

Studying Higgs Boson Self-Interactions at the ATLAS Experiment

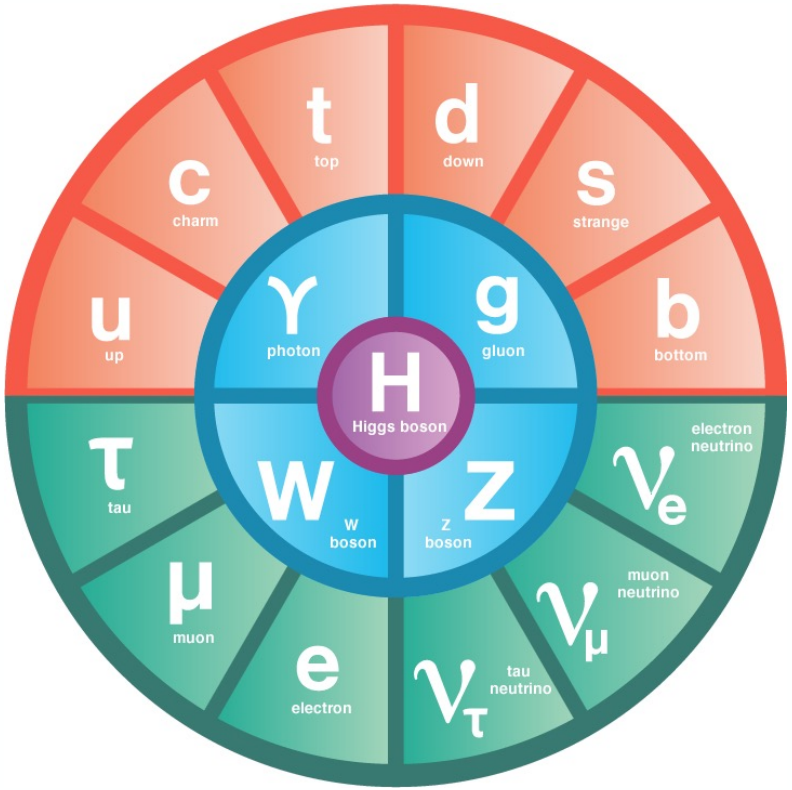
Seminar – Brown University
16th April 2025

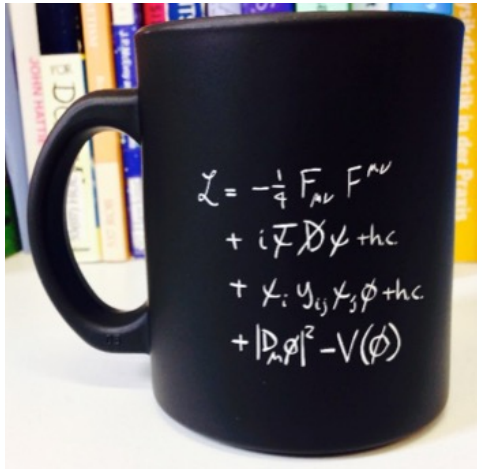
Rachel Hyneman, University of Arizona

Introduction

Why do we care about Higgs Boson self-interactions?

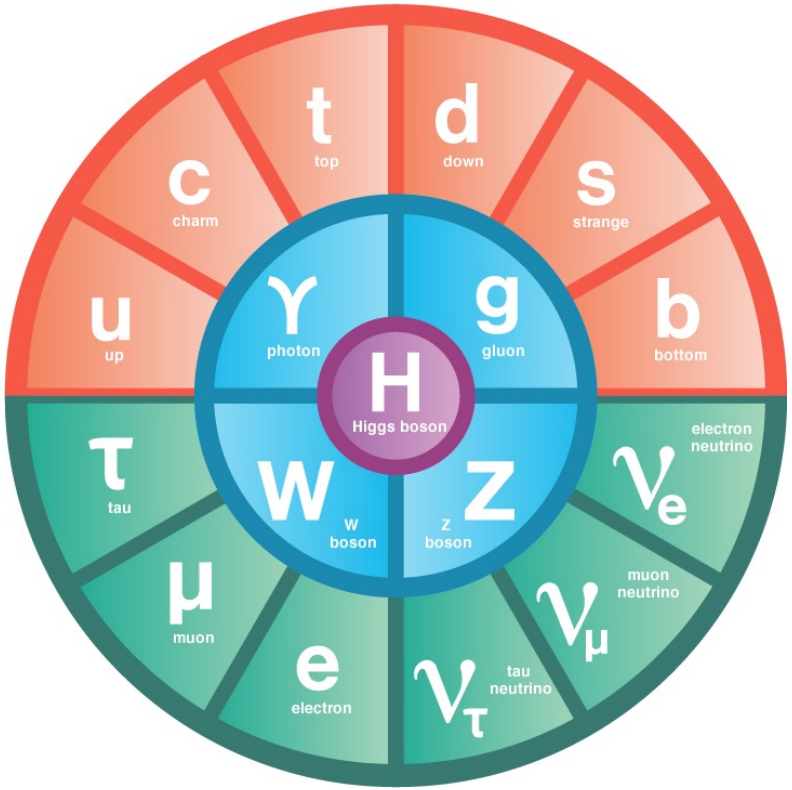
The Standard Model of Particle Physics



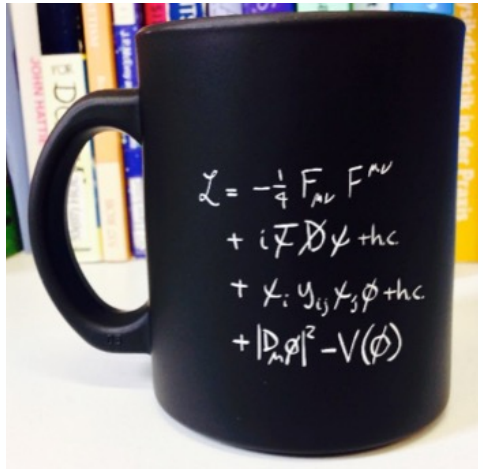


Symmetry Magazine

The Standard Model of Particle Physics



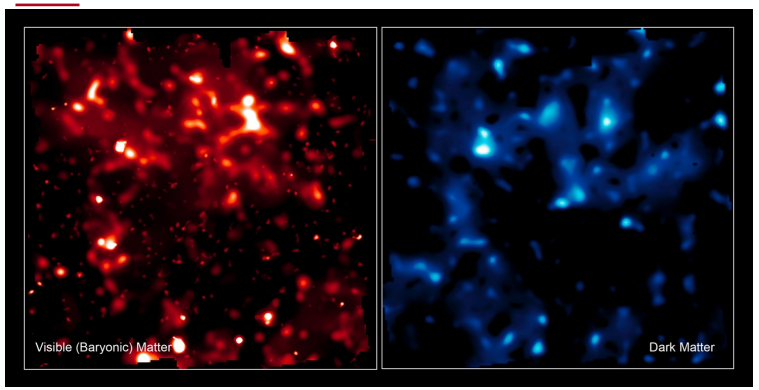
Symmetry Magazine



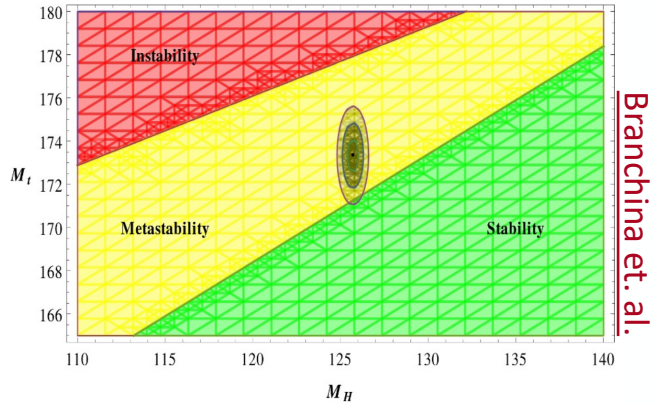


Why is there more Matter than Anti-Matter?

ESA What is Dark Matter?



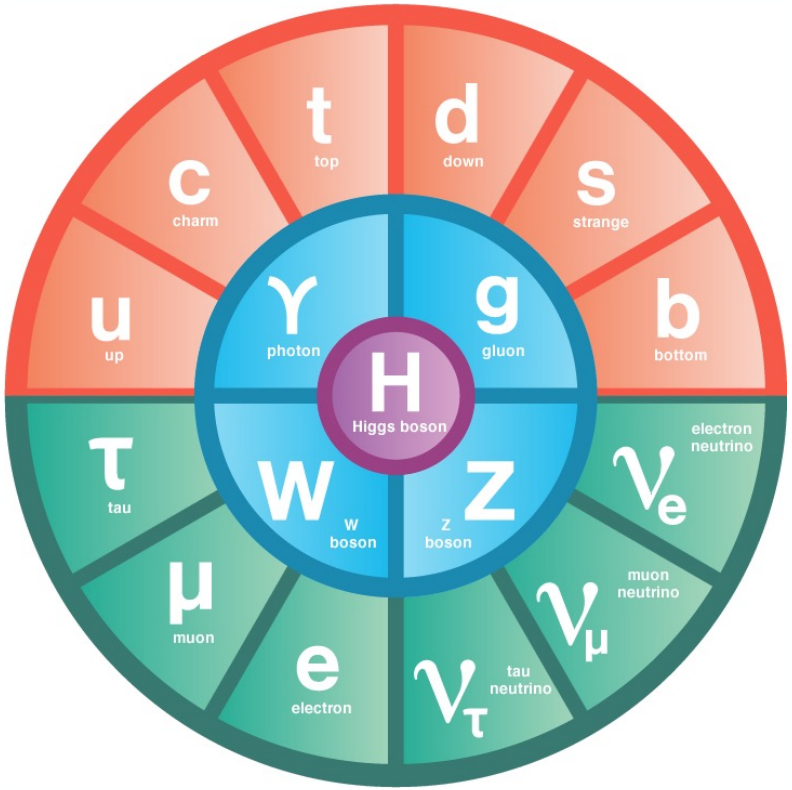
Is our universe stable?



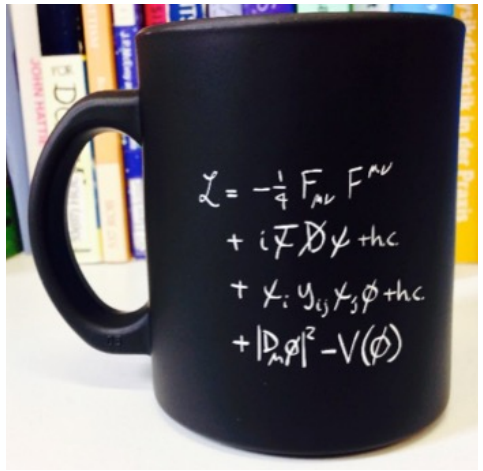
Branchina et. al.

The Standard Model of Particle Physics





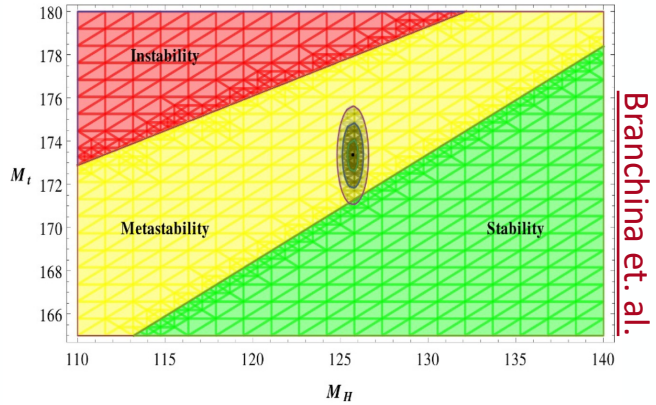
Symmetry Magazine





Why is there more Matter than Anti-Matter?

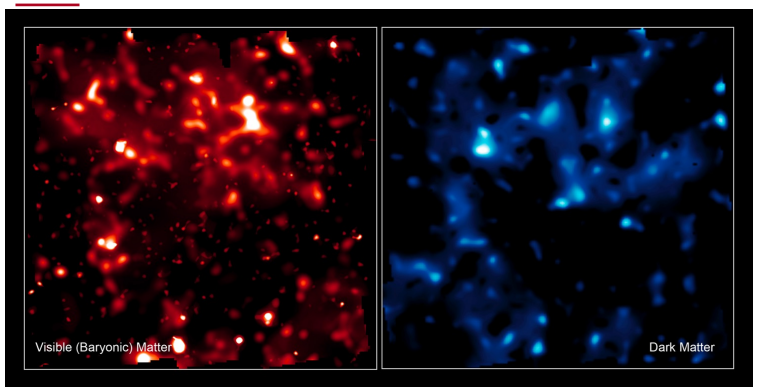
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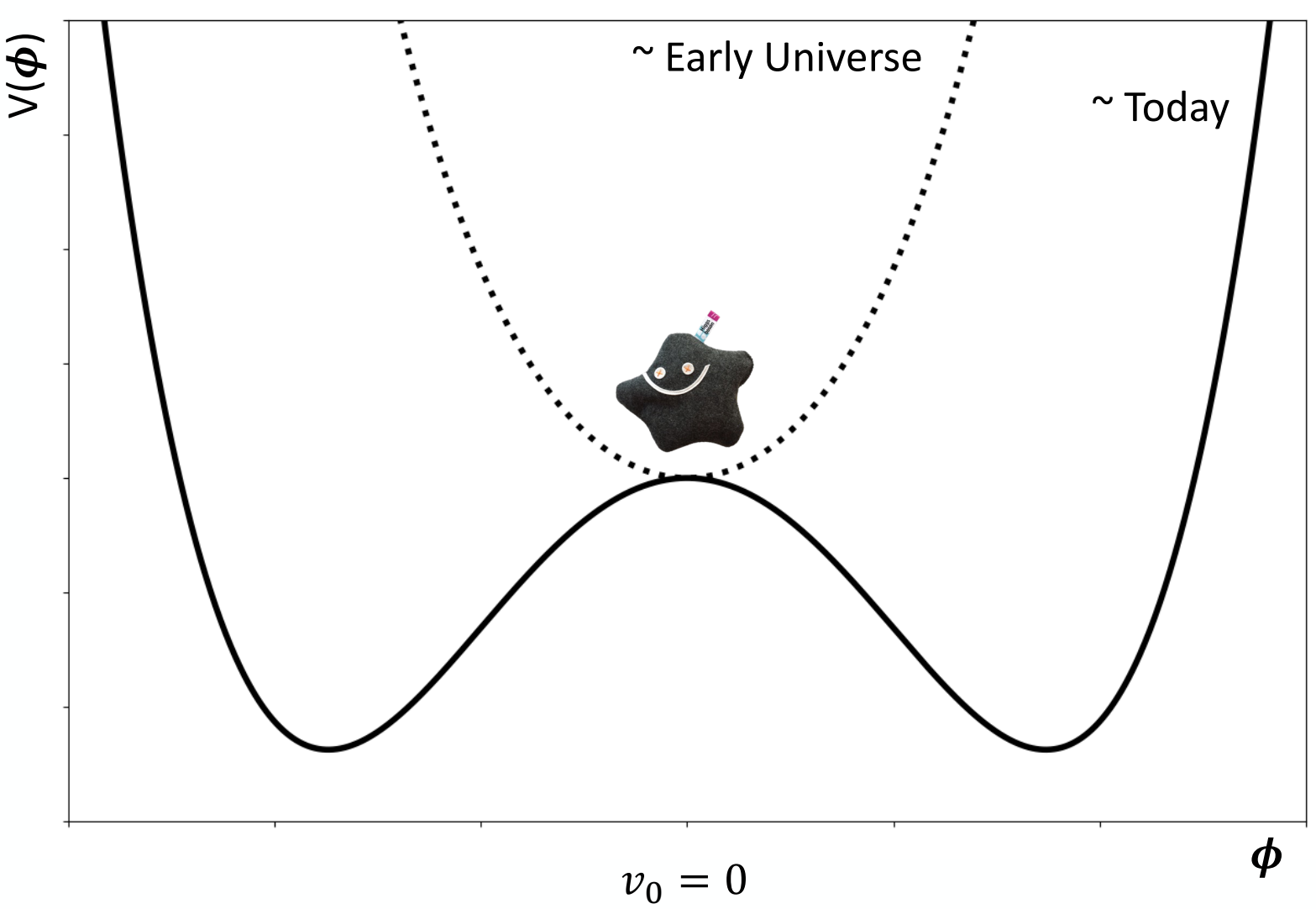
Branchina et. al.

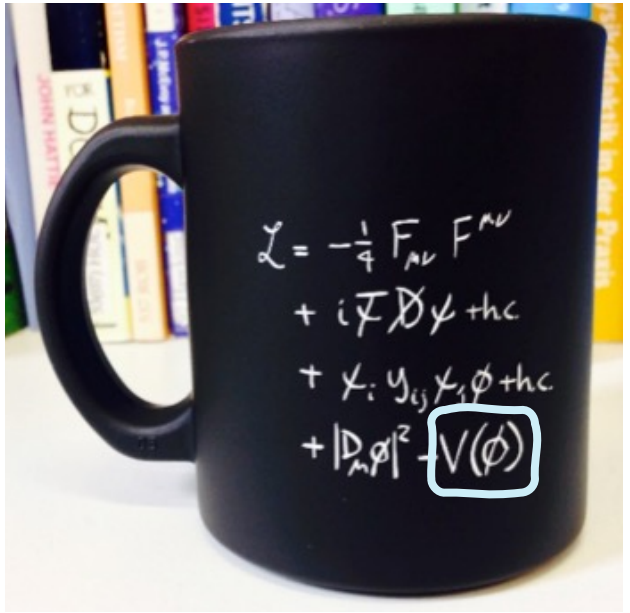
ESA

What is Dark Matter?



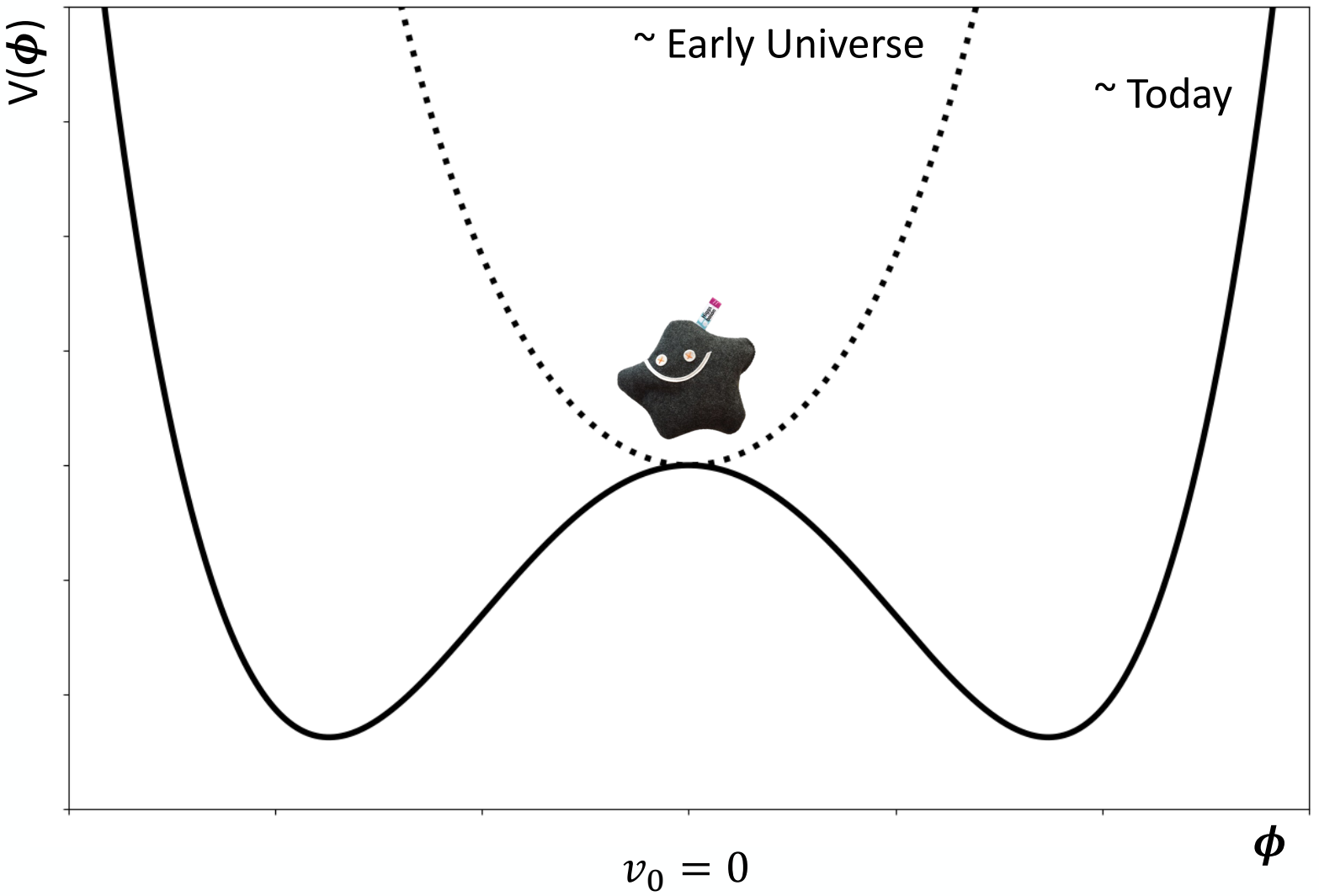
The Higgs Boson and its Potential

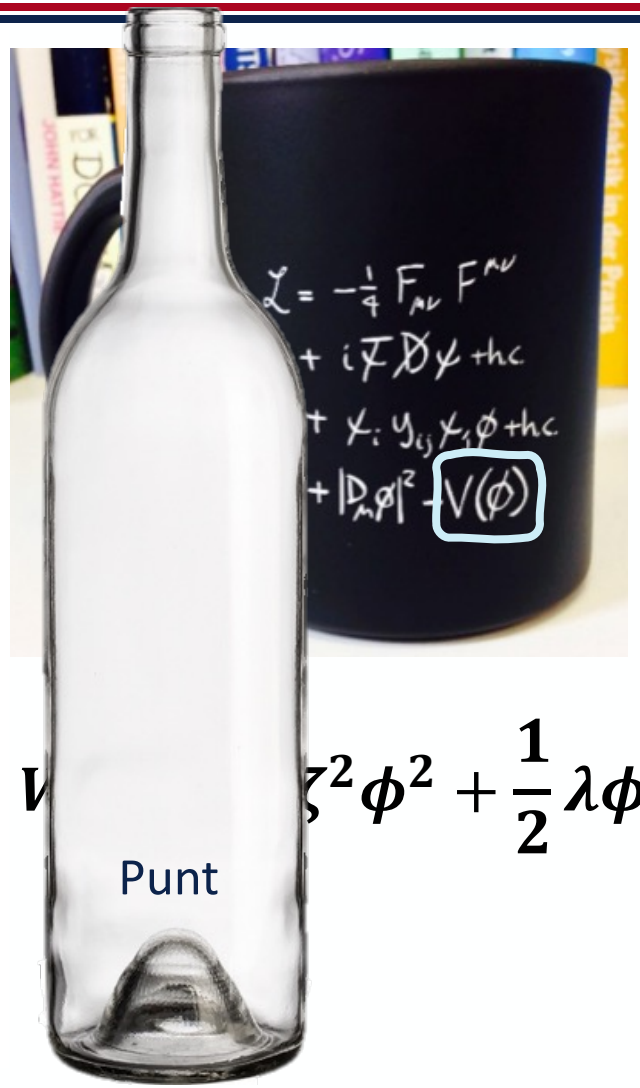




$$V(\phi) = \frac{1}{2}\zeta^2\phi^2 + \frac{1}{2}\lambda\phi^4$$

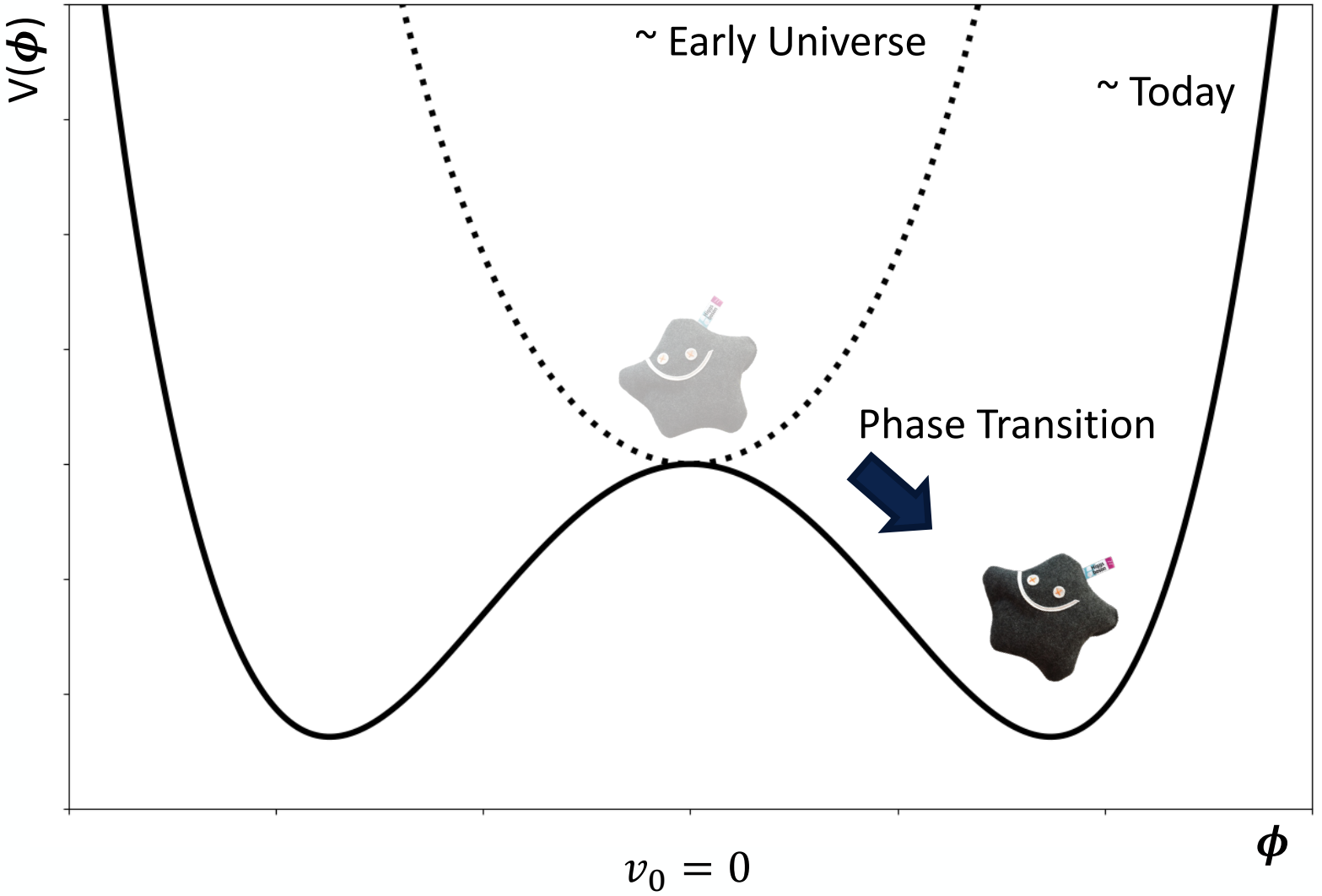
The Higgs Boson and its Potential





$$V = \frac{1}{2}\zeta^2\phi^2 + \frac{1}{2}\lambda\phi^4$$

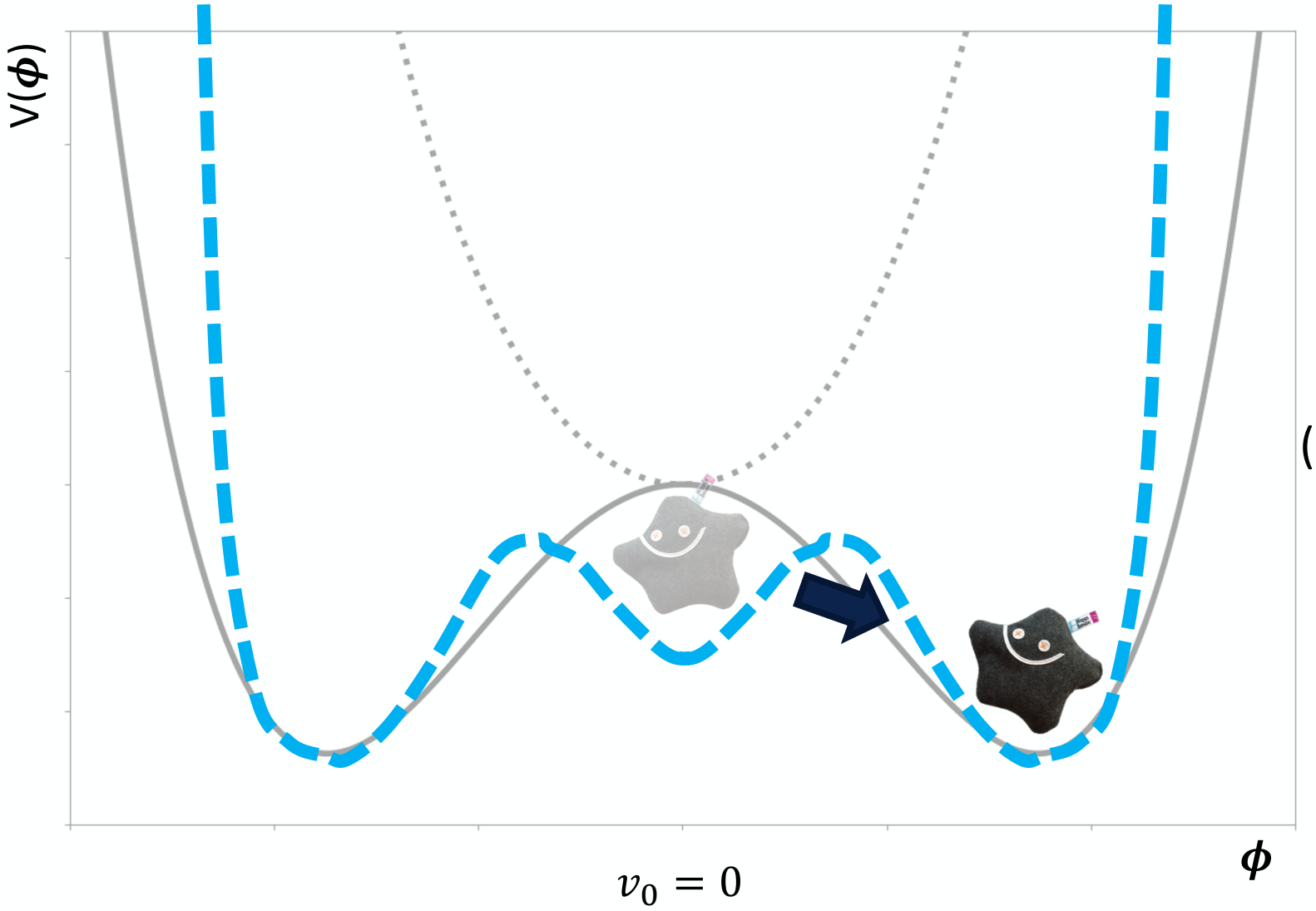
The Higgs Boson and its Potential



$$V(h) \sim \lambda v h^3 + \frac{1}{4}\lambda h^4$$

What if the potential looks a little different?

New Physics and the Higgs Potential

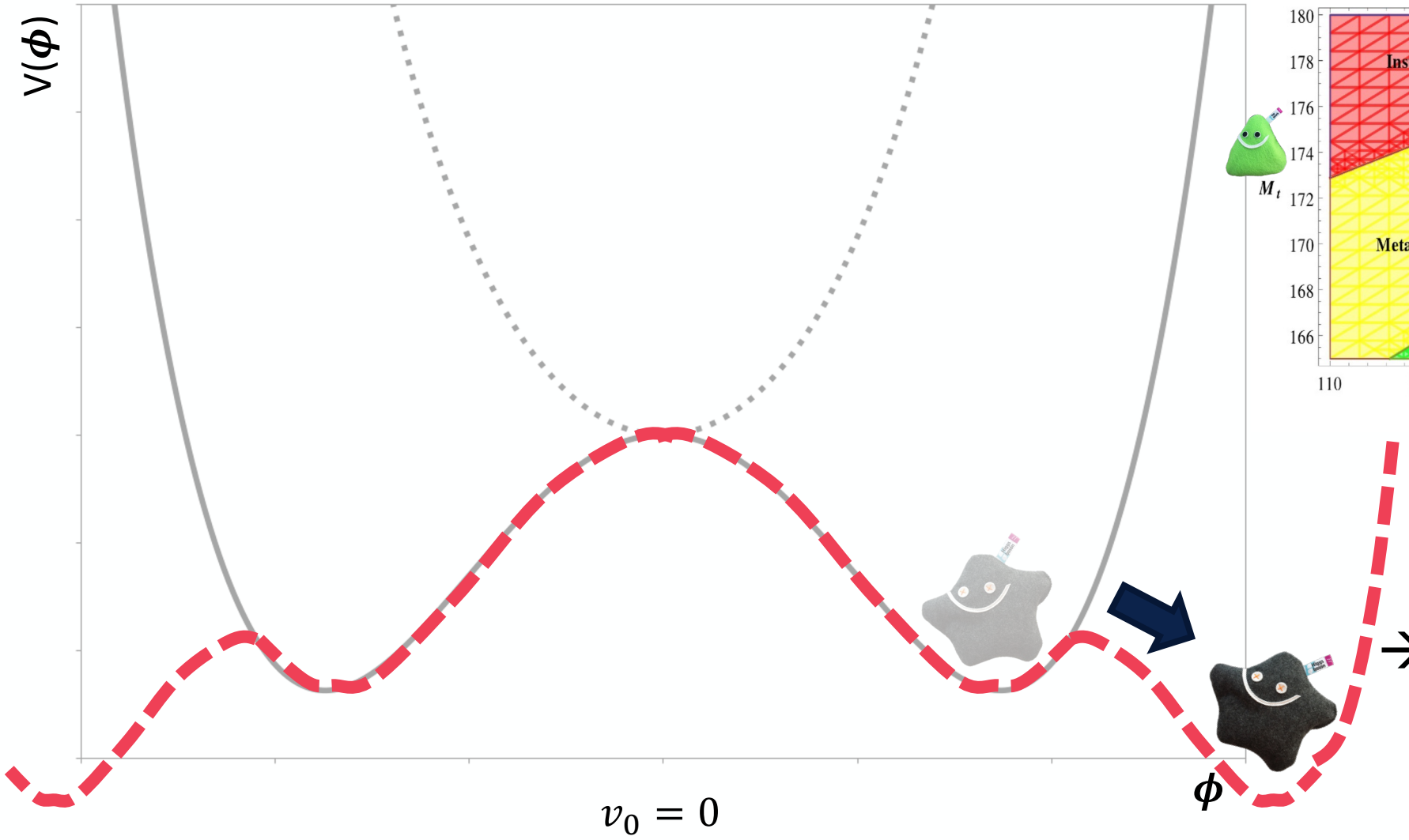


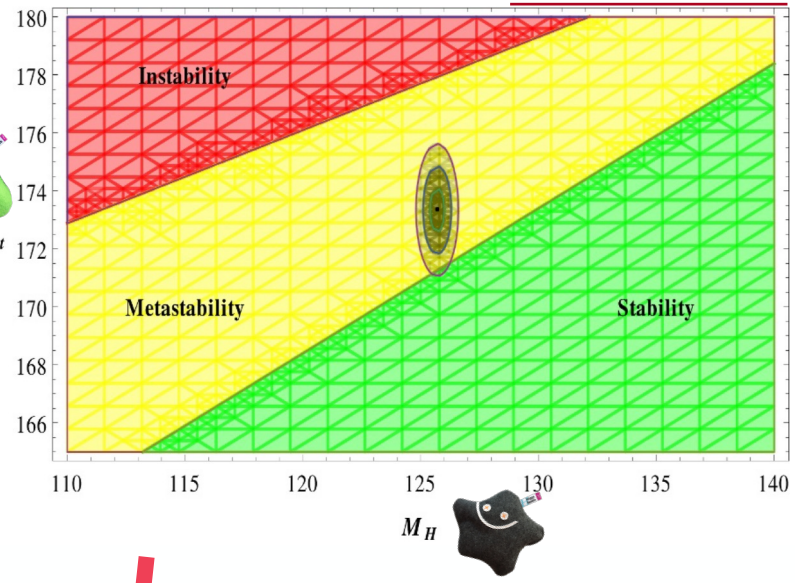
First Order phase transition in early universe

→ required for *Electroweak Baryogenesis*
(= Electroweak Phase Transition as the source of Matter-Antimatter Asymmetry)

New Physics and the Higgs Potential

Branchina et. al.

