The Higgs Boson and the fate of our Universe

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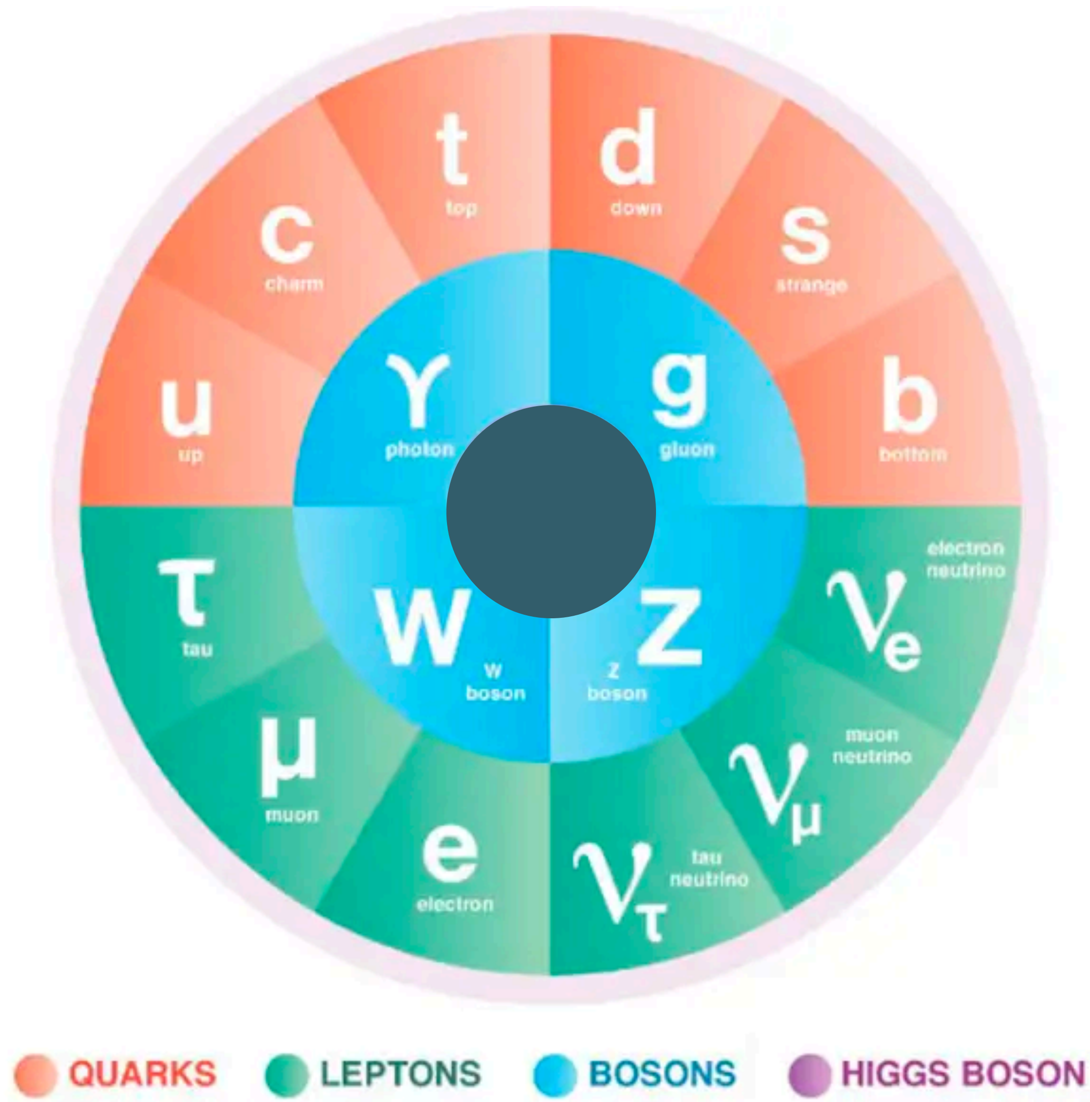
BNL Physics Colloquium

ATLAS EXPERIMENT

Brookhaven National Laboratory

The Standard Model

The Standard Model of particle physics is a powerful theory that explains the fundamental particles and their interactions

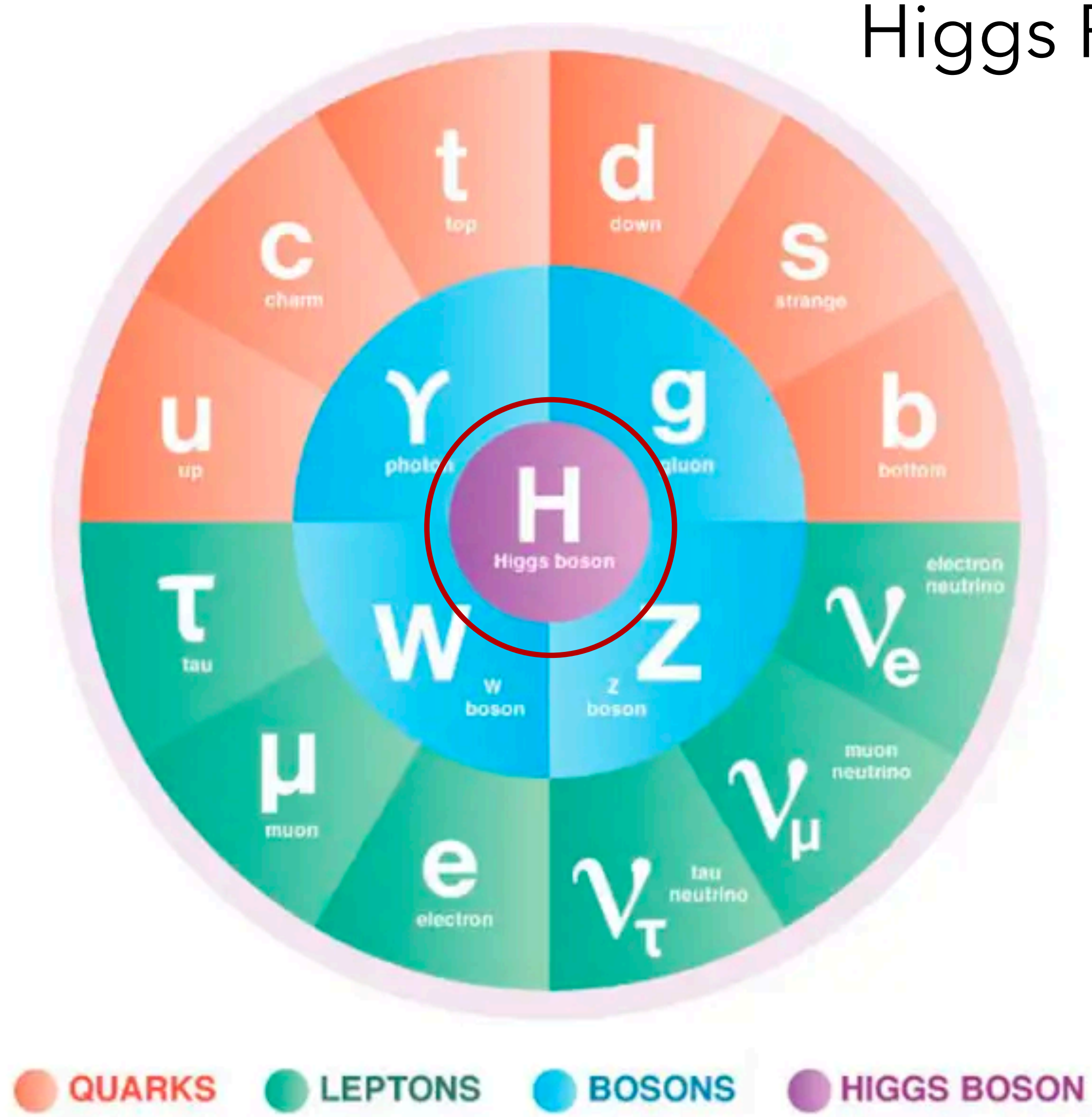


- Constituents: matter particles are fermionic
- Interactions: dictated by principles of symmetry
  - particle associated with each interaction ==> Force carriers

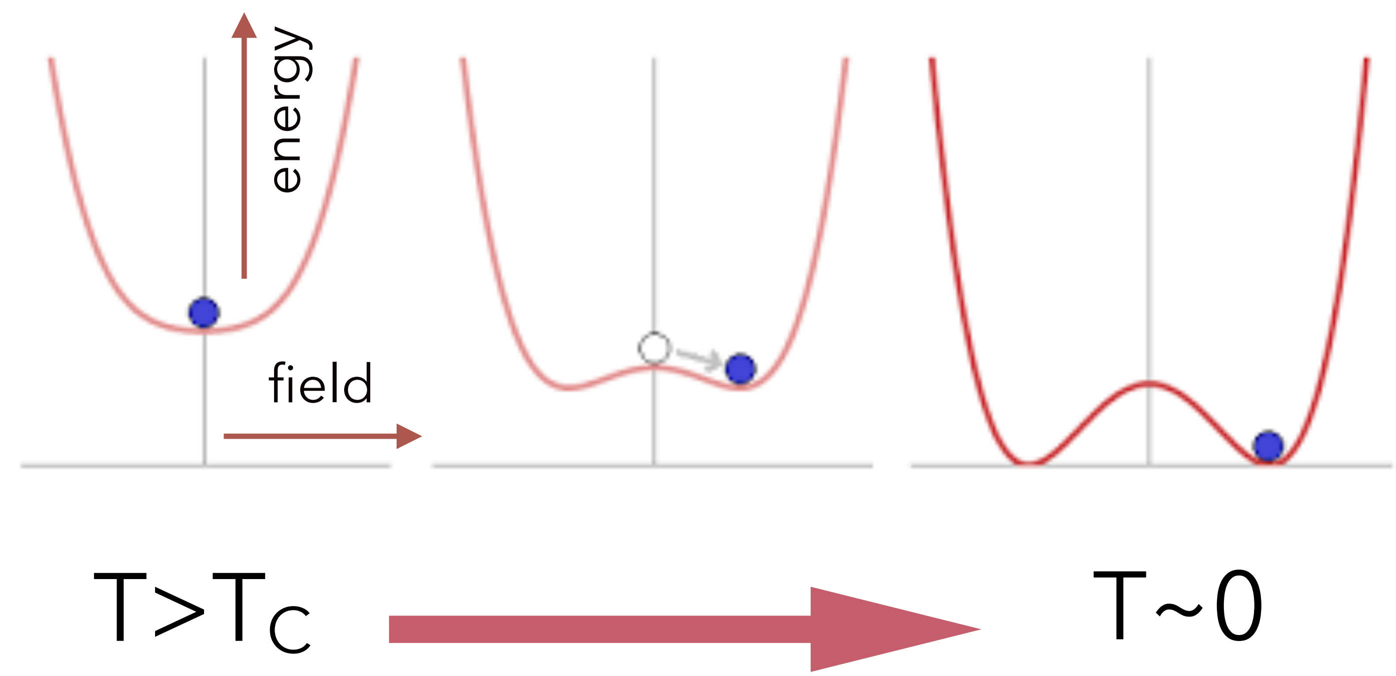
Consistent theory of electromagnetic, weak and strong forces … provided massless Matter and Force Carriers

The Higgs boson

Introduce a complex scalar field with a particular potential (the Higgs potential)



Higgs Potential vs. Energy Scale (T of the Universe)

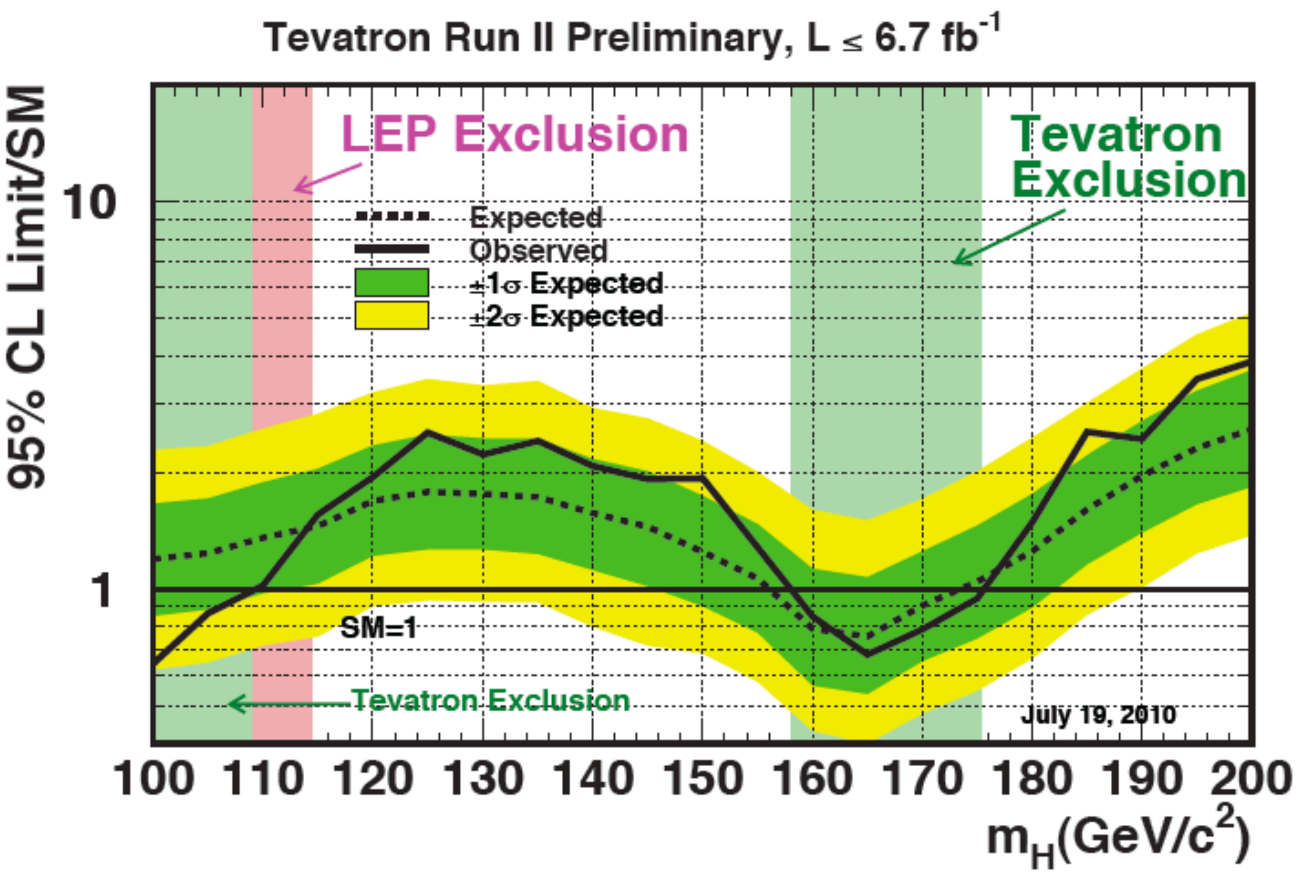


spontaneous symmetry breaking

Starting with a massless gauge boson, spontaneous symmetry breaking will lead to a massive gauge boson and a massive scalar particle, **the Higgs boson!**

At the Dawn of the LHC era

- By mid-2010 we knew that IF the Higgs boson existed its mass was:
  - greater than about 115 GeV from LEP
  - m_H <158 or m_H> 175 GeV
- Not much information!



Need a collider that could probe for a Higgs boson anywhere in the allowed mass range, and detectors that could find it!

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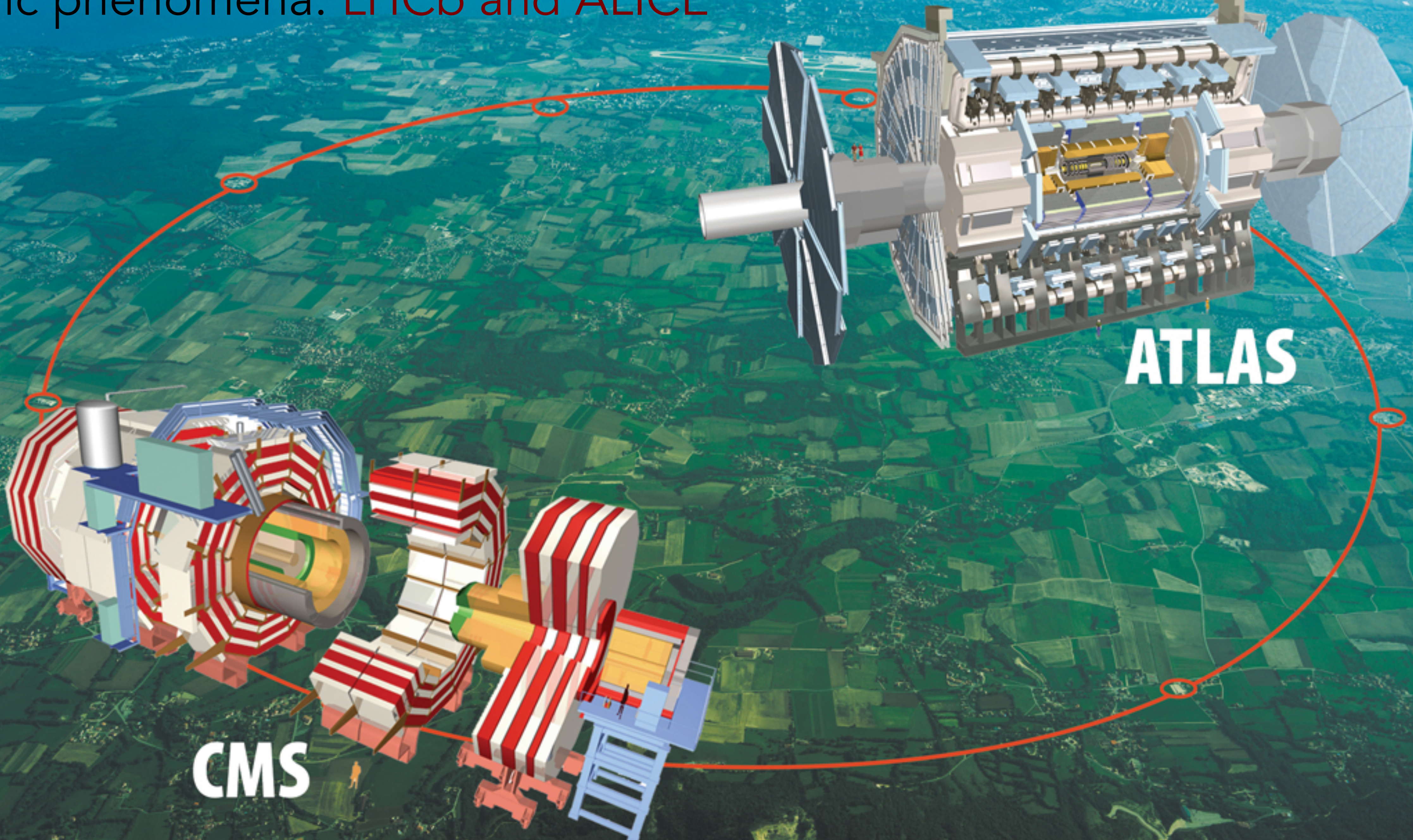
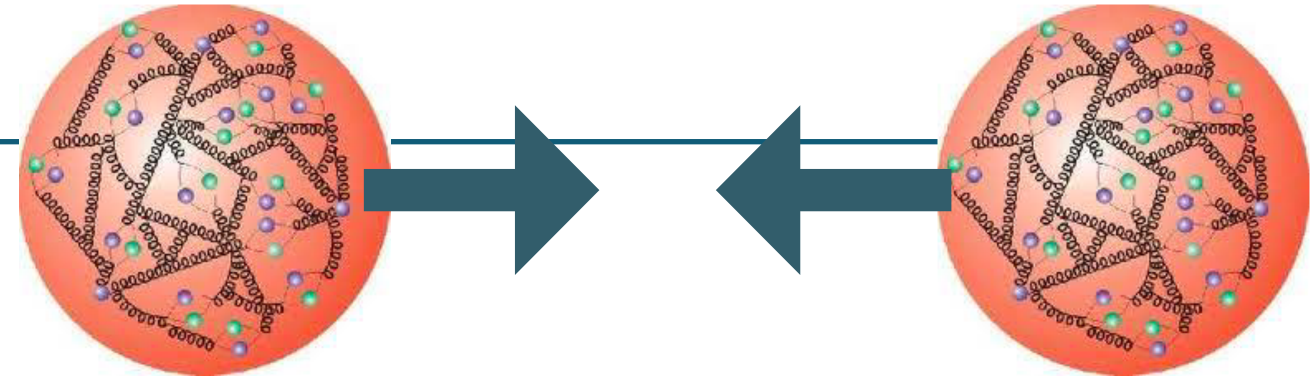
The LHC is a 27km proton synchrotron 100m below the Swiss and French countryside near Geneva. It is designed to collide protons at center of mass energies up to 14 TeV

2 multipurpose experiments: CMS and ATLAS. 2 detectors that look for specific phenomena: LHCb and ALICE

