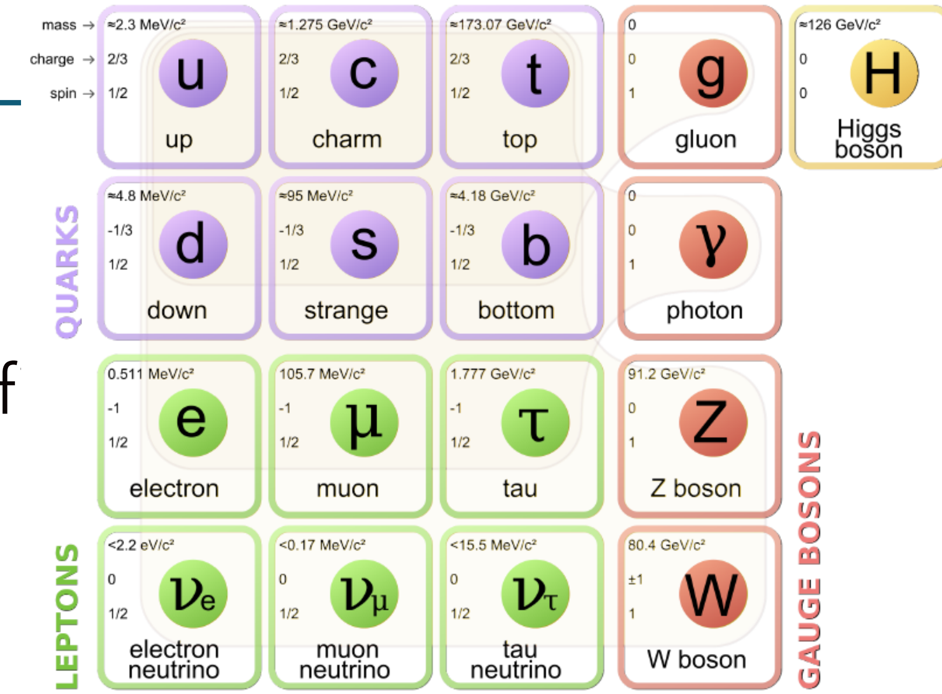
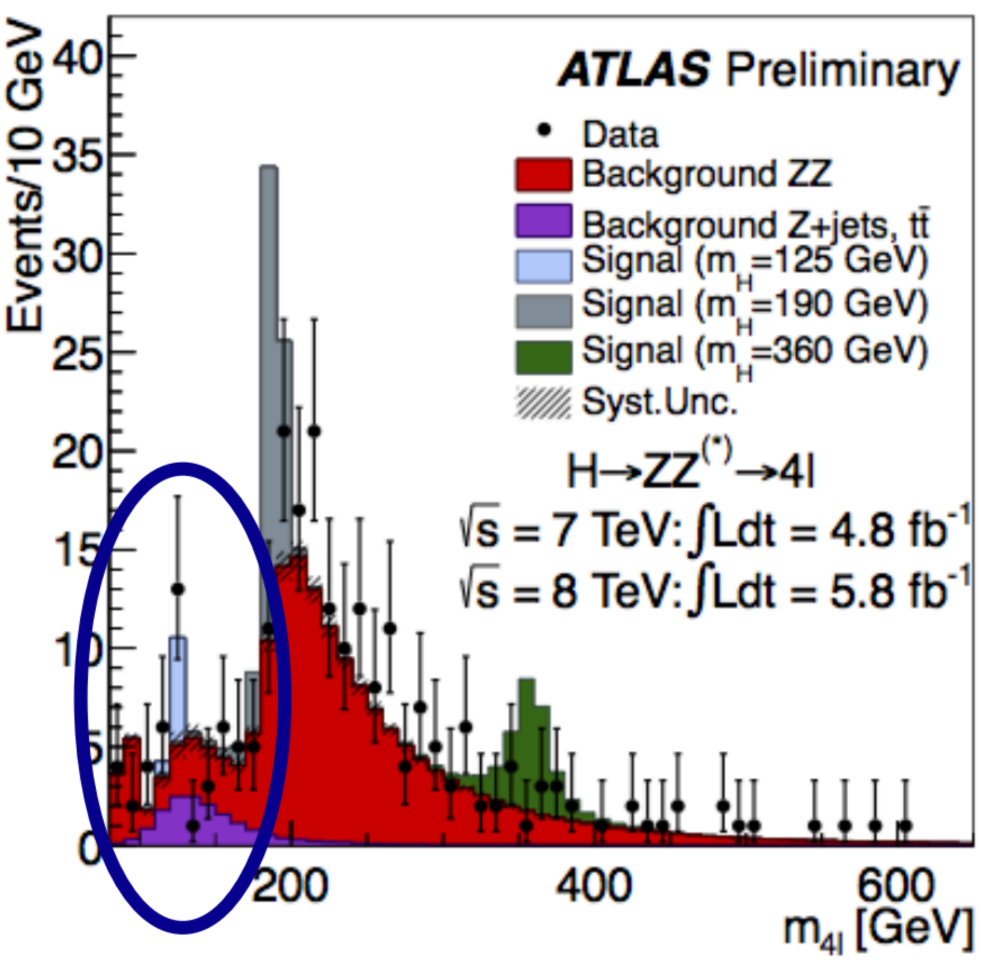
Higgs as a probe into the the unknown

Viviana Cavaliere (BNL),
Sept 9th 2022
Early Career Scientist retreat

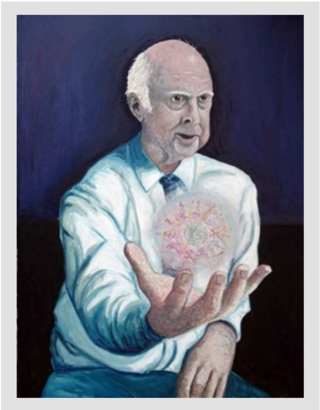
The Standard Model

- The Standard Model of particle physics is a powerful theory that describes three of the four known fundamental forces in the universe and classif all known elementary particles.
  - Wonderful agreement with experiments





2012 Higgs Discovery



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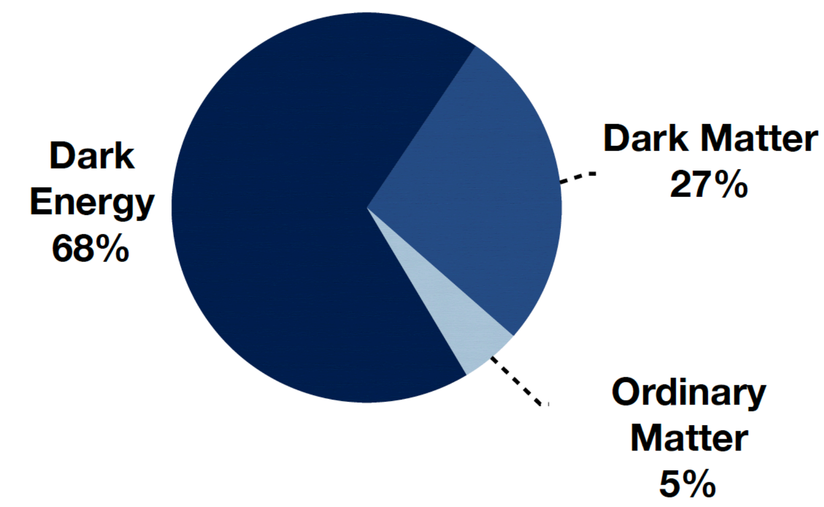
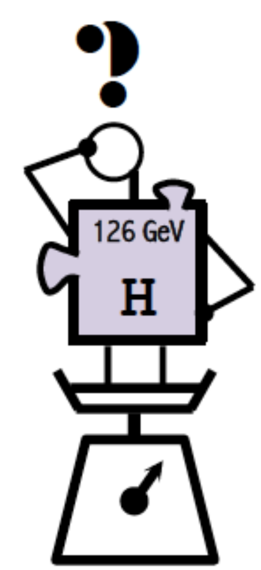
"Observation of a new particle consistent with a Higgs Boson Historic Milestone but only the beginning" R. Heuer

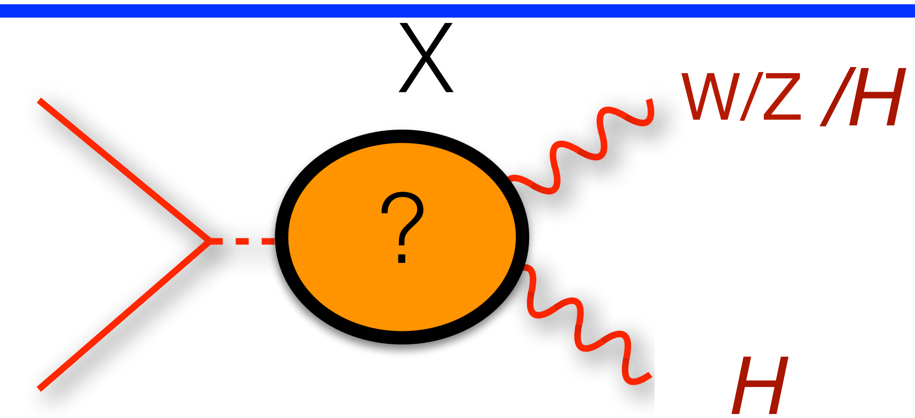
Is this all there is to know?

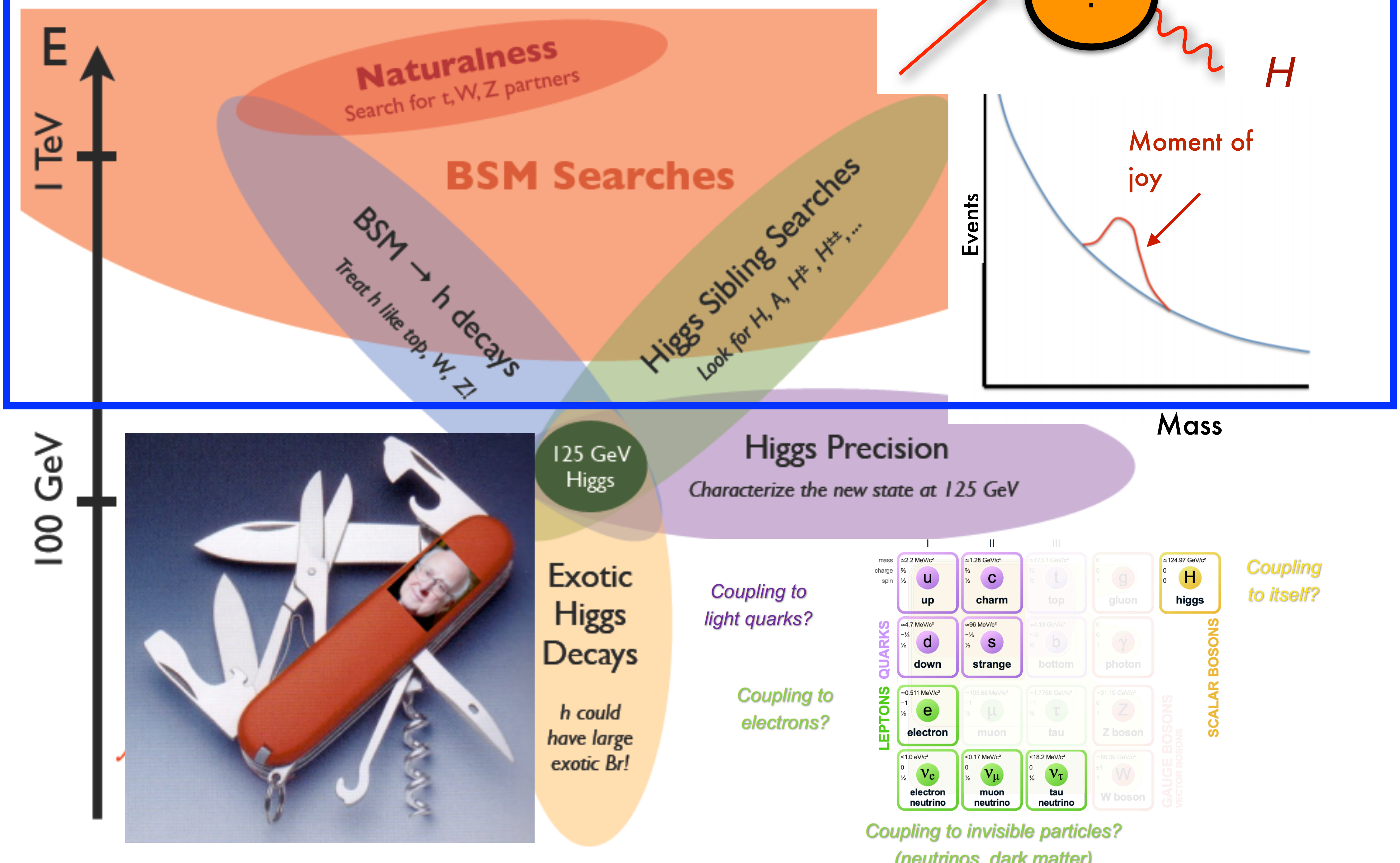
- The Standard Model is an extremely successful theory, but it leaves many questions unanswered.
  - Is the Higgs the only responsible for electroweak symmetry breaking (EWSB), the mechanism which is responsible for generating the masses of the fundamental particles
- A few, but major, pieces are missing in the puzzle:
  - Neutrino masses (and flavour oscillation) not predicted
  - Matter-antimatter imbalance
  - Unification of forces
  - No gravity
  - Dark Matter, Energy? Ordinary matter only 5%
  - Naturalness or hierarchy problem:
    - Observed M^2_{Higgs} 10^{32} times smaller than predicted





