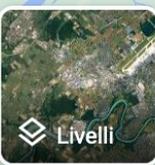


CERNO

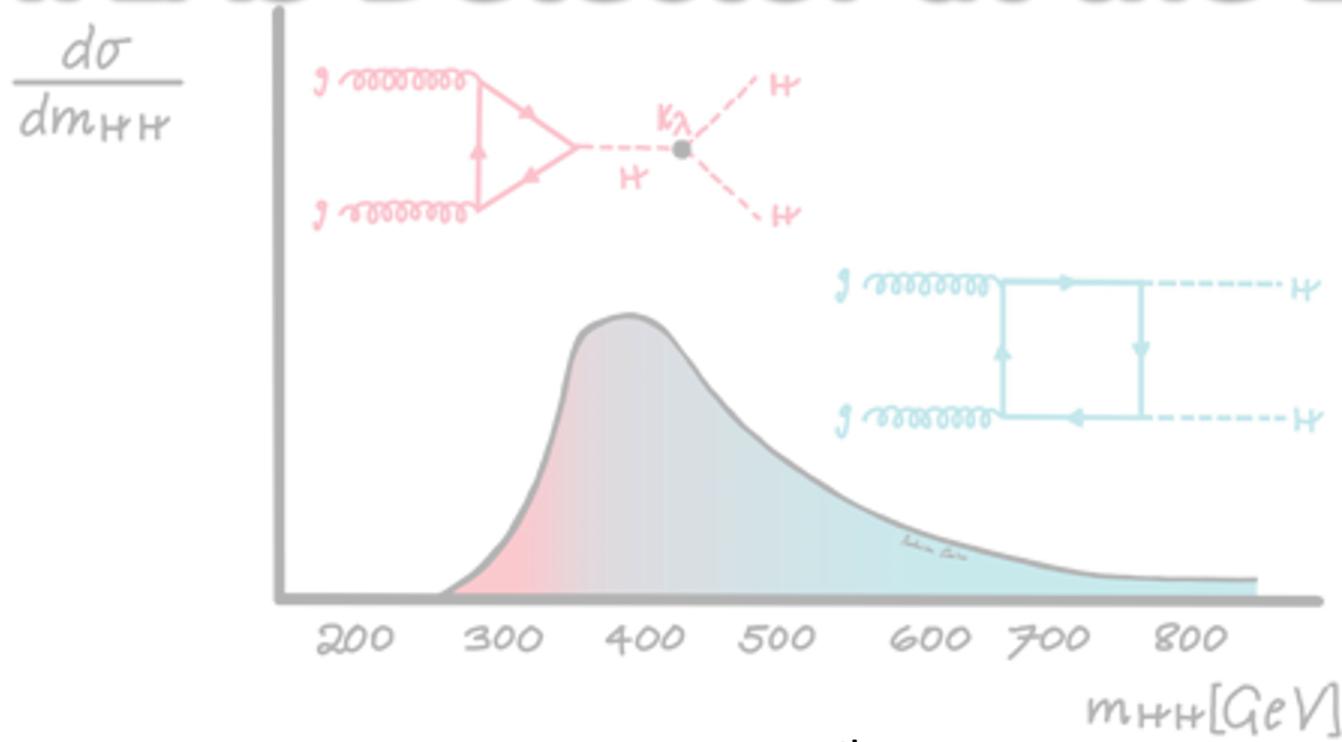
31 min

31 min

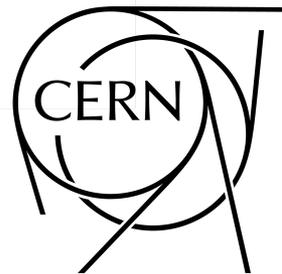
Ginevra



Probing the Higgs self-coupling with the ATLAS Detector at the LHC



February 9th 2022



Valentina Maria Martina Cairo

A very popular research topic...

Video

ATLAS Experiment @ATLASexperiment

Twice the Higgs, twice the challenge! 📺

Physicists at @CERN's ATLAS Experiment explain their new search for pairs of Higgs bosons in the rare bby decay channel. Find out more: cern.ch/go/NLs7

ATLAS searches for pairs of Higgs bosons

3:56 15.8K views

10:34 AM · Mar 31, 2021 · Twitter for Advertisers

91 Retweets 12 Quote Tweets 351 Likes

Twice-higgs-twice-challenge

CERN Accelerating science

ATLAS EXPERIMENT

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Collaboration Site | Physics Results

All News Briefings Features Portraits Press Blog

Updates > Briefing > Twice the Higgs, twice the challenge

Physics Briefing

Twice the Higgs, twice the challenge

ATLAS searches for pairs of Higgs bosons in the rare bby decay channel

29th March 2021 | By ATLAS Collaboration

Tags: 2021 winter conferences, Higgs boson, physics results

CERN Bulletin (April 2021)

ATLAS searches for pairs of Higgs bosons in a rare particle decay

The ATLAS search achieves the world's best constraints on the size of the Higgs boson's self-coupling, creating a portal of better understanding into the fundamental Higgs mechanism

[more >](#)

Pub: 202104
Issue: 19010078
2021-03-17 23:08:13 CERN

A very popular research topic...

Video

ATLAS Experiment @ATLASexperiment

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Updates > Briefing > Twice the Higgs, twice the challenge

Physics Briefing

Twice the Higgs, twice the challenge

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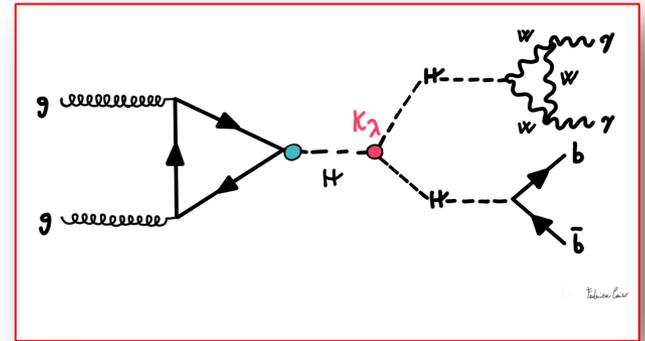
[more >](#)

Why so exciting?

Outline

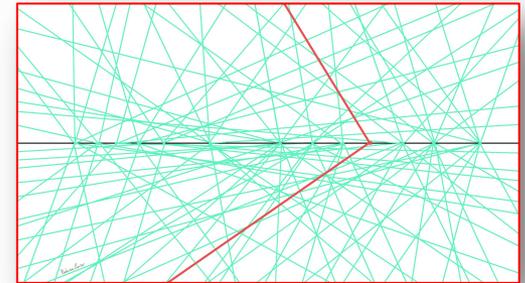
- The missing piece in the Higgs picture

- **Higgs self-coupling**



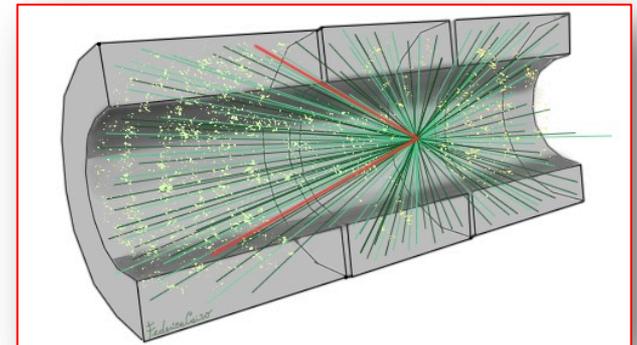
- How to tackle dense collision environments

- **Primary vertexing**



- A new camera for the detector

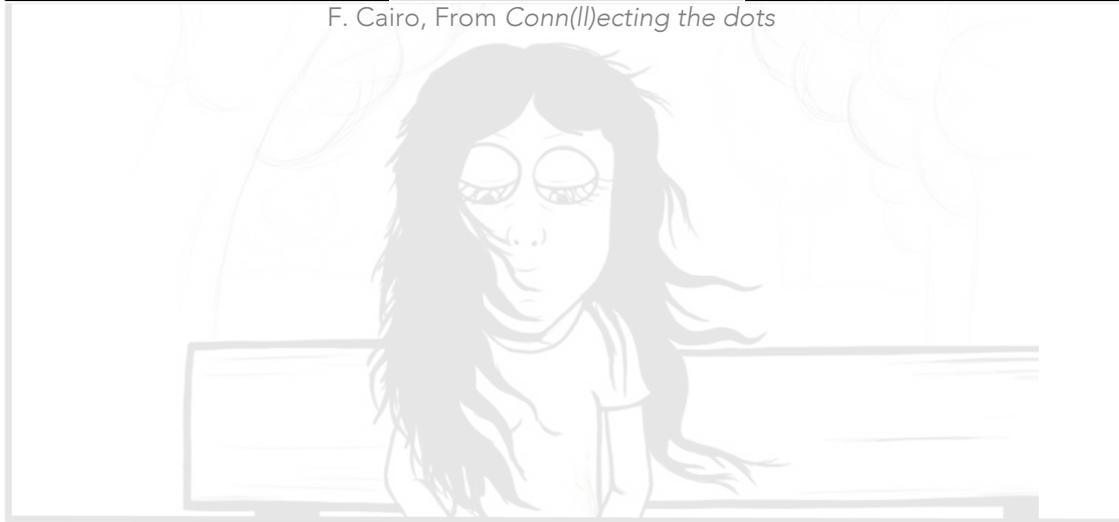
- **ATLAS Inner Tracker**



The Theory...



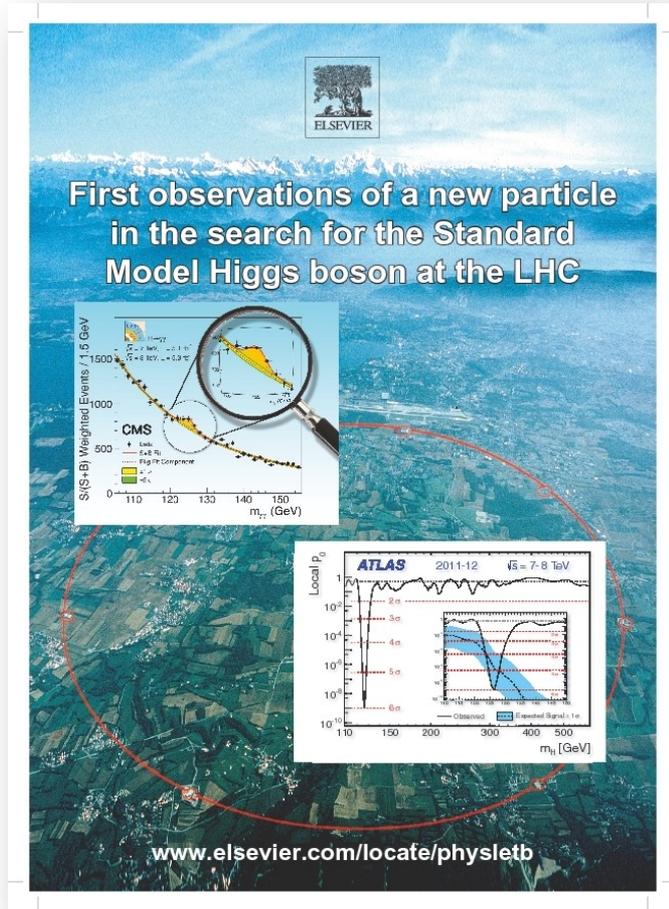
F. Cairo, From Conn(II)ecting the dots



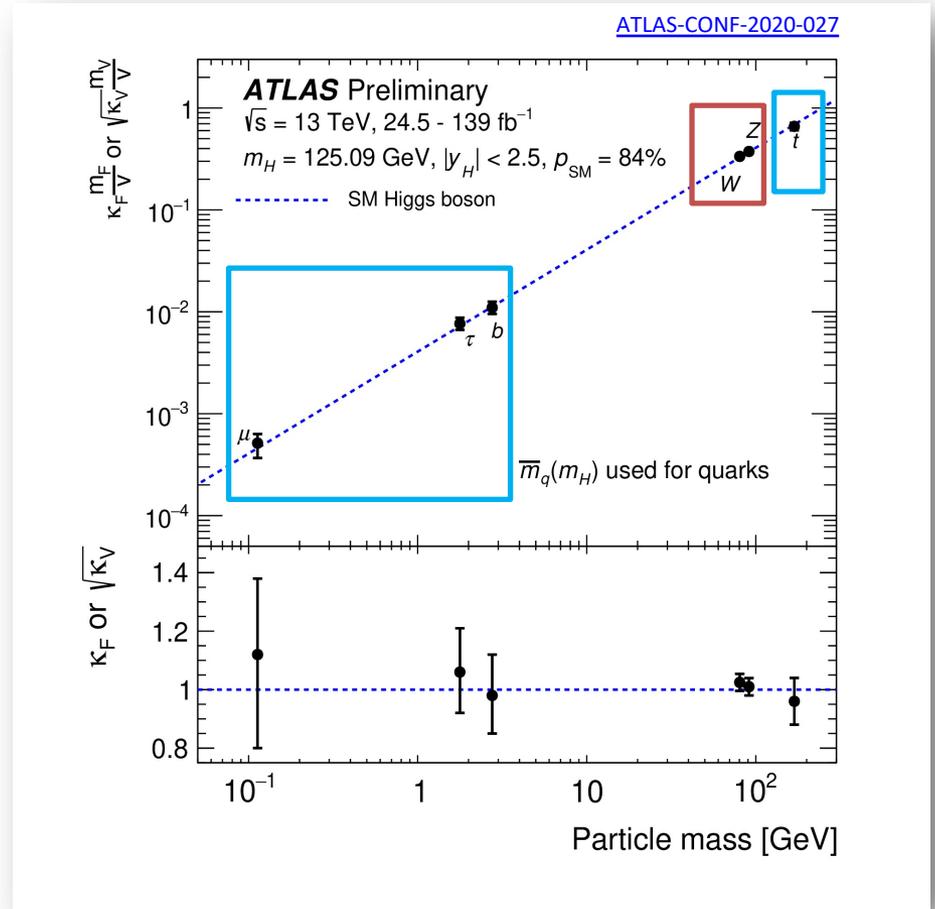
The Post Higgs boson era

2012

Now



A Higgs boson-like particle was found!



So far, the SM rules, but the exploration has just begun...

The Higgs Potential and Self-Coupling

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c.$$

$$+ \chi_i y_{ij} \chi_j \phi + h.c.$$

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

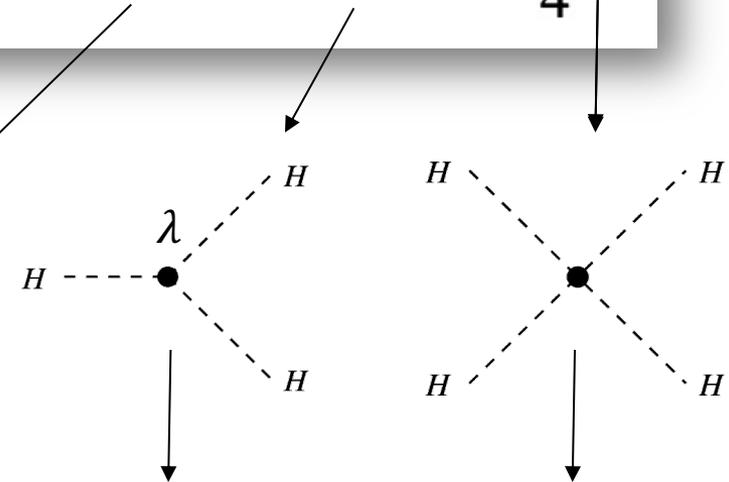
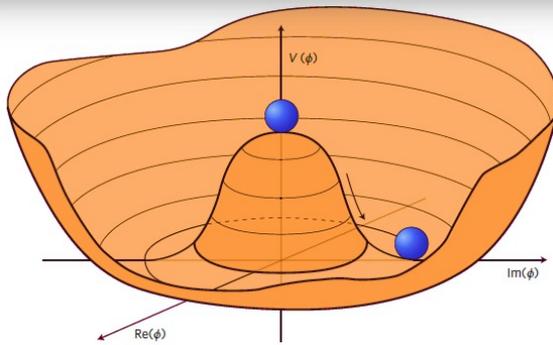
$$V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

$$\supset \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

$$m_H = \sqrt{2\lambda}v^2$$

$$v \simeq 246 \text{ GeV.}$$

$$\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$$



Direct access to λ in HH pair production

Out of reach even for HL-LHC

Known m_H (~ 125 GeV), SM predicts λ (~ 0.13)

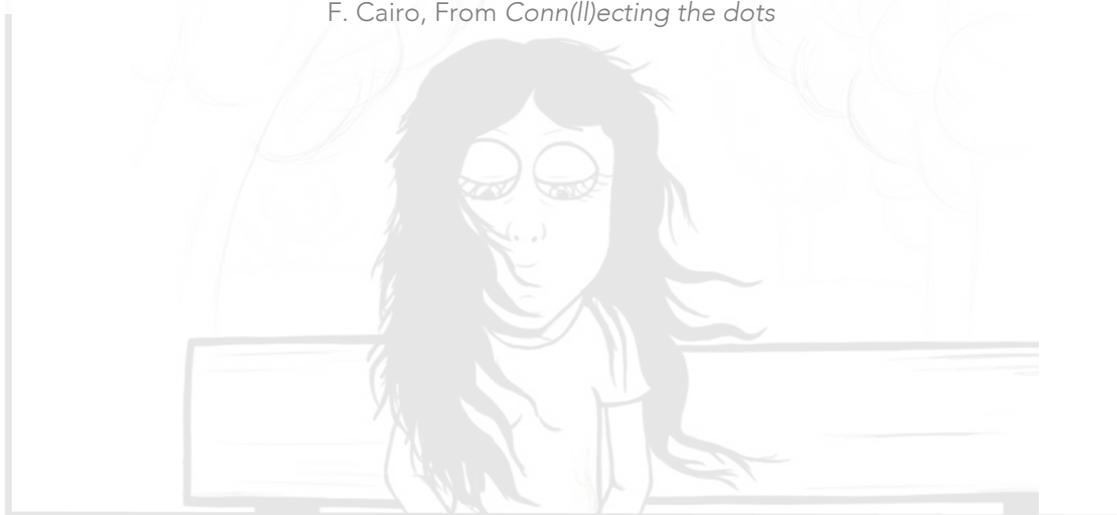
New physics can alter this number \rightarrow Implications on the stability of the Universe

\rightarrow Probing the **Higgs-self coupling** is a key goal for HL-LHC, but much can be done now!

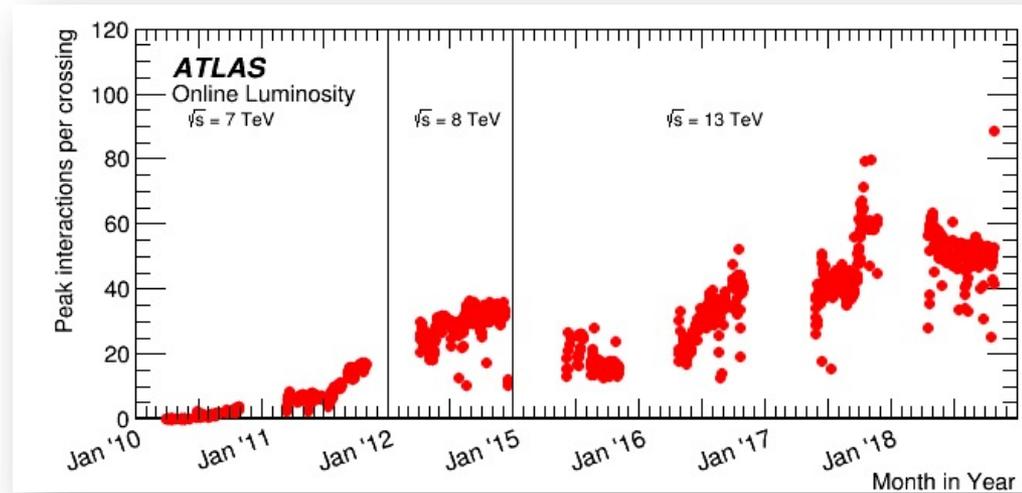
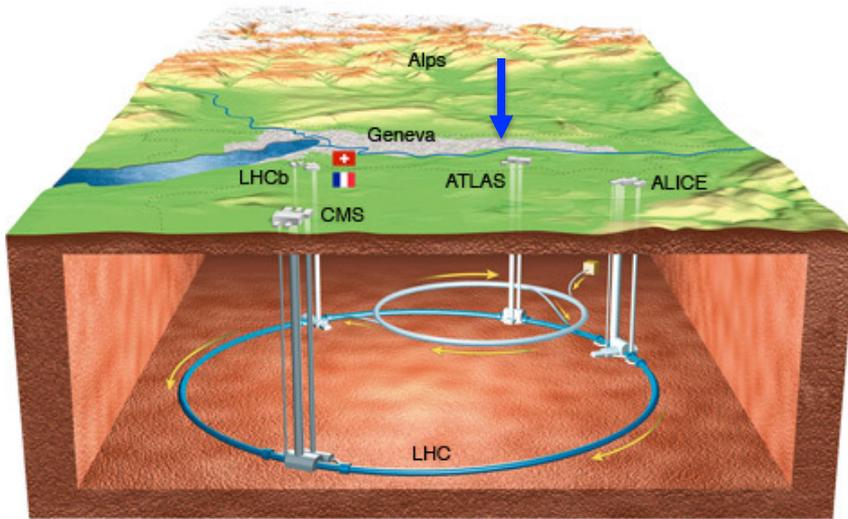
...the tools...



