Research at the energy frontier

(with the ATLAS detector)

A tiny selected sliver of topics that my group works on

Jahred Adelman

A (long) historical view of particle physics

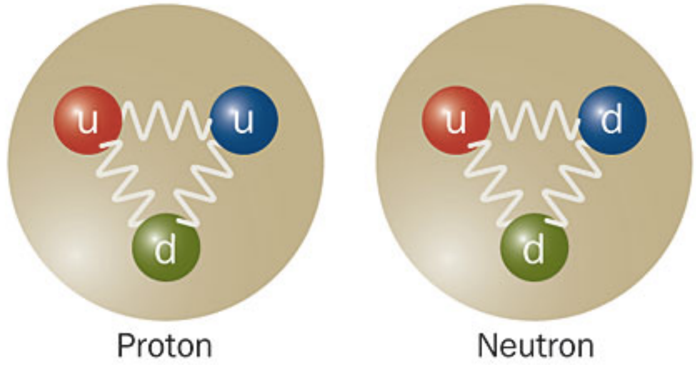
Ancient Greeks (atomists): Everything in the world can be broken down into basic building blocks of matter (atoms) that we might call "fundamental particles" these days

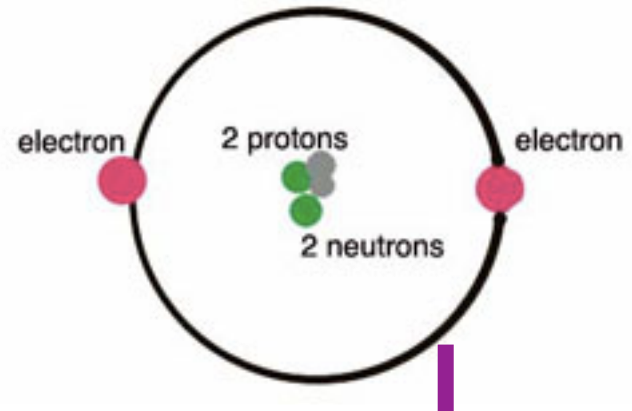
Democritus: "Nothing exists except atoms and empty space, everything else is opinion."

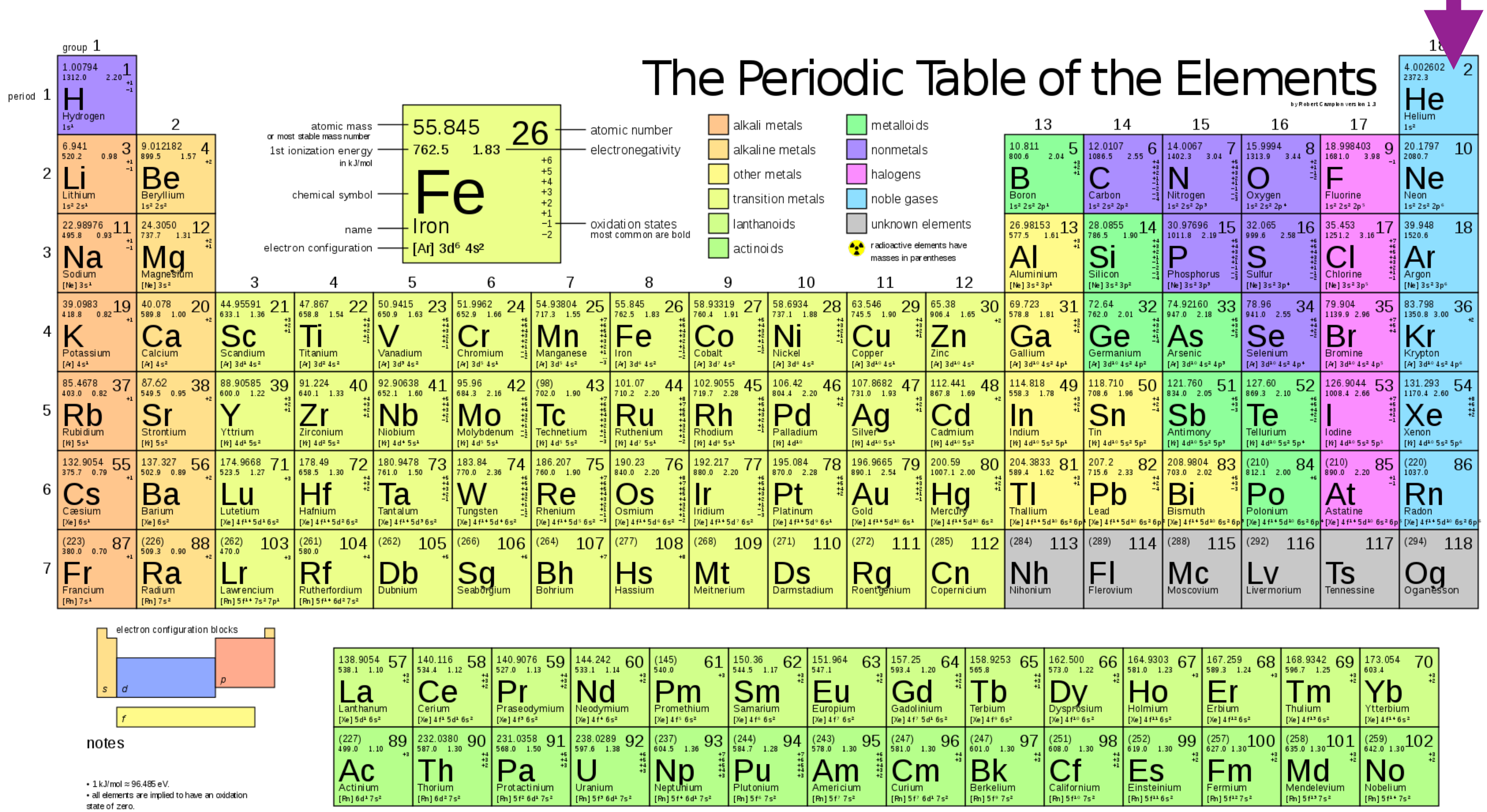
Conclusion: Faculty members know something about everything else

Democritus: "Nothing exists except atoms and empty space, everything else is opinion."

Atoms: Not fundamental objects!







How do we study the makeup of an object?

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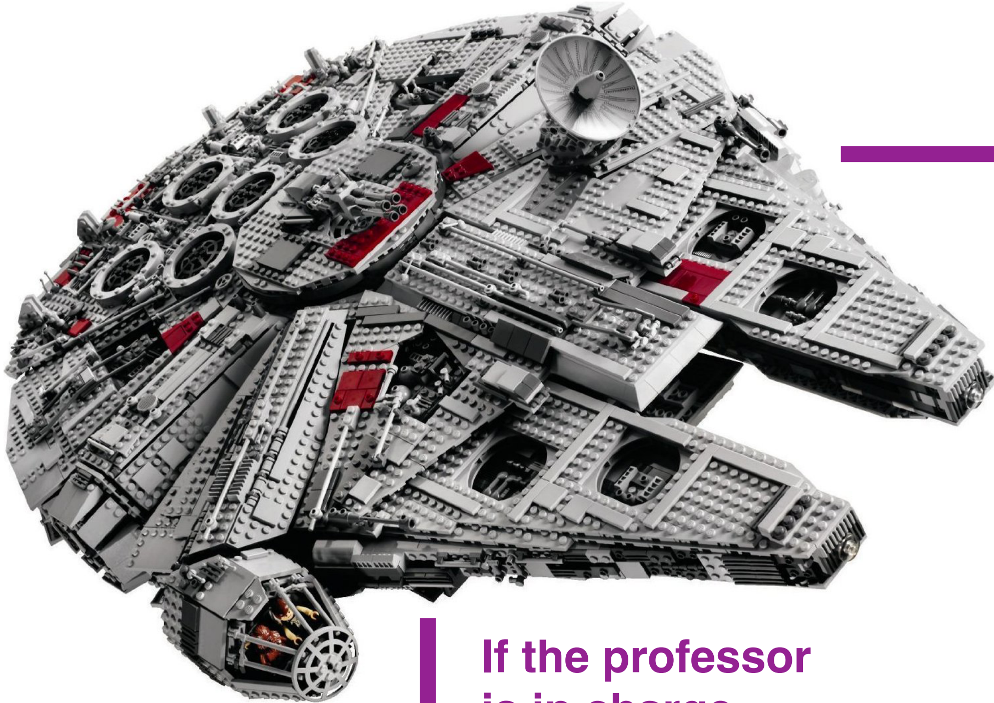
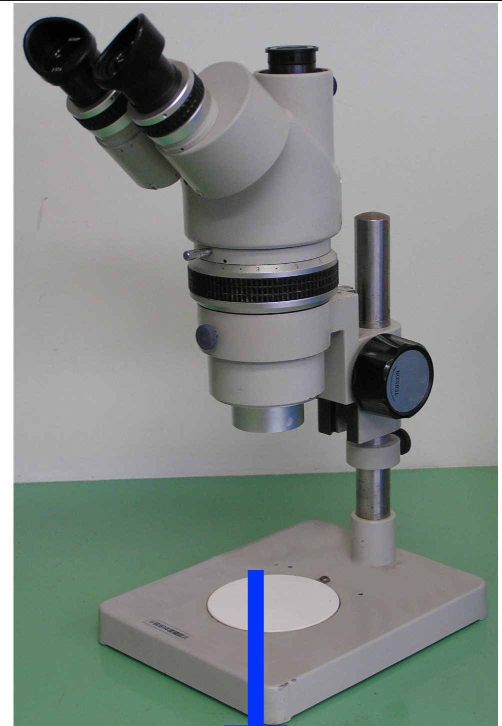


If the professor is in charge

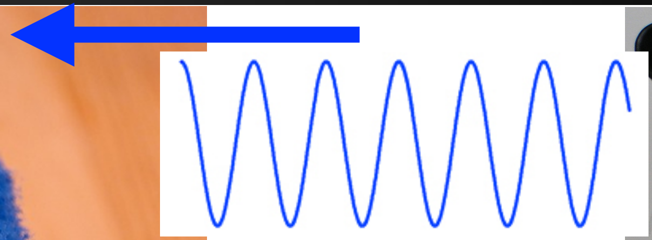
If funding allows

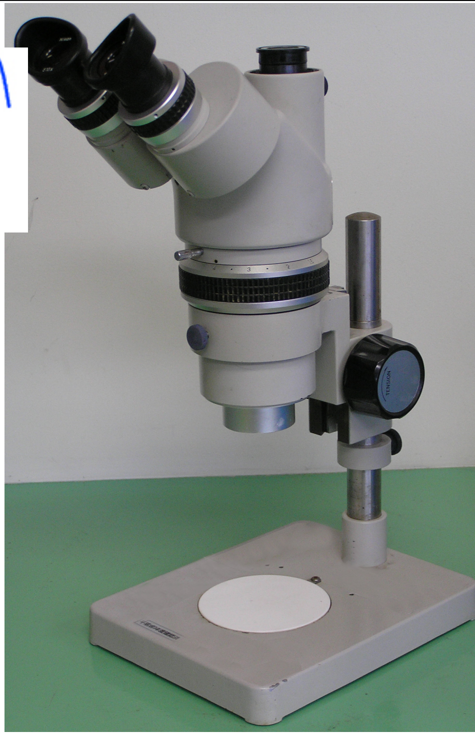
How to study small objects?

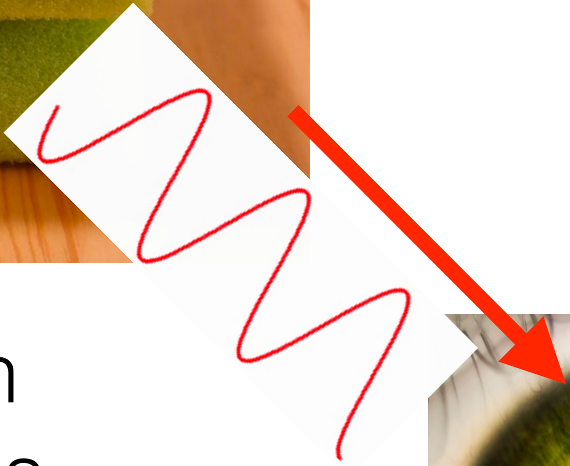
How to study small objects?



How does the microscope work?

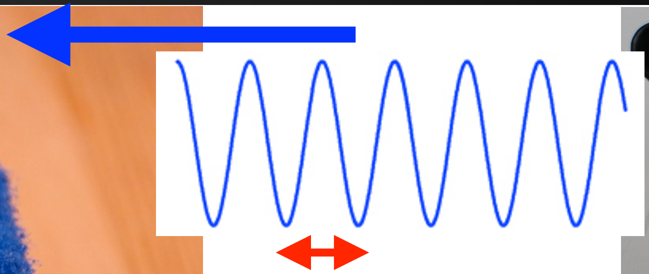


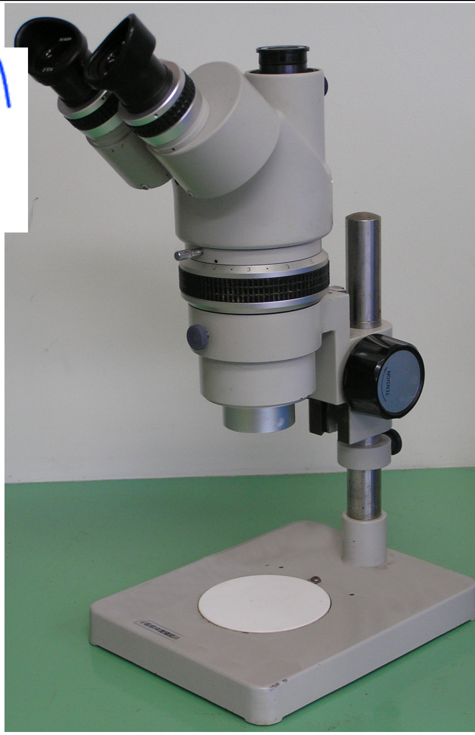




Shine light on an object. It bounces back and hits a sensor (your eye is a type of sensor)

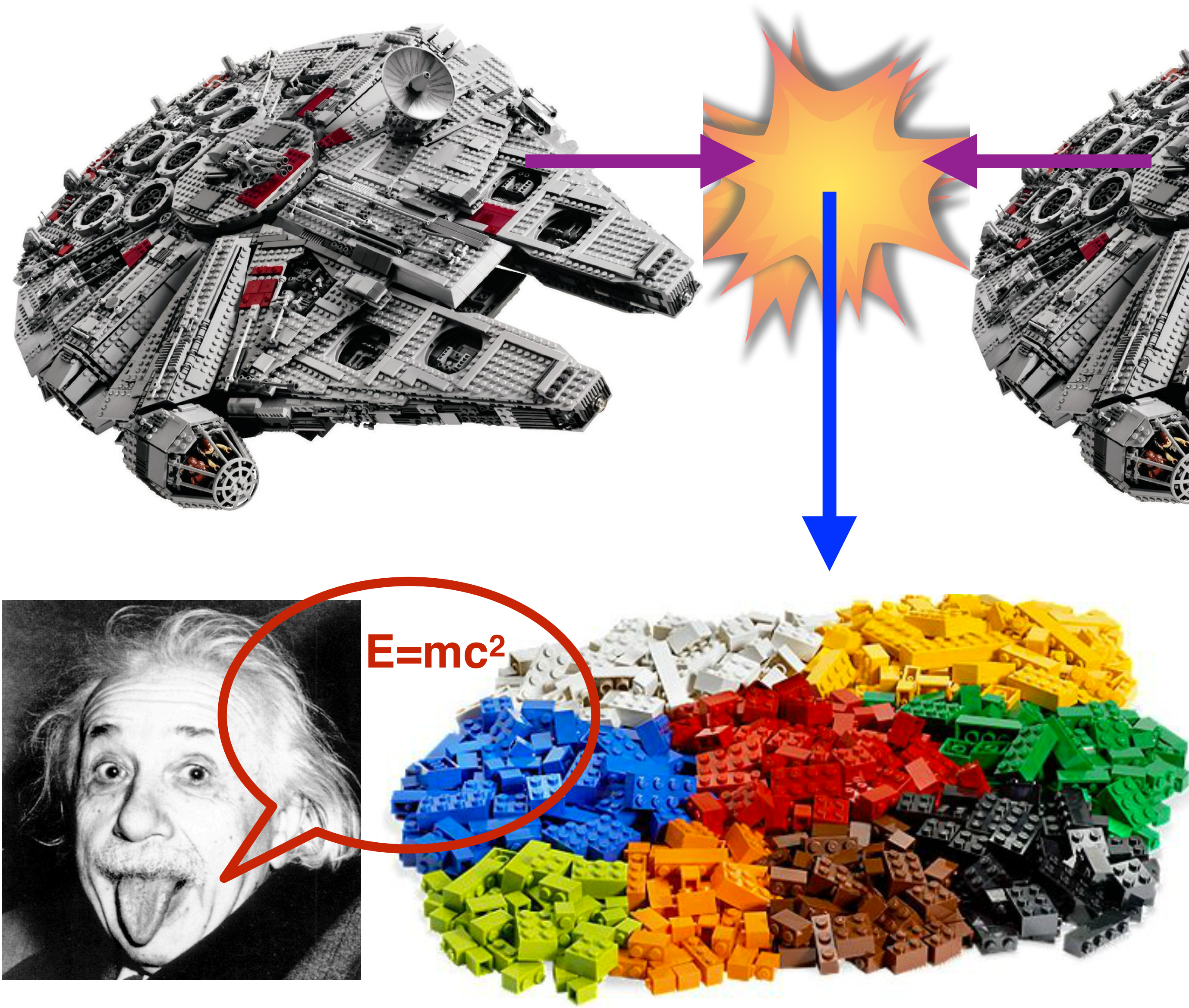
How does the microscope work?





BUT … we can’t distinguish things smaller than the wavelength of light that we use!

