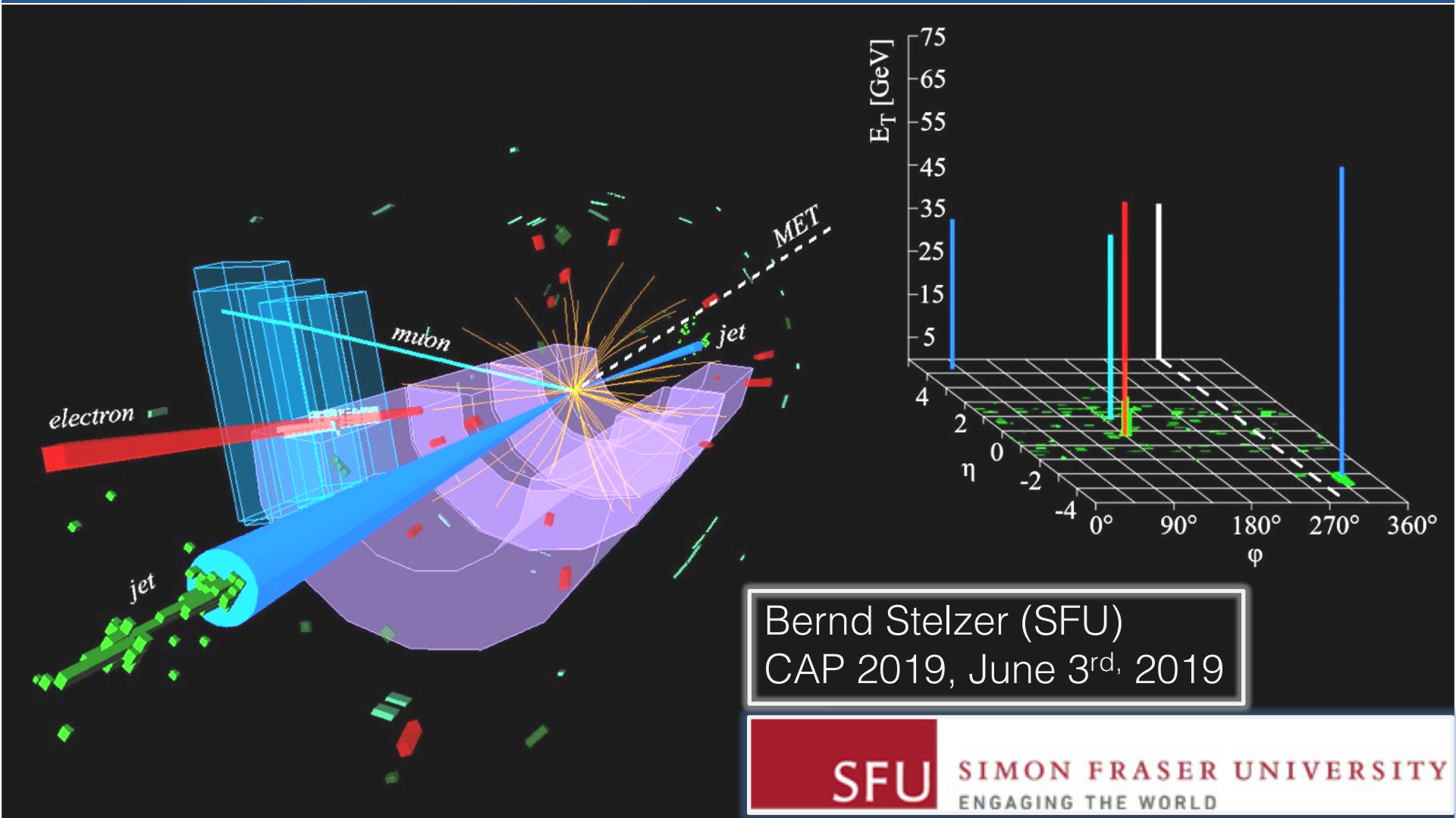
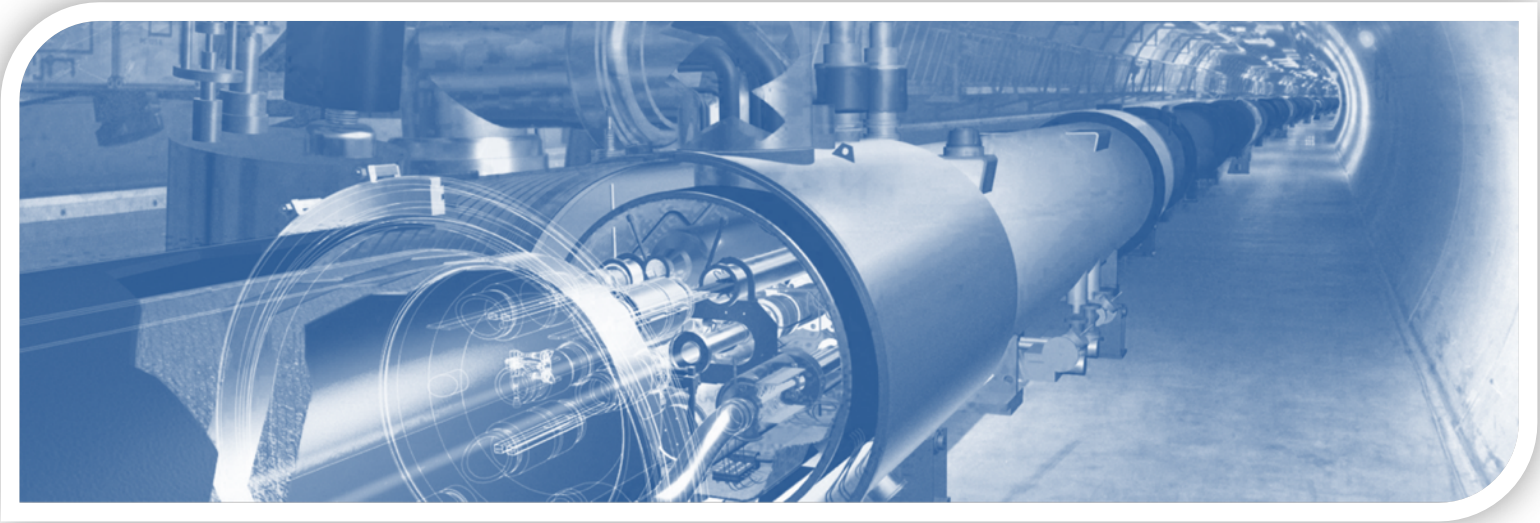
Run-2 Physics Results from ATLAS at the LHC

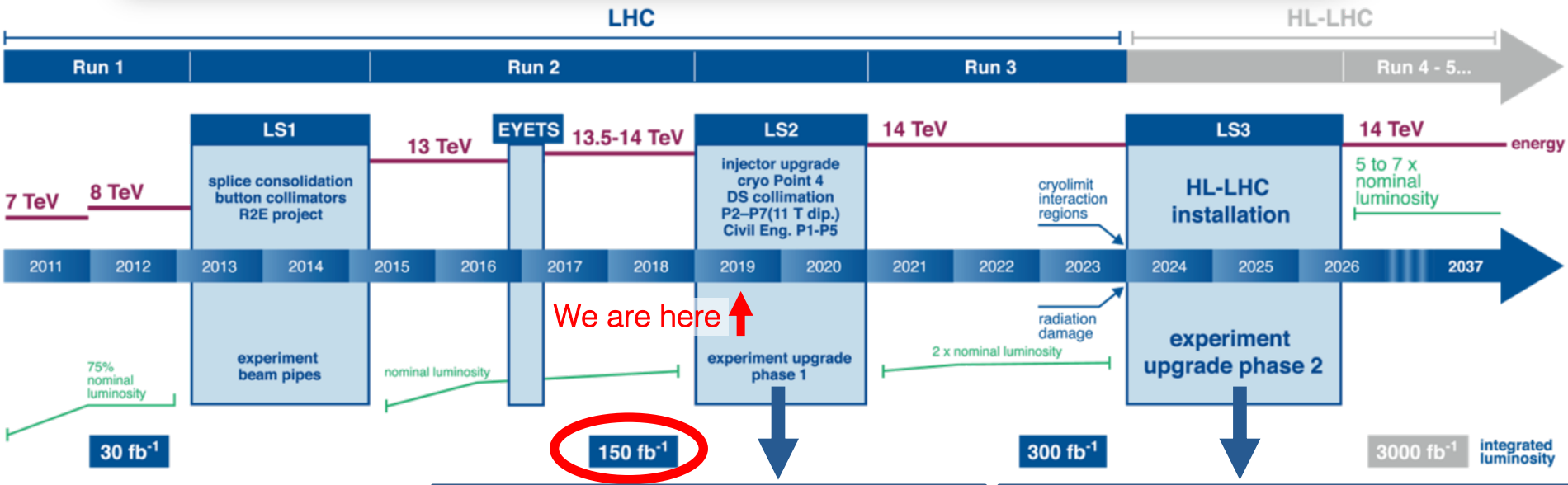


Bernd Stelzer (SFU)
CAP 2019, June 3rd, 2019

SFU SIMON FRASER UNIVERSITY
ENGAGING THE WORLD

LHC Schedule



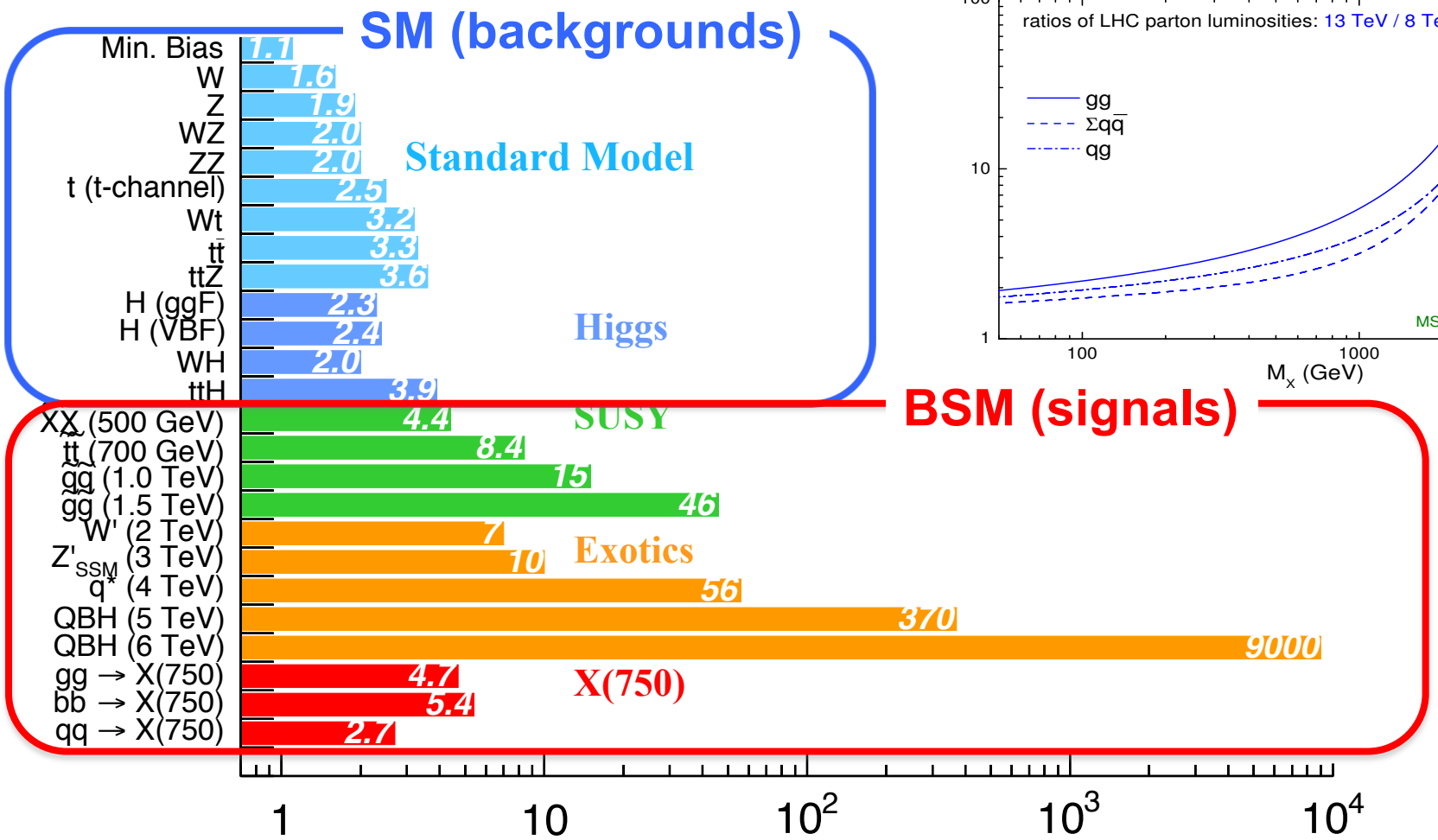


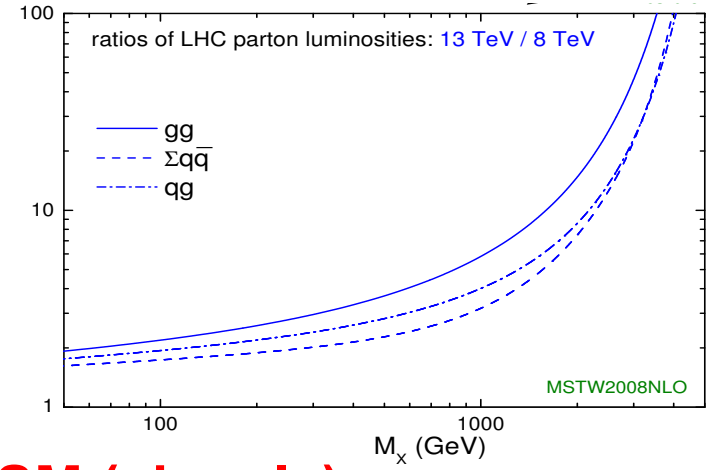
- sTGC for Muon New Small Wheel
- LAr Calorimeter trigger electronics

