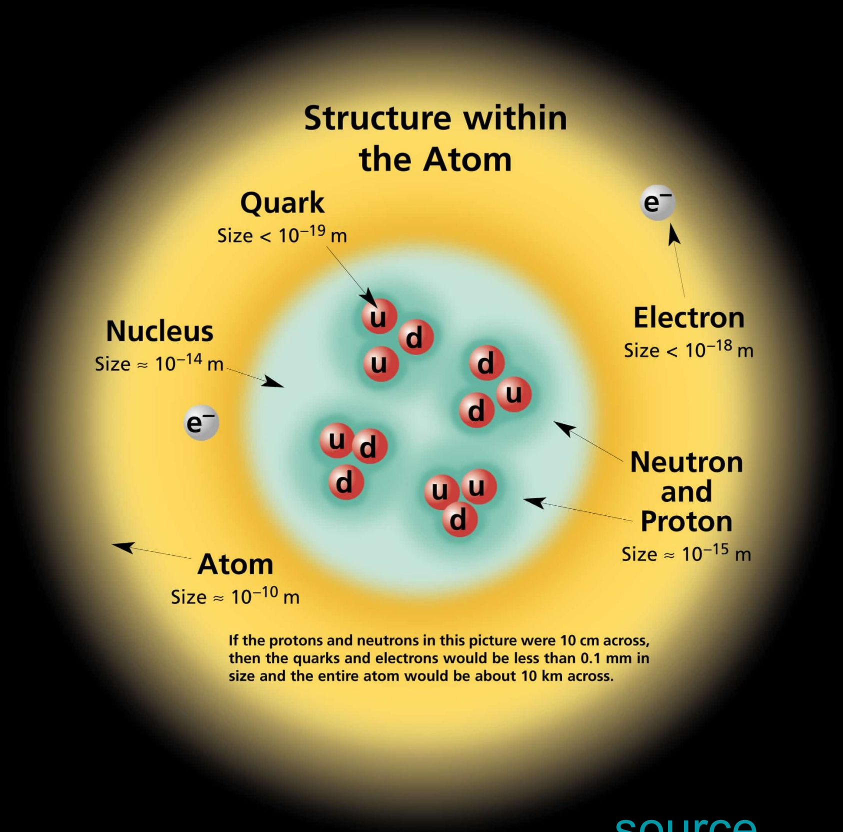
Searching for new physics in the Higgs sector at the LHC

Matt Klein, Southern Methodist University

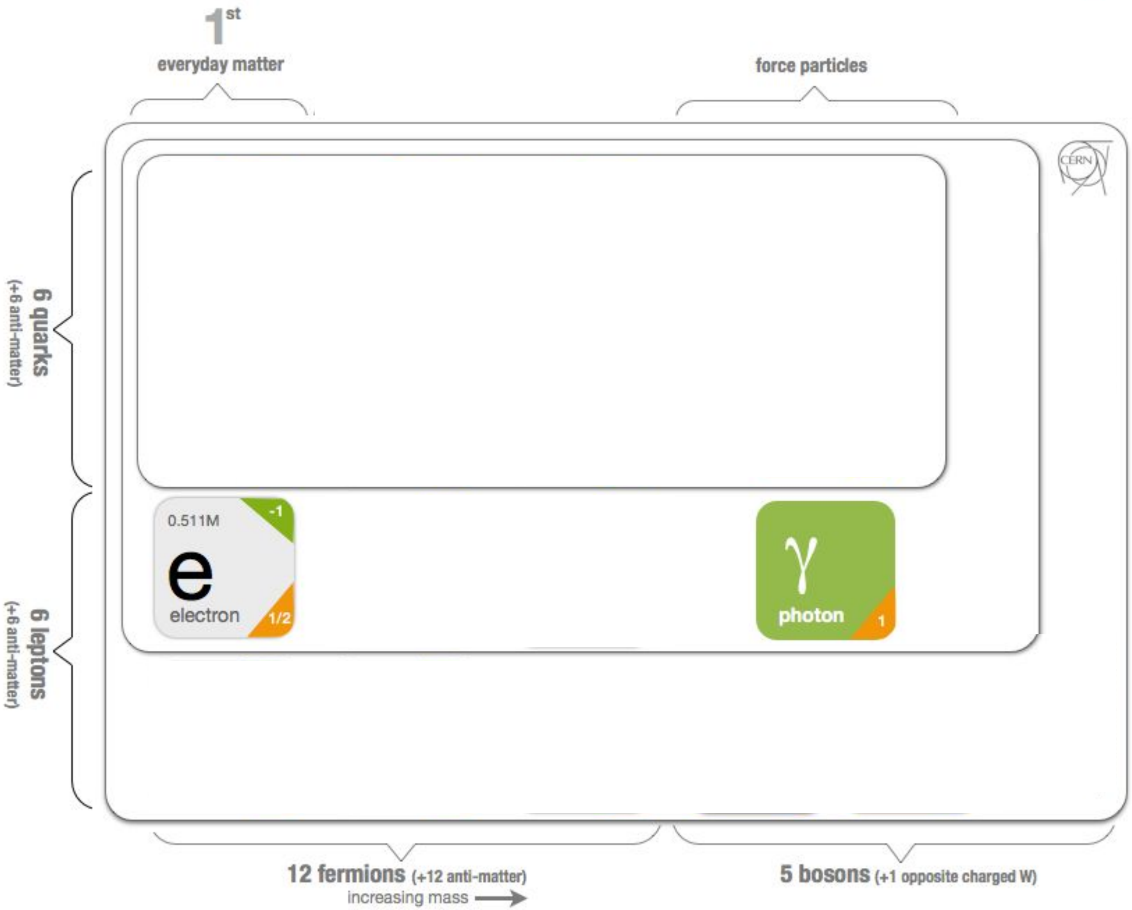
QuarkNet, 2026

Fundamental Particles



source

Particle Physics in 1900



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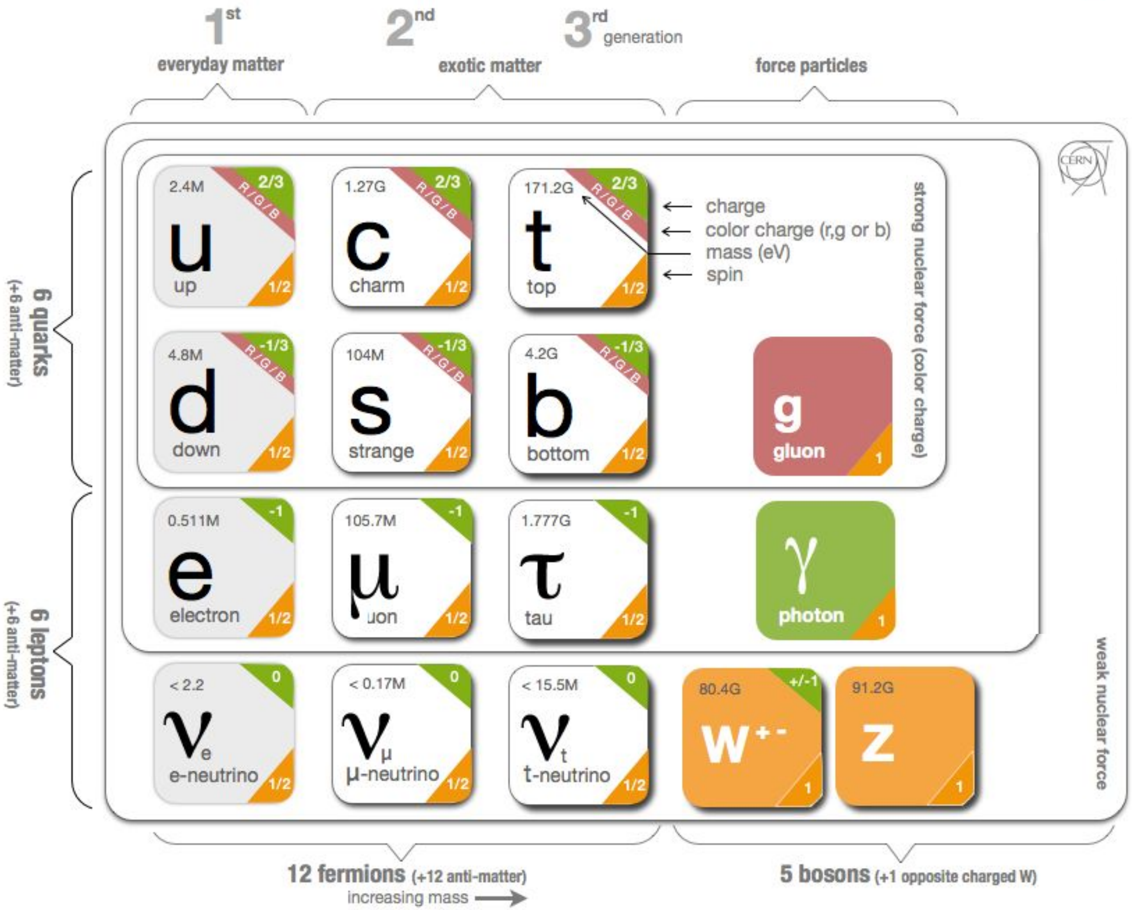
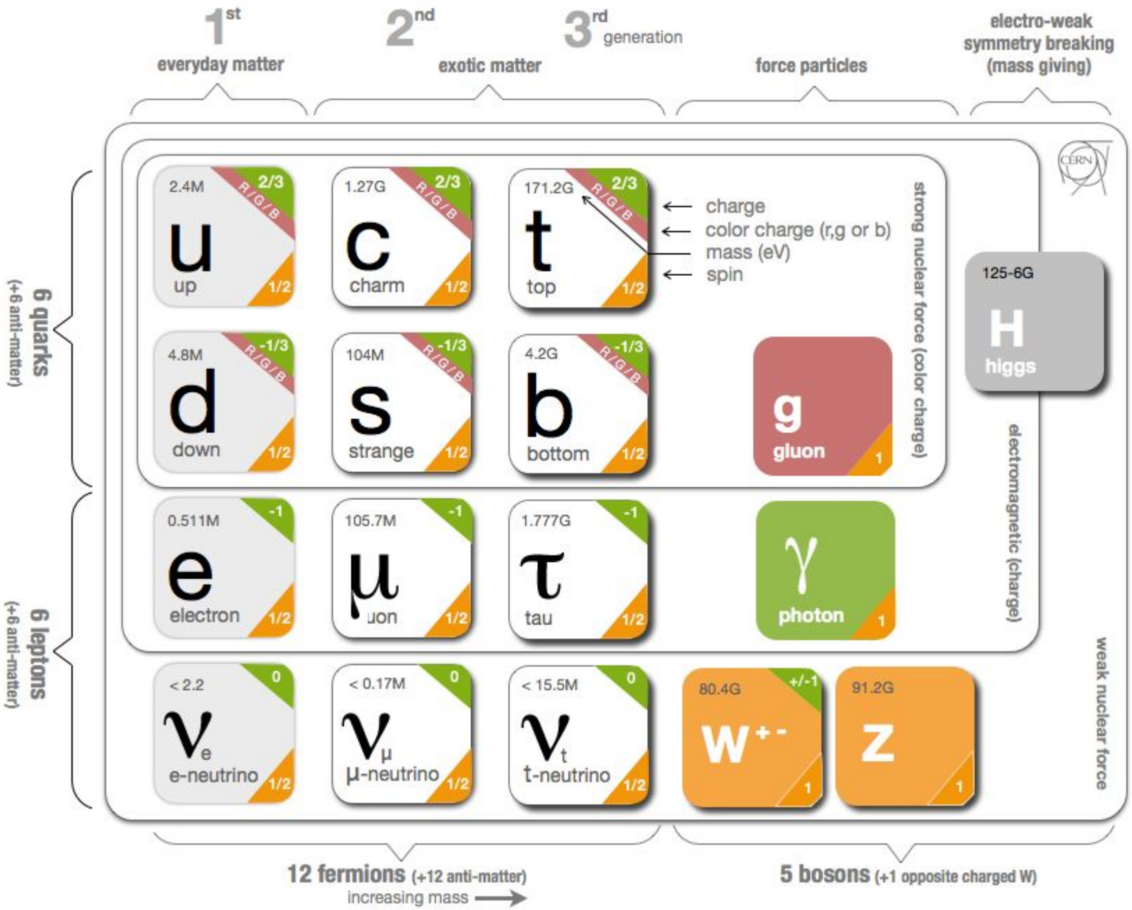
Particle Physics in 2000



source

Particle Physics in 2012



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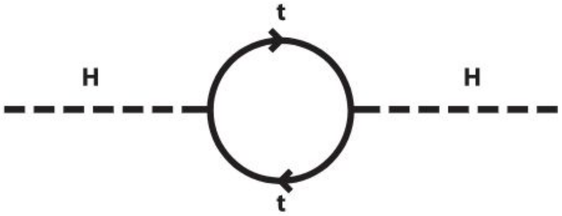
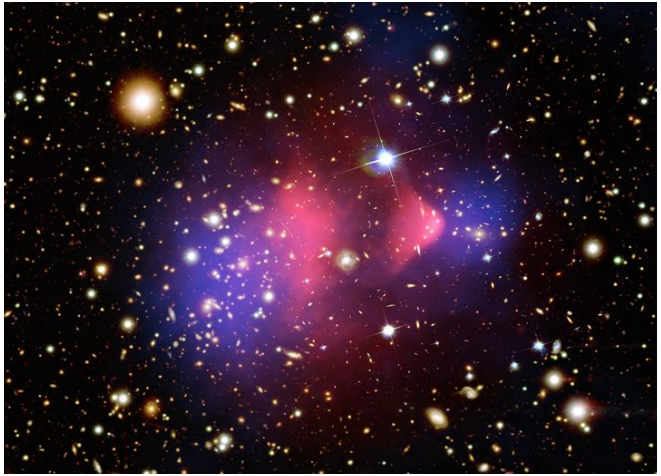
Missing Pieces

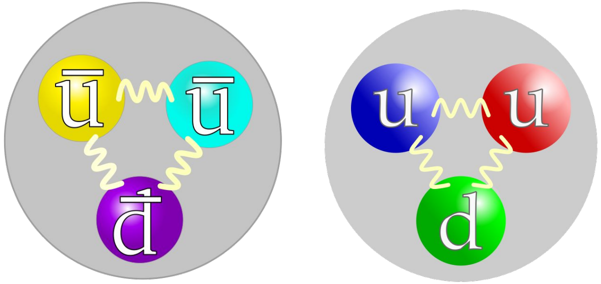
Hierarchy problem



Dark Matter



Matter-antimatter asymmetry

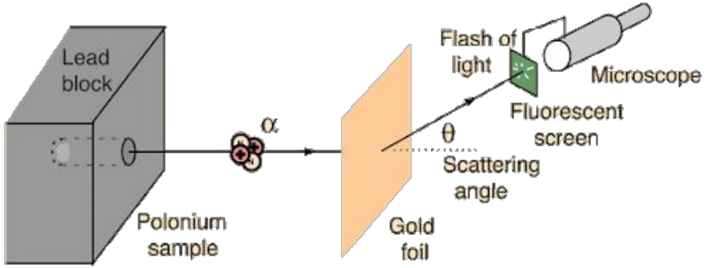


and neutrino mass, matter-antimatter asymmetry, g-2, etc..

Particle Scattering

Small scale physics driven by simple strategy→
throw one thing at another thing and see what happens

Example: Rutherford experiment mapped the atom (1911)



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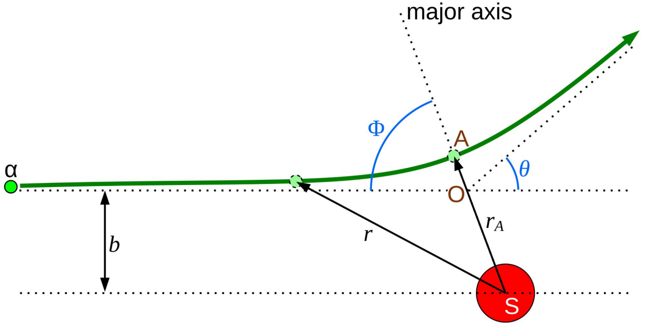

