Studying Higgs Boson Self-Interactions at the ATLAS Experiment

Fermilab – Physics Forum

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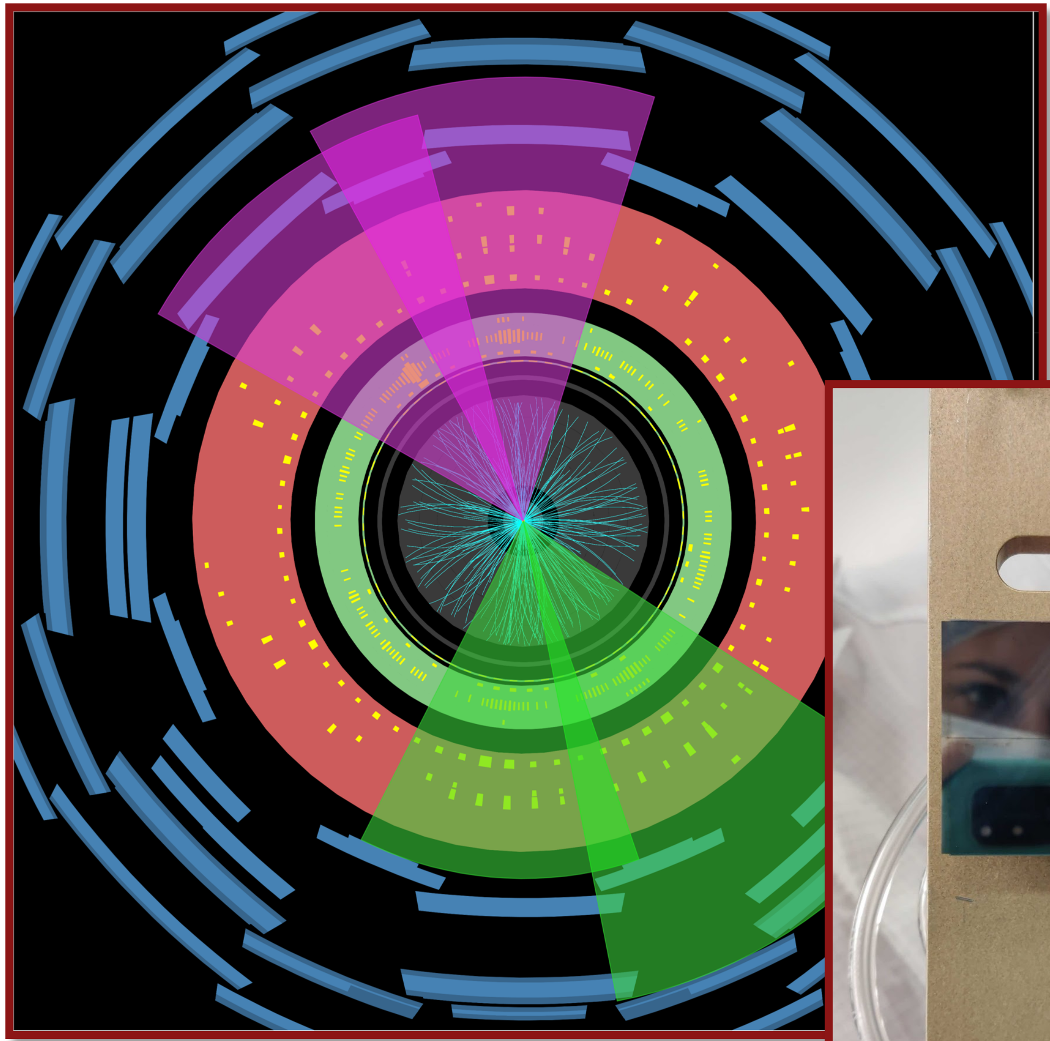
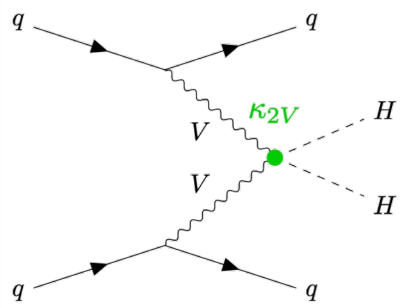
SLAC NATIONAL ACCELERATOR LABORATORY

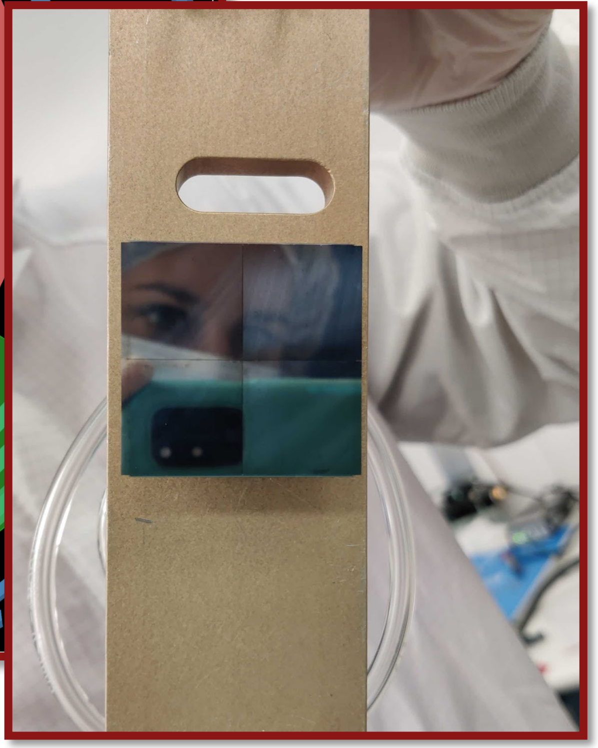
Stanford University | U.S. DEPARTMENT OF ENERGY

Outline

- Why do we care about Higgs Boson self-interactions?
- How do we measure Higgs Boson self-interactions?
- A measurement probing Higgs Boson self-interactions
- How does this result fit into the broader ATLAS Higgs Boson Self-Interactions Program?





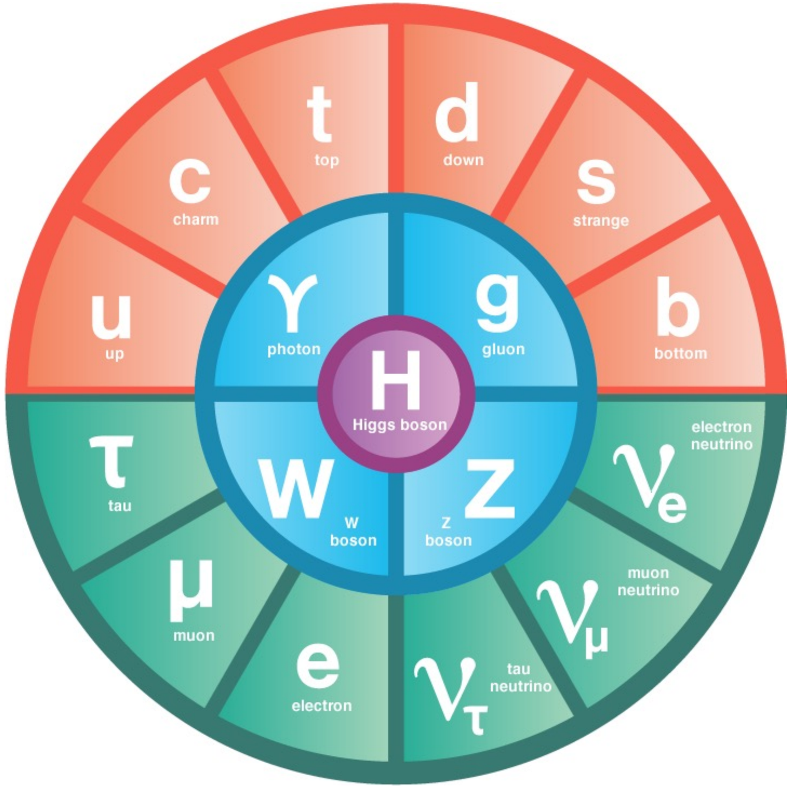


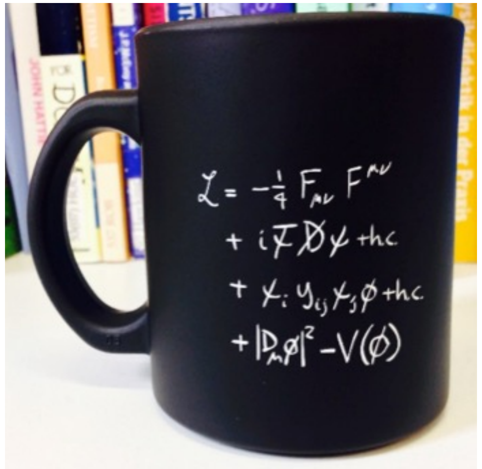
Why do we care about Higgs Boson self-interactions?

Introduction

The Standard Model of Particle Physics

A theory of fundamental particles and how they interact

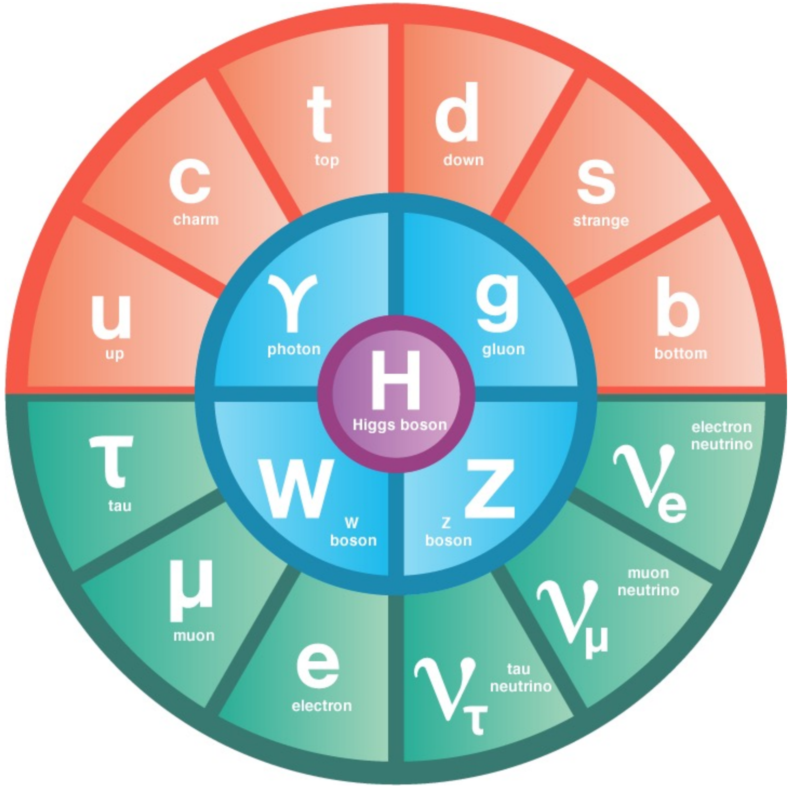




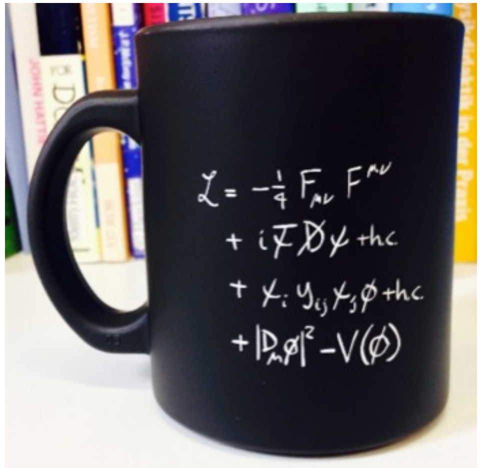
Symmetry Magazine

The Standard Model of Particle Physics

A theory of fundamental particles and how they interact

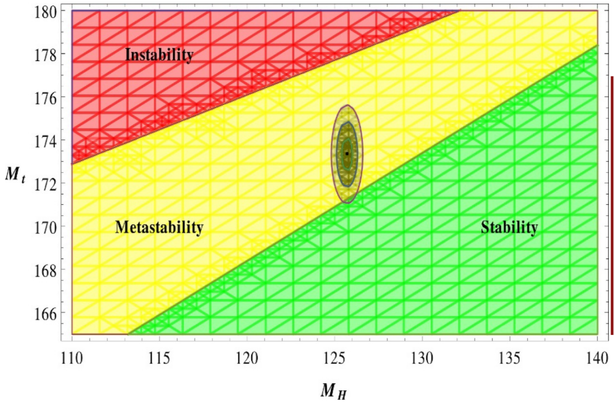


Symmetry Magazine



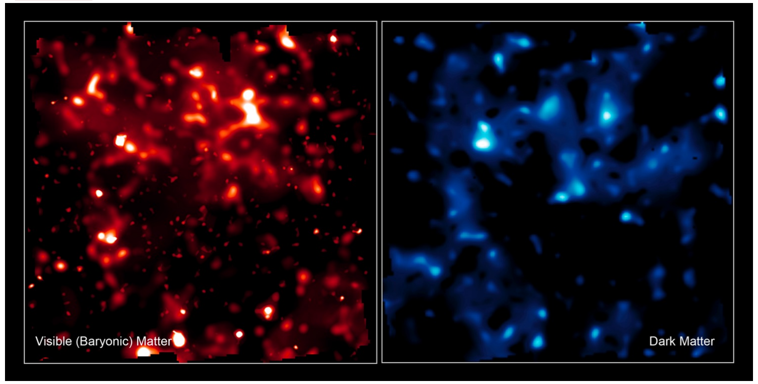
Why is there more Matter than Anti-Matter?

Is our universe stable?



Branchina et. al.

ESA **What is Dark Matter?**



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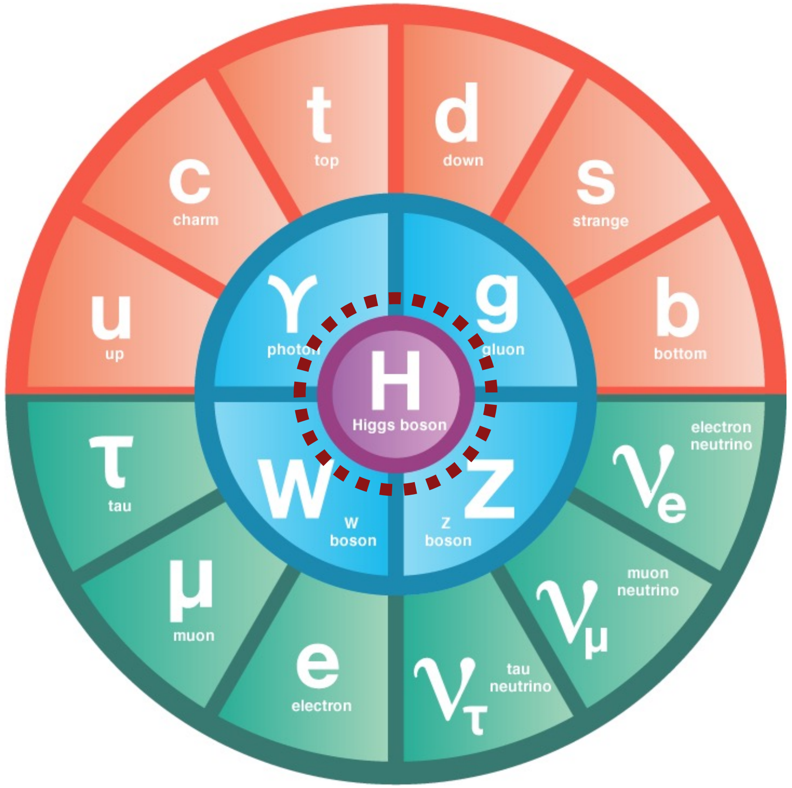

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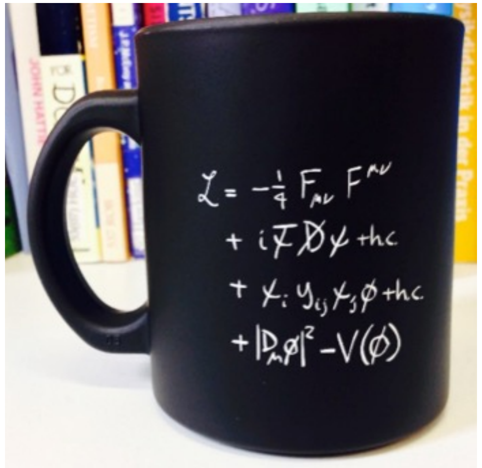

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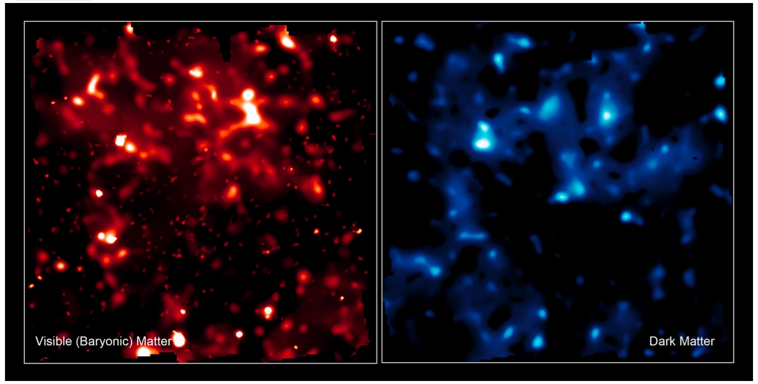

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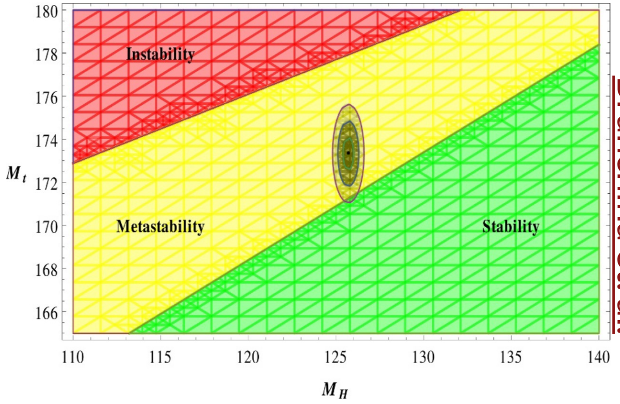
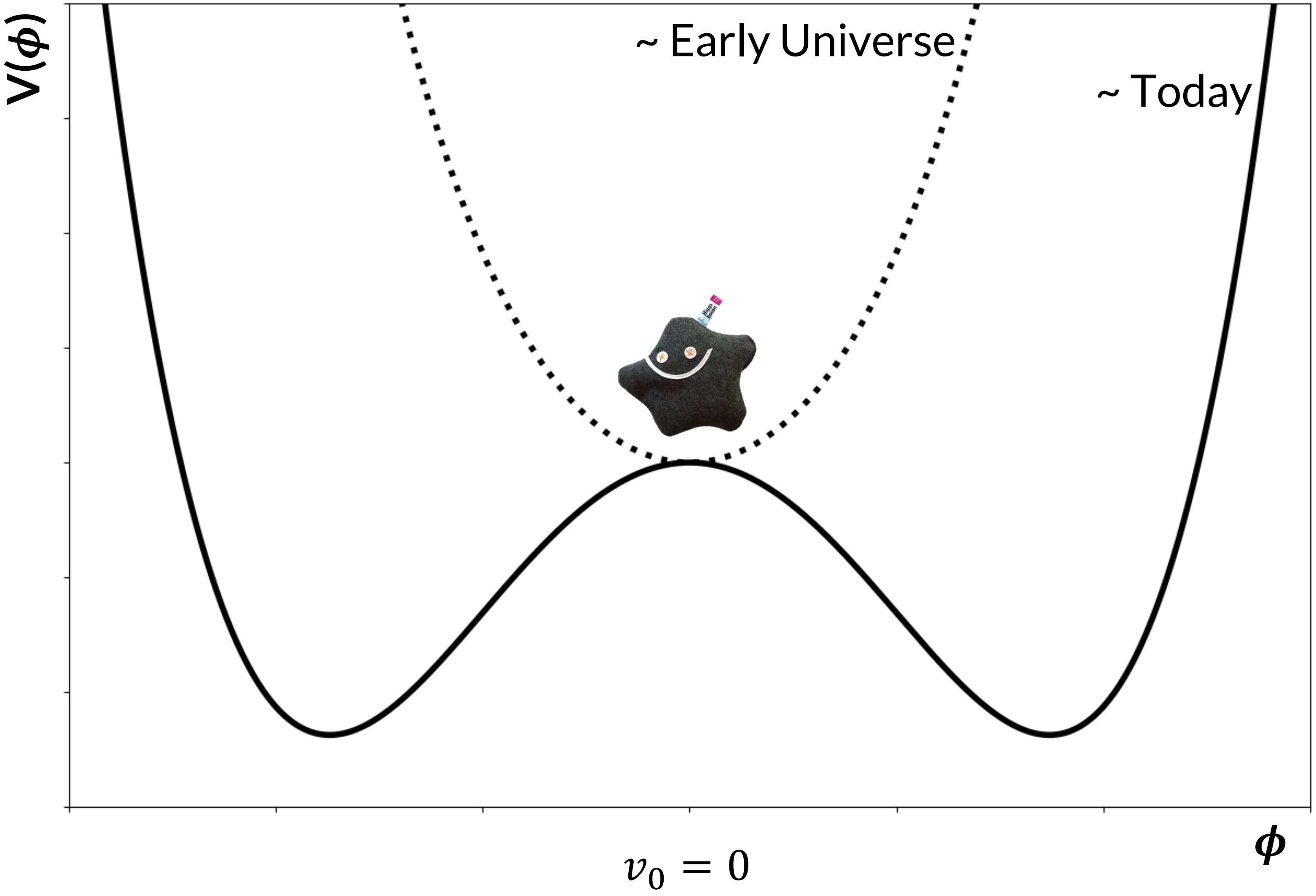
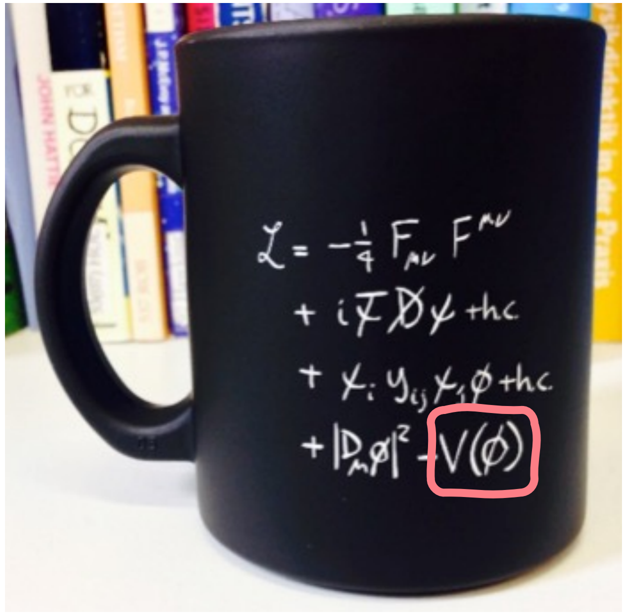


Branchina et. al.

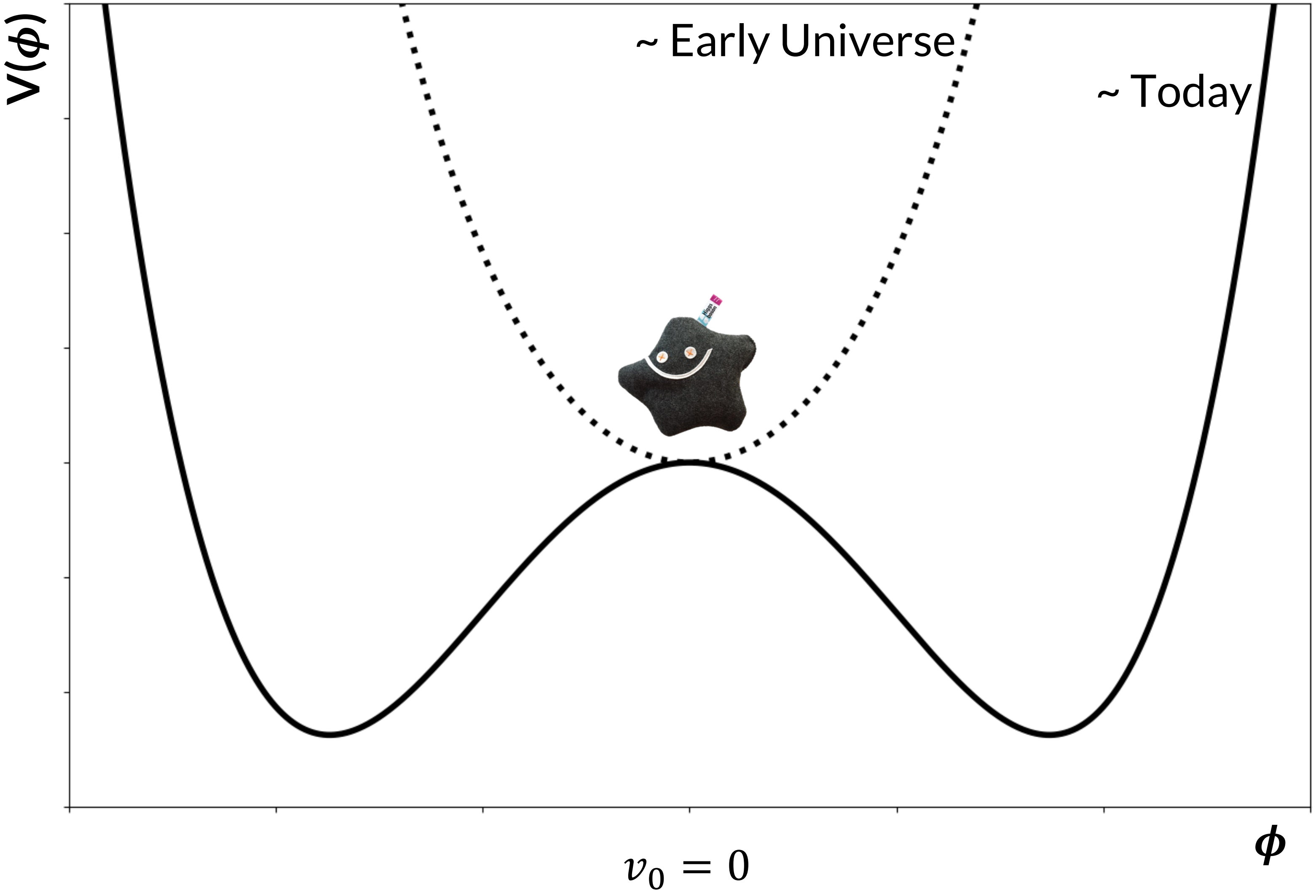
The Higgs Boson and its Potential

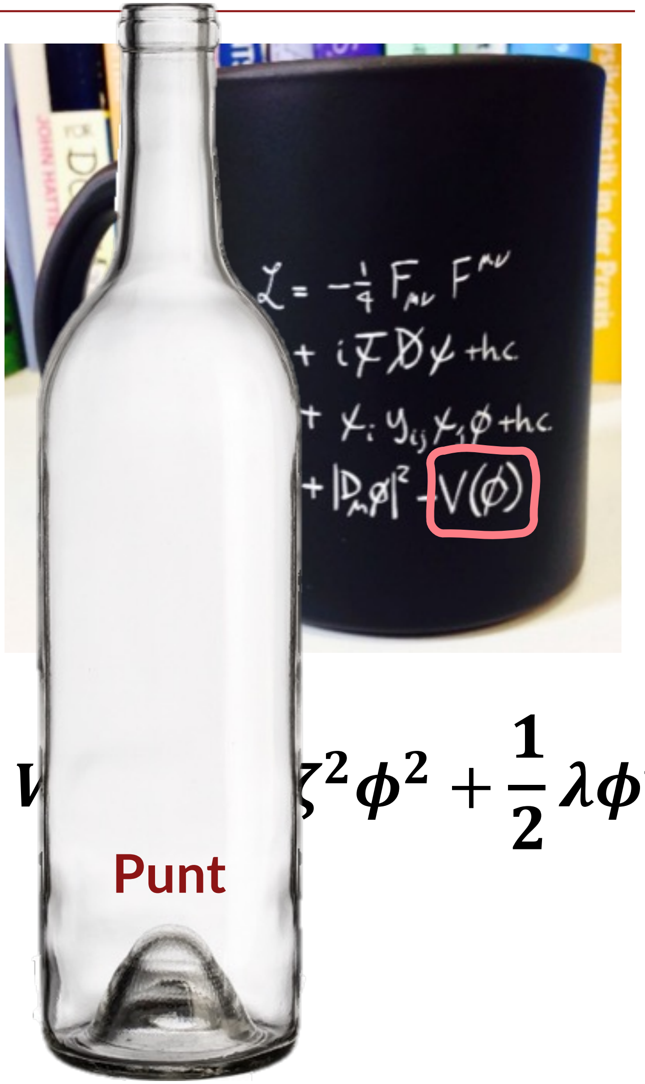




$$V(\phi) = \frac{1}{2}\zeta^2\phi^2 + \frac{1}{2}\lambda\phi^4$$

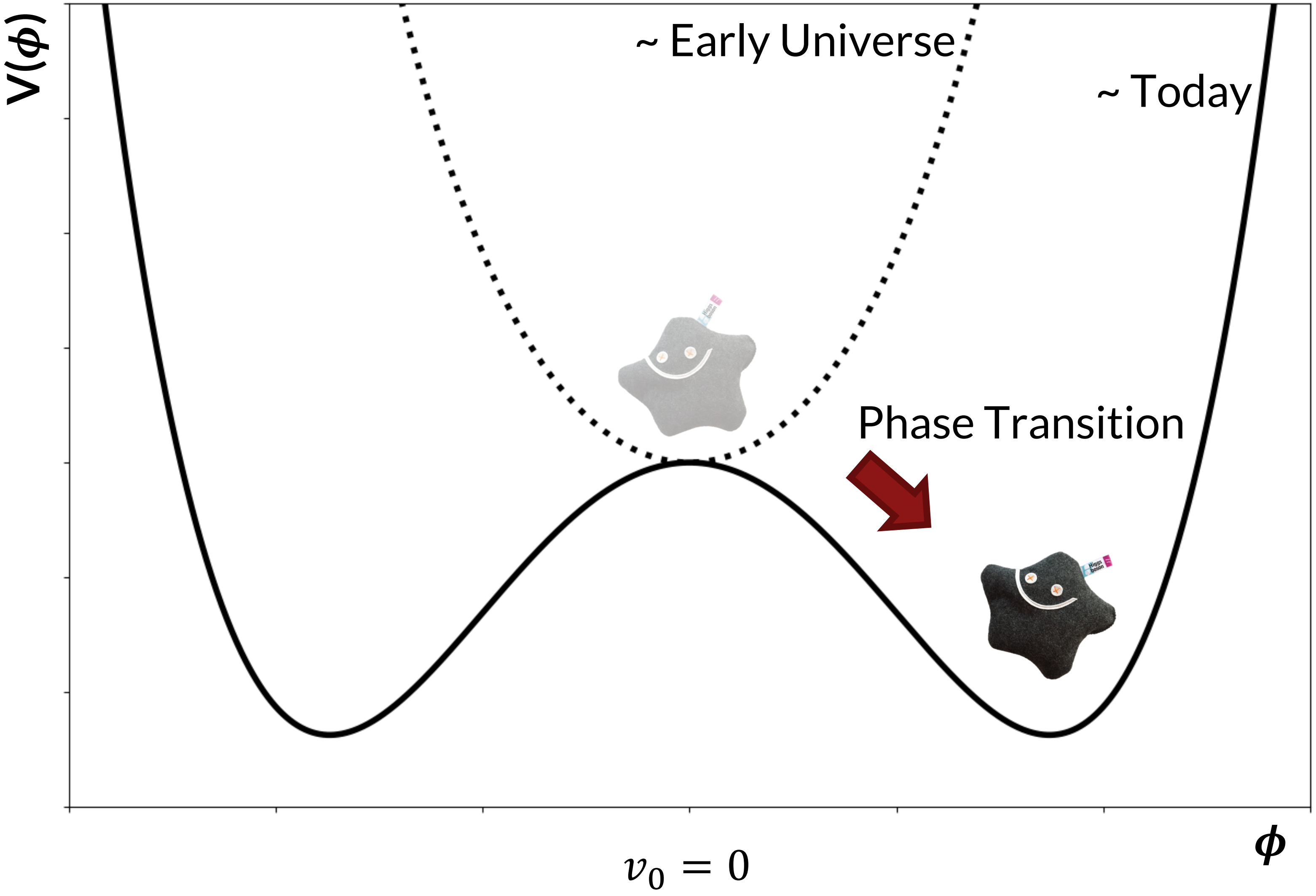
The Higgs Boson and its Potential





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

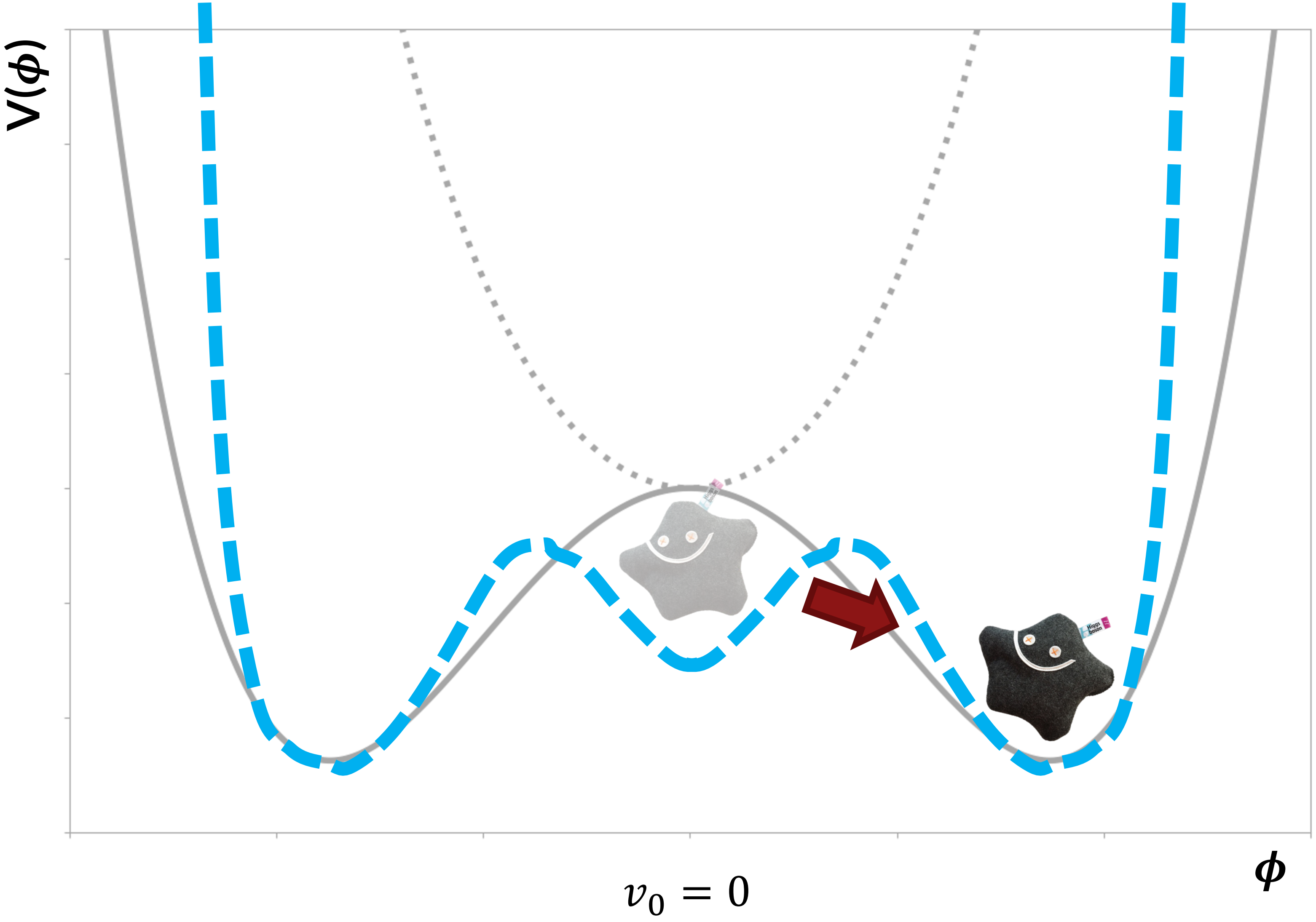
The Higgs Boson and its Potential



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

What if the potential looks a little different?