- New ATLAS Inner Tracker (ITk)
- LAr Calorimeter readout electronics

See Jesse Heilman's talk

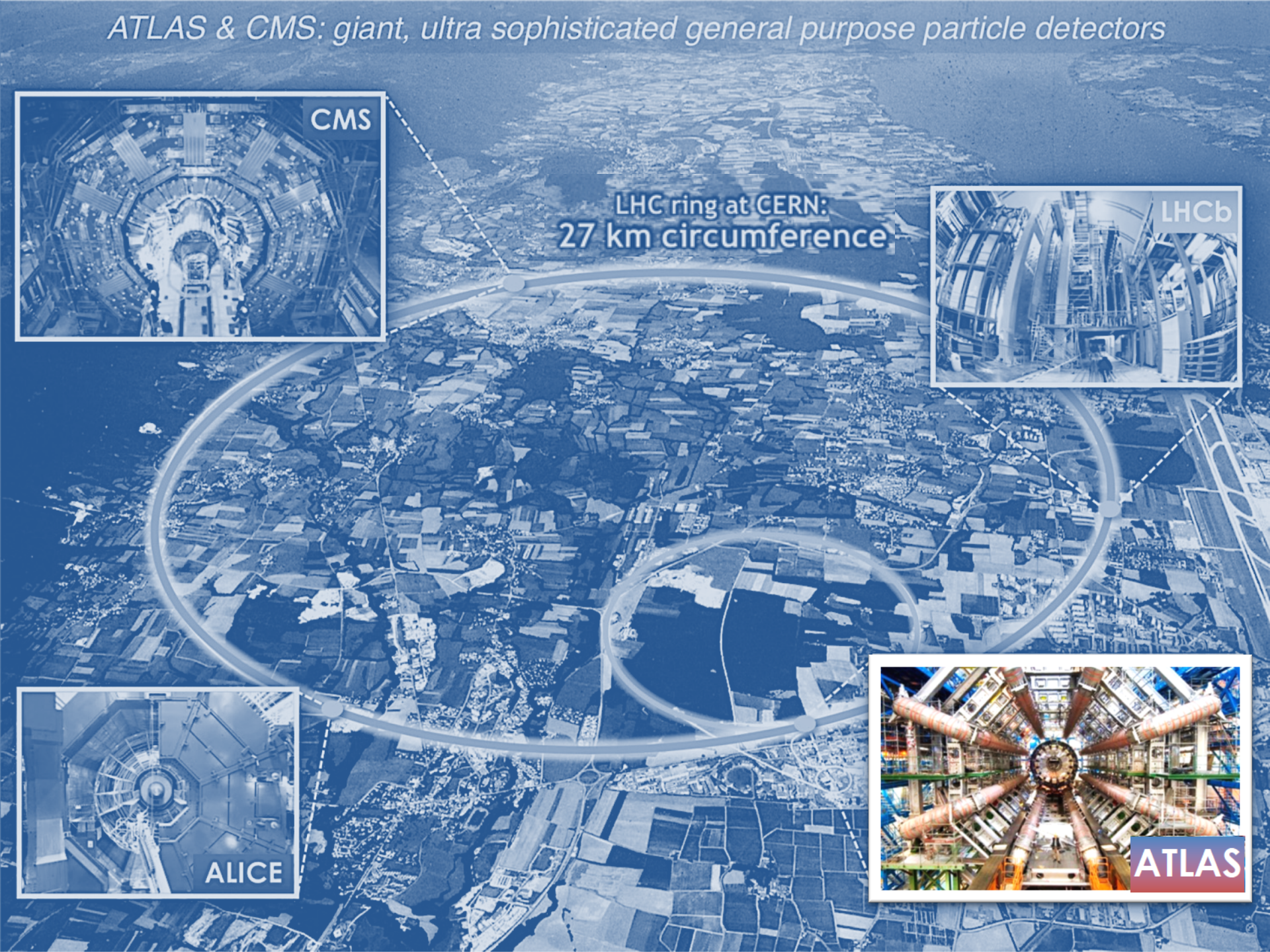
LHC-Run 2 Physics Benefits





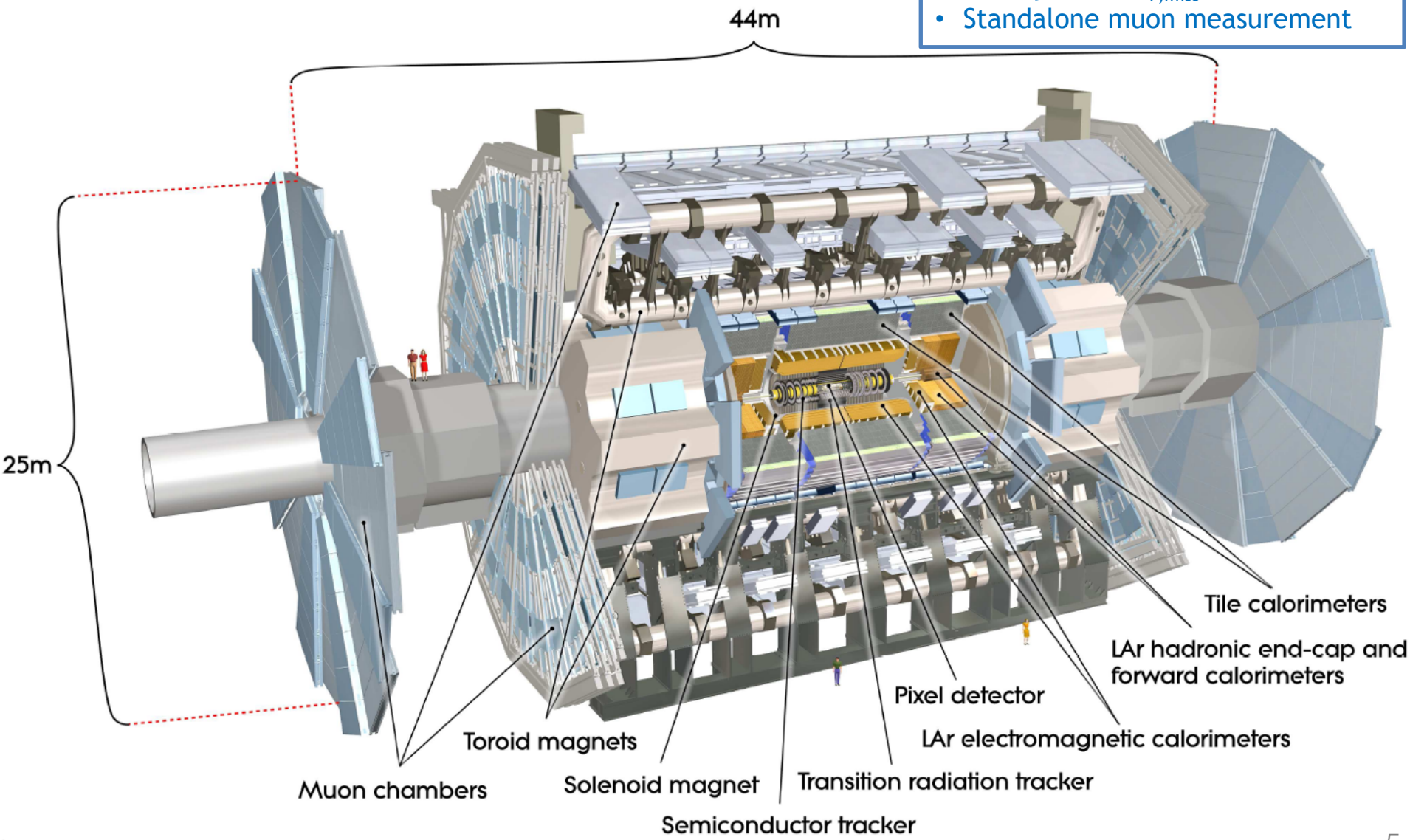
Run-2 was clearly a game-changer…

ATLAS & CMS: giant, ultra sophisticated general purpose particle detectors



The ATLAS Experiment

Emphasis on:
- Large acceptance and hermeticity
- Excellent particle identification
- Excellent lepton and γ resolution
- Good jet and $E_{T,\mathrm{miss}}$ resolution
- Standalone muon measurement



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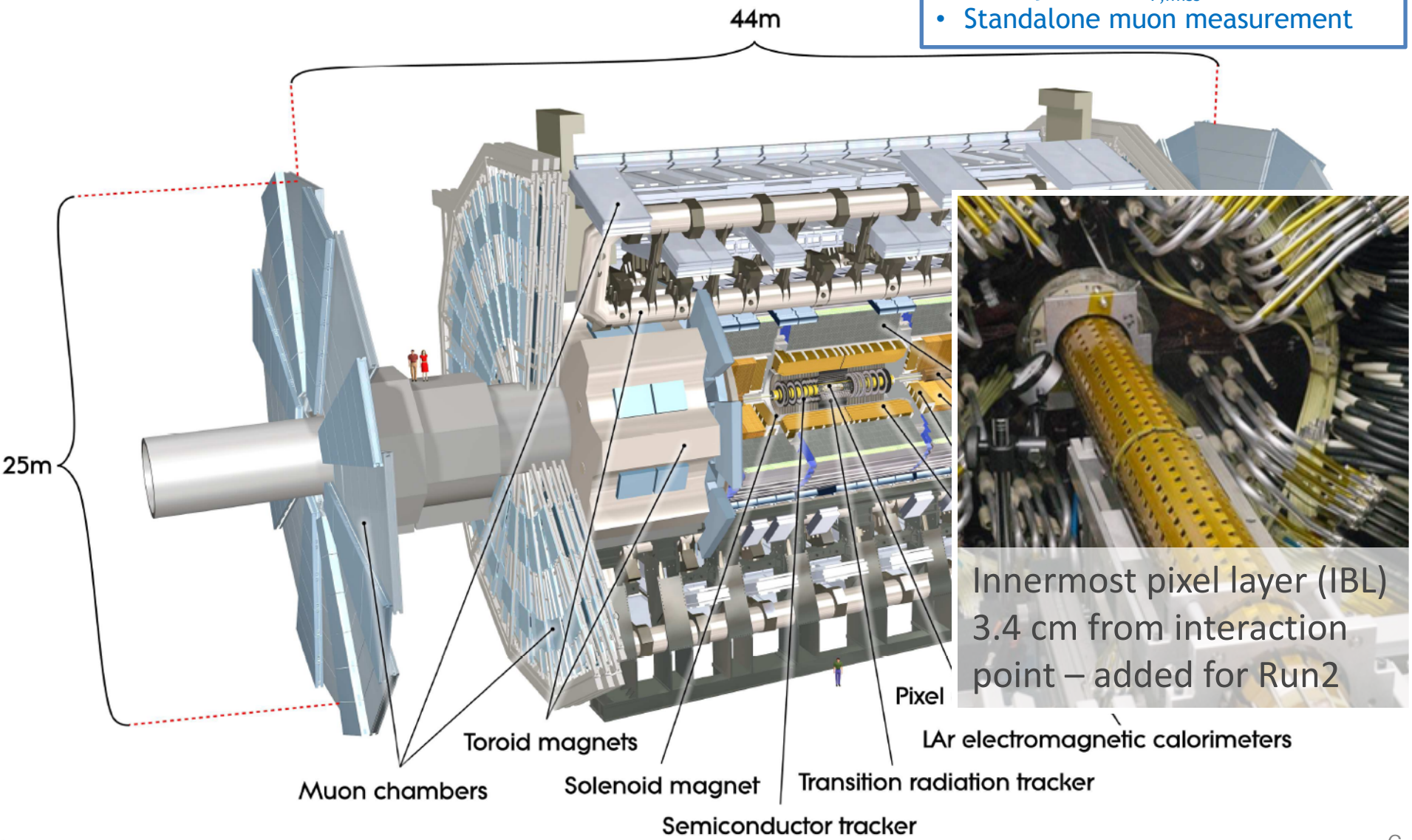
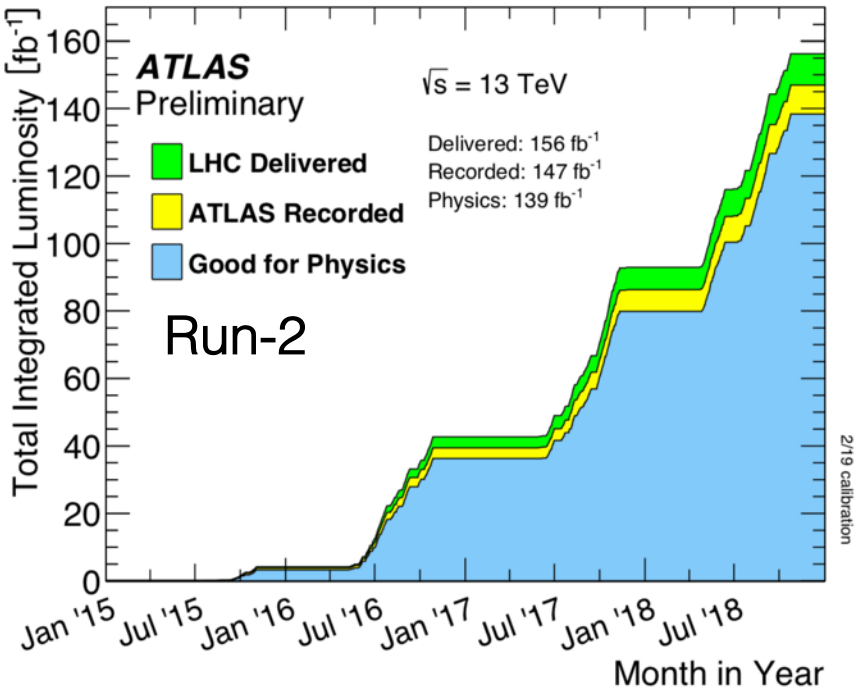
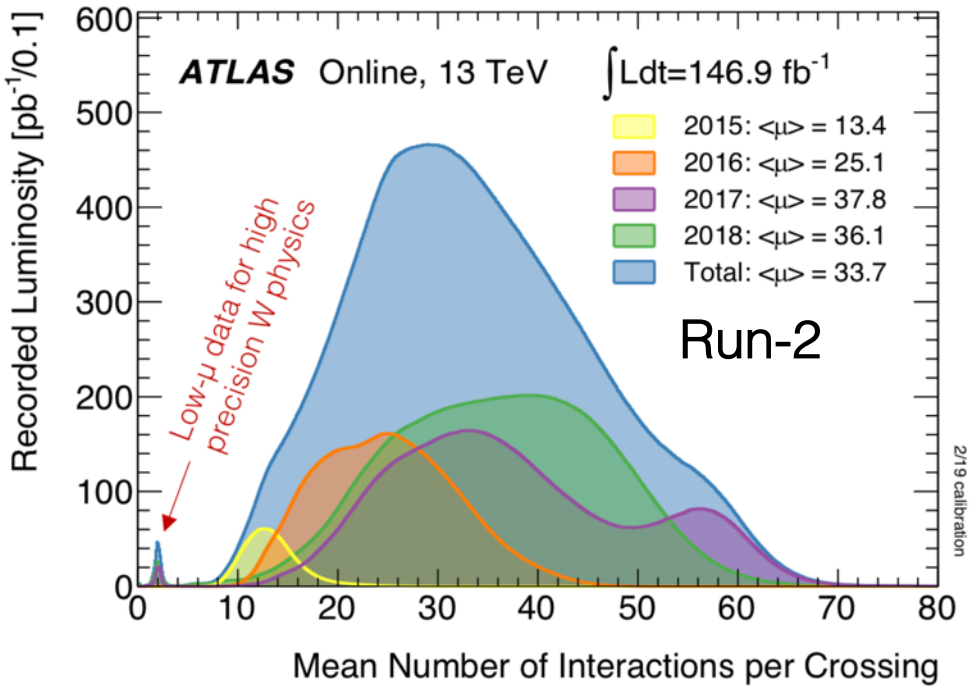