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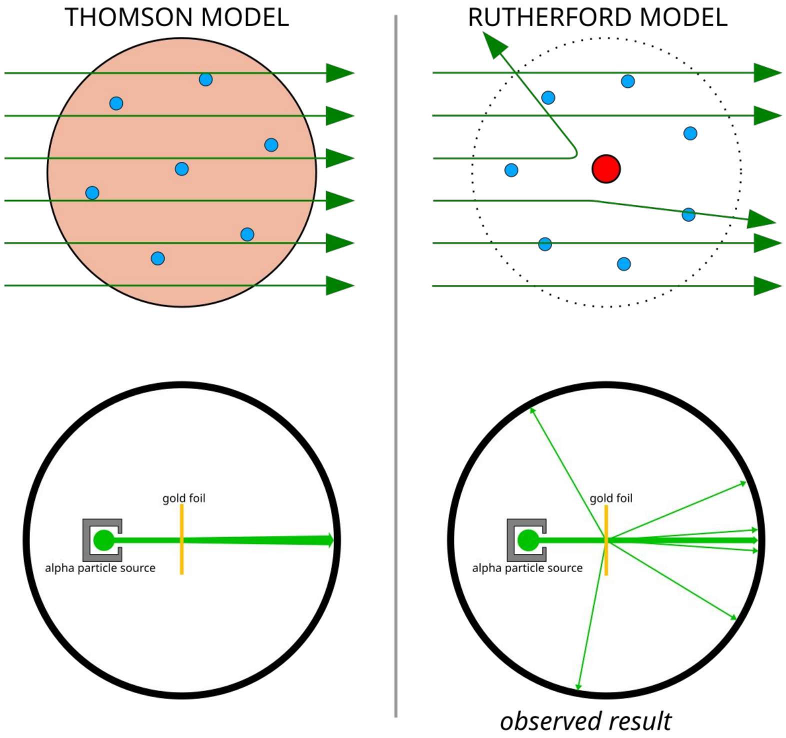
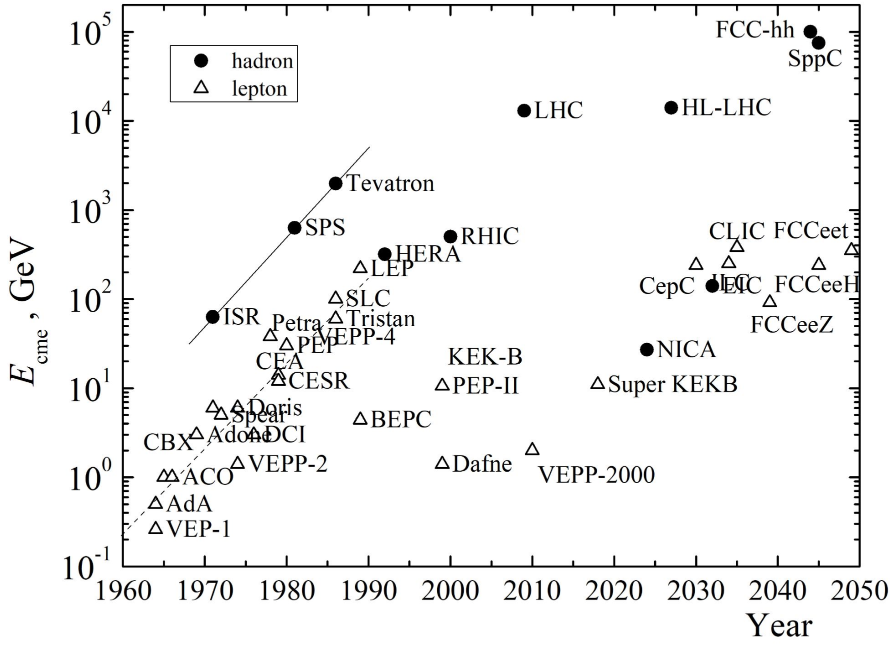
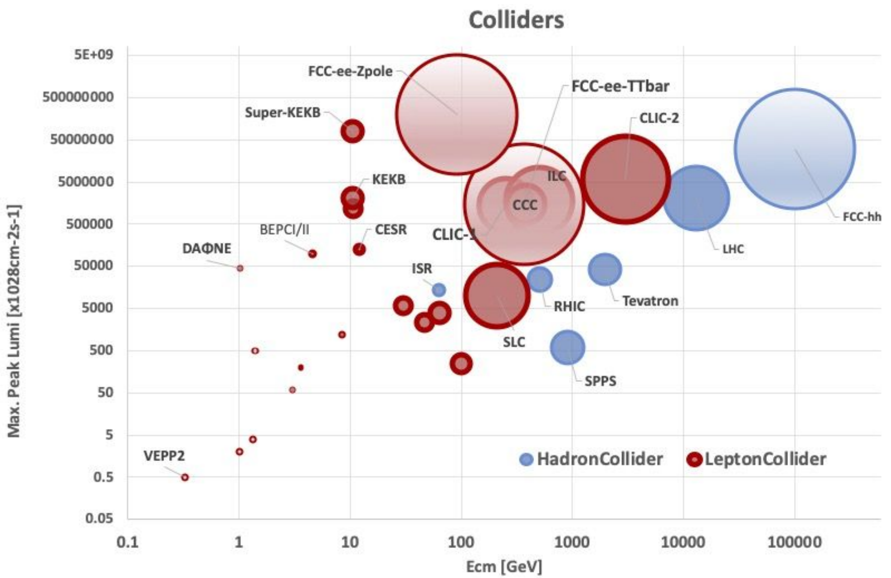