New Physics and the Higgs Potential

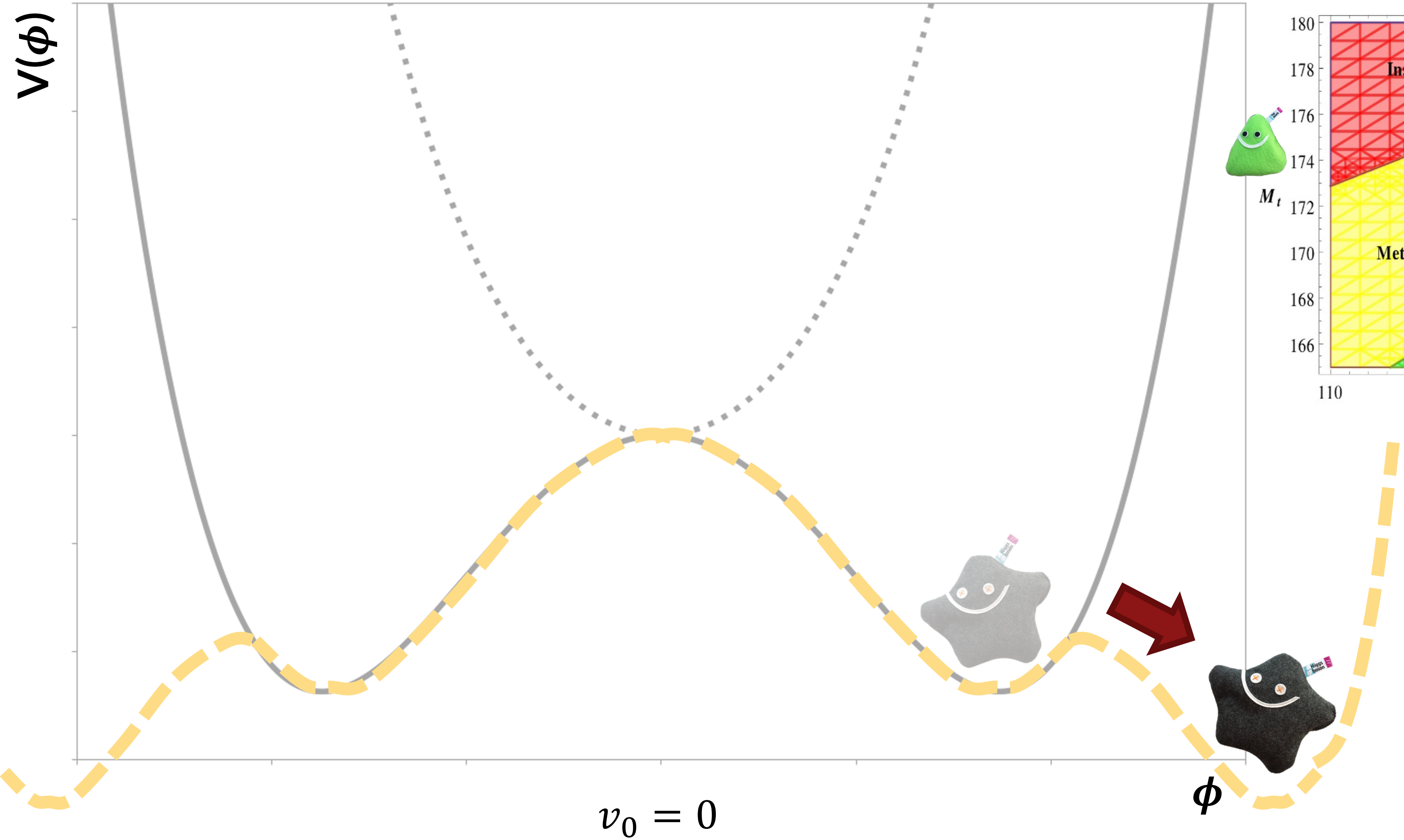


"Second Order" phase transition in early universe

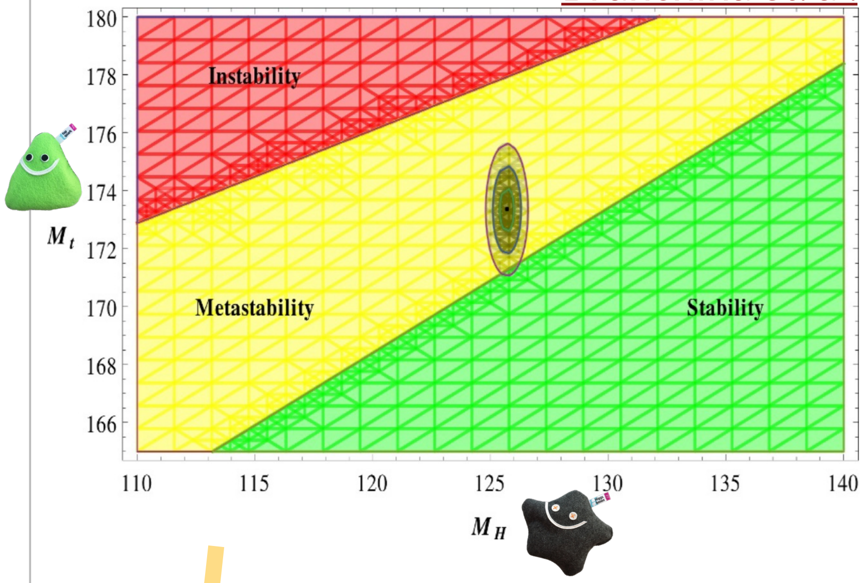
→ required for "Electroweak Baryogenesis"

(= Electroweak Phase Transition as the source of Matter-Antimatter Asymmetry)

New Physics and the Higgs Potential



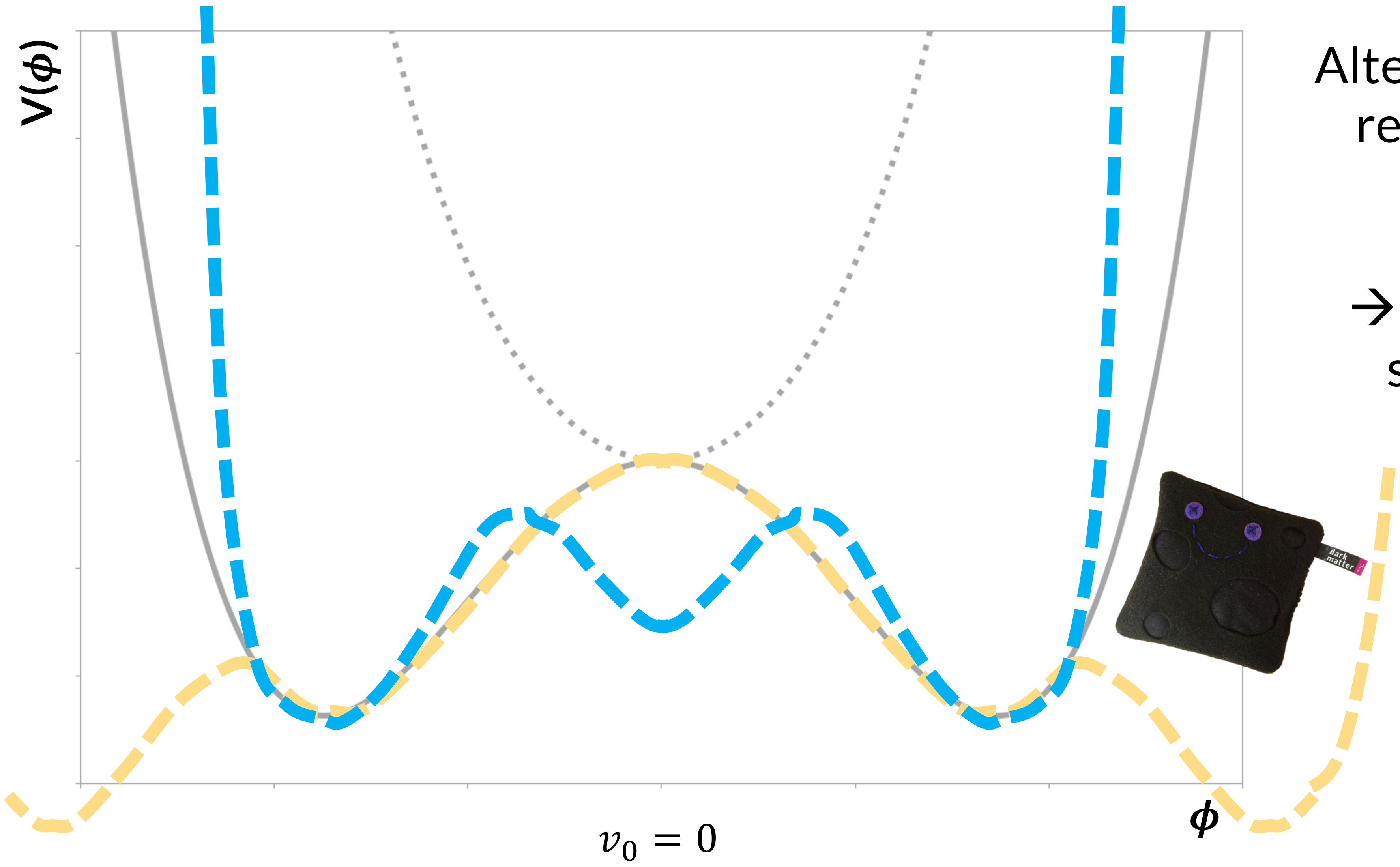
Branchina et. al.



Lower Minimum?

→ Metastable Universe!

New Physics and the Higgs Potential

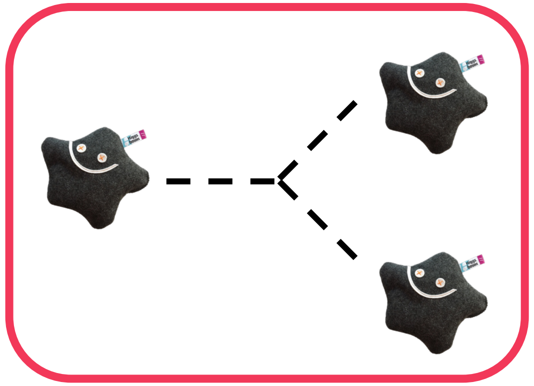


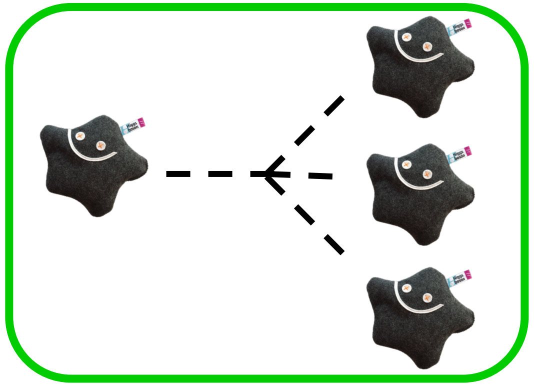
Alternative potentials require new Higgs interactions

→ from a new dark sector particle?

How Do We Measure the Higgs Potential?

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





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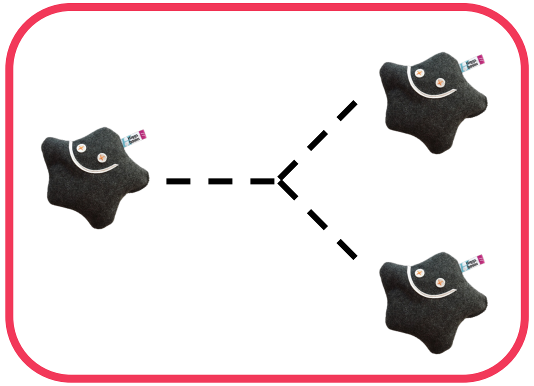
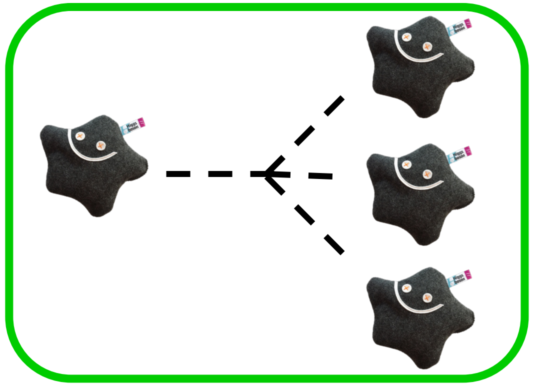
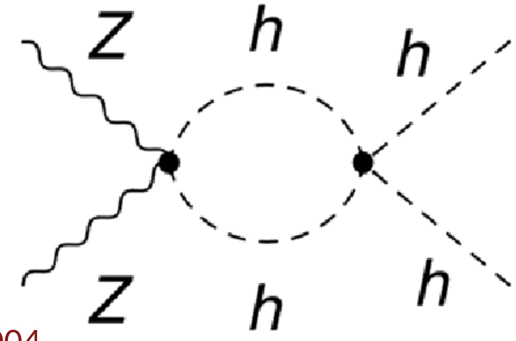


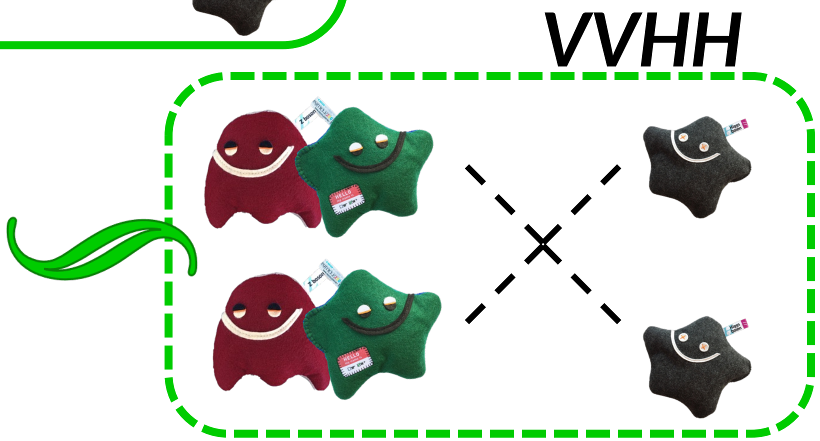


Can constrain coupling to within an order of magnitude… at 100 TeV Hadron Collider!

PhysRevD.93.013007



PhysRevD.98.093004



How Can We Study the Higgs Potential at Colliders?

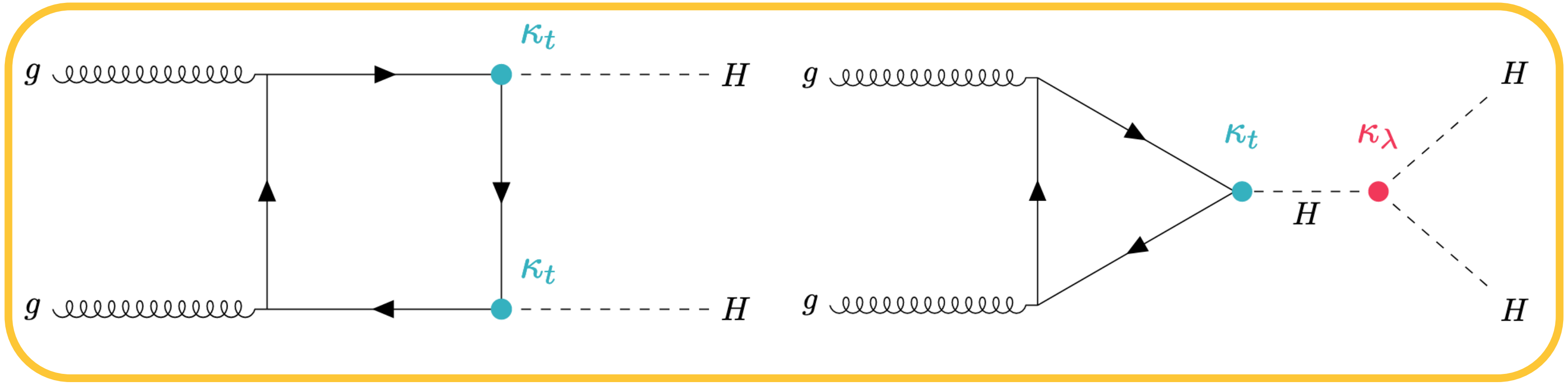
Higgs boson pair production (*HH*)

"Kappa framework"

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

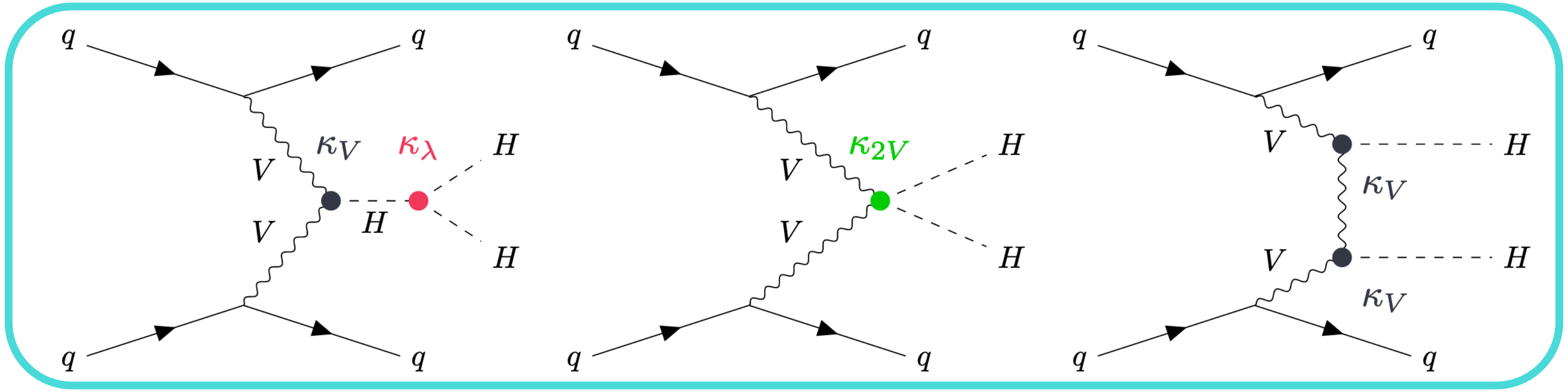
gluon-gluon-Fusion

σ_{ggF} ~31 fb [1]



Vector Boson Fusion

σ_{VBF} ~ 1.7 fb [2]



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

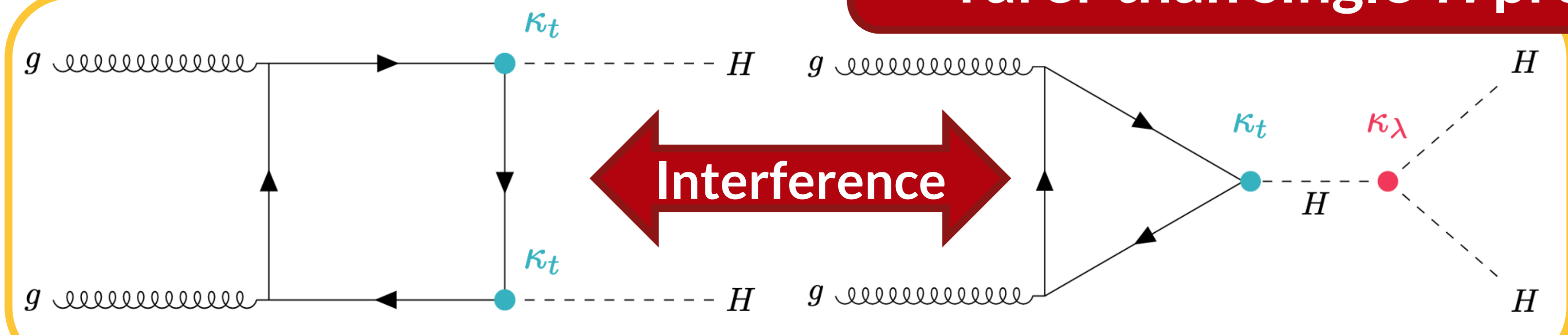
How Can We Study the Higgs Potential at Colliders?

Higgs boson pair production (*HH*)

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

gluon-gluon-Fusion

σ_{ggF} ~31 fb [1]



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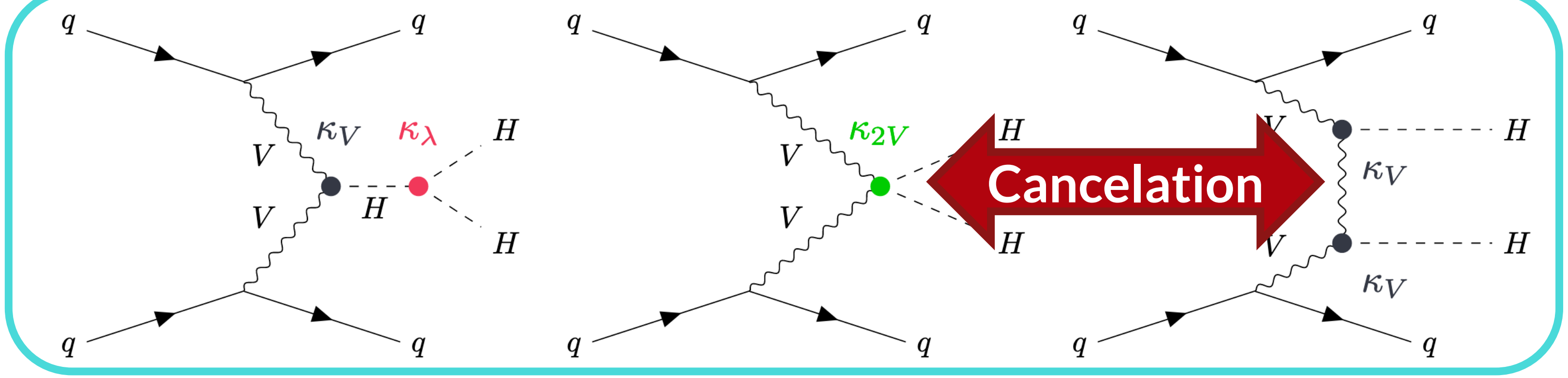

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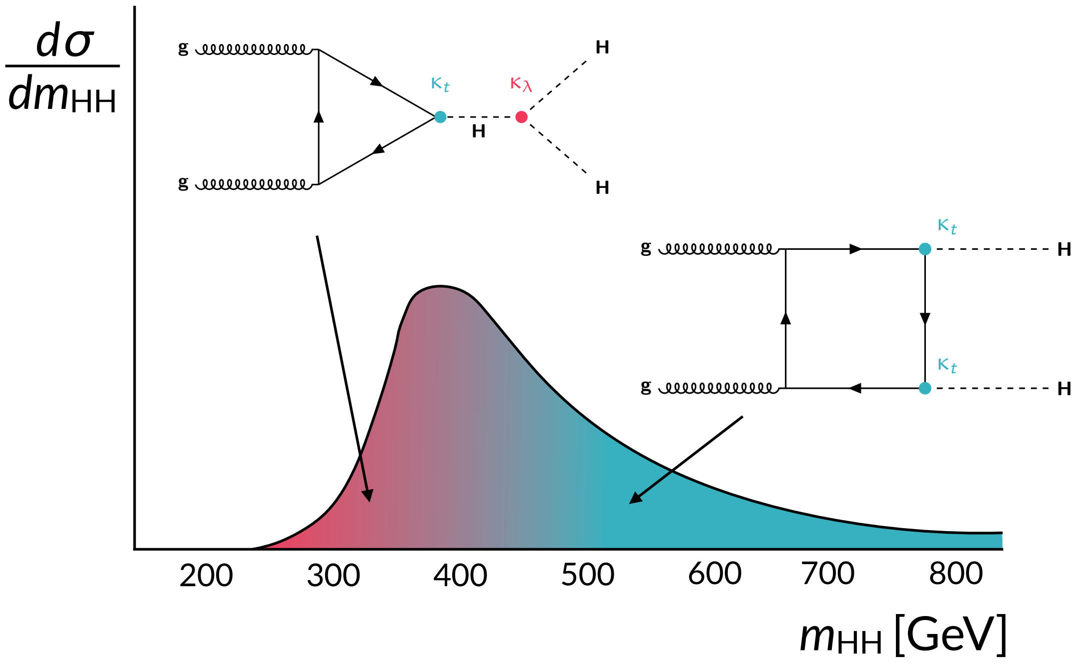
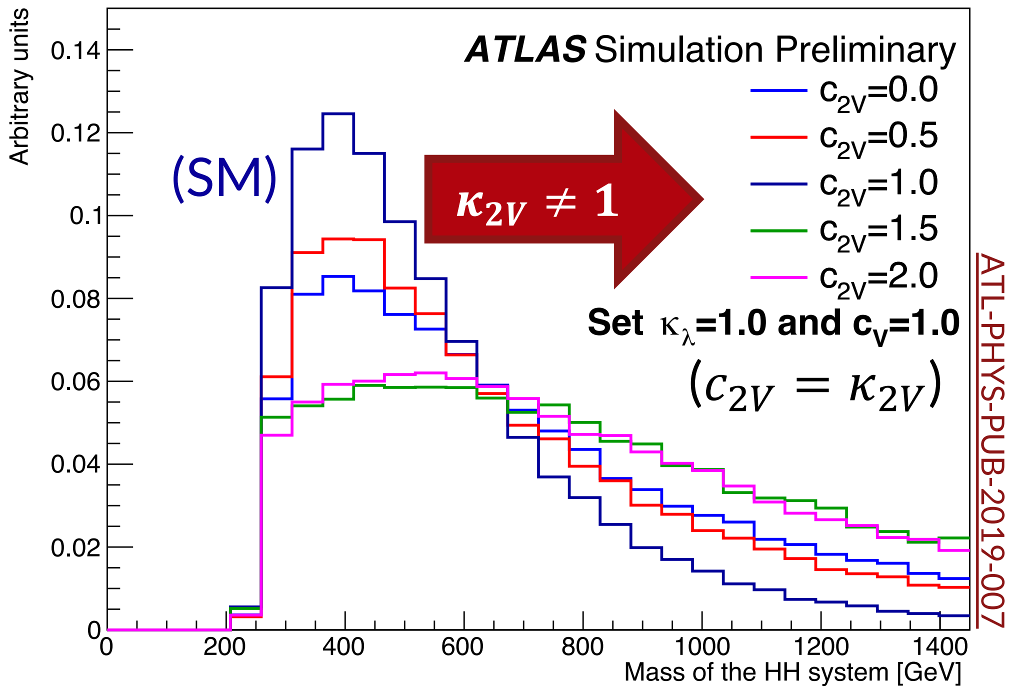
Sensitivity to New Physics in the Self-Couplings

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



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



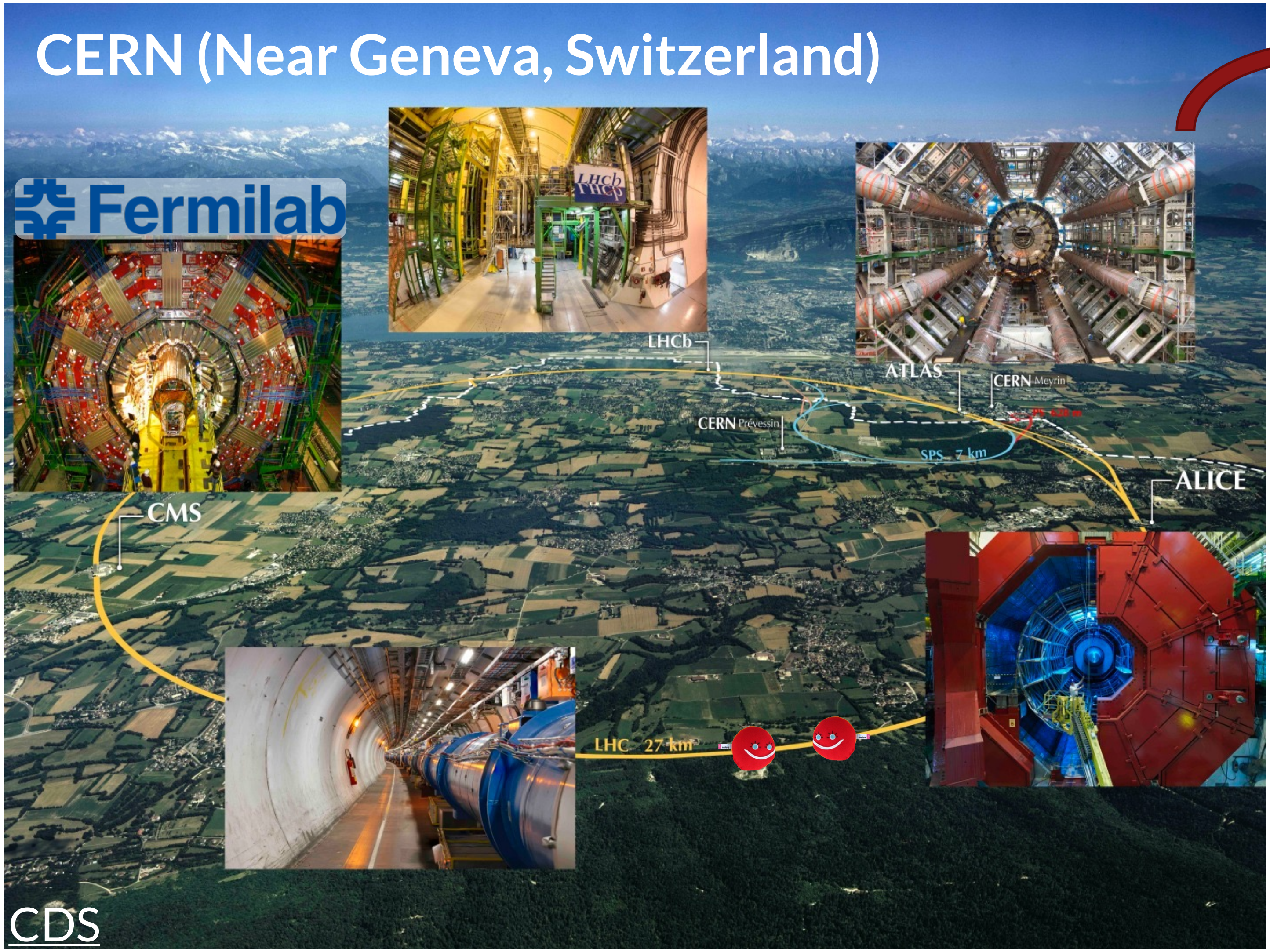
ggF: disrupt interference
→ more signal, *softer* events

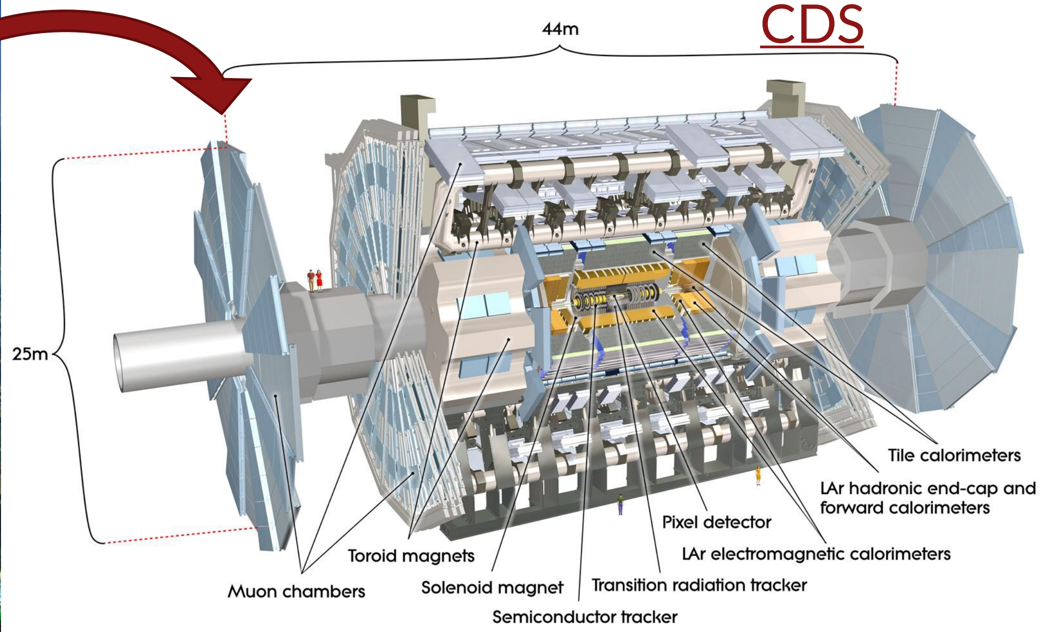
VBF: break cancellation
→ more signal, *harder* events

How do we measure Higgs Boson self-interactions?

The ATLAS Detector

ATLAS and the Large Hadron Collider





ATLAS
→ General purpose detector

Today: Run 2 (2015-2018)

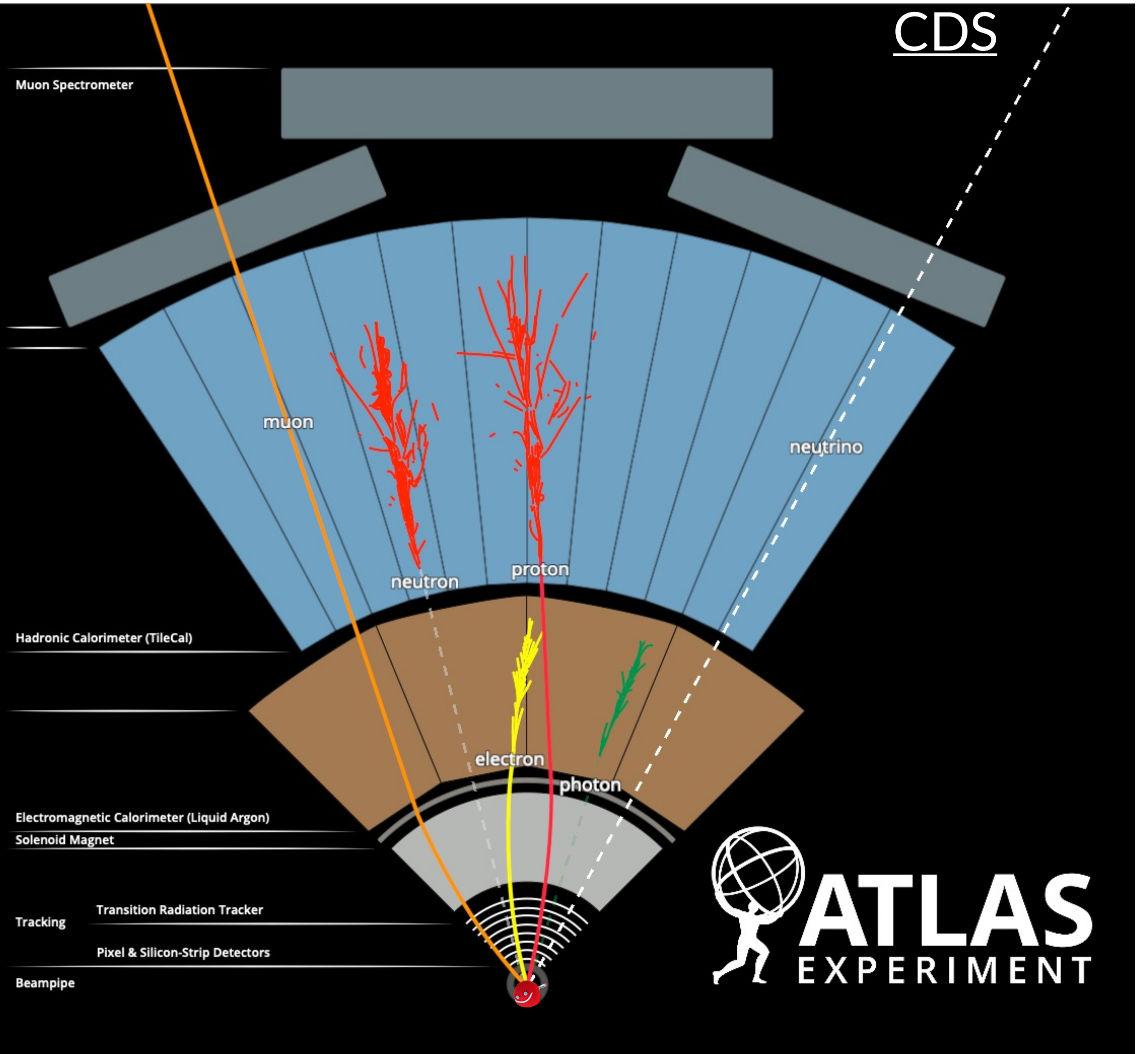
The ATLAS Detector

Muon Spectrometer

Hadronic Calorimeter

Electromagnetic Calorimeter

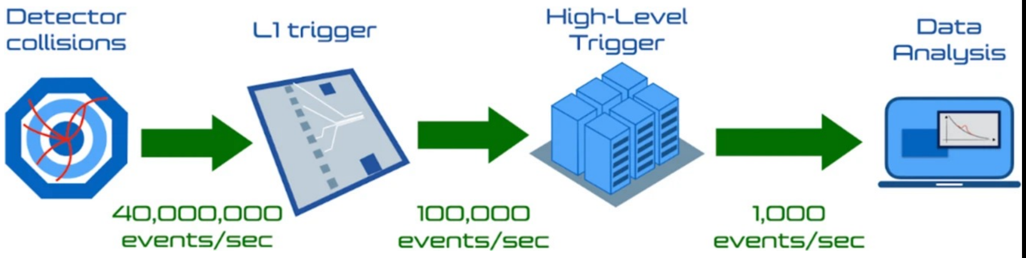
Tracking



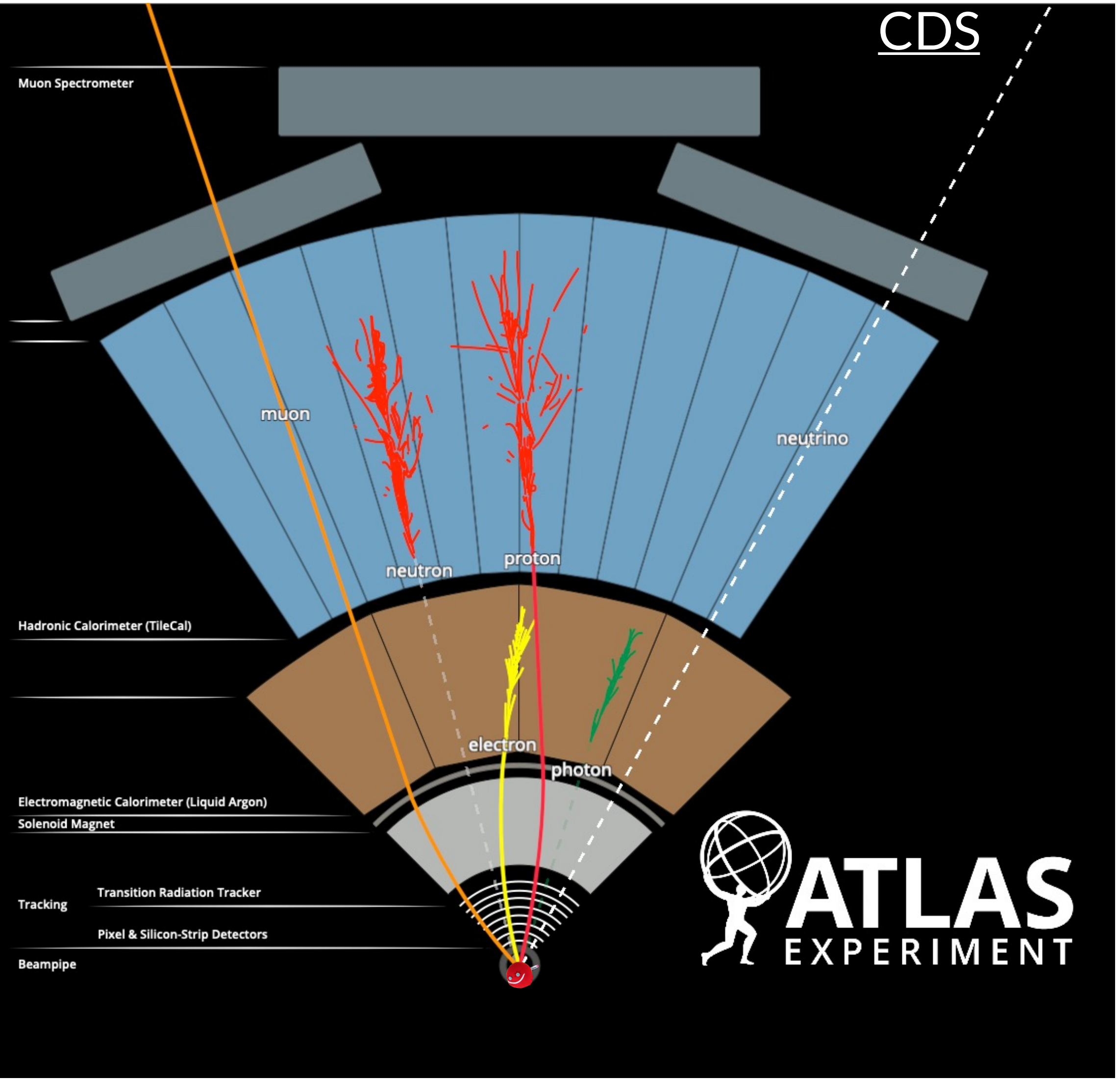
The ATLAS Detector

- Muon Spectrometer
- Hadronic Calorimeter
- Electromagnetic Calorimeter
- Tracking

Hardware & Software Trigger System

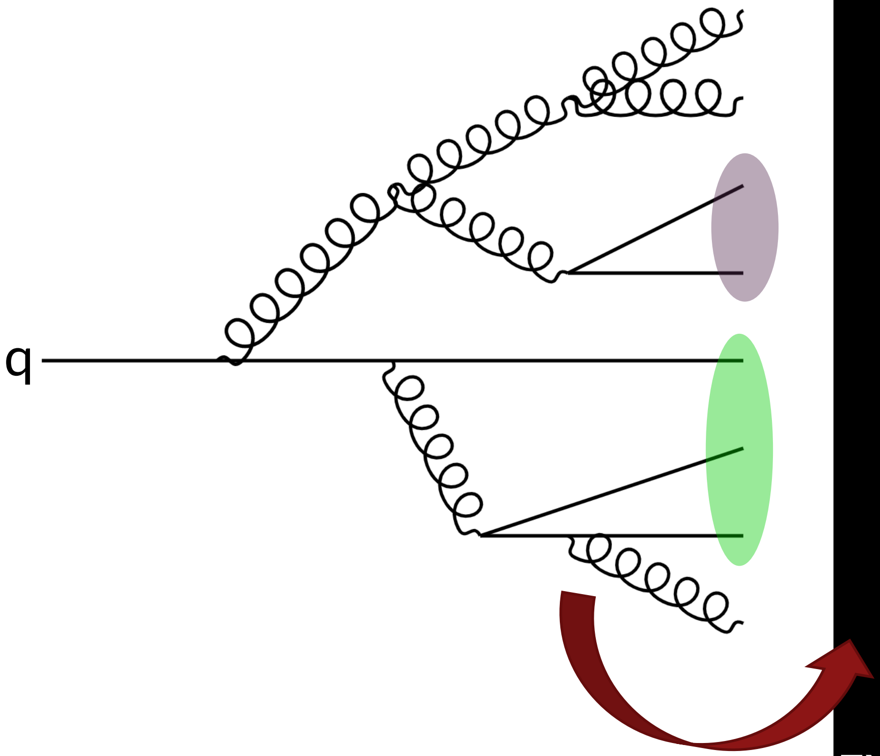


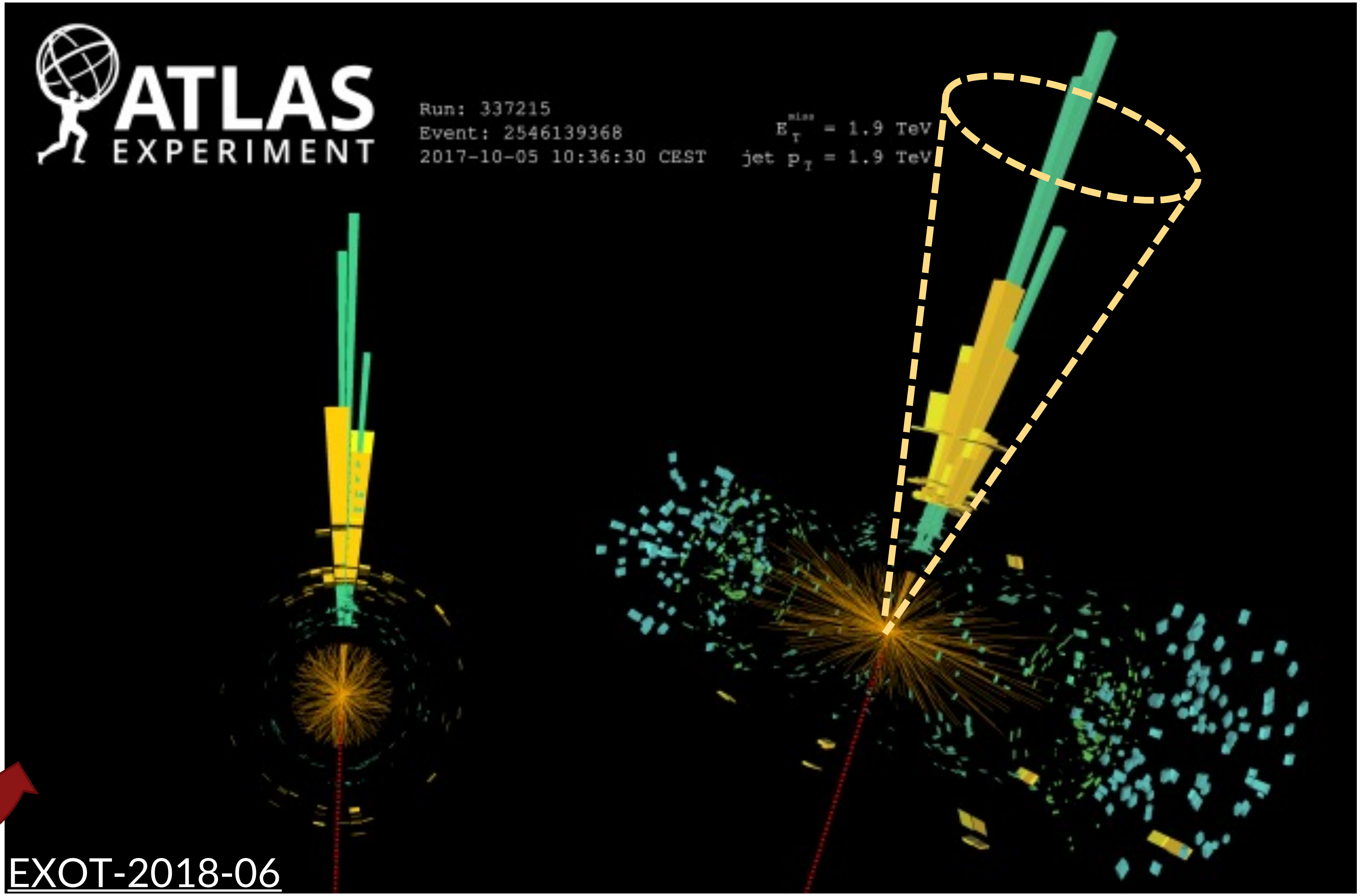
Govorkova et. al.