Innermost pixel layer (IBL) 3.4 cm from interaction point – added for Run2

Integrated Luminosity During Run-2





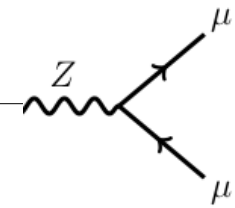
Challenging conditions with 10-70 interactions per bunch crossing (pileup)

- High data taking efficiencies
- All subdetectors running smoothly
- Learn to live with high pileup
- **139 fb^{-1} of good data** collected
- **Outstanding Performance!**

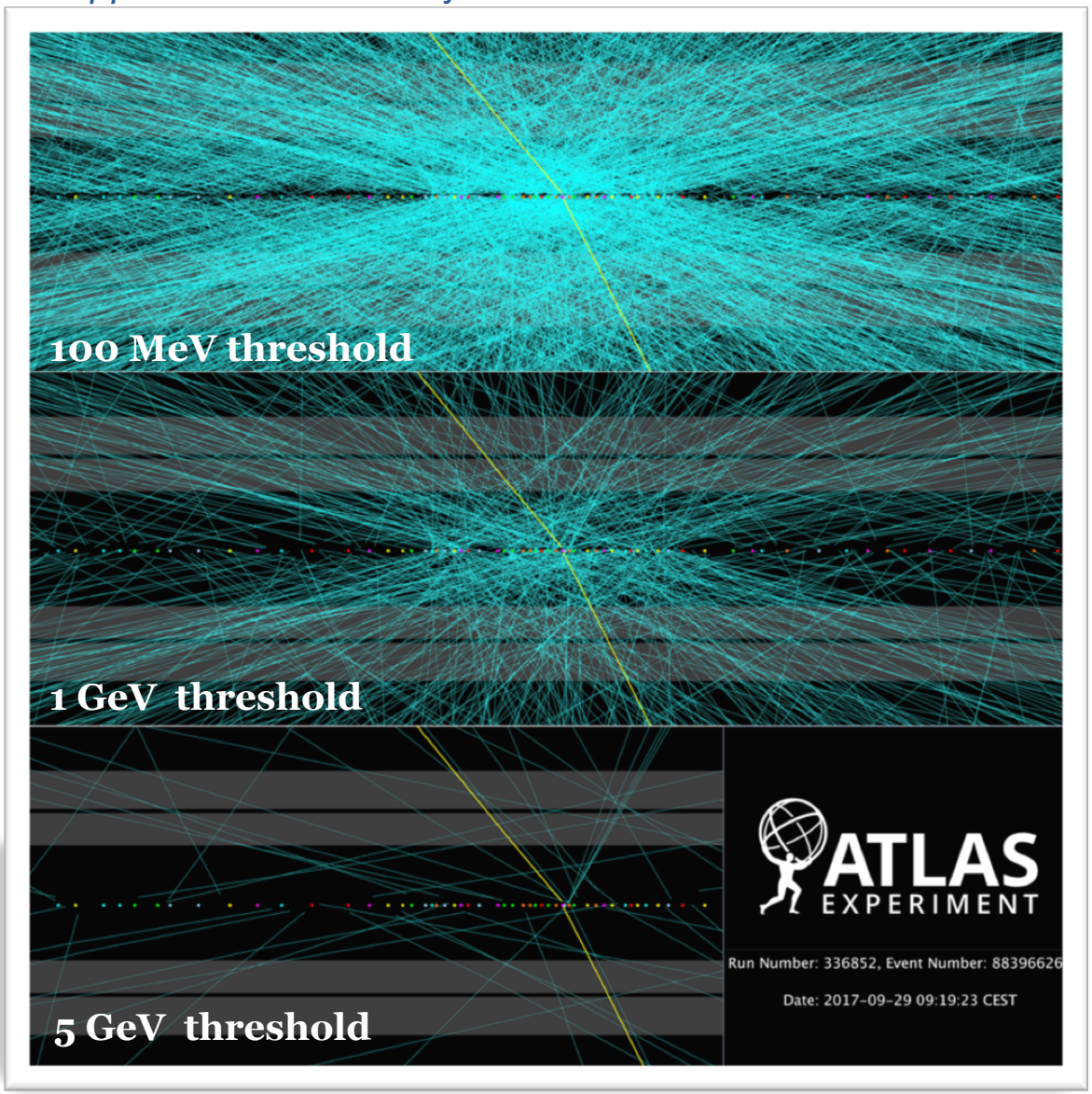
Data quality efficiency

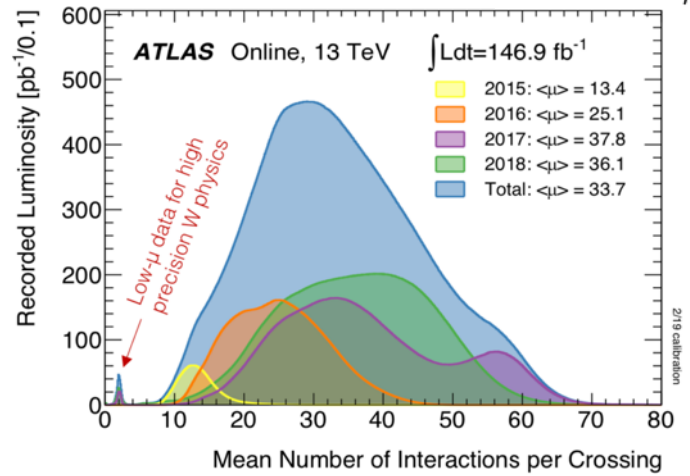
ATLAS pp data: April 25-October 24 2018										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.8	100	99.7	100	99.8	99.7	100	100	100	99.6
Good for physics: 97.5% (60.1 fb^{-1})										

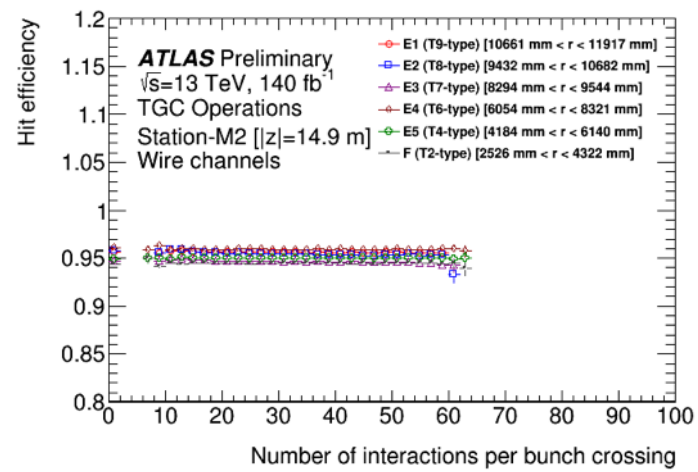
ATLAS Detector Performance and Pile-Up Conditions



Z→ $\mu\mu$ with 65 additionally reconstructed vertices!



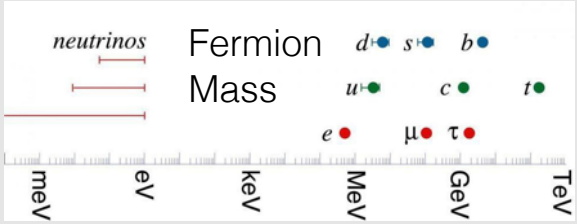




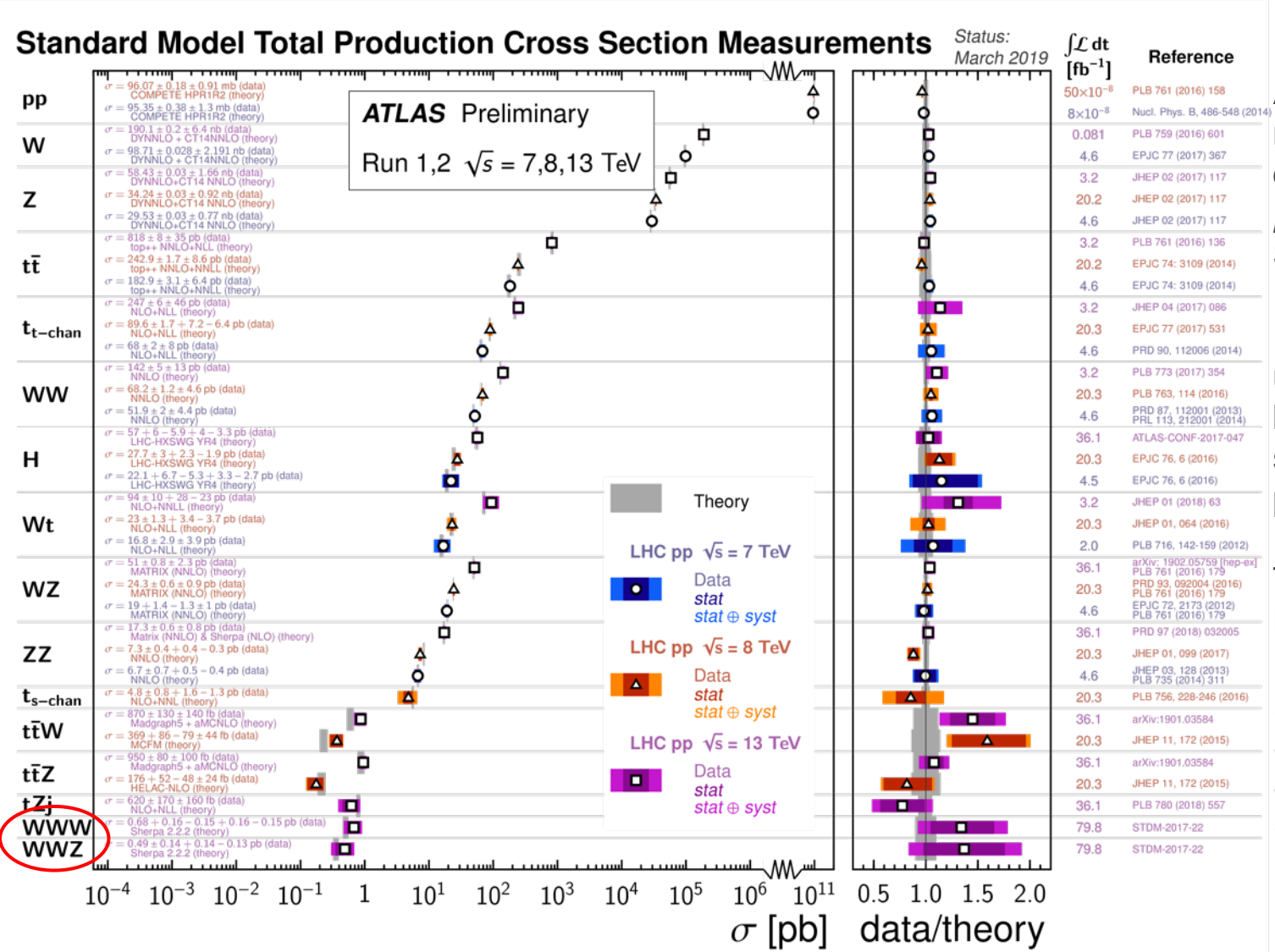
Efficiency to reconstruct physics objects remains high even with pileup

The Standard Model of Particle Physics

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
& + i\bar{\Psi}\not{D}\psi \\
& + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) \\
& + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.
\end{aligned}
$$



ATLAS is putting the Standard Model to the test



ATLAS cross section measurements confirm ***predictive power*** of the Standard Model

Important to understand all backgrounds to searches for new physics

Theory progress on NNLO calculations

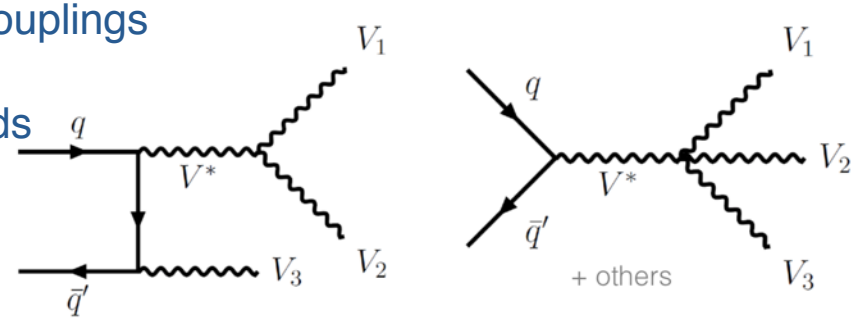
Many detailed fiducial and differential cross section measurements ongoing.