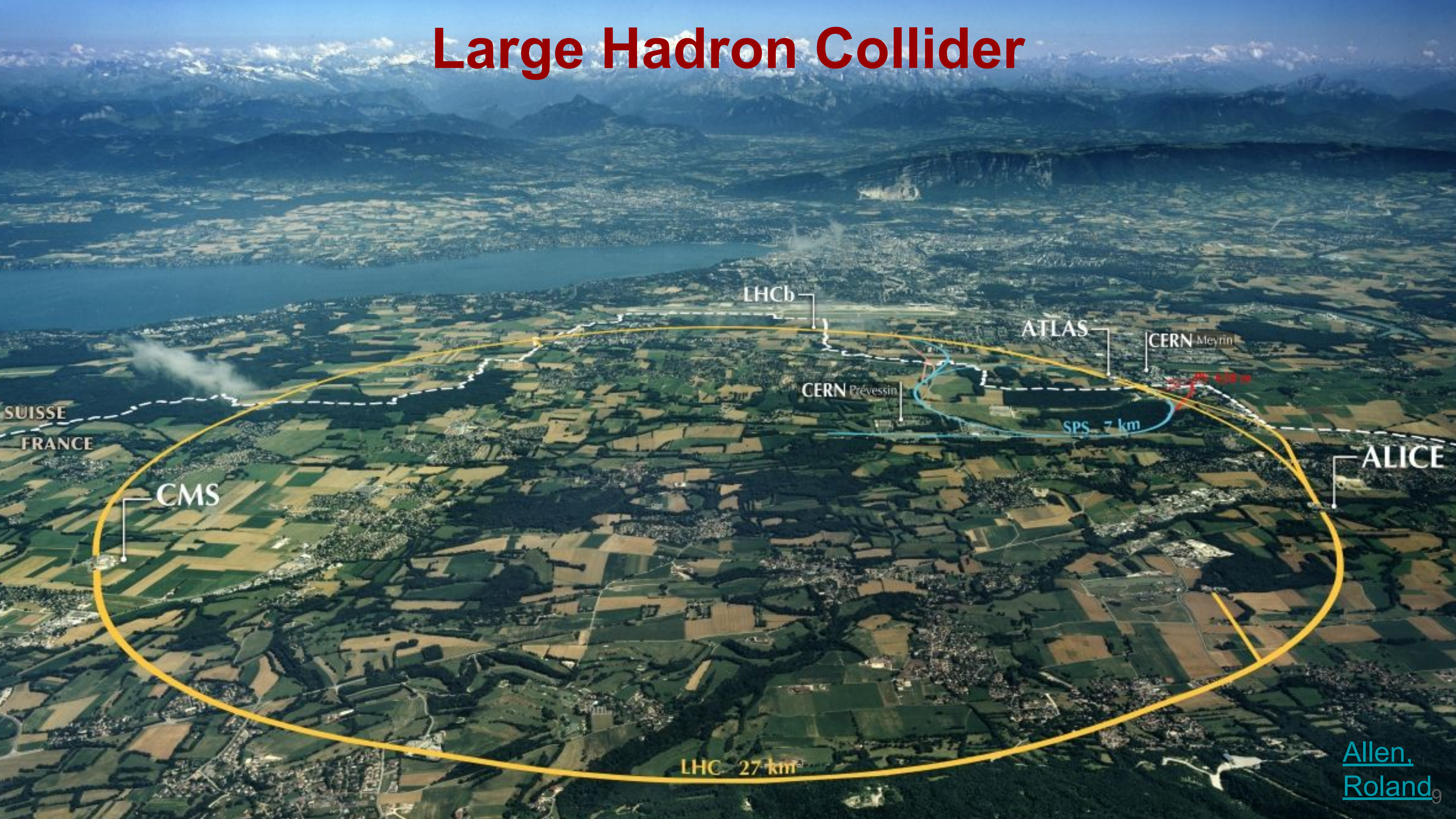
Particle Collider History





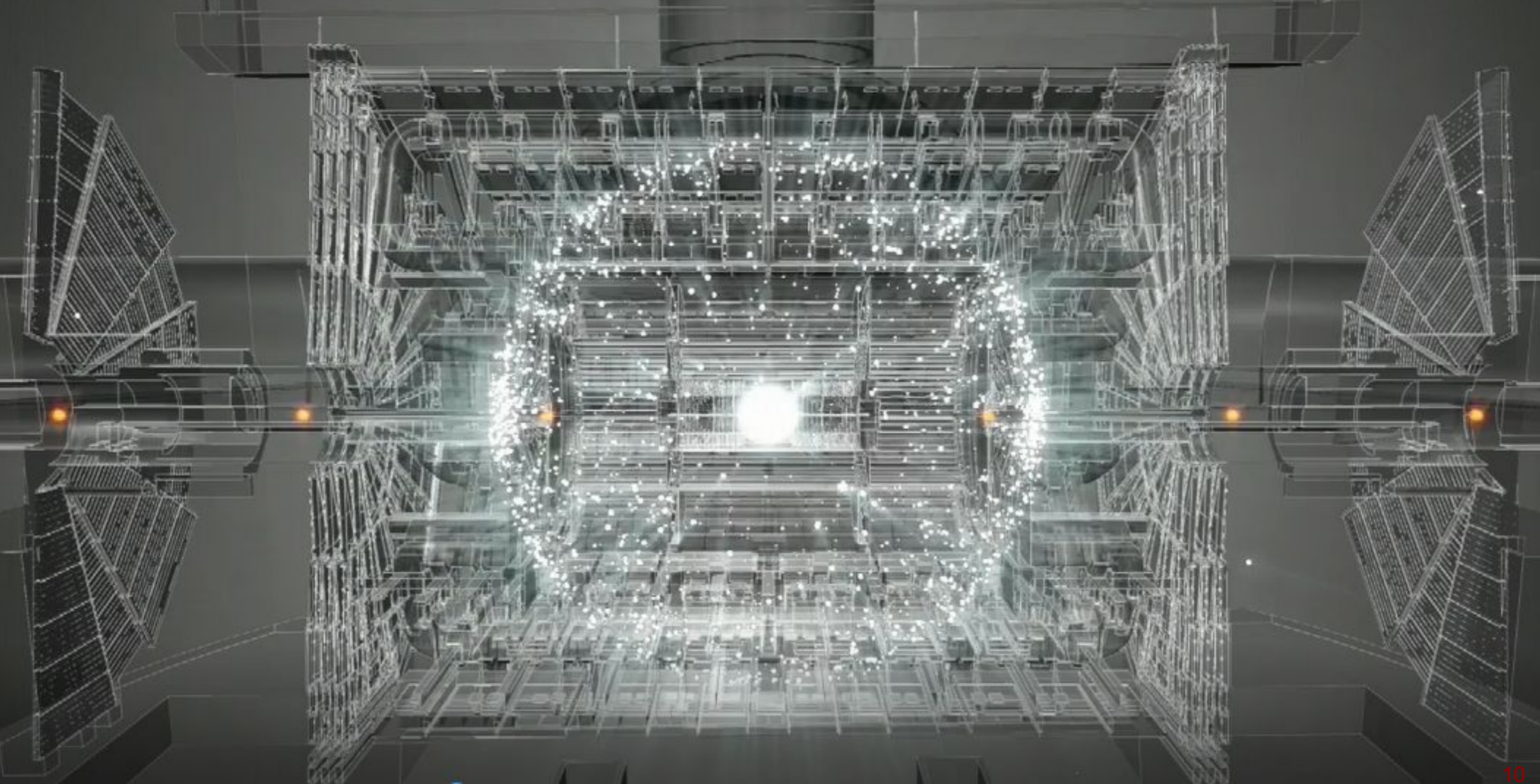
https://cds.cern.ch/record/2826883/

Large Hadron Collider

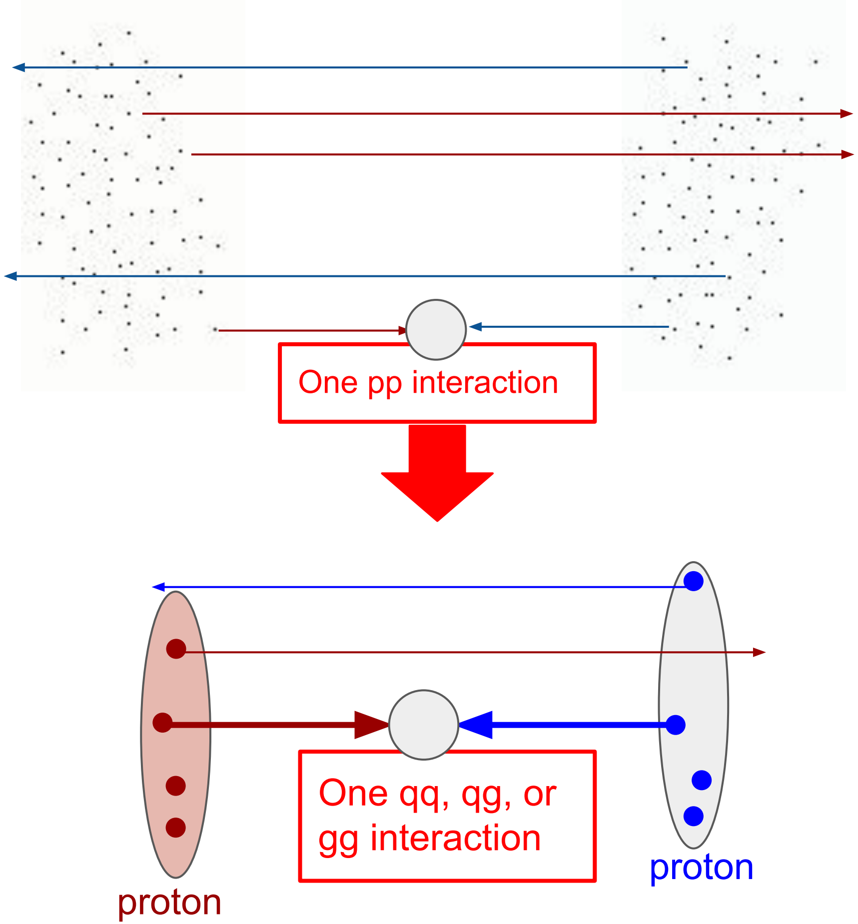


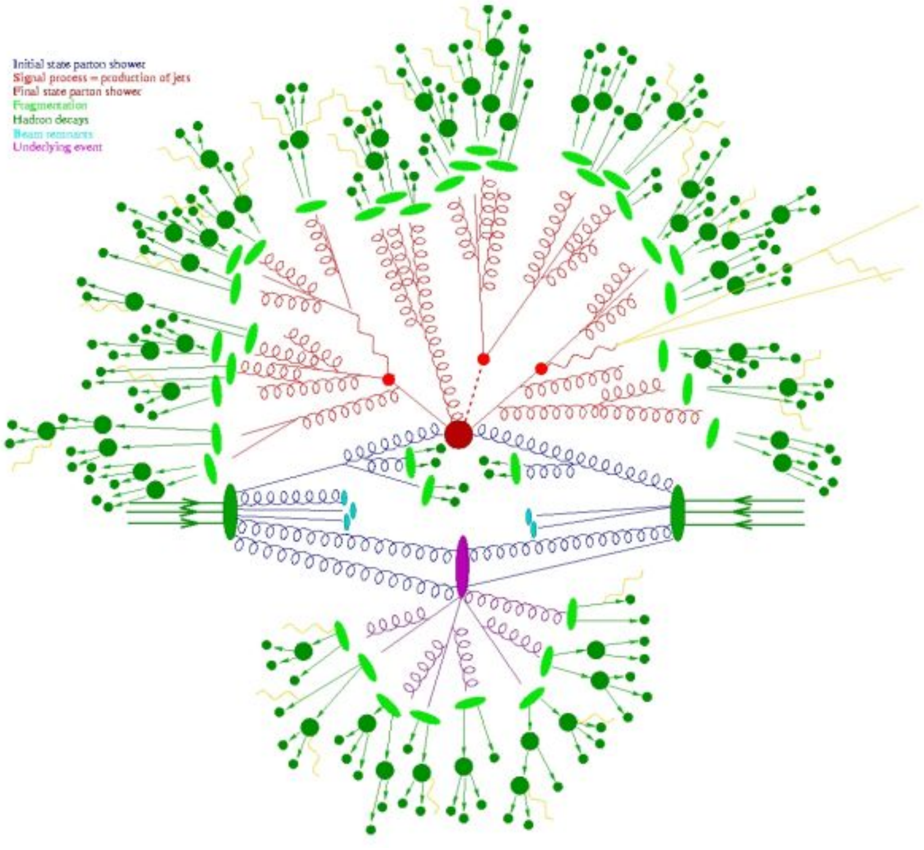
Allen, Roland

Proton Bunch Collisions



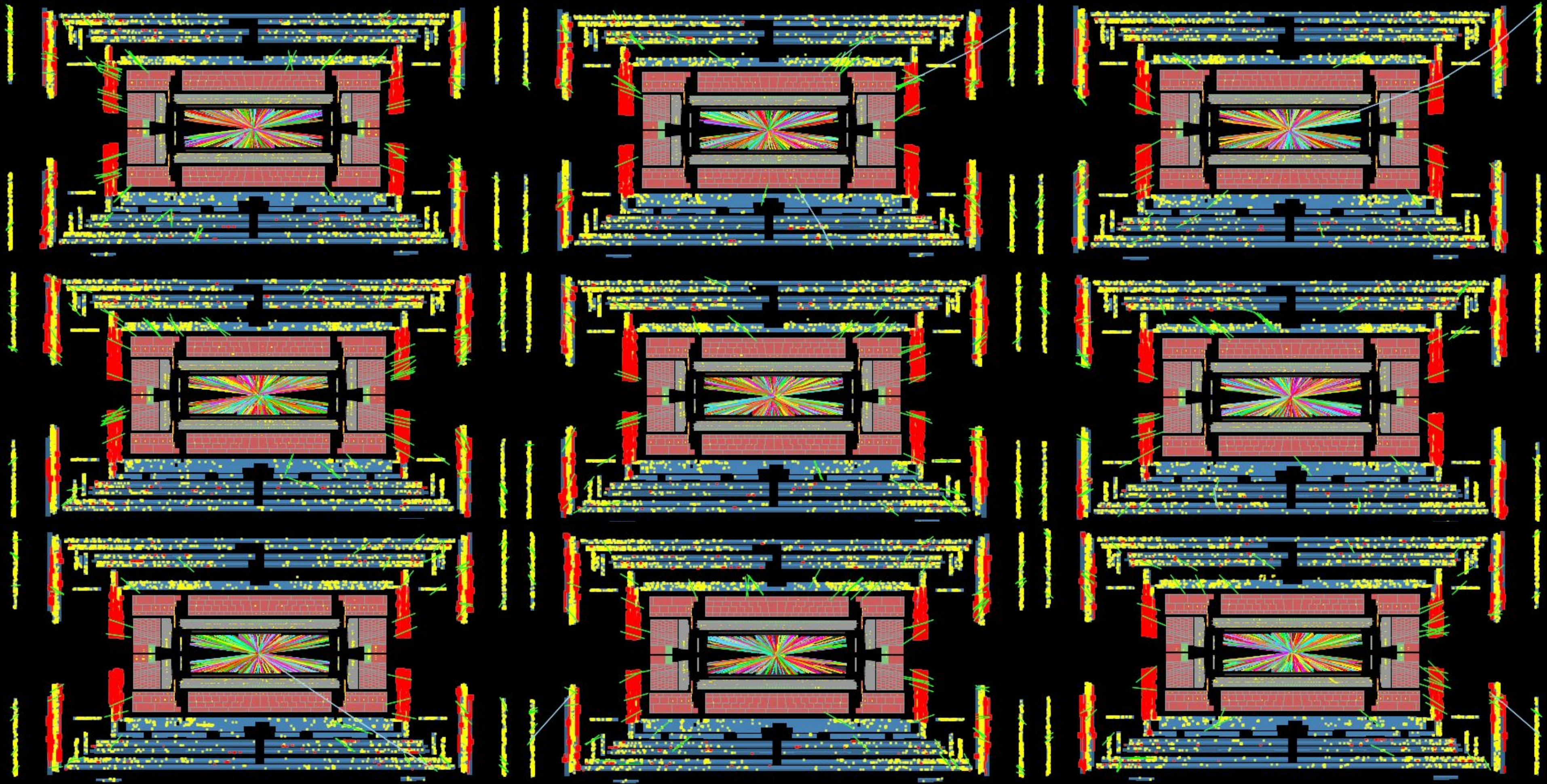
Proton Collisions



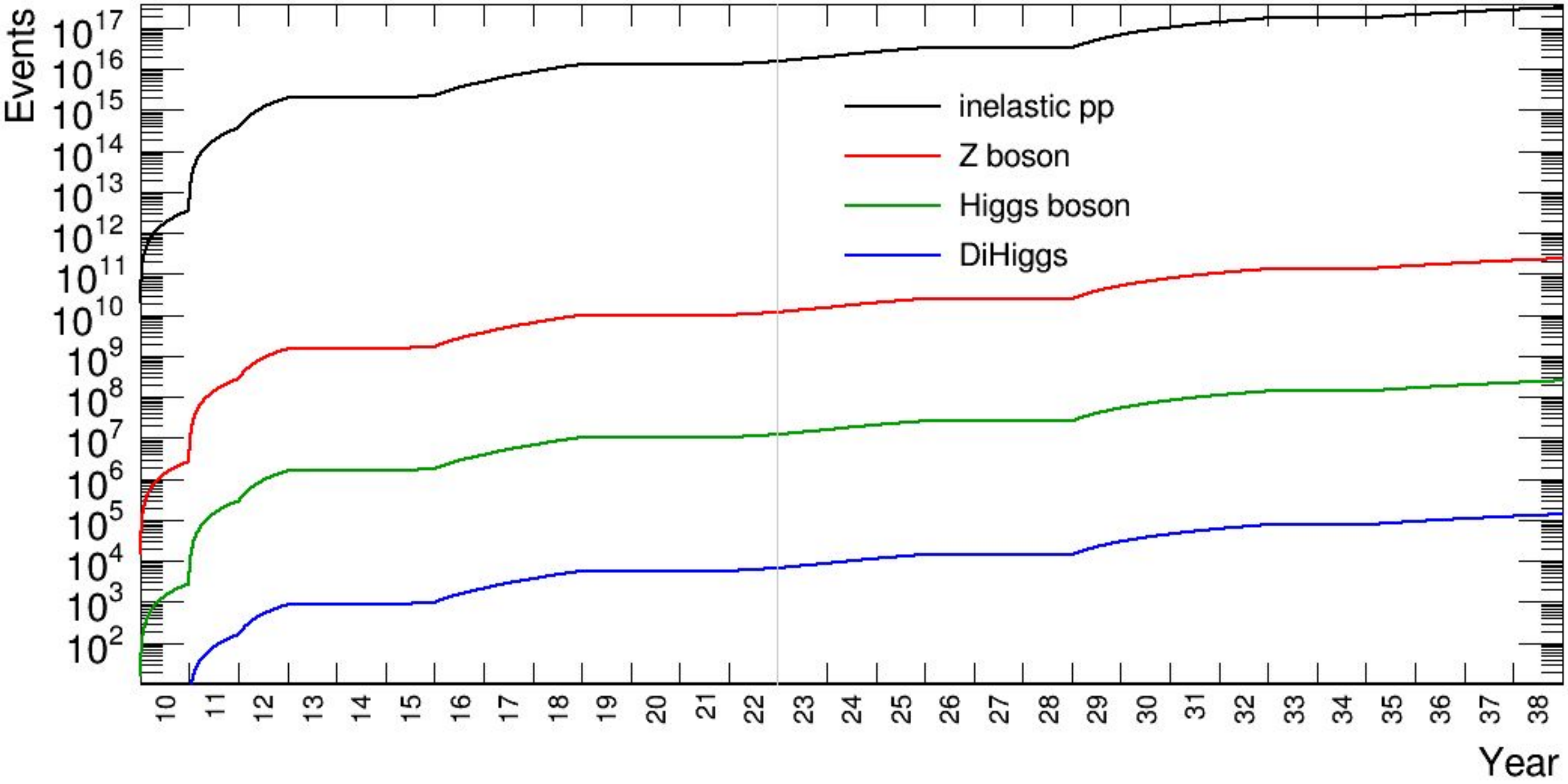


source

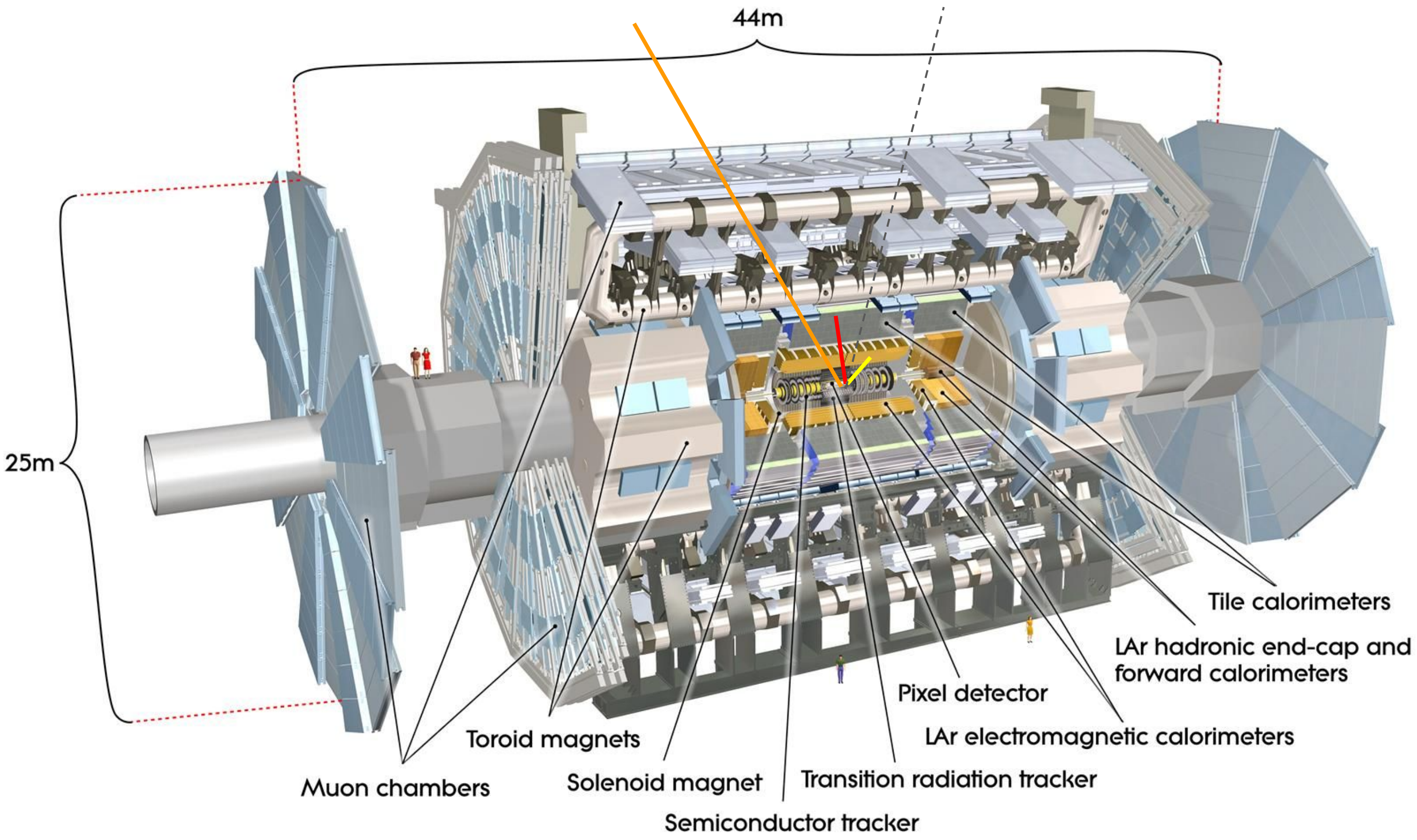
Events (A small sample...)



