ATLAS Prospects

PPAP Meeting
July 16th

Gabriel Facini
on behalf of ATLAS-UK

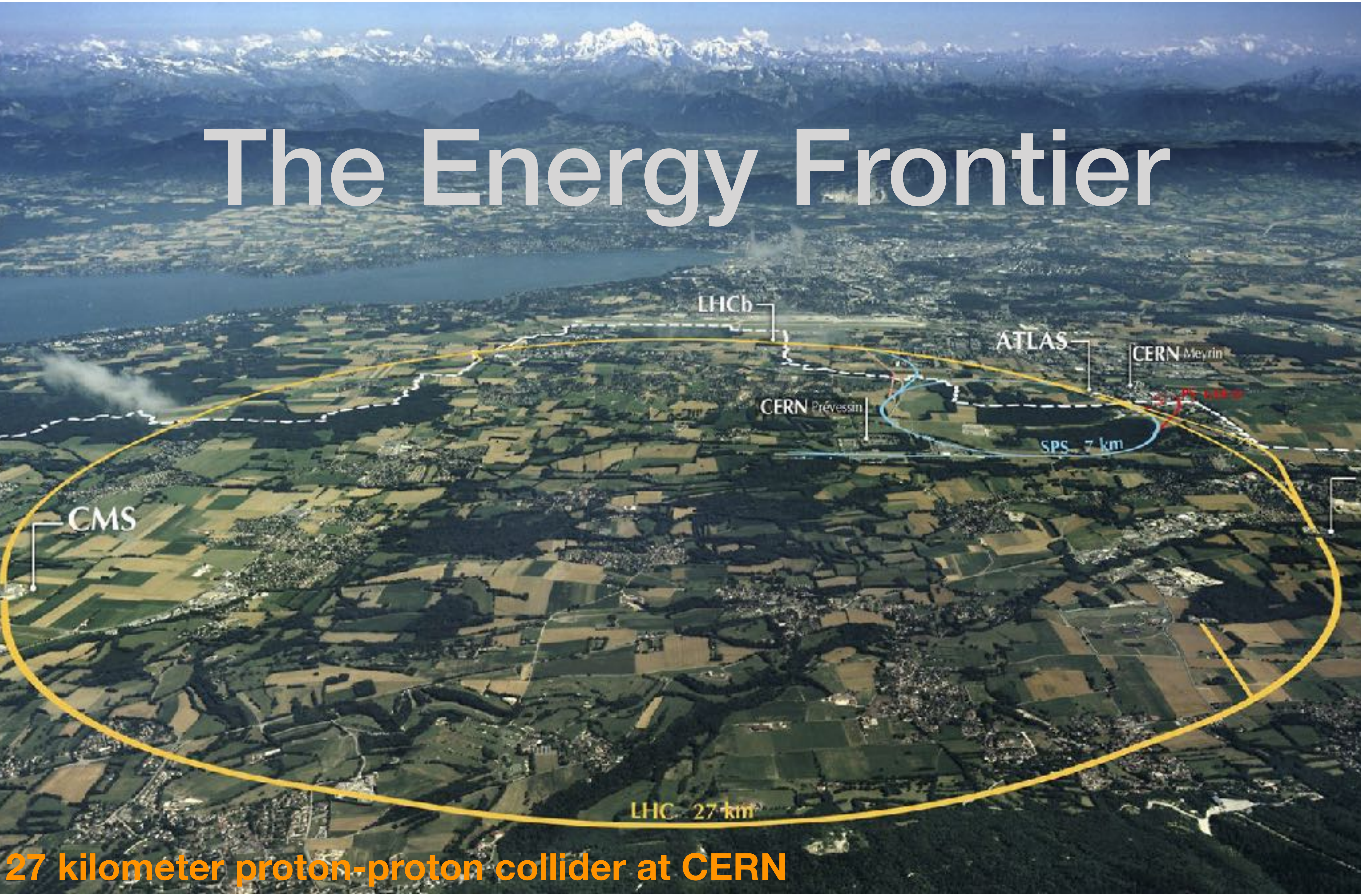
Overview

- Machine Overview: from LHC status to HL-LHC (common material)

- Discussion of physics over the next 5 years.
  The HL-LHC case and prospects have been discussed and documented. Let's focus on years leading up to it

- The next 5 years are critical in further developing the physics program in preparation for the extreme dataset of the HL-LHC.

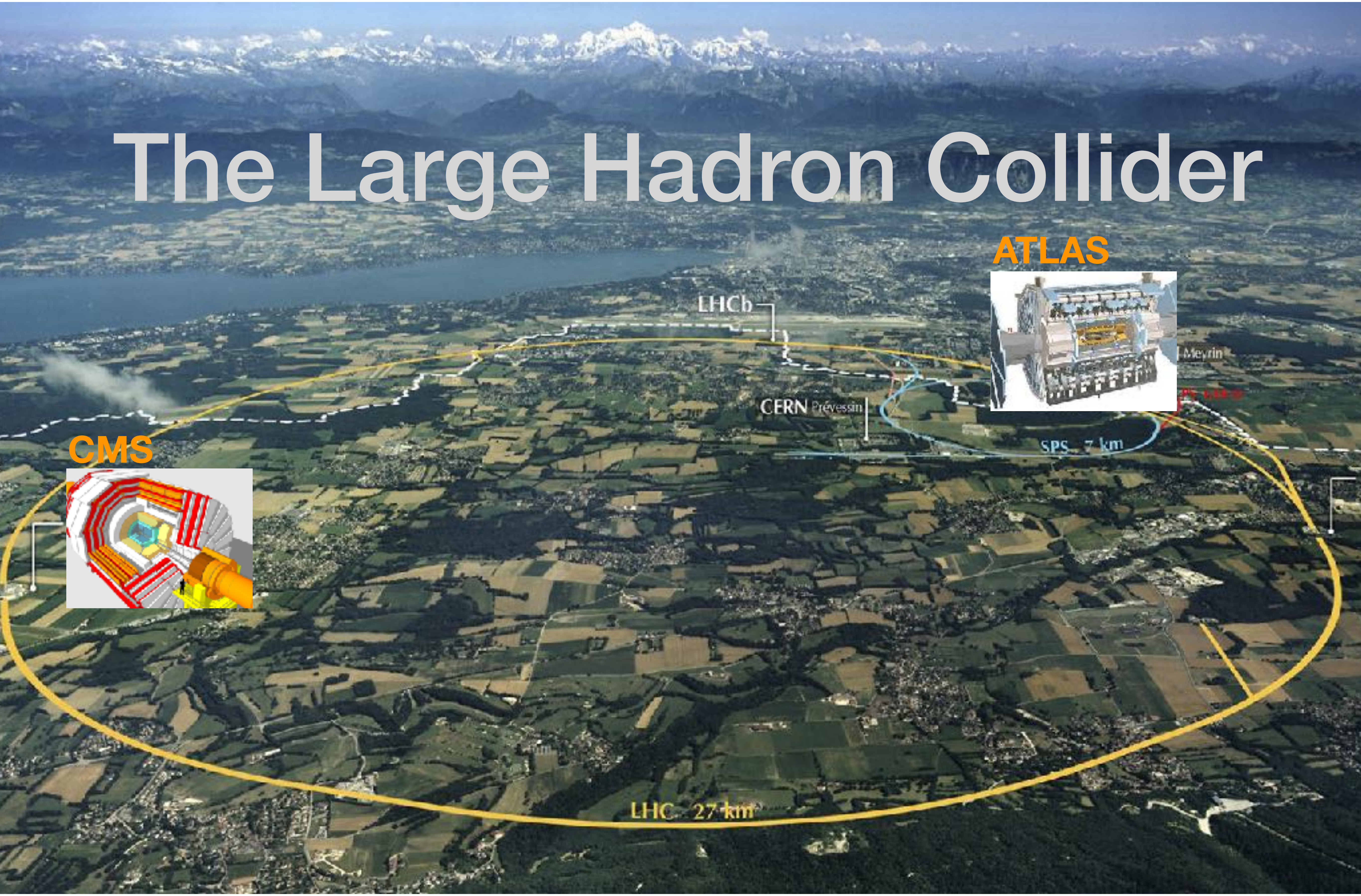
The Energy Frontier



27 kilometer proton-proton collider at CERN

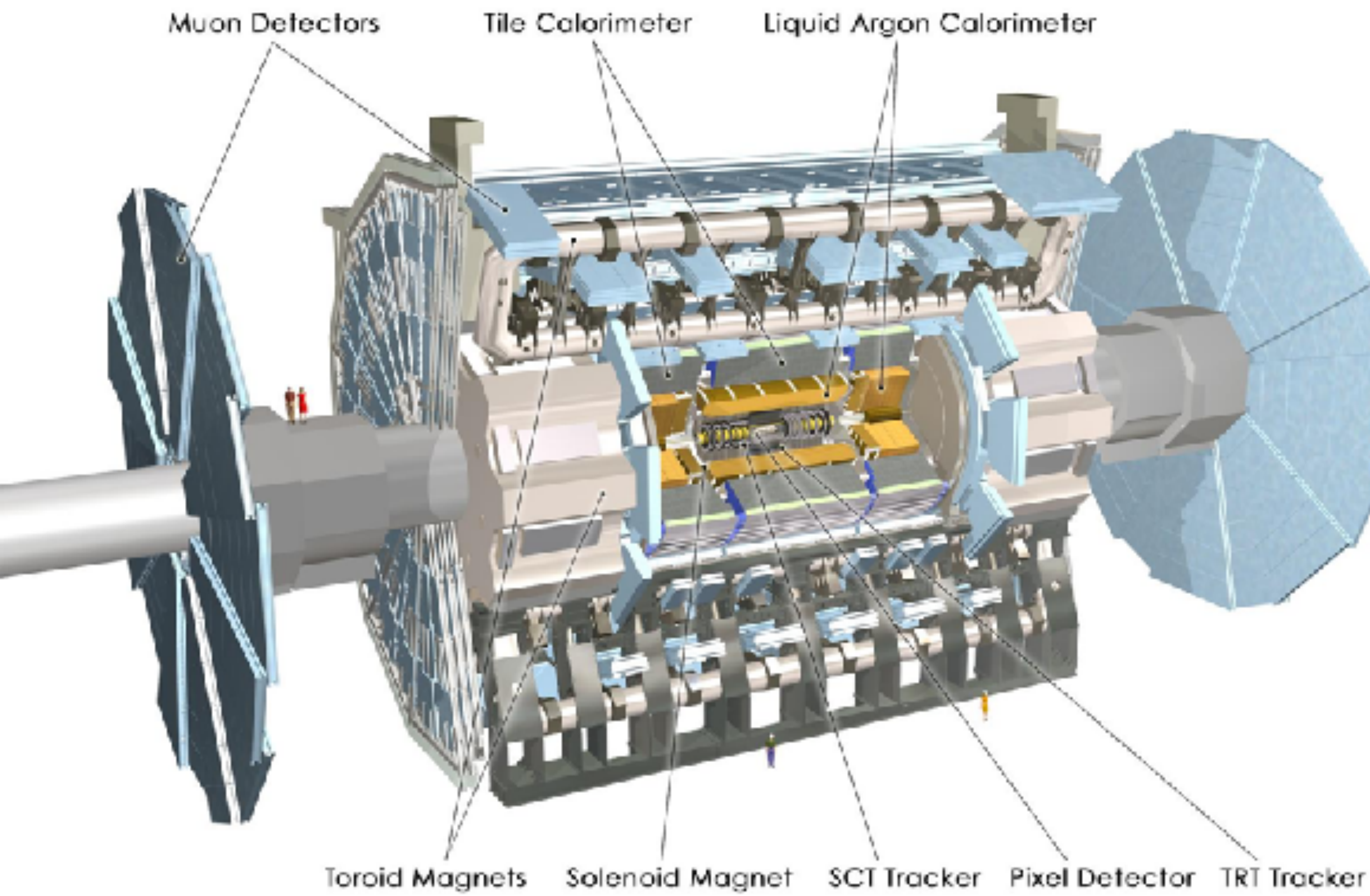
A big machine to probe small distances

The Large Hadron Collider



Two general purpose detector (ATLAS, CMS), two specialized detectors (LHCb, Alice)

General Purpose Detectors

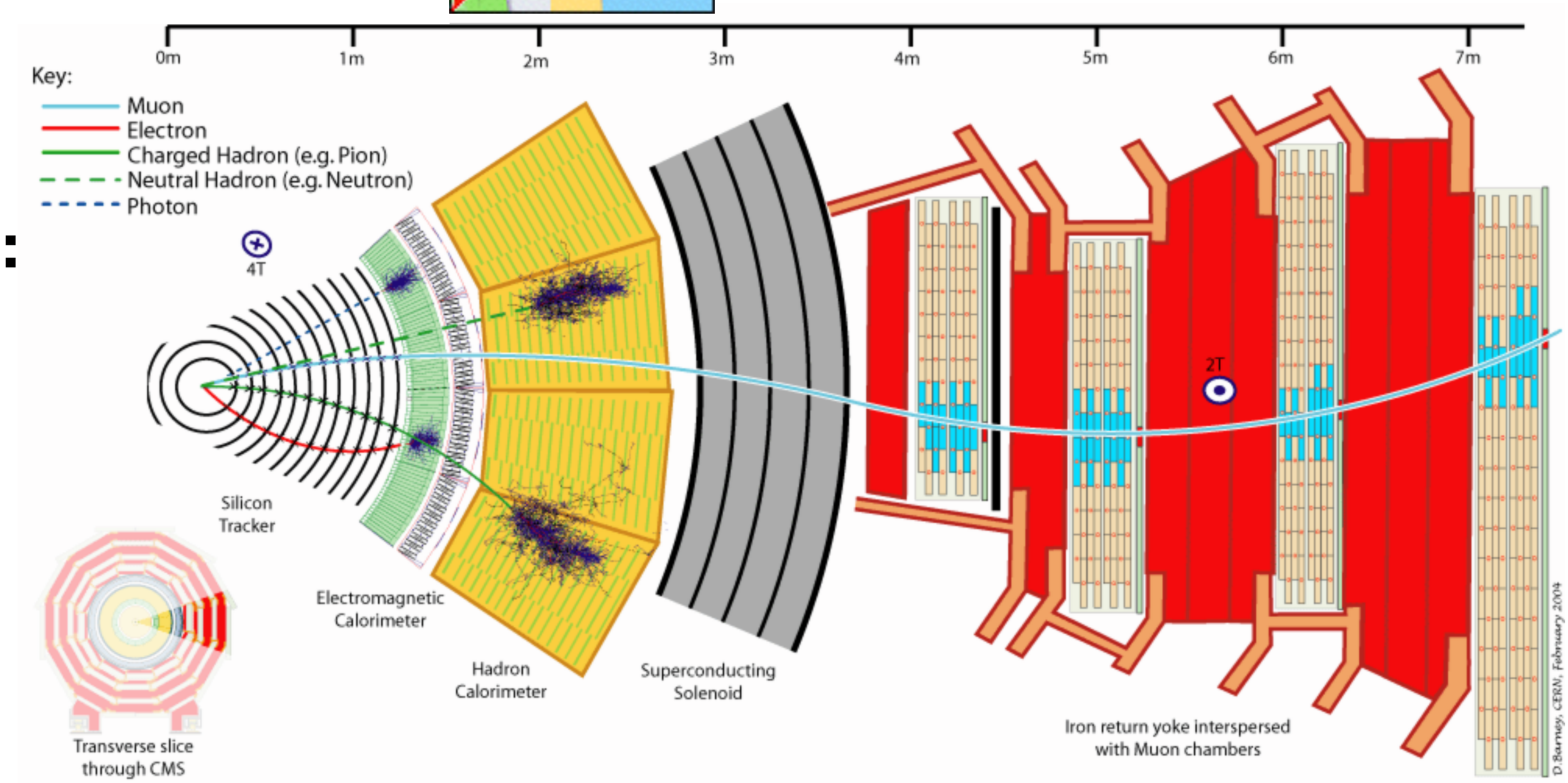


Not show: Trigger system which selects the most interesting ~0.0025% of collisions

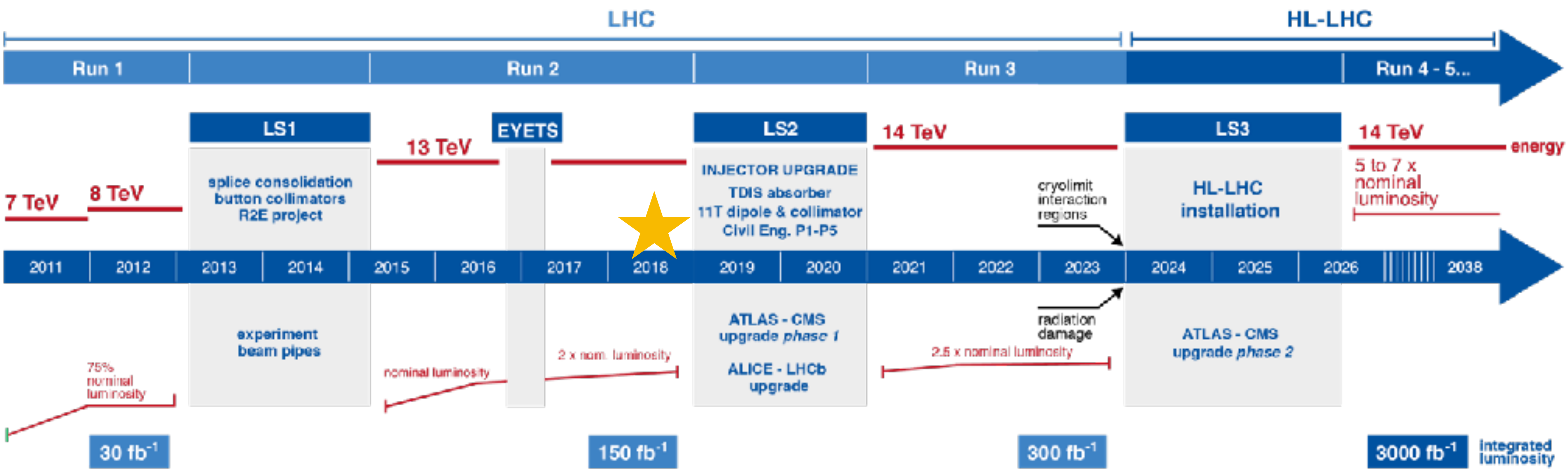
3 major sub-detectors (from in, out):

1. **Charged Particle reconstruction**
2. **Calorimetery**
3. **Muon Reconstruction**

Imbalance in transverse energy signals non-interacting particles

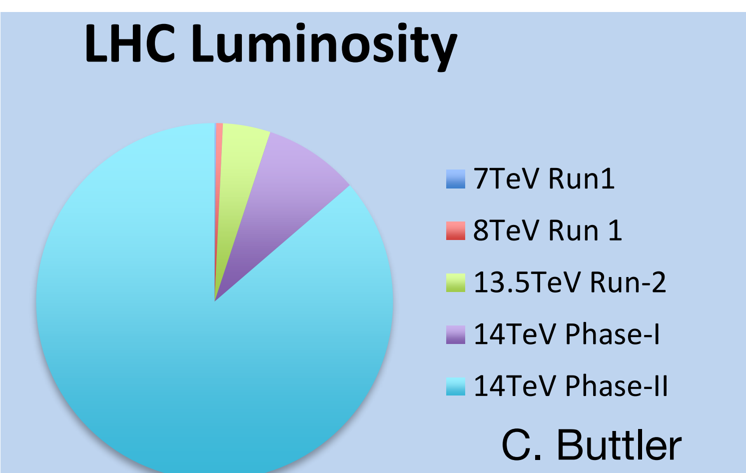


LHC Project Timeline



Summary of next major steps:

- 13 TeV data collection will end with Run at end of 2018
- 14 TeV data collection for 3 years after 2 year shut down
- LS3: Major upgrades and preparation for the high-luminosity (HL) LHC

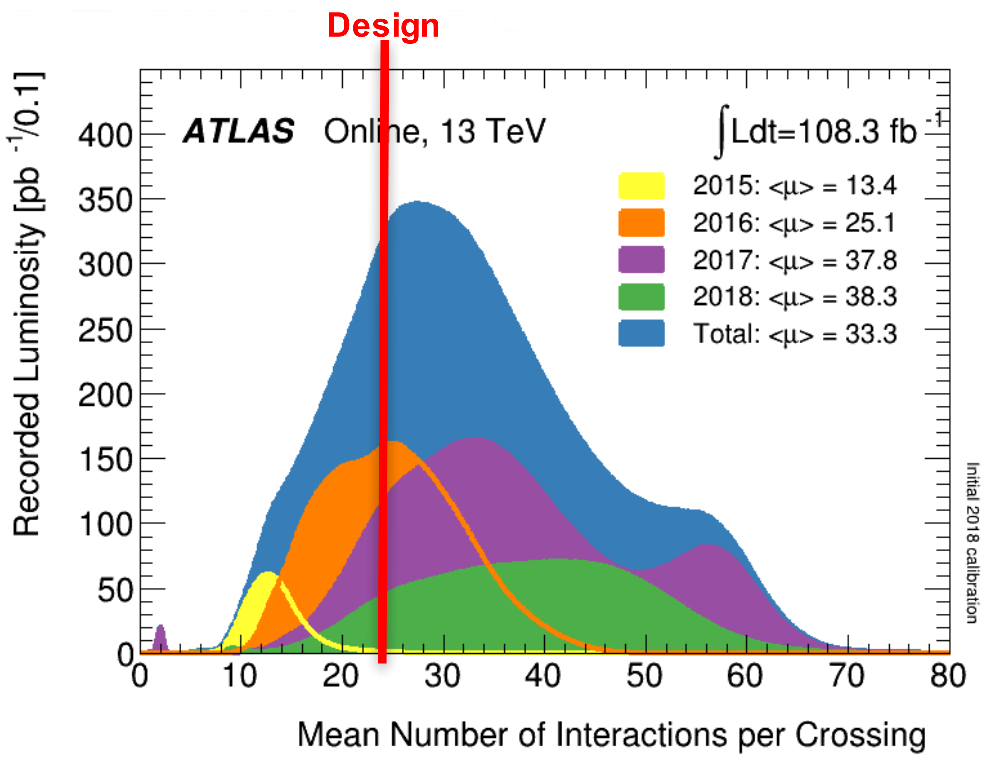


C. Buttler

HL-LHC Project In Words

- Higgs discovery raises immediate scientific questions
  - How is the hierarchy problem resolved in nature?
  - If Standard Model and cosmology apply at TeV scale, where is dark matter?
- Key science topics
  - Precise measurements of Higgs couplings and self-couplings
    - This tells us whether and how far the SM applies; self-couplings just within reach at HL-LHC
  - Inclusive supersymmetry searches, including hard-to-observe scenarios
    - Complementary to limits on new physics from other techniques; keep an open mind
  - Direct searches for BSM physics, including dark matter production
    - Complementary to direct DM searches and astrophysical measurements
- Implications for detector upgrade
  - High statistics needed to explore high masses, small couplings, rare decays
  - Need high lumi, high trigger acceptance, high reconstruction efficiency
    - Acceptance for W/Z/γ, and jet / energy flow resolution, must be as good or better than Run 2
  - **The UK programme addresses these points *directly***
  - Global reconstruction requires a balanced approach to sub-detector upgrades

LHC Data Collection

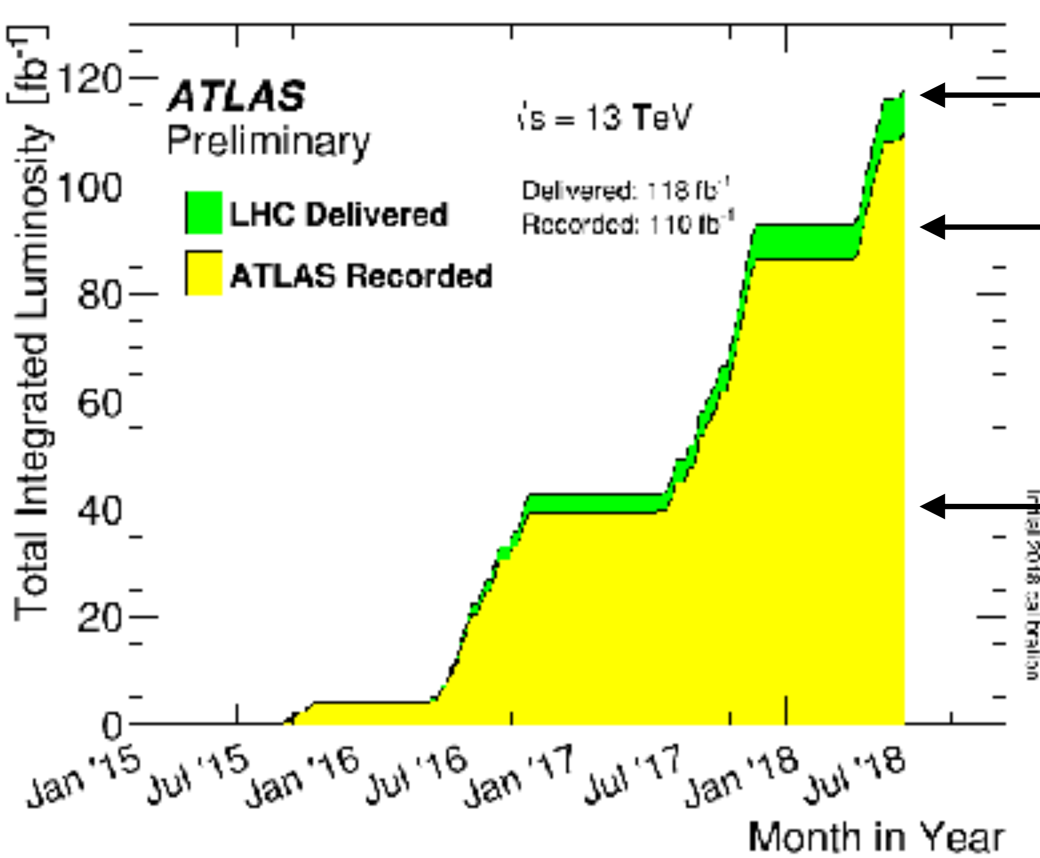


Pile-up conditions have been much more challenging in Run-2 than foreseen before data-taking.

Experiments have been up to the challenge!

Detailed understanding of LHC and detectors yield amazing precision for luminosity measurement <2% (10% was often assumed in the 90's).

similar plots from as CMS

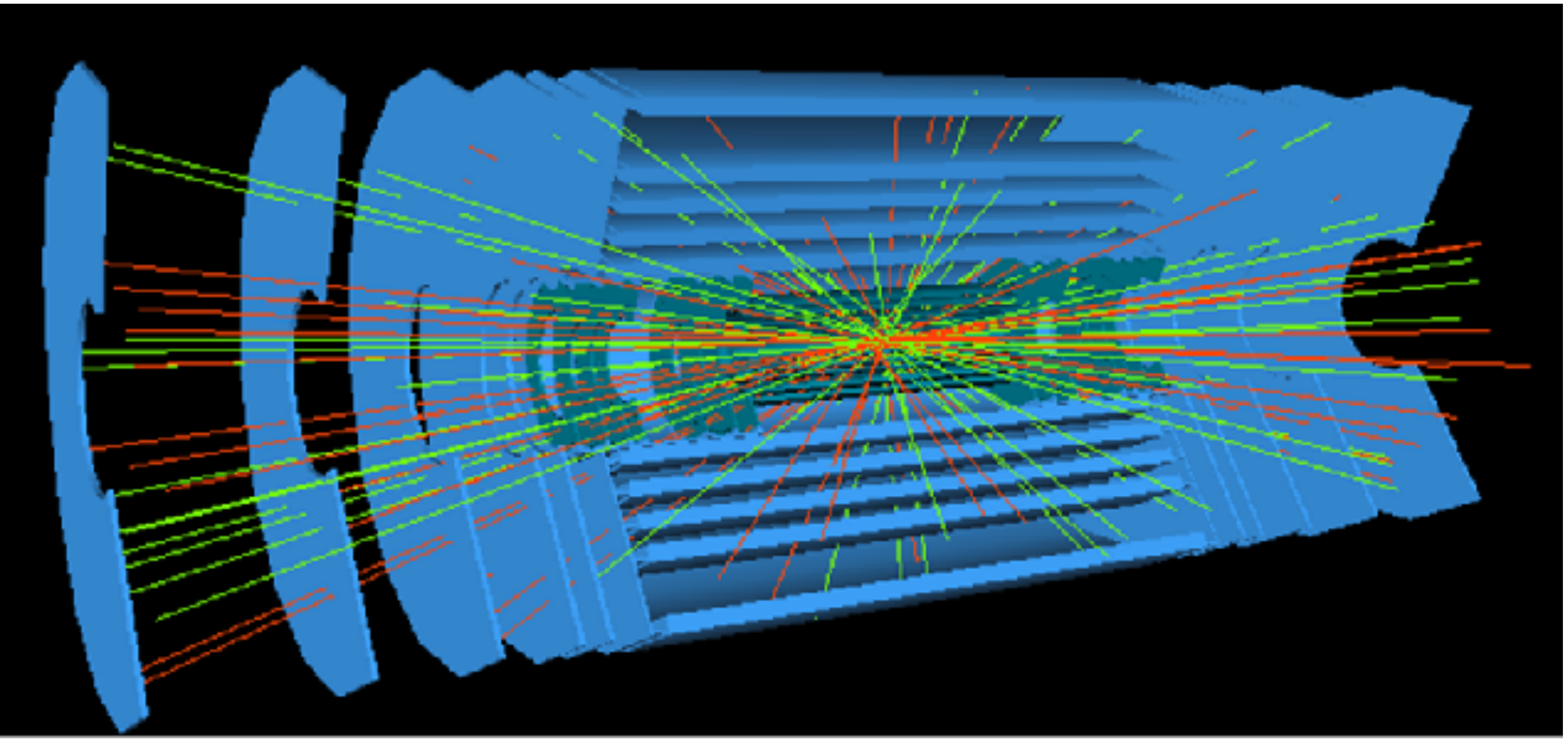


2015-2018 data-set
L=110/fb recorded

2015-2017 data-set
L=80/fb
Nice set of early results in recent conferences

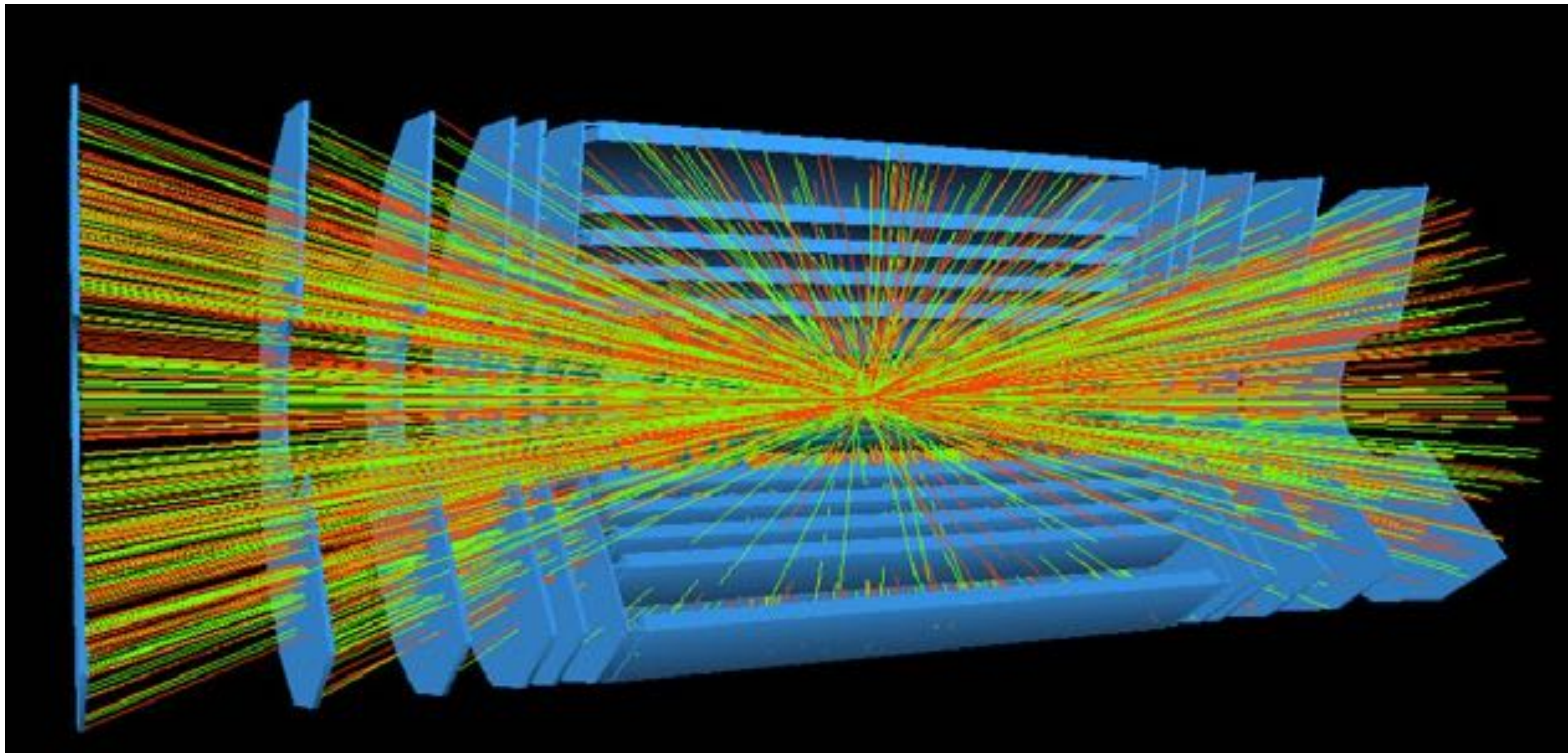
2015-2016 data-set
L=36/fb
Extensive set of publications on many topics

HL-LHC Conditions



A collision with O(20) interactions: ~now

A collision with O(200) interactions: HL-LHC



ATLAS Program

A subset of the ATLAS-UK program is shown
i.e. Flavor physics not mentioned,
Measurement program is under represented

Connections

How the general physics area of this project fits within a possible future European Strategy (timeline of 2020-2030)?