So we get back to the hammer approach



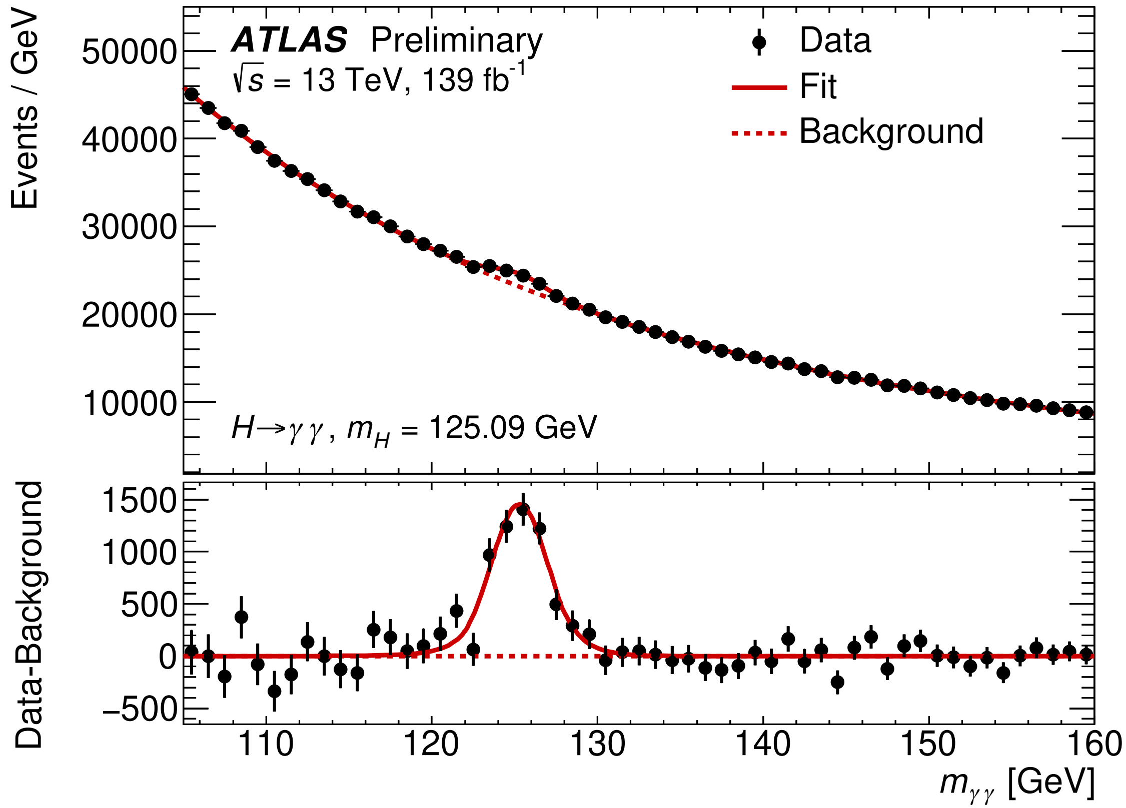
Put enough energy in a tiny space and Einstein tells us that we can make new types of matter

Smash things together and watch what comes out!

Peter Higgs receiving the Nobel Prize 1 year after the 2012 Higgs-dependence day announcement

ATLAS $h \to \gamma\gamma$ these days

arXiv:1802.04146

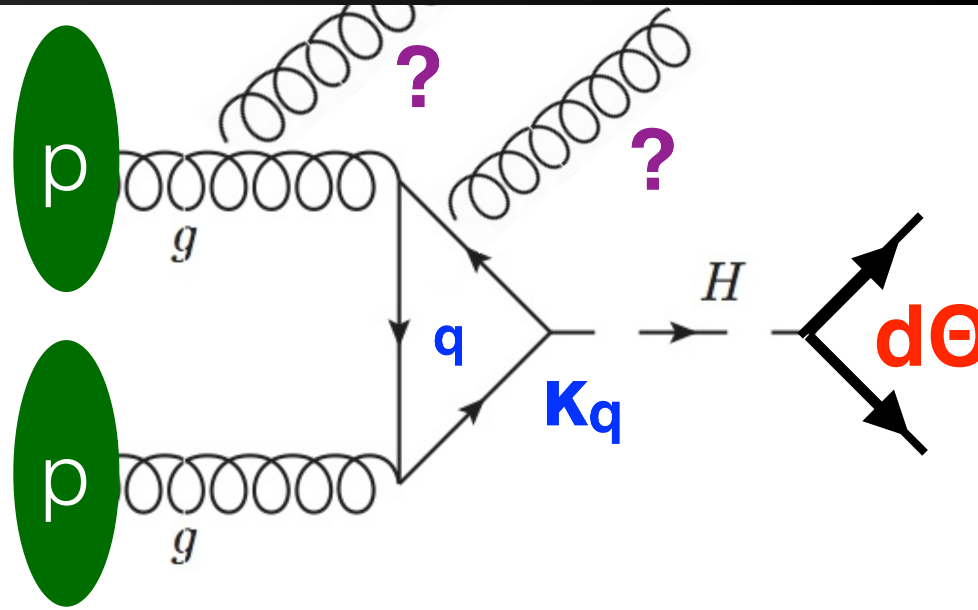


Can clearly see diphoton mass bump on top of large background in this big data set!

Challenge is knowing that you have modeled the background correctly

Higgs Boson differential cross sections - why?

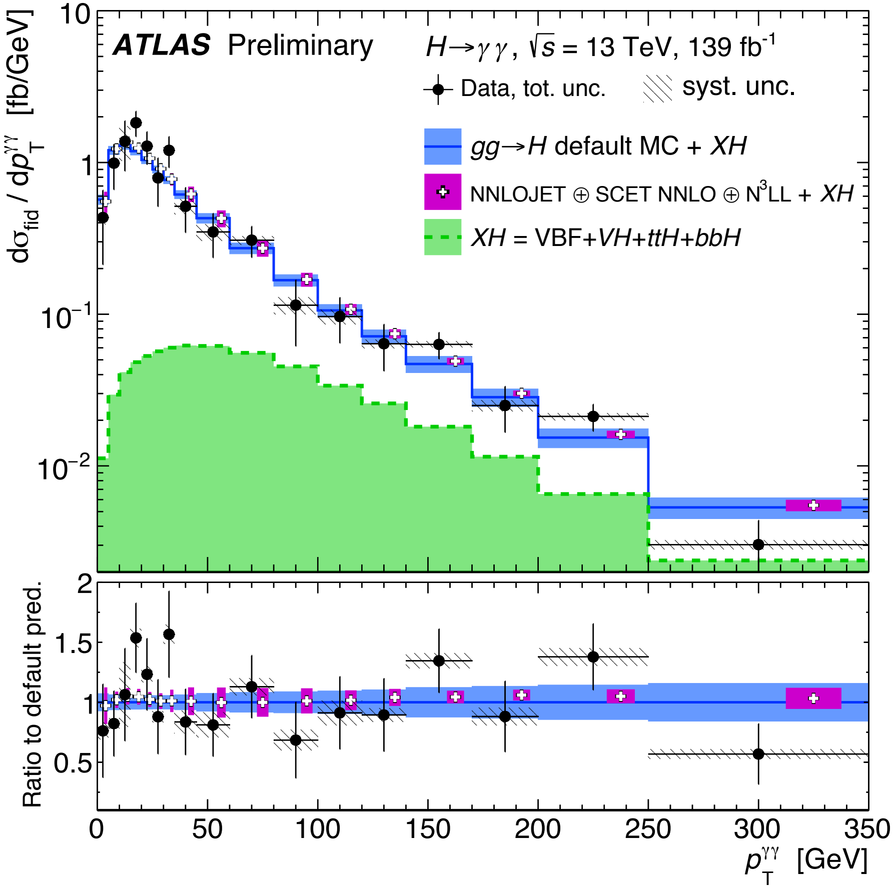
- $p_T(h)$ probes QCD modeling of dominant triangle diagram, including potential new heavy particles in loop
- y(h) sensitive to modeling of Higgs production and partons (quarks + gluons) inside proton
- p_T and rapidity of jets (quarks + gluons) sensitive to Higgs modeling and different production mechanics
- Angular variables sensitive to spin and CP of Higgs

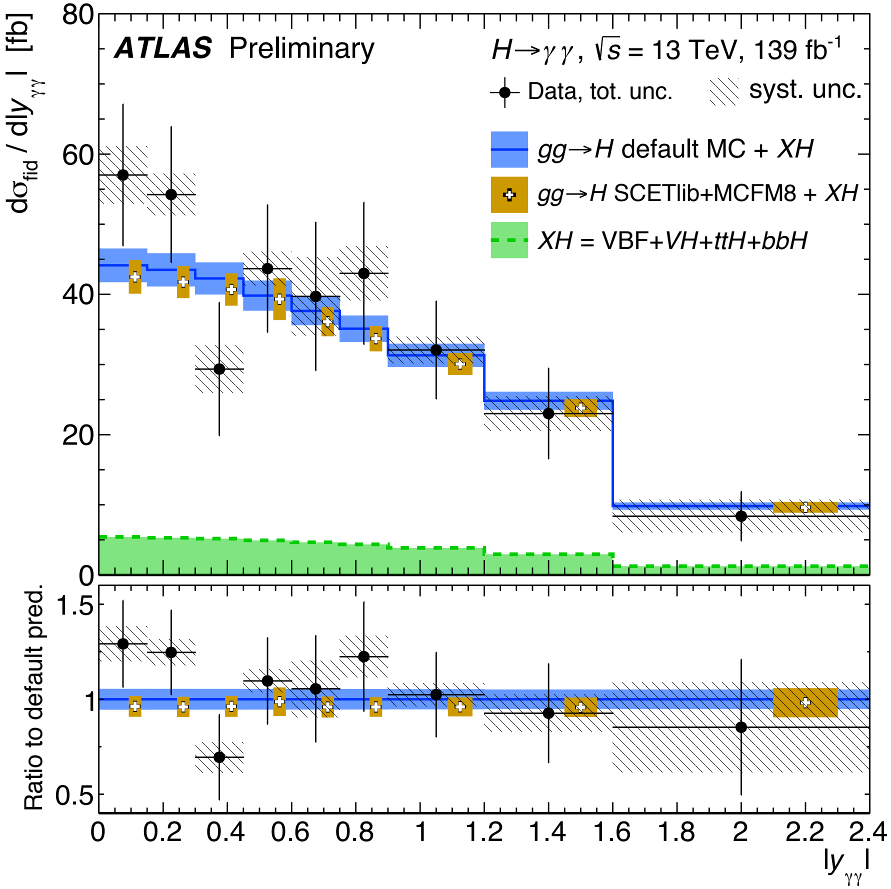


Measure Higgs boson cross sections in bins of various kinematic quantities sensitive to Higgs boson modeling and new physics (Bri has spent a lot of time on this)

ATLAS h→γγ differential

ATLAS-CONF-2019-029





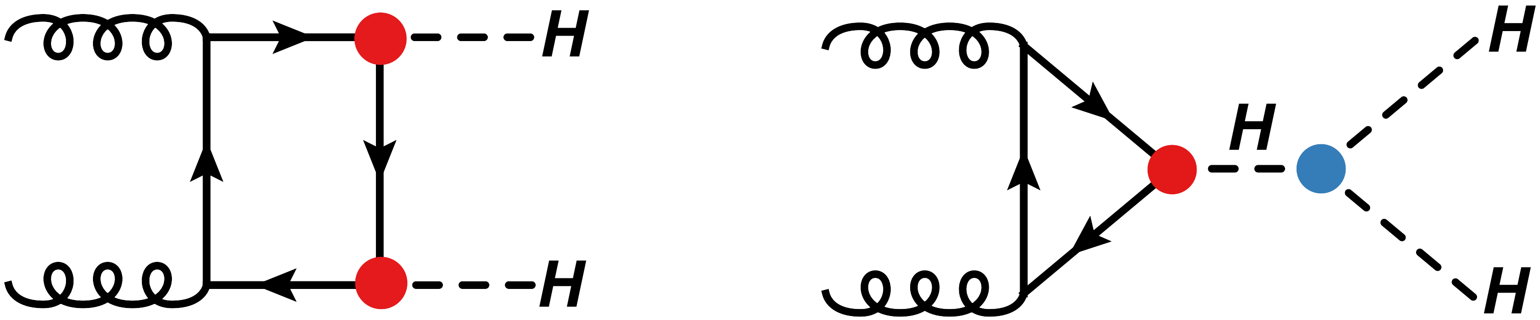
Each of these bins has a diphoton mass fit!

So - you are surrounded ...

Everywhere by a non-zero **Higgs field**! Crazy idea. If we look at electricity and magnetism, the default value of the field is **zero** (this is important!)

Let's pause to think about this

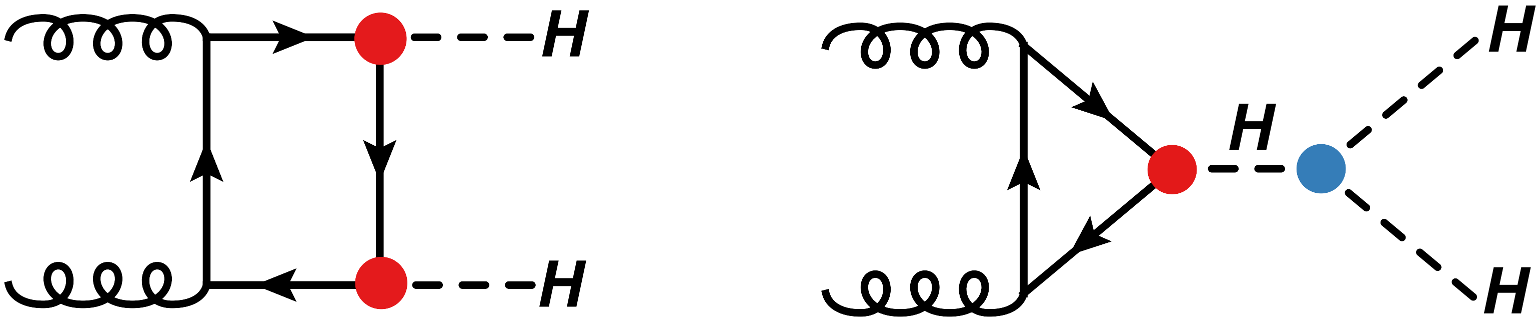
You are surrounded by a non-zero field ...



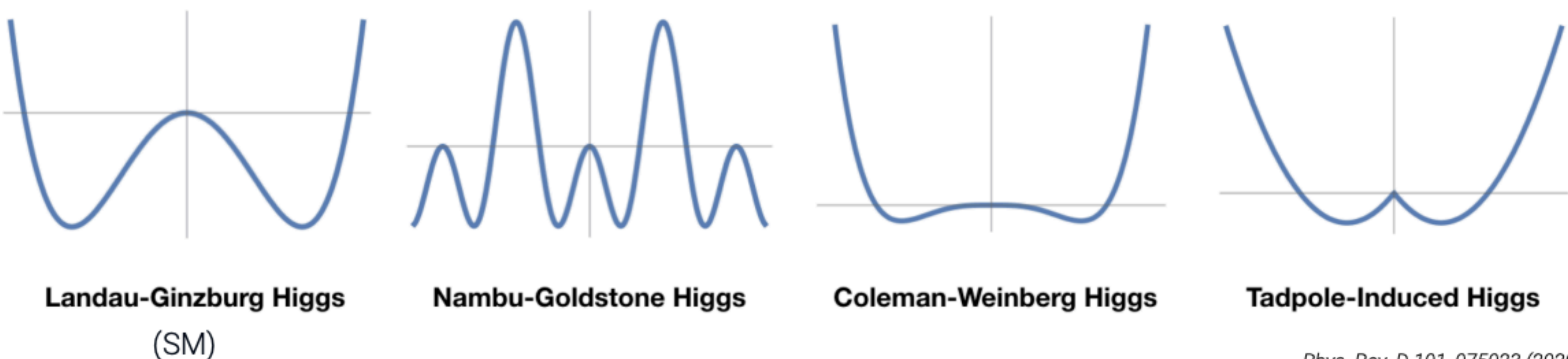
Pair production of Higgs bosons directly probes the Higgs boson-self coupling, electroweak symmetry breaking and also the non-zero vacuum expectation value of the Higgs field!

Problem: The above two diagrams contribute, and only one is of interest. And they interfere destructively

Looking for pair production of Higgs bosons



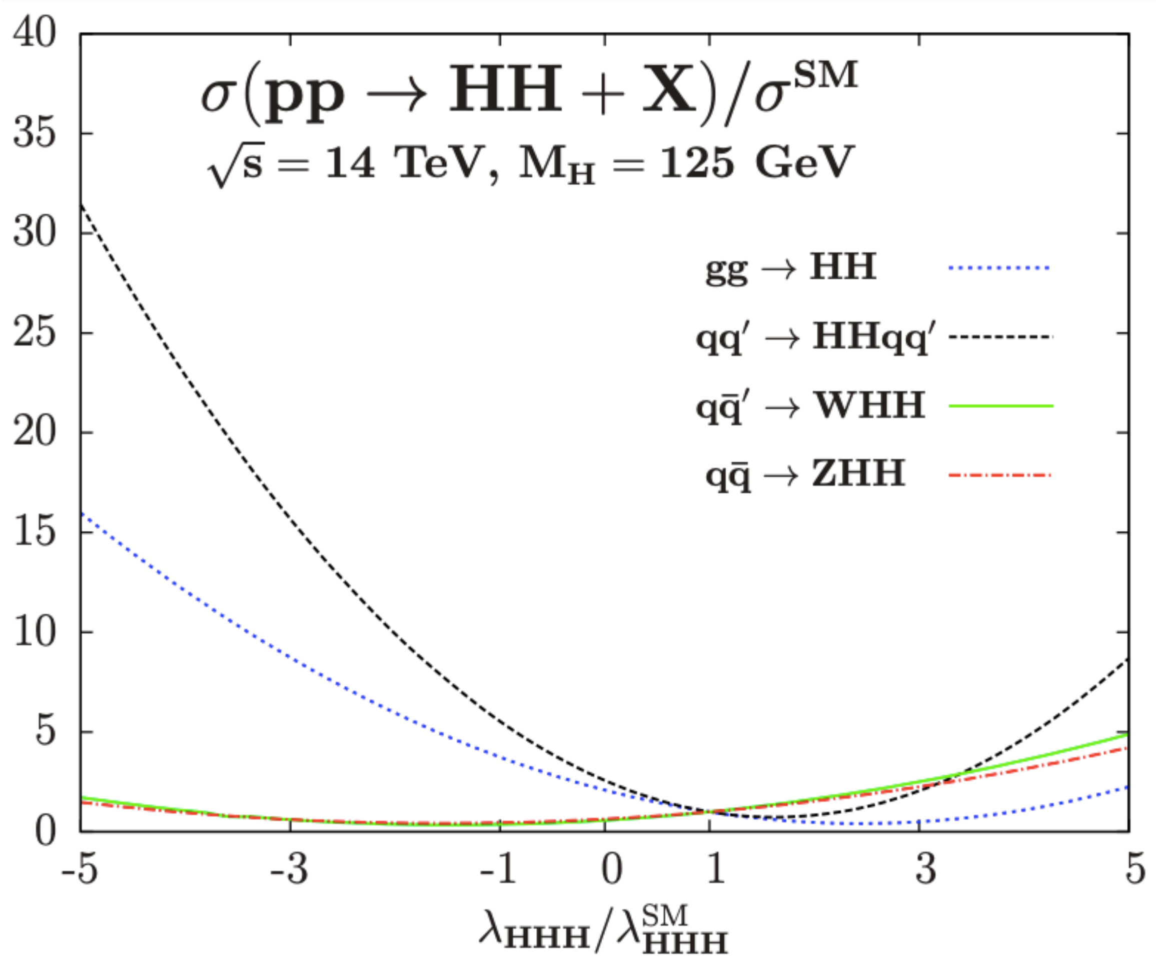
Study Higgs boson self-coupling to understand the Higgs potential shape! (And are we in a stable or metastable minimum?!?!)