What is a Jet?

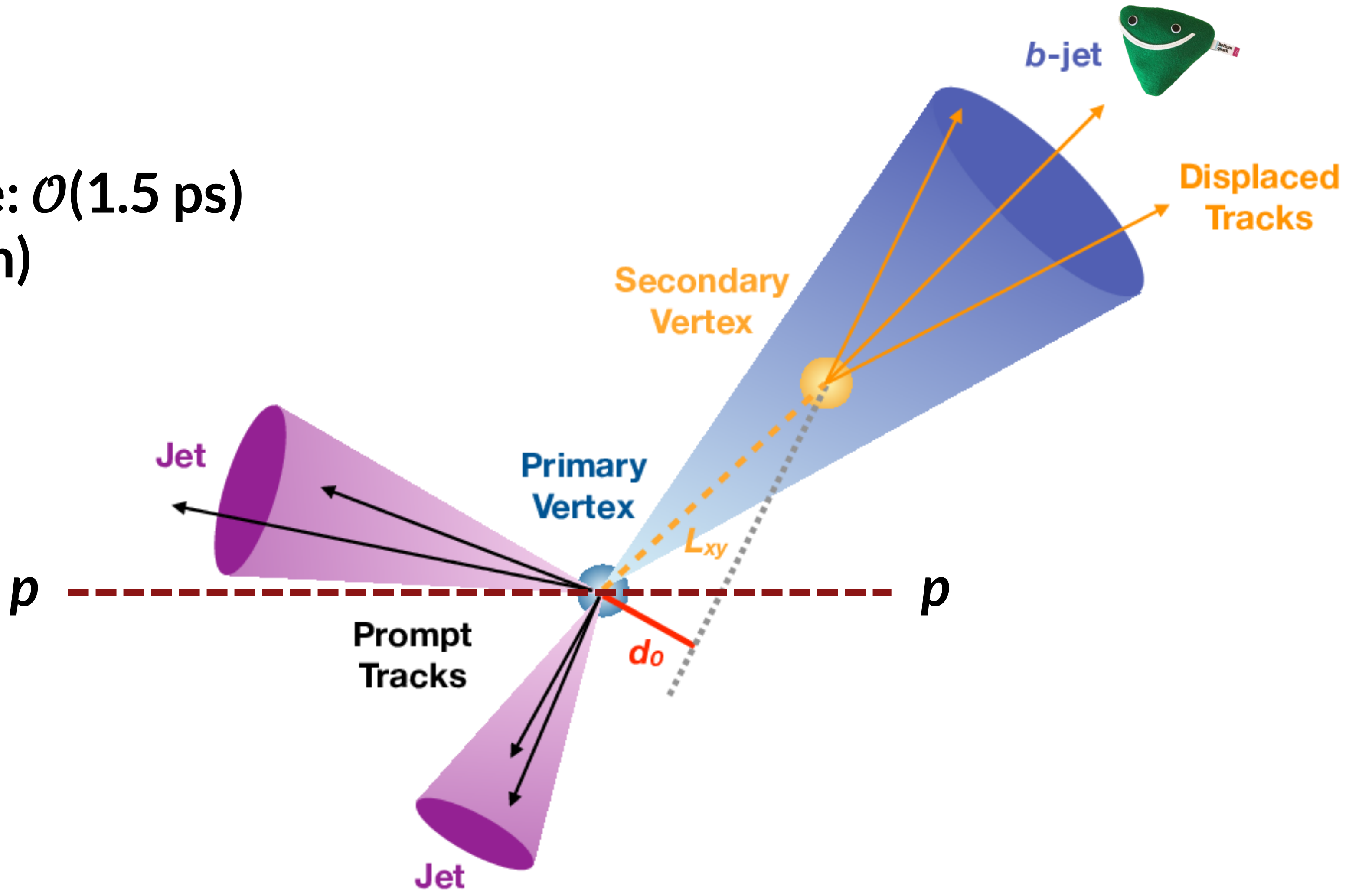
No single quarks → Spray of high-energy particles





Identifying jets from *b*-quarks

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



TRIG-2018-08

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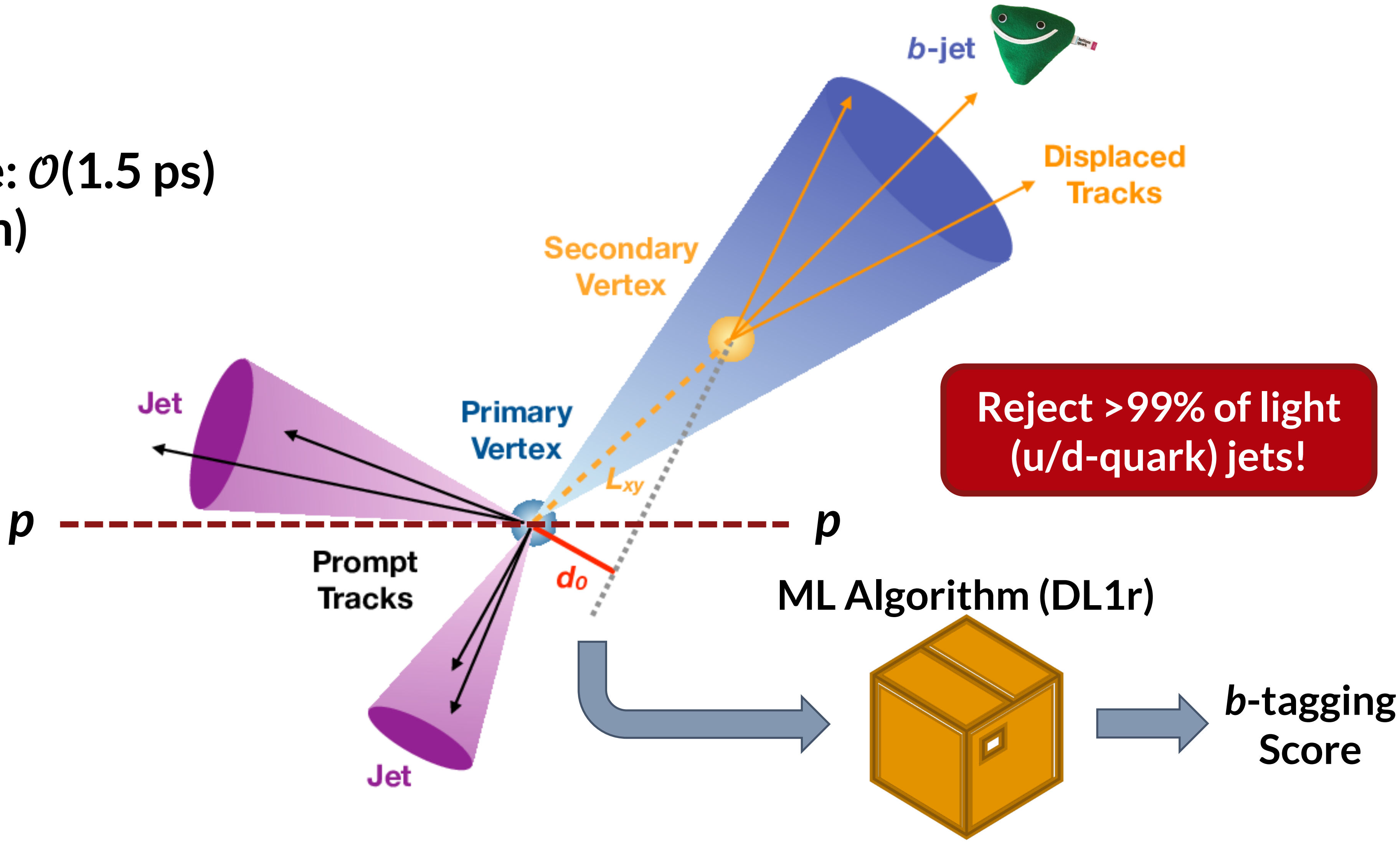


Reject >99% of light (u/d-quark) jets!

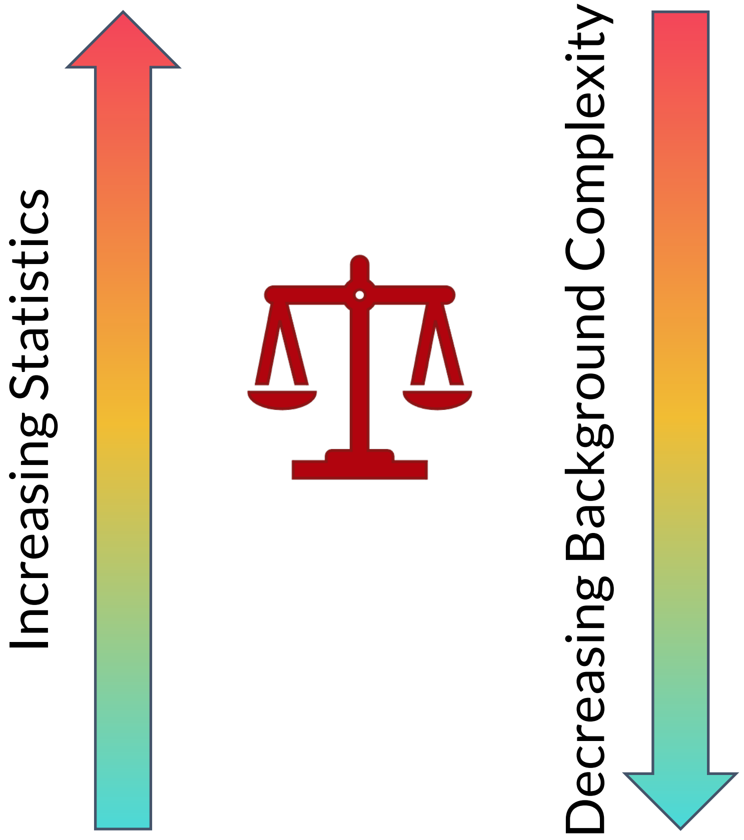
TRIG-2018-08

A measurement probing Higgs Boson self-interactions

arxiv:2301.03212

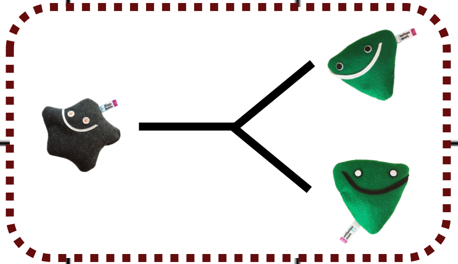
The ATLAS $HH \rightarrow b\bar{b}b\bar{b}$ Analysis

Di-Higgs Boson Decays



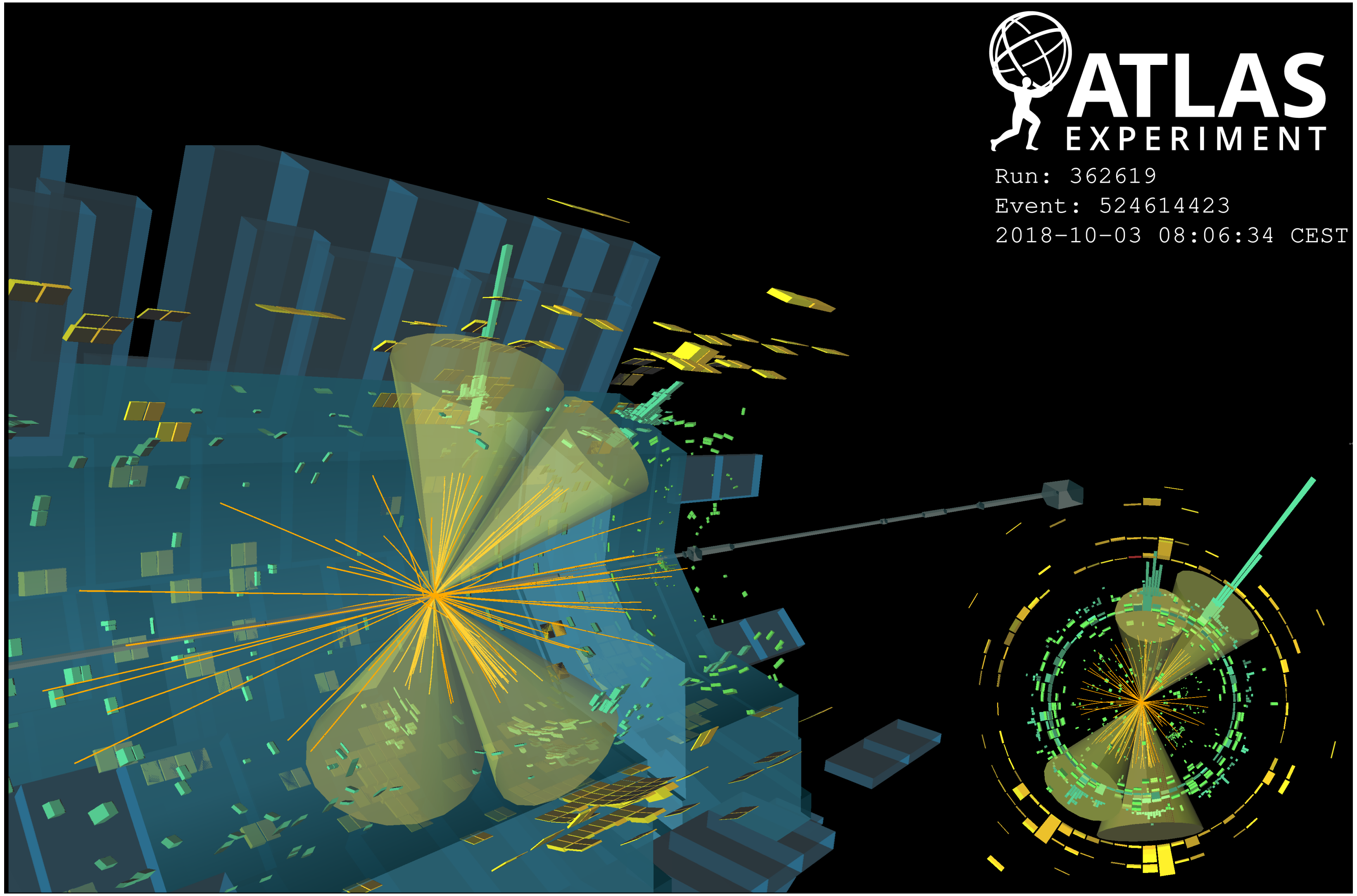
"Main" ATLAS Channels

	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?

~2400 *HH* Events
(ATLAS Run 2)



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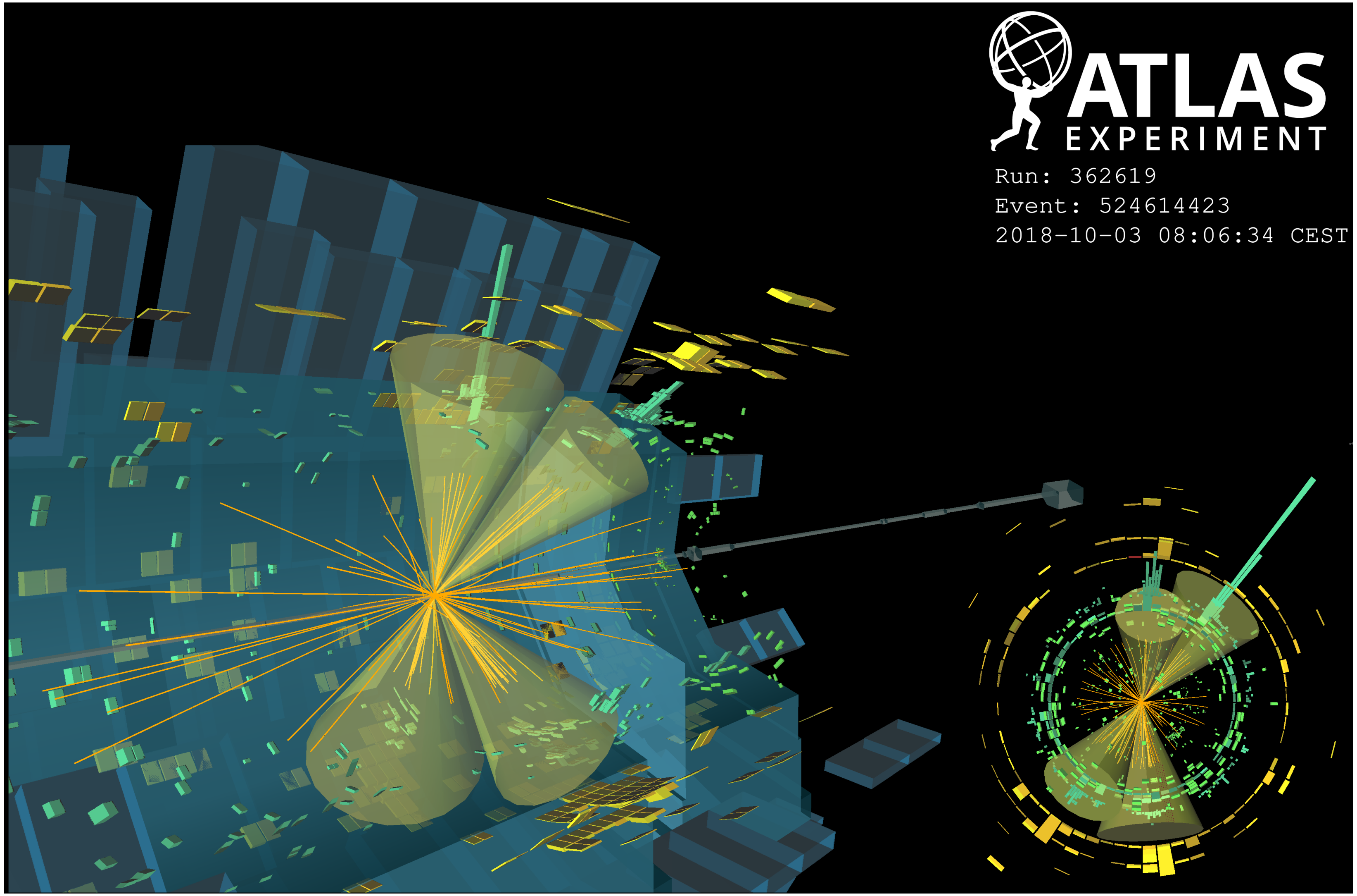
~2400 *HH* Events (ATLAS Run 2)

$BR(HH \rightarrow b\bar{b}b\bar{b}) \sim \frac{1}{3}$

~800 $HH \rightarrow b\bar{b}b\bar{b}$ Events



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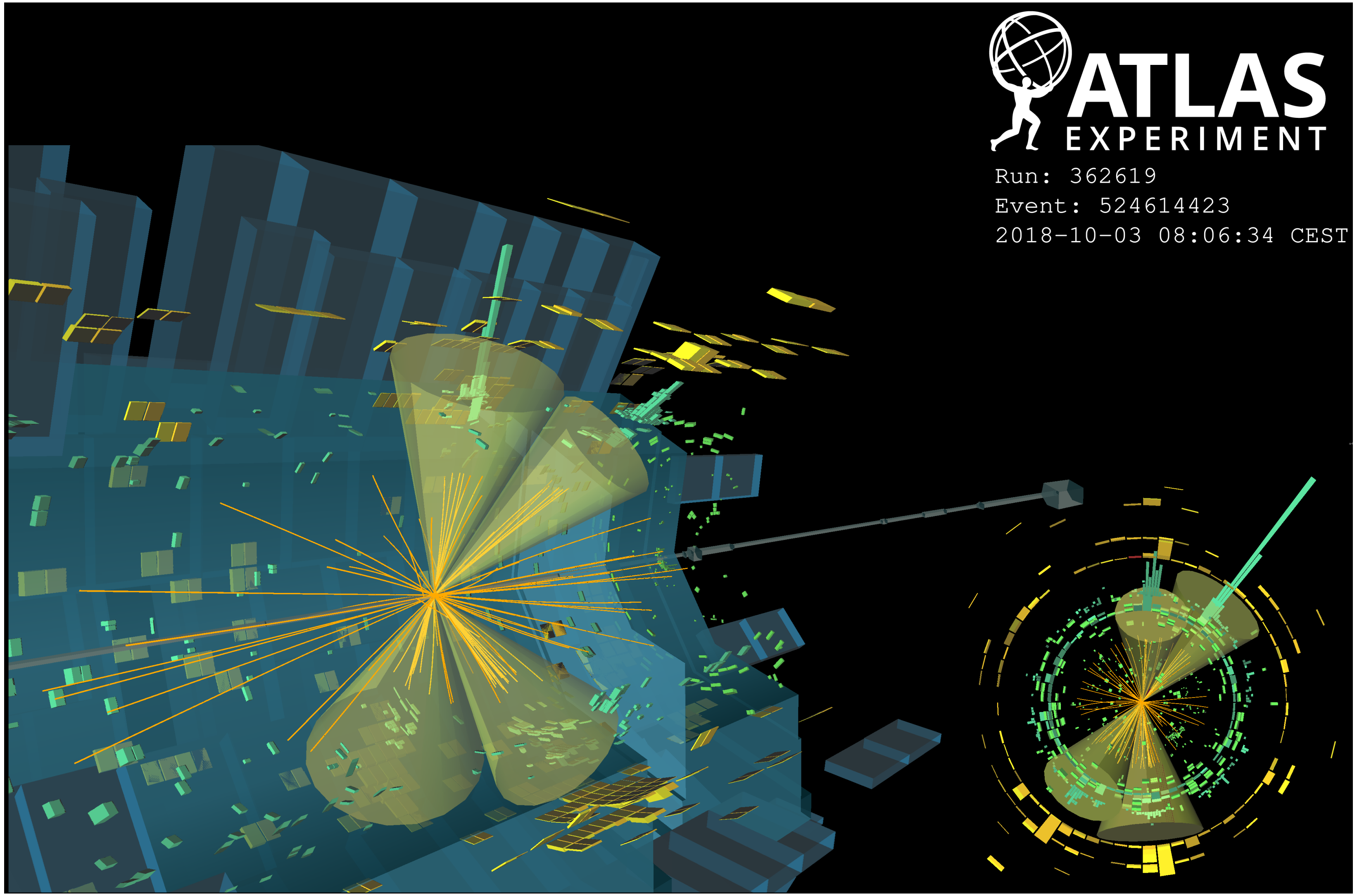
Trigger+Acceptance

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



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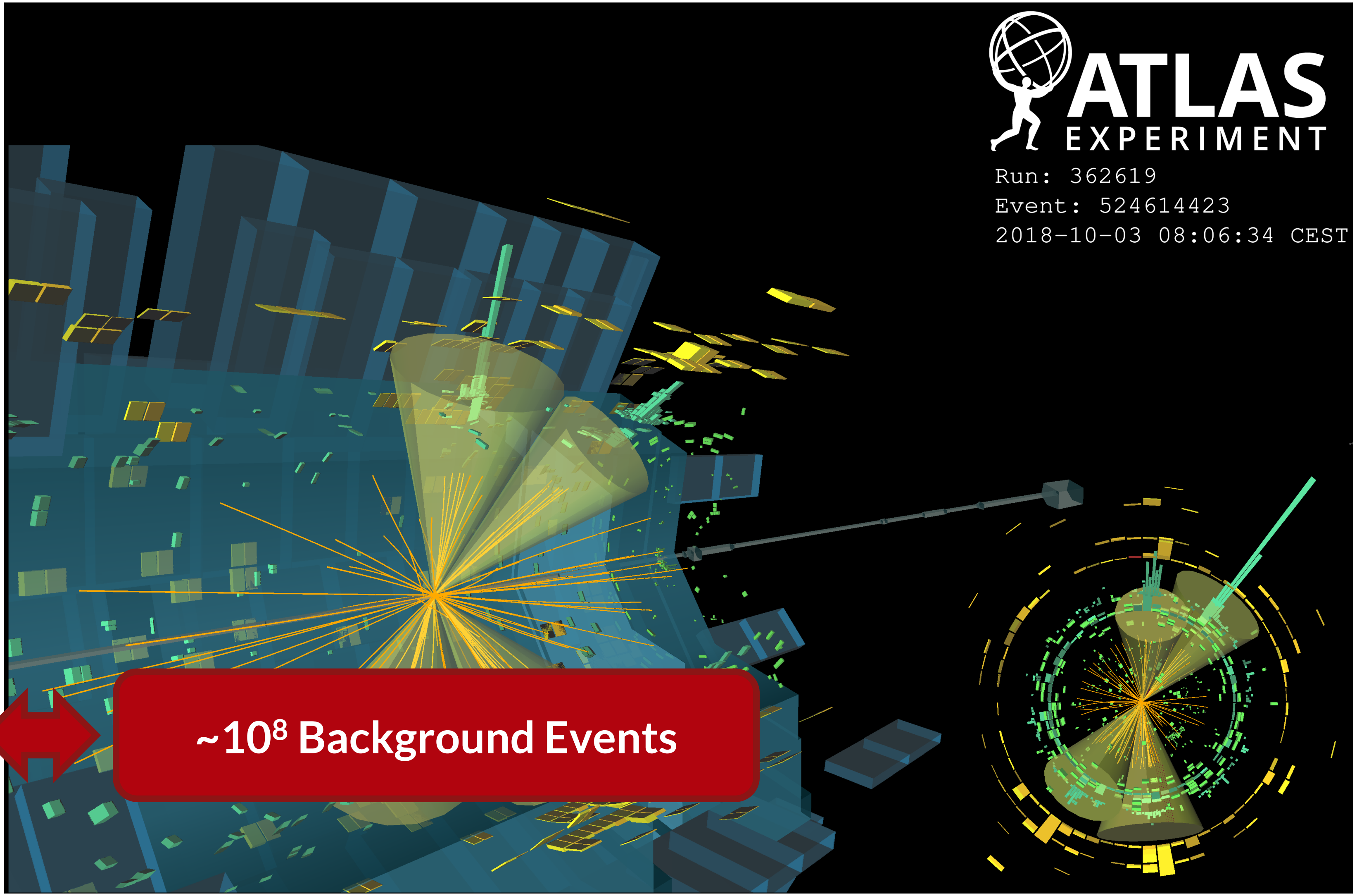


~10^8 Background Events

What Makes 4*b* a Challenging Final State?

~2400 *HH* Events (ATLAS Run 2)

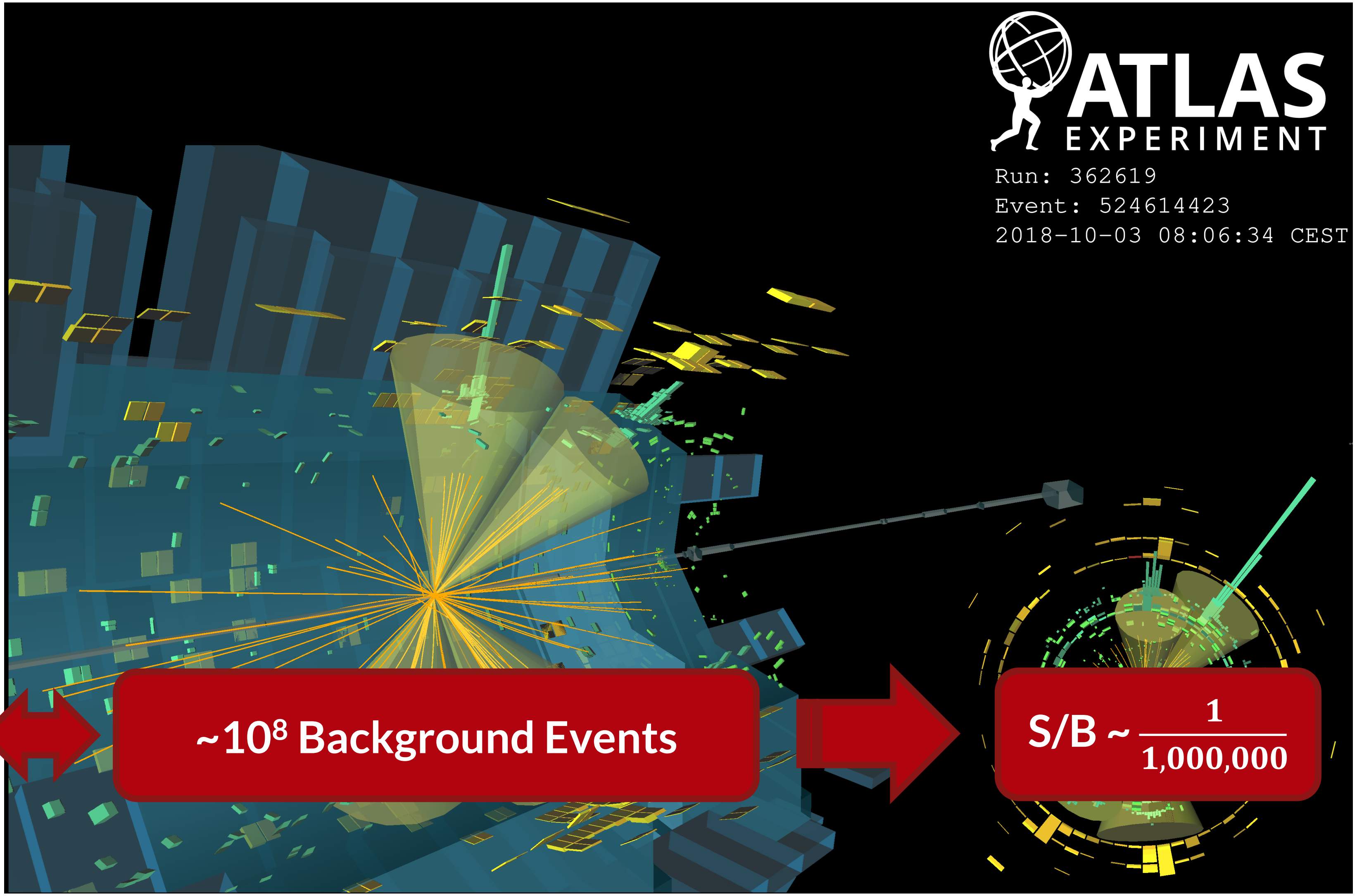
↓ $BR(HH \to b\bar{b}b\bar{b}) \sim \frac{1}{3}$

~800 $HH \to b\bar{b}b\bar{b}$ Events

↓ Trigger+Acceptance

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

↔ **~10^8 Background Events** → **S/B ~ $\frac{1}{1,000,000}$**



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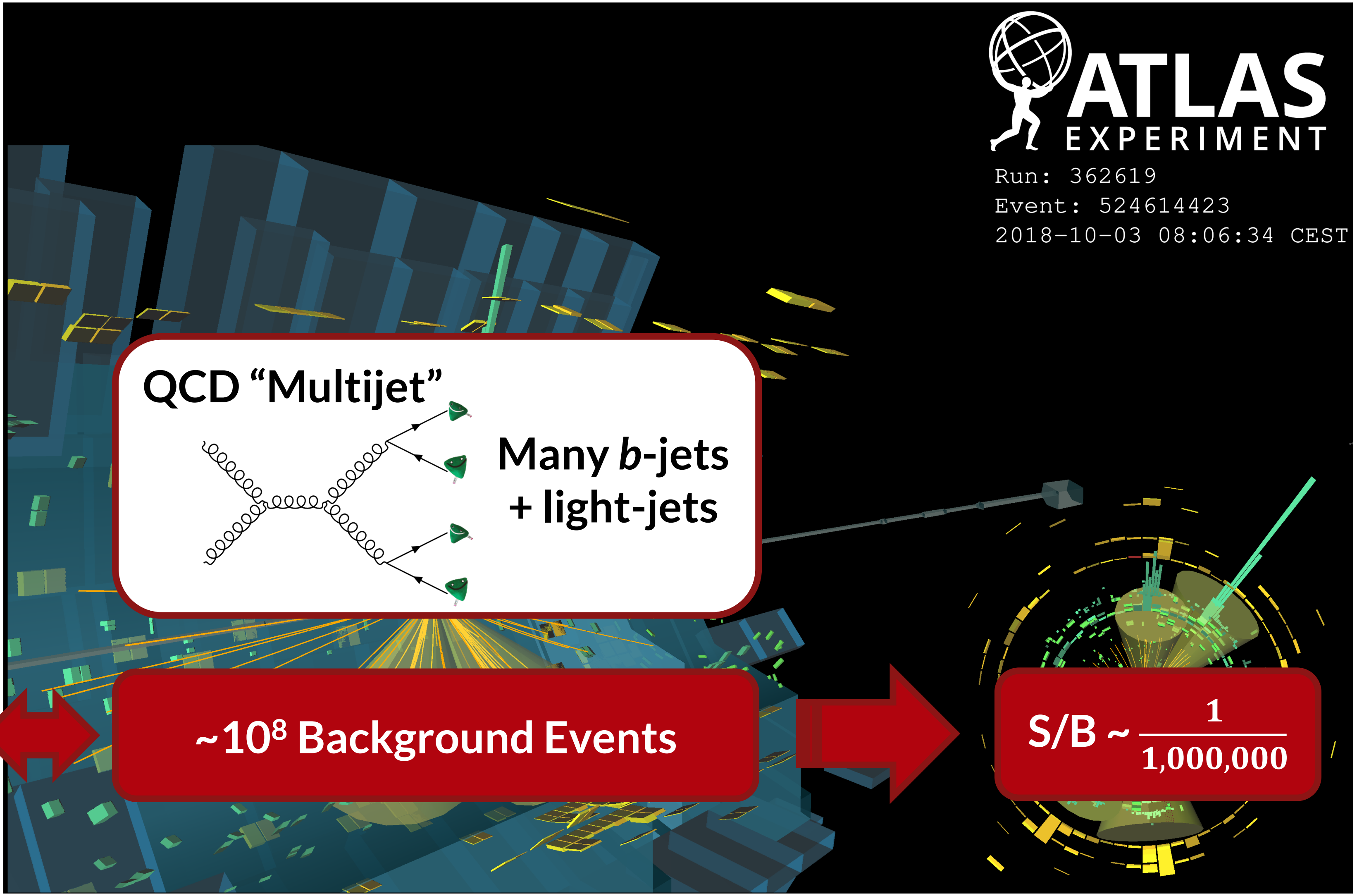

QCD “Multijet”

Many *b*-jets
+ light-jets

~10^8 Background Events

S/B ~ $\frac{1}{1{,}000{,}000}$

What Makes 4*b* a Challenging Final State?

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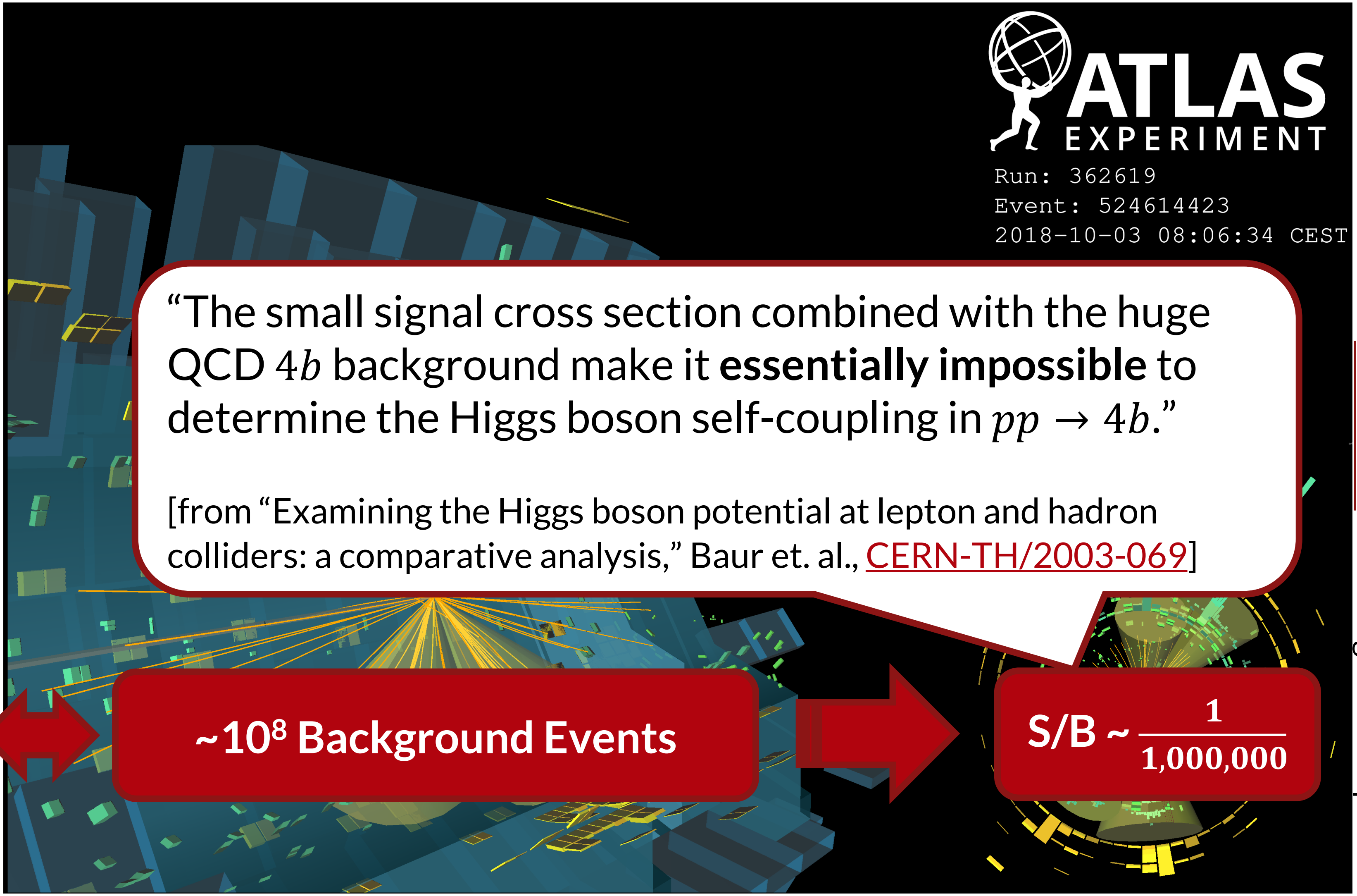

"The small signal cross section combined with the huge QCD $4b$ background make it **essentially impossible** to determine the Higgs boson self-coupling in $pp \rightarrow 4b$."