Higgs as a tool for discovery





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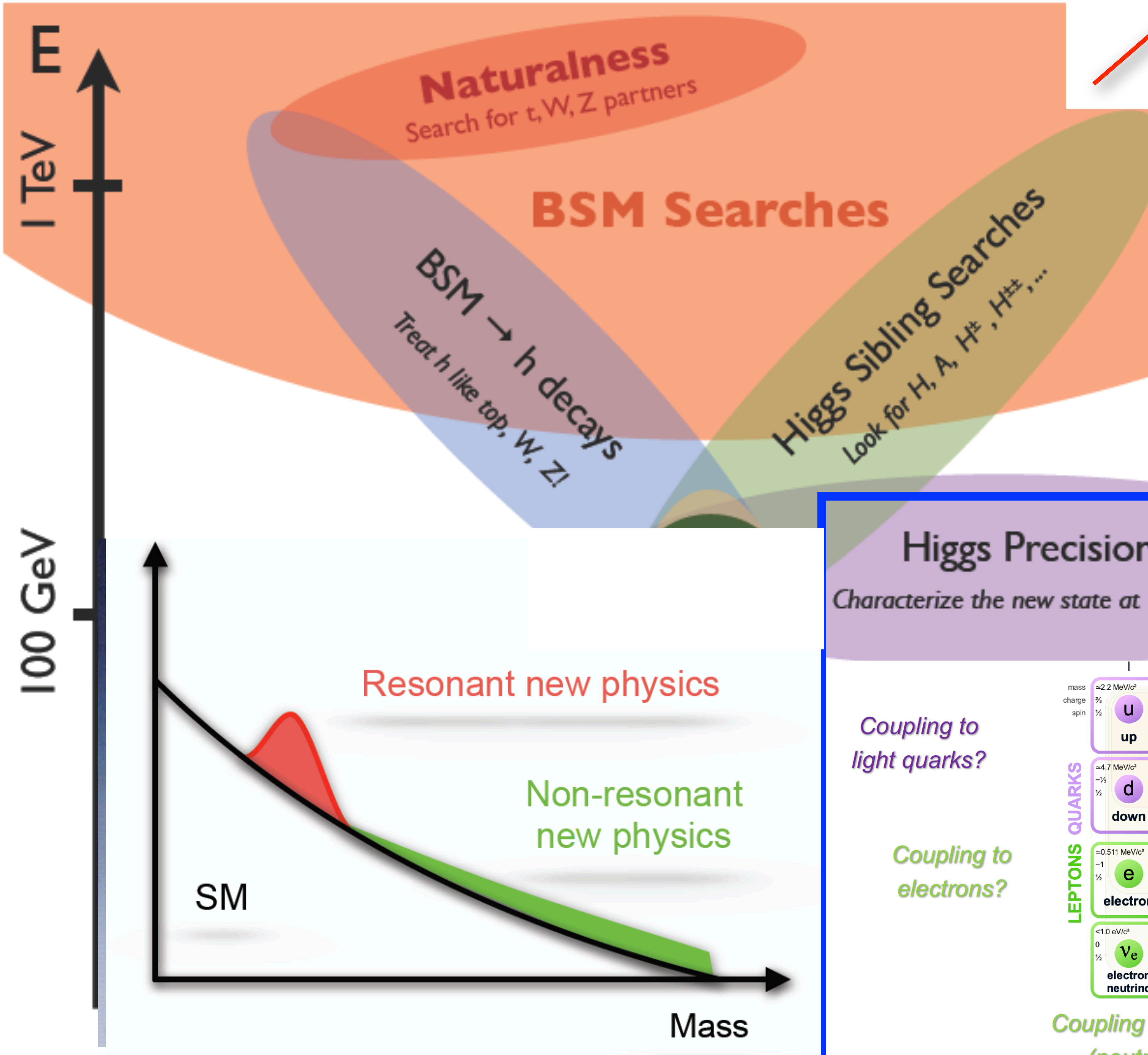
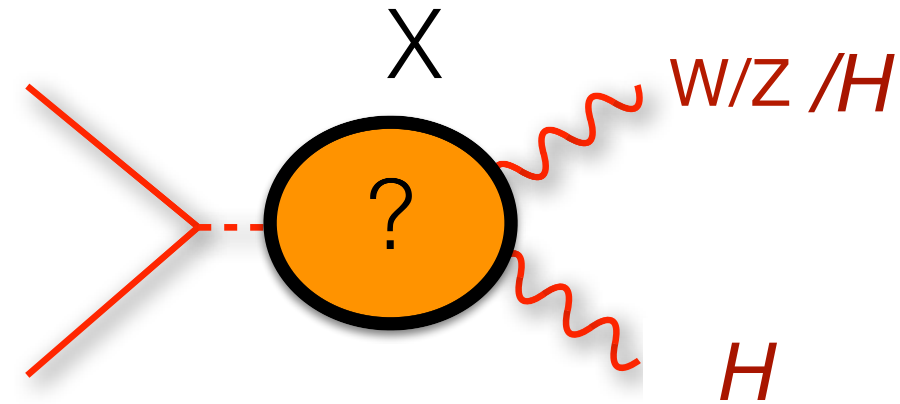
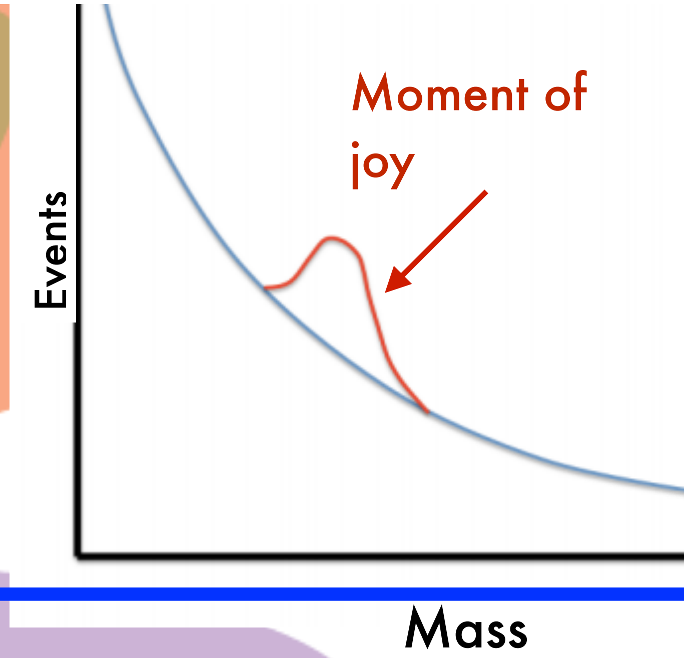
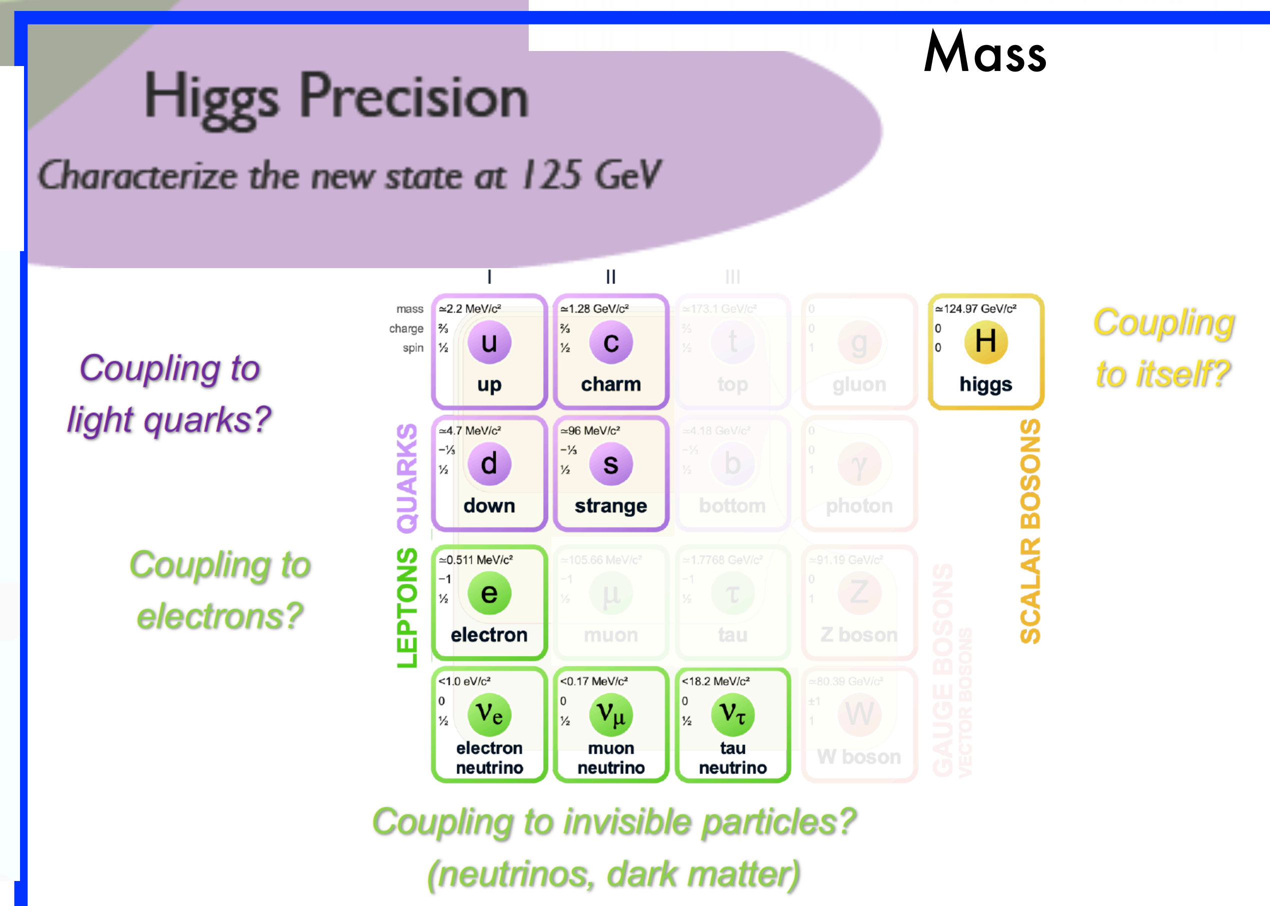
https://www.nature.com/articles/s41586-022-04893-w

Higgs as a tool for discovery









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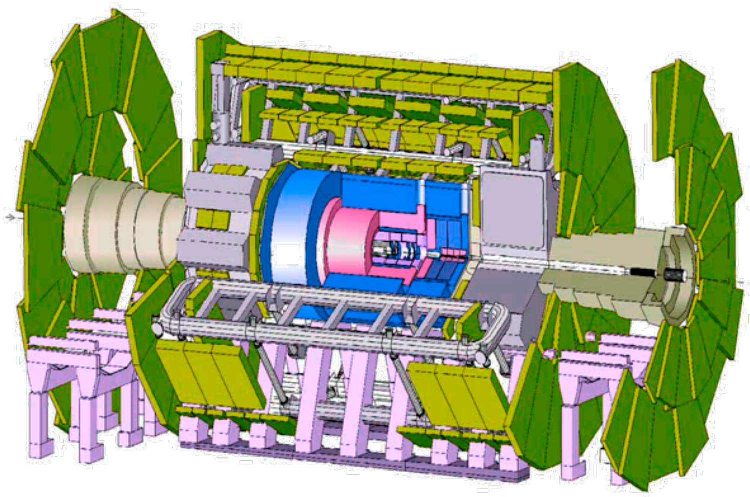
From the detector to the physics results