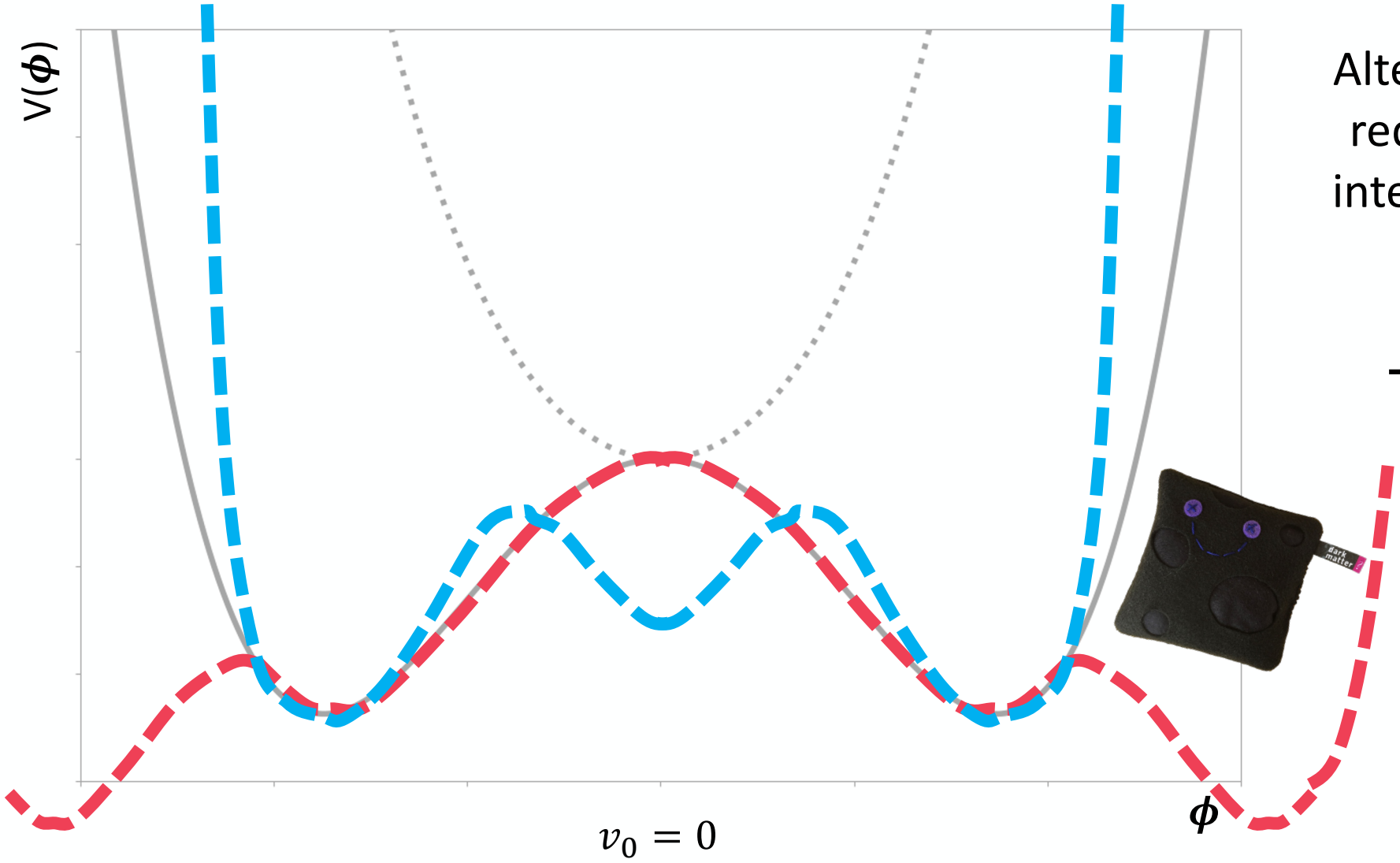




Lower Minimum?

→ Metastable Universe!

New Physics and the Higgs Potential



Alternative potentials require Higgs Boson interactions with new particles

→ a dark matter mediator?

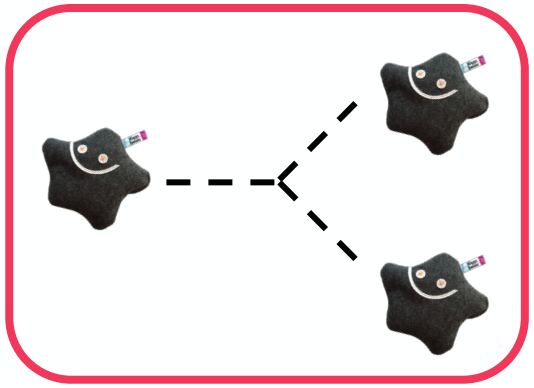
How Do We Measure the Higgs Potential?

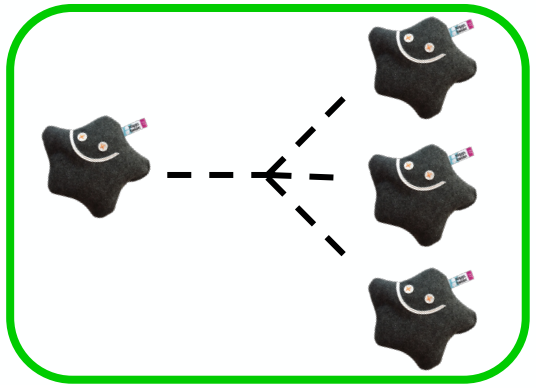
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How Do We Measure the Higgs Potential?

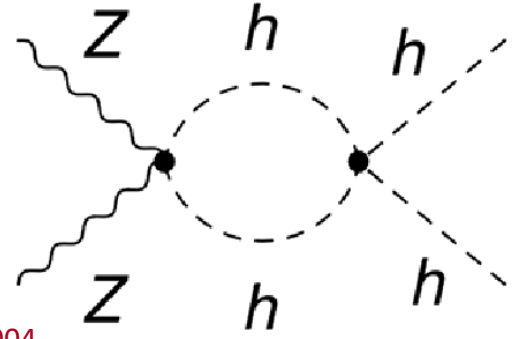
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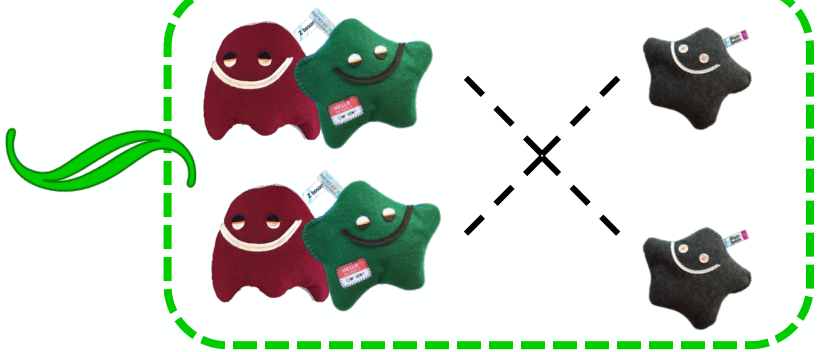
Can constrain coupling to within an order of magnitude…
at 100 TeV Hadron Collider!

PhysRevD.93.013007



PhysRevD.98.093004

VVHH



How Can We Study the Higgs Potential at the LHC?

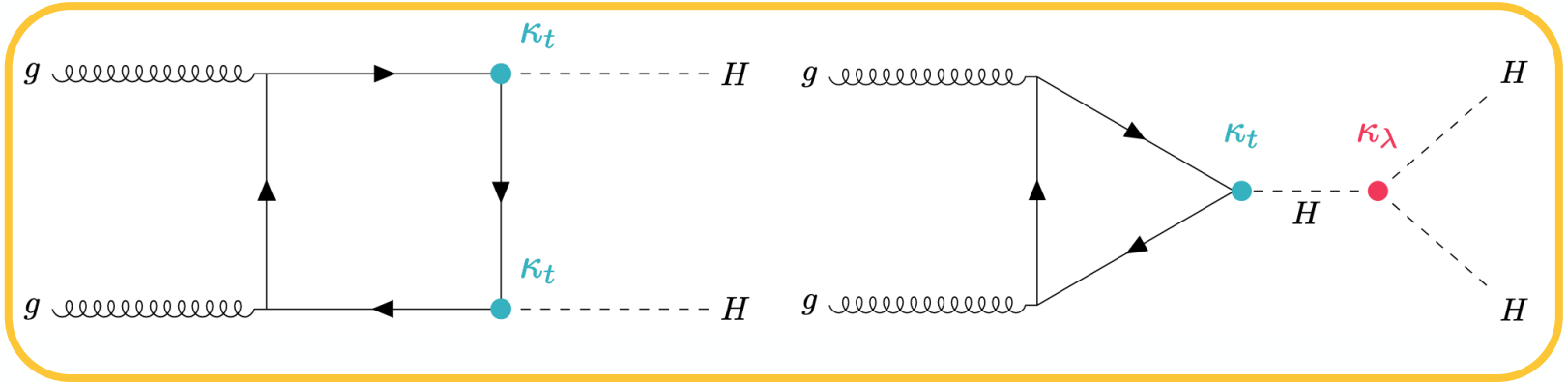
→ Higgs boson pair production (*HH*)

"Kappa framework"

$$\kappa_c = \frac{c}{c_{SM}}$$

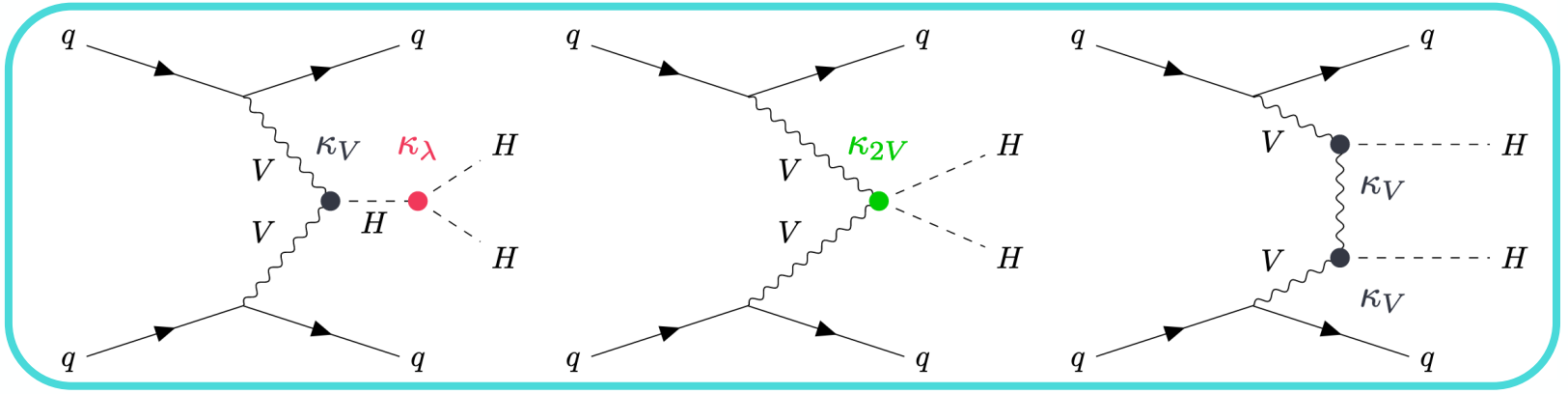
gluon-gluon-Fusion

σ_{ggF} ~31 fb [1]



Vector Boson Fusion

σ_{VBF} ~ 1.7 fb [2]



[1] arxiv:1803.02463
[2] arxiv:1811.07906

How Can We Study the Higgs Potential at the LHC?

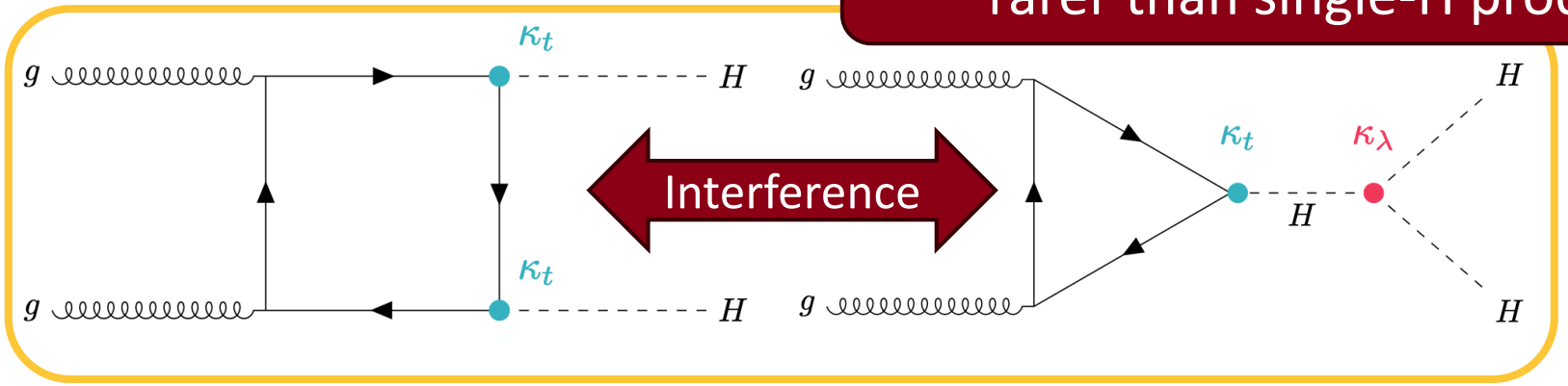
→ Higgs boson pair production (*HH*

HH production is a factor of ~1000x rarer than single-H production!

c_{SM}

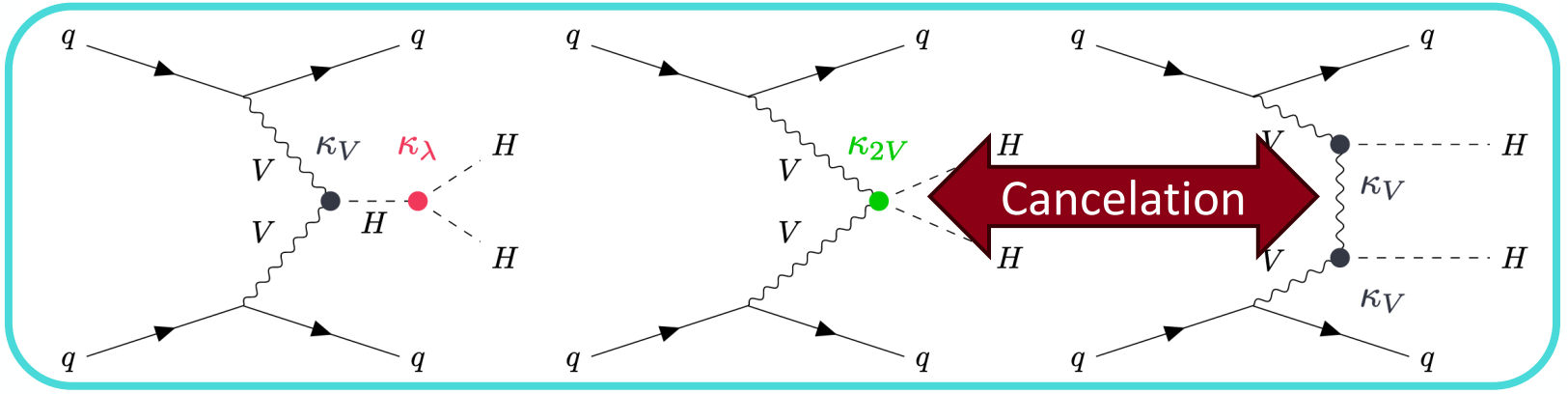
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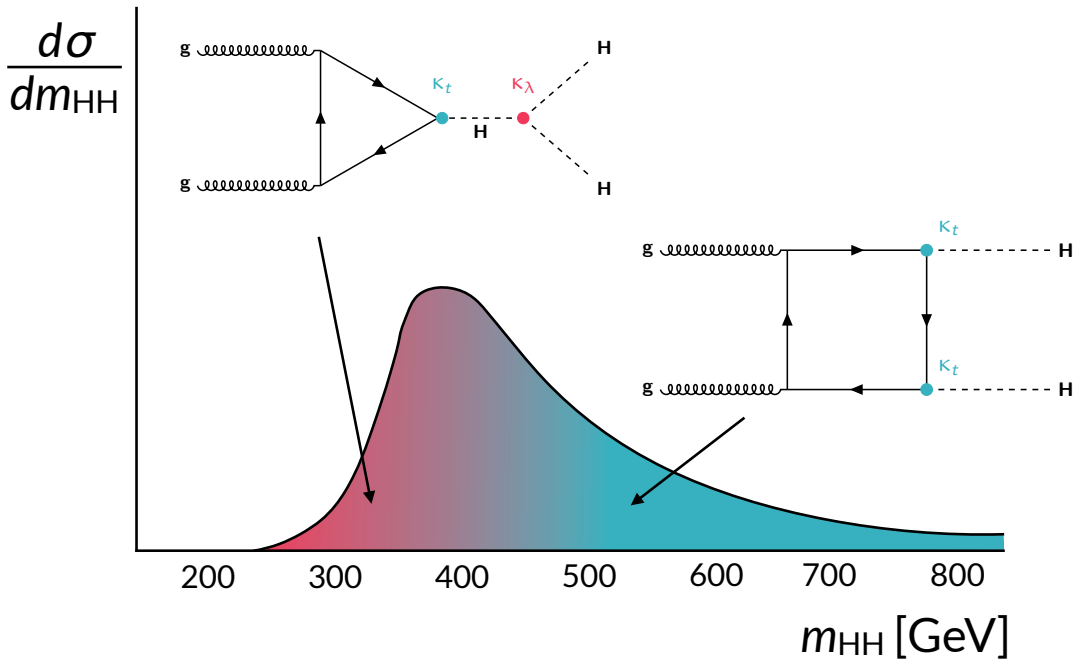
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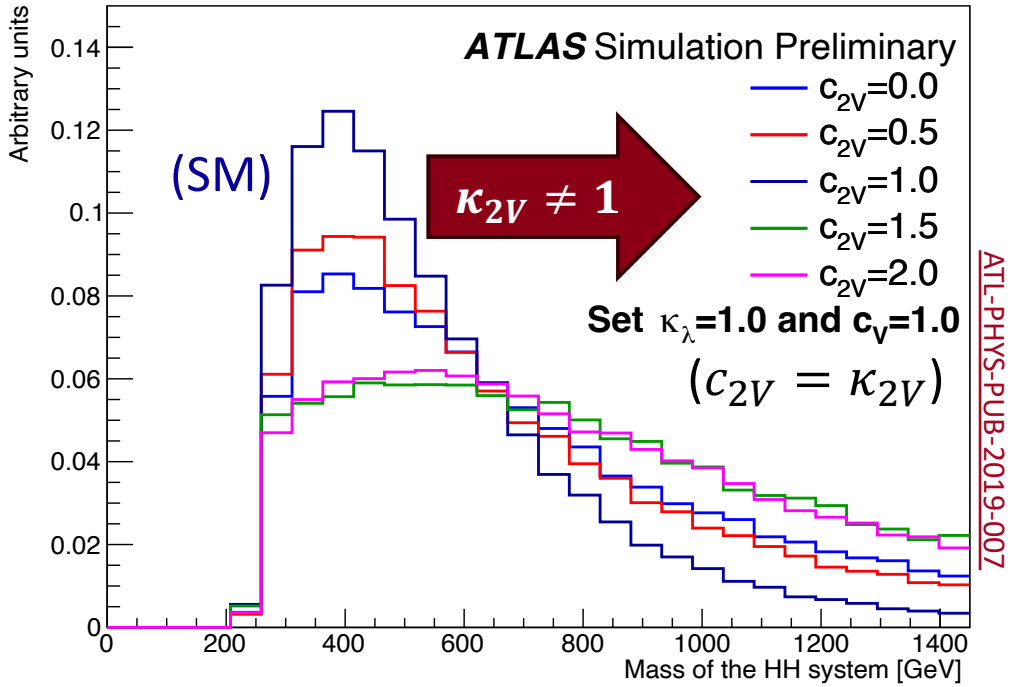
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Sensitivity to New Physics in the Self-Couplings

Contribution of ggF diagrams to di-Higgs invariant mass spectrum (~energy)



VBF Di-Higgs invariant mass spectrum (~energy) for various κ_{2V}



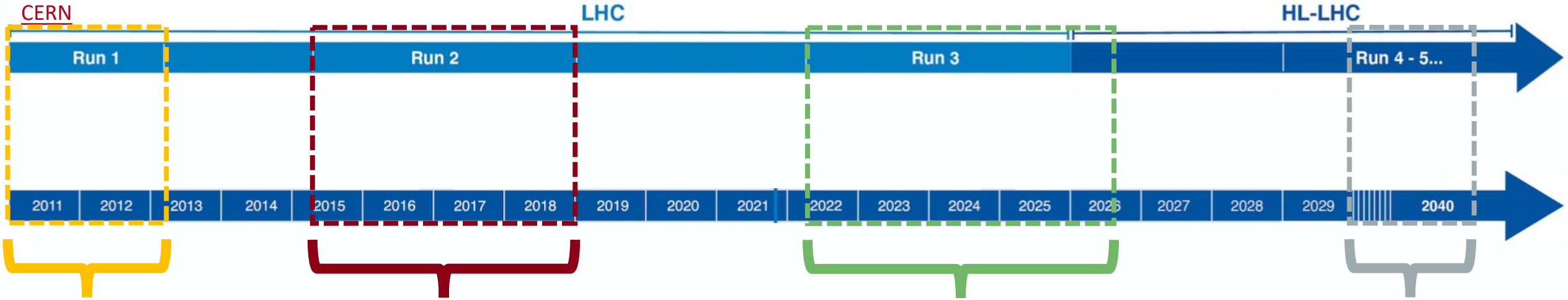
ggF: disrupt interference
→ more signal, softer events

VBF: break cancellation
→ more signal, harder events

The ATLAS Detector

How do we measure Higgs Boson self-interactions?

The Lifetime of the Large Hadron Collider



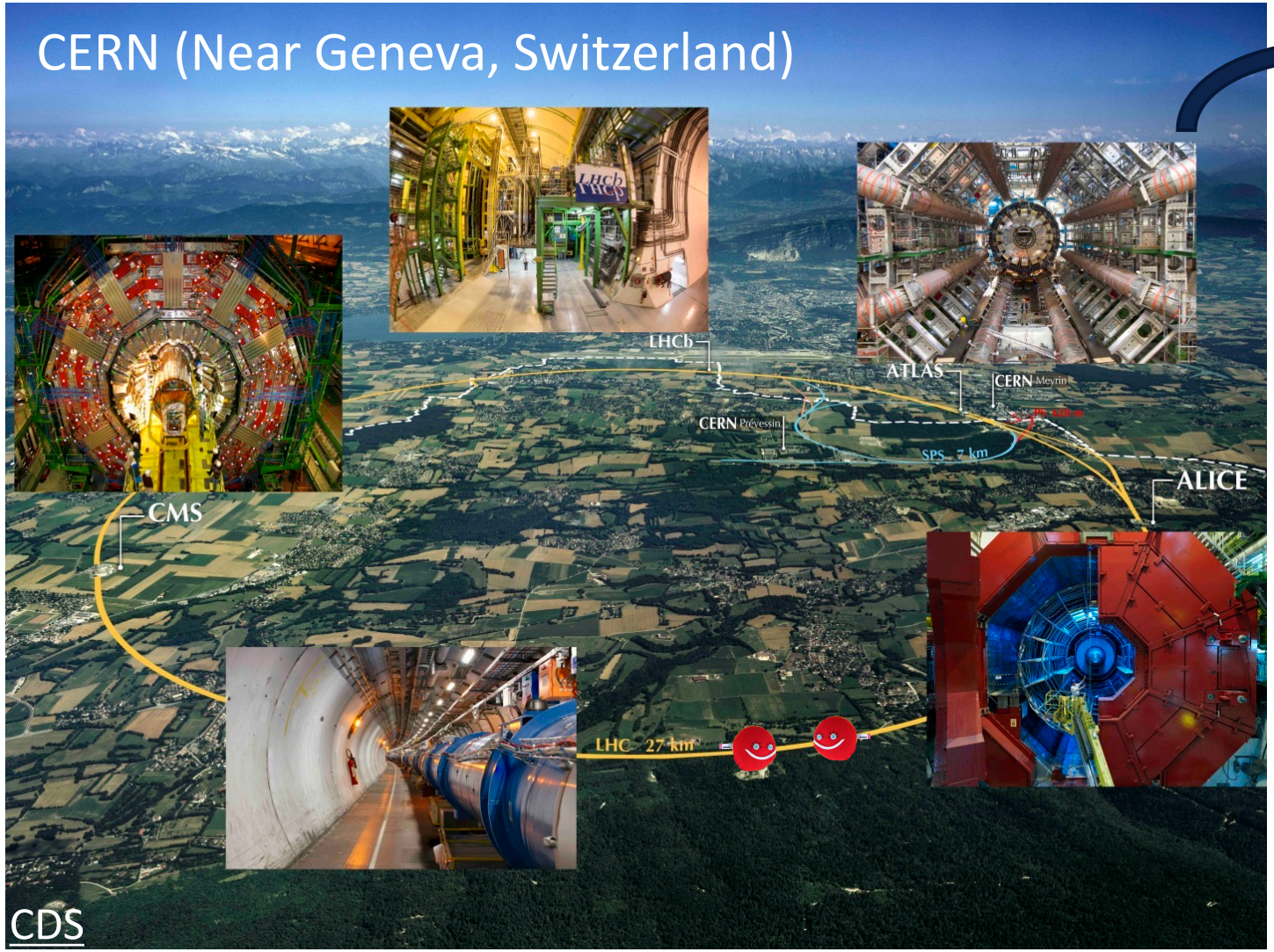
Run 1
Higgs
Discovery!

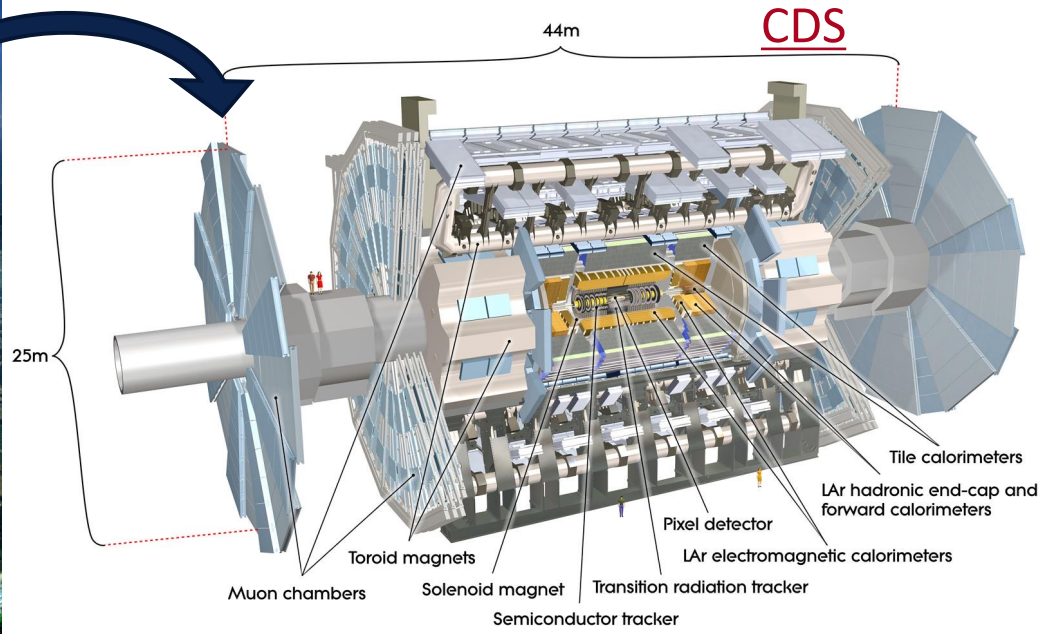
Run 2
Data Shown Today

Run 3
Happening Now!