Phys. Rev. D 101, 075023 (2020)

What about extensions to the SM?

arXiv:1212.5581 (Baglio et al)

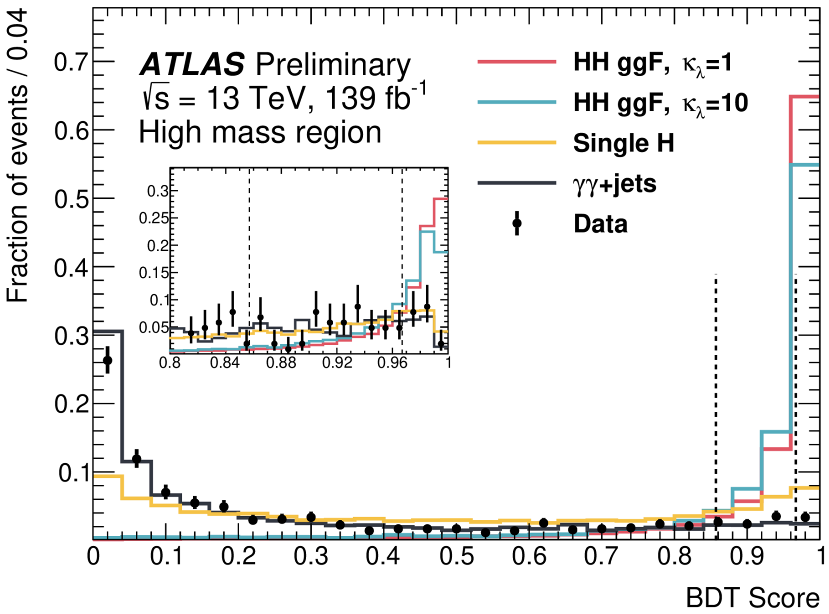


Altered self-coupling can significantly increase hh production rates (as can lots of other beyond Standard Model physics)

Looking for hh→bbγγ

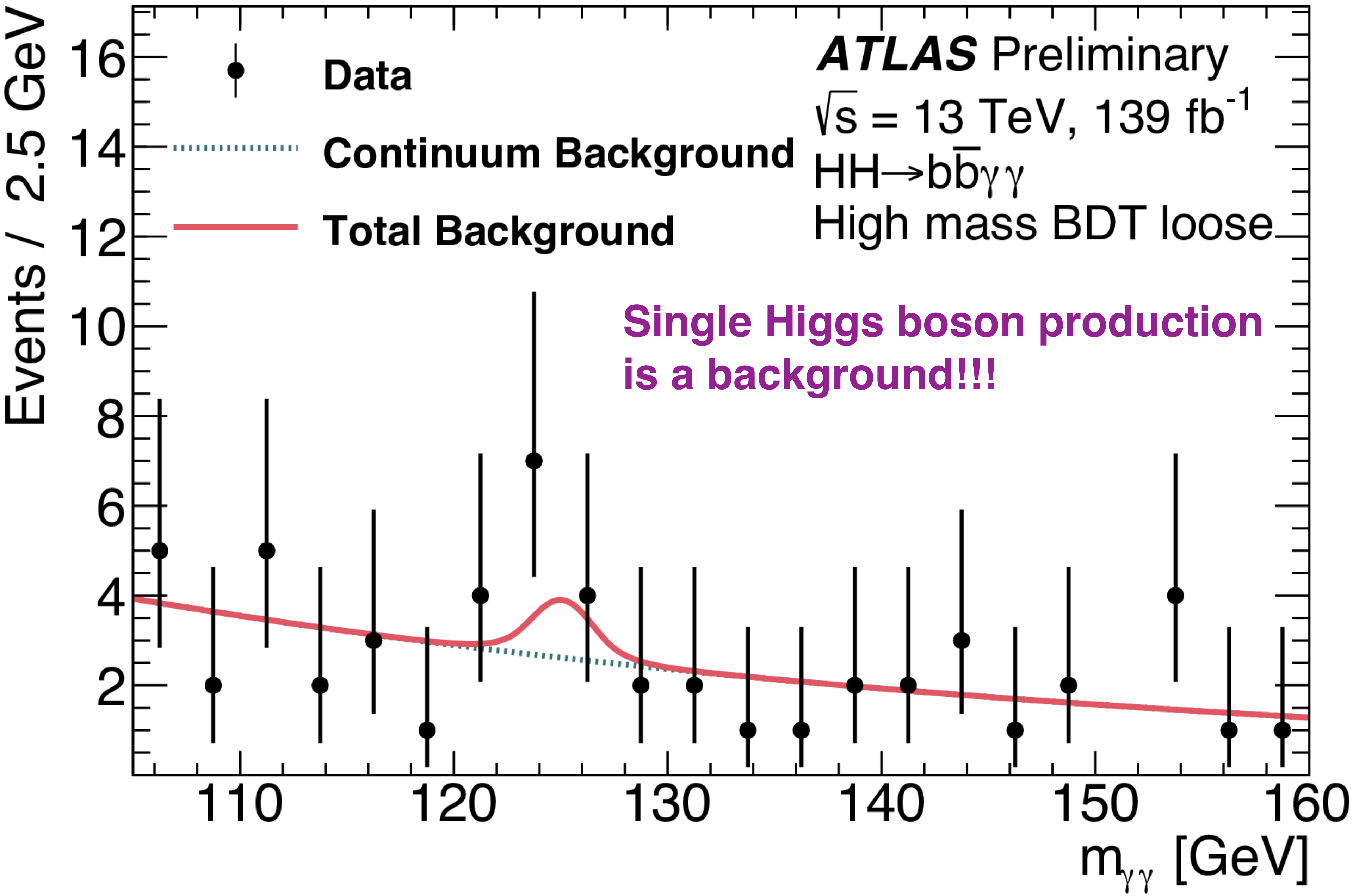
ATLAS-CONF-2021-016

- h→bb has largest Higgs branching ratio
- h→γγ has high efficiency and good mass resolution
- Use a Boosted Decision Tree to separate out small potential signal from large backgrounds

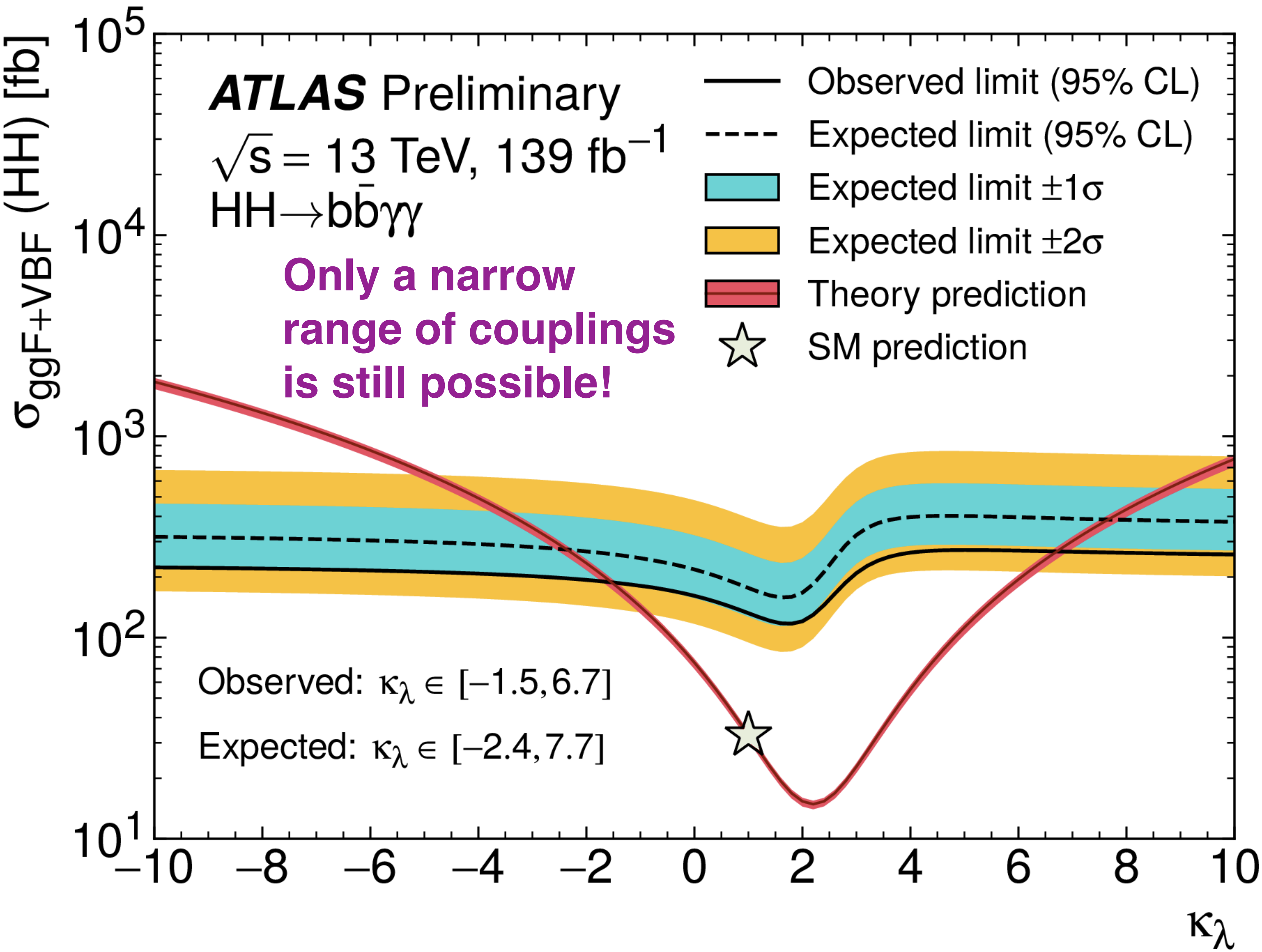


Big contributions from Louis (postdoc), who leads the ATLAS analysis effort, Bri (studied b-tagging and vertexing for photon events) and Tyler (earlier version of analysis as part of his thesis)

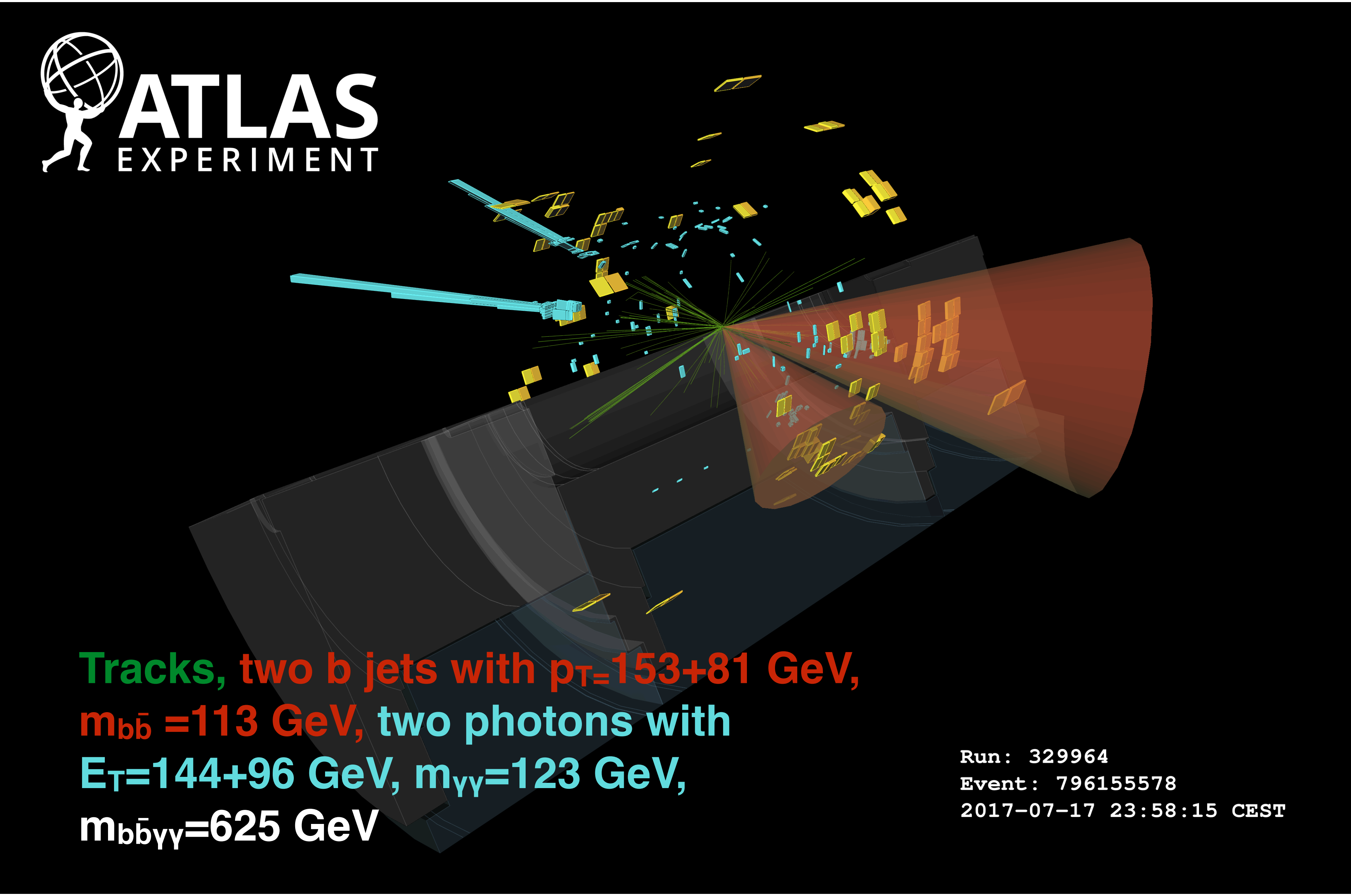
One of the final fits



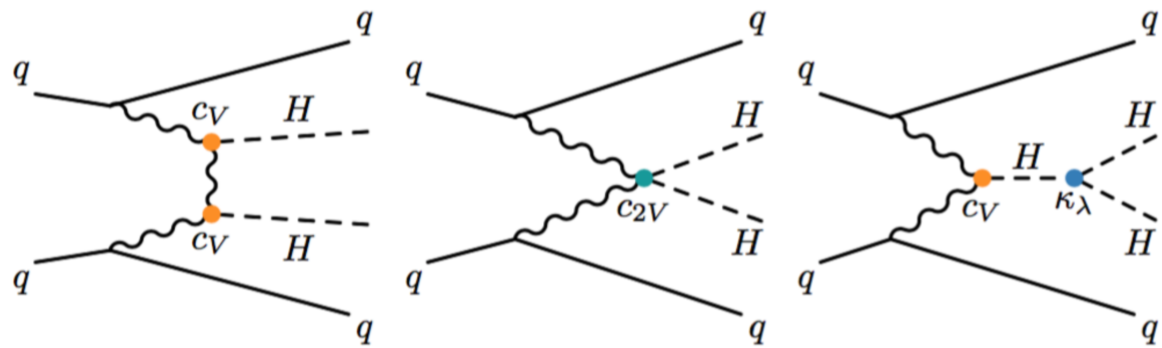
Limits on Higgs self-coupling



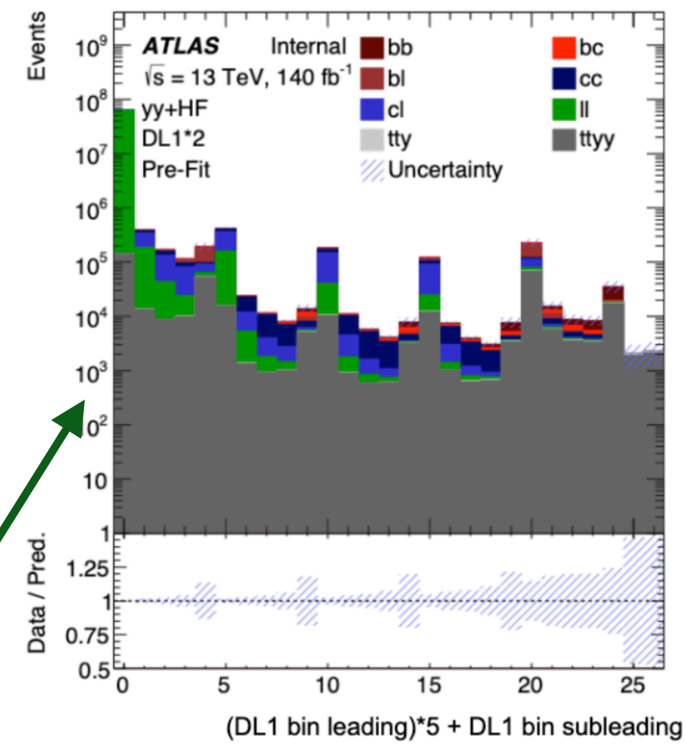
One of the candidate signal events



For the future



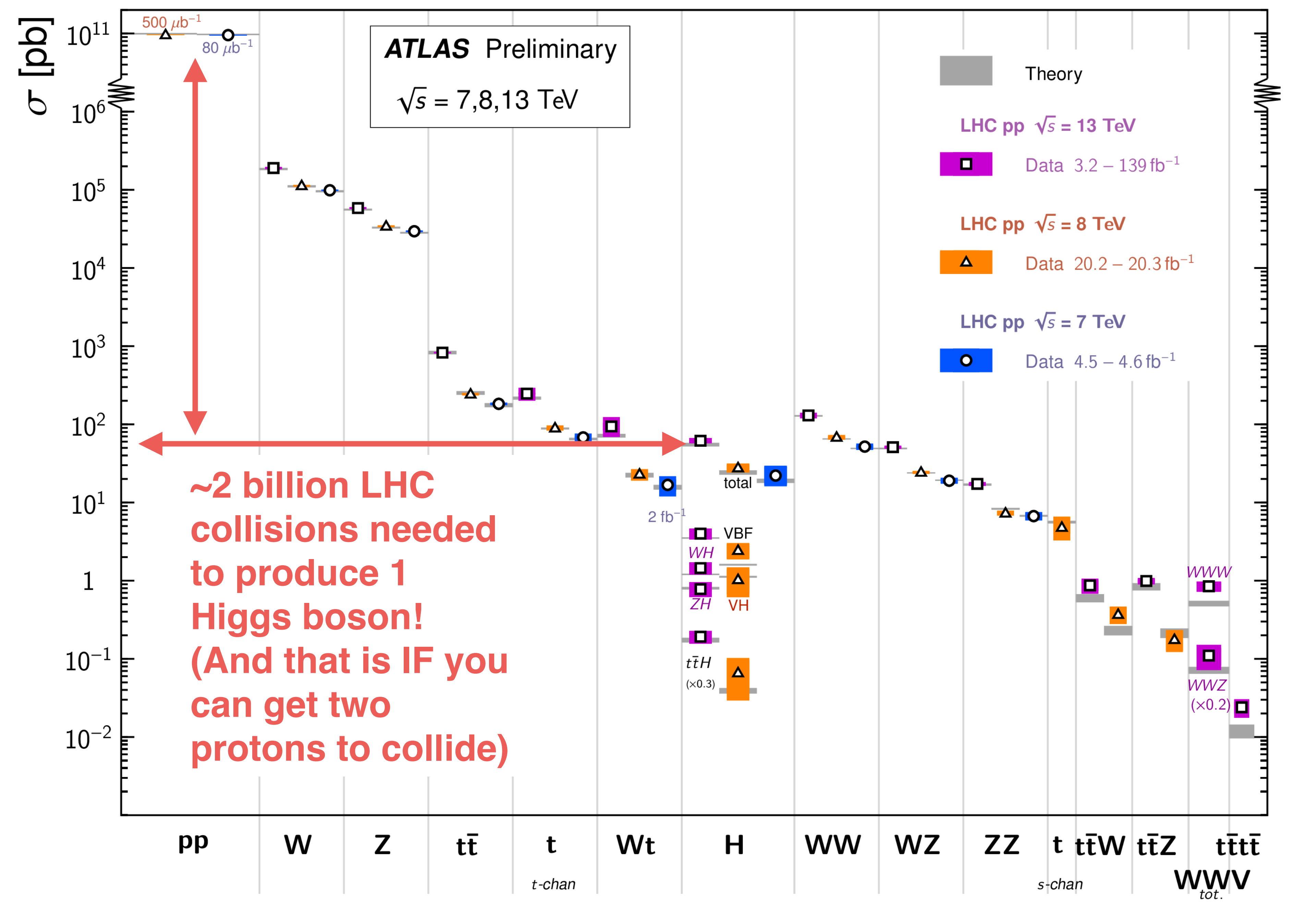
- Think about improvements to photon identification (Tyler and Gretel have worked on this)
- New channels to improve limits on Higgs self-coupling and also to provide sensitivity to hhVV vertex (Tyler, Gretel, August, Louis)
- Combination w/other channels (Louis)
- SM measurement of diphoton + heavy flavor backgrounds - NEVER been measured before, Bri is working on this at ANL



How are we finding all this rare physics?