40 million collisions per second

Detector

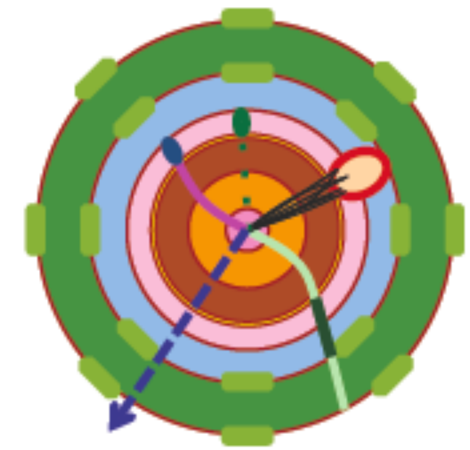


40 MHz

Trigger

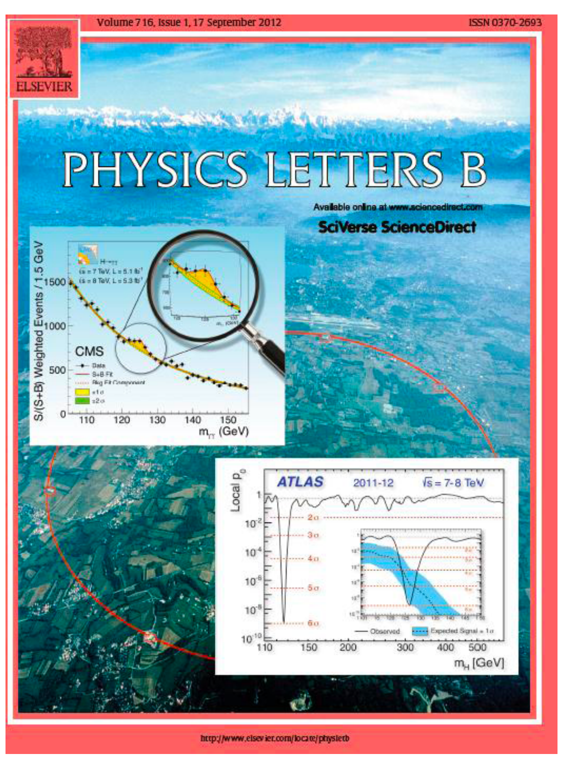
1KHz

Reconstruction

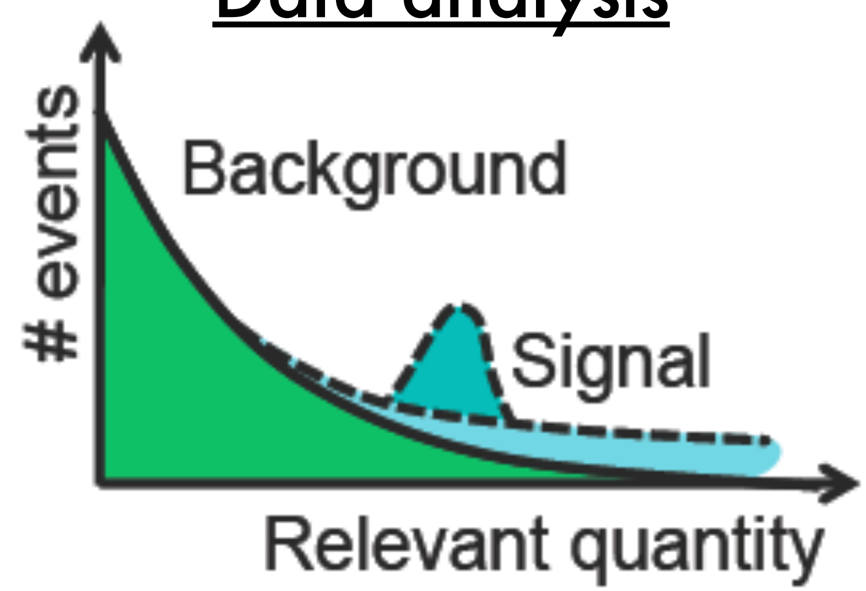


Sophisticated filtering to keep only 0.001% of events

Publication

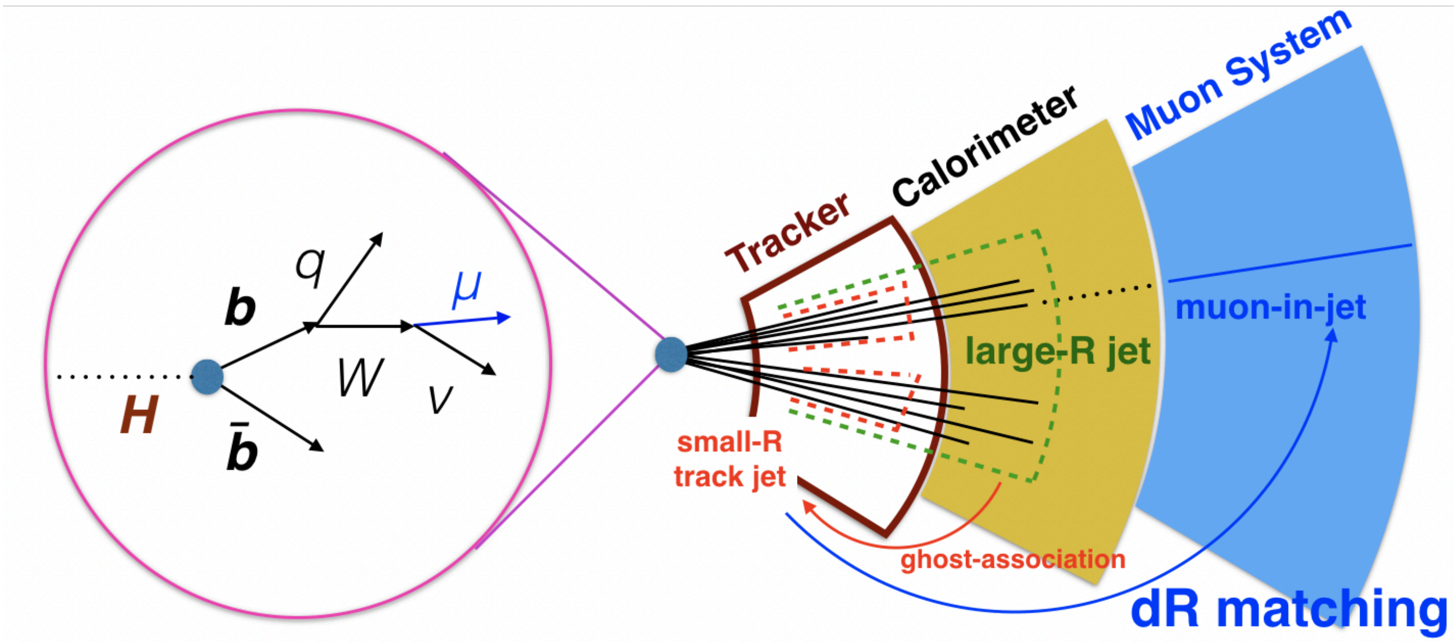


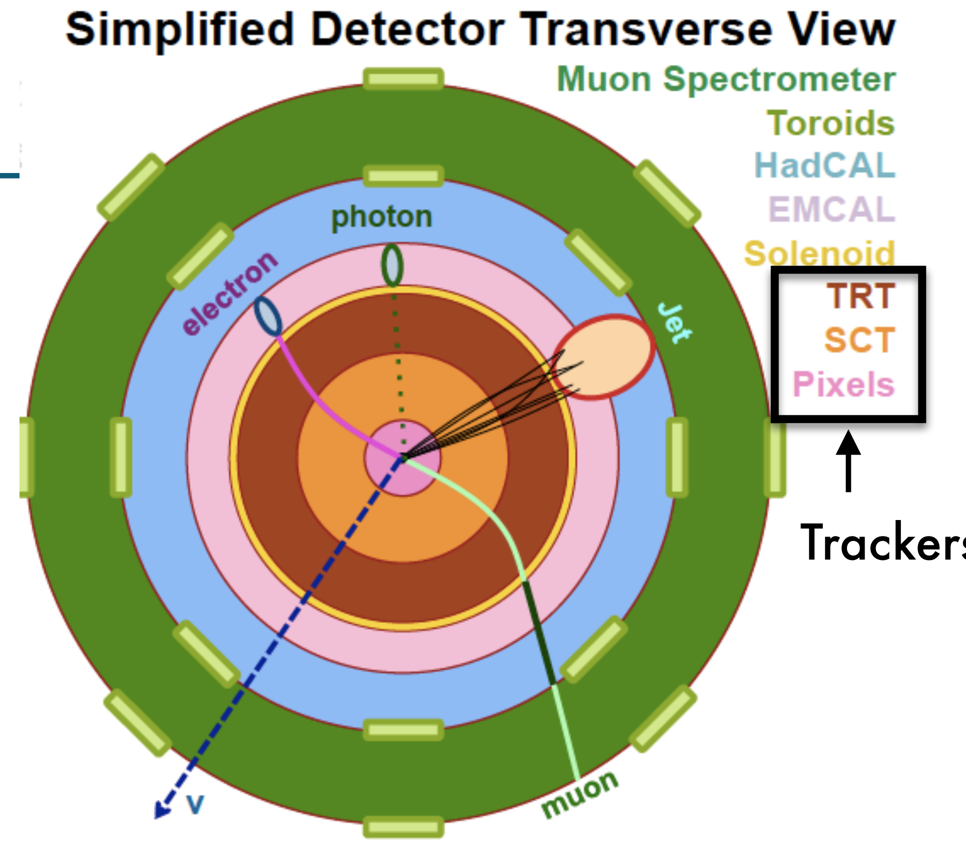
Data analysis



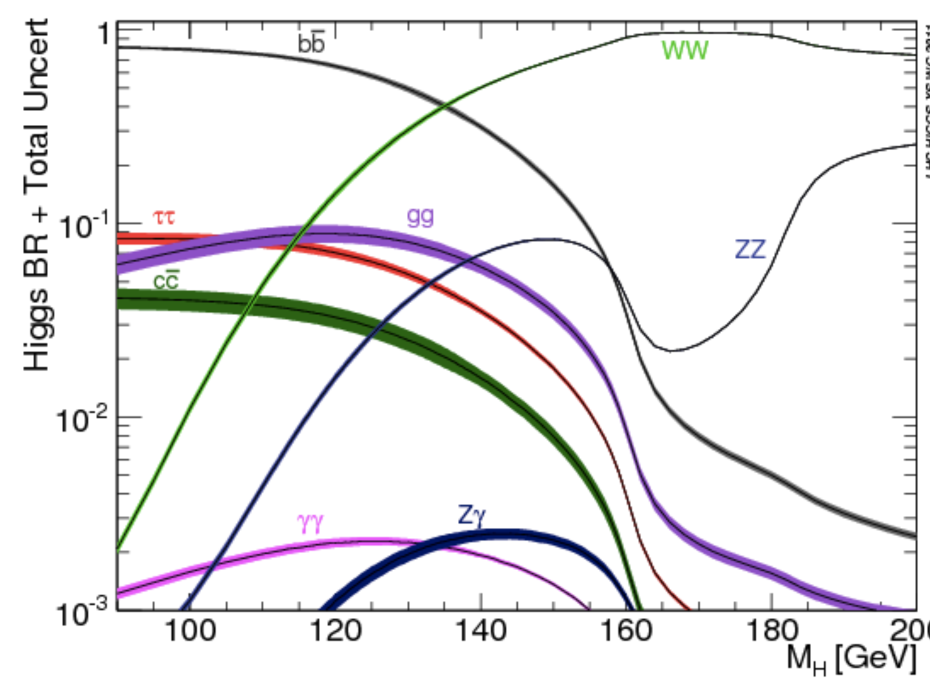
1 observed Higgs event in a trillion (10^{12}) pp collisions

H->bb reconstruction





- Weakly decaying b-hadron: $\tau \sim 1.5 \times 10^{-12}$ s and mass ~ 5 GeV
  - – A b-hadron with pT~30 GeV has decay length of 3mm ==> 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! all ML based