First Evidence for Three Vector Boson Production

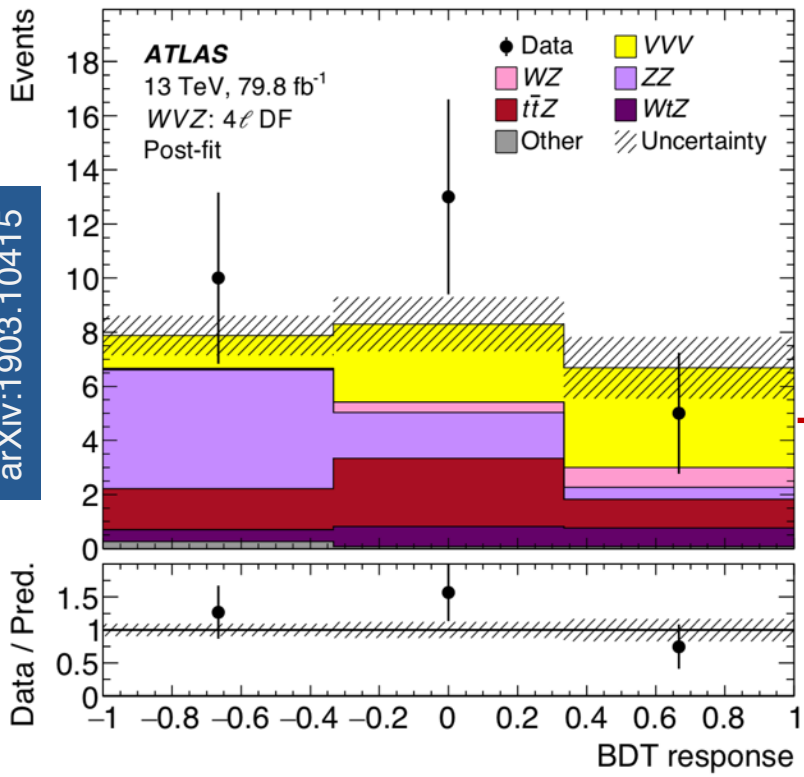
ATLAS is reaching sensitivity to processes with very small cross sections (< 1pb)

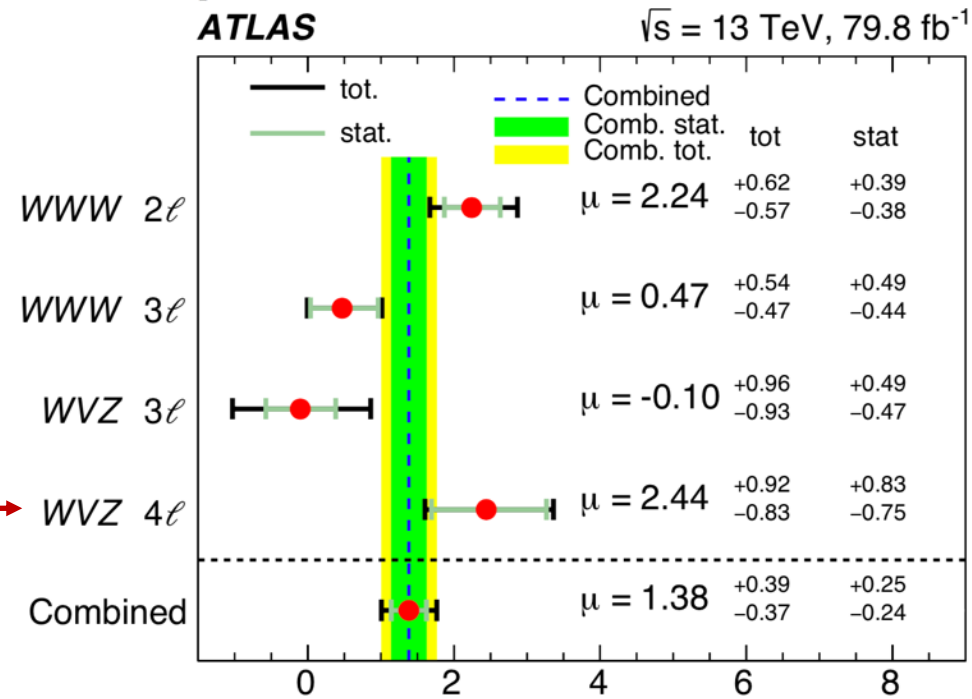
Evidence for production of three vector bosons (WVV, V = W, Z)

- Sensitive to anomalous *triple* and *quartic* gauge couplings
- Combination of several final states (2 - 4 leptons)
- Use dijet mass and MVAs to suppress backgrounds
- First evidence with 4.0 σ observed (3.1 σ expected) significance !



arXiv:1903.10415





Overall σ(exp) / σ(SM) = $1.38^{+0.39}_{-0.37}$

$\mu = \sigma^{VVV}/\sigma^{VVV}_{SM}$

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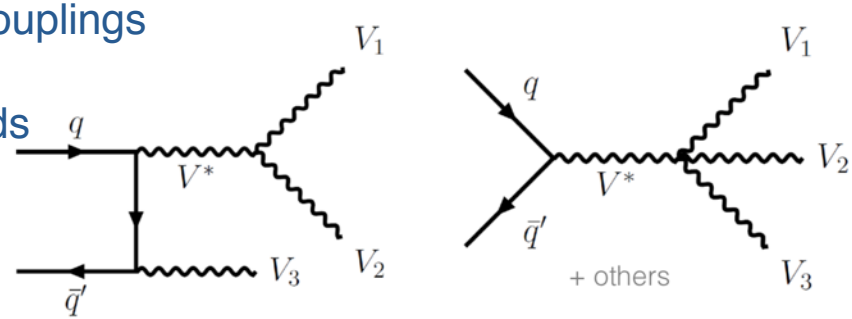

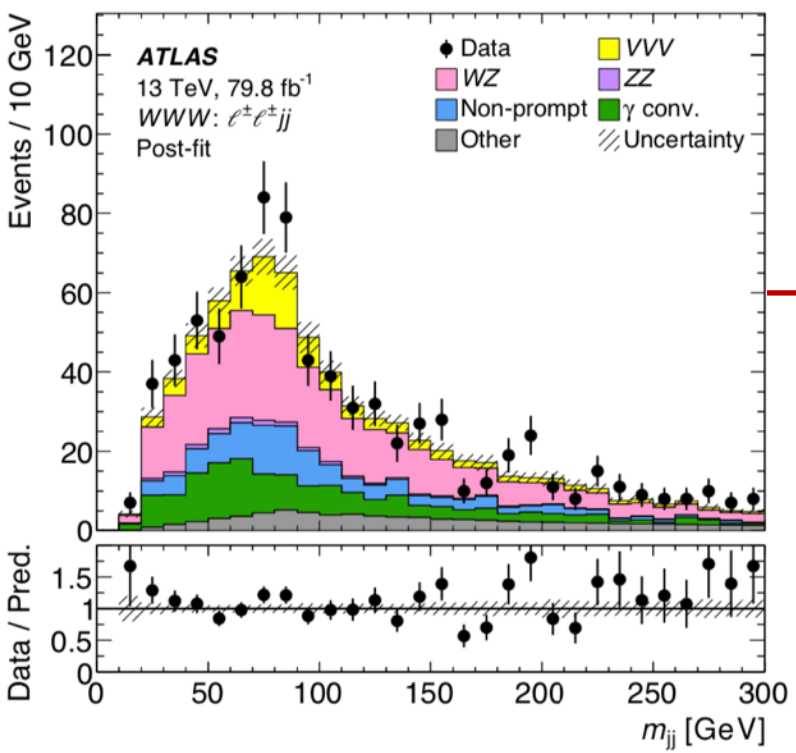

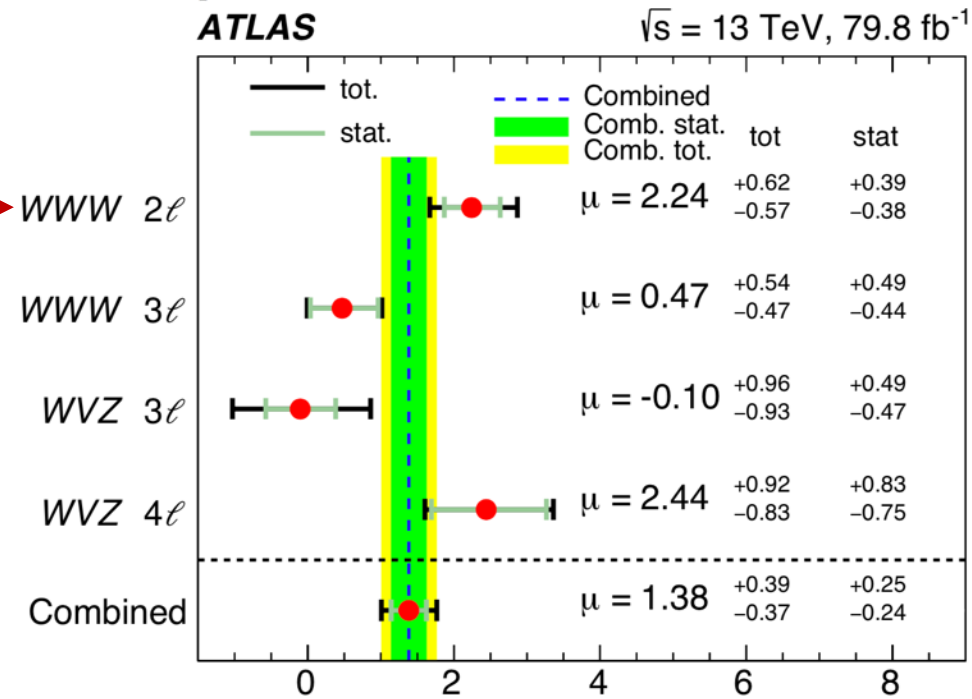

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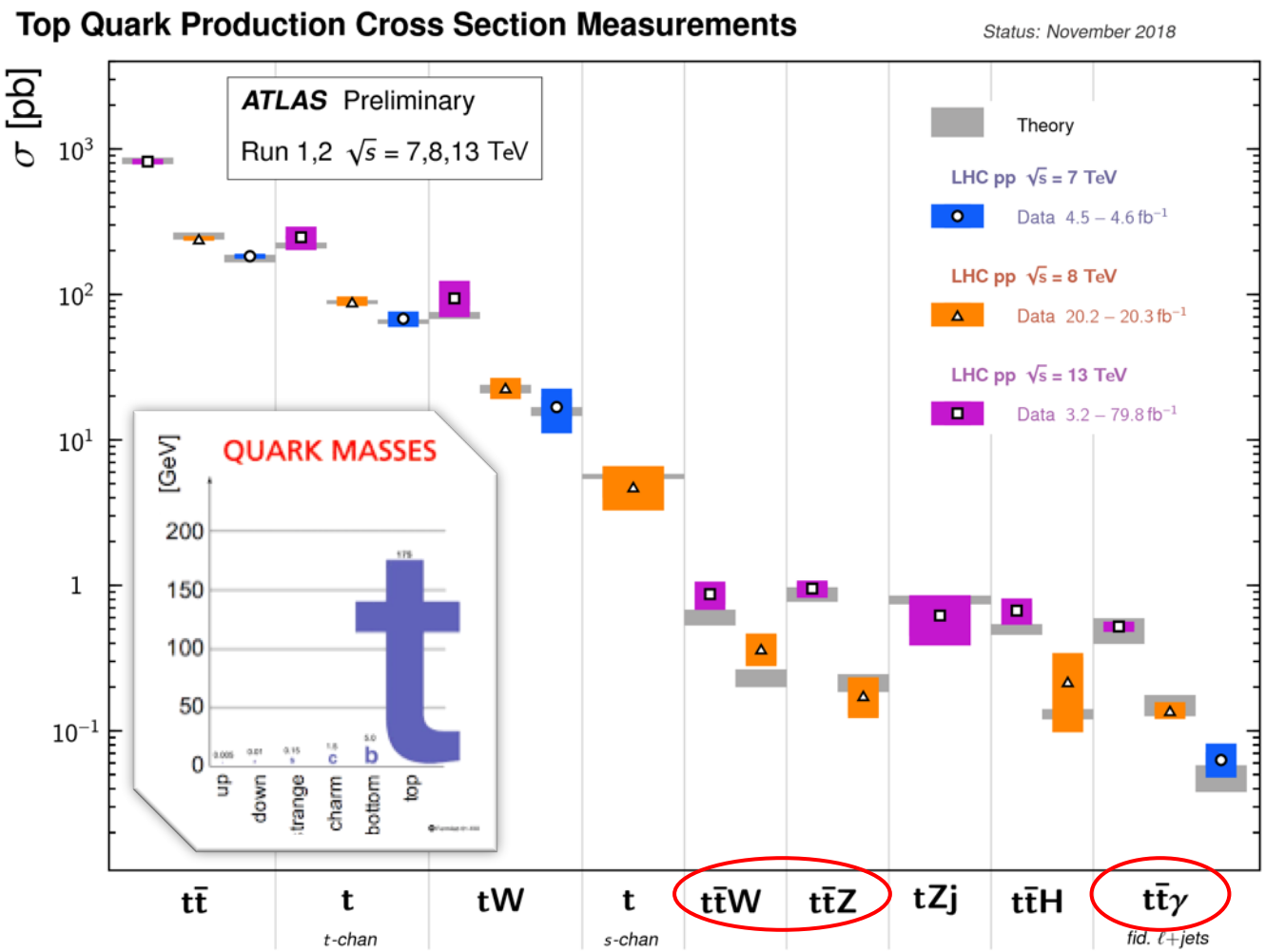
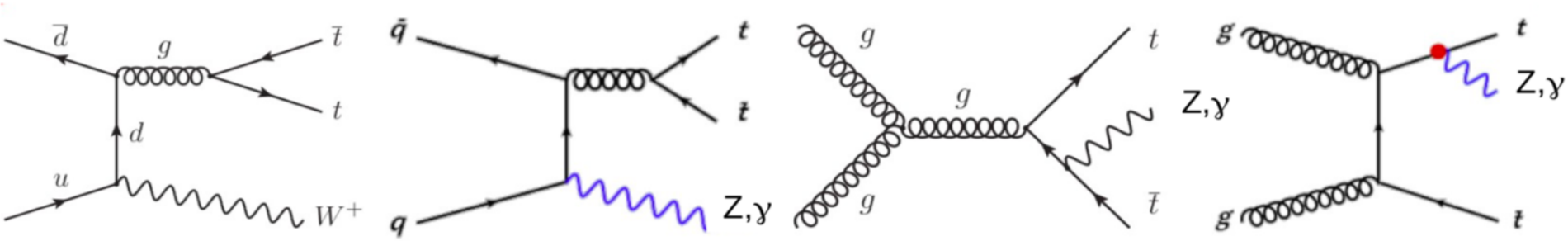
ATLAS is putting the Standard Model to the test

Rare production of processes (~ 1pb) involving top quarks: **ttW, ttZ, ttγ and ttbb**

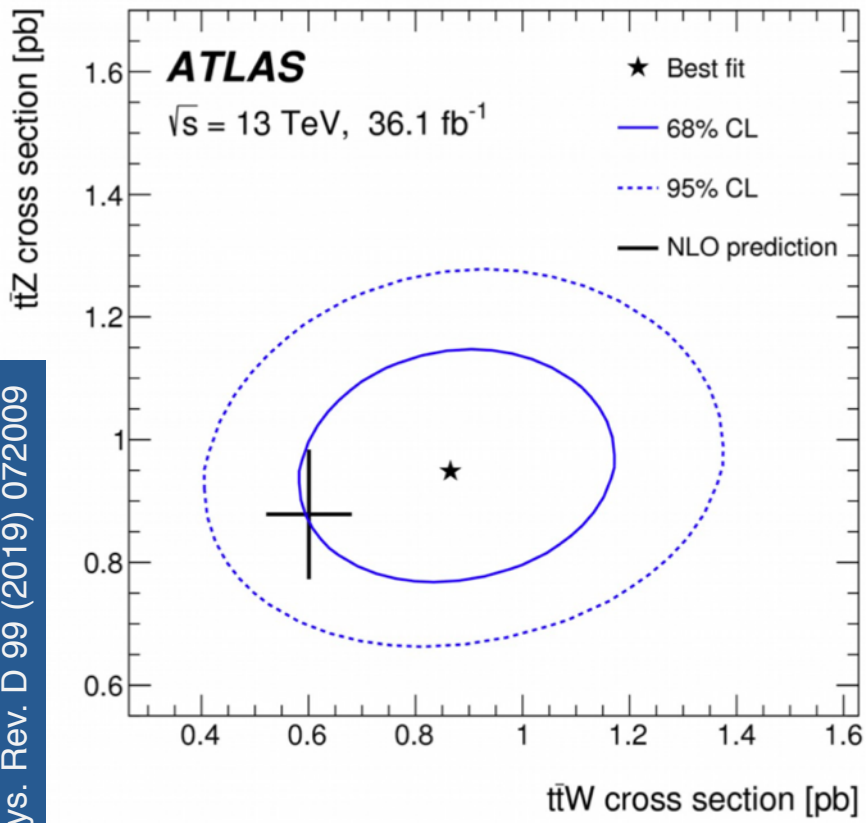


- Test of QCD predictions
  - ✓ Multiple energy scales involved in process
  - ✓ Matching/Merging: parton-shower vs matrix-element
- Important background for searches with multiple leptons and/or b-jets (e.g. ttH)
- Deviation of tt+X coupling from SM would indicate new physics (e.g. vector-like quarks, etc)