[from "Examining the Higgs boson potential at lepton and hadron colliders: a comparative analysis," Baur et. al., CERN-TH/2003-069]

~10^8 Background Events

S/B ~ $\frac{1}{1{,}000{,}000}$

Credit to L. Cadamuro for finding this nice quote!

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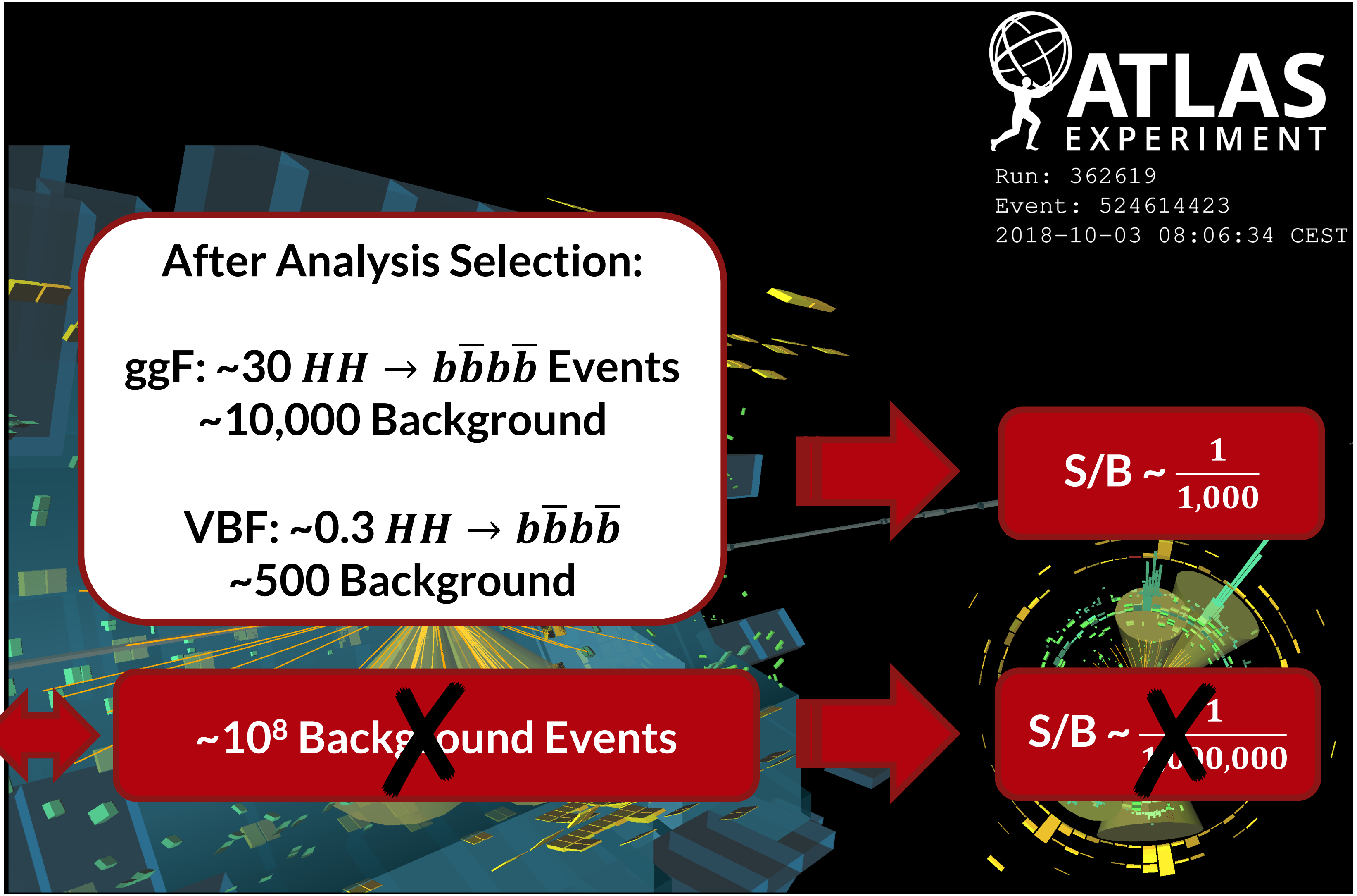


After Analysis Selection:

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

VBF: ~0.3 $HH \to b\bar{b}b\bar{b}$
~500 Background

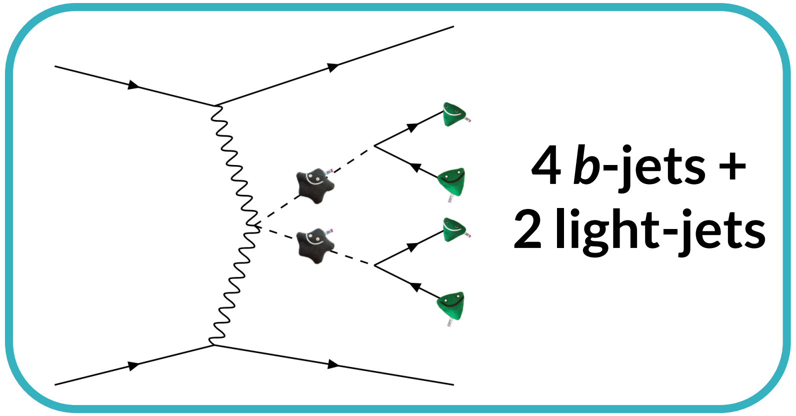
~10^8 Background Events

S/B ~ $\frac{1}{1,000}$

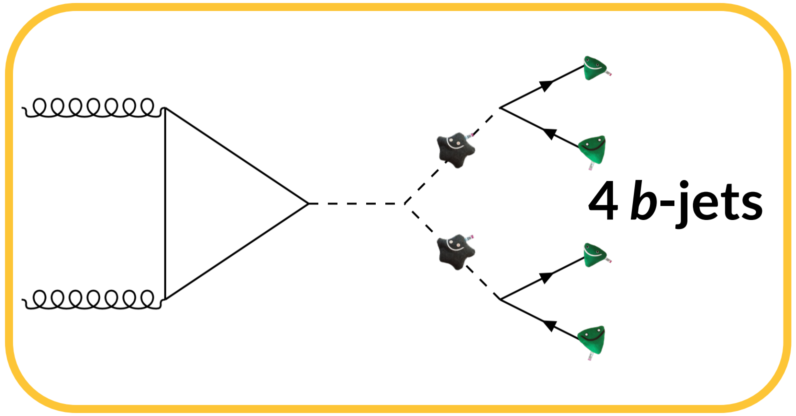
S/B ~ $\frac{1}{100,000}$

Isolating $HH \rightarrow b\bar{b}b\bar{b}$ Events

VBF



ggF



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

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

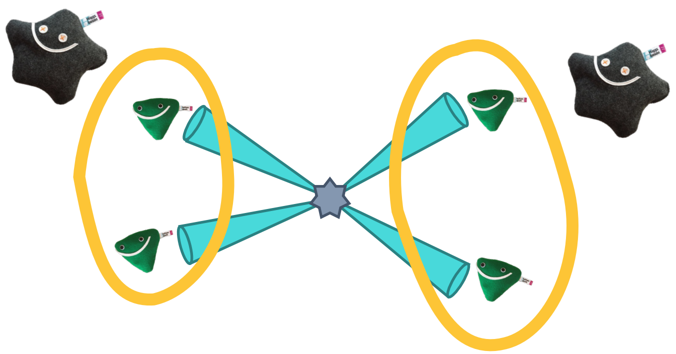
4 "Higgs Candidate" Jets are *b*-tagged — $\sim 10^4$ (VBF) / $\sim 10^6$ (ggF)

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

Not $t\bar{t}$-like — $\sim 10^4$ (VBF) / $\sim 10^5$ (ggF)

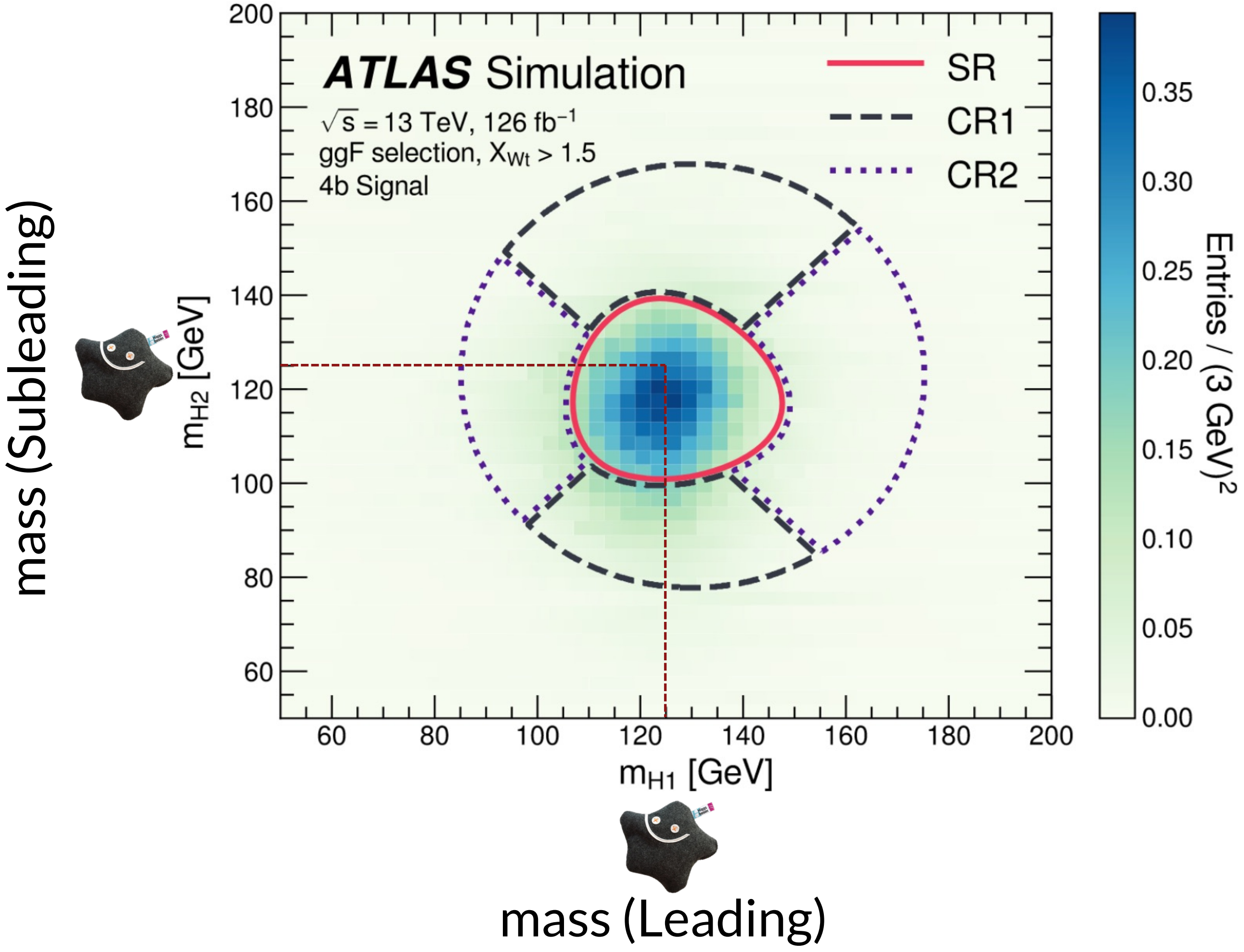
Mass("Higgs Candidates") ~ 125 GeV — $\sim 10^2$ (VBF) / $\sim 10^4$ (ggF)

The "Mass-Plane"

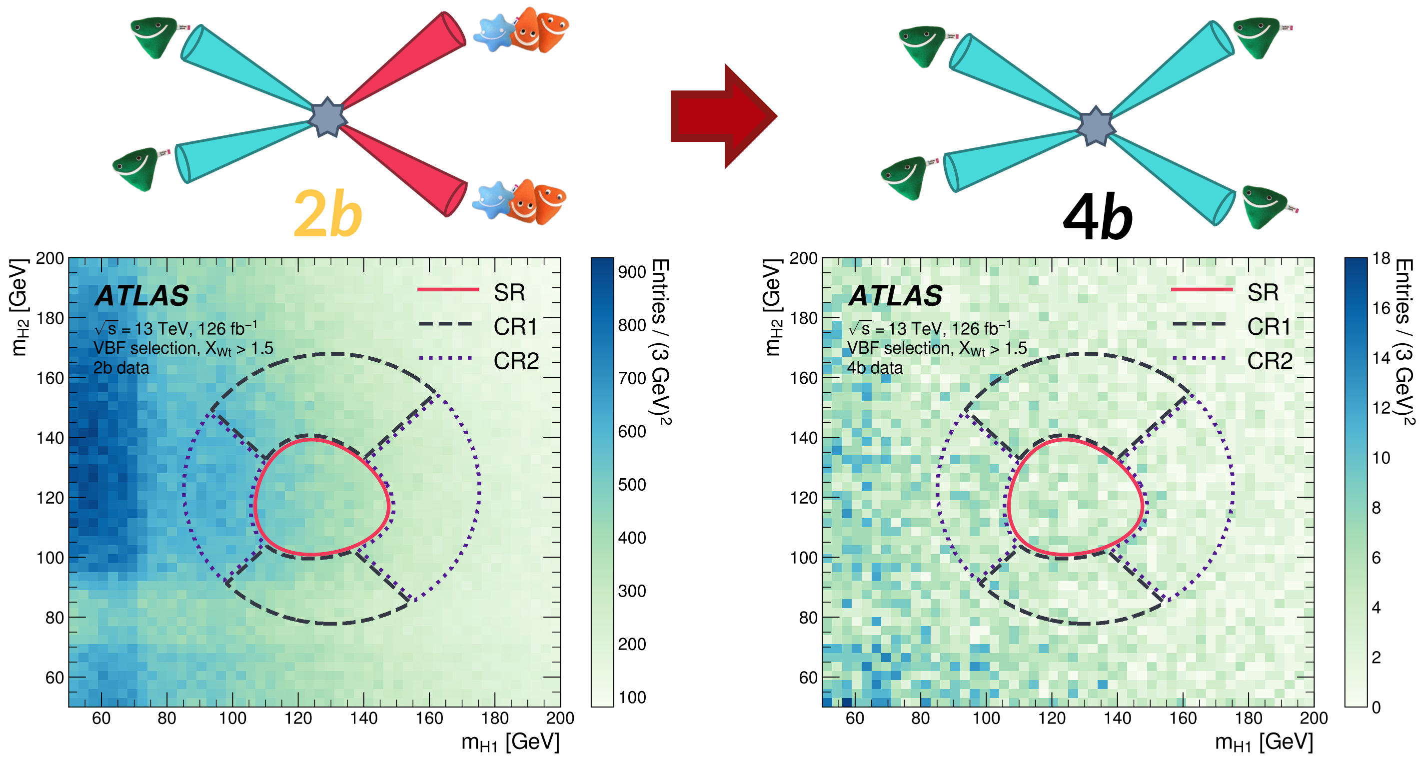


Require reconstructed Higgs Boson candidate masses ~ 125 GeV

→ Define "Signal Region"



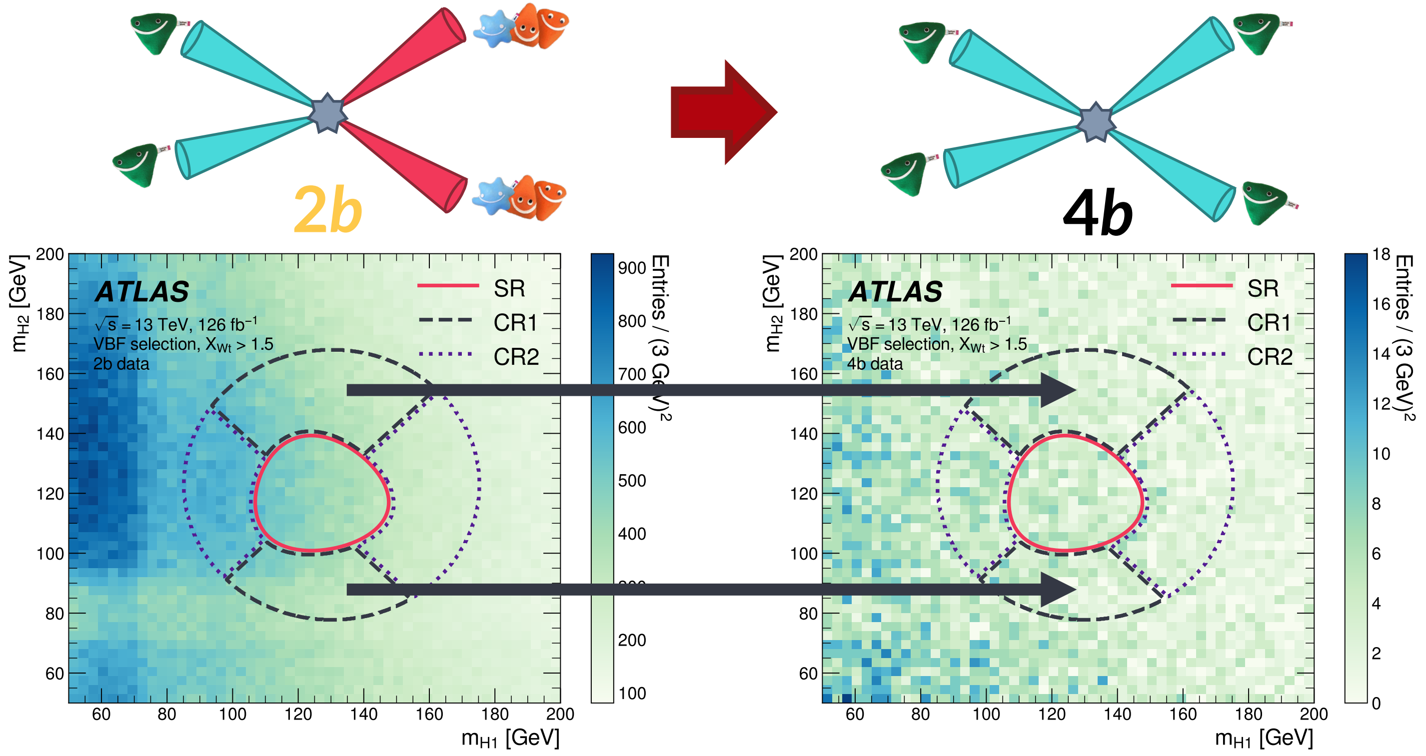
Background Modeling Strategy

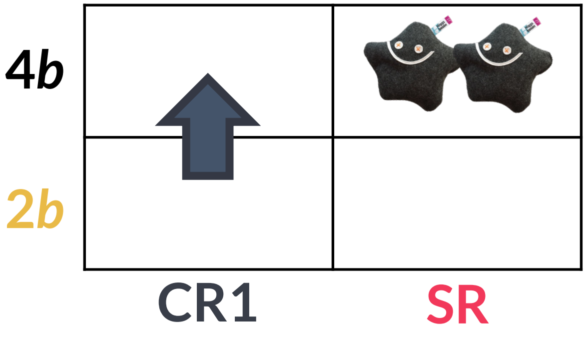


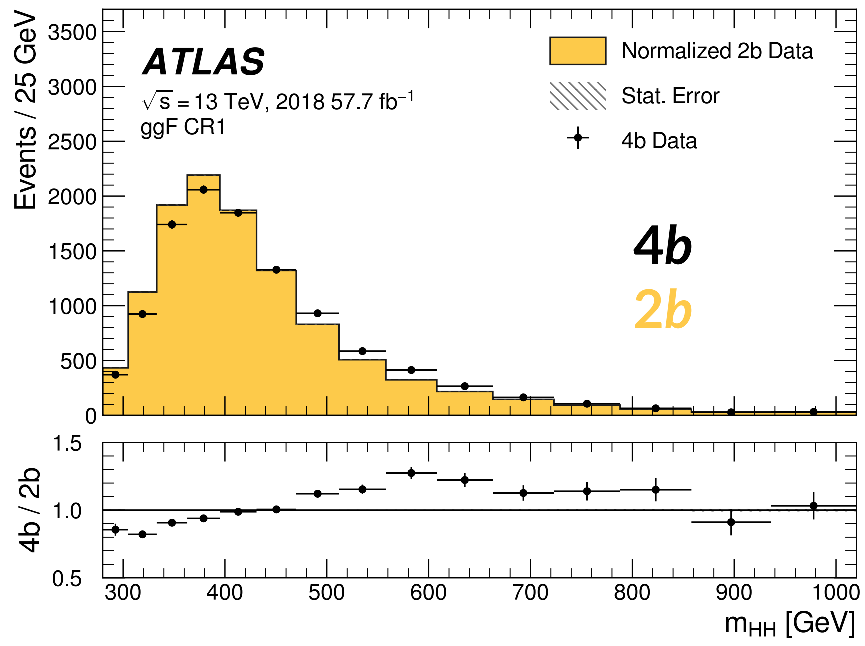
2b background processes
~ *4b* background processes

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

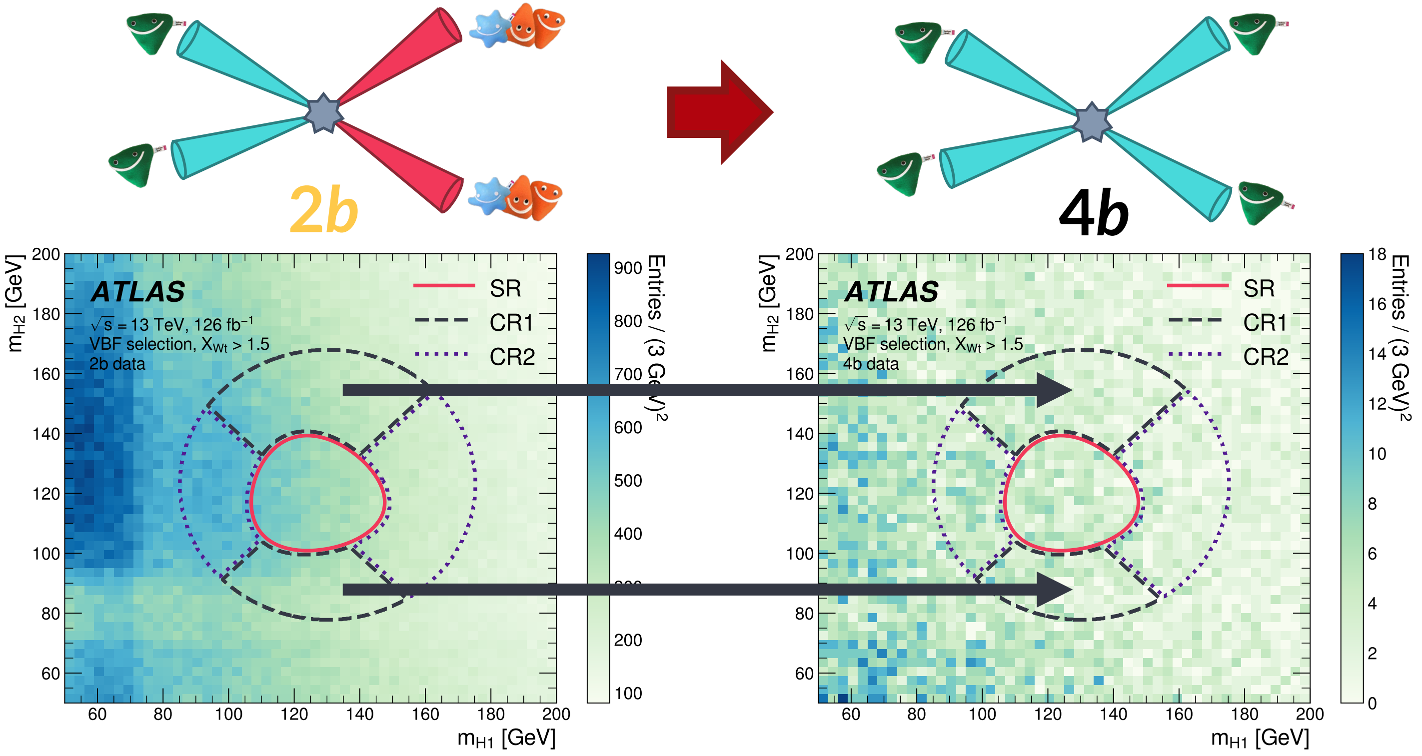
Background Modeling Strategy

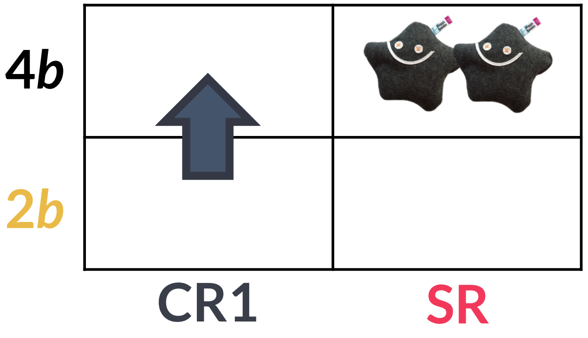


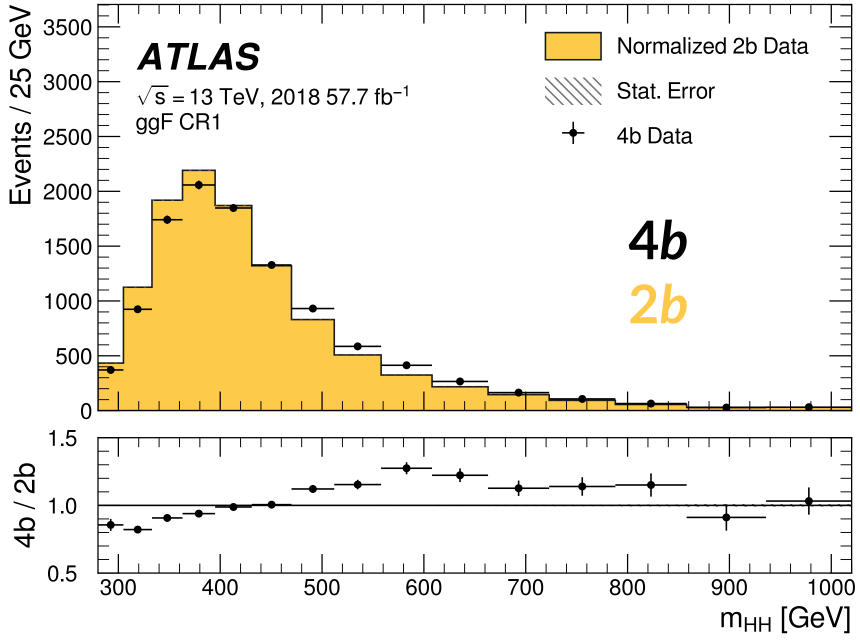




Background Modeling Strategy



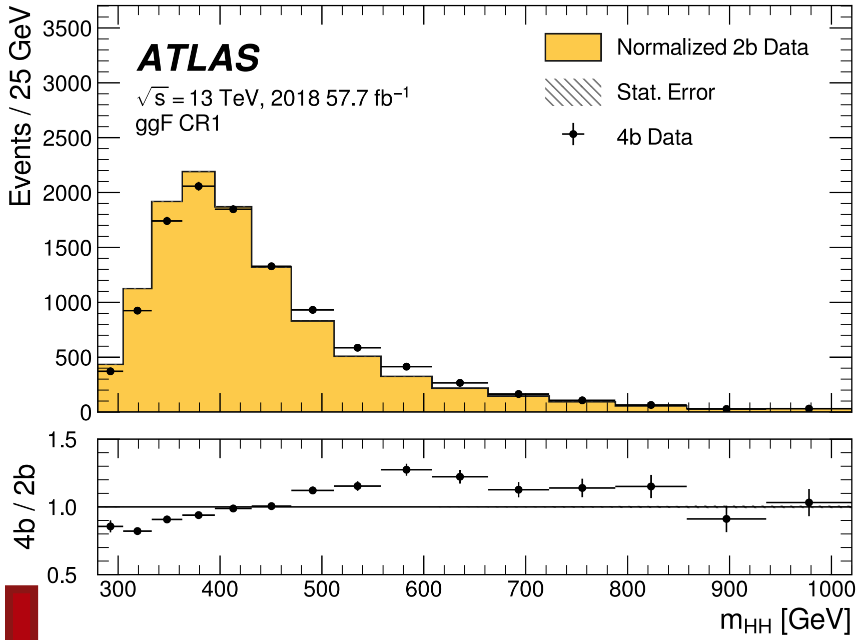




1-Dimensional *density ratio*

$$w(x) = p_{4b}(x)/\,p_{2b}(x)$$

Density Ratio Estimation with Histograms

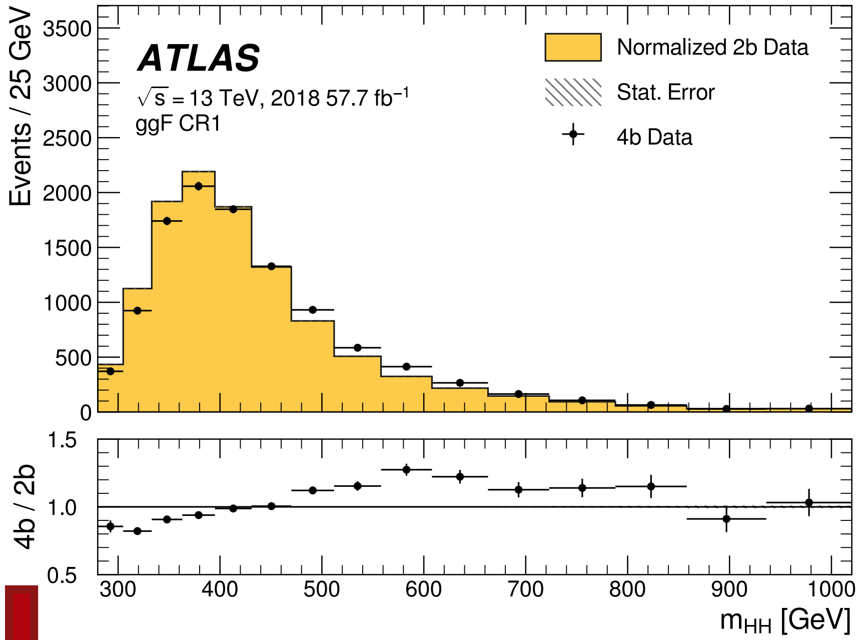


1-Dimensional Reweighting

→ Prone to statistical fluctuations

→ No correlation with other kinematics (assumes similar domain $p_{2b}^{\mathrm{CR}} \sim p_{2b}^{\mathrm{SR}}$)

Density Ratio Estimation with Histograms

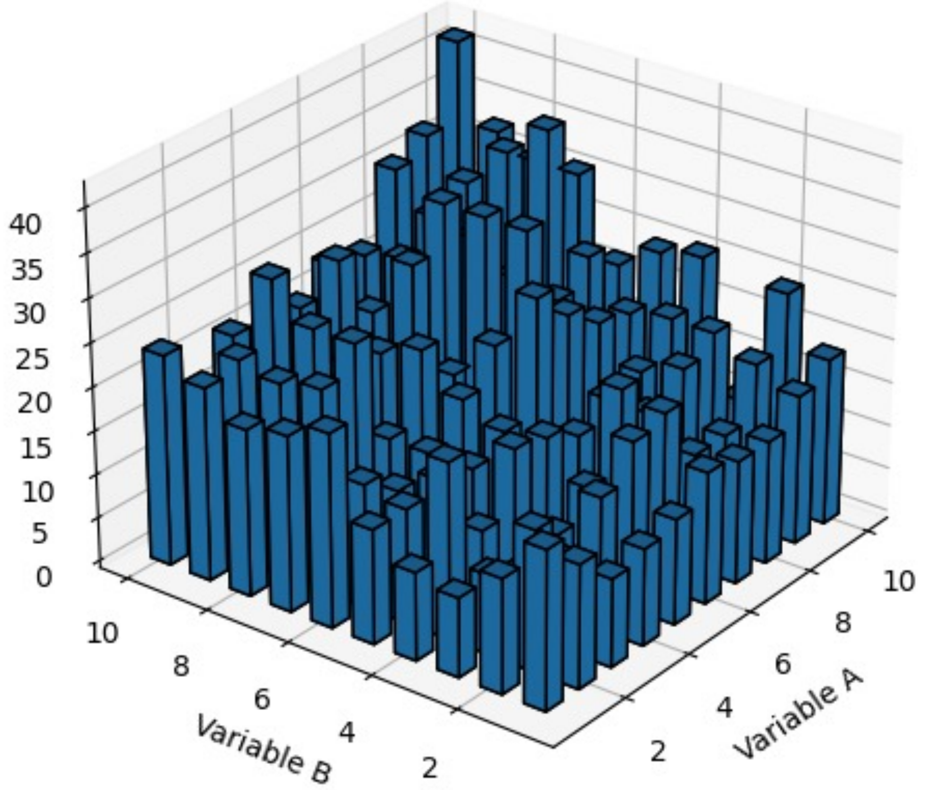


1-Dimensional Reweighting

→ Prone to statistical fluctuations

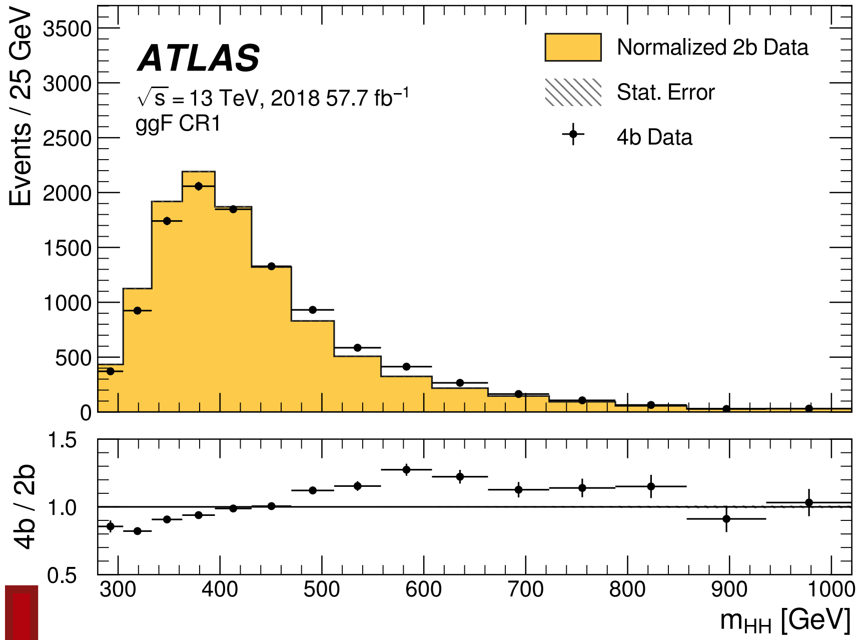
→ No correlation with other kinematics (assumes similar domain $p_{2b}^{\mathrm{CR}} \sim p_{2b}^{\mathrm{SR}}$)

Multi-Dimensional Histogram Reweighting?



Curse of Dimensionality

Density Ratio Estimation with Neural Networks



1-Dimensional Reweighting
→ Prone to statistical fluctuations
→ No correlation with other kinematics
(assume similar domain $p_{2b}^{\mathrm{CR}} \sim p_{2b}^{\mathrm{SR}}$)

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

Train Neural Network with specific Loss function:

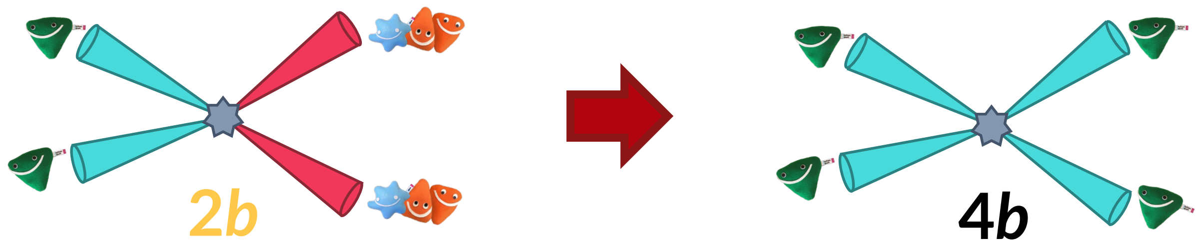
$$\mathcal{L}\big(R(\vec{x})\big) = \mathbb{E}_{x\sim p_{2b}}\left[\sqrt{R(\vec{x})}\right] + \mathbb{E}_{x\sim p_{4b}}\left[\frac{1}{\sqrt{R(\vec{x})}}\right]$$

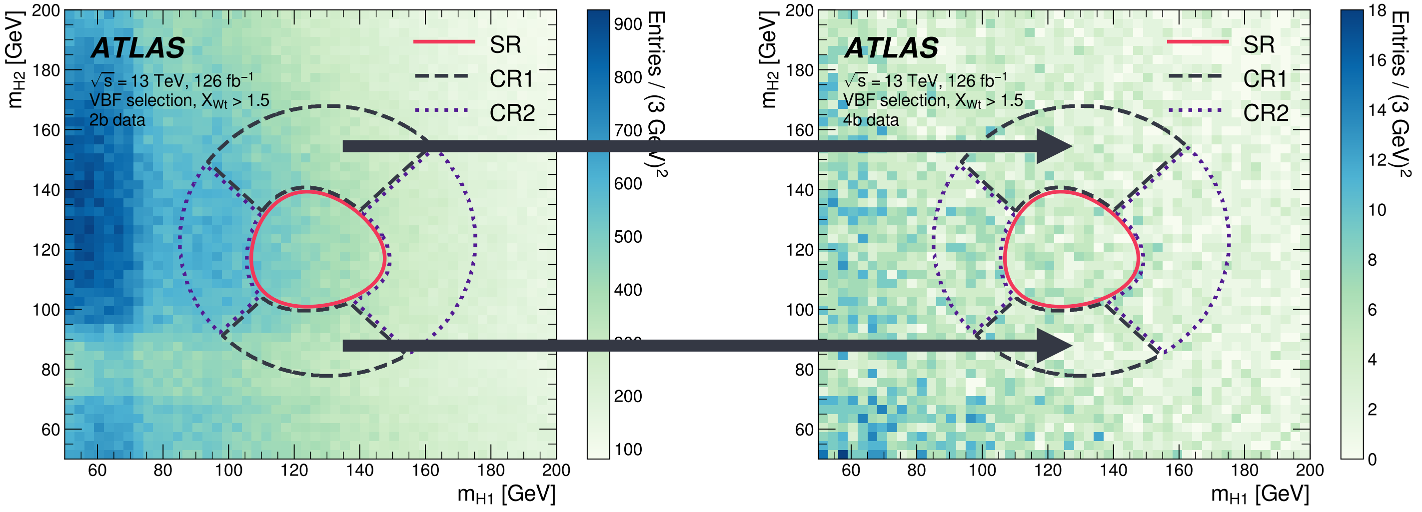
$$\rightarrow \arg\min_{R} \mathcal{L}\big(R(\vec{x})\big) = w(\vec{x})$$

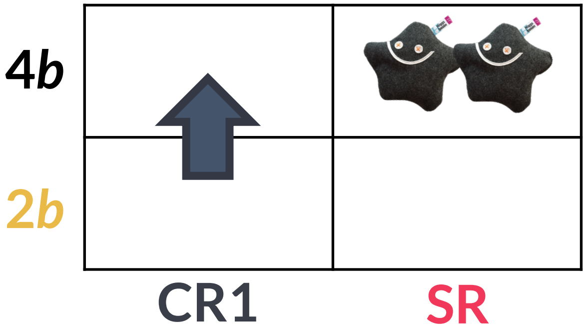
High-dimensional, "Event-level" reweighting!

