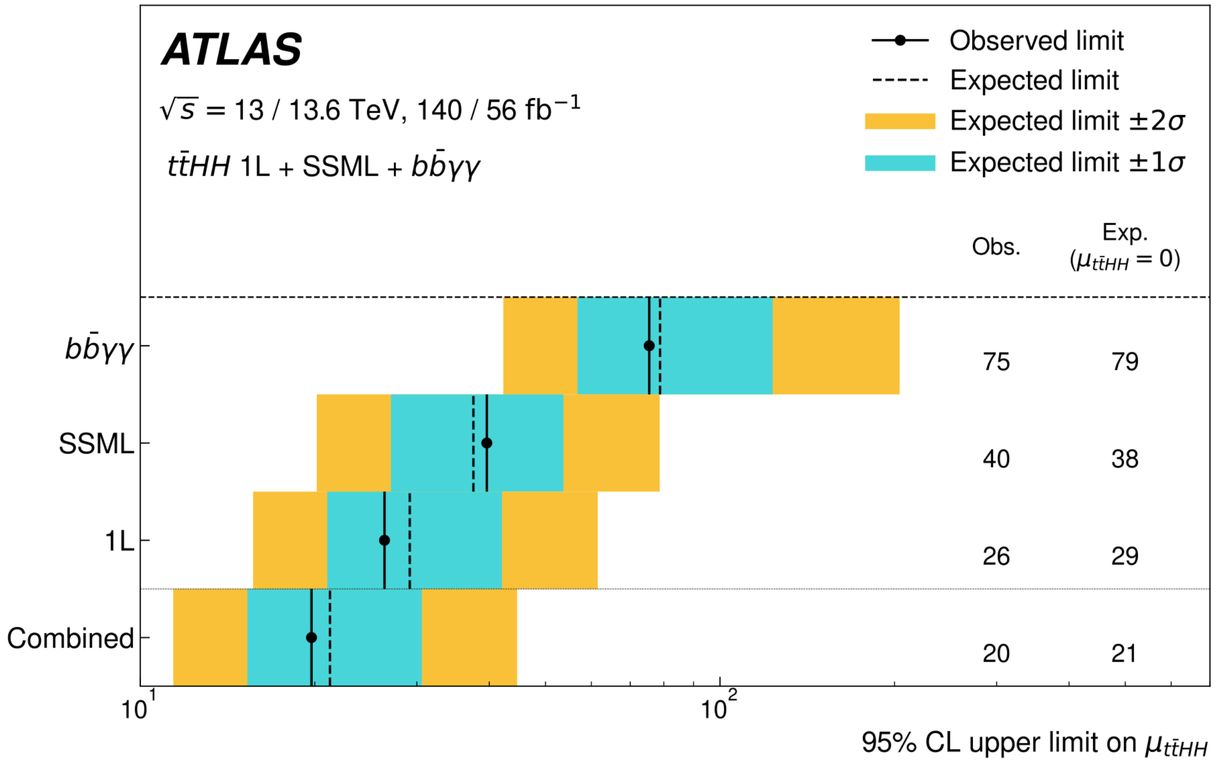
The transformer model is very similar to GN2. The tokens are the jets and leptons in place of tracks!





Results and EFT

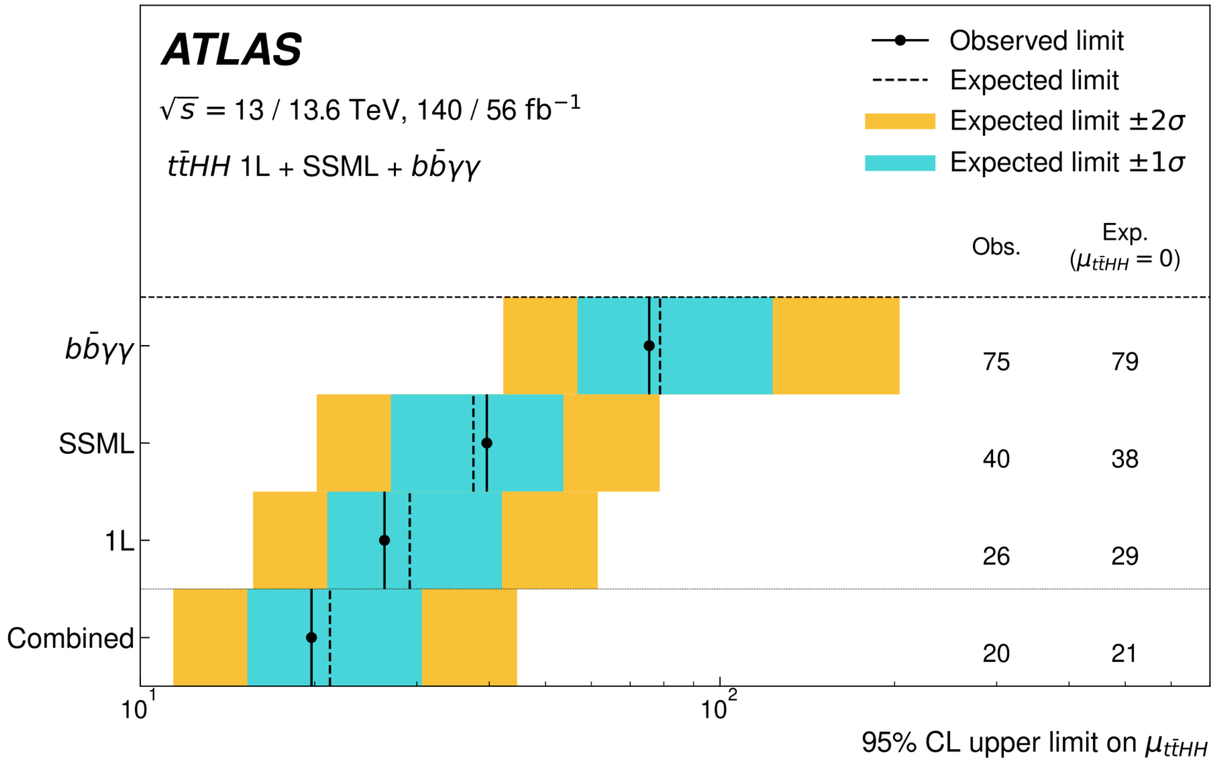
Combining 1L with the other two channels (ML, $b\bar{b}\gamma\gamma$)