Measurement of ttbar in association with Vector Bosons



Simultaneous fit for tt+W and tt+Z



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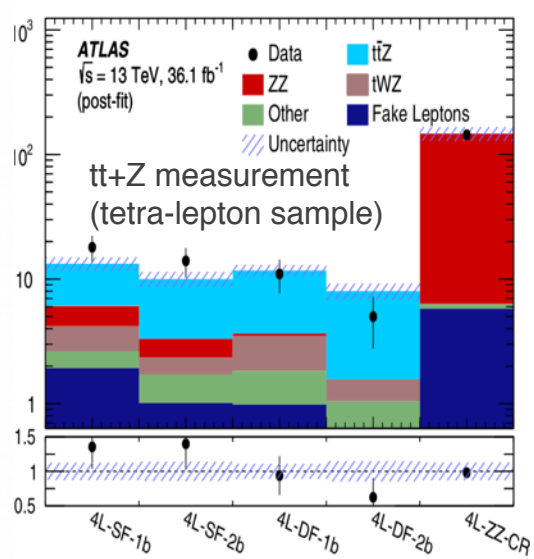
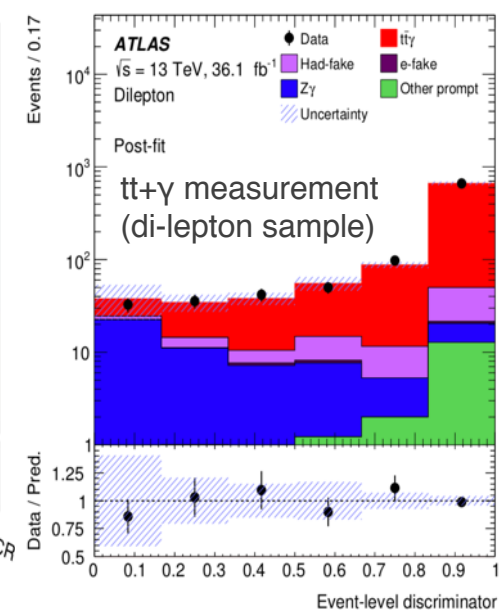
tt + W, Z, γ final states observed at 13 TeV

- Split data in lepton/charge/flavor multiplicity bins
- Differential measurements and EFT interpretations
- **Fiducial measurement of tt+γ production**





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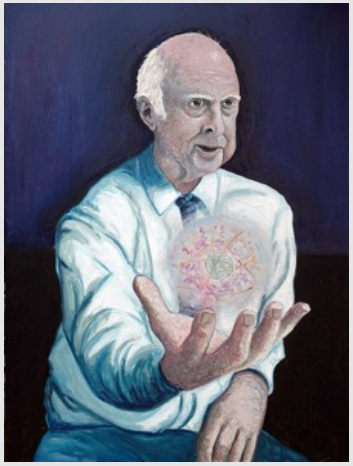
$\sigma_{t\bar{t}\gamma}/\sigma^{\mathrm{NLO}}_{t\bar{t}\gamma} = 1.06^{+0.06}_{-0.06}$

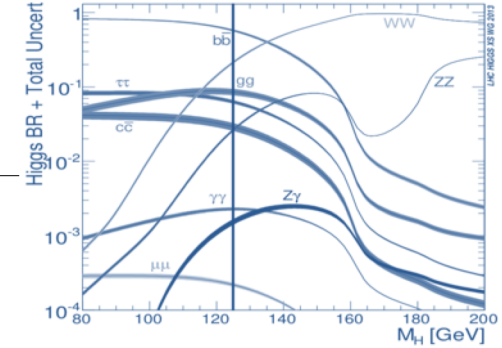
The Higgs boson

a LHC responsibility

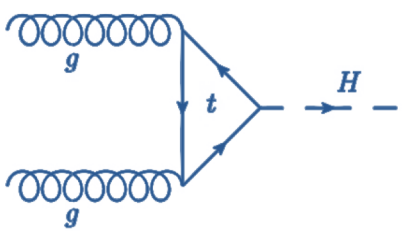


Higgs mechanism:
F. Englert and R. Brout, PRL 13 (1964) 321.
P.W. Higgs, PRL 13 (1964) 508.
G. Guralnik, C. Hagen, and T.W.B. Kibble, PRL 13 (1964) 585.

Higgs boson production at the LHC

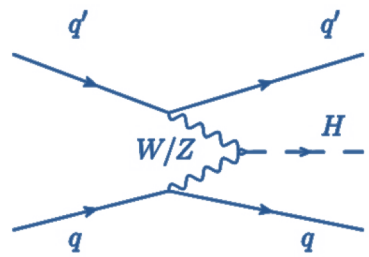


Gluon Fusion



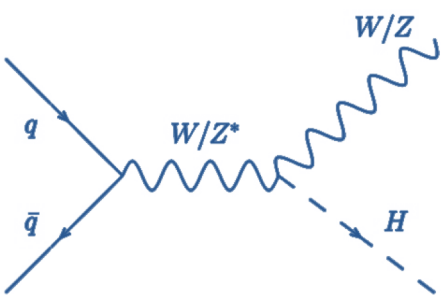
$\sigma_{H,ggF}$ ~ 49 pb

Vector Boson Fusion



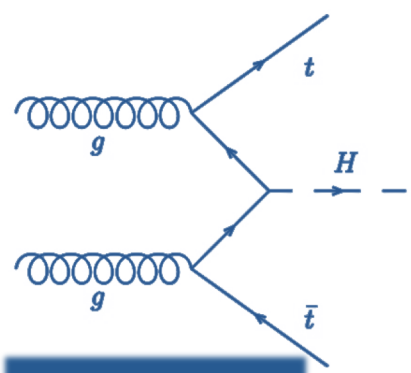
σ_{VBF}~ 3.8 pb

Higgs-Strahlung

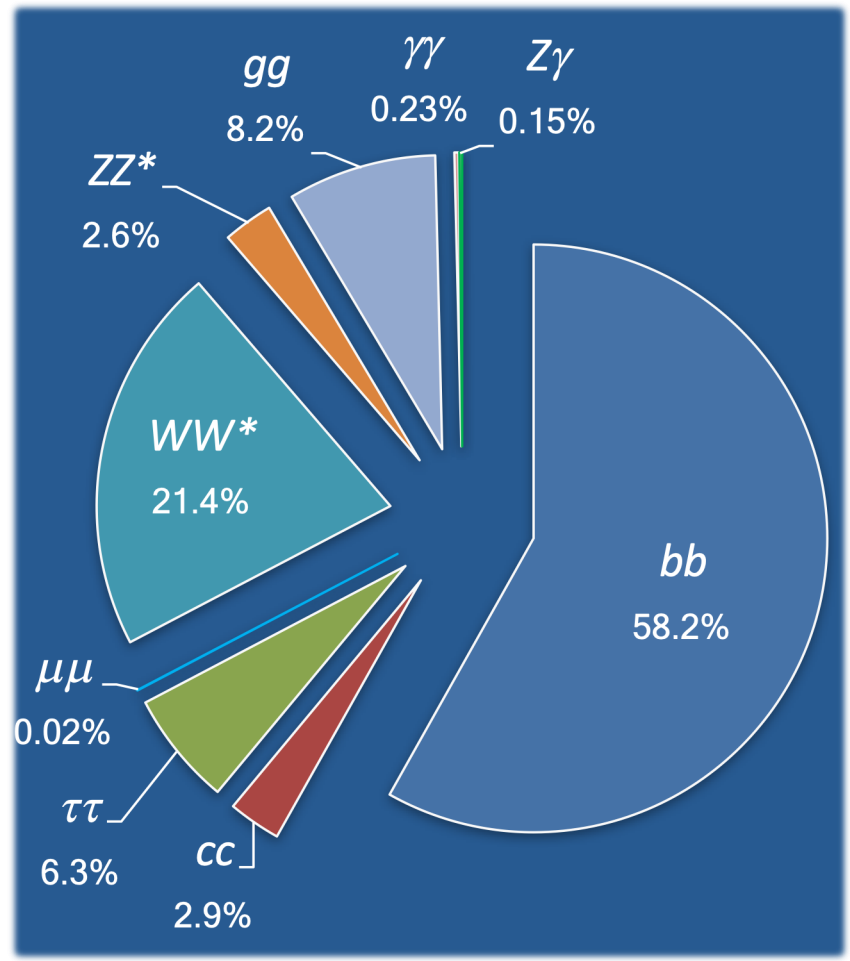


$\sigma_{W/Z+H}$ ~ 1.4/0.9 pb

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)

Higgs boson production at the LHC (in Run-2 numbers)

LHC = *'Large Higgs Creator'*

During Run-2, the LHC produced almost **8 million Higgs bosons**!

H(125 GeV) — approximate numbers

Channel	Produced		Selected	Mass resolution
$H \to \gamma\gamma$	18,200		6,440	1–2%
$H \to ZZ^*$	210,000	$(\to 4\ell)$	210	1–2%
$H \to WW^*$	1,680,000	$(\to 2\ell 2\nu)$	5,880	20%
$H \to \tau\tau$	490,000		2,380	15%
$H \to bb$	4,480,000		9,240	10%

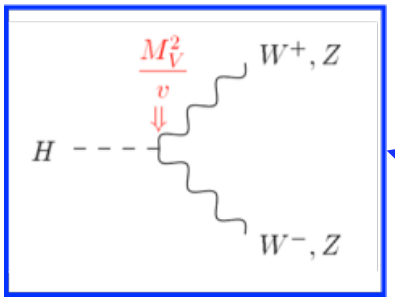
A. Hoecker, CERN

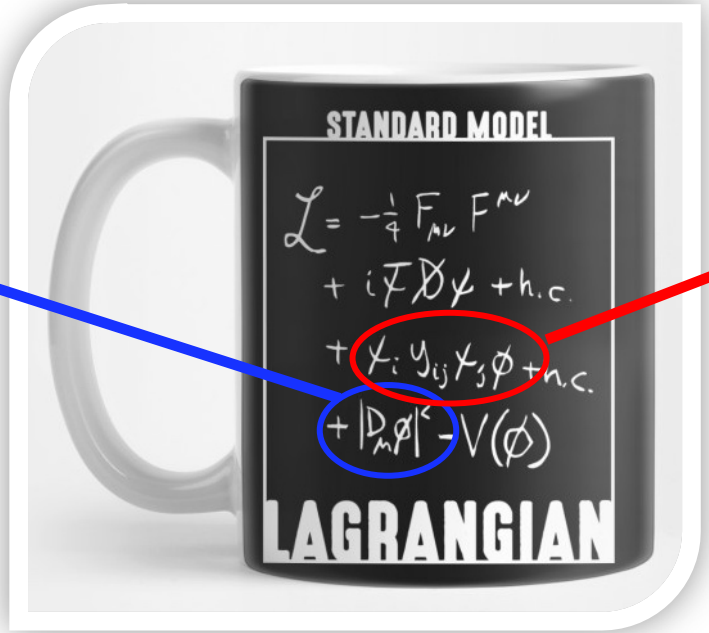
While this is enormous, the number of selected events is much smaller, due to:

- *Need to select final states with small backgrounds (typically require a lepton) and good resolution to measure the small Higgs signal*
- *Small branching ratios for lepton final states*

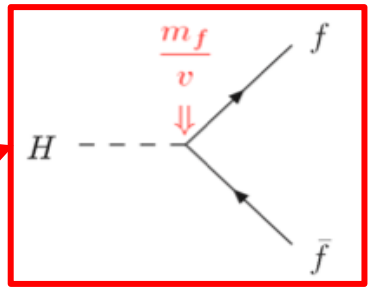
Higgs Boson Interactions

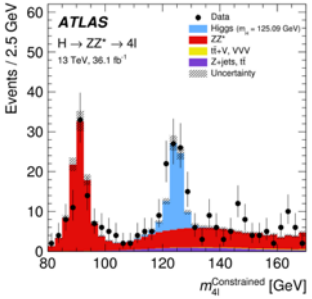
Gauge couplings: Key in Higgs discovery (ZZ, WW, $\gamma\gamma$)

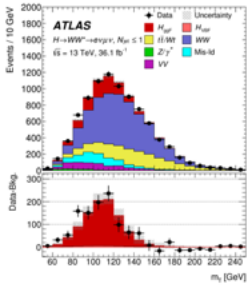


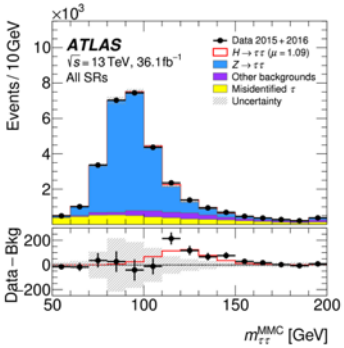


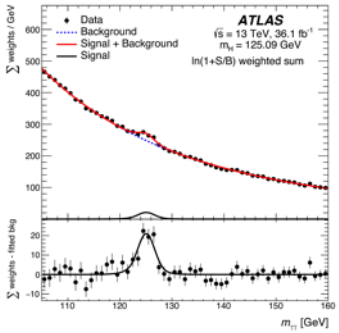
Yukawa couplings: Higgs boson properties











Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 $\pm$ 0.35	1.01 $\pm$ 0.20	1.34 $\pm$ 0.21 *
CMS	Exp. Sig.	5.9 σ	5.6 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.5 σ	5.2 σ
	mu	1.09 $\pm$ 0.27 *	1.04 $\pm$ 0.20	1.26 $\pm$ 0.26 **

* 13 TeV only derived from cross section measurements

Key Run 2 milestones accomplished - Discovery of 3rd generation (direct) Higgs Yukawas!