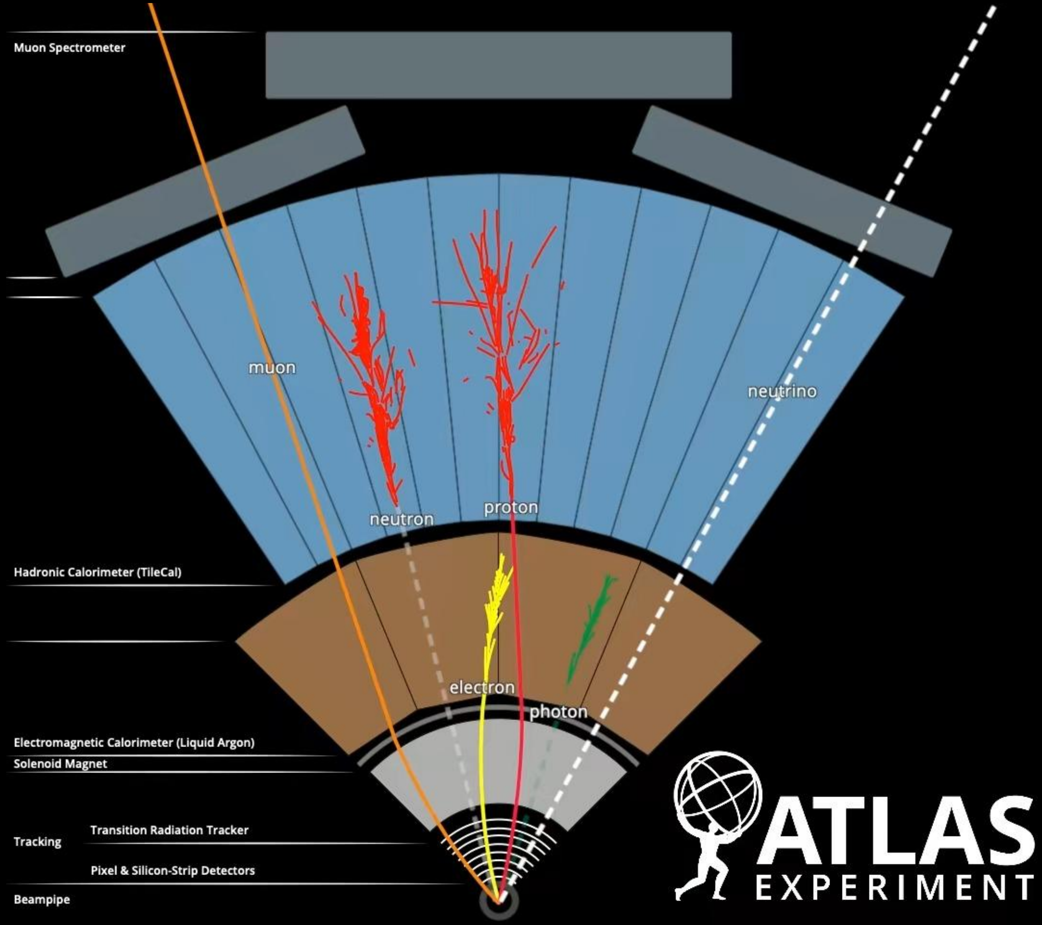
Event Yields over Time



ATLAS Detector



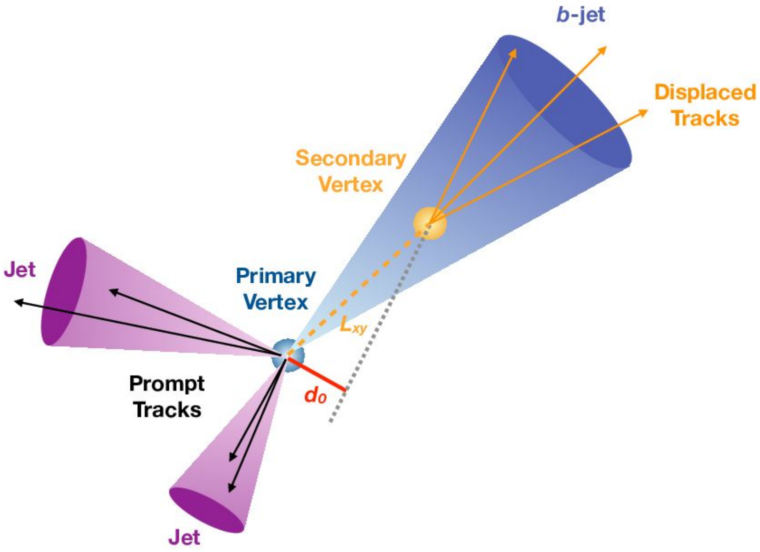
Types of Objects

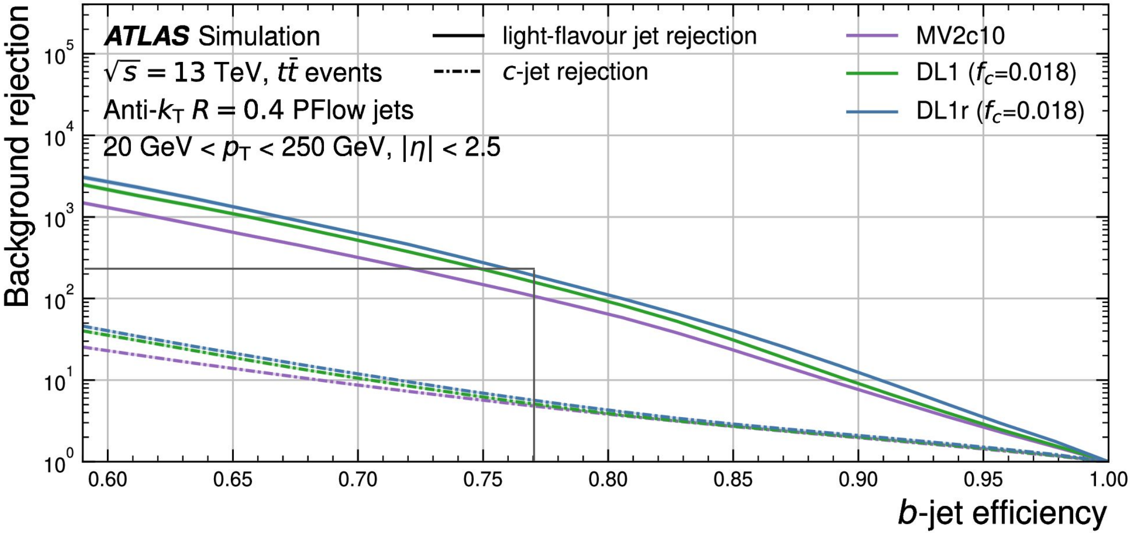


Example Object Reconstruction: (B-)jets

“Jets” reconstructed from bunches of hadrons produced from quarks/gluons

Can identify jets containing b-hadrons (“b-jets”) due to their lifetimes



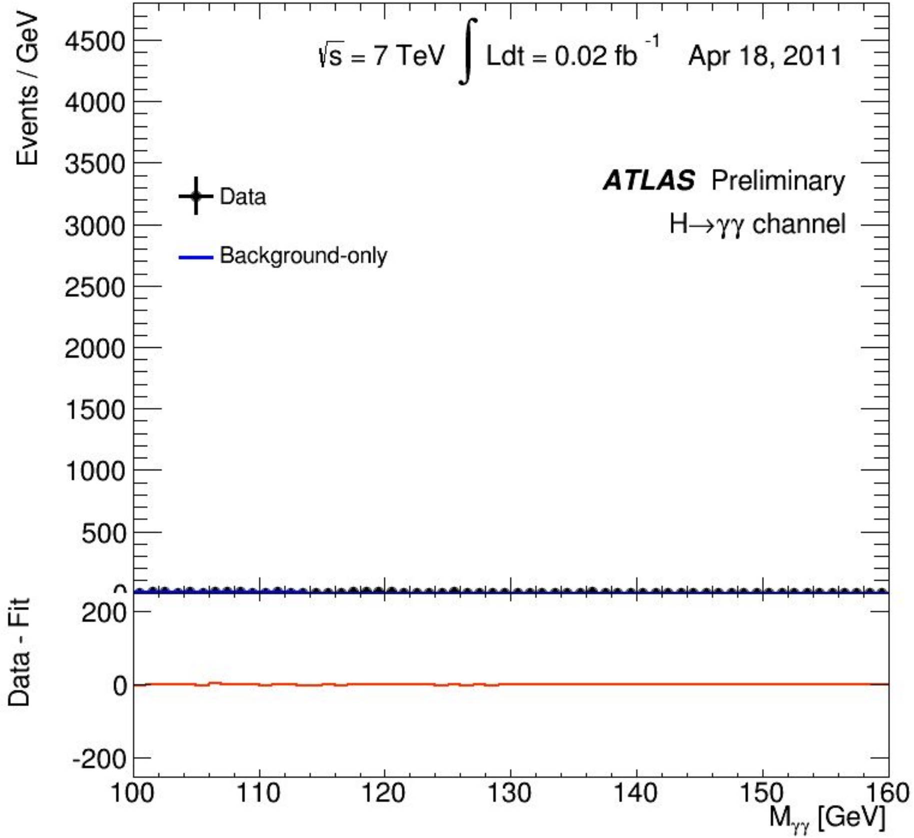


Dataset

Order 100,000,000,000 recorded pp events

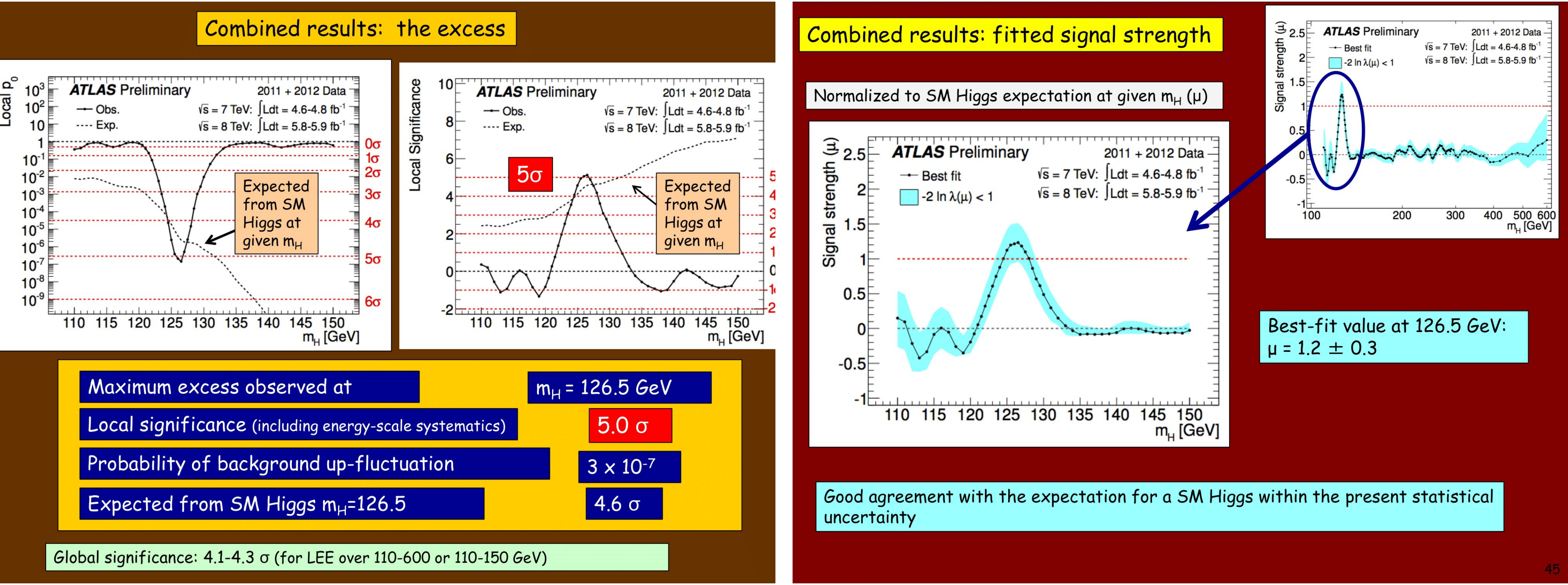
~360 PB of disk space

Seems like a lot, but need a lot of data to find rare processes



https://cds.cern.ch/record/2230893?ln=en

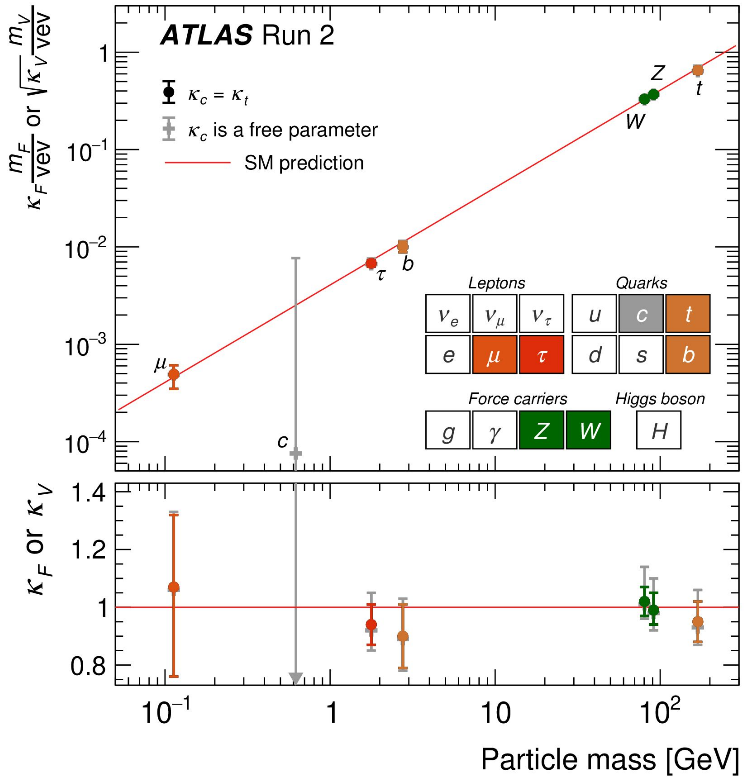
Discovery of a New Particle

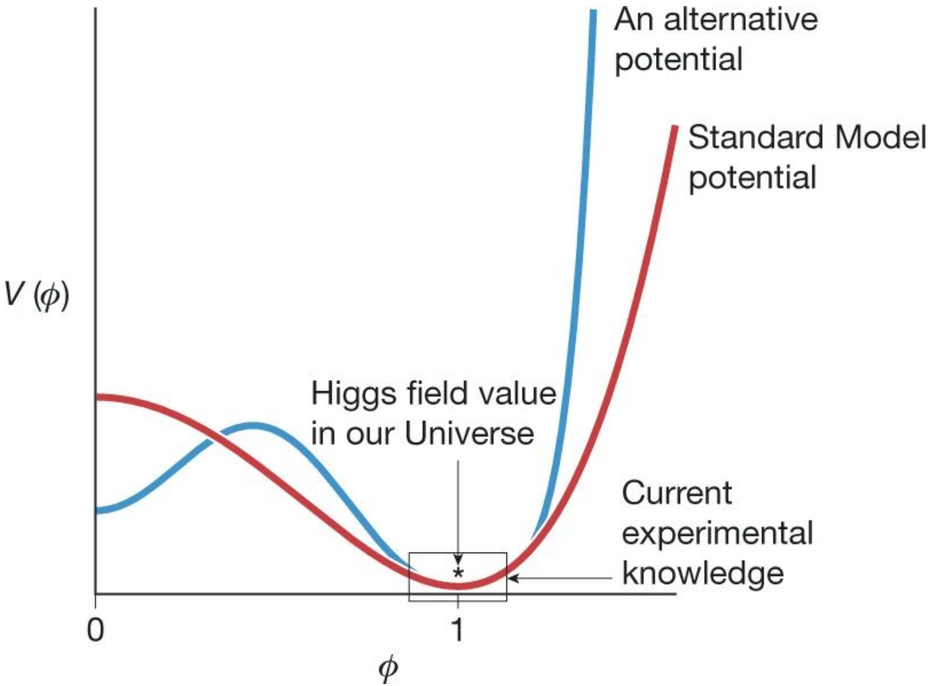


2011-2012 data

Unanswered Questions (1)

- Is the new particle the SM Higgs?
  - Deviations expected from many BSM models (e.g., other new particles, modified couplings?)

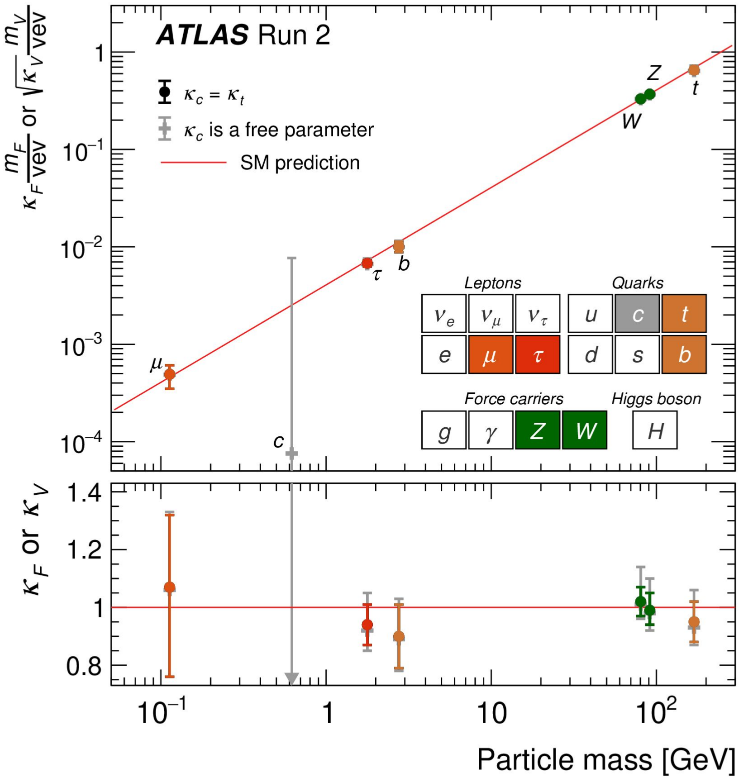


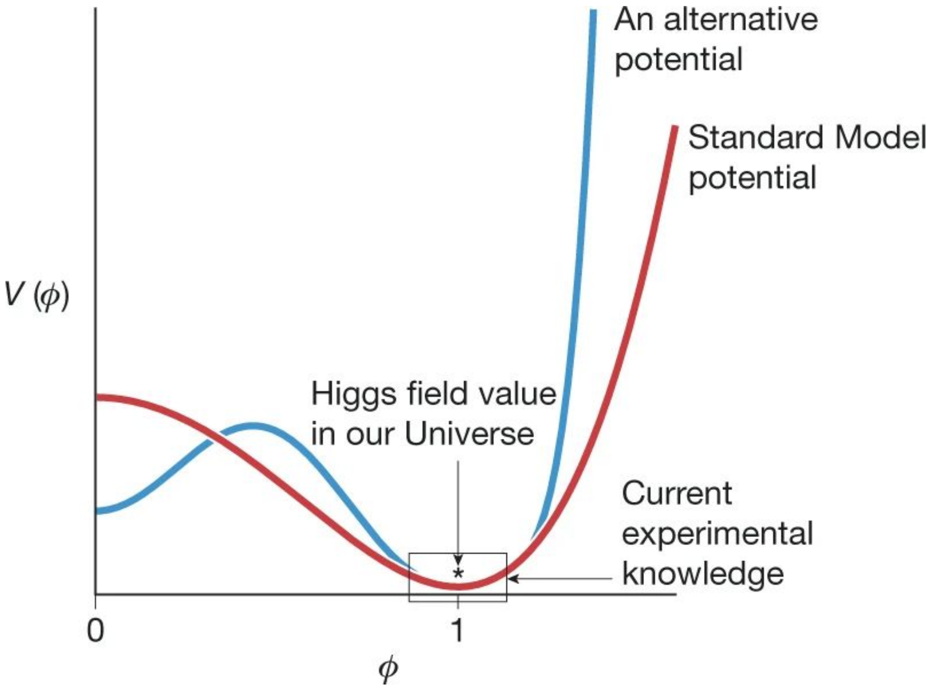


source

Unanswered Questions (2)

- Is the observed boson part of some larger theory?
  - Many theories predict more new particles.

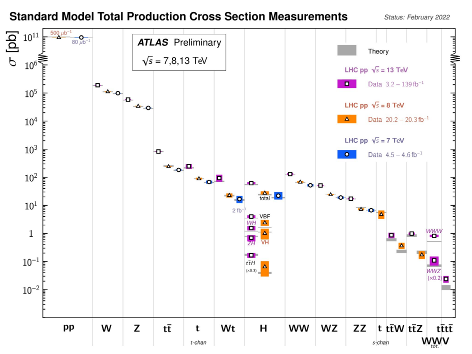




Searches vs. Measurements

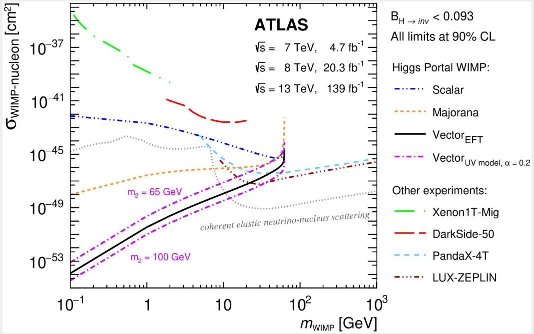
Two avenues for finding potential BSM physics:

Measurements



Example: VBF H(bb)

Searches

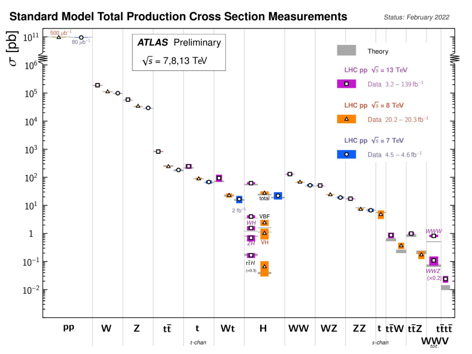


Example: VHH

Searches vs. Measurements

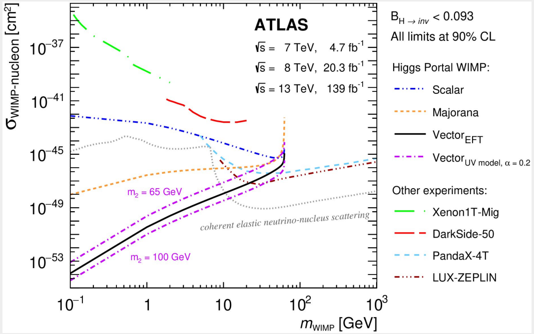
Two avenues for finding potential BSM physics:

Measurements



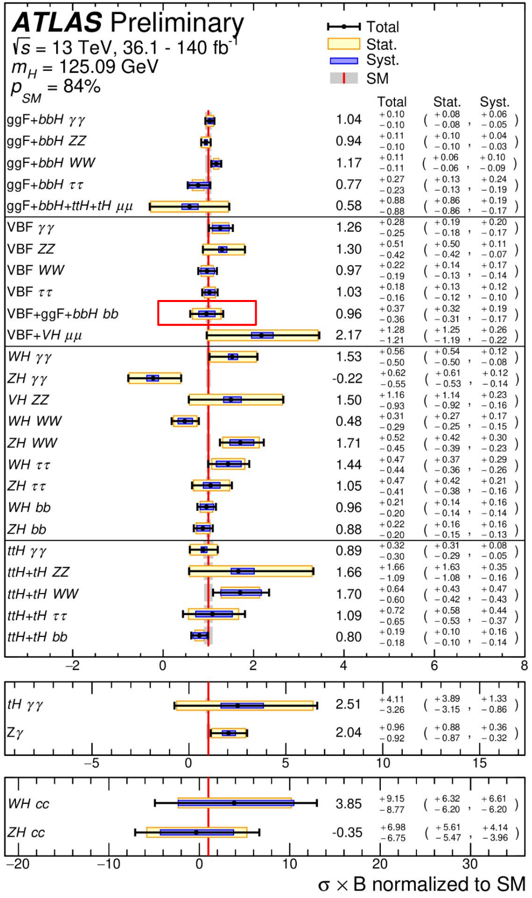
Example: VBF H(bb)

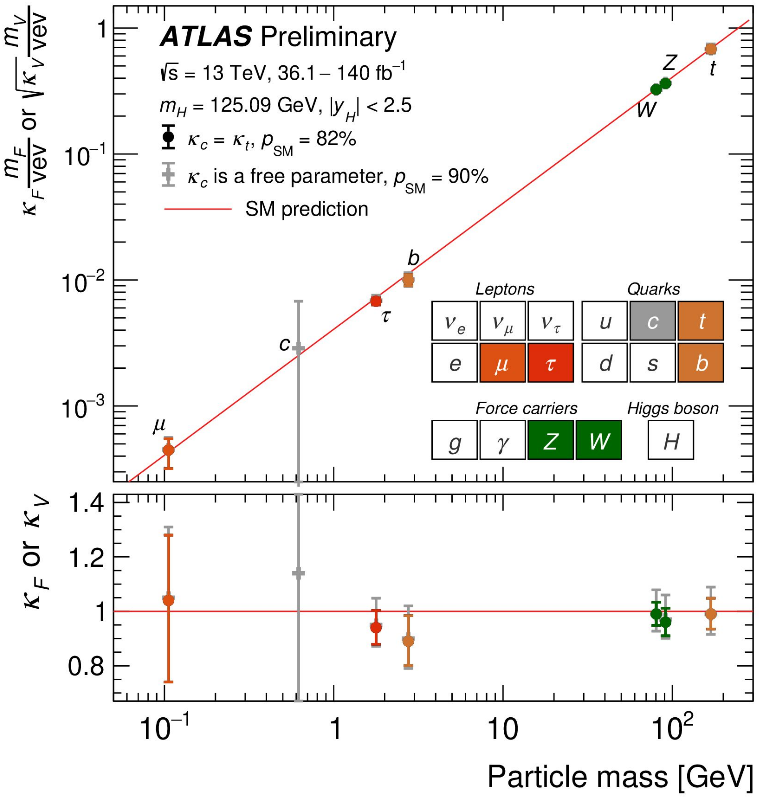
Searches



Example: VHH

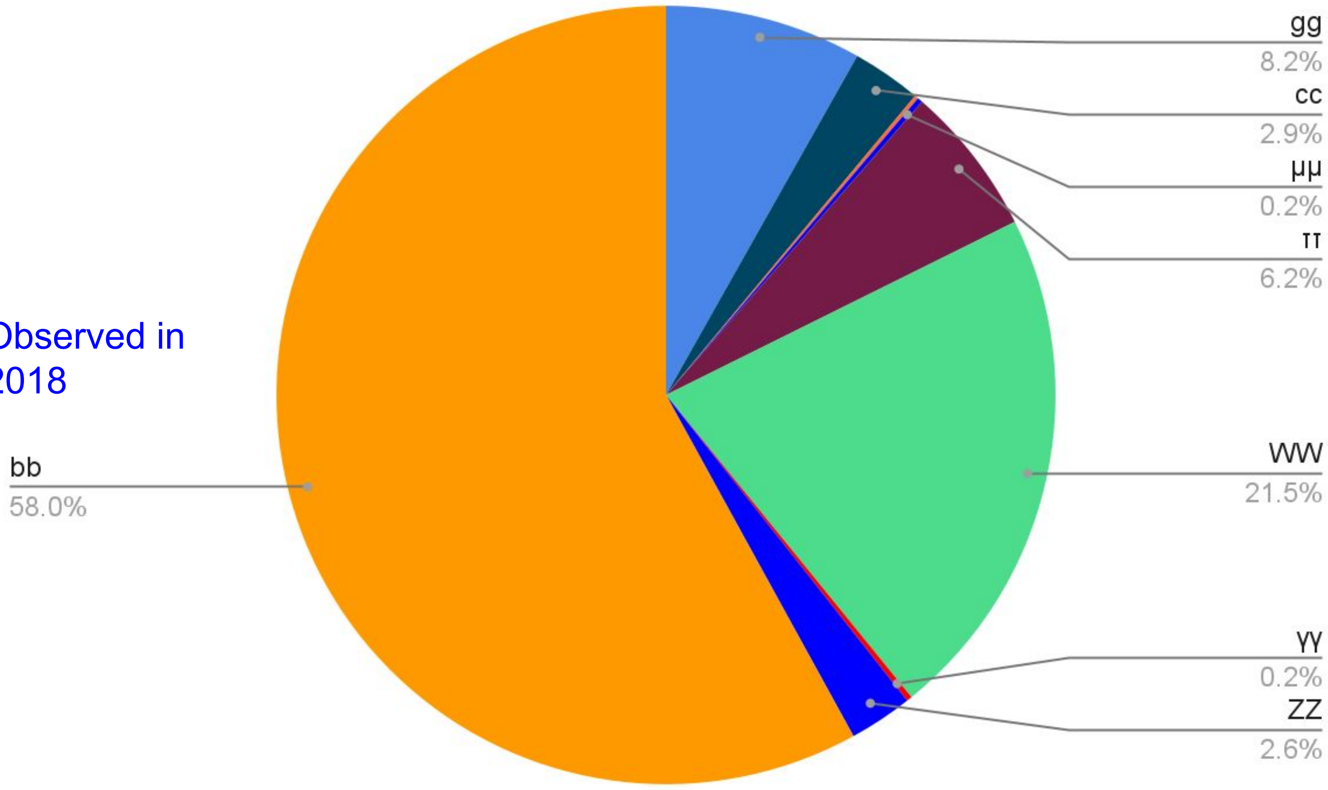
Higgs Measurement Summary





Expected Higgs Decays

Observed?



gg, cc: No (future collider?)