Upper limits on μ_{ttHH} is 20(21) x SM

Results and EFT

Combining 1L with the other two channels (ML, $b\bar{b}\gamma\gamma$)



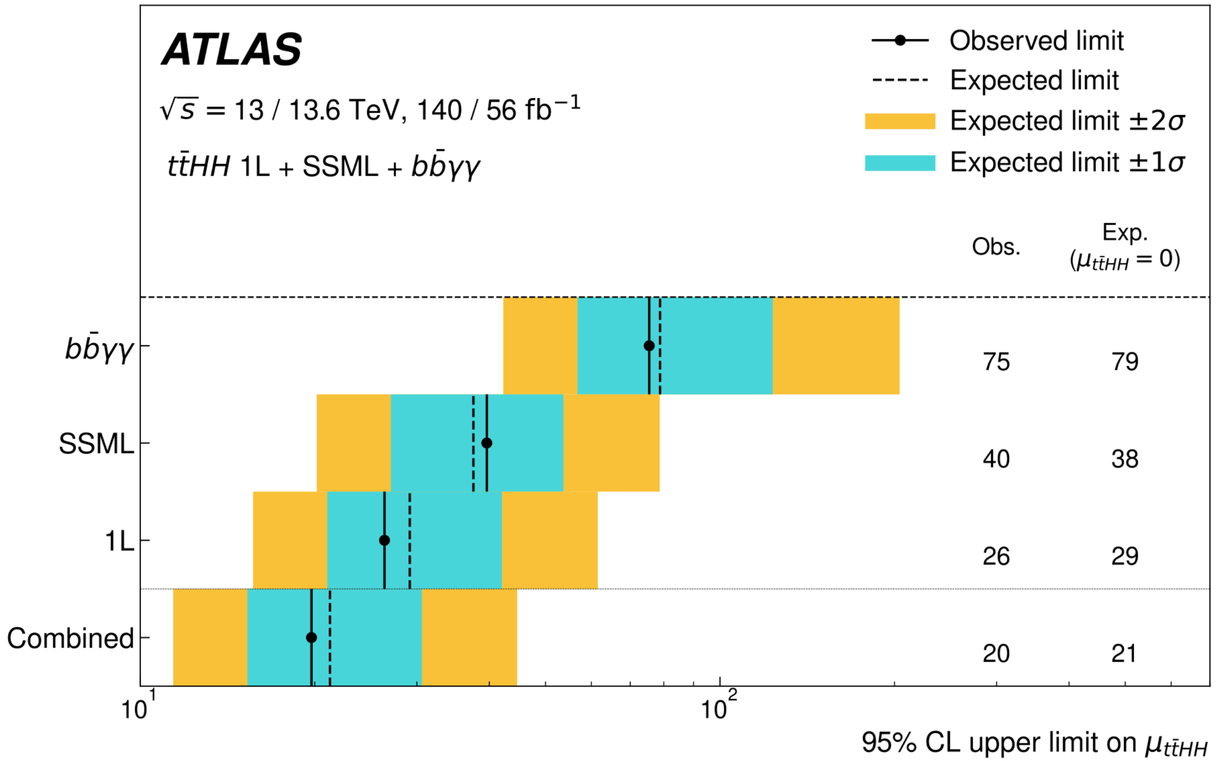
Channel	Best fit $\mu_{t\bar{t}HH}$
1L	-5^{+15}_{-15}
SSML	5^{+17}_{-21}
$b\bar{b}\gamma\gamma$	-13^{+35}_{-6}
Combination	-3^{+11}_{-12}

Signal Strength compatible with the SM!