F. Cairo, From Conn(II)ecting the dots



The Large Hadron Collider



Outperformed specifications during **Run 2**:

- **Peak Luminosity**: x2 ($2.14 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$)
- **Integrated Luminosity**: 140 fb^{-1}
- **Avg interaction per crossing** $\langle \mu \rangle$: x2 (~ 40)

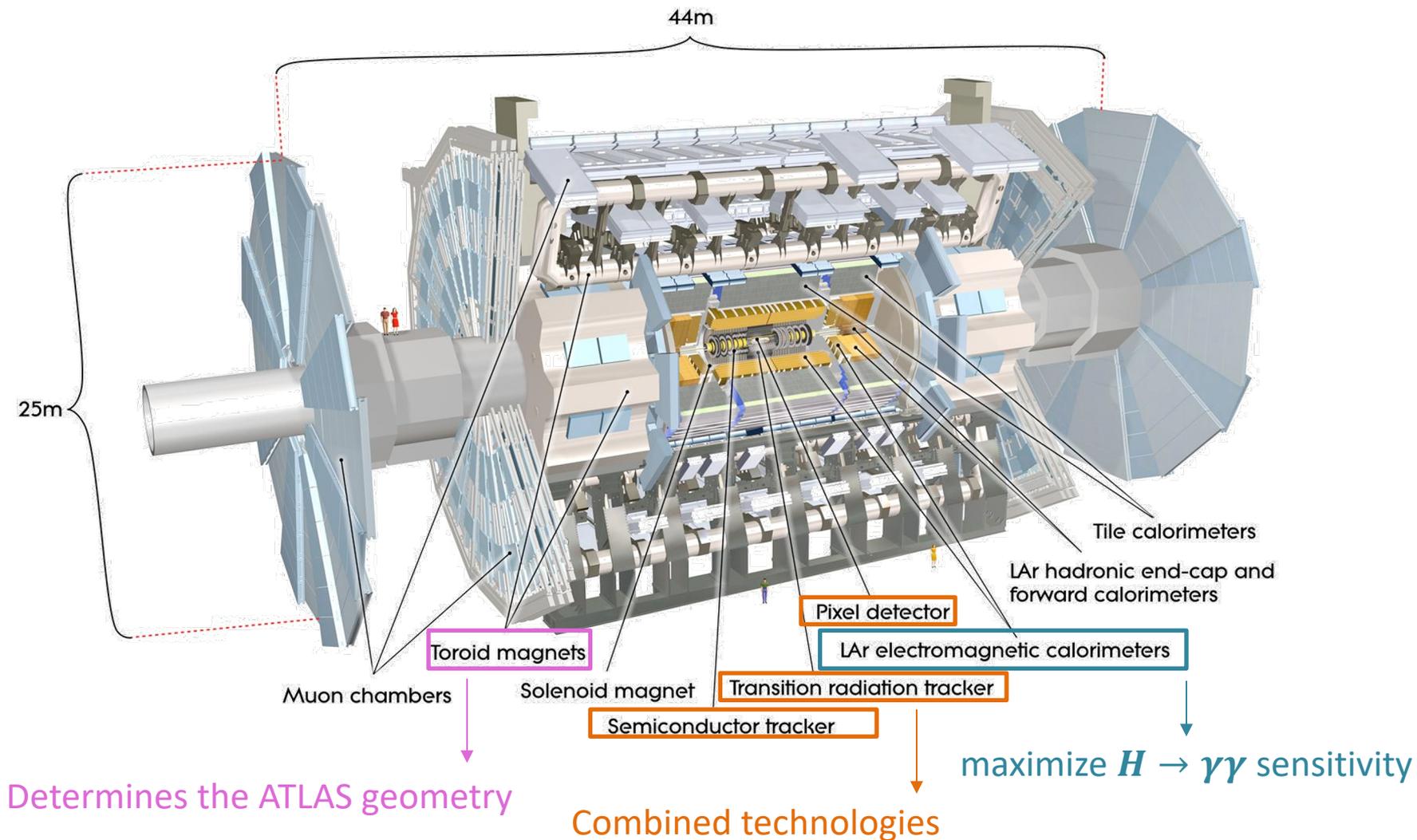
Two more runs to go:

- **Run 3**: 13.6 TeV, $\langle \mu \rangle \sim 60$
- **Run 4**: 14 TeV, $\langle \mu \rangle \sim 200$

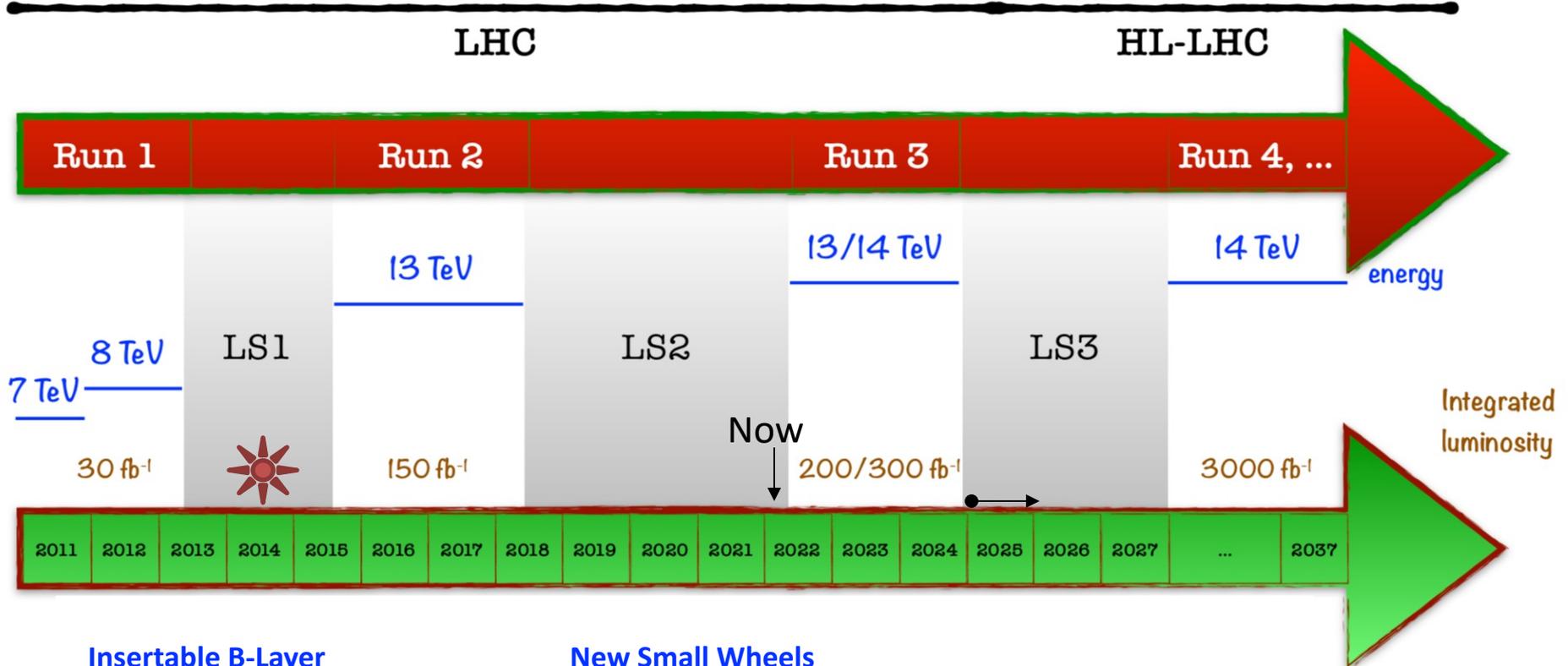
The ATLAS Detector

Physics benchmarks drove the design of the detector

- Excellent stand-alone reconstruction capabilities



The ATLAS Timeline



Insertable B-Layer



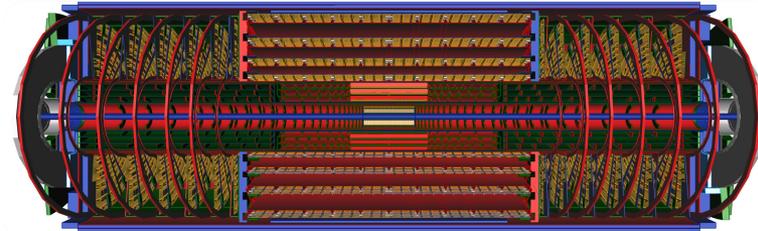
[source](#)

New Small Wheels



[source](#)

Inner Tracker



[source](#)

...the work...

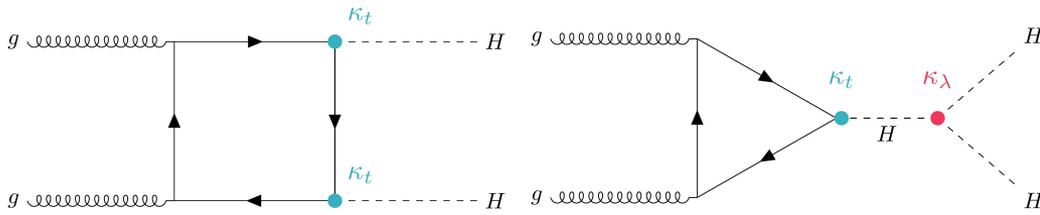


Higgs Self-Coupling

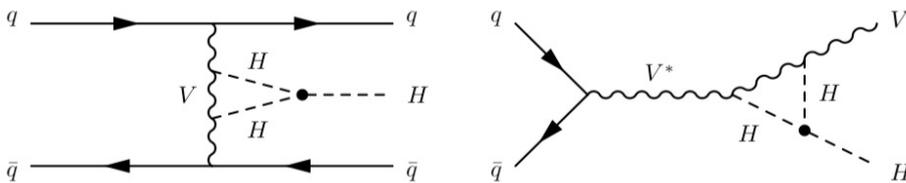
λ_{HHH} can be measured in two complementary ways

di-Higgs

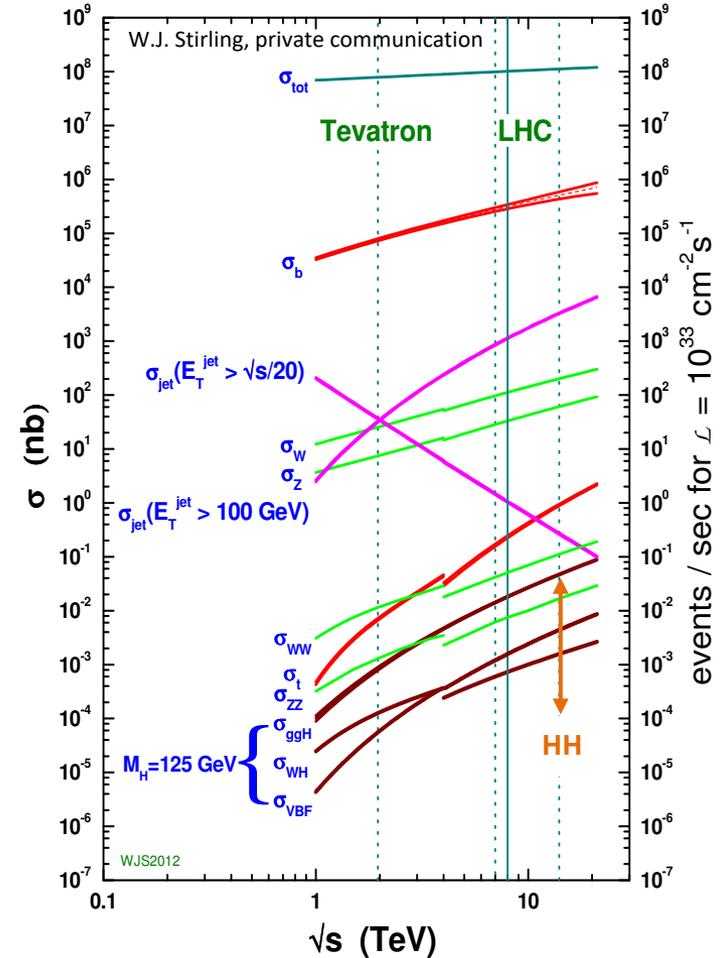
Today's focus



Single-Higgs

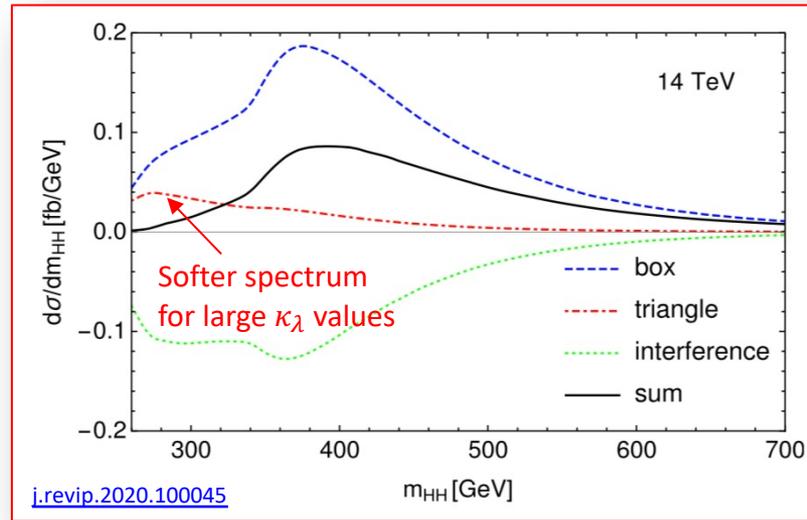
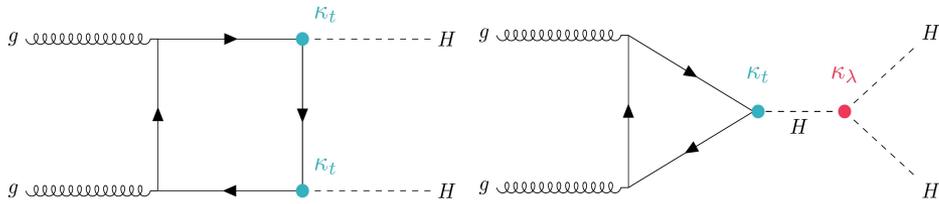


proton - (anti)proton cross sections



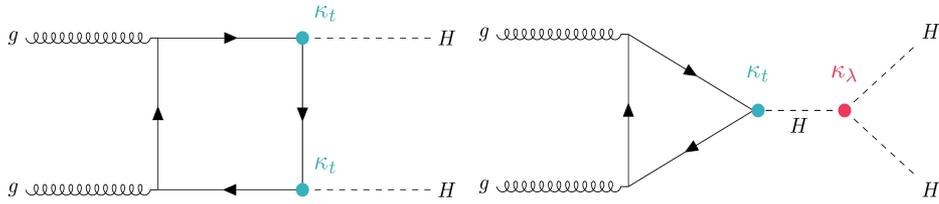
HH Production at the LHC

Non-resonant $\sigma_{HH}^{ggF} = 31.05 \text{ fb}$ at 13 TeV for $m_H = 125.00 \text{ GeV}$

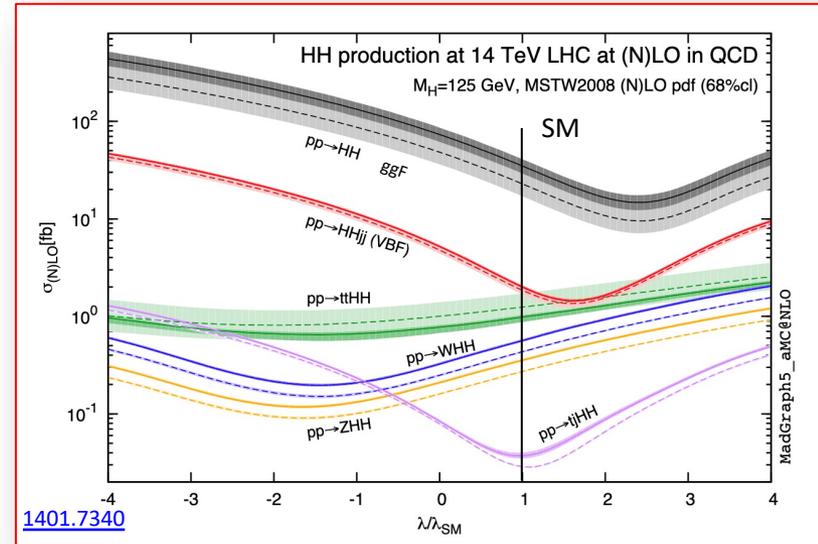
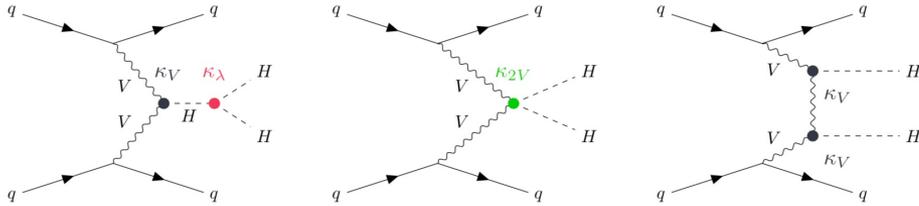


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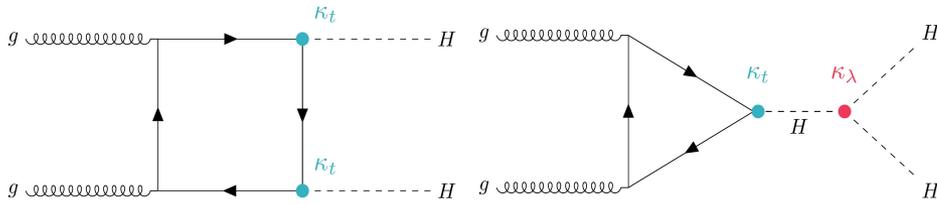


Non-resonant $\sigma_{HH}^{VBF} = 1.73 \text{ fb}$ at 13 TeV for $m_H = 125.00 \text{ GeV}$

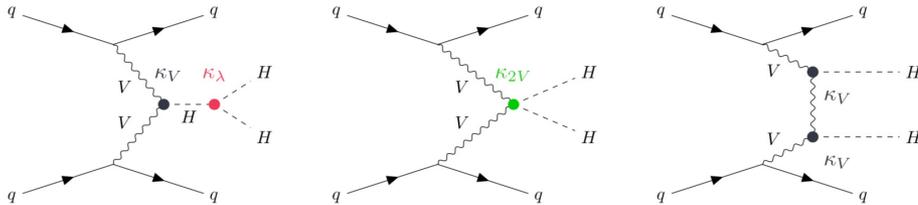


HH Production at the LHC

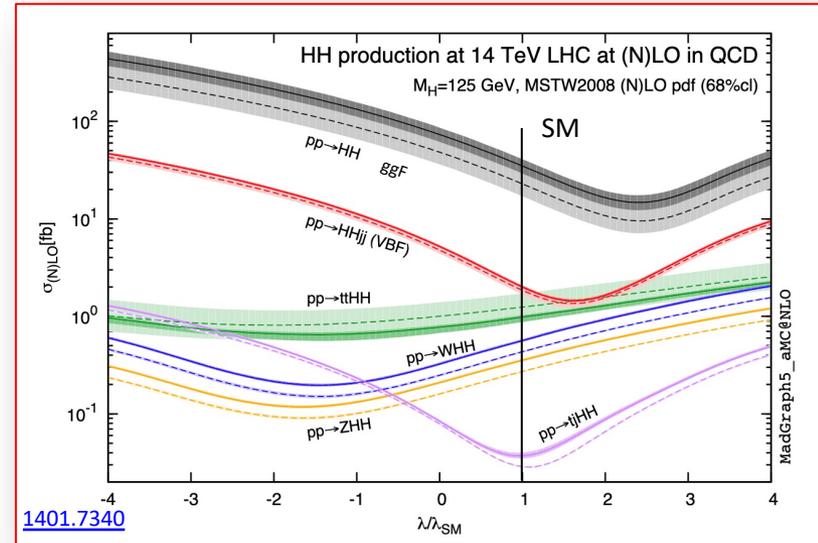
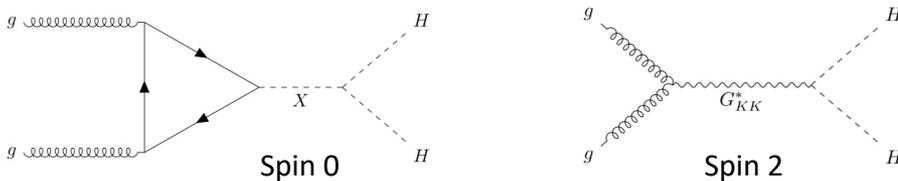
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Non-resonant $\sigma_{HH}^{VBF} = 1.73 \text{ fb}$ at 13 TeV for $m_H = 125.00 \text{ GeV}$



Resonant ggF



σ_{HH} and kinematics depend on the **couplings** and presence of new **resonances**

New physics can manifest as deviation in σ_{HH}

HH Final States

σ_{HH} @ 13 TeV ~ **30 fb**
(1000 x smaller than single H)

Run 2 $\int L \sim$ **140 fb⁻¹**

~ **4k HH** events

Scales up to about
10⁵ in HL-LHC

Combination
(and complementarity)
of various final states
fundamental for
observation!