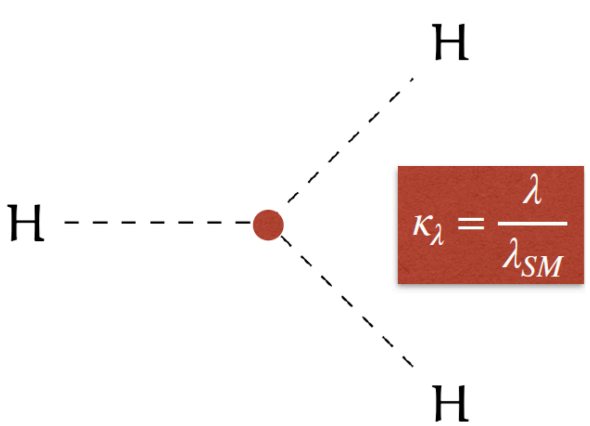
HH combination

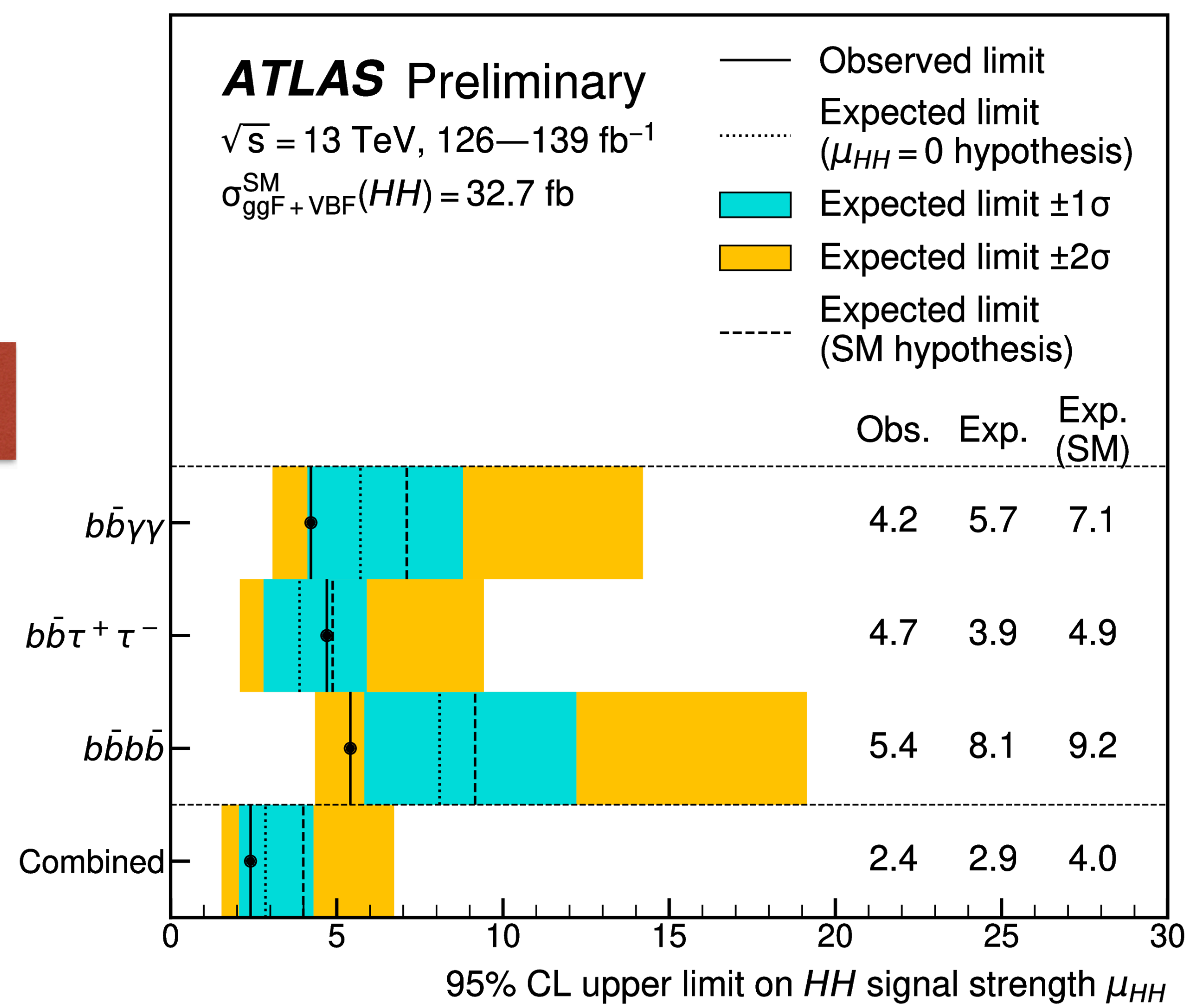
ATLAS-CONF-2022-050

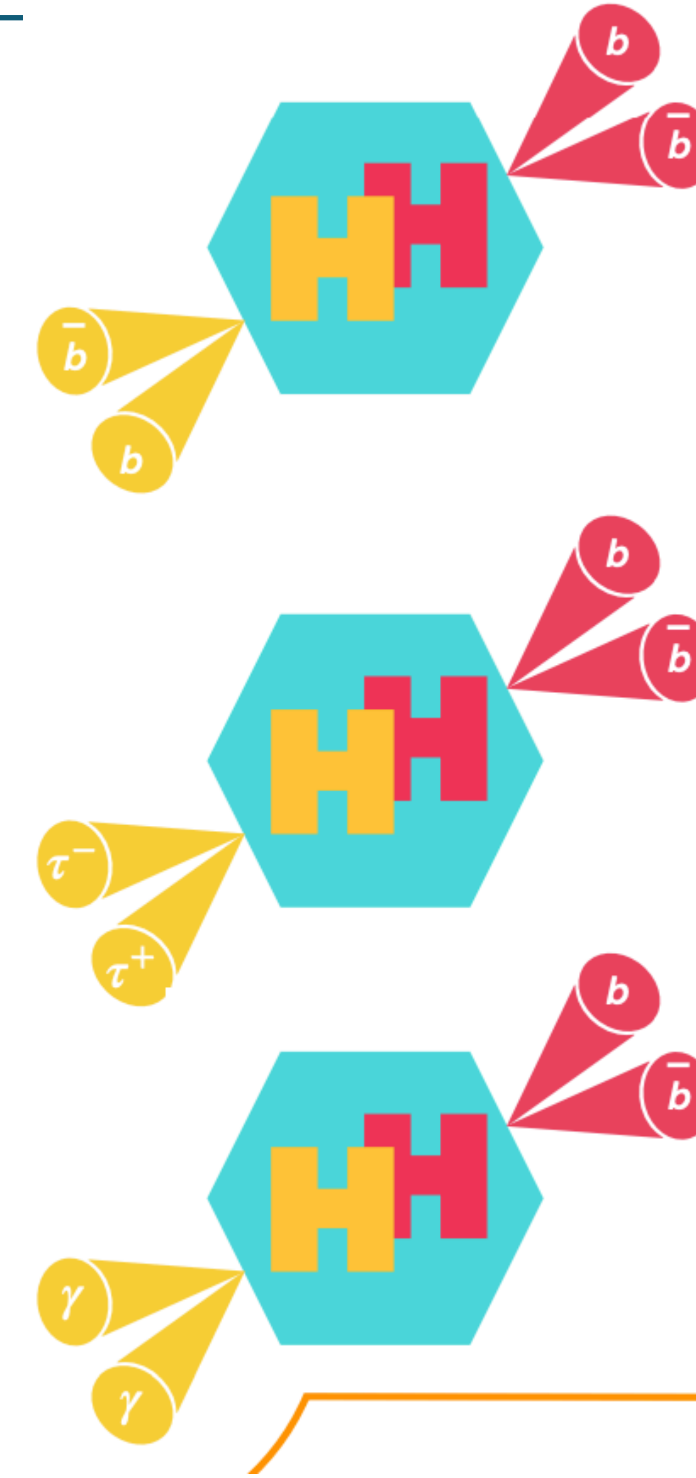
- The **Higgs self-interaction** is an **extremely interesting process** to measure at the LHC:
- Deviations from SM (κ_λ=1) **well motivated by cosmology** (e.g. EWK baryogengesis).
- Direct access to λ through Higgs pair creation
- Accessible only with HL-LHC statistics, but important deviations **could already be probed with the Run 2+3 datasets**.

Combining the results is necessary for observation.

$$\sigma_{HH}^{ggF} = 31.02 \text{ fb}$$







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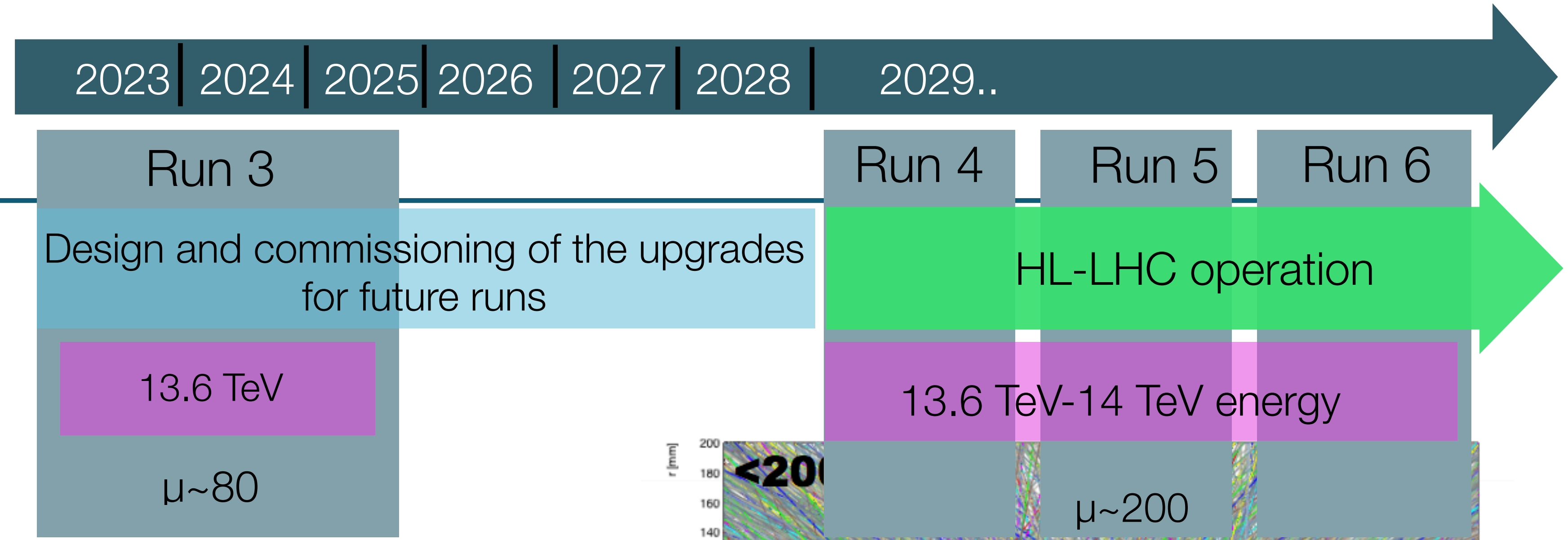
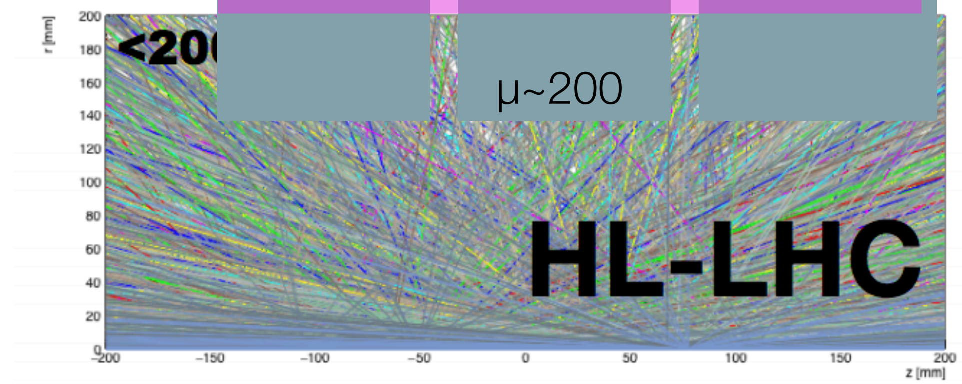
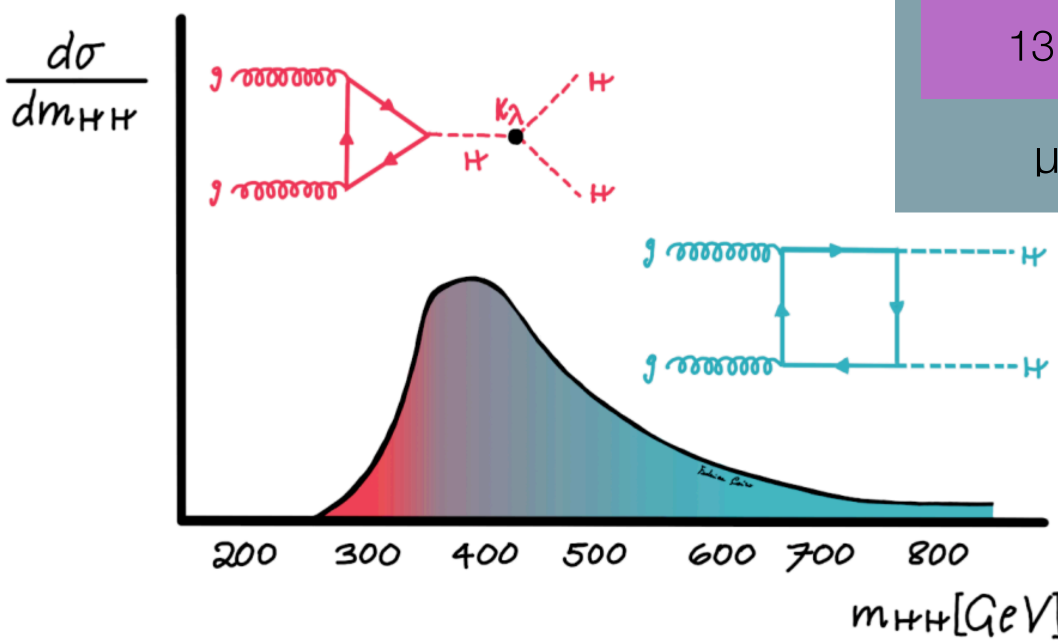
Moving ahead

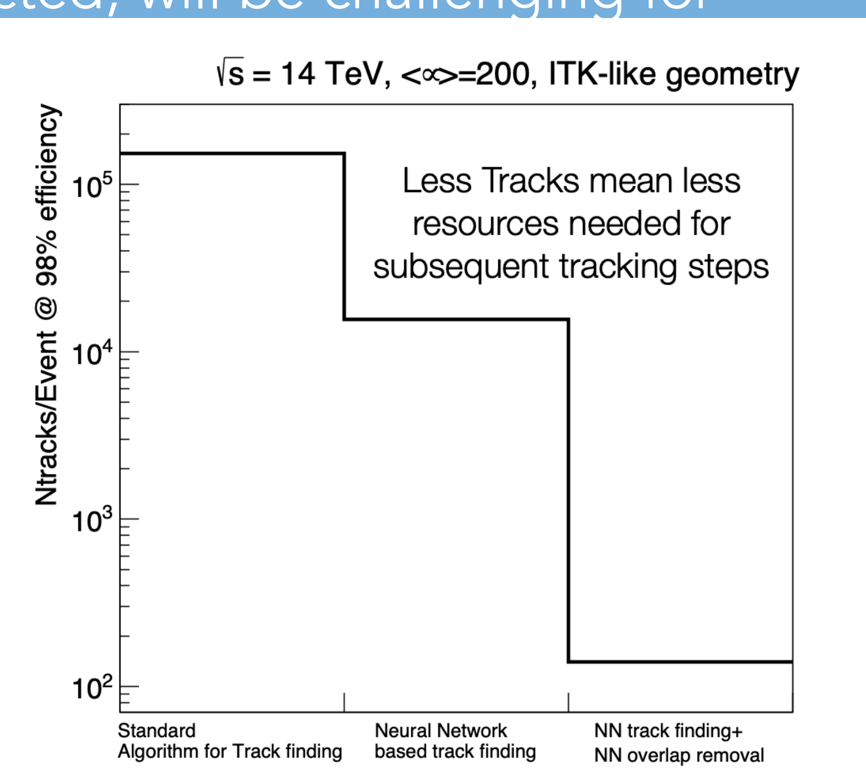






- Low m_{HH} essential to constrain trilinear coupling κ_λ
- Trigger on low p_T events critical at HL-LHC:
- Conditions at the **HL-LHC,** with an average of 200 simultaneous collisions (pile-up) per bunch crossing expected, will be challenging for experiments

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



"Real-time particle tracking with Deep Learning on FPGAs" (LDRD-19-027): Developed new tracking algorithms using ML algorithms