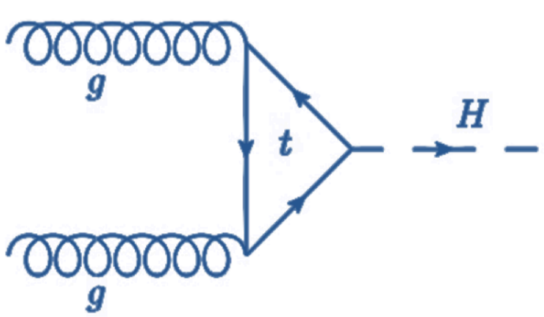


Higgs production



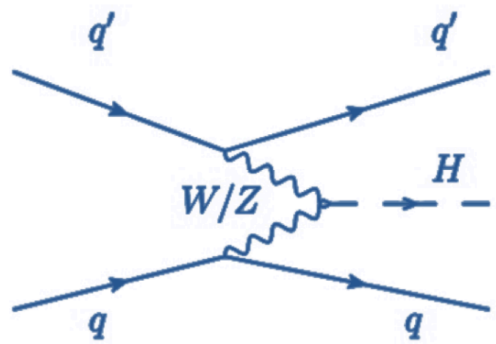
Proton Proton

Gluon Fusion



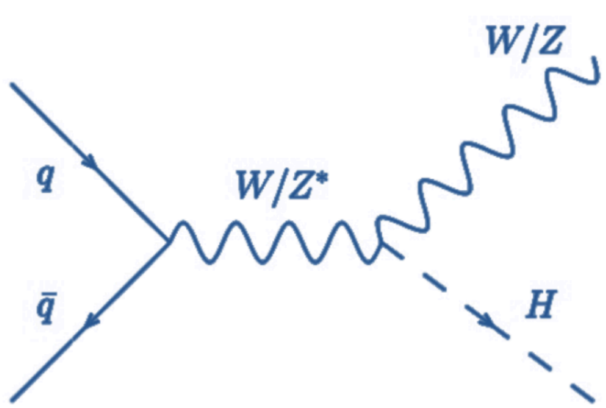
$\sigma_{H,ggF} \sim 49$ pb

Vector Boson Fusion



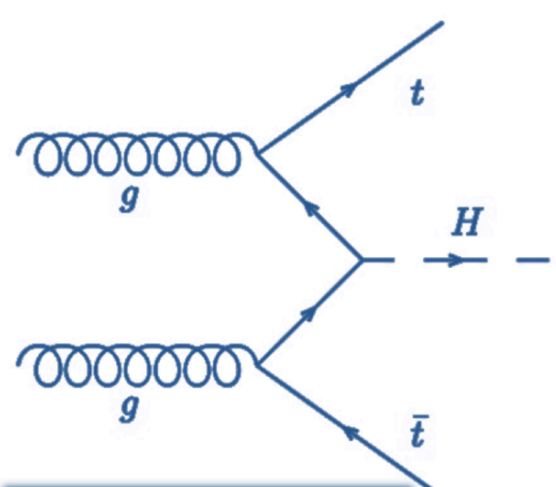
$\sigma_{VBF} \sim 3.8$ pb

Higgs-Strahlung

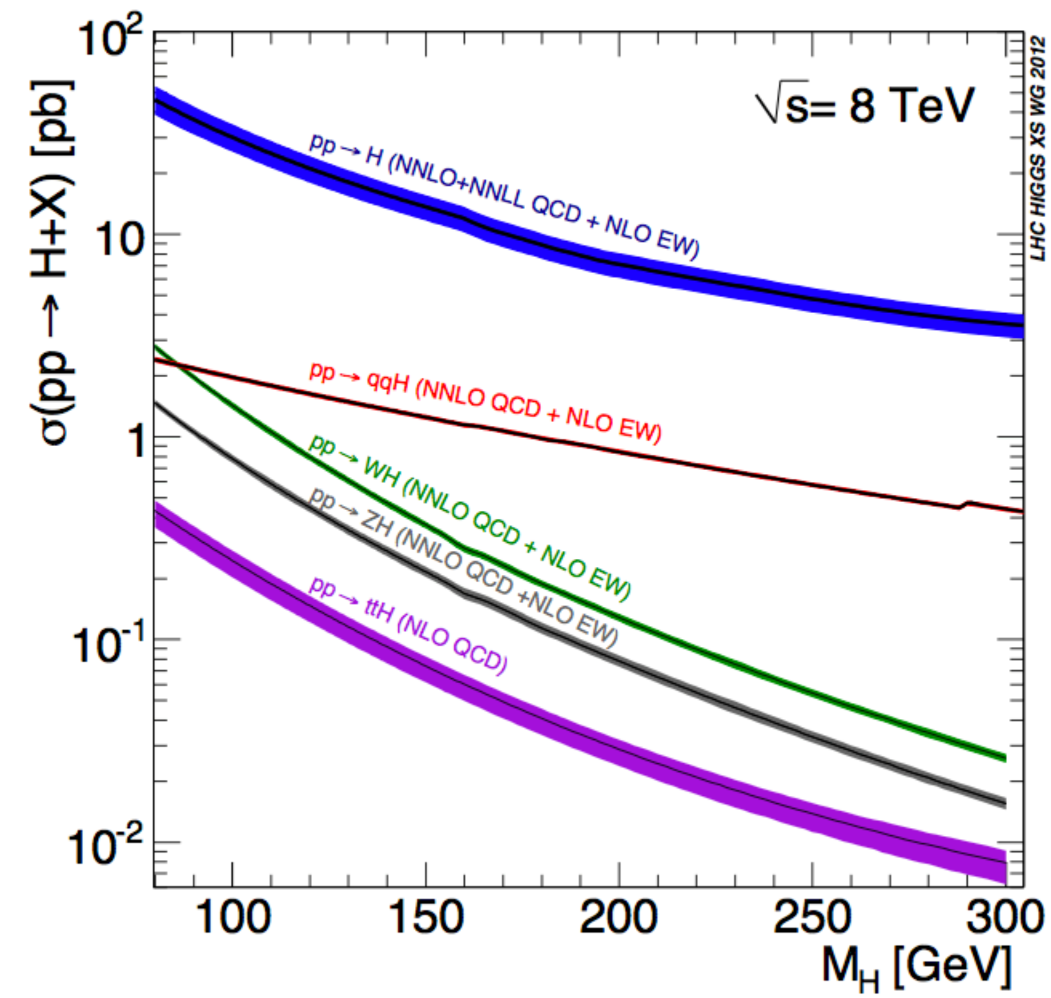


$\sigma_{W/Z+H} \sim 1.4/0.9$ pb

ttH Production



$\sigma_{ttH} \sim 0.5$ pb



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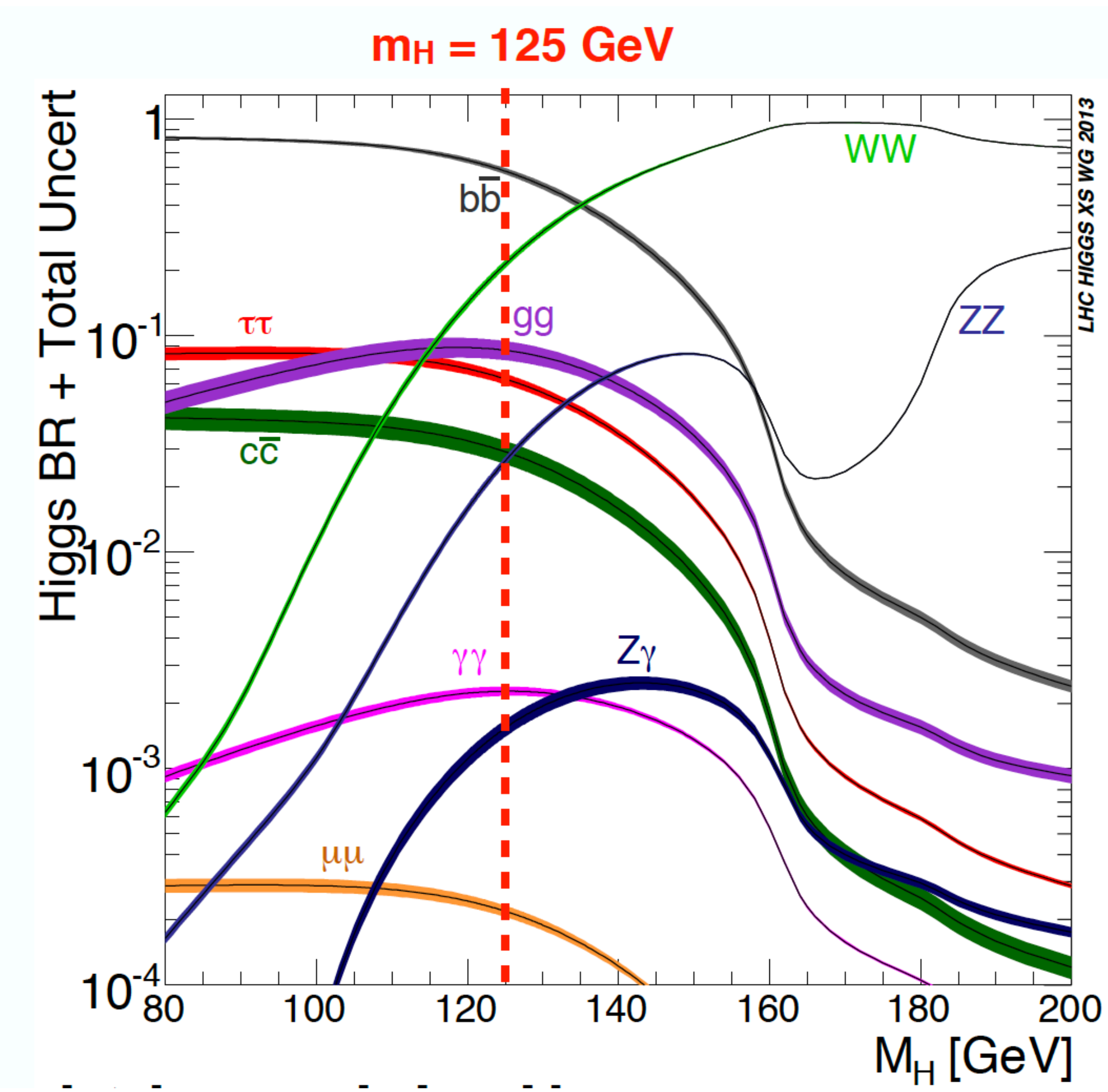
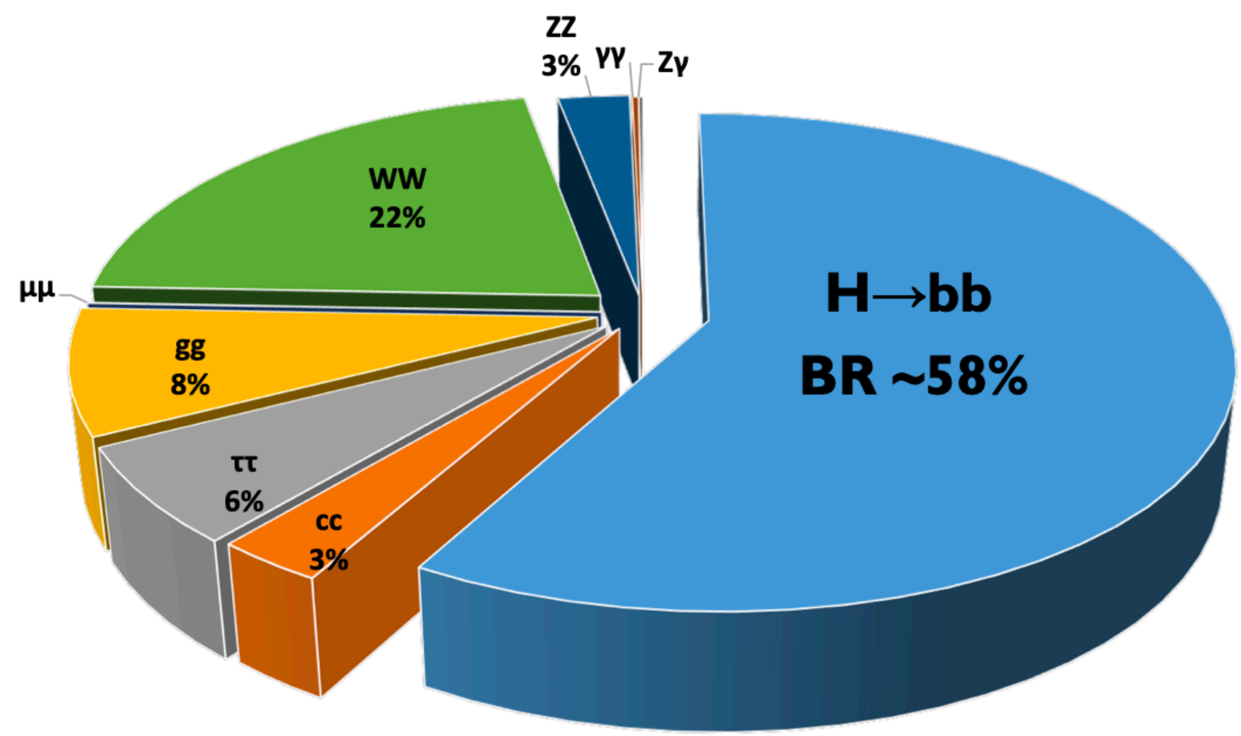
Higgs production and decay





Need detectors that can efficiently and accurately detect photons, electrons, muons, taus, and 'jets', WHILE minimizing backgrounds

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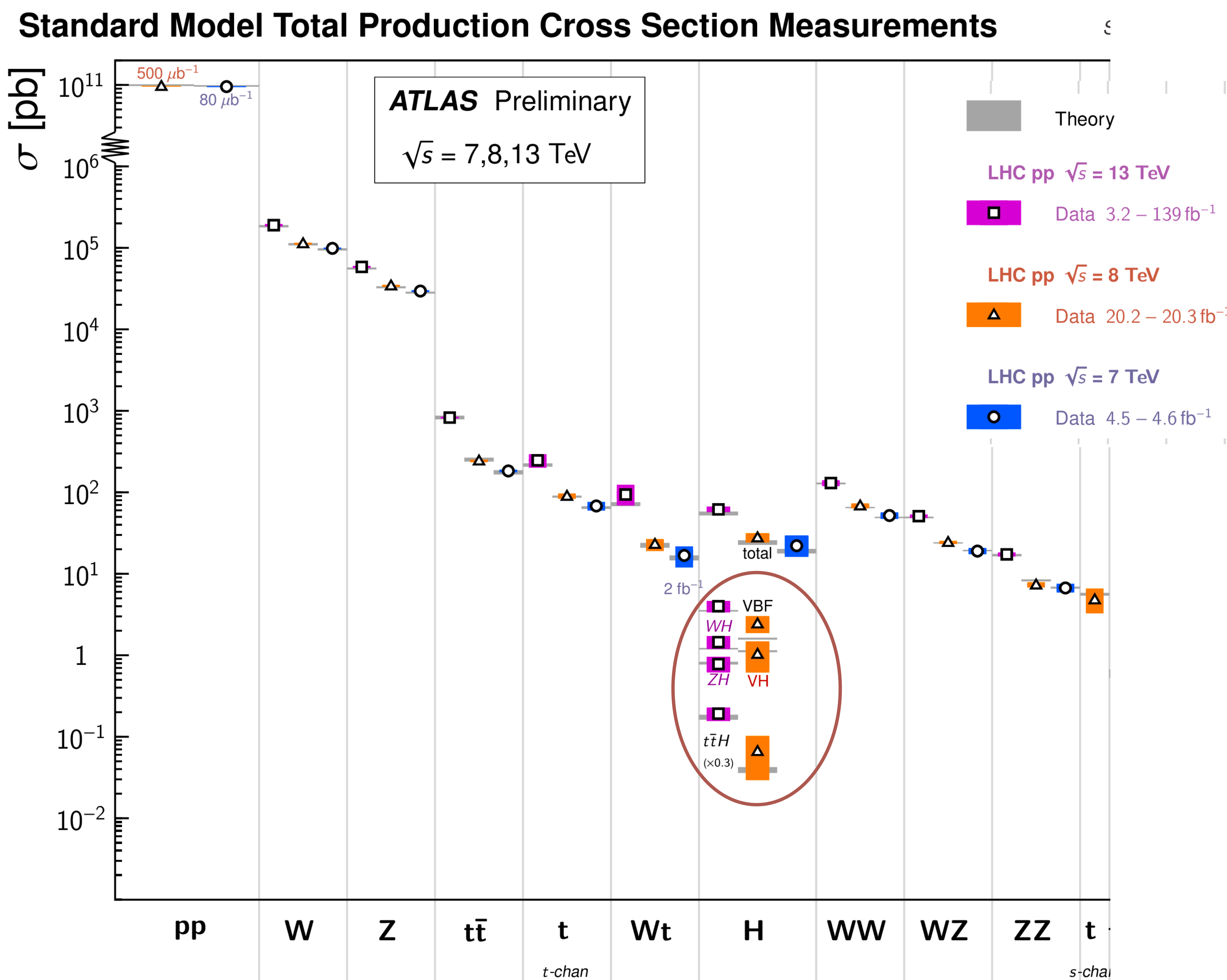
Huge Standard Model Backgrounds



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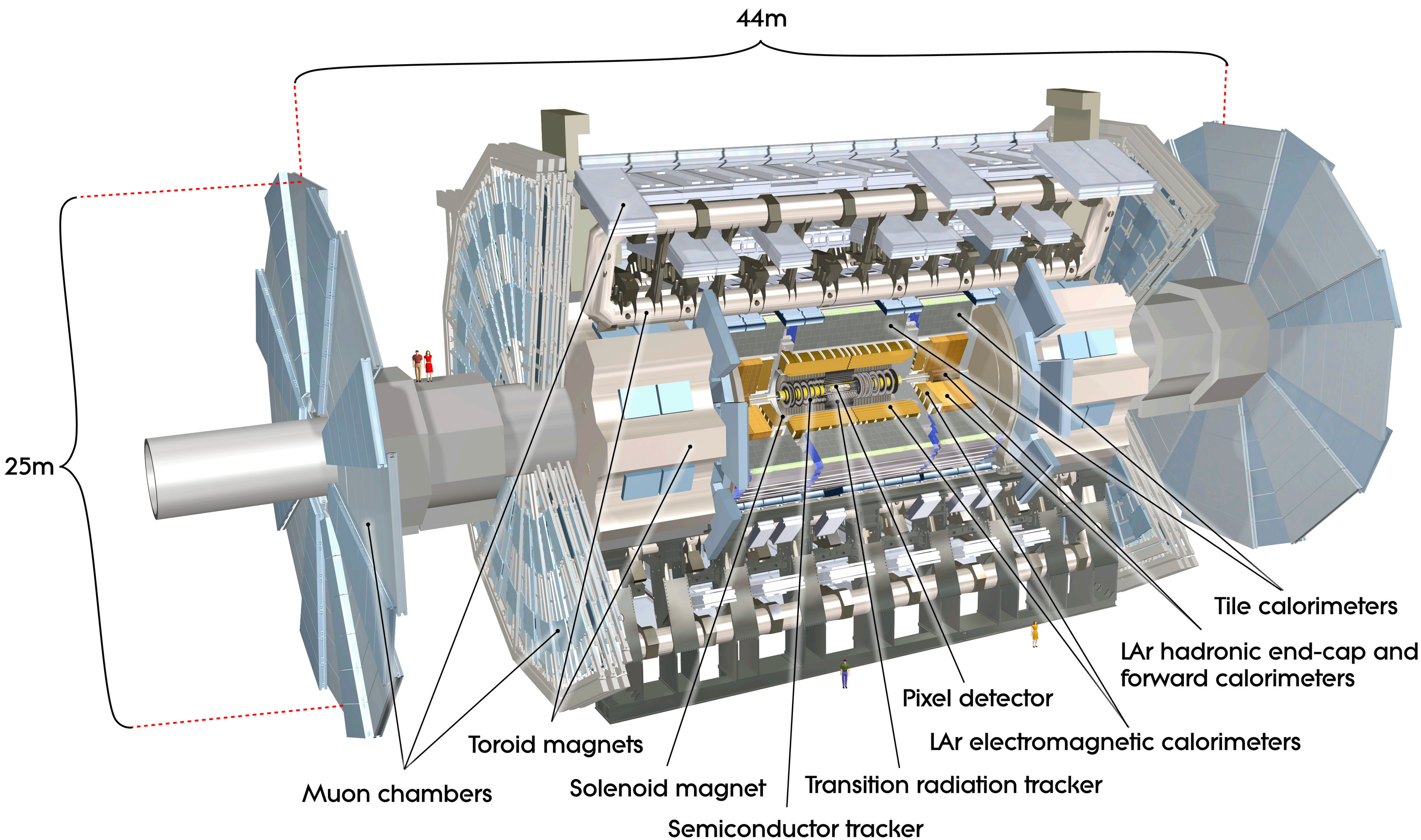
1 observed Higgs event in a trillion (10^{12}) pp collisions

Large Detector needed: ATLAS



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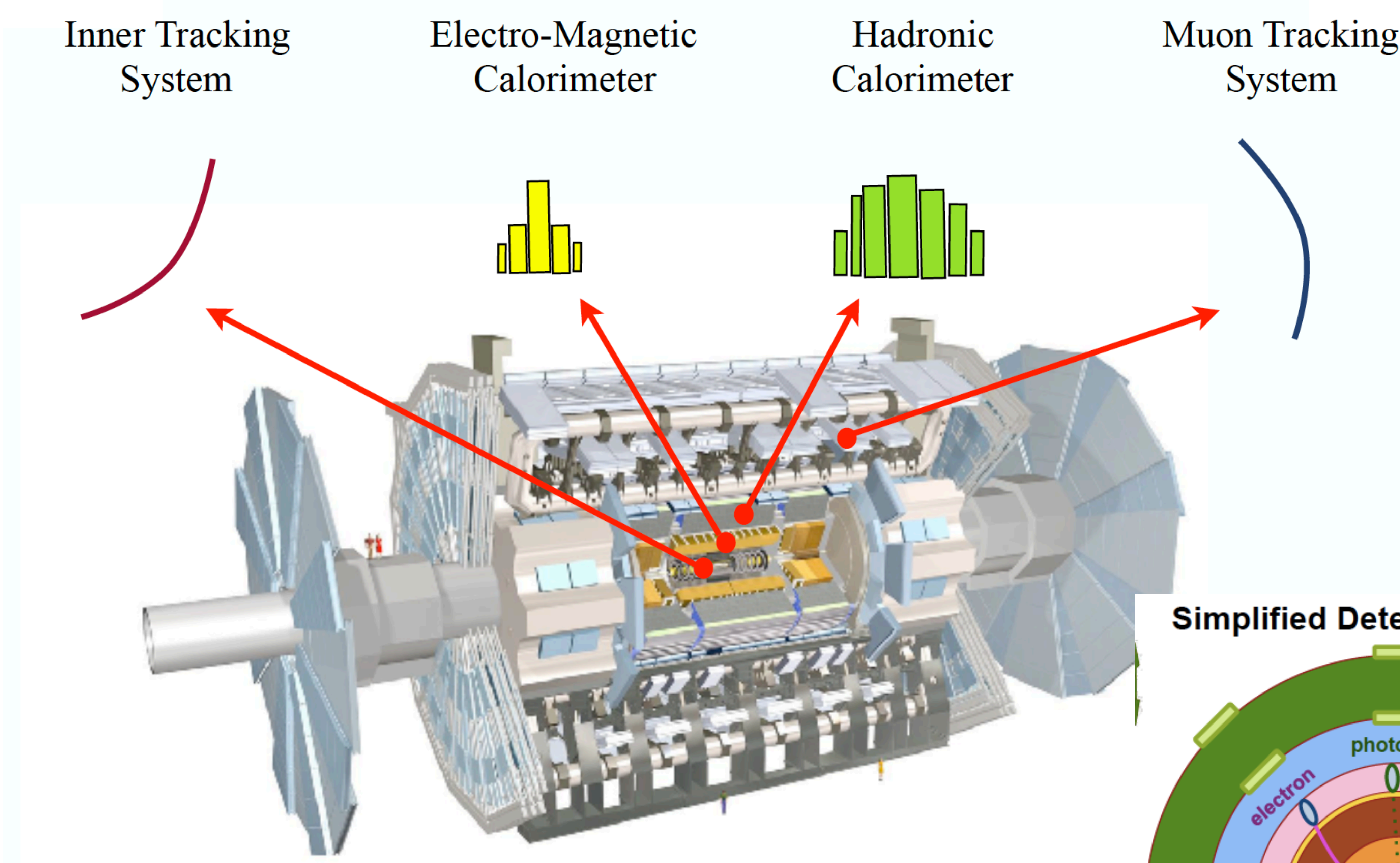
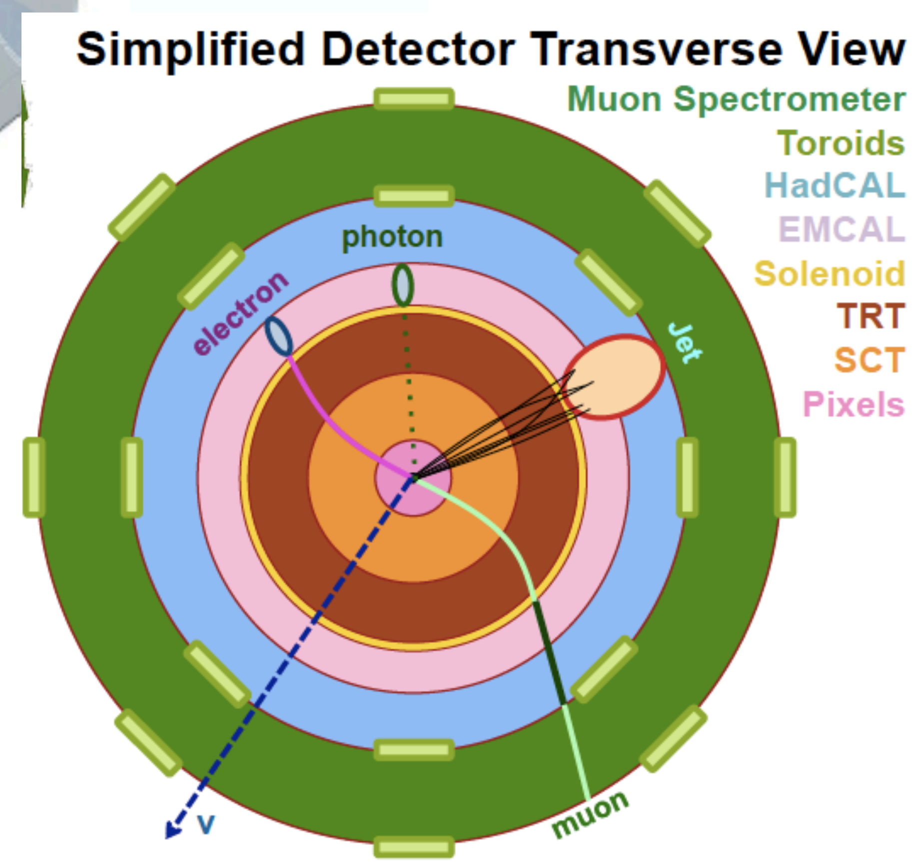
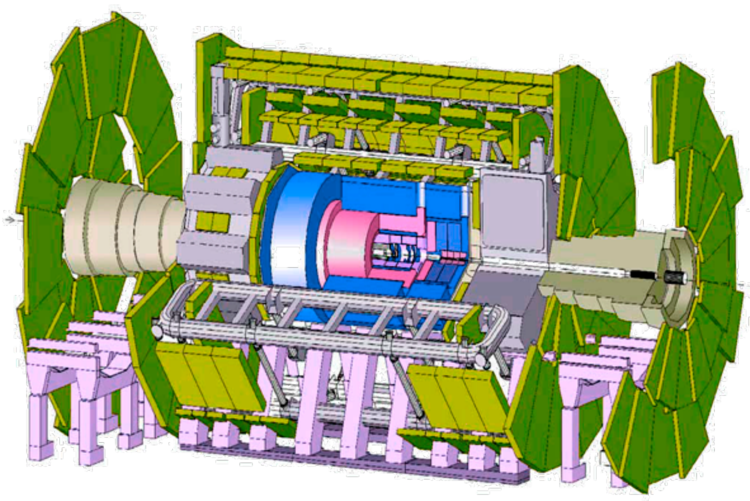
Large Detector needed: ATLAS