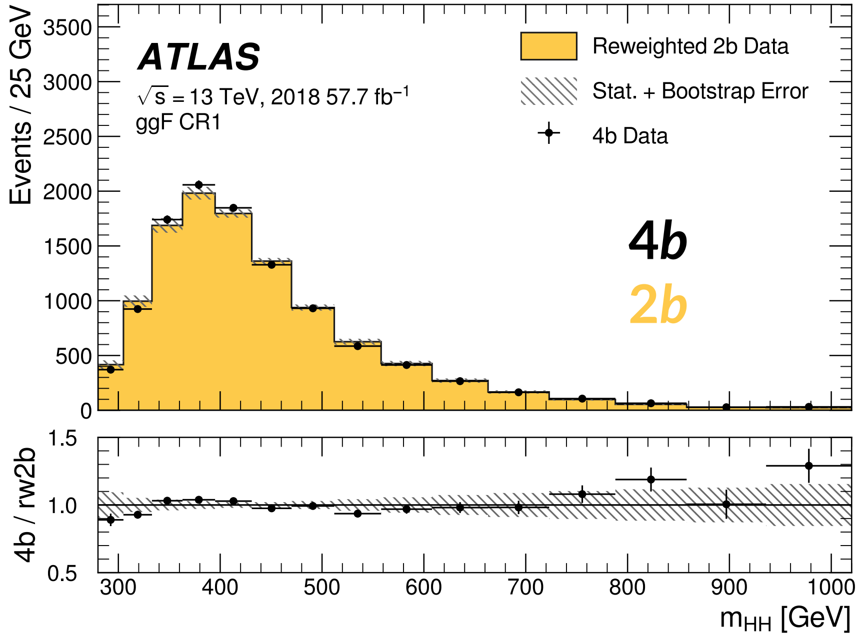
arxiv:1911.00405
Kanamori et. al. (JMLR)

Background Modeling Strategy



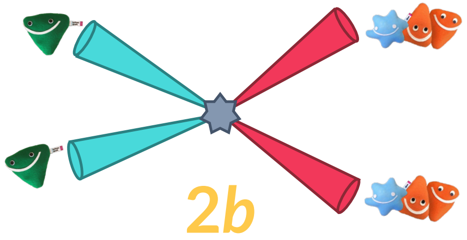


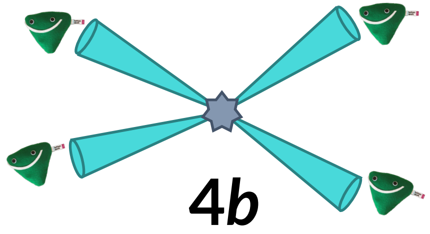


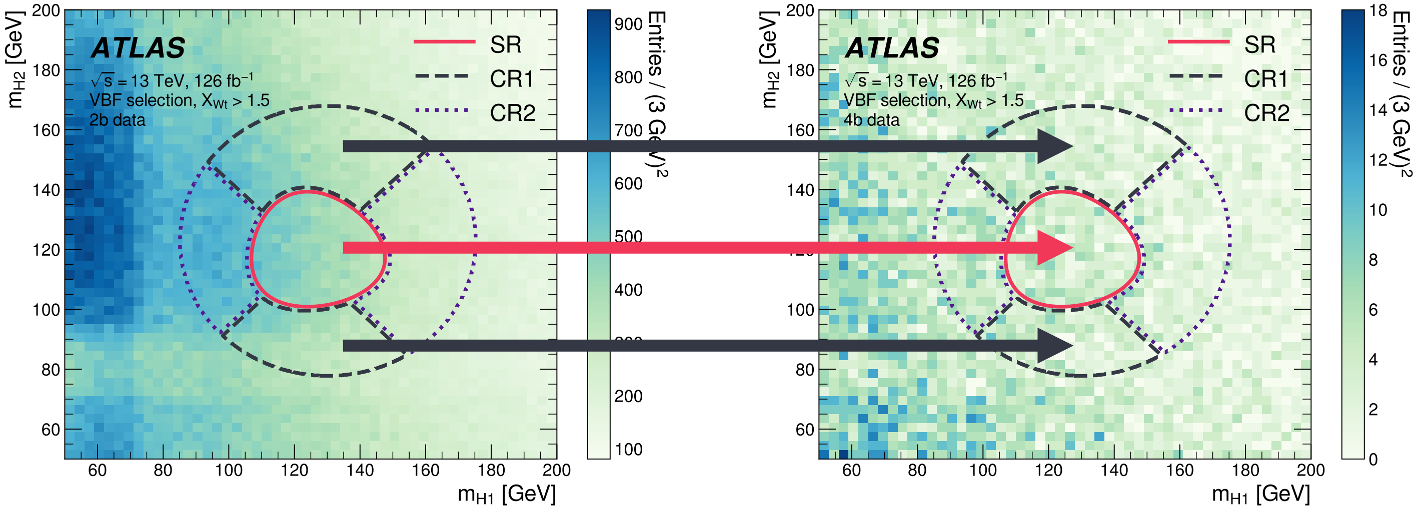


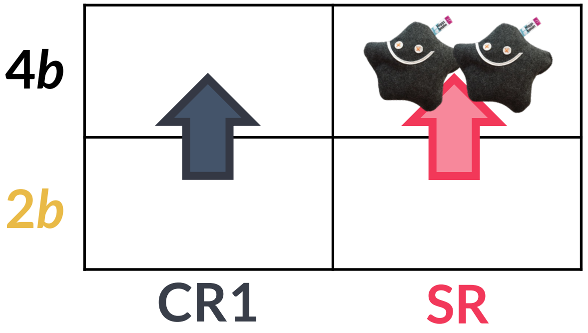
Train in CR1

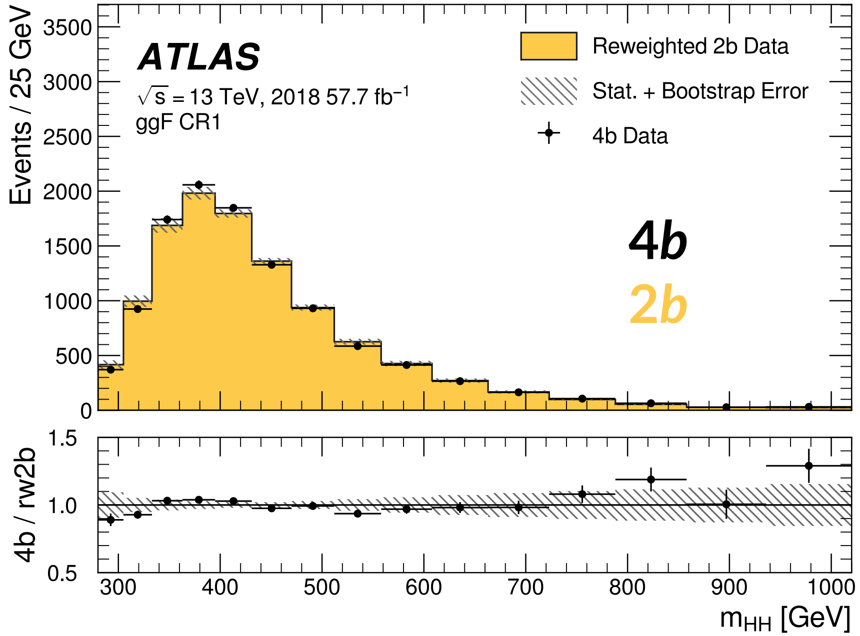
Background Modeling Strategy









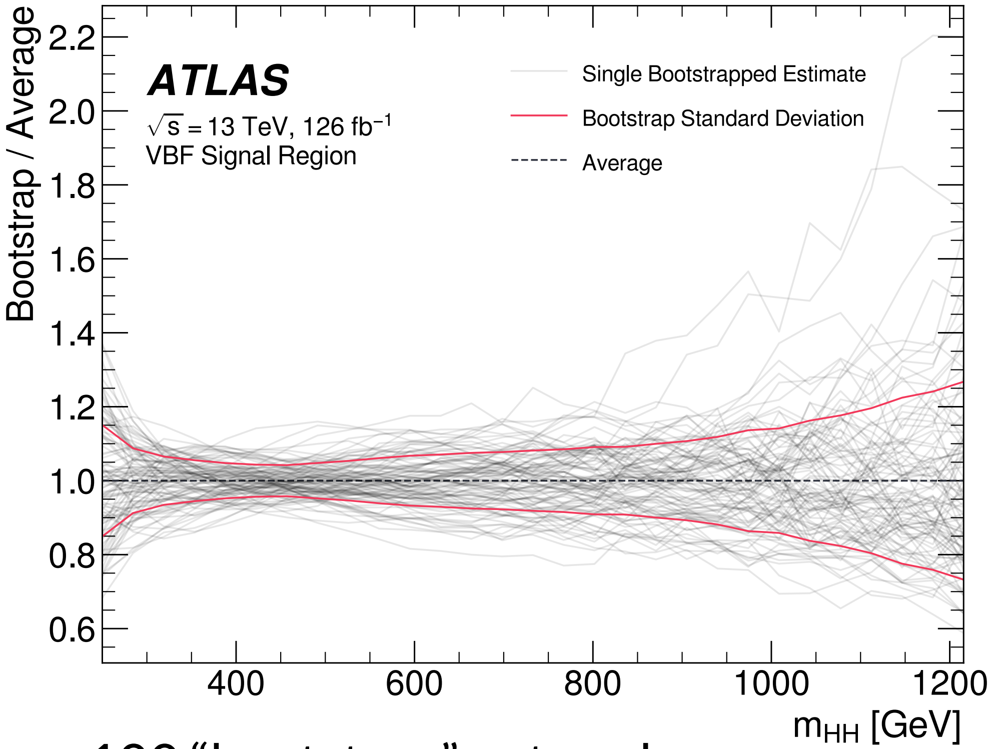


Train in CR1

Apply in SR

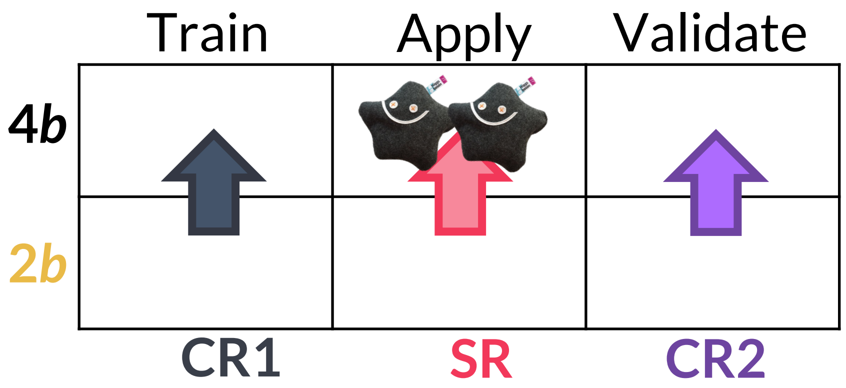
Background Modeling Strategy: Uncertainties

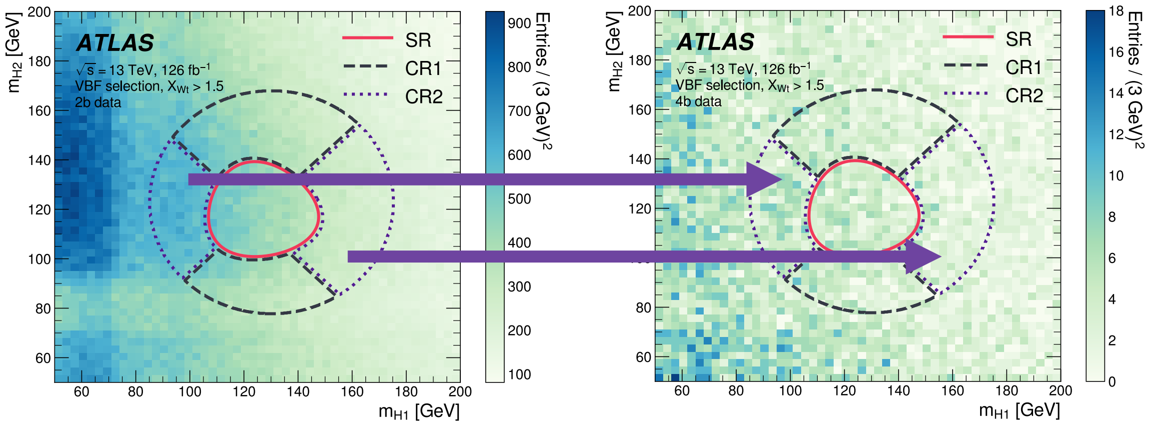
Uncertainty from limited training statistics/network initialization



100 “bootstrap” networks

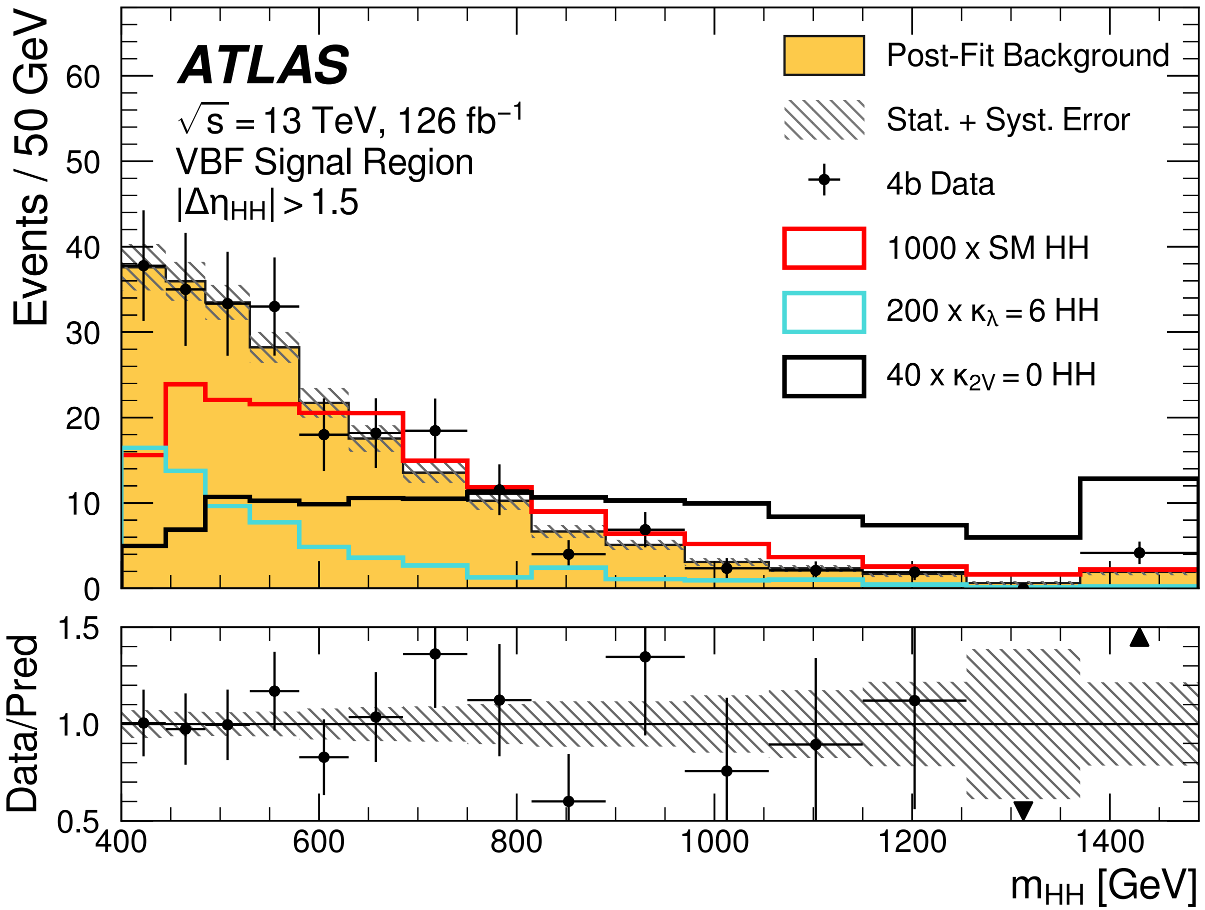
Uncertainty from domain transfer





Observed Data

Observed Data in a VBF Category



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

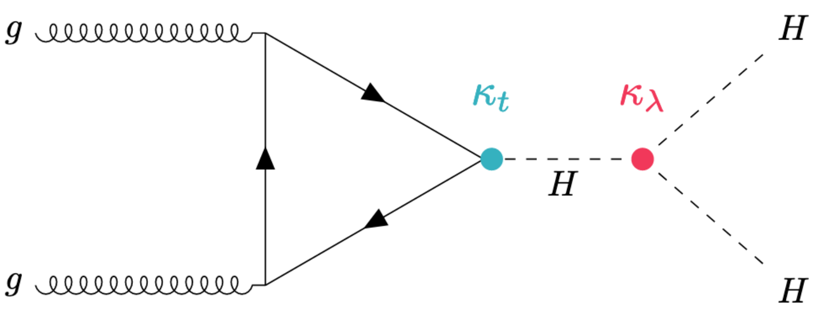
$\boldsymbol{\kappa_\lambda = 10\ (\kappa_{2V} = 1)}$

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

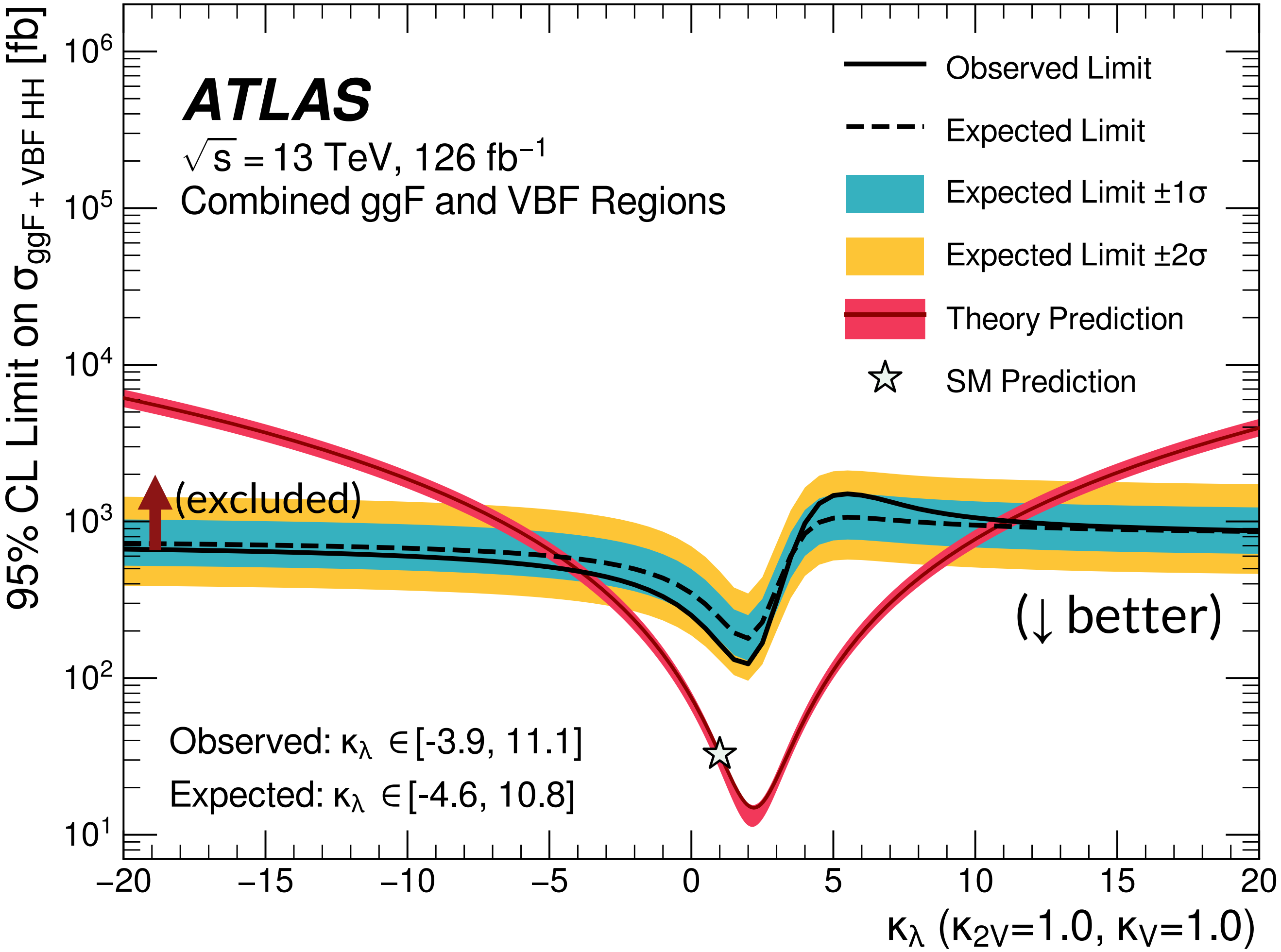
Neural-network reweighted background agrees well with **observed data**

Results - κ_λ

Constraining the *HHH* coupling

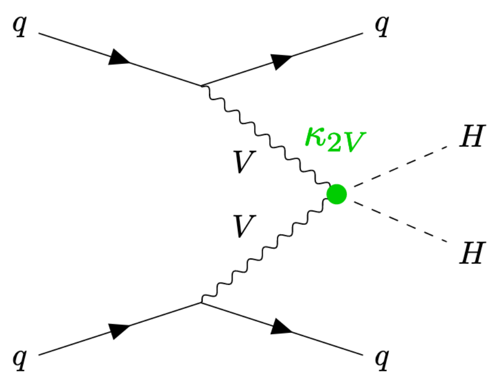


BSM softer → less sensitive

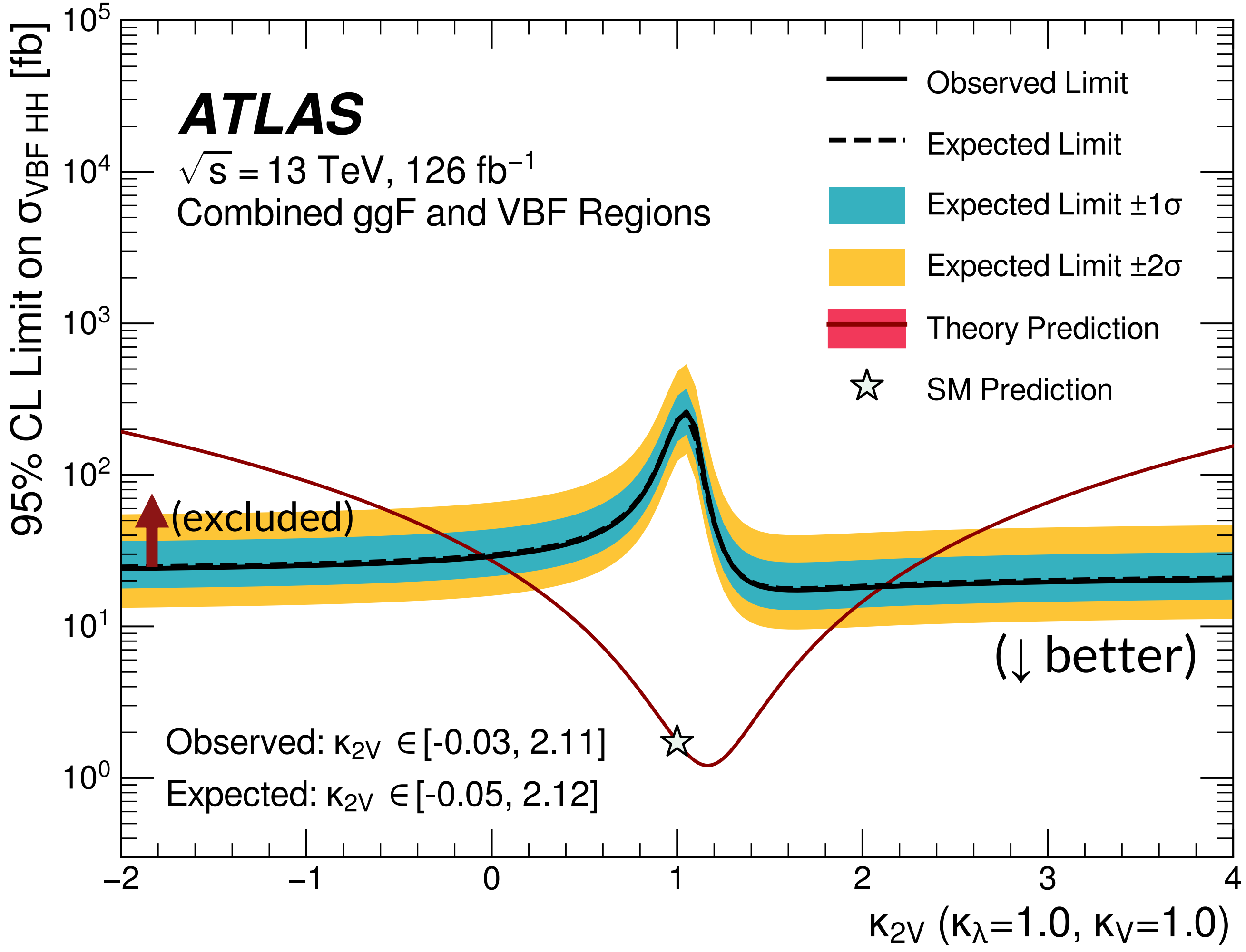


Results - κ_{2V}

Constraining the *HHVV* coupling

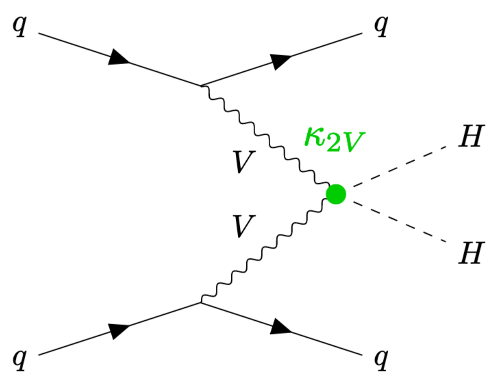


BSM harder → more sensitive



Results - κ_{2V}

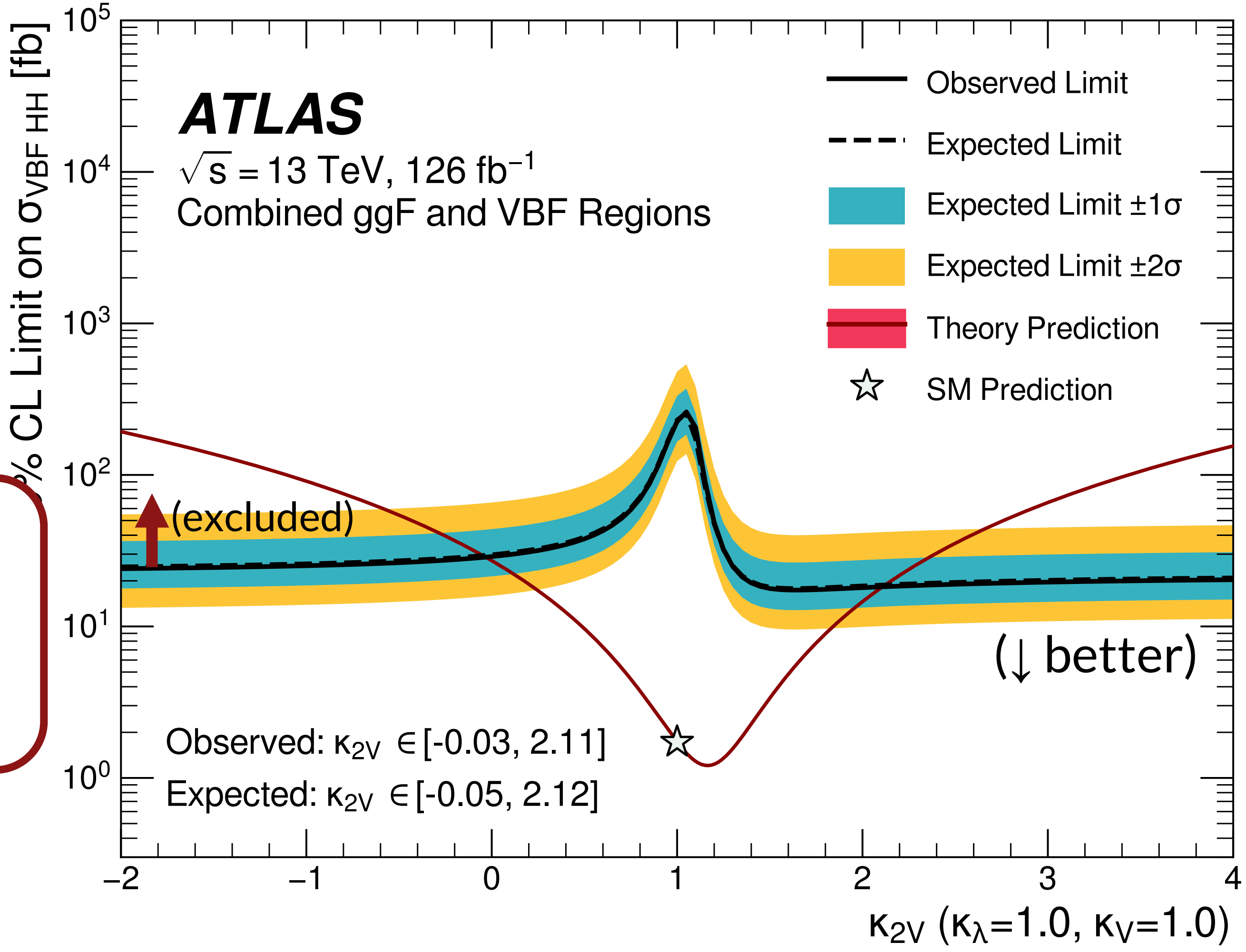
Constraining the *HHVV* coupling



Compared to previous ATLAS result:

~75% improvement on $\sigma_{\text{VBF}}^{\text{SM}}$ upper limit!
~30% improvement on allowed κ_{2V} range!

arxiv:2001.05178

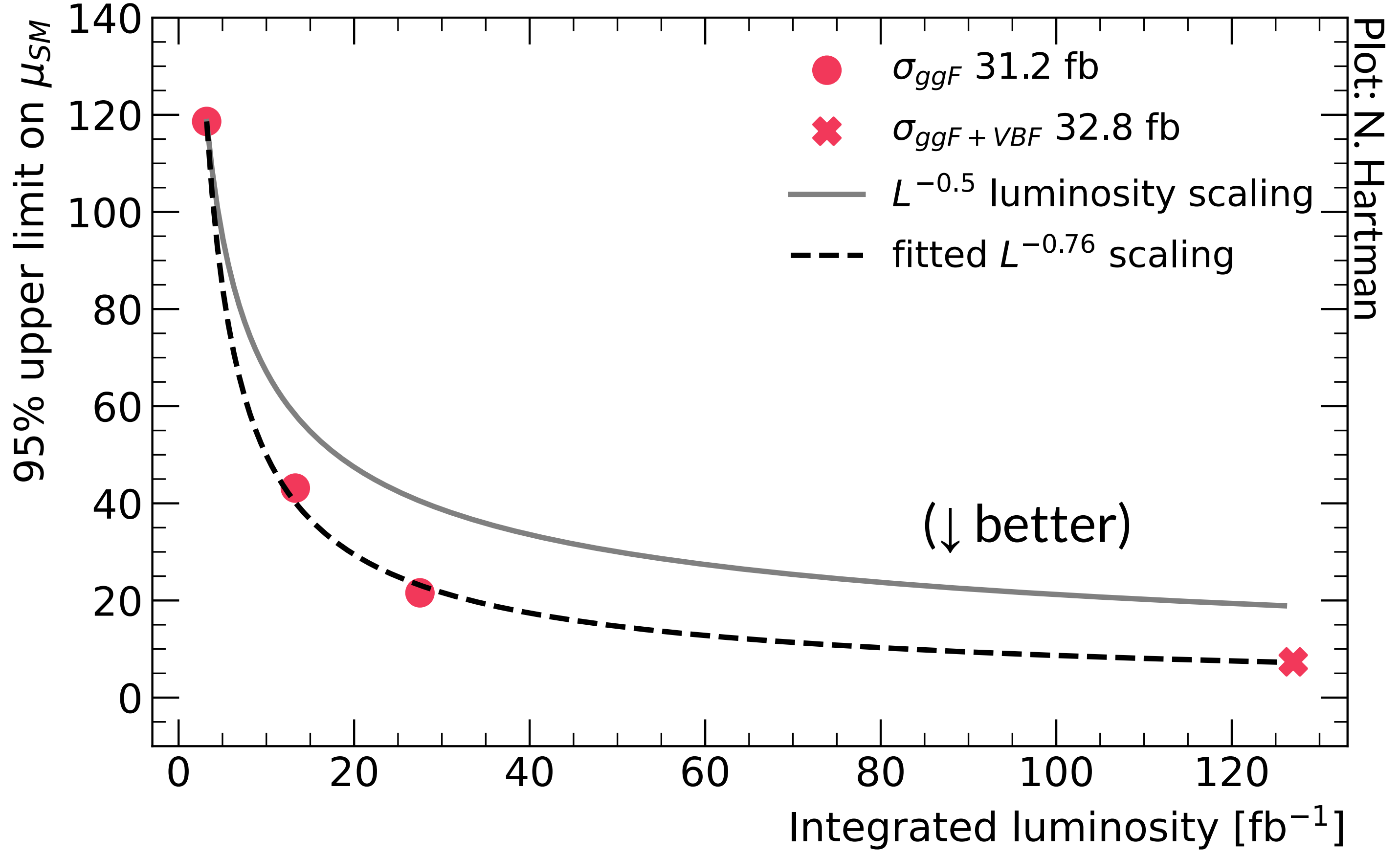


How Have We Been Improving *HH* Measurements?

More data
&
Better techniques to analyze data

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

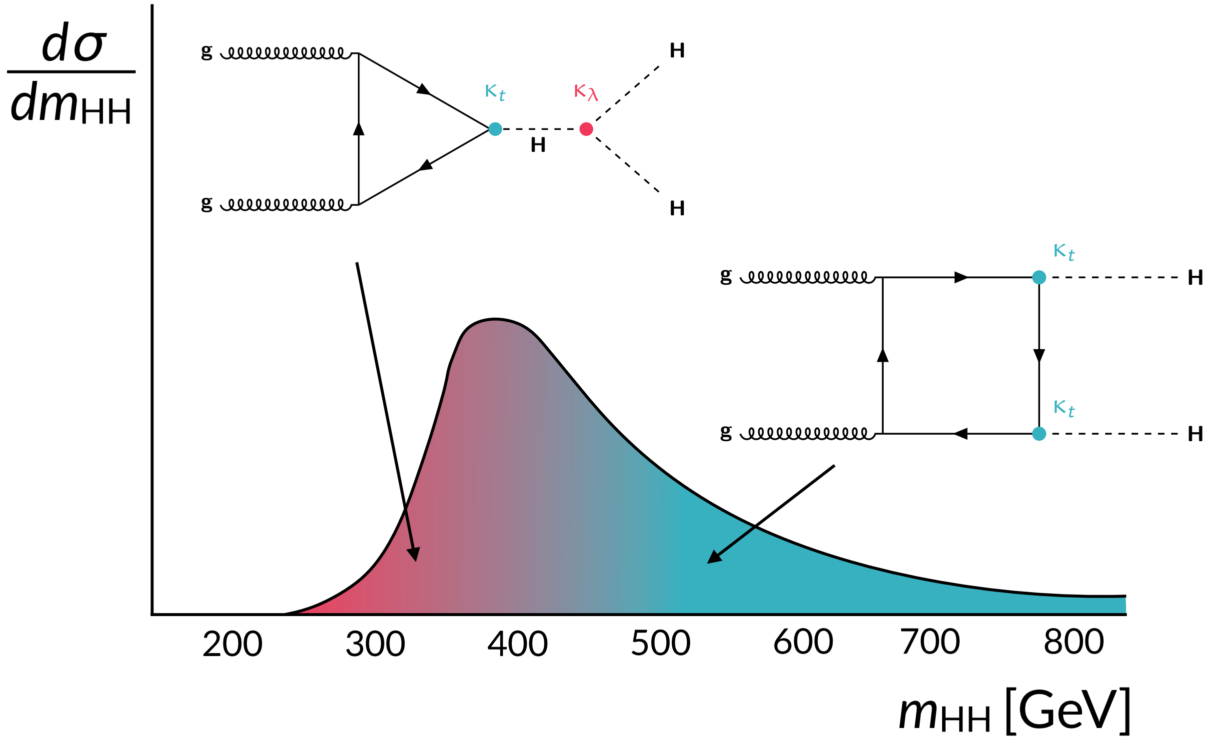
Results improving by factor of ~ $x^{-0.76}$



How does this result fit into the broader ATLAS *HH* Program?

Combination and Future Prospects

Combination: $HH \to b\bar{b}b\bar{b}, b\bar{b}\tau\tau, b\bar{b}\gamma\gamma$



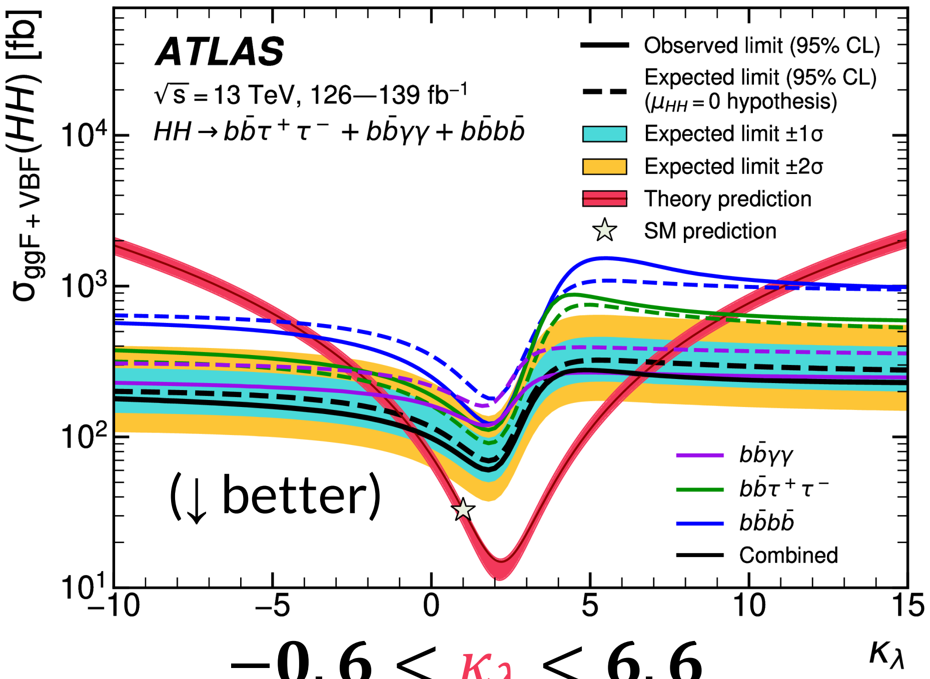
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

← $b\bar{b}\gamma\gamma$ $b\bar{b}\tau\tau$ $b\bar{b}b\bar{b}$ →

~ Sensitive region by decay channel

Combination: $HH \rightarrow b\bar{b}b\bar{b}, b\bar{b}\tau\tau, b\bar{b}\gamma\gamma$

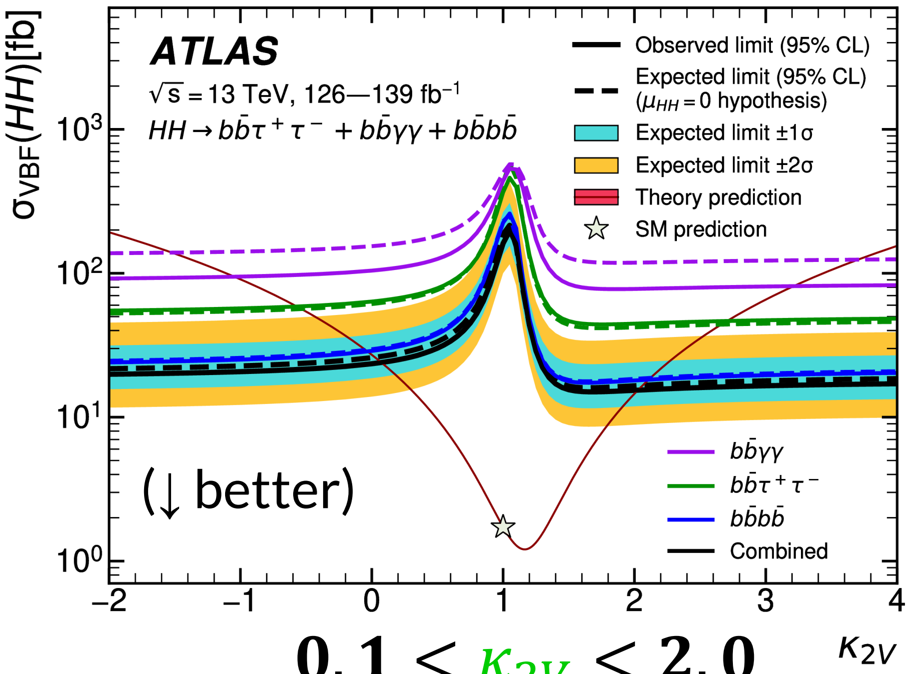
Combined Constraint on κ_λ



$-0.6 < \kappa_\lambda < 6.6$

$(-2.1 < \kappa_\lambda < 7.8)$ (Exp.)

Combined Constraint on κ_{2V}



$0.1 < \kappa_{2V} < 2.0$

$(0.0 < \kappa_{2V} < 2.1)$ (Exp.)