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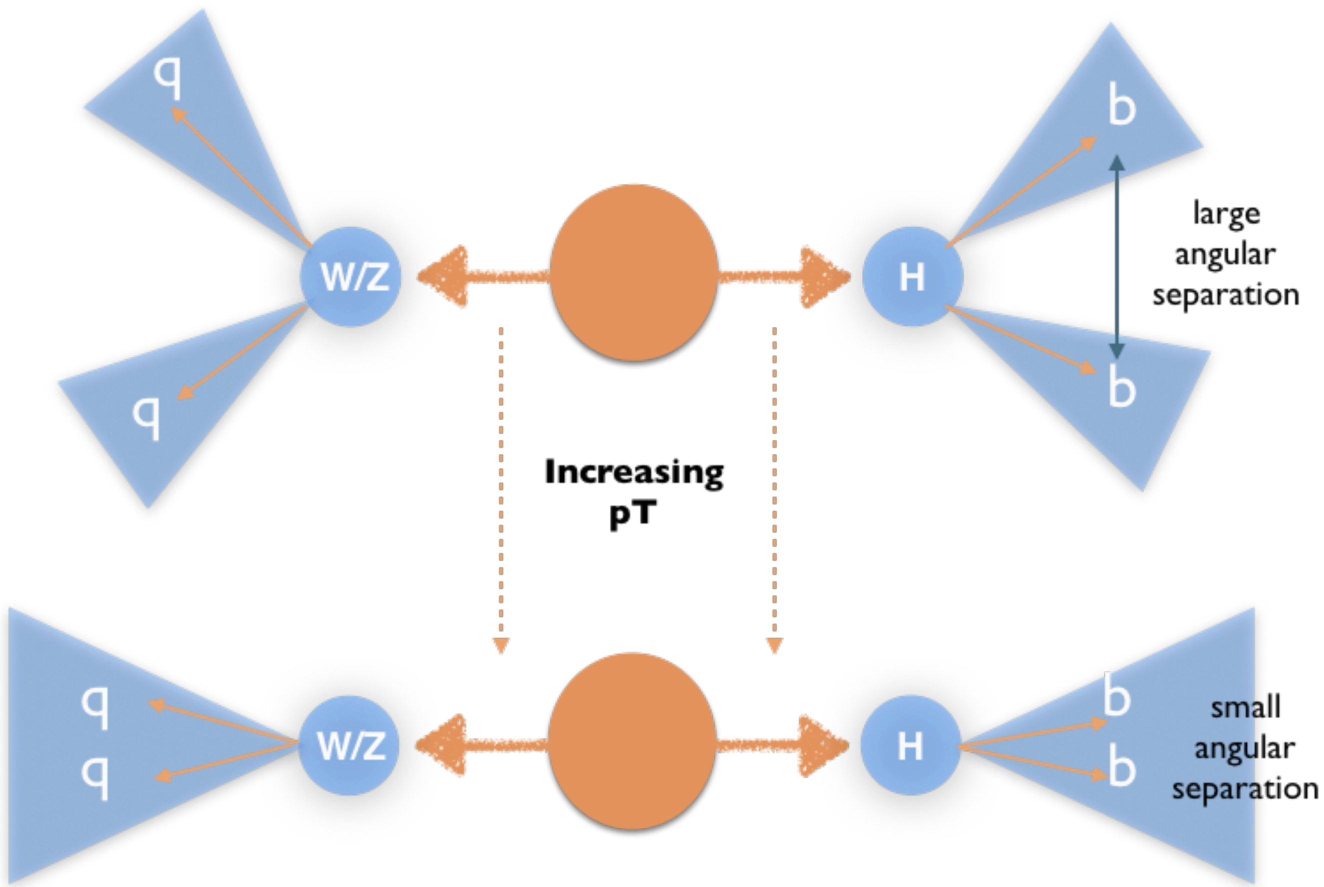
backup

Reconstructing boson decays



- **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

Distinguishing signal from 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

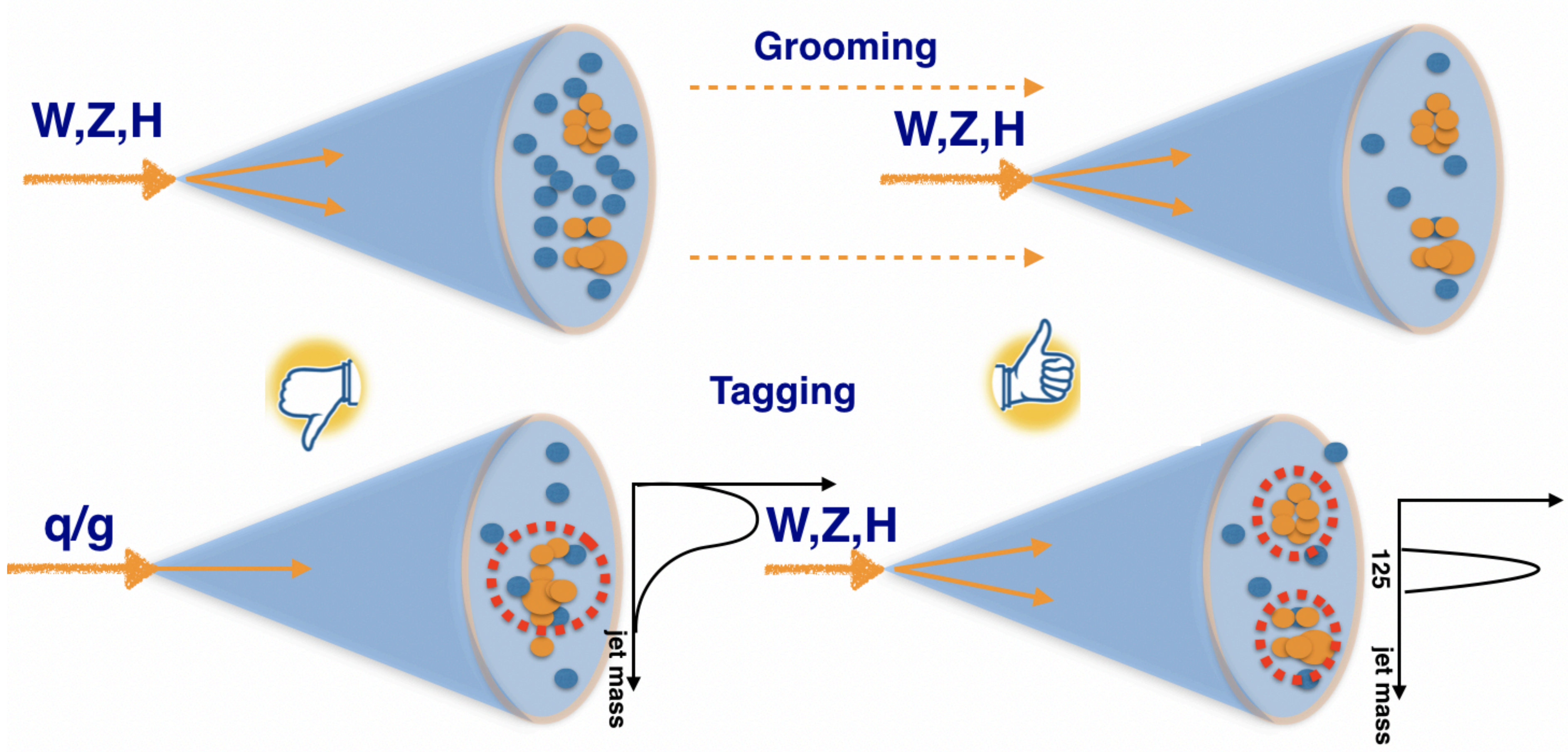
QCD jets

- 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

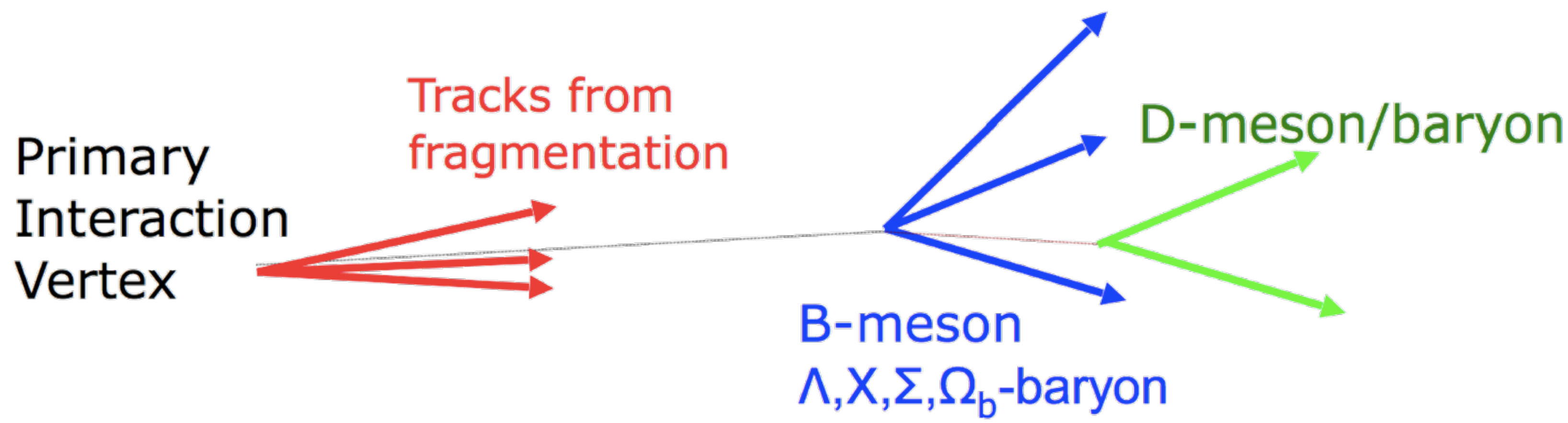
At very high mass the two narrow regions from the boson decay will start to overlap in the detector. New algorithms needed!

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



H->bb 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:

$$L = \beta\gamma c\tau = (\frac{p}{m})c\tau \sim 3\text{mm}$$

Measurable displace vertex!

- |Vcb| >> |Vub| → most b-hadrons decay to c-hadrons
  – c-hadron τ~0.4 – 1.0 x 10^{-12} s → tertiary vertex in b-hadron decay chain
- Approximately 40% of b-hadron decays are semi-leptonic
  – ~10% (b→l) directly and ~10% (b→c→l), where l=e,μ
- Use all this information to design b-taggers!

H->bb tagging

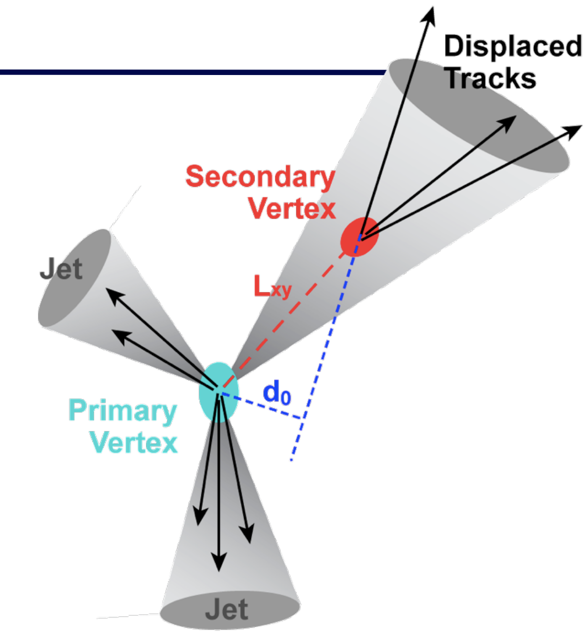
B-tagging Algorithms: Lifetime based

– Impact parameter algorithm

Exploit (in)compatibility of track with PV

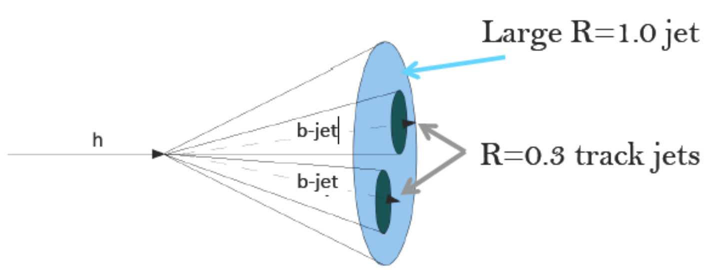
– Inclusive Secondary vertex algorithm

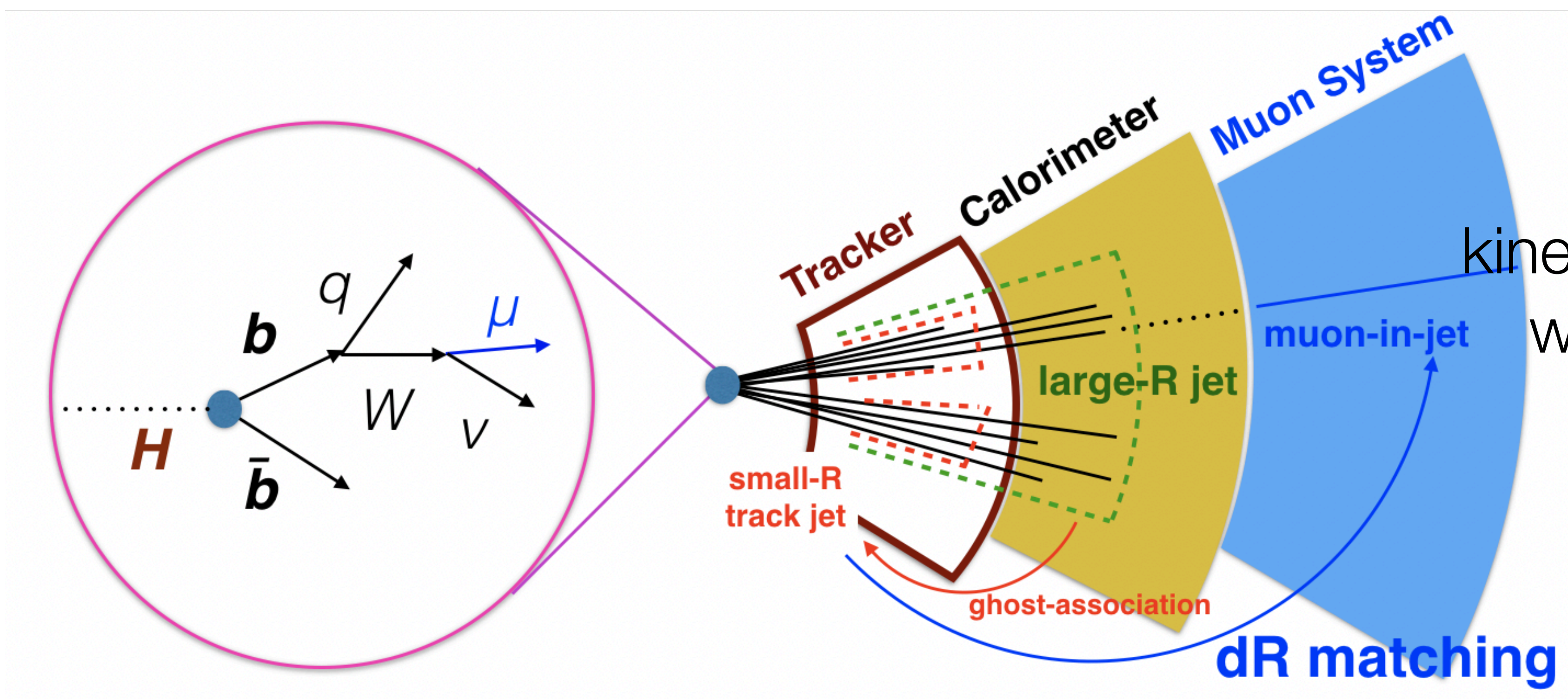
Determination of single inclusive weak b-hadron decay vertex