Most final states rely on
b-tagging

Branching Ratio	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	33%				
WW	25%	4.6%			
$\tau\tau$	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
$\gamma\gamma$	0.26%	0.10%	0.029%	0.013%	0.0005%

Most recent full Run 2 ATLAS Results covered today:

$HH \rightarrow b\bar{b}\gamma\gamma$ (resonant & non-resonant)

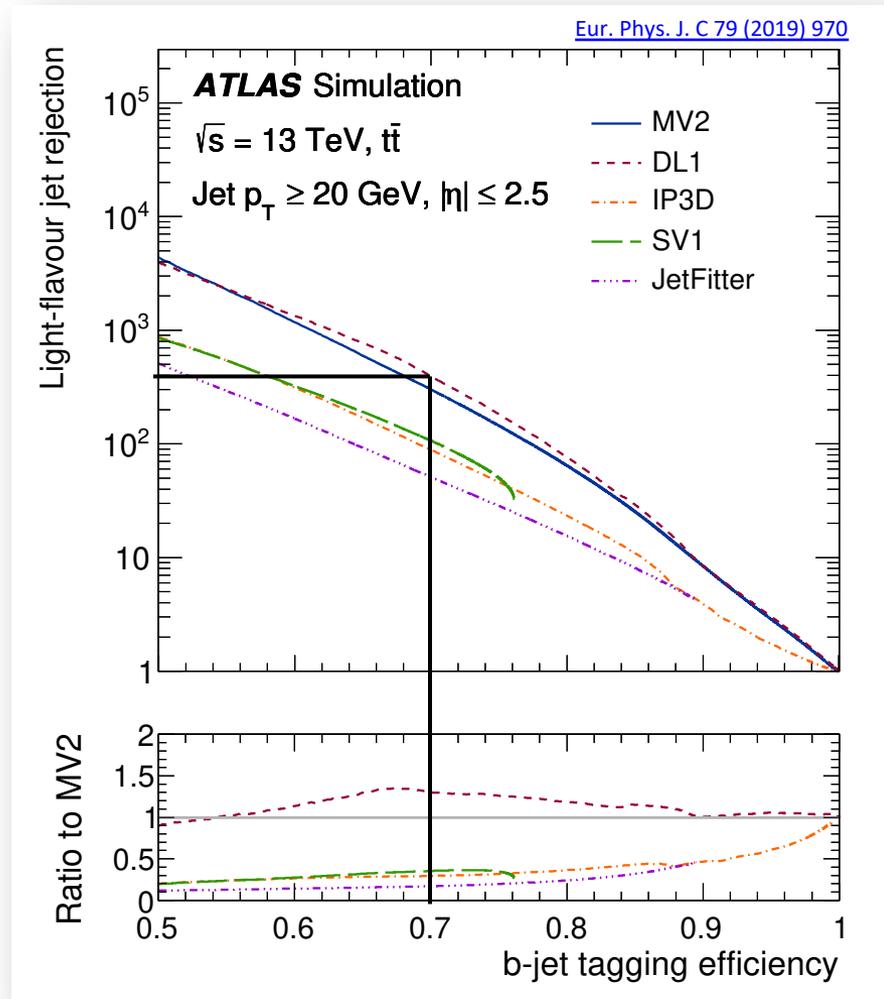
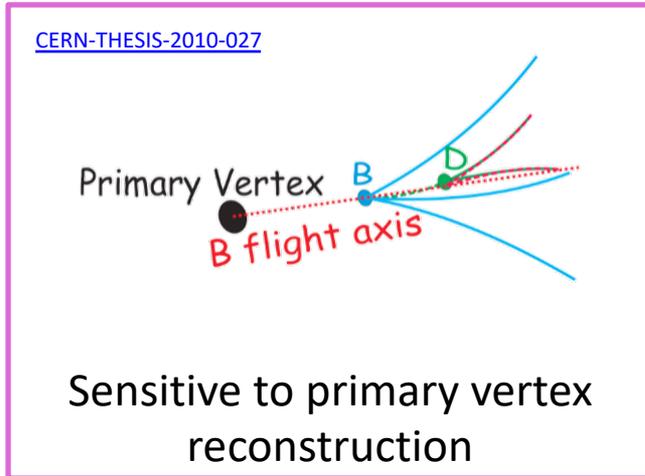
$HH \rightarrow b\bar{b}\tau\tau$ (resonant & non-resonant)

$HH \rightarrow b\bar{b}b\bar{b}$ (resonant)

What is a b-jet in ATLAS?

High-Level ML b-taggers utilize low-level taggers' outputs

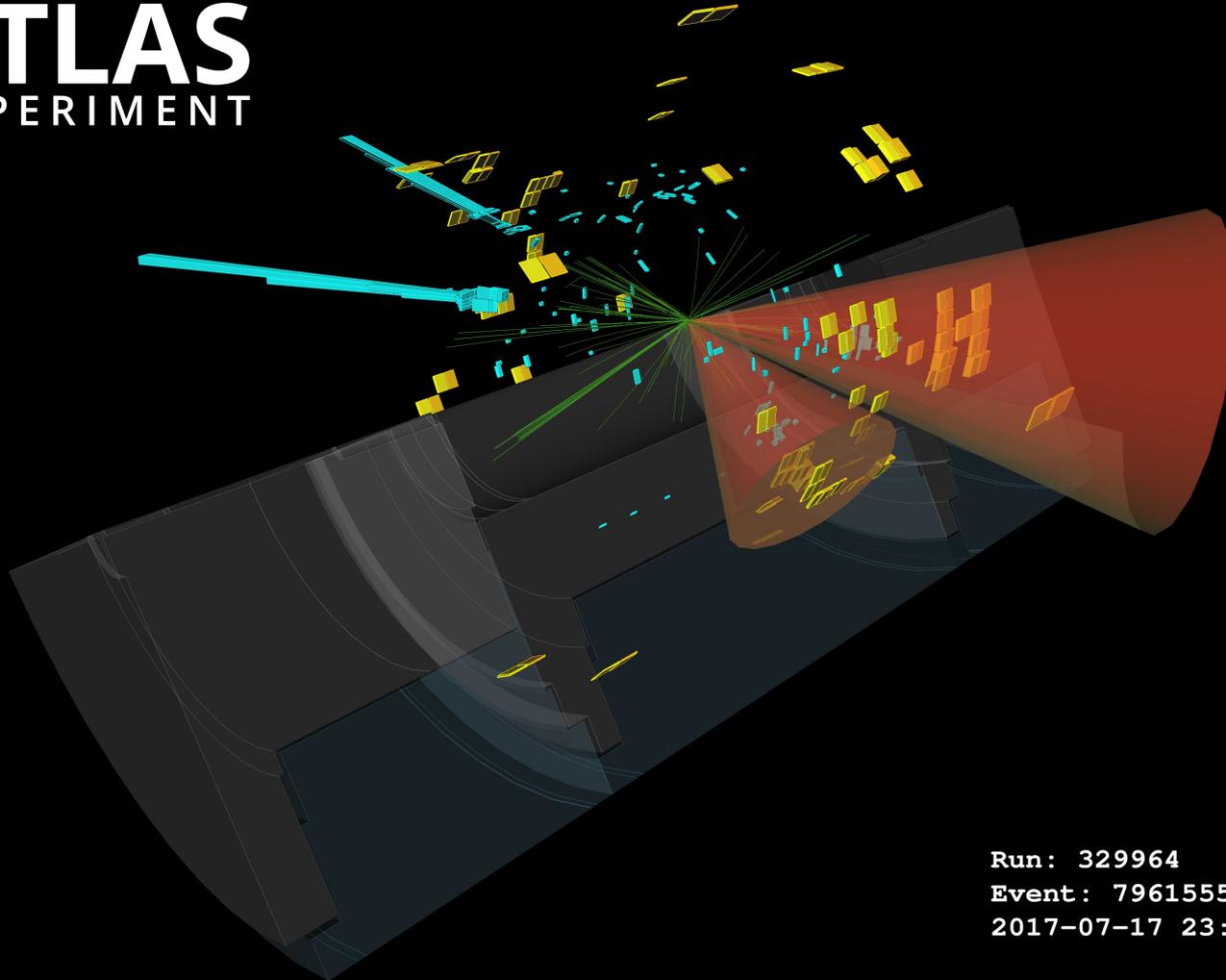
- Impact Parameter based
- Secondary Vertex finding
- Decay chain Multi-Vortex Algorithm (JetFitter)



70% b-tag efficiency, ~0.3% light-jet

About 1 order of magnitude lower fake rate compared to Tevatron! Ref [1](#), [2](#)

$$HH \rightarrow b\bar{b}\gamma\gamma$$



Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

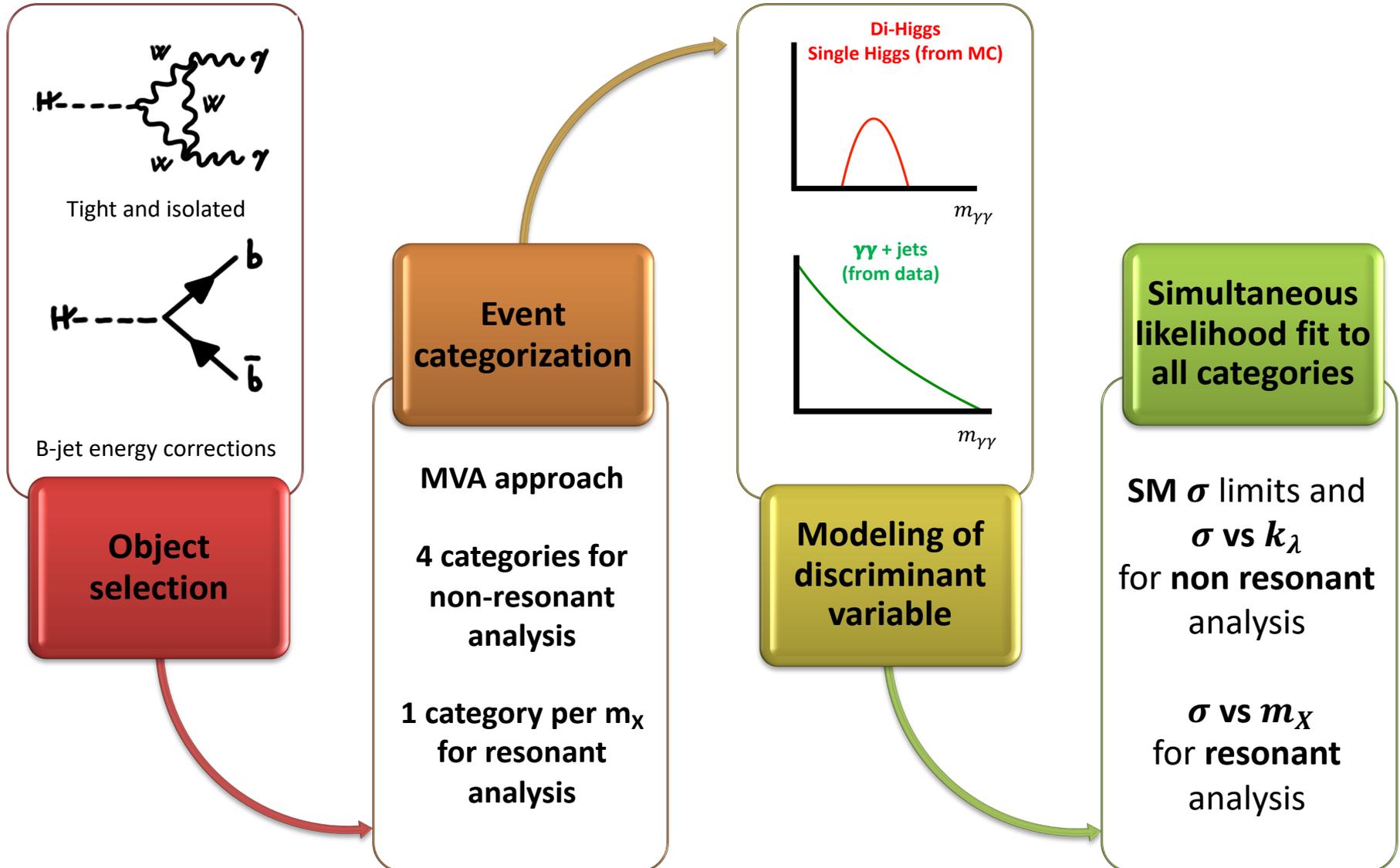
Publication: [HDBS-2018-34](#)

Physics Briefing: <https://atlas.cern/updates/briefing/twice-higgs-twice-challenge>

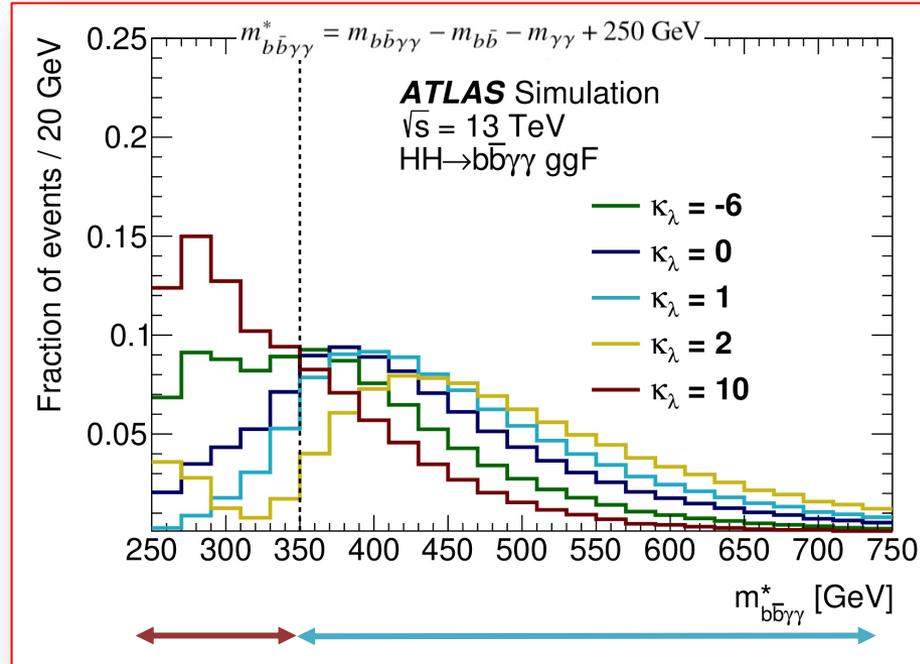
$HH \rightarrow b\bar{b}\gamma\gamma$ analysis in a nutshell

Small BR, but fully reconstructable final state, clean signal extraction

Di-photon triggers with $E_T > 35, 25$ GeV (82.9% efficiency for non-resonant signal, 69.5% for $m_X = 300$ GeV)

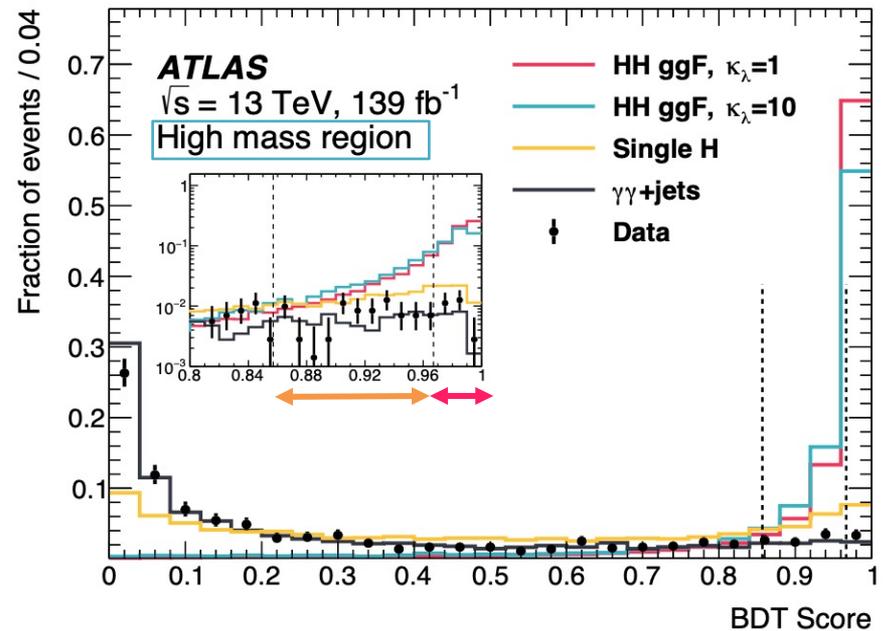
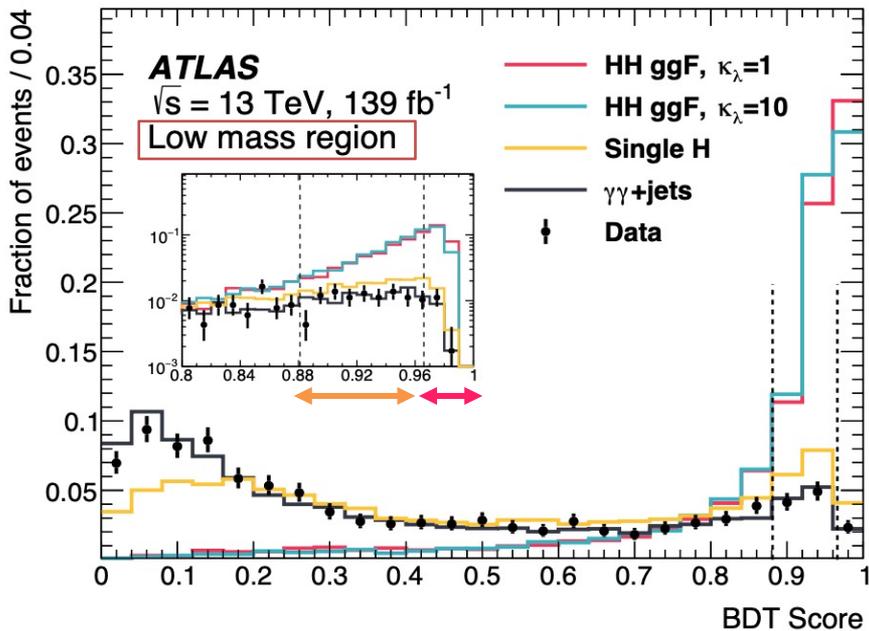


Non-Resonant $HH \rightarrow b\bar{b}\gamma\gamma$ (1)



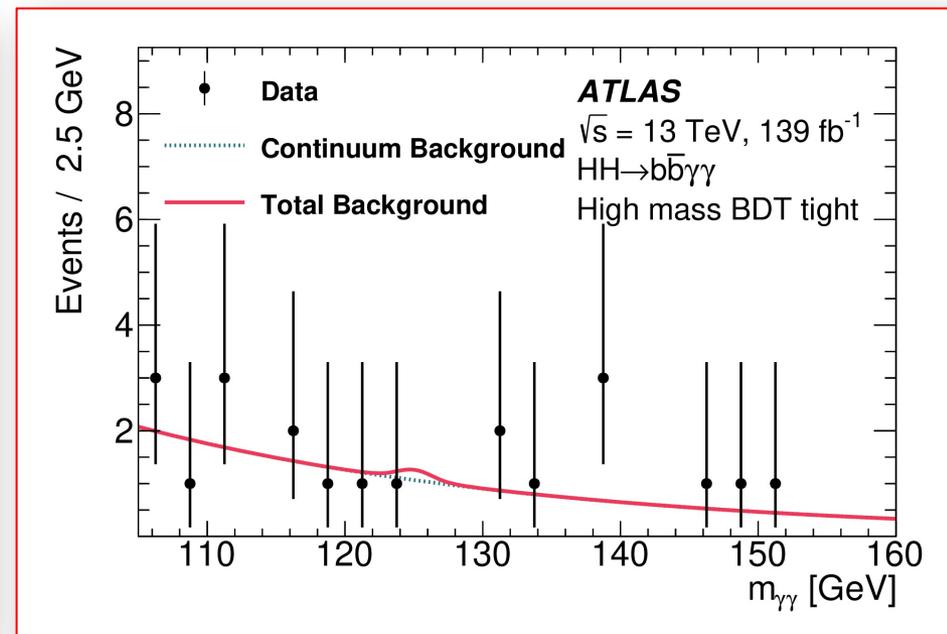
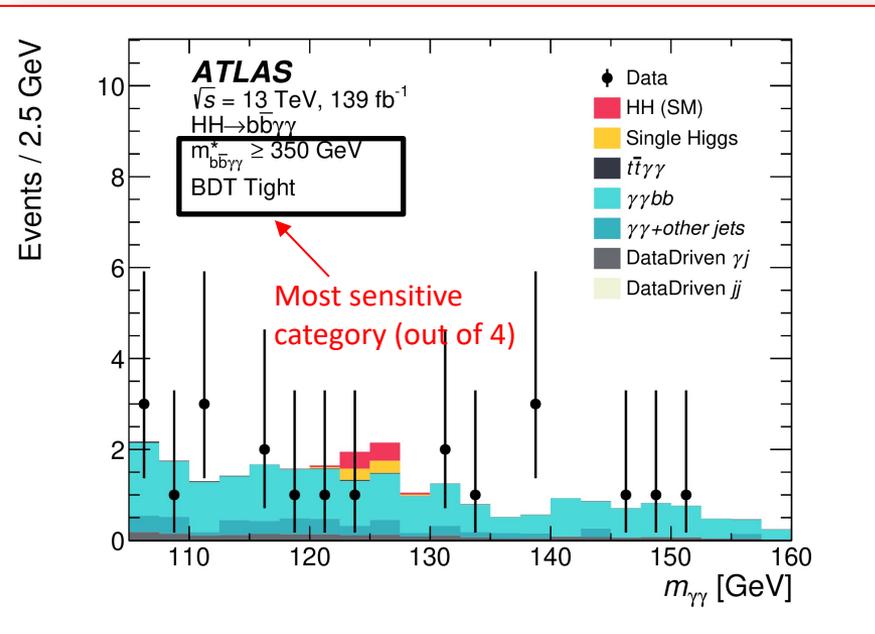
- **Low** and **High** $m_{b\bar{b}\gamma\gamma}^*$ (very important!)
 - **< 350 GeV** for **BSM**, **> 350 GeV** for **SM**