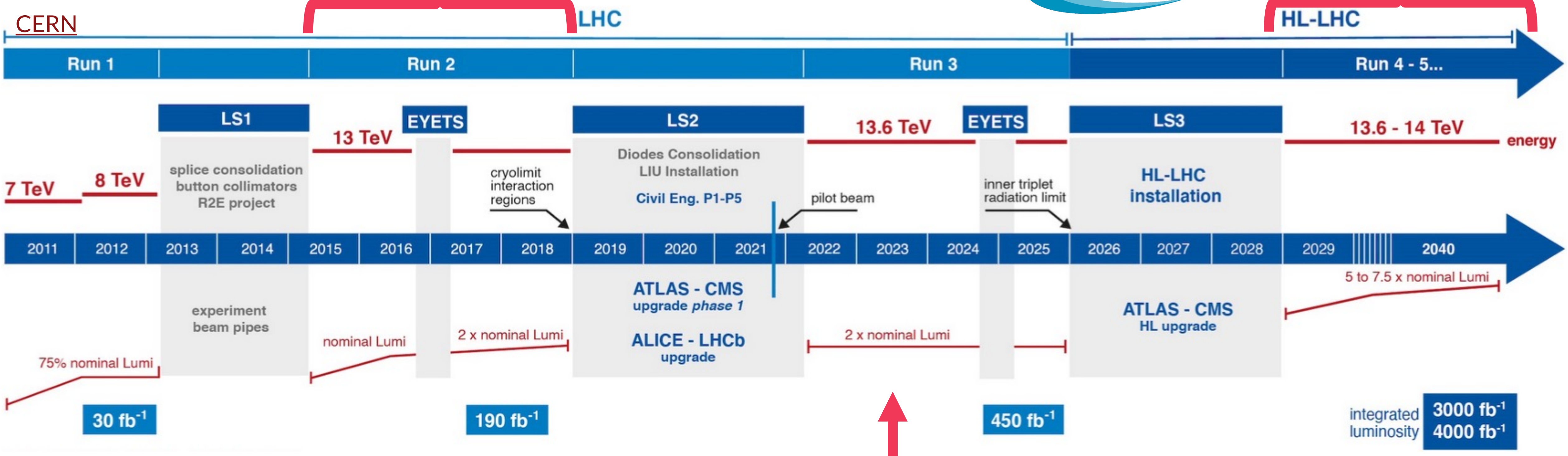
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

→ $b\bar{b}b\bar{b}$ final state less sensitive to BSM κ_λ, but most sensitive to BSM κ_{2V}

Looking to the Future: The High-Luminosity LHC

Data shown today ~ Run 2

Future: HL-LHC



Today (Run 3 Ongoing)

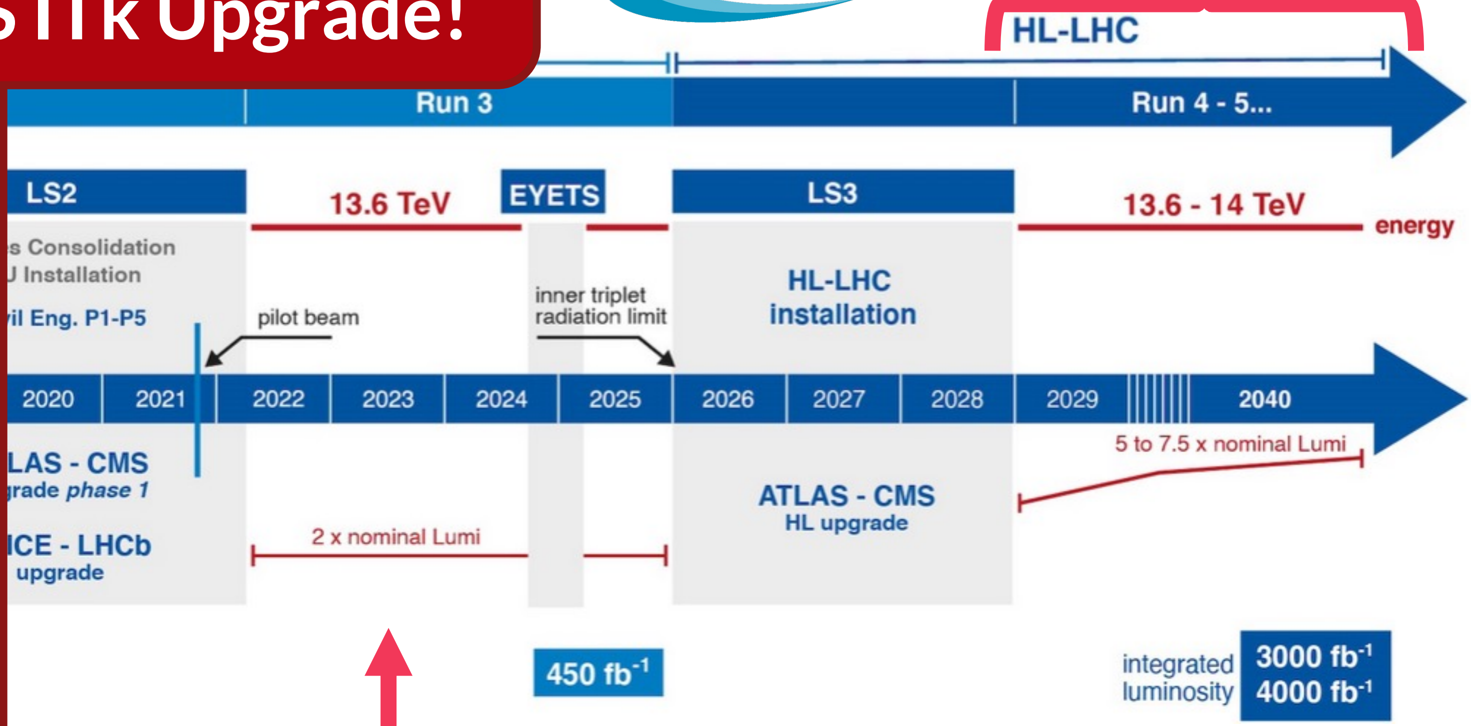
Expect ~20x more data than collected in Run 2!

Looking to the Future: The High-Luminosity LHC

Ask me about the ATLAS ITk Upgrade!

HiLumi HL-LHC PROJECT

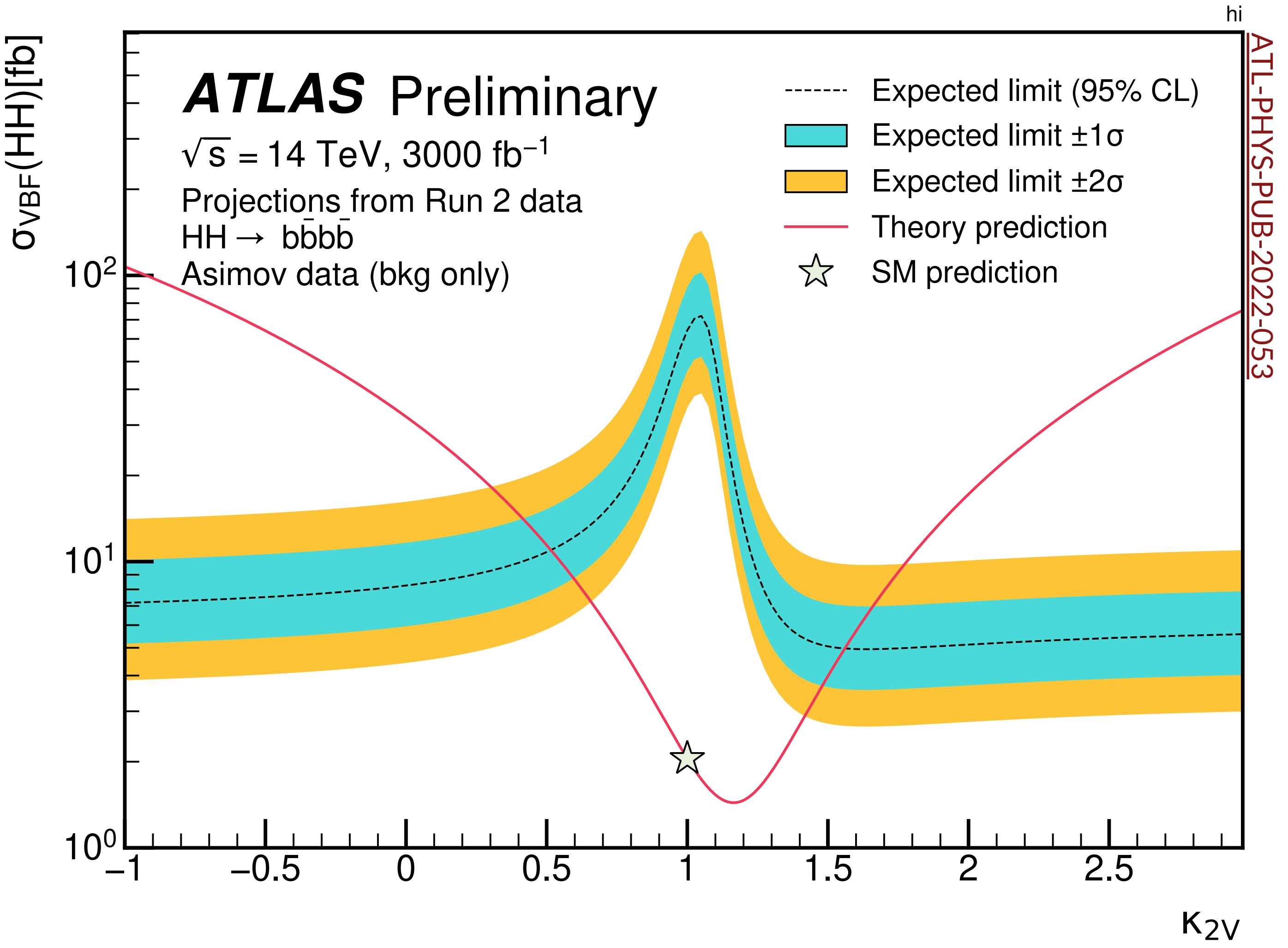
Future: HL-LHC



Today (Run 3 Ongoing)

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

HH Prospects at the High-Luminosity LHC: κ_{2V}

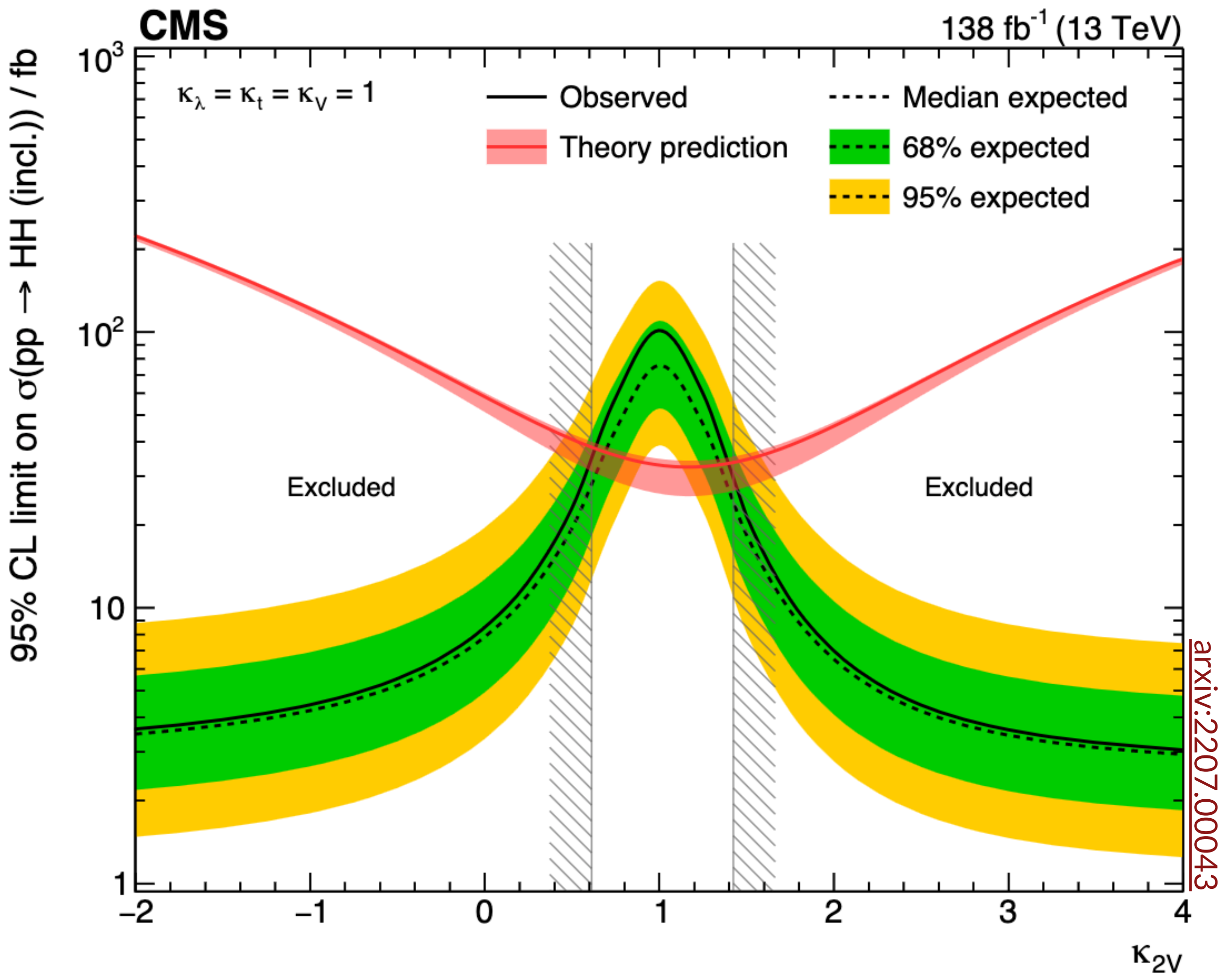


Full HL-LHC Dataset,
$HH \rightarrow b\bar{b}b\bar{b}$ only:

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

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

How is CMS Doing?

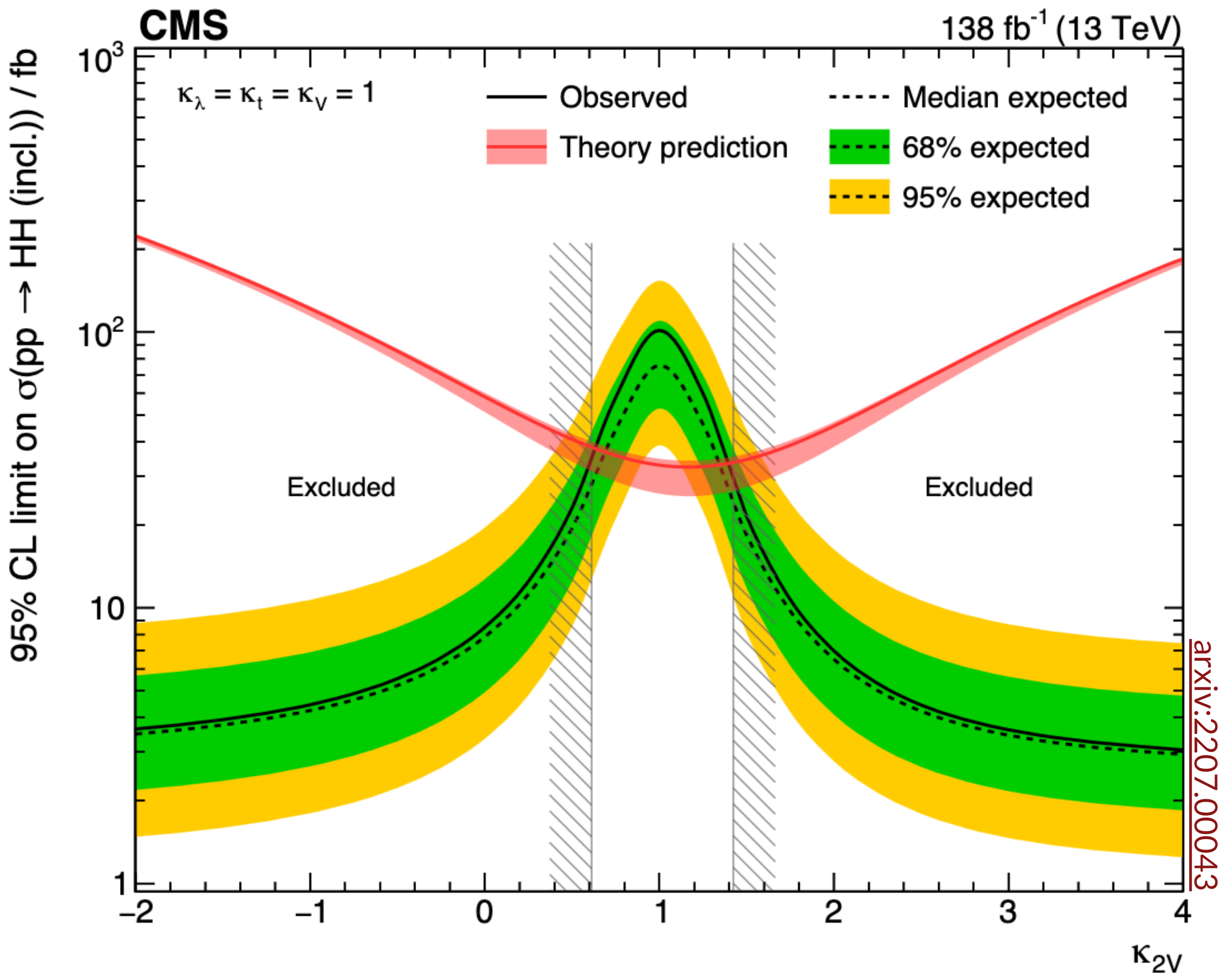


CMS *HH* Combination (Run 2):

$$\mathbf{0.67} < \kappa_{2V} < \mathbf{1.38}$$

... better than ATLAS HL-LHC Projection??

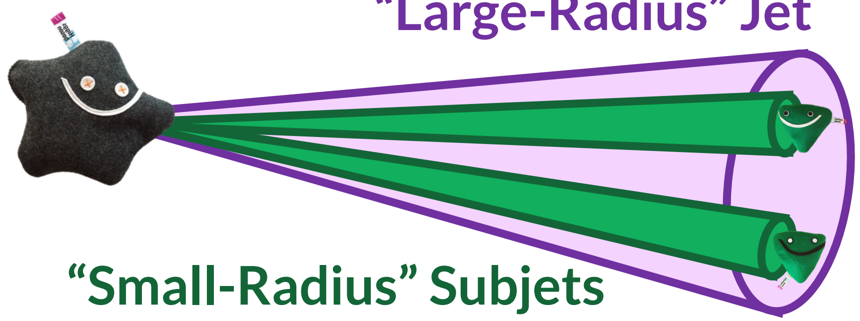
How is CMS Doing?



CMS *HH* Combination (Run 2):

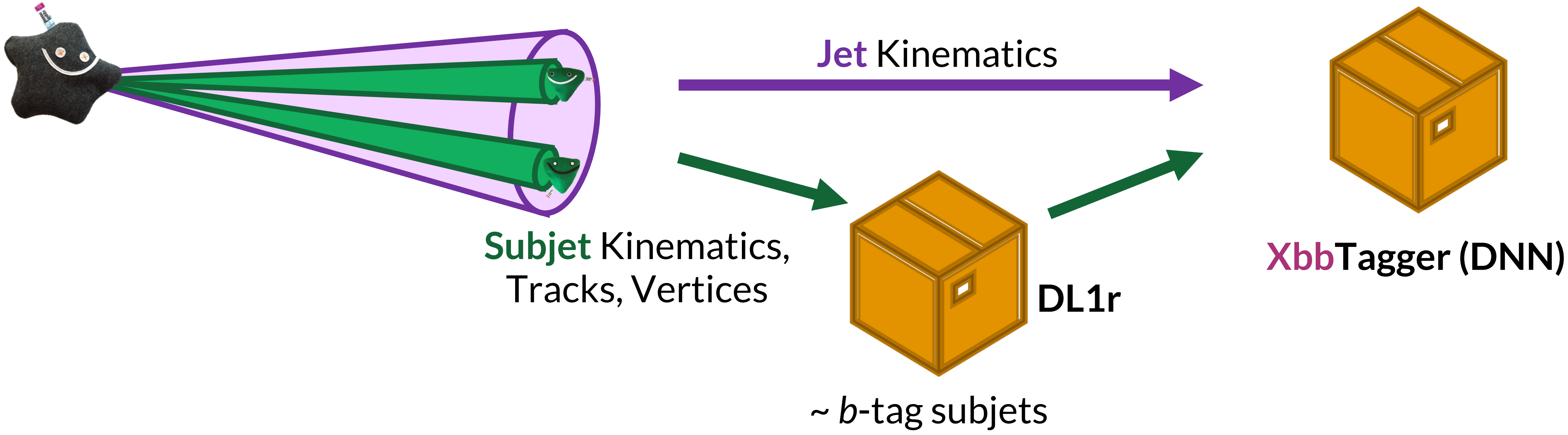
$$\mathbf{0.67} < \kappa_{2V} < \mathbf{1.38}$$

→ Driven by "boosted" $b\bar{b}b\bar{b}$ analysis!



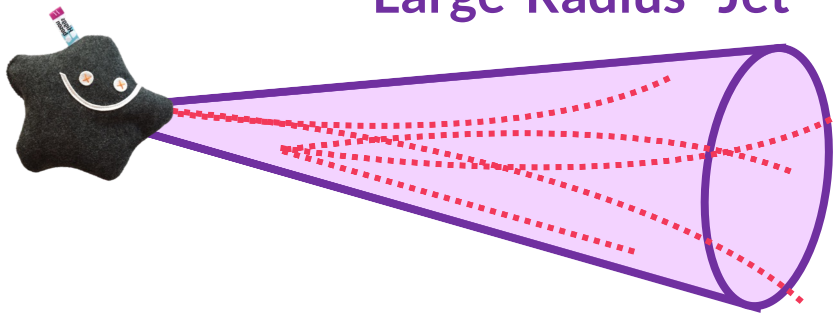
Less background at higher energy +
Dedicated ML-based $H \rightarrow b\bar{b}$ tagging

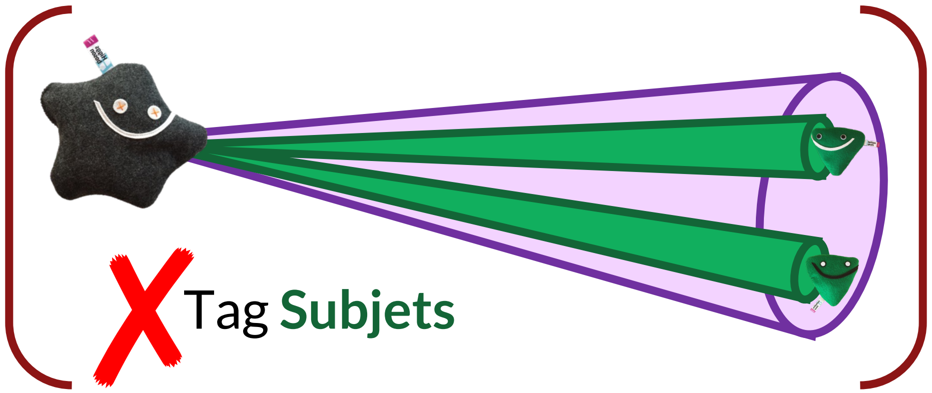
Boosted $X \to b\bar{b}$ Tagging in ATLAS



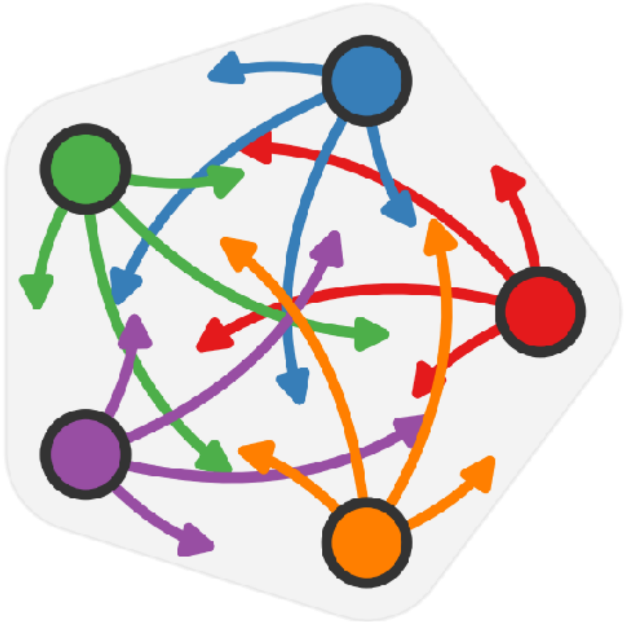
Boosted $X \rightarrow b\bar{b}$ Tagging in ATLAS

"Large-Radius" Jet





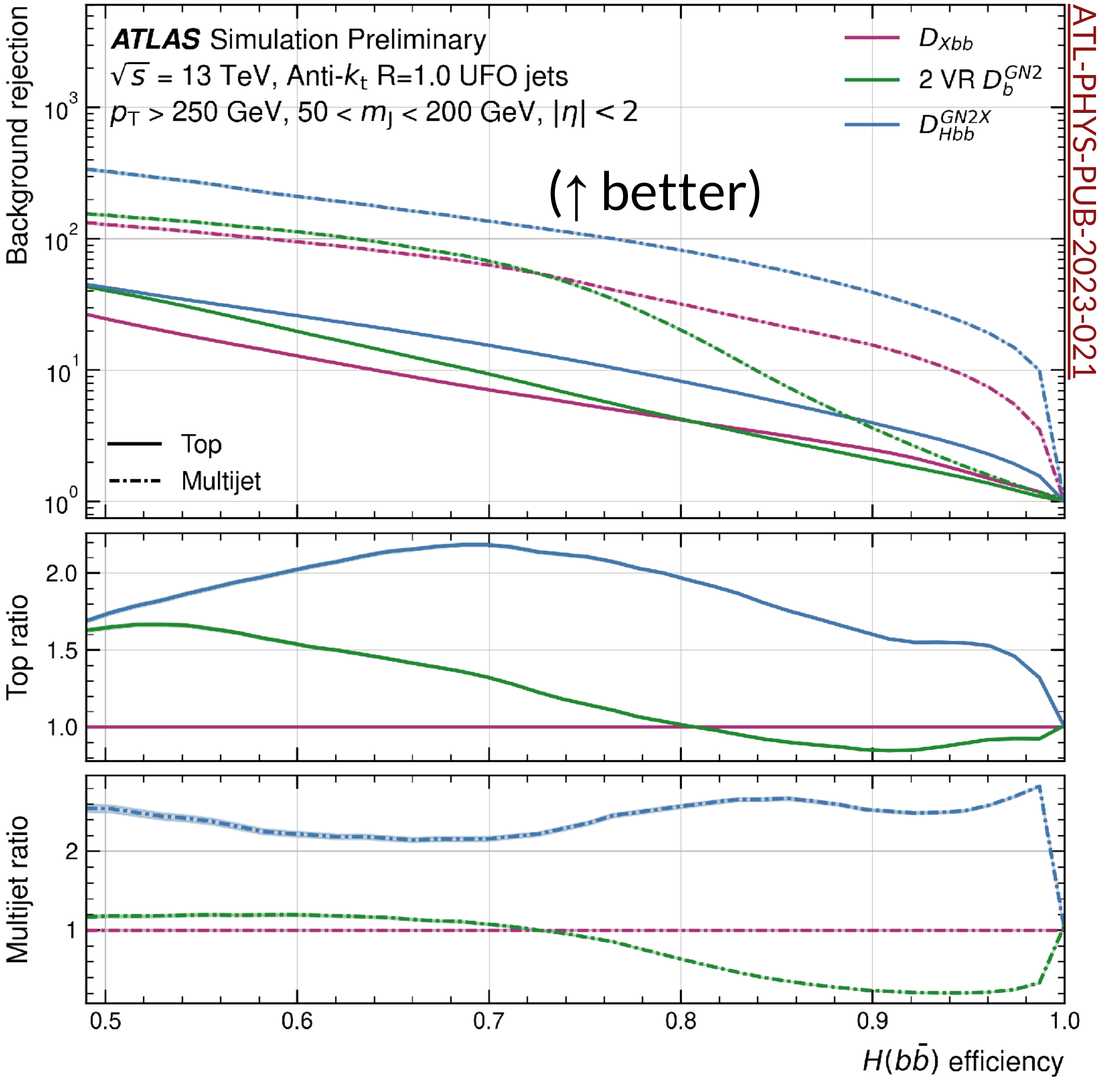
Jet Kinematics, Tracks, Vertices



GN2X Tagger
(Transformer Neural Network)

ATL-PHYS-PUB-2023-021

Boosted $b\bar{b}$ Tagging in ATLAS Today



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

Significantly more correlations accessible to **GN2X**

Enabled by new architectures (GNNs/Transformers)

Conclusions

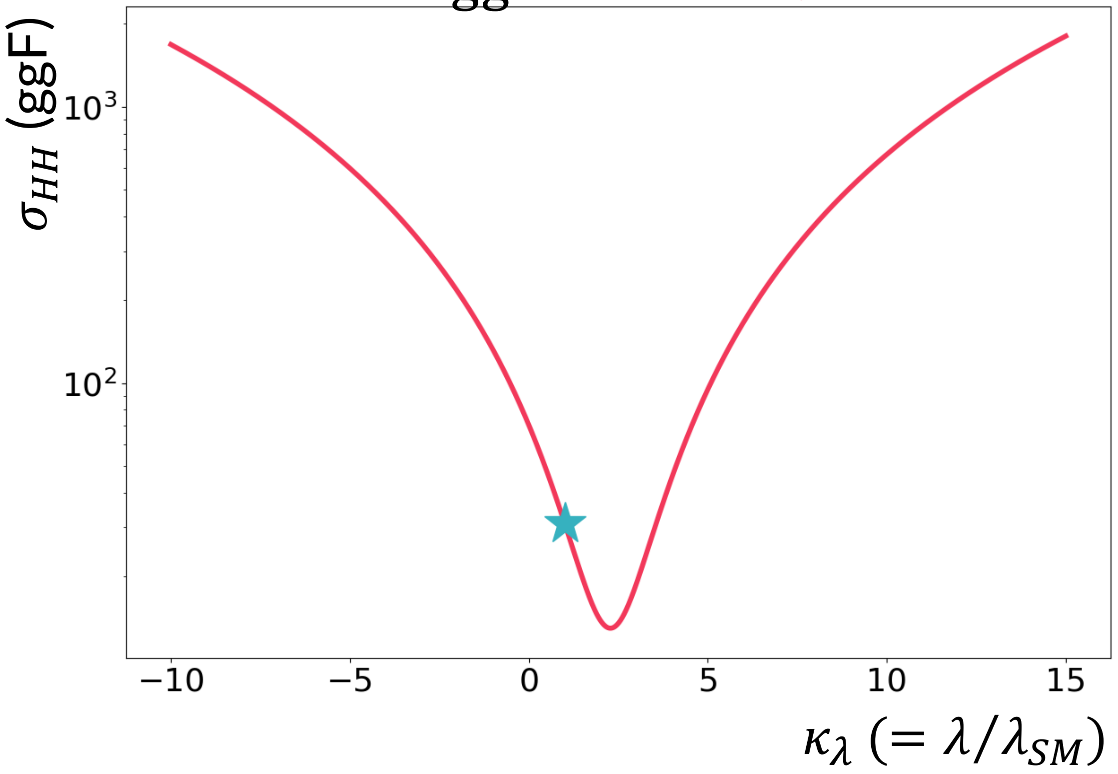
- **Measuring *HH* production probes the Higgs boson potential, which could hold the key to big question left unanswered by the Standard Model**
  - **… but, it's hard to measure!**
- **Machine learning is enabling measurements in "impossible" channels, like $b\bar{b}b\bar{b}$**
- **Clever analysis strategies will allow us to make the best use of upcoming data**

Thanks for listening!

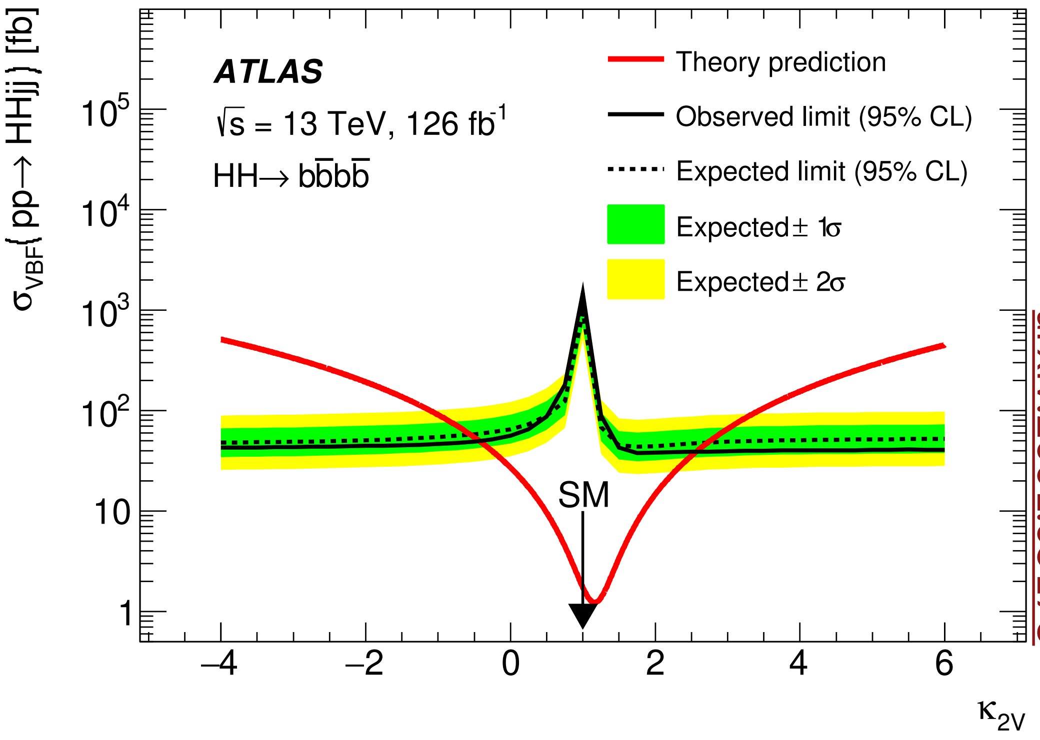
Additional Material

Sensitivity to New Physics in the *HHVV* Coupling

$\sigma_{\text{ggF}\,HH}$ vs κ_λ



$\sigma_{\text{VBF}\,HH}$ vs κ_{2V}



arxiv:2001.05178

New physics → more signal!

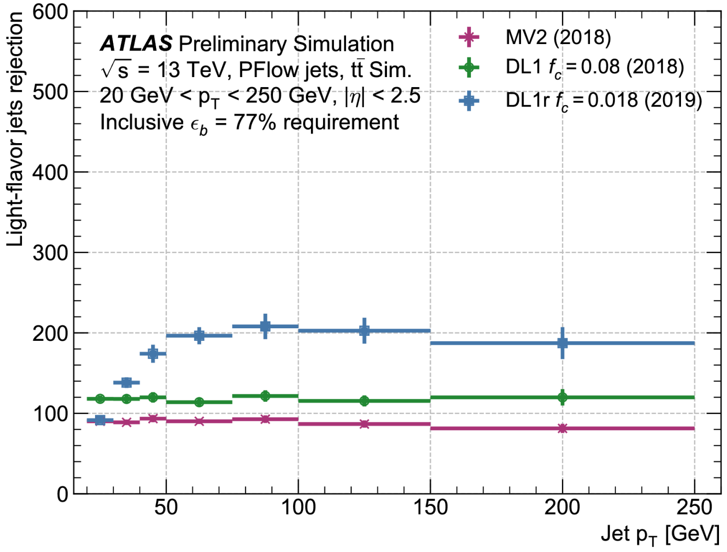
b-Tagging in ATLAS

Improving ATLAS analyses through Machine Learning-based object identification

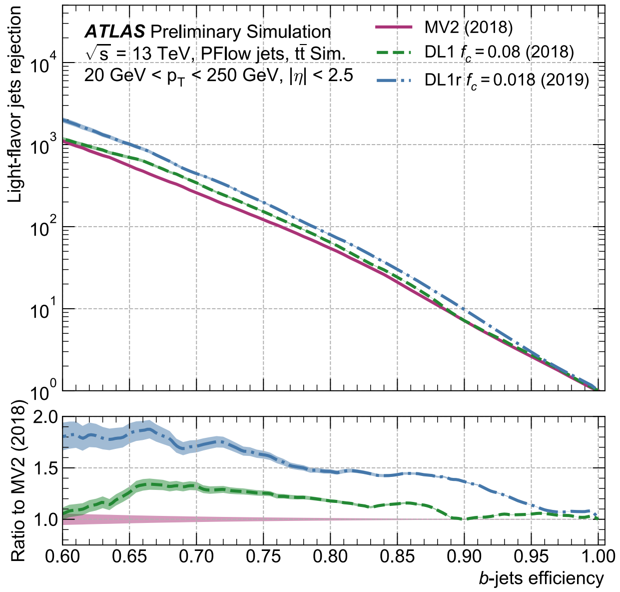
MV2C10: Boosted Decision Tree

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

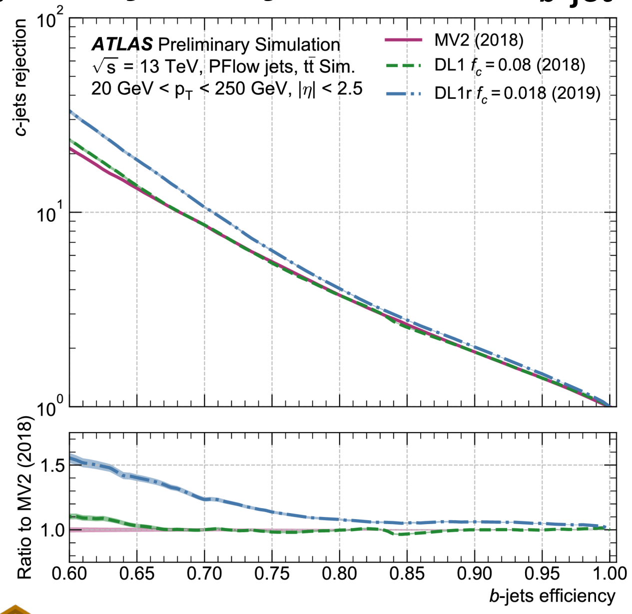
Light jet Rejection vs. p_T



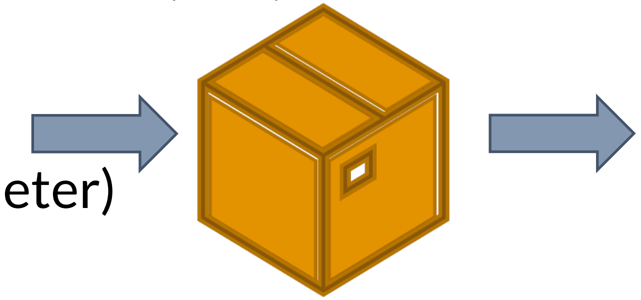
Light jet Rejection vs. $\epsilon_{b\text{-jet}}$



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

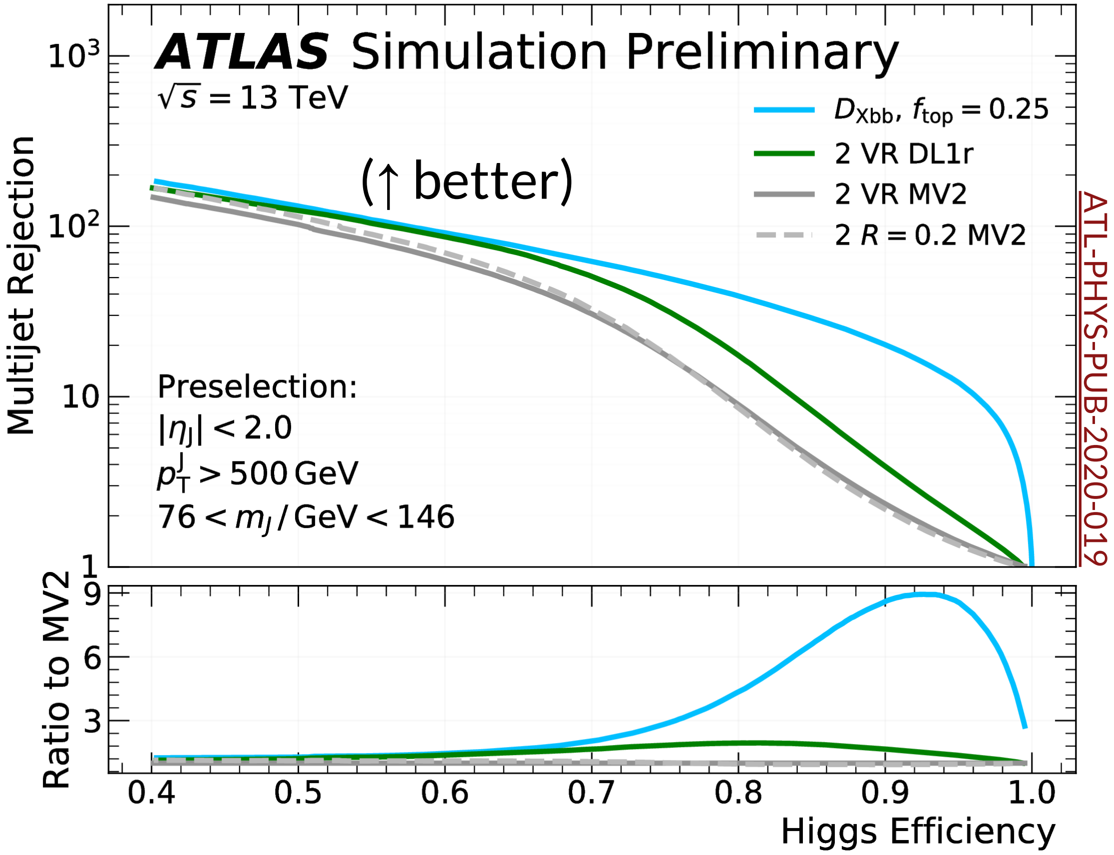


RNNIP (Recurrent NN)
JetFitter (Kalman Filter)
IP2D/IP3D (Impact Parameter)
SV1 (Secondary Vertex)



DL1r Score

The Evolution of Boosted $b\bar{b}$ Tagging in ATLAS



Unlike **subjet tagging**, **Xbb tagger** accounts for *correlations* between subjets

Jet Inputs (Kinematics)

Subjet Inputs (Tracks + Vertices)

Low-Level Algorithms: Utilize Impact Parameter, Secondary Vertices, Reconstructed B decay

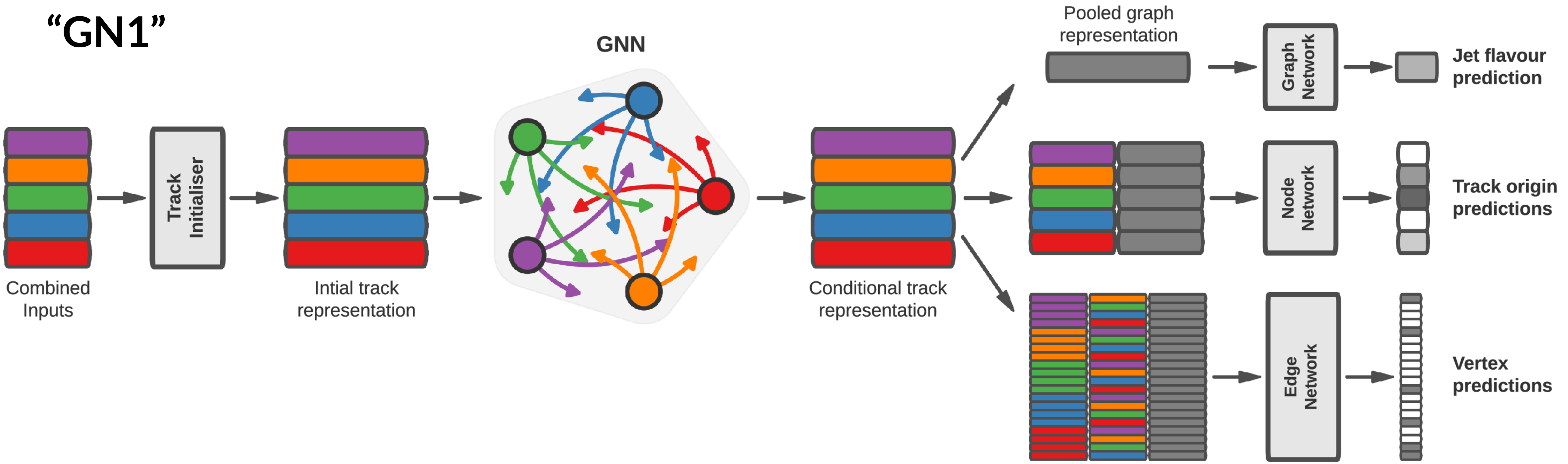
High-Level Algorithms: Utilize Outputs from Low-Level Algorithms

ML!