From detector to results

Detector

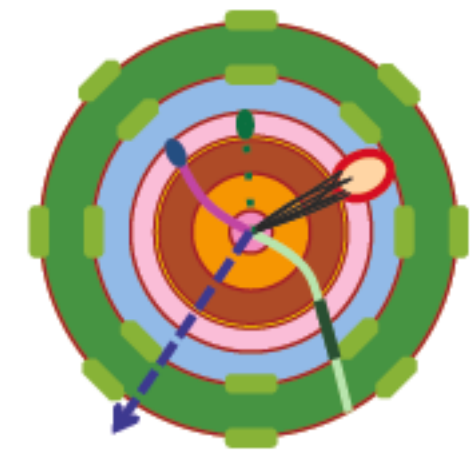


40 MHz

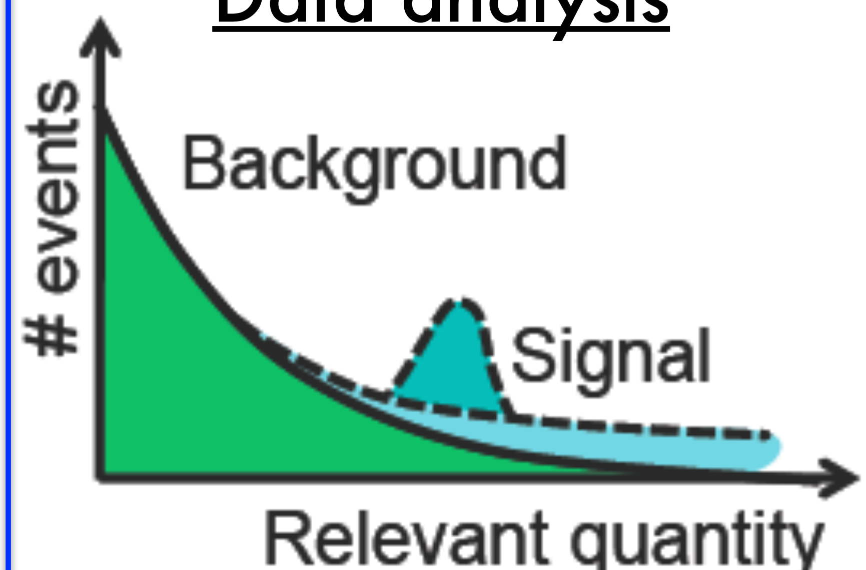
Trigger

1KHz

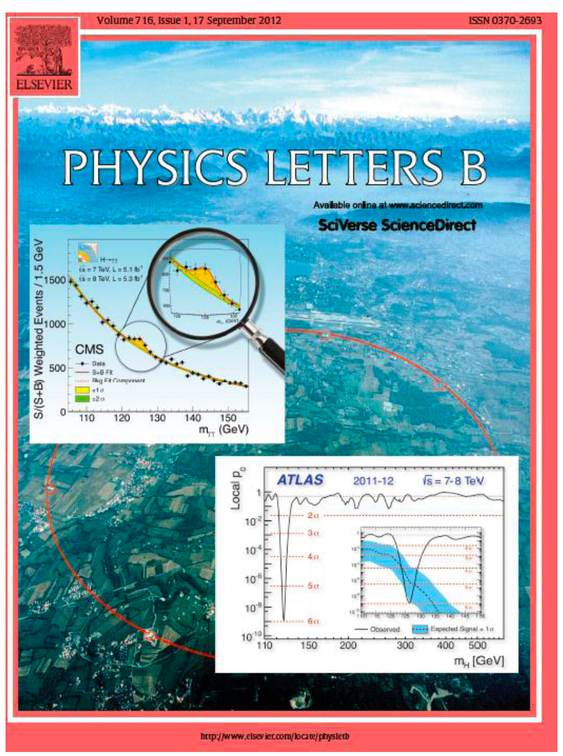
Reconstruction



Data analysis

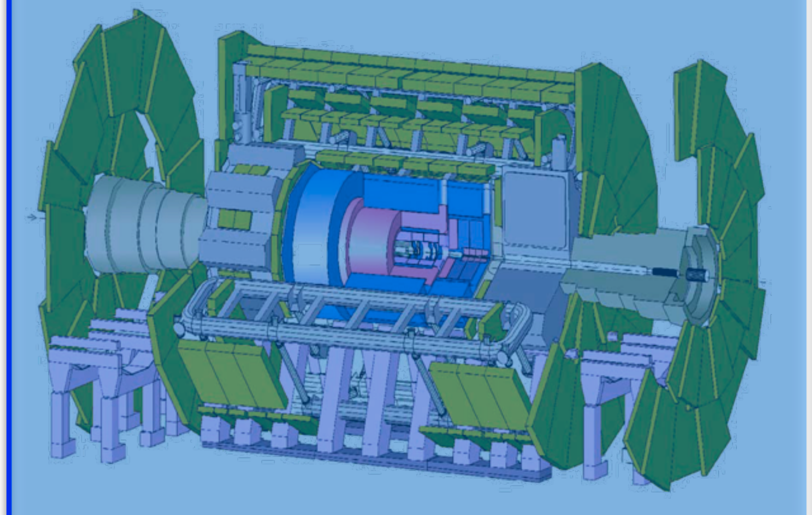


Publication



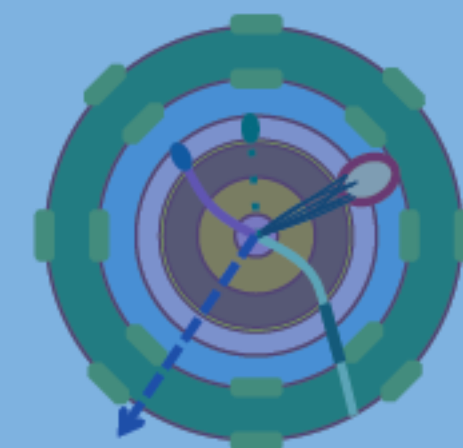
From detector to results

Detector



Trigger

Reconstruction

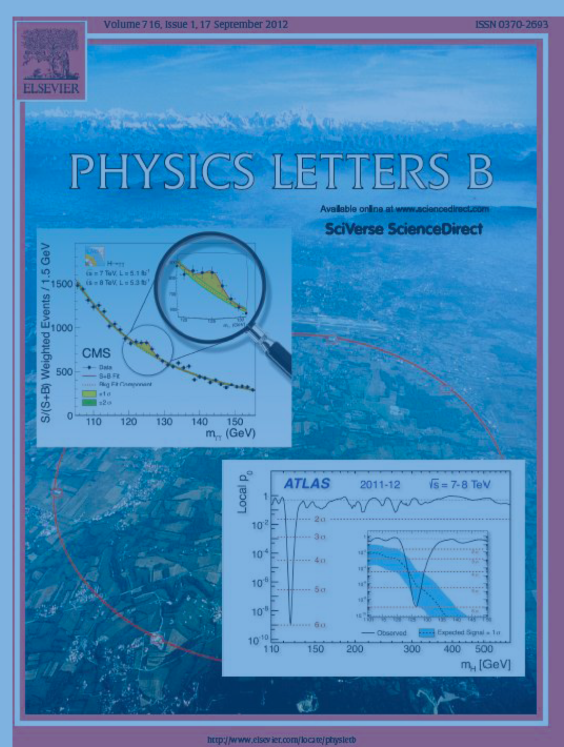


40 MHz

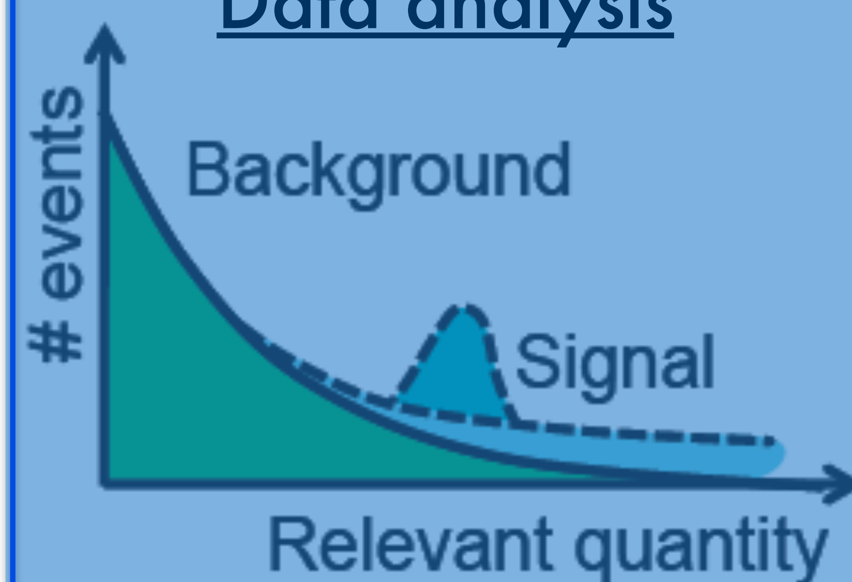
1KHz

save only 0.1% of events in few micro-seconds

Publication

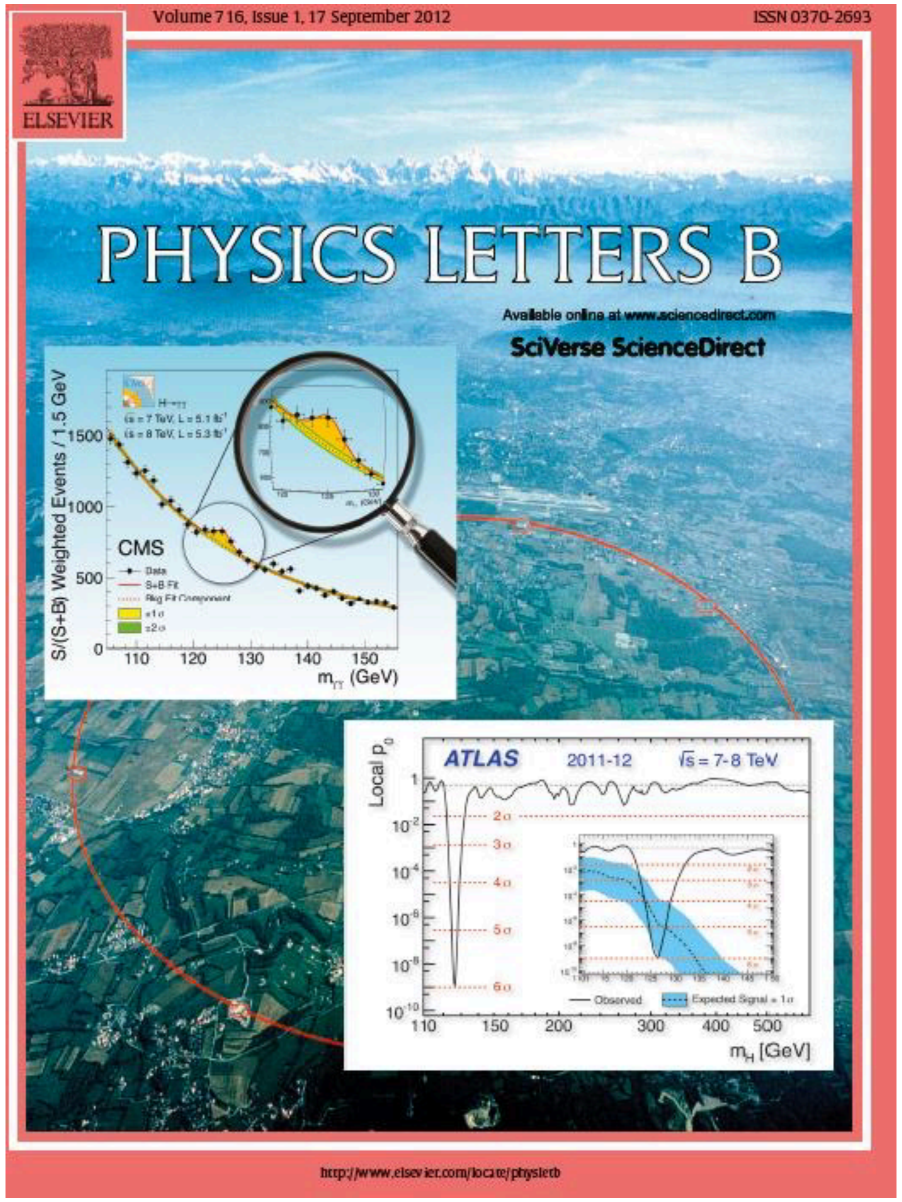


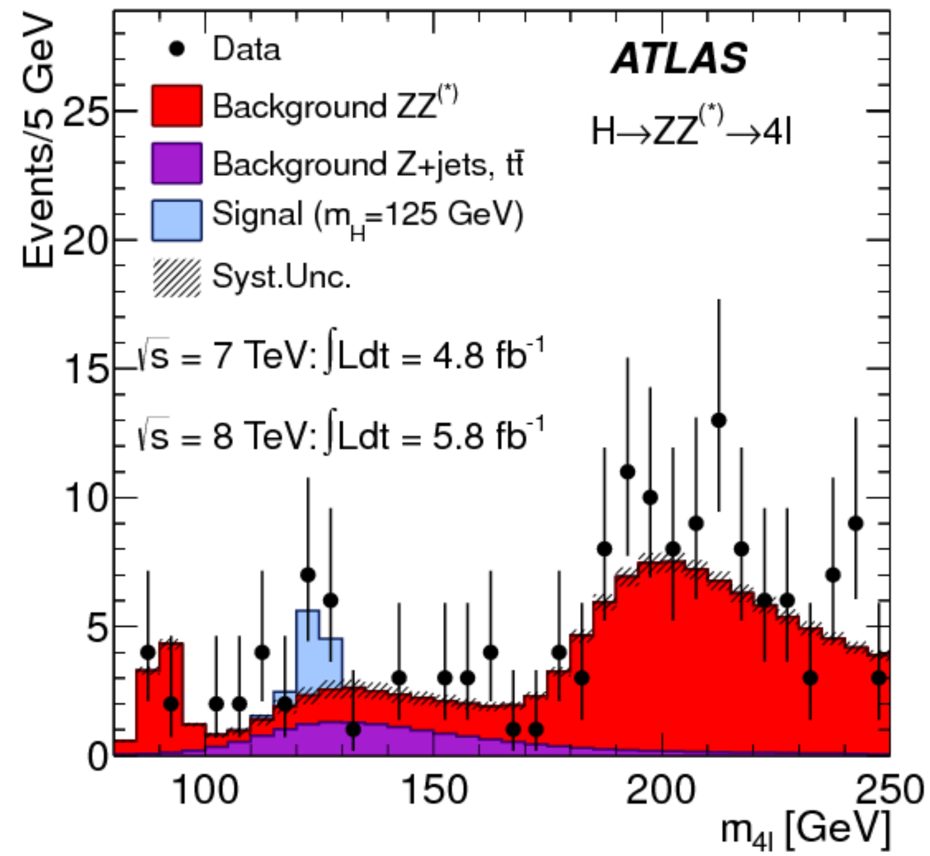
Data analysis



The Higgs boson discovery!

"Observation of a new particle consistent with a Higgs Boson
Historic Milestone but only the beginning" R. Heuer





July 4th 2012

m_H ~125 GeV

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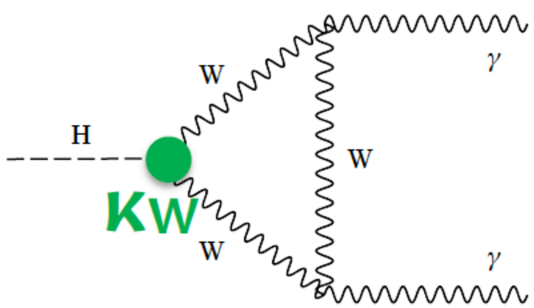
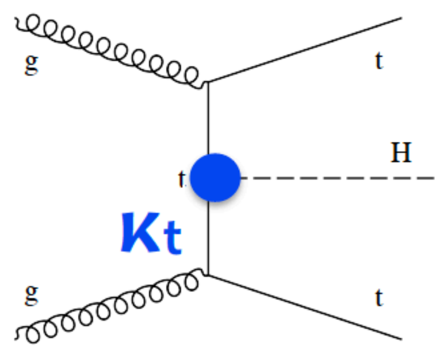
After 12 years…

- Higgs boson mass measurements getting very precise…
- Through a combination of the different production and decay processes, we can extract the couplings to SM particles and compare to the trend predicted in the SM

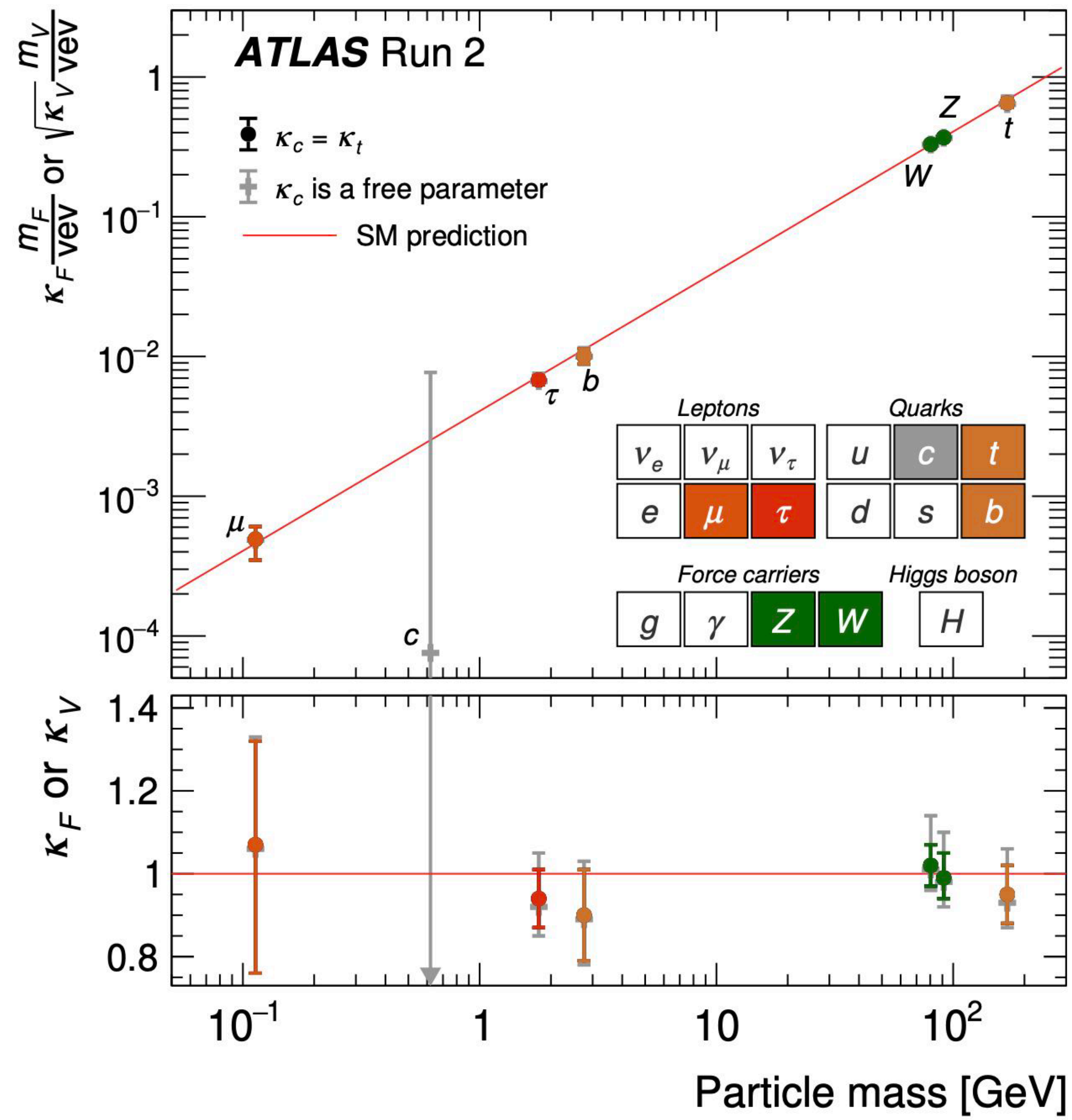
[Nature 607, pages 52-59 (2022)]





$$\kappa_X = \frac{\text{Higgs coupling to X}}{\text{SM prediction}}$$

($\kappa_X = 1$ in the SM)



So aren't we done?

- The Higgs boson was the missing of the SM and we've had it for more than 10 years now..
  - Is the Higgs sector SM-like ? Do all the SM particles lie on that line?

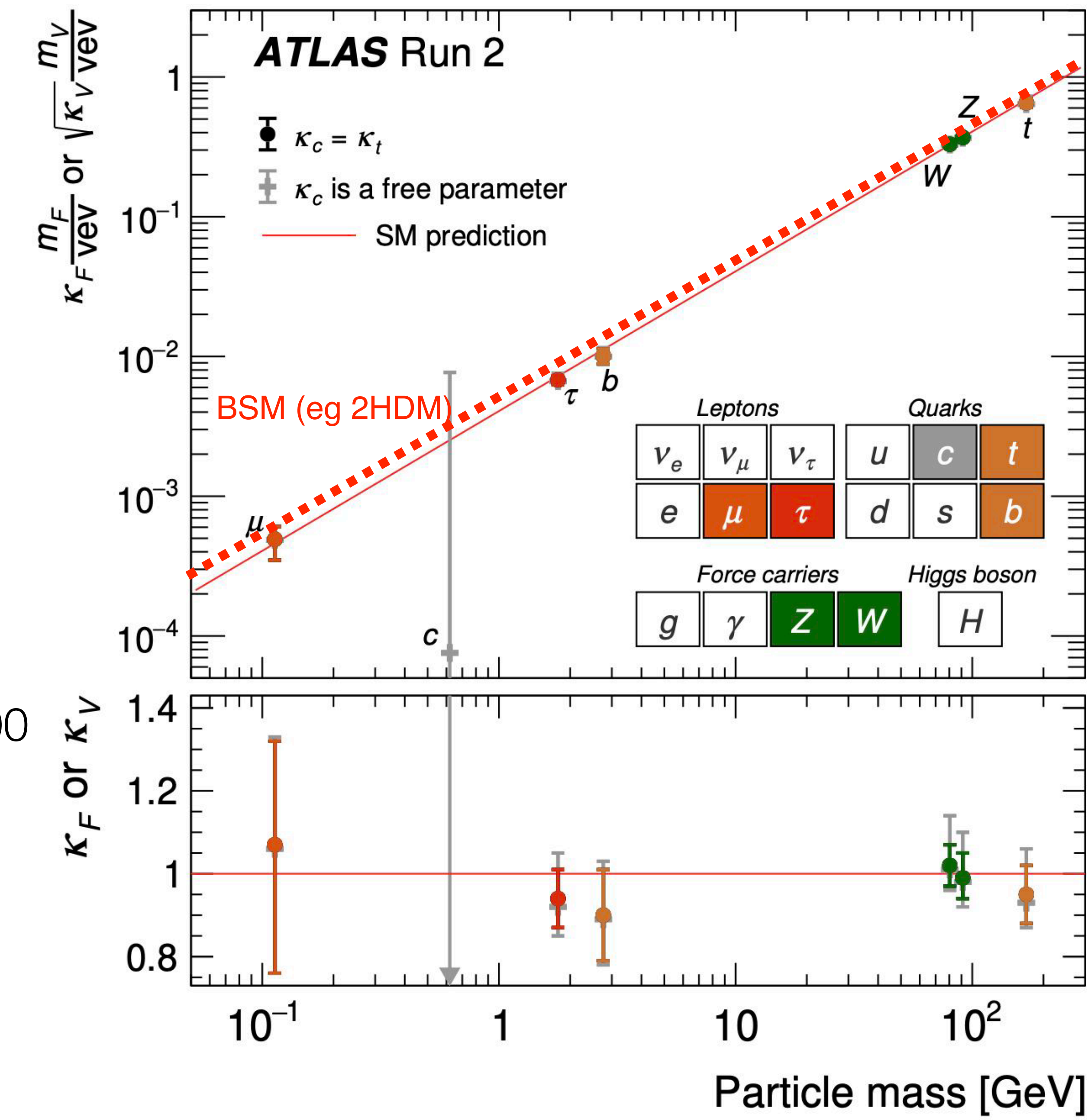
GeV

10^{19} Planck Mass (maximum mass of a point charge)

Why is the Planck mass 100,000,000,000,000,000 times larger than the physical Higgs mass?

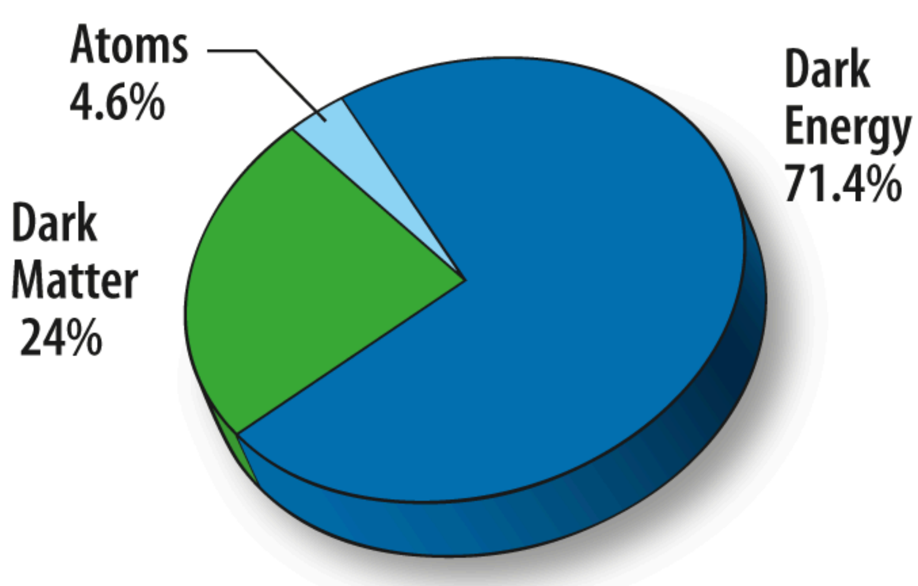
10^{2} Electroweak scale (Higgs Field)

[Nature 607, pages 52-59 (2022)]



So aren't we done?

- The Higgs boson was the missing of the SM and we've had it for more than 10 years now..
  - Is the Higgs sector SM-like ? Do all the SM particles lie on that line?
  - What does Dark Matter (DM) fit in ? if DM are massive particles, wouldn't they couple to the Higgs too?



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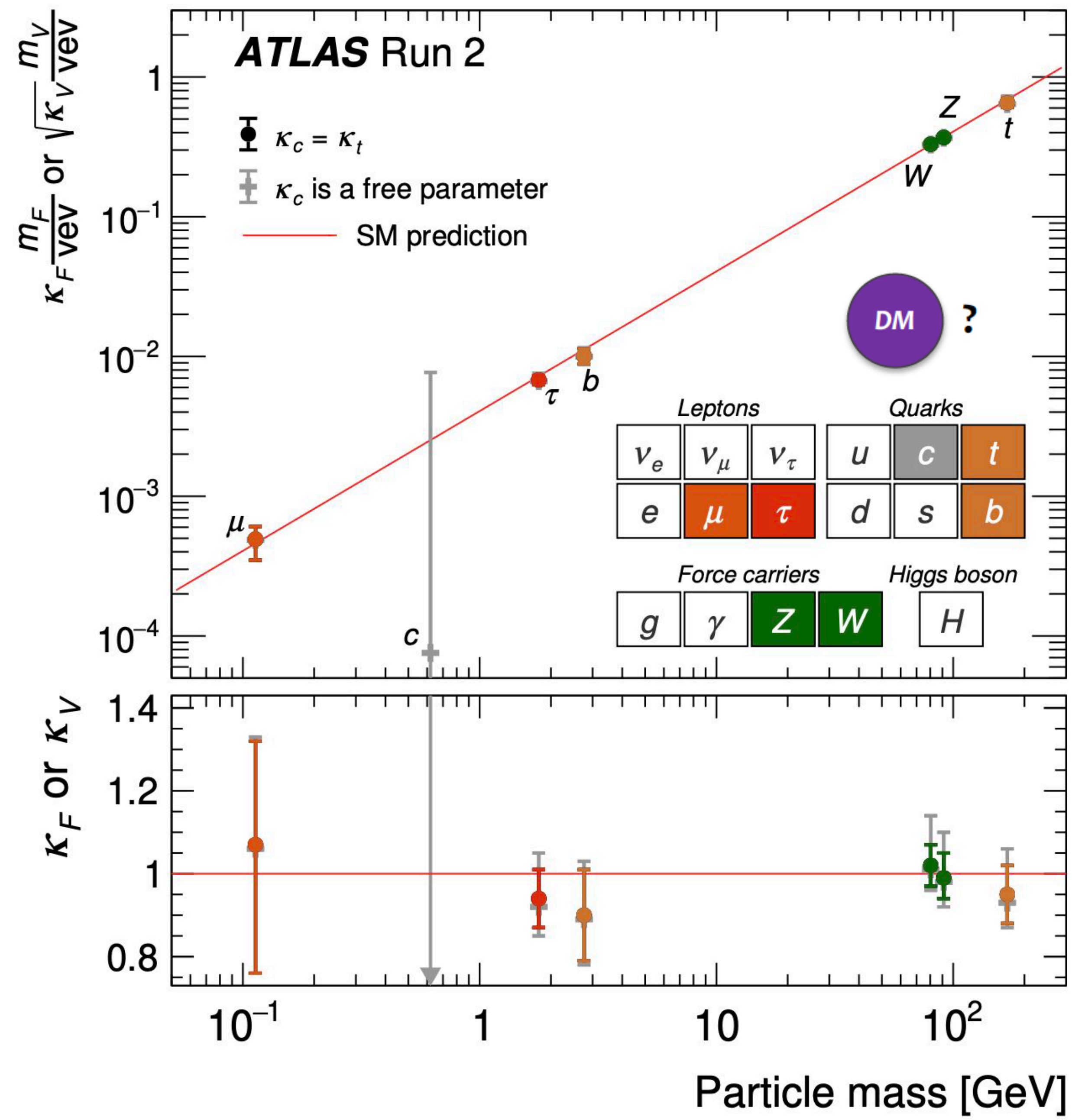
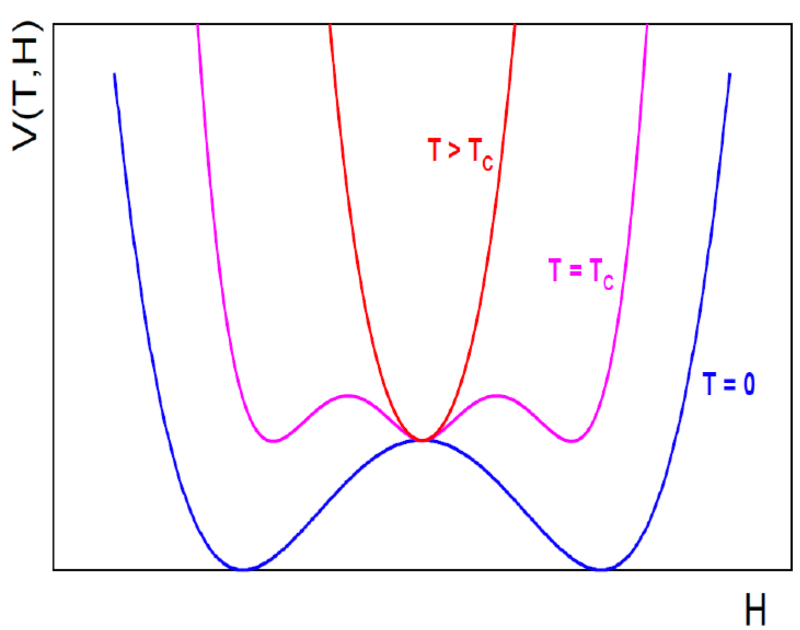


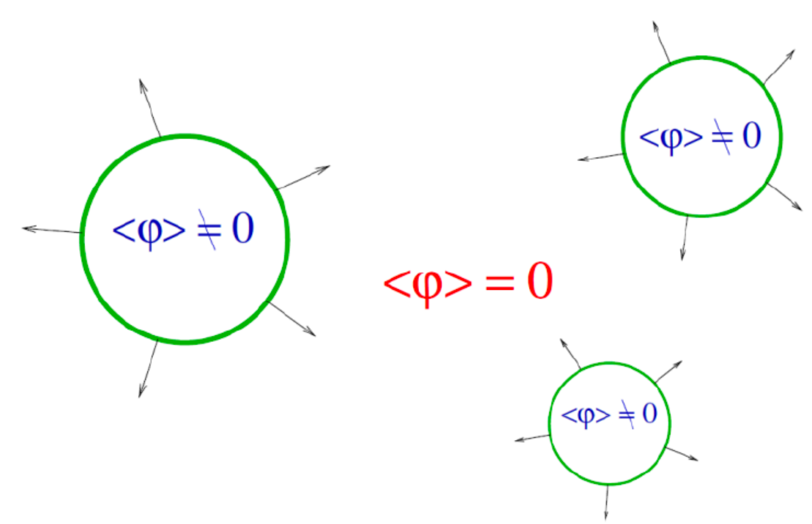
The Higgs and the fate of our universe

- The Higgs boson was the missing of the SM and we've had it for more than 10 years now..
  - Why is there more matter in the universe? Could the Higgs explain the evolution of the early universe (baryogenesis)?