> *"Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030."*
> *-ES 2013*

UK involvement: All plots shown and analyses highlighted have strong UK involvement but only a subset of the full ATLAS-UK activities. Individual institute are not noted as the subset chosen was a personal choice.

ATLAS-UK is 10.7% of ATLAS authors, but punches above it's weight (when funded properly)

Higgs Physics Program

Higgs measurements at the LHC test a new part of SM
This is a unique deliverable of the LHC

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

Everything experimentally confirmed before 2012

$$+|D_\mu\phi|^2$$

Gauge boson interactions with new scalar.
Discovery channels and measured mass to 0.2%

$$+\psi_i y_{ij}\psi_j\phi + h.c.$$

Yukawa coupling with new scalar. New interaction type
Single experiment observations this year!

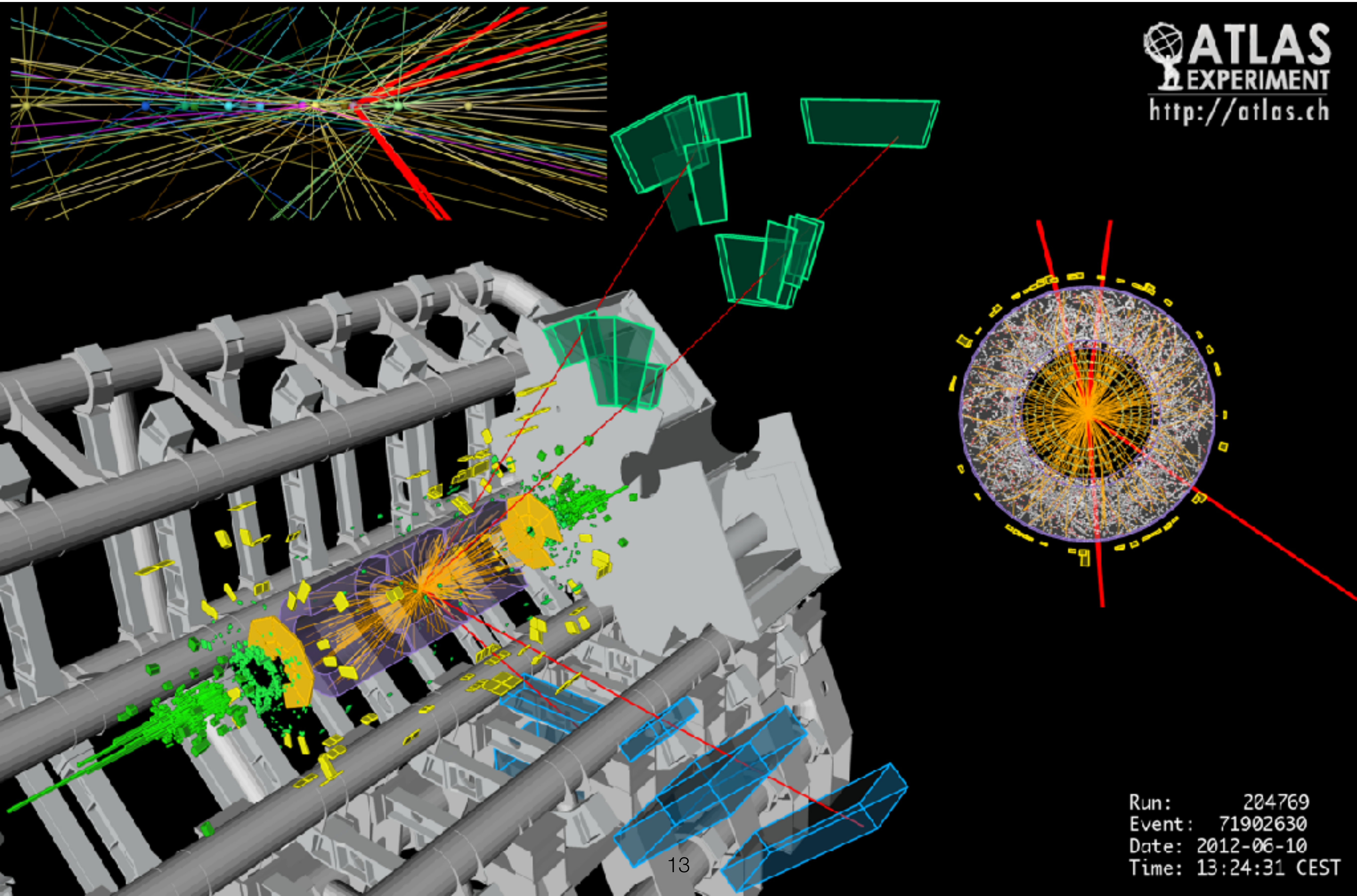
$$-V(\phi)$$

Higgs potential
To be fully explored with the HL-LHC

Also:
Determined CP nature
Observed all major production modes

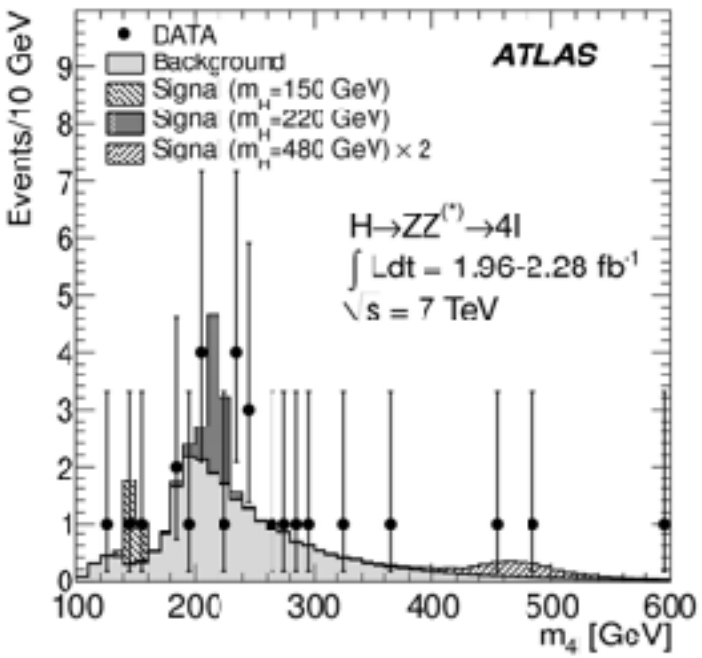
Higgs

A “simple” example elucidates the program

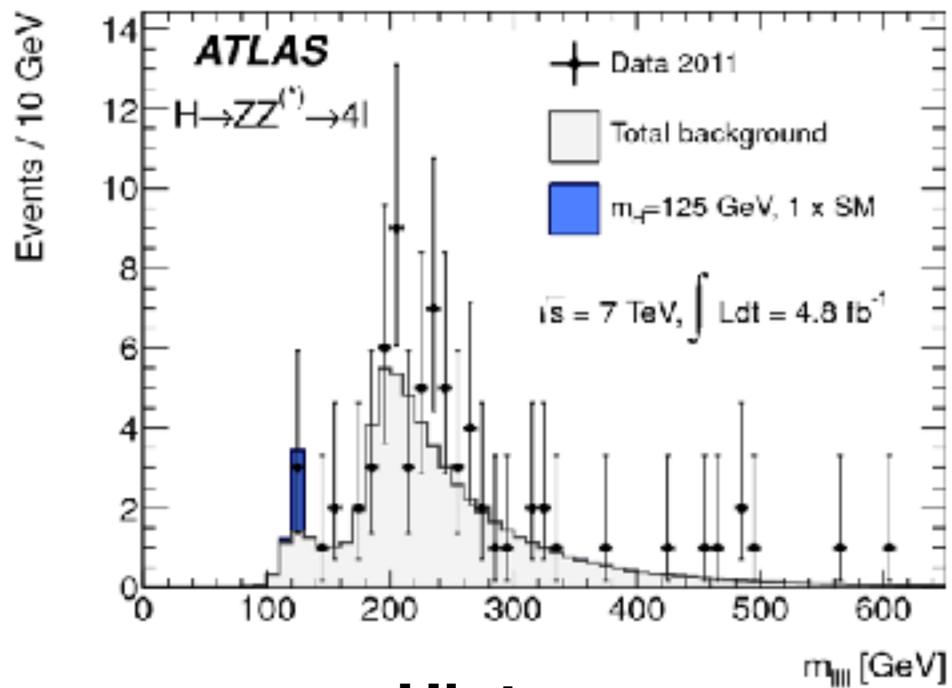


Higgs Example

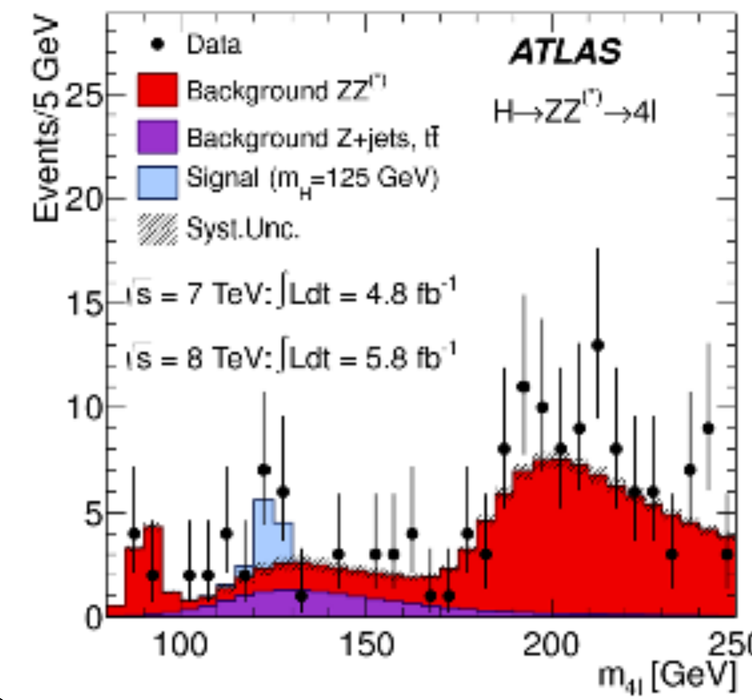
With a “simple” example, most of the program is elucidated



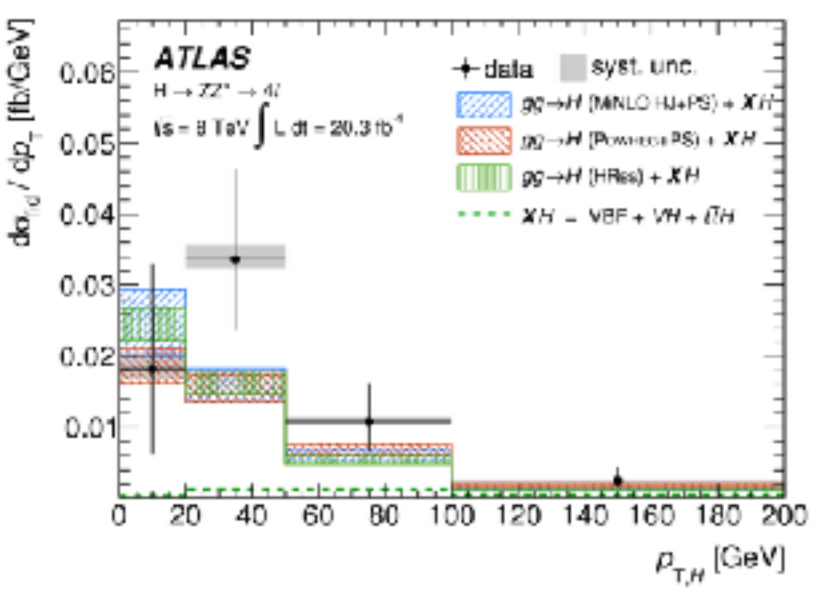
Search



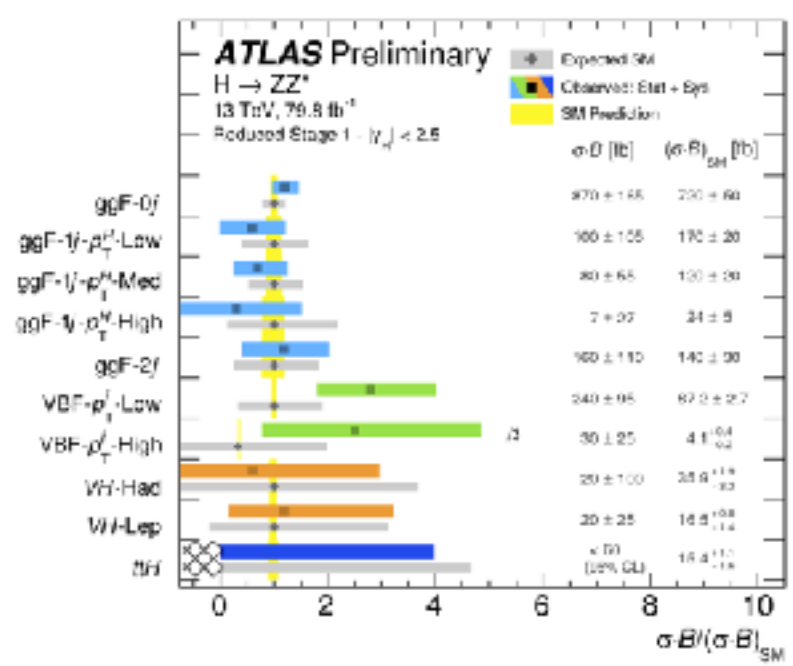
Hints

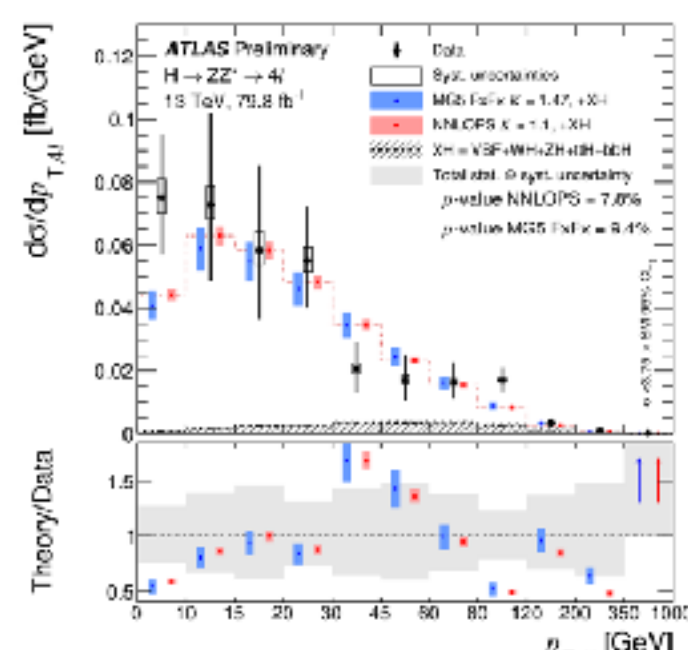


There is it!



Start measurements





detailed measurements

Higgs Progress

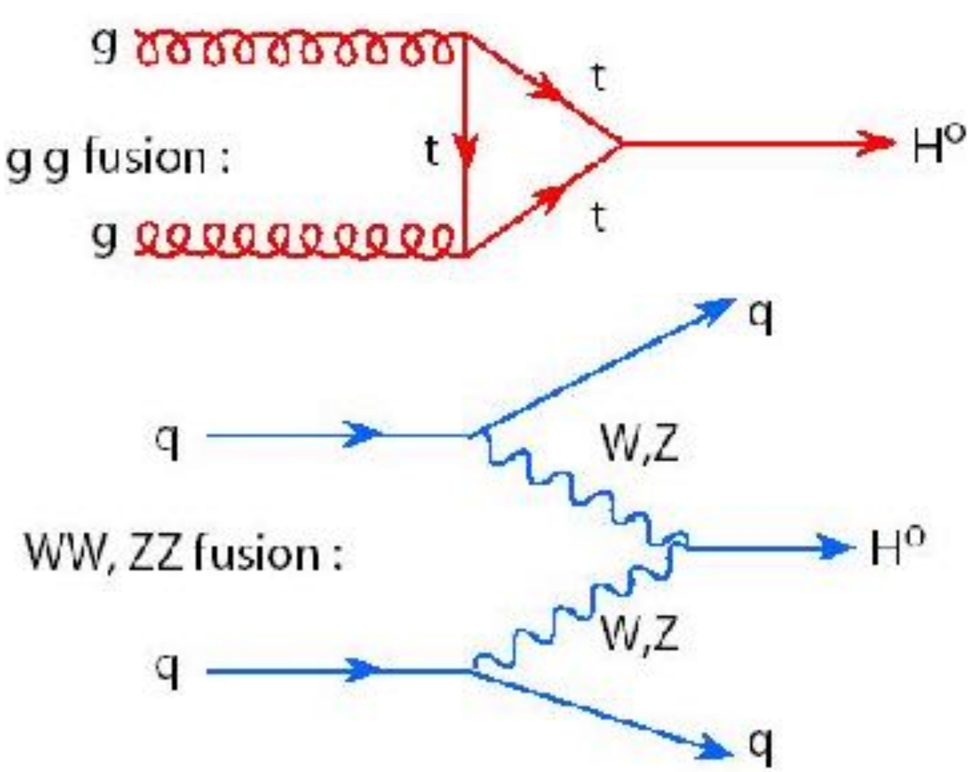
- Run 1
- Run 2
- Run 3
- HL-LHC
- ☆ Current

Run 1 and **Run 2** gave us the first-ever *detailed* measurements

exploring Higgs & coupling to gauge bosons

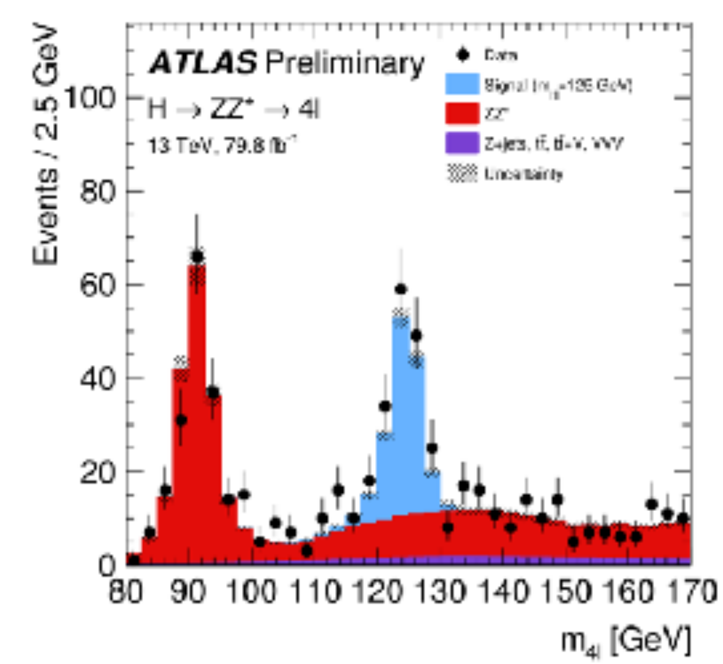
Looking ⟶ **Learning about Higgs** ⟶

Production	Decay	Search	Hints	There it is!	Simple Measurements	Detailed Measurements	Ultimate Precision
ggF, VBF (ttH, VH)	H(yy)	Gauge Bosons Interactions				★	
	H(ZZ)					★	
	H(WW)				★		



	H → bb	58%
☞	H → WW*	21%
	H → ττ	6%
☞	H → ZZ*	2.6%
☞	H → γγ	0.2%

For H→WW and H→ZZ only leptonic decays



Higgs Progress

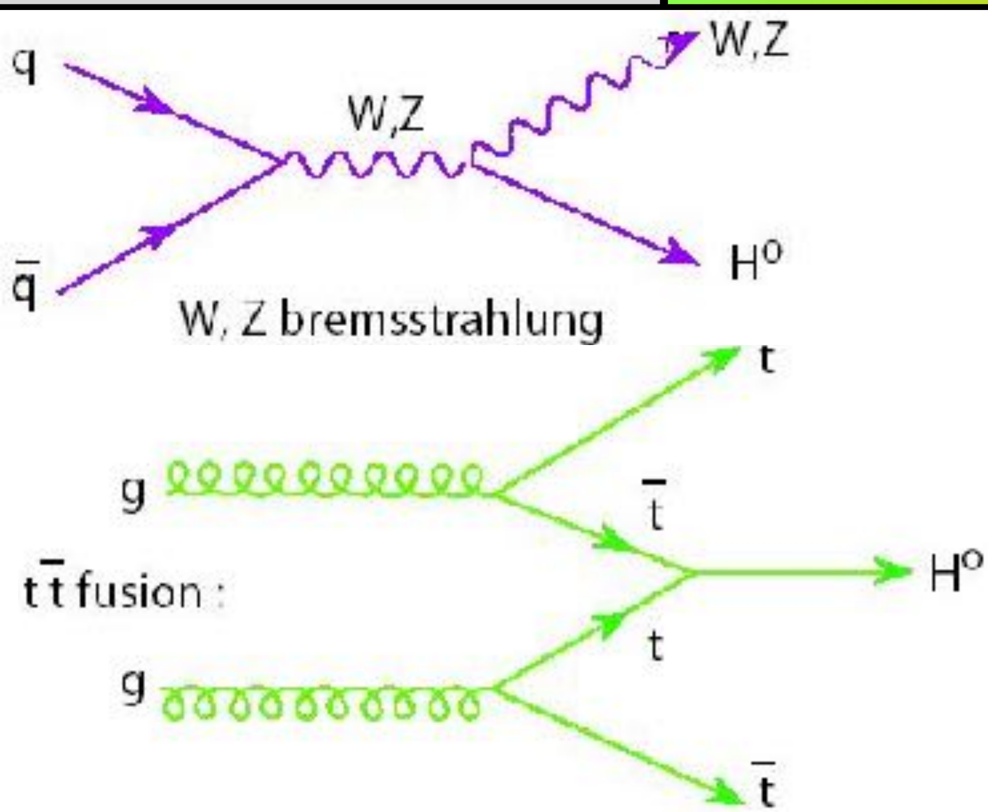
- Run 1
- Run 2
- Run 3
- HL-LHC
- ☆ Current

Now through **Run 3** will see first-ever *detailed* measurements

exploring Higgs coupling to heavy fermions

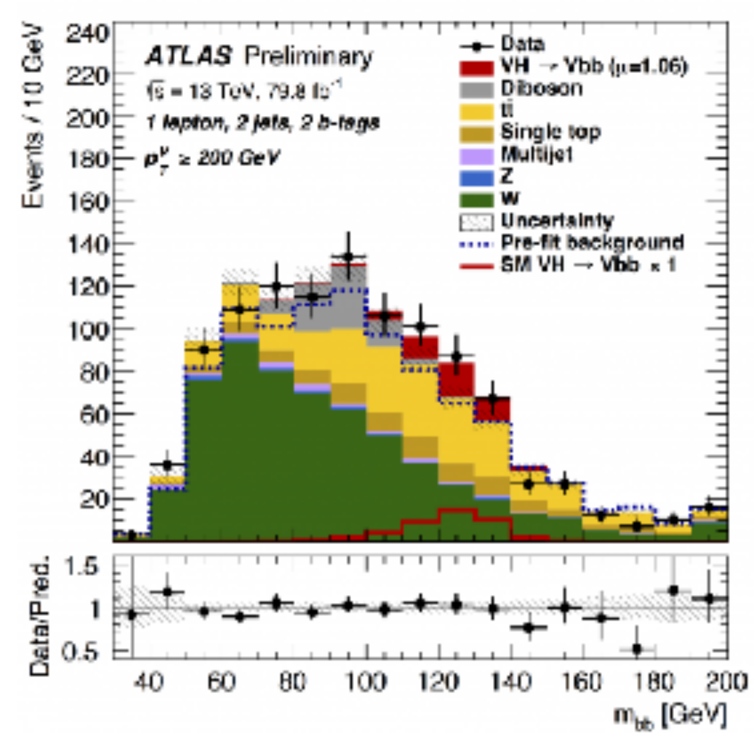
Looking ⟶ **Learning about Higgs** ⟶

Production	Decay	Search	Hints	There it is!	Simple Measurements	Detailed Measurements	Ultimate Precision
ggF, VBF (ttH, VH)	H(tau tau)				★		Run 3
ttH	any	3rd Generation Fermion Yukawa Couplings		★		Run 3	
VH	H(bb)			★		Run 3	



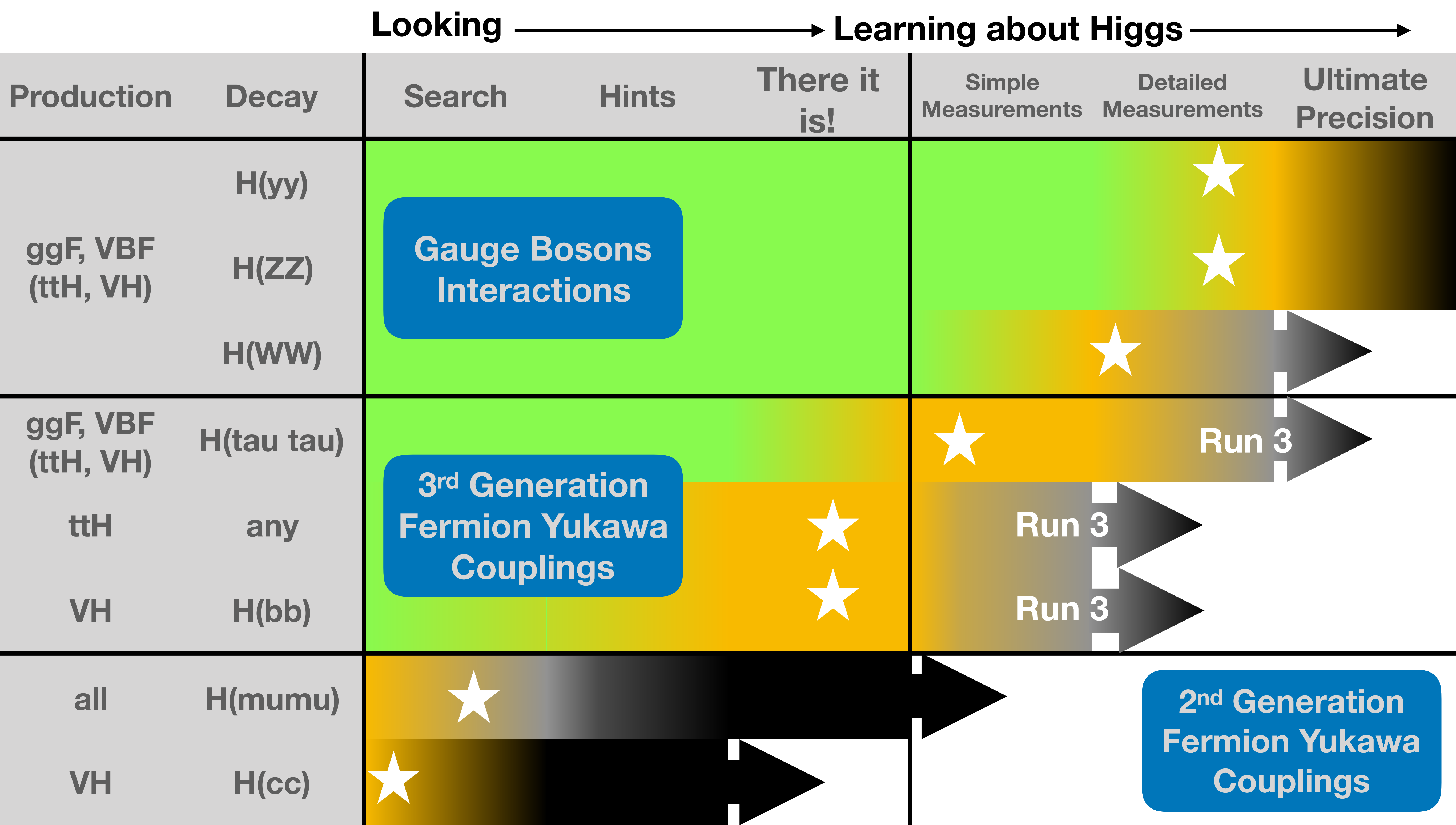
☞ $H \to bb$	58%
$H \to WW^*$	21%
☞ $H \to \tau\tau$	6%
$H \to ZZ^*$	2.6%
$H \to \gamma\gamma$	0.2%