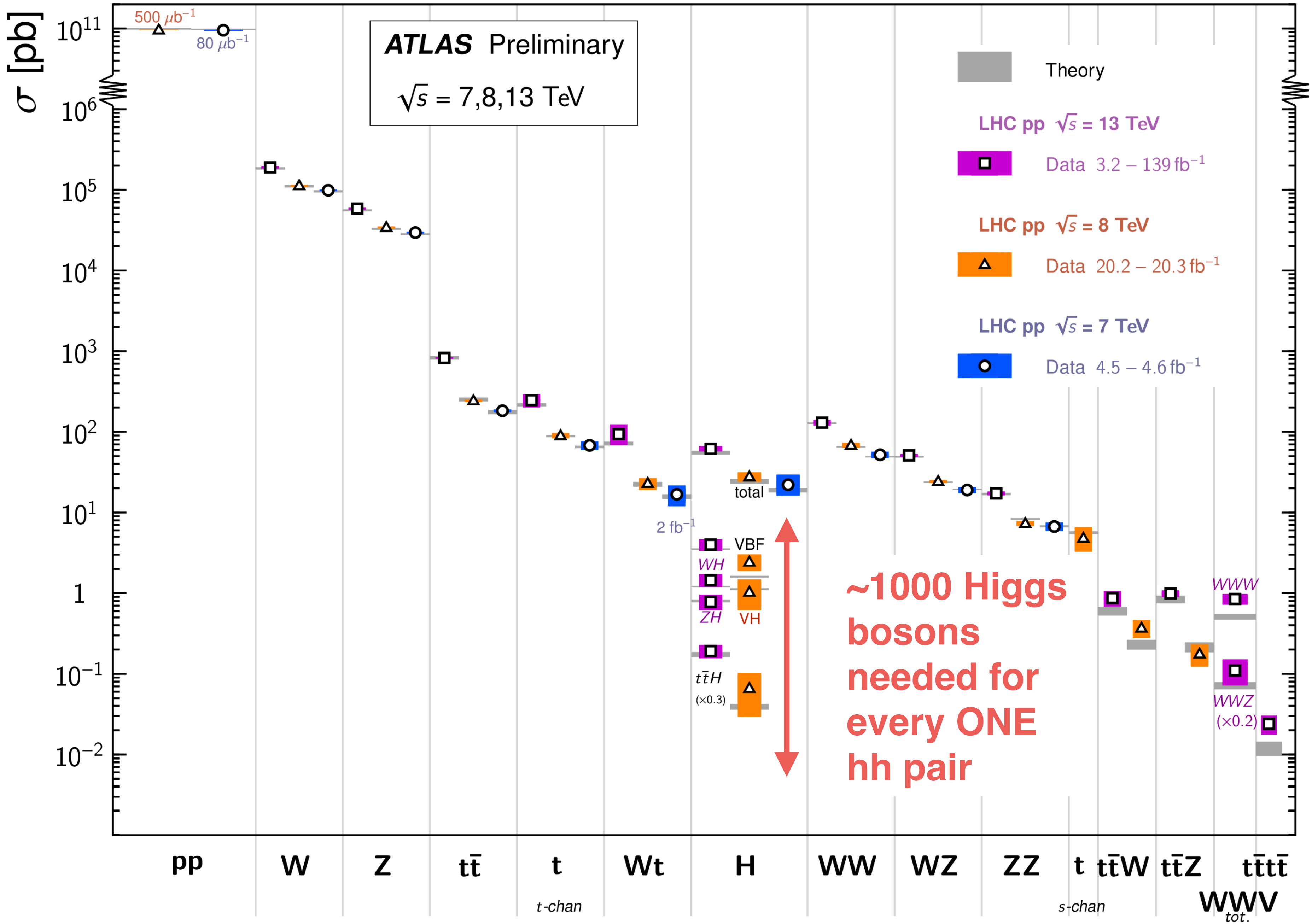
How often do processes occur at the LHC?

ATL-PHYS-PUB-2021-032



How often do processes occur at the LHC?

ATL-PHYS-PUB-2021-032

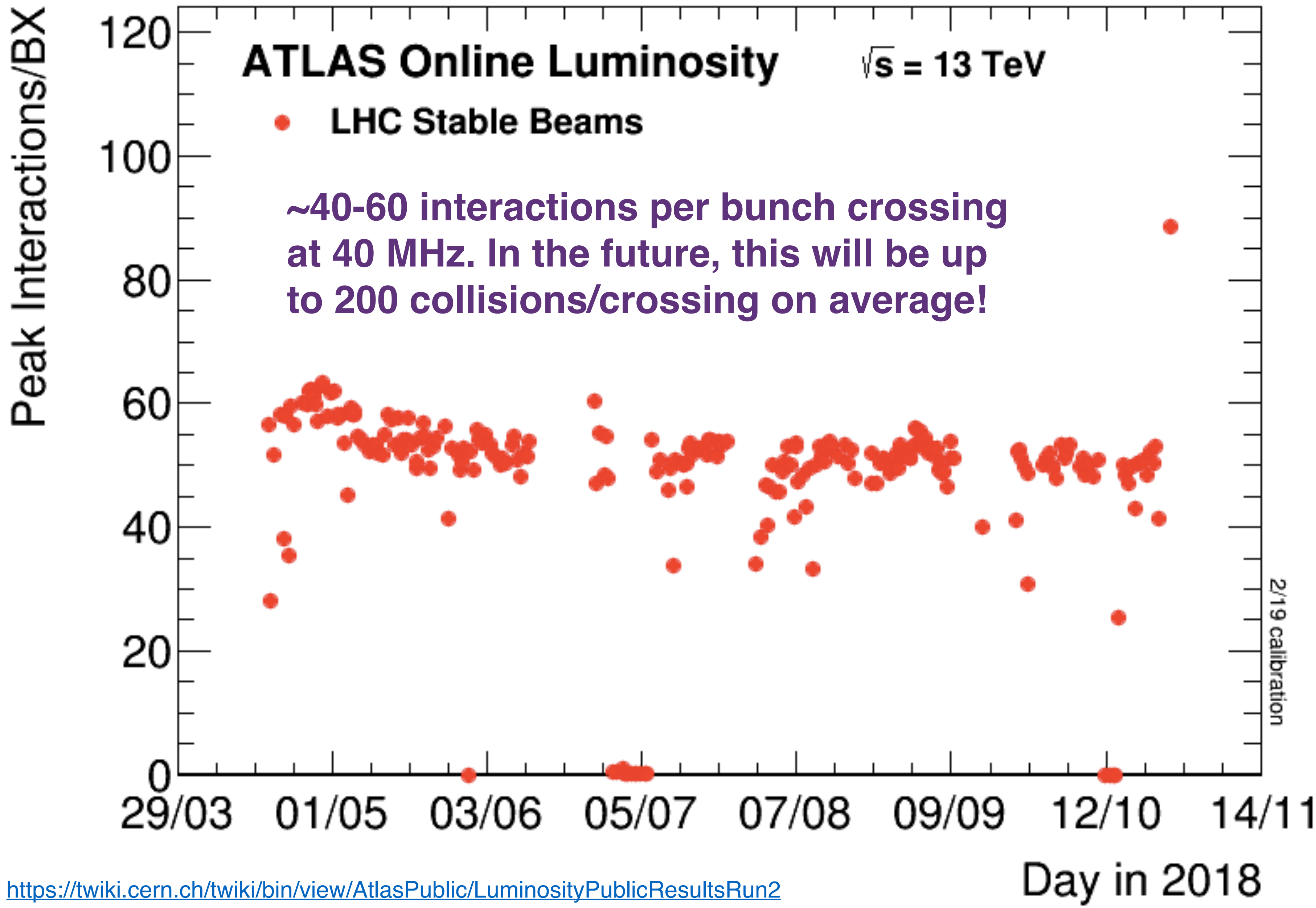


Our friends in beams physics do wonderful things

2808 bunches of 10^{11} protons

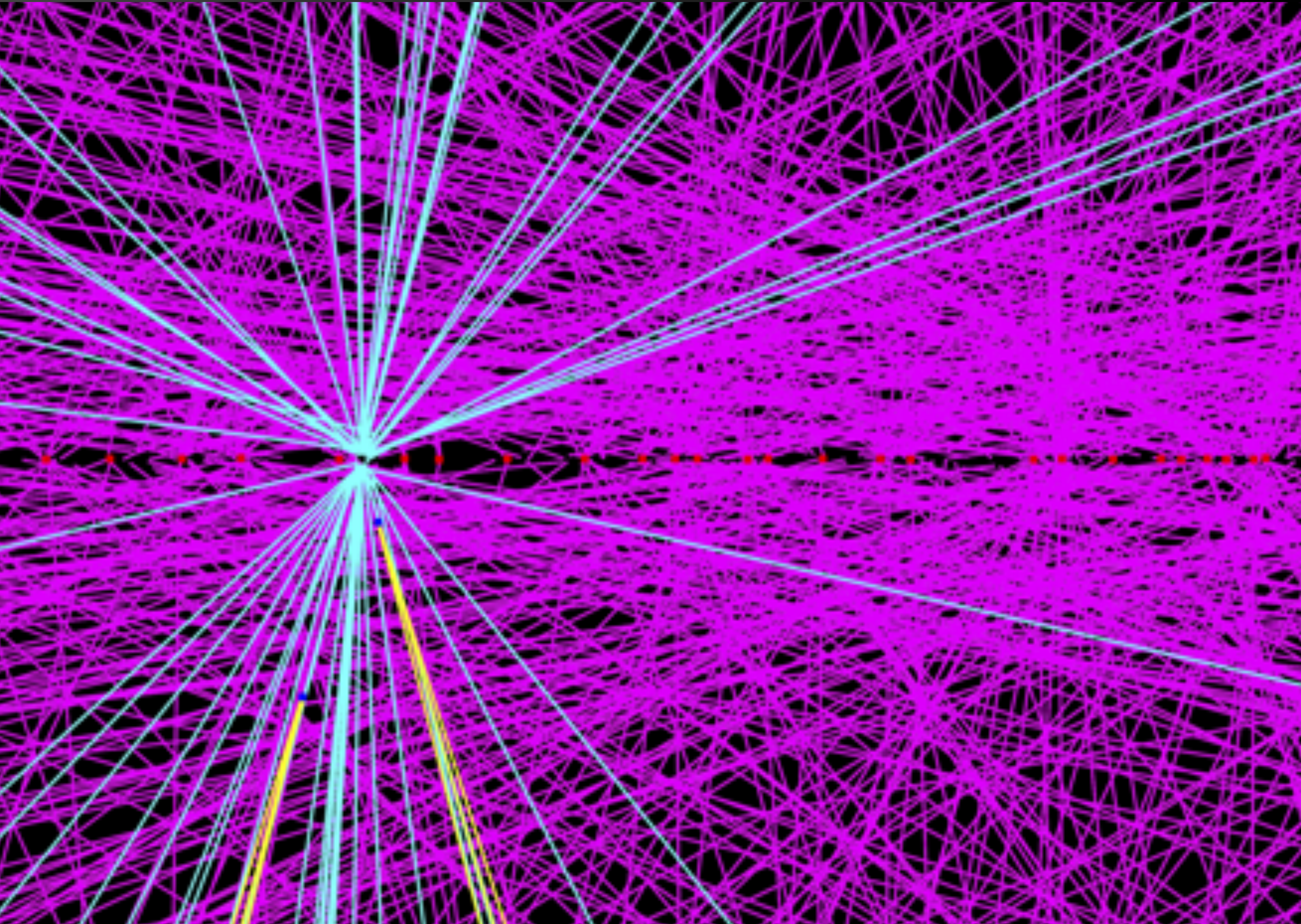
Bunches collide @40 MHz

We end up with lots of uninteresting collisions



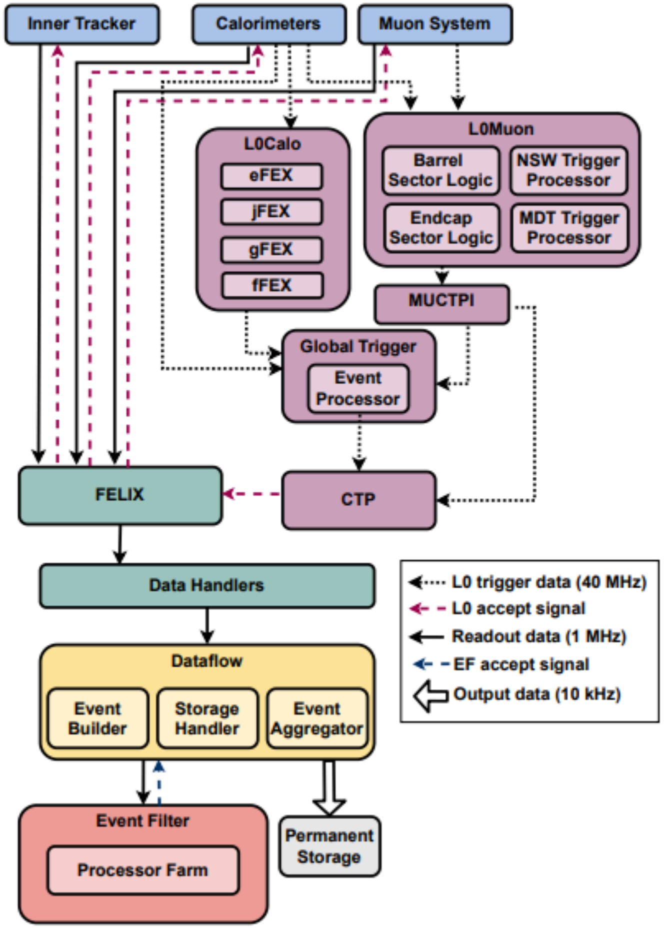
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

That's pretty tough on detectors and computers!



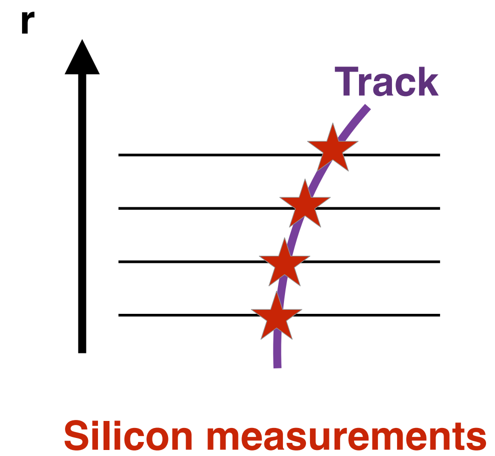
Need to “trigger” on interesting bunch crossings, but that’s hard!

- Future: Can keep only 10,000 out of every 40 million bunch crossings in the detector / sec
- The multi-stage trigger system makes quick rapid decisions, first in custom hardware (40 MHz → 1 MHz) and then in commodity systems (1 MHz → 10 kHz)
- Finding the trajectory of charged tracks is a time-consuming process in CPUs. Can we do this in a more clever way?