Evolution of Higgs potential in a first-order EW phase transition



Vacuua bubbles with non-zero Higgs field



CP violation

Baryogenesis

BSM particles

Gravity Waves

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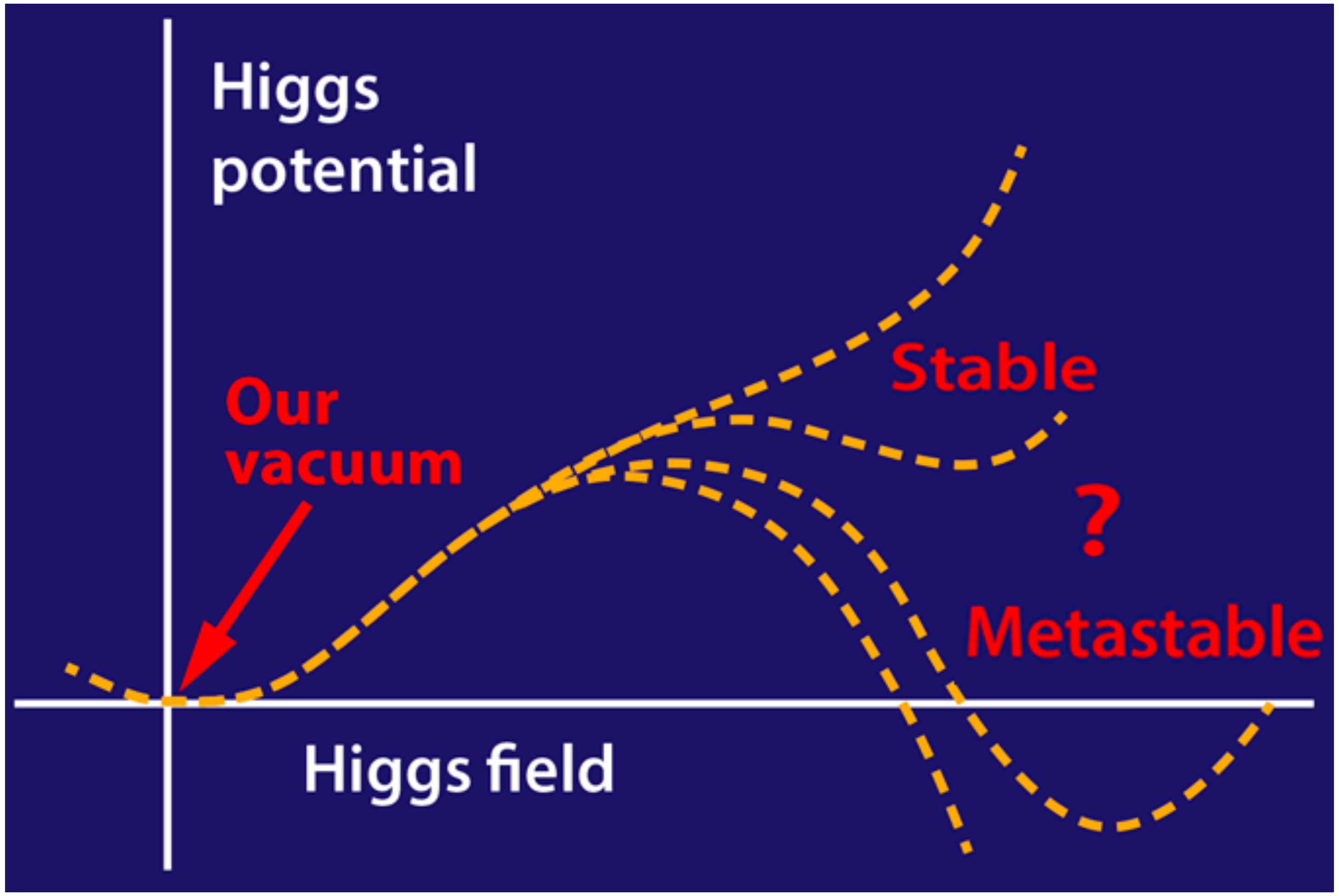
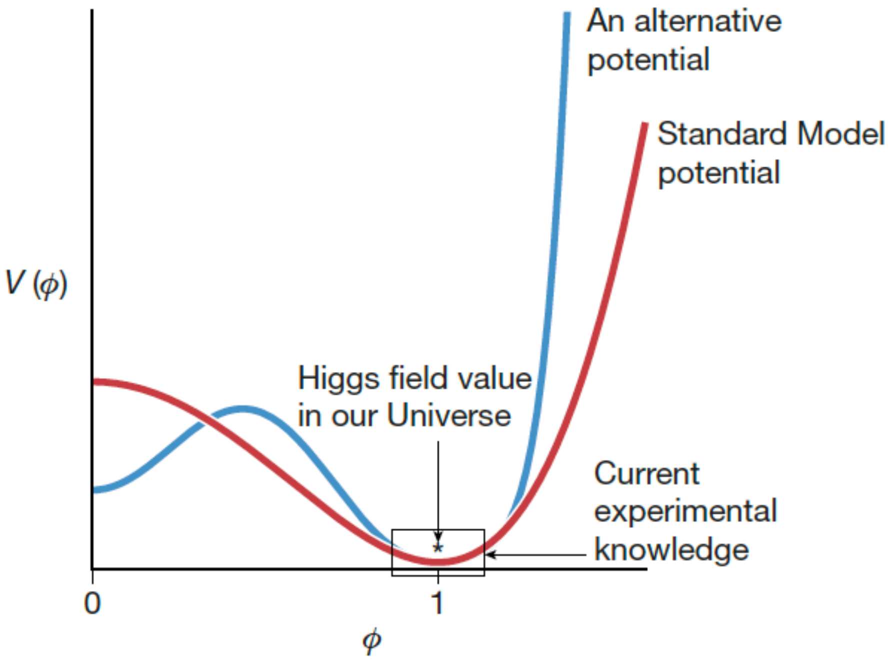
The Higgs and the fate of our universe

- The Higgs boson was the missing of the SM and we've had it for more than 10 years now..
  - Is our universe stable or metastable?





$V(h) = 1/2\, m^2_H\, h^2 + \lambda_3 v h^3 + 1/4\, \lambda_4 v h$

Higgs self-coupling

The Higgs and the fate of our universe

- These are fundamental questions in physics==> The Higgs boson in a unique tool for beyond the SM physics

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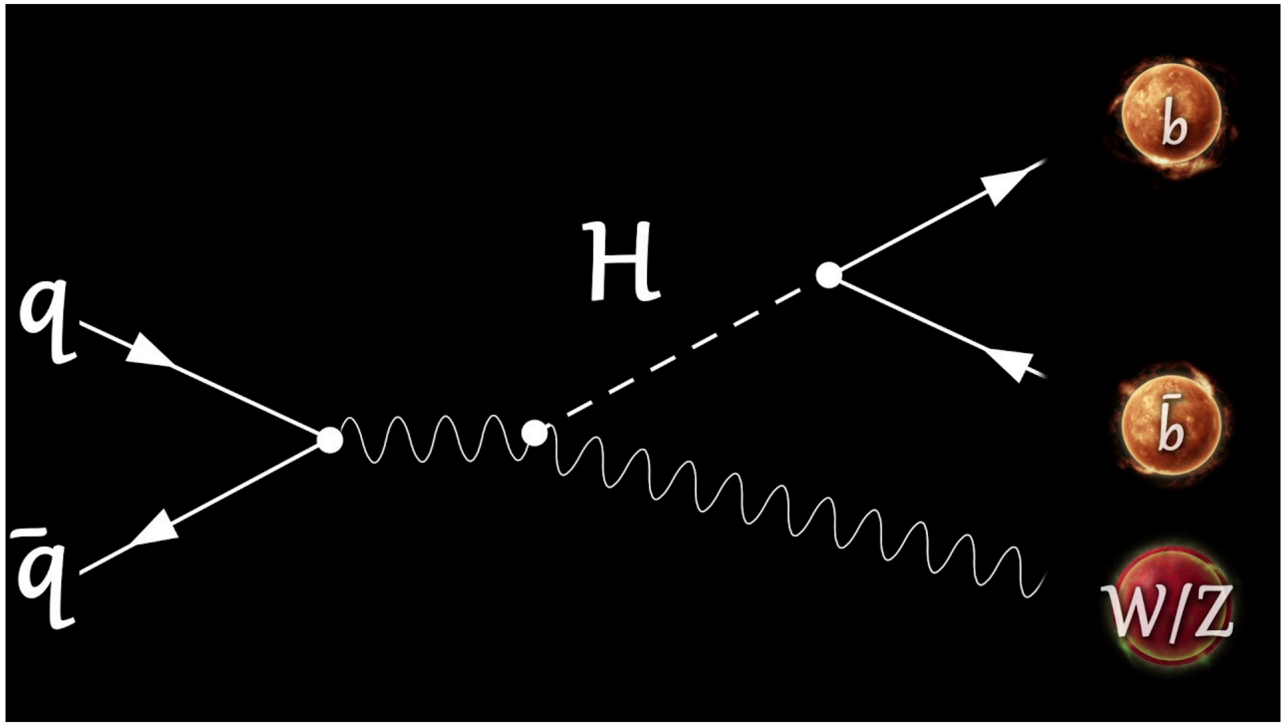
Measuring the beauty of the Higgs boson



- Higgs-Strahlung (associated production) used to observe bb decay of the Higgs
  - Unique final state to measure coupling with down-type quarks

- Drives the uncertainty on the total Higgs boson width
- Limits the sensitivity to BSM contributions

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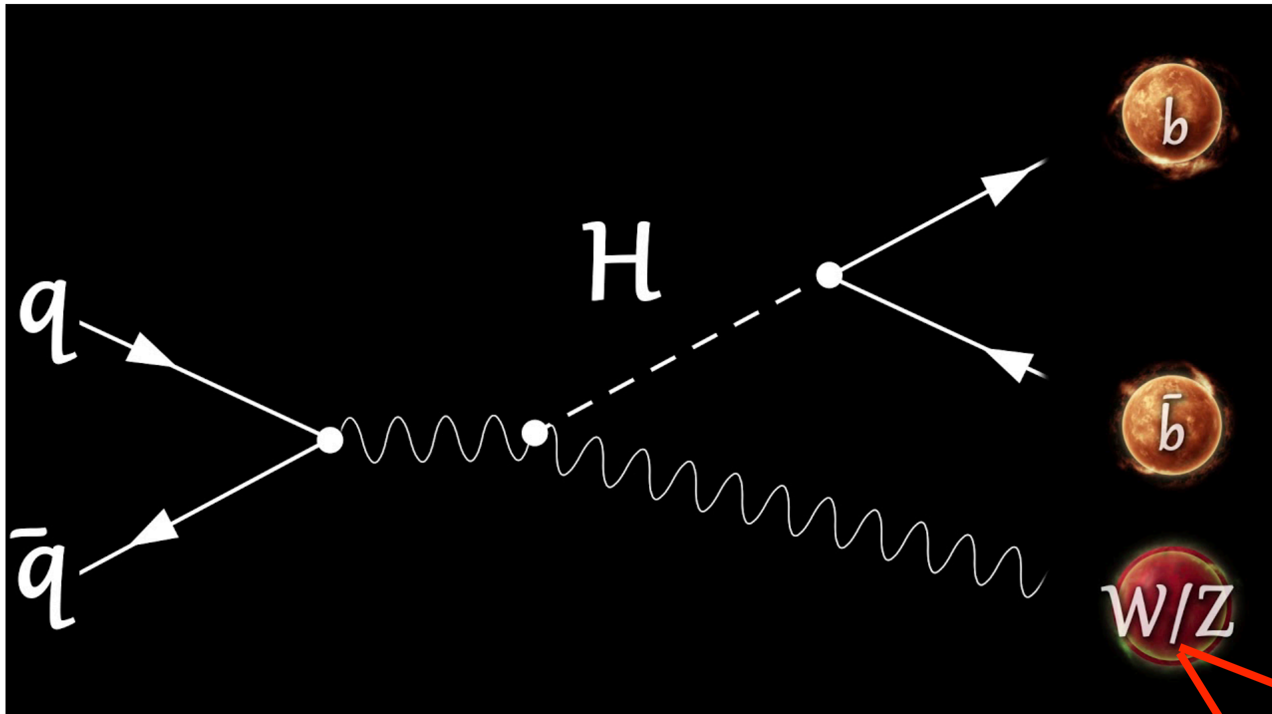
Measuring the beauty of the Higgs boson

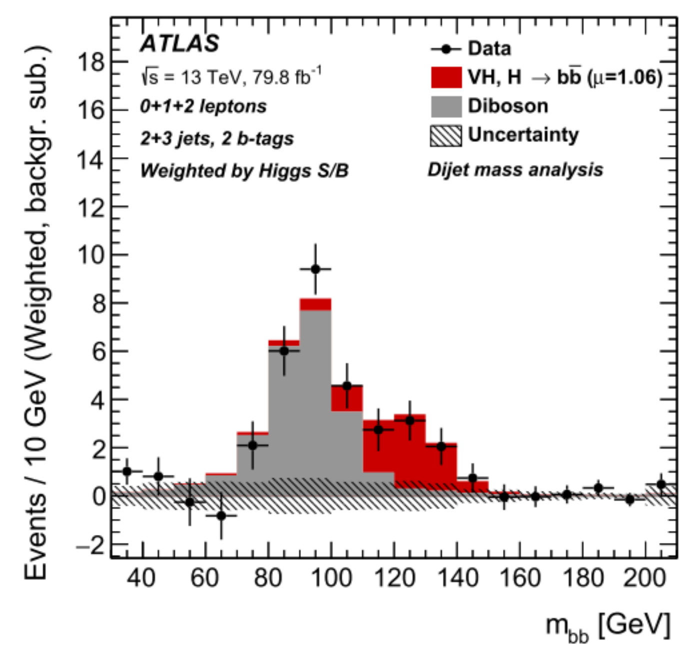


- Higgs-Strahlung (associated production) used to observe bb decay of the Higgs
  - Unique final state to measure coupling with down-type quarks

l,v

l,v

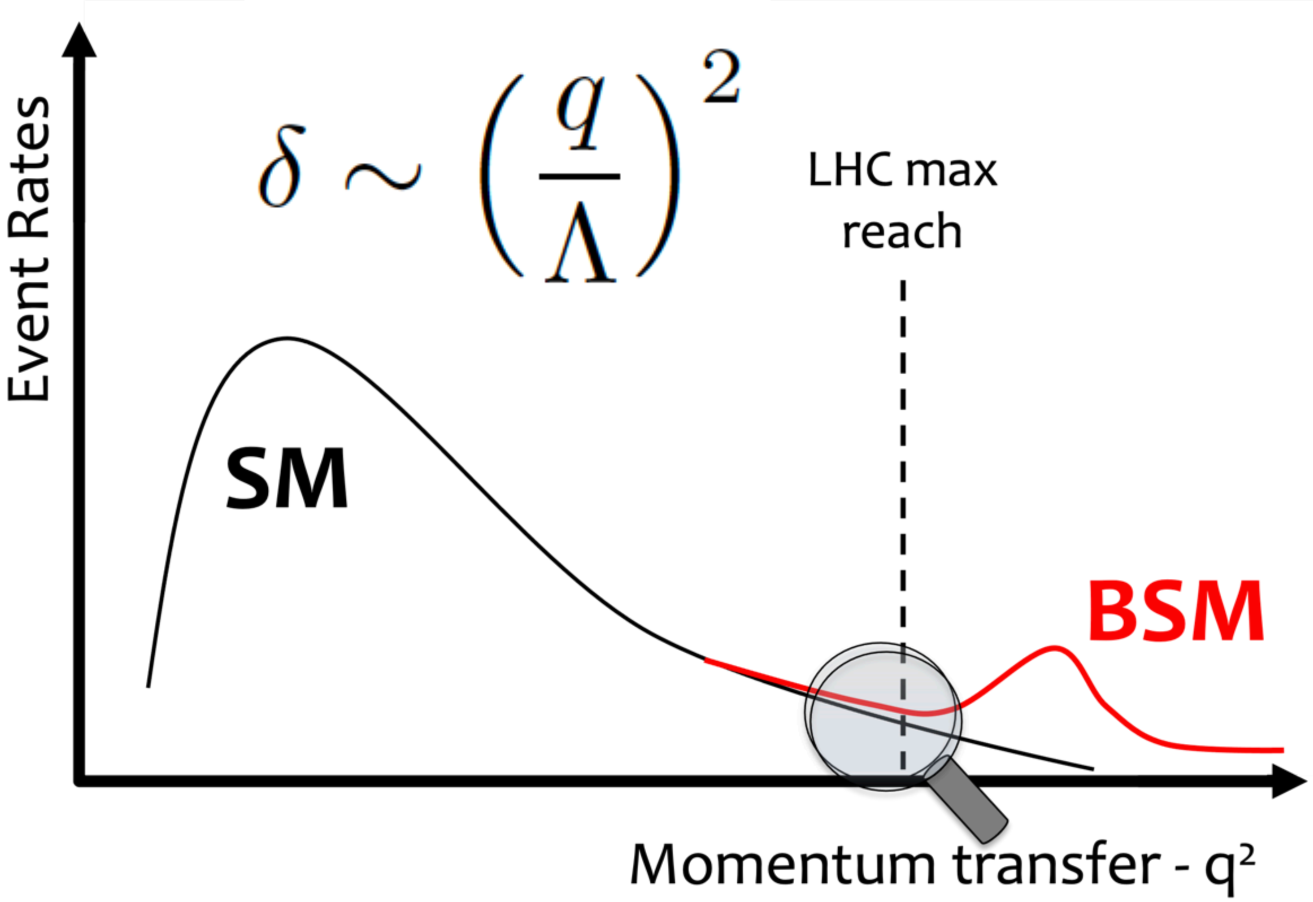
- Use semileptonic final state
- Trigger on leptons



Motivation for Boosted All-Hadronic Higgs-Boson Searches

- Shifting interest from static to dynamic properties of the Higgs boson
- Increased impact expected from new physics at high momentum

- Inclusive measurements: high-precision yields precision on new physics scale δ_μ = 1% ==> Λ ~ 2.5 TeV
- Differential: High momentum production sensitive to new physics δ_σ = 15% (q=1TeV) ==> Λ ~ 2.5 TeV



Fully hadronic final state more events at high momentum

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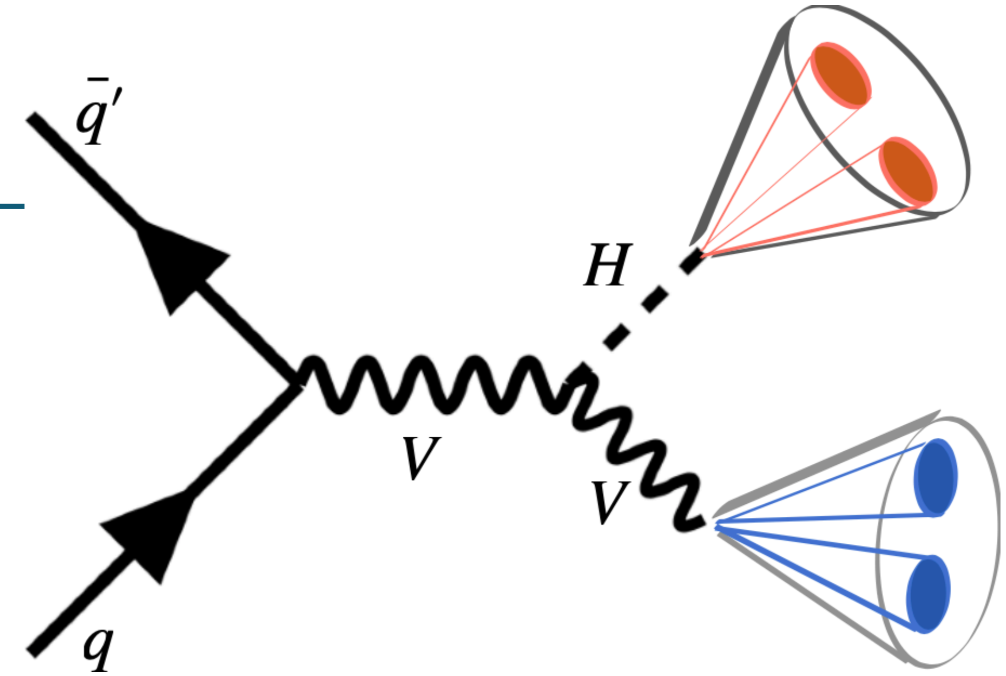
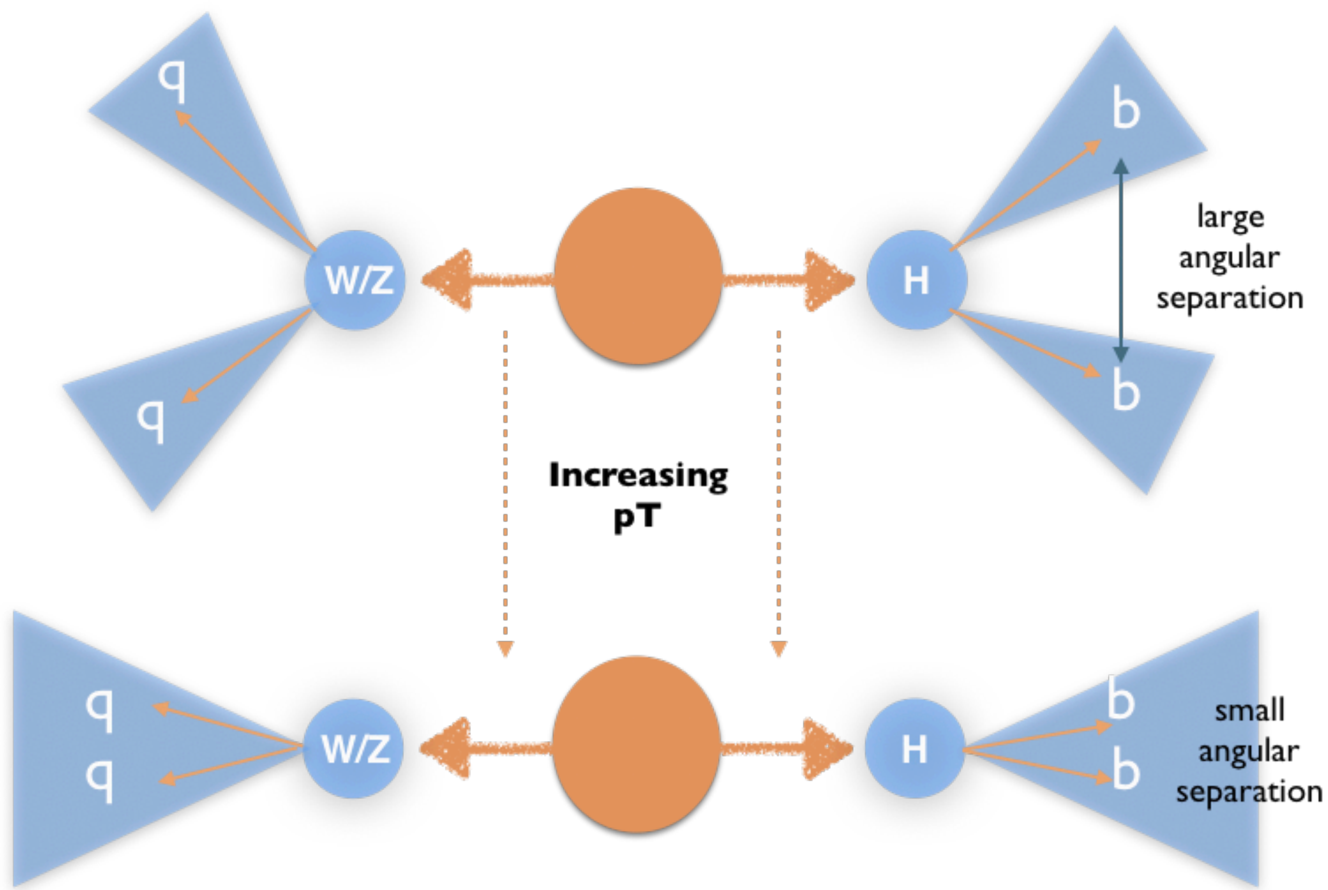
Main experimental challenges



- Trigger: Jet triggers have a high pT threshold ==> need to reduce overwhelming QCD background

- Look at boosted jets



- **Low mass**: the boson has relative low momentum in the lab frame so we are able to reconstruct one jet for each quark

- **High mass**: the boson has high momentum in the lab frame - the outgoing quarks are very close so the jets begin to merge

Use a large radius jet to pick all the radiation from the decay

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Distinguishing signal from the background

Boson jets

- Two narrow regions with high energy for each quark
- Each of the quark carries comparable fraction of the boson momentum in the lab frame
- Jet mass originates from the boson mass, i.e. peaked

QCD jets

- Narrow region with high energy density
- High energy density region has most of the momentum of the jet
- Jet mass originates from the spread of the energy deposition by the single parton/any final state radiation, i.e. essentially random

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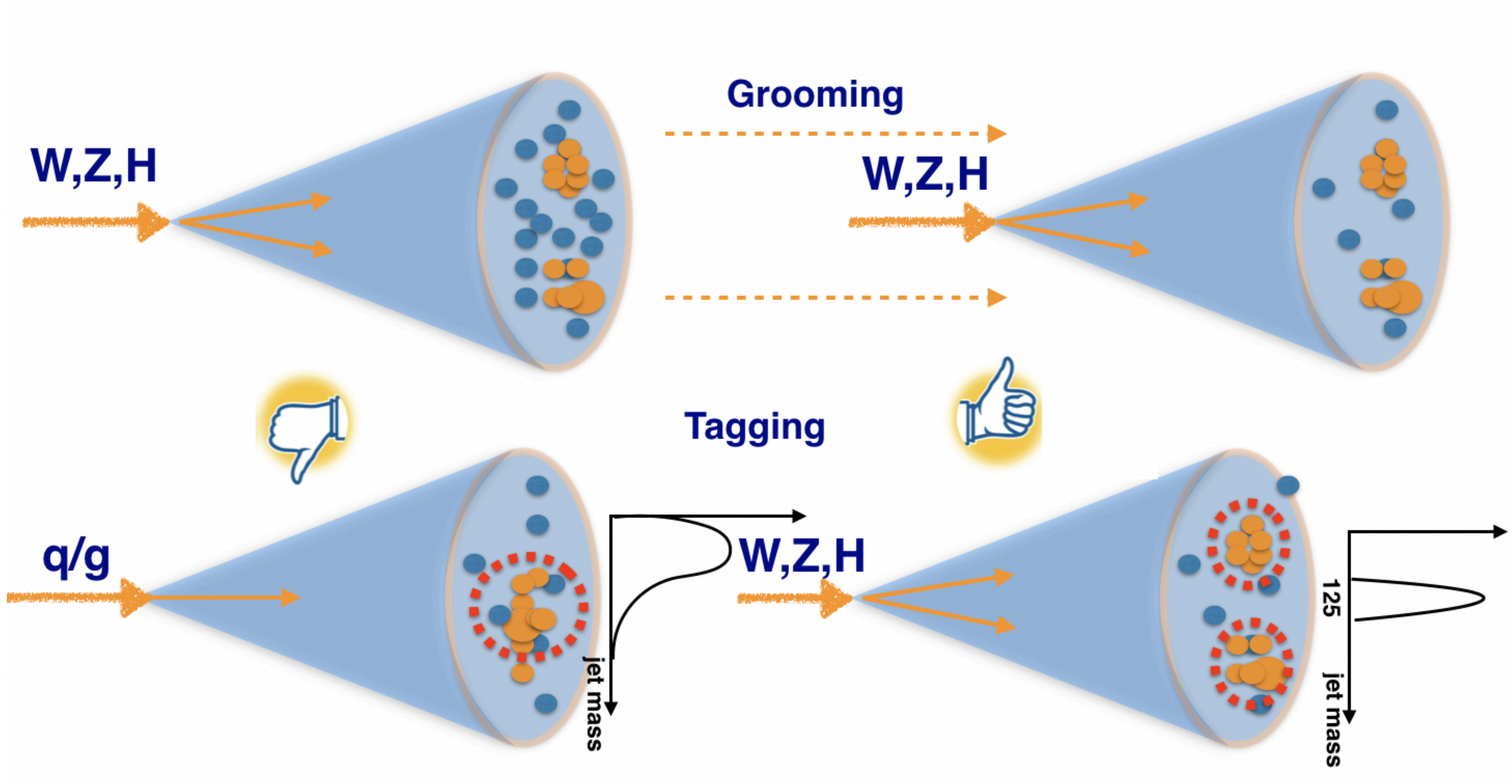
Boosted boson tagging concepts