For H→WW and H→ZZ only leptonic decays

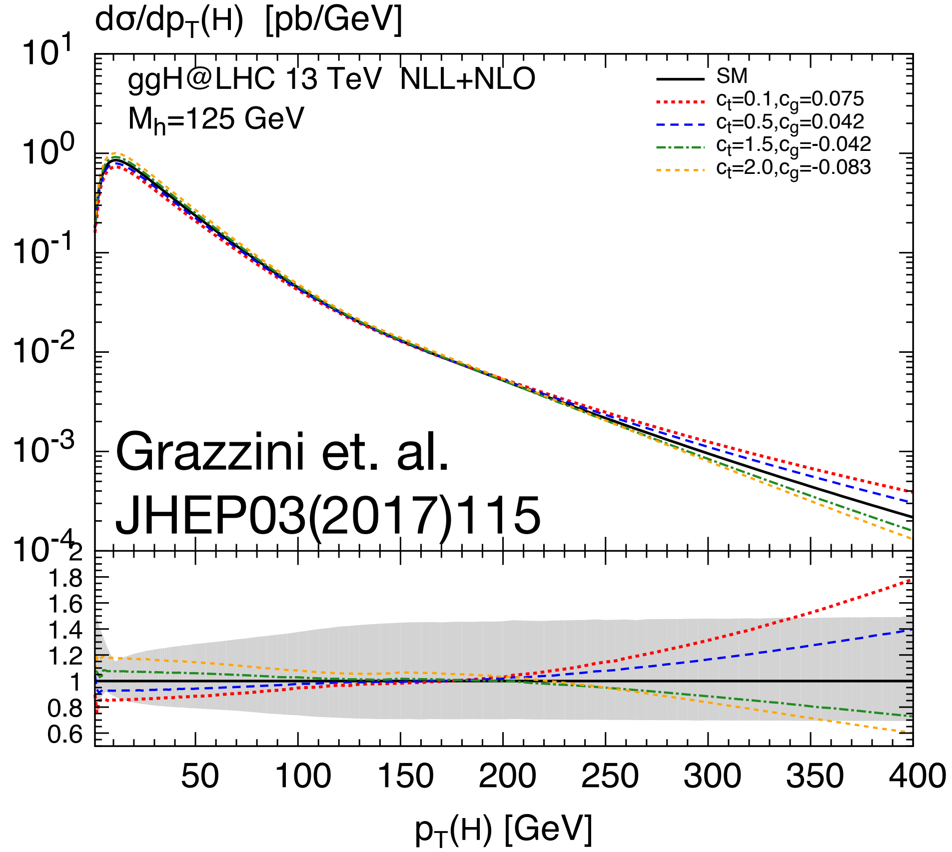


Higgs Progress

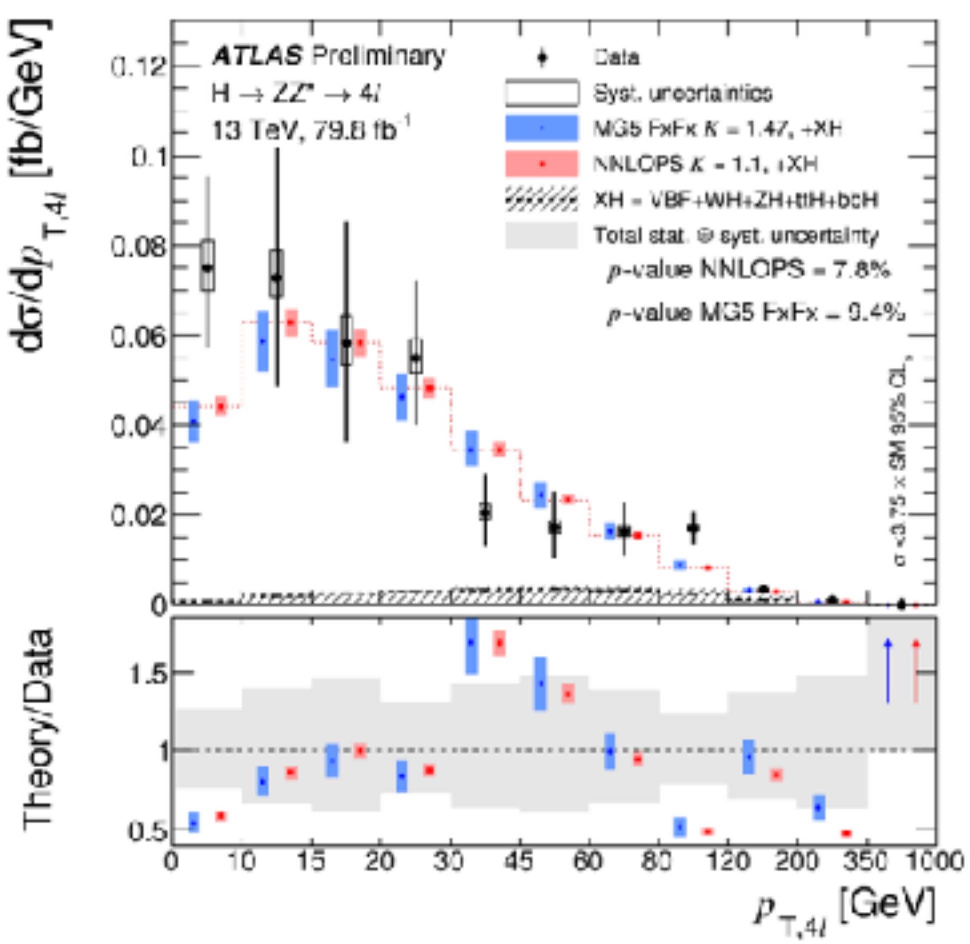
Beyond heavy fermions, **the long-term future include**
exploring Higgs coupling to second generation fermions



Excitement in Run 3

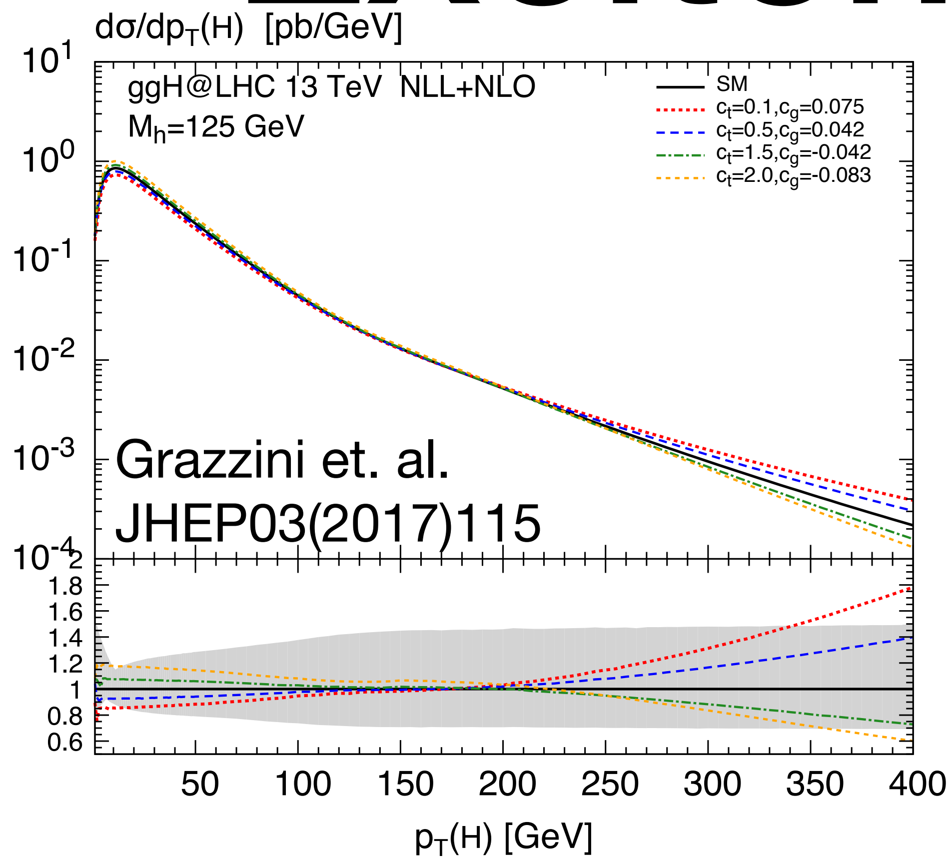


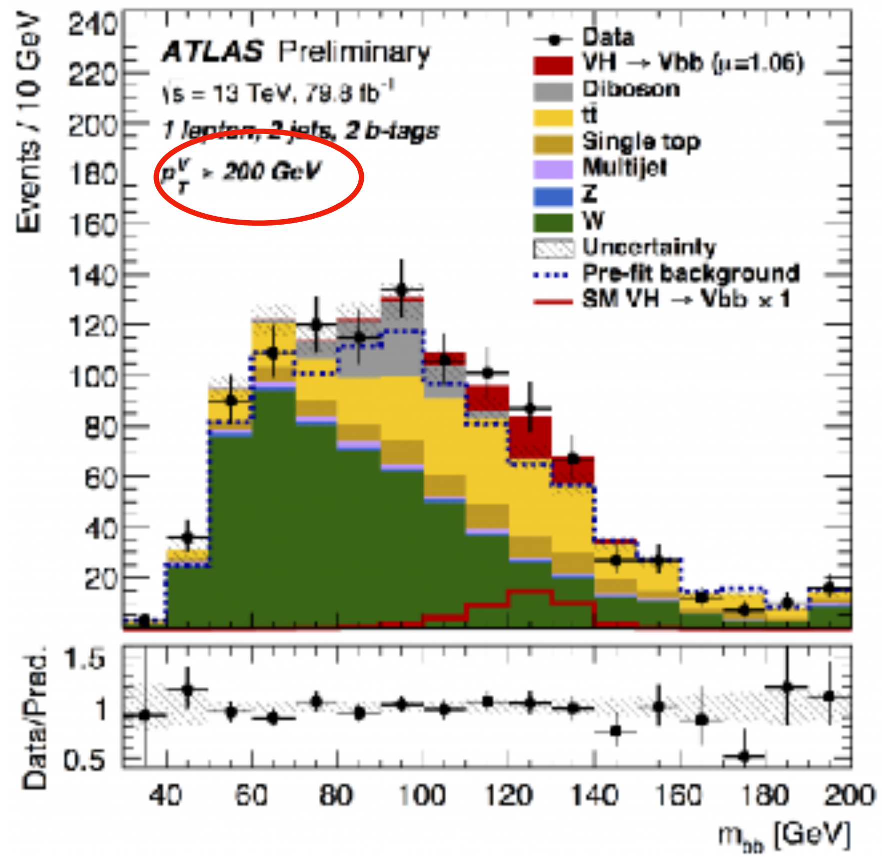
Higgs pT spectrum is sensitive to BSM effects and Yukawa couplings to light fermions



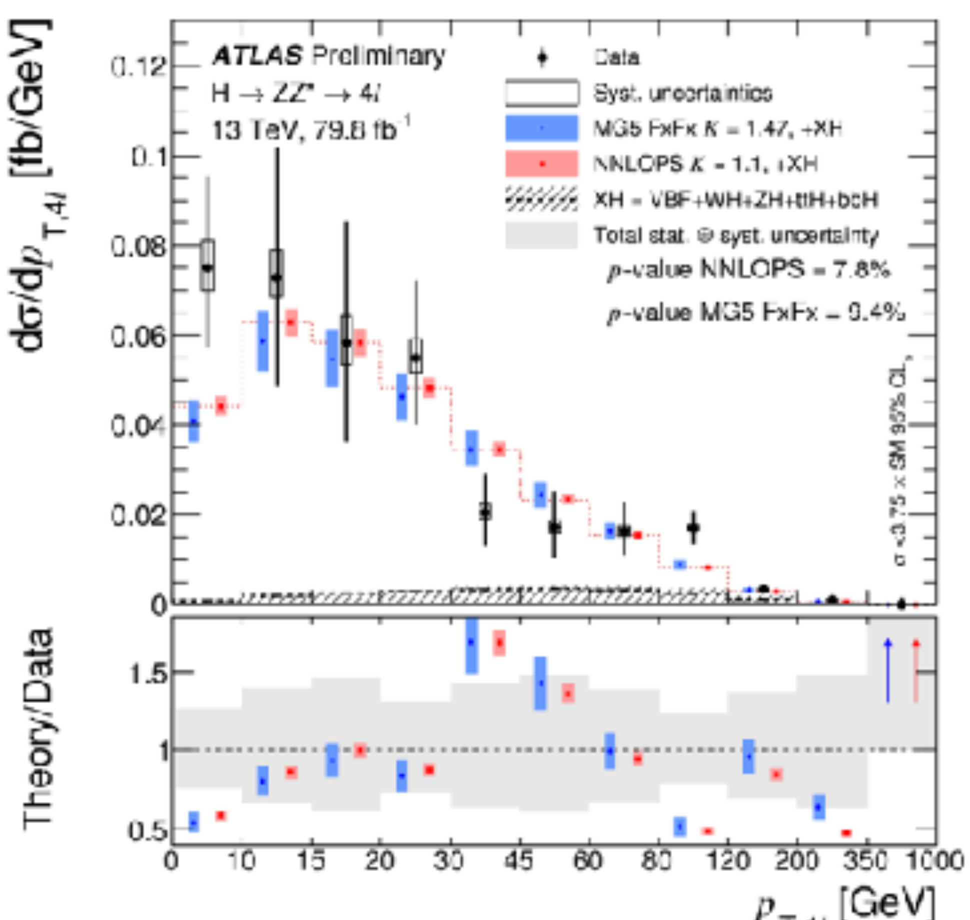
Current measurements run out of statistics at larger pT(H)

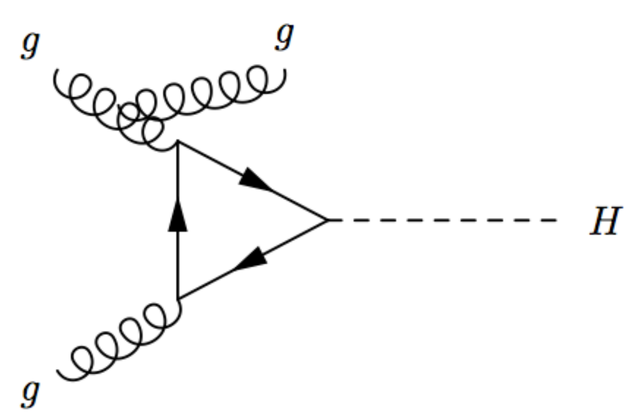
Excitement in Run 3

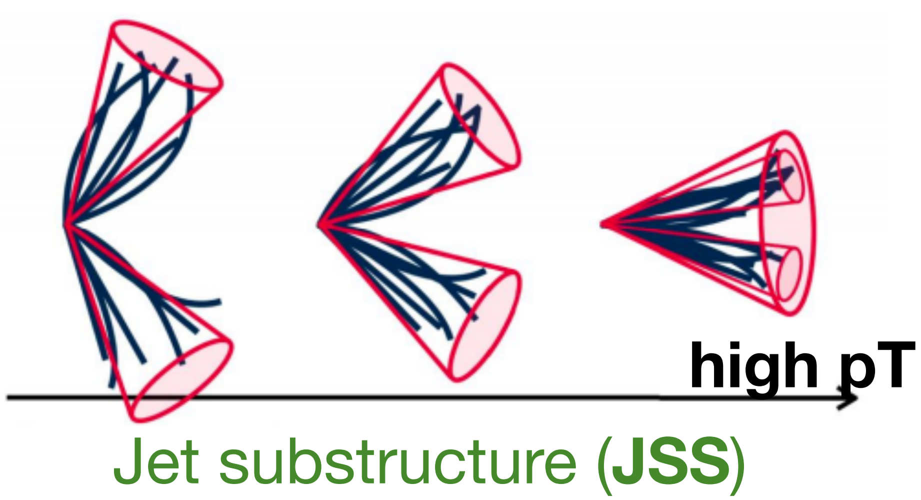




VH and ttH will contribute in Run 2/3





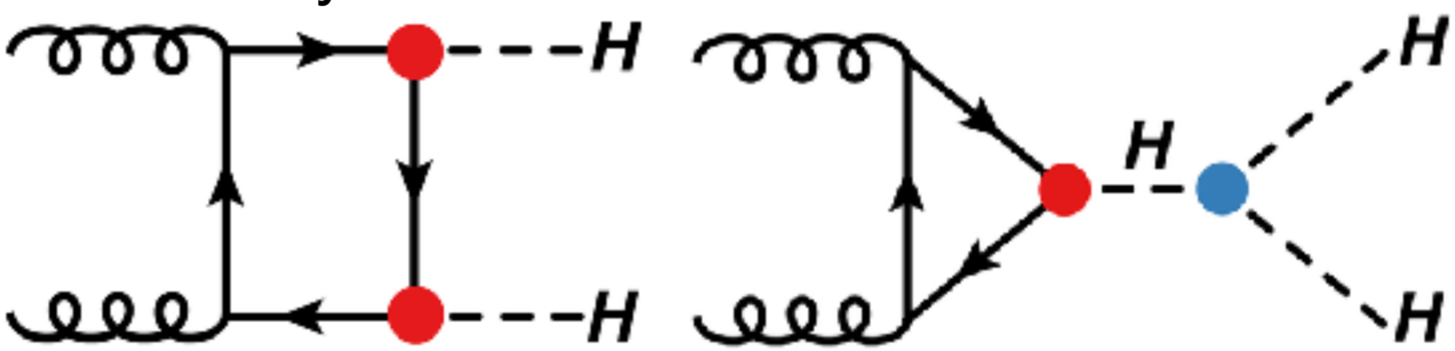


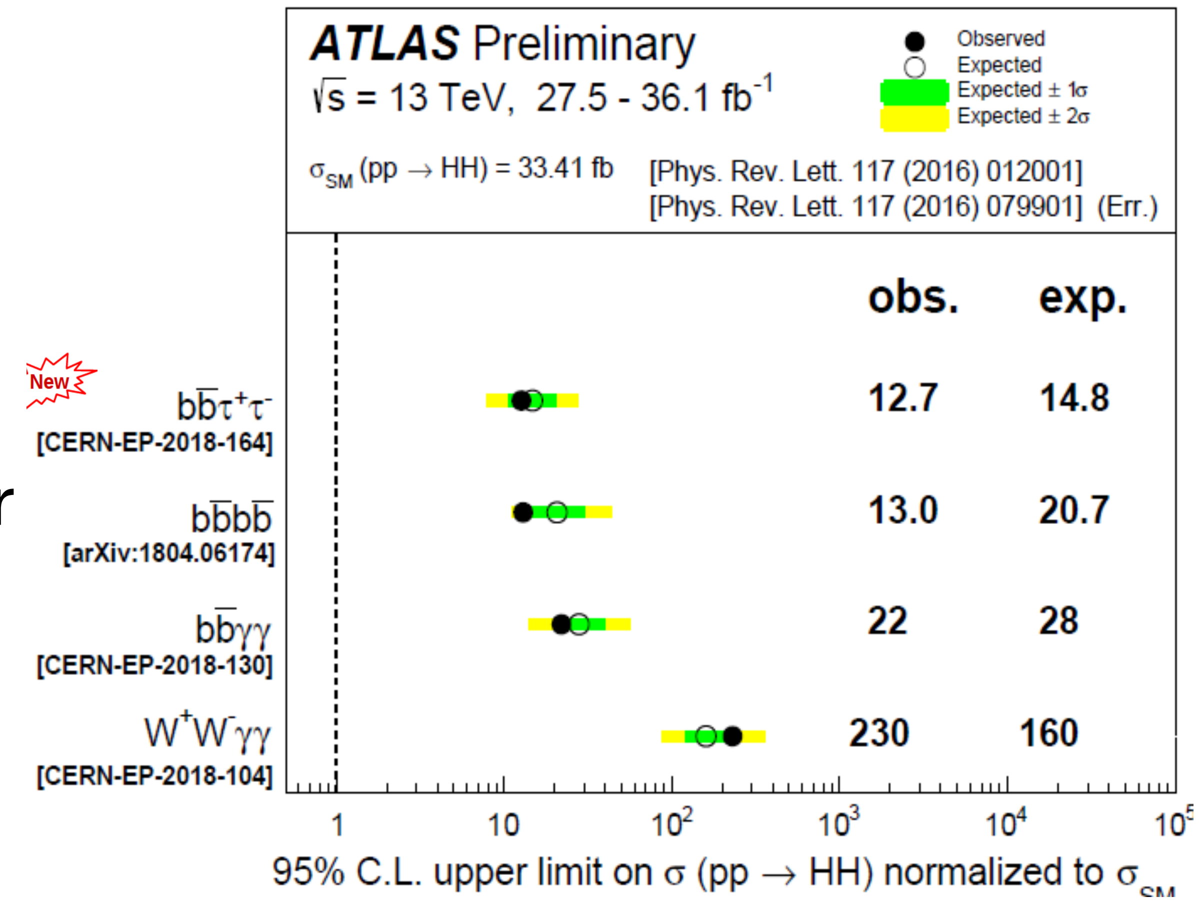
gg->H->bb will soon be established at ATLAS and **start** at 450 GeV

More Higgs

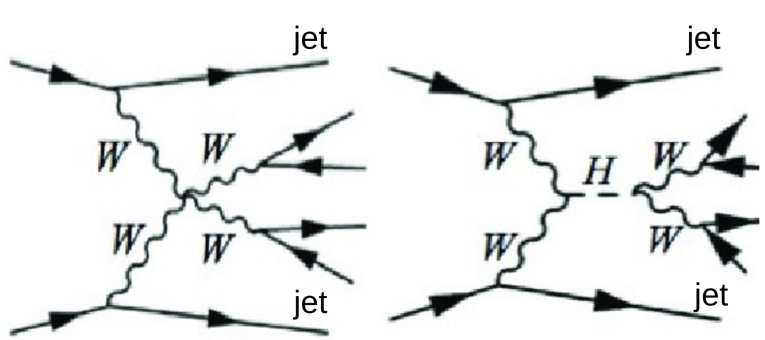
Cannot cover all in interesting stuff…so flash somethings

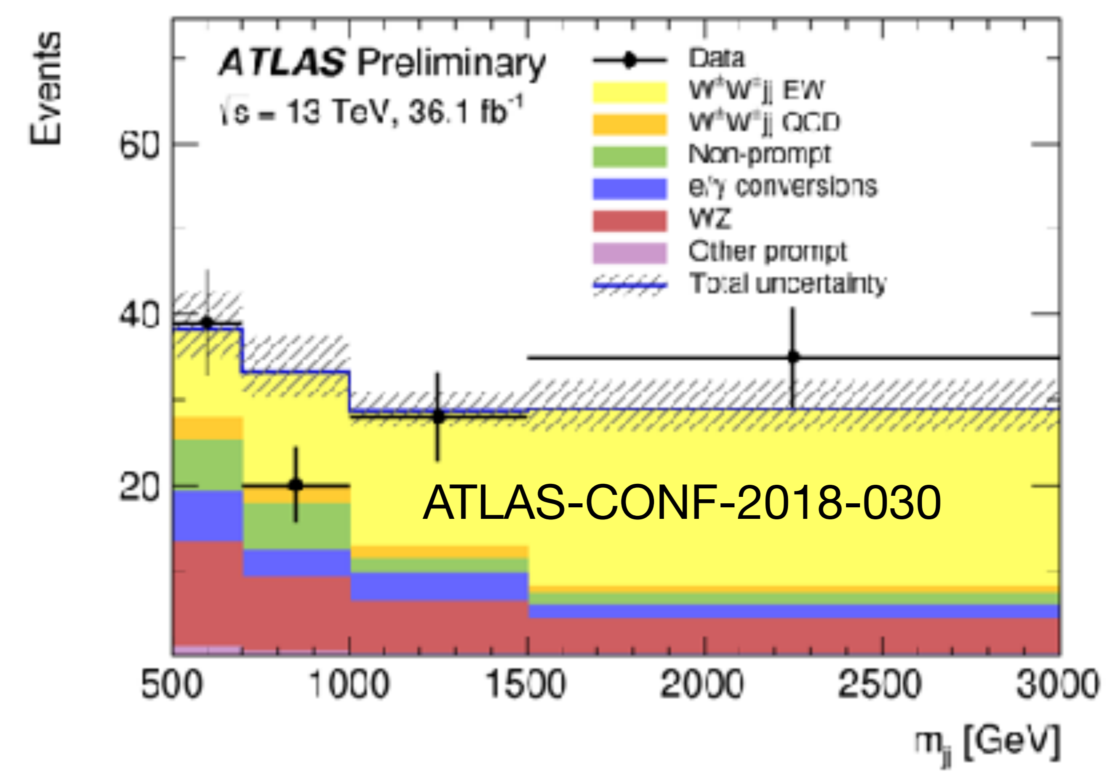
- **Higgs self coupling is probed via HH production measurements.** Watch out how the HH program is optimized in preparation for sensitivity with the HL-LHC





- **Higgs boson needed to restore unitarity of the WW scattering cross-section.** Watch out for the evolution of the program which had 1st observation in one channel



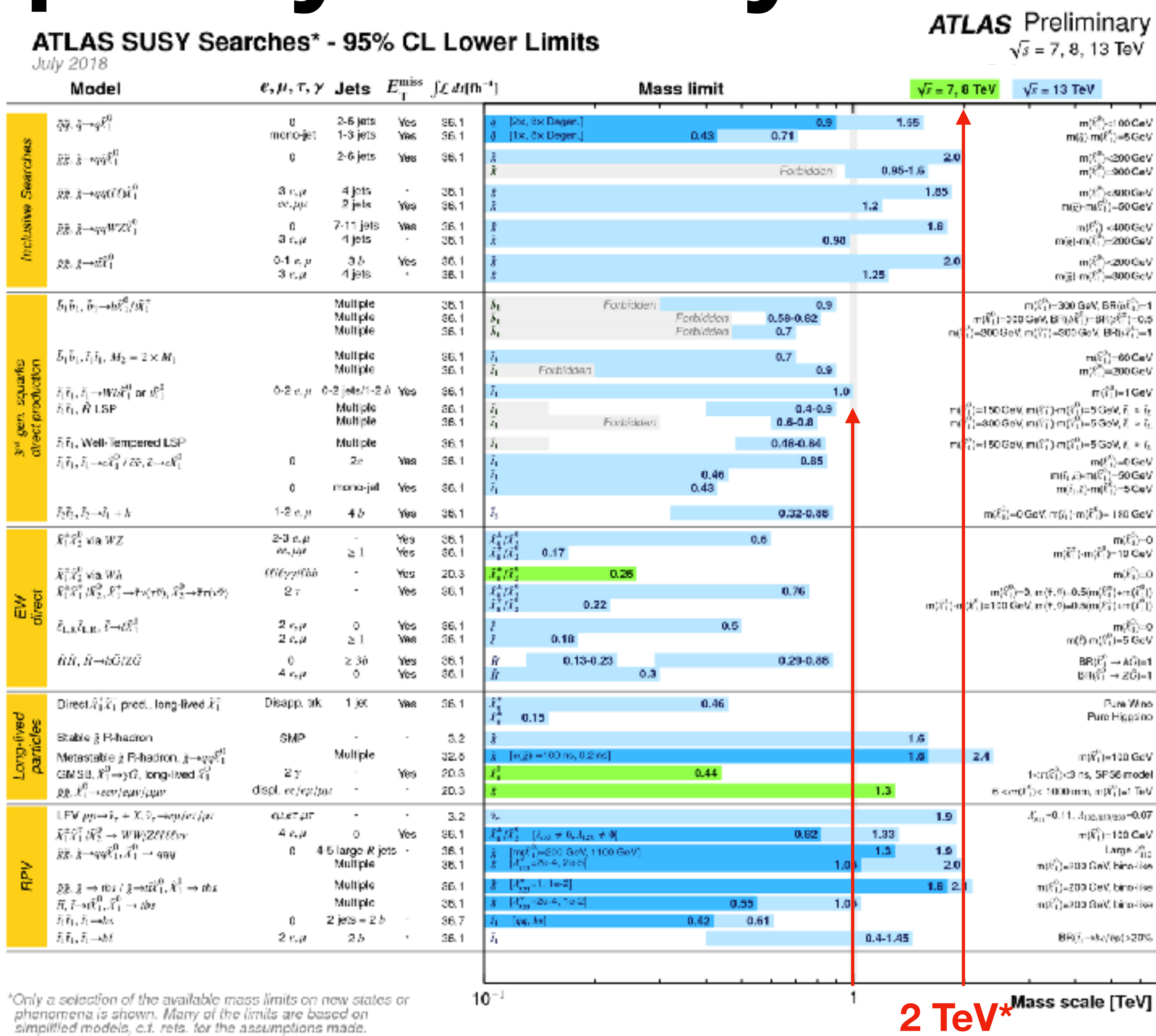


BSM Physics Program

- The LHC is a discovery machine built to find physics beyond the SM (BSM)
- Large expansion in discovery potential with jump from 8 -> 13 TeV
- Often hear discovery potential drying up or only returning with the HL-LHC.
    - This is an exaggeration! A few examples to follow

Supersymmetry

- Very satisfying theoretically as it provides
    - Dark Matter candidates
    - solves hierarchy problem
    - unification of the forces



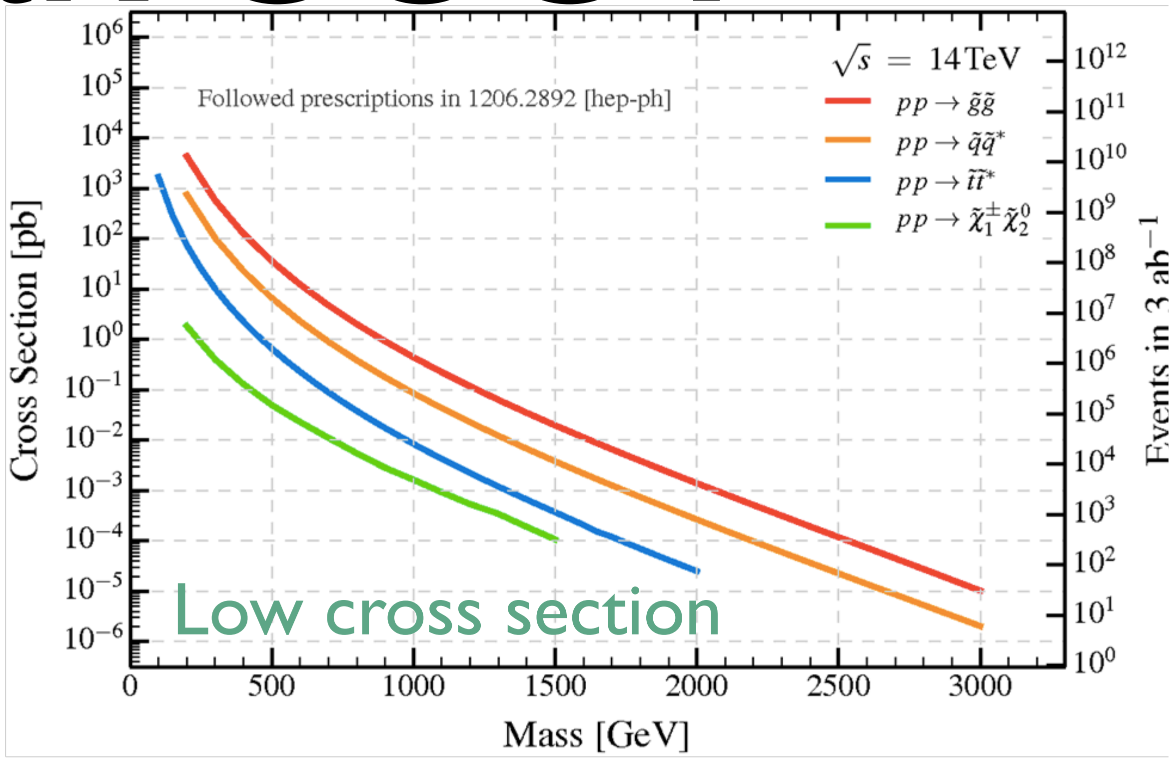
Limits on gluino @ 2 TeV physiological boundary of "naturalness" (Barbieri-Giudice)

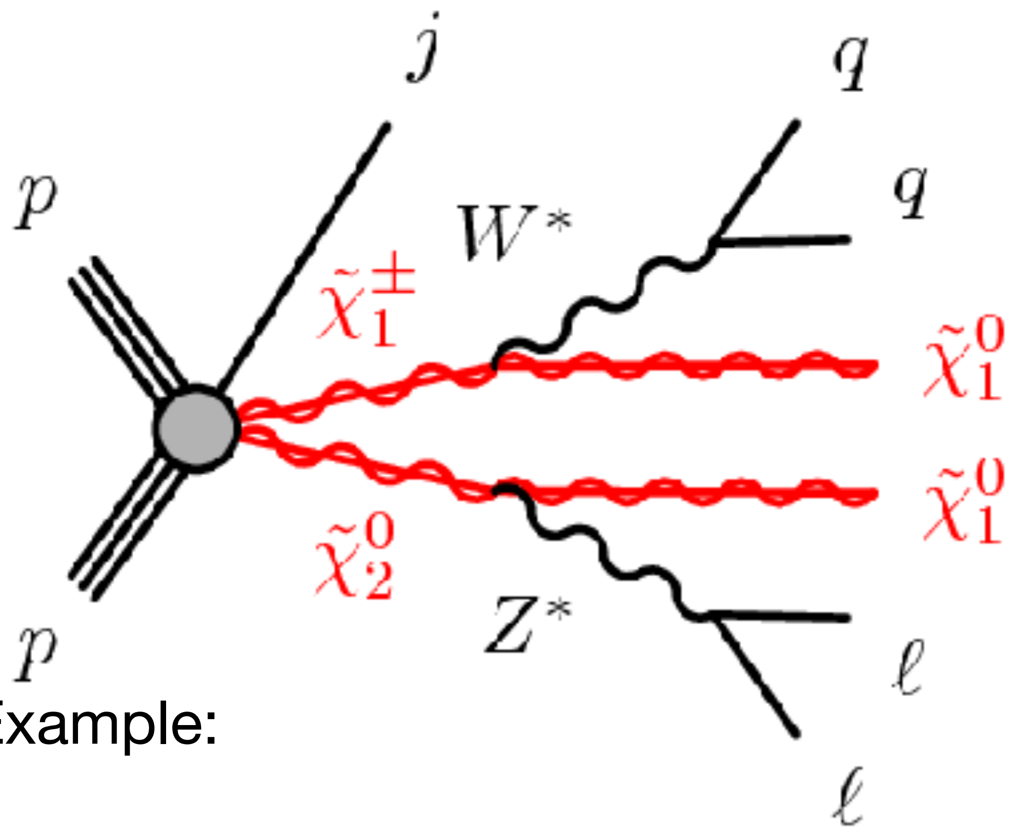
Many regions of parameter space *are still viable*

*ATLAS TDR: sensitivity with 300/fb collected!