Xbb Tagger (Neural Network)

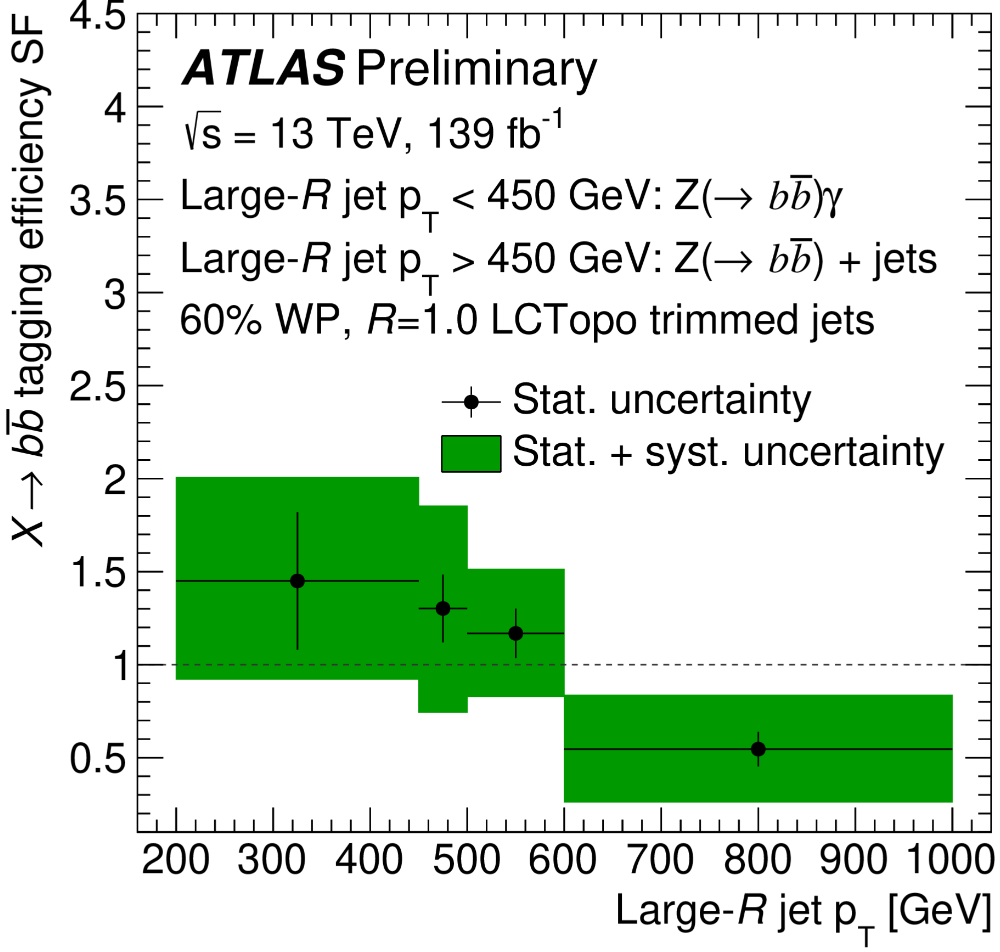
More ML!

GN1 Architecture



Performance is not the End of the Story

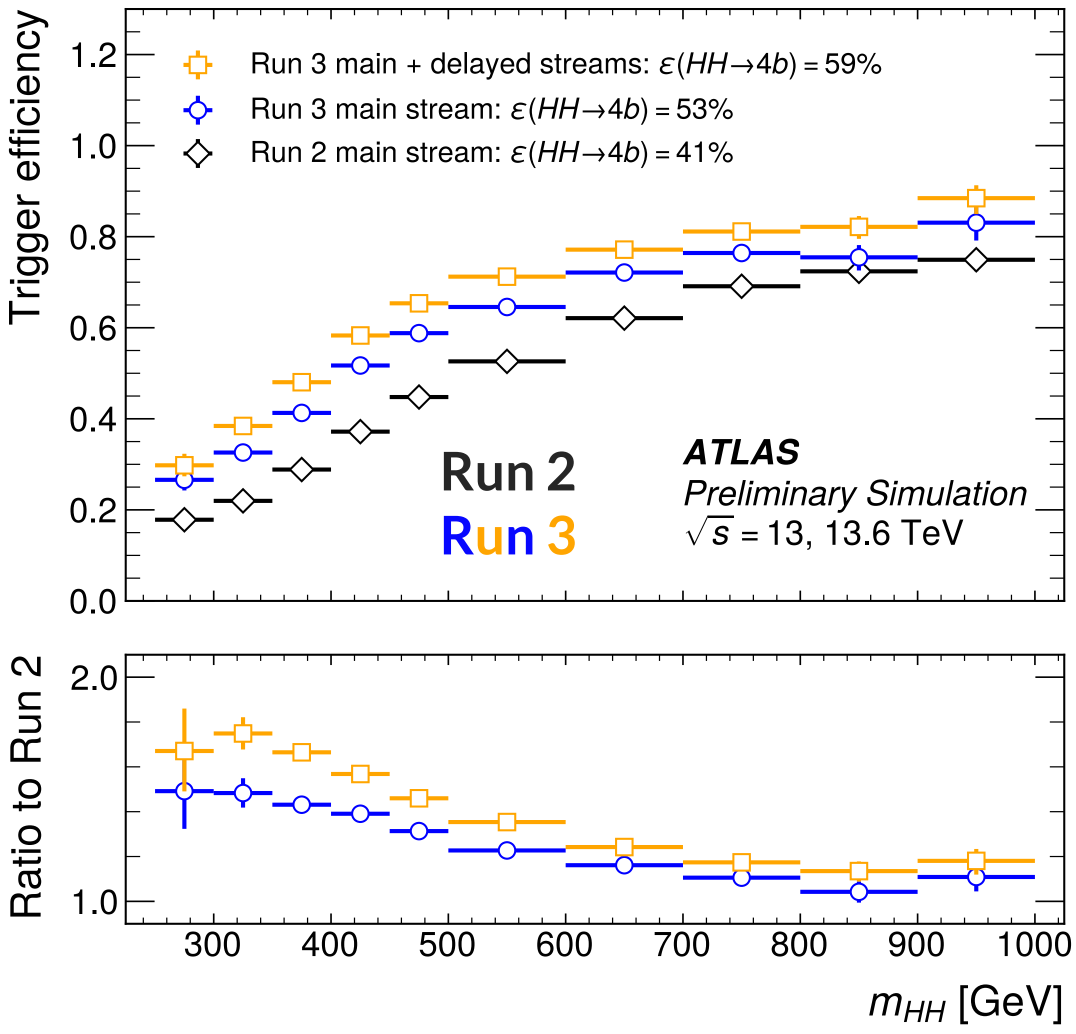
Xbb Tagger: Signal $\frac{\epsilon_{\text{Data}}}{\epsilon_{\text{Simulation}}}$



$\mathcal{O}$(30%) uncertainty on the selection efficiency of $H \to b\bar{b}$ signal events by the Xbb tagger

Precise calibration critical for the future of GN2X!

Trigger Efficiency for ggF $HH \to b\bar{b}b\bar{b}$ Events



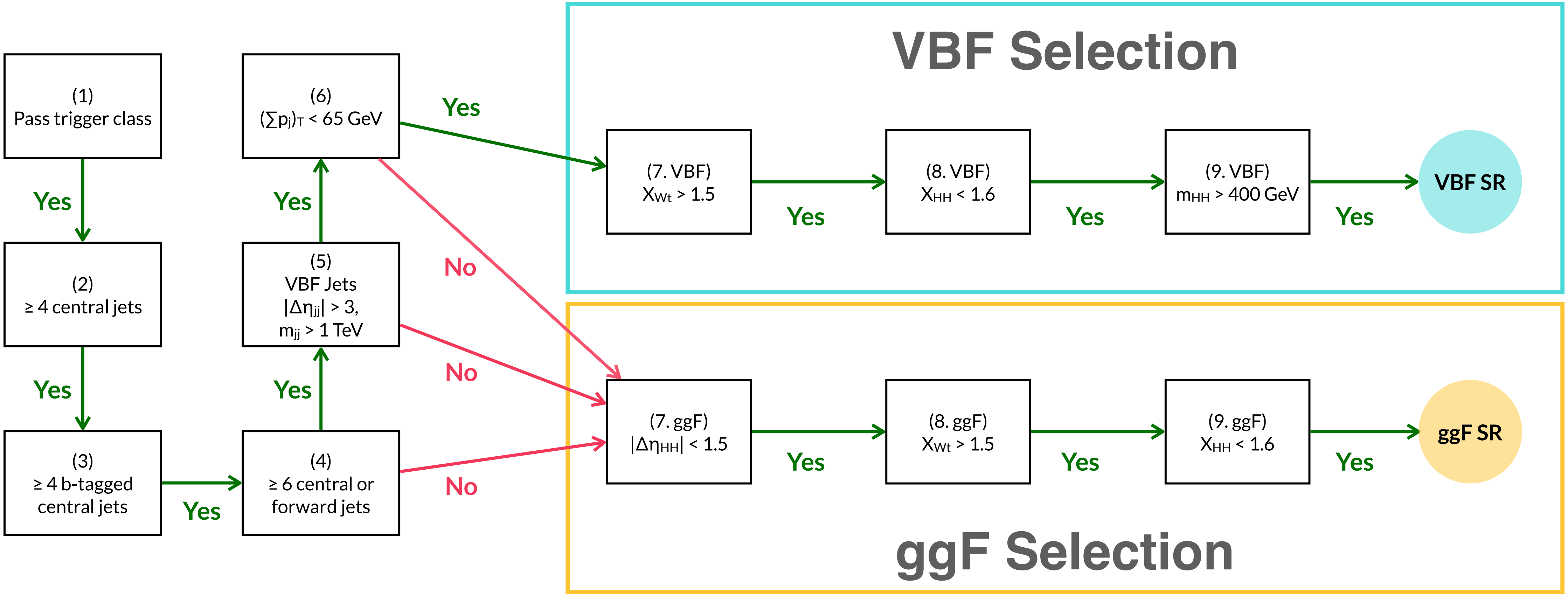
Combination of Triggers (Run 2):

- 2 b-jet + 1 jet
- 2 b-jet + 2 jet

Run 3:
"Asymmetric" requirements on jet p_T

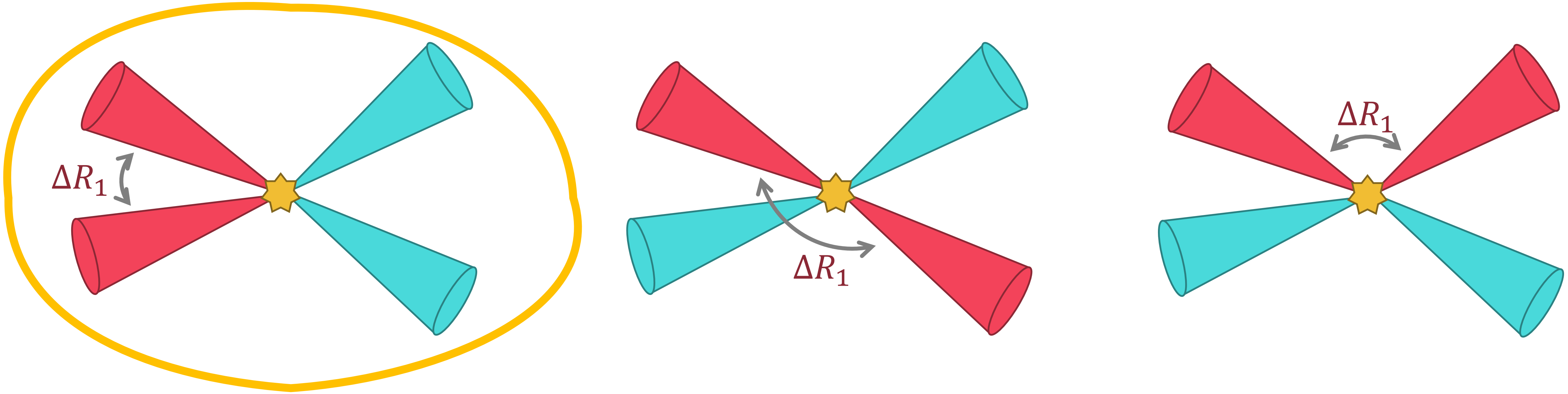
Full Analysis Selection

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

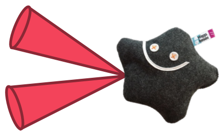


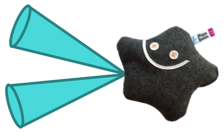
"Pairing" Higgs Bosons

Combinatorics: three possible pairings given four *b*-tagged jets



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


"Leading" Reconstructed Higgs Boson

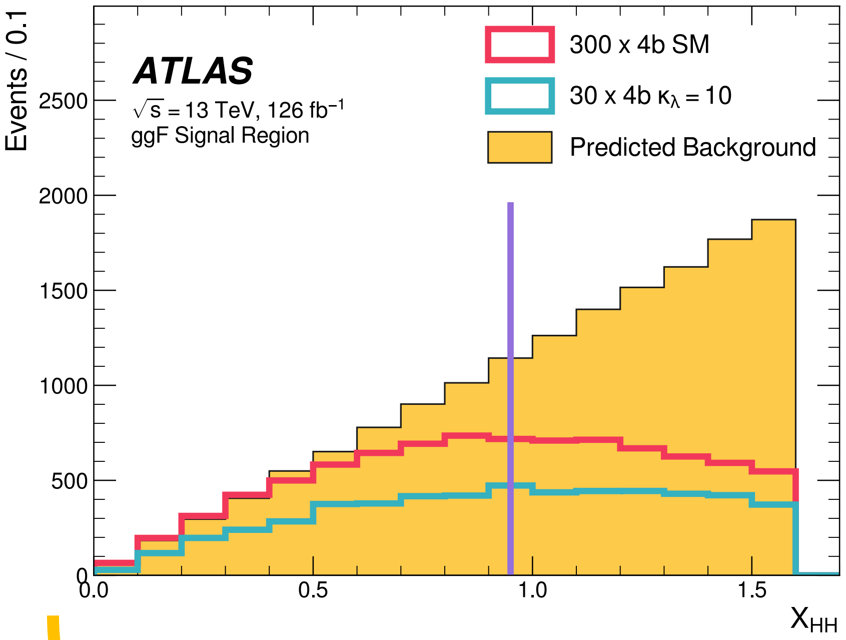

"Subleading" Reconstructed Higgs Boson

Categorization

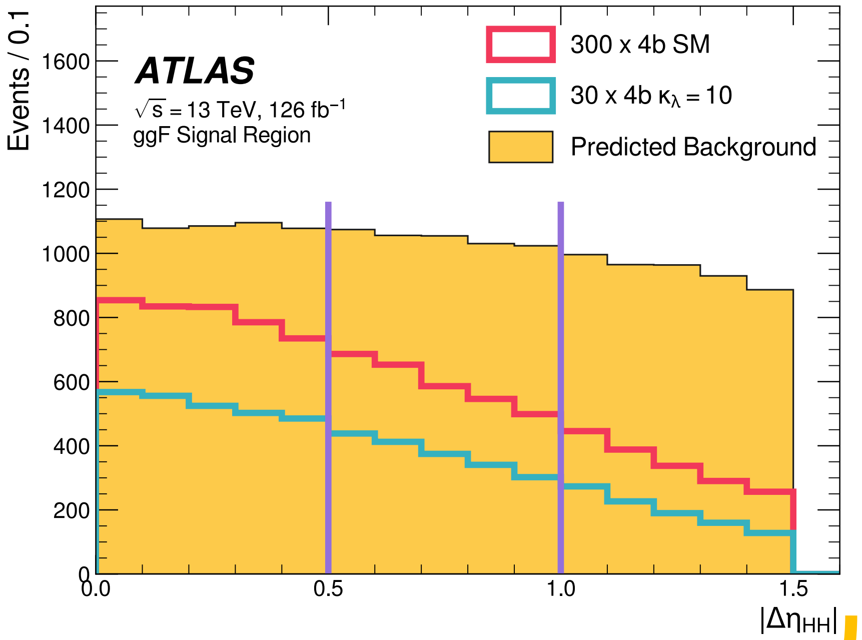
Isolate different physics ($\kappa_\lambda, \kappa_{2V}$) scenarios

Standard Model ($\kappa_\lambda = \kappa_{2V} = 1$)
$\kappa_\lambda = 10$ ($\kappa_{2V} = 1$)
$\kappa_{2V} = 0$ ($\kappa_\lambda = 1$)

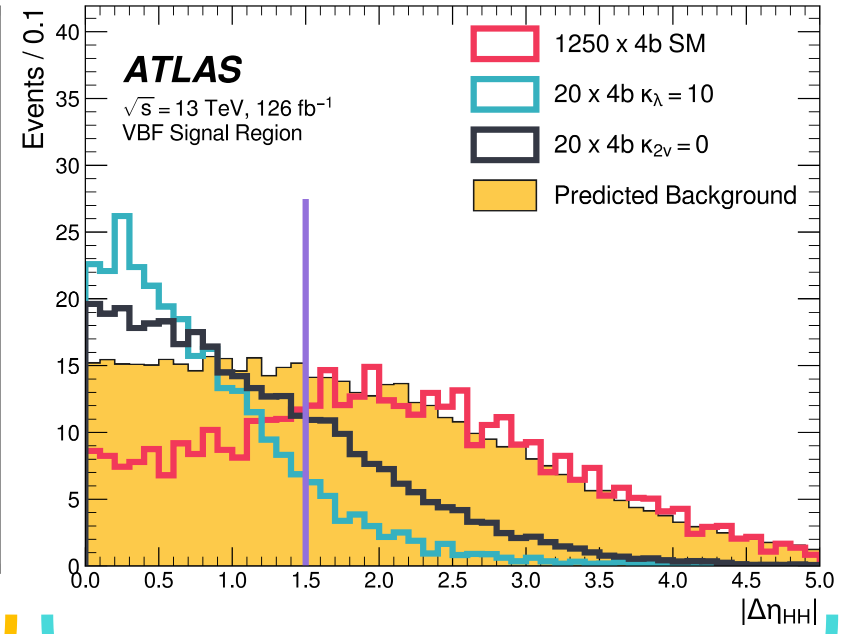
X_{HH}



$|\Delta\eta_{HH}|$

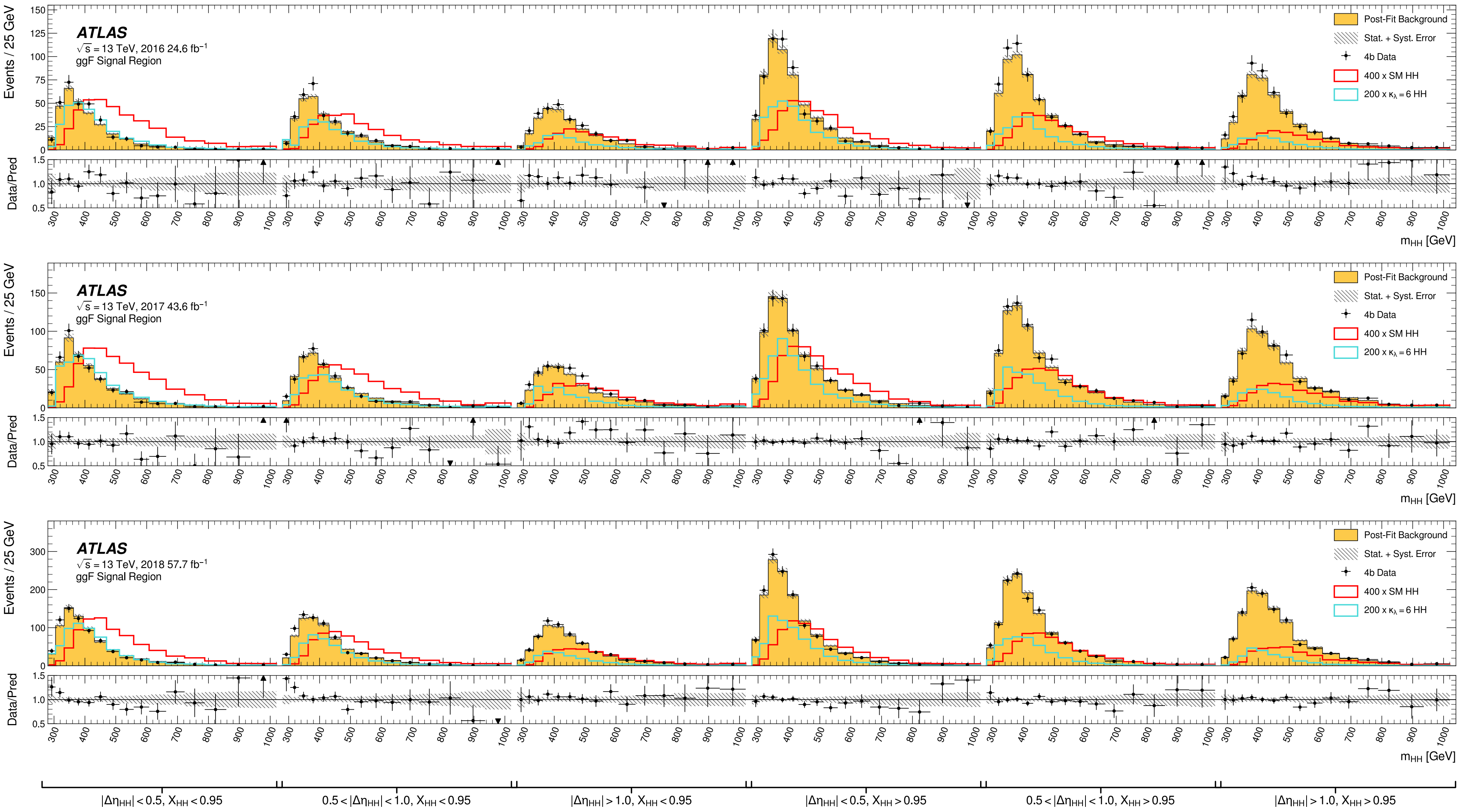


$|\Delta\eta_{HH}|$

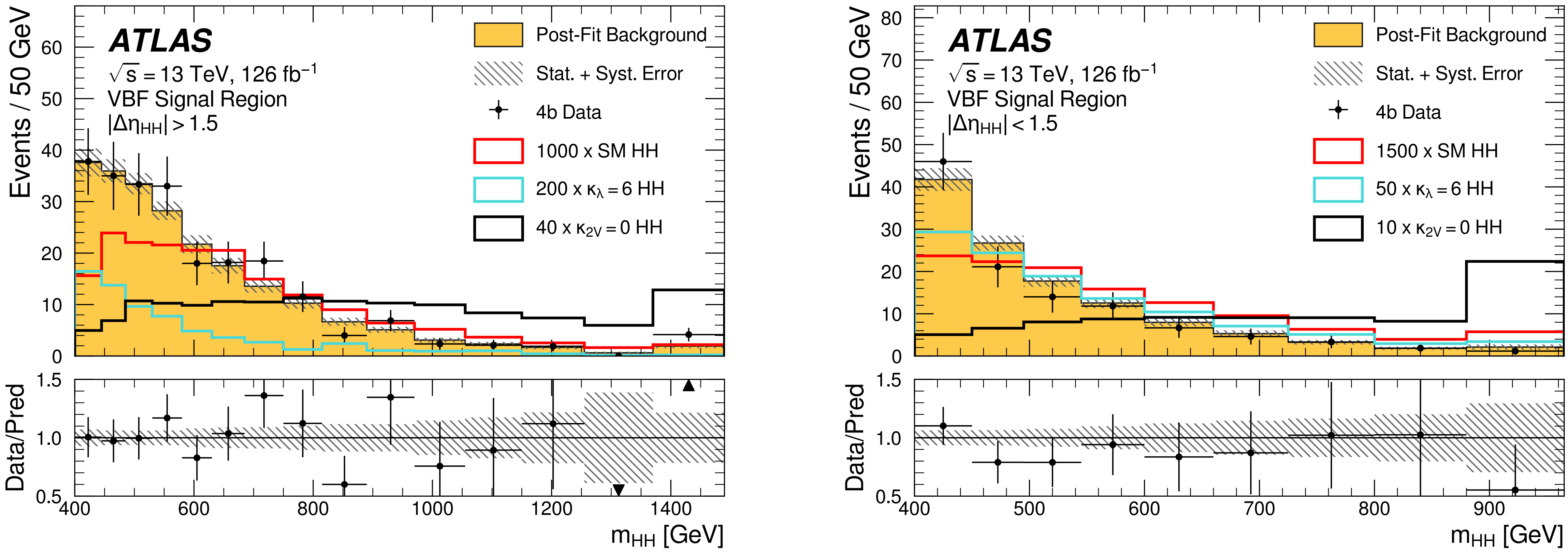


ggF **VBF**

Observed m_{HH} Distributions in ggF Categories

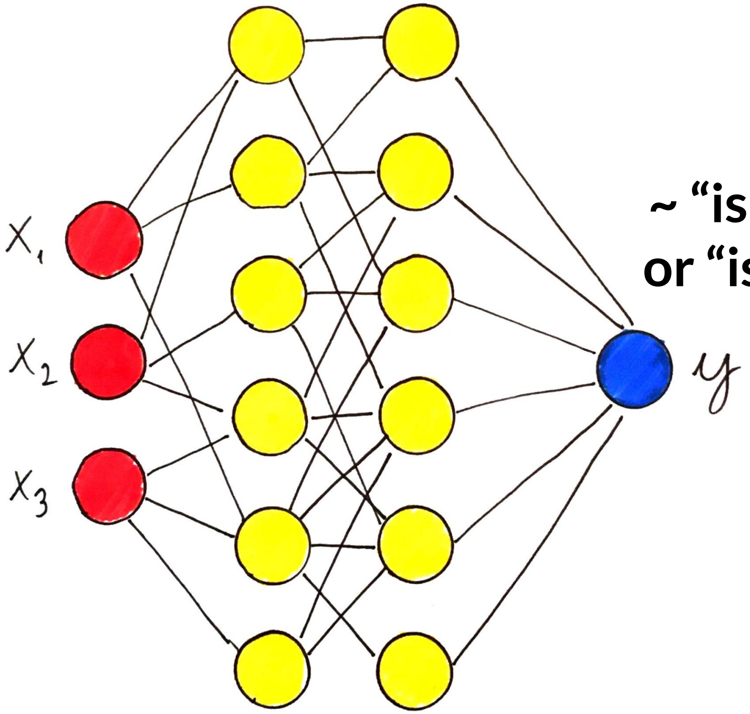


Observed m_{HH} Distributions in VBF Categories



Neural Networks for Density Estimation

Event Features



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

towardsdatascience.com

(Lemma) best discriminator between two classes:

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

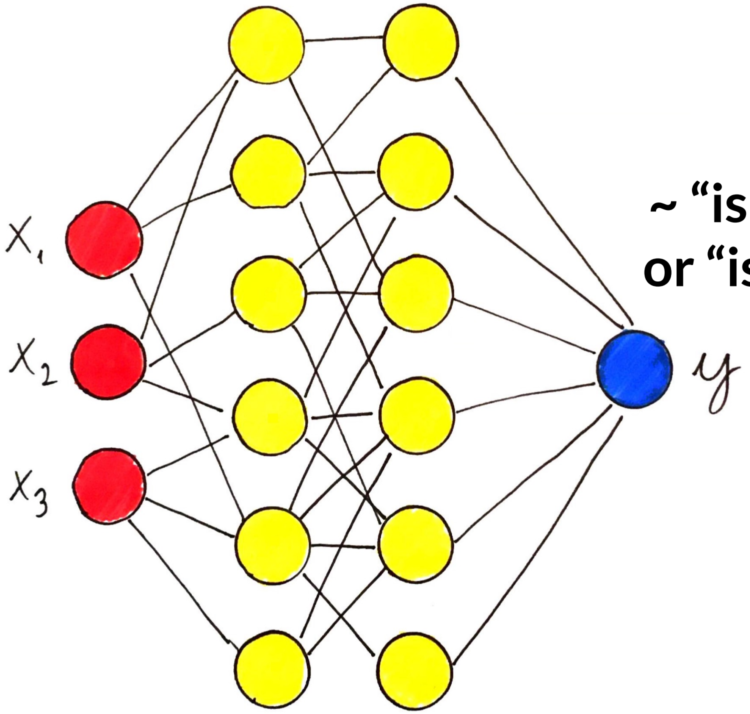
NNs classify data well → approximate λ

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

→ a classification NN can approximate the density ratio!

Neural Networks for Density Estimation

Event Features



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

towardsdatascience.com

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

Train NN with specific Loss function:

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

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

"Event-level" reweighting!

arxiv:1911.00405
Kanamori et. al. (JMLR)

Reweighting Neural Network – Details

Architecture and Input Variables

3 Densely-Connected Hidden Layers (50 Nodes Each)

Single-Node Output

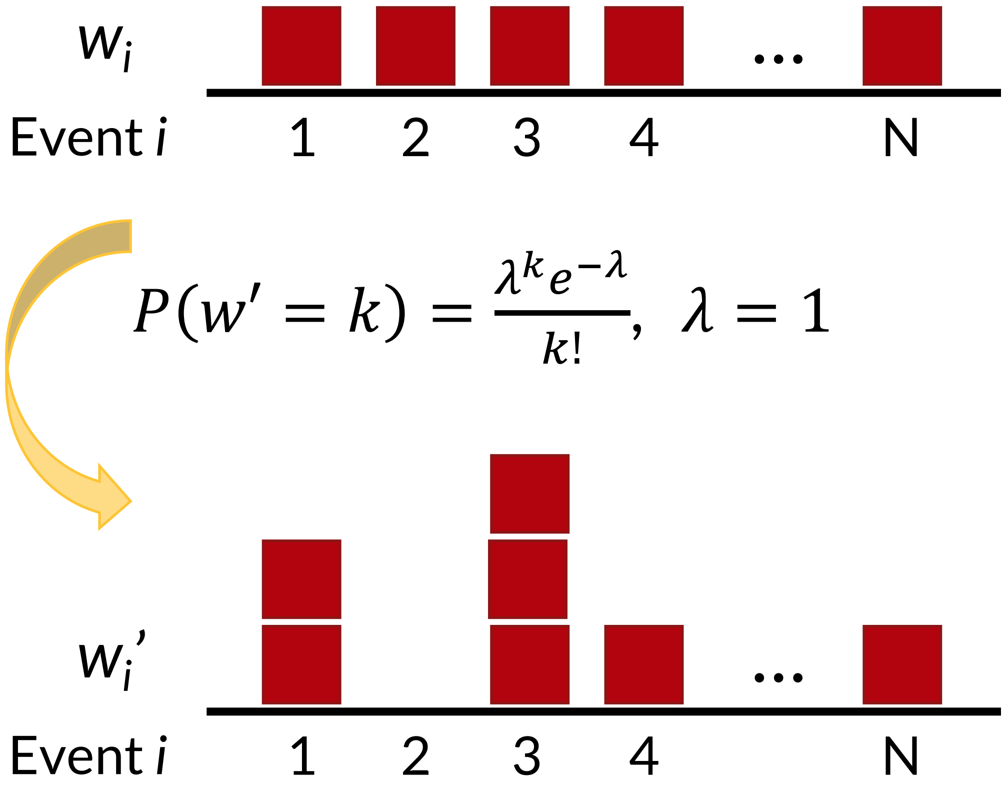
ggF	VBF
1. $\log(p_{\mathrm{T}})$ of the 2^{nd} leading Higgs boson candidate jet 2. $\log(p_{\mathrm{T}})$ of the 4^{th} leading Higgs boson candidate jet 3. $\log(\Delta R)$ between the closest two Higgs boson candidate jets 4. $\log(\Delta R)$ between the other two Higgs boson candidate jets 5. Average absolute η value of the Higgs boson candidate jets 6. $\log(p_{\mathrm{T}})$ of the di-Higgs system 7. ΔR between the two Higgs boson candidates 8. $\Delta\phi$ between jets in the leading Higgs boson candidate 9. $\Delta\phi$ between jets in the subleading Higgs boson candidate 10. $\log(X_{Wt})$ 11. Number of jets in the event 12. Trigger class index as one-hot encoder	1. Maximum dijet mass from the possible pairings of the four Higgs boson candidate jets 2. Minimum dijet mass from the possible pairings of the four Higgs boson candidate jets 3. Energy of the leading Higgs boson candidate 4. Energy of the subleading Higgs boson candidate 5. Second-smallest ΔR between the jets in the leading Higgs boson candidate (from the three possible pairings for the leading Higgs candidate) 6. Average absolute η value of the four Higgs boson candidate jets 7. $\log(X_{Wt})$ 8. Trigger class index as one-hot encoder 9. Year index as one-hot encoder (for years inclusive training)

3 Densely-Connected Hidden Layers (20 Nodes Each)

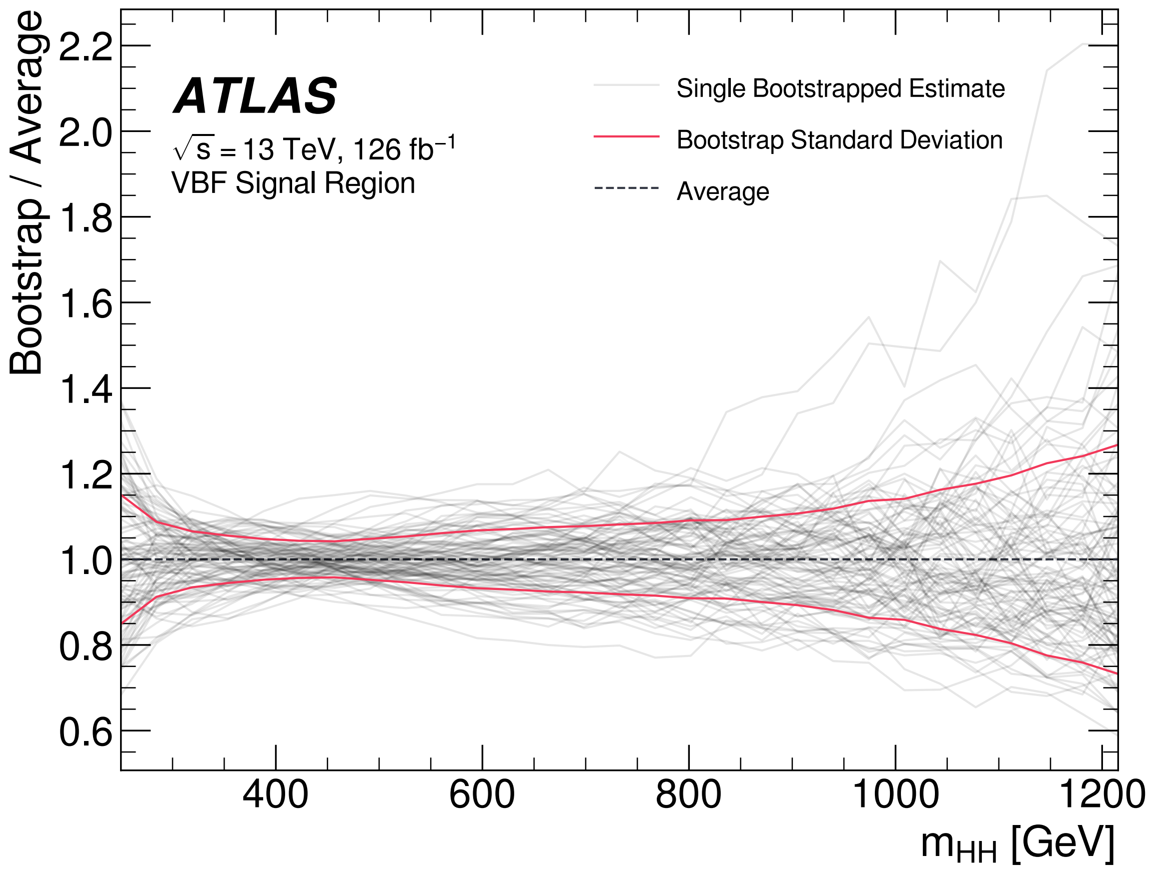
Single-Node Output

Background Modeling – Uncertainties

Bootstrap Uncertainty – quantifying "noise" in the neural network training



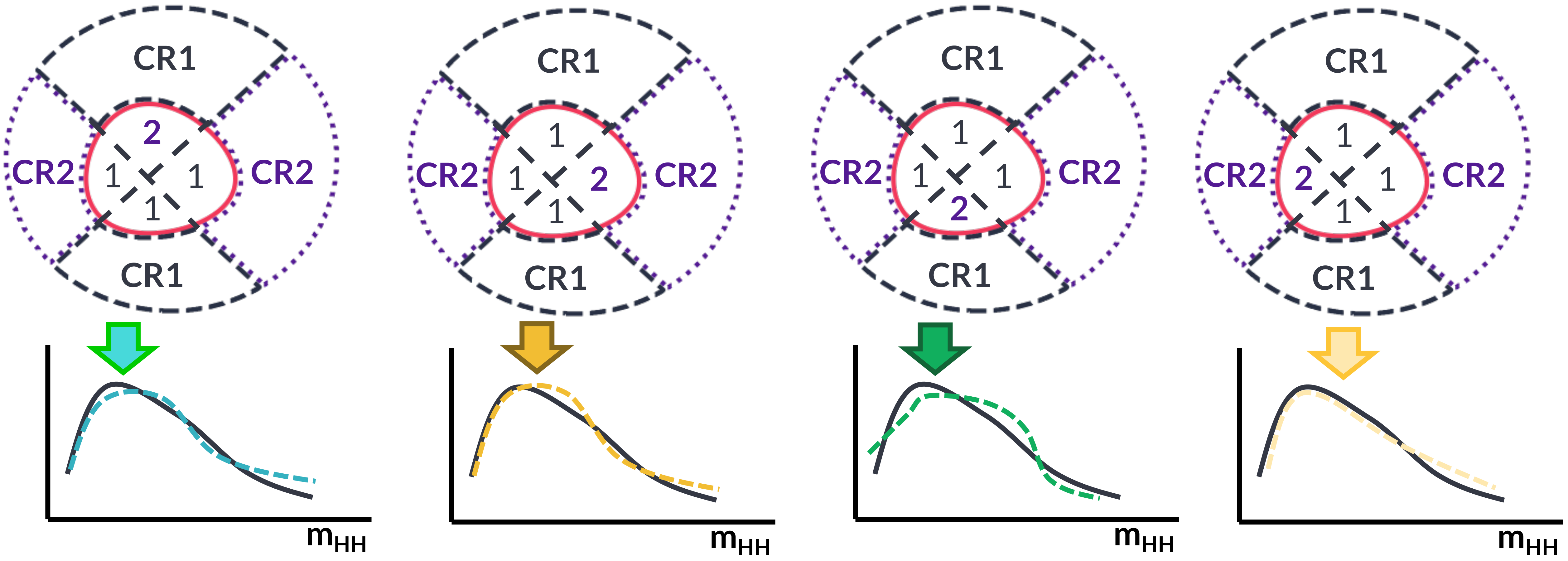
$$P(w' = k) = \frac{\lambda^k e^{-\lambda}}{k!}, \;\; \lambda = 1$$