Idea we are exploring (my group + others on ATLAS)

- Hough Transforms in FPGAs. The idea is to take the trajectory of charged tracks in the plane perpendicular to the B field and convert coordinates to something better for track-finding
    - Followed by a small neural network or linearized χ^2 fit to filter duplicates and remove fake tracks



BASIC E&M!

$$\frac{qA}{p_T} = \frac{\sin(\phi_t - \phi_h)}{r_h} \sim \frac{(\phi_t - \phi_h)}{r_h}$$

q = ±1

p_T = momentum component perpendicular to B field

A = constant for a given magnetic field

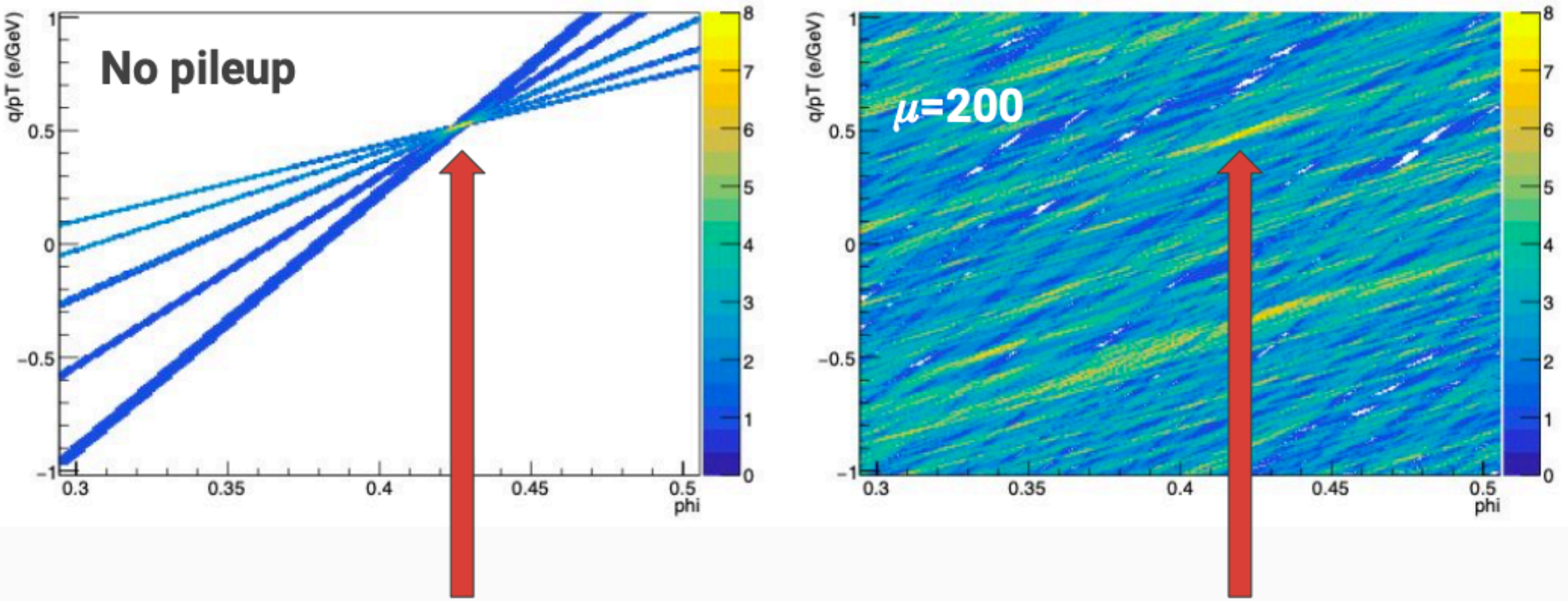
r_h = radial position of each measurement

Φ_t is azimuthal angle at origin/production

Φ_h is azimuthal angle of each measurement

Does the Hough Transform work?

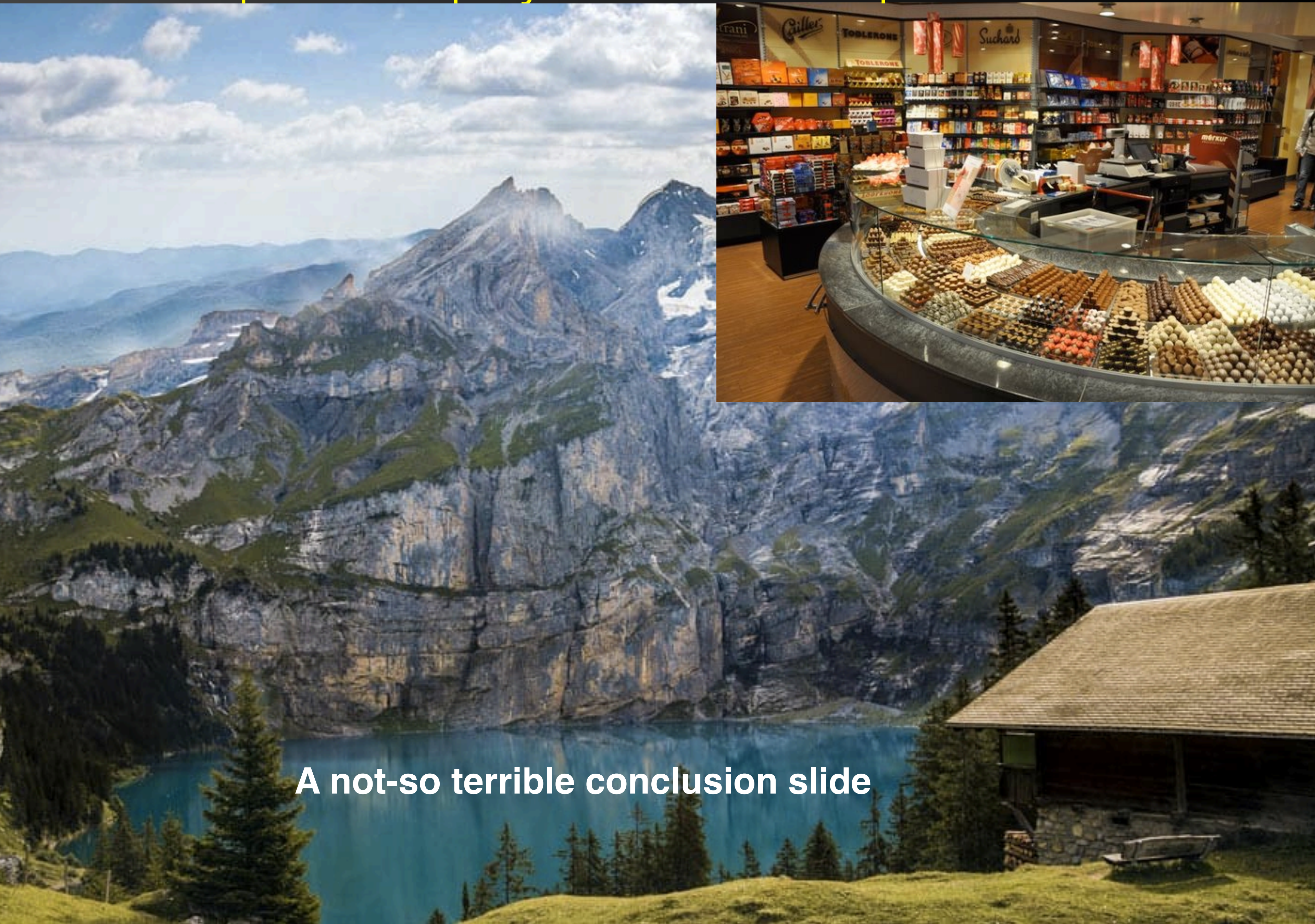
$$\frac{qA}{p_T} = \frac{\sin(\phi_t - \phi_h)}{r_h} \sim \frac{(\phi_t - \phi_h)}{r_h}$$



True muon $\varphi_t = 0.43$, $q/p_T = 0.52$, more challenging to find in pileup

Yes! Though lots of work remains to be done here (Tyler, Bri and Louis have all worked or are working on various stages of track trigger design)

Life as a particle physicist in Europe?



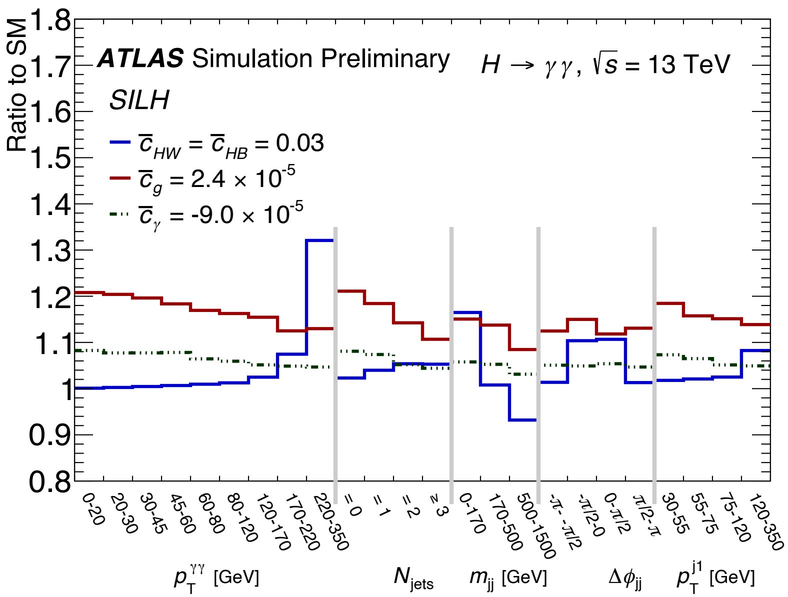
A not-so terrible conclusion slide

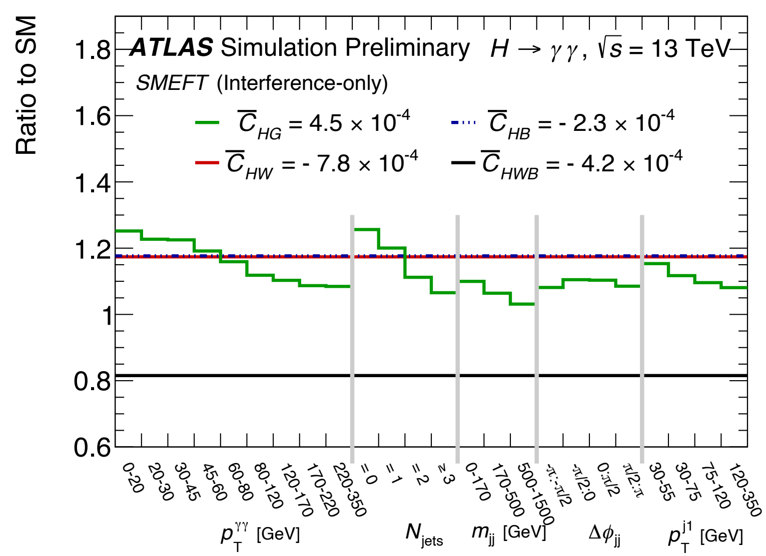
BACKUP

ATLAS $h \to \gamma\gamma$ differential interpretation

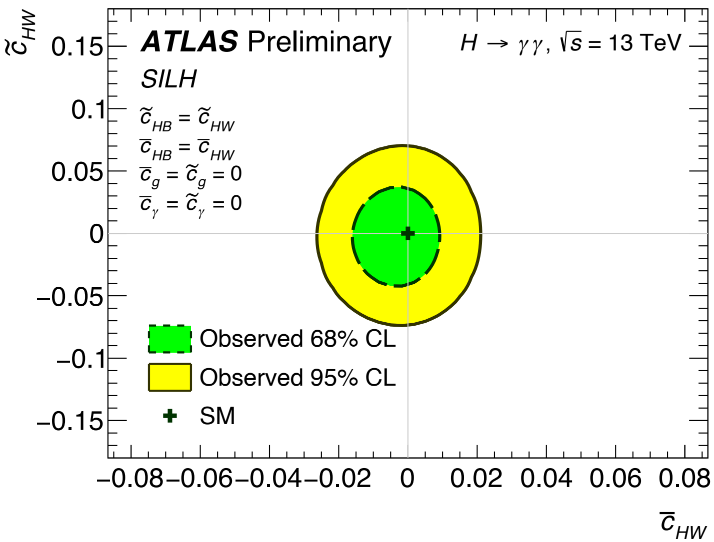
- Study strength and structure of Higgs boson interaction using effective field theory approach
- All coefficients in effective Lagrangian are zero in the SM, non-zero values change rates and overall shapes

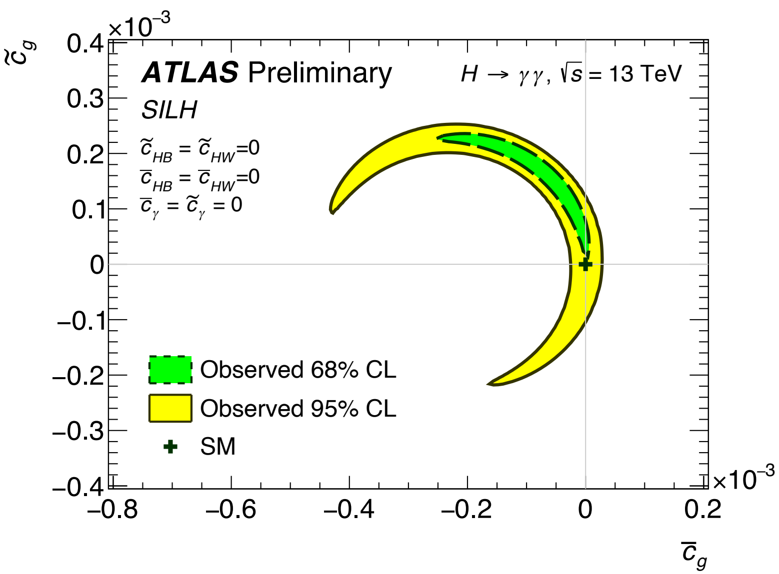
$$\mathcal{L}_{\text{eff}} = \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB}$$

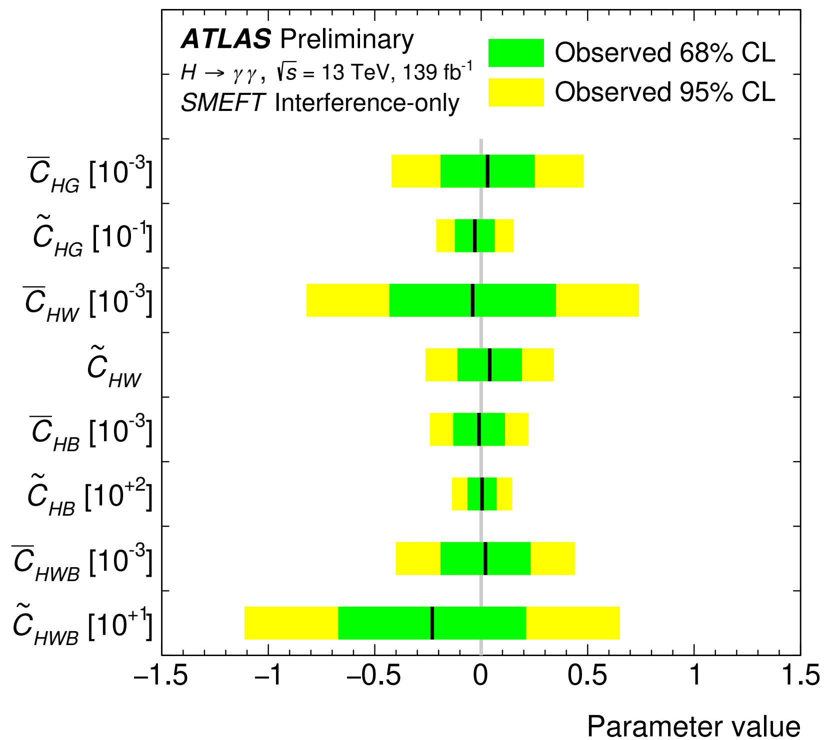




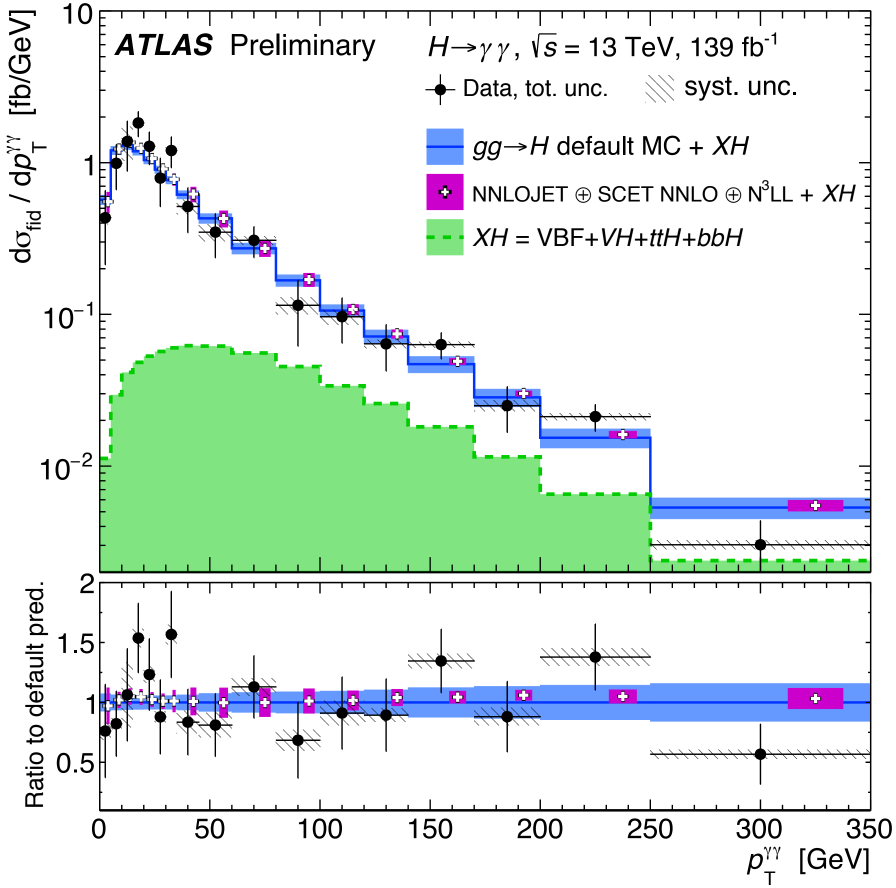
ATLAS h→γγ EFT results

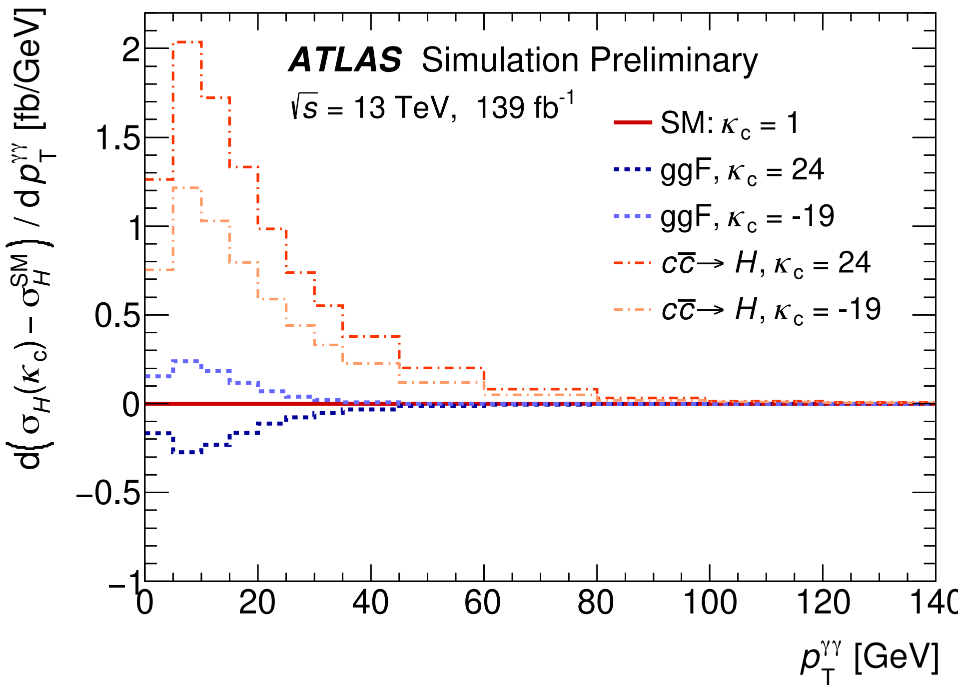






Using Higgs boson p_T





Higgs boson p_T distribution changes if Yukawa couplings change, including the charm Yukawa coupling, which is difficult to study otherwise

Do we really produce that much physics? YES!