Future Runs 4+5
(HL-LHC)

ATLAS and the Large Hadron Collider





Today: Run 2 (2015-2018) Data

Collide protons every 25 ns
at $\sqrt{s}$ = 13 TeV

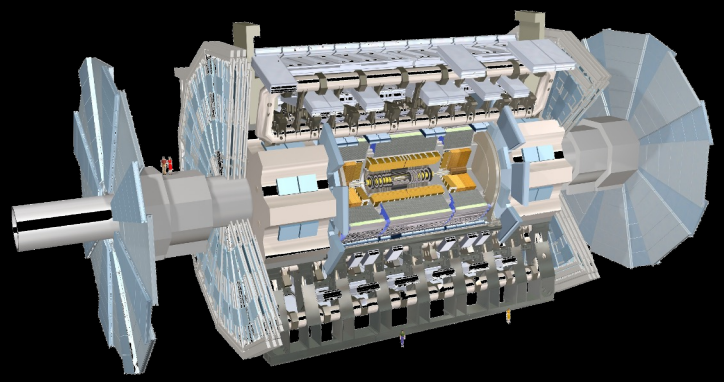
The ATLAS Detector

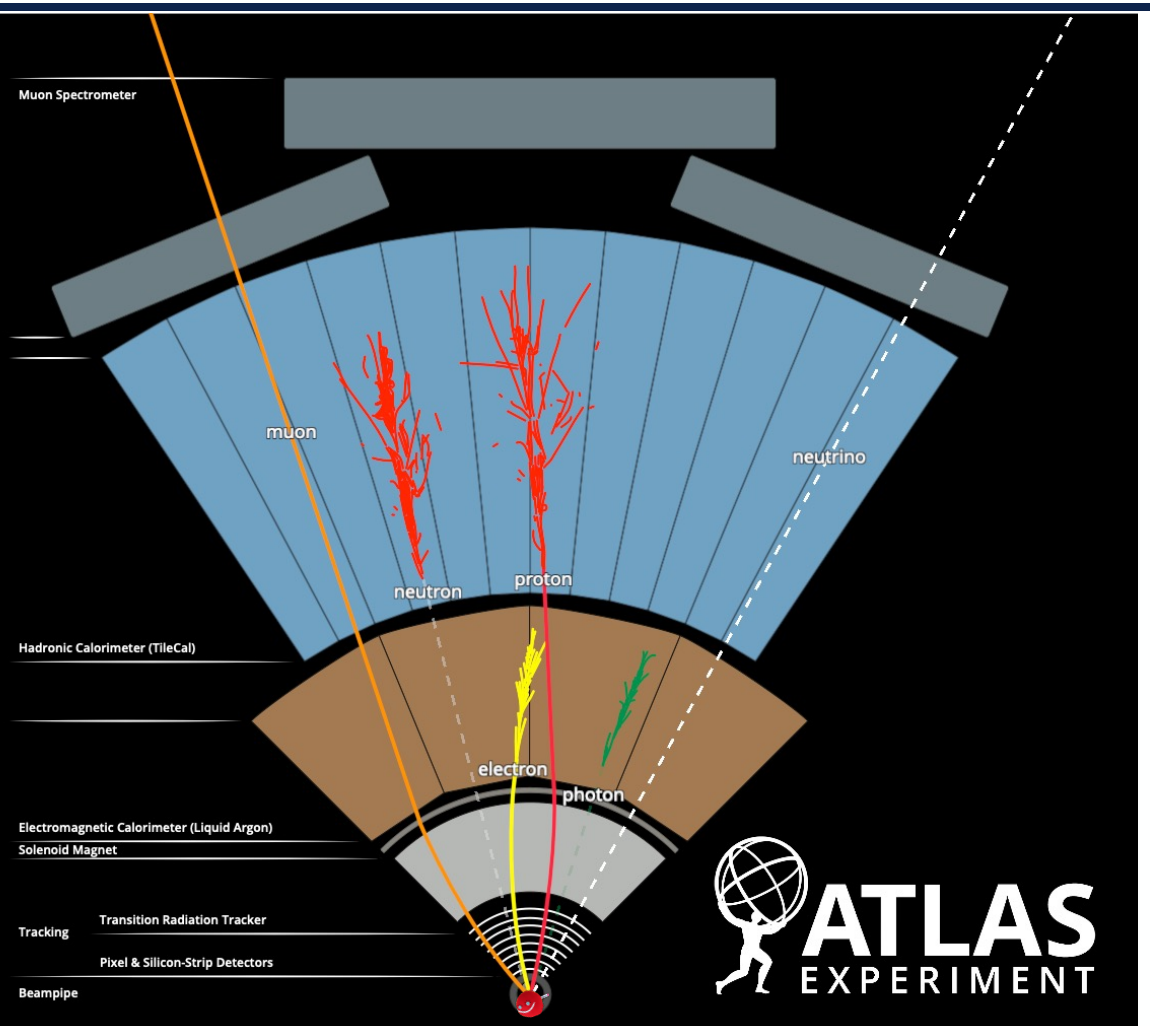
Muon Spectrometer

Hadronic Calorimeter

Electromagnetic Calorimeter

Tracking





CDS

The ATLAS Detector

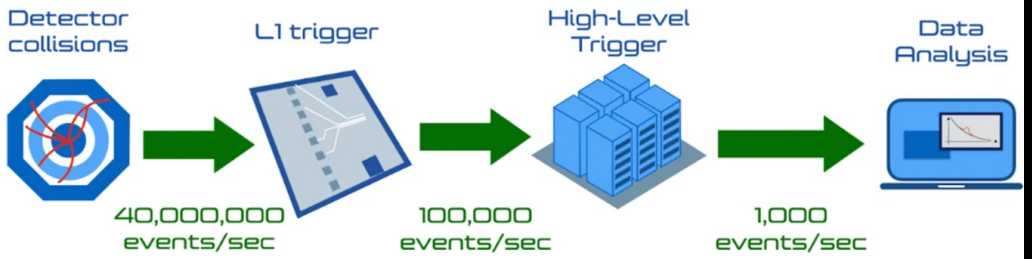
Muon Spectrometer

Hadronic Calorimeter

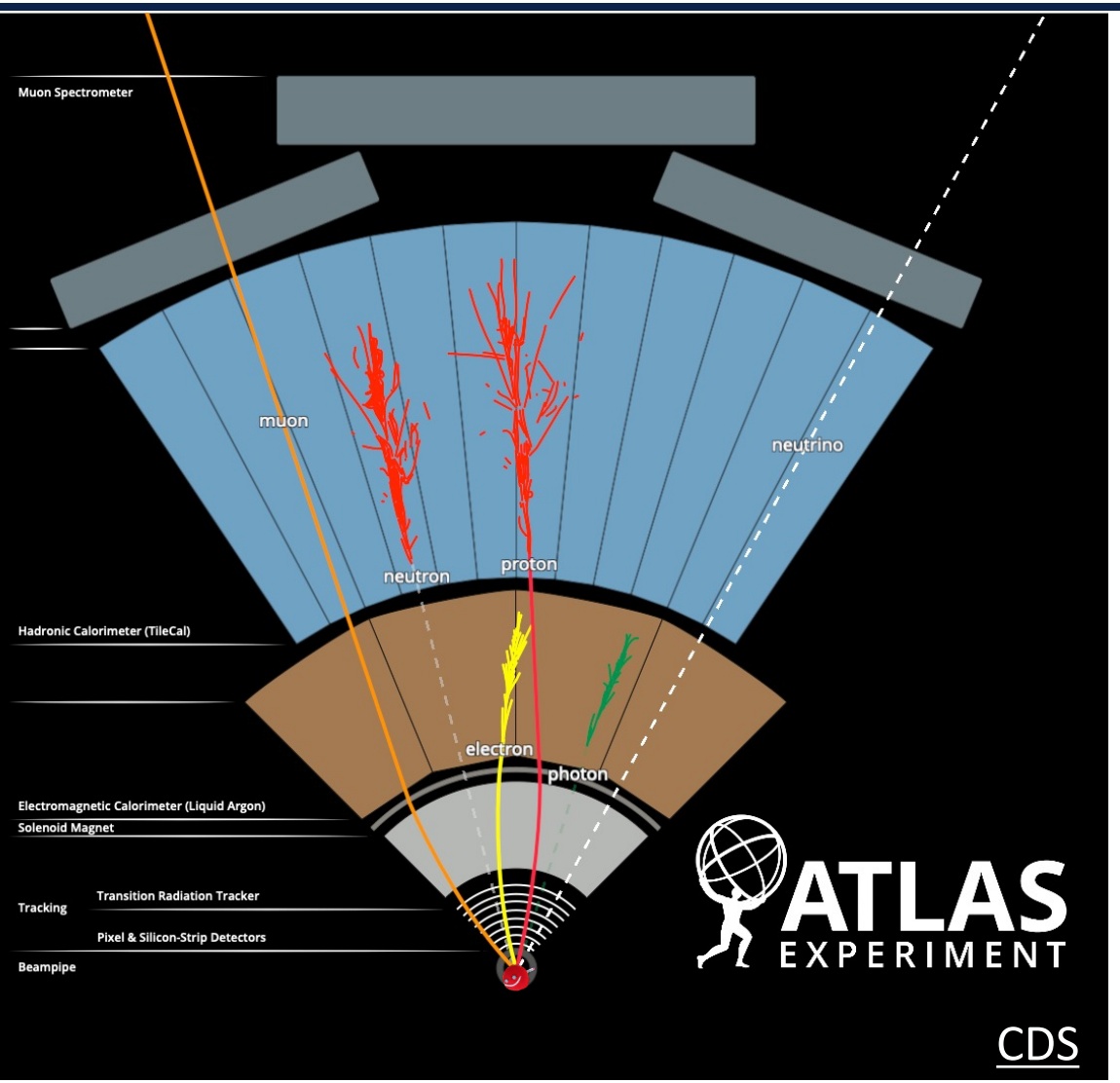
Electromagnetic Calorimeter

Tracking

Hardware & Software Trigger System



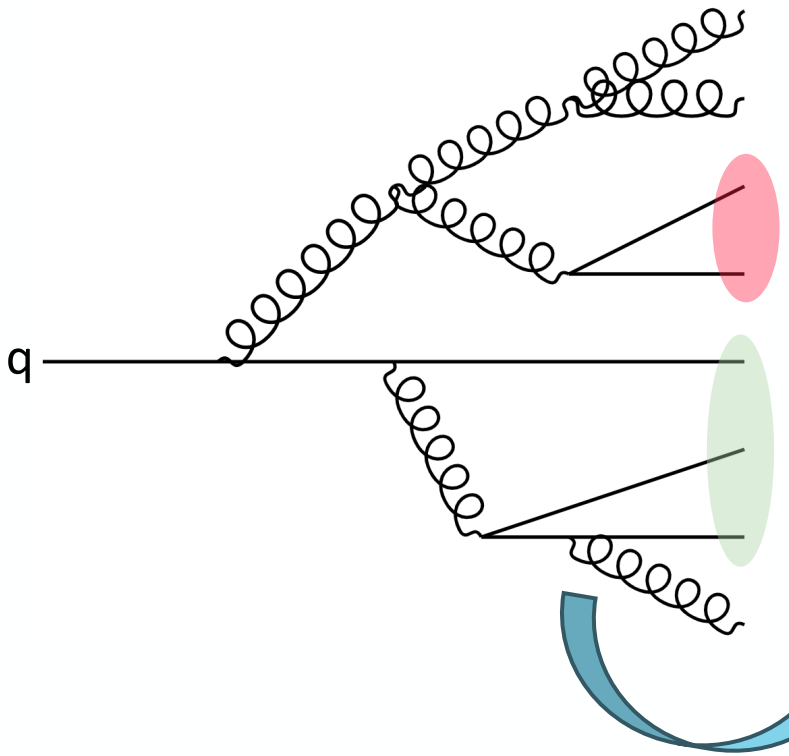
Govorkova et. al.

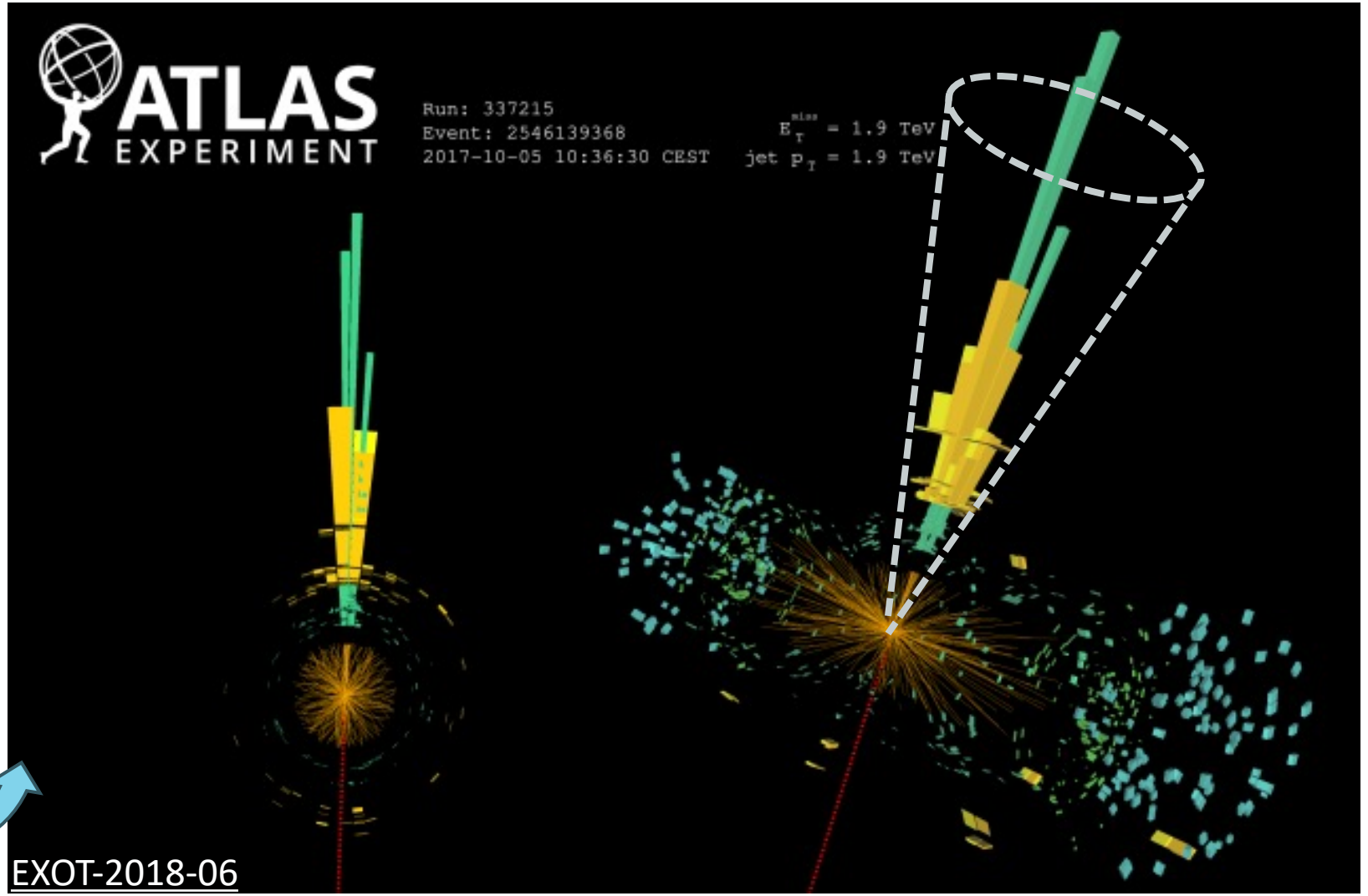


CDS

What is a Jet?

No single quarks →
Spray of high-energy particles

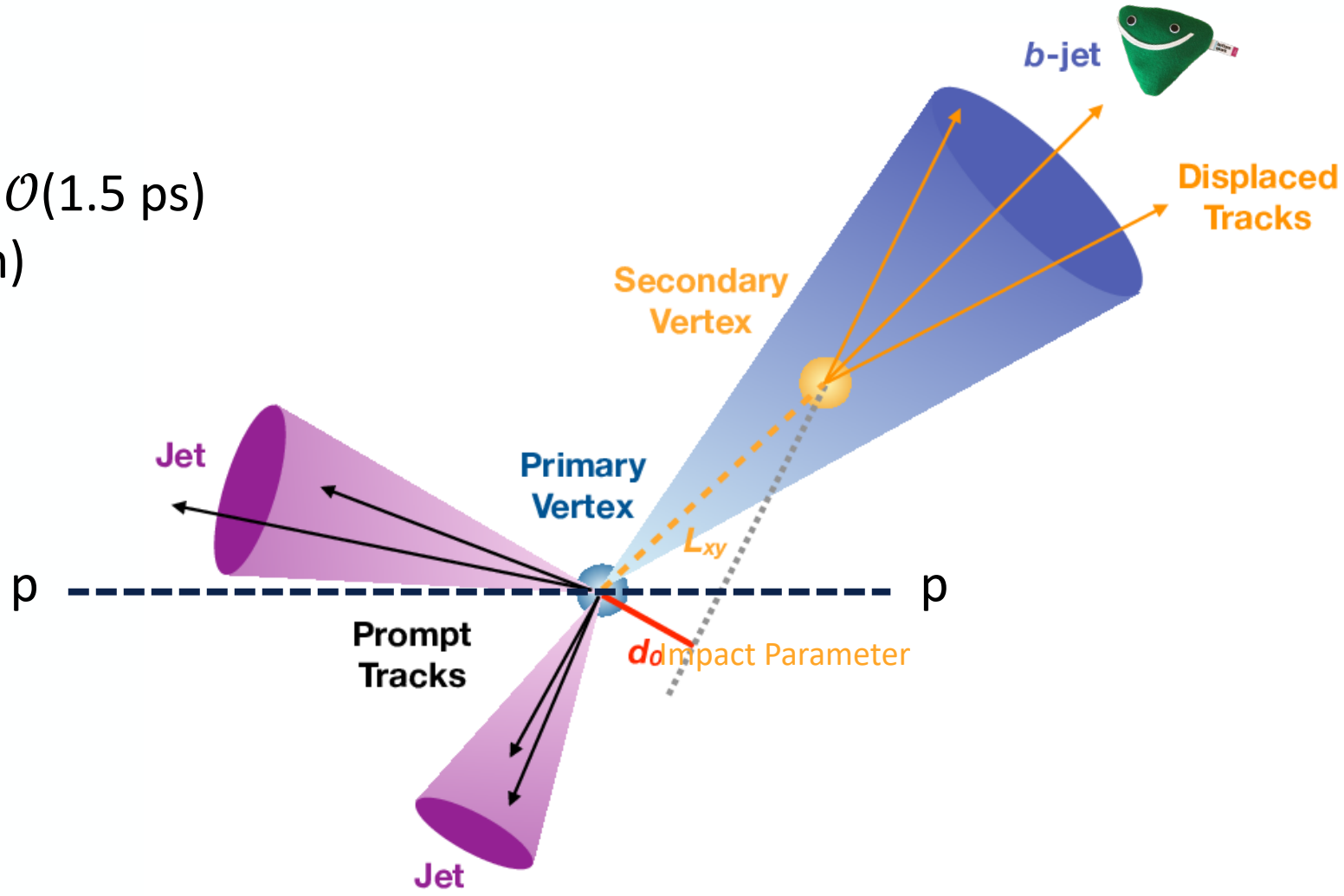




EXOT-2018-06

b-Tagged Jets

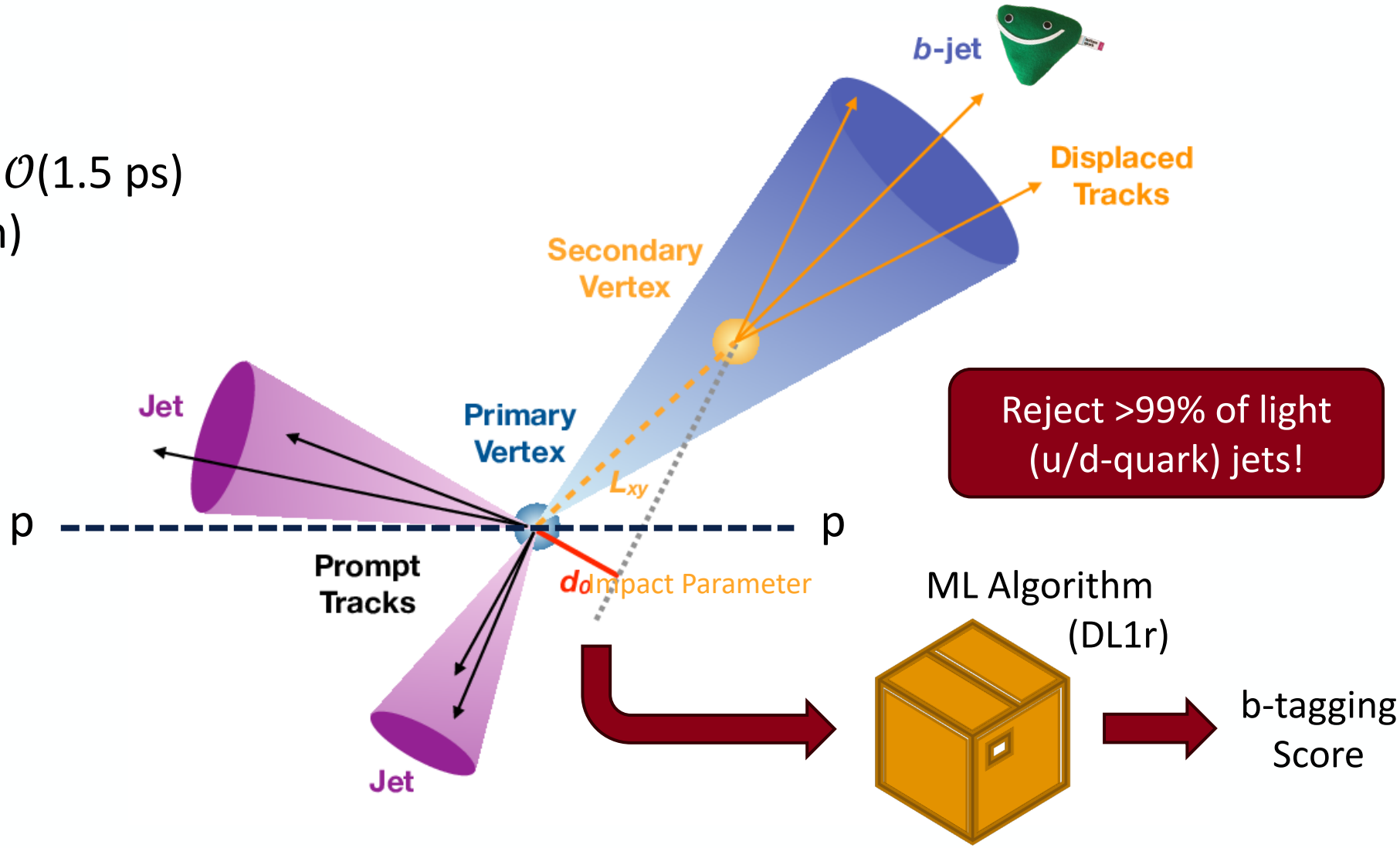
B-hadron lifetime: $\mathcal{O}$(1.5 ps)
→ L: $\mathcal{O}$(mm)



TRIG-2018-08

b-Tagged Jets

B-hadron lifetime: $\mathcal{O}$(1.5 ps)
→ L: $\mathcal{O}$(mm)



Reject >99% of light (u/d-quark) jets!

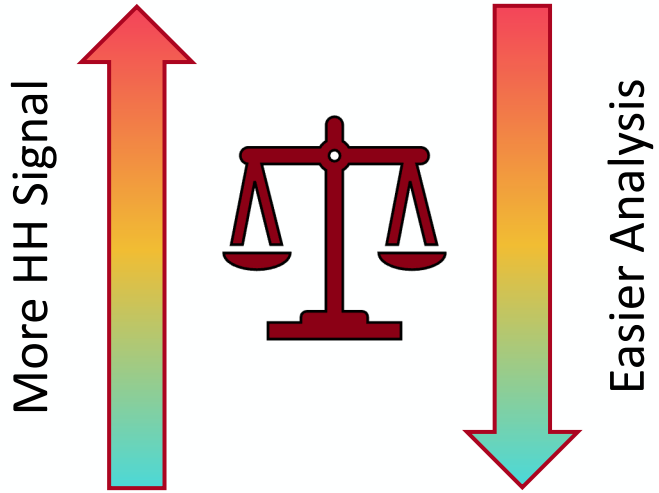
TRIG-2018-08

The ATLAS $HH \rightarrow b\bar{b}b\bar{b}$ Analysis

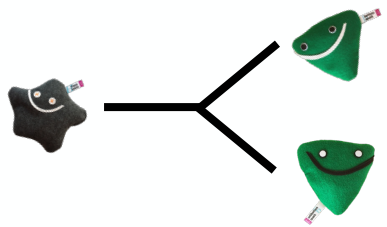
arxiv:2301.03212

A measurement probing Higgs Boson self-interactions

Di-Higgs Boson Decays



$H \to b\bar{b}$:



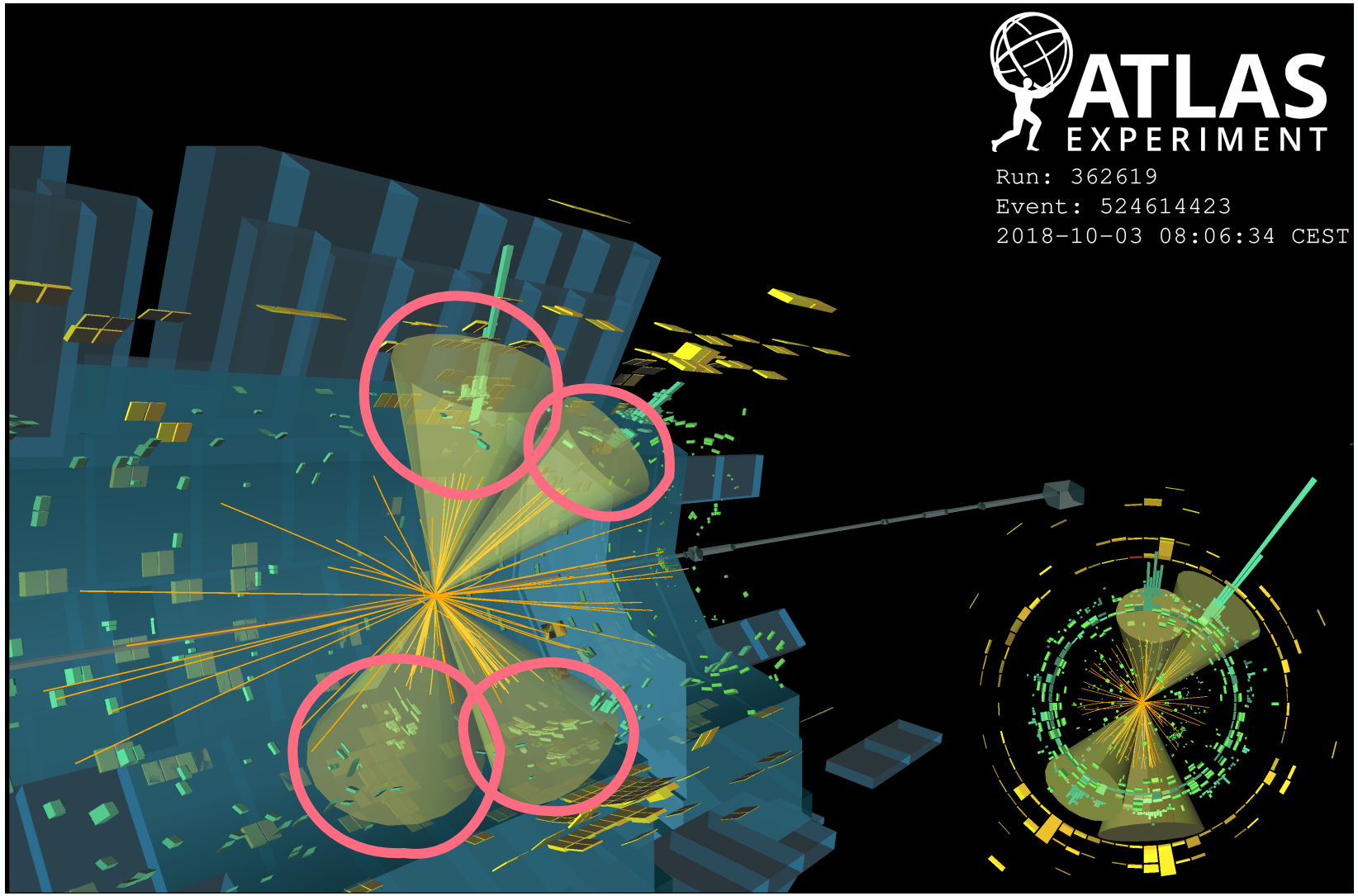
Higgs #1 Decay

Higgs #2 Decay	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%

What Makes 4*b* a Challenging Final State?

Searching for events with 4 jets

~500 $HH \rightarrow b\bar{b}b\bar{b}$ Events
(~20 from VBF)



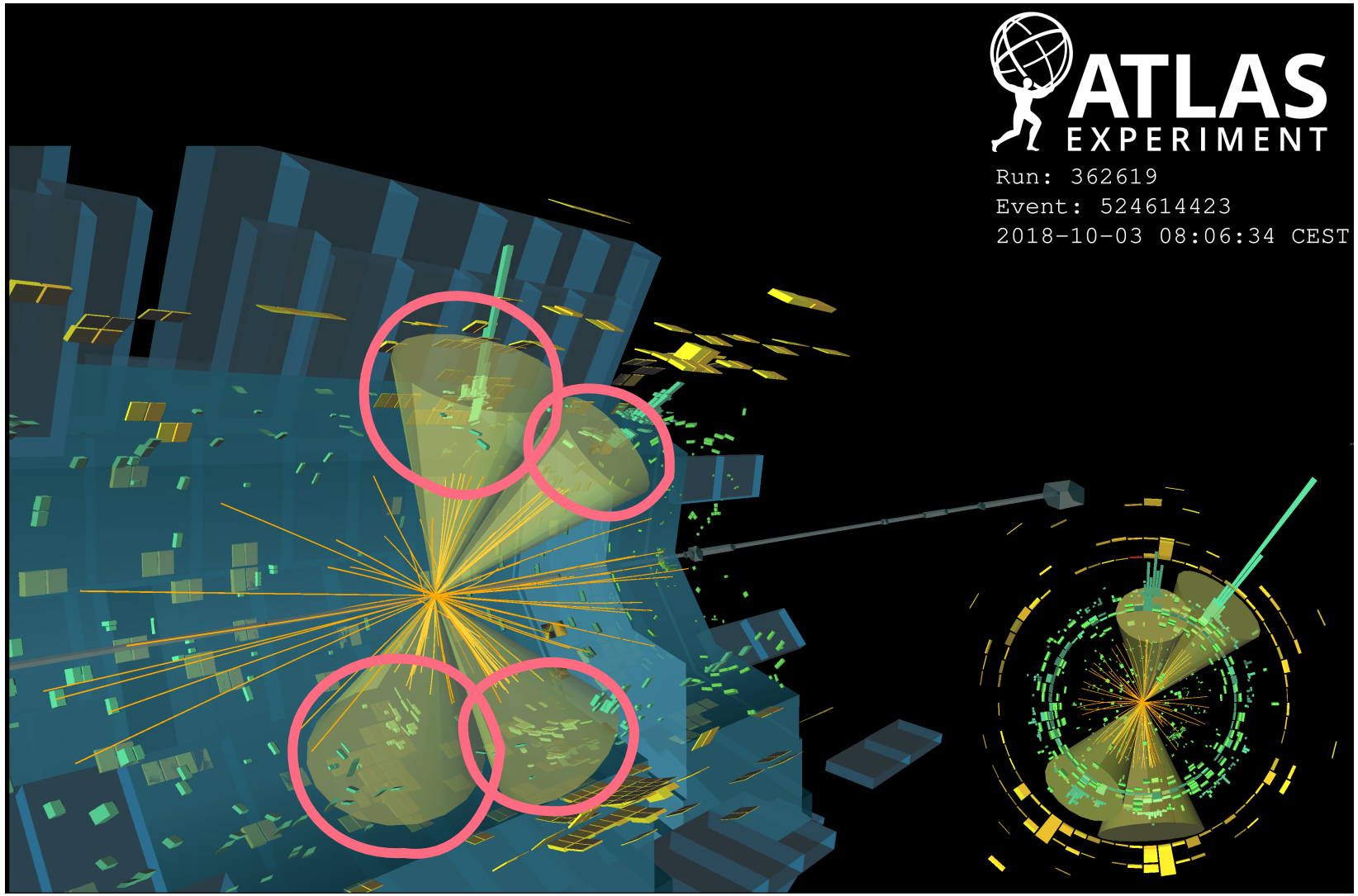
What Makes 4*b* a Challenging Final State?

Searching for events with 4 jets

~500 $HH \rightarrow b\bar{b}b\bar{b}$ Events
(~20 from VBF)

~10^8 Background

→ S/B ~ 1 in 1 Million



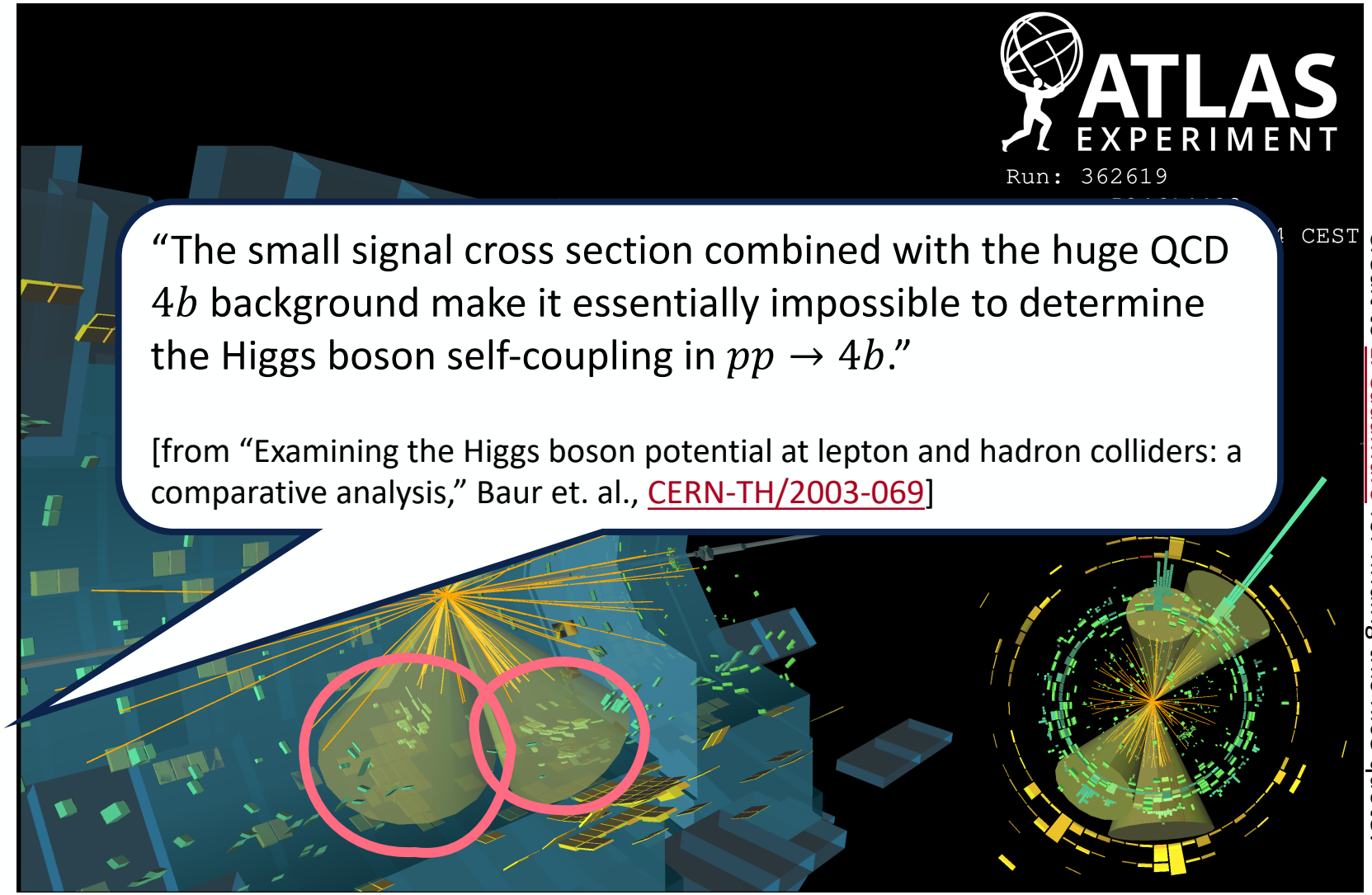
What Makes $4b$ a Challenging Final State?

Searching for events with 4 jets

~500 $HH \rightarrow b\bar{b}b\bar{b}$ Events
(~20 from VBF)

~10^8 Background

→ S/B ~ 1 in 1 Million



Credit to L. Cadamuro for finding this nice quote!

What Makes 4*b* a Challenging Final State?