Non-Resonant $HH \rightarrow b\bar{b}\gamma\gamma$ (2)

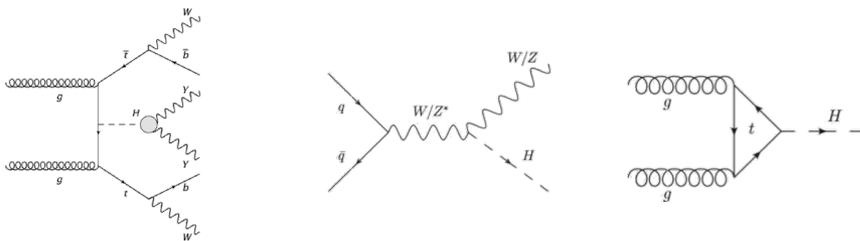


- **BDT to discriminate signal ($\kappa_\lambda = 1, 10$) from backgrounds**
 - m_{bb} with b-jet energy corrections (improves resolution by $\sim 20\%$)
 - *Topness* (rejects up to 35% ttH)
- **Loose and Tight BDT**
 - Boundaries chosen to maximize combined expected significance

Non-Resonant $HH \rightarrow b\bar{b}\gamma\gamma$ (3)

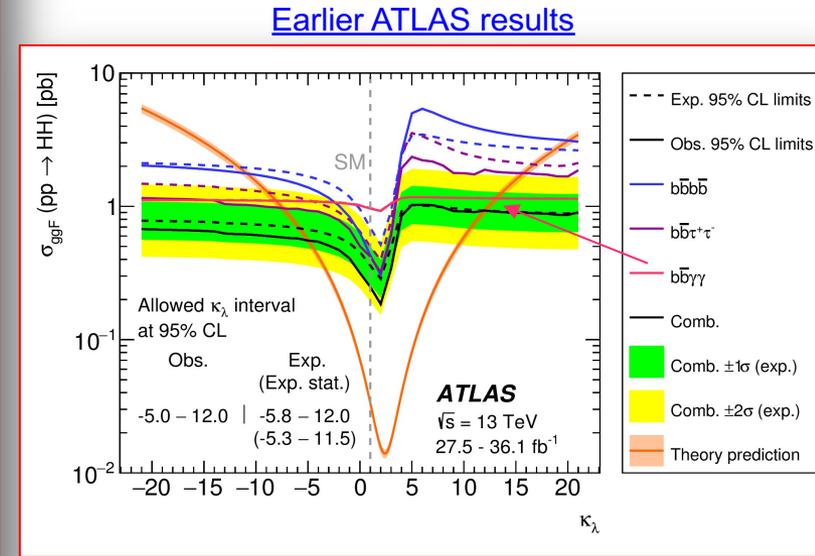
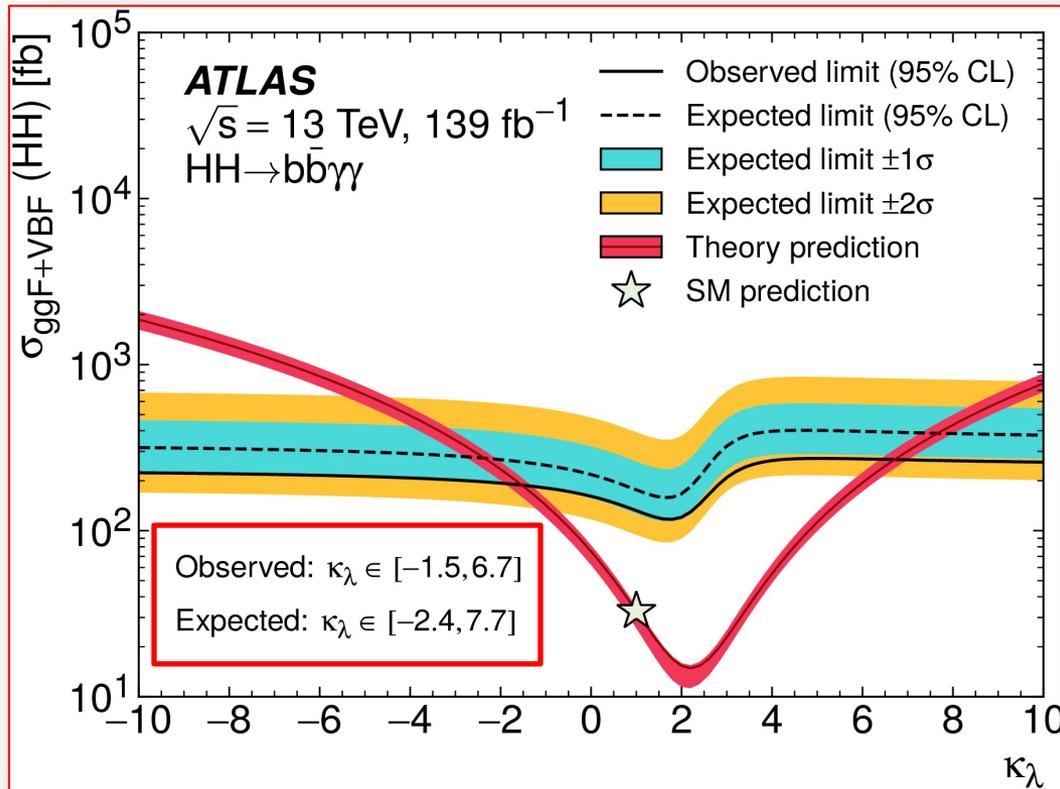


Main Single Higgs backgrounds



Maximum likelihood fit of $m_{\gamma\gamma}$
 performed simultaneously over all
 categories

Non-Resonant $HH \rightarrow b\bar{b}\gamma\gamma$ results



4.1 (5.5) x SM σ_{HH}

5x improvement wrt previous result ($\sim 26 \text{ x SM}$), $\sim 3\text{x}$ due to analysis techniques

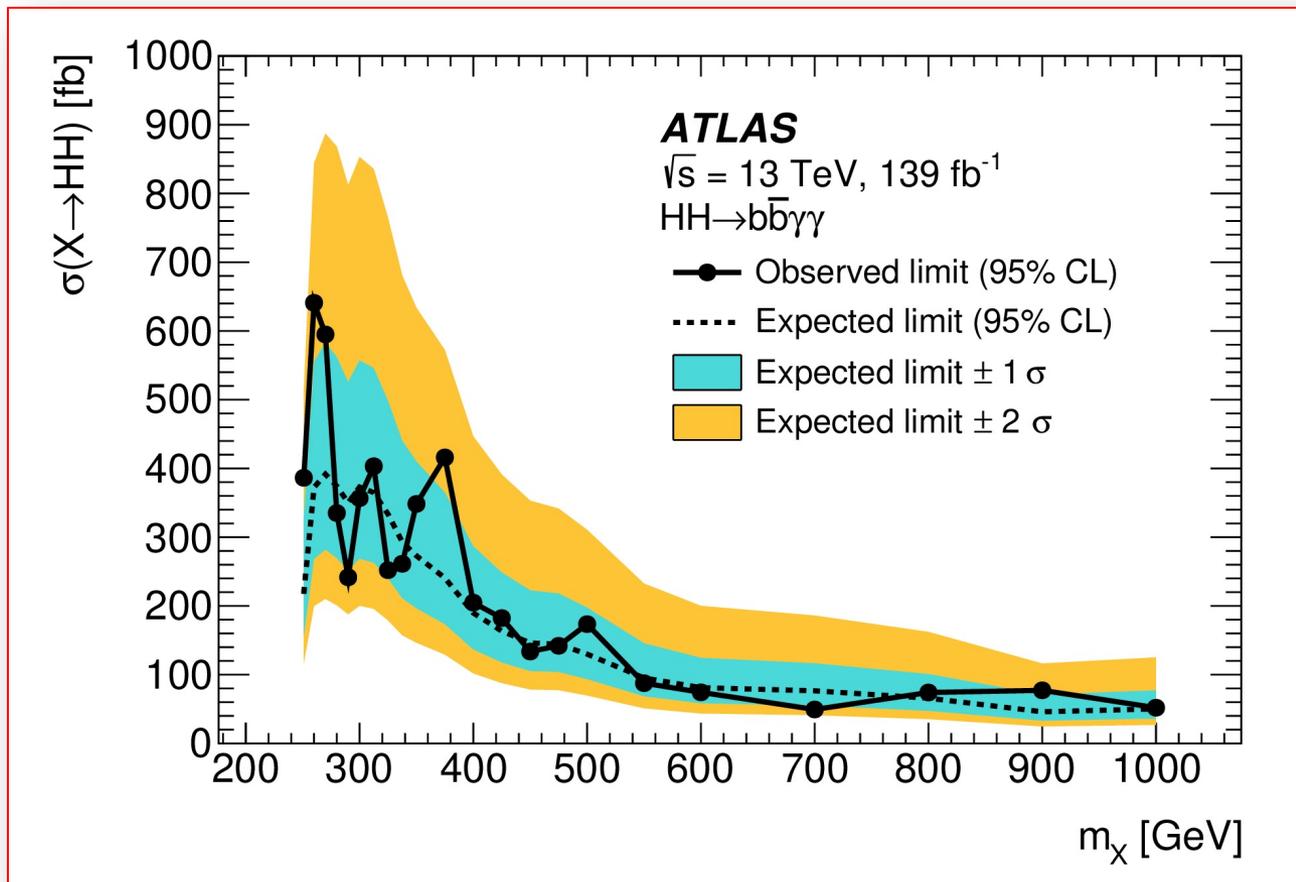
driven by m_{HH} categorization & MVA as well as b-jet corrections

Statistically dominated, few % impact from systematics

World's best constraints to date on Higgs boson's self coupling!

Resonant $HH \rightarrow b\bar{b}\gamma\gamma$ results

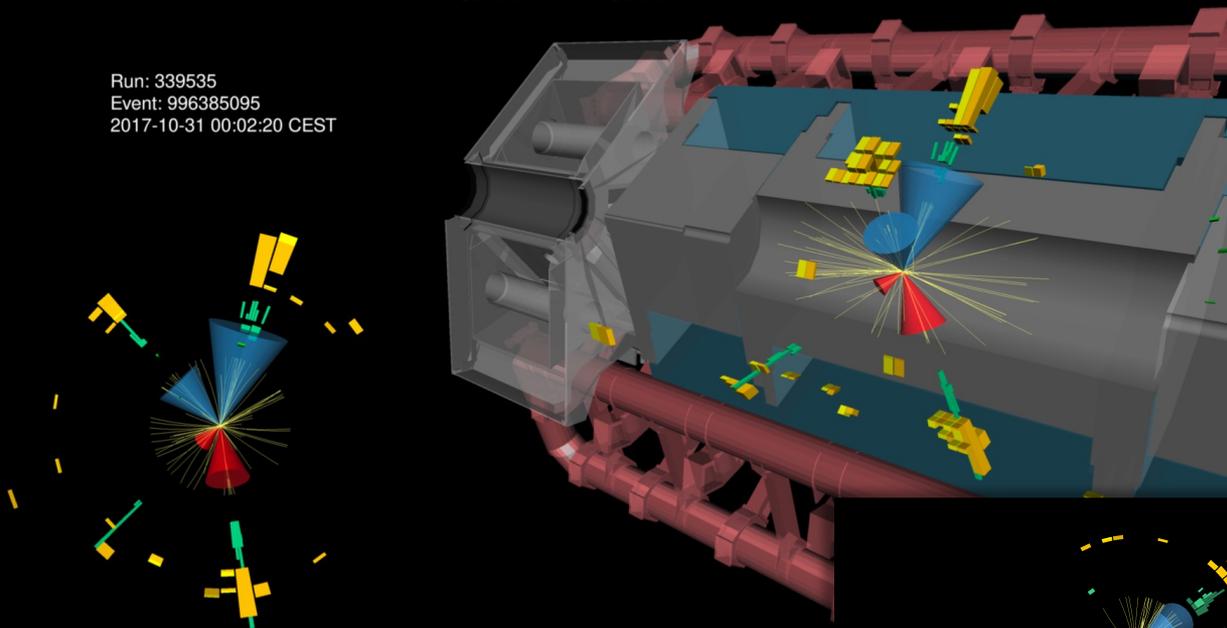
- **Single BDT for all resonances (mass dependent cut), 2 BDTs to separate signal vs continuum and single Higgs backgrounds, scores combined in BDT_{tot} , signal extracted from $m_{\gamma\gamma}$**



~ 30% improvement from BDT strategy on top of luminosity increase wrt 36 fb^{-1} results

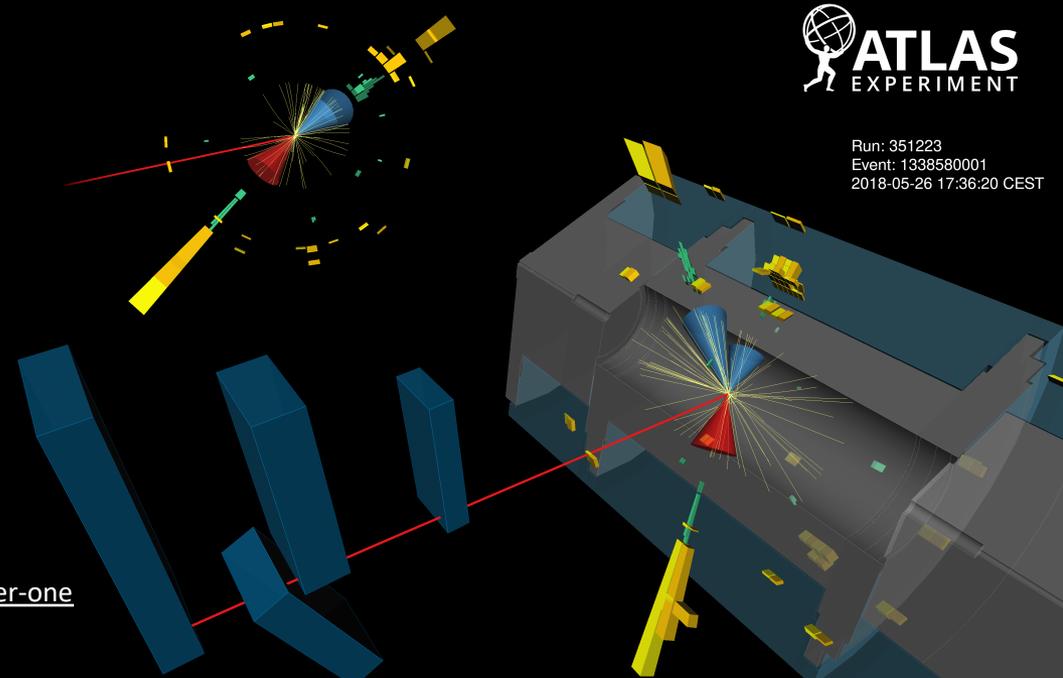
$\tau_{had} - \tau_{had}$

Run: 339535
 Event: 996385095
 2017-10-31 00:02:20 CEST



$\tau_{lep} - \tau_{had}$

Run: 351223
 Event: 1338580001
 2018-05-26 17:36:20 CEST



Publication: ATLAS-CONF-2021-030

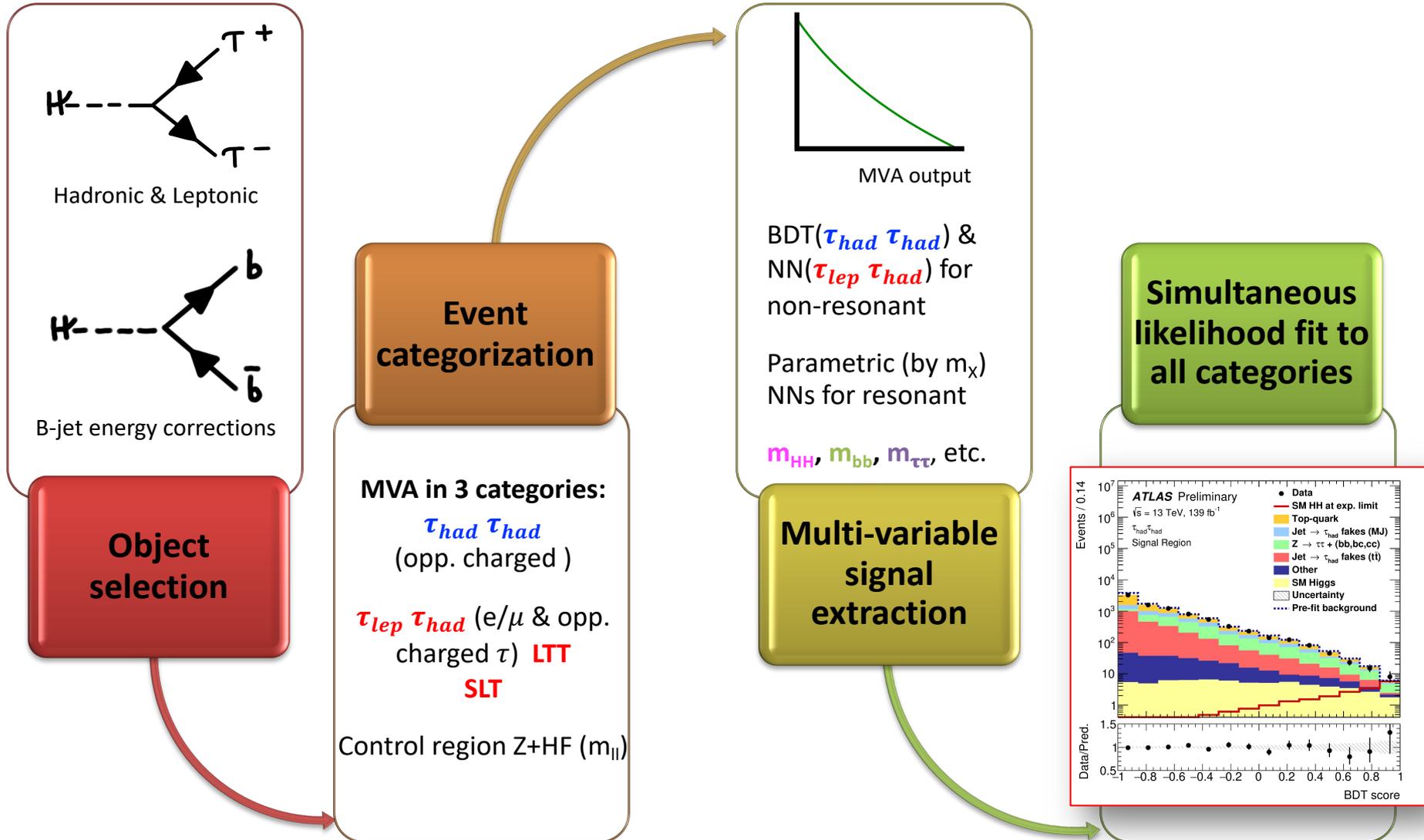
Physics Briefing: <https://atlas.cern/updates/briefing/two-Higgs-better-one>

$HH \rightarrow b\bar{b}\tau\tau$ analysis in a nutshell

Relatively large BR and relatively clean final state

Single Tau Trigger & Di-Tau Trigger for $\tau_{had} \tau_{had}$

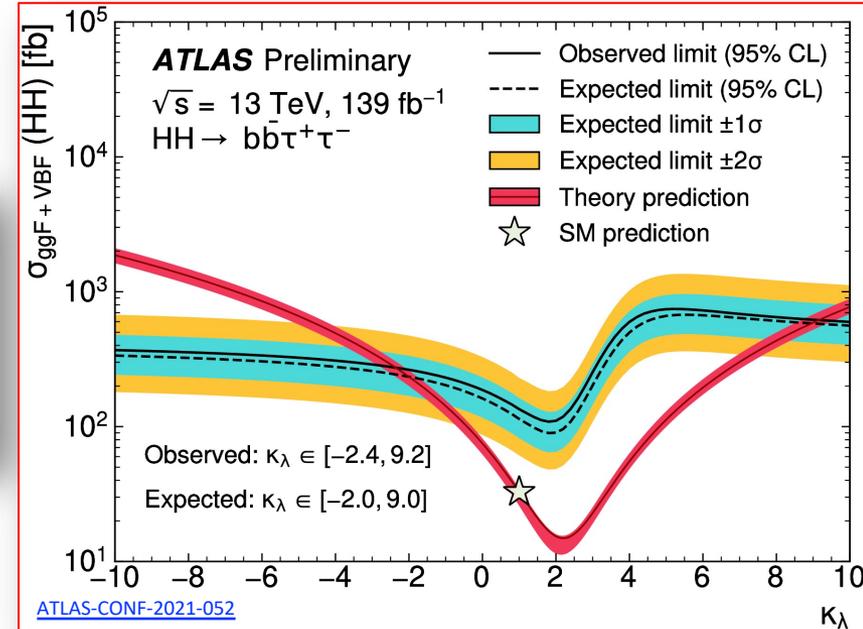
Single Lepton Trigger (SLT) and Lepton+Tau Trigger (LTT) in $\tau_{lep} \tau_{had}$



Non-resonant $HH \rightarrow b\bar{b}\tau\tau$ results

Non-resonant analysis thoroughly optimized for SM cross-section limit!

		Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
$\tau_{\text{had}}\tau_{\text{had}}$	$\sigma_{\text{ggF+VBF}}$ [fb]	145	70.5	94.6	131	183	245
	$\sigma_{\text{ggF+VBF}}/\sigma_{\text{ggF+VBF}}^{\text{SM}}$	4.95	2.38	3.19	4.43	6.17	8.27
$\tau_{\text{lep}}\tau_{\text{had}}$	$\sigma_{\text{ggF+VBF}}$ [fb]	265	124	167	231	322	432
	$\sigma_{\text{ggF+VBF}}/\sigma_{\text{ggF+VBF}}^{\text{SM}}$	9.16	4.22	5.66	7.86	10.9	14.7
Combined	$\sigma_{\text{ggF+VBF}}$ [fb]	135	61.3	82.3	114	159	213
	$\sigma_{\text{ggF+VBF}}/\sigma_{\text{ggF+VBF}}^{\text{SM}}$	4.65	2.08	2.79	3.87	5.39	7.22

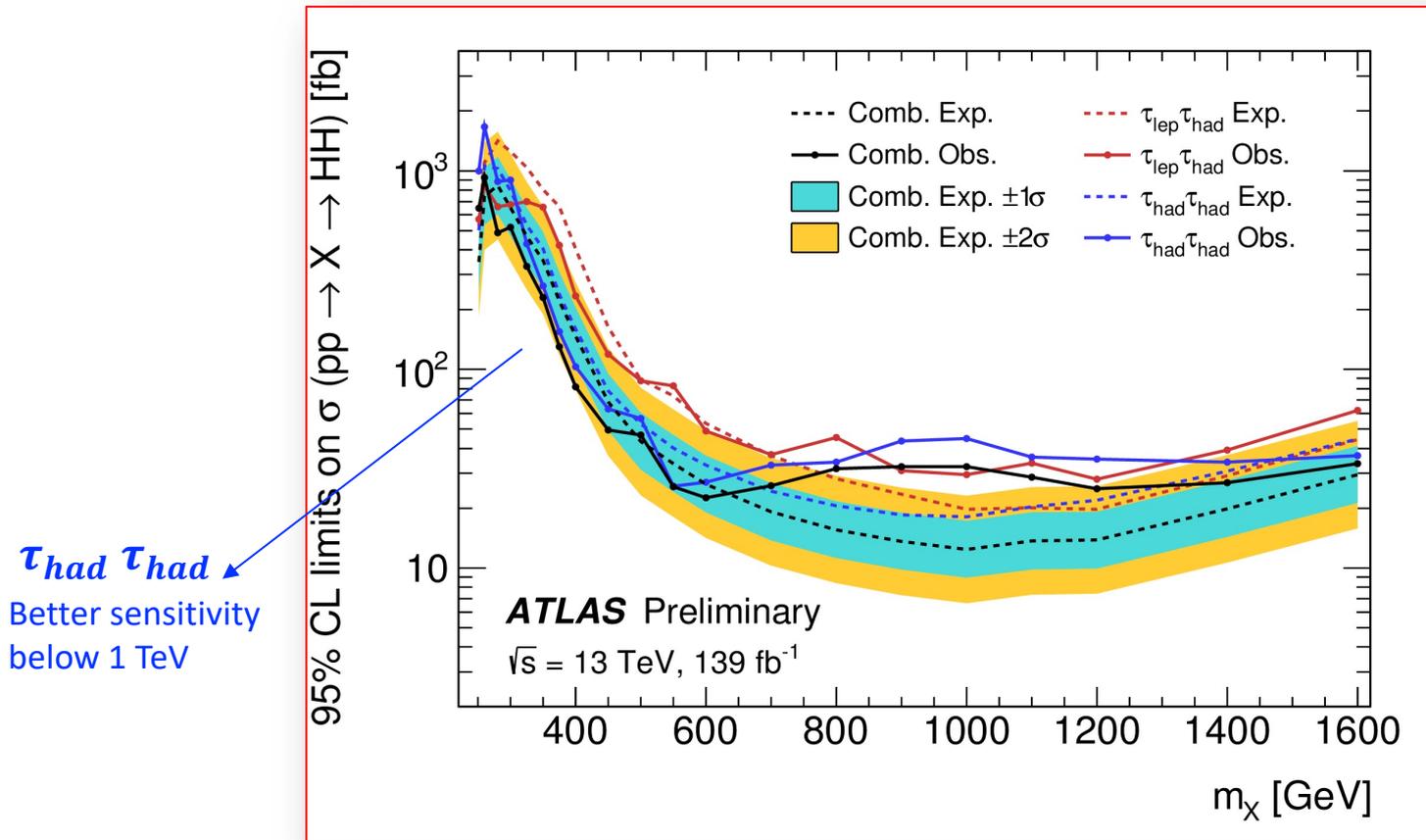


4x improvement wrt to previous results! (12.7 x SM),

2x due to the τ and b -jet reconstruction and identification improvements and to analysis techniques (MVA & fake- τ estimation methods).

- Statistically dominated, largest systematics from background modeling

Resonant $HH \rightarrow b\bar{b}\tau\tau$ results



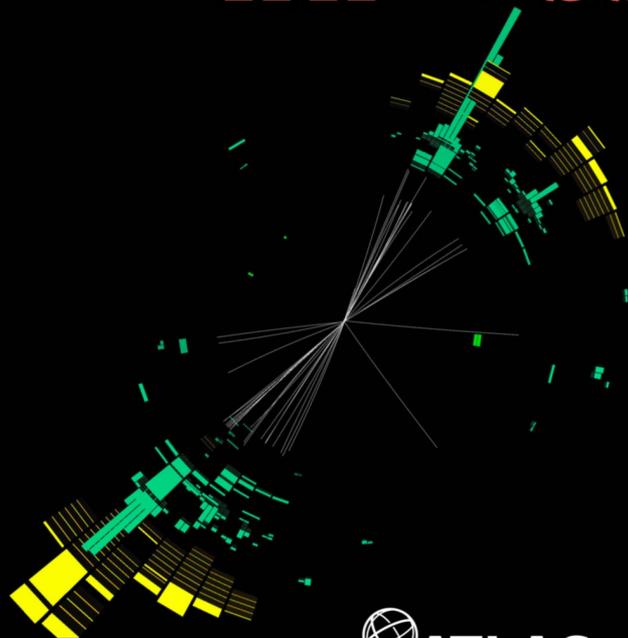
- Broad excess @ $700 \text{ GeV} < m_\chi < 1.2 \text{ TeV}$.
- Most significant excess for $\tau_{had}\tau_{had}$ ($\tau_{lep}\tau_{had}$) found @ 1 TeV (1.1 TeV), local significance of 2.8σ (1.6σ).
- Combined: @1 TeV, local significance 3.1σ , global significance of $2.1^{+0.4}_{-0.2}\sigma$.

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



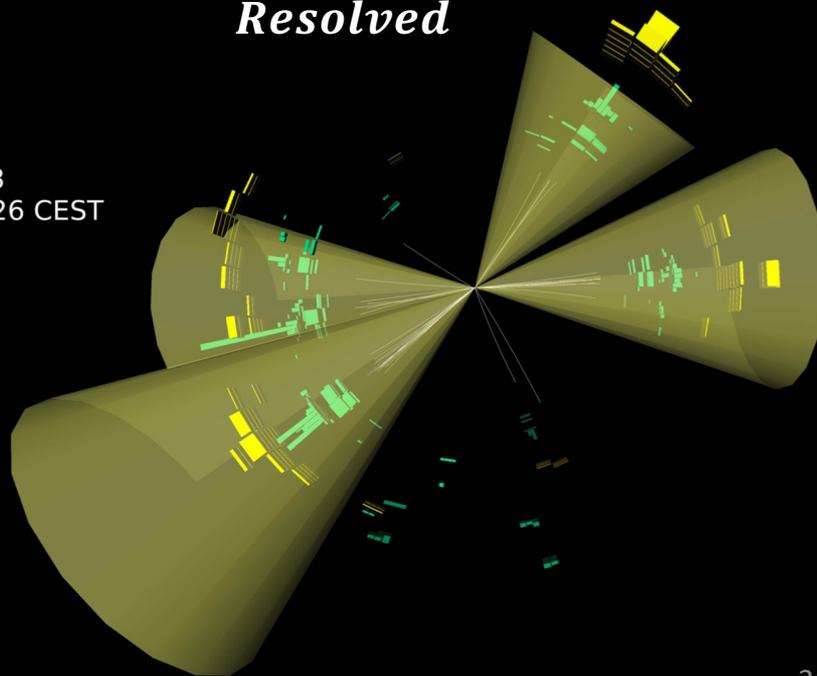
Run: 356259
Event: 311347503
2018-07-22 20:00:32 CEST

Boosted



Run: 350013
Event: 1556168518
2018-05-11 01:39:26 CEST

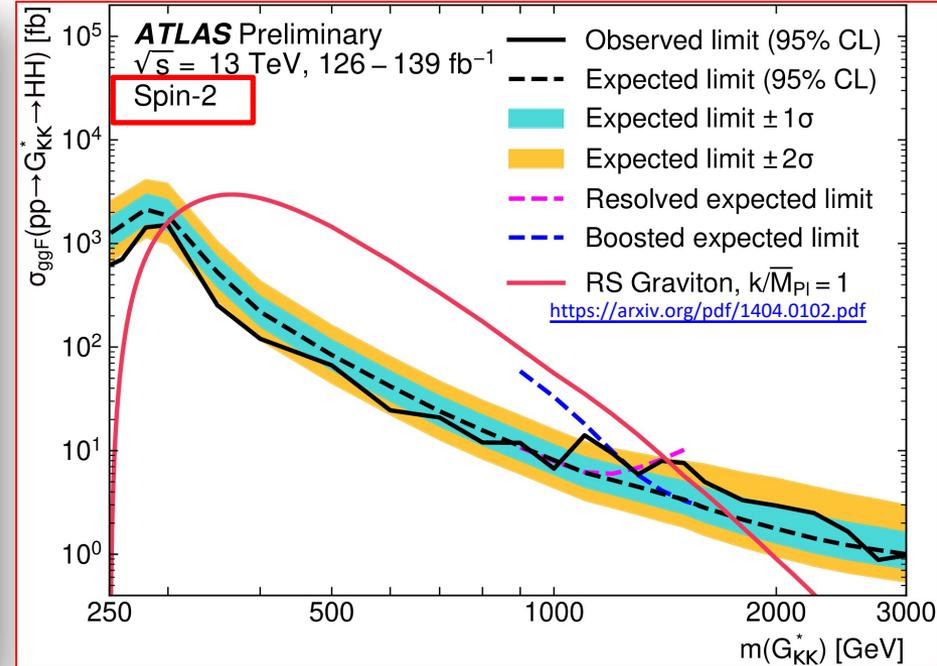
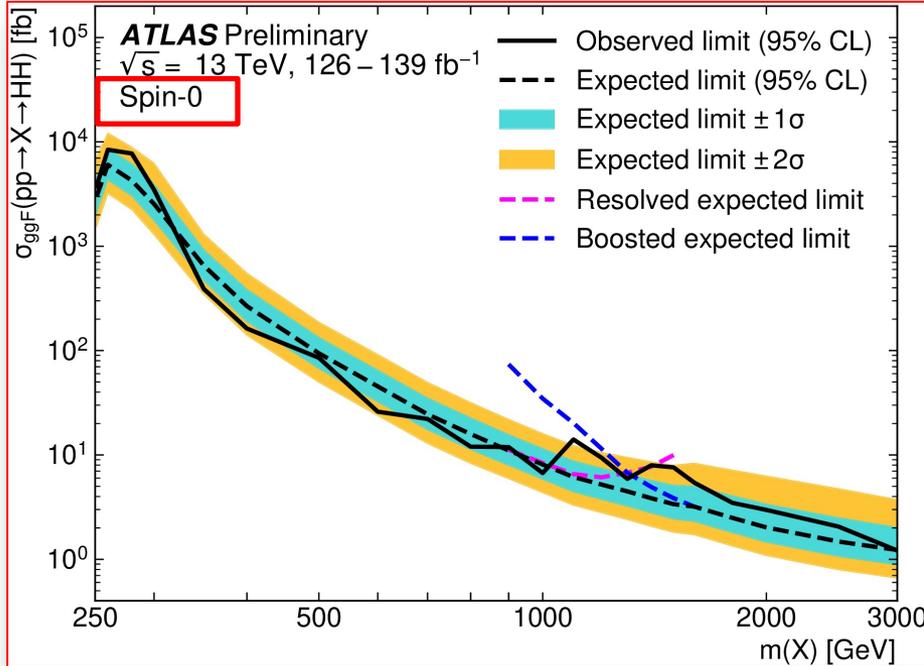
Resolved



Publication: [ATLAS-CONF-2021-035](#)
Physics Briefing: <https://atlas.cern/updates/briefing/double-Higgs-to-bottoms>

$HH \rightarrow \overline{b}b\overline{b}b$

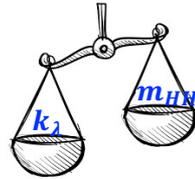
Largest BR, but large multi-jet backgrounds and challenging combinatorics
 Only ggF **resonant** production considered



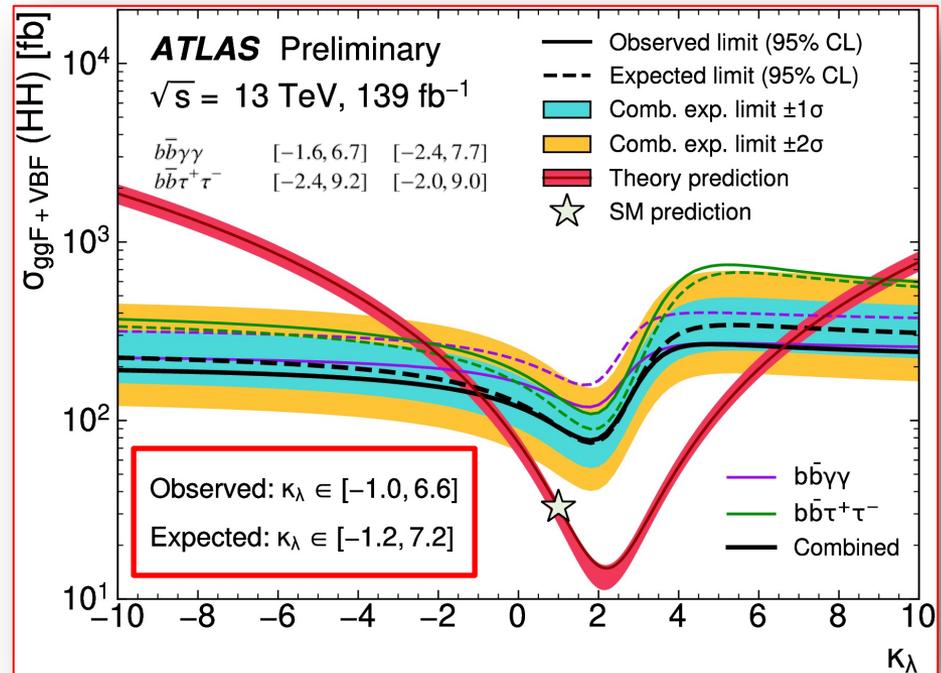
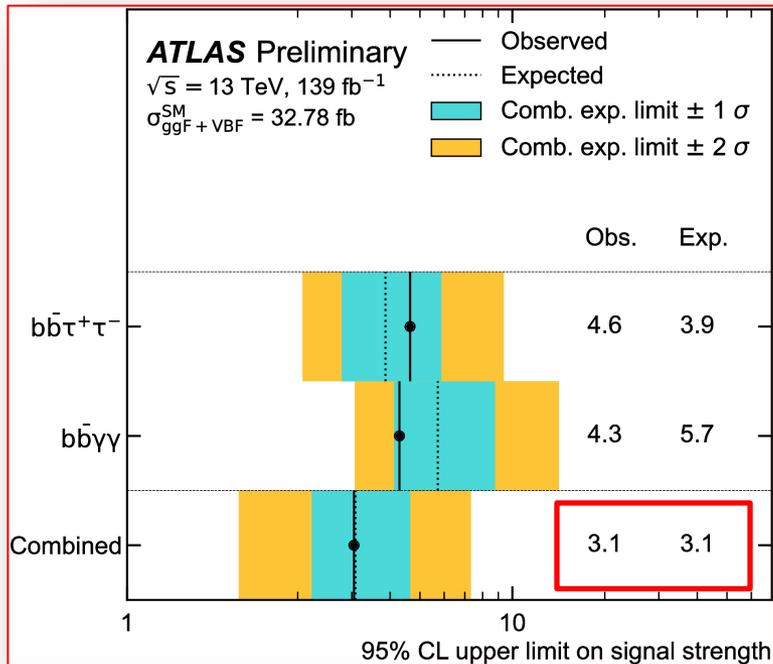
model excluded for graviton masses between 298 GeV and 1440 GeV.