- Grooming (different techniques available):
  - Signal: take out jet constituents that don't belong to the signal decay
  - Remove soft comp. PU+UE
- Tagging:
  - Use differences in Signal and Background jet characteristics to reject background jets



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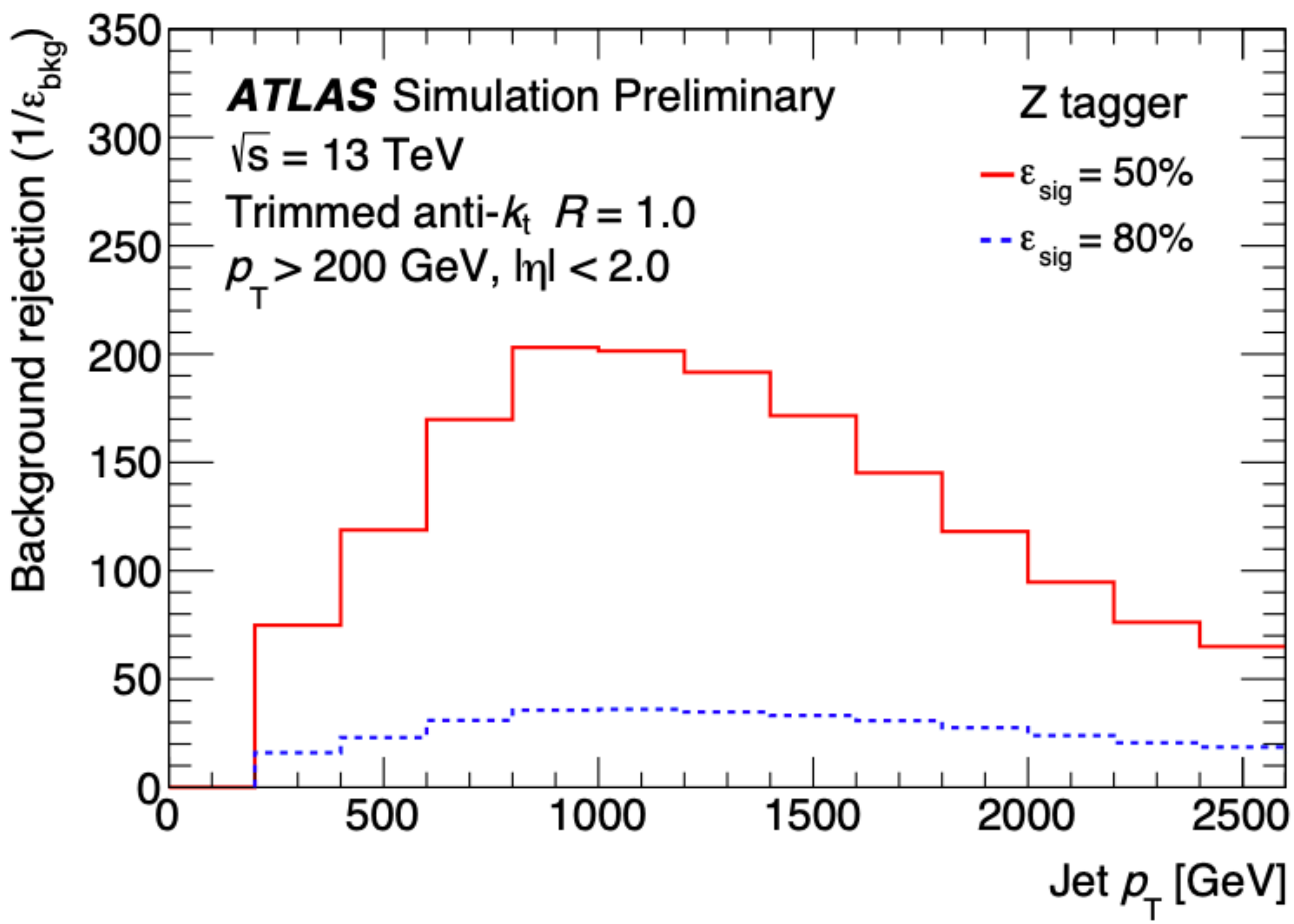
ATLAS V-tagger

ATL-PHYS-PUB-2020-017

- V-tagger : tag jets likely coming from V-boson decay
- Requirements on jet mass, two-prongness & number of tracks yielding a signal efficiency of 50%



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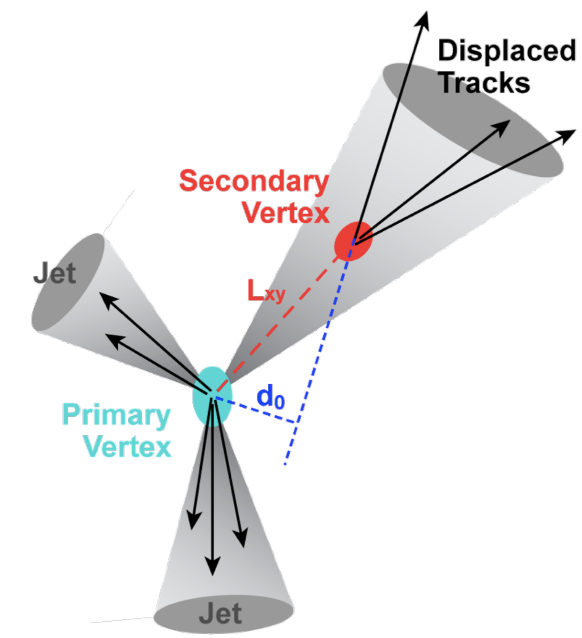
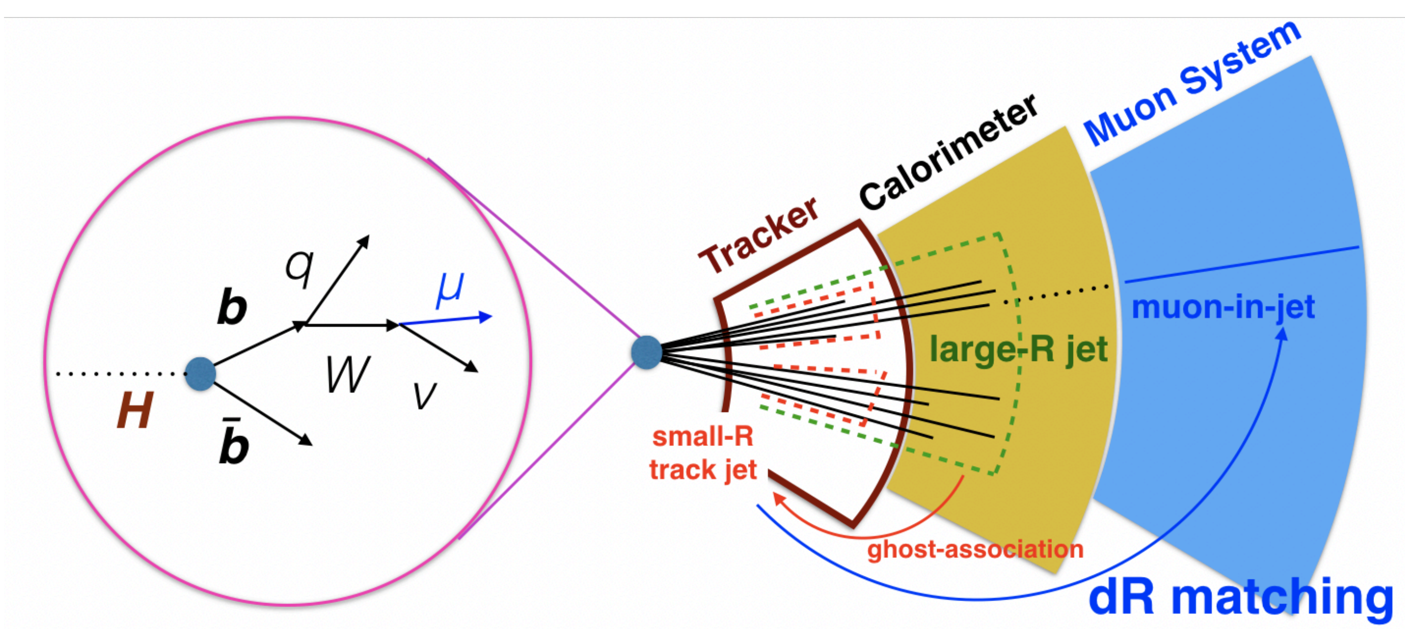
Flavour Tagging

- Weakly decaying b-hadron: τ~1.5 x 10^{-12} s and mass ~ 5 GeV
  - A b-hadron with pT~30 GeV has decay length of few mm ⇒ Measurable displace vertex!
- most b-hadrons decay to c-hadrons ==> tertiary vertex in b-hadron decay chain
- Approximately 40% of b-hadron decays are semi-leptonic
- Use all this information to design b-taggers!
- Different MVA combinations applied to single jets before





Can we do better?

- Exploit the whole H→bb kinematic especially at high mass with a multivariate technique

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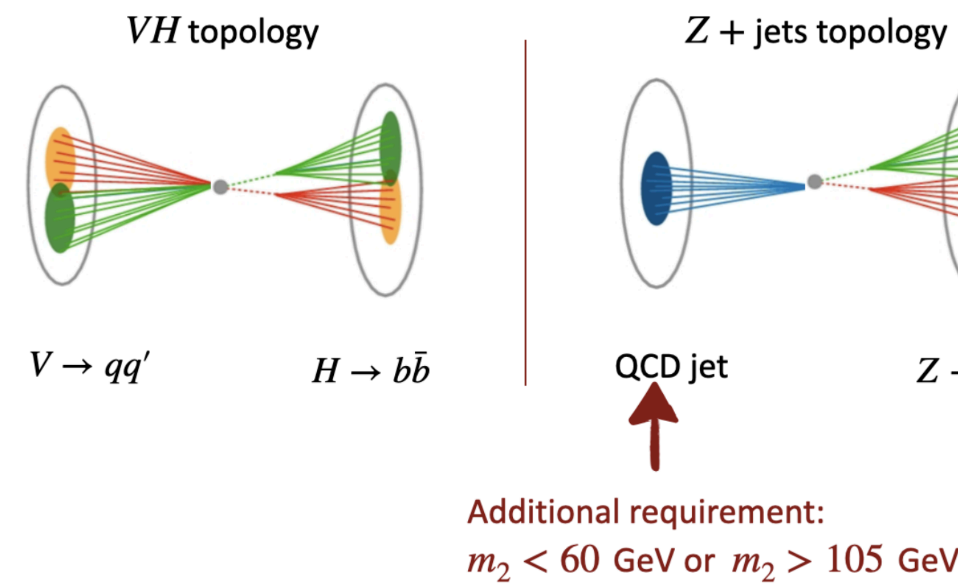
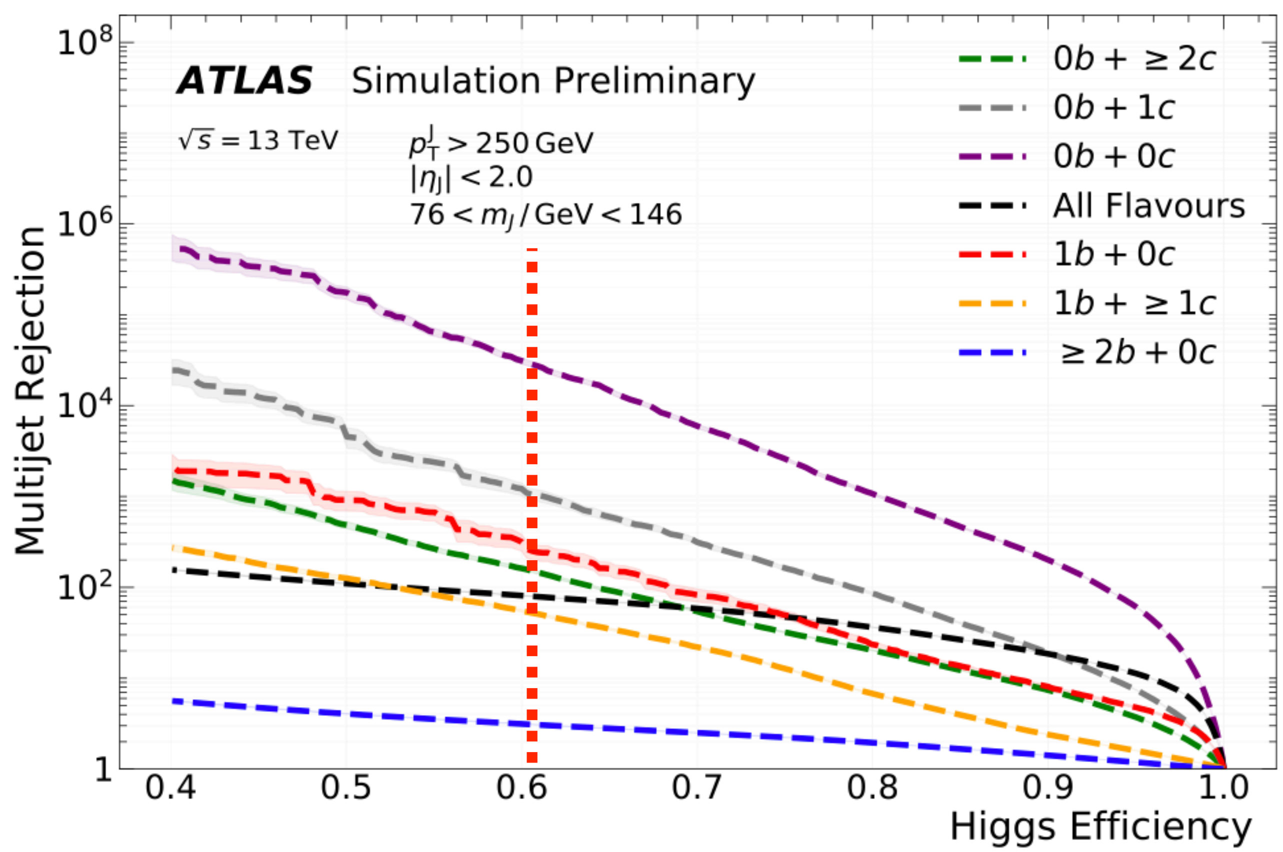
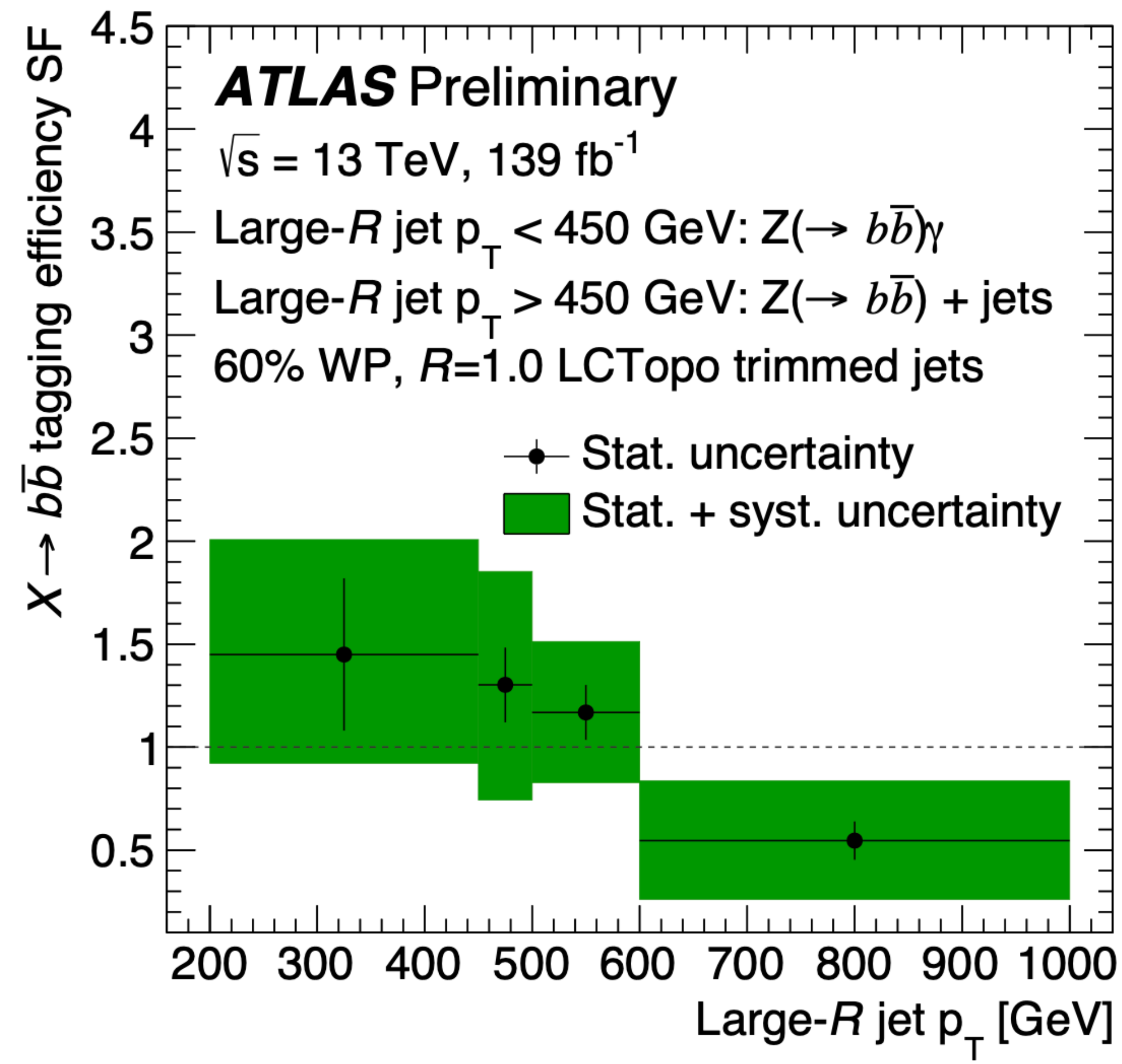
H→bb Tagger

- Neural Network using track & vertex info associated to variable-radius track-jets
  - Fixed 60% H->bb efficiency used
- Dedicated Hbb-tagger calibration with independent boosted Z→bb events







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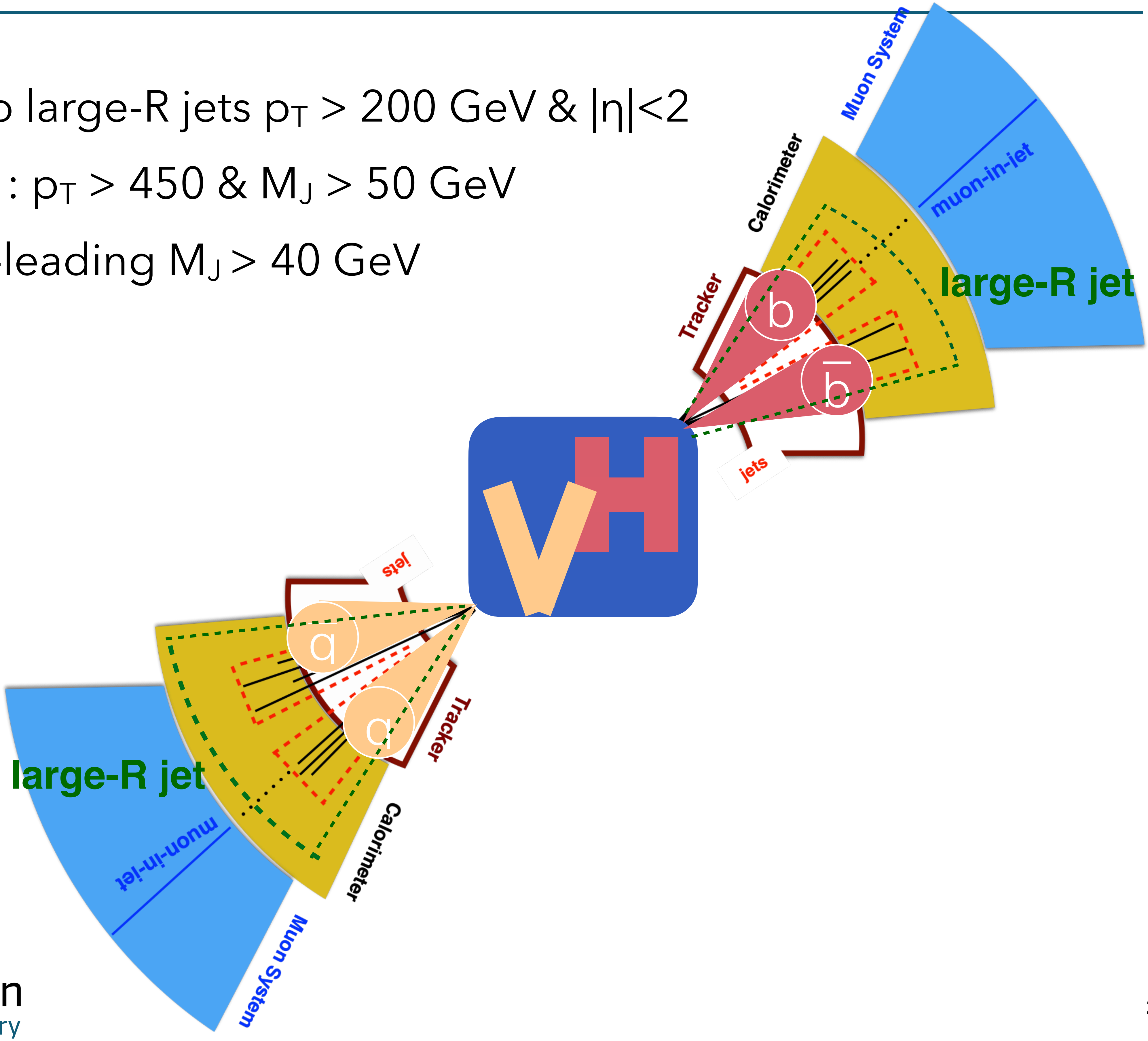
Selection

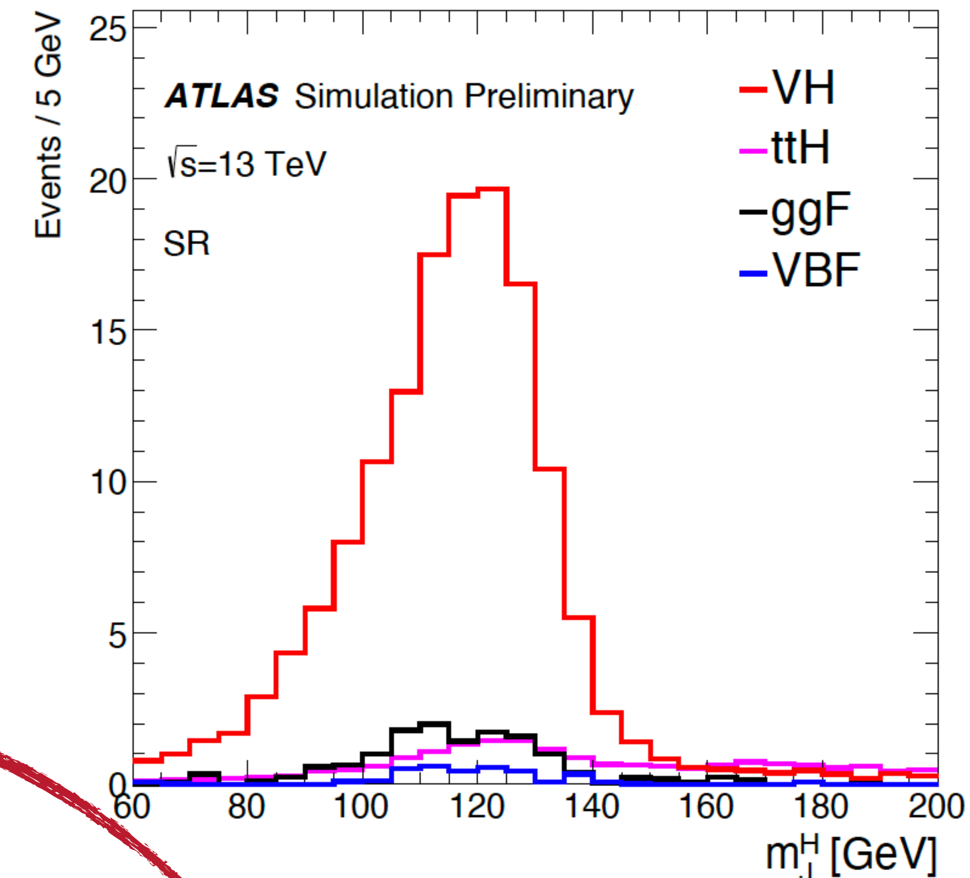
- At least two large-R jets p_T > 200 GeV & $|\eta|<2$
- pT-leading : p_T > 450 & M_J > 50 GeV
- Second p_T-leading M_J > 40 GeV

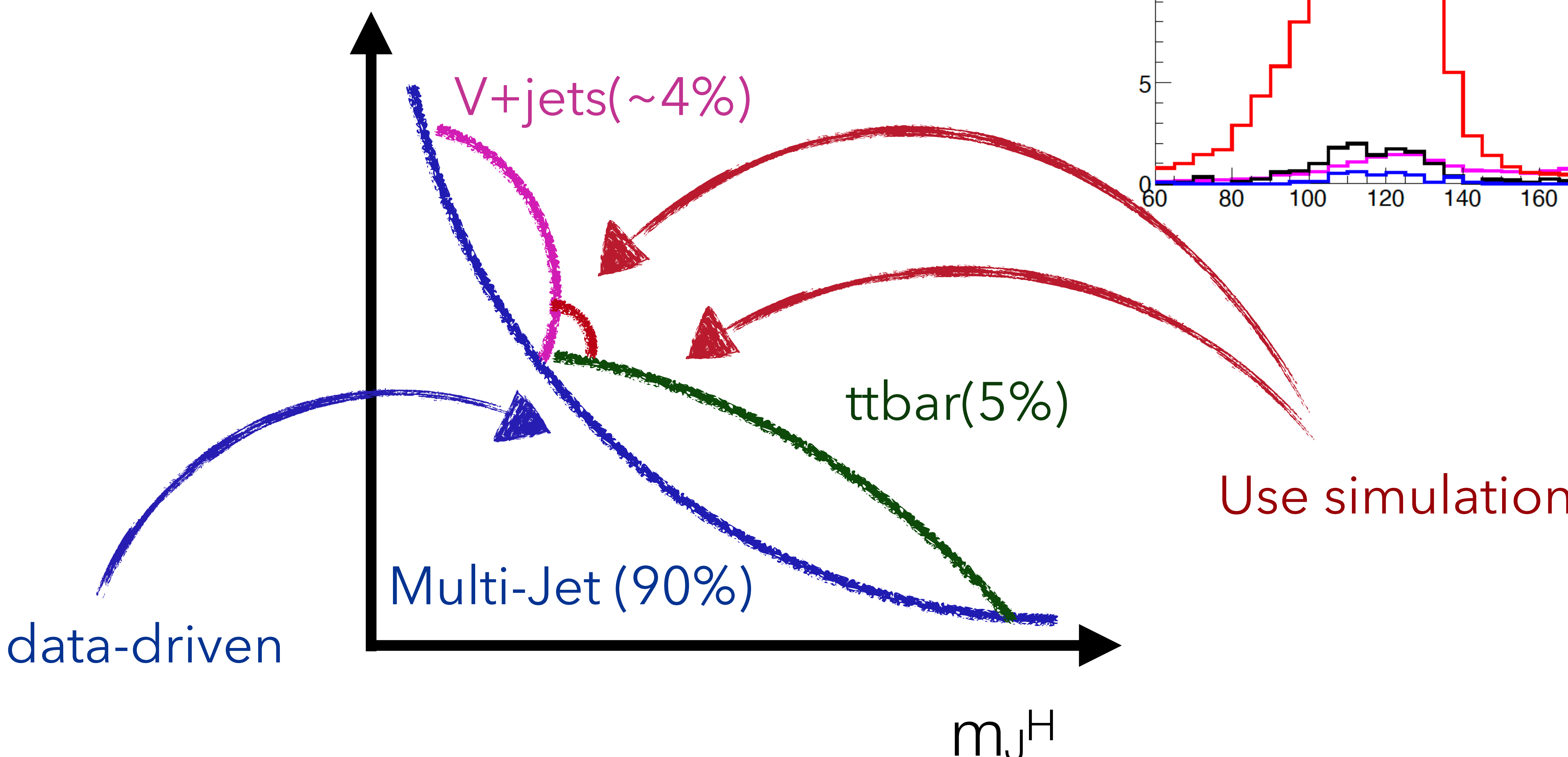


Inclusive Signal & Background Composition

In SR, VH production mechanism dominates: ~85%

- ttH (8%), ggF (6%), VBF (1.4%)