Electroweak SUSY

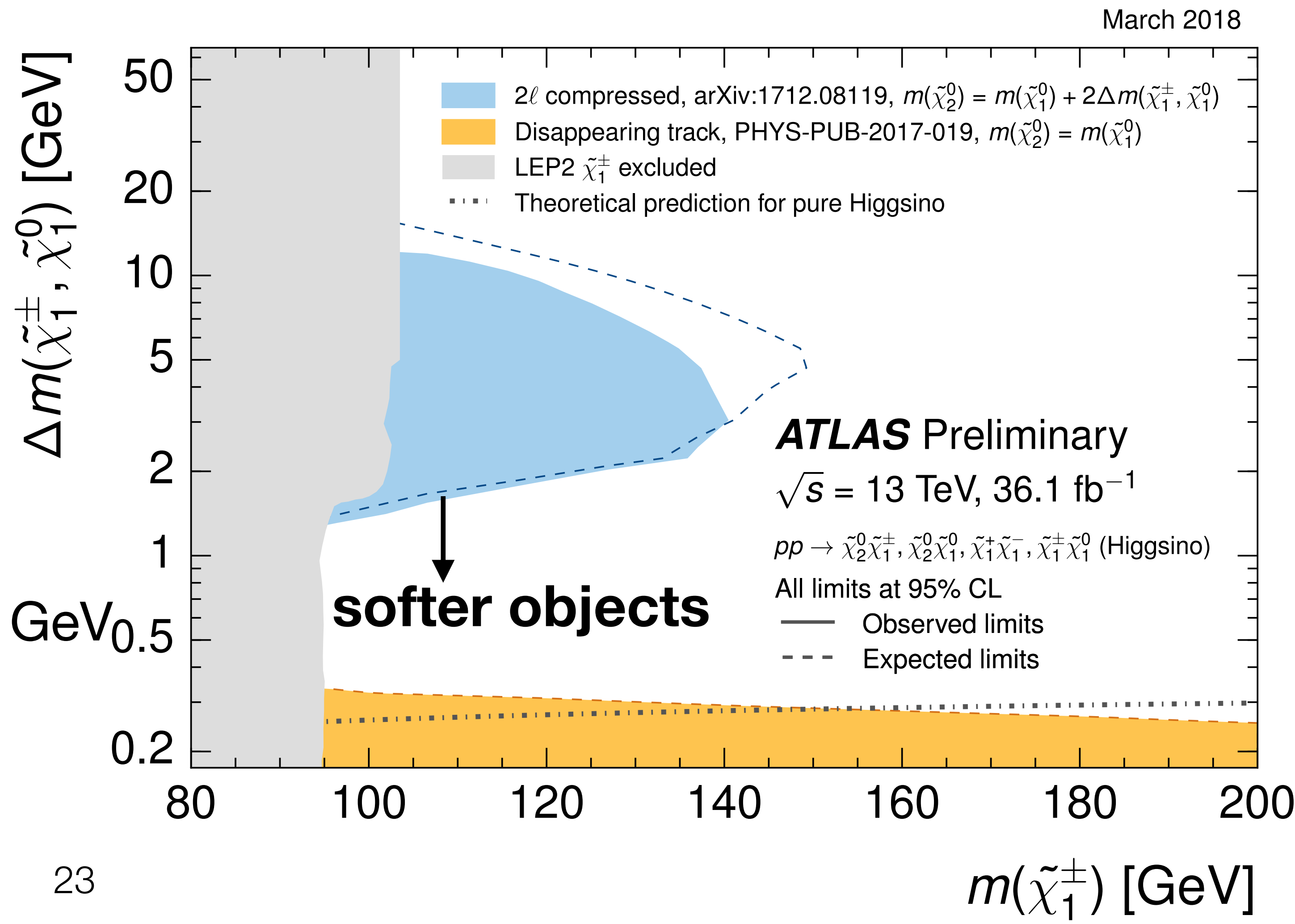
- Strongly production (gluions, squarks) focus of Run 1 & start of Run 2
- EW SUSY: ***Just getting started!*** First limits with Run 2 data





Example:

- **Higgsino** as DM candidate with m ~100-300 GeV
- "Compressed scenario": small mass splitting leads to soft objects - **experimentally challenging**



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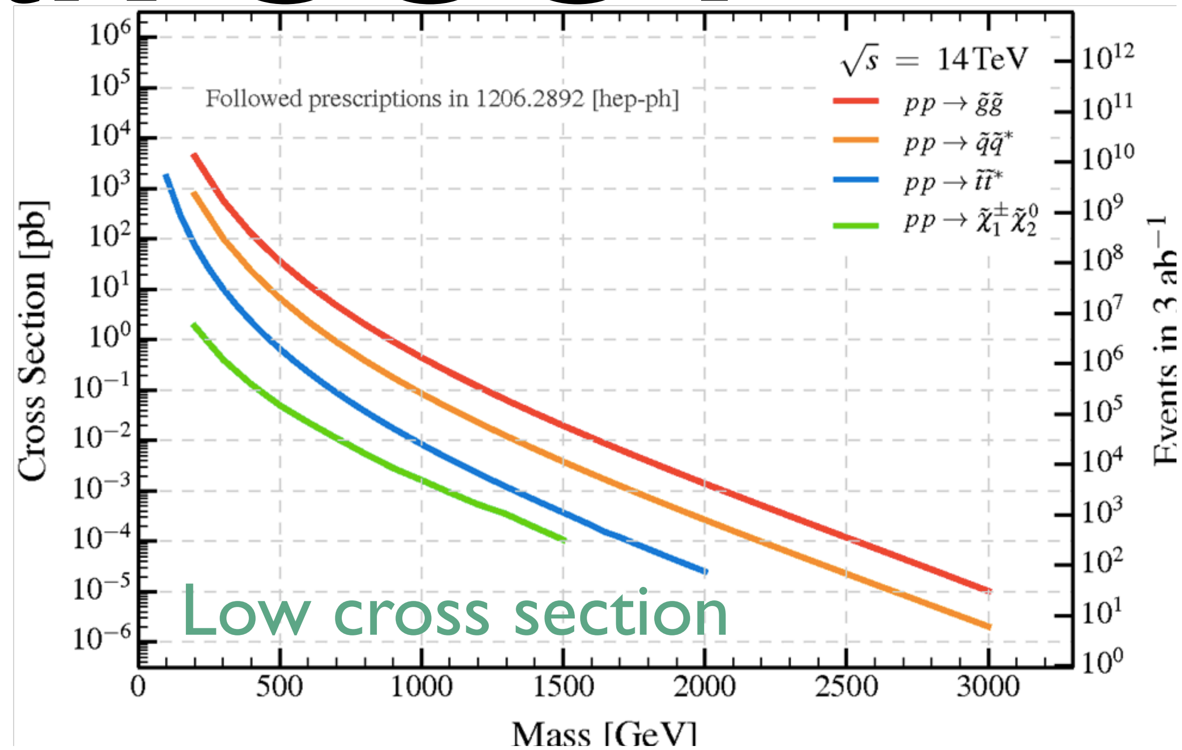
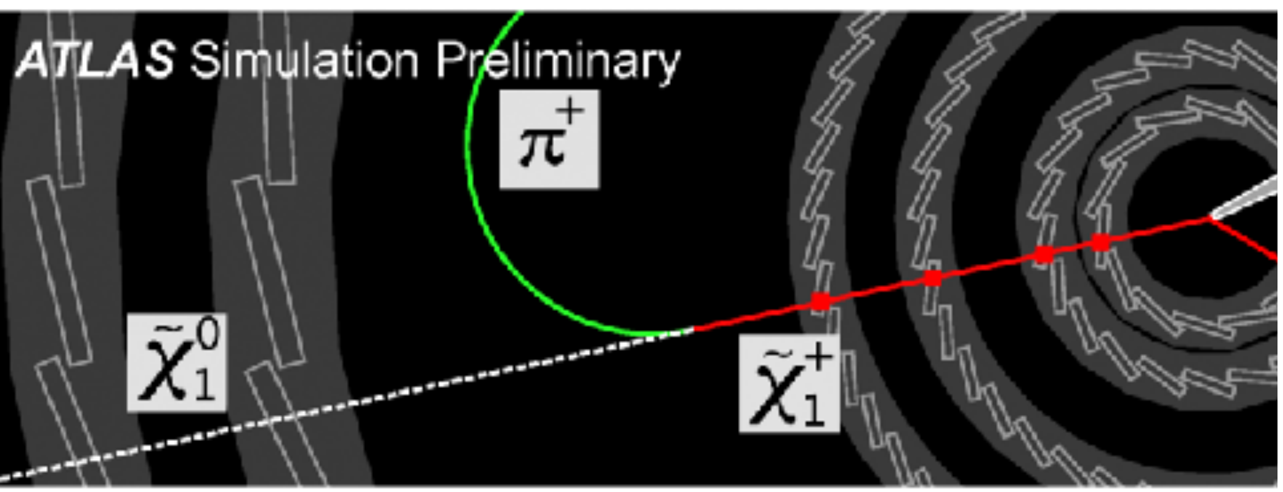
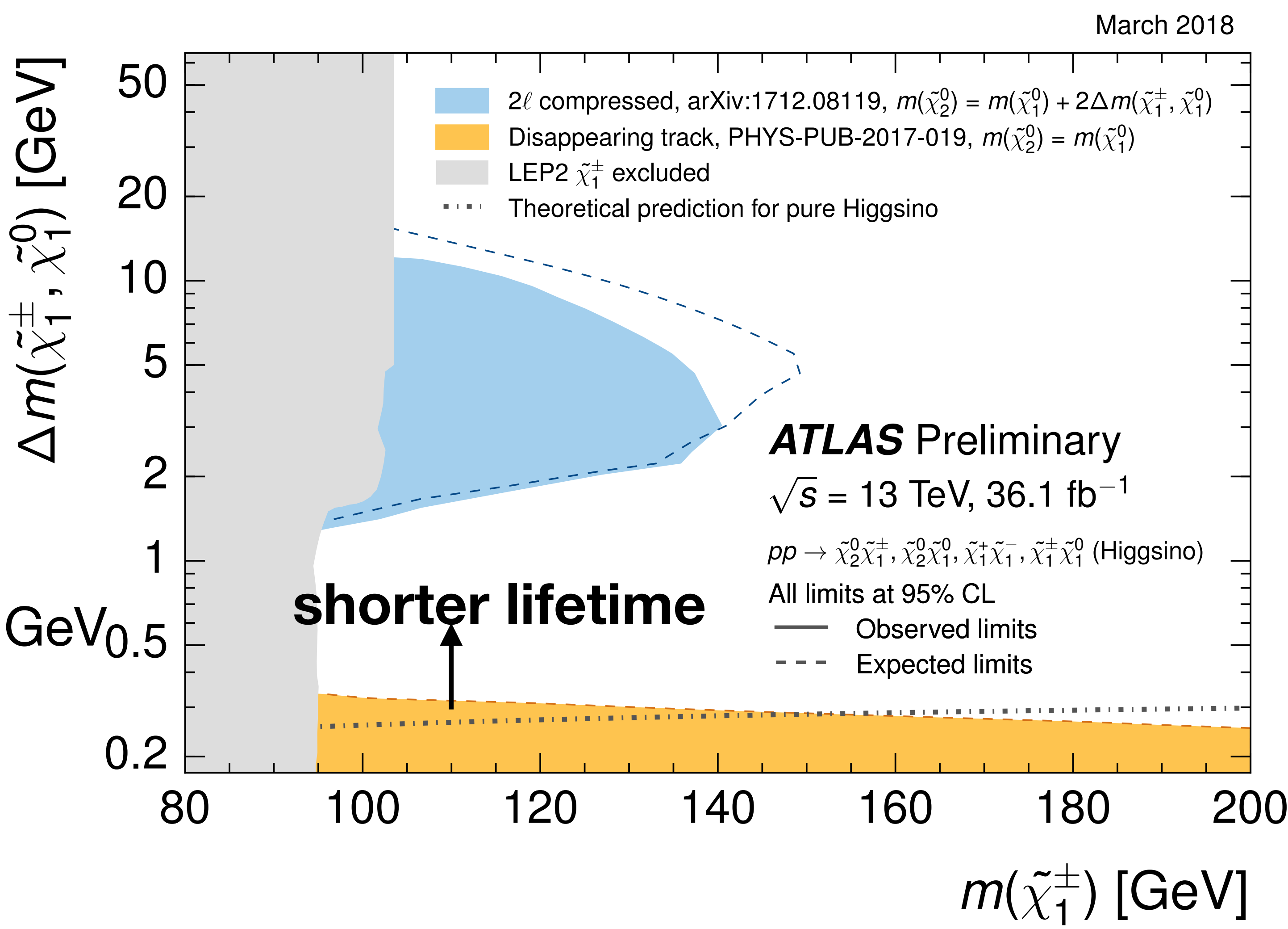




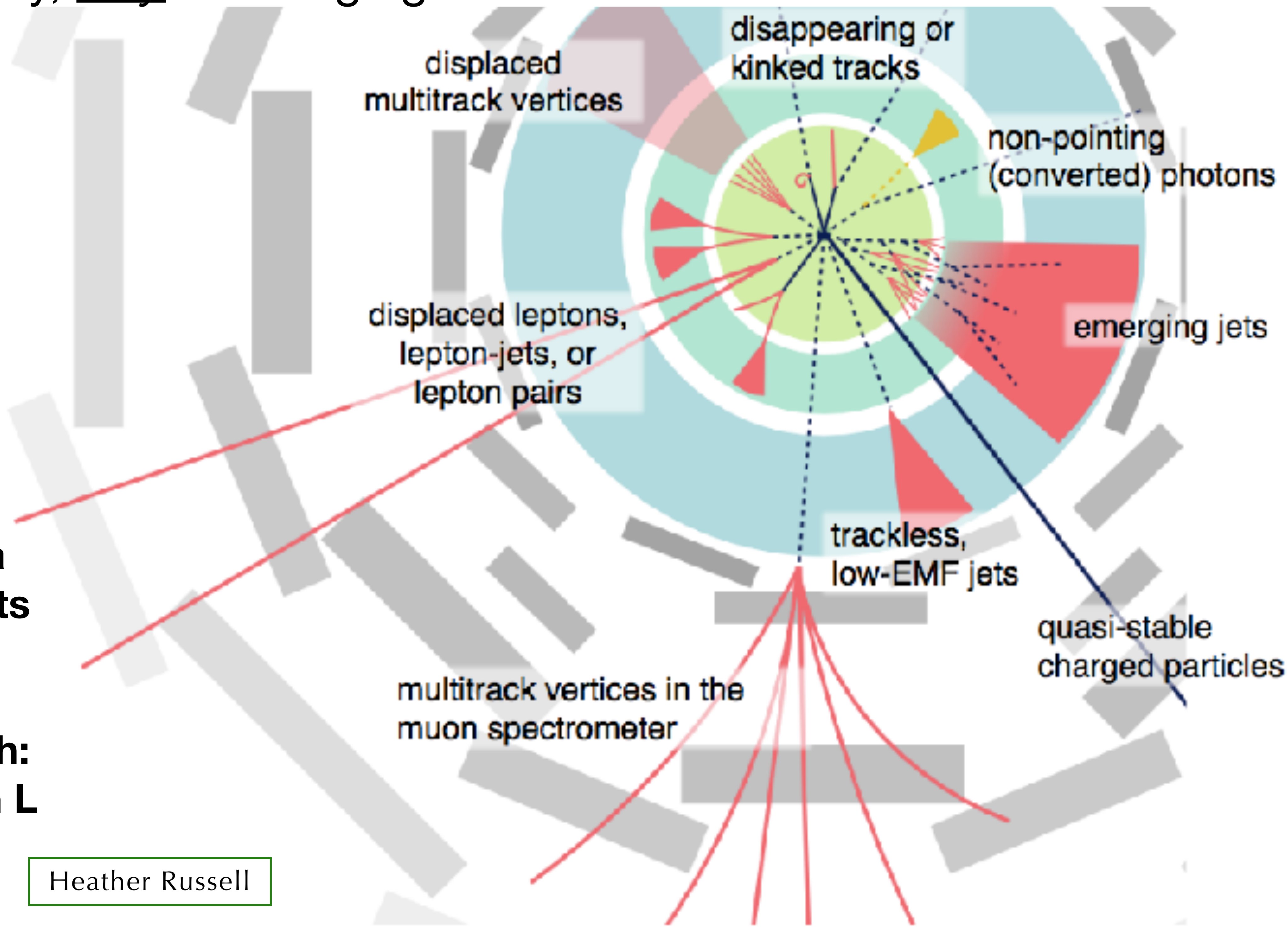
Example: **Shorter lifetime = shorter track**
= higher fake rate



- **Higgsino** as DM candidate with m ~100-300 GeV
- "Compressed scenario": small mass splitting leads to long lived objects - **experimentally challenging**

Non-Standard Signatures

- It is relatively easy to create theoretically i.e. long-lived particles in both SUSY and non-SUSY models
- Experimentally, *very* challenging!



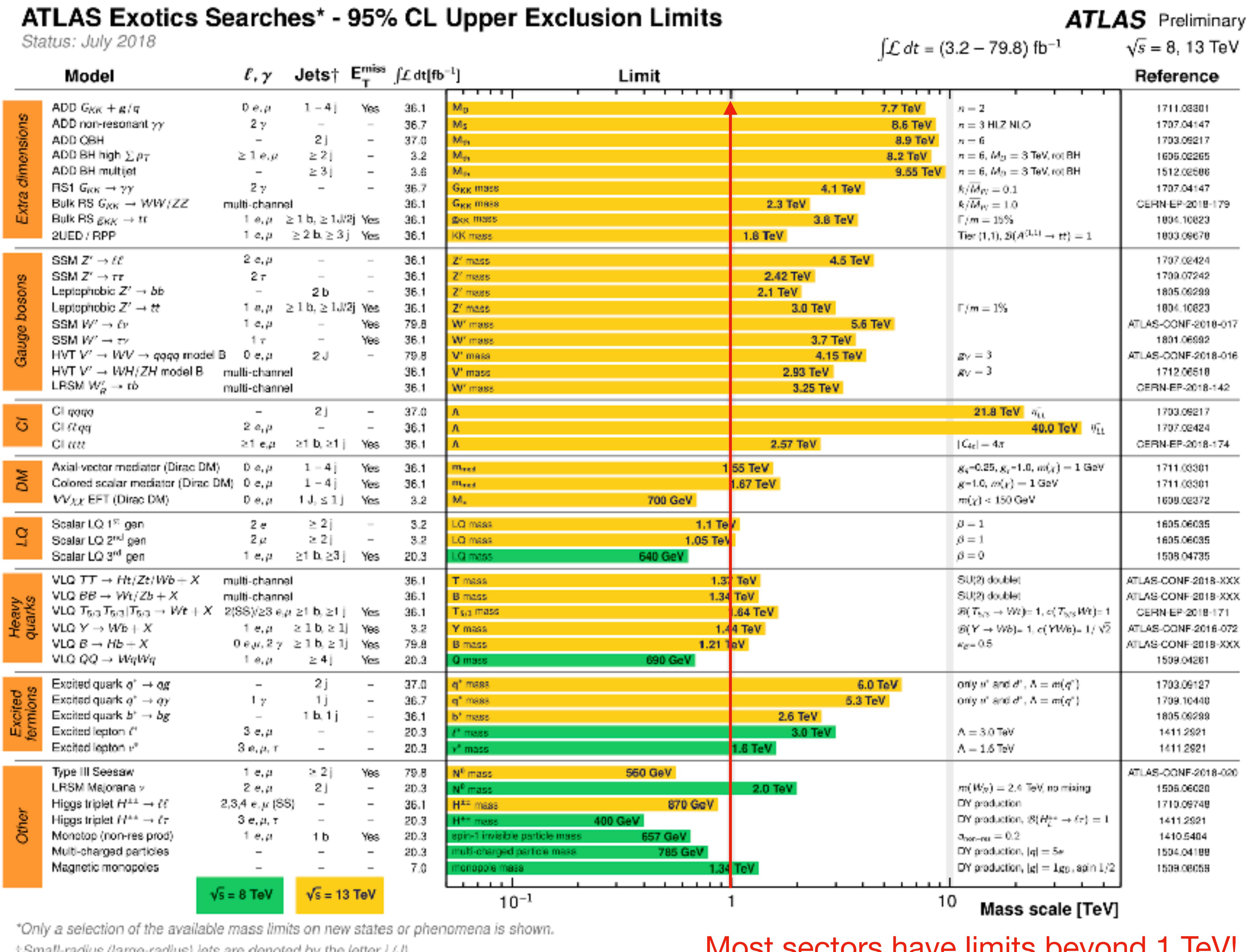
We have seen only a few of the 36/fb results from this program.

~0 background search: sensitivity scales with L

Heather Russell

Exotics*

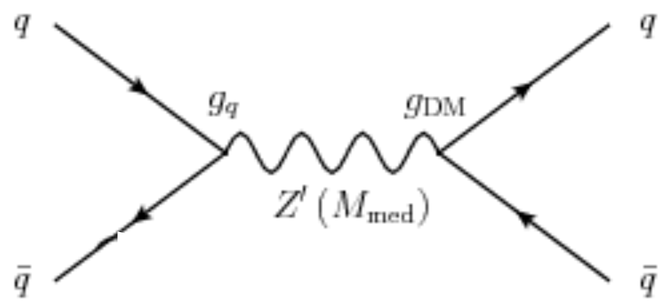
*nearly all searches that are not SUSY-motivated



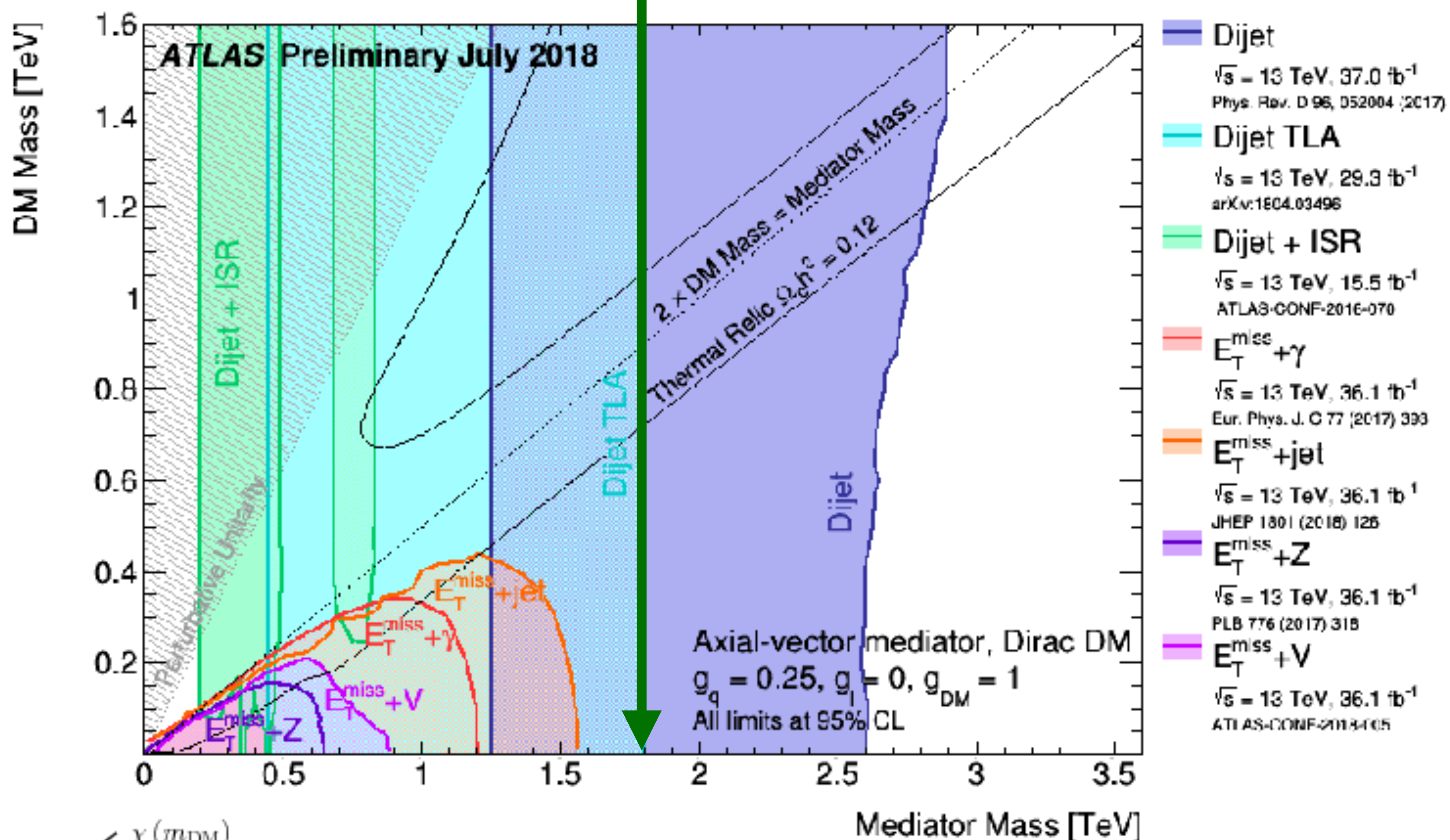
Most sectors have limits beyond 1 TeV!

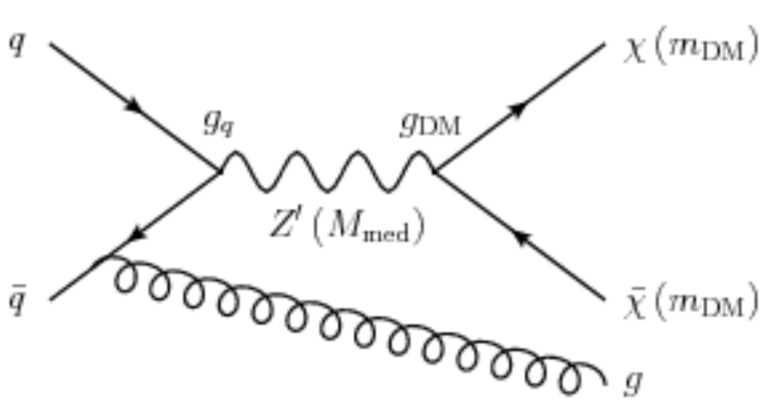
Dark Matter*

*outside of SUSY framework



Added 3 new search techniques in Run 2 to reach lower mass!