Excess @ 1.1 TeV,
 local (global) significance = 2.6σ (1.0σ) for *spin-0* and 2.7σ (1.2σ) for *spin-2*.
 Statistically dominated results, systematic effects up to $\sim 16\%$, mostly from background modeling

Putting everything together



Non-resonant

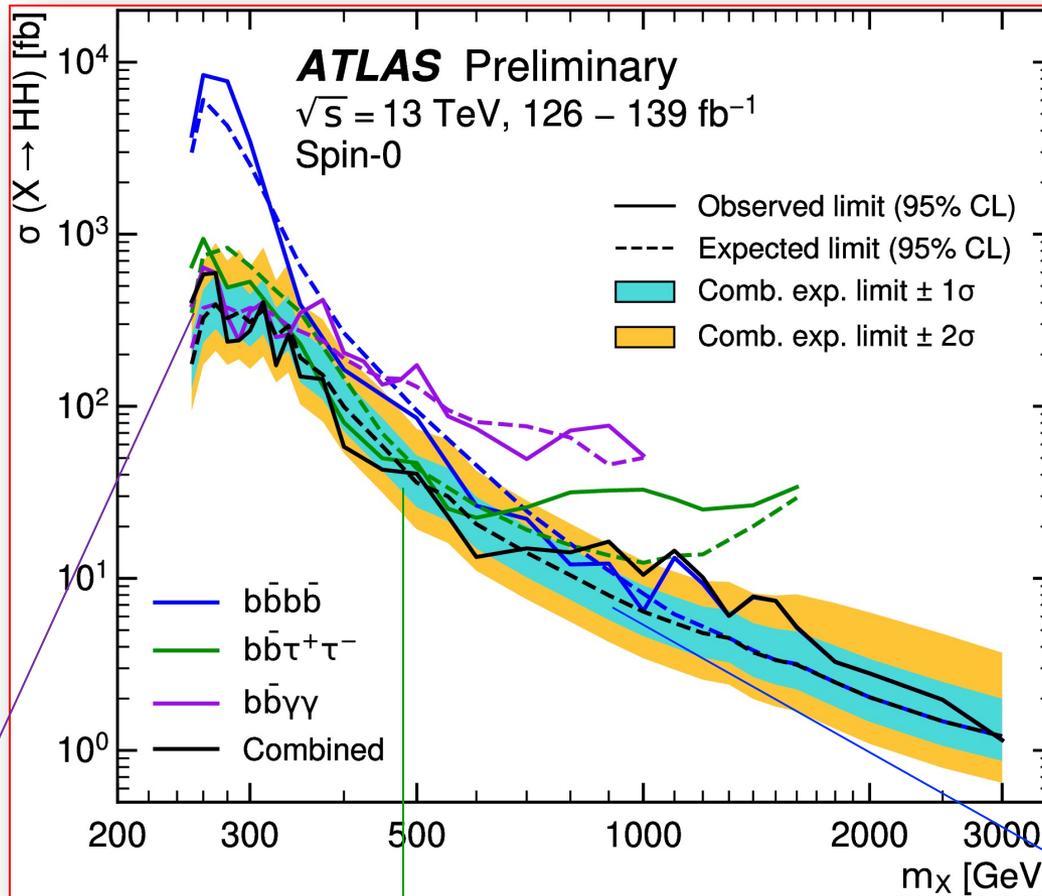


Single channels are now even better than the
36 fb⁻¹ HH combination

HH σ^{SM} 6.9 Obs, 10 Exp
 Observed $k_\lambda \in [-5, 12.0]$
 Expected $k_\lambda \in [-5.8, 11.5]$

Putting everything together

Resonant



$b\bar{b}\gamma\gamma$ dominates the sensitivity at low m_X

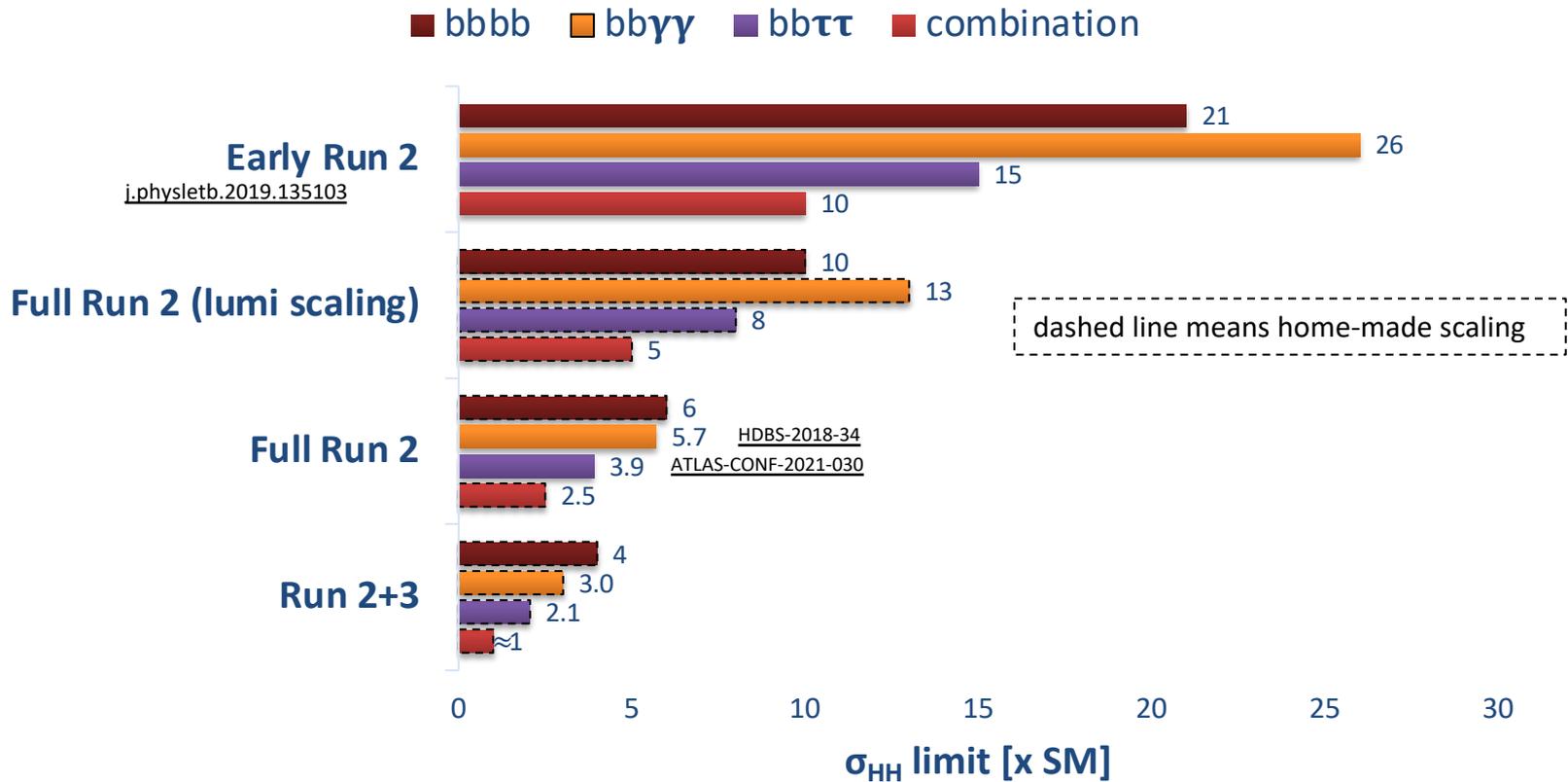
$b\bar{b}\tau\tau$ dominates the sensitivity at medium m_X

$b\bar{b}b\bar{b}$ dominates the sensitivity at high m_X

An exciting time ahead

Run 3 coming up!

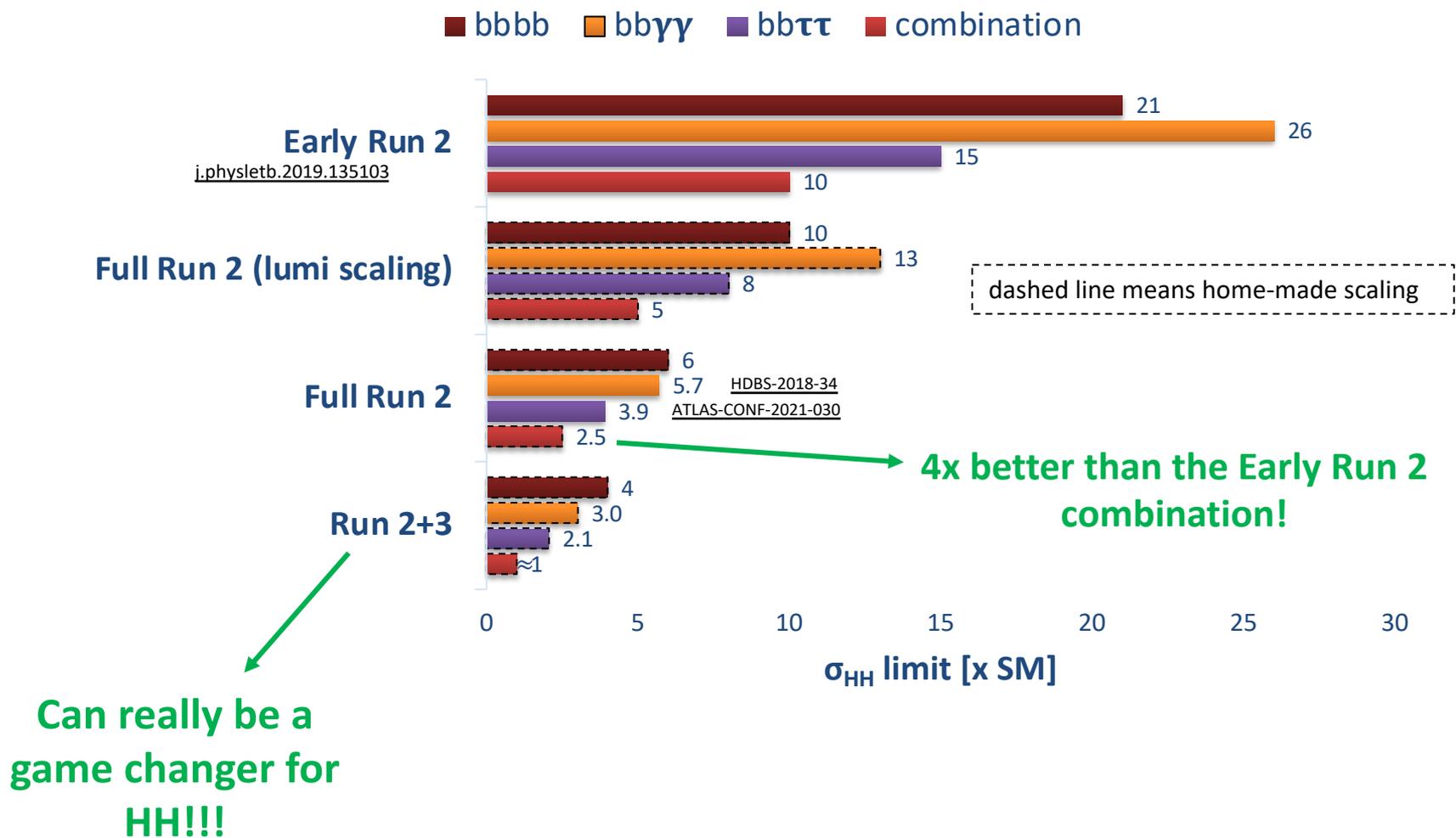
Run 3: σ_{HH} @ 13.6 TeV \approx +11% σ_{HH} @ 13 TeV, $\int L \approx$ +300 fb⁻¹? \approx +10k HH events!



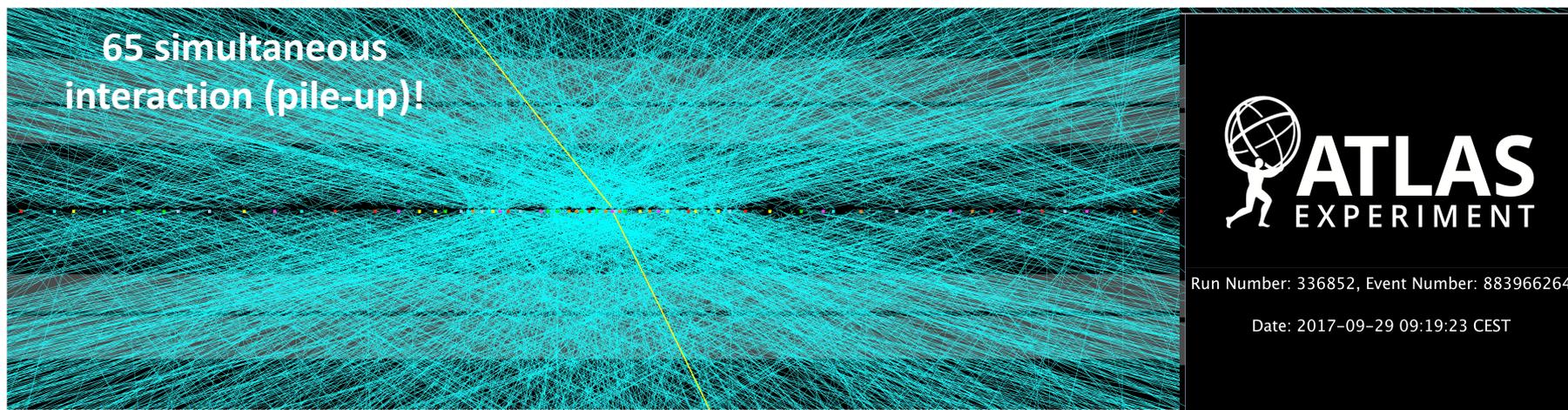
An exciting time ahead

Run 3 coming up!

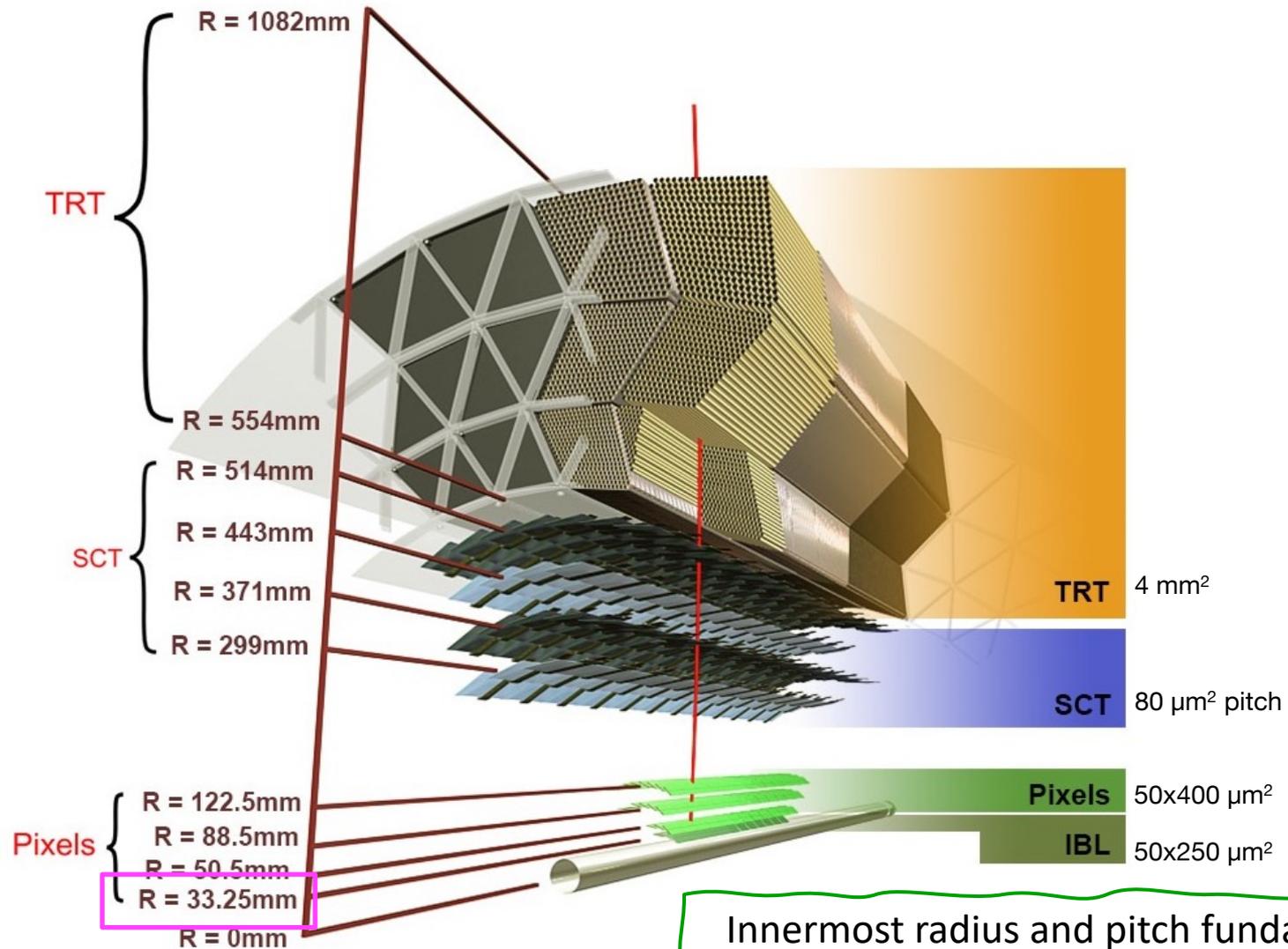
Run 3: σ_{HH} @ 13.6 TeV \approx +11% σ_{HH} @ 13 TeV, $\int L \approx$ +300 fb⁻¹? \approx +10k HH events!



Preparing for Run 3



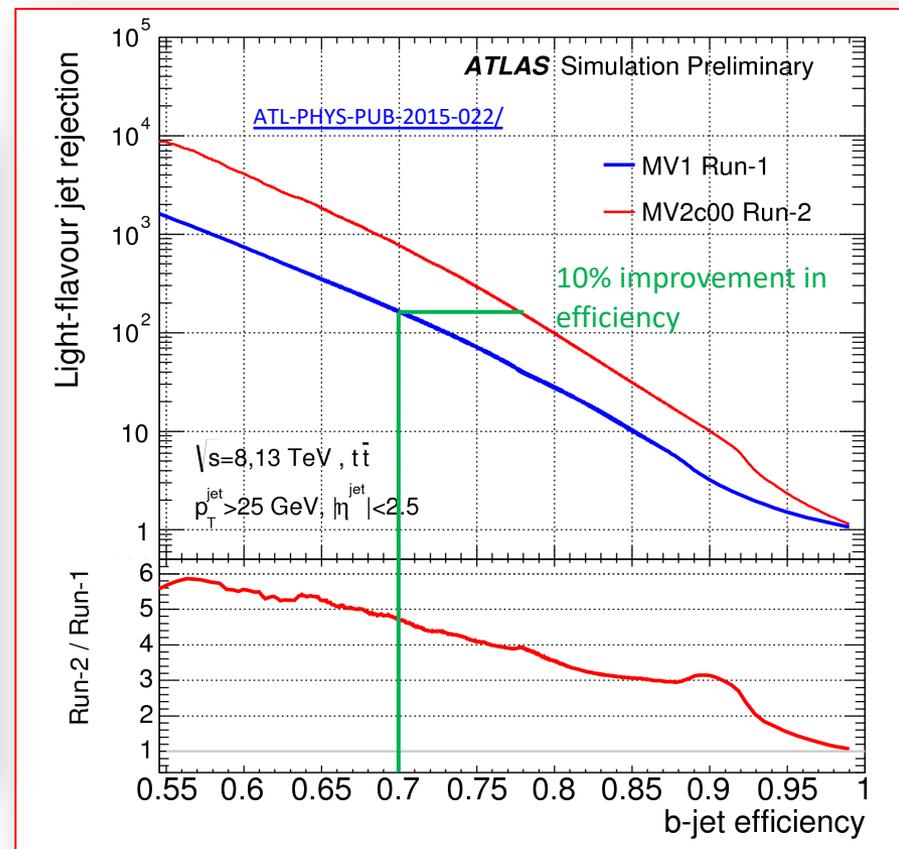
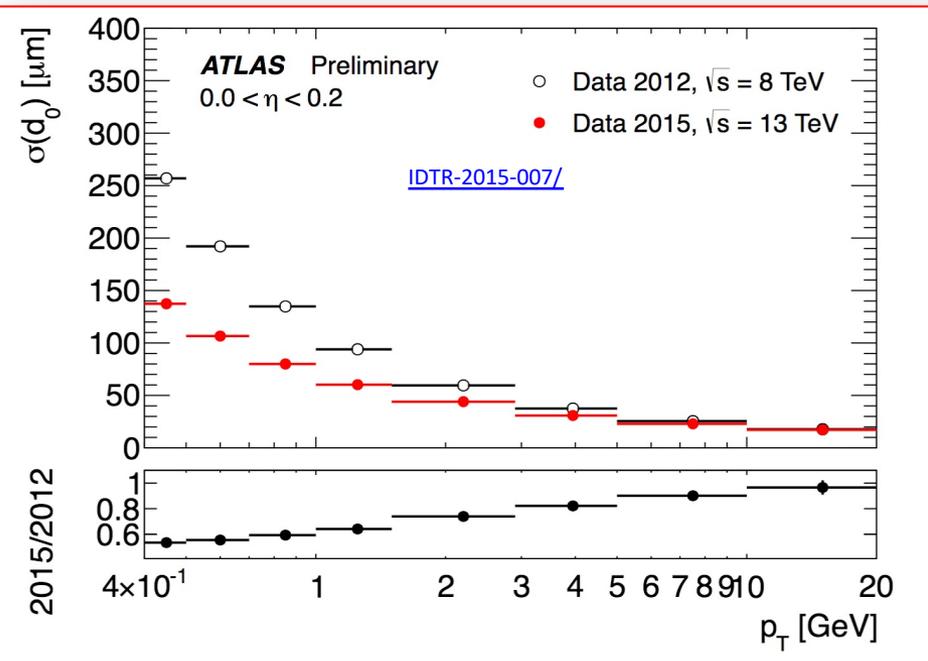
The ATLAS Run2/3 Inner Detector



Innermost radius and pitch fundamental for **impact parameter** determination and thus **b-tagging performance!**

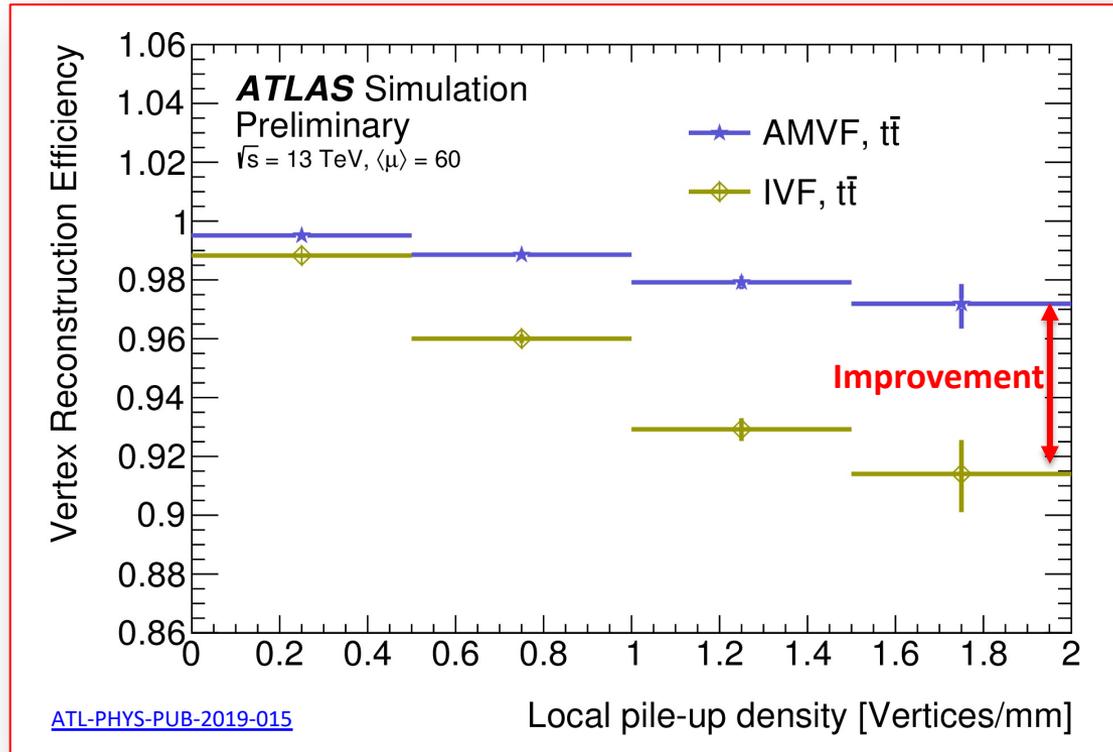
Run 2 Performance Highlights

- Tracking and Vertexing are key ingredients for physics analyses
- **Run 1** → **Run 2**: upgraded detector
 - 2x better IP resolution, 4-5x better light-jet rejection in b-tagging