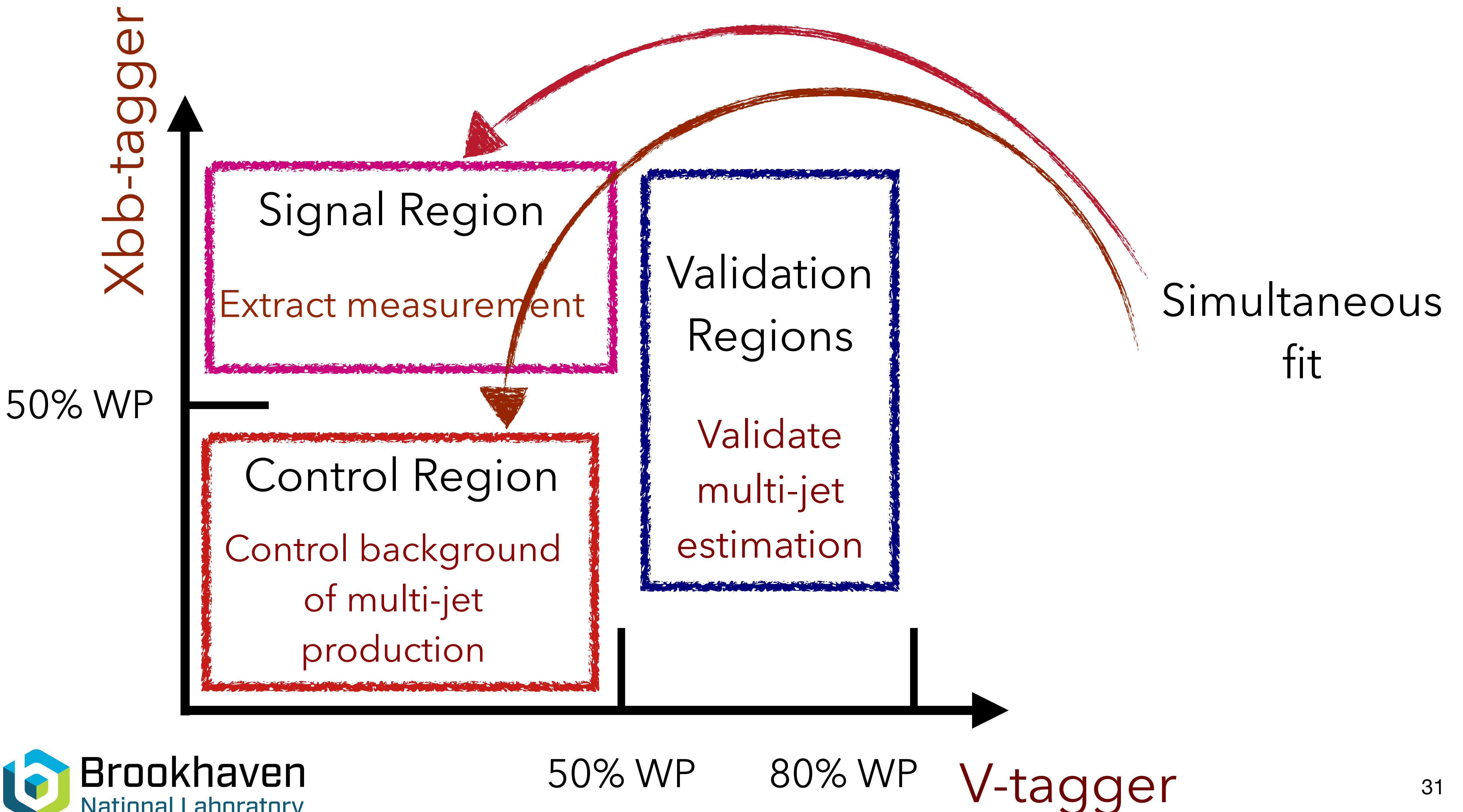




Analysis Strategy & Region Definitions

Higgs-candidate jet mass fit (m_{JH}) to SR and CR

- Reconstructed combining calorimeter & tracking measurements
- Corrected to account for muons from semileptonic b-hadron decays



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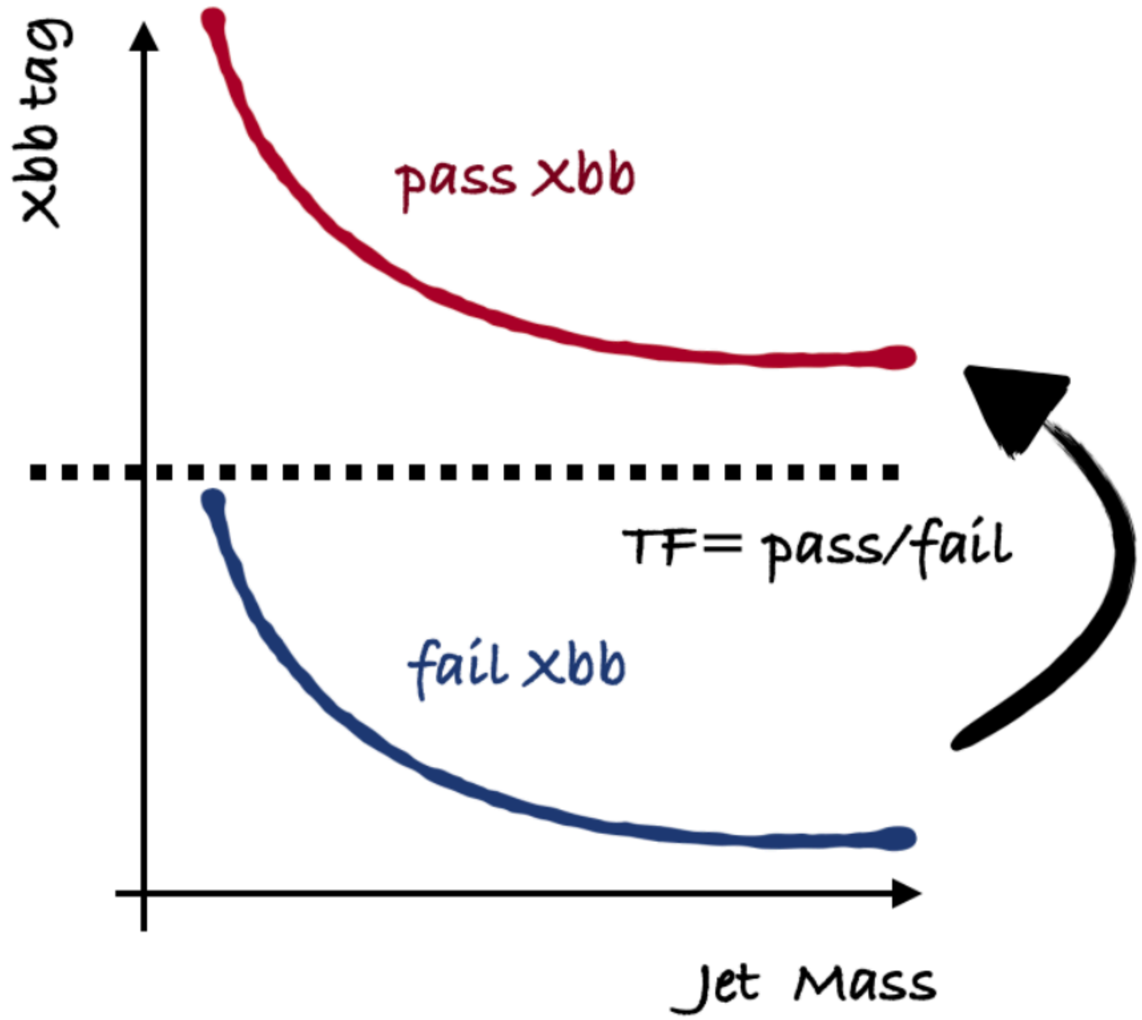
Multi-Jet Background Estimation

- Multi-jet background modeled from CR with Transfer Factor (TF) dependent on candidate-jet p_T & $\rho = \log(m_{J2}/p_{T2})$::
  - $TF(p_T, \rho) = \Sigma_{kl}\, a_{kl}\, \rho^k\, p_T^l$, where a_{kl} are polynomial coefficients
- TF scales CR events to yield number of multi-jet events in SR
- Polynomial order determined via Fisher F-tests in data
  - First order in both p_T & ρ proves to be sufficient, without inducing significant spurious signal



Alternate method: BDT which uses data from the CR and reweighs the kinematic to the SR

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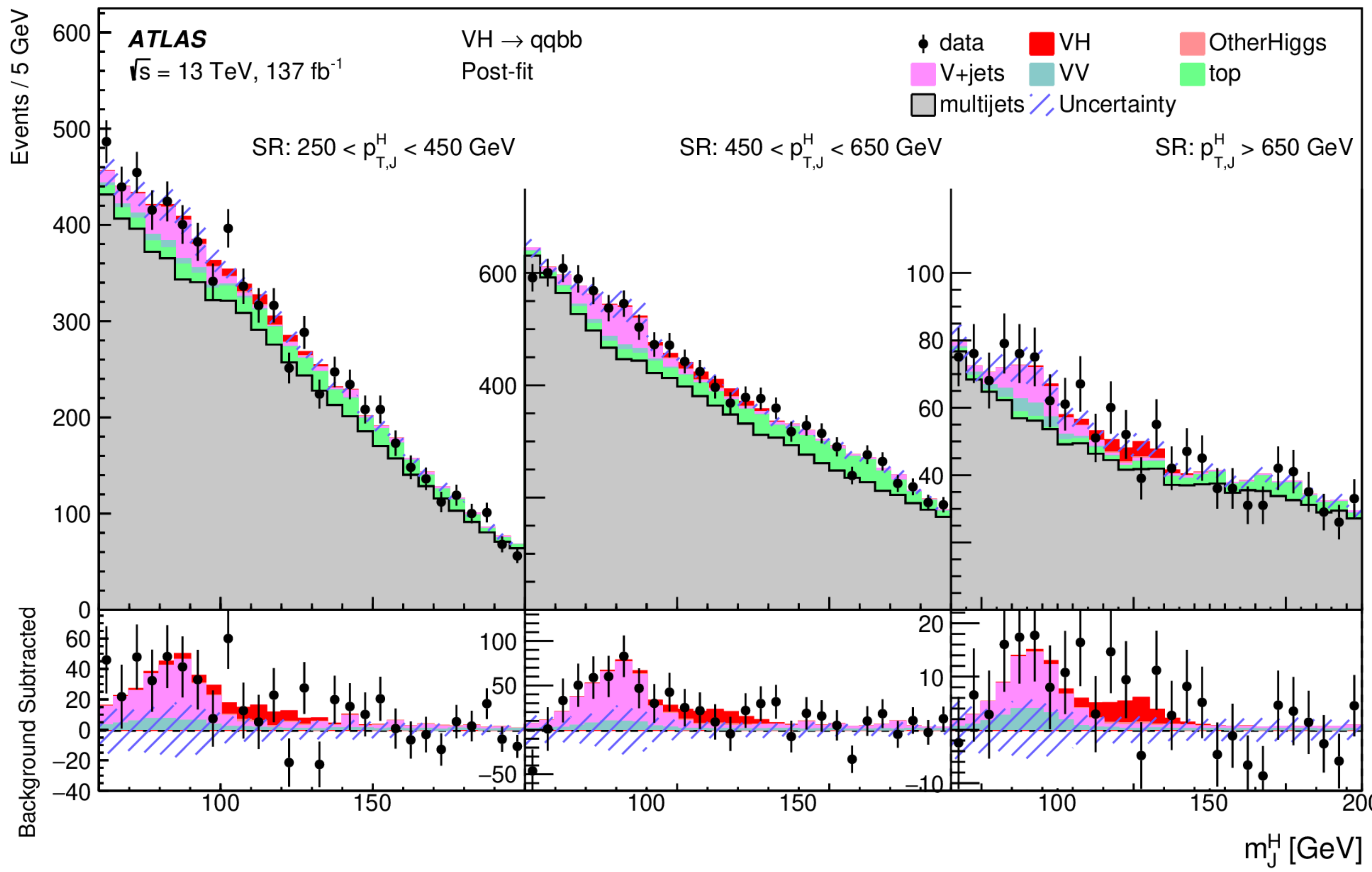
Differential cross section measurement

https://arxiv.org/abs/2312.07605 accepted by PRL



- Observed V(qq)H(bb) best-fit value: $\mu = 1.39^{+1.02}_{-0.88}$
- Observed significance 1.7σ (1.2σ expected) corresponding to an observed cross-section: 3.3±1.5(stat)$^{+1.9}_{-1.5}$(syst) pb

Kinematic region	Observed μ	Observed σ [fb]	Expected σ [fb]
$250 \leq p_{\mathrm{T}}^{H} < 450$ GeV, $\lvert y_H \rvert < 2$	$0.8^{+2.2}_{-1.9}$	47^{+125}_{-109}	57.0
$450 \leq p_{\mathrm{T}}^{H} < 650$ GeV, $\lvert y_H \rvert < 2$	$0.4^{+1.7}_{-1.5}$	2^{+10}_{-9}	5.9
$p_{\mathrm{T}}^{H} \geq 650$ GeV, $\lvert y_H \rvert < 2$	$5.3^{+11.3}_{-3.2}$	6^{+13}_{-4} (<43)	1.2

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Challenges ahead

Uncertainty source	$\delta\mu$
Signal modeling	$^{+0.10}_{-0.02}$
MC statistical uncertainty	$^{+0.13}_{-0.13}$
Instrumental (pileup, luminosity)	$^{+0.012}_{-0.004}$
Large-R jet	$^{+0.13}_{-0.14}$
Top-quark modeling	$^{+0.14}_{-0.15}$
Other theory modeling	$^{+0.050}_{-0.031}$
$H \to b\bar{b}$ tagging	$^{+0.52}_{-0.23}$
Multijet estimate (TF uncertainty)	$^{+0.52}_{-0.41}$
Multijet modeling (TF vs. BDT)	$^{+0.14}_{-0.18}$
Total systematic uncertainty	$^{+0.80}_{-0.61}$
Signal statistical uncertainty	$^{+0.60}_{-0.60}$
Z+jets normalization	$^{+0.42}_{-0.20}$
Total statistical uncertainty	$^{+0.63}_{-0.63}$
Total uncertainty	$^{+1.02}_{-0.88}$

- Systematic and statistical uncertainty on the same level
- Systematic uncertainties dominated by shape of multi-jet data-driven estimate & Hbb-tagger scale factors

Run 3

- double the dataset
- Optimize S/B with multivariate techniques
- Work on better calibration for the H→bb tagger
- Refine multijet background data-estimation
  - stat will help here too

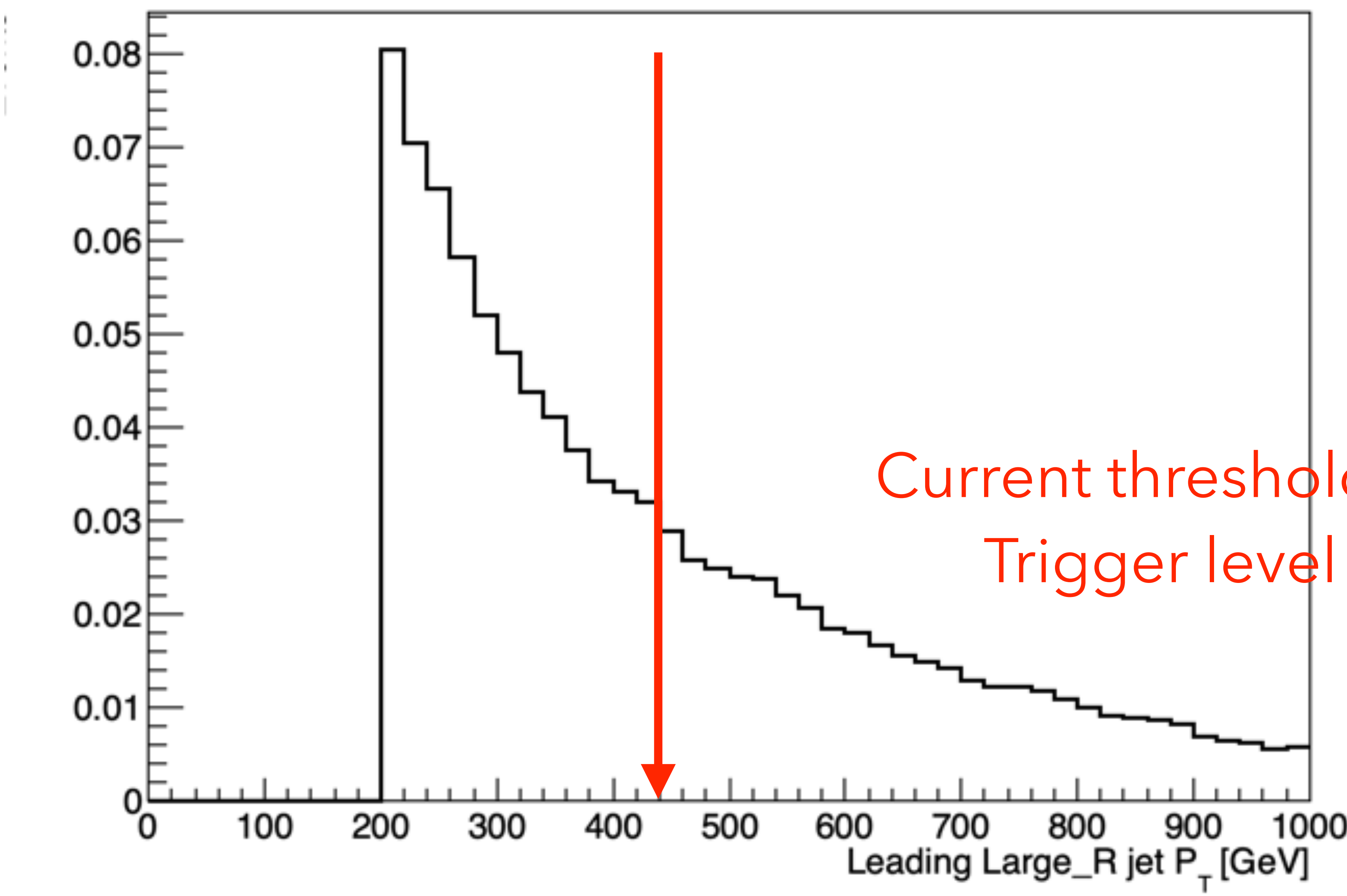
↓

Reduce error of more than a factor of 2 inclusively

Start probing new territory in BSM physics

Can we do even better? Trigger is the key!

VH⇒qqbb signal



rate: 40 MHz ~75 Tb/s

Trigger

1KHz Event size:1.6Mb

Problem:

- Overwhelming background at low p_T
- Trigger rates are too high
- ⇒ Apply a threshold on the jet p_T

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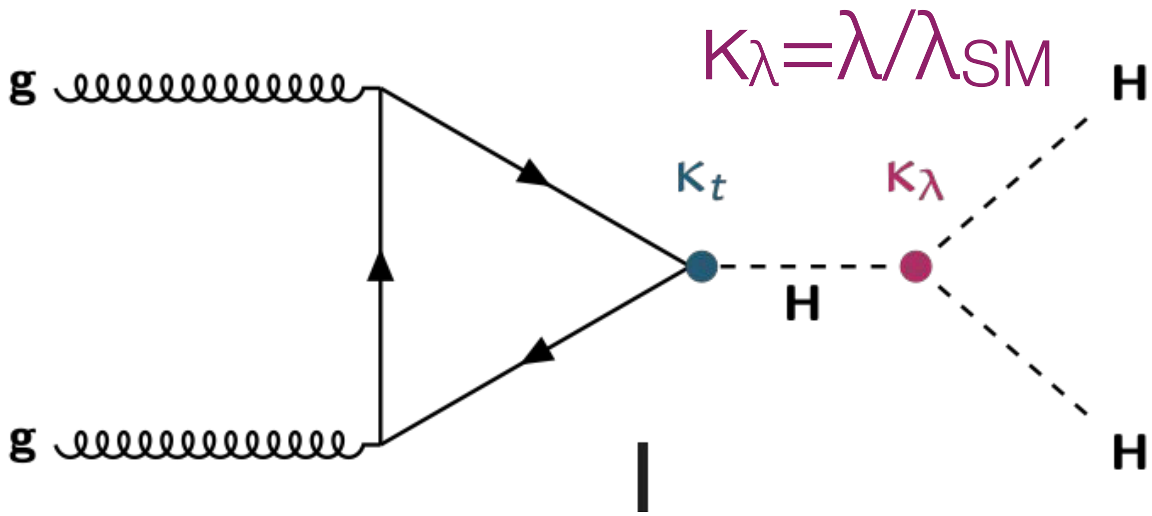
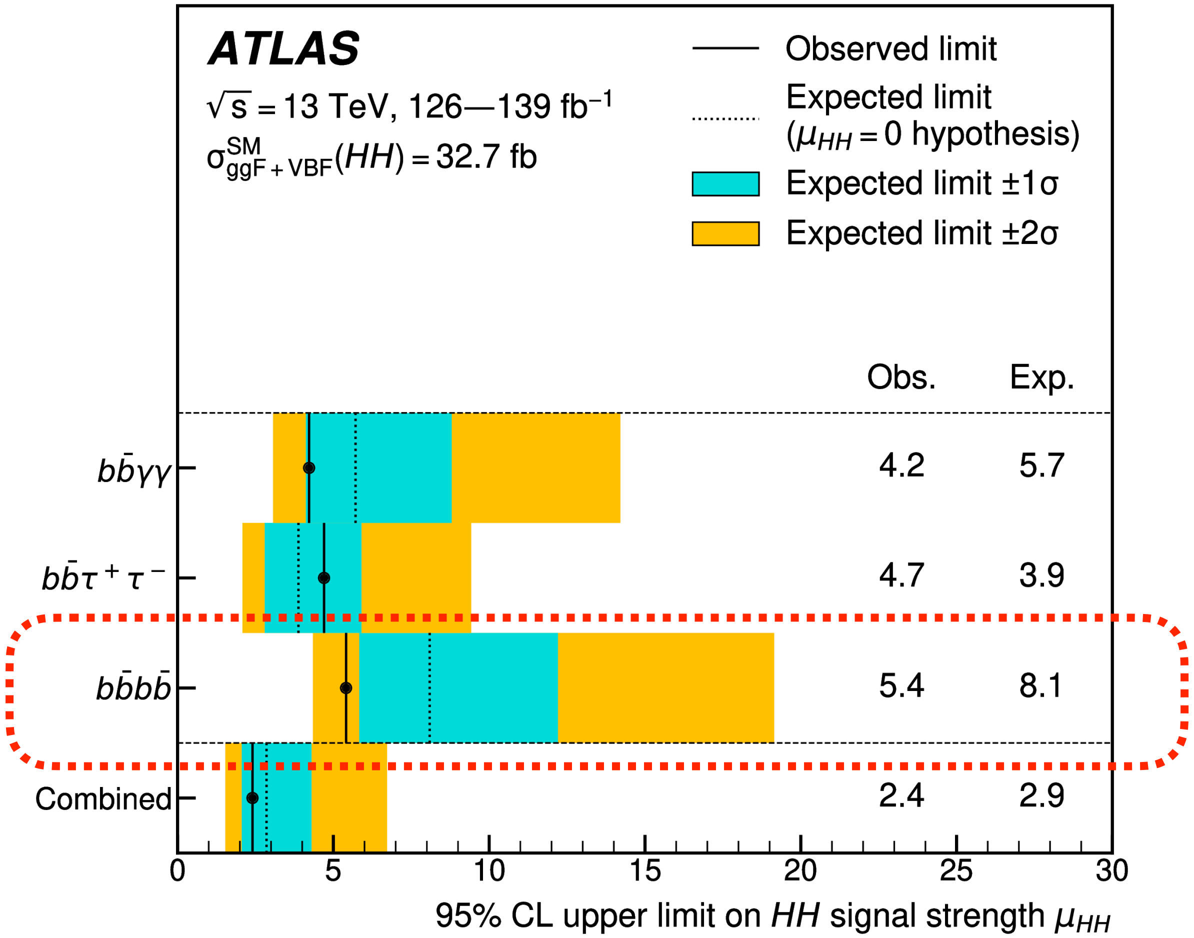
The Higgs and the fate of our Universe: HH

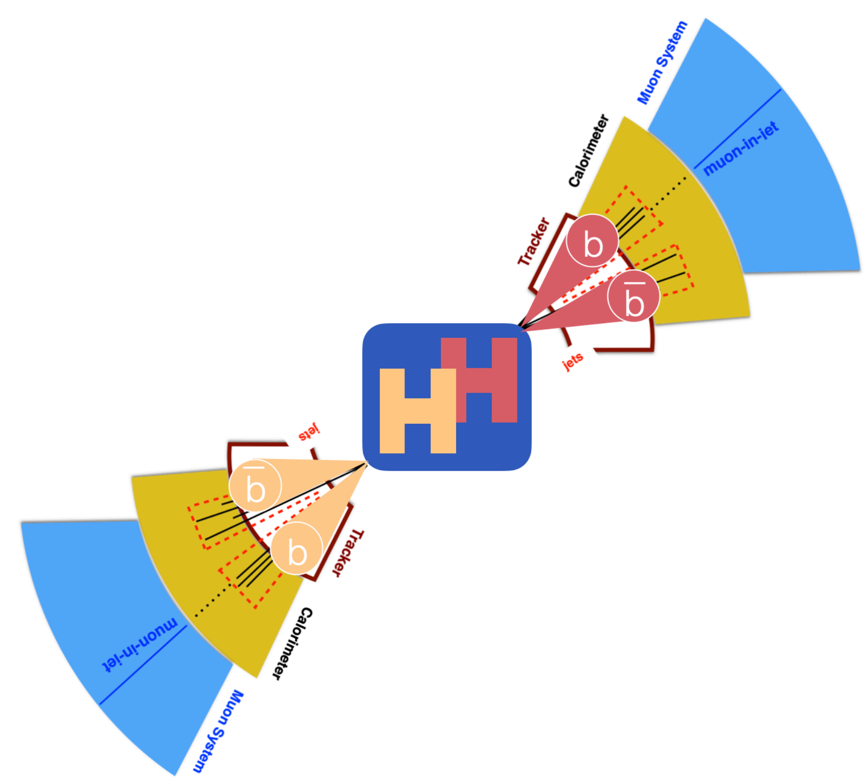


Measure it at the Large Hadron Collider at CERN by looking at HH pair production:

- **Very rare process**

	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%





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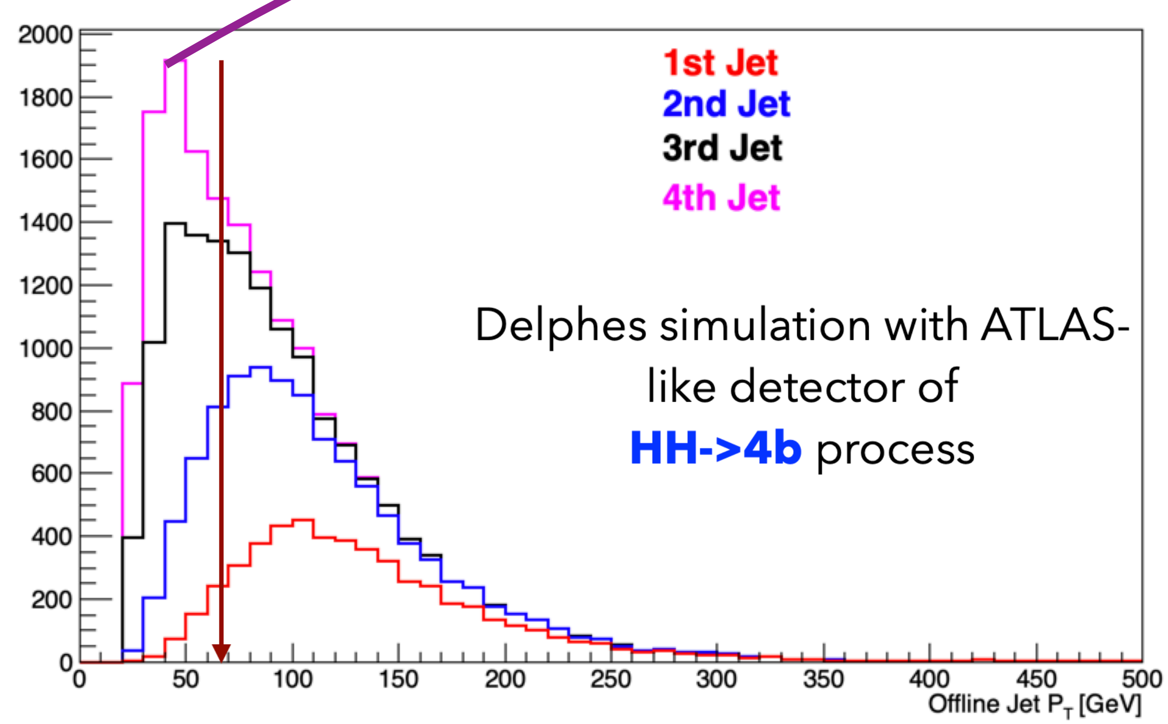
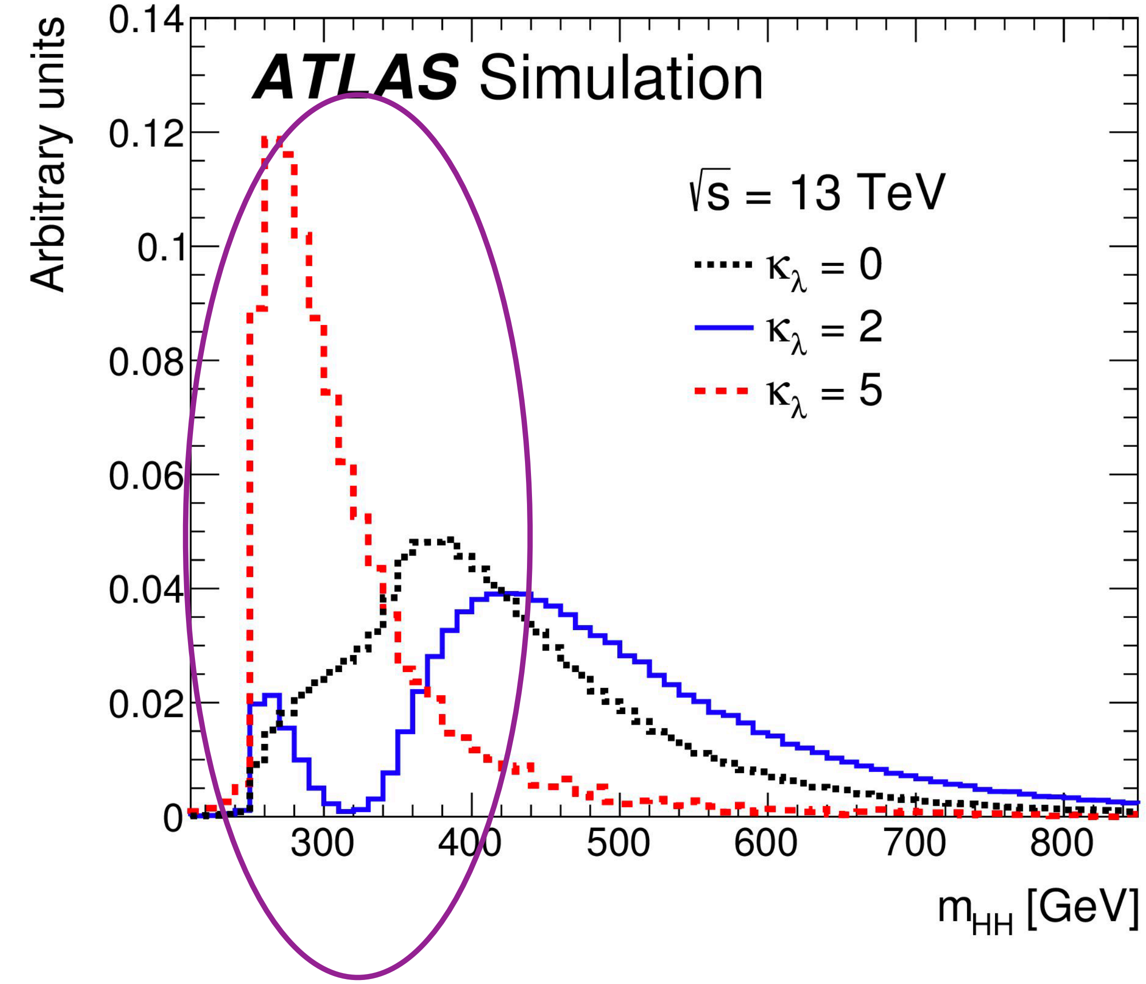
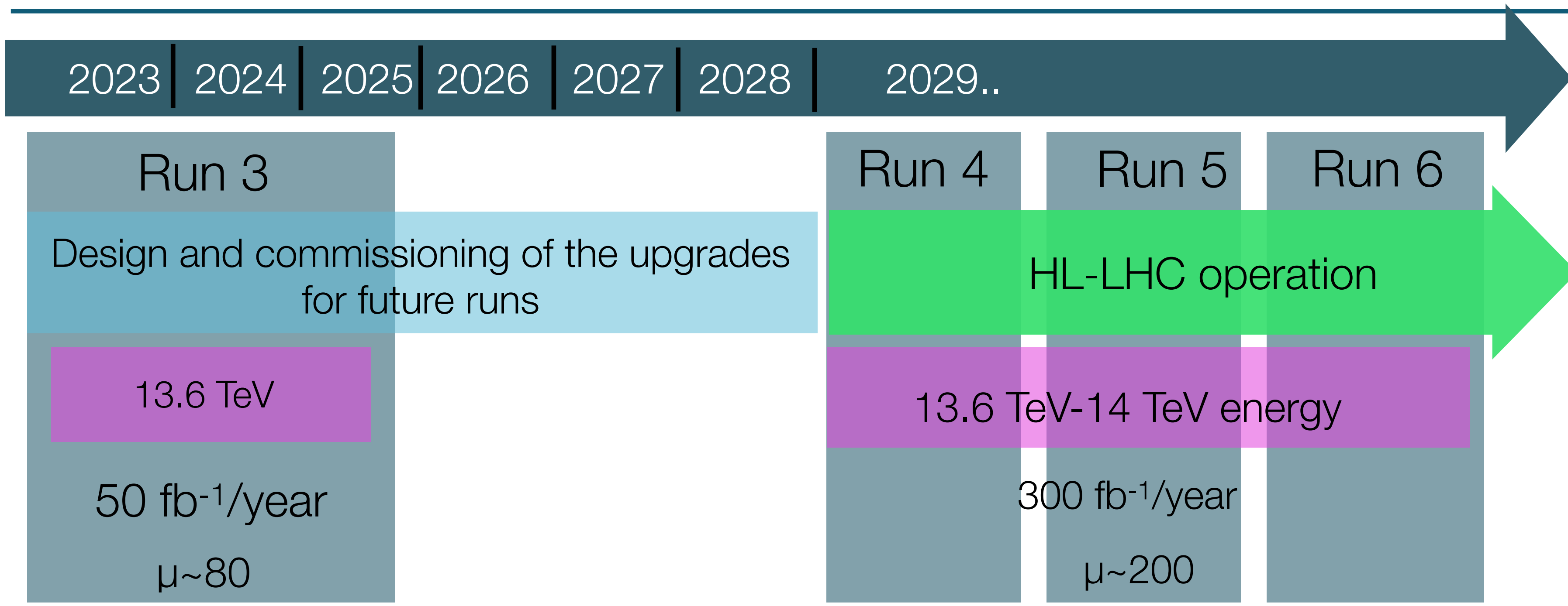
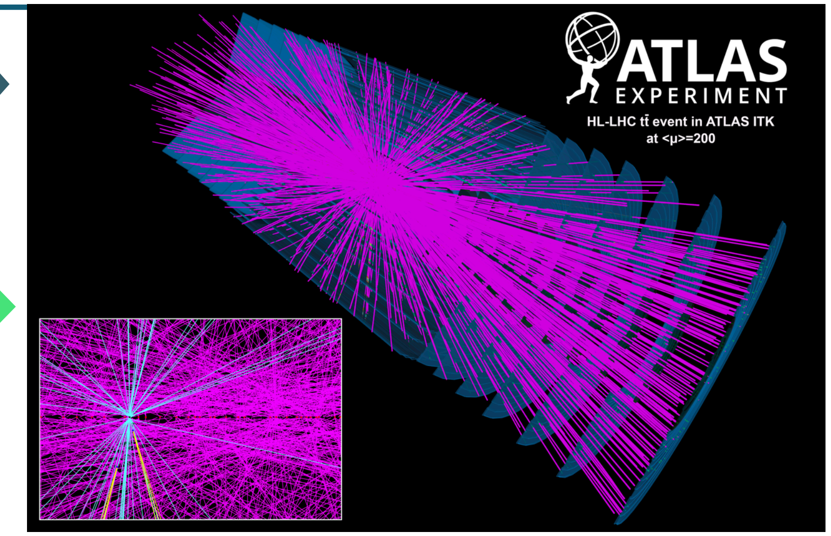
Trigger challenges ahead for HH





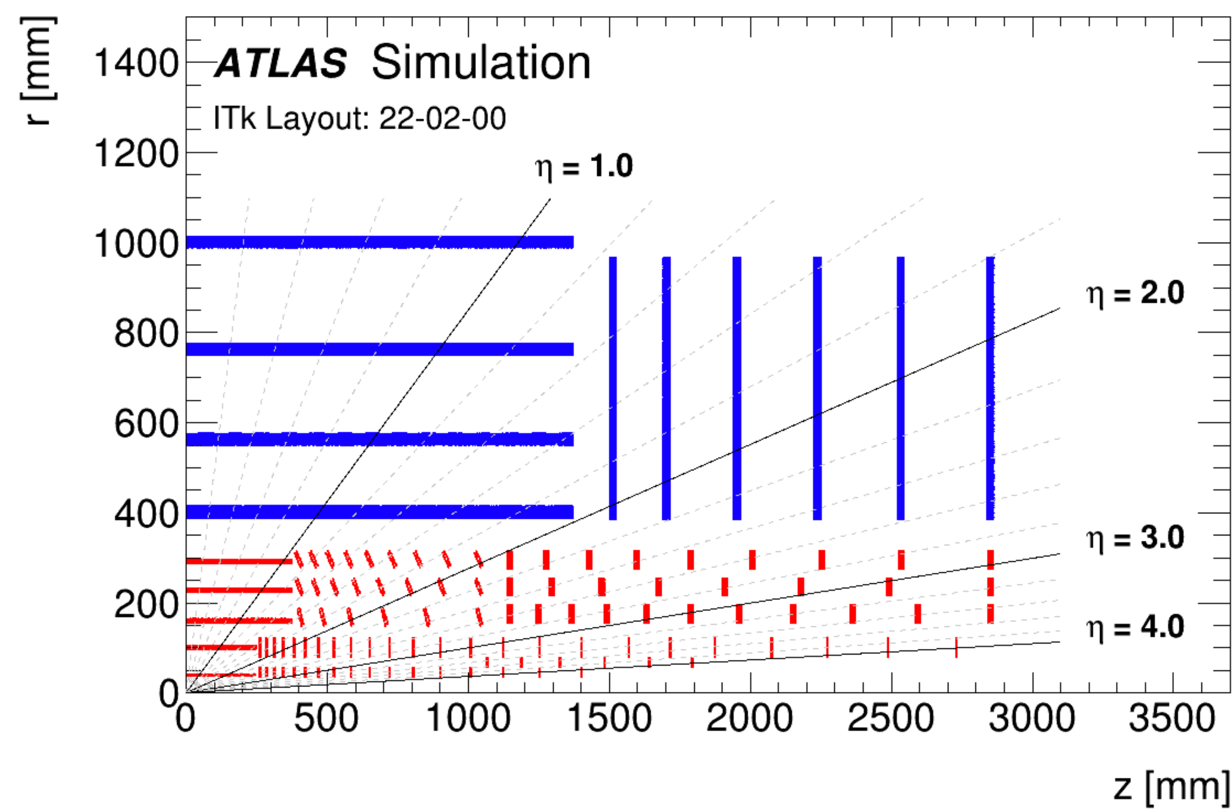
ATLAS in HL-LHC





tt̄ event at average pile-up of 200 collisions per bunch crossing.

- Conditions at the **HL-LHC,** with an average of 200 simultaneous collisions (pile-up) per bunch crossii expected, will be challenging for experiments:
  - ATLAS is planning a major, including a new inner tracking detector, a lighter and more granular all-silicon tracking detector to allow high-precision reconstruction of charged particle tracks (ITk)
  - **Triggering will become more difficult and time consuming**



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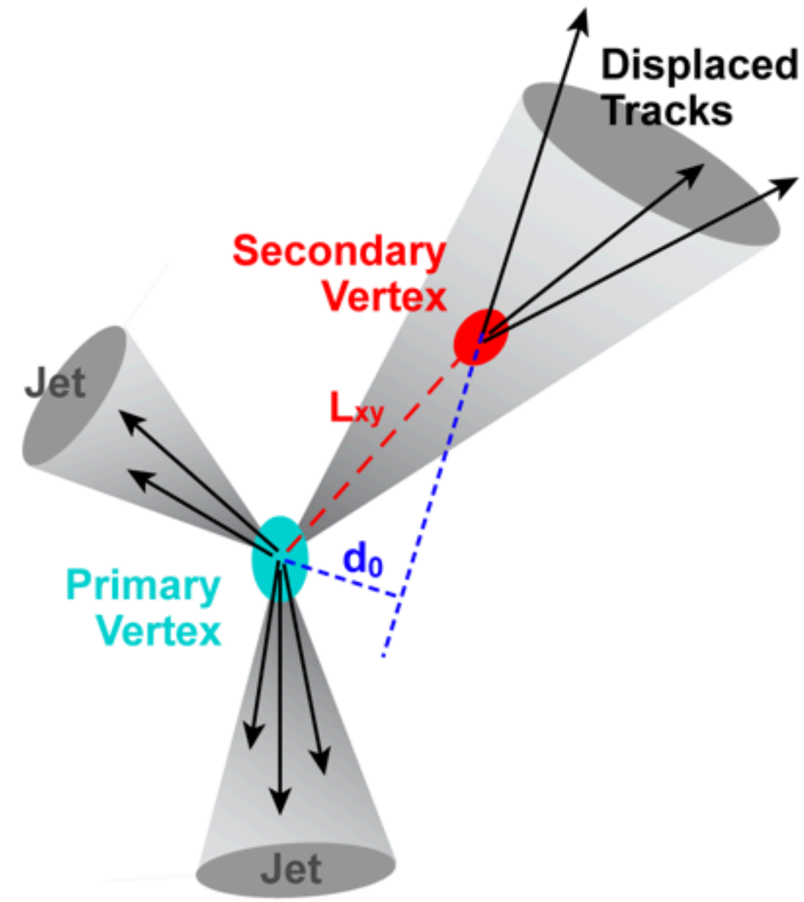
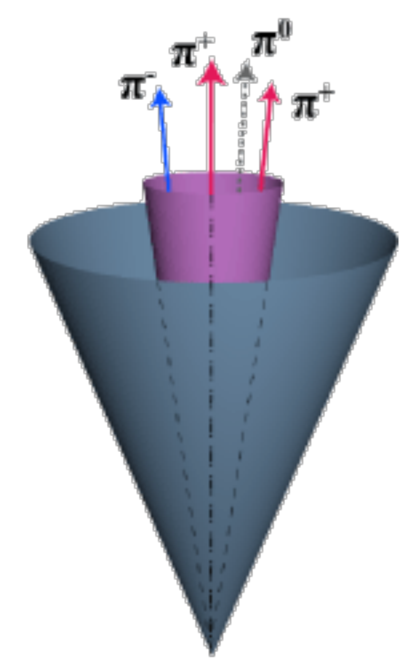
Carrying out the physics program



- Need to be able to identify:
  - 3rd generation particles: taus, b-quarks
    - Displaced vertices from B-hadron decays
    - 1- and 3-prong tau decays
  - Leptons from electroweak decays:
    - Isolated electrons and muons
  - Jets and Missing Energy



- Overcome the pileup problem by
  - tracing all the paths left by the particles back to the center of the detector, pinpointing all the collisions points (called vertices) that occurred at a proton-bunch crossing
  - decide which particles originated from which vertex

Tracking at trigger level is essential to control rates while maintaining good efficiency for relevant physics processes

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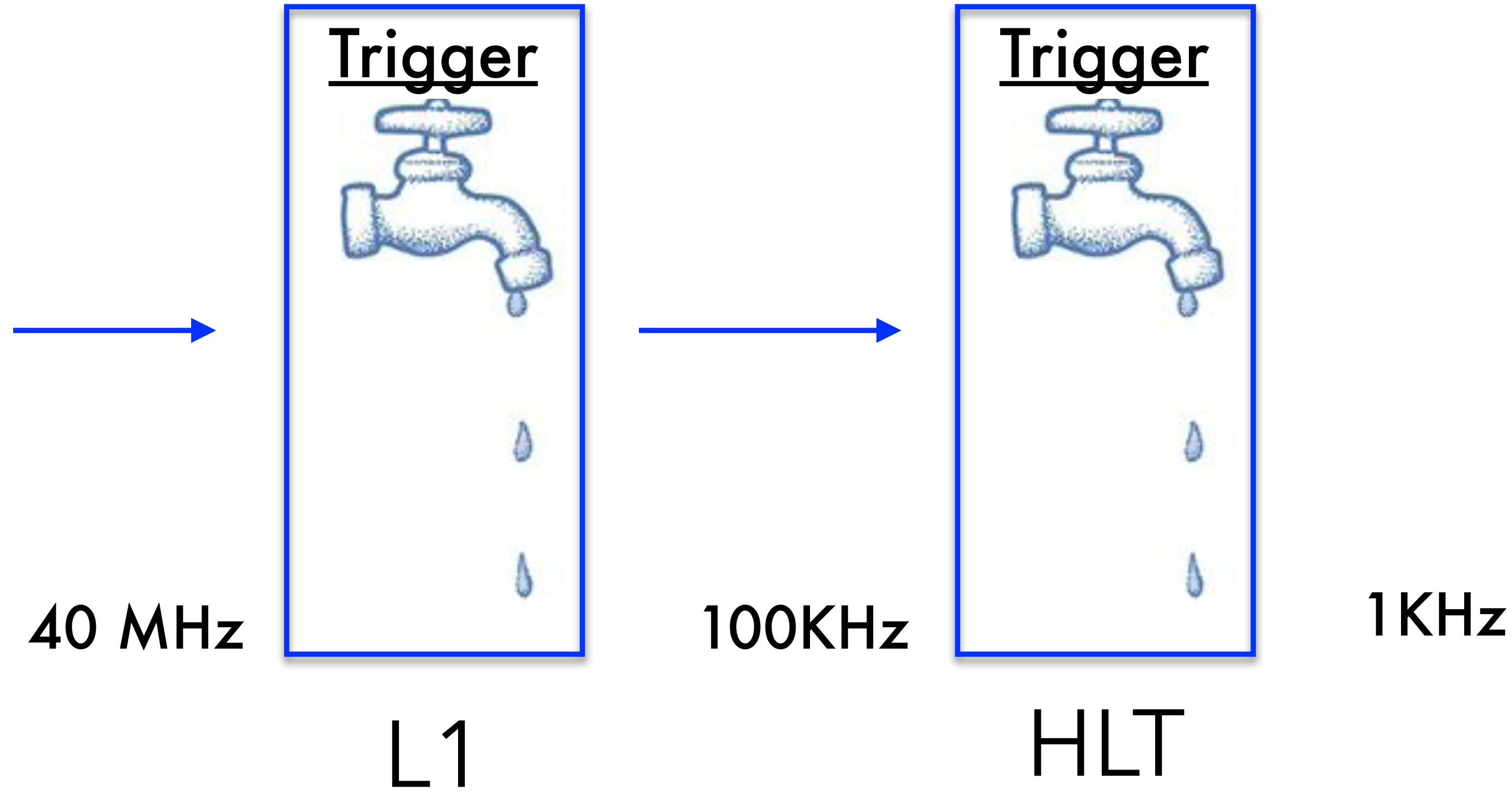
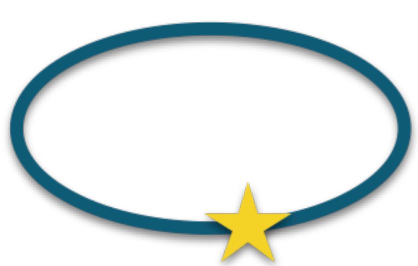
From detector to results



LHC bunch crossing rate: 40 MHz

Hardware Trigger (L1)

Software trigger (HLT)

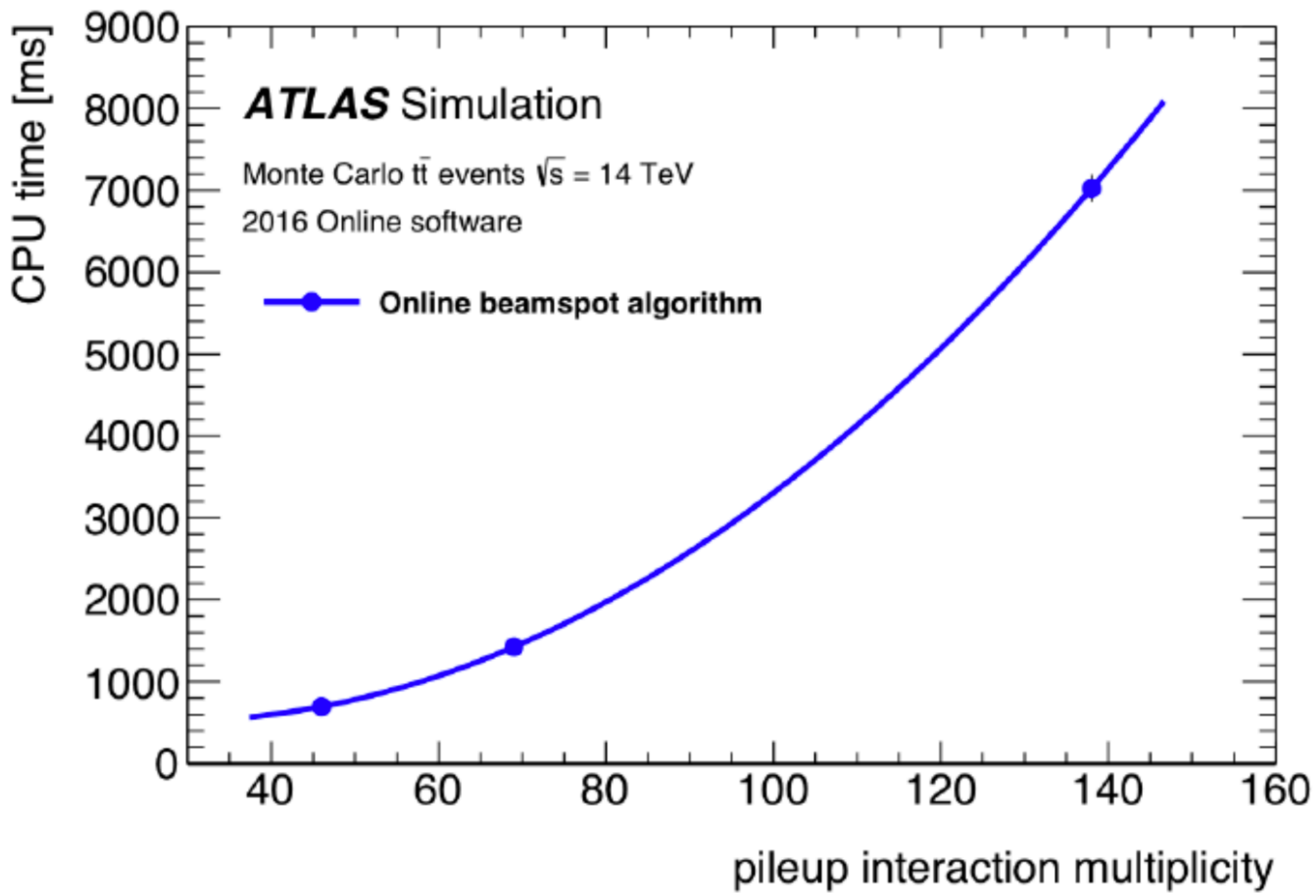


Select events with fast, coarse algorithms O(microseconds)

Refine selection with more sophisticated algorithms O(seconds)

ATLAS Trigger System

The challenge!