Dark Matter*

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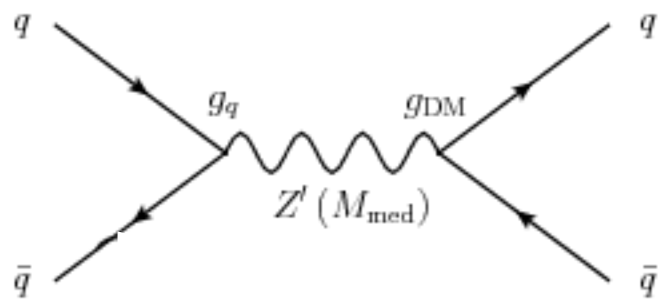

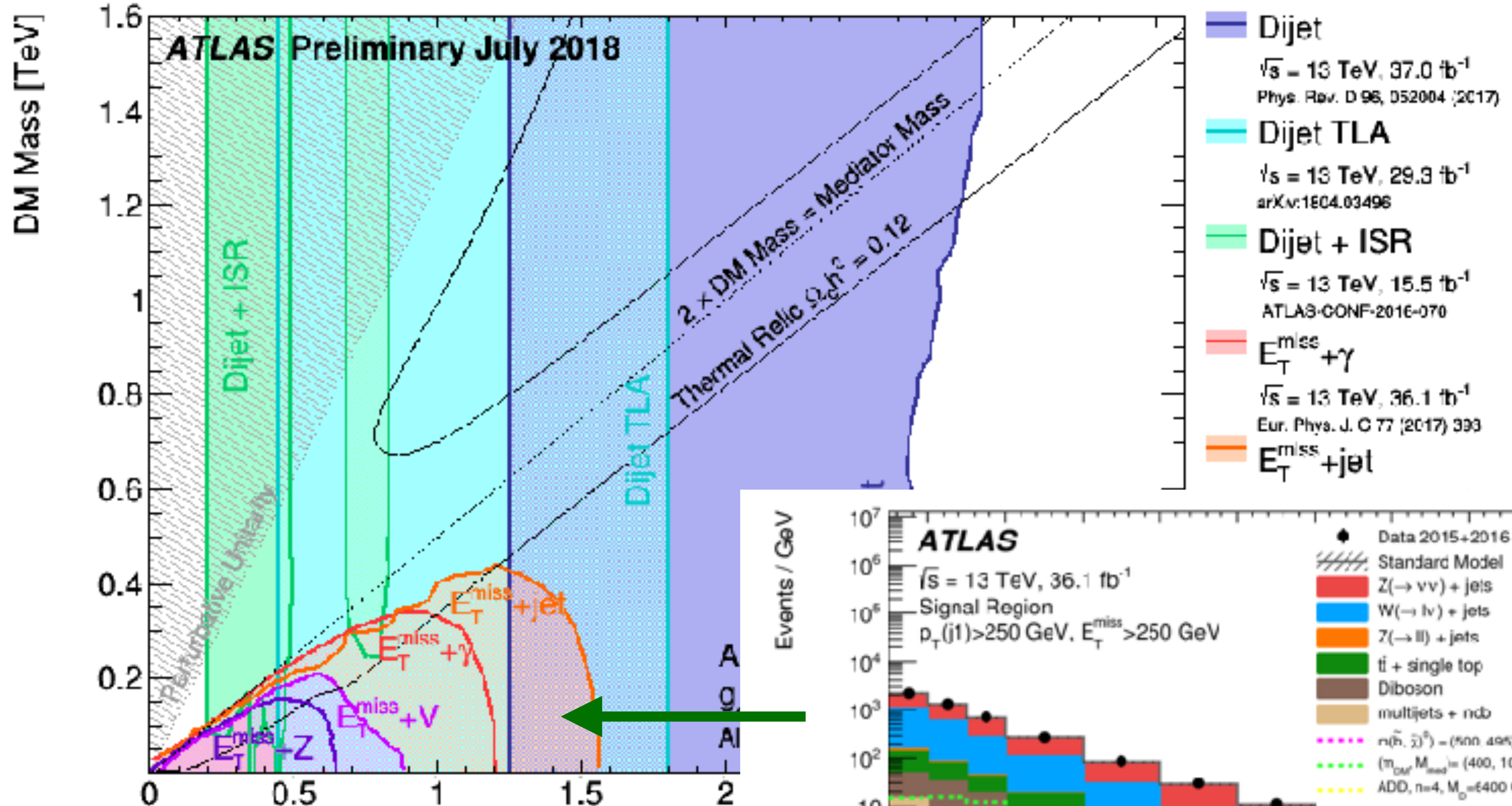

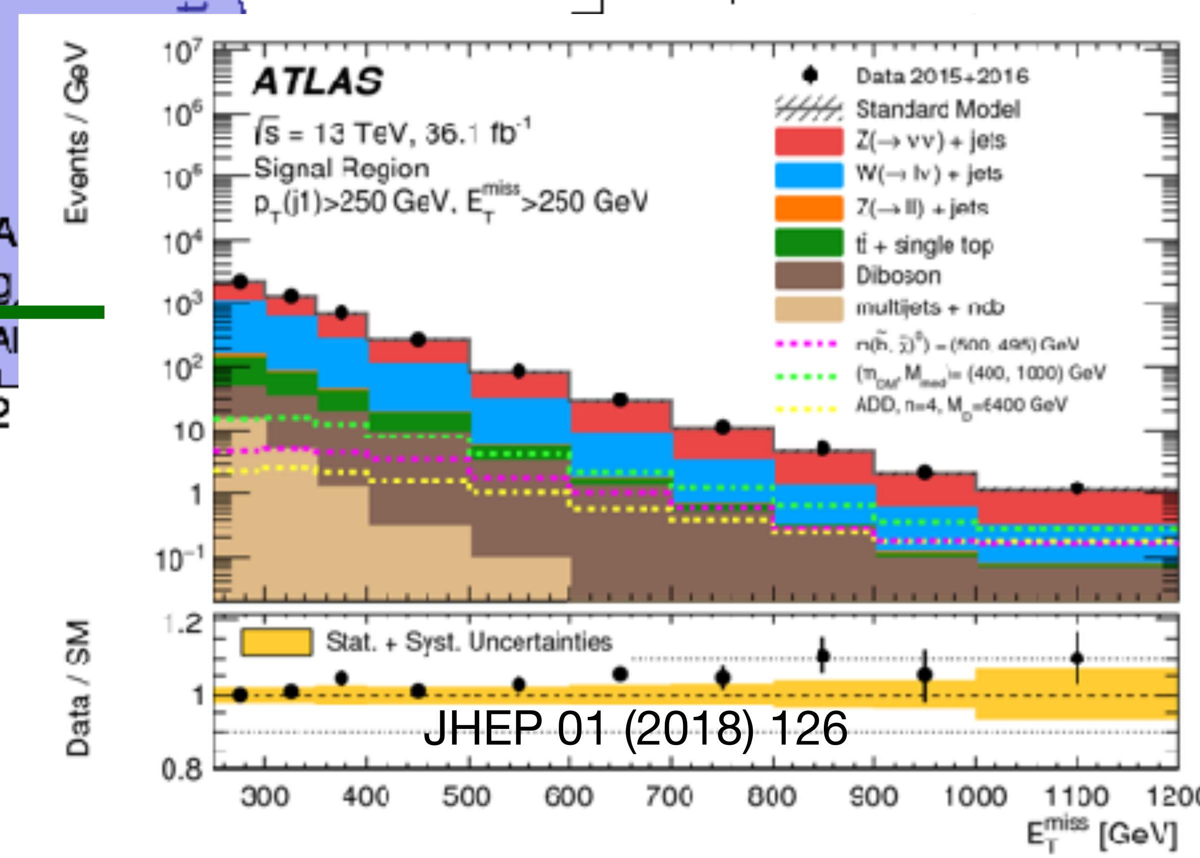

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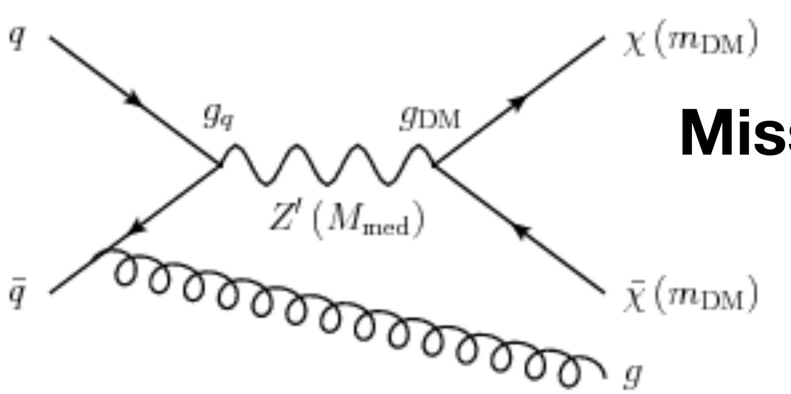
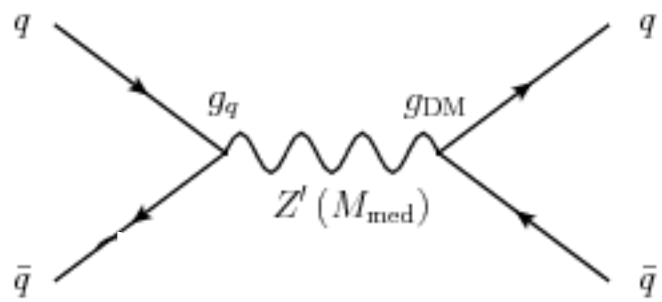
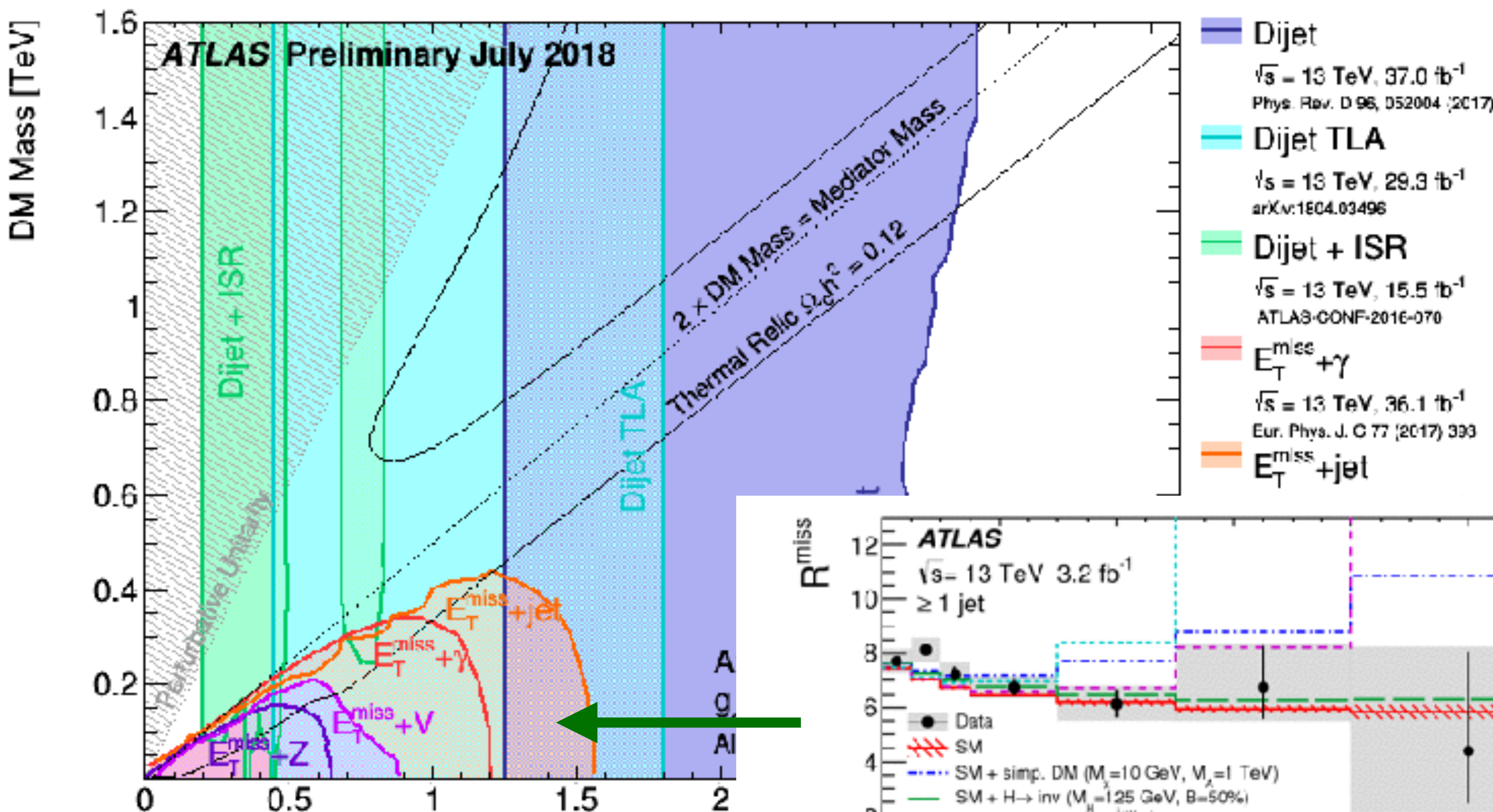
Missing ET distribution

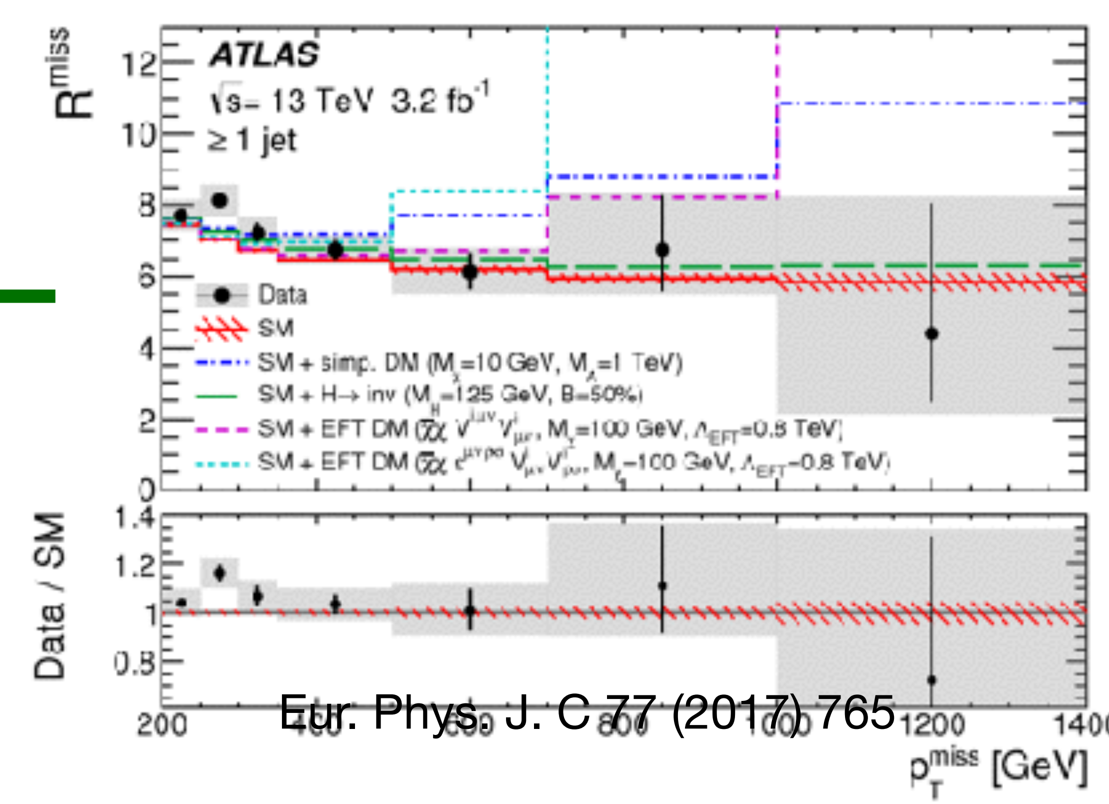


Dark Matter*

*outside of SUSY framework







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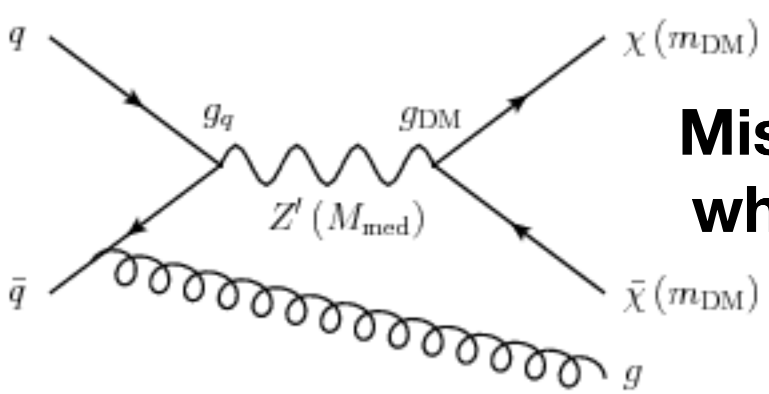
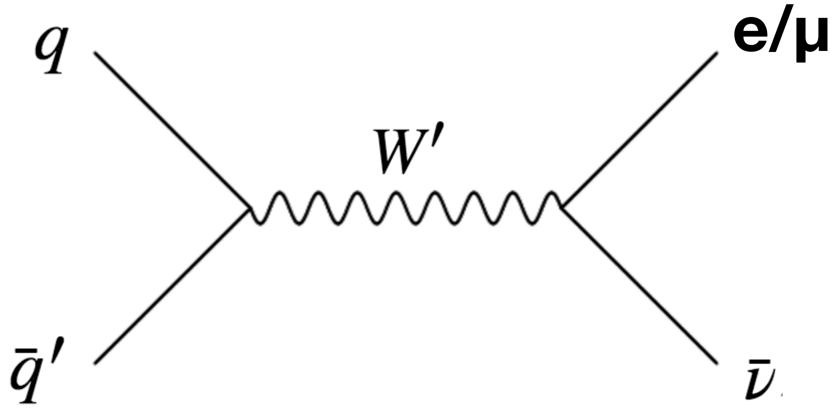


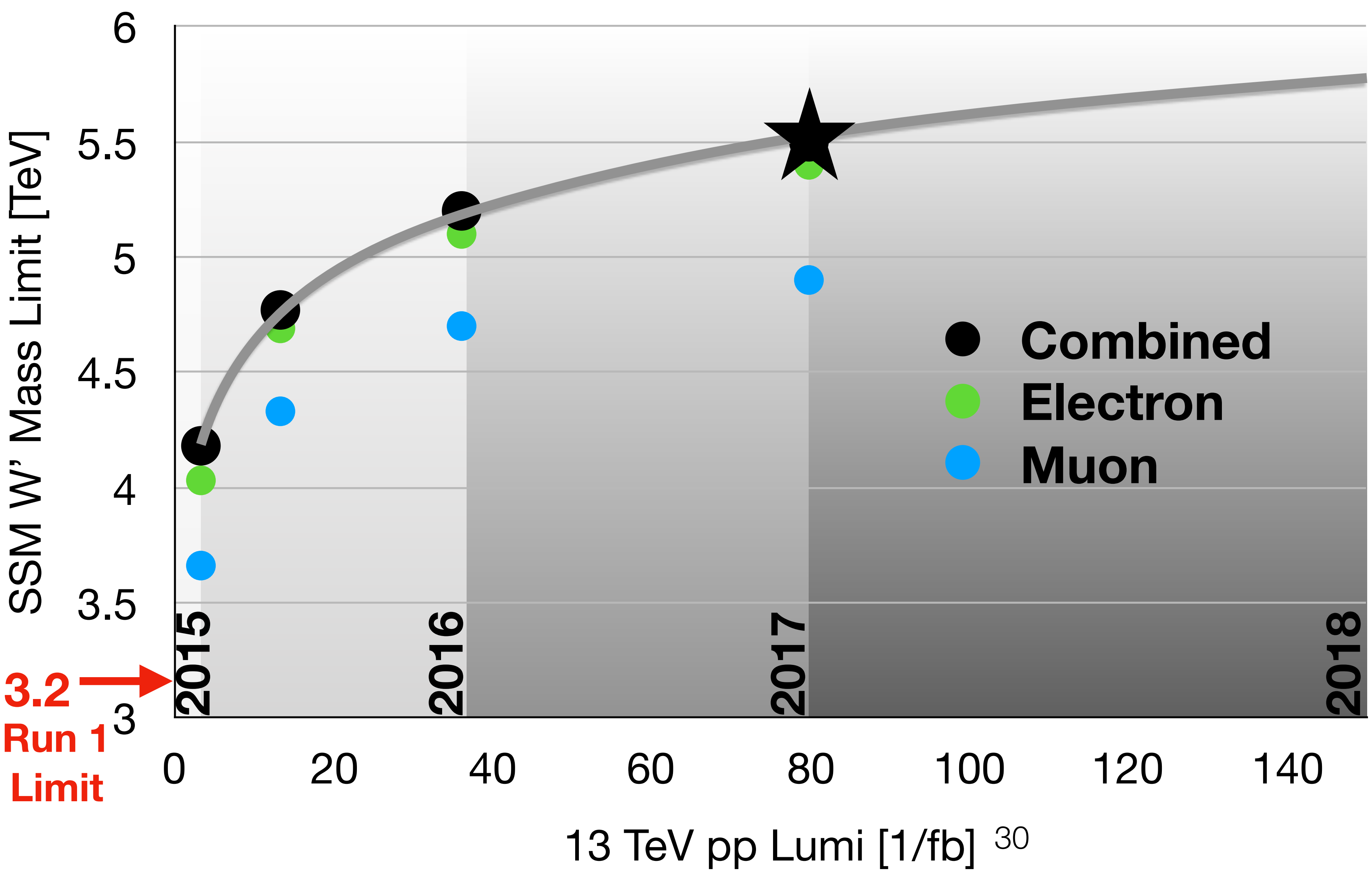
Missing ET distribution which we turned into a measurement

Slowing Down?

Resonance search sensitivity increase with luminosity is slowing *for some*



High-energy searches roughly:
mass reach grows ~linearly with the ~log of the luminosity



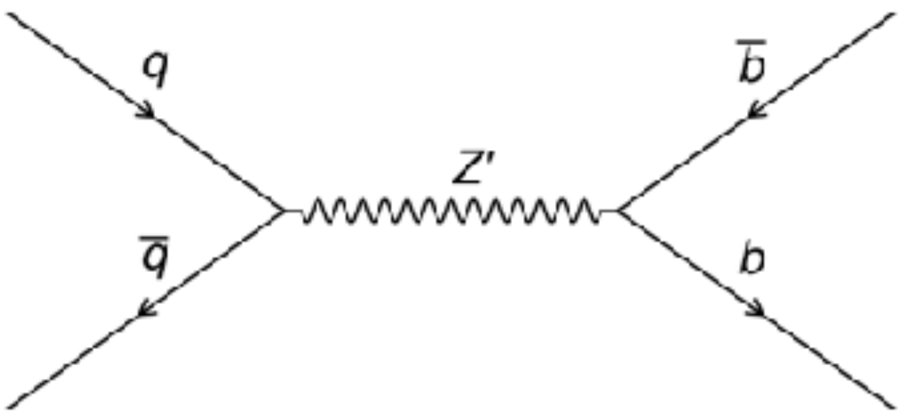
Approximation of sensitivity with full Run 2 dataset

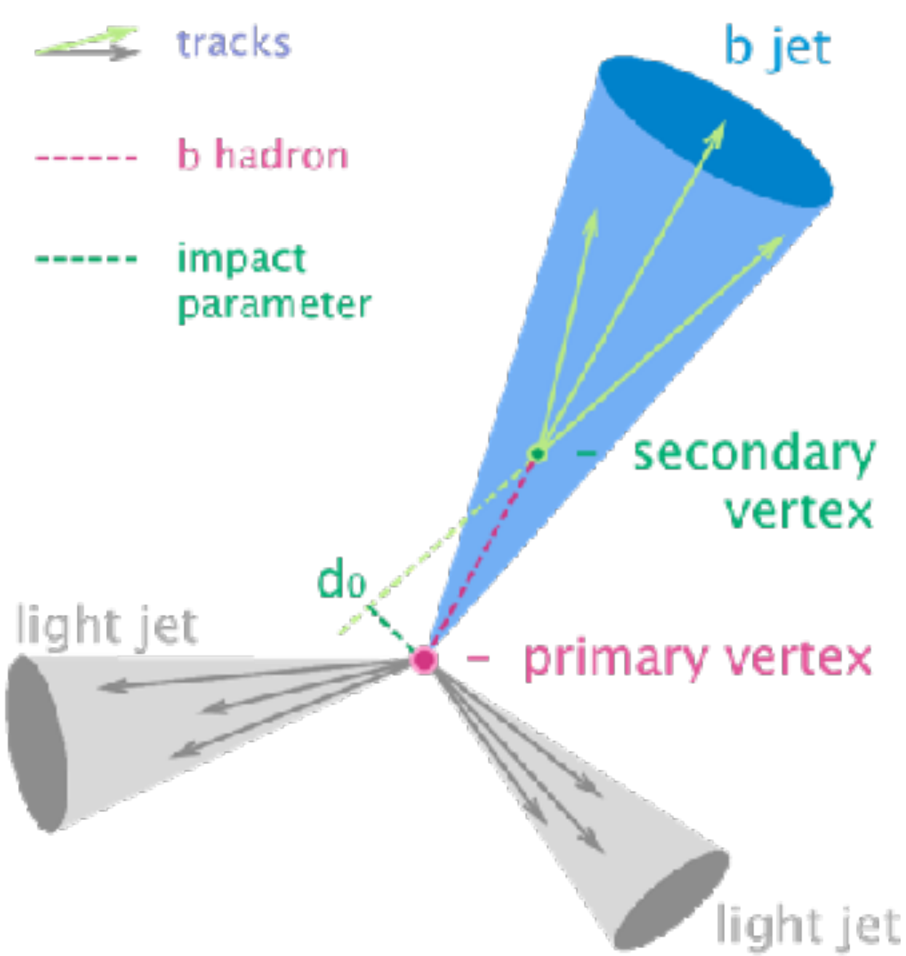
Reach:
Run 3 (300/fb): ~6.2 TeV
HL-LHC (3000/fb): ~7.2 TeV

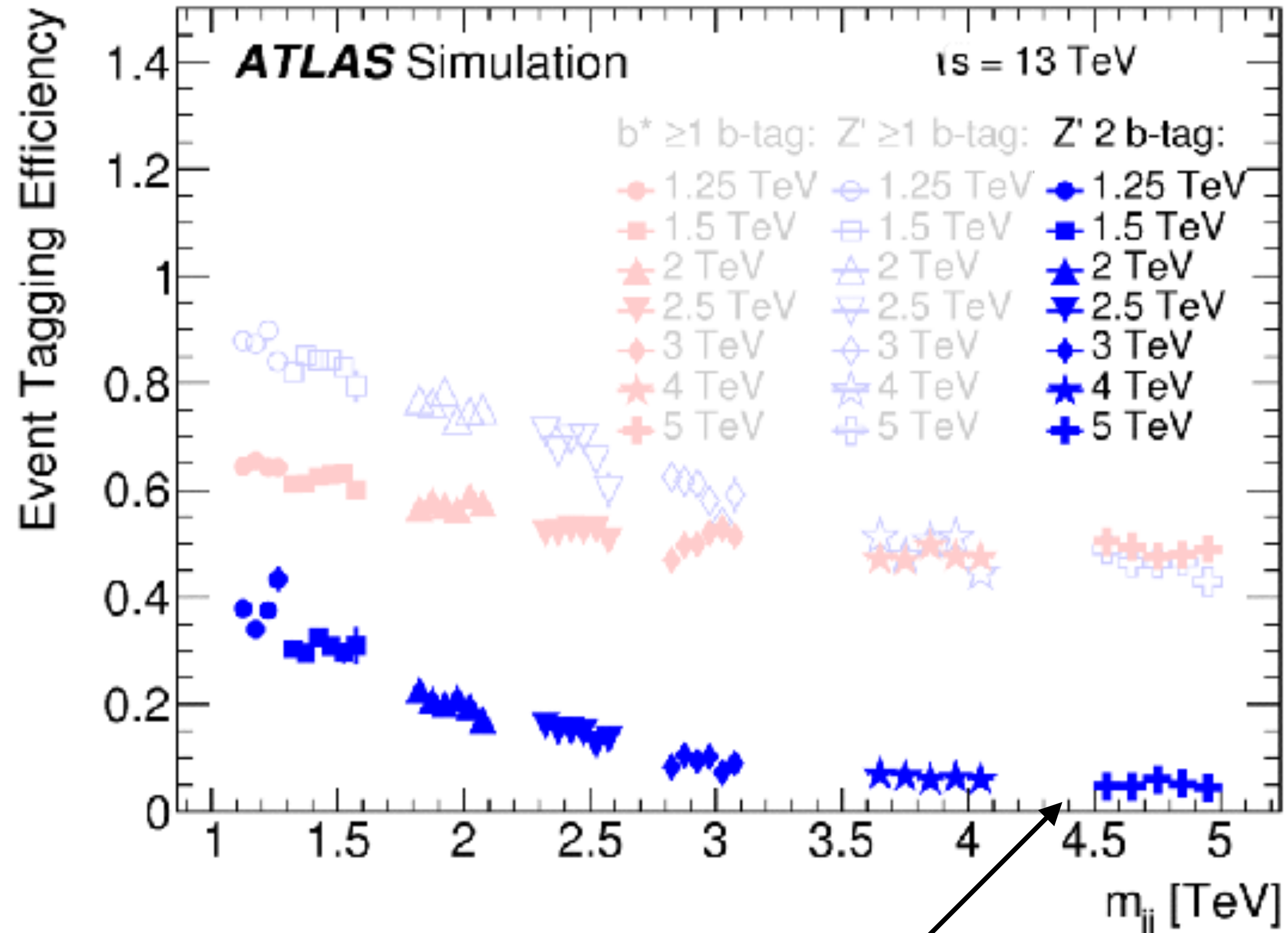
Year of data collection

Performance

Gains from luminosity can be outpaced by gains in performance



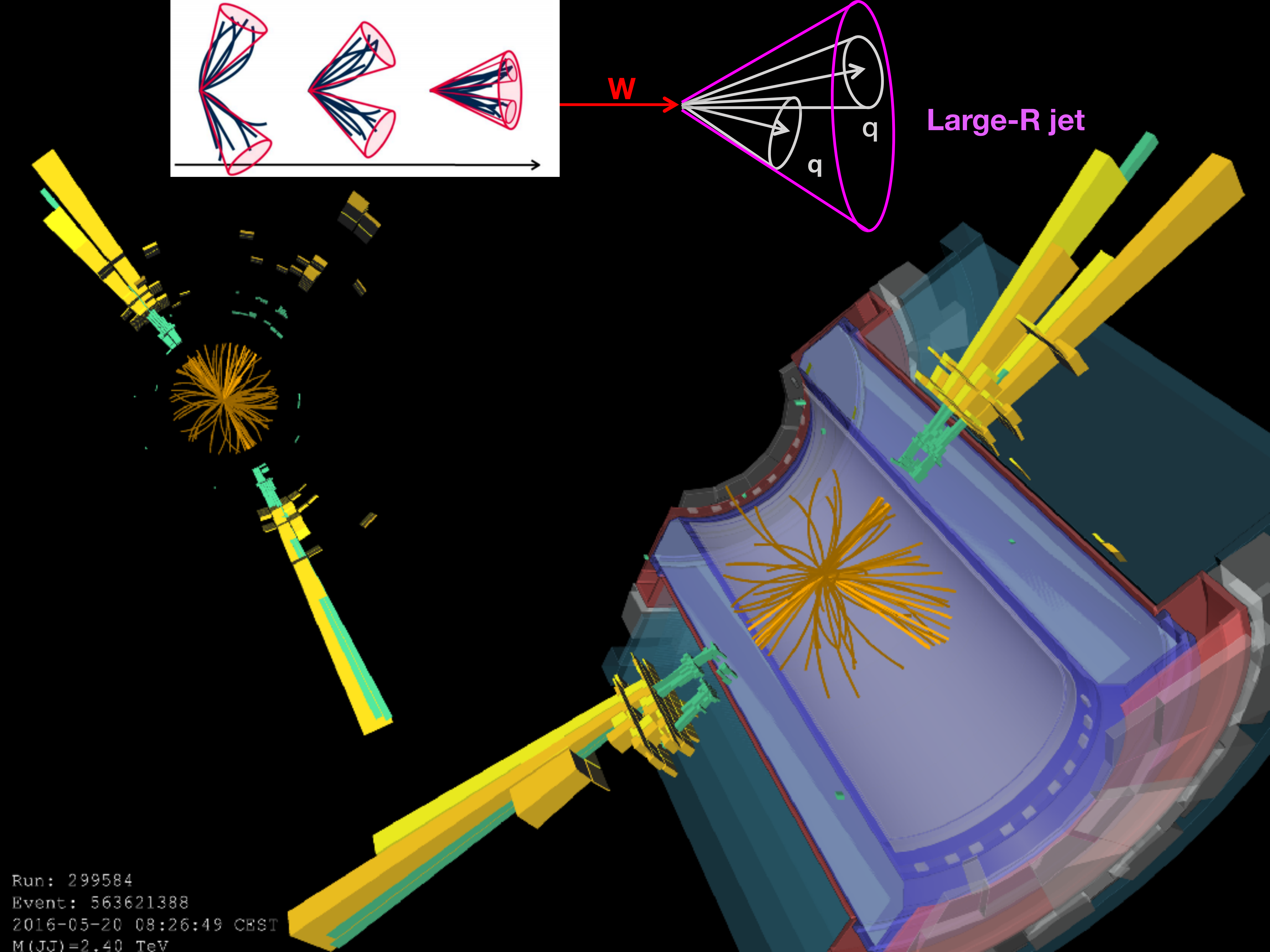


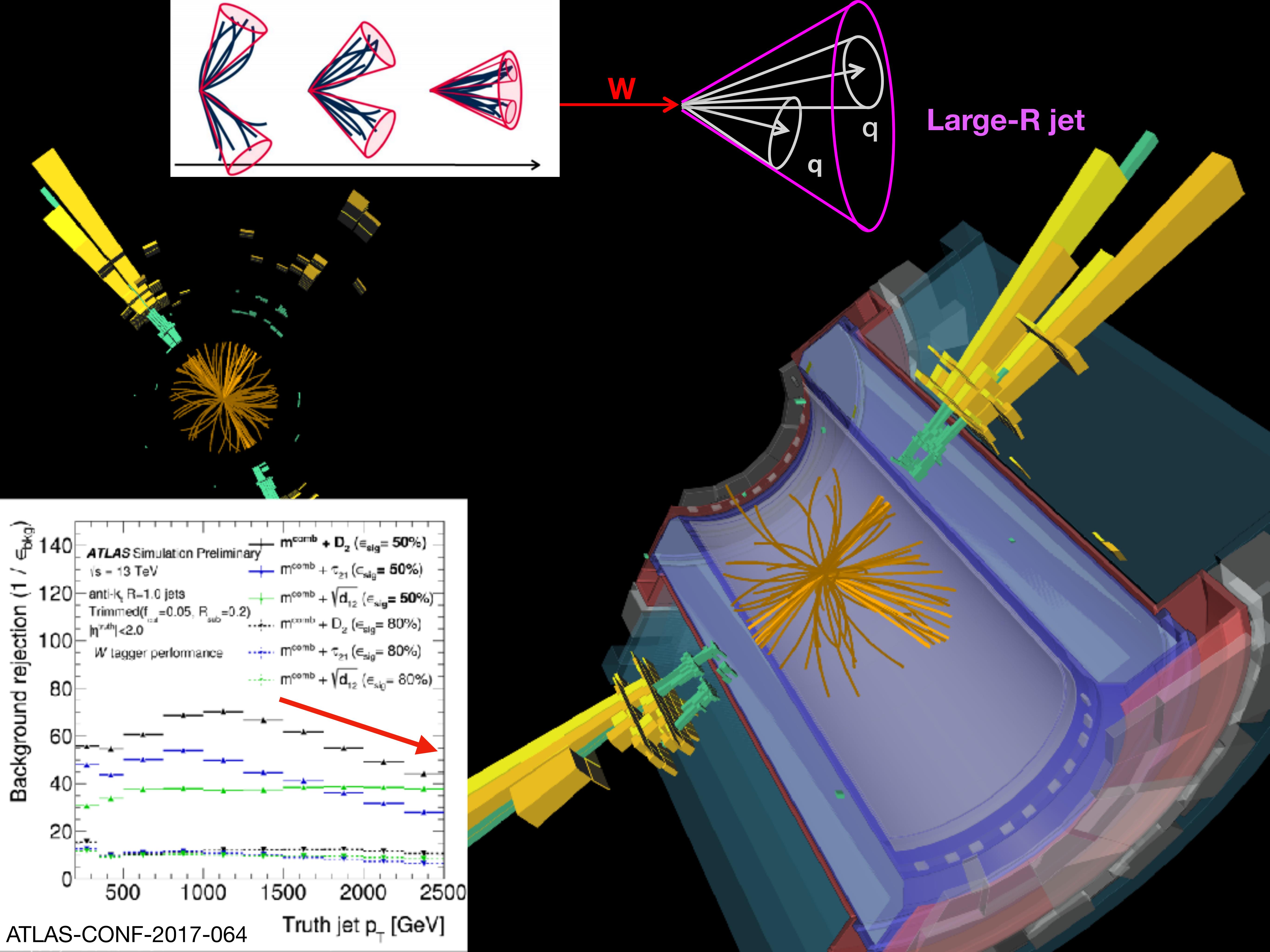


Efficiency to identify both b-jets is 5%

At lower pTs, can tag b's with 70% efficiency

Increasing that to 15% would improve the sensitivity roughly as much as the full Run 3 dataset