Background Modeling

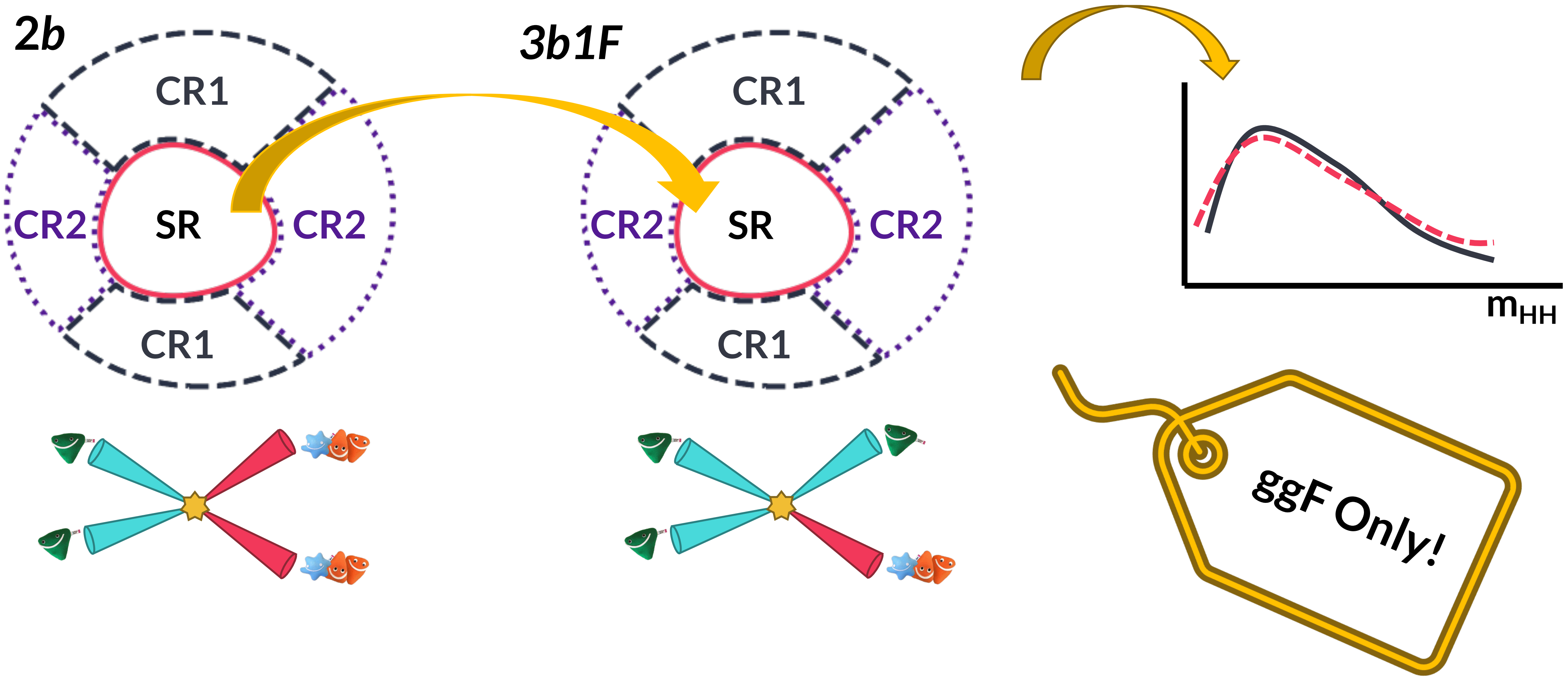
"Shape" Uncertainty – quantifying variations across the mass plane

Alternative Training in CR2 for each SR "Quadrant"



Background Modeling

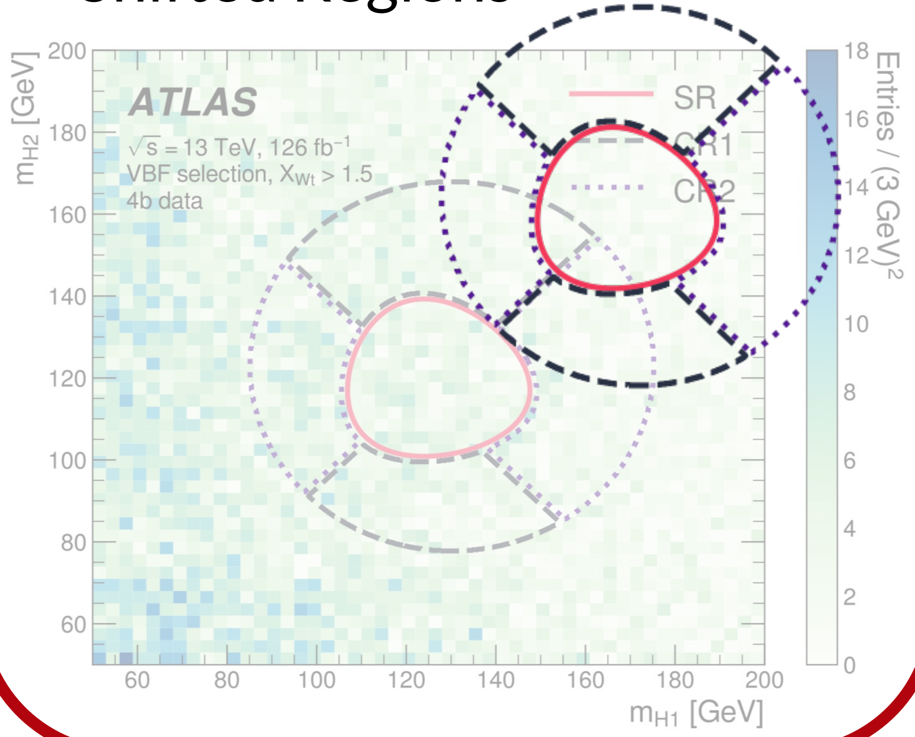
"Non-closure" Uncertainty – testing the background modeling in an orthogonal dataset



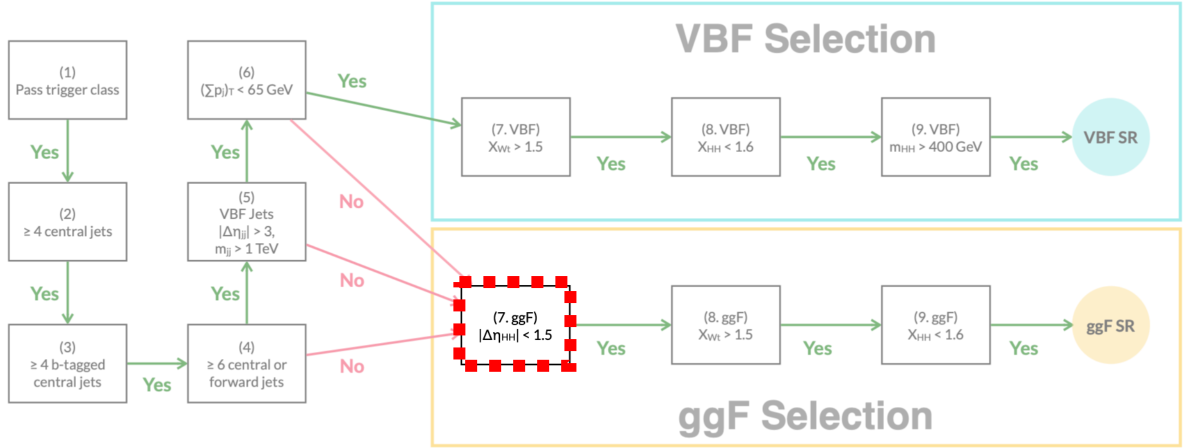
Other Background Modeling Checks

Further validating the procedure

"Shifted Regions"



"Reverse $|\Delta\eta_{HH}|$"



Simulated $t\bar{t}$ and multiple-b-jet events

ggF Only!

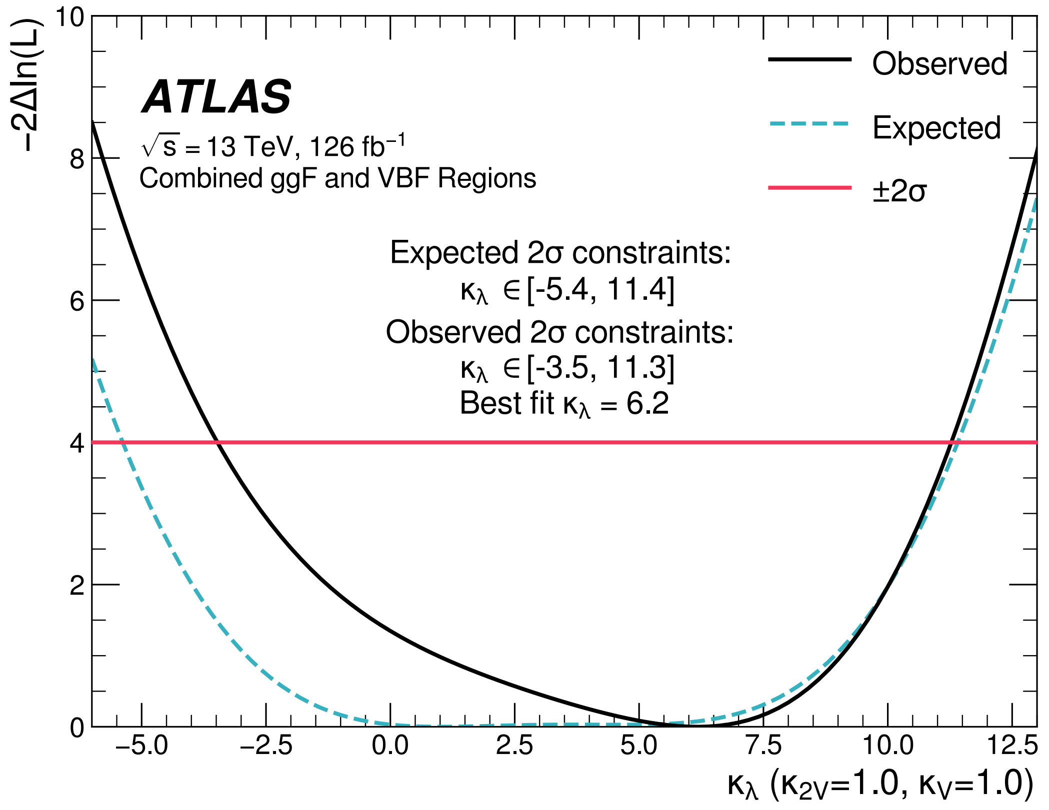
Table of Event Yields

Both ggF (top) and VBF (bottom) signal regions

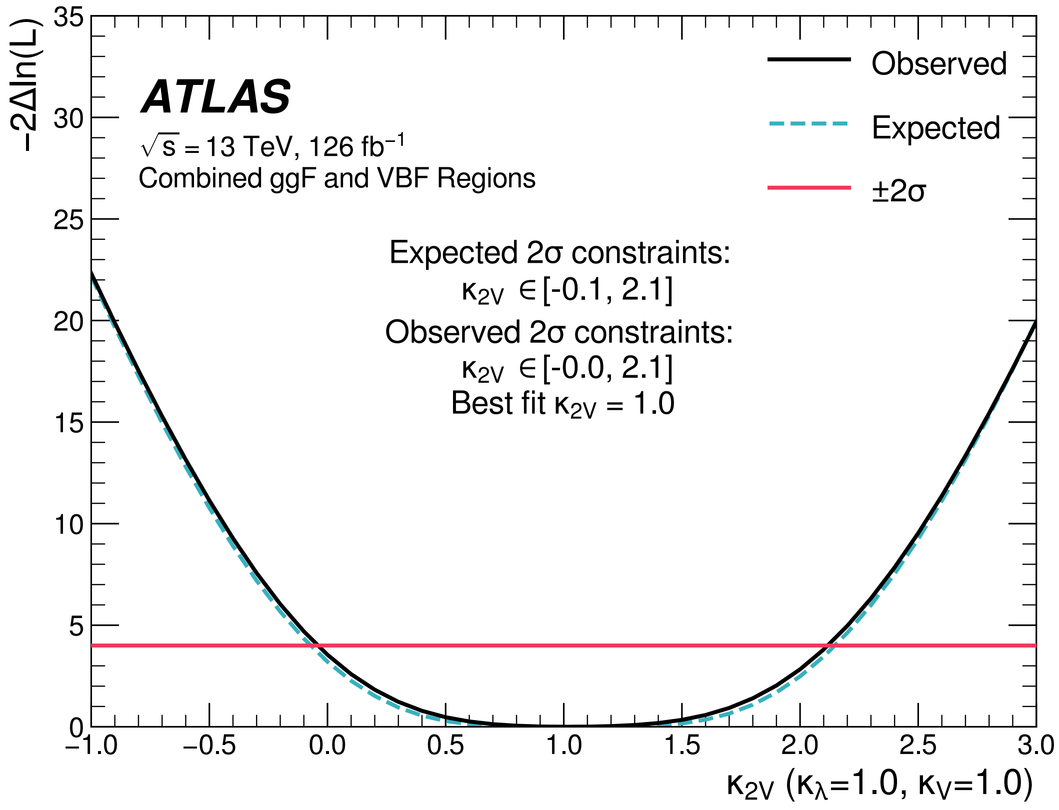
Category	Data	Expected Background	ggF Signal SM	VBF Signal SM
ggF signal region				
$\lvert\Delta\eta_{HH}\rvert < 0.5,\ X_{HH} < 0.95$	1940	1935(25)	7.0	0.038
$\lvert\Delta\eta_{HH}\rvert < 0.5,\ X_{HH} > 0.95$	3602	3618(37)	6.5	0.036
$0.5 < \lvert\Delta\eta_{HH}\rvert < 1.0,\ X_{HH} < 0.95$	1924	1874(21)	5.1	0.037
$0.5 < \lvert\Delta\eta_{HH}\rvert < 1.0,\ X_{HH} > 0.95$	3540	3492(35)	4.7	0.040
$\lvert\Delta\eta_{HH}\rvert > 1.0,\ X_{HH} < 0.95$	1880	1739(22)	2.9	0.043
$\lvert\Delta\eta_{HH}\rvert > 1.0,\ X_{HH} > 0.95$	3285	3212(37)	2.8	0.041
VBF signal region				
$\lvert\Delta\eta_{HH}\rvert < 1.5$	116	125.3(44)	0.37	0.090
$\lvert\Delta\eta_{HH}\rvert > 1.5$	241	230.6(53)	0.06	0.21

More Results (Likelihood Scans)

κ_λ

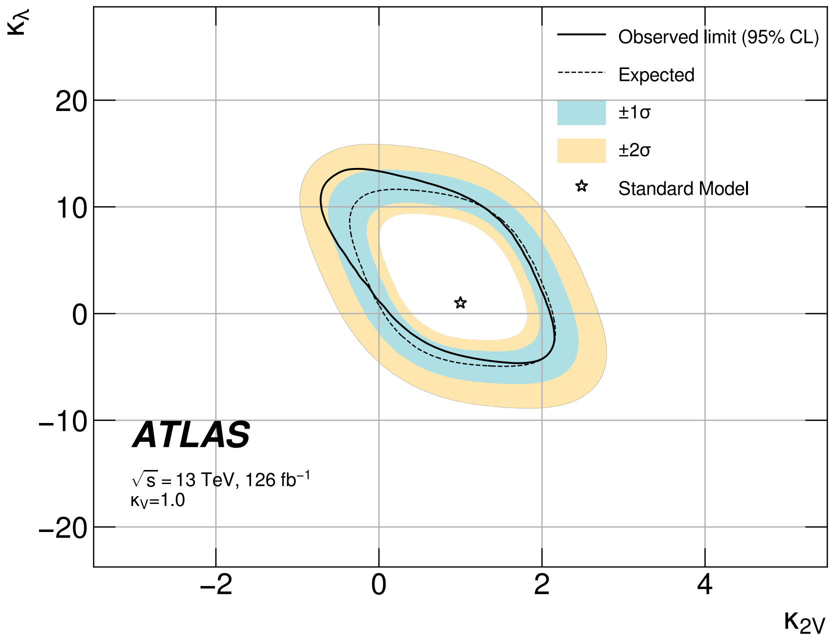


κ_{2V}



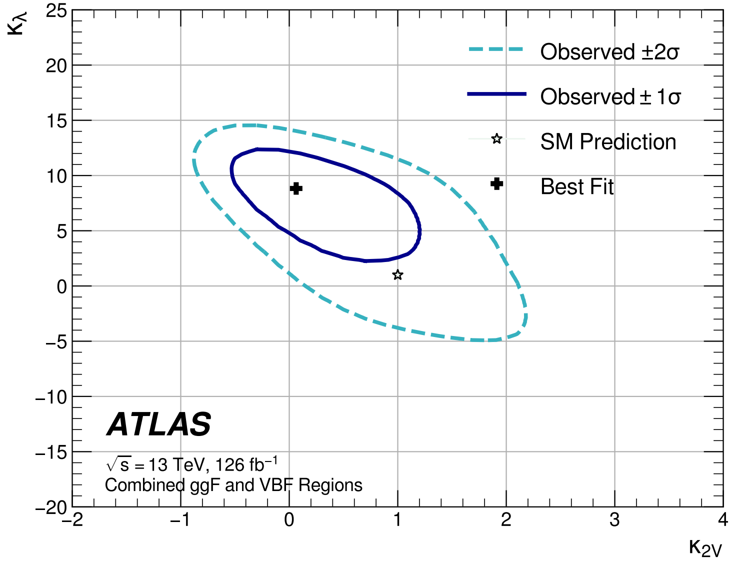
More Results (2D Limits)

"95% CL" (2D in κ_λ vs. κ_{2V})

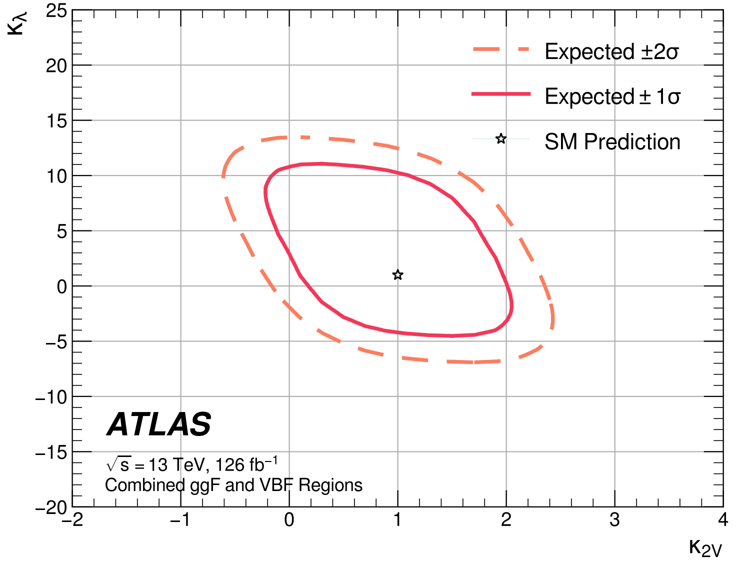


"Log Likelihood Scan" (2D in κ_λ vs. κ_{2V})

Observed

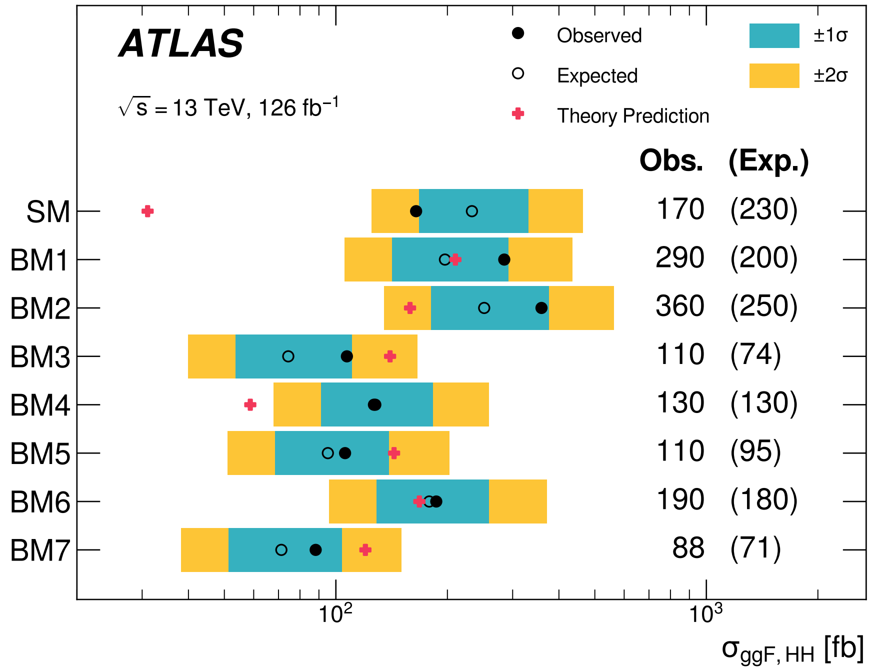


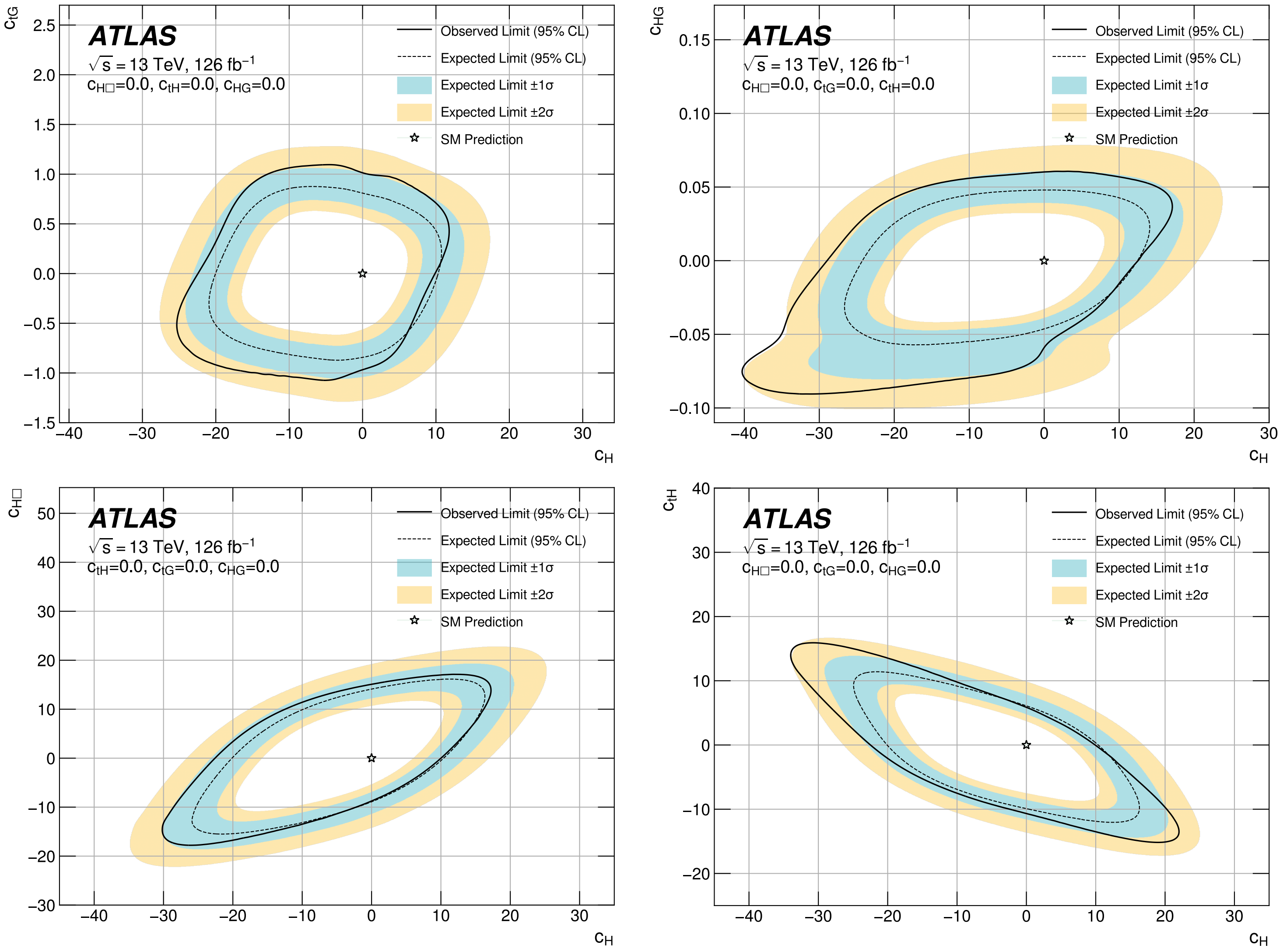
Expected



HEFT and SMEFT Constraints

ggF only





Uncertainties

Dominant uncertainties:

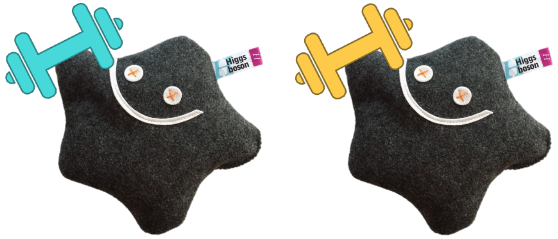
Theoretical signal modeling

Experimental background modeling

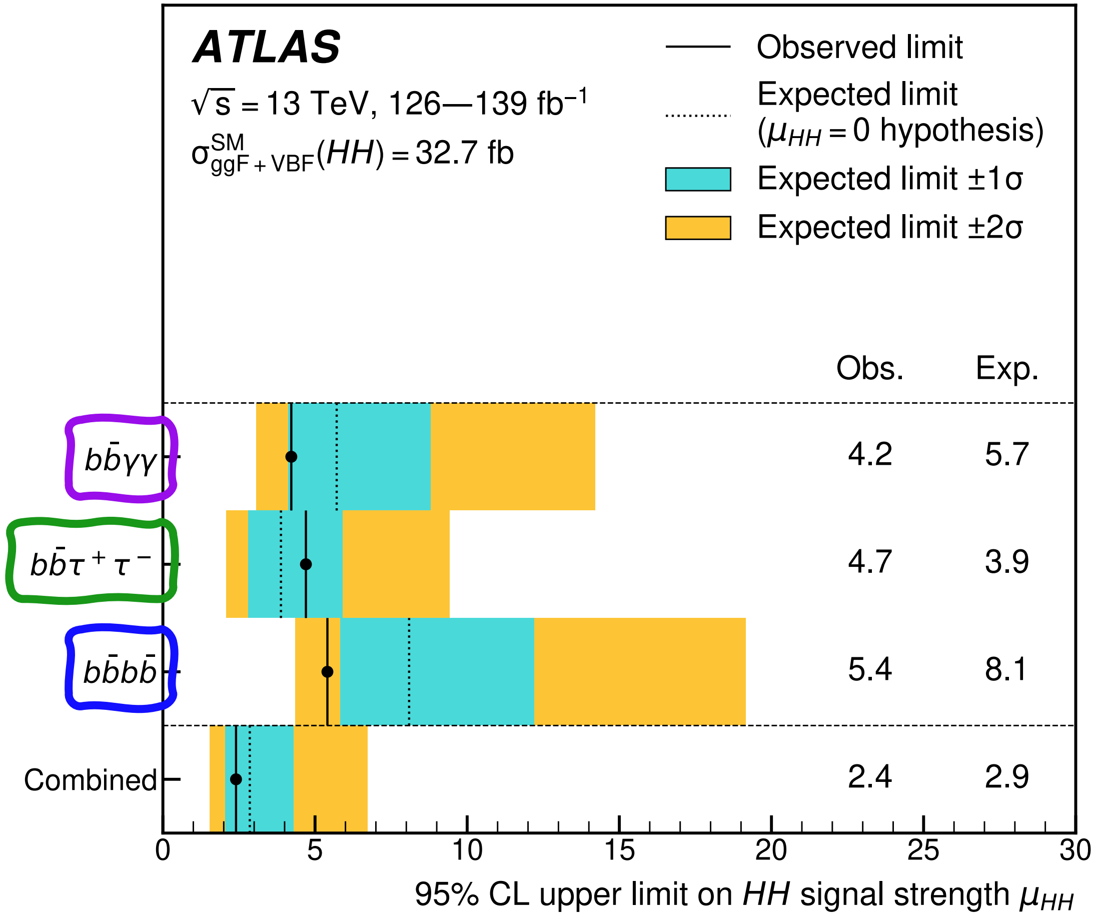
Uncertainties	$\mu_{\text{ggF+VBF}}$
Statistical Only	6.0
+ Background Modeling	7.1
+ Theoretical	8.1

$\mu_{\text{ggF+VBF}}$ (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%



Combination: $HH \rightarrow b\bar{b}b\bar{b}, b\bar{b}\tau\tau, b\bar{b}\gamma\gamma$



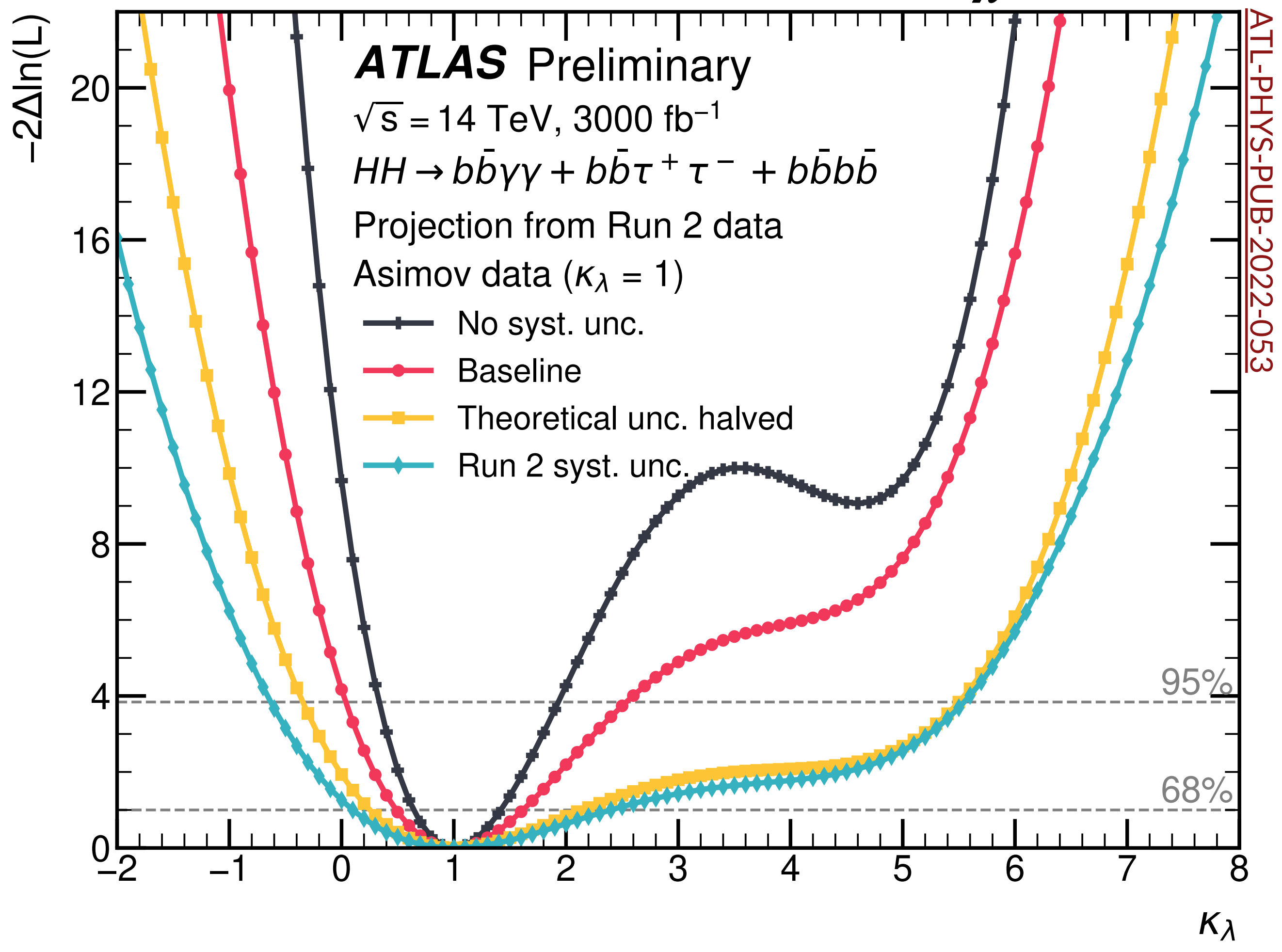
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Combined upper-limit on SM *HH* Cross-Section:

2.4 $\times \boldsymbol{\sigma_{SM}}$ (2.9 Exp.)

HH Prospects at the High-Luminosity LHC: κ_λ

Likelihood Scan vs. κ_λ



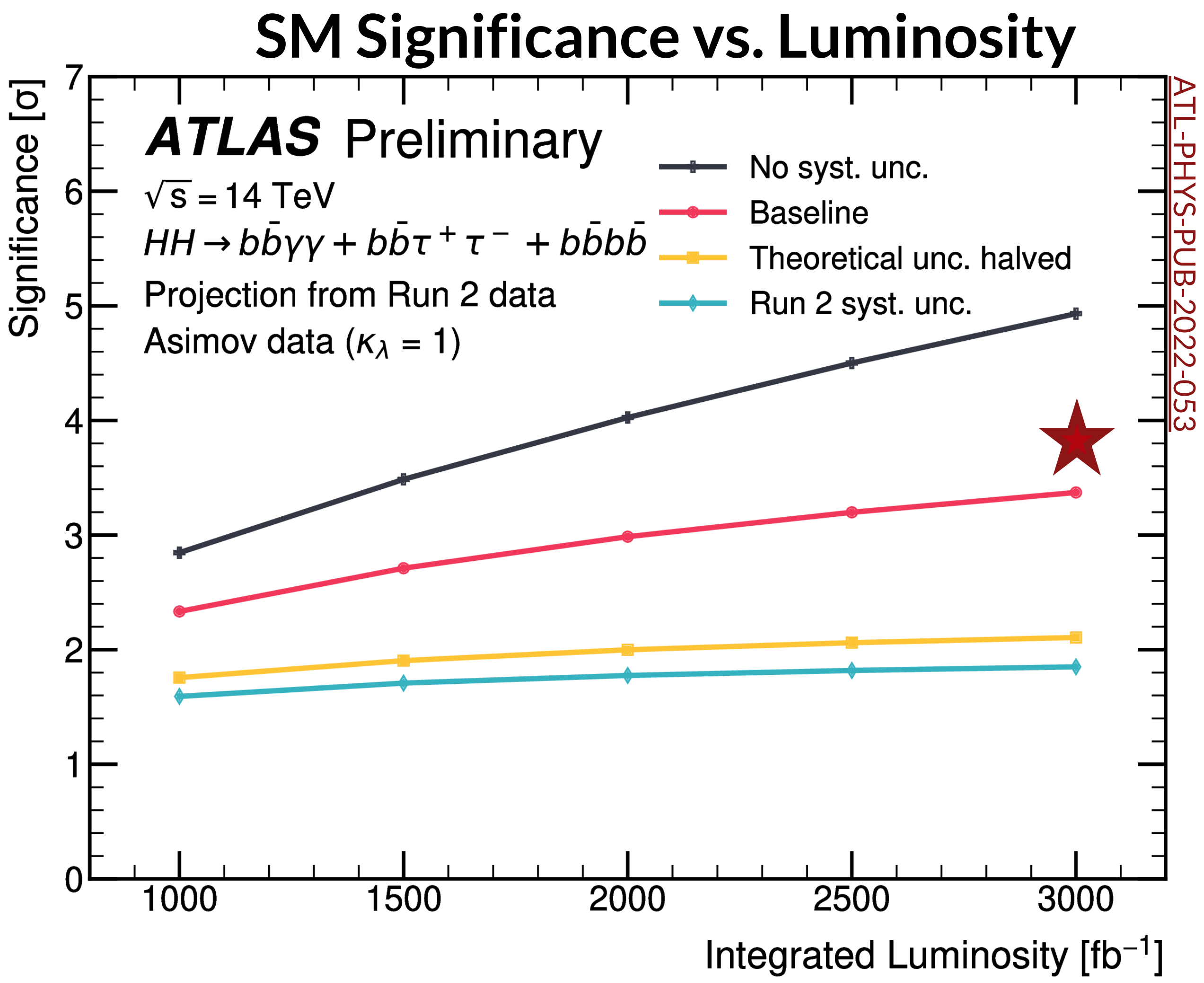
Full HL-LHC Dataset,
"Baseline" Uncertainty Scenario:

$$\mathbf{0.0 < \kappa_\lambda < 2.5}$$

→ Move from probing $\mathcal{O}(\sim 10)$ effects to $\mathcal{O}(\sim 1)$ effects

☆ "Log Likelihood Scan" limits utilize different assumptions (expected background *includes* SM *HH* signal)

HH Prospects at the High-Luminosity LHC



~ Observation sensitivity (3.4σ) to SM *HH* signal by end of HL-LHC!

→ If our understanding of the Higgs potential is roughly correct, we should be able to see a “bump”

HH Prospects @ HL-LHC: Uncertainty Scenarios

Baseline Scenario

Systematic uncertainties	Scale factors for HL-LHC baseline scenario
Theoretical uncertainty	0.5
b-jet tagging efficiency	0.5
c-jet tagging efficiency	0.5
Light-jet tagging efficiency	1.0
Jet energy scale and resolution	1.0
Luminosity	0.6
Background bootstrap uncertainty	0.5
Background shape uncertainty	1.0

Other Scenarios:

- No Systematic Uncertainties (Statistical Only)

- Run 2 Systematic Uncertainties

- Run 2 Systematic Uncertainties, with theoretical uncertainties halved