Searching for events with
4 b-tagged jets, plus
kinematic cuts

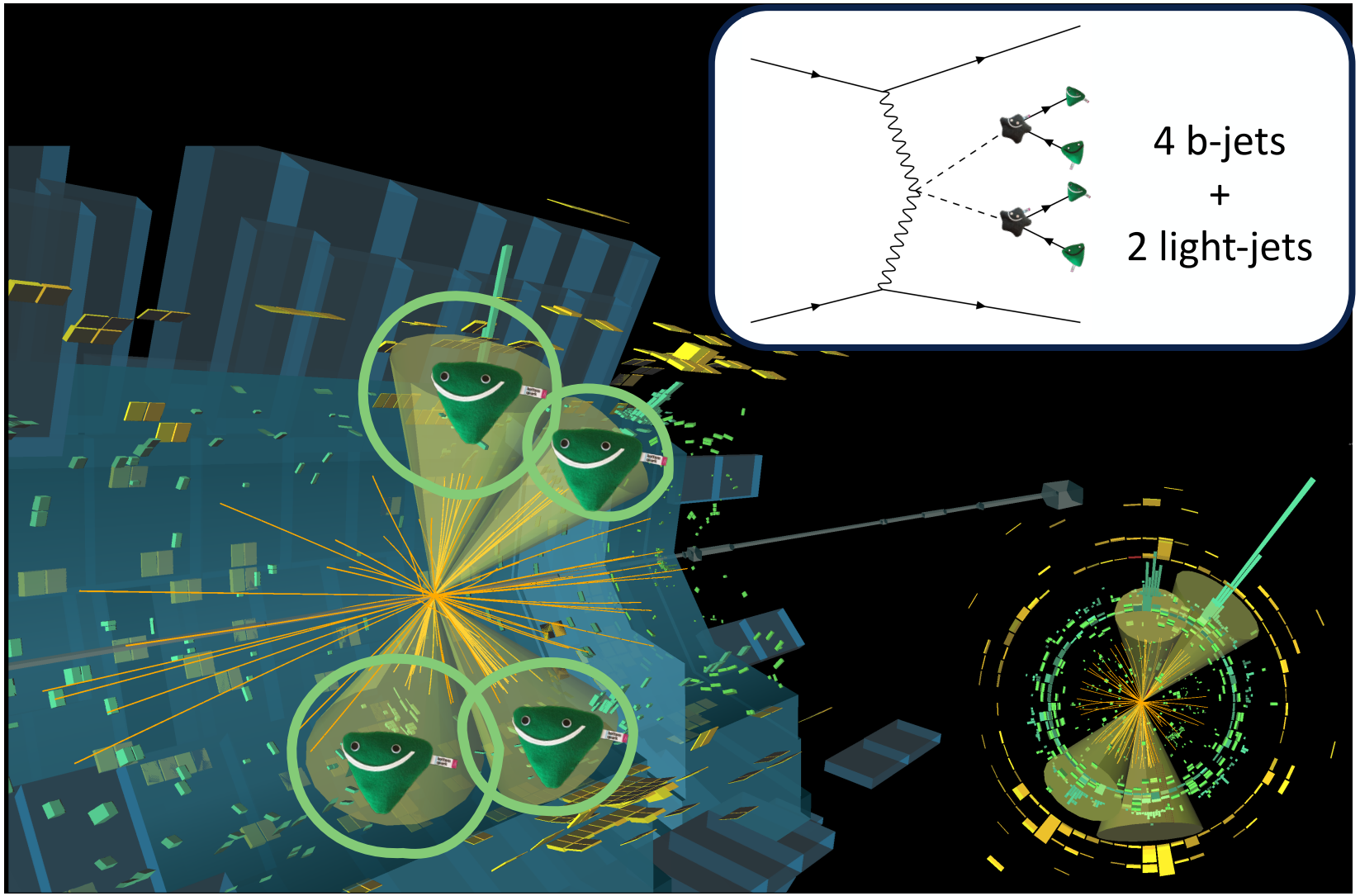
(+ 2 VBF jets)

After Analysis Selection:

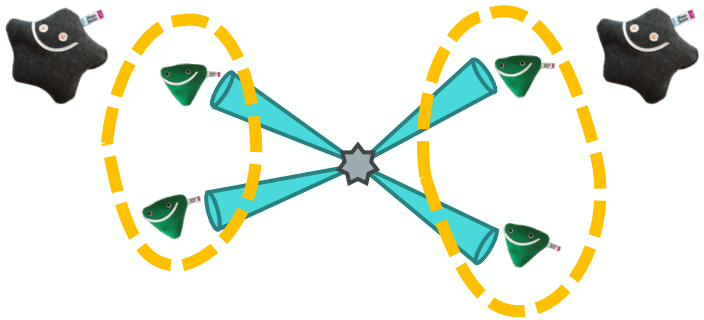
ggF: ~30 $HH \to b\bar{b}b\bar{b}$ Events
~10,000 Background

VBF: ~0.3 $HH \to b\bar{b}b\bar{b}$
~350 Background

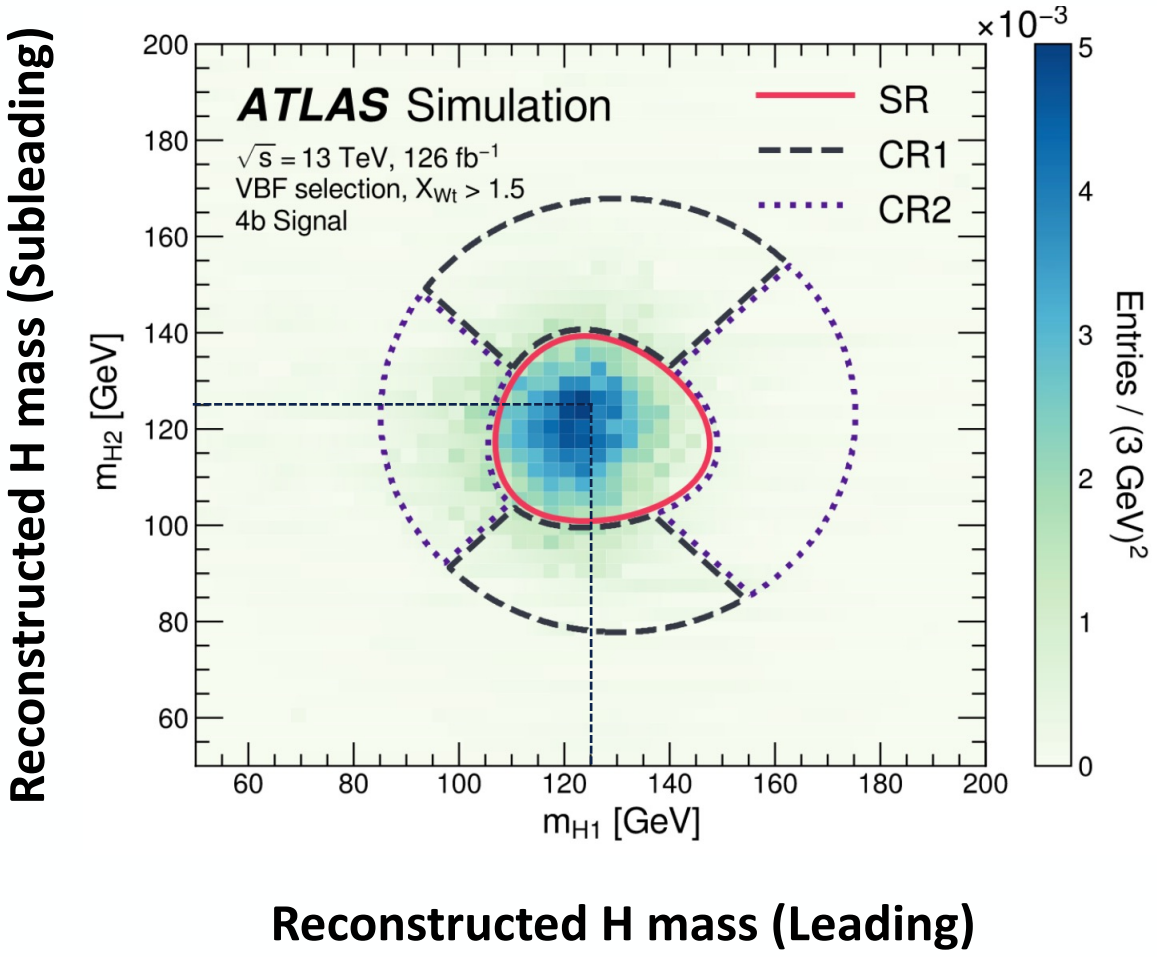
→ S/B ~ 1 in 100,000



Background Modeling: The Mass-Plane



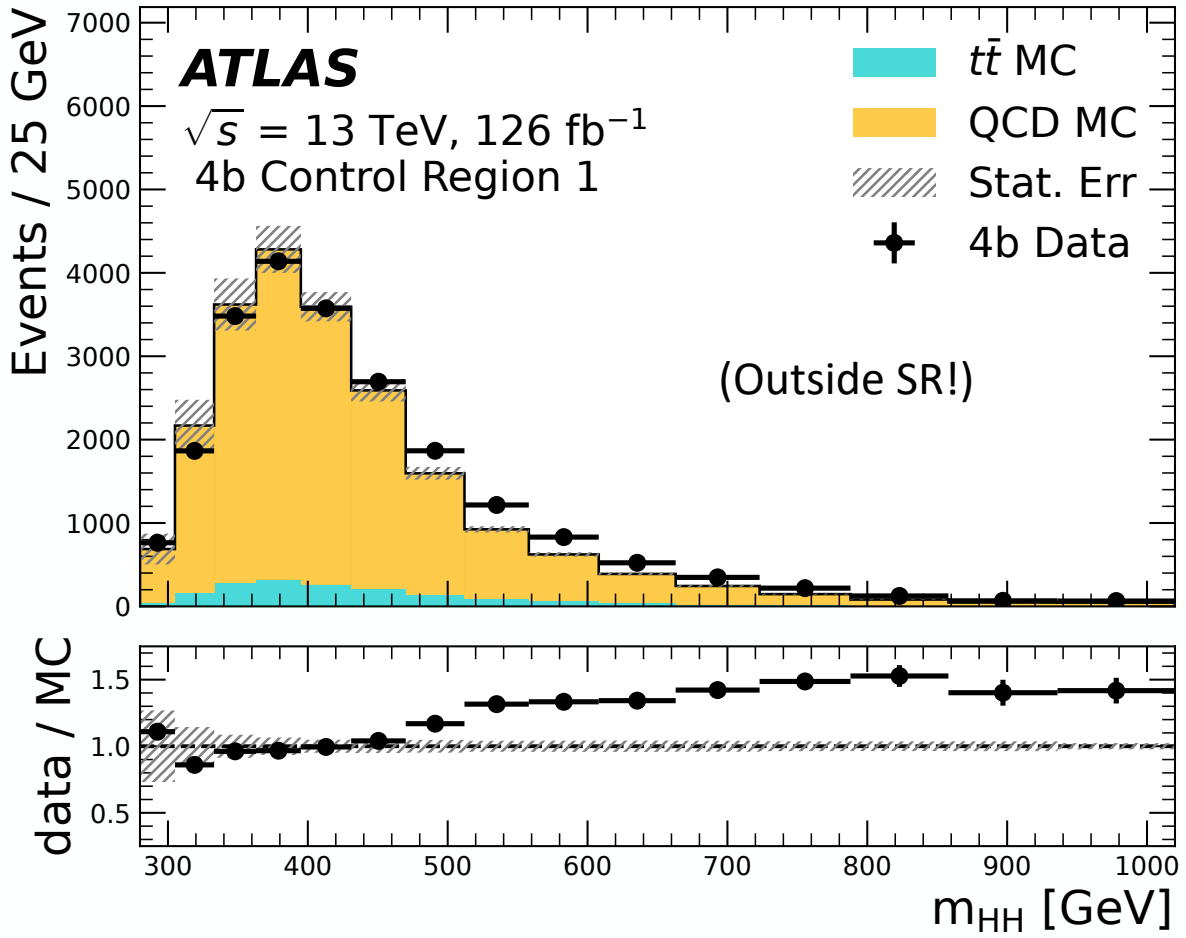
Require reconstructed Higgs Boson candidate masses ~ 125 GeV
→ Define Signal Region



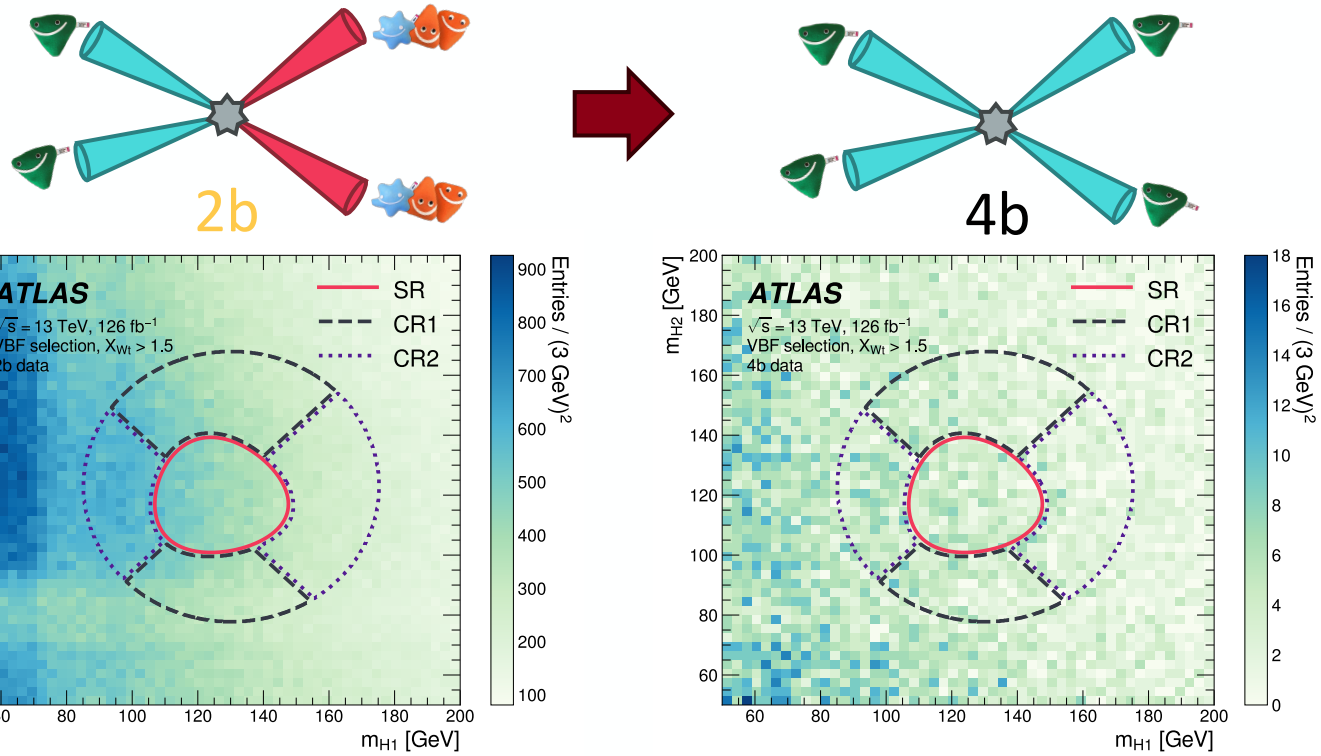
Limitations of Simulation

Challenging to accurately simulate QCD multijet backgrounds

→ Need data-driven approach instead



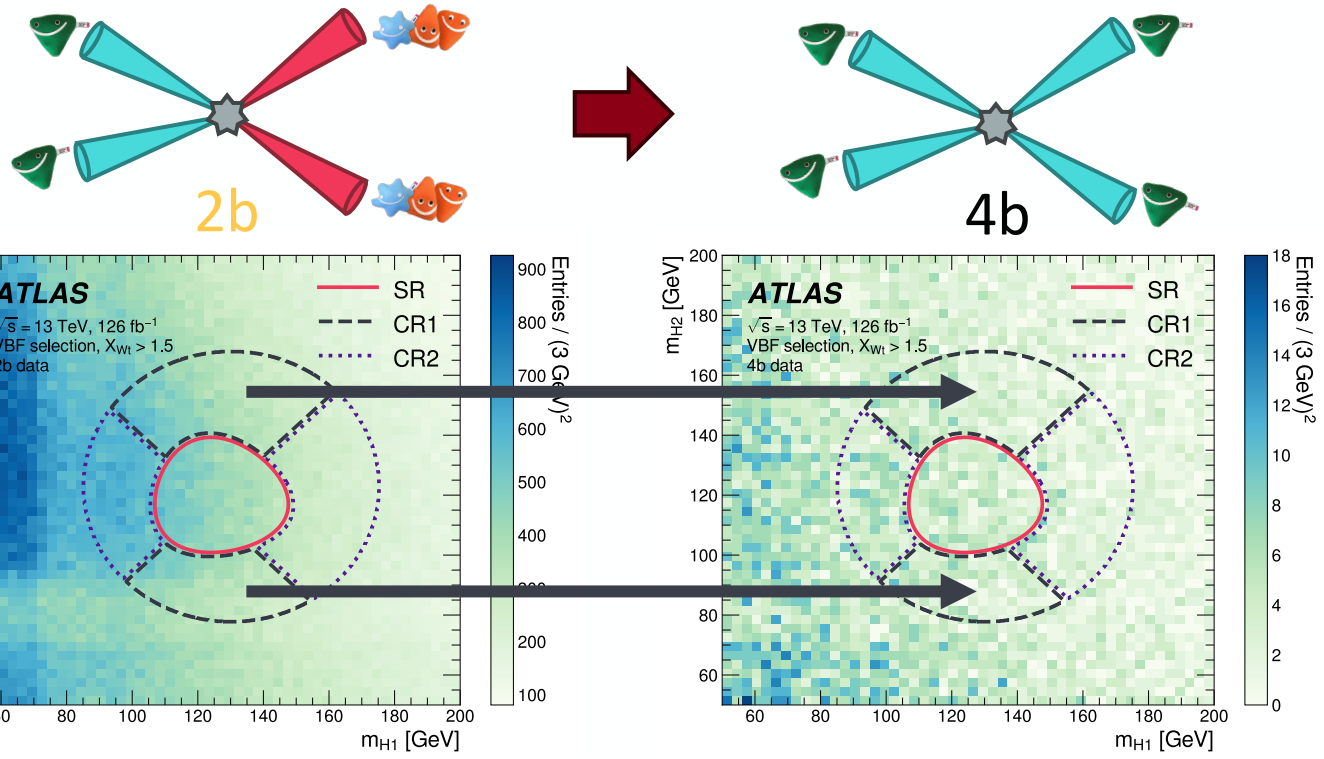
Background Modeling Strategy

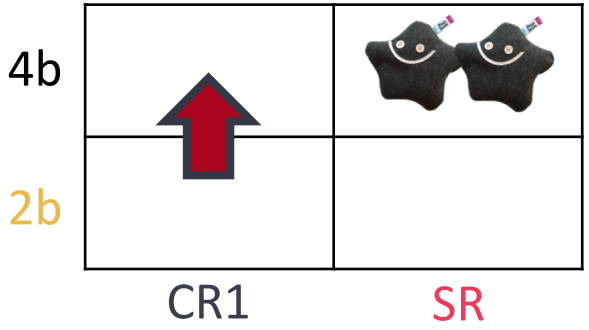


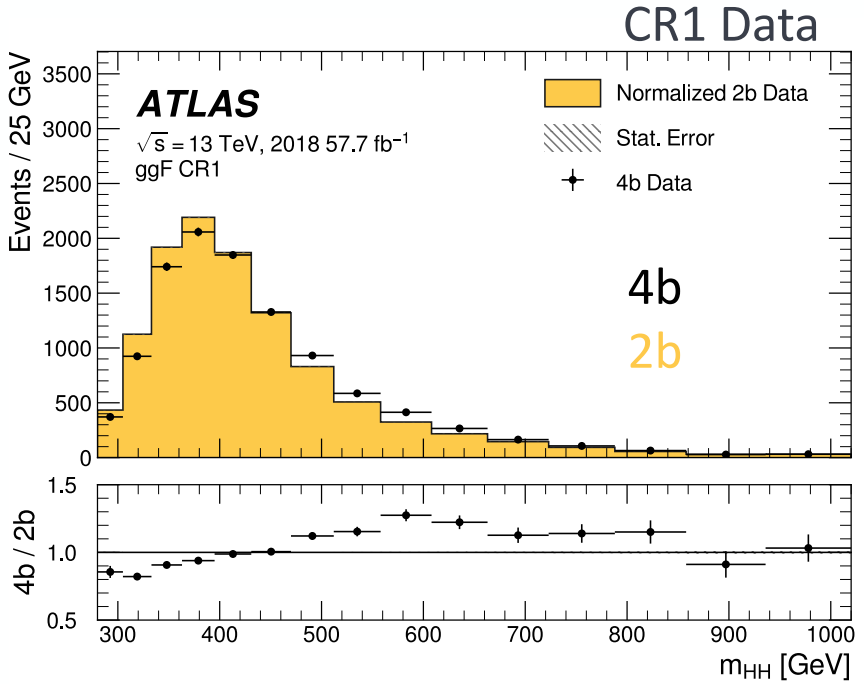
2b background processes
~ 4b background processes

→ use 2b data to estimate backgrounds in the 4b region?

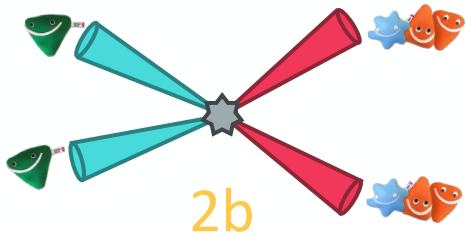
Background Modeling Strategy

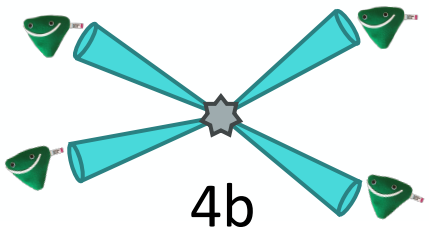


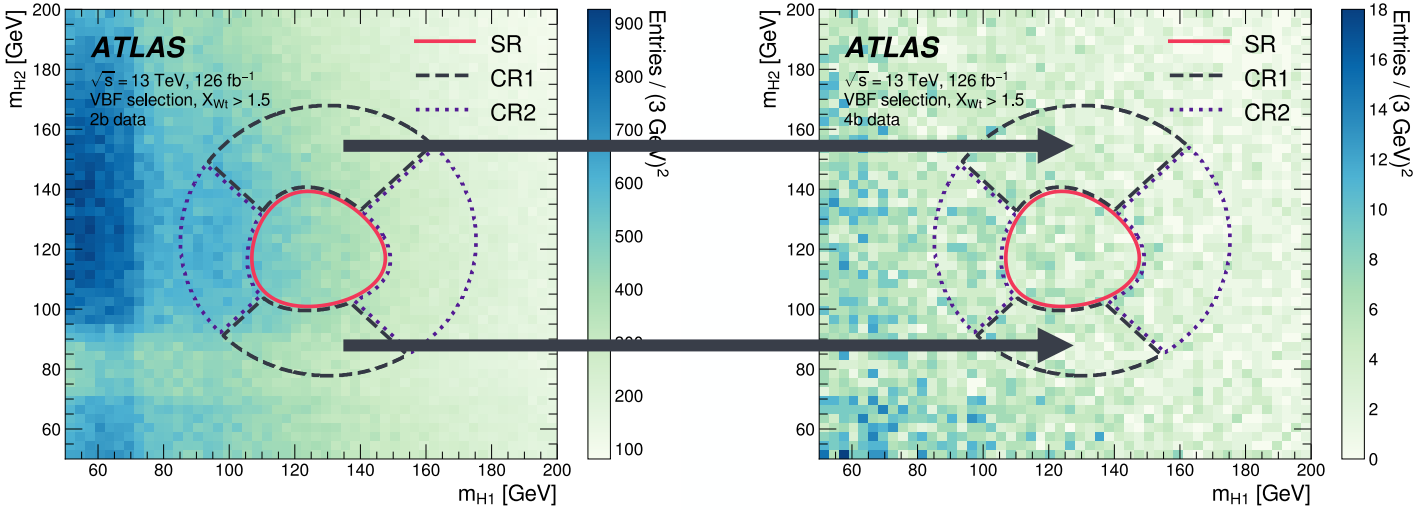


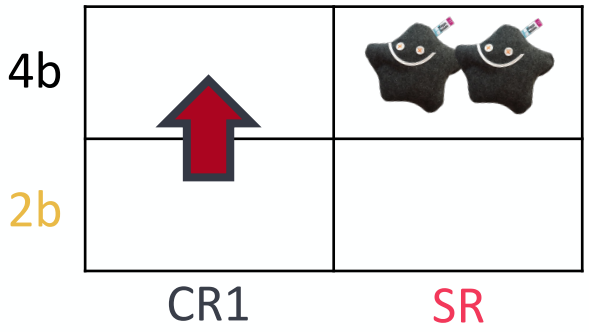


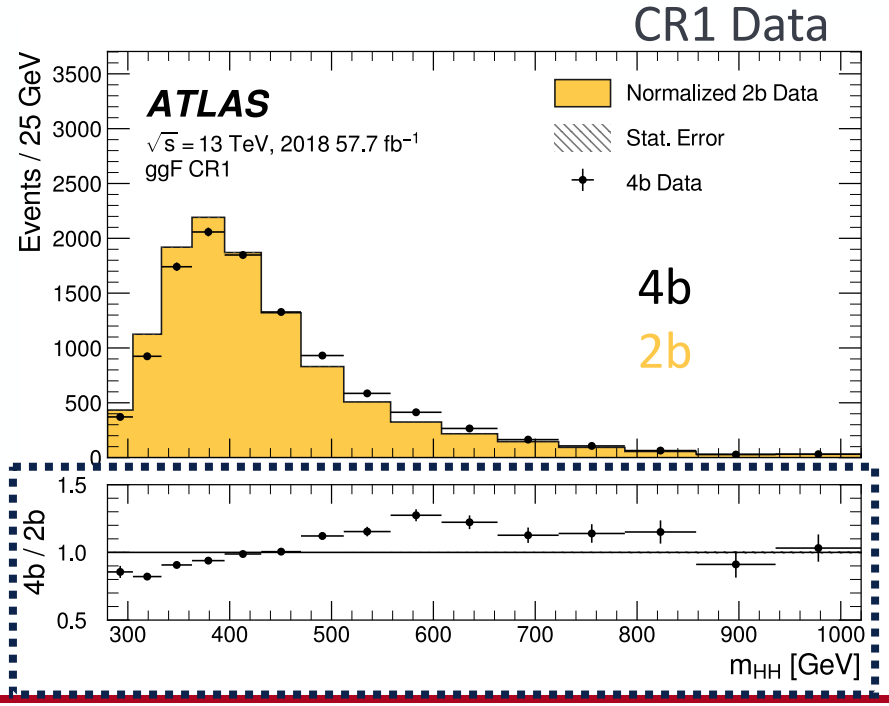
Background Modeling Strategy





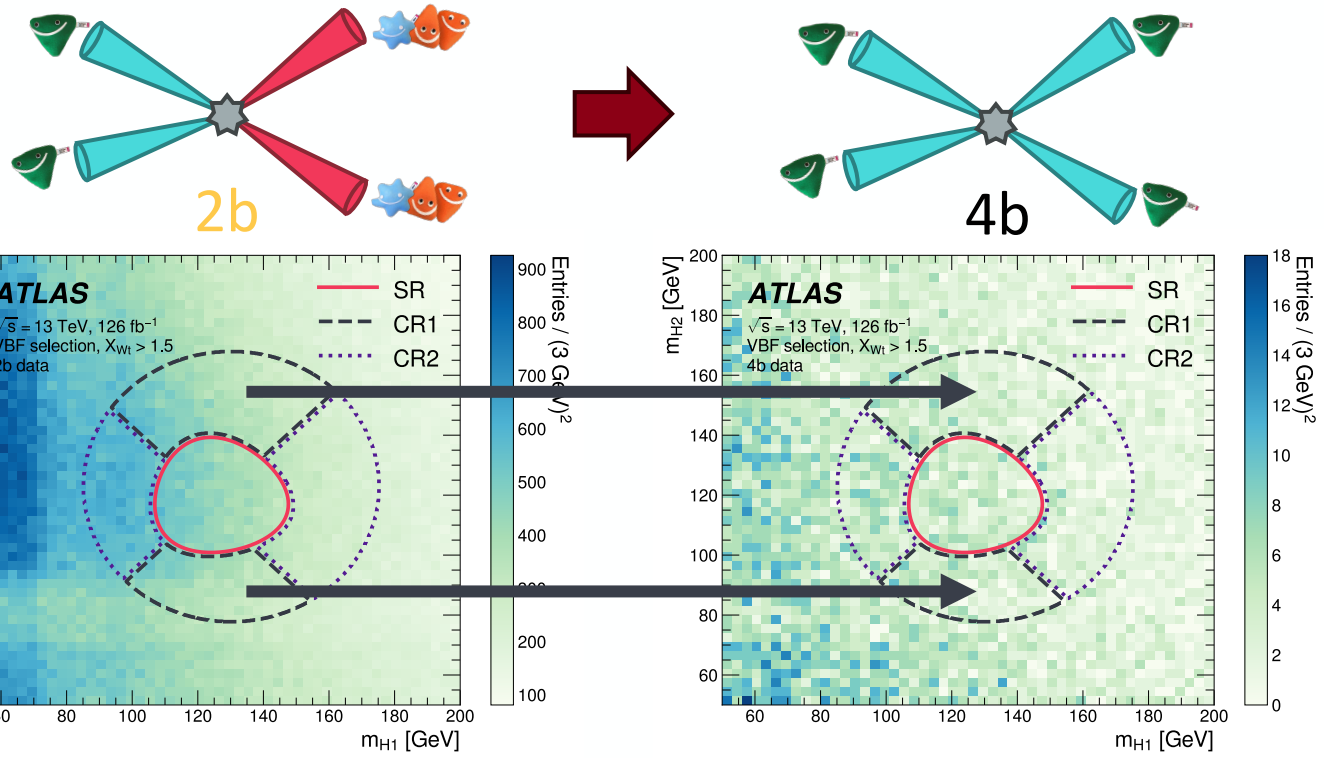


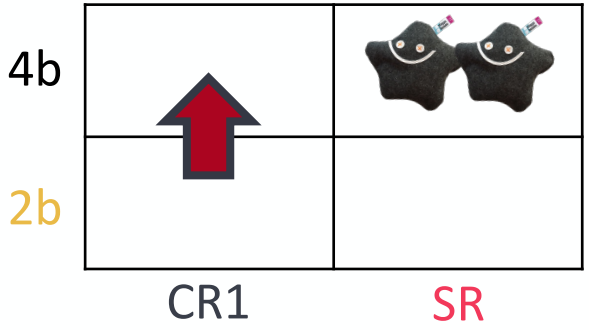


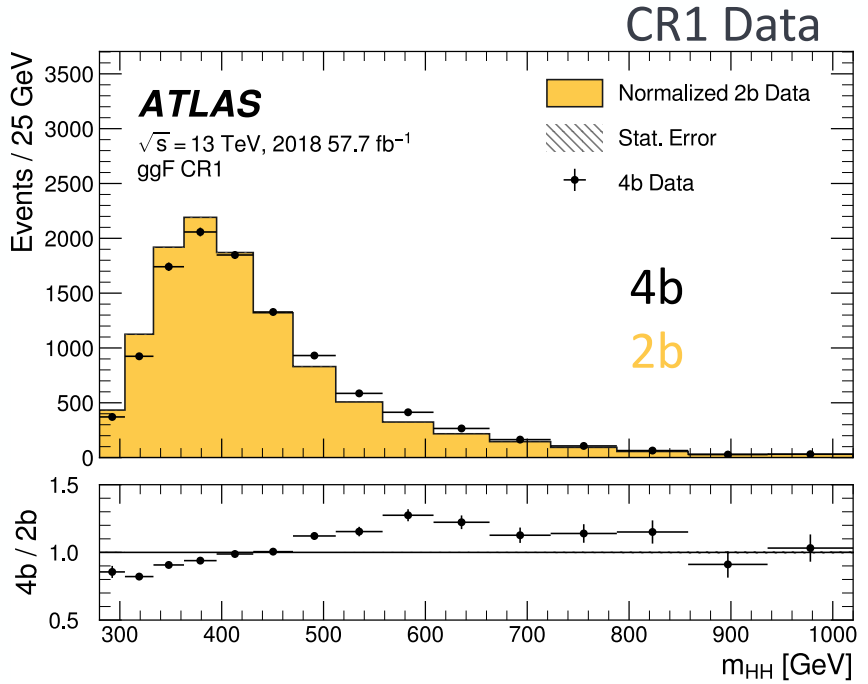


1-Dimensional density ratio: $w(x) = p_{4b}(x)/\, p_{2b}(x)$
(ignores correlations + prone to fluctuations)

Background Modeling Strategy

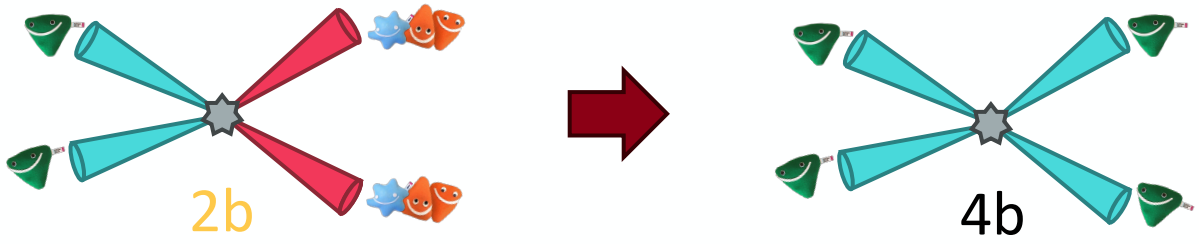






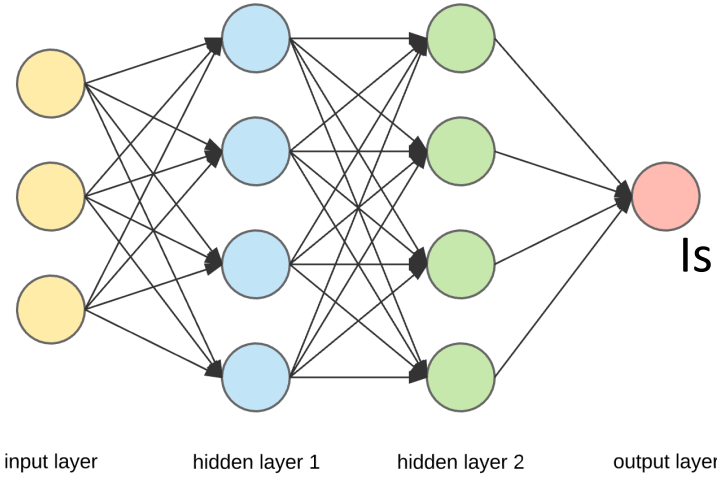
Train Neural Network to approximate high-dimensional, event-level $w(\vec{x})$!

Neural Network Reweighting



Classification

Input Features
(~kinematics of
jets in event)



Output
Is 2b or 4b ?