- Lepton-ID based
- MVA combinations

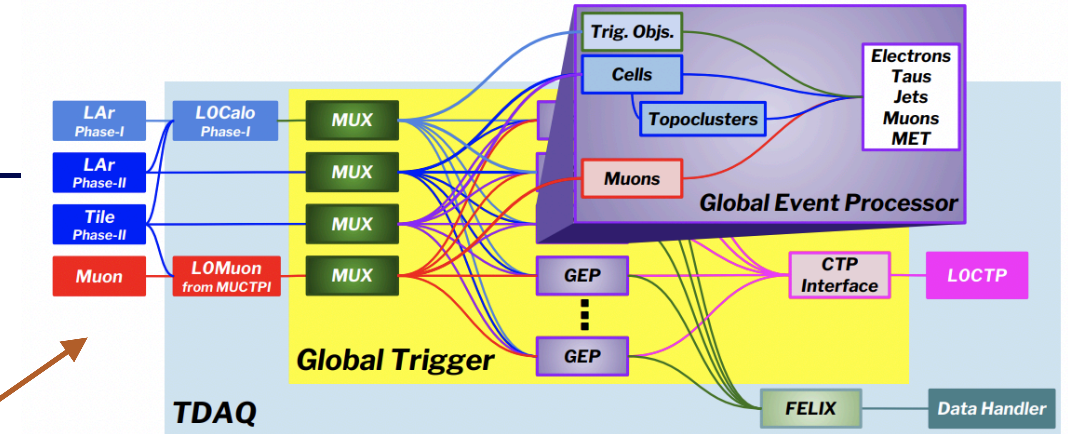
- Large Rjets:
  - **Tag small (R=0.3 or 0.2) jets made of tracks** (charged particles)



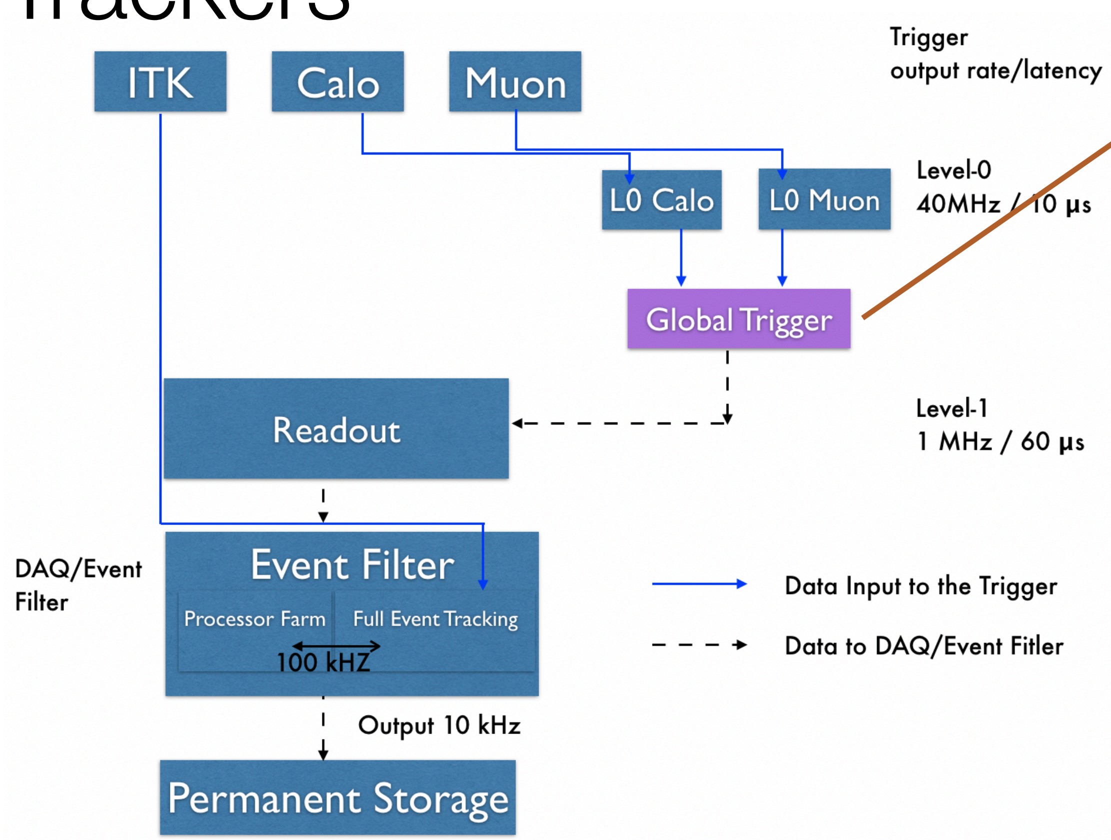


Can we do better? ==>
Exploit the whole H->bb kinematic especially at high mass with a multivariate technique

Trigger



Trackers



The main risk with the proposed structure is due to the uncertainty in the projected trigger rates for hadronic objects at μ =200

- Particularly affected are the rates for E^{miss} triggers and jet triggers, for which the thresholds are expected to be even higher than the current ones.
- This can be mitigated by adding a hardware-level trigger that uses regional tracks built from the tracking detector and sends the information to the Global Trigger ==> in the plans but not ATLAS approved
- This would open up the possibility for a rudimentary primary vertex selection, allowing for additional hadronic background rejection and b-tagging
- Link to Laboratory Directed Research and Development (LDRD) grant to study real-time tracking using Machine Learning techniques. The first year (FY19) is dedicated to performance studies to assess the feasibility of doing tracking at μs latencies (first level of Trigger) for HL-LHC.

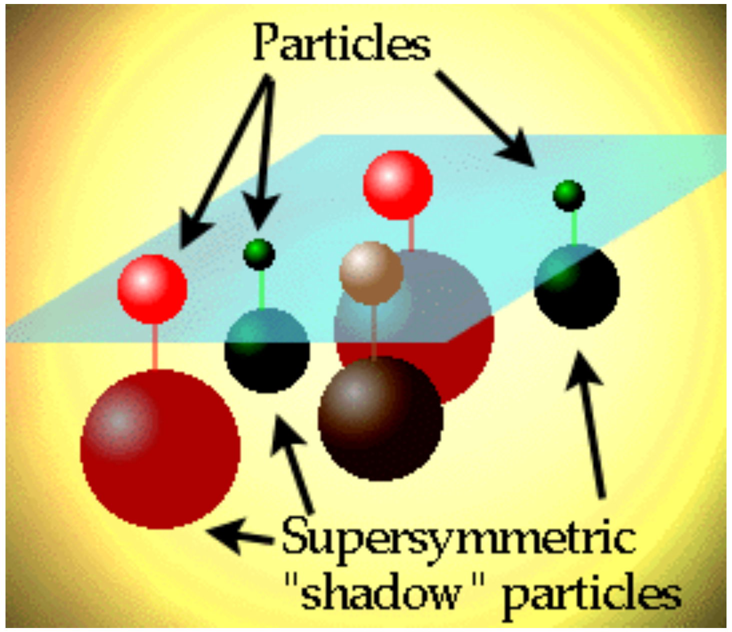
Many tracks (of charged particles) to find in a short time > 60 M/s:

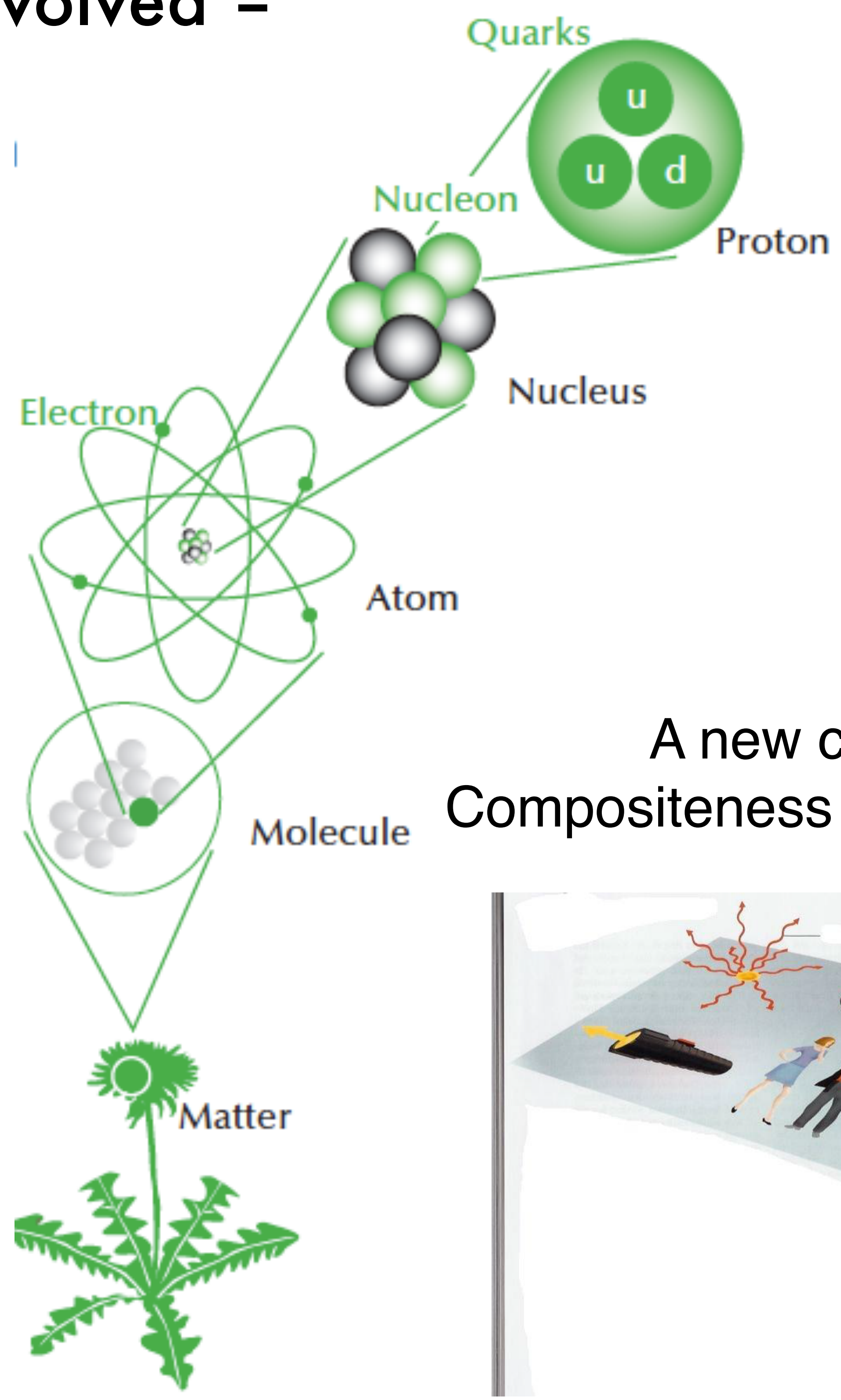
Need Hardware Track Finding

Two grand ideas

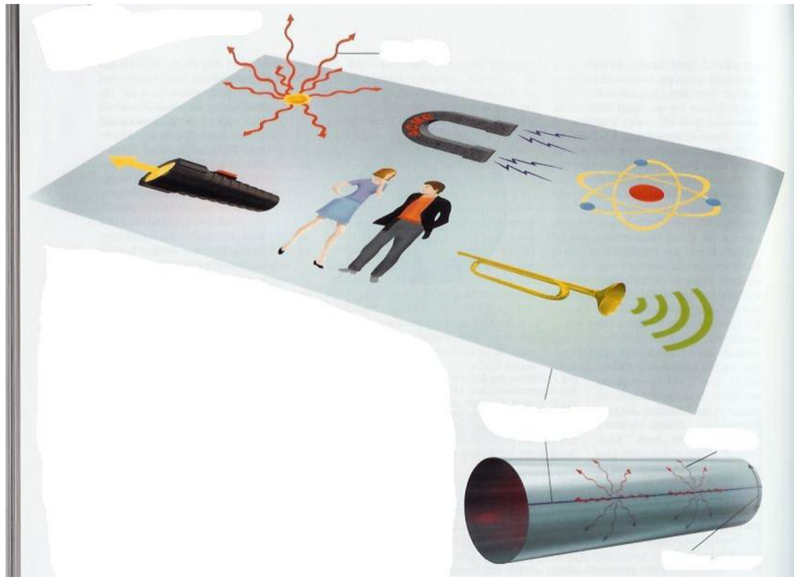
Two very different scales involved – hierarchy problem