μμ: No (expected with more data)

ττ: Yes (2018)

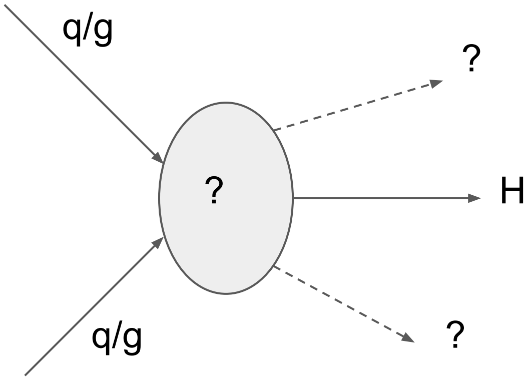
WW: Yes (2014)

γγ: Yes (2013)

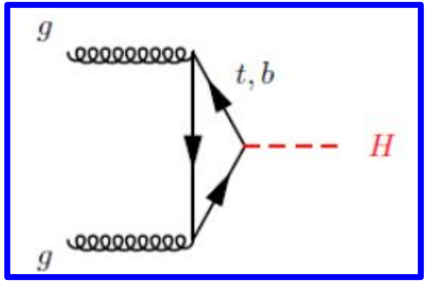
ZZ: Yes (2013)

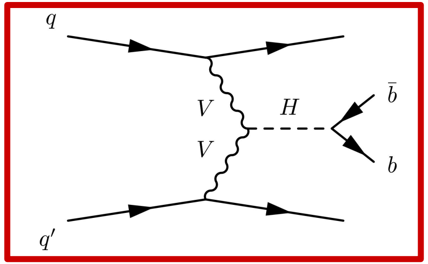
bb: Observed in 2018

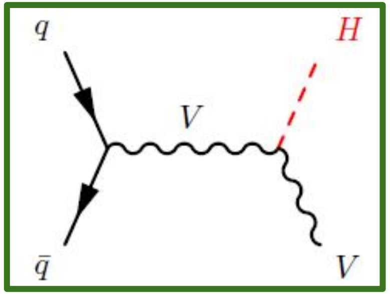
Higgs Production

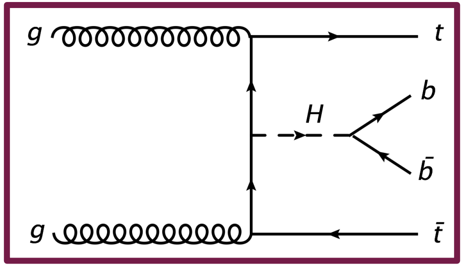


Decreasing cross-section



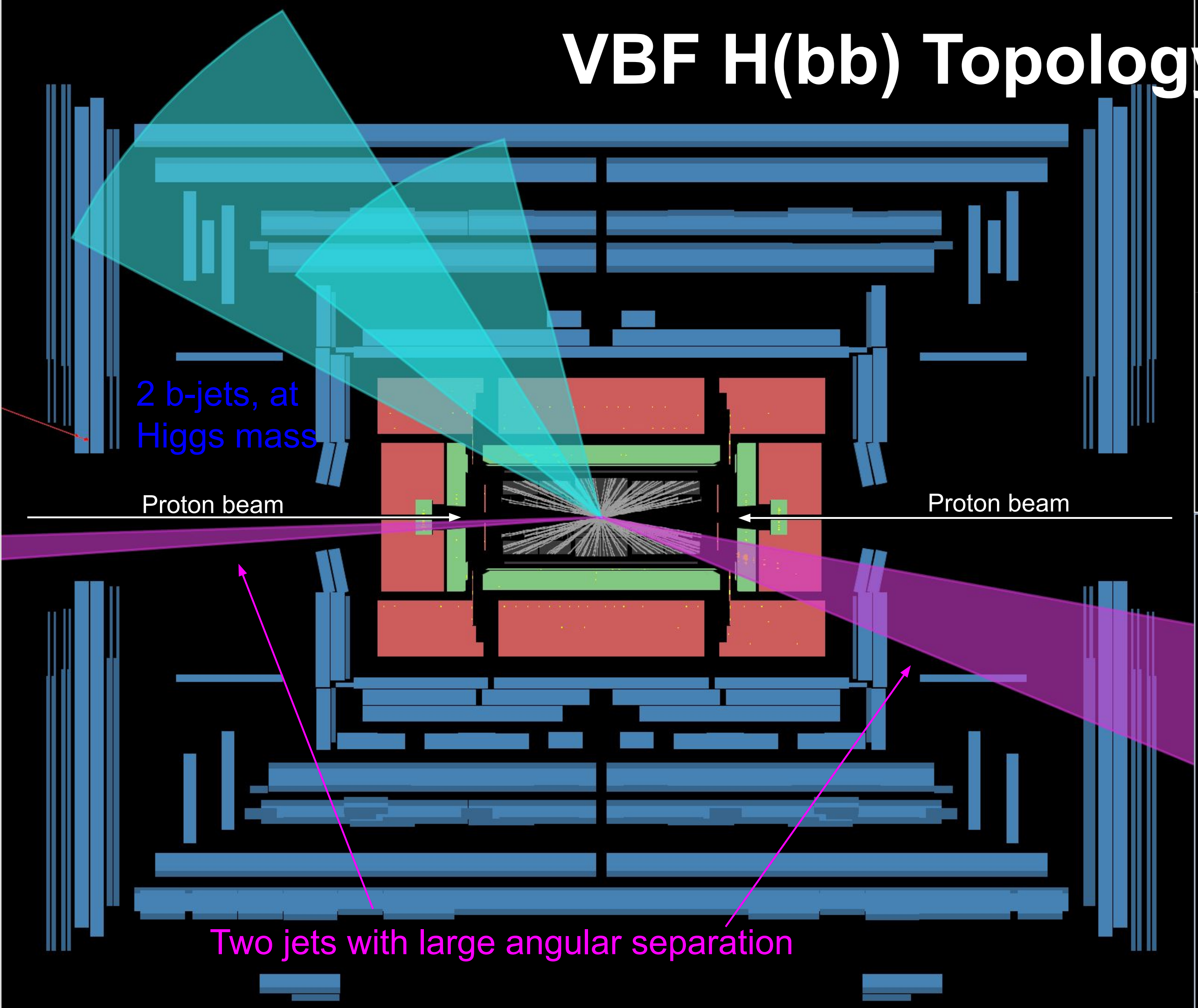






Decreasing background

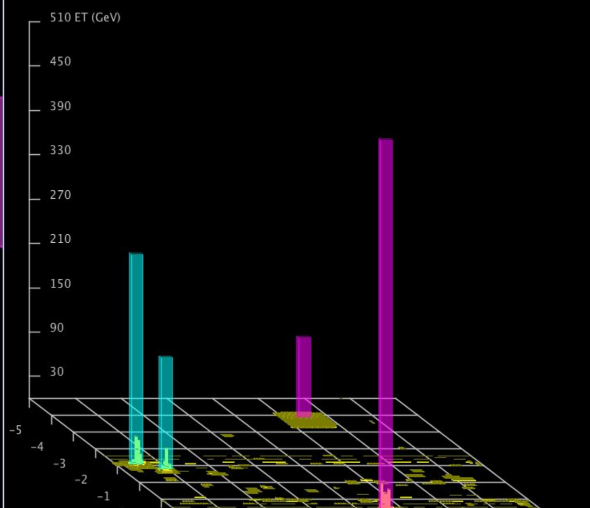
VBF H(bb) Topology



ATLAS EXPERIMENT

Run Number: 362776, Event Number: 2718397323

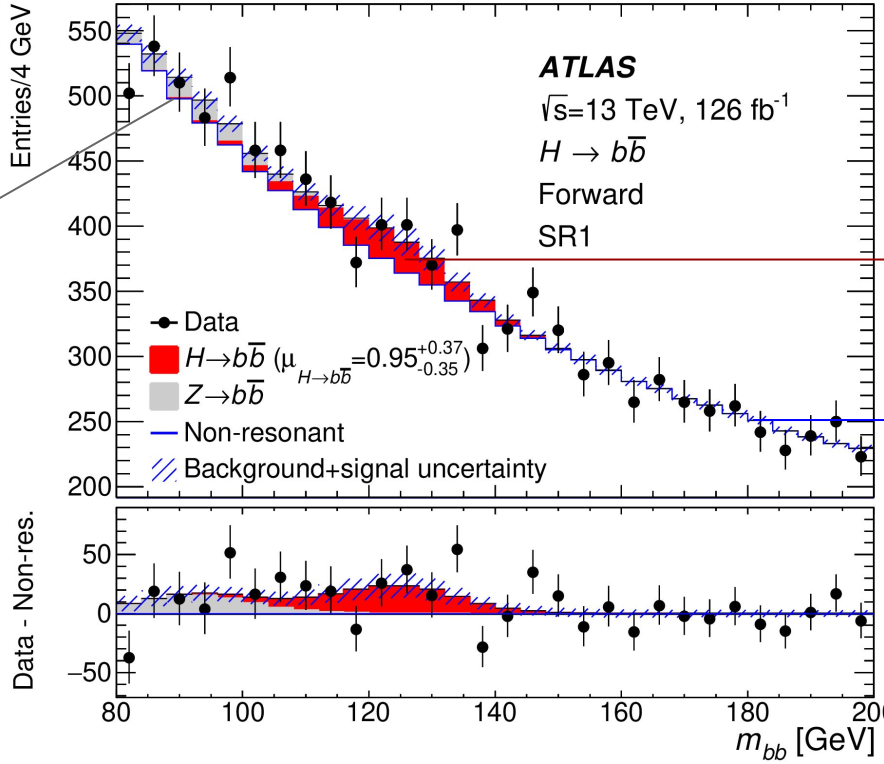
Date: 2018-10-05 07:49:10 CEST



arxiv.org:2011.08280

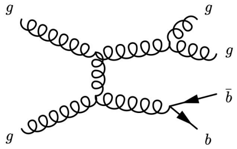
VBF H(bb) Measurement

Estimated Z(bb) background



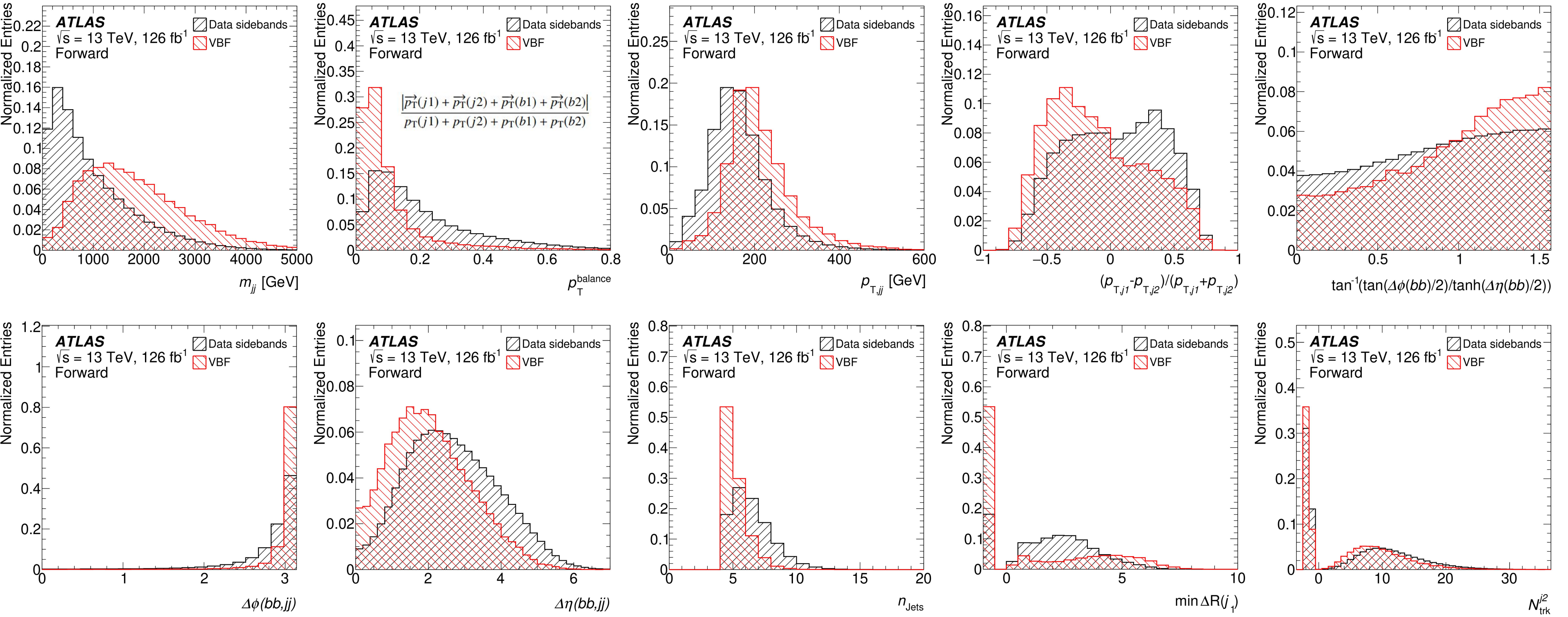
Measured H(bb)

Estimated non-resonant background



Signal/Background Discrimination

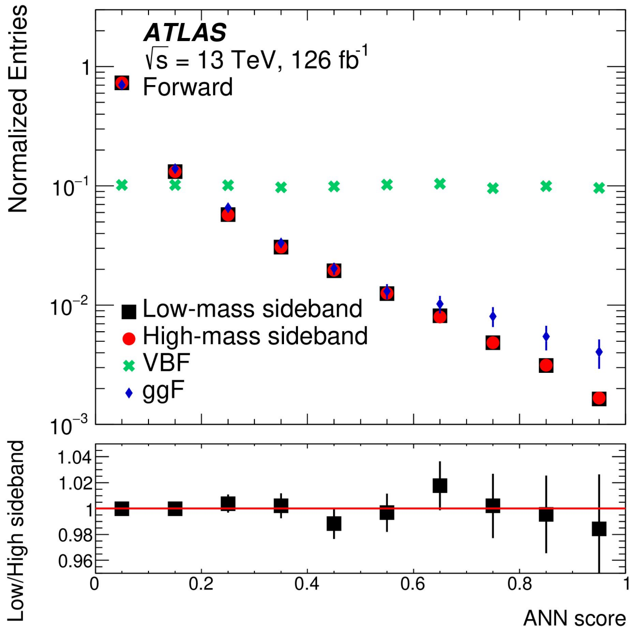
Small signal, large background → Use MVA



Multivariate Analysis

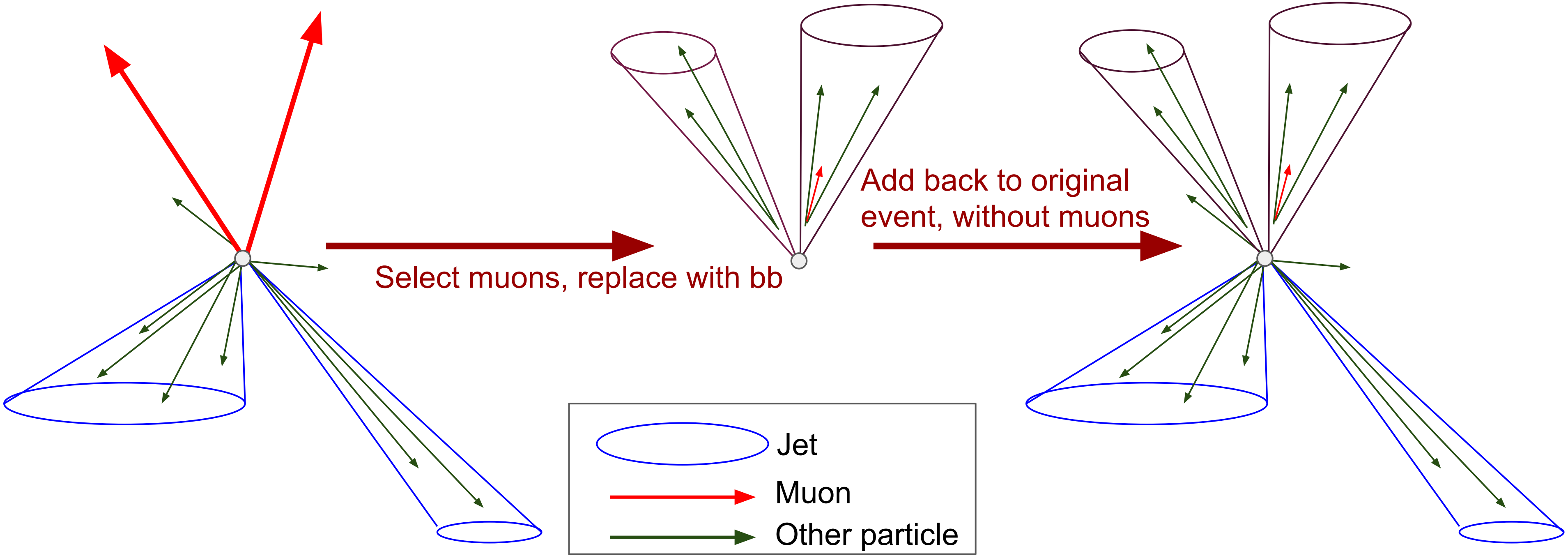
Consistent shapes in high and **low** mass sidebands