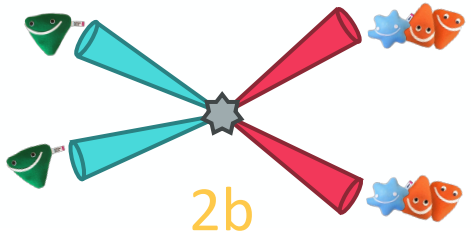
Want reweighting, not classification…

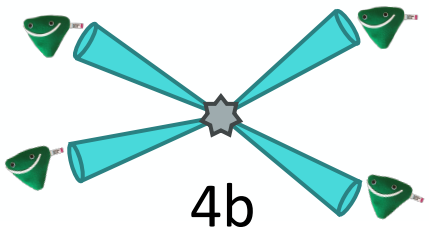
Classification NN identifies most-differentiating features

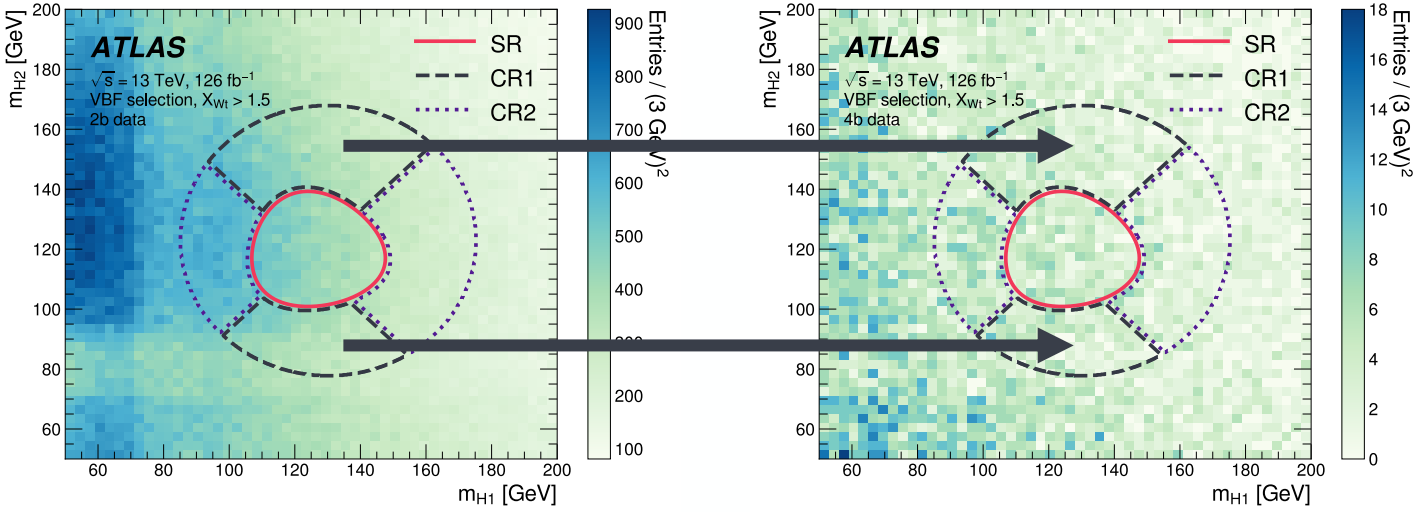
→ analogous to “what features do very 4b-like events have?”

(Minimizing special form of loss function)

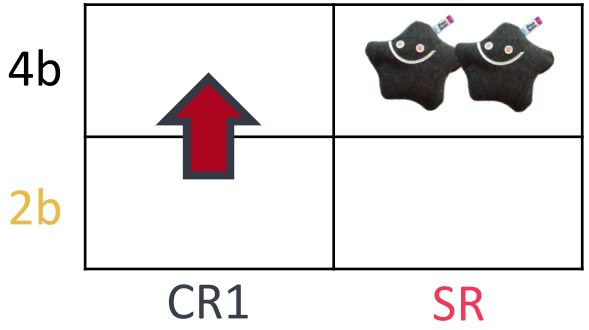
Background Modeling Strategy

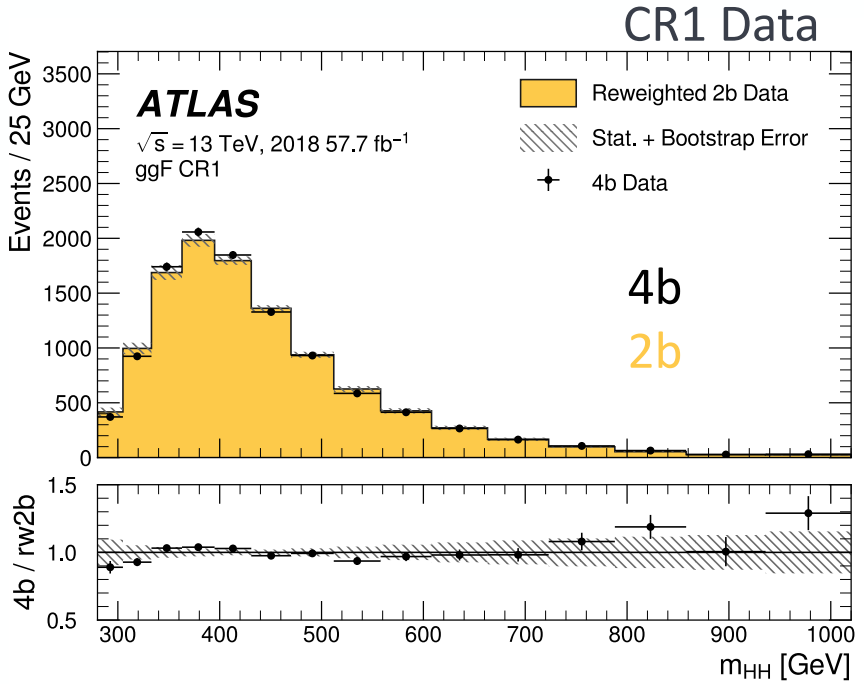




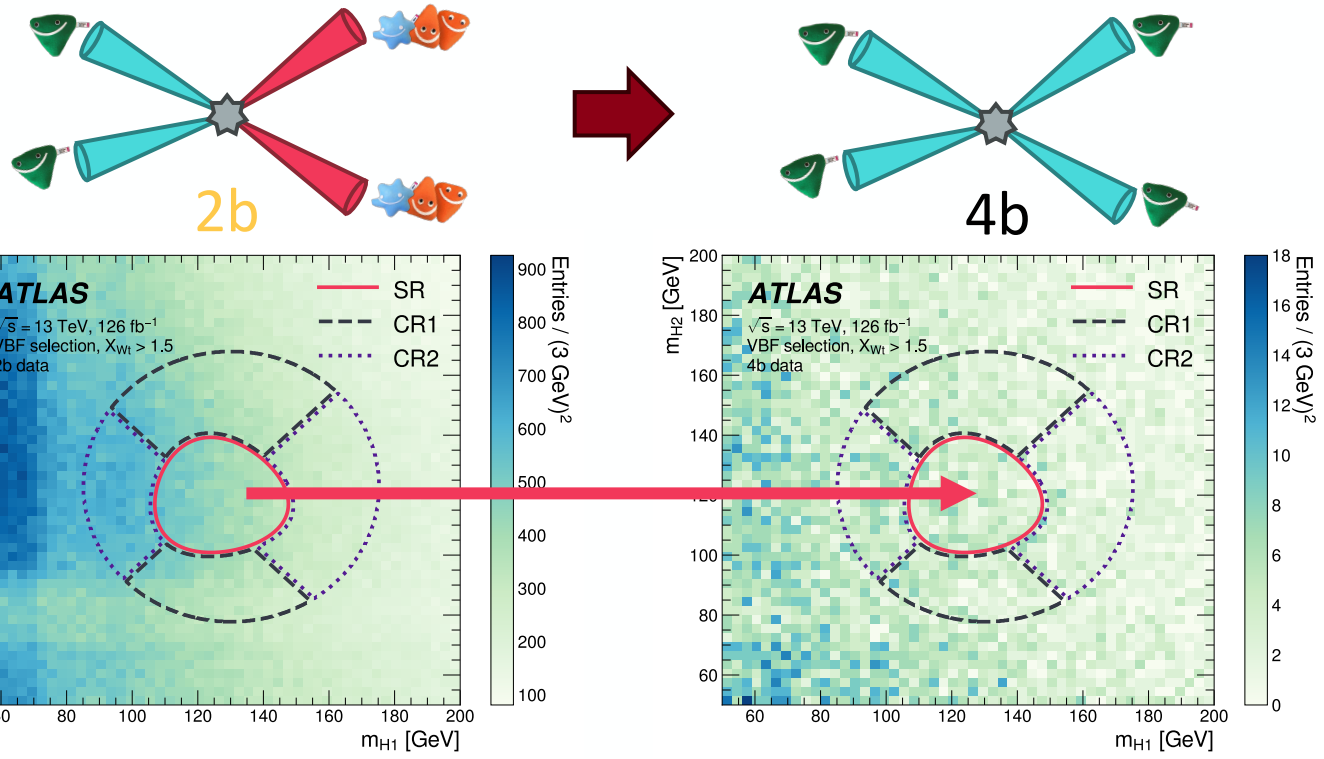


Train in CR1



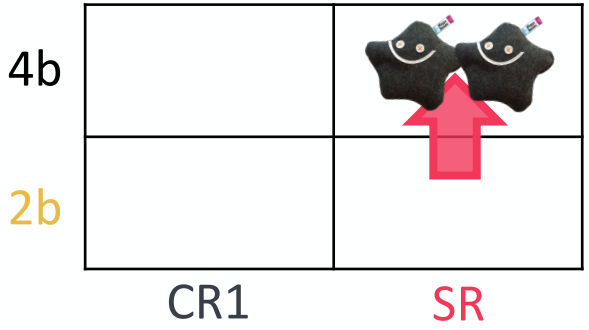


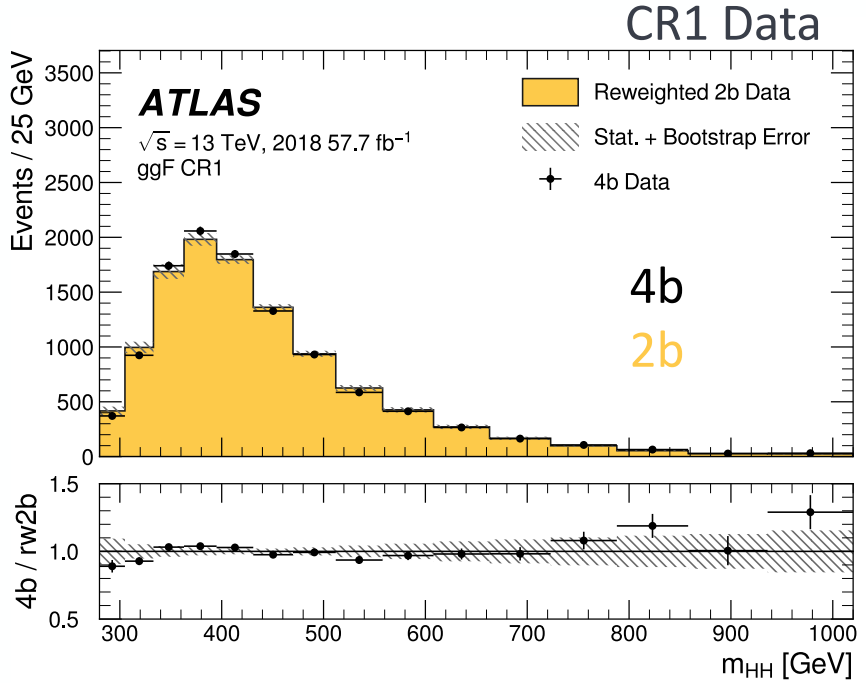
Background Modeling Strategy



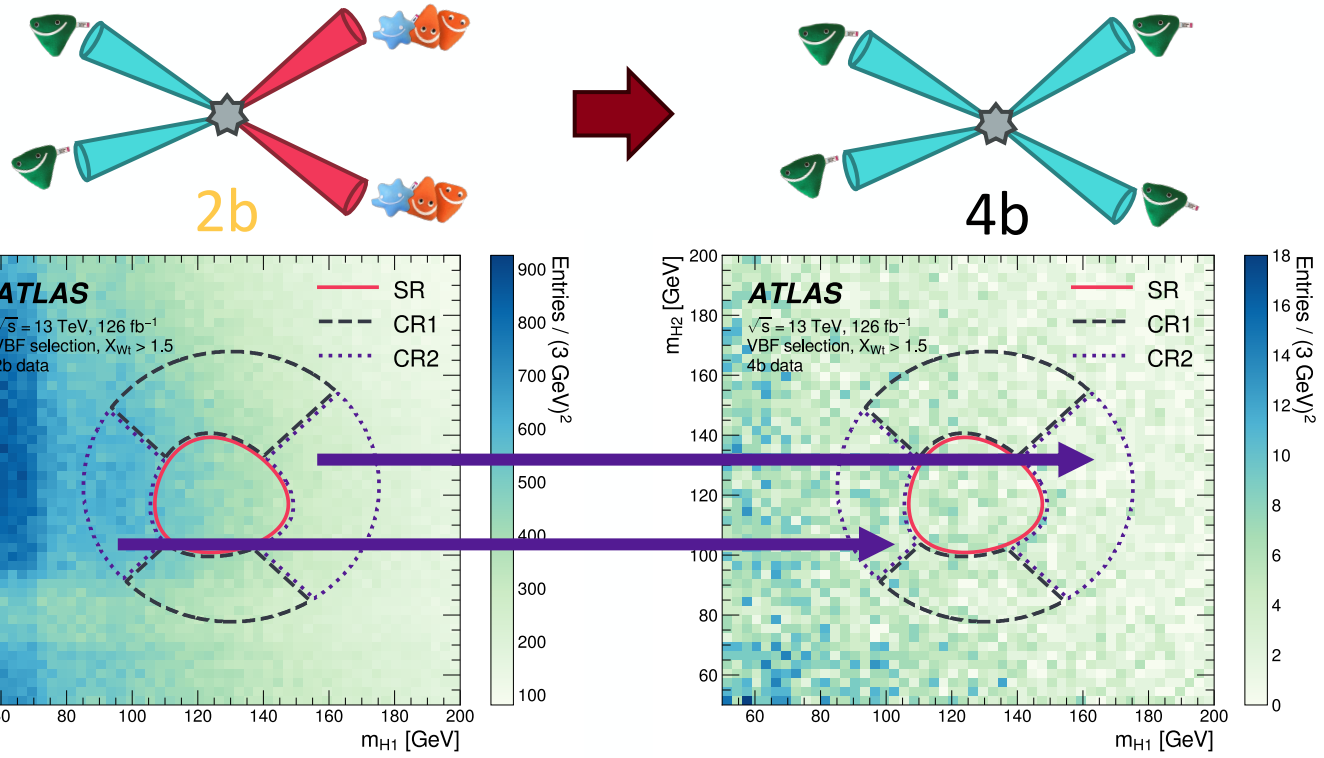
Train in CR1

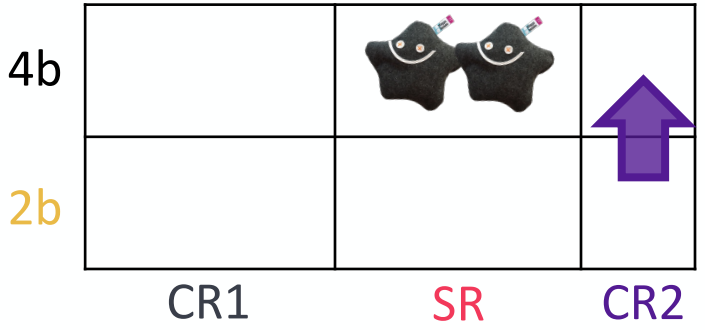
Apply in SR





Background Modeling Strategy

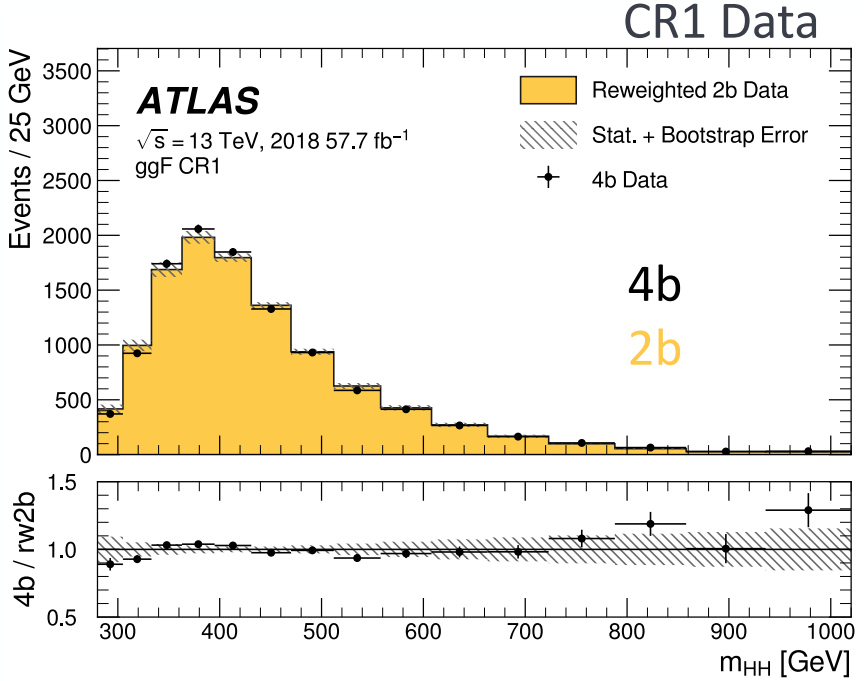




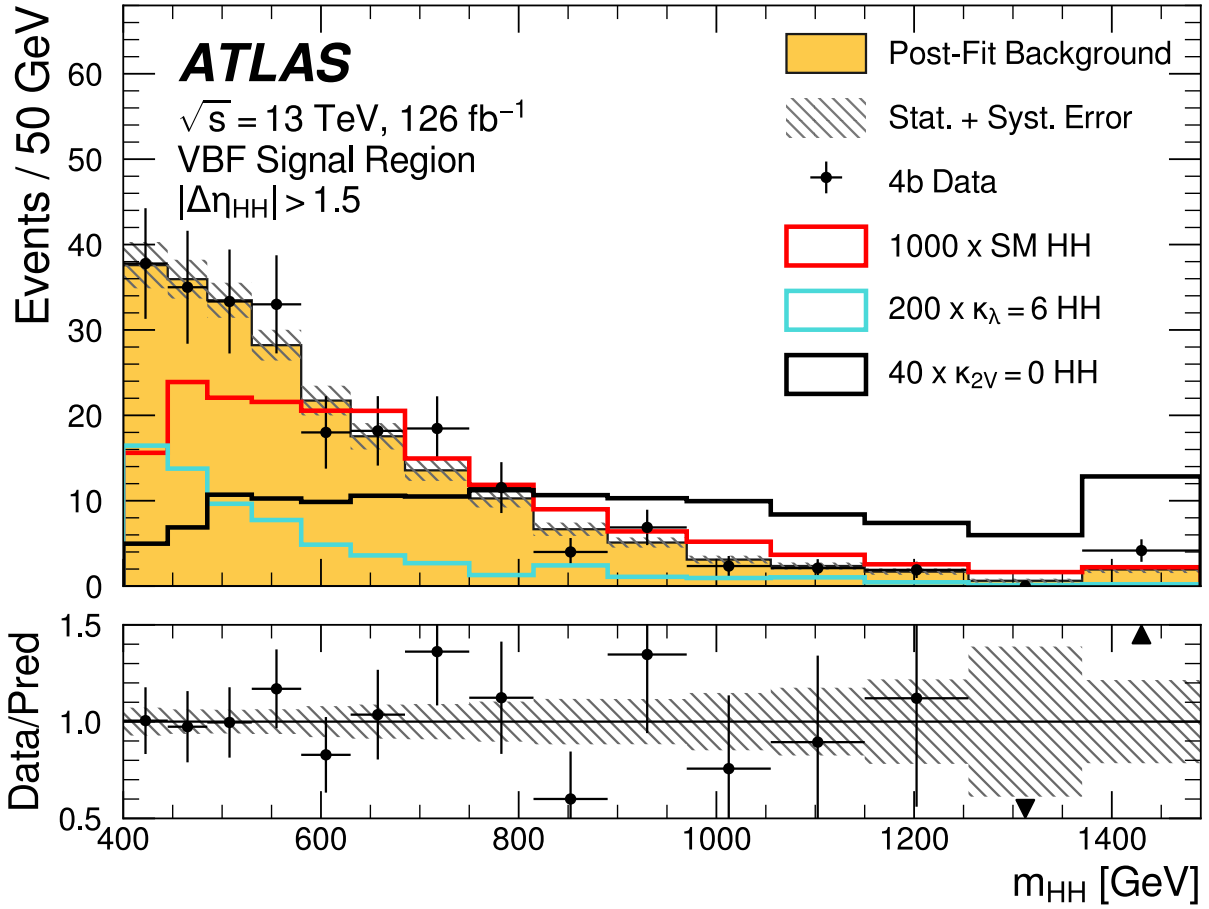
Train in CR1

Apply in SR

(Validate in CR2)



Observed Data in an SR Category



Standard Model ($\kappa_\lambda = \kappa_{2V} = 1$)

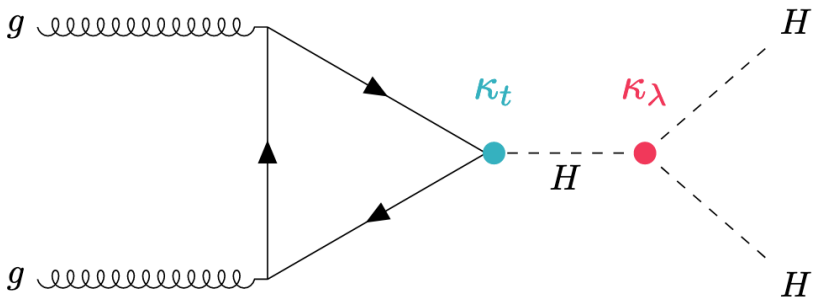
$\kappa_\lambda = 10$ ($\kappa_{2V} = 1$)

$\kappa_{2V} = 0$ ($\kappa_\lambda = 1$)

Neural-network reweighted background agrees well with observed data

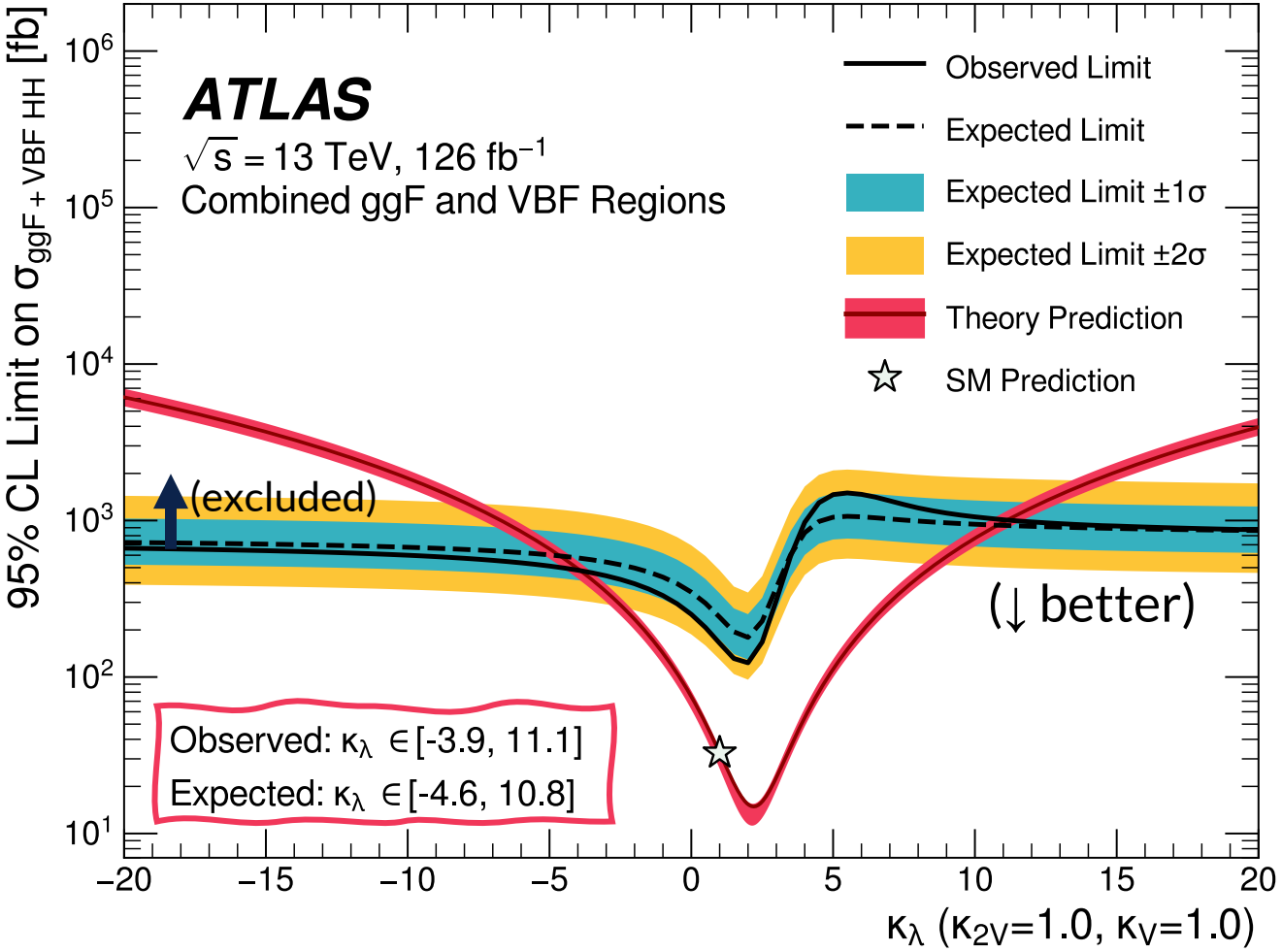
→ No signal bump

Constraining the *HHH* Coupling

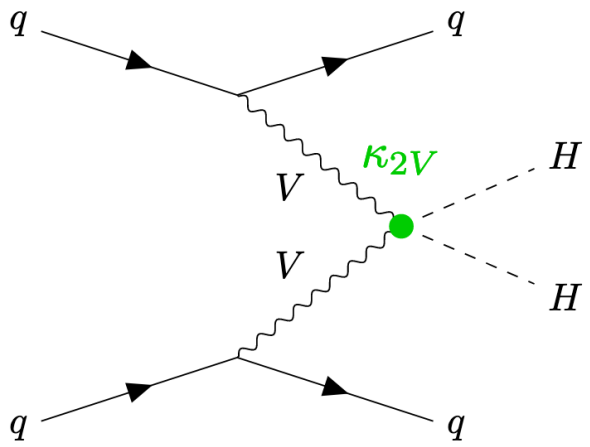


Probing $\mathcal{O}(10)$ deviations to κ_λ

$b\bar{b}b\bar{b}$ most sensitive to high-m_{HH}
BSM softer → less sensitive

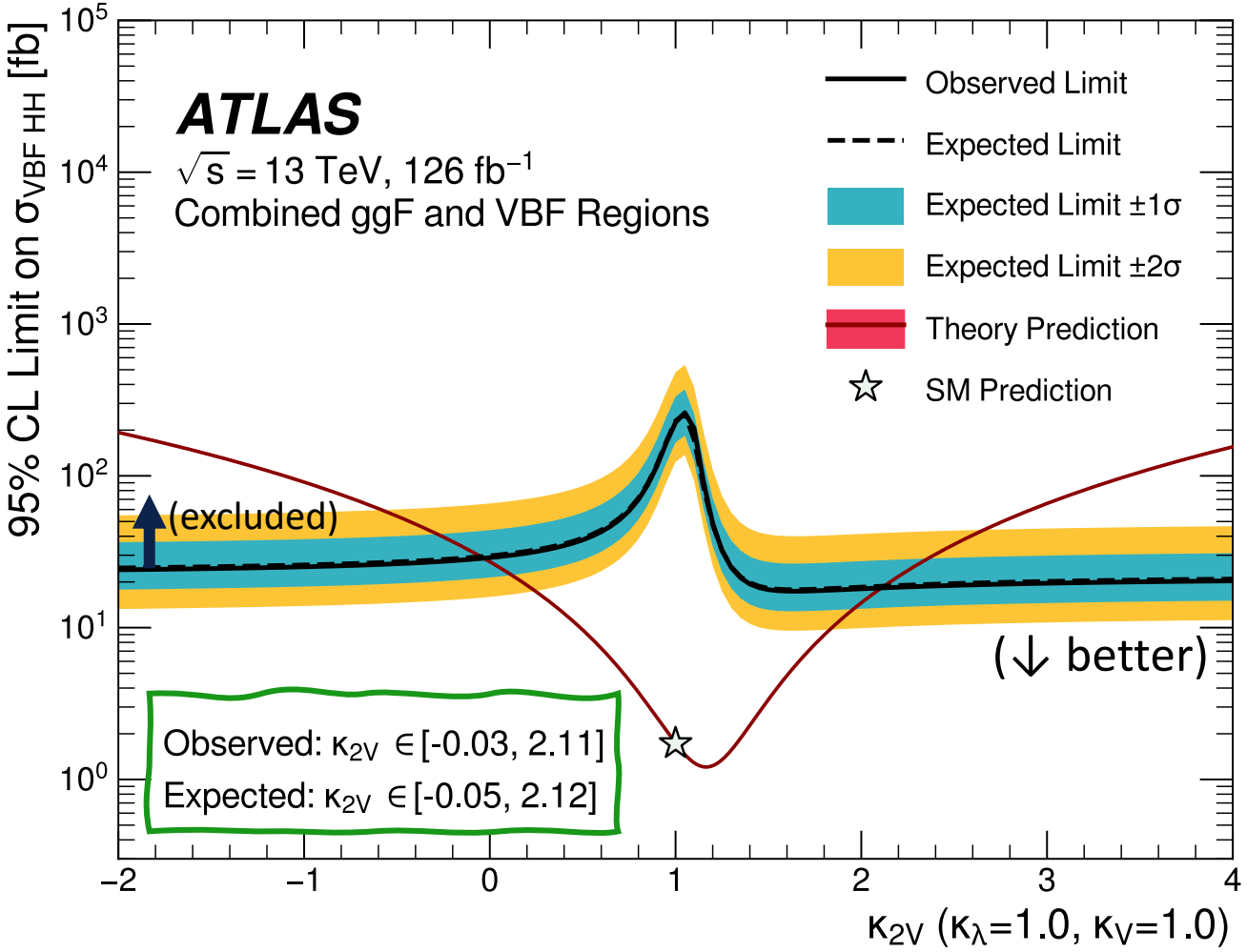


Constraining the *VVHH* Coupling



Probing $\mathcal{O}(1)$ deviations to κ_{2V}

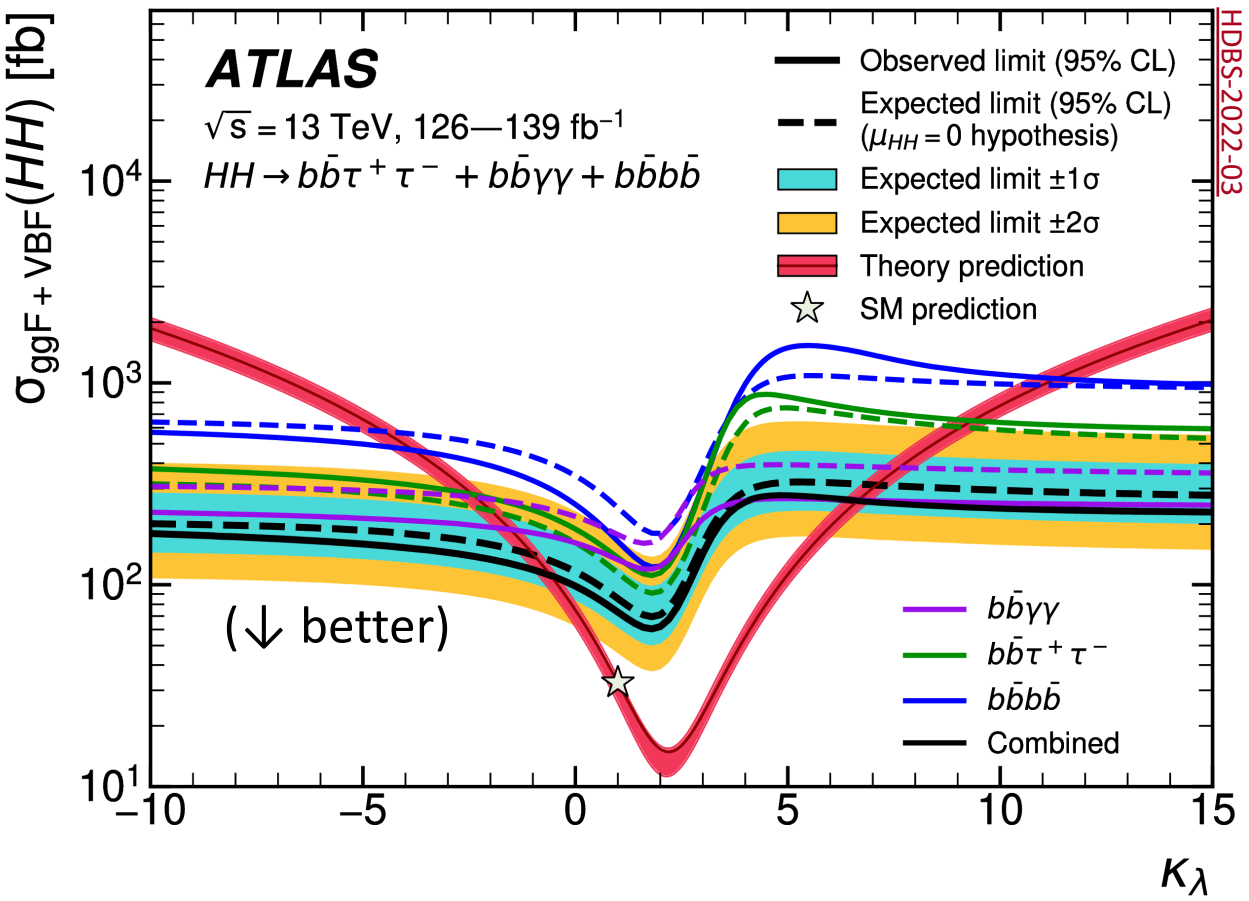
$b\bar{b}b\bar{b}$ most sensitive to high-m_{HH}
BSM harder → more sensitive



Combination with $b\bar{b}\tau\tau$ and $bb\gamma\gamma$: κ_λ

	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%

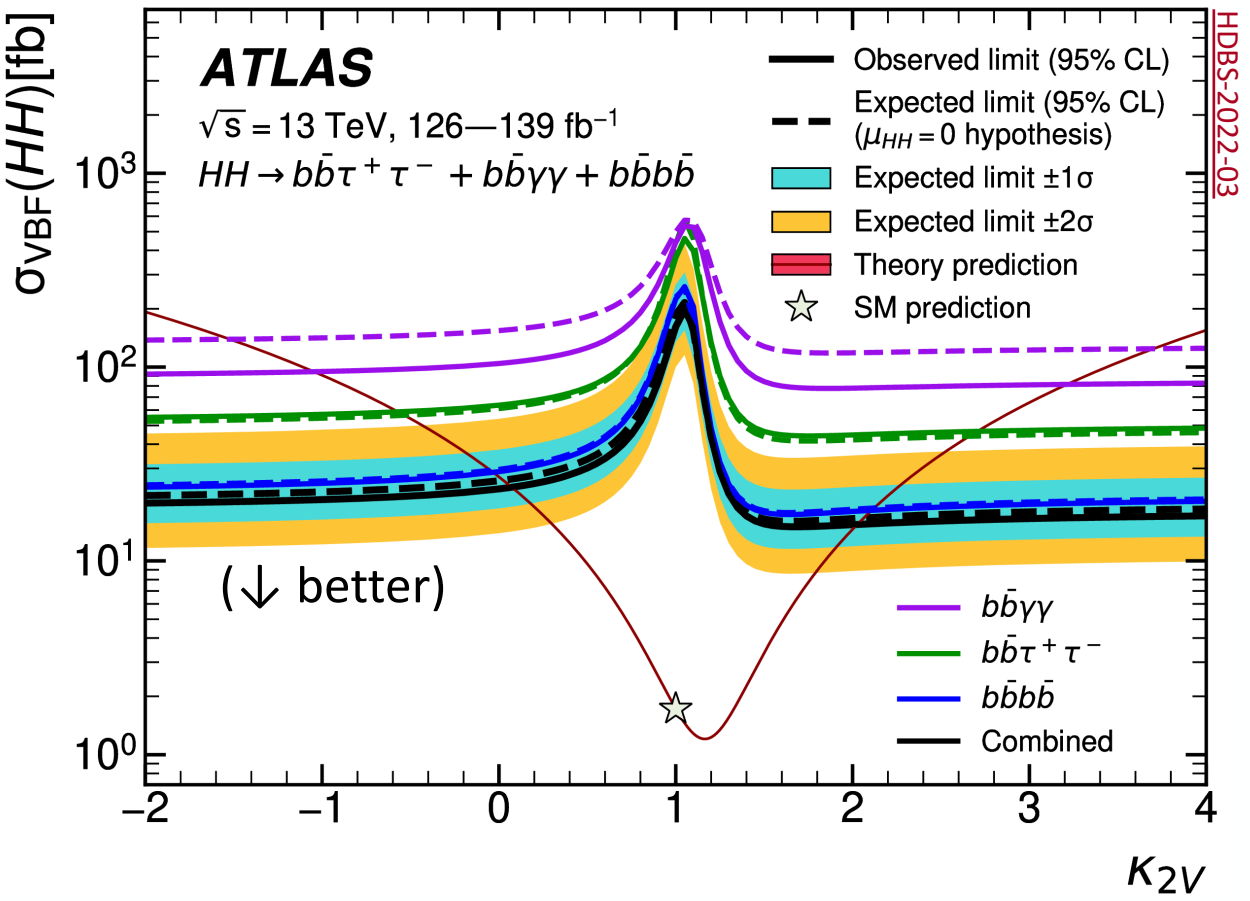
$b\bar{b}b\bar{b}$ most sensitive to high-m_{HH}
→ less sensitive to BSM κ_λ



Combination with $b\bar{b}\tau\tau$ and $bb\gamma\gamma$: κ_{2V}

	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%

$b\bar{b}b\bar{b}$ channel currently driving ATLAS sensitivity to VVHH coupling!