ATLAS EXPERIMENT

Collaboration Site | Physics Results

ABOUT DISCOVER RESOURCES UPDATES SEARCH

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Updates > News > ATLAS celebrates results of 1000 collision papers

News

Tags: physics results

ATLAS celebrates results of 1000 collision papers

18th June 2021 | By Katarina Anthony

The ATLAS Collaboration celebrates the creativity, wealth and scientific impact enshrined in its 1000 papers using LHC collision data. This work – together with that carried out by its sister experiments at the LHC – represents a diversified physics programme that is unprecedented and unequalled in physics research to date.

On 18 June 2021, the ATLAS Collaboration submitted for publication its 1000th paper studying collision data from the Large Hadron Collider (LHC). It has been over a decade since the LHC started colliding beams of particles at record energies. In that time, it has produced the greatest wealth of physics data ever accumulated by a particle collider.

This treasure-trove of information about our Universe has been tirelessly explored by ATLAS physicists. Their scientific contributions cover a broad range of subjects, including the discovery of the Higgs boson and the study of its properties; the observation and measurement of previously uncharted high-energy processes; precise measurements of the properties and production rates of fundamental particles; the exploration of flavour and heavy-ion physics; deep and broad searches for new physics phenomena; and the development of countless new analysis methods and algorithms. Explore ATLAS' research programme in the timeline below.

Earlier this year!

https://atlas.cern/updates/news/1000-collision-papers

Finally, the LHC status

Hough transform

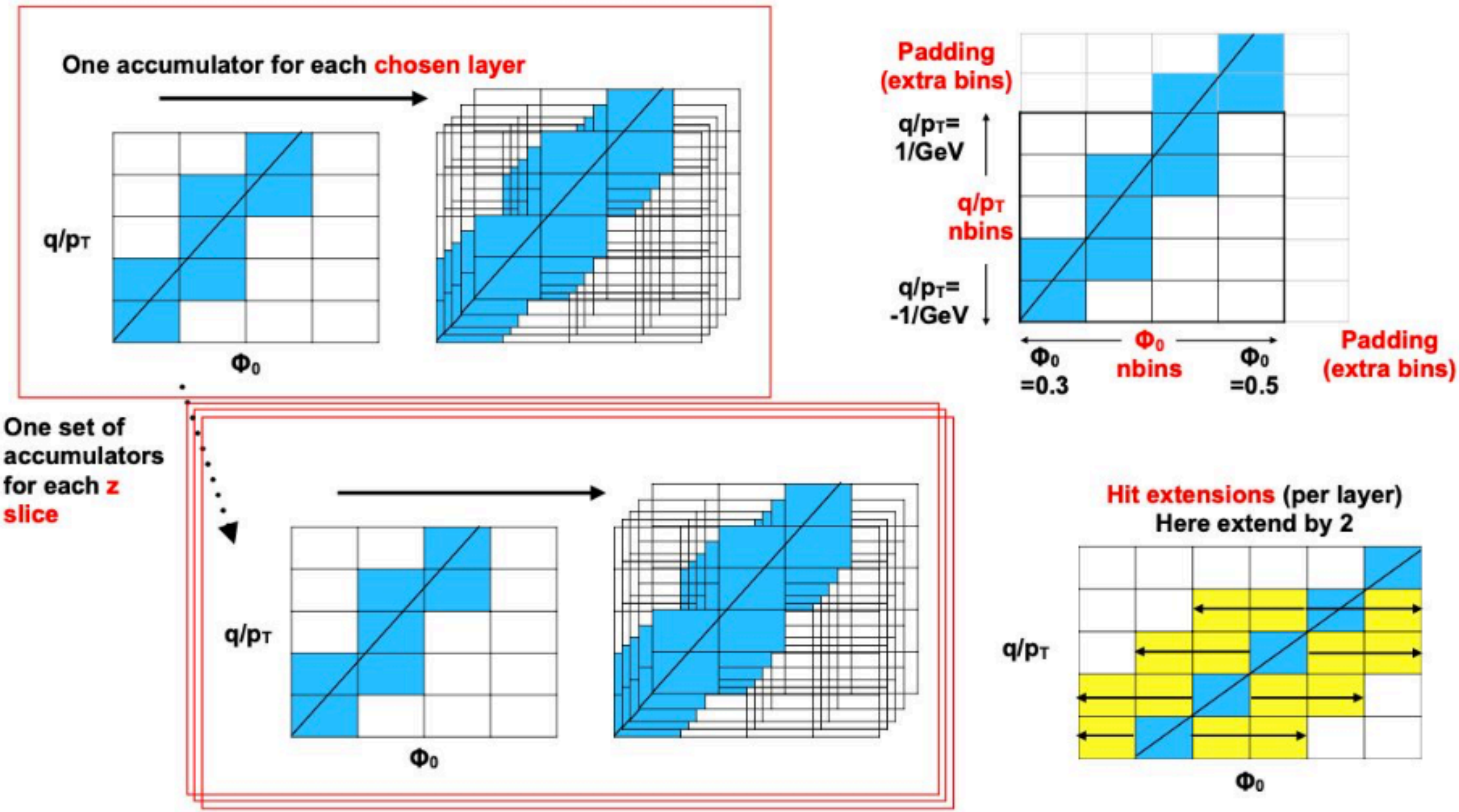
- **Curved circular arc of track** in the x-y plane (perpendicular to beamline) due to B field in the z direction can be **transformed onto the q/p_T vs Φ_t plane**
  - Each hit on a track with form a straight line in this view
  - Assume a given q/p_T for the track and for each Φ_h (hit on track) you can calculate Φ_t
  - True tracks will "accumulate" in a given bin in this 2D space

$$\frac{qA}{p_T} = \frac{\sin(\phi_t - \phi_h)}{r_h}$$

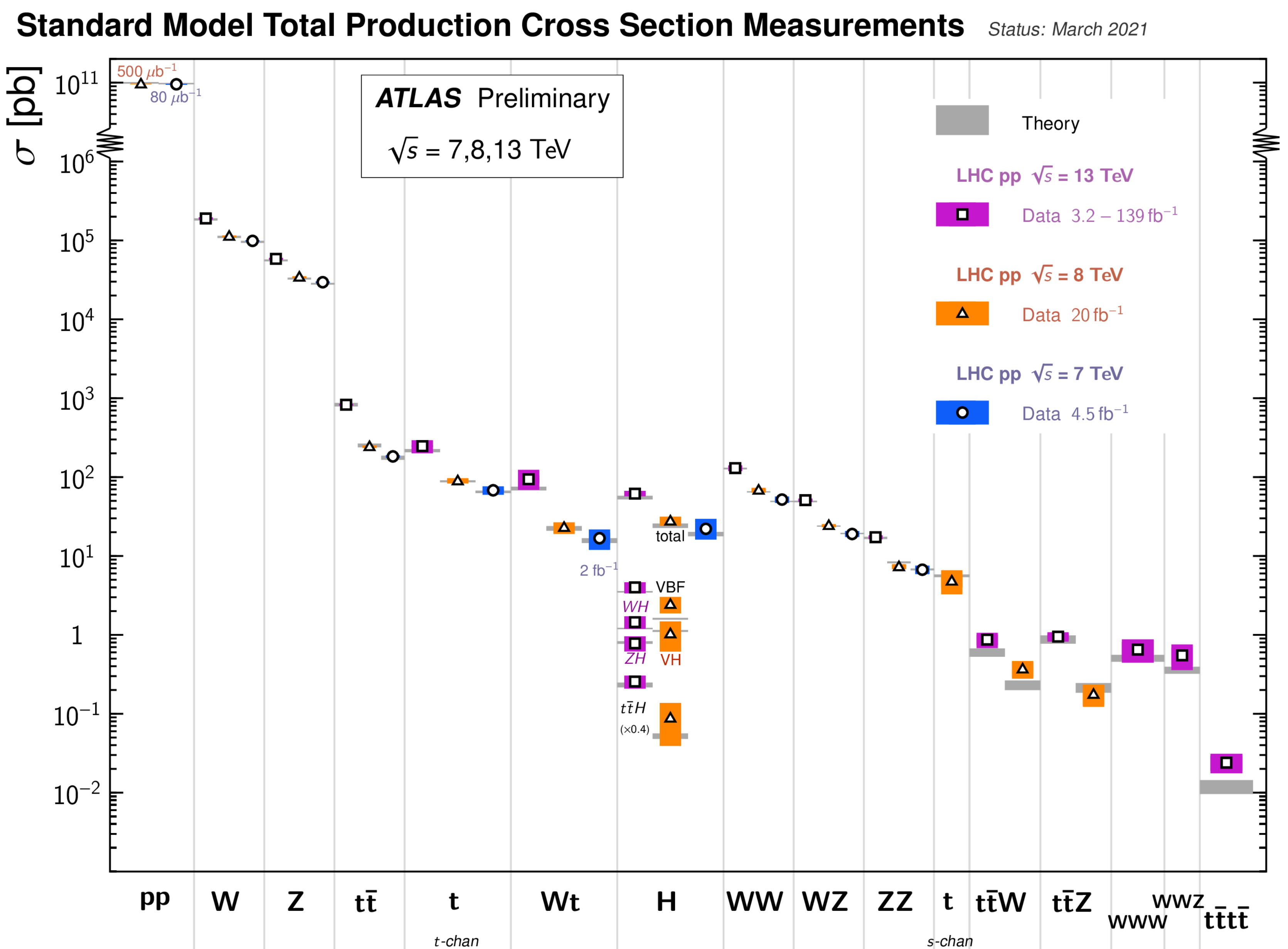
$q = \pm 1$
A = constant for a given magnetic field
r_h = radius of hit in the detector
Φ_t is azimuthal angle at origin
Φ_h is azimuthal angle of each hit

Done for each $\eta \times \varphi = 0.2 \times 0.2$ region (1280 across the detector)

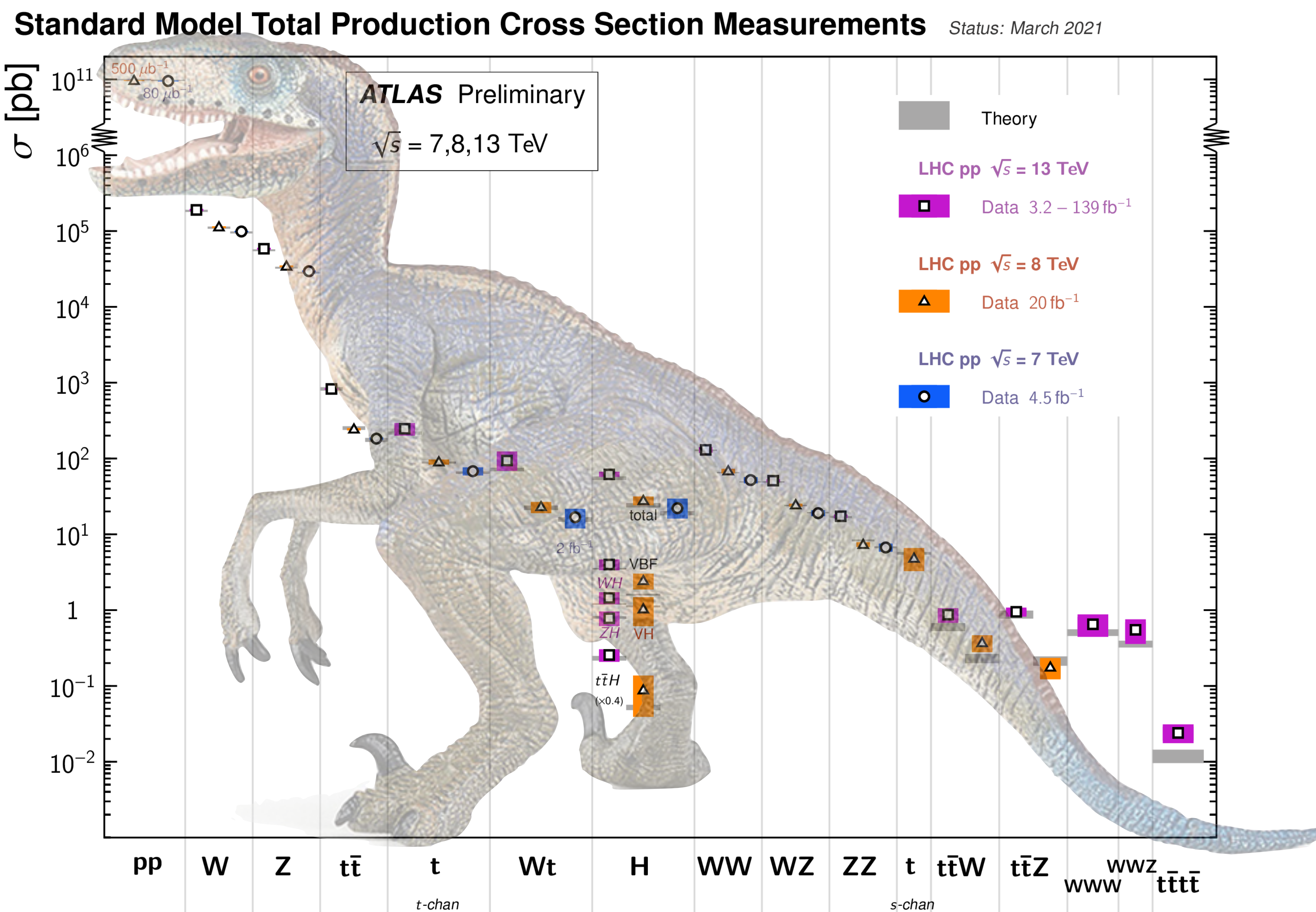
Hough transform



An aside, what is this plot called?

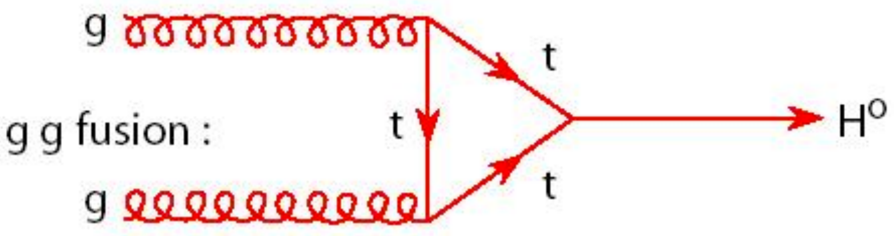


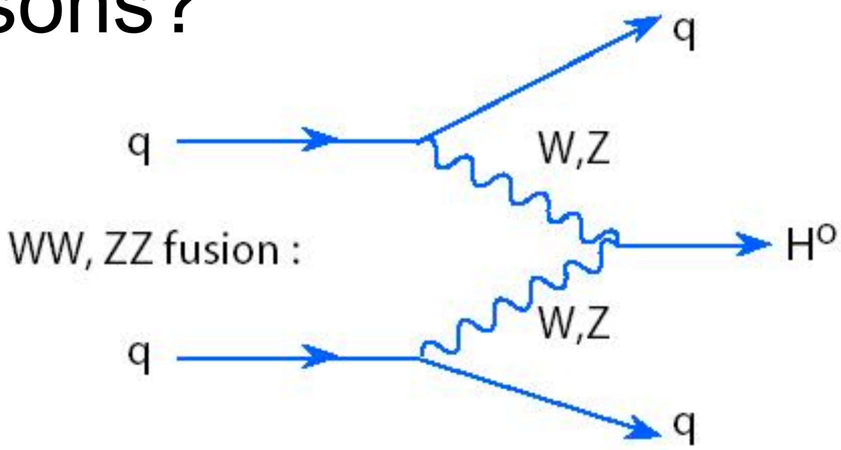
Dinosaur plot

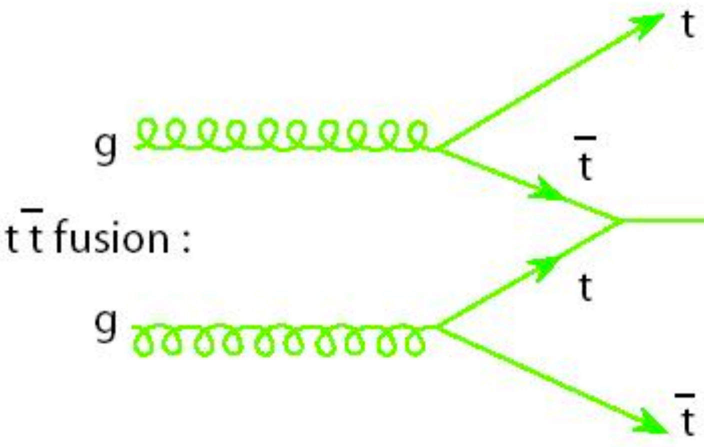


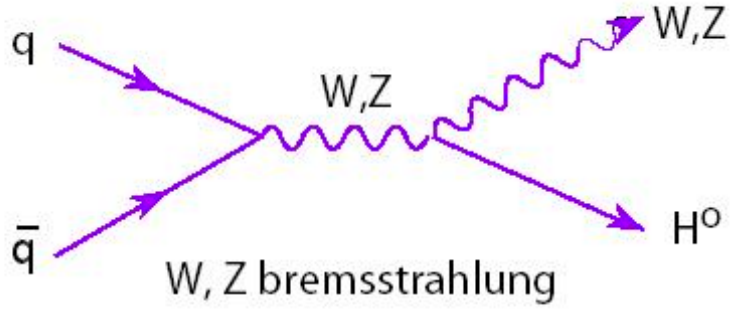
http://sites.uci.edu/energyobserver/2012/11/26/higgs-production-and-decay-channels/

How does the LHC produce Higgs bosons?