ggF similar to multijet background, VBF flat by design



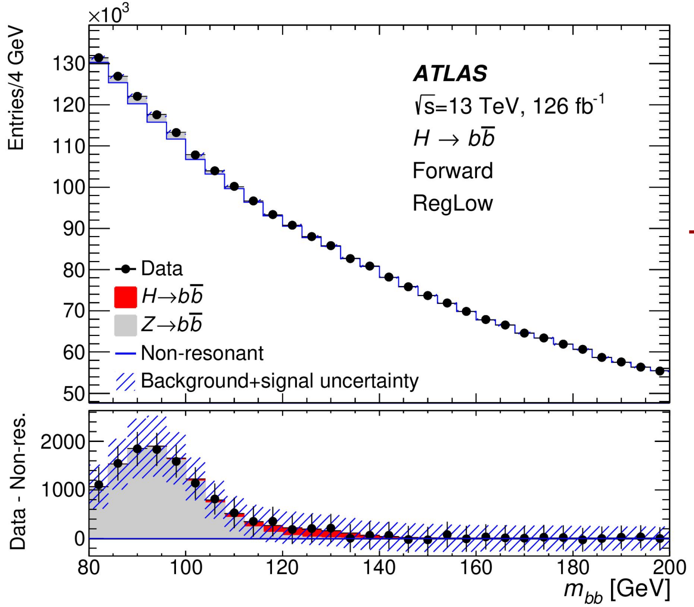
Background Estimate: Z→bb

Estimate Z→bb from Z→μμ

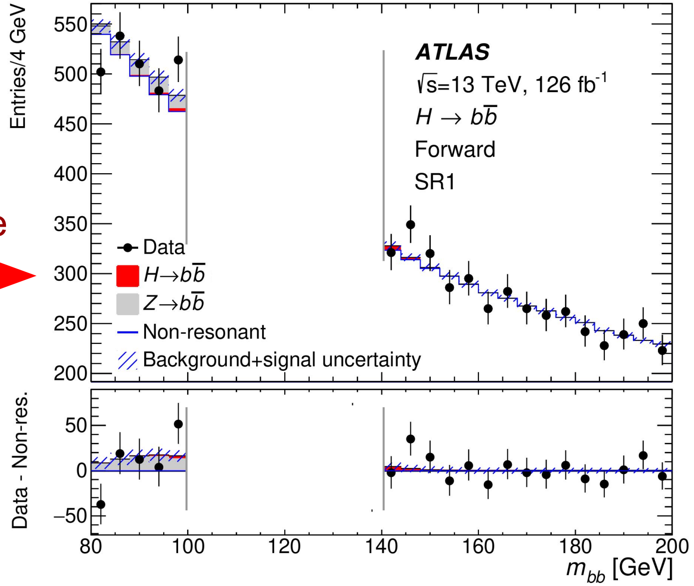


Background Estimate: Non-resonant

MVA is Adversarial Neural Network → decorrelate m_{bb} and score



Take background shape



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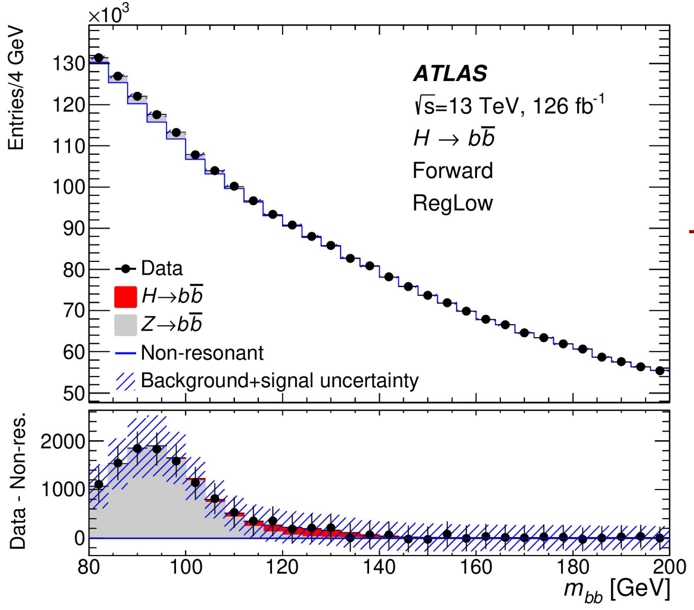
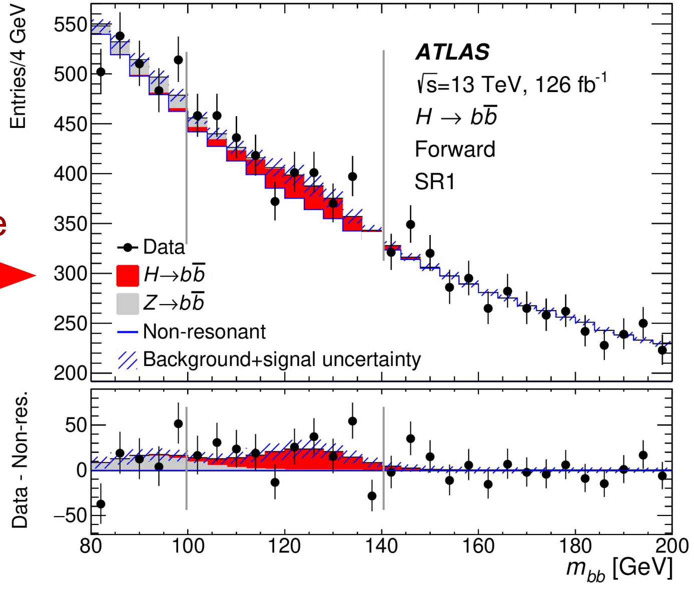
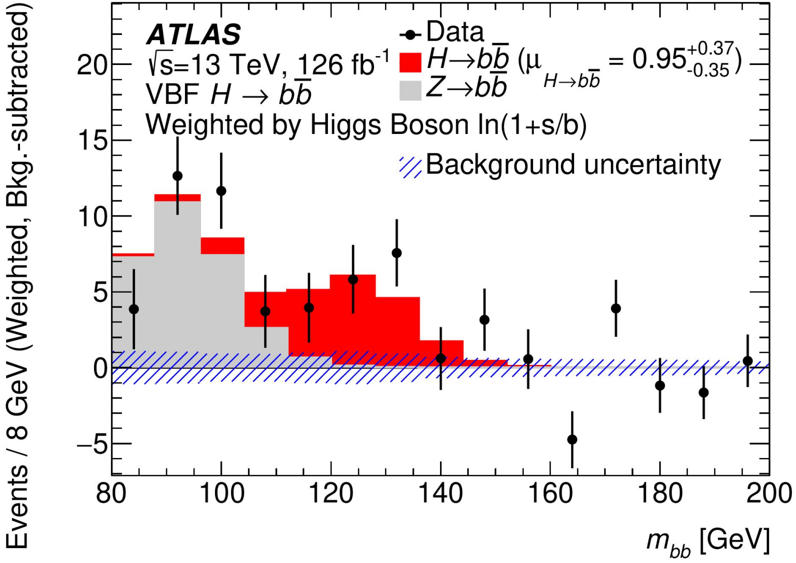


Take background shape



Results

Results	Inclusive Production	VBF Production	$p_T > 200$ GeV
Expected significance	2.9σ	2.8σ	2.3σ
Observed significance	2.7σ	2.6σ	2.2σ
Expected signal strength	$1.00^{+0.37}_{-0.36}$	$1.00^{+0.38}_{-0.37}$	$1.00^{+0.45}_{-0.43}$
Observed signal strength	$0.95^{+0.37}_{-0.35}$	$0.95^{+0.38}_{-0.36}$	$0.93^{+0.45}_{-0.43}$

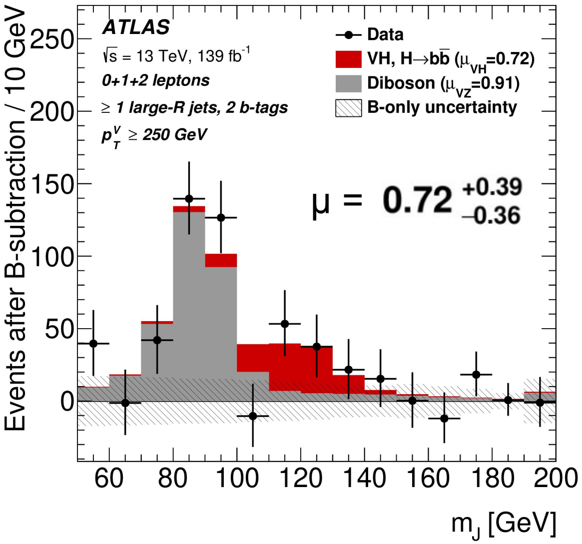


Other H→bb Results

V(lep)H(bb) and ttH(bb) have also released results with the full Run 2 dataset

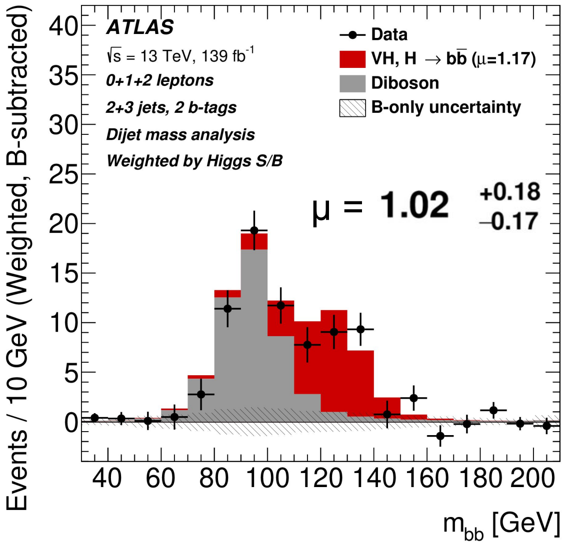
Boosted V(lep)H(bb)

(p_T^H>250 GeV)



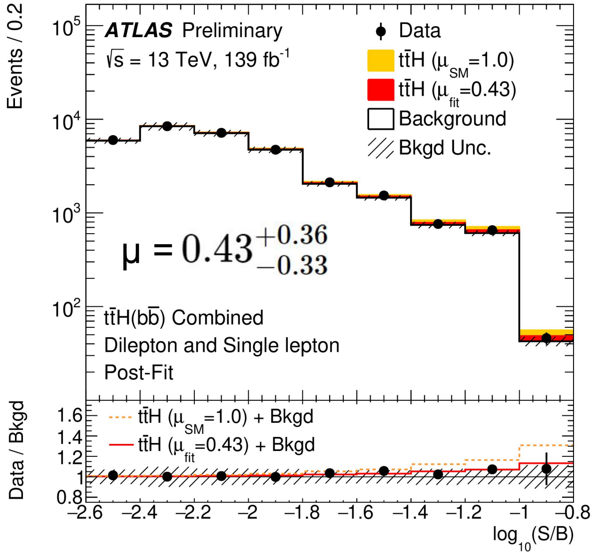
[arXiv:2008.02508]()

Resolved V(lep)H(bb)



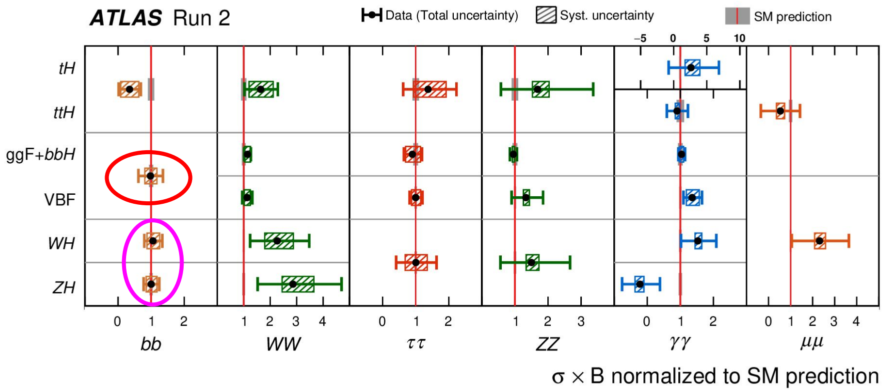
[arXiv:2007.02873]()

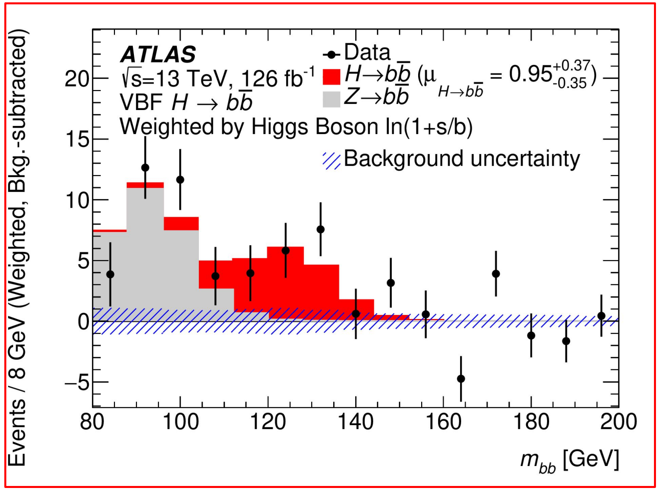
ttH(bb)

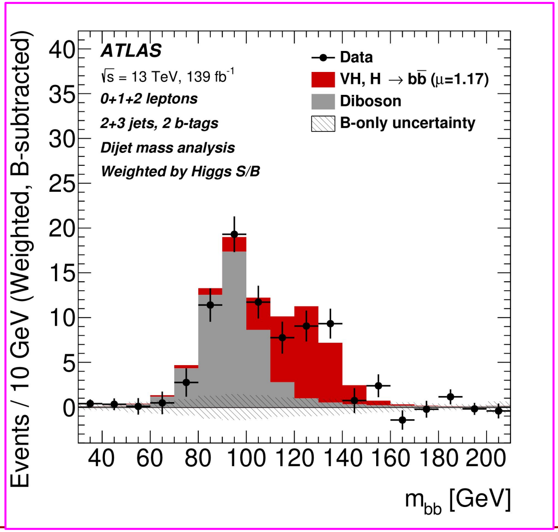


[ATLAS-CONF-2020-058/]()

H(bb), in Context

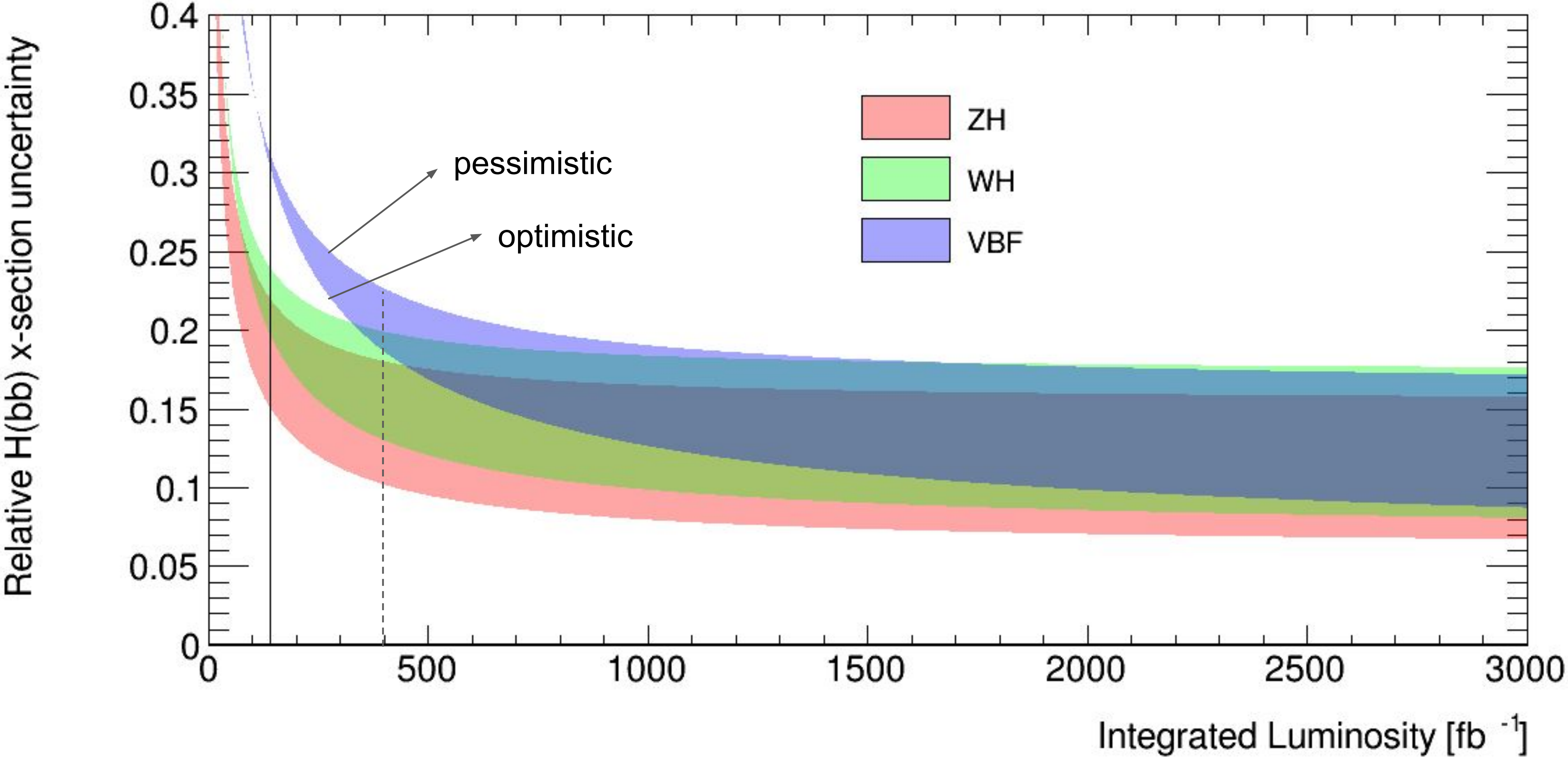






source

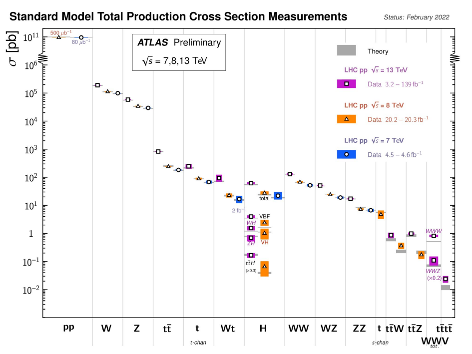
Toward the Future: Sensitivity vs. Time



Searches vs. Measurements

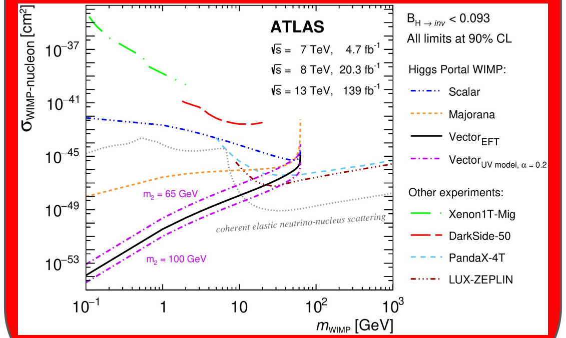
Two avenues for finding potential BSM physics:

Measurements



Example: VBF H(bb)

Searches

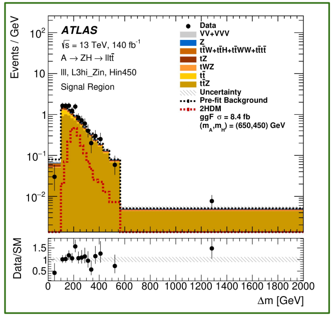


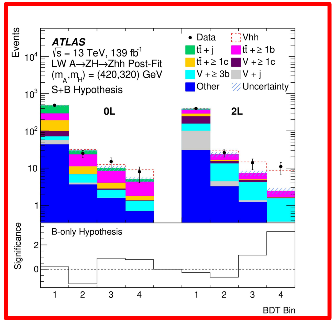
Example: VHH

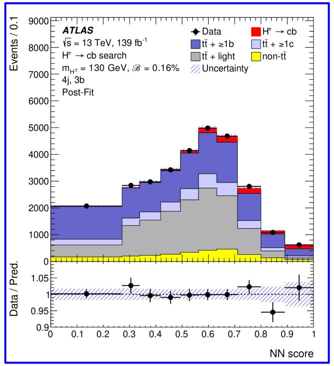
Summary of (Higgs-related) Searches

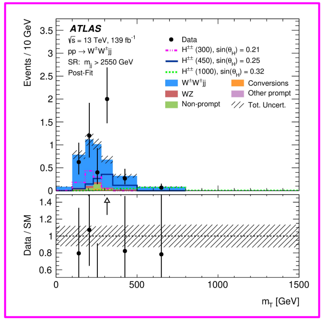
2405.04914

Low mass	125 GeV	High mass
$pp \to a$ $h_{125} \to aa$, $h_{125} \to a_1a_2$ $h_{125} \to Za$	h_{125} rare decays h_{125} exotic decays $h_{125} \to$ invisible	$pp \to H/A$, $pp \to H^\pm$ $H \to h_{125}h_{125}$ $H \to Sh_{125}$, $H \to SS$ $A \to ZH$, $A \to Zh_{125}$





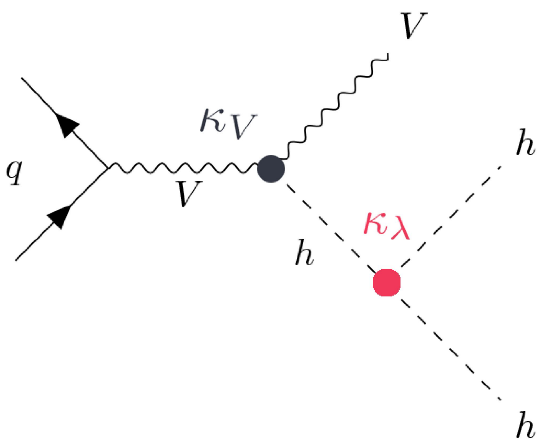


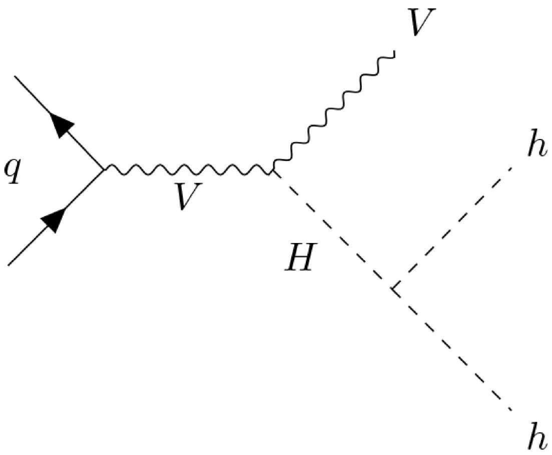


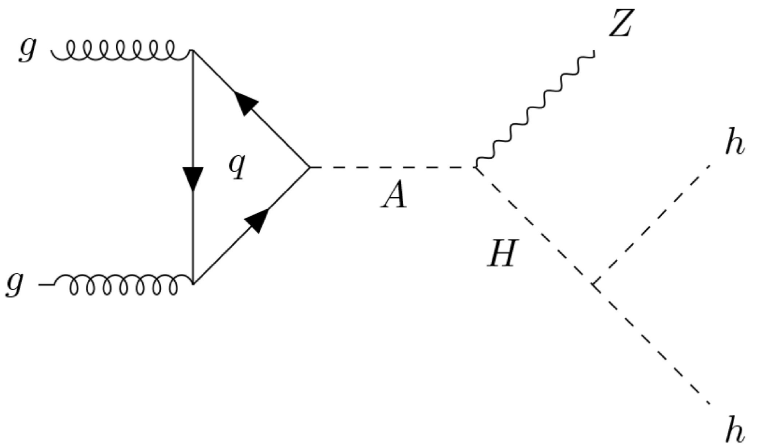
Decay channel	Production mode	Mass [GeV]	Significance local	Significance global	L [fb^{-1}]
$H \to \tau\tau$	b-associated	400	2.7σ	n.a.	139
$H \to \tau\tau$	ggF	400	2.2σ	n.a.	139
$H \to \mu\mu$	b-associated	480	2.3σ	0.6σ	36
$H \to t\bar{t}$	ggF	800	2.3σ	n.a.	140
$H \to t\bar{t}/tq$	qq and qg	900	2.8σ	n.a.	139
$H \to ZZ \to 4\ell/2\ell 2\nu$	ggF	240	2.0σ	0.5σ	139
$H \to ZZ \to 4\ell/2\ell 2\nu$	VBF	620	2.4σ	0.9σ	139
$H \to \gamma\gamma$	ggF	684	3.3σ	1.3σ	139
$H \to \gamma\gamma$	ggF	95.4	1.7σ	n.a.	140
$H \to Z(\ell\ell)\gamma$	ggF	420	2.3σ	n.a.	140
$H \to Z(q\bar{q})\gamma$	ggF	3640	2.5σ	n.a.	139
$A \to Zh_{125}(b\bar{b})$	ggF	500	2.1σ	1.1σ	139
$A \to Zh_{125}(b\bar{b})$	b-associated	500	1.6σ	n.a.	139
$A \to ZH \to \ell\ell b\bar{b}$	ggF	610 (A), 290 (H)	3.1σ	1.3σ	139
$A \to ZH \to \ell\ell b\bar{b}$	b-associated	440 (A), 220 (H)	3.1σ	1.3σ	139
$A \to ZH \to \ell\ell WW$	ggF	440 (A), 310 (H)	2.9σ	0.8σ	139
$A \to ZH \to \ell\ell t\bar{t}$	ggF	650 (A), 450 (H)	2.9σ	2.4σ	140
$A \to ZH \to Zh_{125}(b\bar{b})h_{125}(b\bar{b})$	VH	420 (A), 320 (H)	3.8σ	2.8σ	139
$H^+ \to cb$	$t\bar{t}$ decay	130	3.0σ	2.5σ	139
$H^+ \to Wa(\mu\mu)$	$t\bar{t}$ decay	120–160 (H^+), 27 (a)	2.4σ	n.a.	139
$H^+ \to WZ$	VBF	375	2.8σ	1.6σ	139
$H^{++} \to WW$	VBF	450	3.2σ	2.5σ	139
$H \to h_{125}h_{125} \to 4b$	ggF	1100	2.3σ	0.4σ	126–139
$H \to h_{125}h_{125} \to 4b$	VBF	550	1.5σ	n.a.	126
$H \to h_{125}h_{125} \to b\bar{b}\tau\tau$	ggF	1000	3.1σ	2.0σ	139
$H \to h_{125}h_{125}$ combination	ggF	1100	3.3σ	2.1σ	126–139
$X \to Sh_{125} \to b\bar{b}\gamma\gamma$	ggF	575 (X), 200 (S)	3.5σ	2.0σ	140
$h_{125} \to Z_dZ_d \to 4\ell$	ggF	28	2.5σ	n.a.	139
$h_{125} \to ZZ_d \to 4\ell$	ggF	39	2.0σ	n.a.	139
$h_{125} \to aa \to b\bar{b}\mu\mu$	ggF, VBF, VH	52	3.3σ	1.7σ	139
$h_{125} \to aa \to 4\gamma$	ggF	10–25	1.5σ	n.a.	140
$h_{125} \to e\tau$ and $h_{125} \to \mu\tau$	ggF, VBF, VH	125	2.1σ	n.a.	138

Searches Beyond the Standard Model: VHH

Broad range of models with similar final states
Consider only h→bb, for statistics and simplicity

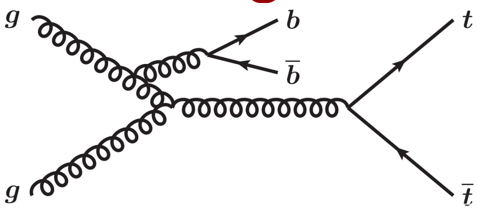


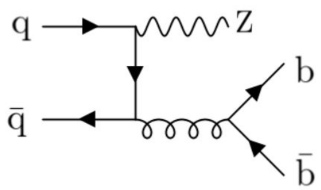


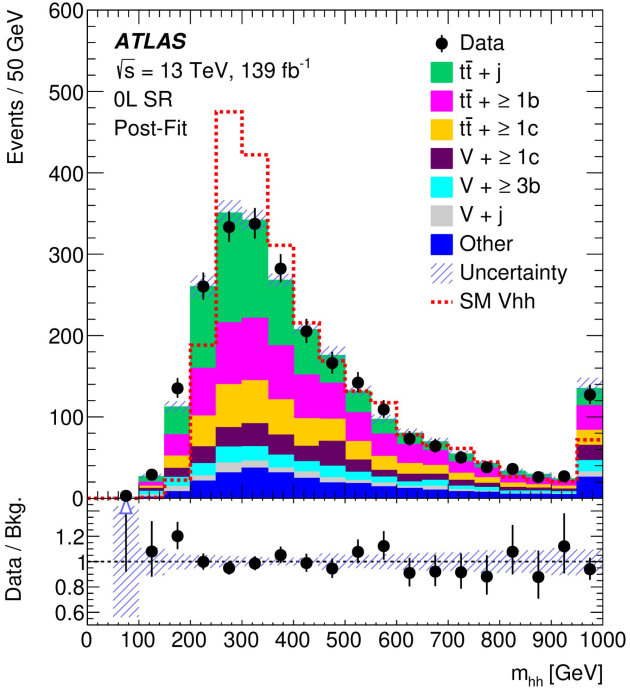


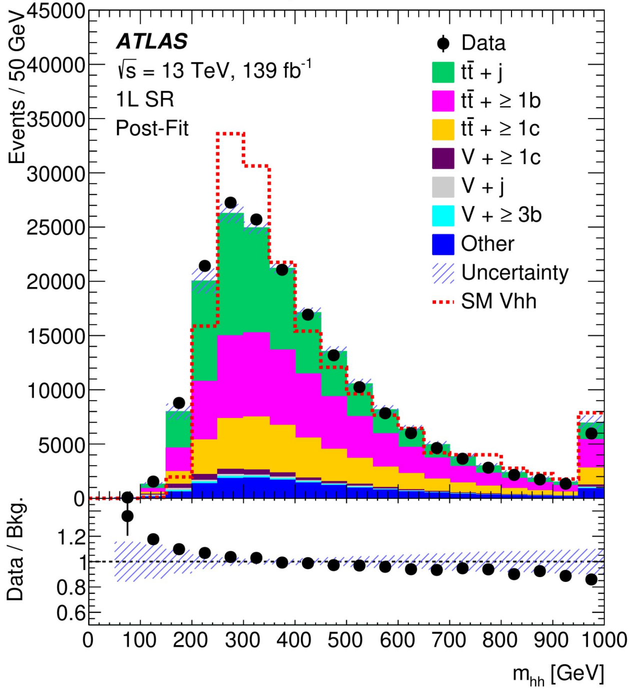
Background Composition

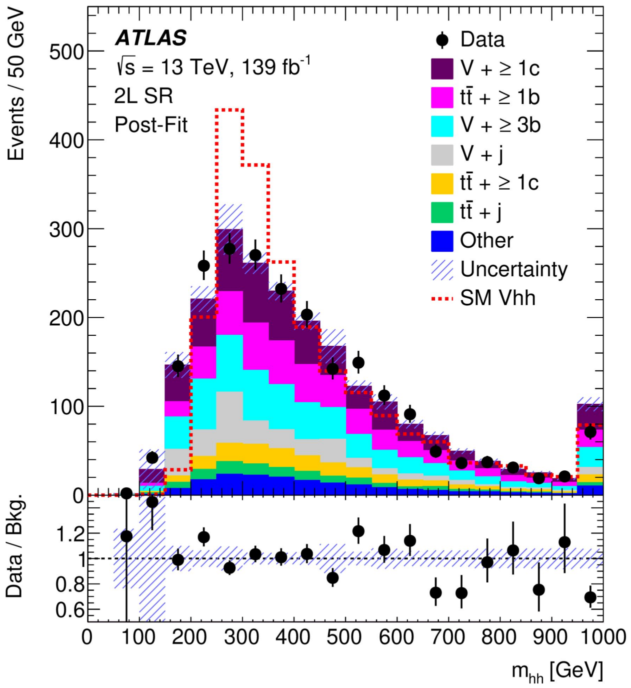
Main background:



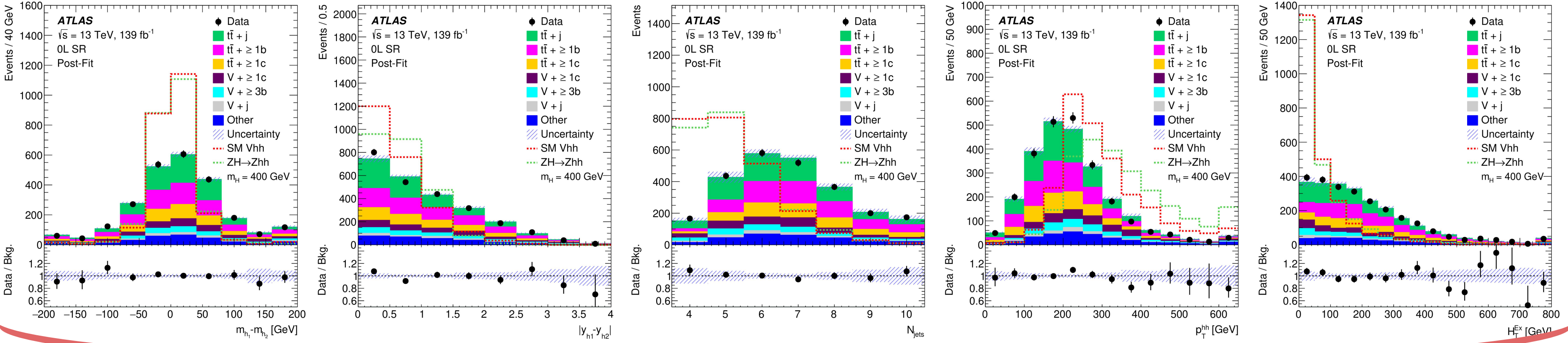




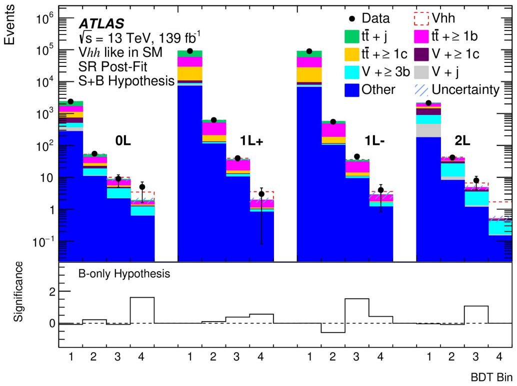




Signal Discrimination



Combine many input variables in a BDT

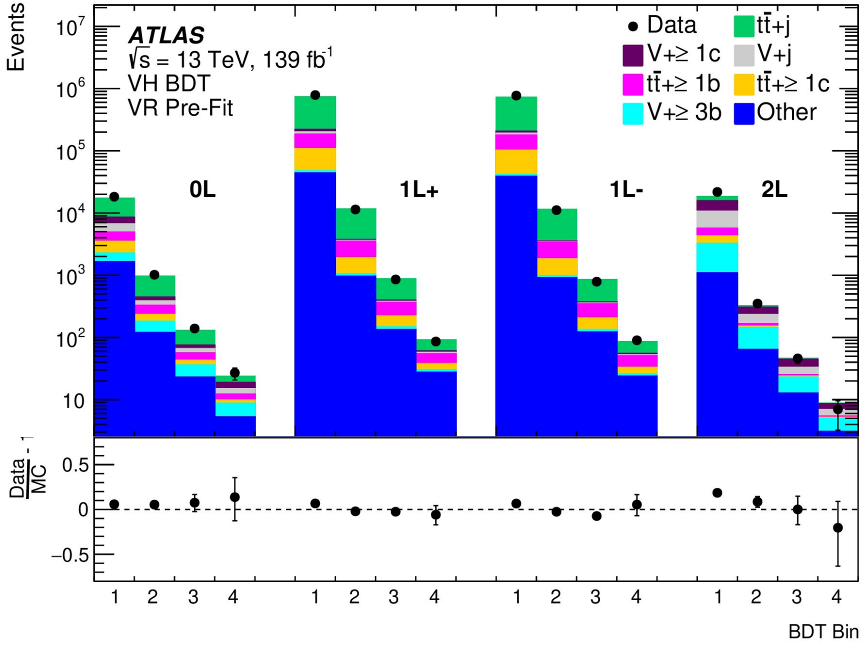


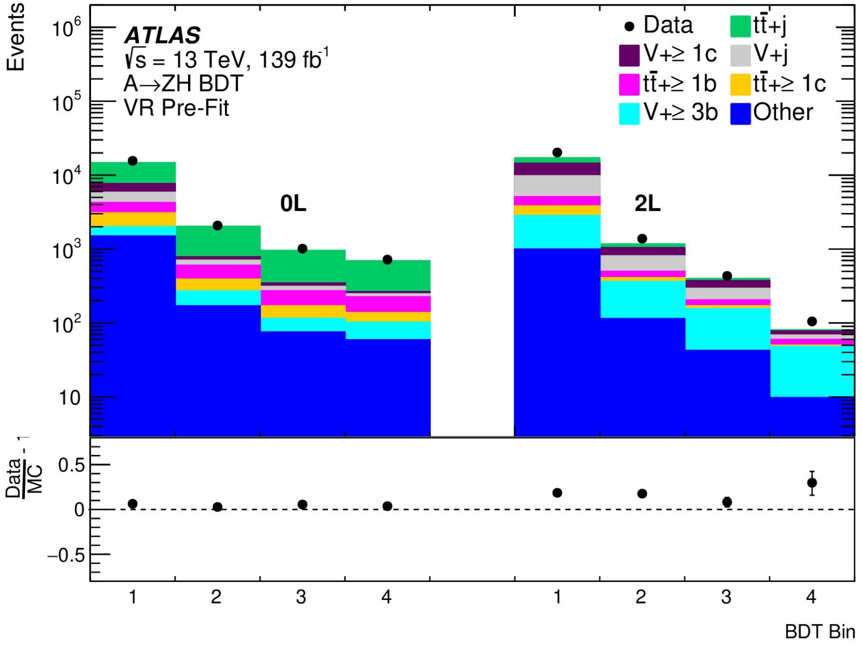
Separate BDT for each channel and signal type