A new symmetry





A new cut-off scale:
Compositeness or extra dimensions

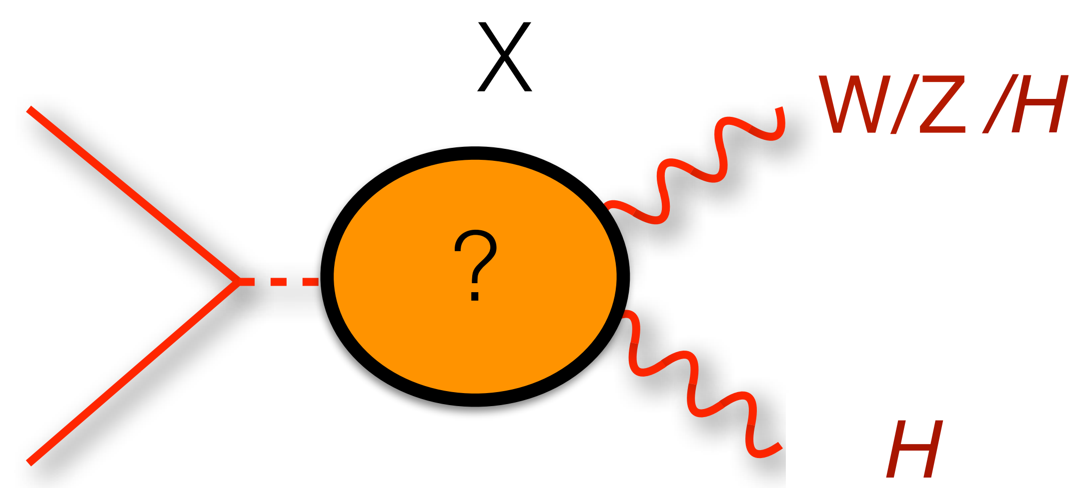


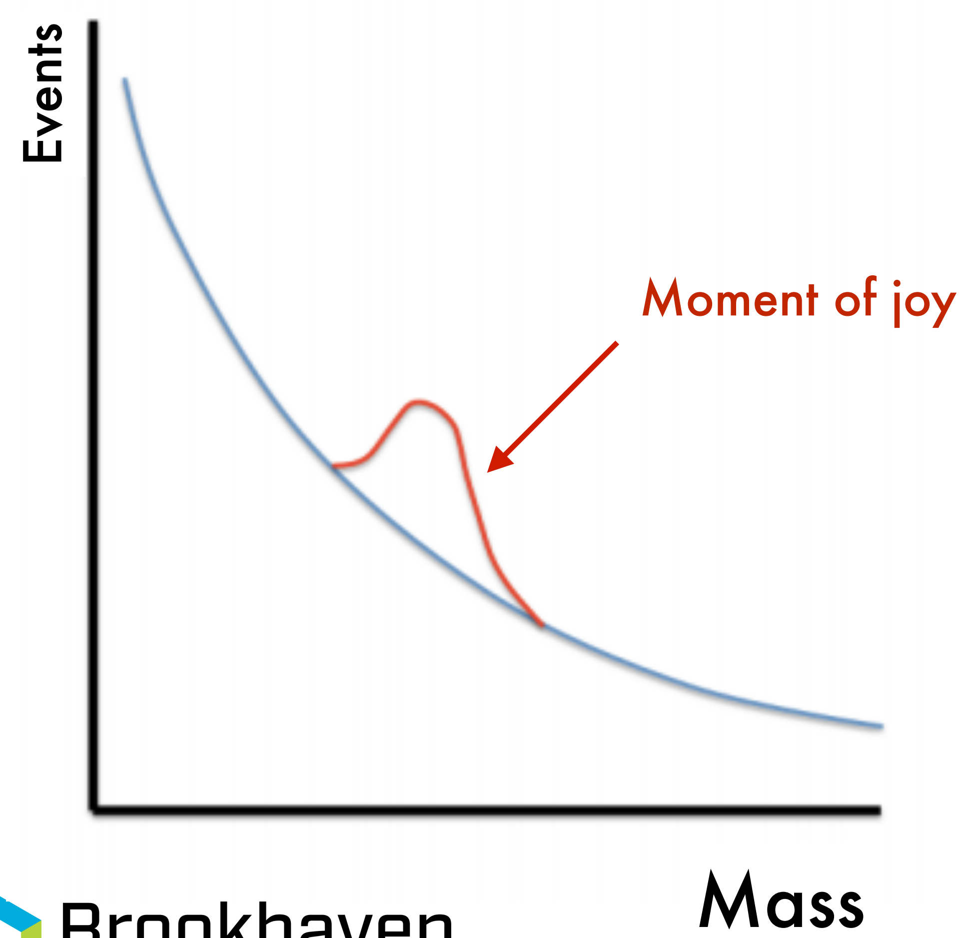
Higgs as a tool for discovery

- Many extension of the Standard Model predict new particles decaying into pair of bosons

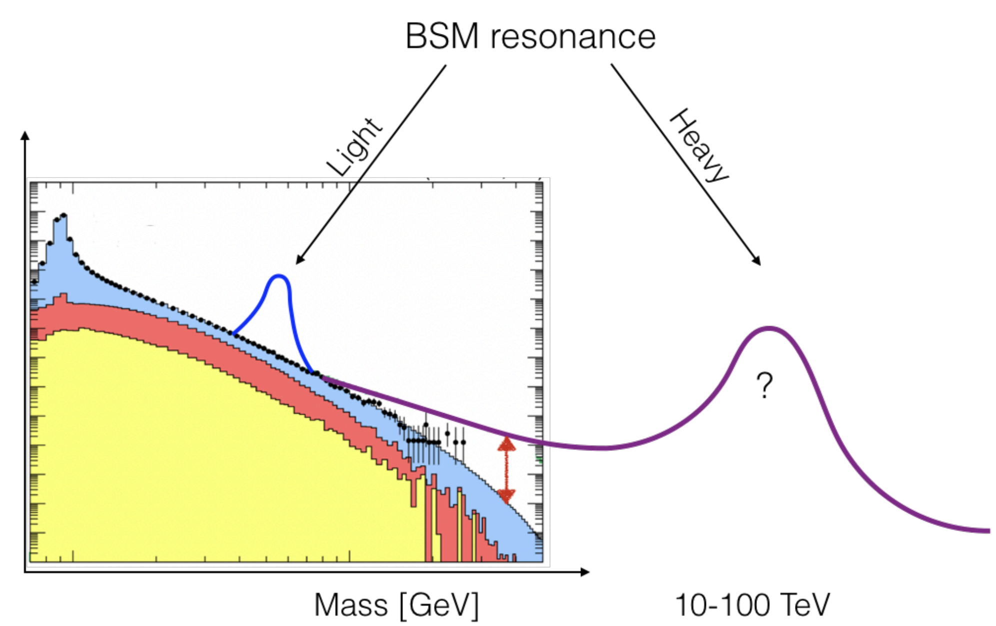
Searches for new resonances decaying into pairs of bosons

- **Look for a peak on a smooth background**





- While the presence of resonances is the most dramatic signal for new phenomena, they may be too heavy or broad to be clearly seen at the LHC.



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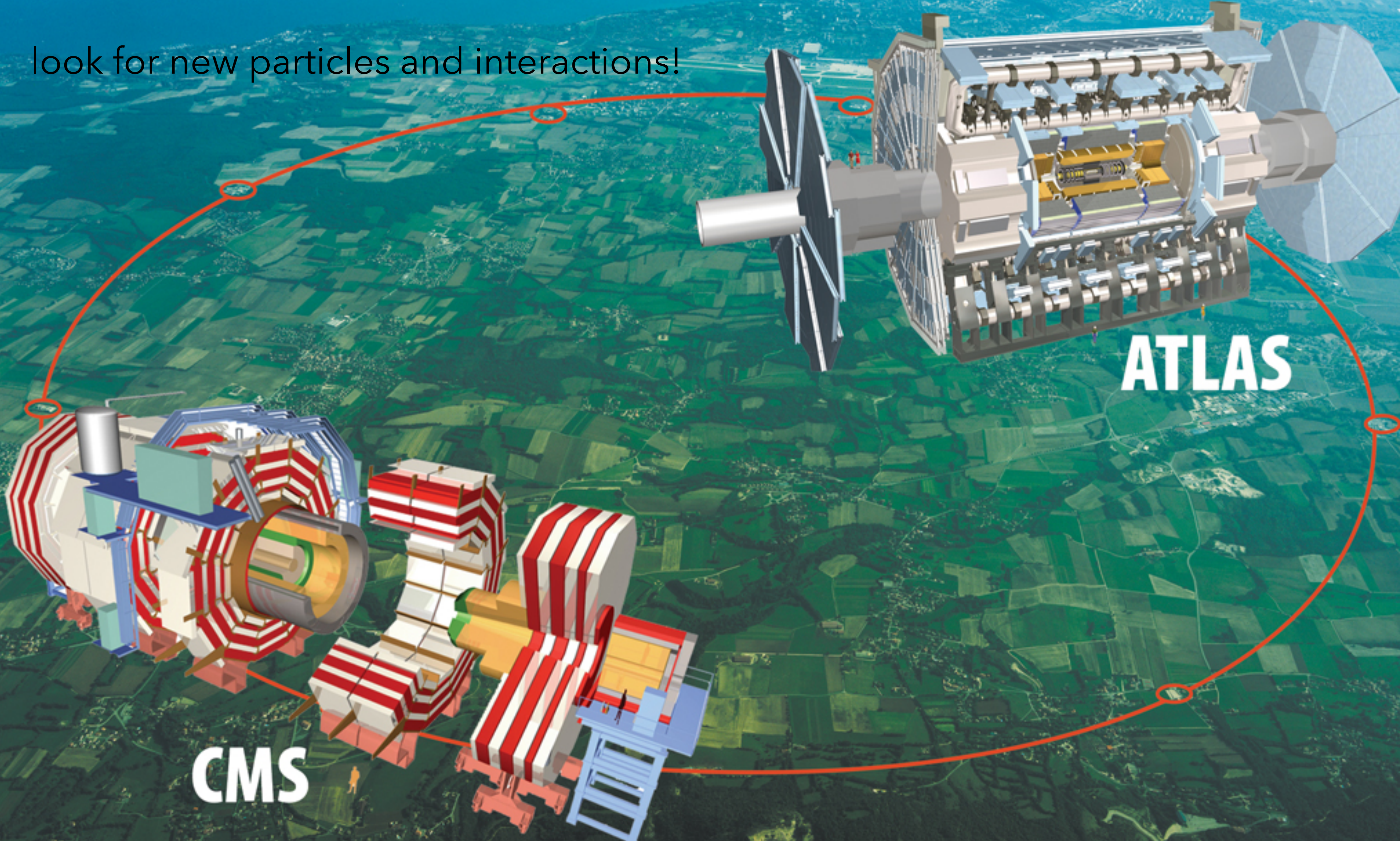
LHC and ATLAS/CMS

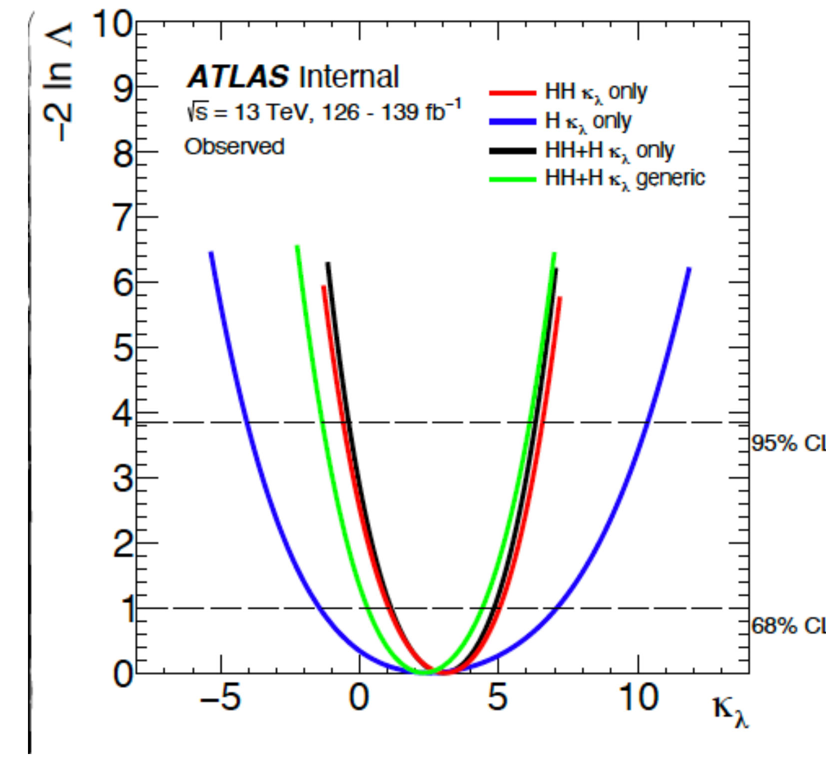
- proton-proton collision at 13 TeV
- 2 multipurpose experiments: CMS and ATLAS. 2 detectors that look for specific phenomena: LHCb and ALICE
  - look for new particles and interactions!