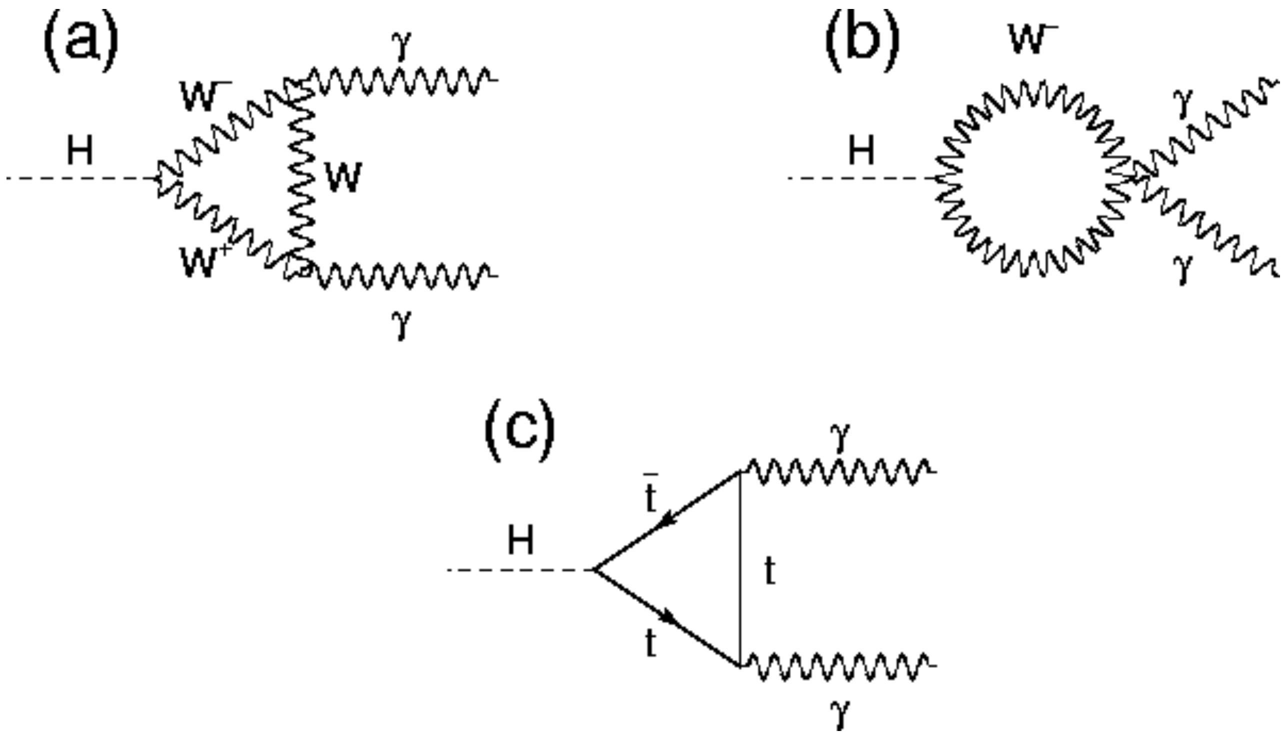






How do Higgs bosons decay to photons?

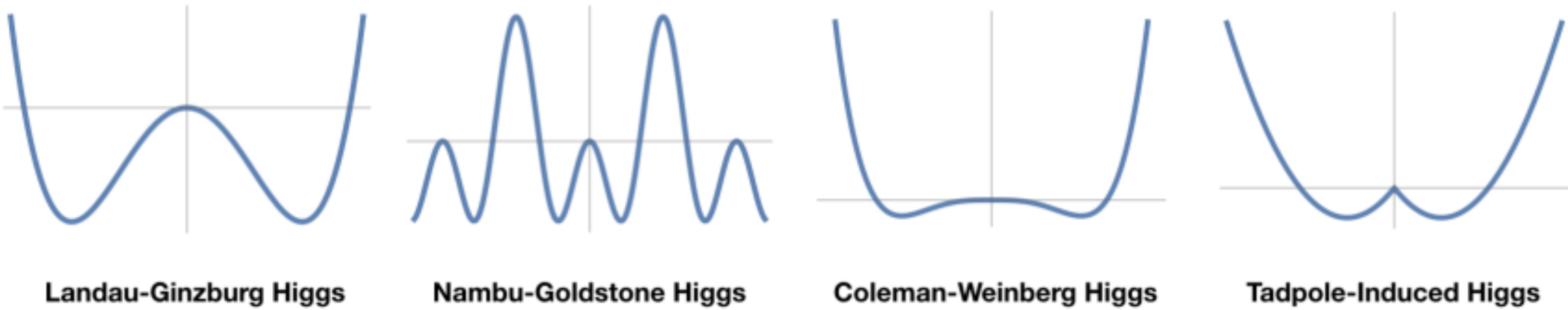
http://www.hep.lu.se/atlas/thesis/egede/thesis-node17.html



Higgs bosons couple to objects proportional to their mass. Decays to photons are indirect and induced! (And thus rare)

But is the Higgs potential as predicted?

1907.02078

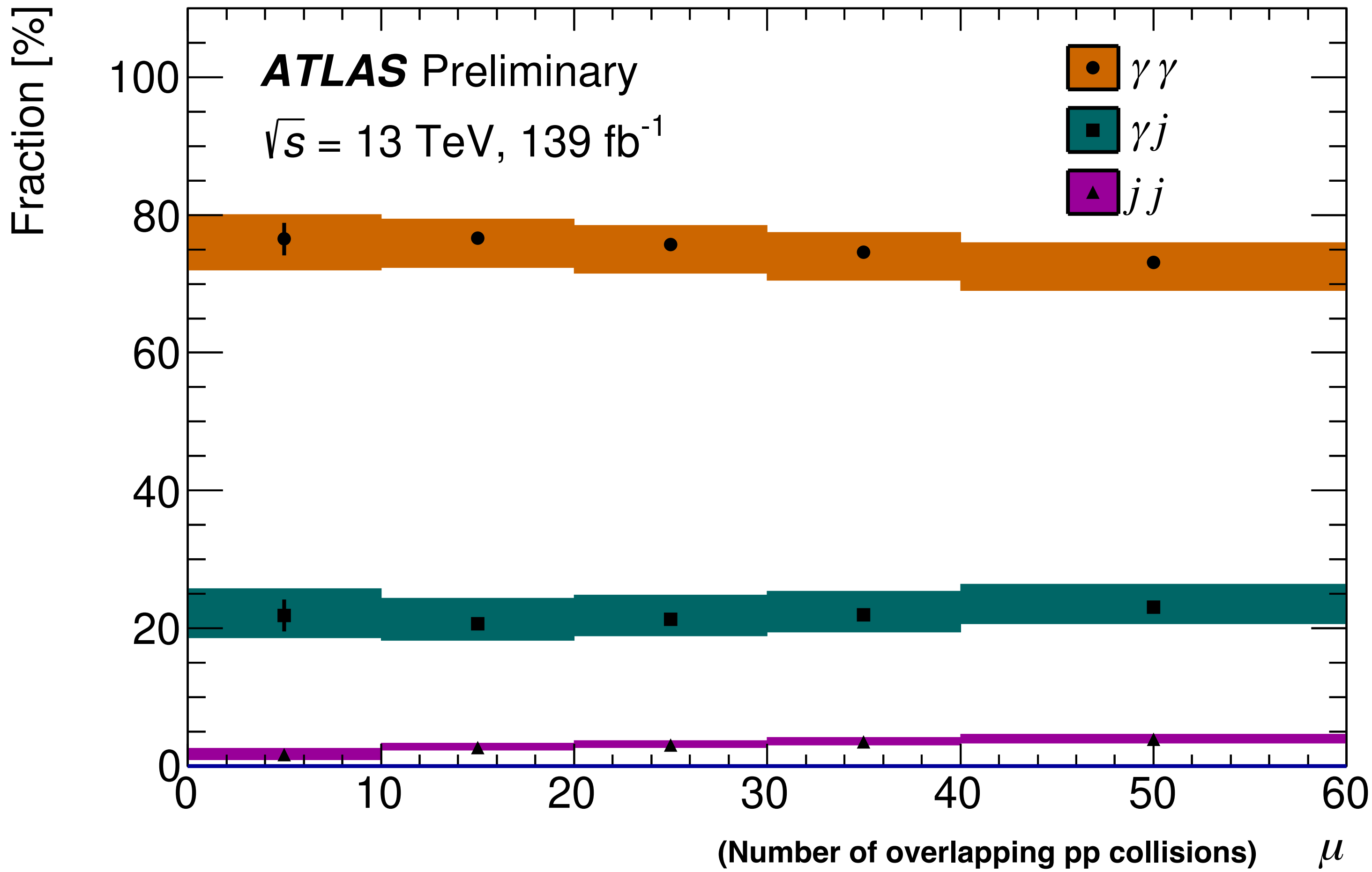


$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2}(H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

- Nambu-Goldstone Higgs: pseudo Nambu-Goldstone boson emerging from strong dynamics at a high scale
- Coleman-Weinberg Higgs: EWSB is triggered by renormalization group (RG) running effects
- Tadpole-induced Higgs: EWSB is triggered by the Higgs tadpole

ATLAS $h \rightarrow \gamma\gamma$ differential

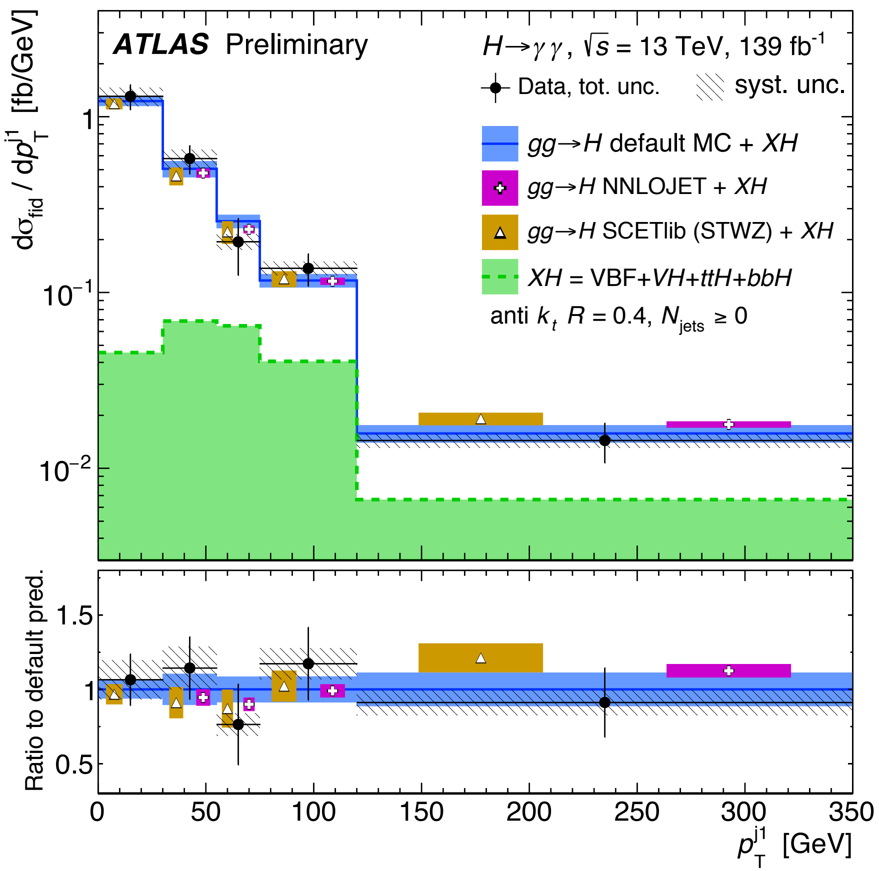
ATLAS-CONF-2019-029

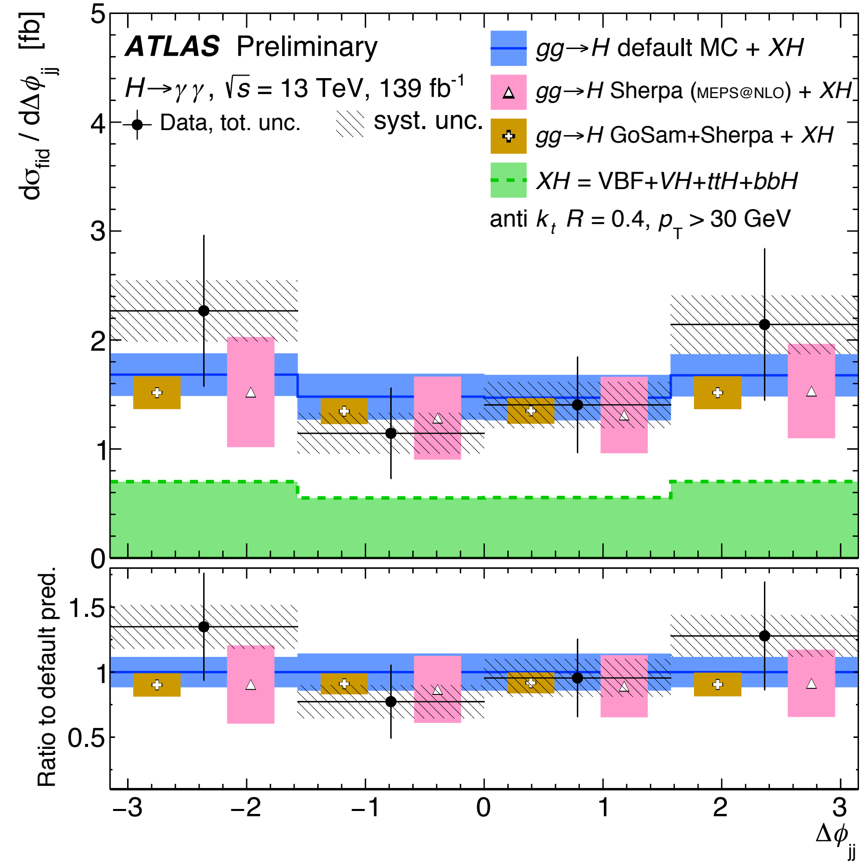


$\gamma\gamma$ simulation to study the irreducible background, fractions of other components from double 2D sideband fit in photon ID and isolation - Bri has spent a lot of time worrying about the irreducible backgrounds!

ATLAS h→γγ differential

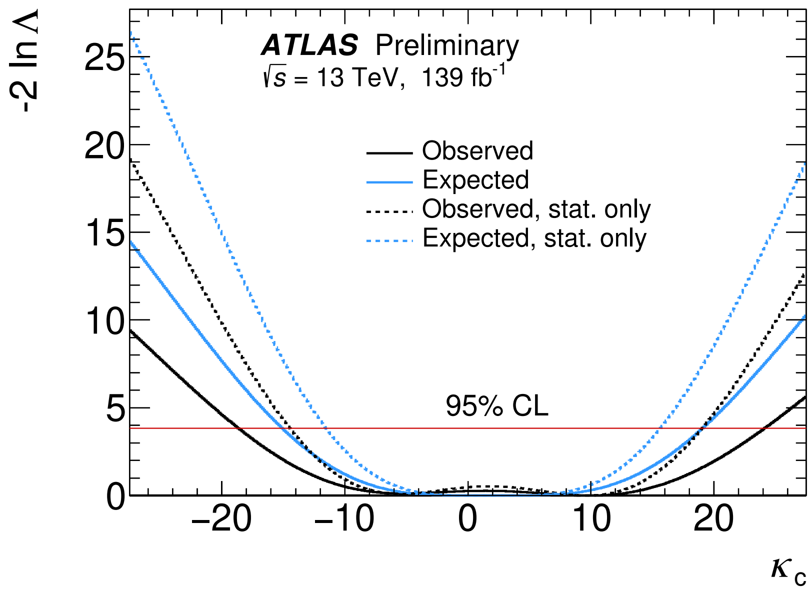
ATLAS-CONF-2019-029

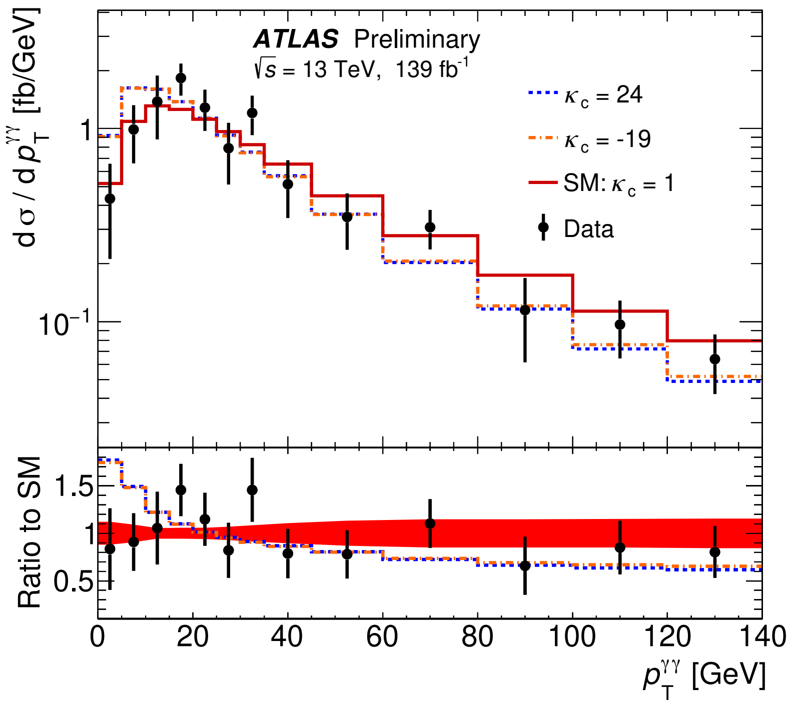




No obvious discrepancies

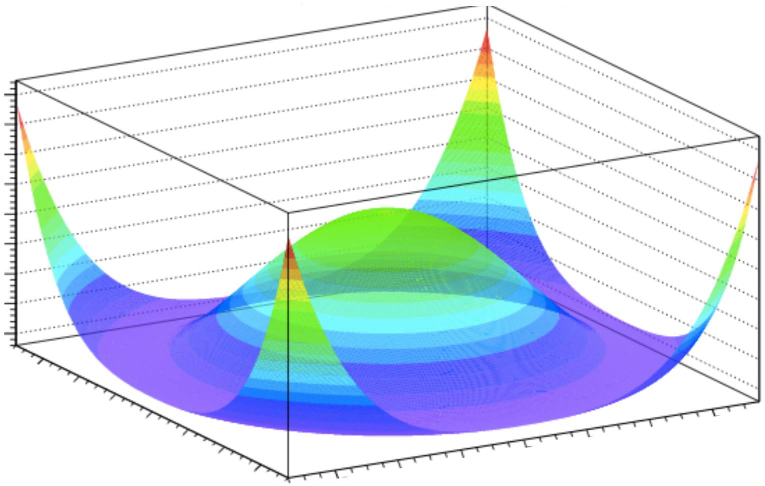
Charm Yukawa results





Higgs boson p_T distribution changes if Yukawa couplings change, including the charm Yukawa coupling, which is difficult to study otherwise

Higgs field potential



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

$$\phi(vacuum) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\phi \rightarrow \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$V(\phi) = \frac{\mu^2}{2}\left(v^2 + h^2 + 2vh\right) + \frac{\lambda}{4}\left(v^4 + h^4 + 4v^2h^2 + 2v^2h^2 + 4v^3h + 4vh^3\right)$$