W
q
q
Large-R jet
Run: 299584
Event: 563621388
2016-05-20 08:26:49 CEST
M(JJ)=2.40 TeV


W
q
q
Large-R jet
ATLAS Simulation Preliminary
$\sqrt{s}$ = 13 TeV
anti-k_t R=1.0 jets
Trimmed(f_{cut}=0.05, R_{sub}=0.2)
$|\eta^{truth}|$<2.0
W tagger performance
m^{comb} + D_2 (ϵ_{sig}= 50%)
m^{comb} + τ_{21} (ϵ_{sig}= 50%)
m^{comb} + $\sqrt{d_{12}}$ (ϵ_{sig}= 50%)
m^{comb} + D_2 (ϵ_{sig}= 80%)
m^{comb} + τ_{21} (ϵ_{sig}= 80%)
m^{comb} + $\sqrt{d_{12}}$ (ϵ_{sig}= 80%)
Background rejection (1 / ϵ_{bkg})
0
20
40
60
80
100
120
140
500
1000
1500
2000
2500
Truth jet p_T [GeV]
ATLAS-CONF-2017-064

Performance Improvements

Identification efficiency at the high energy frontier is difficult

Expect to see a lot of **R&D and innovation during Run 3**

Wonderful playground for Machine Learning applications!

If my favorite search for a heavy resonance includes very high pT…

(b-)jet

W/Z had

Jet substructure (**JSS**) technique pioneered in UK!

… can performance improvements lead to big gains?

Yes!

Yes!

Performance Improvements

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Expect to see a lot of **R&D and innovation during Run 3**

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If my favorite search for a heavy resonance includes very high pT…

Jet substructure (**JSS**) technique pioneered in UK!

… can performance improvements lead to big gains?

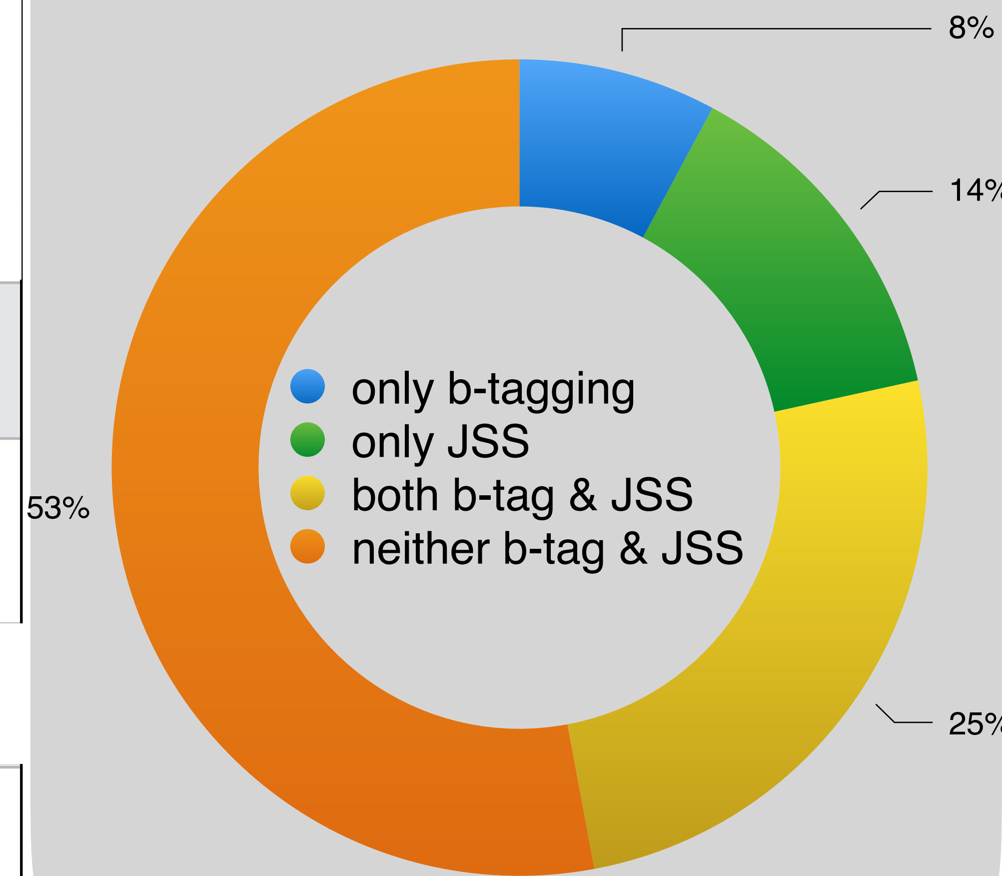
Yes!

Yes!

Yes!

Yes!

What fraction of the resonance program* does this cover?



***does not include SUSY**

Performance Improvements

Identification efficiency at the high energy frontier is difficult

Expect to see a lot of **R&D and innovation during Run 3**

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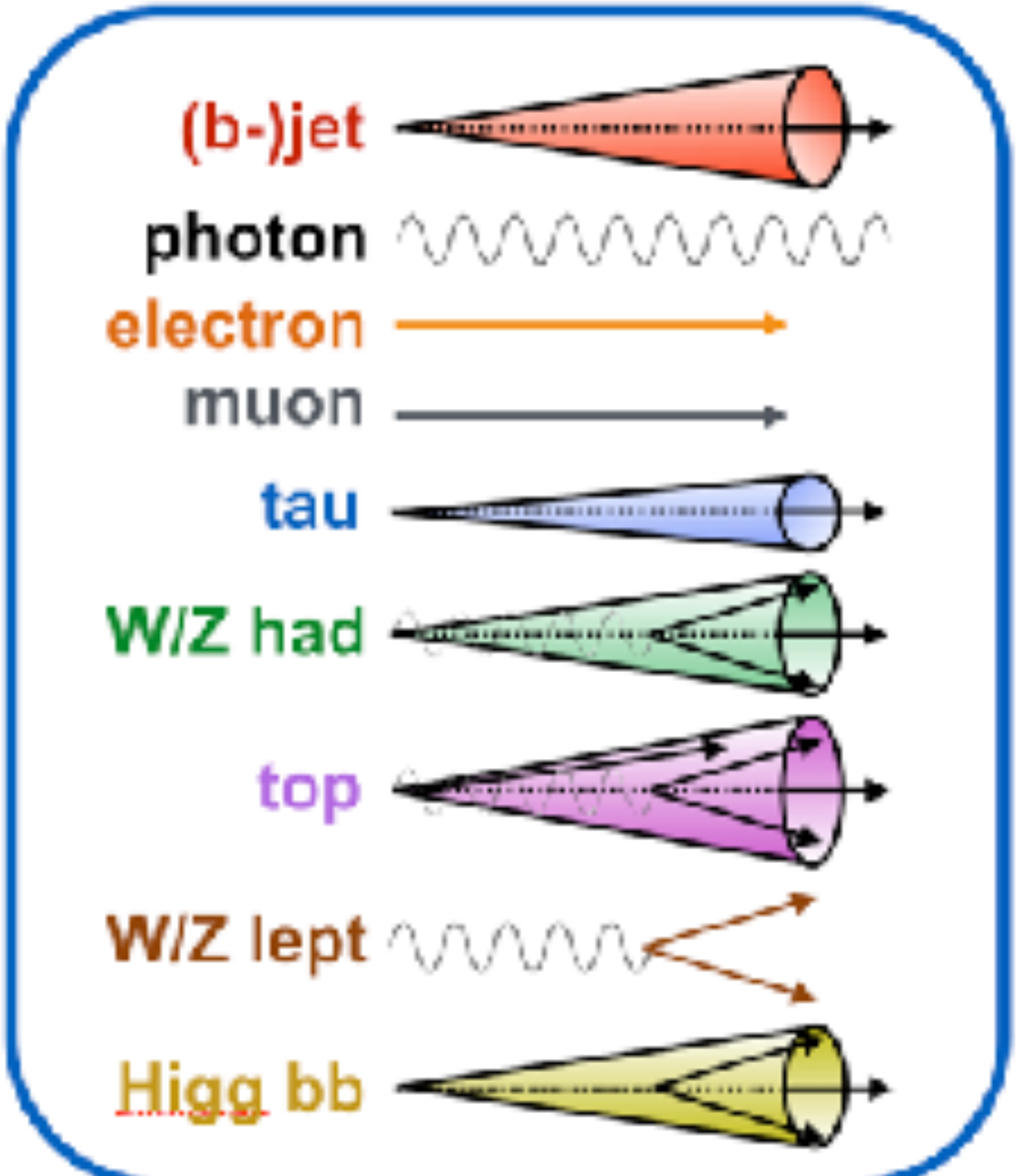
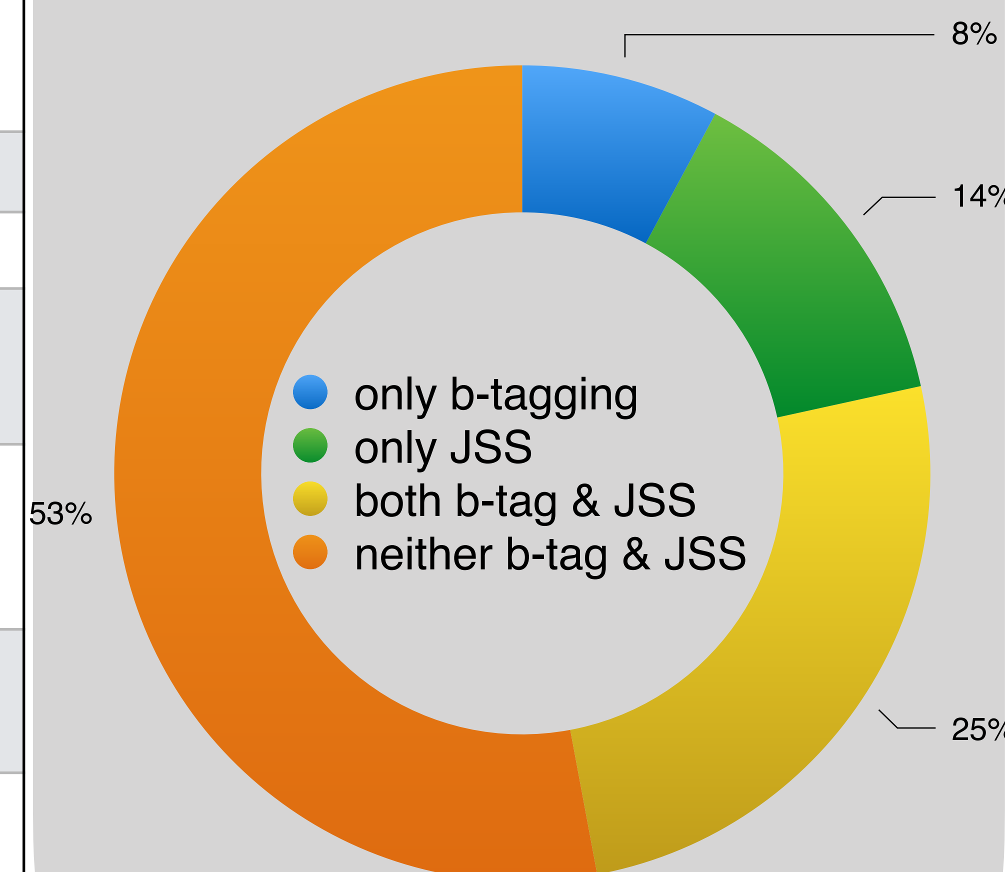
If my favorite search for a heavy resonance includes very high pT…



… can performance improvements lead to big gains?

Yes!
for X->yy if highly boosted
for X->ee if highly boosted
yes, but limited
Yes!
Yes!
Yes!
at high pT
Yes!

What fraction of the resonance program* does this cover?

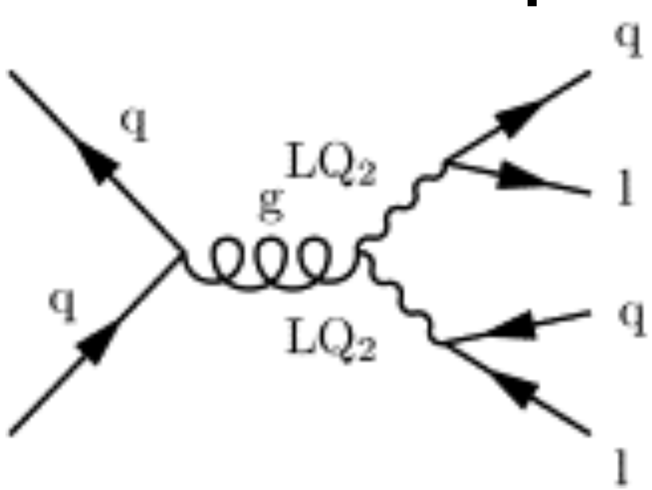


***does not include SUSY**

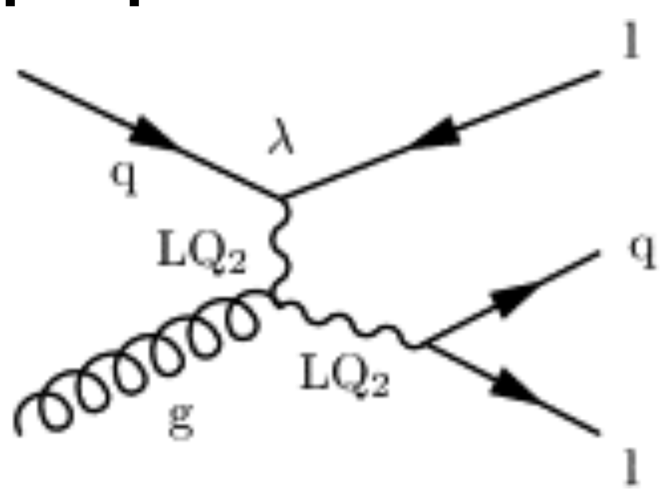
Keep Searching

- We don’t know the description of nature so we really don’t know what new physics will look like in our detector.
    - Therefore we must look in many places in many ways
- We could also have hints in the recent anomalies in the flavor sector.
    - Not yet fully probed all the models proposed
- *It would terrible to learn in 10 years we missed new physics*

Example: Leptoquarks



pair-production
target lower masses



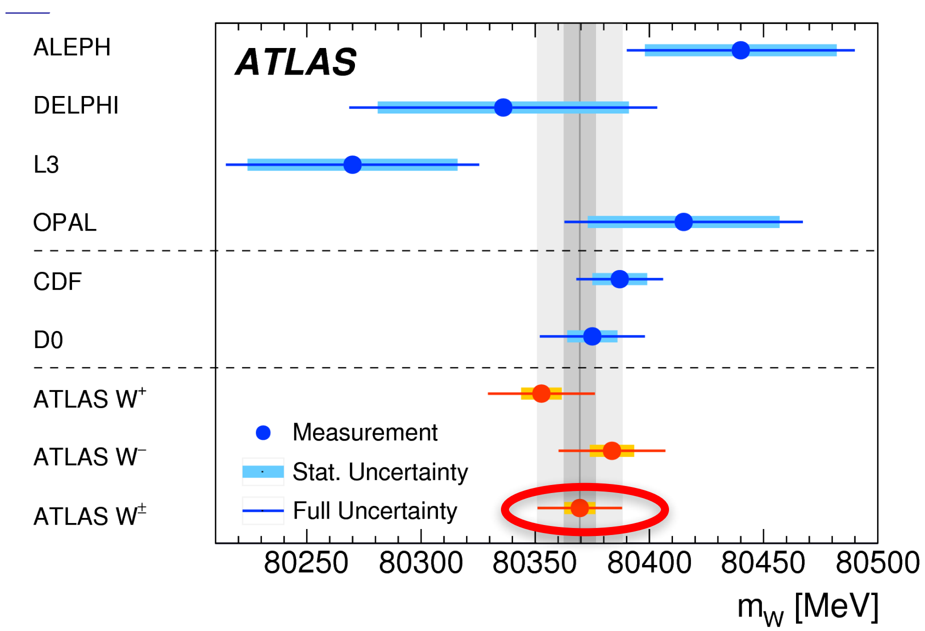
single-production
target higher masses

Measuring the SM

With the large dataset collected, measurement precision is already surpassing LHC lifetime expectations

W boson mass

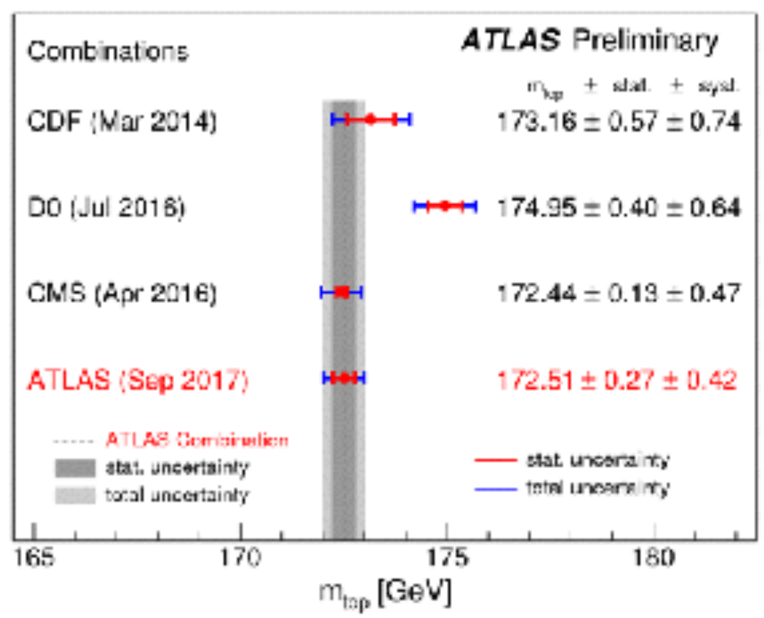
EPJ C78 (2018) 110



Similar precision to best previous single exp (CDF)
Precision: ~0.02%

top quark mass

ATLAS-CONF-2017-071

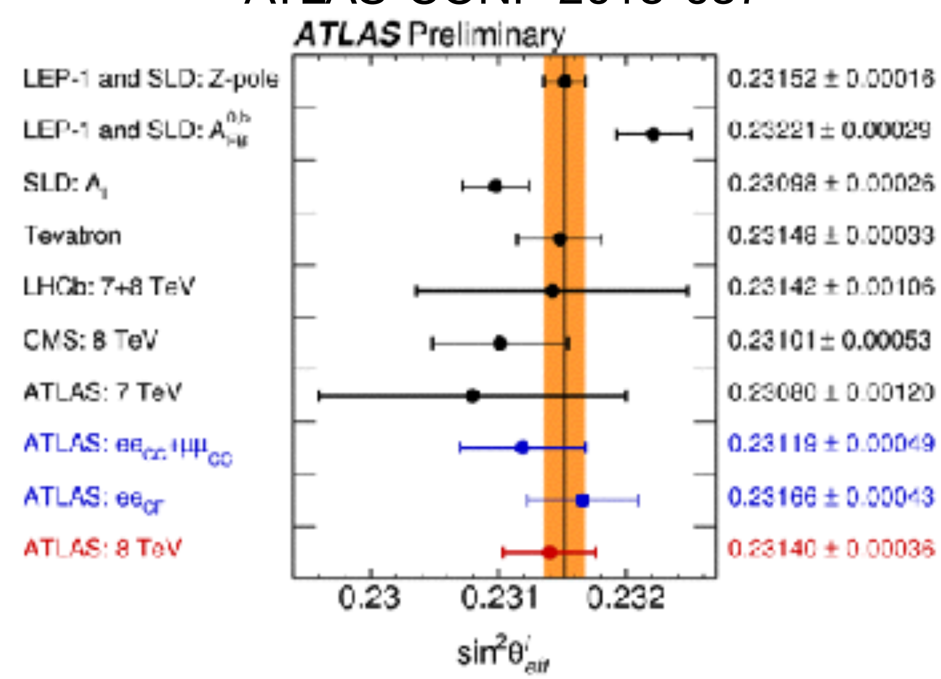


Precision: ~0.3%

Watch out for new techniques for mass measurement less reliant on experimental systematics

electroweak parameters

ATLAS-CONF-2018-037

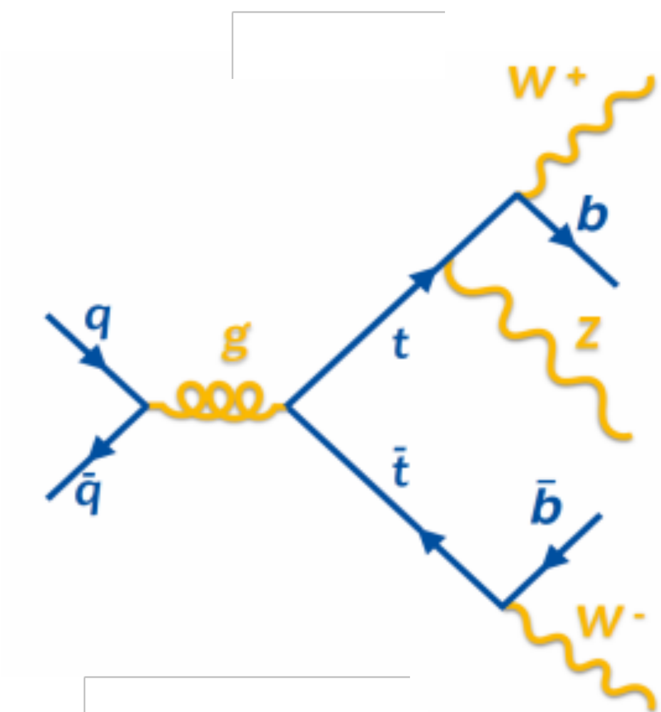


0.15 %precision
using novel approach

Further progress requires improved modeling

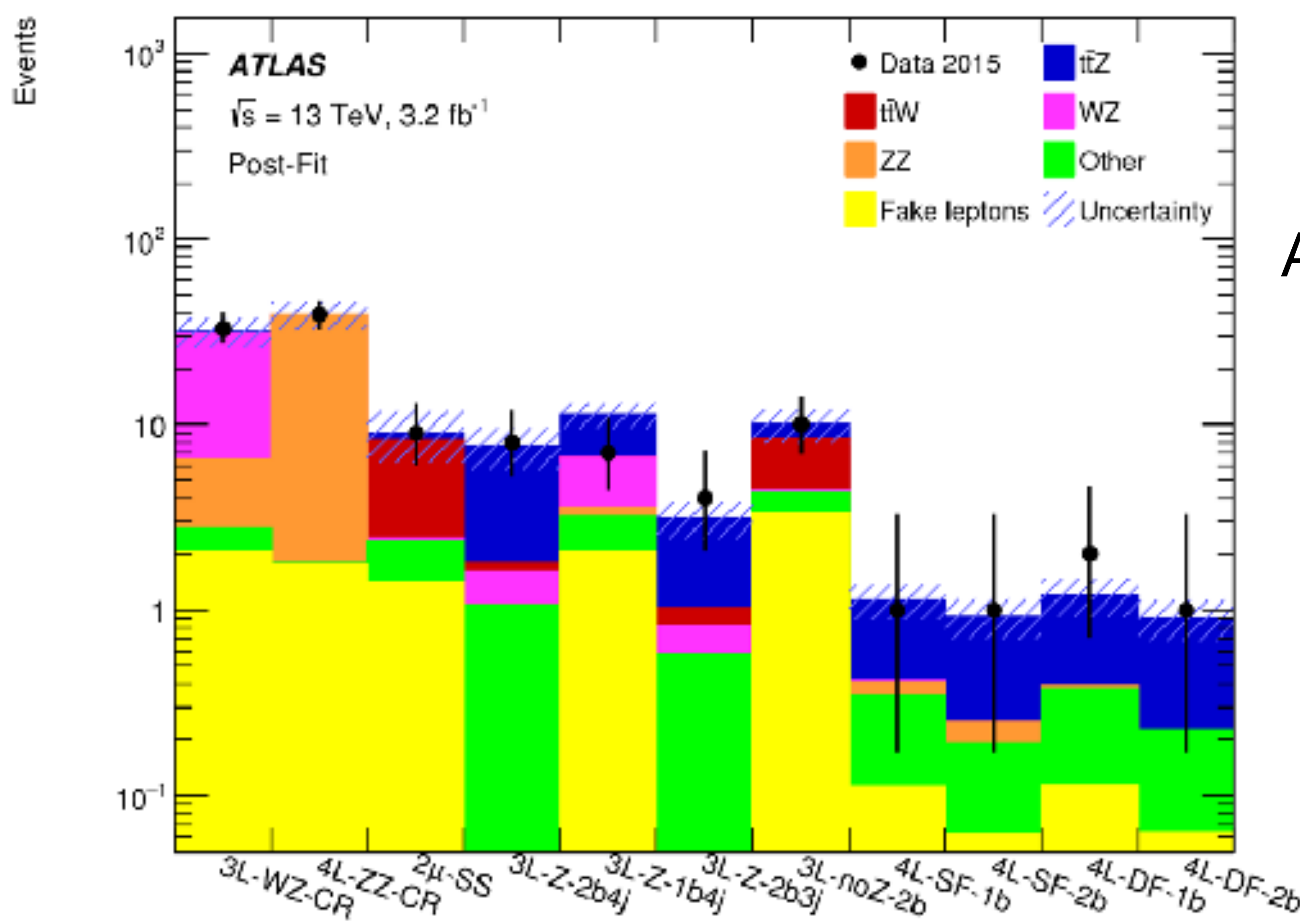
Run 3: Measurements

Differential measurements in newly established associated production channels i.e. Wt, ttZ, tZq

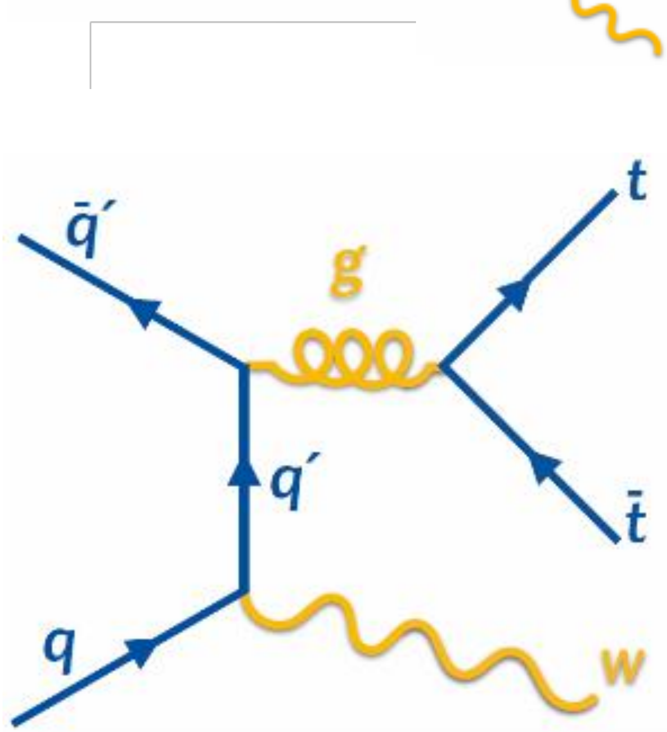


ttZ

- Coupling modified in many BSM models
- Important background in *ttH* measurements



A factor of 10 more data (Run 3) will provide *very interesting measurements*



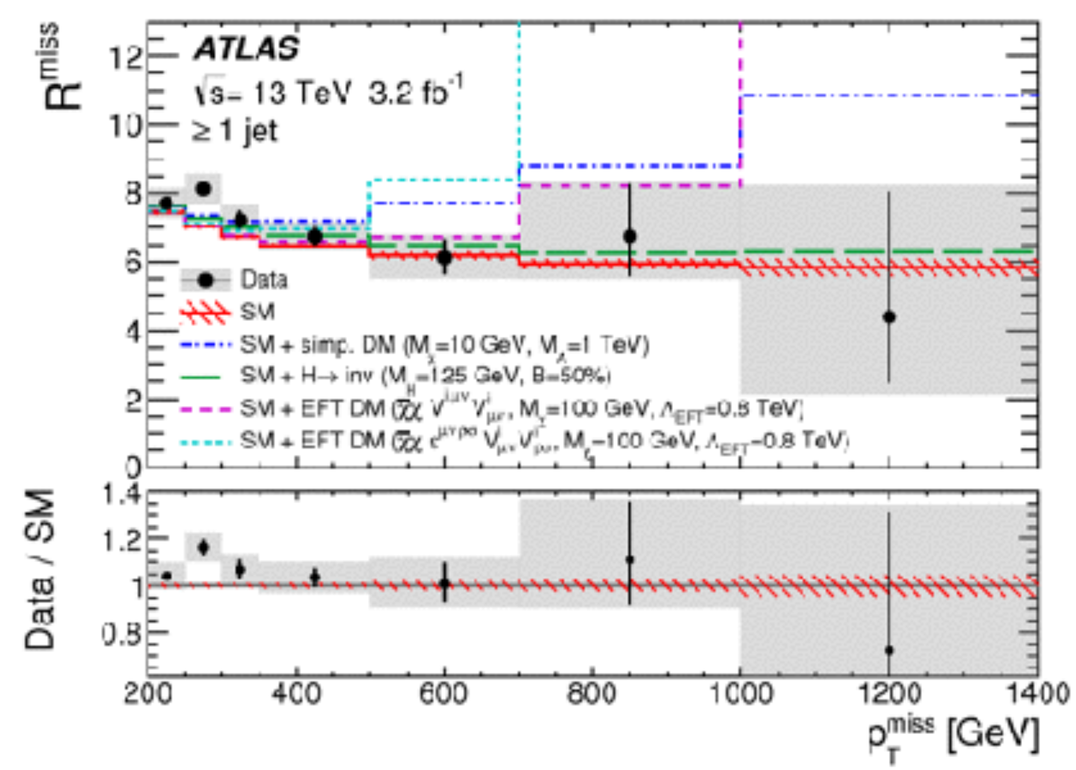
ttW

- Rare SM source of same-sign dilepton pairs
- Important bkgd in same-sign BSM searches

Run 3: Measurements

- Measurements tend to be in the bulk of the phase-space far from where the searches are carried out.
- **Watch out** for new measurements bridging the gap to:
  - improve modeling of SM in search areas (prepare for HL-LHC!)
  - search through measurements i.e. non-resonant physics, Y & W propagators form factors in high mass Drell-Yann, etc
  - allow for easier reinterpretation

Once these measurements are released, continue strong UK connection with theory community to maximally leverage the information.