Background Modeling Validation

Signal region have 4 b-jets

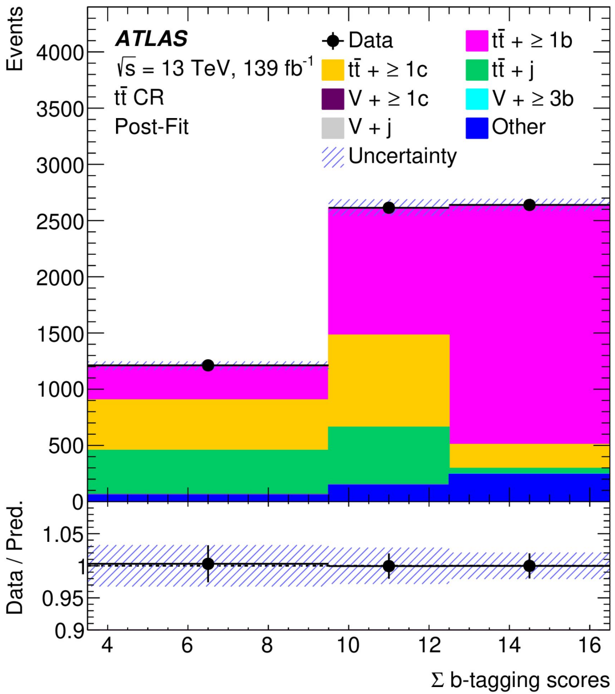
Validate modeling in events with 3 b-jets



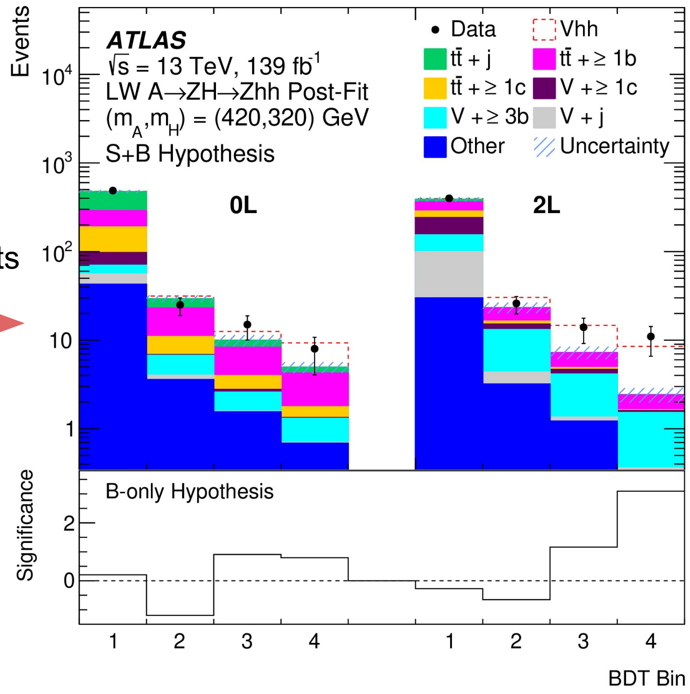


Controlling Backgrounds

Measure main backgrounds using separate control regions
Example: tt



3 bins, 3 unknowns - measure tt+b-jets, charm-jets, and light jets

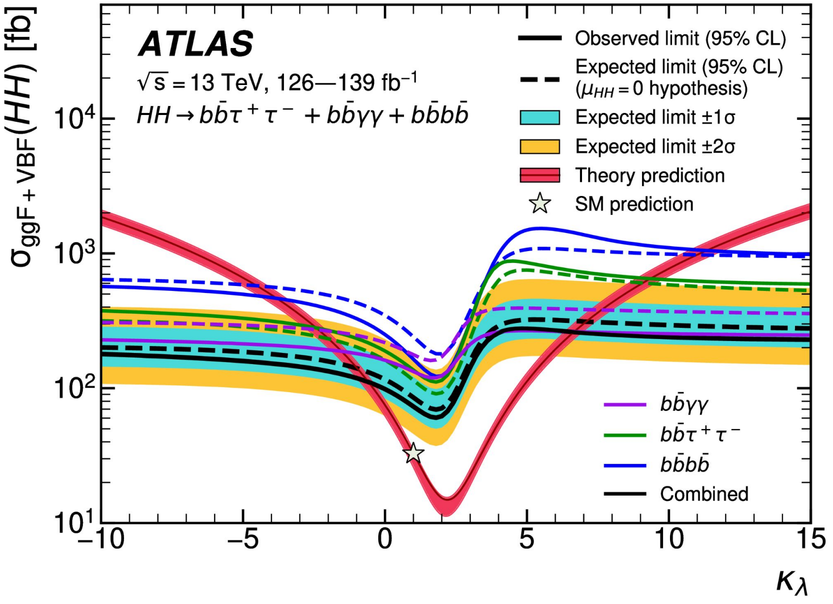


Results: Non-resonant Production

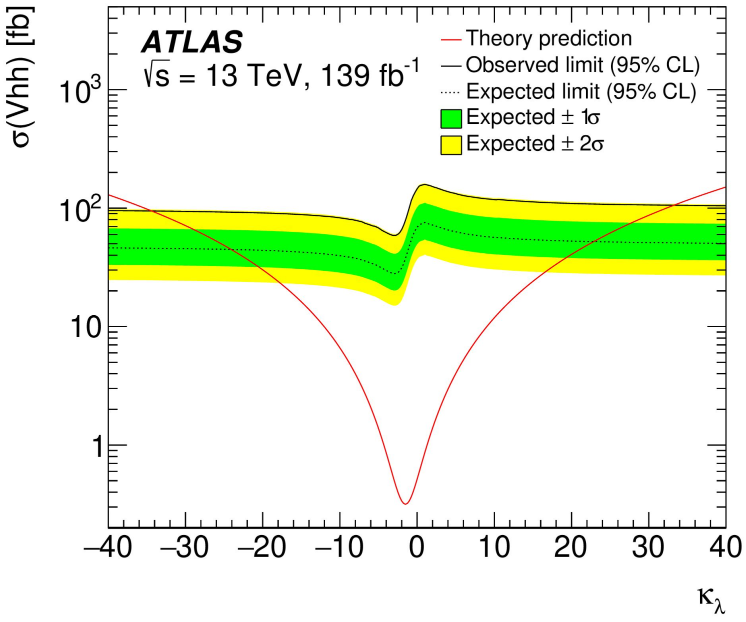
No real self-coupling sensitivity compared to existing limits
Serves a couple purposes:

- Validation check for the resonant analysis
- Prototype for a future non-resonant analysis with a much larger dataset

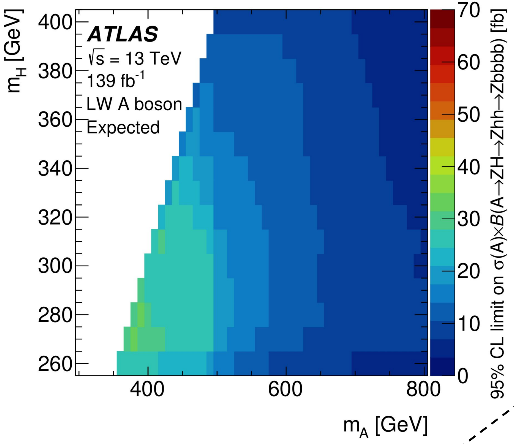
Limits from ggF+VBF

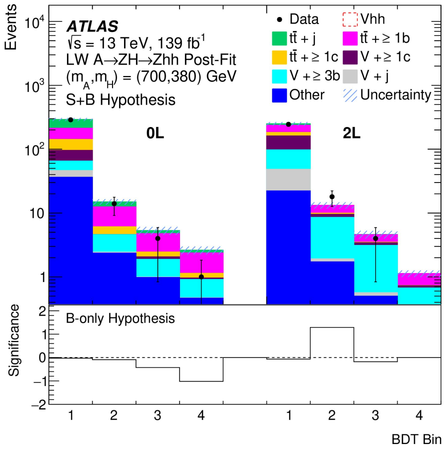


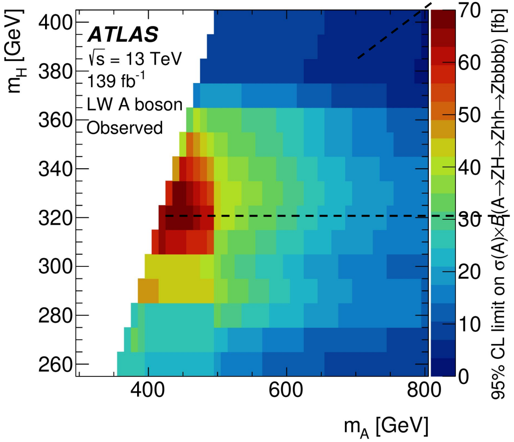
Limits from VHH

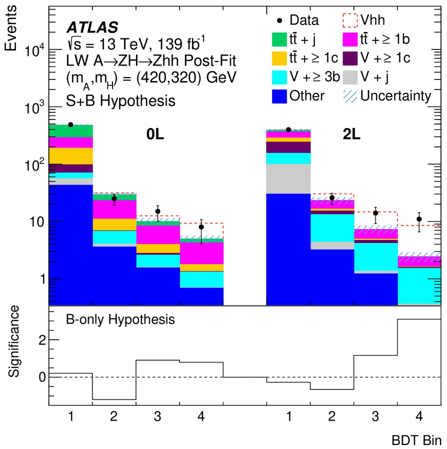


Results: A→ZH→Zhh

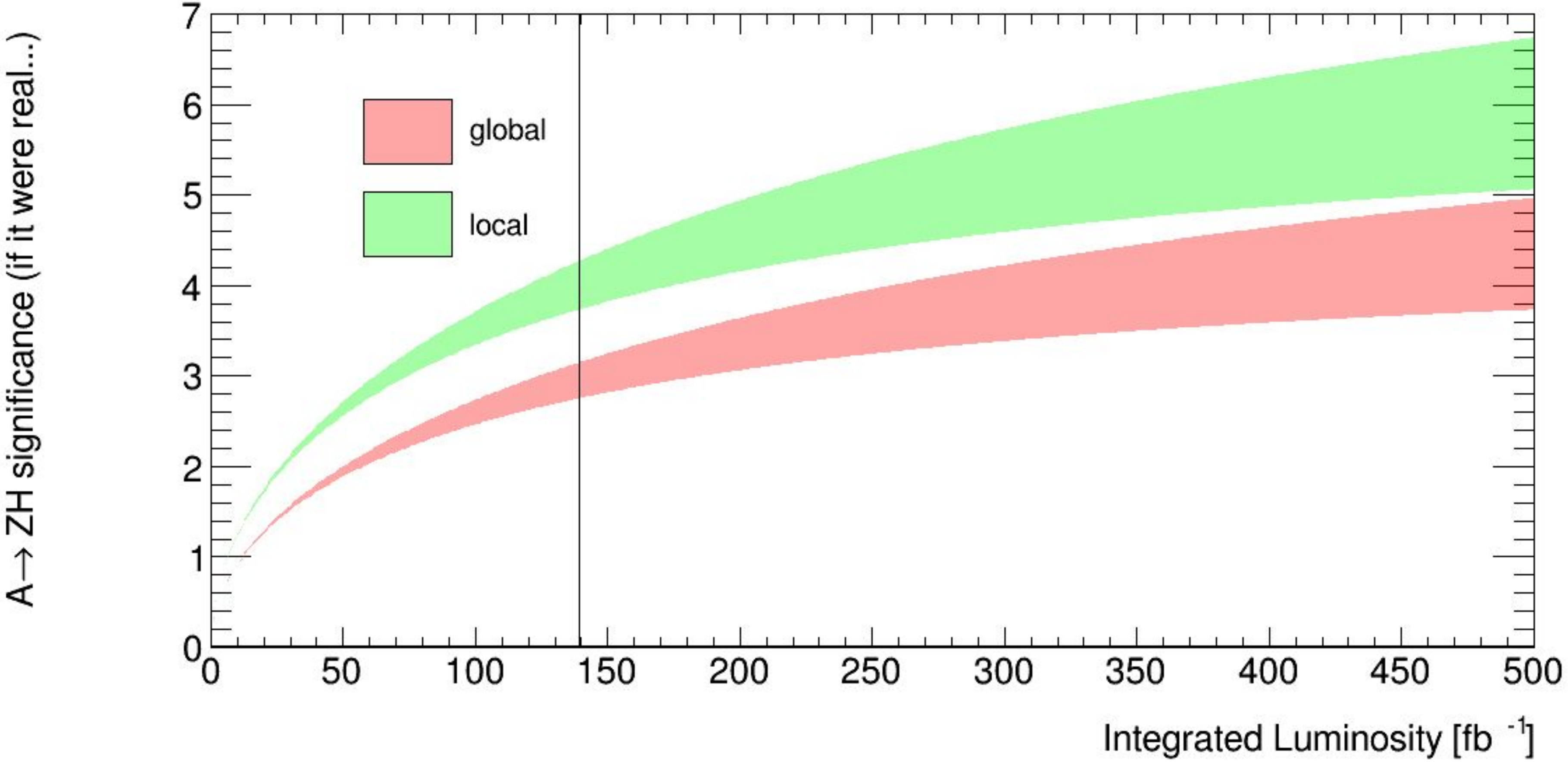




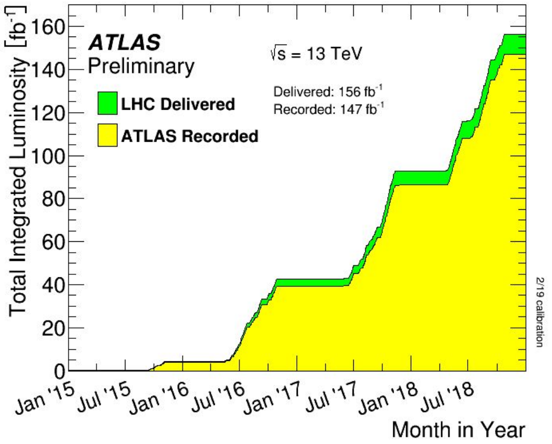


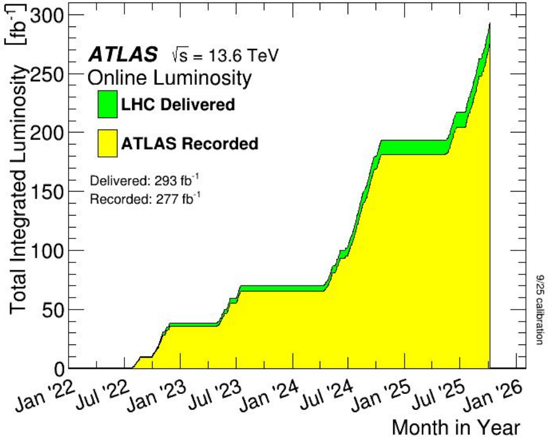


Toward the Future: Sensitivity vs. Time

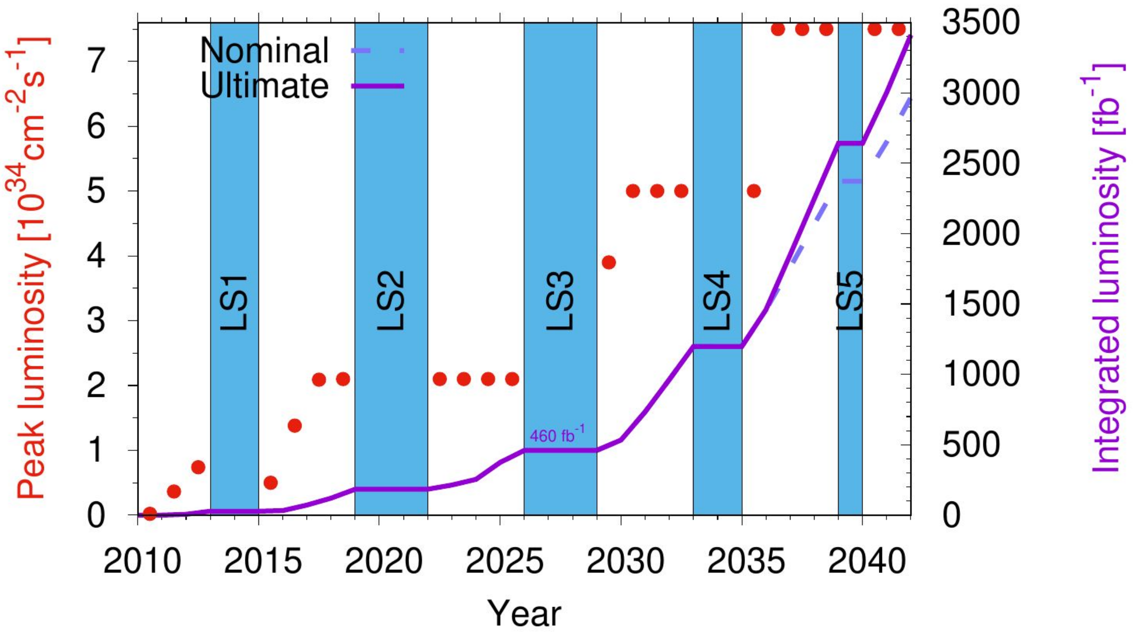


Toward the Future





- Shown results only include ~1/3 of the total collected data
- Ultimate LHC plan would multiply the currently used dataset by >20



Conclusions

- So far, there is no evidence that the new particle is inconsistent with the SM Higgs
- We can expect significant increases in precision in the future
- Many small hints of BSM physics in direct searches... They may all disappear with more data, but we will have much more data in the next 15 years

Backup