Run 3 Performance Highlights

- **Run 2** → **Run 3** : aging detector and more challenging pile-up conditions
- All physics objects must be reconstructed wrt the correct primary vertex
- **New primary vertexing algorithm** deployed to improve pile-up robustness



Significant performance improvements:

~**10%** better vertex selection efficiency, ~**20%** better longitudinal resolution,
~**30%** inclusive efficiency recovery

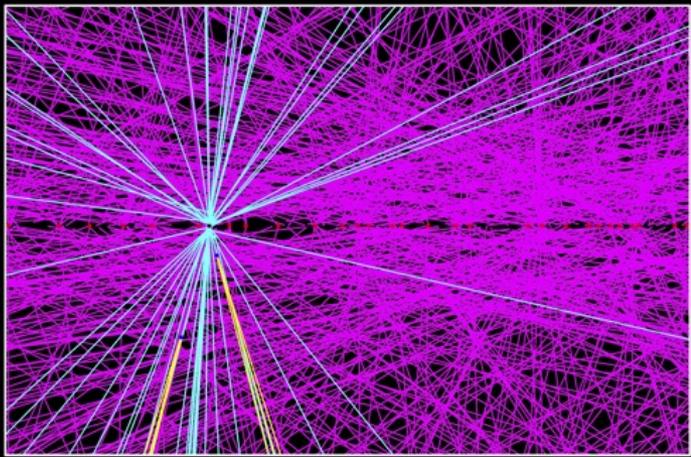
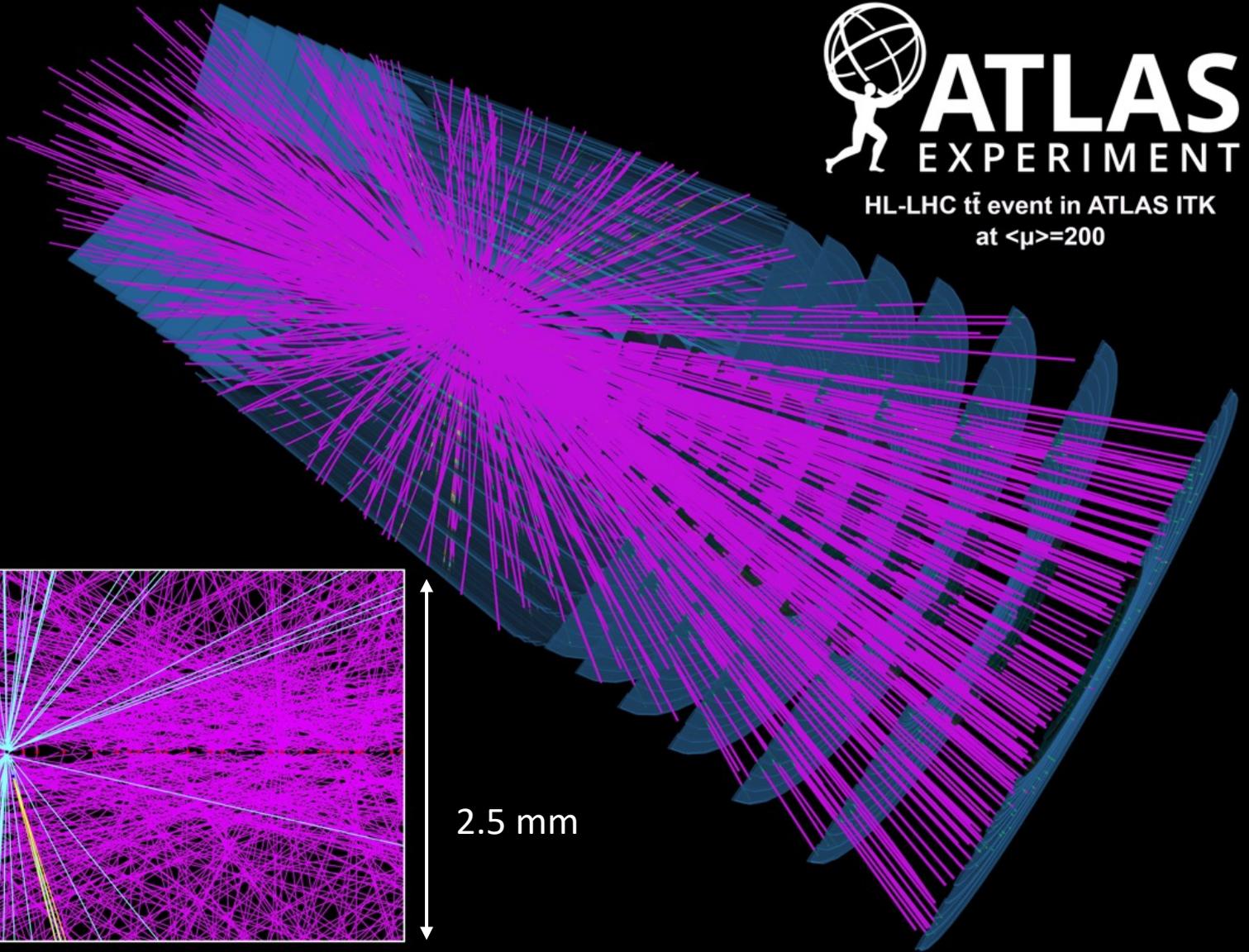
All relevant for **the HL-LHC ATLAS silicon Inner Tracker (ITk)**

Preparing for Run 4



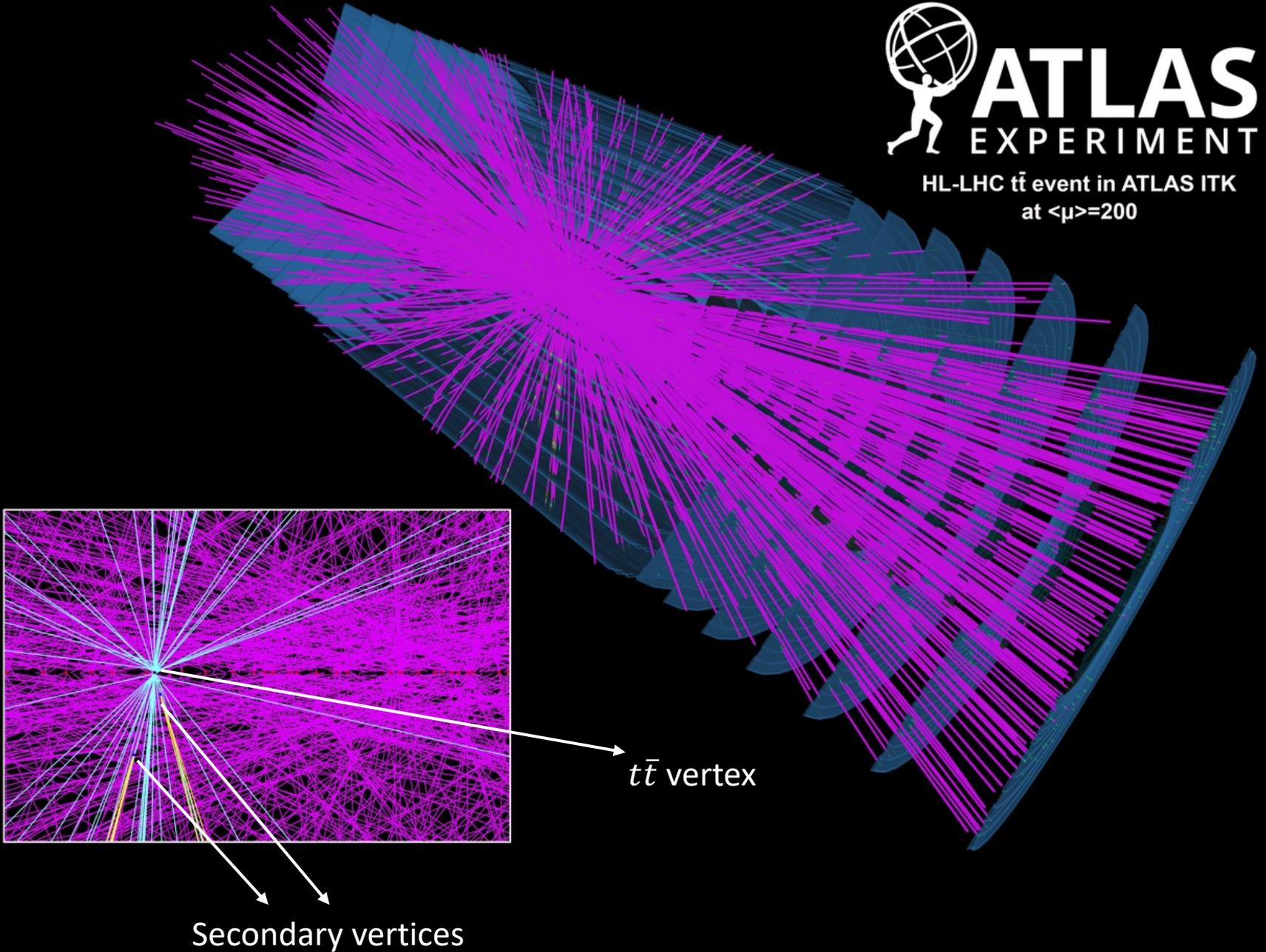
F. Cairo, From Conn(II)ecting the dots

HL-LHC $t\bar{t}$ event in ATLAS ITK
at $\langle\mu\rangle=200$



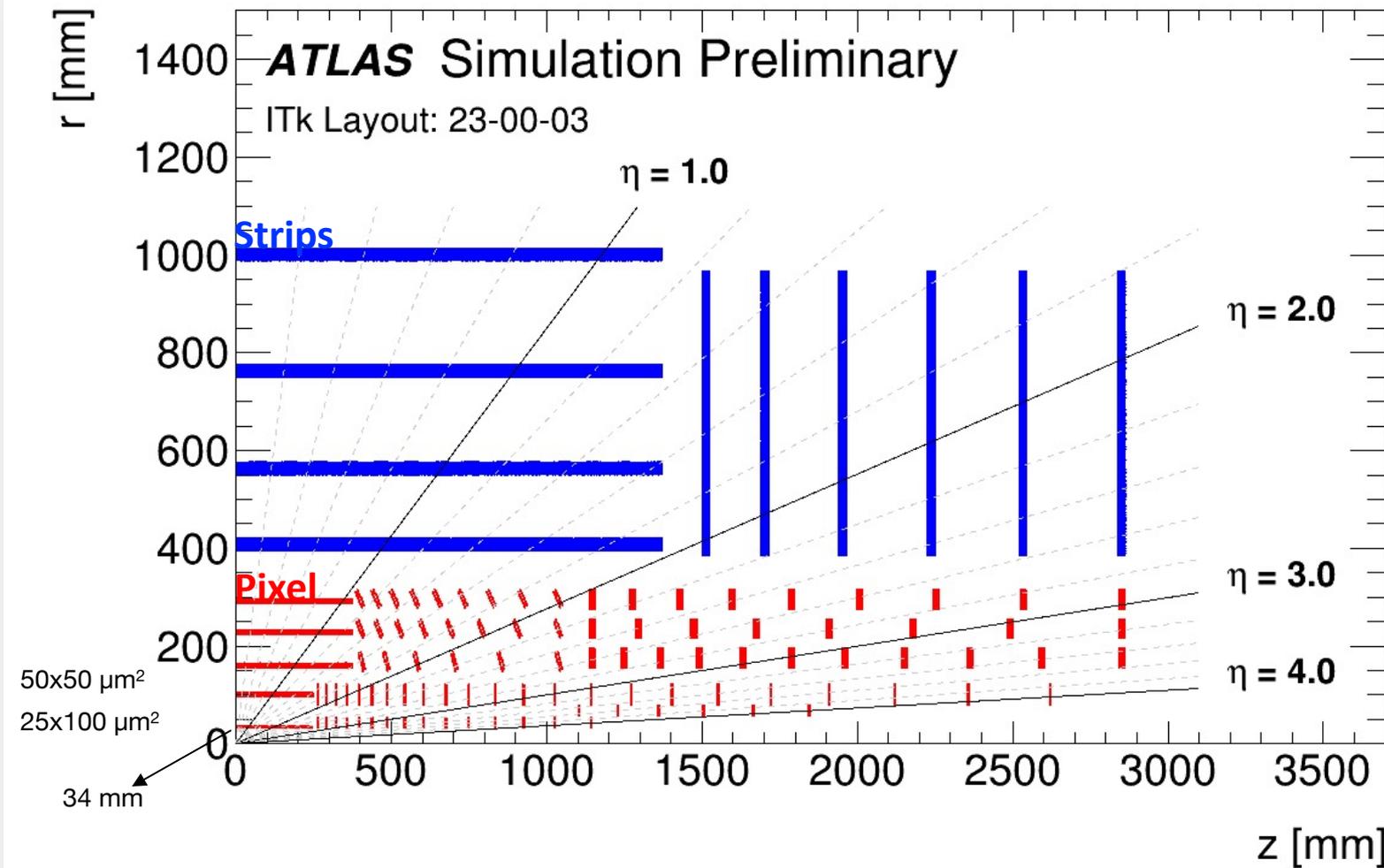
2.5 mm

12 cm



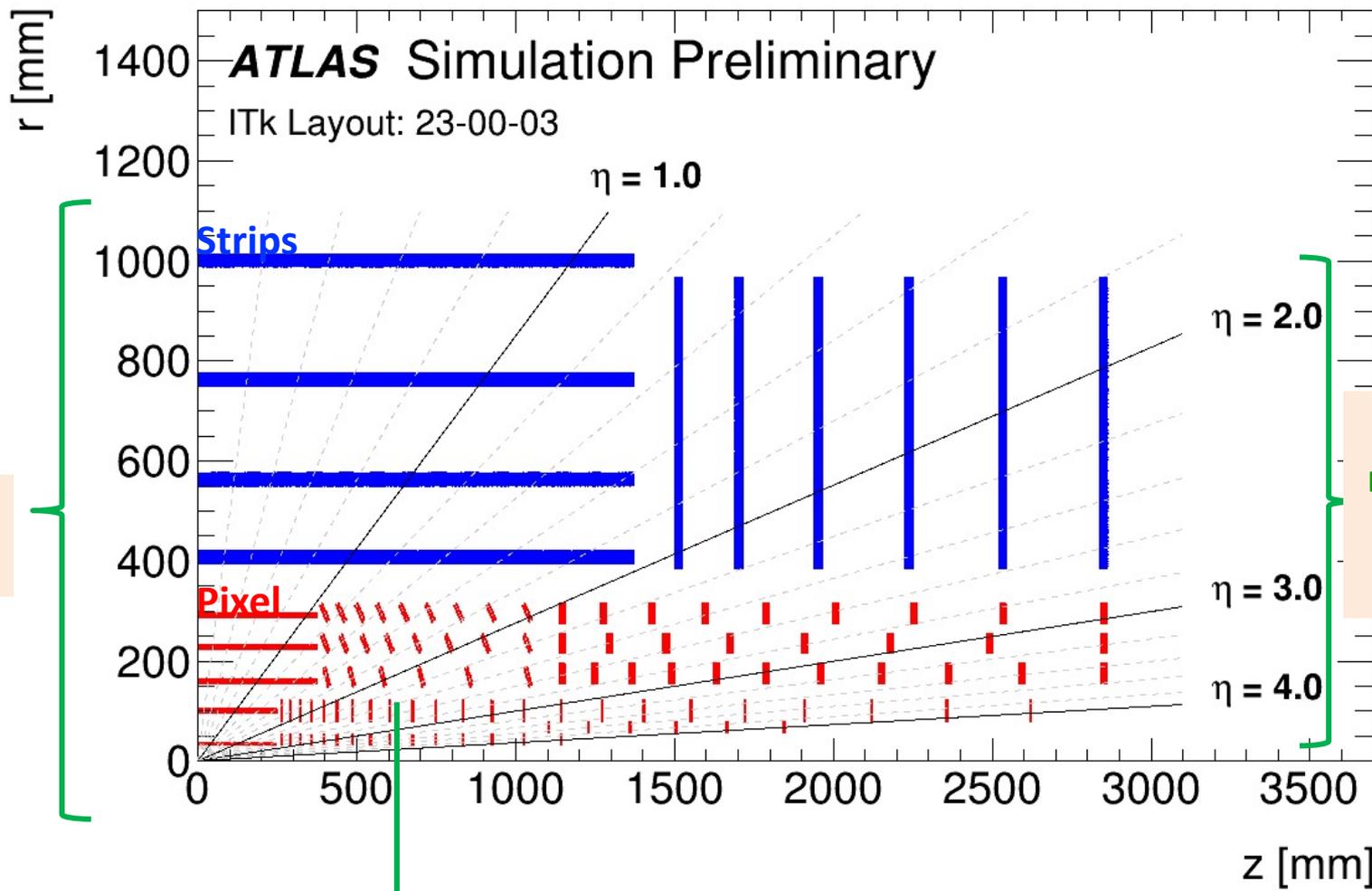
The ATLAS Run 4 Inner Tracker

[ATL-PHYS-PUB-2021-024-](#)



The ATLAS Run 4 Inner Tracker

ATL-PHYS-PUB-2021-024-



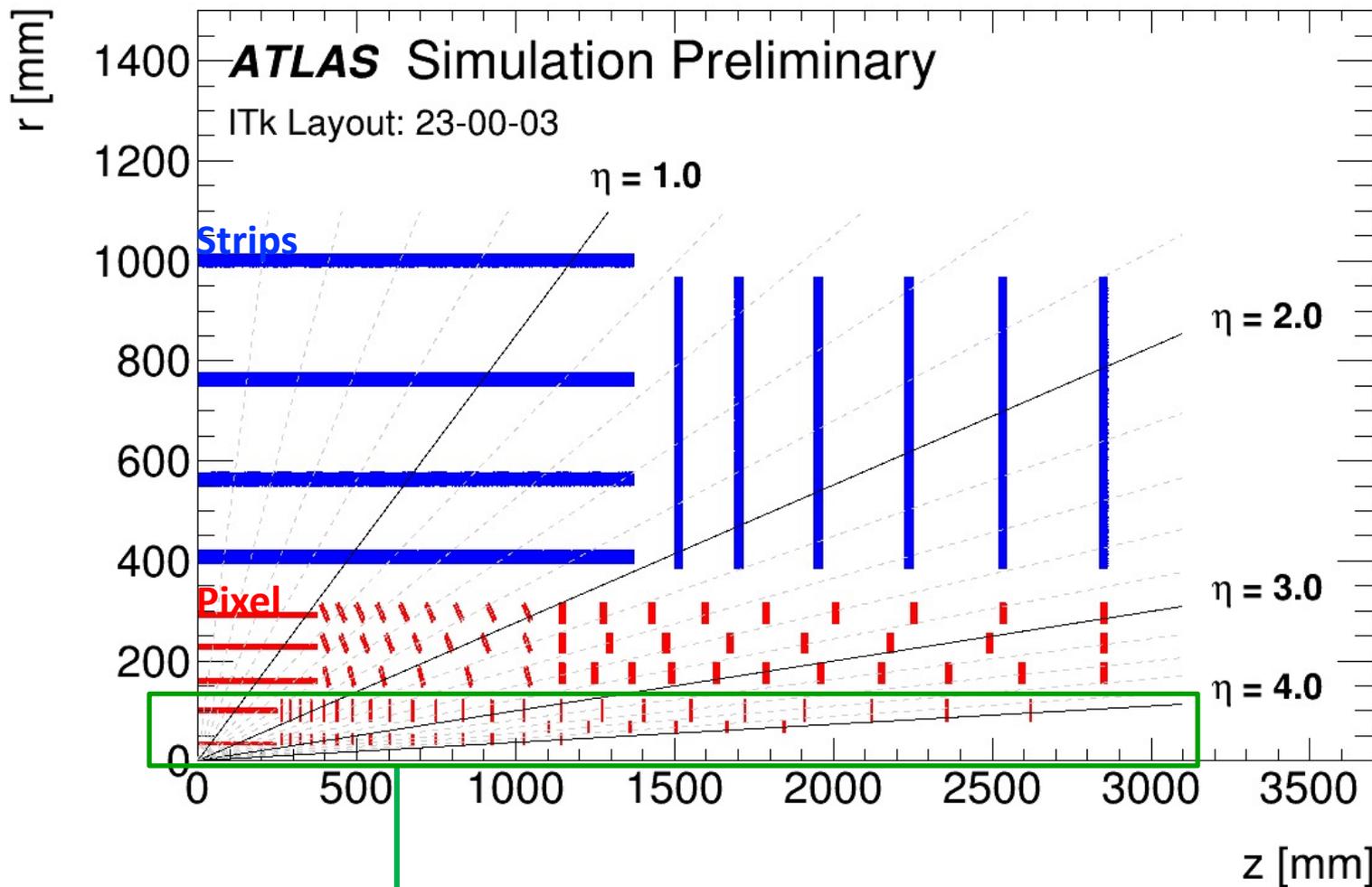
All silicon

Increased η coverage (from 2.4 to 4.0)