Maintaining Leadership

- Currently activities in ***3 areas***! More than “usual”
  - Operation of current ATLAS detector
  - Construction of upgraded ATLAS detector
    Highly driven by UK involvement
  - Data analysis (both directly in physics and in performance)
- Any diminishment in one area jeopardized UK leadership and impact as all are intertwined. Not a time to cut funds.
- 10% diminishment in previous round decreased our contribution to the basic needs of the experiment.

Conclusion

In full swing of Run 2 of the LHC. Run 3 is exciting with 14 TeV collisions and HL-LHC will build upon that further.

ATLAS-UK is driving the physics program forward with many exciting results and impactful work done in the next 5 years

We live in ***data-driven times***!
It is for the **experimental community** to continue a **broad program** in order to advance humanity's understanding of the Universe.

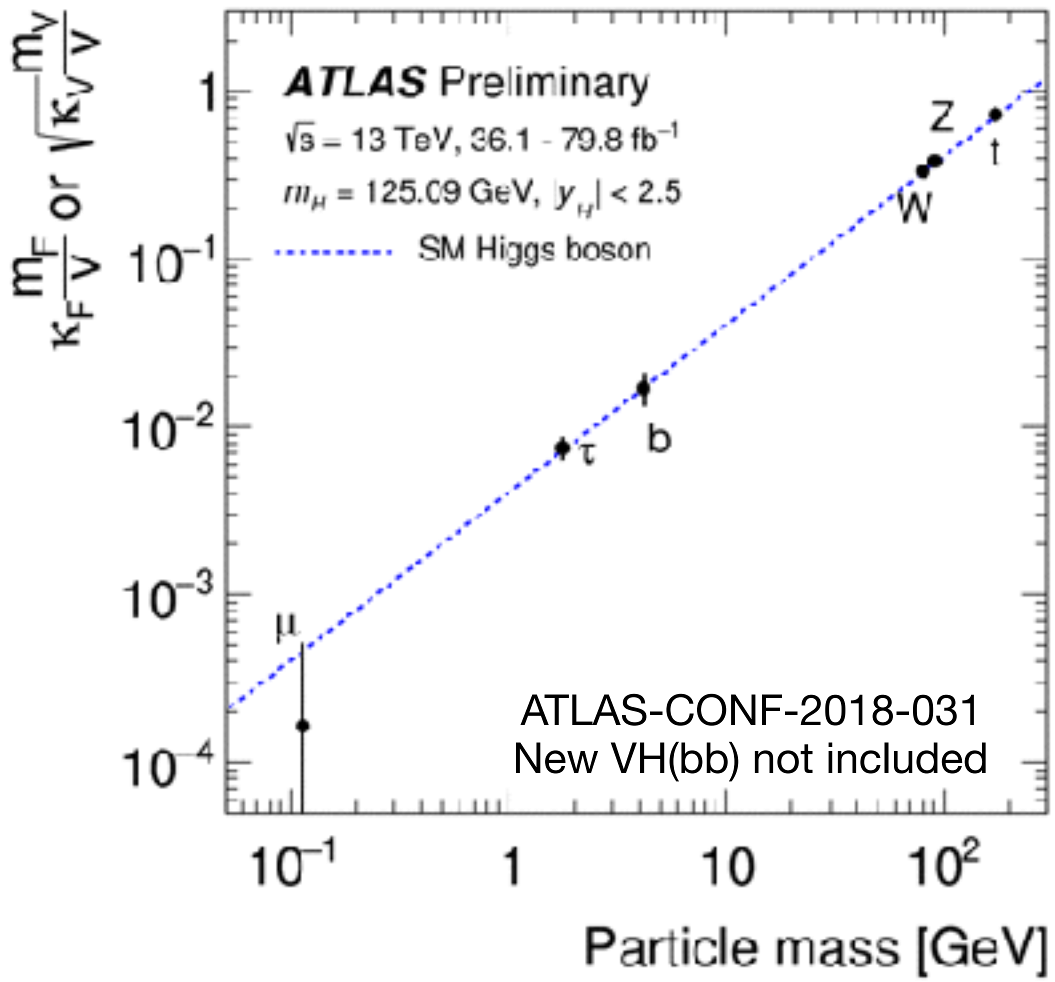
Colliders are a centerpiece of this program!

extras

Higgs Physics Program

- Higgs Boson: first and only fundamental scalar in the SM
- Understanding its properties is a unique deliverable of the LHC programme
- Run 1: Discovery and establish couplings to bosons. First hints of coupling to heavy fermions
- Run 2: First differential measurements in boson channels. Establish couplings to heavy fermions
- Run 3 -> HL-LHC: Differential measurements in all channels further constraining BSM physics. Reduce space for new physics i.e. BR(invisible)
- HL-LHC: Establish couplings to 2nd generation fermions H(cc), H(mumu)

Higgs Physics Program



Interaction with gauge bosons:

$H \to ZZ^*$ ATLAS-CONF-2018-018

Well established in run-1

$H \to WW^*$ ATLAS-CONF-2018-004

6.3 (5.2) σ obs (exp) (run-2 only)

Run 1

Yukawa coupling to fermions:

Top-quark: ttH **80 fb^{-1}**

6.3σ (5.1σ) obs (exp) arXiv:1806.00425

Beauty-quark $H \to bb$: **80 fb^{-1}** New

5.4σ (5.5σ) obs (exp) ATLAS-CONF-2018-036

Tau-lepton: $H \to \tau\tau$

6.4σ (5.4σ) obs (exp) ATLAS-CONF-2018-021

Muon $H \to \mu\mu$: **80 fb^{-1}** New

$\sigma_{limit}/\sigma_{SM}$<2.1 (obs) ATLAS-CONF-2018-026

Charm-quark: $H \to cc$:

$\sigma_{limit}/\sigma_{SM}$<104 (obs) PRL 120 (2018) 211802

Run 2

HL-LHC

The Higgs Boson is only 6 years old! Rapidly moving field has accomplished much:

- 2% precision in mass measurement
- Observation of
  - coupling to bosons
  - coupling to heavy fermions
  - all 4 major production modes

Gauge boson and Yukawa fermion coupling

$|D_\mu \phi|^2$ **Interaction with gauge bosons:**

$\psi_i y_{ij} \psi_j \phi$ **Yukawa coupling to fermions:**

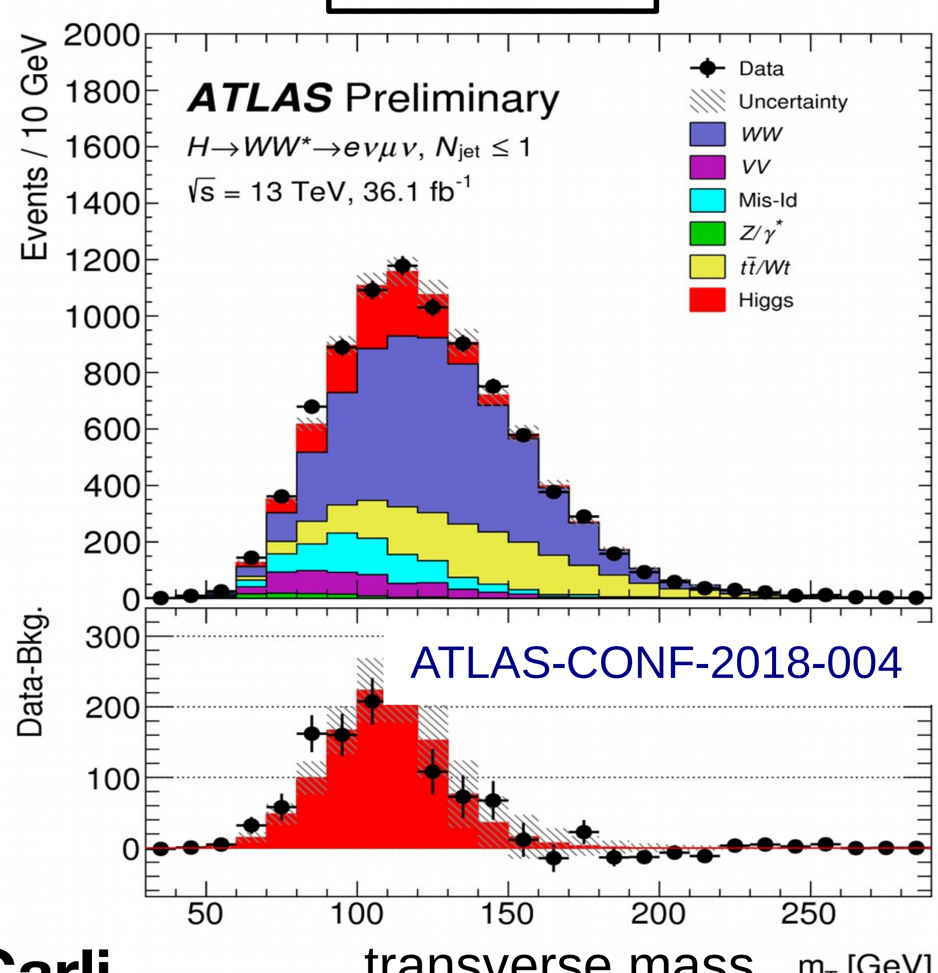
Earlier 7 and 8 TeV results:

At 7 and 8 TeV Higgs boson discovered.
Main channels: $H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$

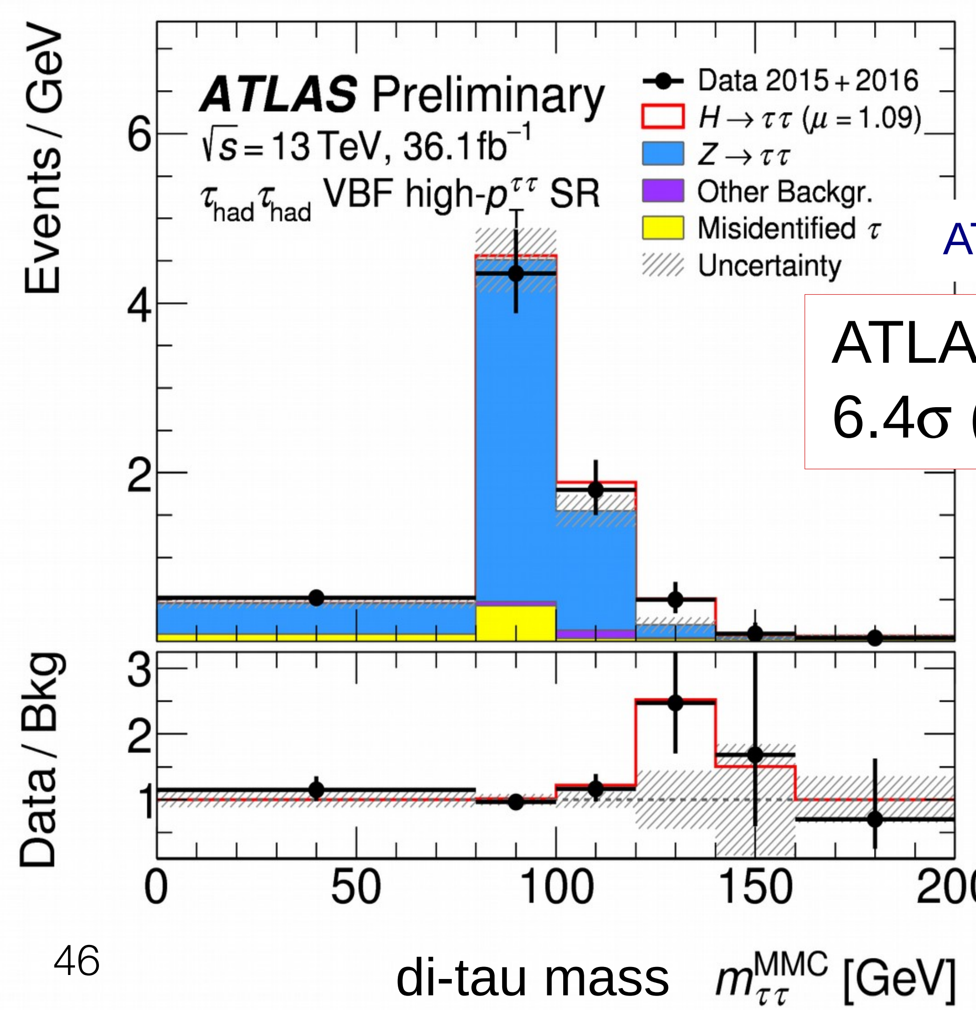
Only glimpse at 7 and 8 TeV (2012)
ATLAS/CMS combined $H \to \tau\tau$:
5.5σ (5.0σ) obs (exp) for 7/8/13 TeV
JHEP 08 (2016) 045

Recent 13 TeV results:

$H \to WW$



$H \to \tau\tau$



ATLAS-CONF-2018-021

ATLAS 7/8/13 TeV:
6.4σ (5.4σ) obs (exp)

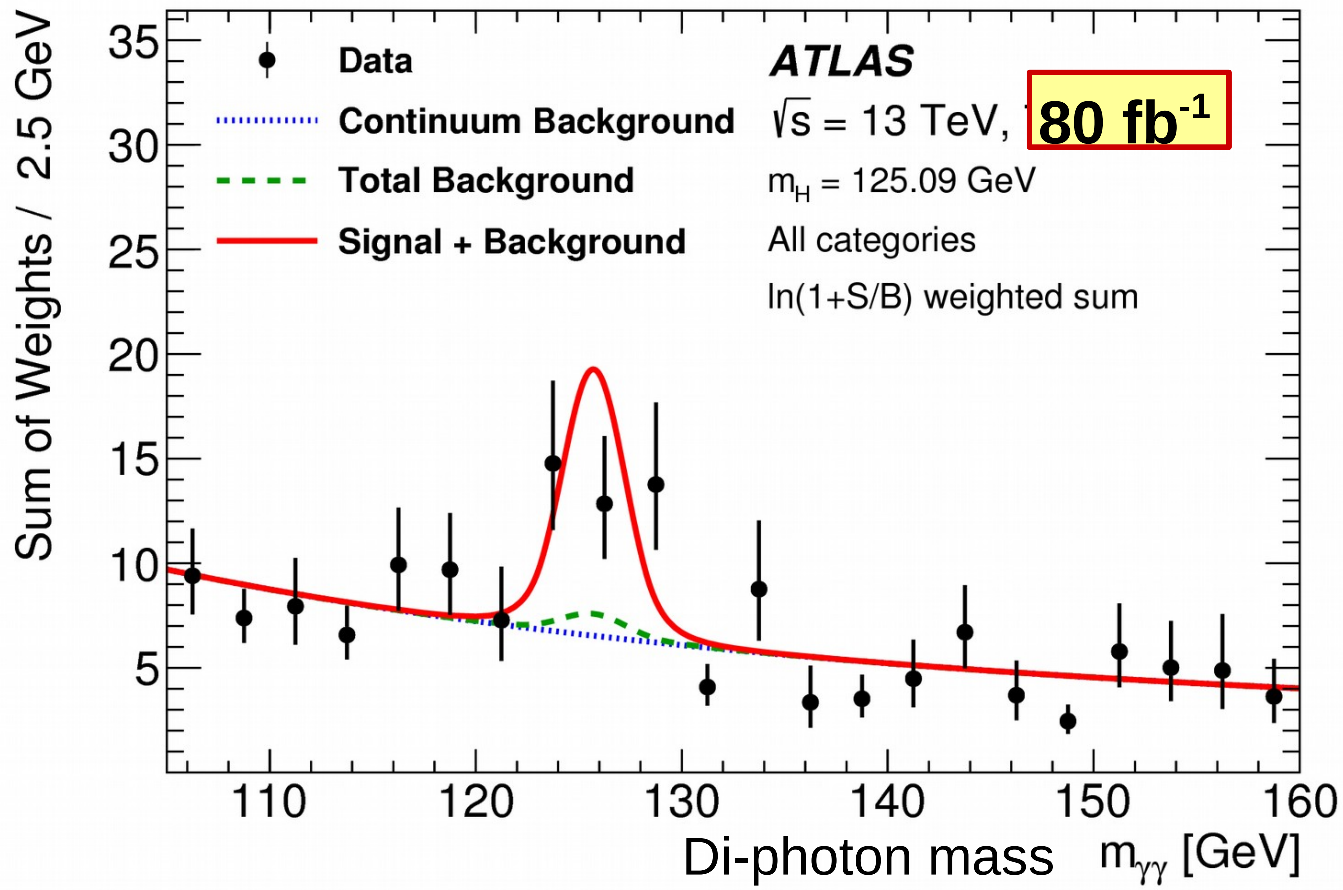
Example of mass in 1/13 signal categories

Observation of ttH production

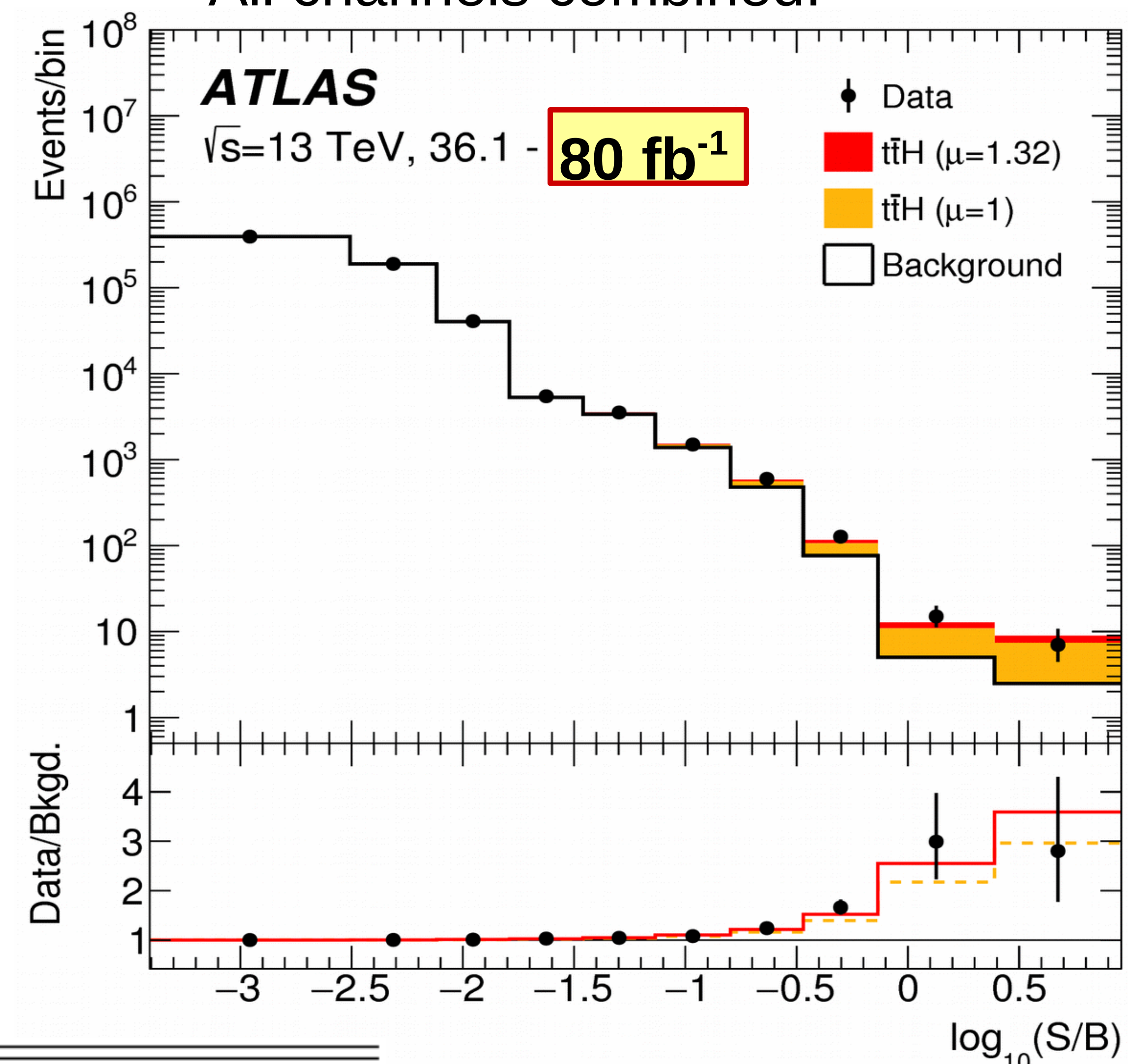
arXiv:1806.00425

June 2018 update: ttH(→γγ) and ttH(ZZ→4l) with 80 fb^{-1}

ttH(→γγ):



All channels combined:



Analysis	Integrated luminosity [fb^{-1}]	Expected significance	Observed significance
$H \to \gamma\gamma$	79.8	3.7 σ	4.1 σ
$H \to$ multilepton	36.1	2.8 σ	4.1 σ
$H \to b\bar{b}$	36.1	1.6 σ	1.4 σ
$H \to ZZ^* \to 4\ell$	79.8	1.2 σ	0 σ
Combined (13 TeV)	36.1–79.8	4.9 σ	5.8 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	5.1 σ	6.3 σ

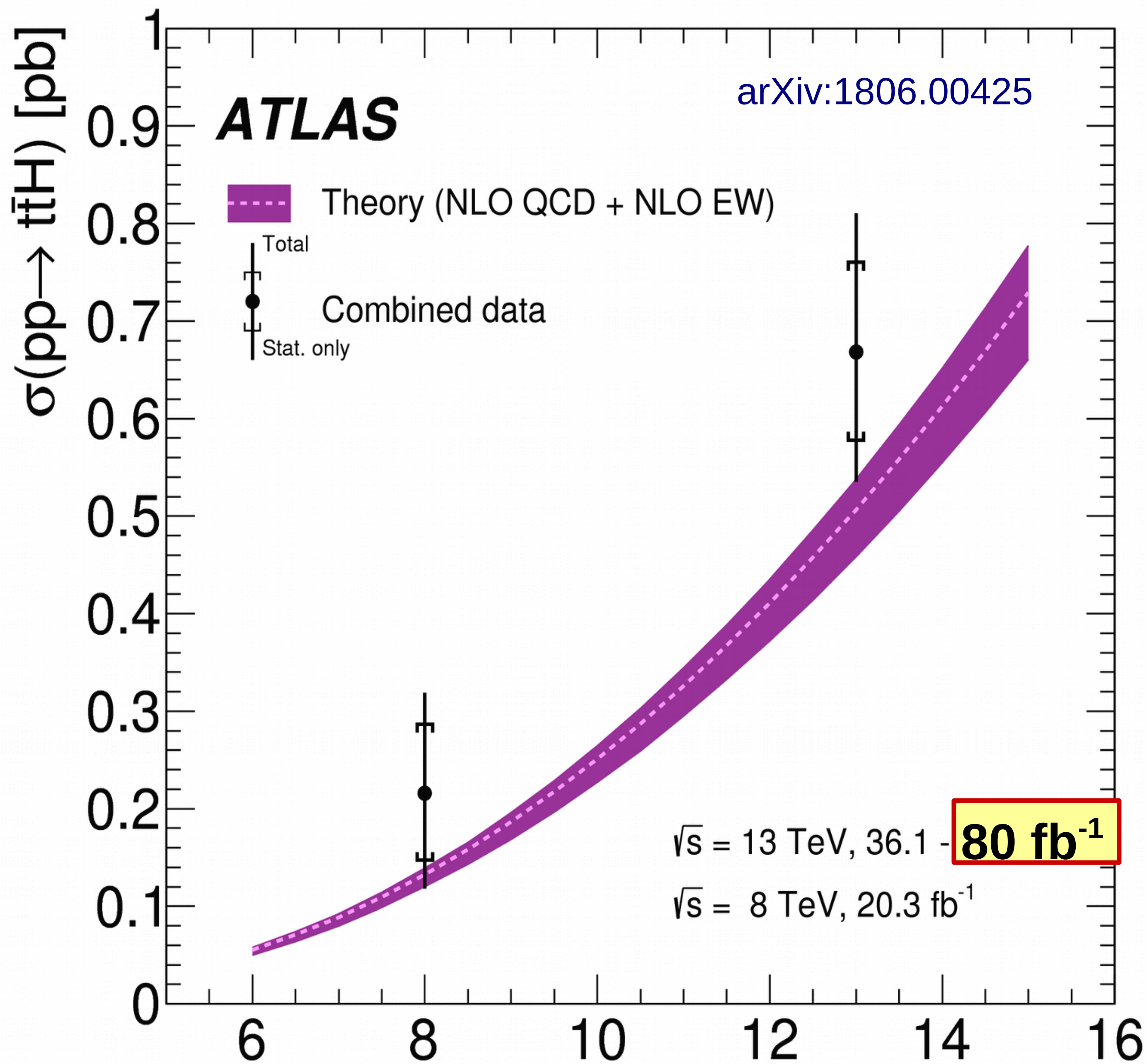
Direct observation of top Higgs coupling.
Confirmation of Yukawa coupling for fermions.

ttH production cross-section

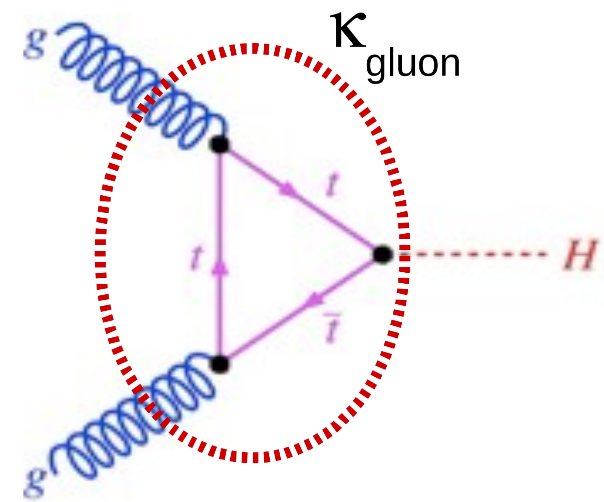
June 2018 update: ttH($\rightarrow\gamma\gamma$) and ttH($\rightarrow ZZ \rightarrow 4l$) with 80 fb^{-1}

ATLAS-CONF-2018-031

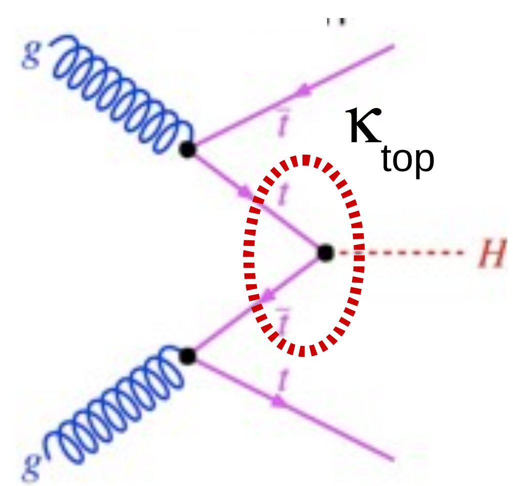
Inclusive ttH production cross-section



Gluon-gluon fusion



Associated ttH production



Already 20% precision !

Effective coupling κ_{gluon} / κ_{top} =1.09+-0.14
Consistent with Higgs boson coupling as in SM.
Constrains BSM contributions.