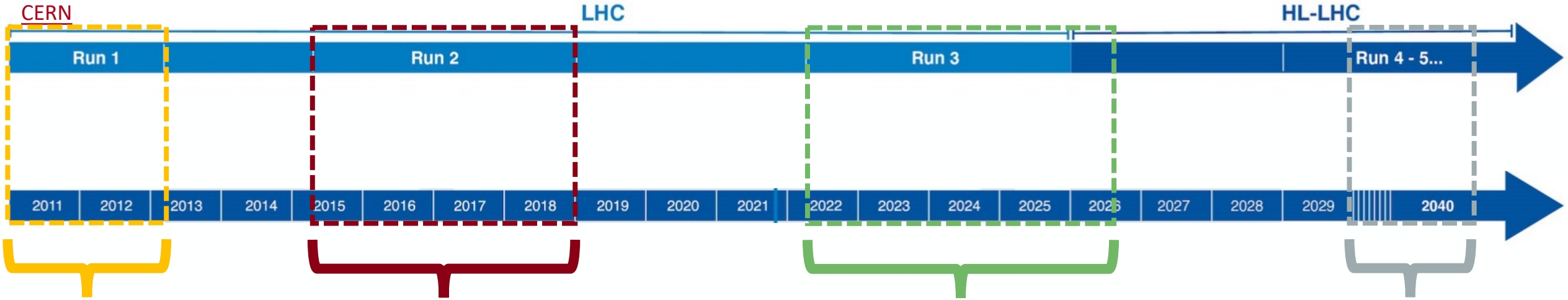


Prospects and Boosted Topologies

arxiv:2404.17193

Can we be smarter with our data?

Looking to the Future: The High-Luminosity LHC



Run 1
Higgs
Discovery!

Run 2
Data Shown Today

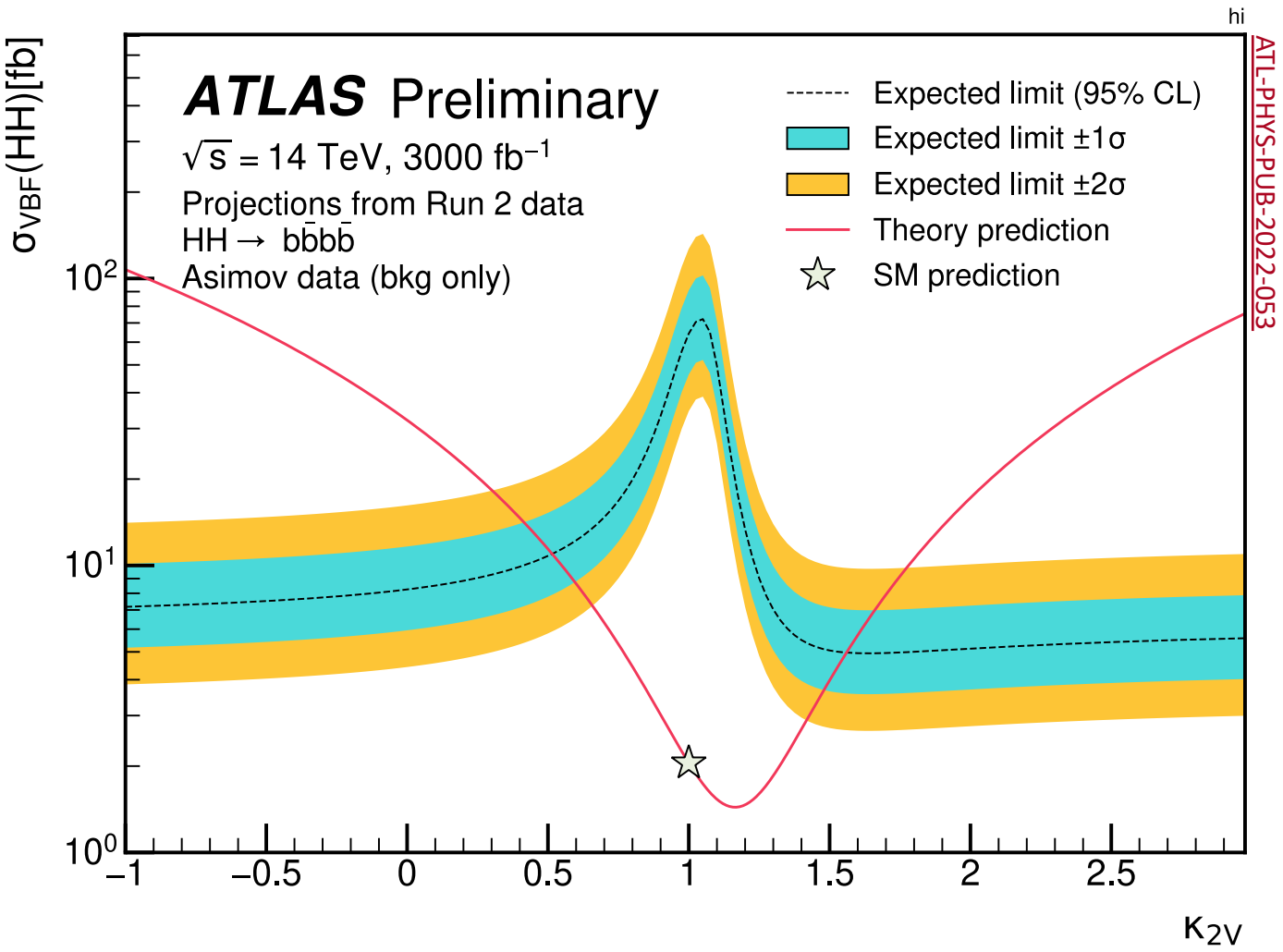
Run 3
Happening Now!

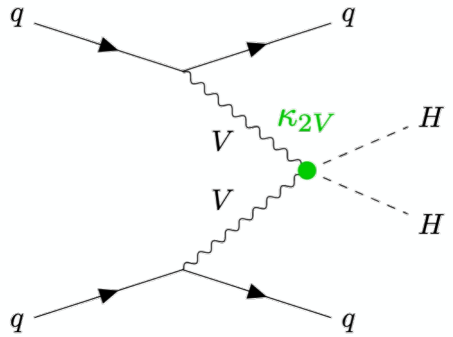
Future: HL-LHC

HiLumi
HL-LHC PROJECT

Expect ~20x more data than collected in Run 2!

Projecting κ_{2V} at the HL-LHC



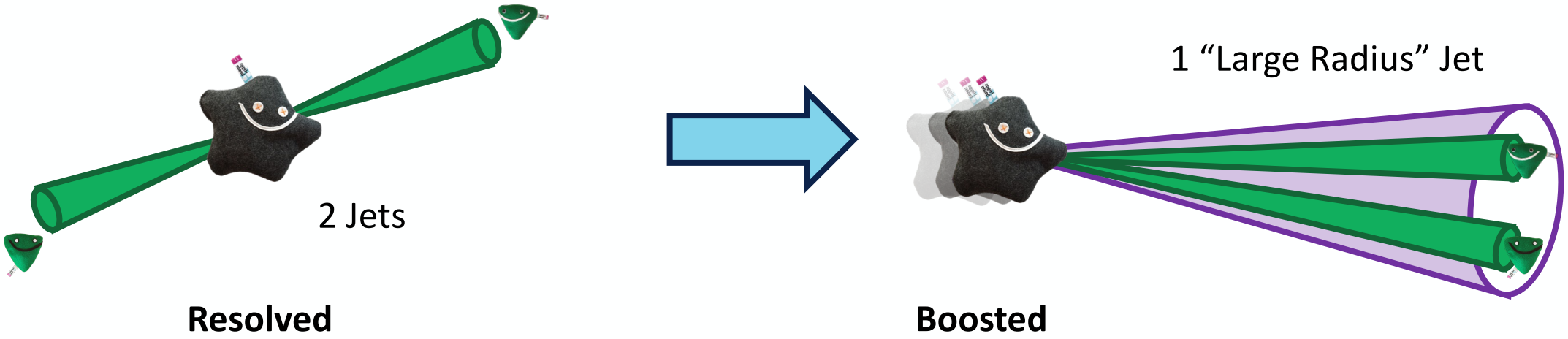


Full HL-LHC Dataset,
$HH \rightarrow b\bar{b}b\bar{b}$:

$$\mathbf{0.5} < \kappa_{2V} < \mathbf{1.6}$$

→ Sensitive to $\mathcal{O}$(~50%) effects!

The Boosted Topology



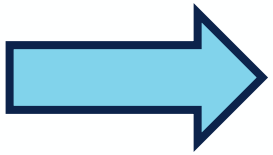
Very energetic Higgs Bosons:

Special Relativity → Lorentz boost the Higgs Boson’s decay in the lab frame

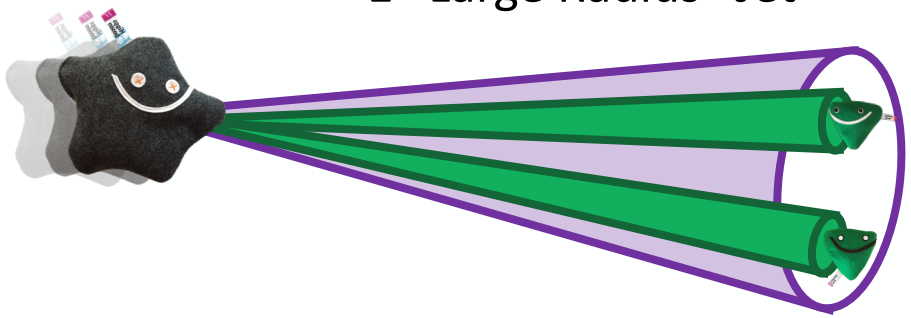
The Boosted Topology



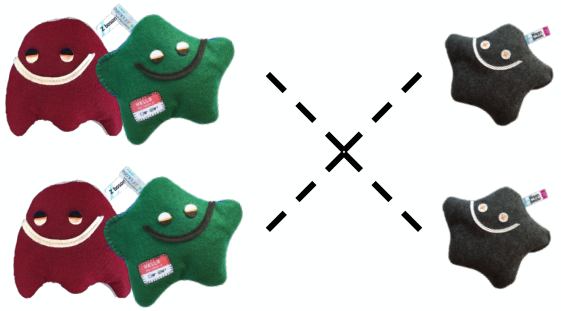
2 Jets



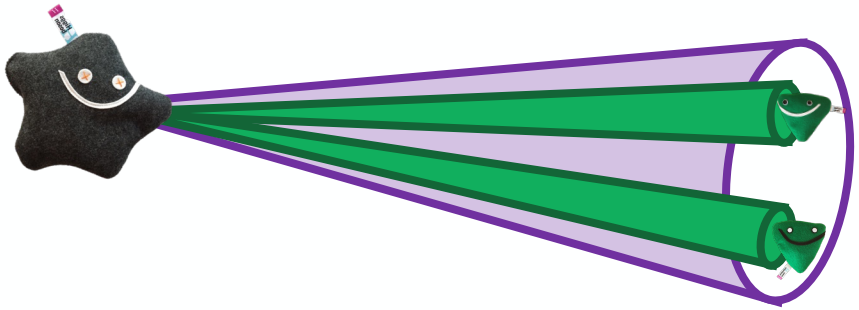
1 “Large Radius” Jet



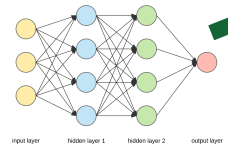
Change *VVHH* interaction
→ more energetic Higgs Bosons



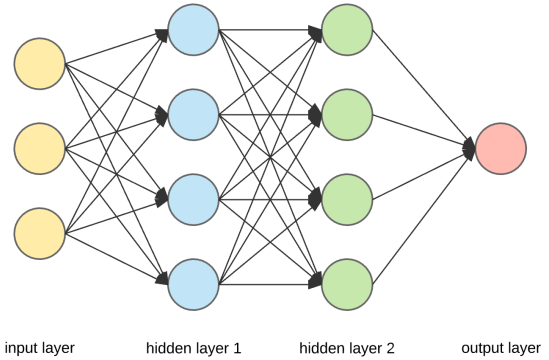
Boosted $H \to b\bar{b}$ Tagging in ATLAS



Large-Radius Jet
Kinematics



Subjet
b-tagging



Xbb Tagger (Deep NN)

Reject ~99% of large-radius jets from QCD-background !

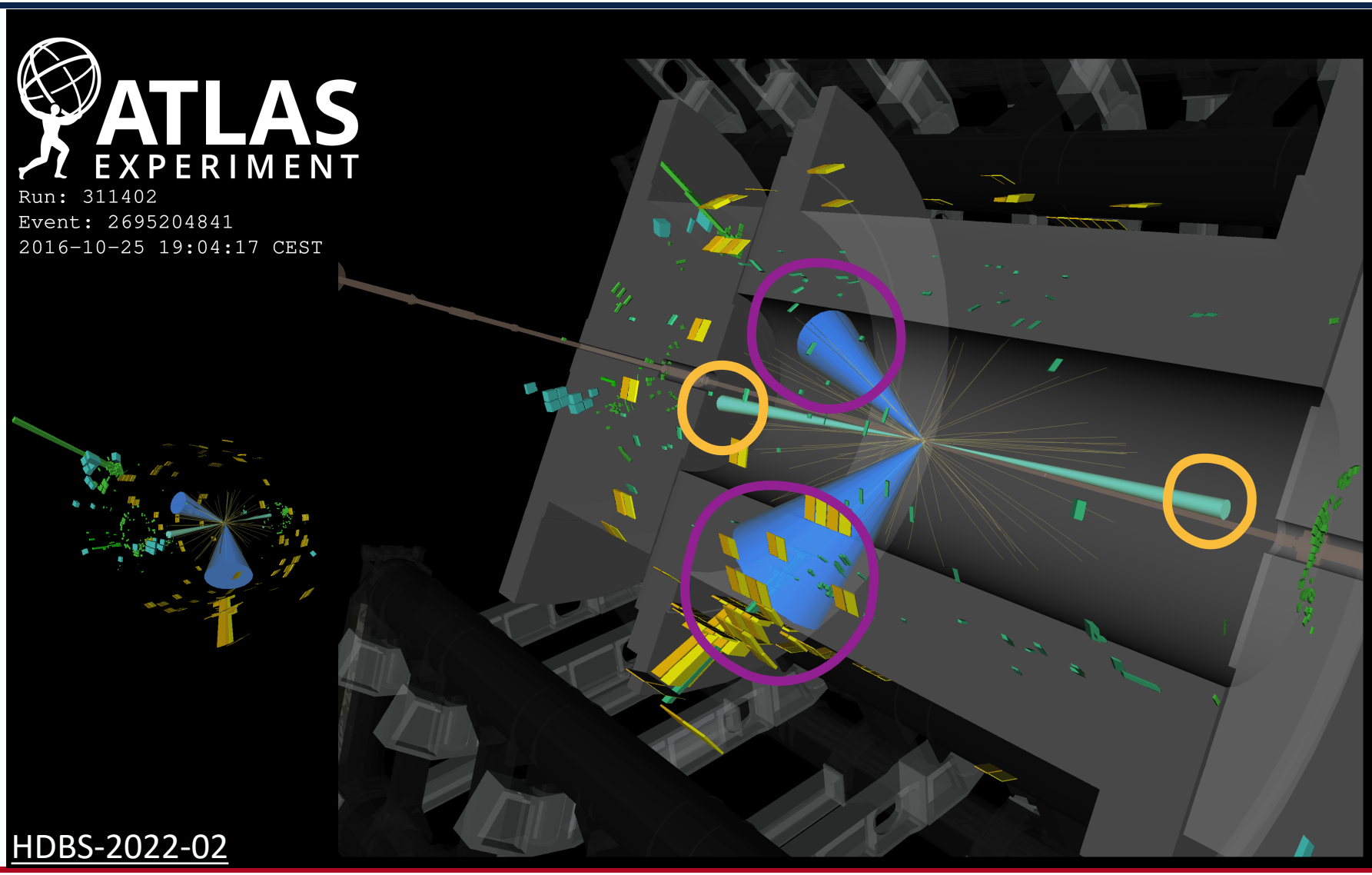
ATL-PHYS-PUB-2020-019

The Boosted VBF $HH \to b\bar{b}b\bar{b}$ Analysis

Searching for events with 2 *Xbb*-tagged large-radius jets, plus VBF small-radius jets (and basic kinematic cuts)

~20 Background Events

~0.02 SM VBF $HH \to b\bar{b}b\bar{b}$ Events…



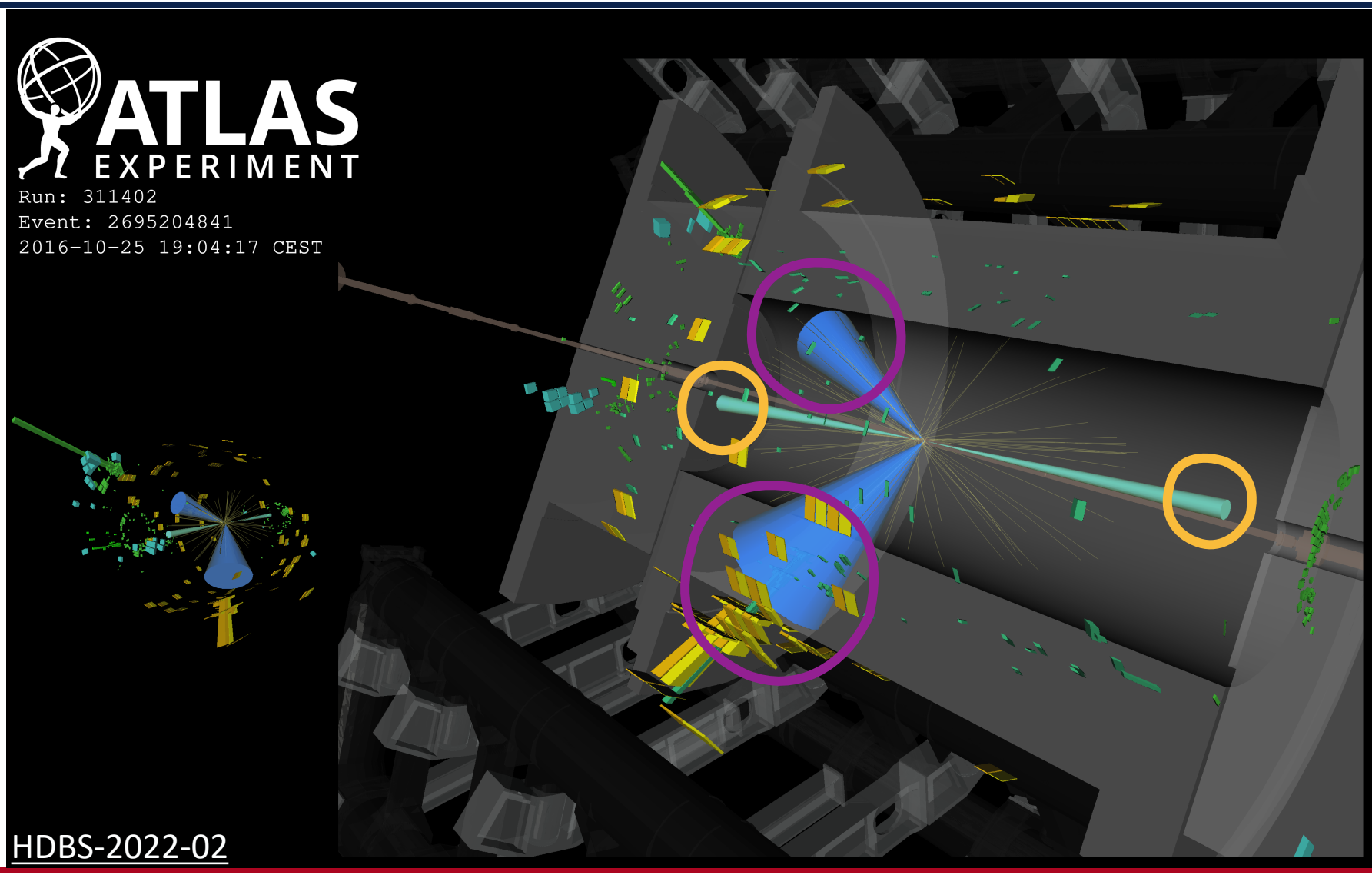
The Boosted VBF $HH \rightarrow b\bar{b}b\bar{b}$ Analysis

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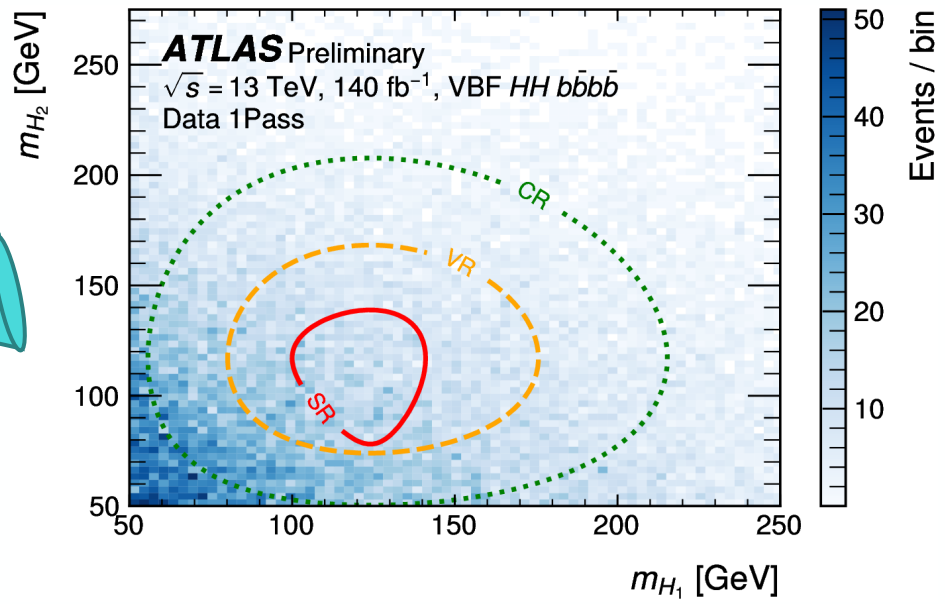
~0.02 SM VBF $HH \rightarrow b\bar{b}b\bar{b}$ Events…

Up to ~20 VBF $HH \rightarrow b\bar{b}b\bar{b}$ Events if $\kappa_{2V} = 0$!

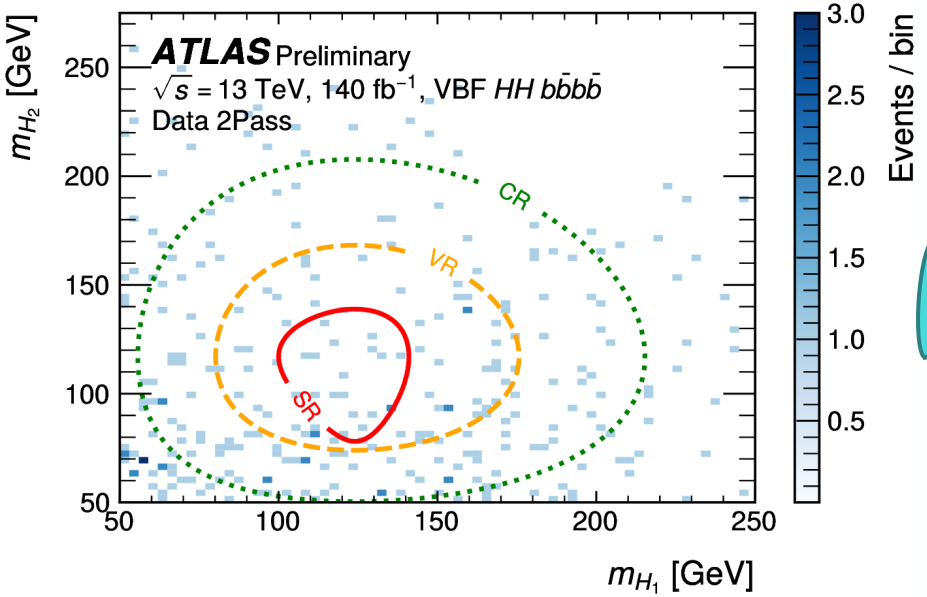


Boosted Background Estimation

1-Pass (1 Xbb-Tagged Jet)

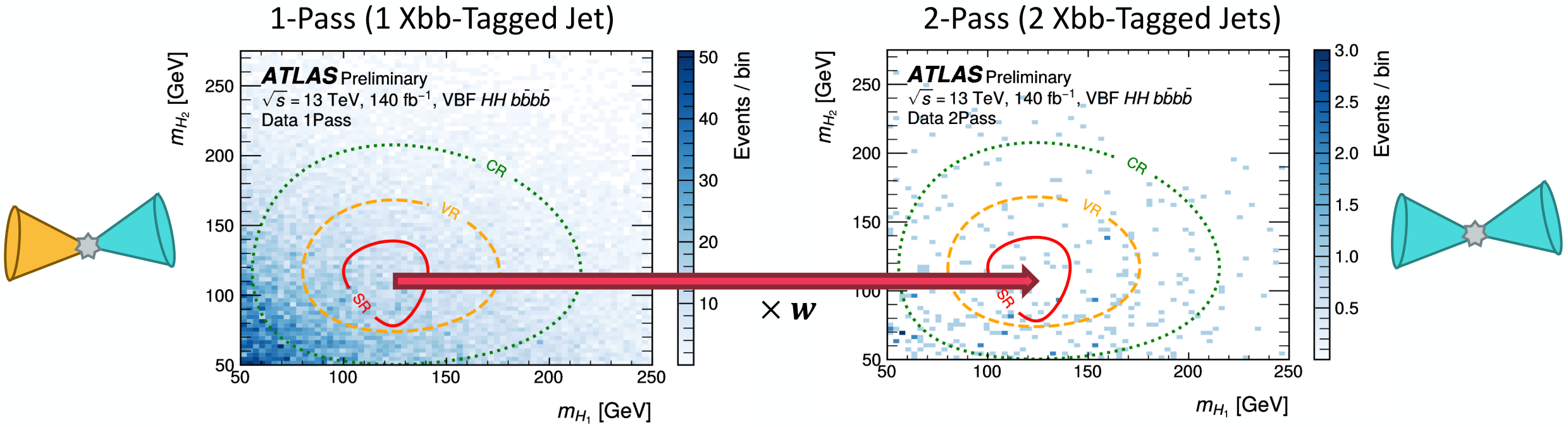


2-Pass (2 Xbb-Tagged Jets)



Rely on data-driven approach,
again using the (m_{H1}, m_{H2}) mass-plane

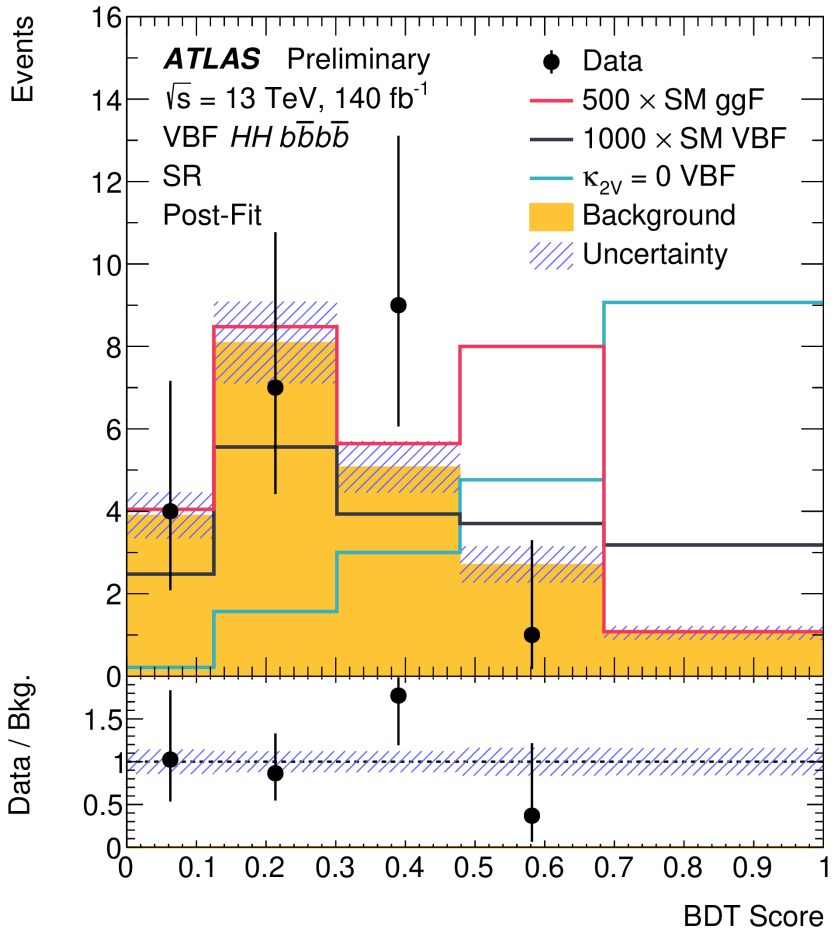
Boosted Background Estimation



Estimate 2-Pass SR Background using 1-Pass SR Events

Normalization derived in CR: $\boldsymbol{w} = \frac{N_{CR}^{2-\mathrm{Pass}}}{N_{CR}^{1-\mathrm{Pass}}} \approx 0.008$

Observed Data



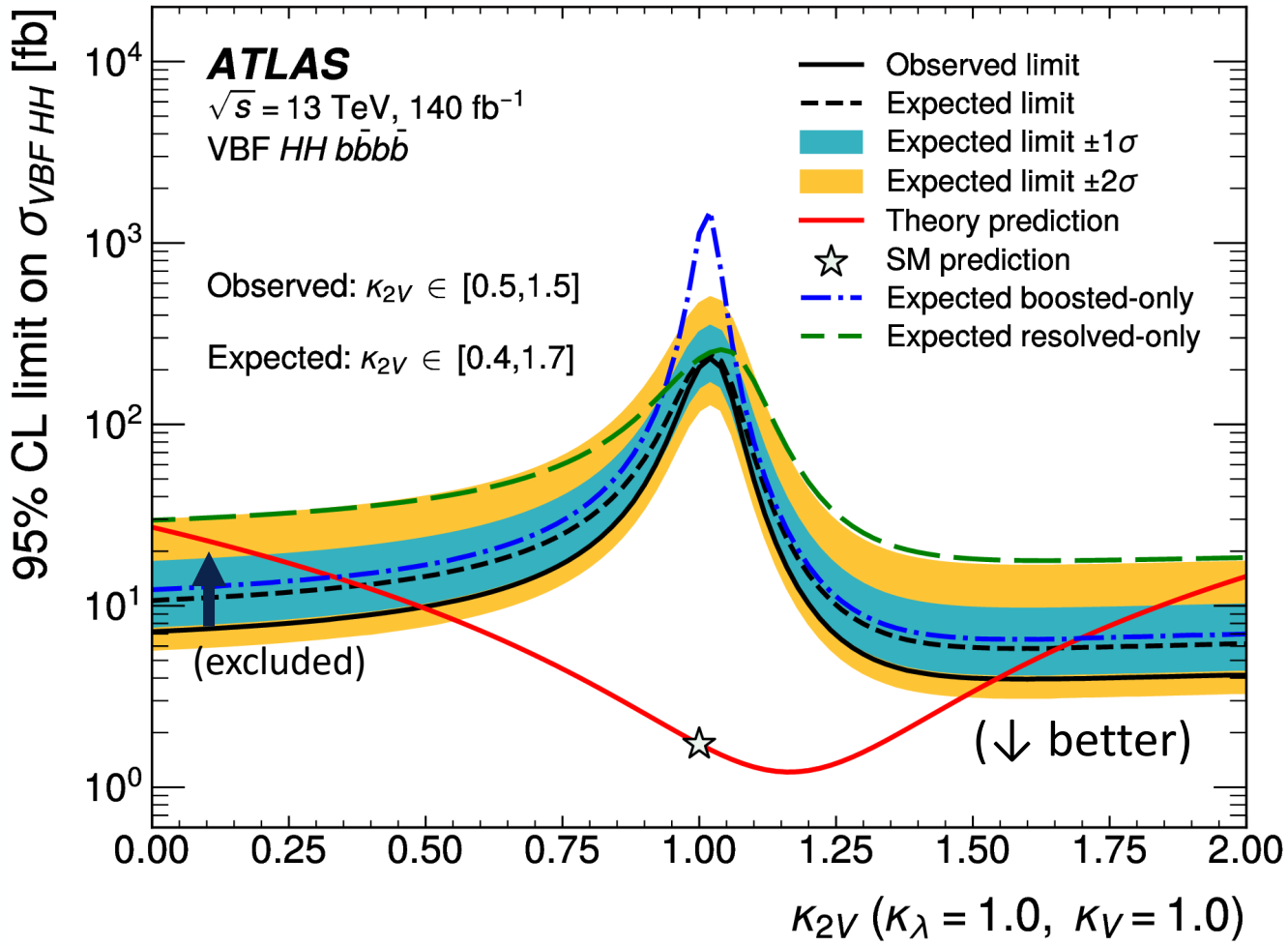
Boosted Decision Tree Score

- Observed Data
- VBF HH (SM)
- VBF HH ($\kappa_{2V} = 0$)
- ggF HH (SM)
- Expected Background