Observation of H→bb in Higgs-Strahlung Production

First observation of H → bb in WH/ZH Higgs-Strahlung (5.3σ observed, 4.8σ expected)

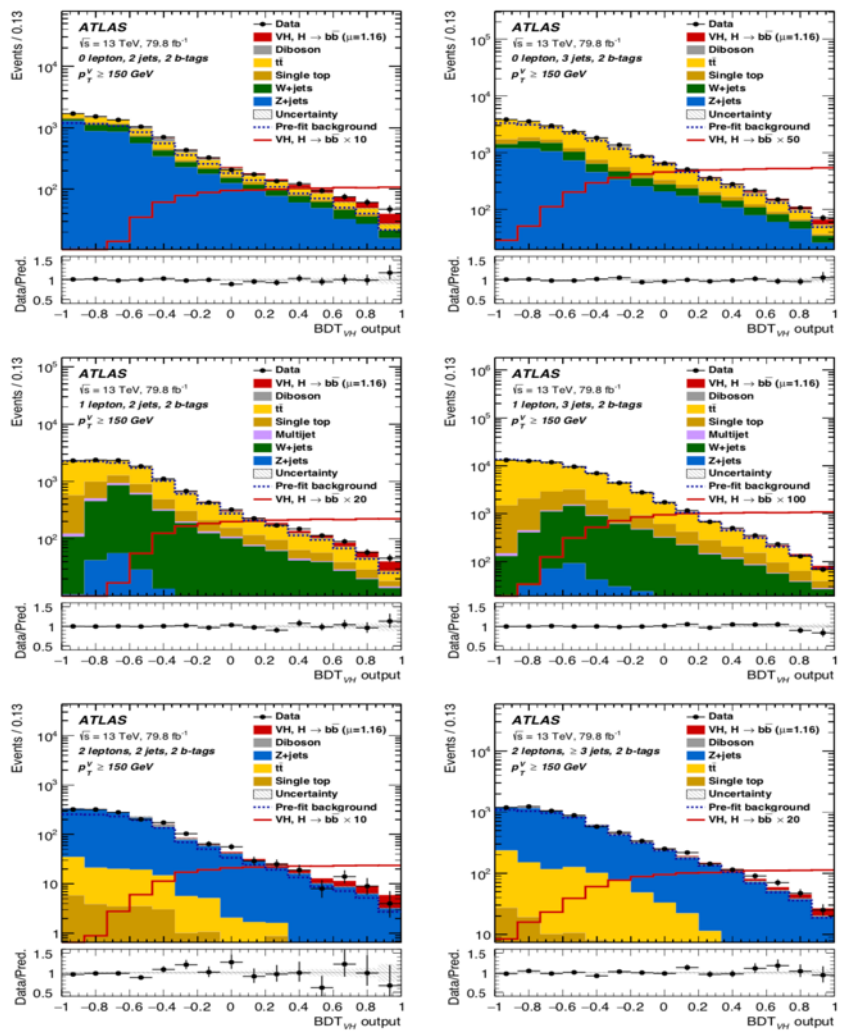
- Confirms the Higgs decay to bb with largest branching ratio ~58%
- Challenging analysis requiring multivariate techniques to suppress background

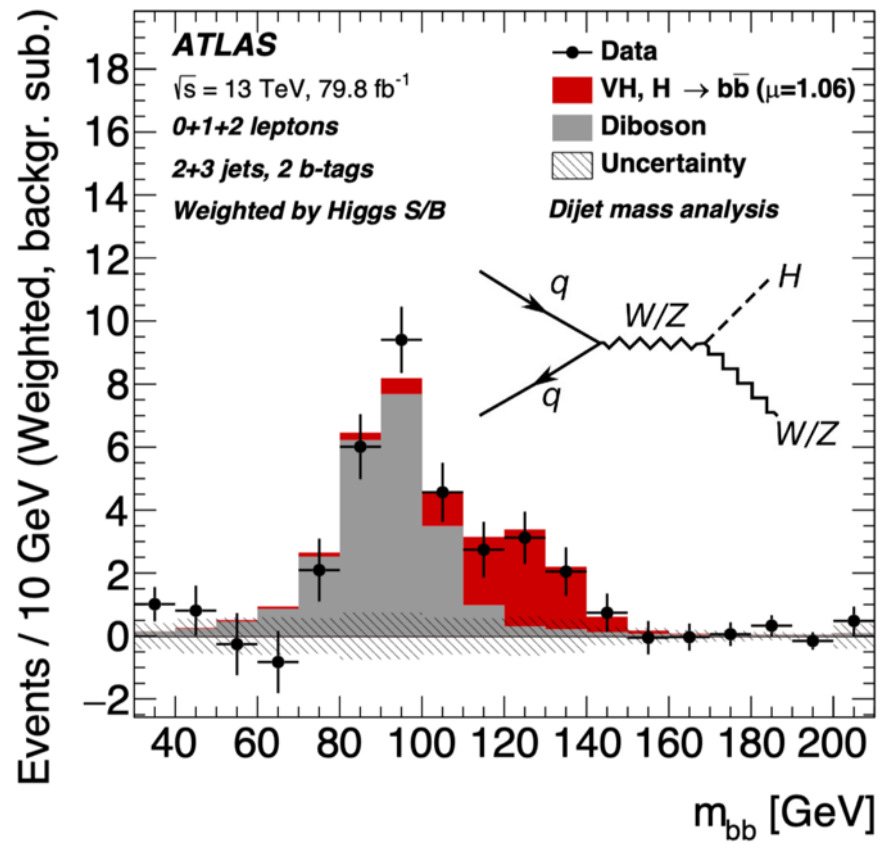
Leptons | 2 Jets | 3 Jets

0

1

2





$\mu_{VH(\rightarrow bb)} = 1.01 \pm 0.20$

arXiv:1808.08238

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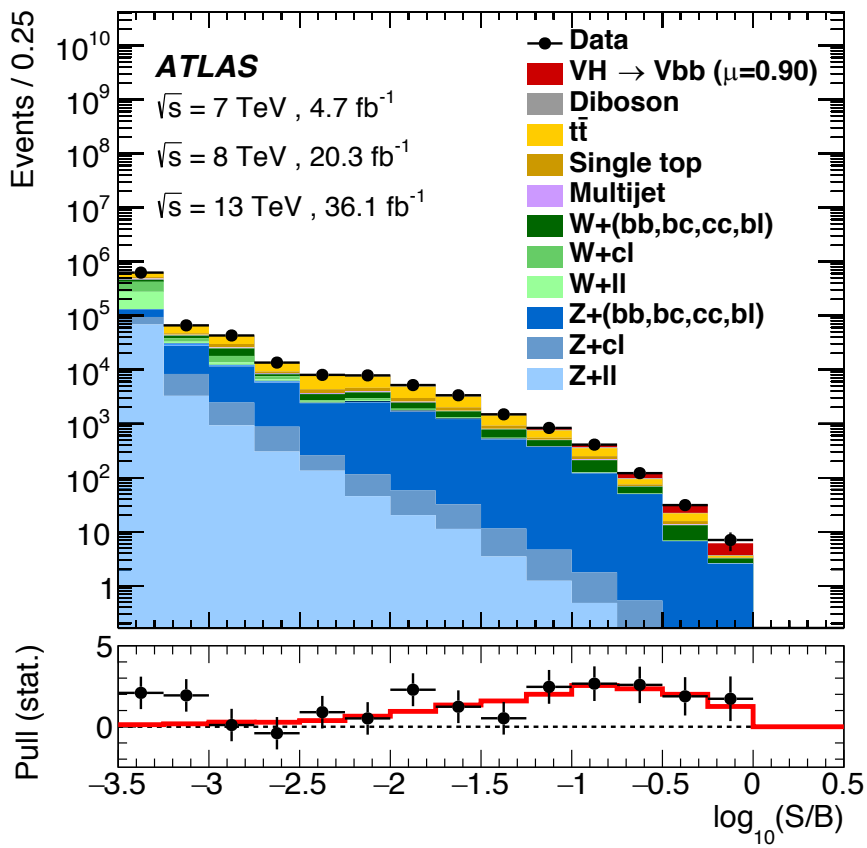
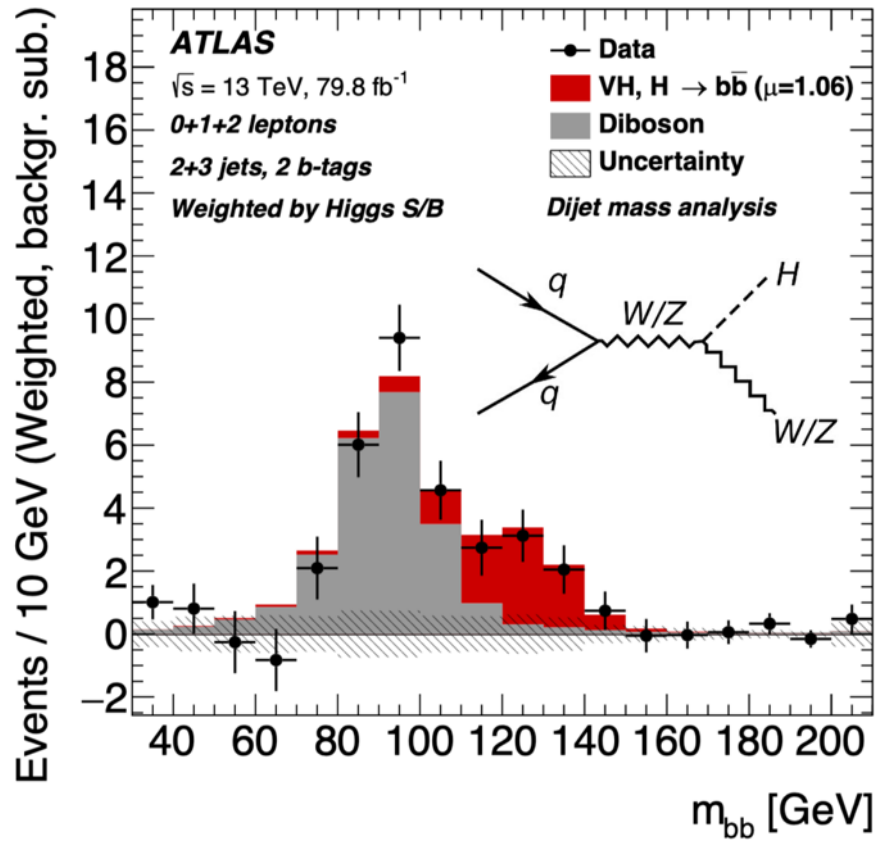
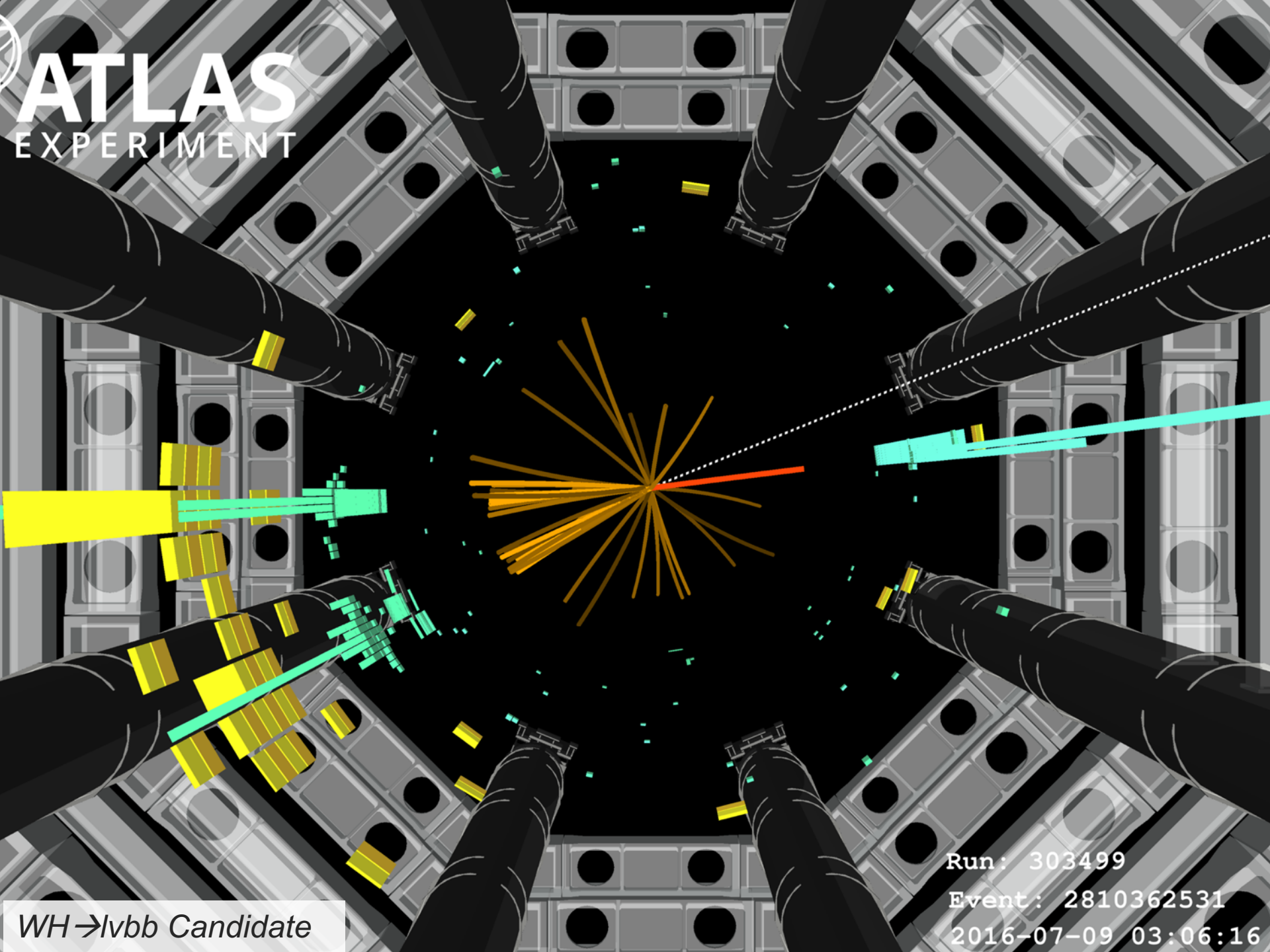




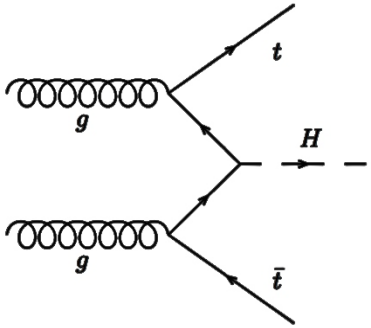
$\mu_{VH(\rightarrow bb)} = 1.01 \pm 0.20$