- Tracking at Trigger Level (ATLAS-TDR-029-ADD-1)
  - New proposed EF design==> flexible, heterogeneous commercial system consisting of CPU cores and possibly accelerators
  - **Develop demonstrators for CPU/GPU/FPGA** with a decision of the technology of the final system in 2025

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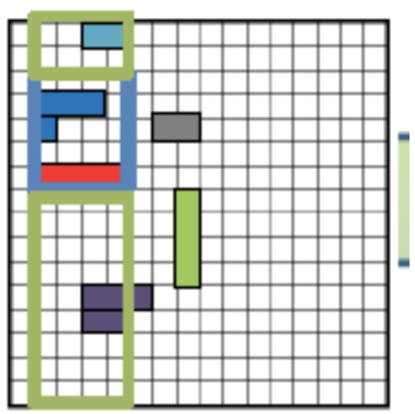
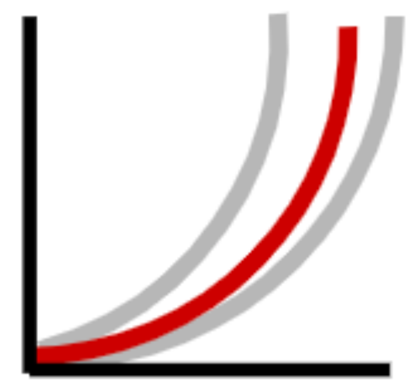
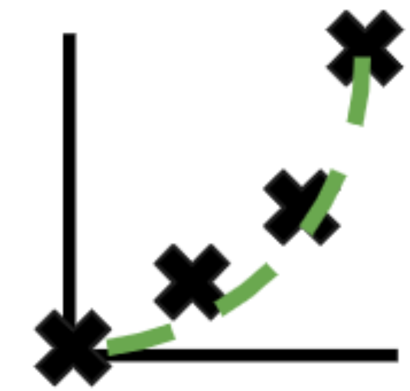
Tracking steps

Figures c.f. J. Oliver, UCI







ITk Data preparation	Pattern Recognition	Fake and duplicate removal	Precision Track Fit
Decode the ITk raw data and cluster the hits in each ITk sensor	Take subset of hits to find likely track candidates and build complete track candidates	Algorithms for duplicate removal, fake rejection	Final high precision track fit to determine the track parameters

Online vs Off-line Tracking

- Offline Tracking
  - ∞ time to run algorithms
  - Huge amount of available cpu
  - Highly specialized precision algorithms

- Online Tracking
  - Latency constraint: L1 but also HLT
  - Limited budget for hardware
  - Balance tracking precision with computational cost/speed

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Machine Learning for Online Tracking

- Online Tracking
  - Latency constraint: L1 but also HLT
  - Limited budget for hardware
  - Balance tracking precision with computational cost/speed

- **Neural networks** have proven to be a powerful and versatile tool over a wide range of problems
- They Excel at exploiting correlations between input parameters
- Can be parallelized

- Problem: GPU/CPU can be still too slow
- **Solution: Use FPGAs** have distributed on-chip memory as well as large degrees of pipeline parallelism, which fit naturally with the feed-forward nature of deep learning inference methods

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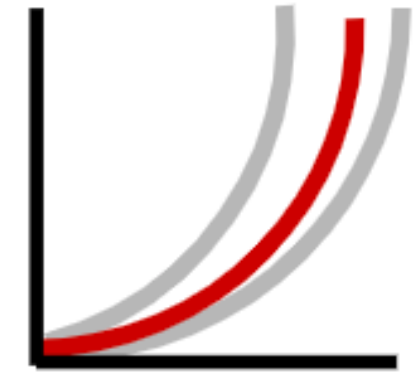
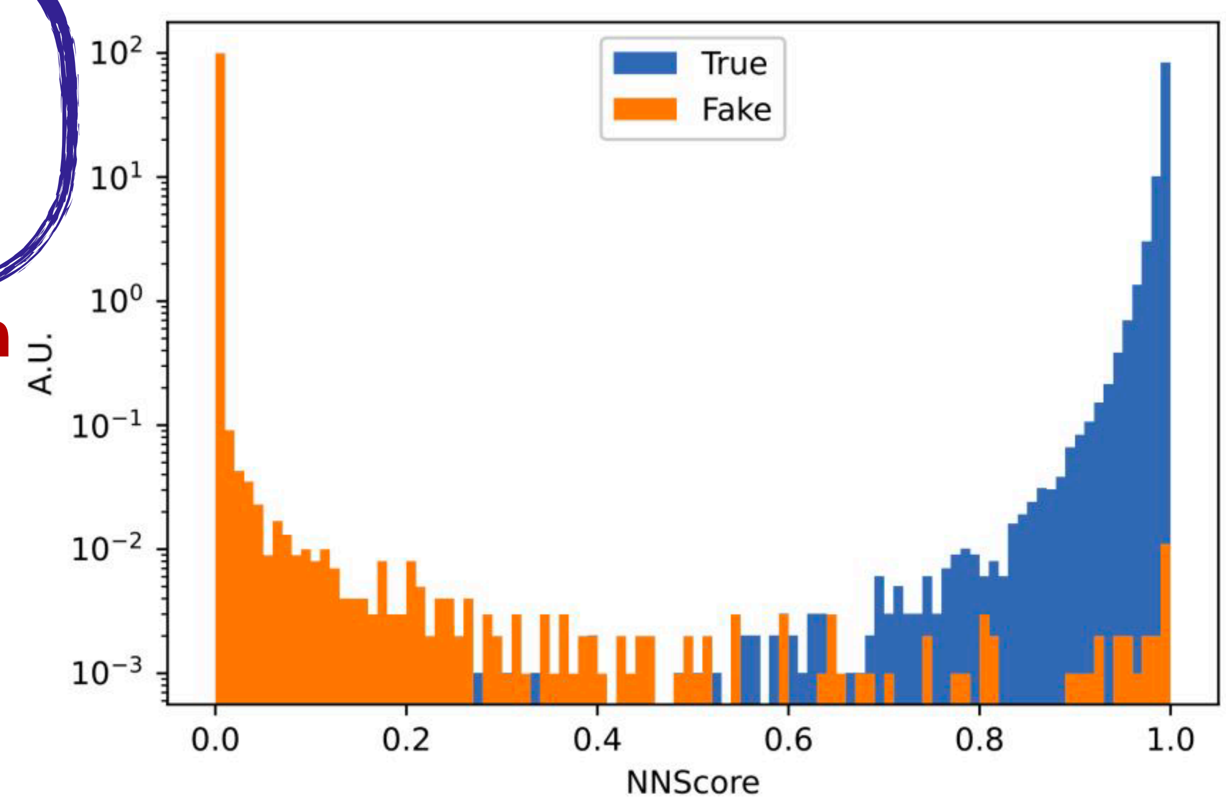
Starting small: classification step



- Classification is the most common task for Neural Networks
- Train a NN to classify track candidates as True/Fake
- Start from candidate tracks found by algorithms in Pattern Recognition Step
  - Input: hit x/y/z coordinate
  - Score each proto-track with NN Classifier

Fake and duplicate removal

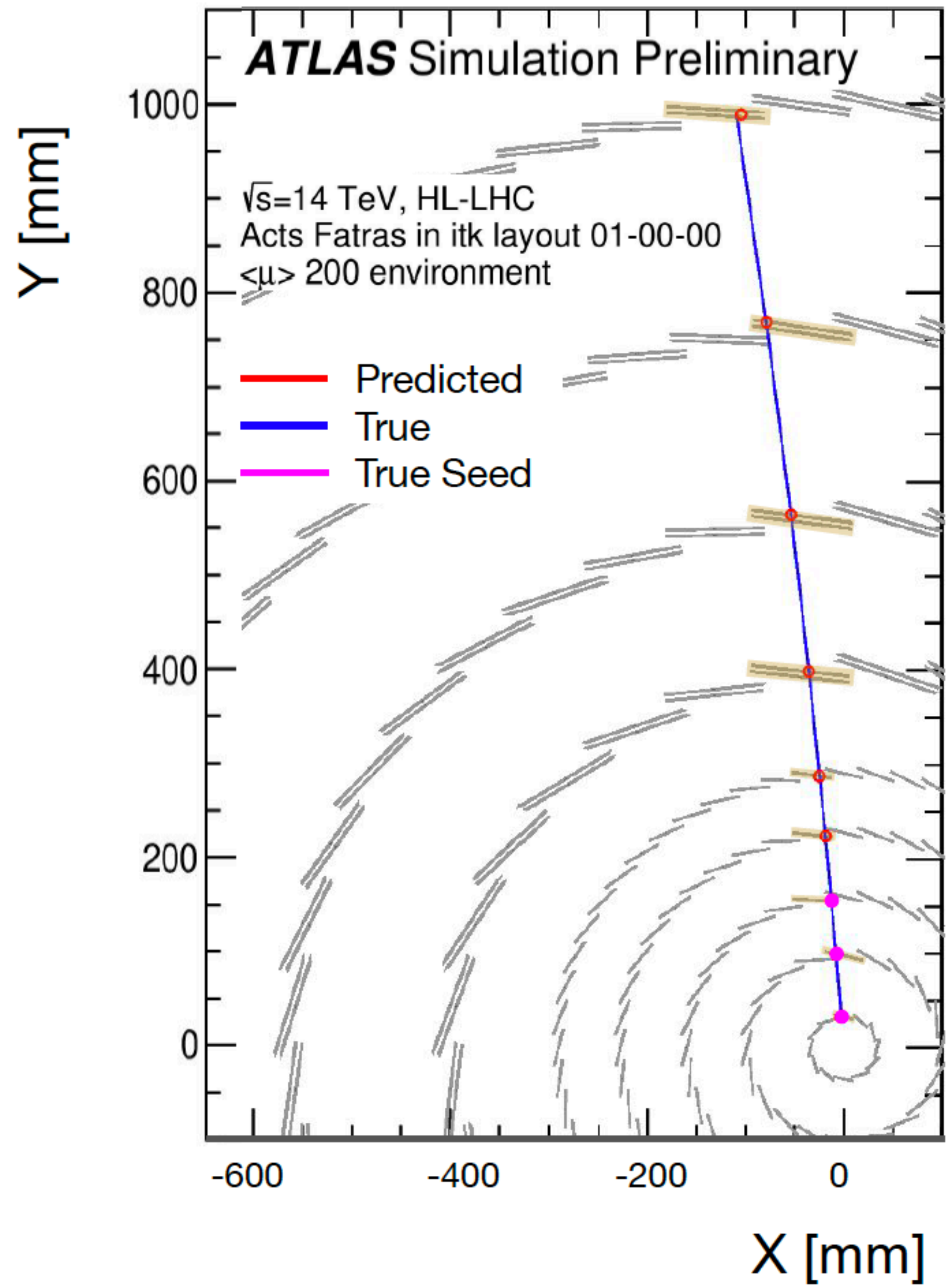
- Compare proto-tracks with more than X shared hits
- Keep only the highest scored proto-track
- **Reduces the number of fake tracks by a factor two orders of magnitude while retaining a high purity of true track candidates**



Pattern Recognition: building track candidates

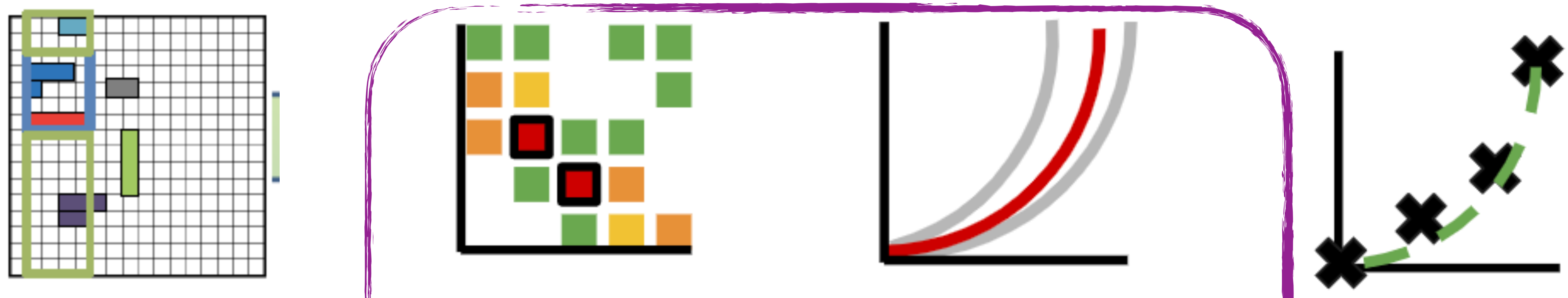
- Assumes seeds of three hits in the inner-most pixel layers are available
    1. Input 3 hits into a NN
    2. Predict the coordinate of the 4th hit
    3. Look for hits in the detector nearby the predicted location
    4. Append all compatible hits to the seed
    5. Repeat until the edge of the detector is reached or no compatible hits are found

Pattern Recognition

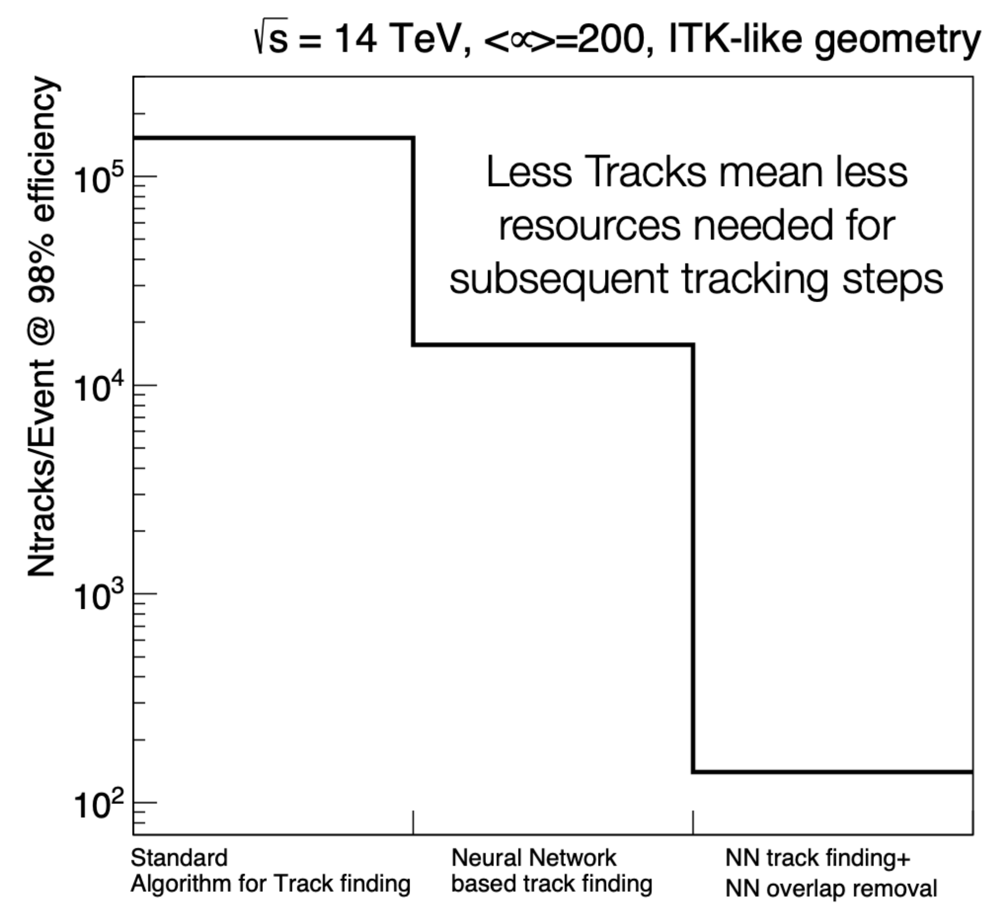


Tracking steps

Figures c.f. J. Oliver, UCI



ITk Data preparation → Pattern Recognition → Fake and duplicate removal → Precision Track Fit



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Pattern Recognition: building track candidates

Advantage: Without external information (i.e magnetic field, detector geometry…) during run time, we can get simultaneous predictions for O(100-1000) proto-tracks at a time

saves time and memory on FPGA

Execution on FPGA takes only 50 ns (10 clock cycles) and is perfectly pipelined
To make N predictions, we require N+10 clock cycles

Xilinx Alveo U250 FPGA resource usage estimates for neural networks
* rough estimates as NN architecture may change

	Latency (ns)	LUT (%)	FF (%)	BRAM/URAM (%)	DSP (%)
Ambiguity Resolution	50	18	1	<0.01	31
Hit Prediction	50	7	0.5	<0.01	21

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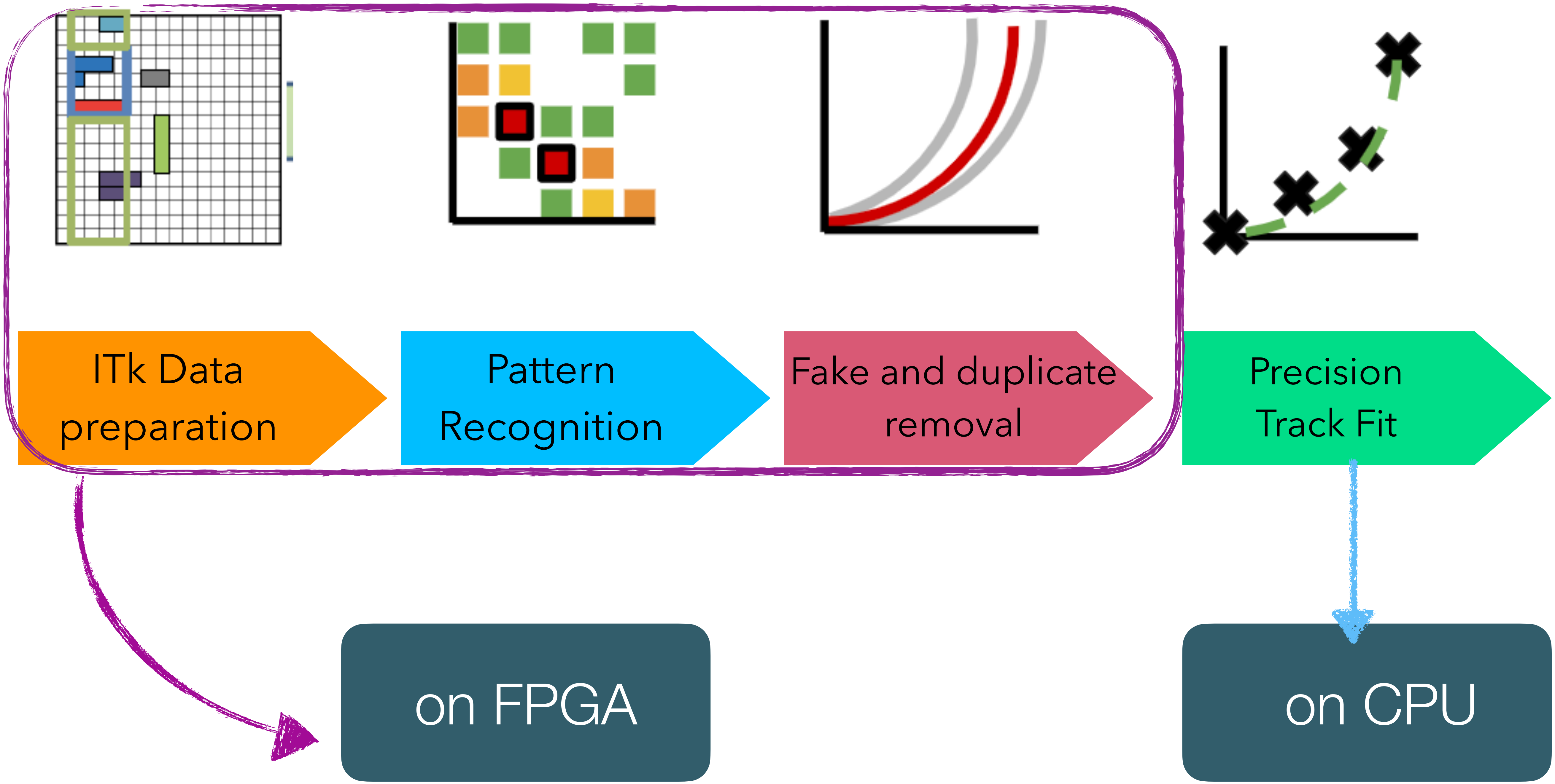
Tracking @HL-LHC

Figures c.f. J. Oliver, UCI



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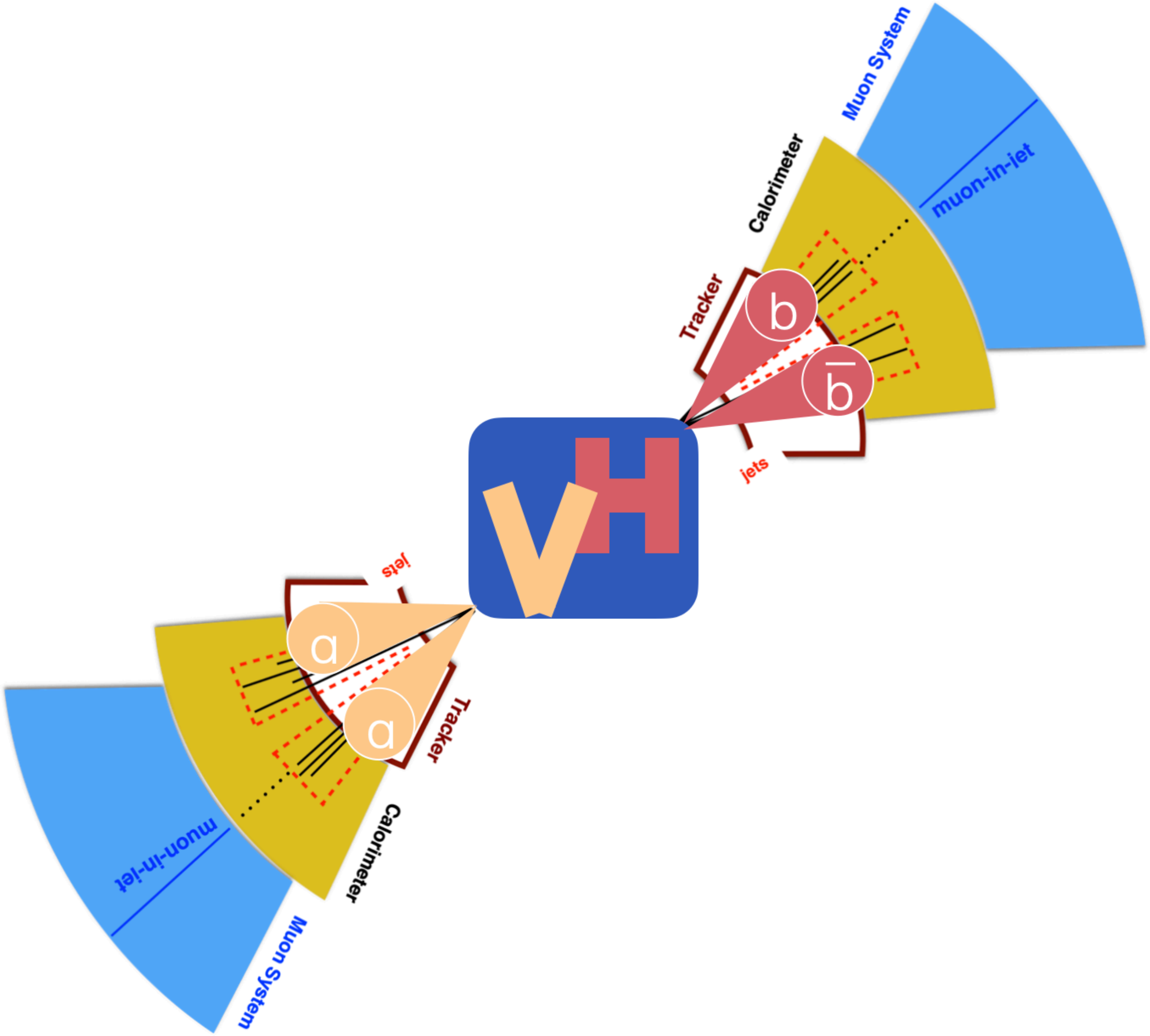
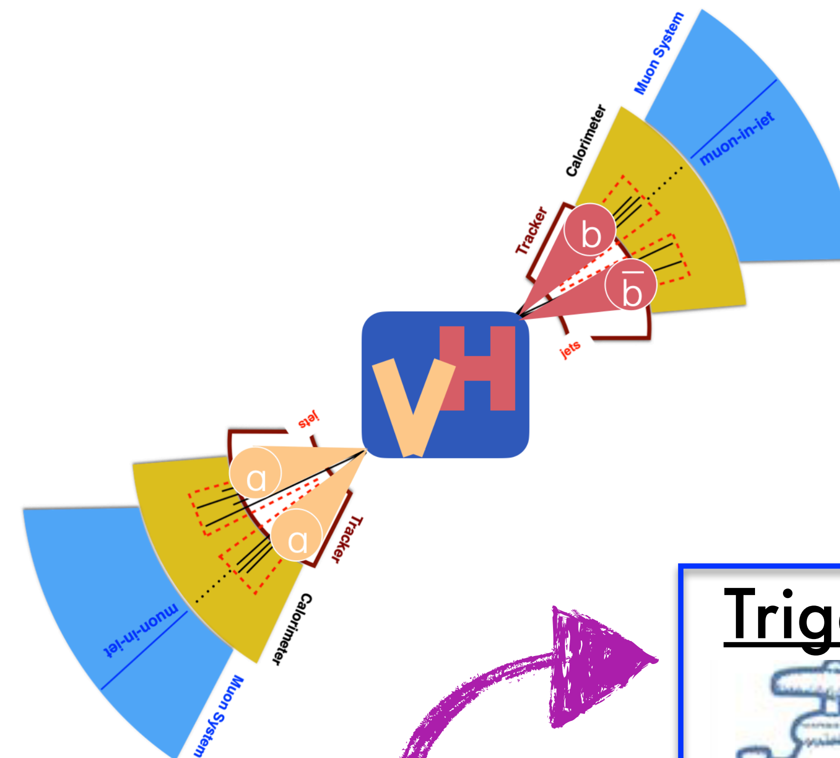
And then what?

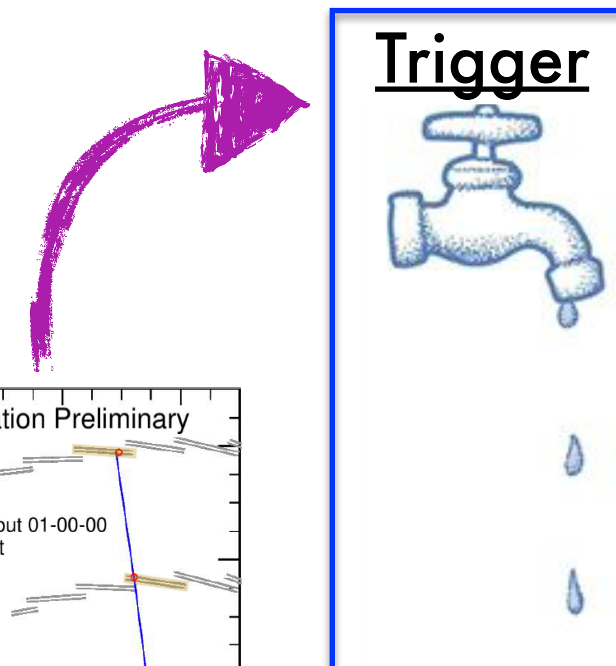


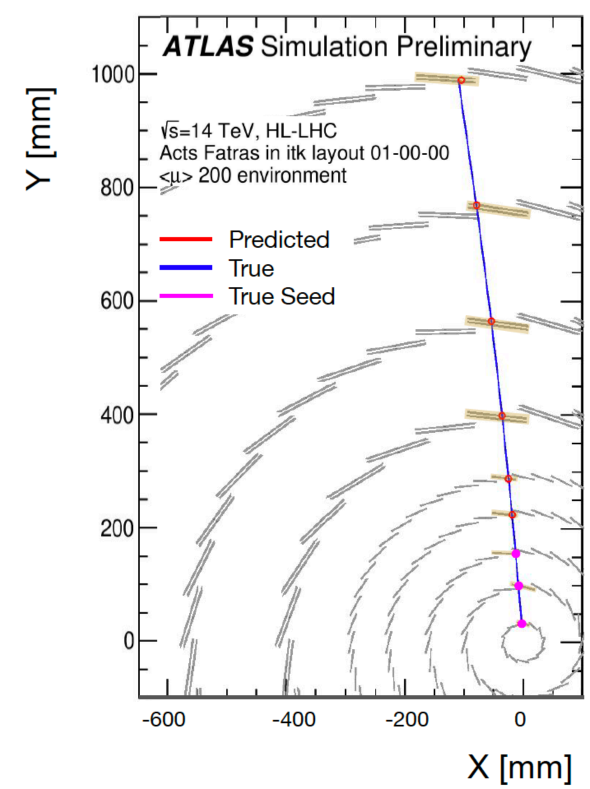
Exploit full event information at trigger level!

Summary

- Precision Higgs boson coupling measurements offer a unique insight into BSM physics & complimentary to direct searches
- Differential measurements pivotal to make the most of LHC data and constrain BSM physics
  - **Fully hadronic final states crucial for this**
- Need to make sure to continue taking and storing interesting events:
  - **Trigger is the key for the future of high-lumi**







Backup