Variable of Interest = BDT Score
(Trained on jet kinematics)

→ **No obvious new physics!**

Results: Constraining the *VVHH* Coupling



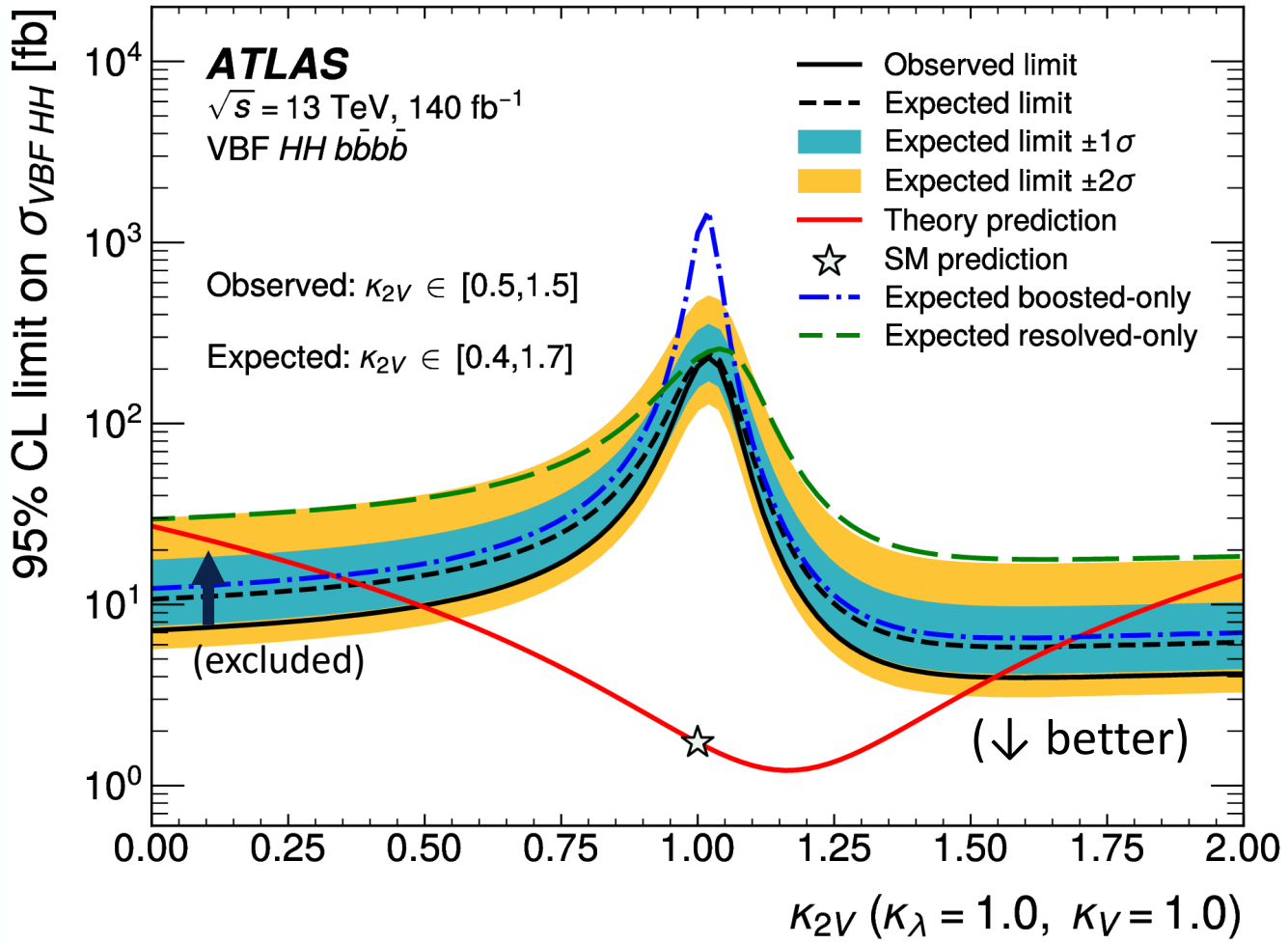
Previous Resolved Analysis

New Boosted Analysis

Combination (Boosted+Resolved)

Allowed $\kappa_{2V} = [0.5, 1.5]$

Results: Constraining the *VVHH* Coupling



Previous Resolved Analysis

New Boosted Analysis

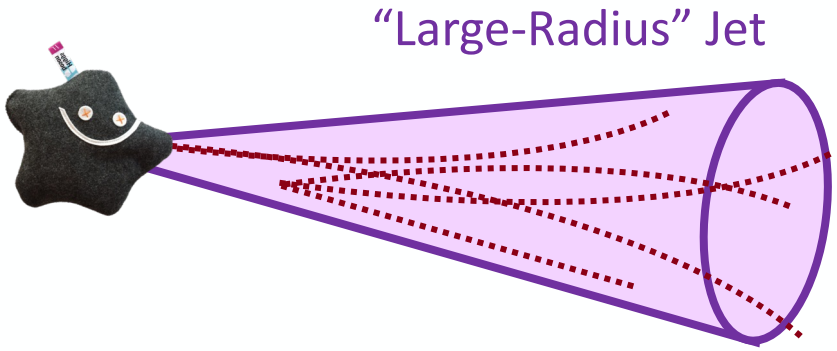
Combination (Boosted+Resolved)

Allowed $\kappa_{2V} = [0.5, 1.5]$

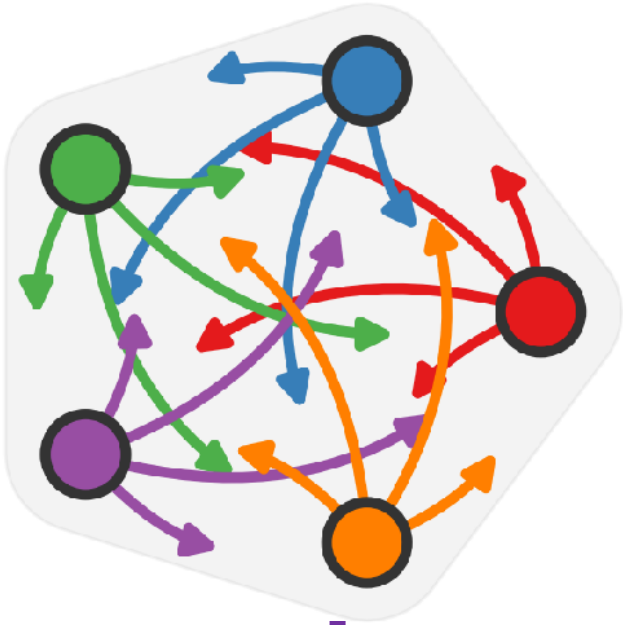
Constraint surpasses the HL-LHC Projections of previous resolved analysis!

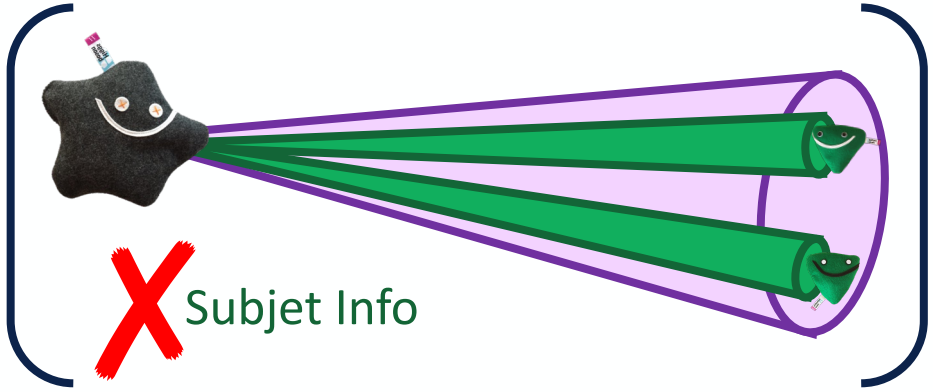
(projected $\kappa_{2V} = [0.5, 1.6]$)

How Can We Do Even Better?



Jet Kinematics,
Track Inputs

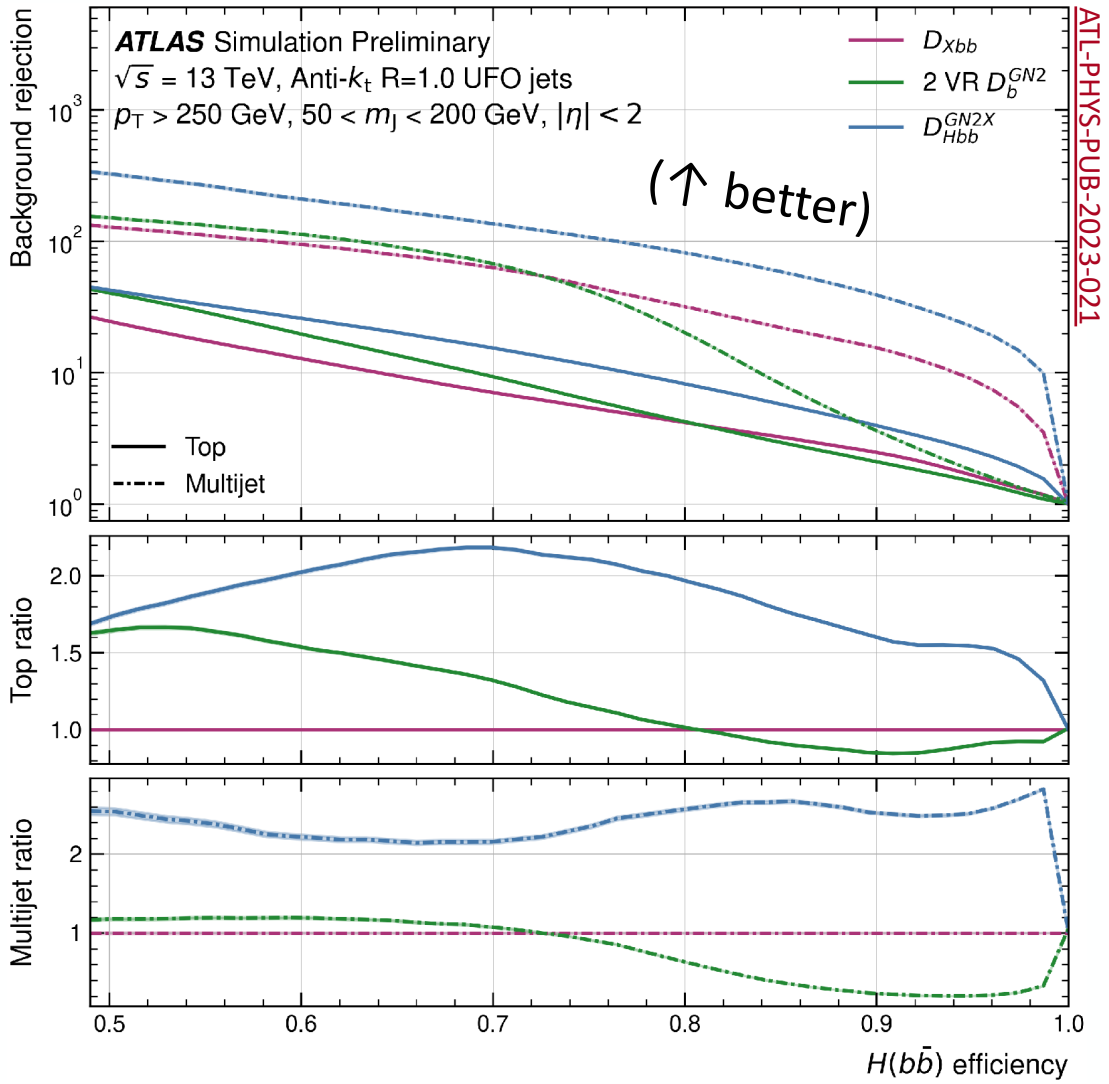




GN2X
Transformer Neural Network
for $H \to b\bar{b}$ Tagging

ATL-PHYS-PUB-2023-021

Improved Boosted $b\bar{b}$ Tagging



Factor of ~2x Improvement in GN2X compared to Xbb!

(Inspired by similar approach for single *b*-tagging; expect improved resolved analysis, too!)

Concluding Remarks

Conclusions

- **Measuring *HH* production probes the Higgs boson potential, which may hold the key to big questions in our universe**
  - **… but, it's hard to measure!**
- **Machine learning is enabling measurements in "impossible" channels ($HH \to b\bar{b}b\bar{b}$)**
- **Novel uses of machine learning and more data from Run 3 + the HL-LHC will open even more possibilities for Higgs Boson studies over the coming decades**

Thanks for listening!

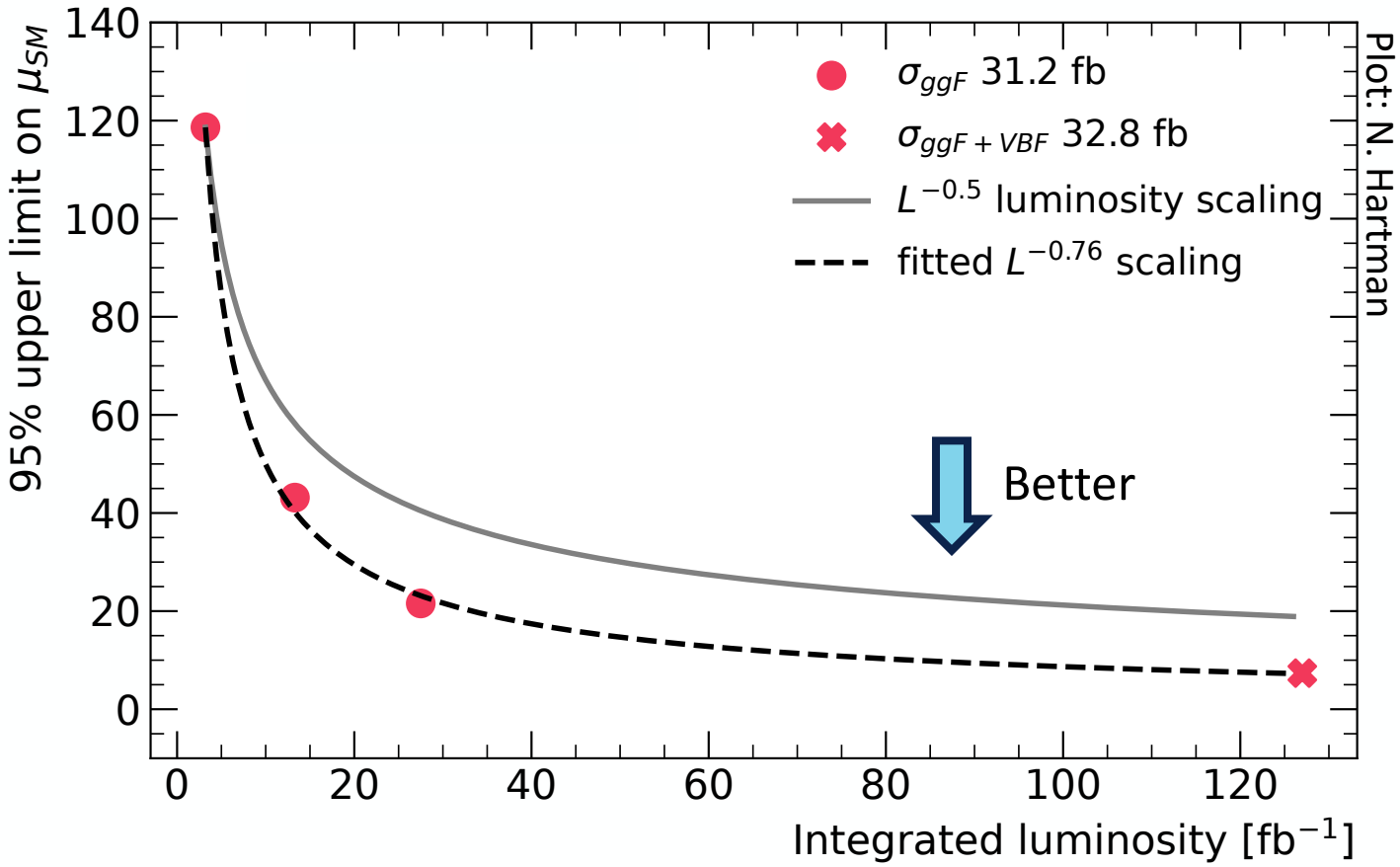
Thank you to the Department of Energy for funding this work
And thank you to my group at Arizona: Hava Schwartz (Postdoc), Zach Eberle (Grad Student), and Tugg Ernster (Undergrad)

Additional Material

$HH \to b\bar{b}b\bar{b}$ Improvements Over Time

Increasing dataset by factor of x improves limits by $x^{-0.5}$

Results improving by factor of ~$x^{-0.76}$



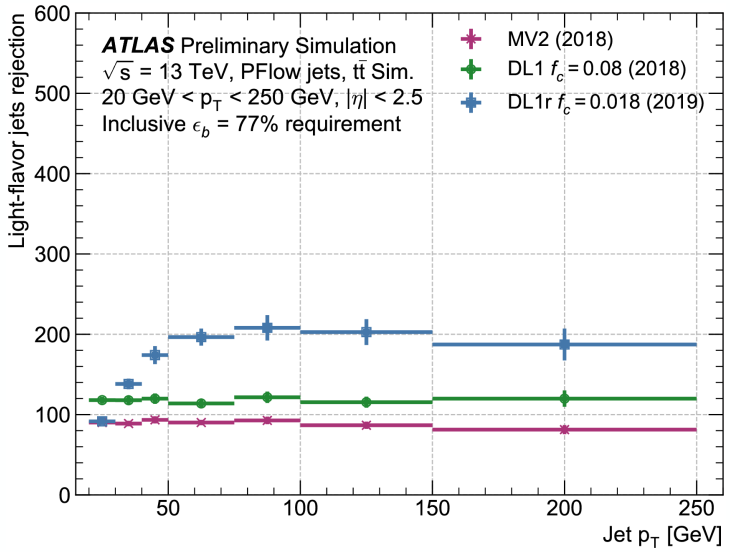
(Resolved analyses only!)

Single *b*-Tagging in ATLAS

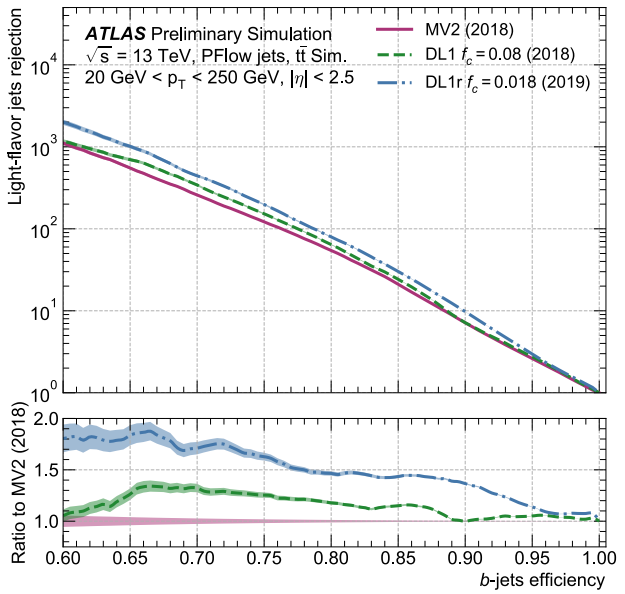
MV2C10: Boosted Decision Tree

DL1r: Deep Neural Network
(FTAG-2019-005)

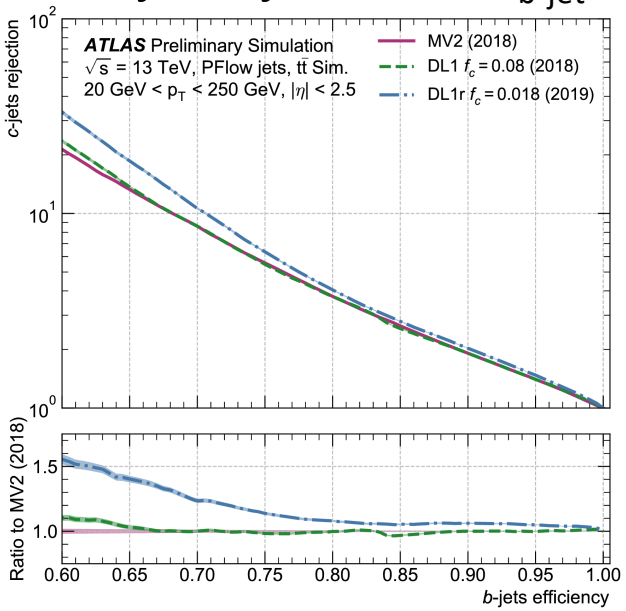
Light jet Rejection vs. p_T



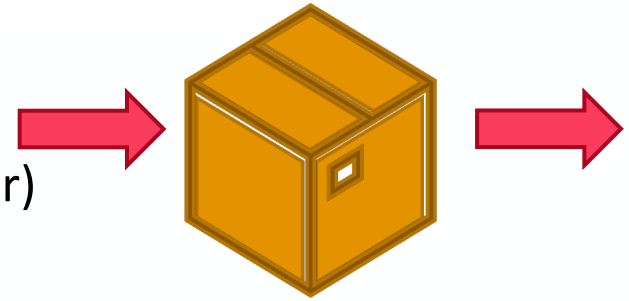
Light jet Rejection vs. $\epsilon_{\text{b-jet}}$



c-jet Rejection vs. $\epsilon_{\text{b-jet}}$



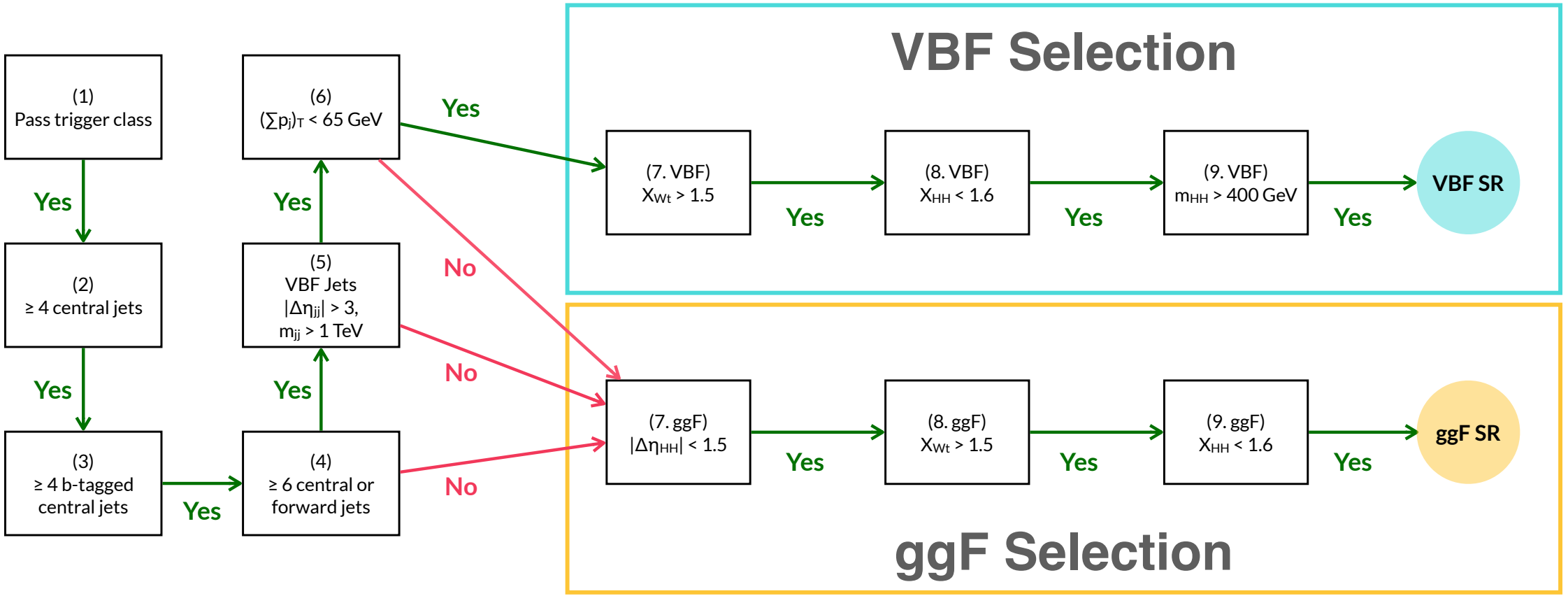
RNNIP (Recurrent NN)
JetFitter (Kalman Filter)
IP2D/IP3D (Impact Parameter)
SV1 (secondary Vertex)



DL1r Score

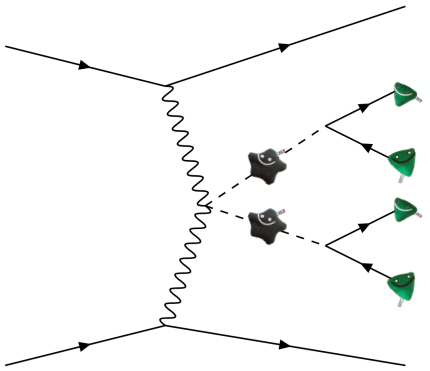
Analysis Selection

$$X_{Wt} = \min\left[\sqrt{\left(\frac{m_{jj} - m_W}{0.1 m_{jj}}\right)^2 + \left(\frac{m_{jjb} - m_t}{0.1 m_{jjb}}\right)^2}\right] \quad X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\ \text{GeV}}{0.1 m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\ \text{GeV}}{0.1 m_{H2}}\right)^2}$$



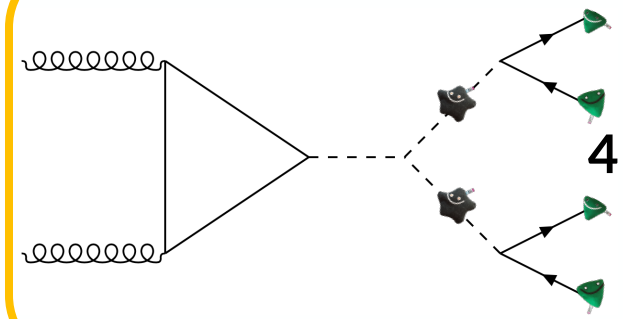
Analysis Selection

VBF



4 *b*-jets +
2 light-jets

ggF



4 *b*-jets

≥4 "Higgs-Candidate" Jets — $\sim 10^8$

$\sim 10^6$ — 2 "VBF" Jets (not *b*-tagged)

$\sim 10^4$ — 4 "Higgs Candidate" Jets are *b*-tagged — $\sim 10^6$

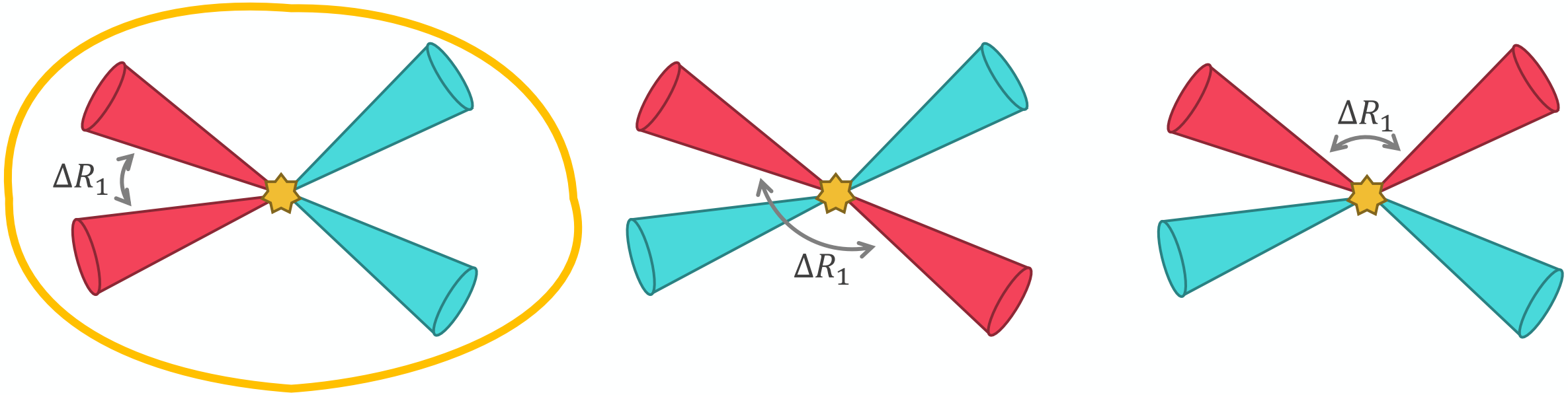
"Higgs Candidates" ~ close together — $\sim 10^6$

$\sim 10^4$ — Not $t\bar{t}$-like — $\sim 10^5$

$\sim 10^2$ — Mass("Higgs Candidates") ~ 125 GeV — $\sim 10^4$

“Pairing” Higgs Bosons

Choose between three possible pairs of four jets



Pairing ≳70% accurate for VBF
(≳90% for κ_{2V} far from 1)



“Leading” Reconstructed Higgs Boson

“Subleading” Reconstructed Higgs Boson

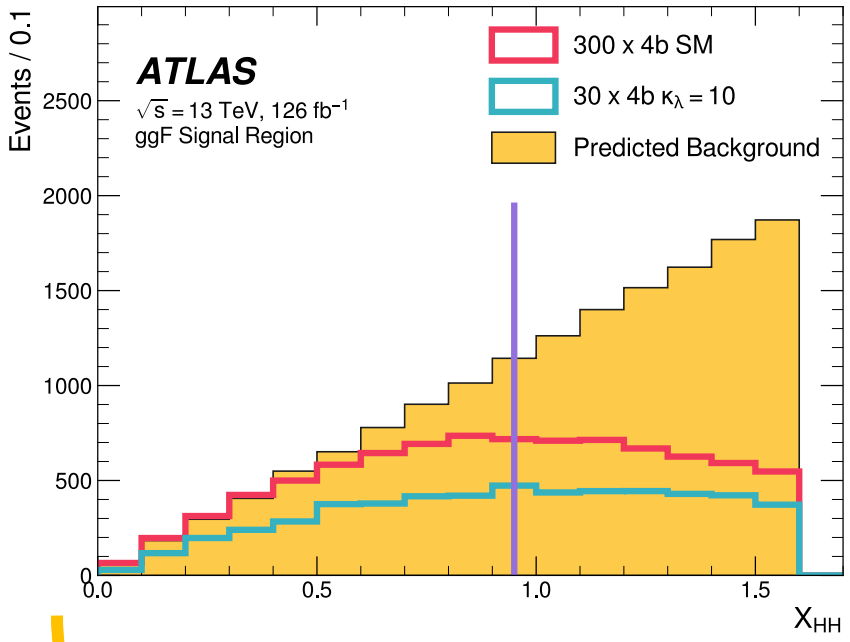
Categorization

Standard Model ($\kappa_\lambda = \kappa_{2V} = 1$)

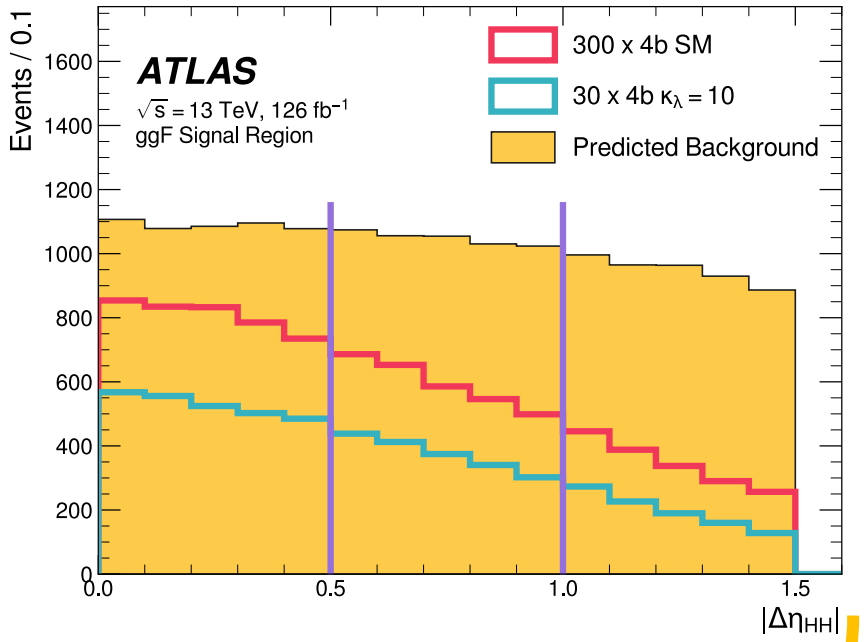
$\kappa_\lambda = 10$ ($\kappa_{2V} = 1$)

$\kappa_{2V} = 0$ ($\kappa_\lambda = 1$)

X_{HH}

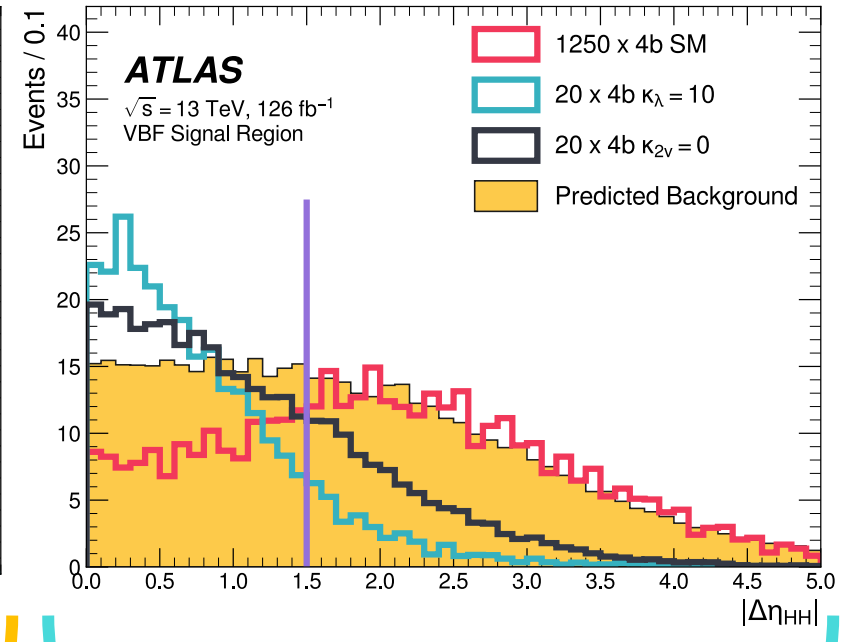


$|\Delta\eta_{HH}|$



ggF

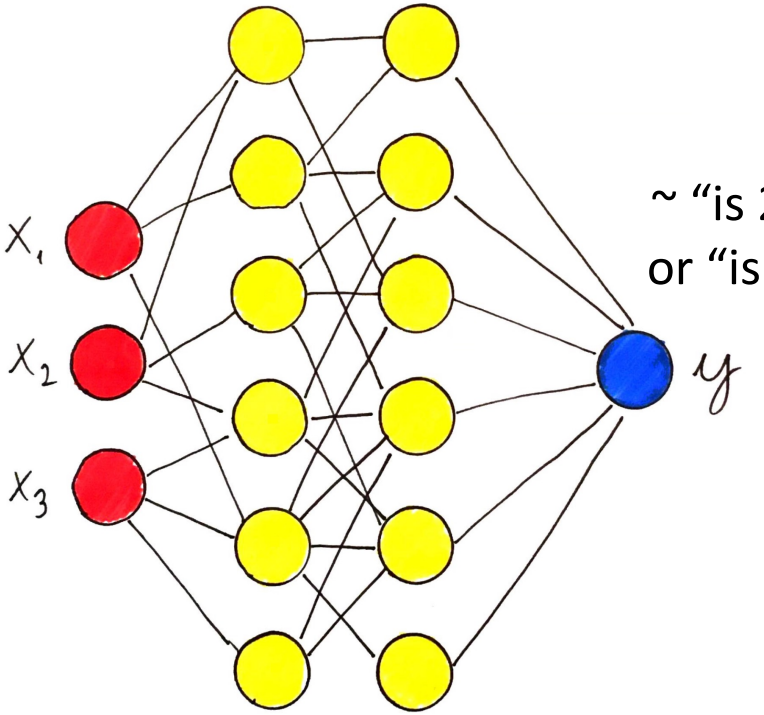
$|\Delta\eta_{HH}|$



VBF

Neural Networks for Density Estimation

Event Features



towardsdatascience.com

~ "is 2b" or "is 4b"

(Lemma) best discriminator between two classes:

$$\lambda = \frac{p_A}{p_A + p_B}$$

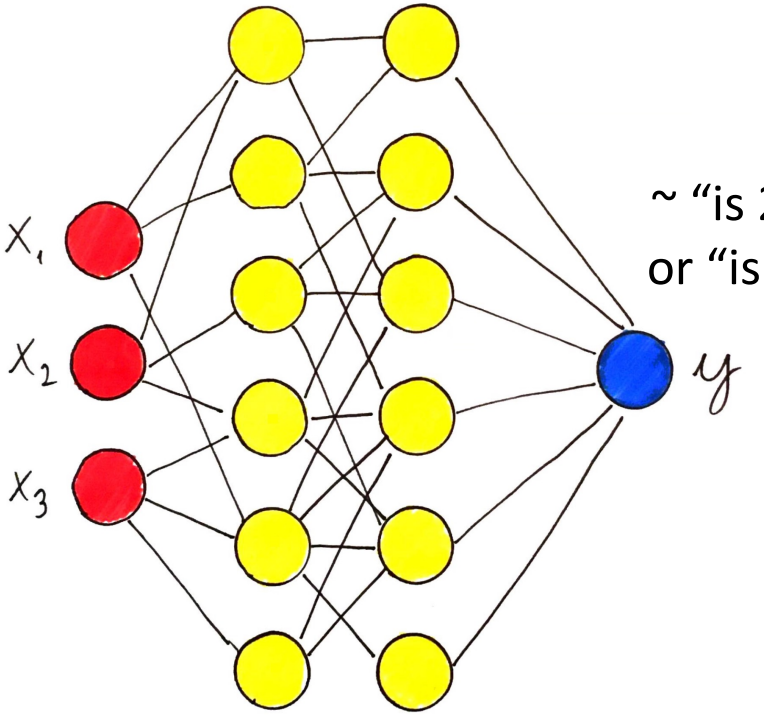
NNs classify data well → approximate λ

$$\frac{p_A}{p_B} = \frac{\lambda}{1-\lambda}$$

→ a classification NN can approximate the density ratio!