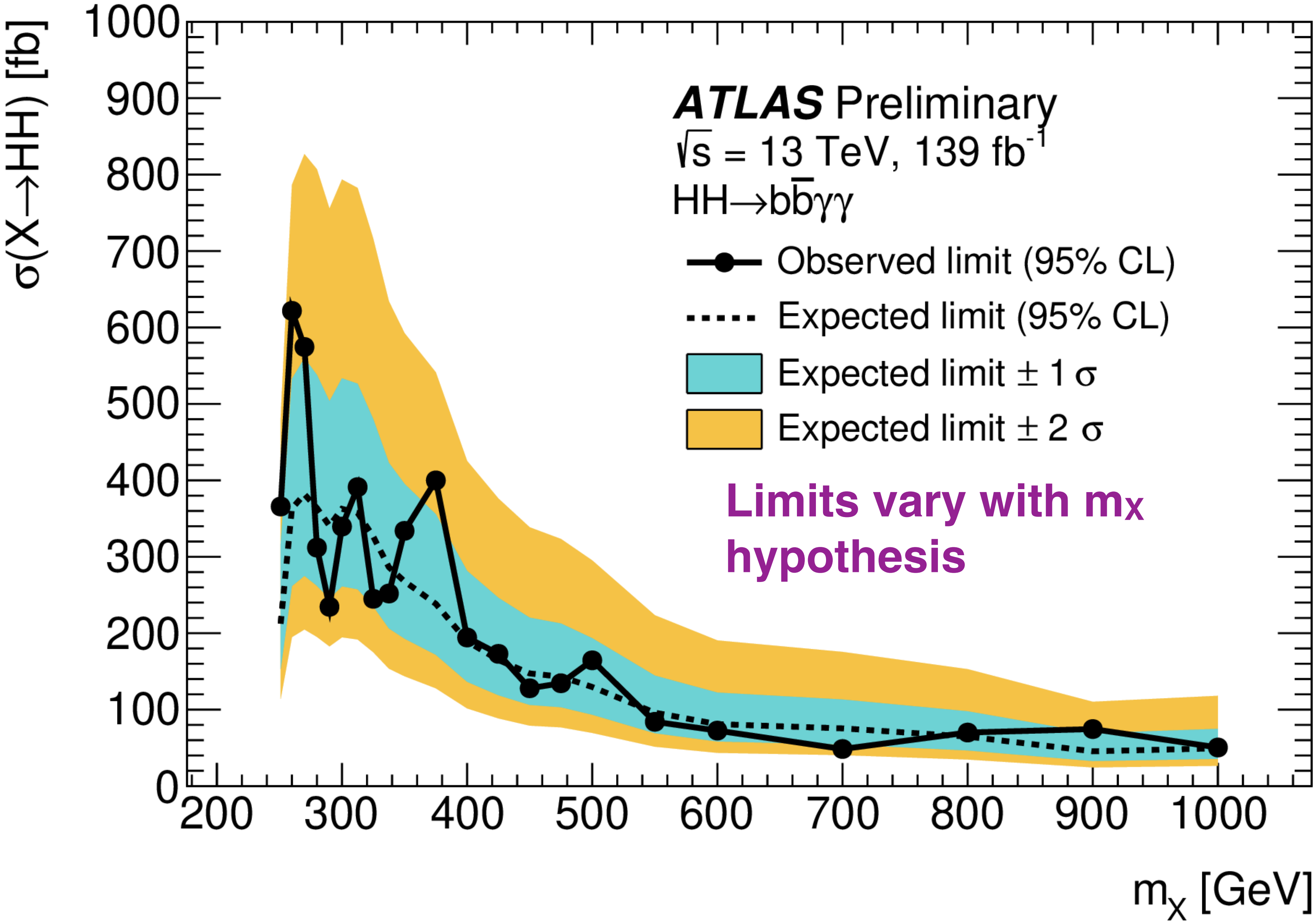
$$V \sim \frac{1}{2}\mu^2h^2 + \lambda vh^3 + \ldots$$

Higgs mass term! We measure this (125 GeV) and thus μ

But $v = (\mu^2/\lambda)^{0.5}$ so we have a precise prediction of the non-zero strength of the hhh vertex (Higgs self-interaction) for the SM Higgs field potential!

Minimum of Higgs potential is not at zero field!

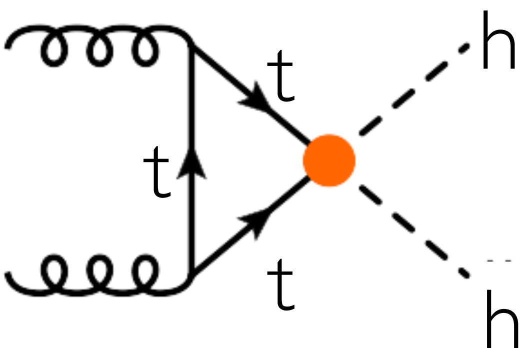
Resonant production limits

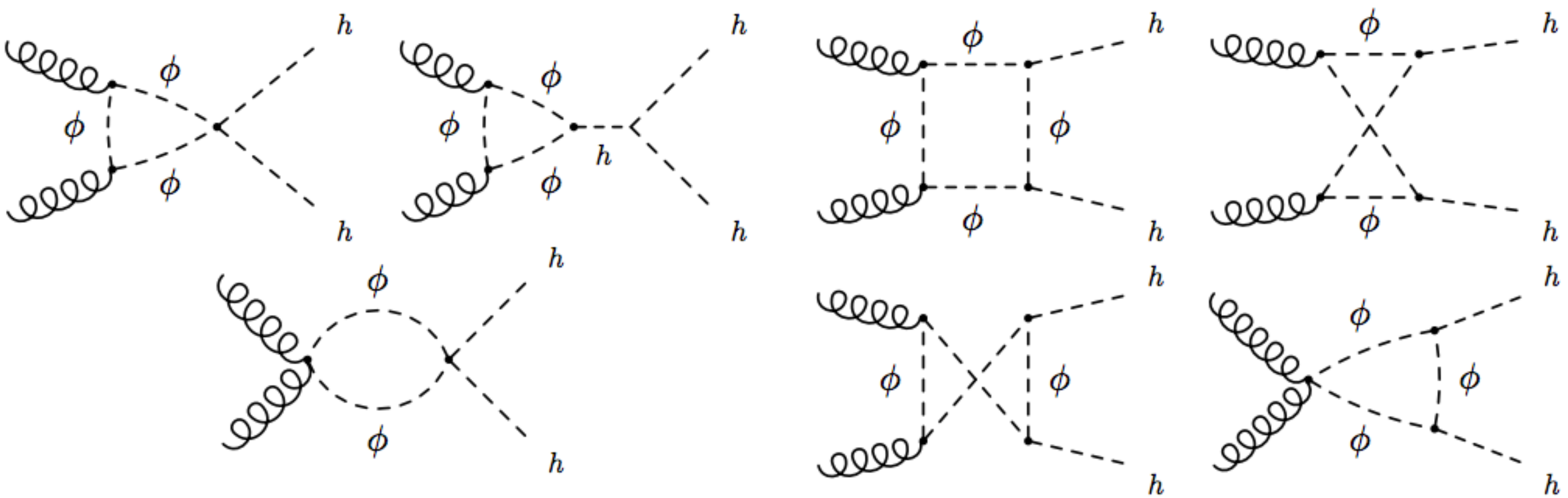


What about new physics?

1205.5444 (Contino et al) 1207.4496 (Kribs and Martin), 1212.5581 (Baglio et al), 1512.00068 (Huang et al) among many

- Can enhance non-resonant hh production in many extensions to the SM
  - tthh interactions, light colored scalars, if Higgs boson self-coupling were altered, or if top quark had non-standard Yukawa coupling





ATLAS $h \rightarrow \gamma\gamma$ differential

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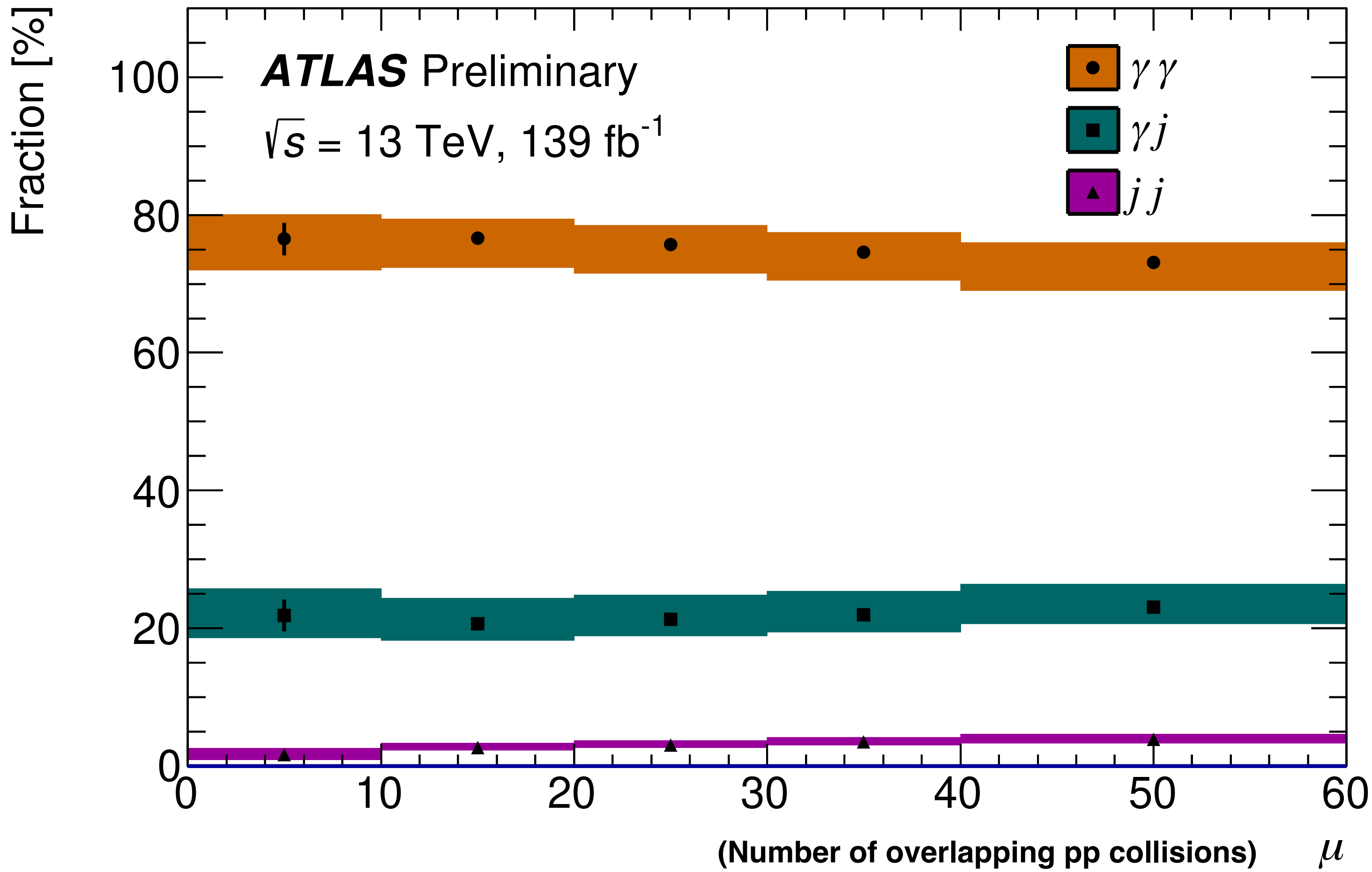

Bri has spent a lot of time worrying about the purity of our diphoton sample to help us understand the background shape!

ATLAS h→γγ differential

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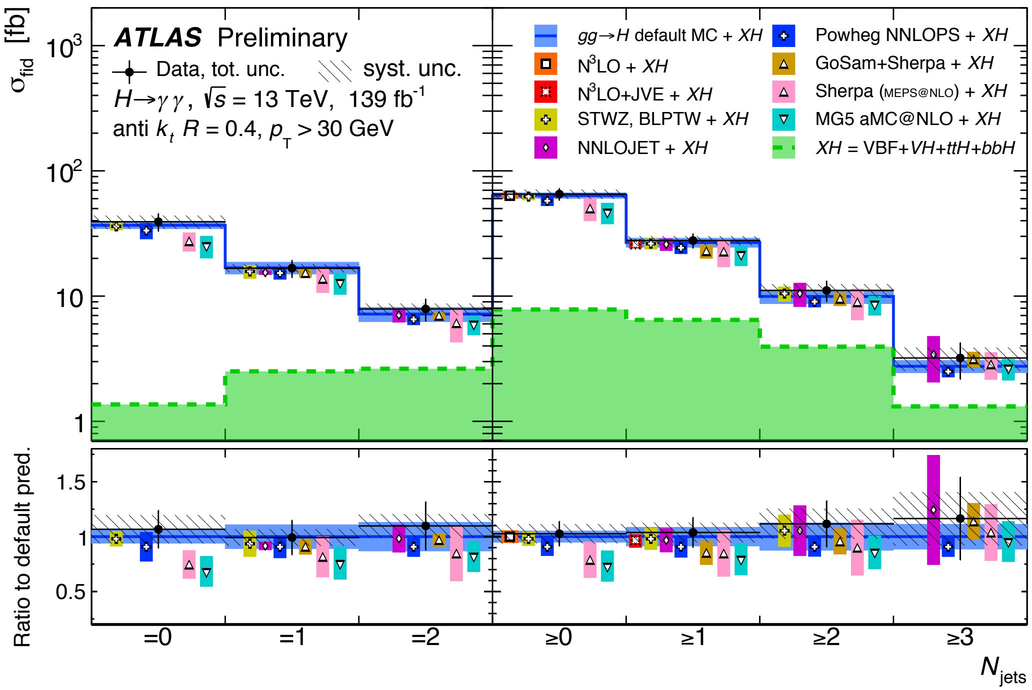
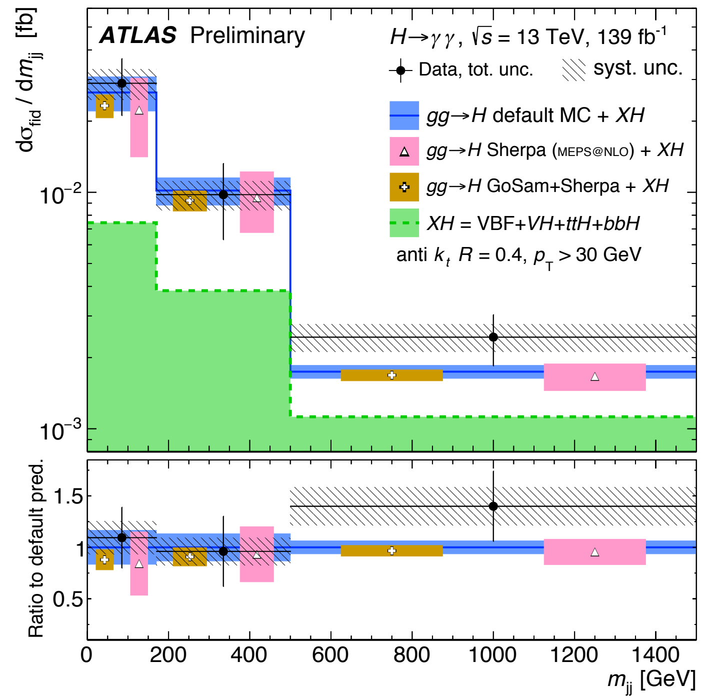




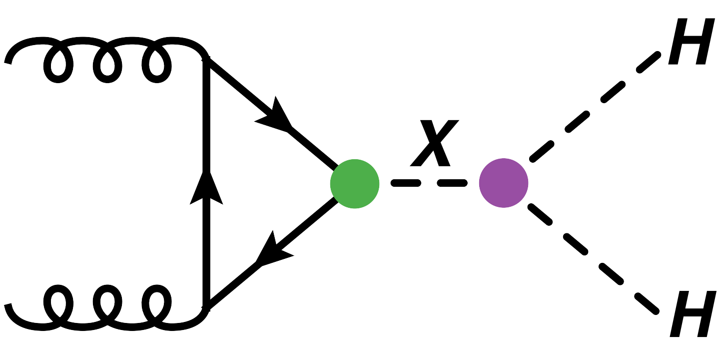
Probing Higgs boson
+ 3 or more jets! No obvious discrepancies, yet…

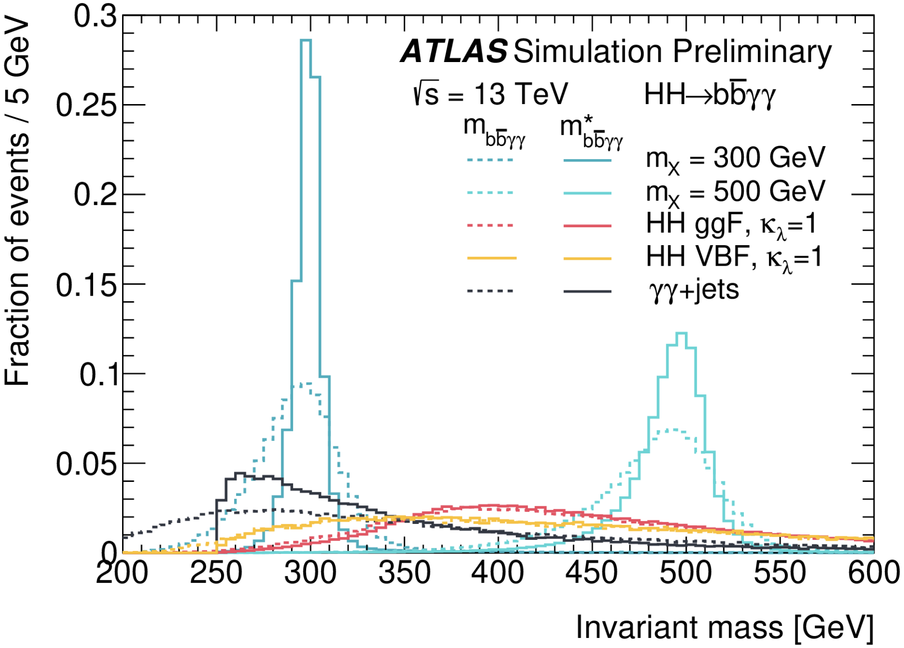
Resonant analysis

- Also look for production of X decaying to a pair of higgs bosons
  - First select events with diphoton mass consistent with Higgs boson mass, then look for bumps in 4-body invariant mass

hep-ph/0009232 (Cheung), hep-ph/0503173 (Djouadi), 1210.8166 (Dolan et al), 1206.6949 (Tang), 1404.0996 (Kumar & Martin), among many many others

Two Higgs doublet models, Randall-Sundrum gravitons, radions, stoponium, ...





Ideas we are exploring (my group + others on ATLAS)

- Continue to improve CPU algorithms, as CPU power consumption is large!
- Graph Neural Networks. Cool machine learning approach - can they fit inside FPGAs?
- Other machine learning approaches don't seem as advanced but there is room to explore (GNNs are the hot topic du jour)
- Speed-up in GPUs. Significant, but data transfer overheads remove much of the benefit. So far