New

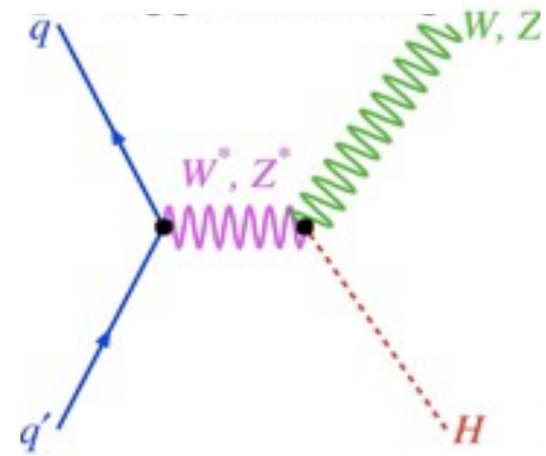
Associated VH production and H → bb

H→bb highest branching ratio: Br=58%

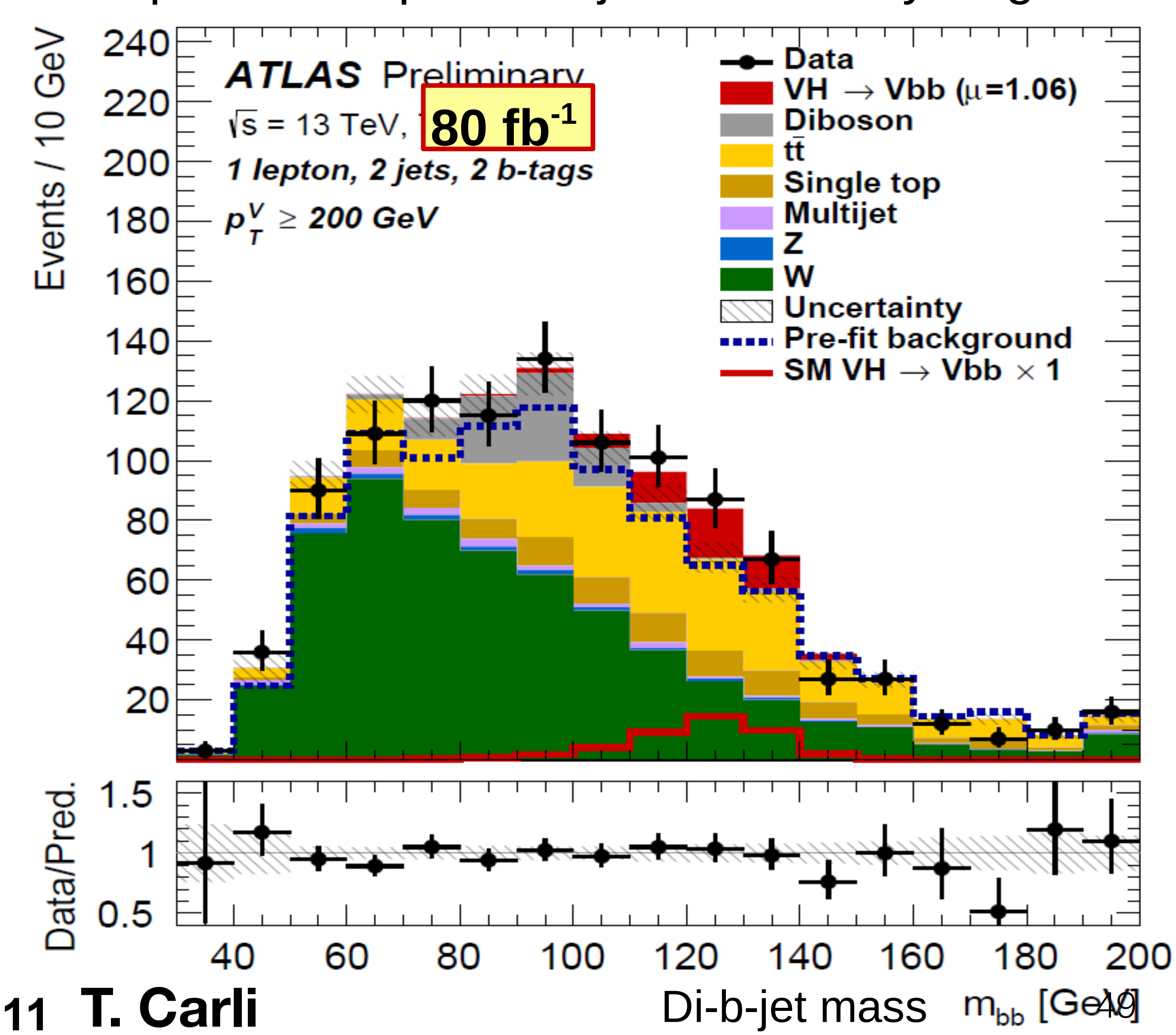
→ Br(H→bb) constrains invisible Higgs decays
→ Tests Higgs Yukawa coupling to fermions

Analysis with large background:
→Use high-p_T boson region
→Multi-variate analysis in 0, 1 and 2 lepton channels
→Dijet mass analysis as cross-check

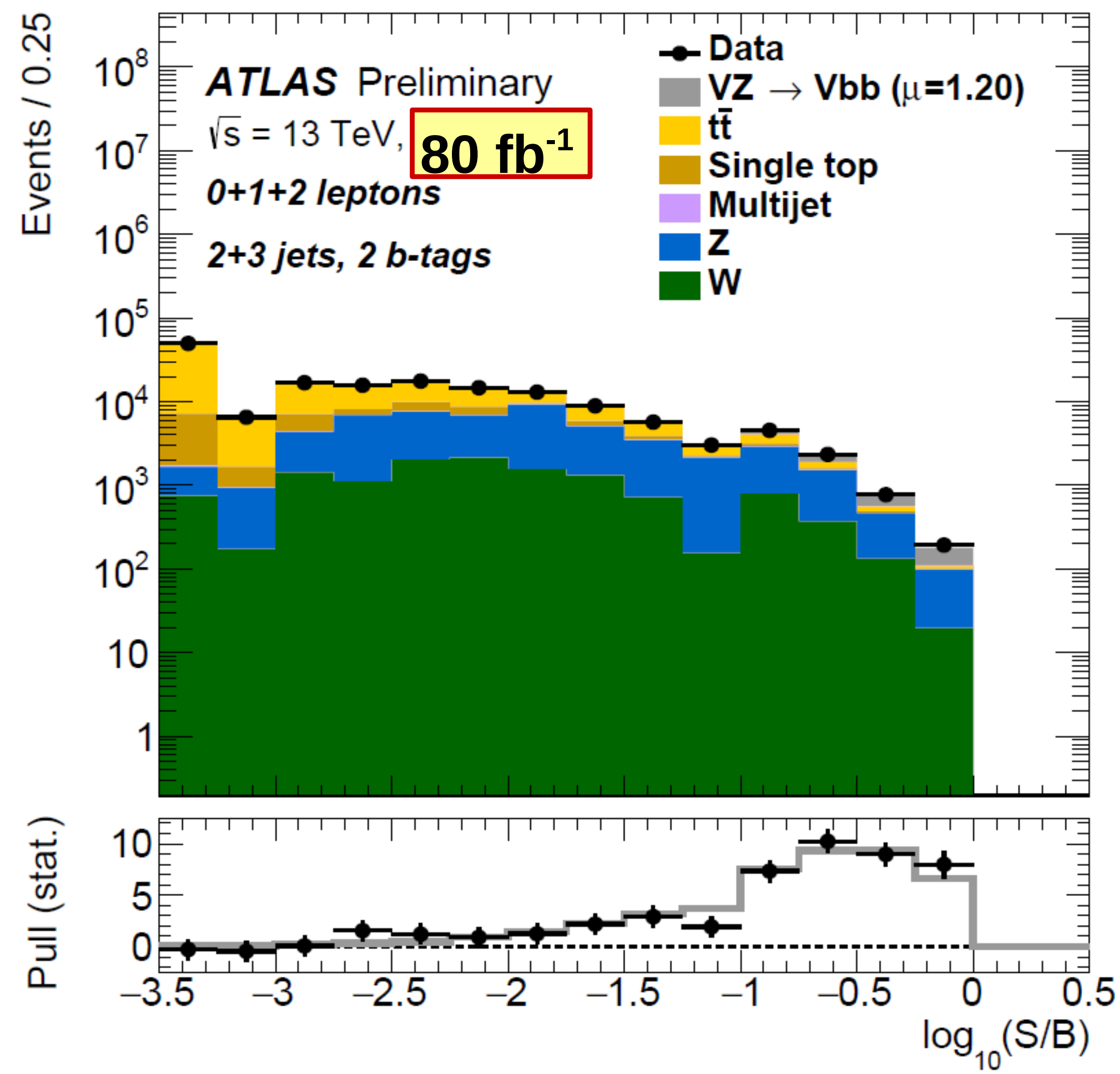
Associated WH or ZH production (VH)



Example: One input to di-jet mass analysis global fit



Di-boson validation analysis VZ(→bb):

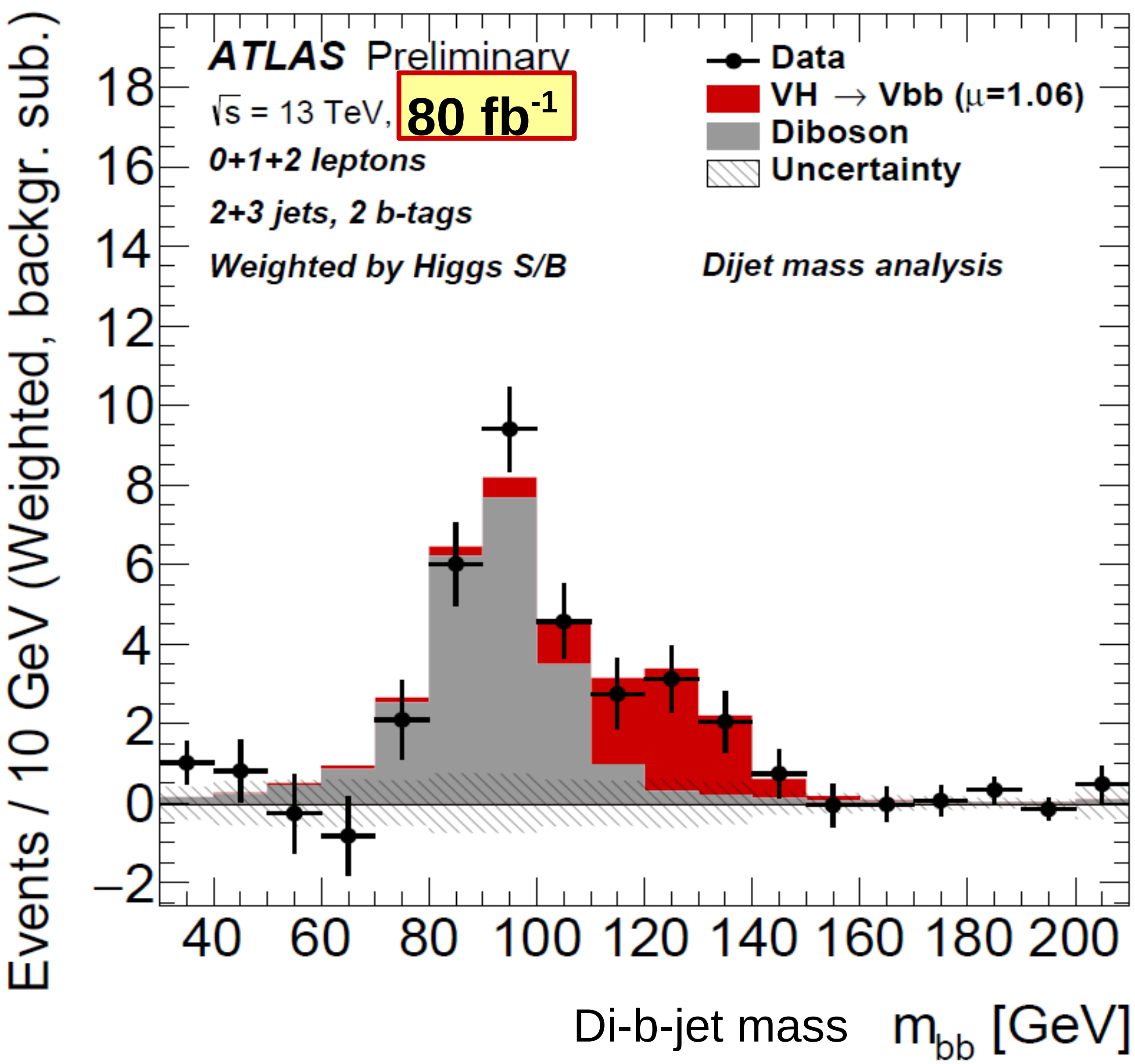


New

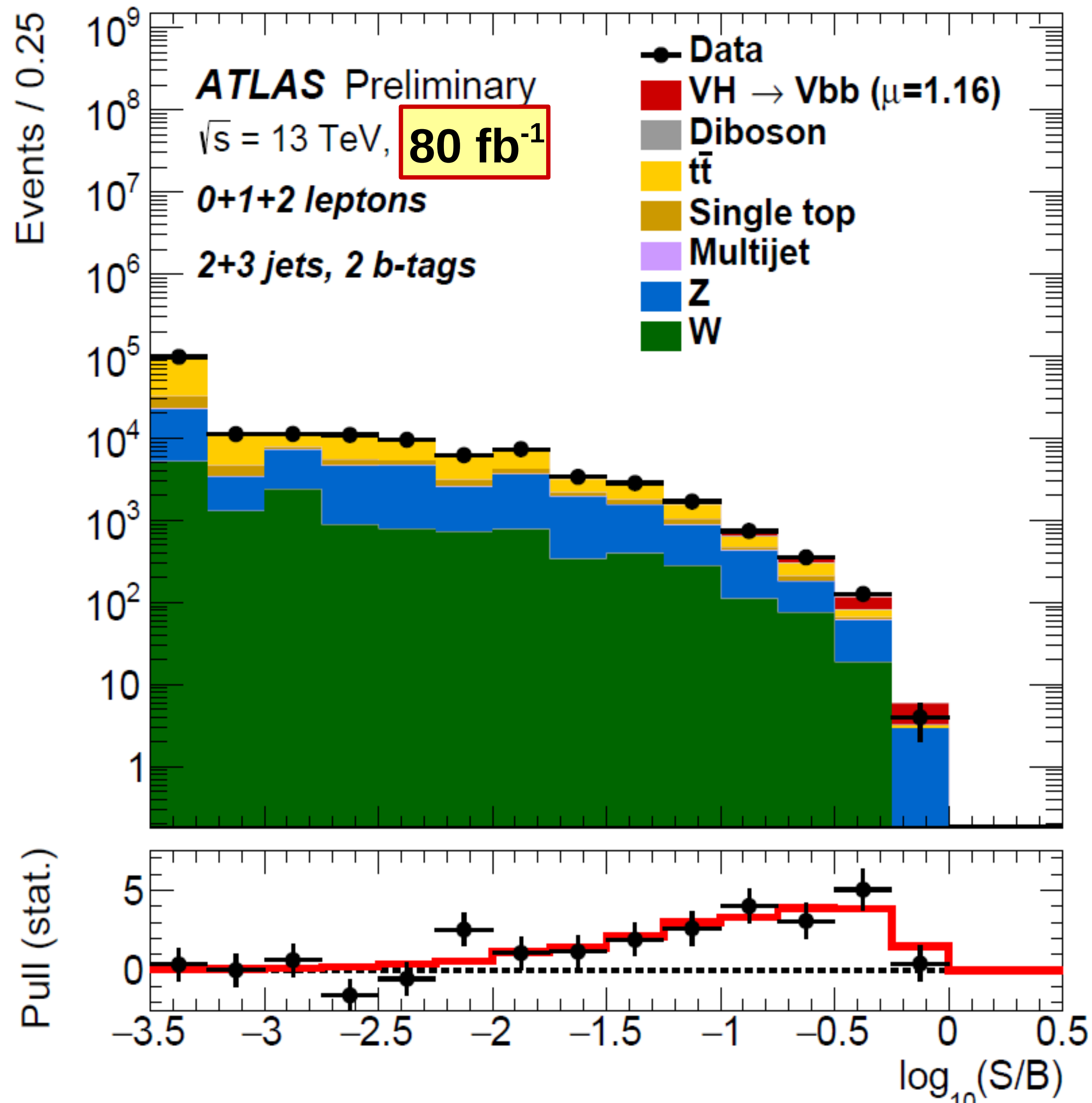
Observation of H → bb

ATLAS-CONF-2018-036

Di-jet mass analysis:



Main multi-variate analysis:



Observation of Higgs decay to beauty quarks !

VH alone: 4.9σ (4.3σ) obs (exp) (13 TeV)

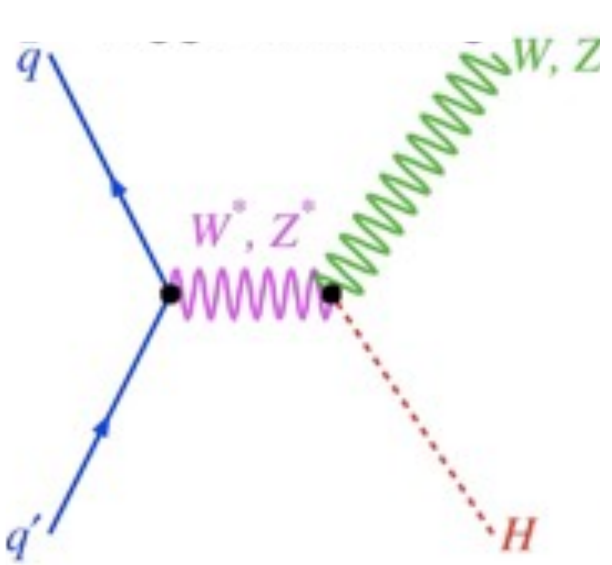
Combined (7,8,13 TeV) VBF, ttH, VH:
5.4σ (5.5σ) obs (exp)

12 T. Carli

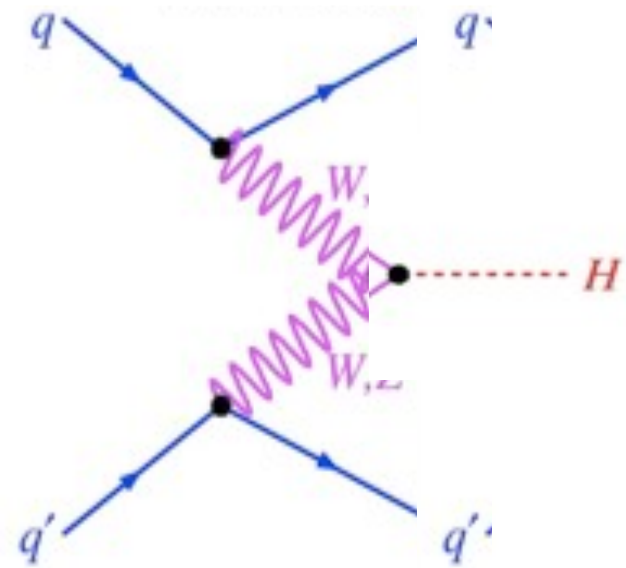
New

Higgs production modes

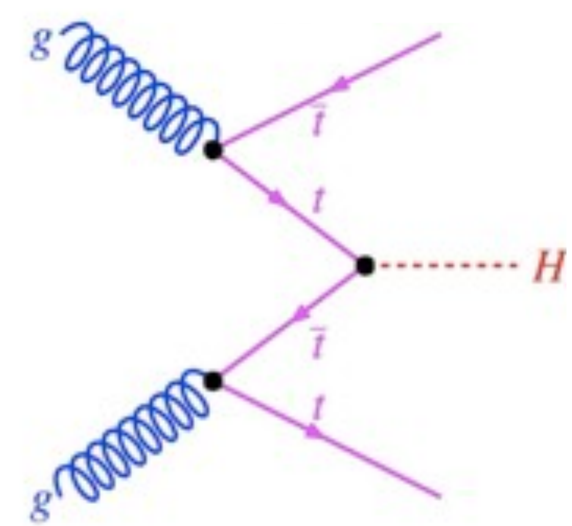
Associated WH or ZH production (VH)

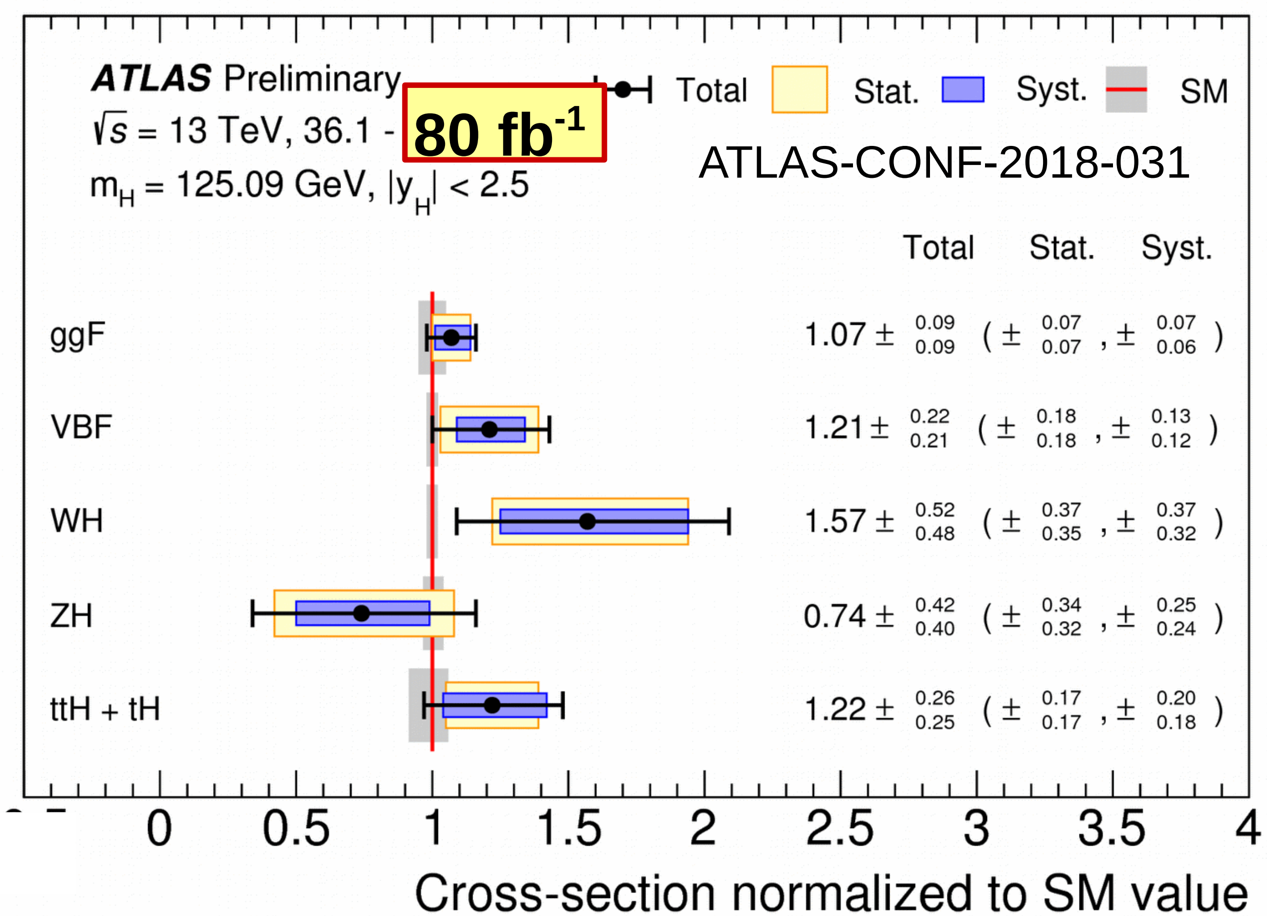


Vector-boson fusion (VBF)



Associated ttH production (ttH)





Gluon-gluon fusion (ggF) observed since 2012 and used for precision measurements (~10%).

VH	5.3σ (4.8σ) obs (exp)	ATLAS-CONF-2018-036
VBF	6.5σ (5.3σ) obs (exp)	ATLAS-CONF-2018-031
ttH	6.3σ (5.1σ) obs (exp)	arXiv:1806.00425

Observed all major Higgs production modes ! Consistent with SM.

Measurements of electroweak parameters

Measurement of electroweak mixing angle:

Drell-Yan cross-section qq→Z→ll expanded as sum of 9 harmonic polynomials (NNLO QCD).
In LO QCD (Z-boson rest frame:)

A_4 (and A_3) sensitive to weak mixing angle

$$\frac{d\sigma}{dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dy^{\ell\ell}\, dm^{\ell\ell}}\left\{(1+\cos^2\theta) + \boxed{A_4 \cos\theta}\right\}$$

ATLAS-CONF-2018-037

A_4 measured using two leptons |η|<2.4 (cc)

and at least one forward electron 2.5<|η|<4.6 (cf).
Using 8 TeV data (2012).

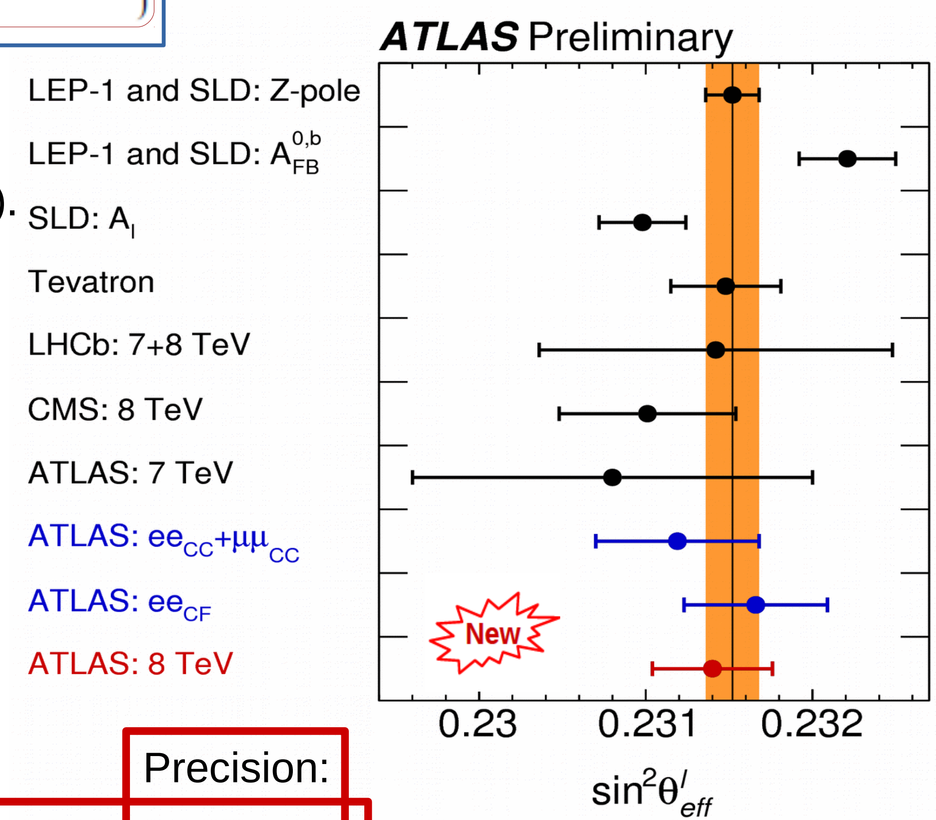
Result from likelihood fit:

$$\sin^2\theta^l_{eff} = 0.23140 \pm 0.00036$$

Uncertainty break-down:

$$0.00021\,(stat) \pm 0.00024\,(PDF) \pm 0.00016\,(syst)$$

Main limitation knowledge initial quark direction.



Other recent electroweak measurements:

			Precision:
W-mass:	80370 +- 19 MeV	EPJ C78 (2018) 110	~0.02%
Higgs mass:	124970 +- 240 MeV	arXiv:1806.00242	~0.2%
Top-mass:	172510 +- 500 MeV	ATLAS-CONF-2017-071	~0.3%

0.15% precision on $\sin\Theta_W$

18

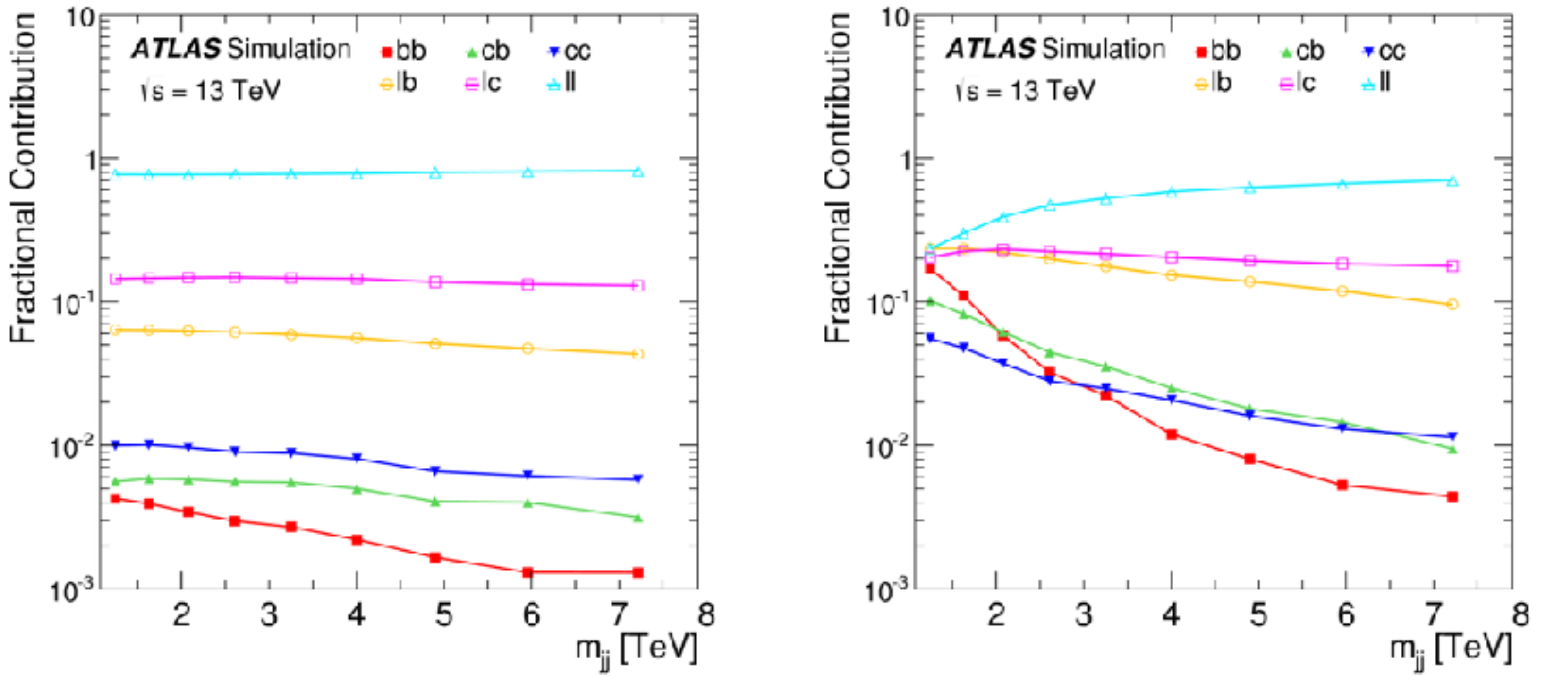
ATLAS Phase-I and II Upgrade Programmes

- Phase-I
  (up to and including LS2: 2019-2020)
  - ***Upgrade TDAQ***
    - ***L1 Calorimeter trigger***
    - L1 Muon trigger
    - Topological triggers
    - ***High Level Trigger***
    - ***Readout***
  - LAr readout electronics
  - New small muon wheel in forward region
  - Forward detector system
  - ***Computing***
- ***UK construction project funded to 2019***

- Phase-II
  (LS3: 2024-2026)
  - ***Replace tracking system***
  - Replace calorimeter and muon detector readout electronics
  - Forward timing detector (HGTD)
  - Replace some muon detectors
  - ***Upgrade TDAQ***
    - New trigger architecture
    - *Phase-I L1 Triggers → L0Trigger*
    - ***Gobal Trigger Processor***
    - ***Hardware Track Trigger***
    - ***Event Filter & DAQ***
    - ***Muon Trigger Electronics***
    - ***Central Trigger Processor***
  - ***Computing***
- ***UK R&D for Tracker and L1 Track Trigger funded to March 2018***
- ***Phase-II construction bid under review by STFC***

ATLAS-UK upgrade projects focus on areas that build on successful delivery of original construction

C. Butler



ATLAS Simulation
$\sqrt{s}$ = 13 TeV
bb
cb
cc
lb
lc
ll
Fractional Contribution
m_{jj} [TeV]
ATLAS Simulation
$\sqrt{s}$ = 13 TeV
bb
cb
cc
lb
lc
ll
Fractional Contribution
m_{jj} [TeV]