Neural Networks for Density Estimation

Event Features



towardsdatascience.com

~ "is 2b" or "is 4b"

$$p_{2b}(\vec{x}) \cdot w(\vec{x}) = p_{4b}(\vec{x})$$

Train NN with specific Loss function:

$$\mathcal{L}\big(R(\vec{x})\big) = \mathbb{E}_{x\sim p_{2b}}\left[\sqrt{R(\vec{x})}\right] + \mathbb{E}_{x\sim p_{4b}}\left[\frac{1}{\sqrt{R(\vec{x})}}\right]$$

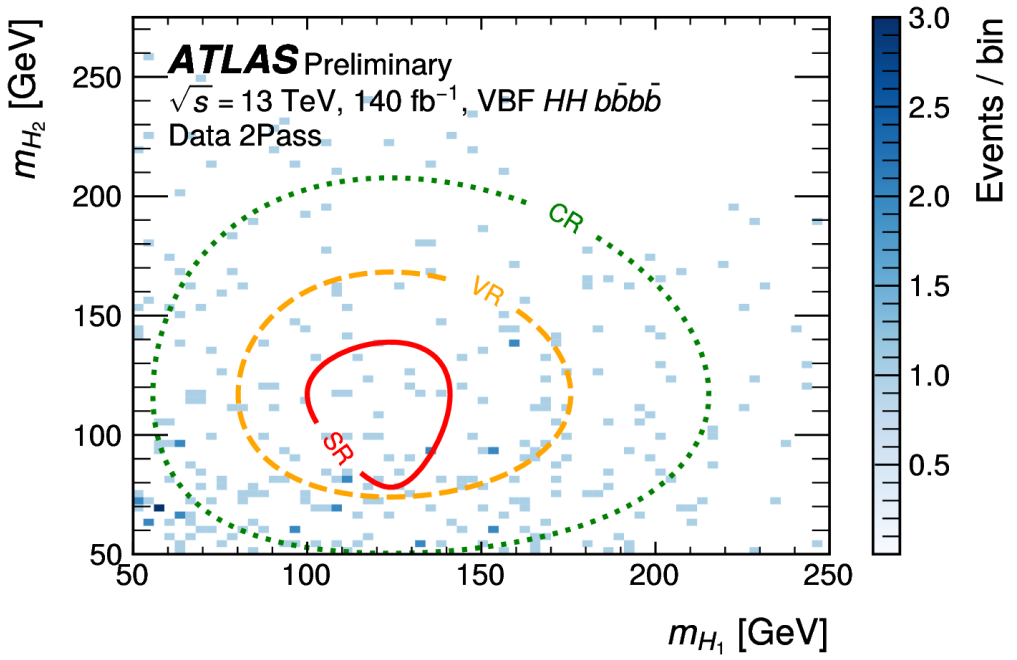
$$\rightarrow \arg\min_{R} \mathcal{L}\big(R(\vec{x})\big) = w(\vec{x})$$

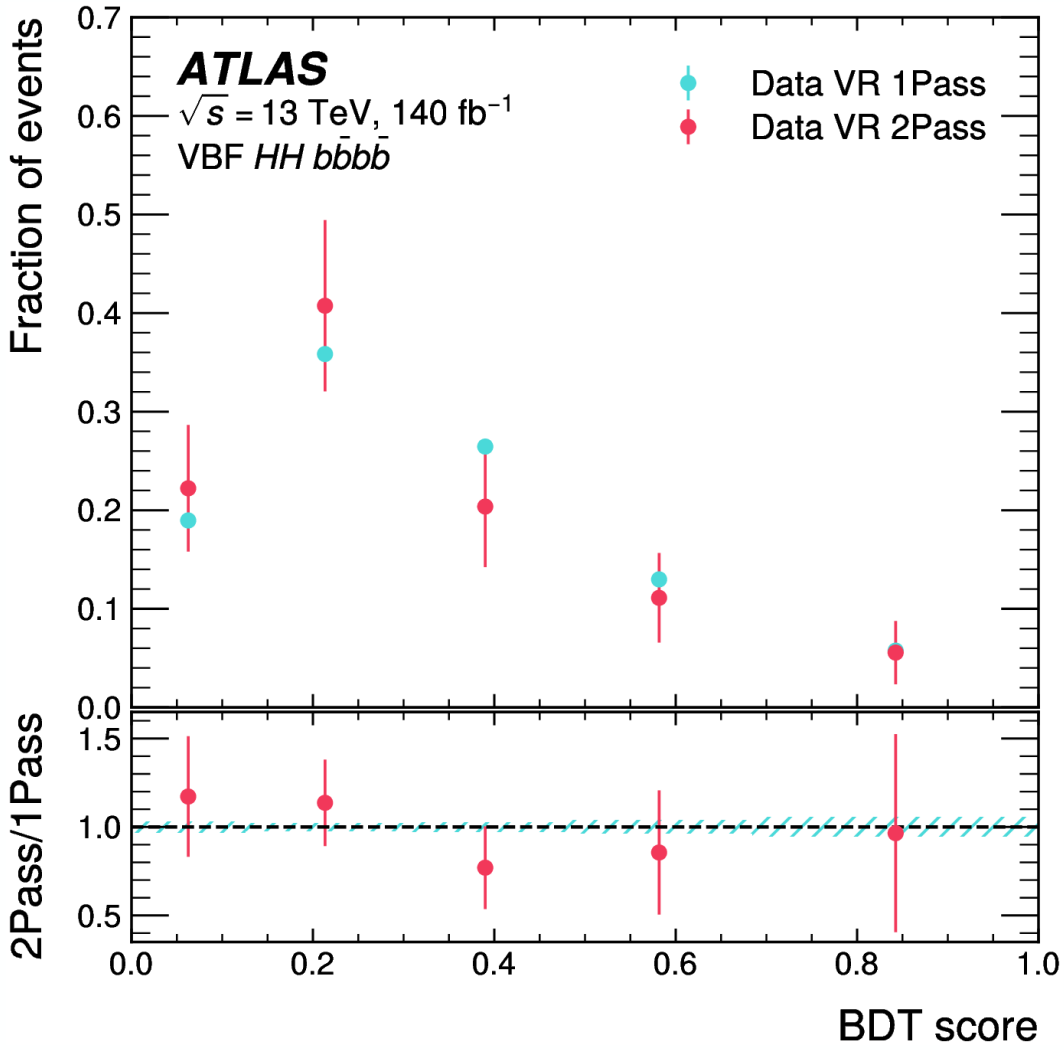
"Event-level" reweighting!

arxiv:1911.00405
Kanamori et. al. (JMLR)

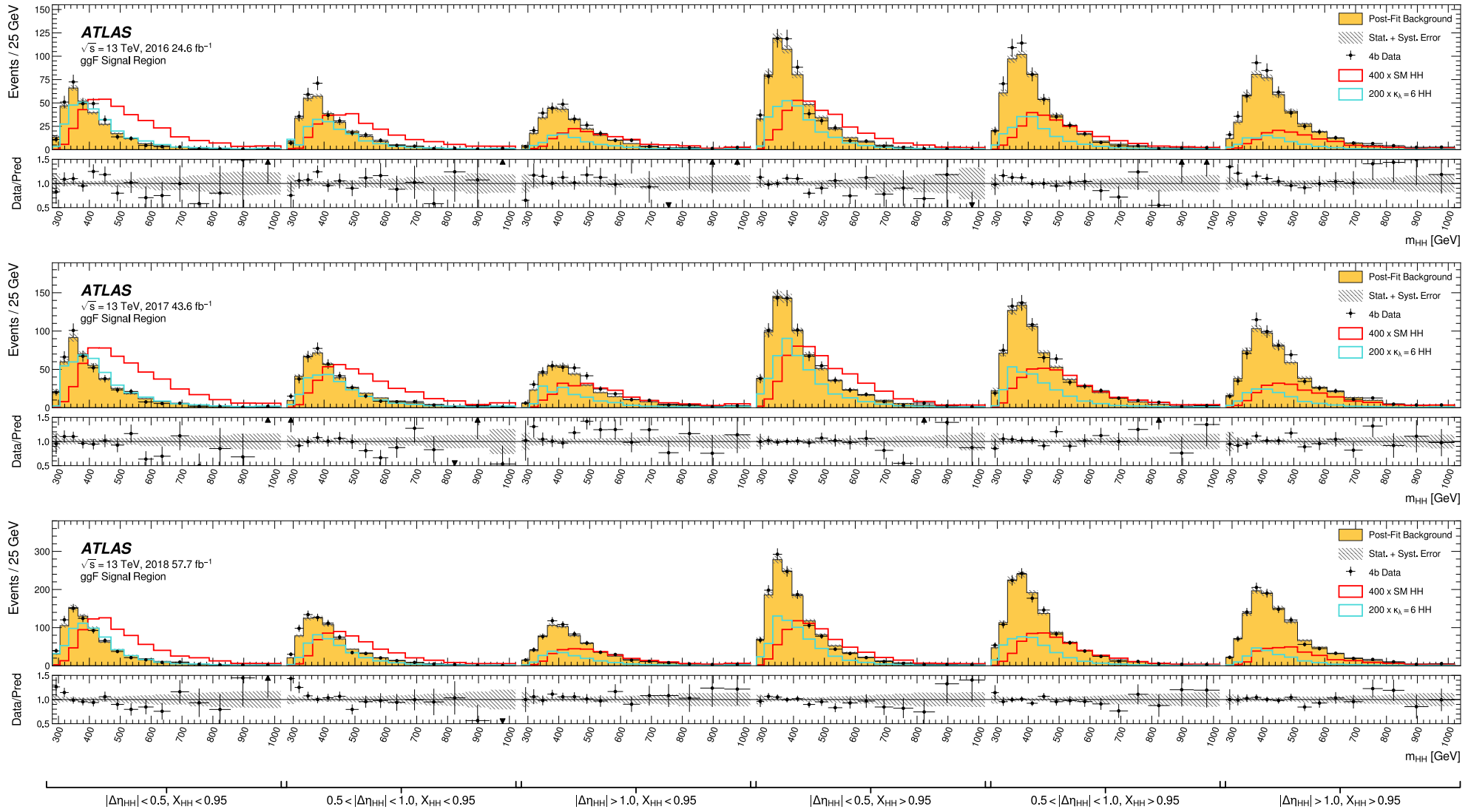
Boosted Background Estimation

Compare 1-Pass and 2-Pass events in **VR**
Good agreement within statistical uncertainty

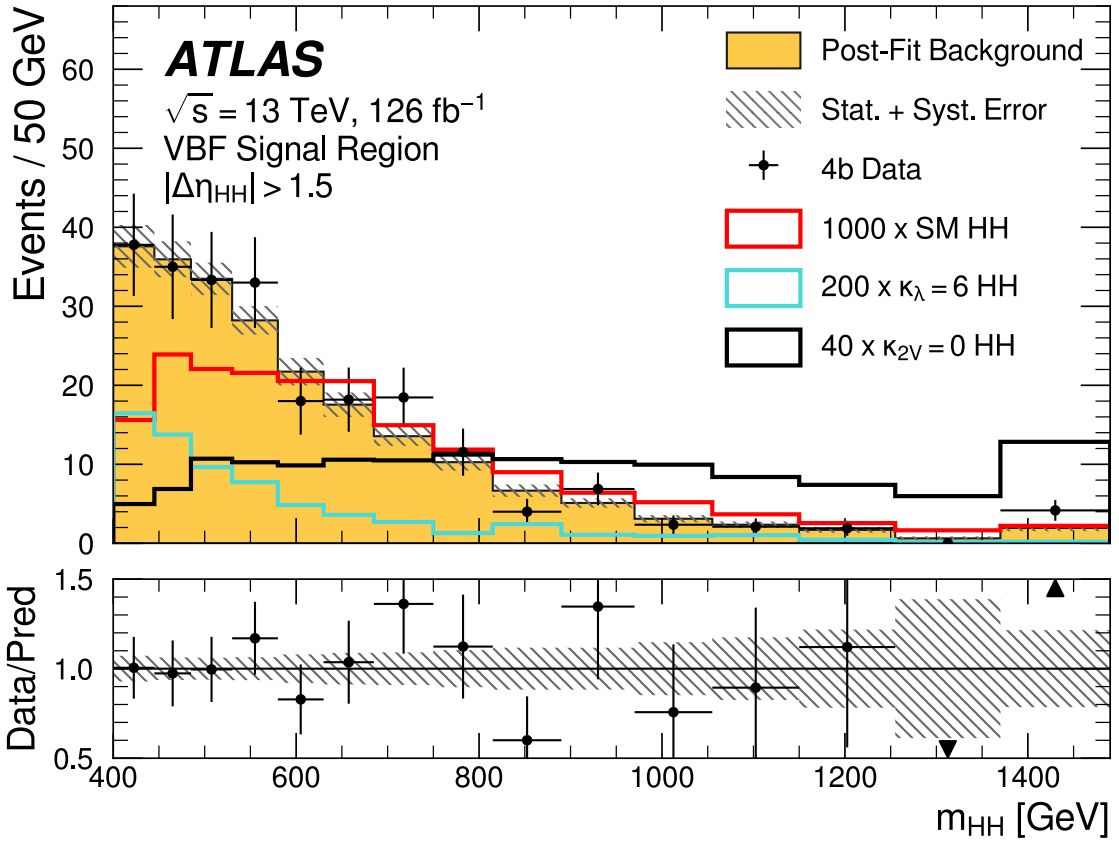


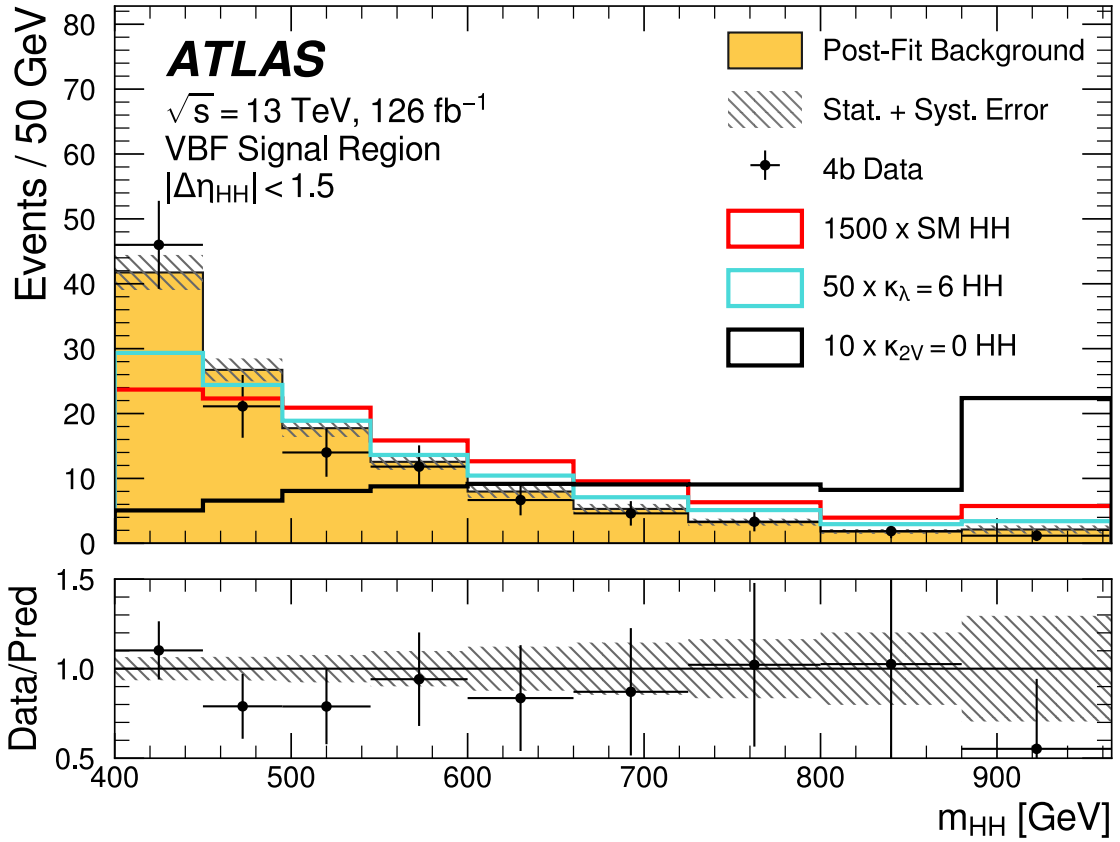


Observed m_{HH} Distributions in ggF Categories



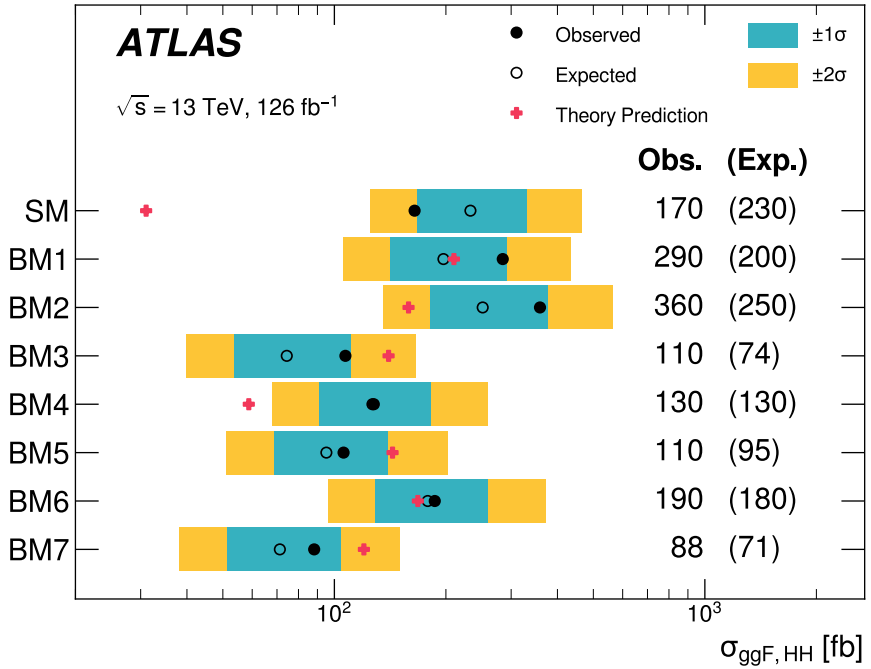
Observed m_{HH} Distributions in VBF Categories

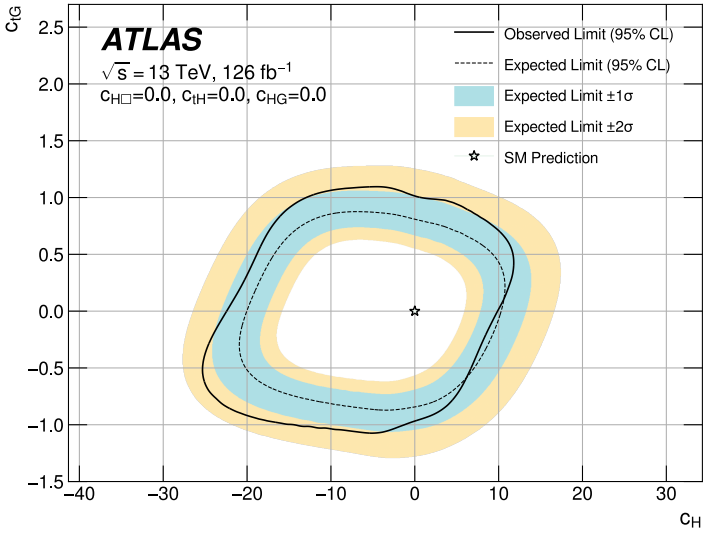


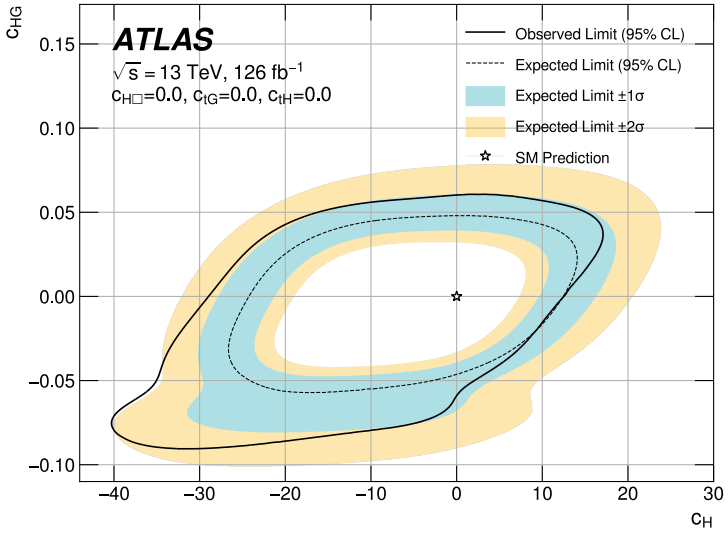


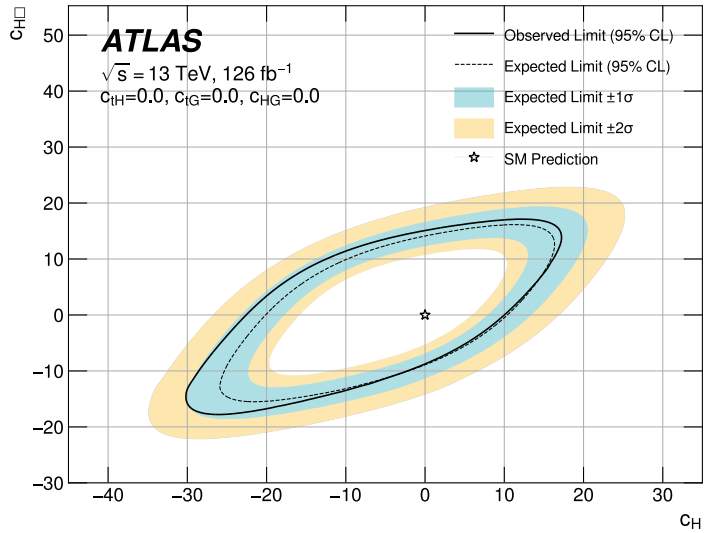
HEFT and SMEFT Constraints

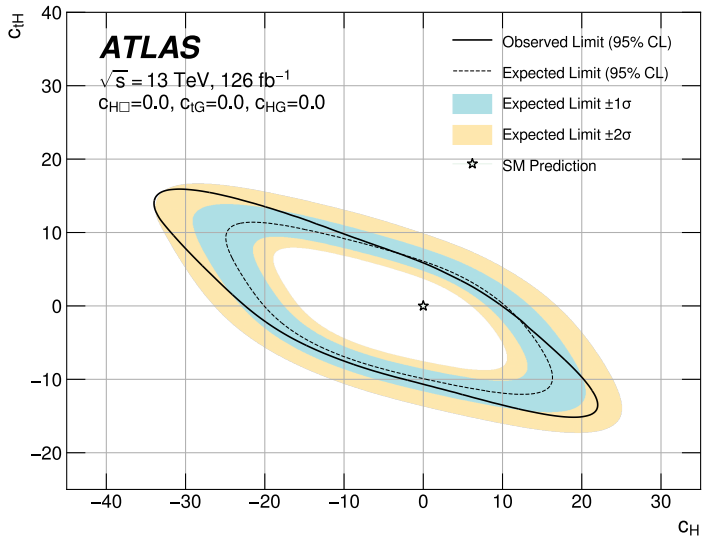
ggF only











Uncertainties

Dominant uncertainties:

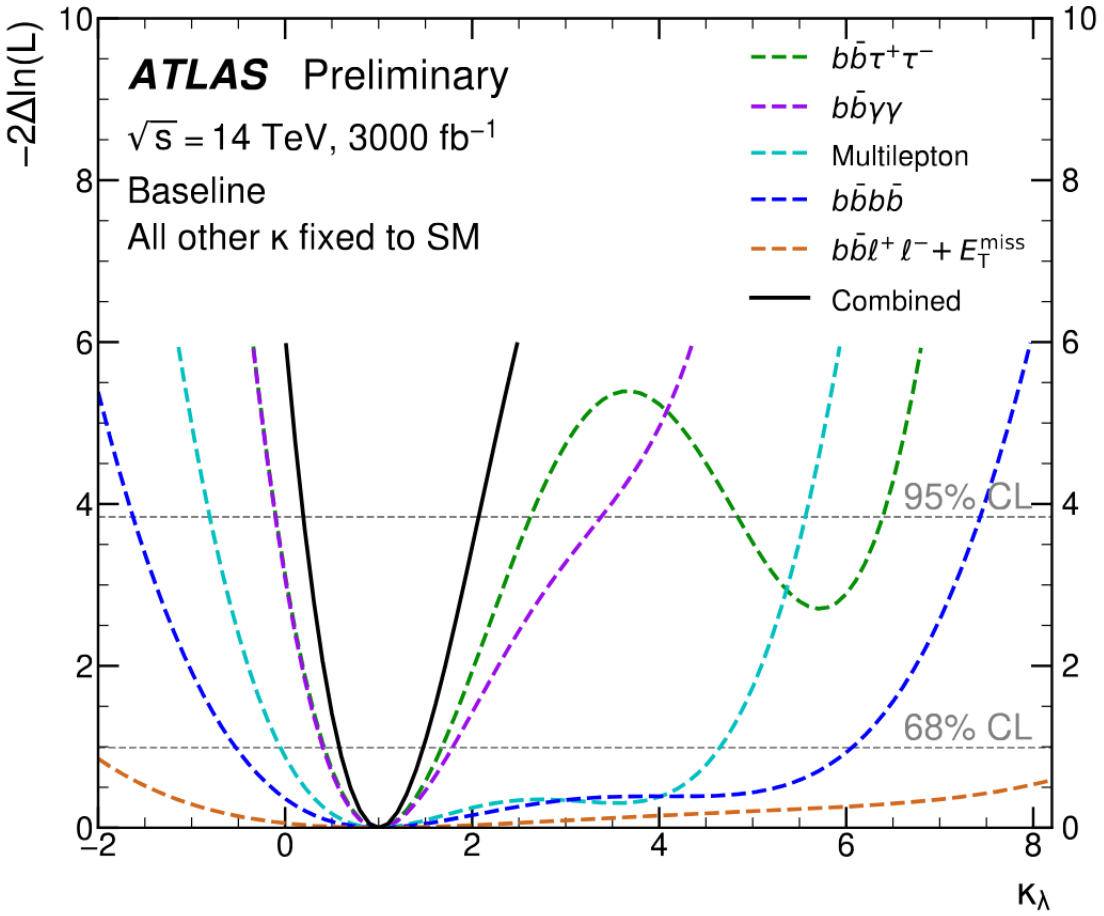
Theoretical signal modeling

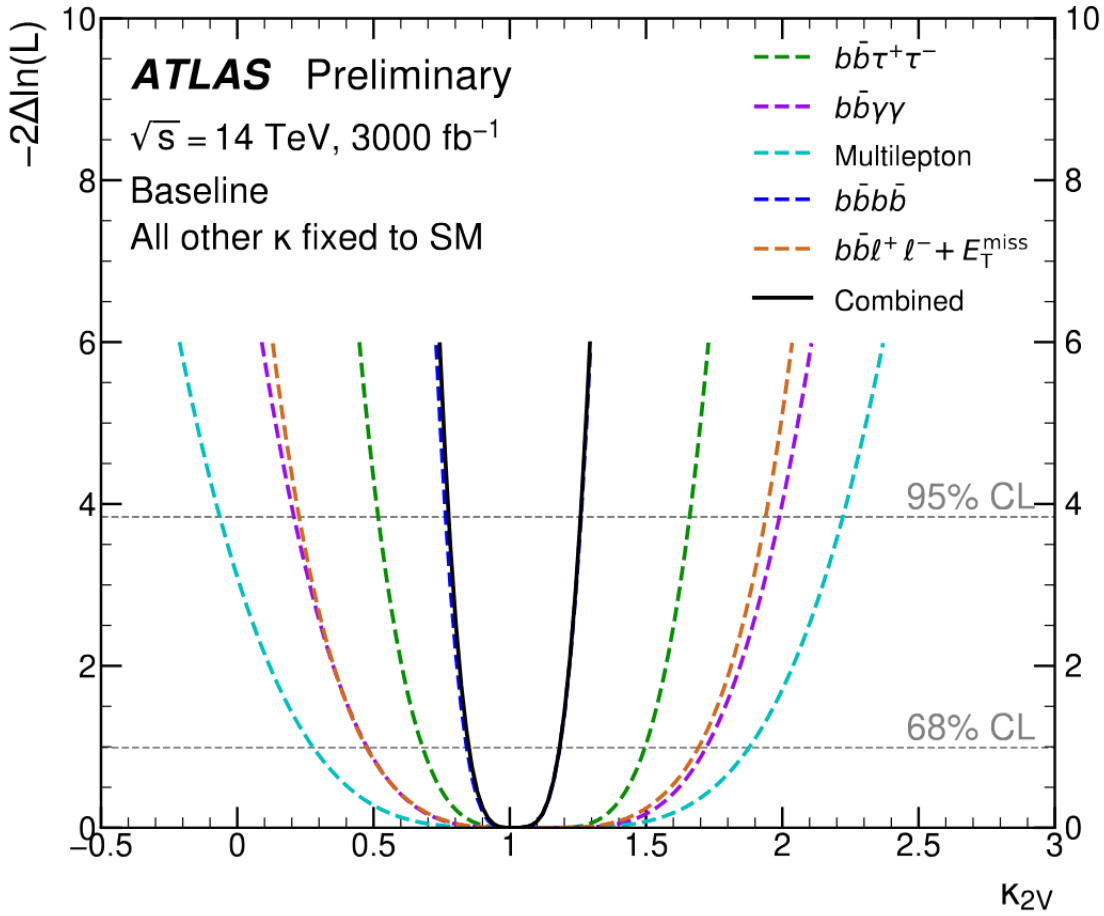
Experimental background modeling

$\mu_{ggF+VBF}$ (Upper limit on HH signal strength)

Source of Uncertainty	$\Delta\mu/\mu$
Theory uncertainties	
Theory uncertainty in signal cross-section	-9.0%
All other theory uncertainties	-1.4%
Background modeling uncertainties	
Bootstrap uncertainty	-7.1%
CR to SR extrapolation uncertainty	-7.5%
$3b1$f nonclosure uncertainty	-2.0%

HL-LHC Projections





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