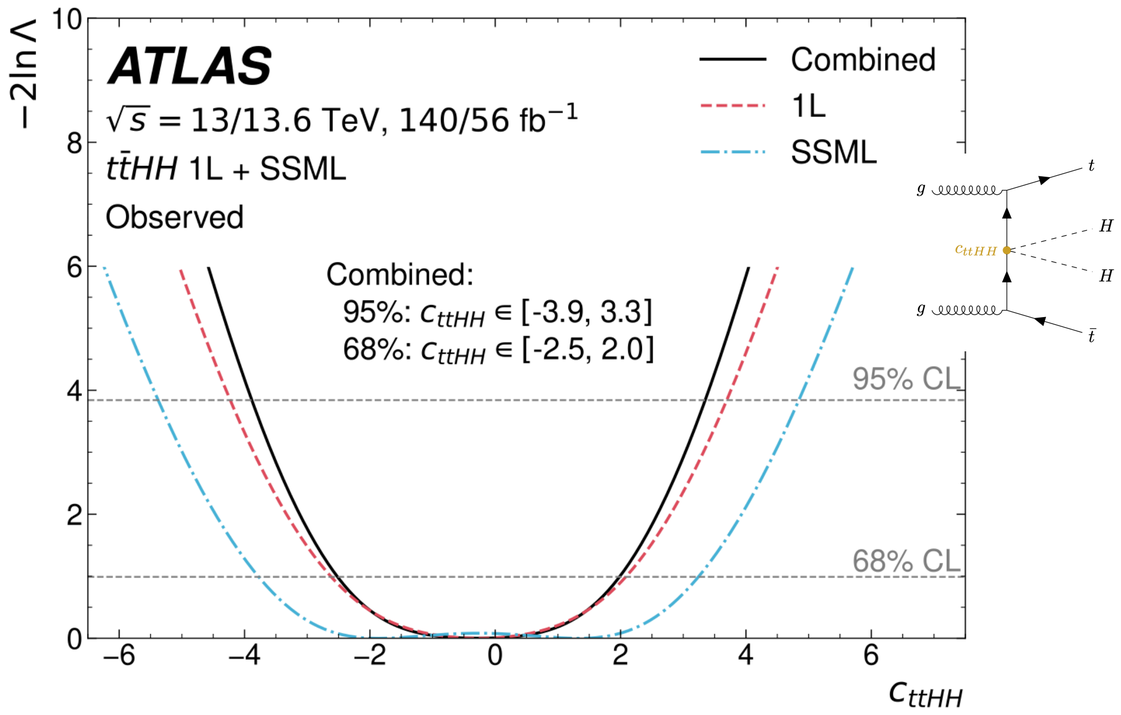
Upper limits on μ_{ttHH} is 20(21) x SM

Results and EFT

Combining 1L with the other two channels (ML, $b\bar{b}\gamma\gamma$)



Upper limits on μ_{ttHH} is 20(21) x SM



Limits at 95% on $c_{ttHH} \in [-2.5,\ 2.0]$

Being weakly dependent from k_λ and knowing precisely k_t an EFT interpretation of k_{ttHH} is performed

Worst limits compared to ggF ($c_{ttHH} \in [-0.2,\ 0.7]$) but less assumptions are made on other couplings!

Conclusions

Flavour tagging:

- GN2 (Nature, 2025): ×3.5 c-jet and ×1.6 light-jet rejection over DL1d at ε_b = 70%
- A new better model GN3 is already approaching hopefully in place for the Full Run 3 analyses

$VH(b\bar{b}\,|\,c\bar{c})$ — **Run 2, 140 fb^{-1}**

- First observation of $WH(b\bar{b})$: 5.3σ observed (5.5 expected)!
- $\mu_{VH}^{bb} = 0.91 \pm 0.15$ => ~15% precision on the b-Yukawa in VH
- Best limit on $VH(c\bar{c})$: 11 × SM observed, |κ_c| < 4.2 at 95% CL

$HH(b\bar{b}\gamma\gamma)$ — **Run 2** + **partial Run 3, 140** + **168 fb^{-1}**

- μ_{HH} < 3.8 (2.6) × SM observed (expected), 0.8σ observed significance
- A single channel now matches the full Run 2 HH combination

$t\bar{t}HH$ — **the first search of its kind**

- μ_{ttHH} < 20 (21) × SM; $c_{ttHH} \in [-3.9, 3.3]$ at 95% CL
- Weaker than ggF/VBF, but with far fewer assumptions on the other couplings

Outlook

- $H(c\bar{c})$: **evidence (3σ) is becoming a realistic** HL-LHC target
- HH: 4.1σ expected from the ATLAS combination at 3 ab^{-1} *assuming no analysis improvements*
  - This assumption is already conservative from DL1r => GN2

- $k_\lambda \in [0.71, 1.48]$ at 68% CL projected: the shape of the Higgs potential is finally within reach
- Run 3 is still being analysed:
  - GN2-based VH(bb|cc)
  - Full Run 3 HH(bbγγ)
  - GN3 deployment and calibration all in progress

Backup