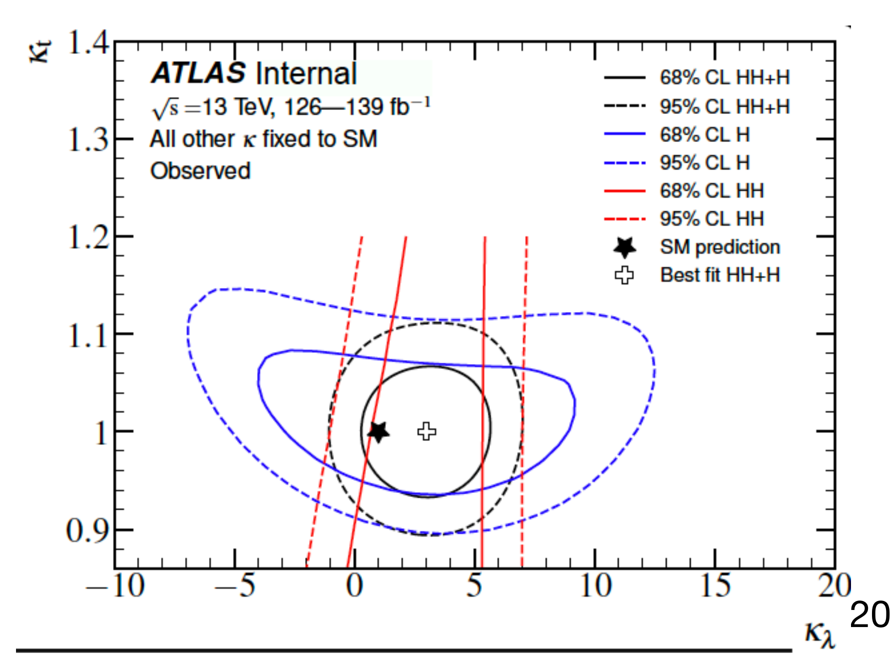


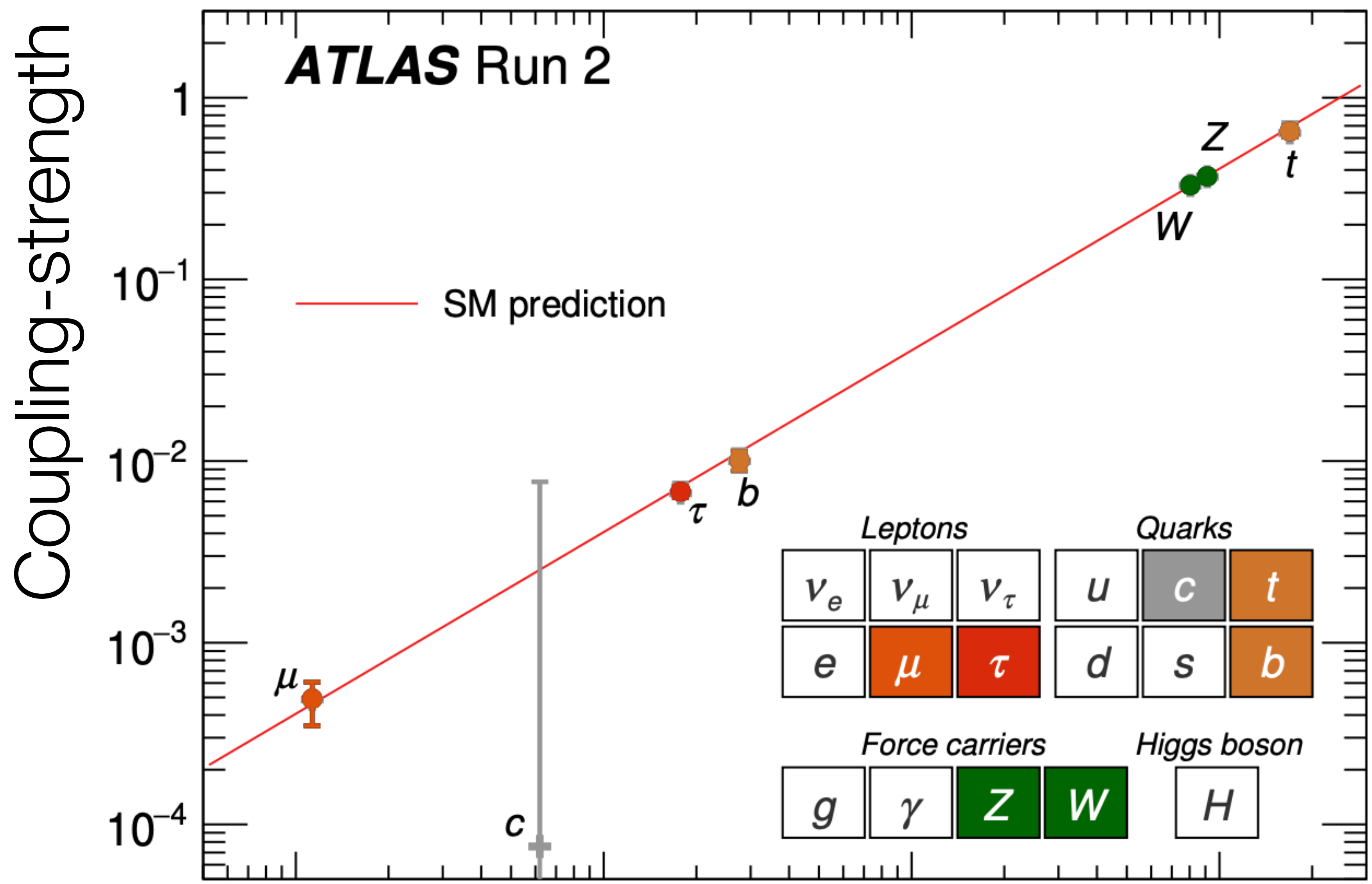
H+HH combination

- λ_{HHH} contributes to single-Higgs at NLO EW corrections (indirect constrain)
- H+HH combination provides the most stringent constraints
  - Exp only confidence interval is 5% better than HH (most sensitive), 78% better than H
- Assumption on κ_t can be relaxed w/o losing sensitivity κ_λ
- More generic model (all coupling modifiers floating) with less model dependences is investigated and still gives strong constraints

Channel		Integrated luminosity (fb^{-1})
$HH \to b\bar{b}\gamma\gamma$	($ggFHH$, $VBFHH$)	139
$HH \to b\bar{b}\tau\bar{\tau}$	($ggFHH$, $VBFHH$)	139
$HH \to b\bar{b}b\bar{b}$	($ggFHH$, $VBFHH$)	126
$H \to \gamma\gamma$	(all production modes)	139
$H \to ZZ^{(*)} \to 4\ell$	(all production modes)	139
$H \to \tau^+\tau^-$	(all production modes)	139
$H \to WW^*$	(ggF,VBF)	139
$H \to b\bar{b}$	(VH)	139
$H \to b\bar{b}$	(VBF)	126
$H \to b\bar{b}$	($t\bar{t}H$)	139

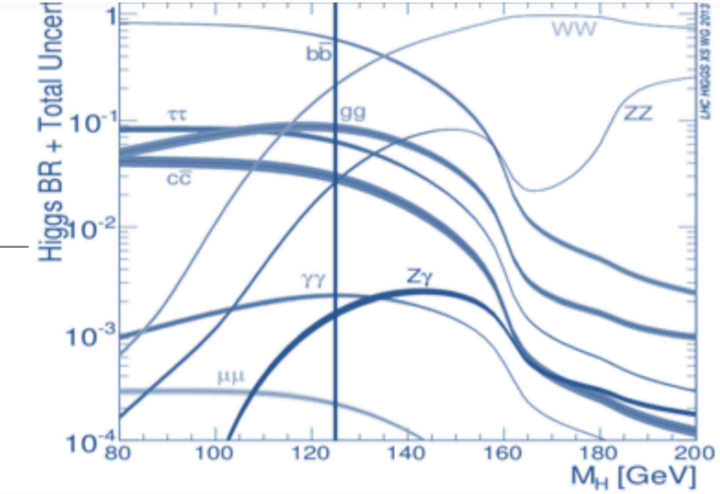




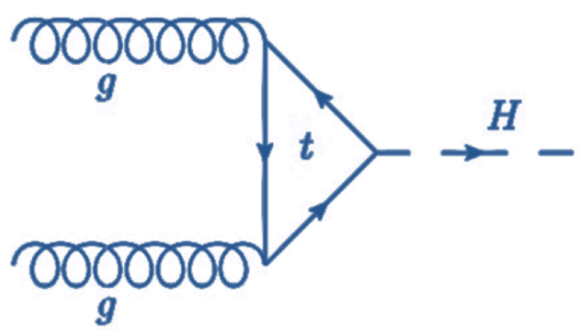


Particle Mass [GeV]

Higgs boson production at the LHC

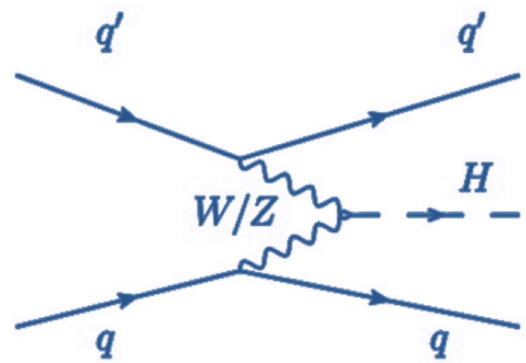


Gluon Fusion



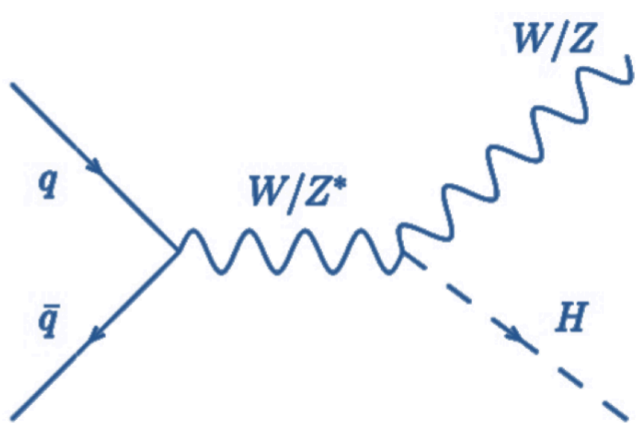
$\sigma_{H,ggF}$ ~ 49 pb

Vector Boson Fusion



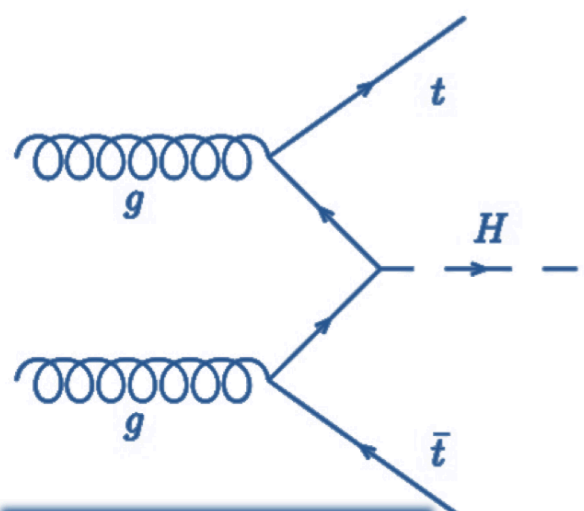
σ_{VBF}~ 3.8 pb

Higgs-Strahlung

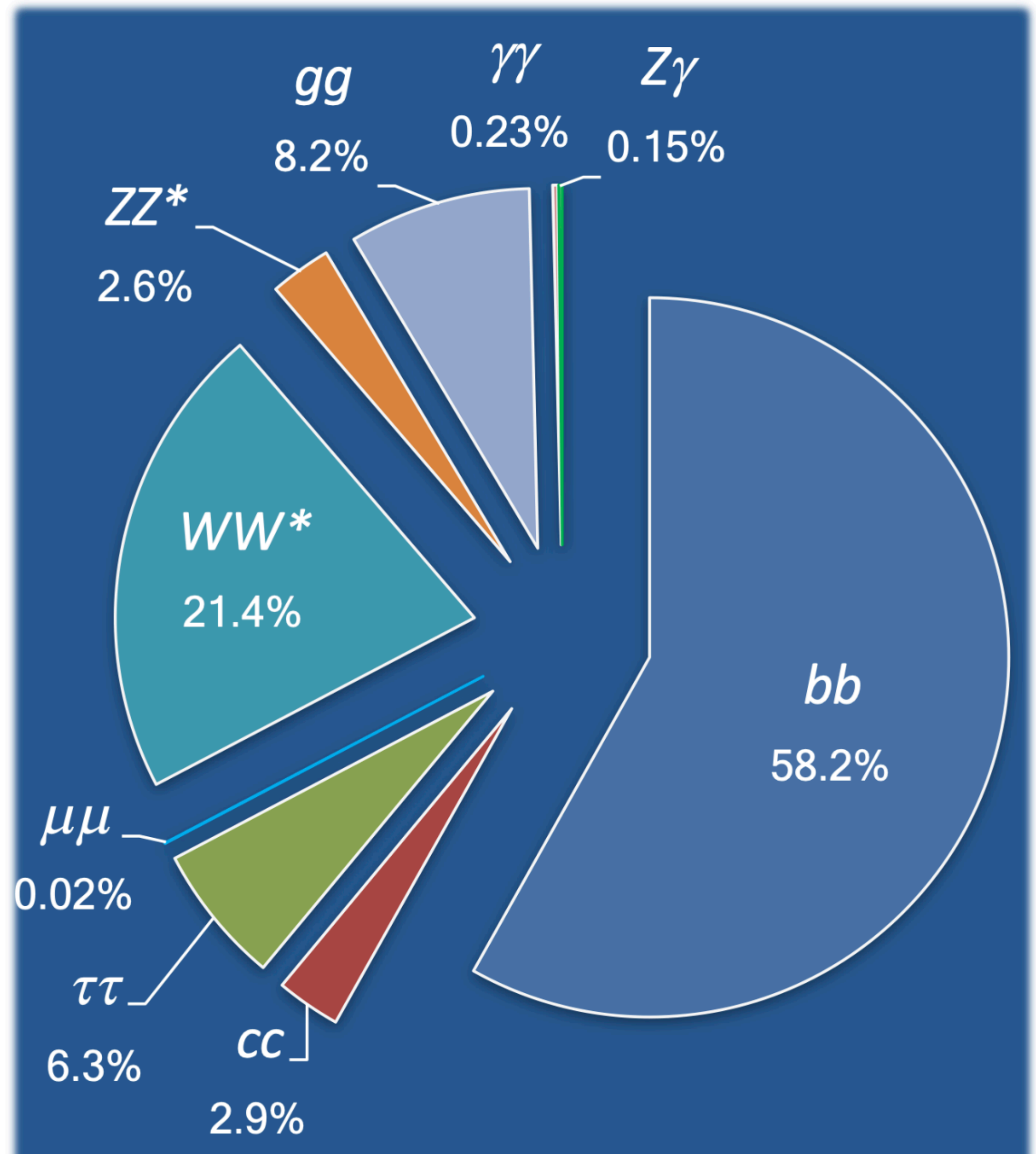


$\sigma_{W/Z+H}$ ~ 1.4/0.9 pb

ttH Production



σ_{ttH} ~ 0.5 pb



Note, we typically provide experimental results in terms of: $\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{obs}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$

μ=1 (if observation agrees with Standard Model, SM)