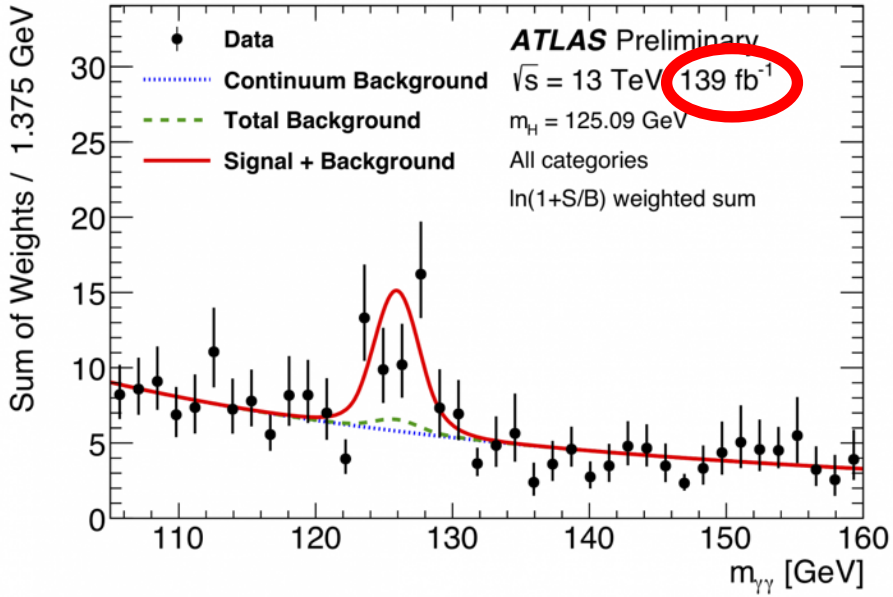
arXiv:1808.08238



WH→lνbb Candidate

Observation of ttH Production in Diphoton Decays

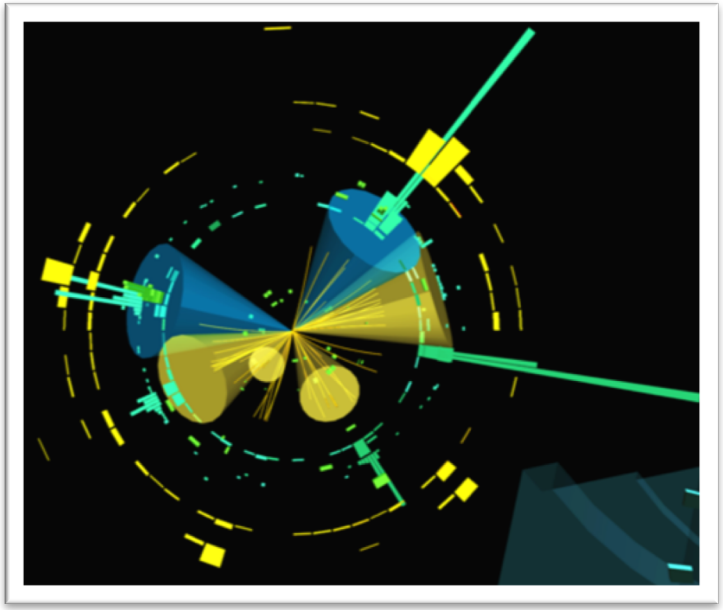


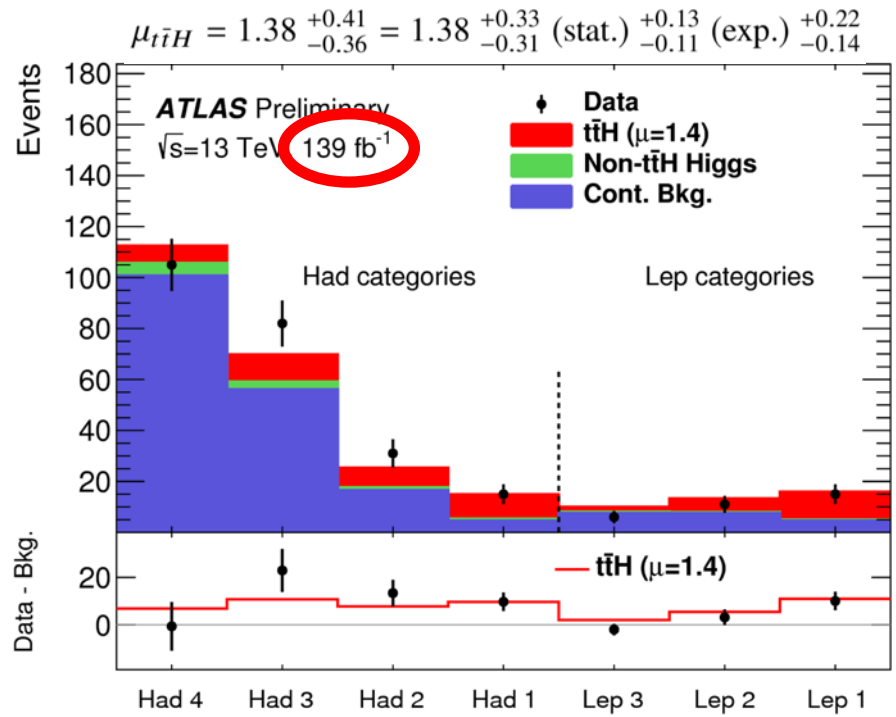


ttH has tiny rate ~1/100 ggF

- Enhance purity by selecting leptonic and hadronic top decays
- Further improve purity using BDT based on lepton, jet, photon 4-vectors (trained mass-independent)

First observation of single-channel ttH (H→γγ) with 4.9σ significance





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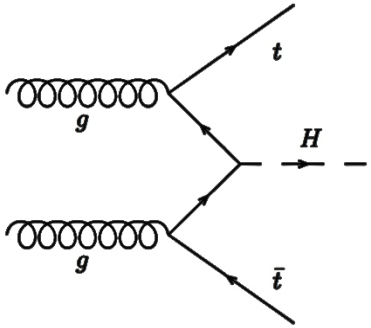
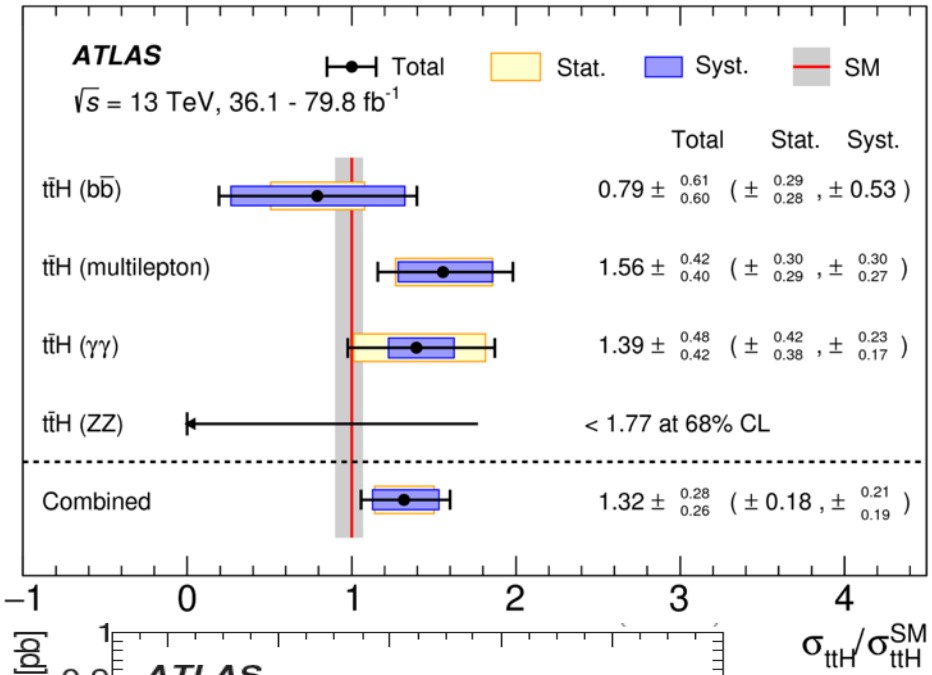
Observation of ttH Production

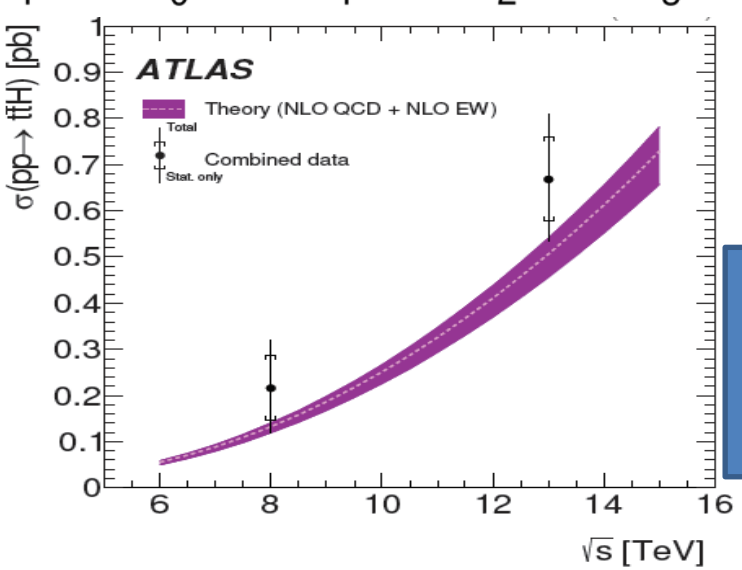


Consider H→bb, multilepton(WW/ZZ/**ττ**) and γγ

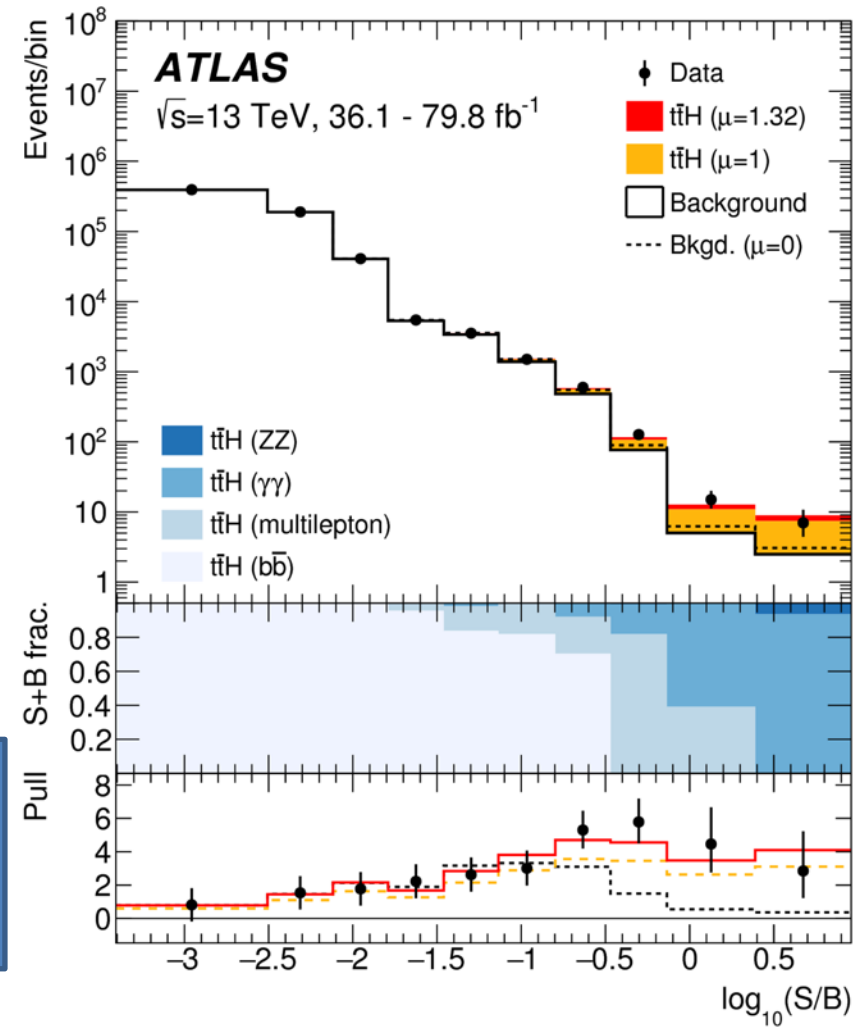
ttH has tiny rate ~1/100 ggF

Combining 4 Higgs decay channels: 6.3σ Observation





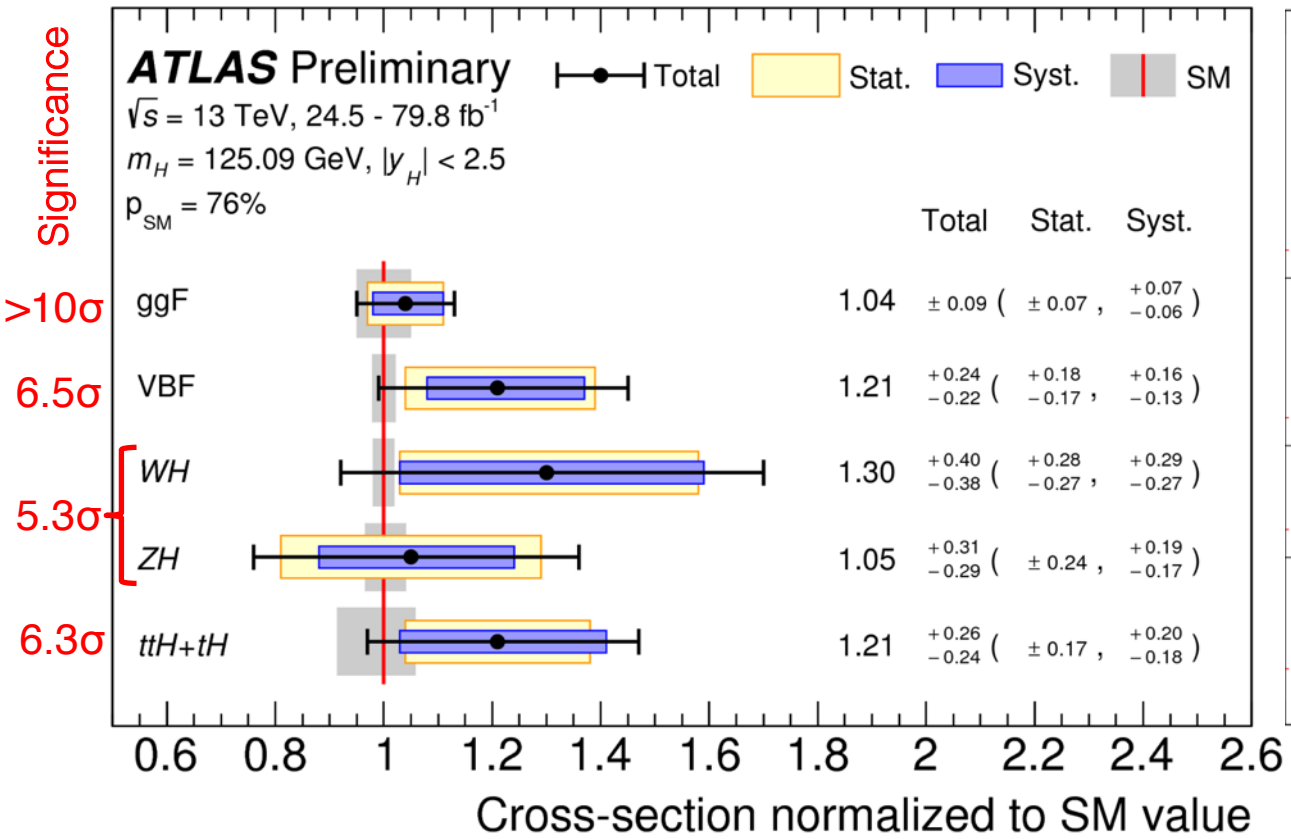
Data agrees with predicted strong (~ 4×) rise in cross-section vs √s