Inclined layout

The ATLAS Run 4 Inner Tracker

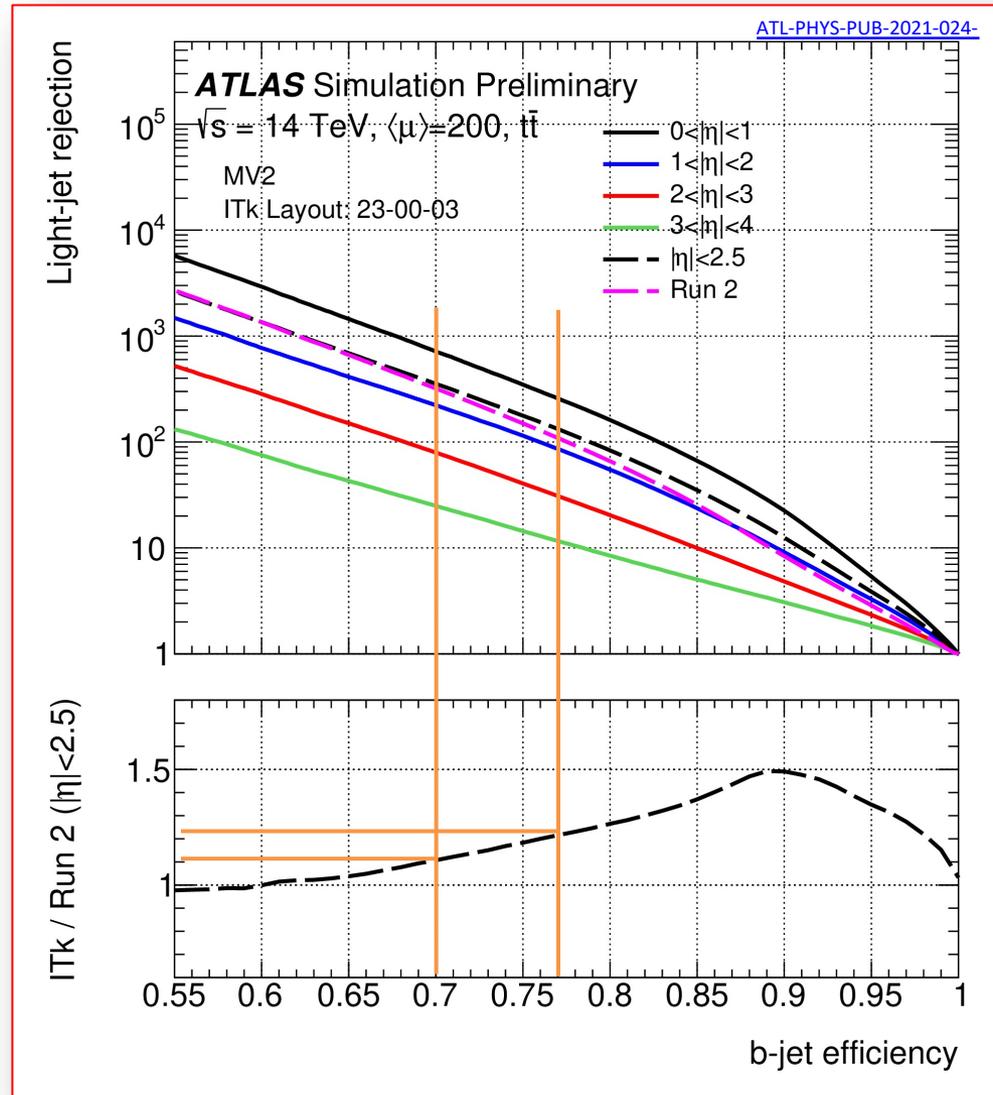
ATL-PHYS-PUB-2021-024-



Extractable & Replaceable

Radiation hardness up to 10-15 MGy

Run 4 Performance Highlights



20% improvement in light-jet rejection at the 77% b-tag WP

High-Luminosity LHC projections

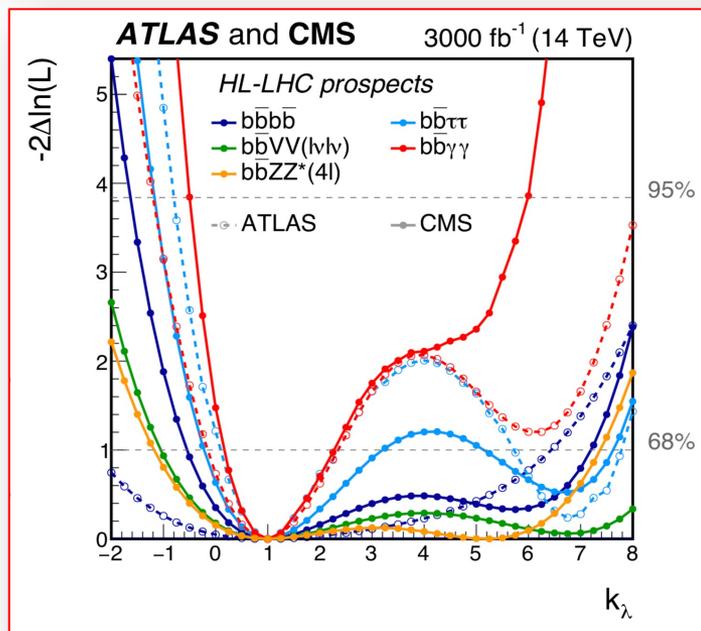
- Existing **combined** projections based on Early Run 2 results!

[ATL-PHYS-PUB-2020-005](#)

ATLAS (old) HL-LHC projections

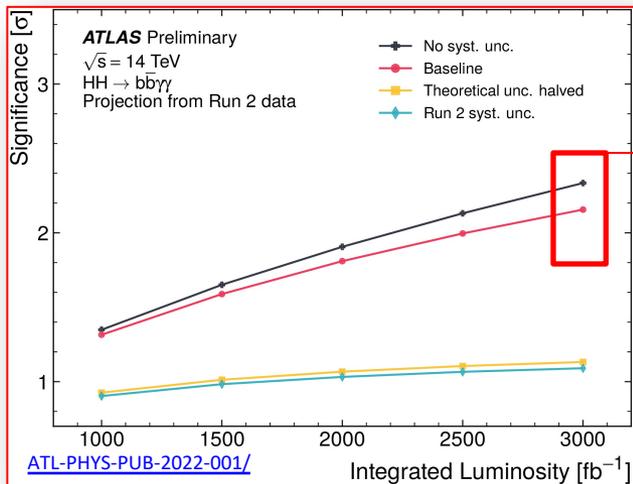
Channel	Statistical-only	Statistical + Systematic
$HH \rightarrow b\bar{b}b\bar{b}$	1.2	0.5
$HH \rightarrow b\bar{b}\tau^+\tau^-$	2.3	2.0
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.3 σ	2.9 σ

ATLAS + CMS
 $\sim 4 \sigma$ (50% precision)
[j.revip.2020.100045](#)



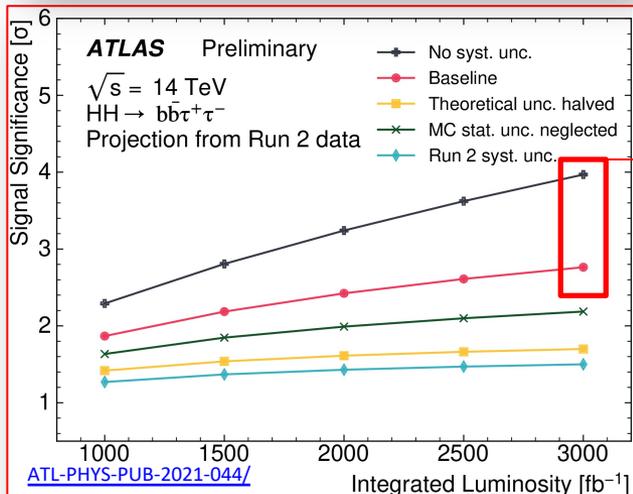
High-Luminosity LHC projections

- Existing **combined** projections based on Early Run 2 results!
 - Now great **analysis improvements** in all final states compared to Early Run 2
 - Single-channel projections have been updated for various systematics scenarios**



$$HH \rightarrow b\bar{b}\gamma\gamma$$

Scenario	95% CL Upper Limit	Significance [σ]
No syst. unc.	0.86	2.3 was 2.1
Baseline	0.93	2.2 was 2.0



$$HH \rightarrow b\bar{b}\tau\tau$$

Uncertainty Scenario	95% CL Upper Limit	Significance [σ]
No syst. unc.	0.49	4.0 was 2.3
Baseline	0.71	2.8 was 2.0

What's next?



Relative view point, by F. Cairo

Further in the future

- **Probing λ** is a **high priority** for the particle physics community both at the LHC and beyond
- Rich set of **di-Higgs** searches ongoing whose final states involve **multiple objects**
 - advanced reconstruction techniques
 - new detector technologies
- Benchmark for the **future HEP machines and driver for their detector design!**

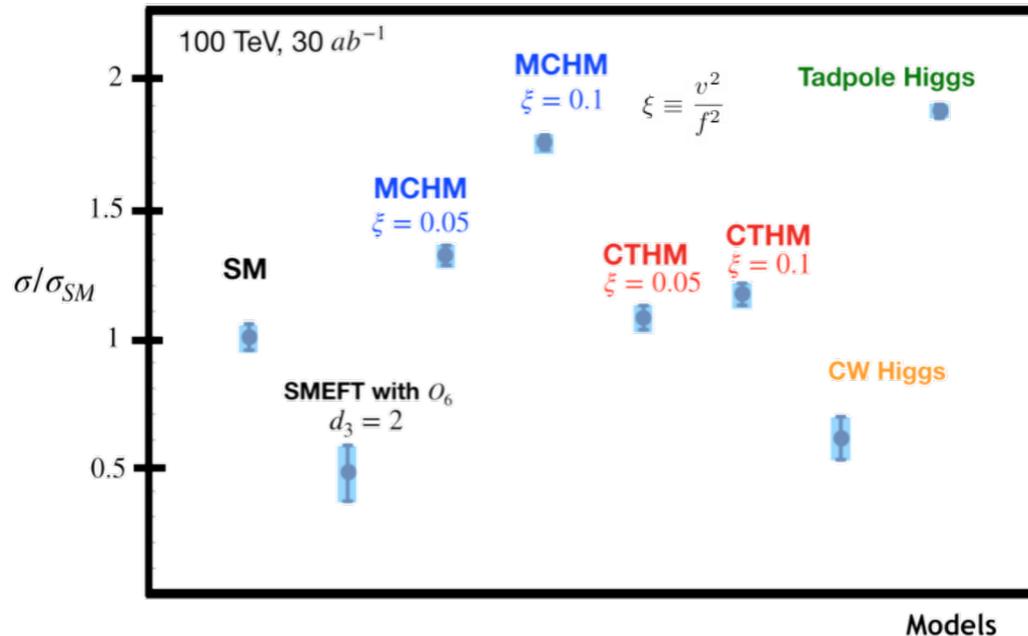
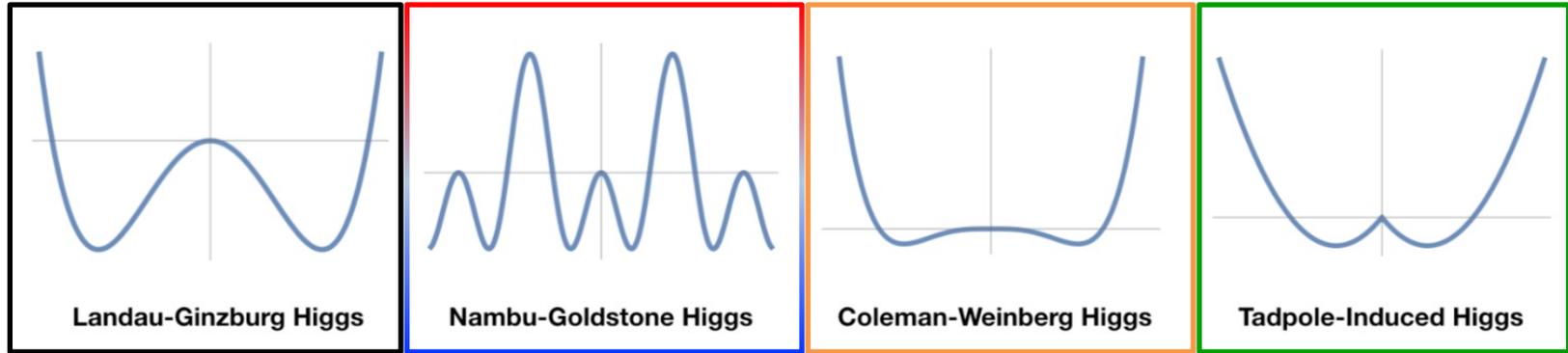
	collider	single- H	HH	combined
	HL-LHC	100-200%	50%	50%
	CEPC ₂₄₀	49%	–	49%
	ILC ₂₅₀	49%	–	49%
	ILC ₅₀₀	38%	27%	22%
	ILC ₁₀₀₀	36%	10%	10%
	CLIC ₃₈₀	50%	–	50%
	CLIC ₁₅₀₀	49%	36%	29%
	CLIC ₃₀₀₀	49%	9%	9%
	FCC-ee	33%	–	33%
	FCC-ee (4 IPs)	24%	–	24%
	HE-LHC 	-	15%	15%
	FCC-hh 	-	5%	5%

[j.revip.2020.100045](https://arxiv.org/abs/2002.01004)

Run 3: 
 bronze precision or
 better?

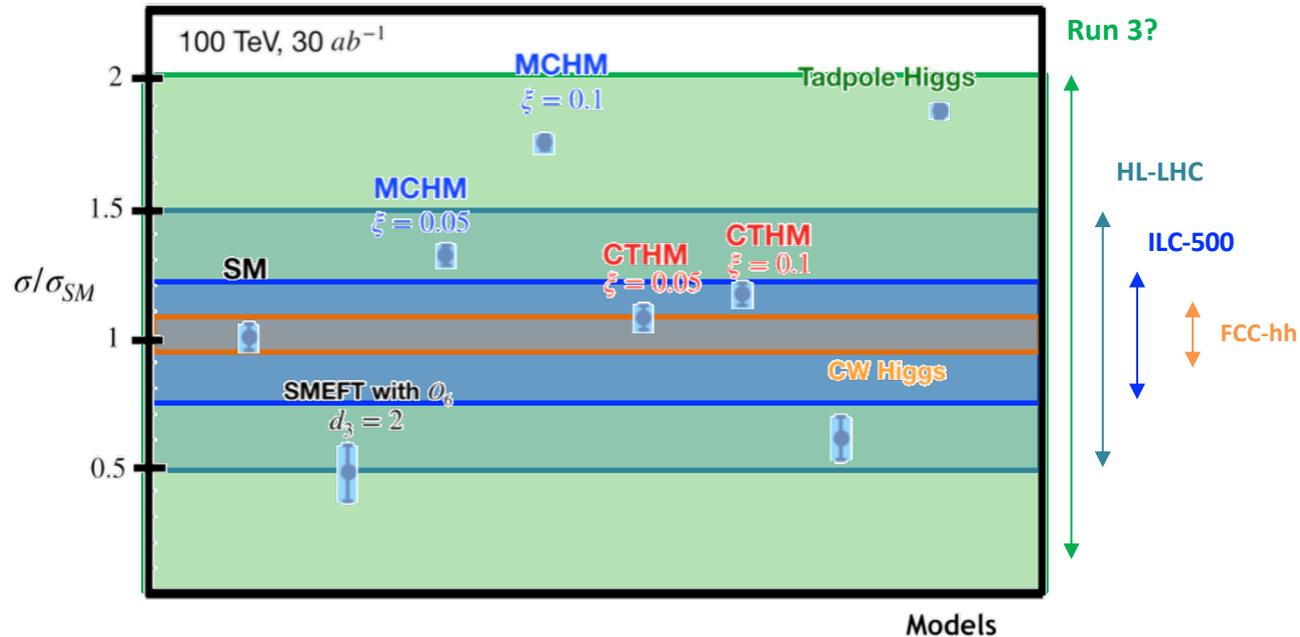
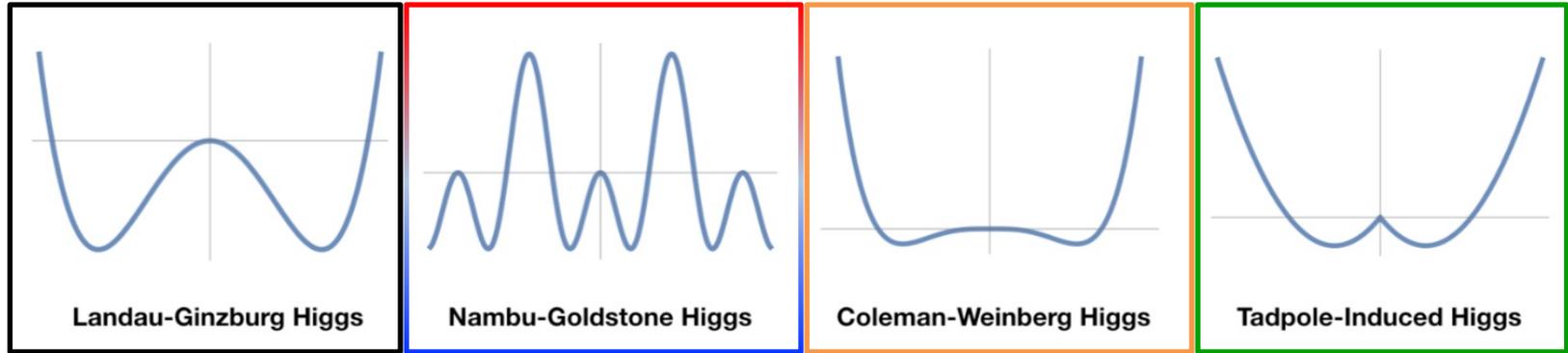
Di-Higgs Prospects for the far future

As an example: [arXiv:1907.02078v2](https://arxiv.org/abs/1907.02078v2)



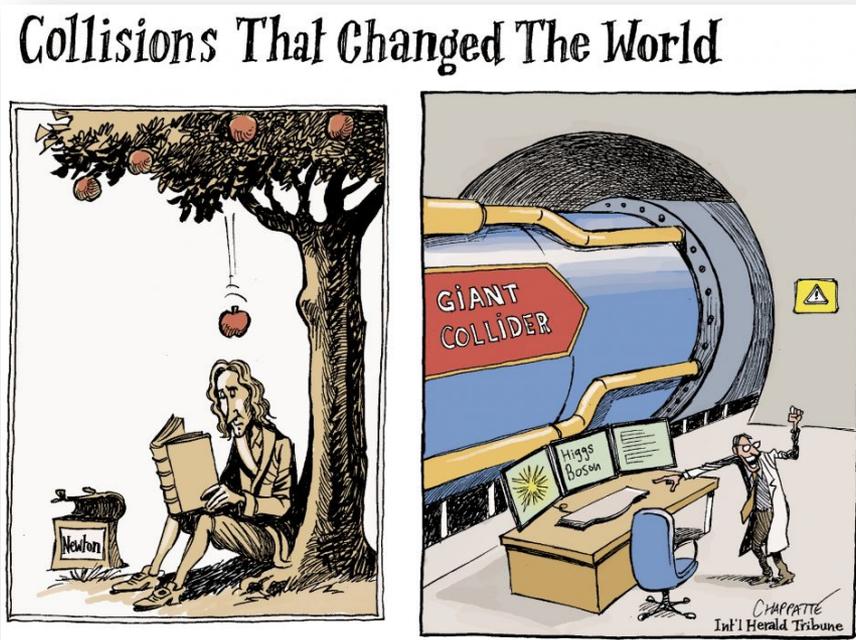
Di-Higgs Prospects for the far future

As an example: [arXiv:1907.02078v2](https://arxiv.org/abs/1907.02078v2)



Conclusions

- Long road ahead to solve some of the yet-to-be answered questions in Particle Physics
- Interplay between detector performance & analysis techniques is of paramount importance!



Thanks for your attention!



F. Cairo, From Conn(II)ecting the dots

Valentina Cairo