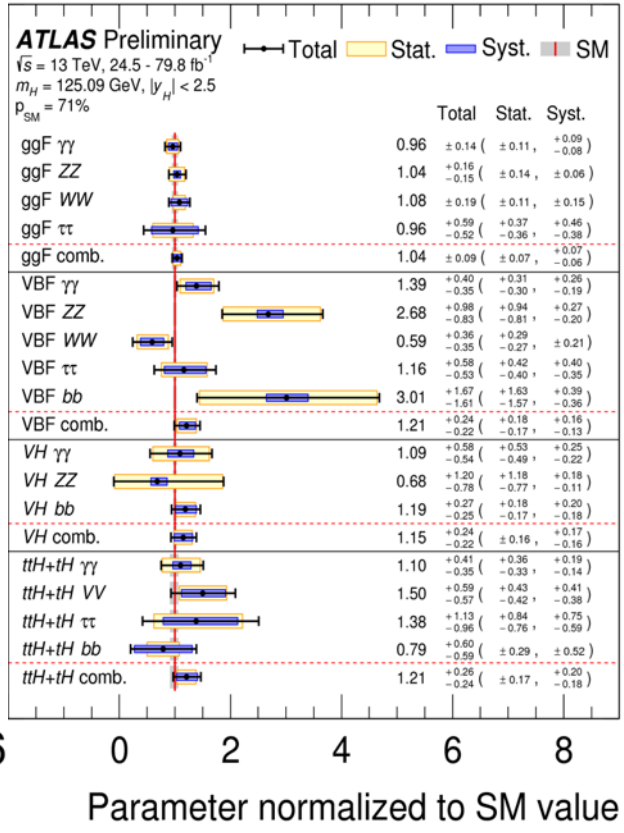
arXiv:1806.00425

Observation of Higgs Boson Production Modes

Latest combination Higgs boson measurements establishes *observation of all Higgs boson production modes* (ggF, VBF, VH, ttH) - another Run 2 milestone



Not including latest ttH result



Overall σ(exp) / σ(SM) $= 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$

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Higgs Boson Coupling Measurements

Coupling modifiers (κ=1 in SM)

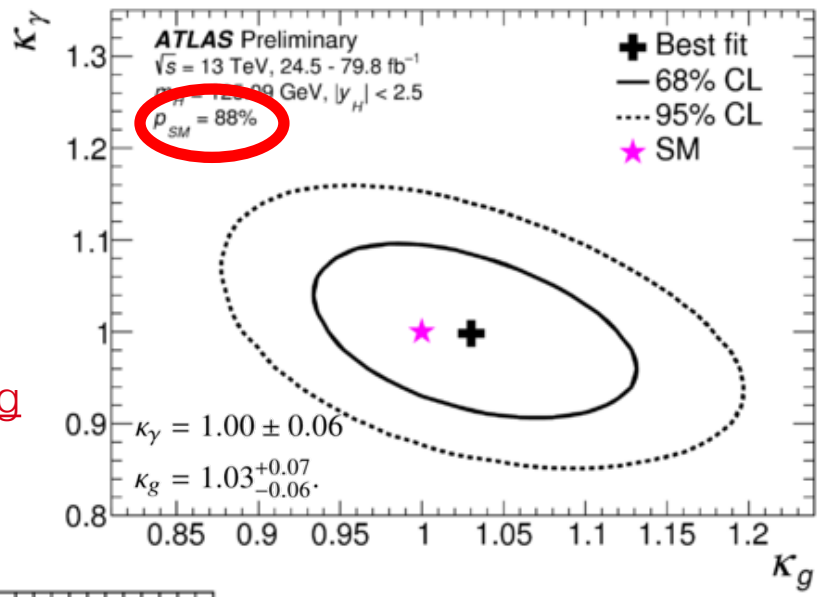
$$\sigma_i \times B_f = \frac{\sigma_i(\kappa) \times \Gamma_f(\kappa)}{\Gamma_H}$$

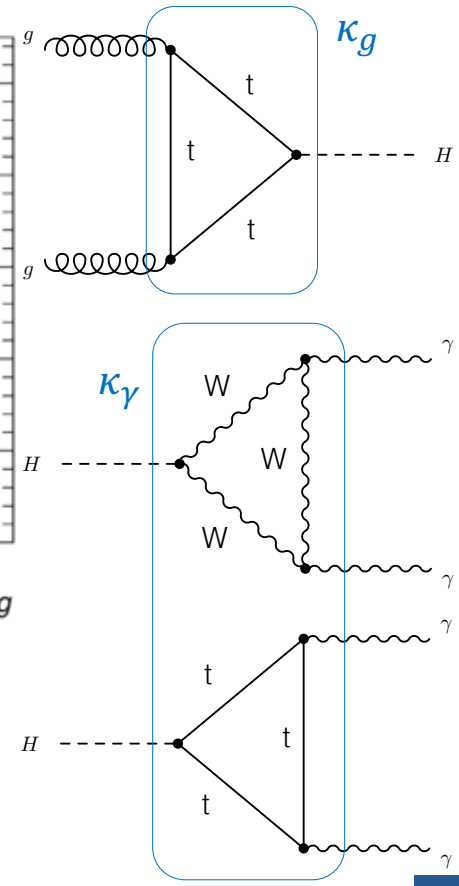
$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$$

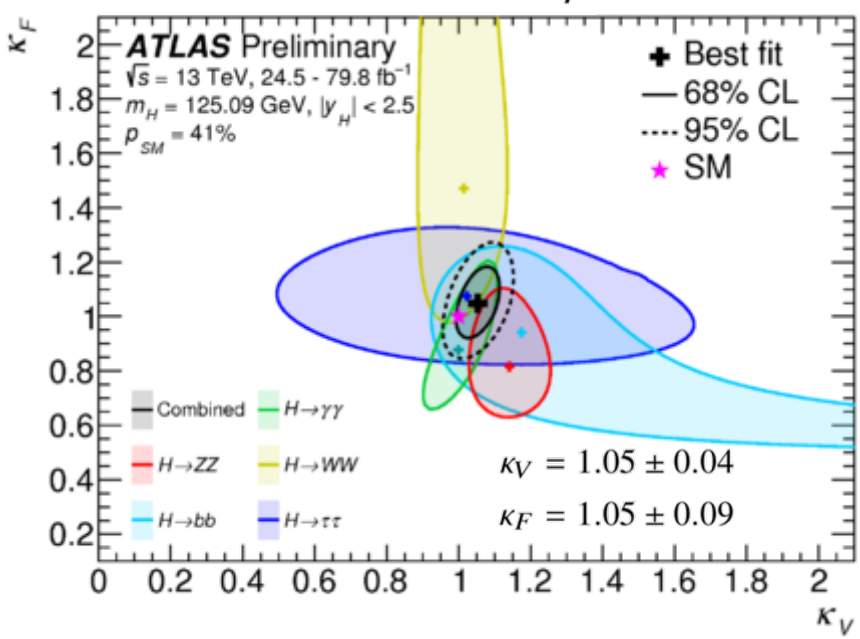
Fermion vs Vector Boson Coupling

Assume: $\kappa_V = \kappa_W = \kappa_Z$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$$







Measure "effective" couplings to photons (κ_γ) and gluons (κ_g) sensitive to new particles in the loops…

Model independent modifier ratios:

$\lambda_{ab} = \kappa_a/\kappa_b$.

λ_{tg}	$1.10^{+0.15}_{-0.14}$	$\lambda_{\gamma Z}$	0.94 ± 0.07
λ_{Zg}	$1.12^{+0.15}_{-0.13}$	$\lambda_{\tau Z}$	0.95 ± 0.13
λ_{WZ}	0.95 ± 0.08	λ_{bZ}	$0.93^{+0.15}_{-0.13}$

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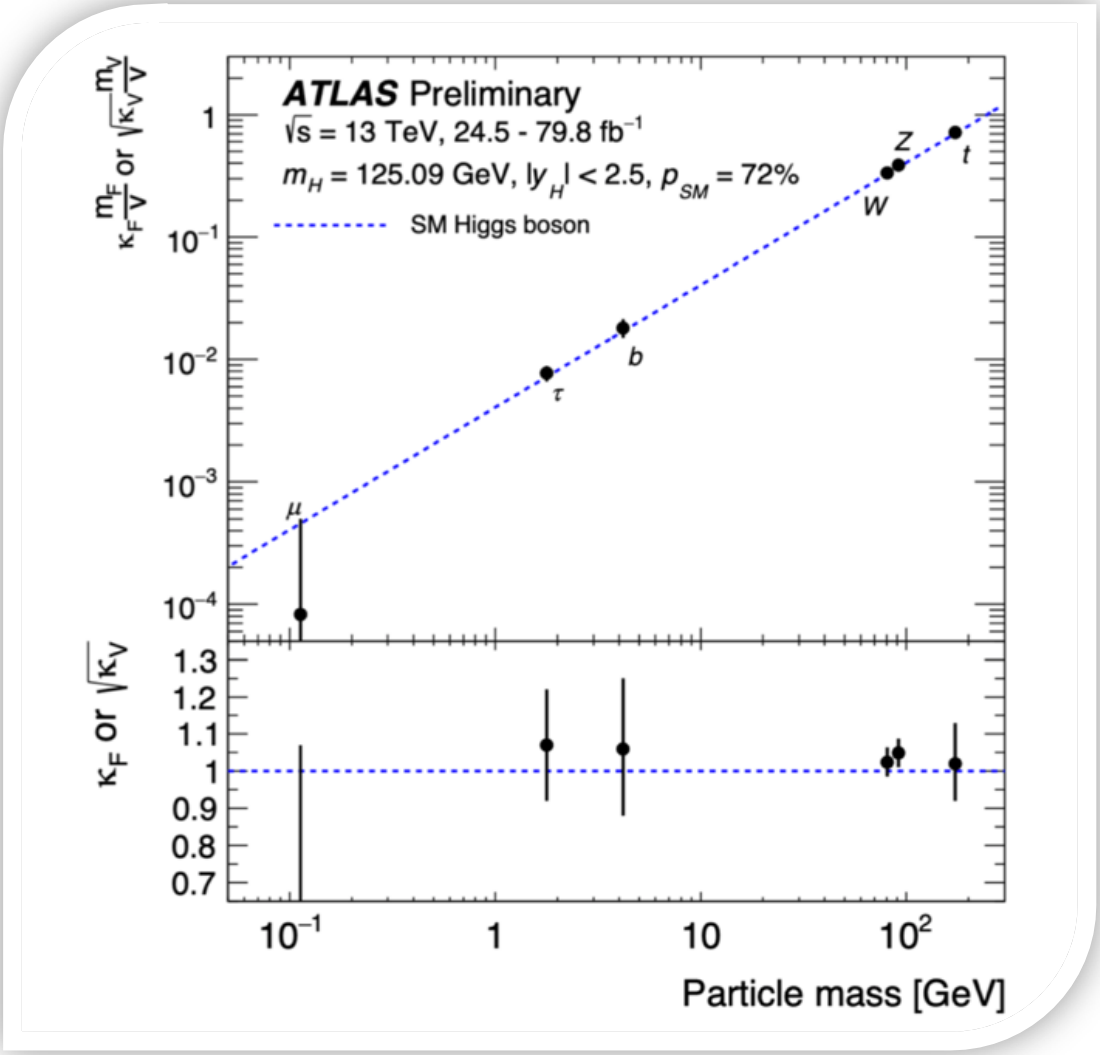
Higgs Boson Measurements

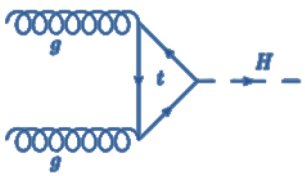


Coupling scale factors for the coupling strengths to W, Z, t, b, τ and μ treated independently.

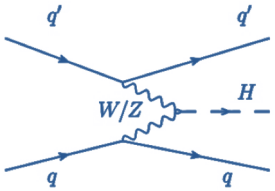
Assume SM structure of loop processes.

Summary of Higgs Boson Status

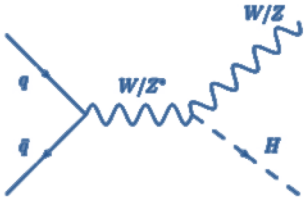
ggF (49 pb)



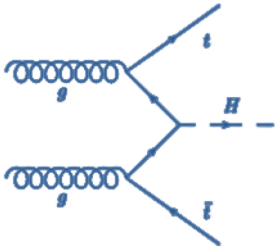
VBF (3.8 pb)

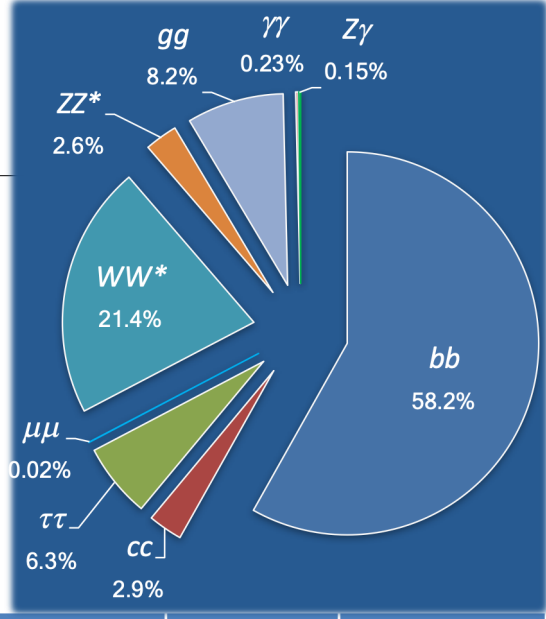


VH (1.4/0.9 pb)



ttH (0.5 pb)





SM production and decay channels:

Upper Limit

Decay → Production ↓	γγ	ZZ*	WW*	bb	cc	ττ	μμ	Zγ	Combined
ggF	Observed	Observed	Observed	UL	–	Evidence	UL	UL	Observed
VBF	UL	UL	Evidence	UL	–	Evidence	UL	–	Observed
VH	UL	UL	UL	Evidence	UL	UL	–	–	Observed
ttH	Evidence	UL	Evidence*	UL	–	Evidence*	–	–	Observed
Combined	Observed	Observed	Observed	Observed	UL	Observed	UL	UL	

* both channels together

M. Kado

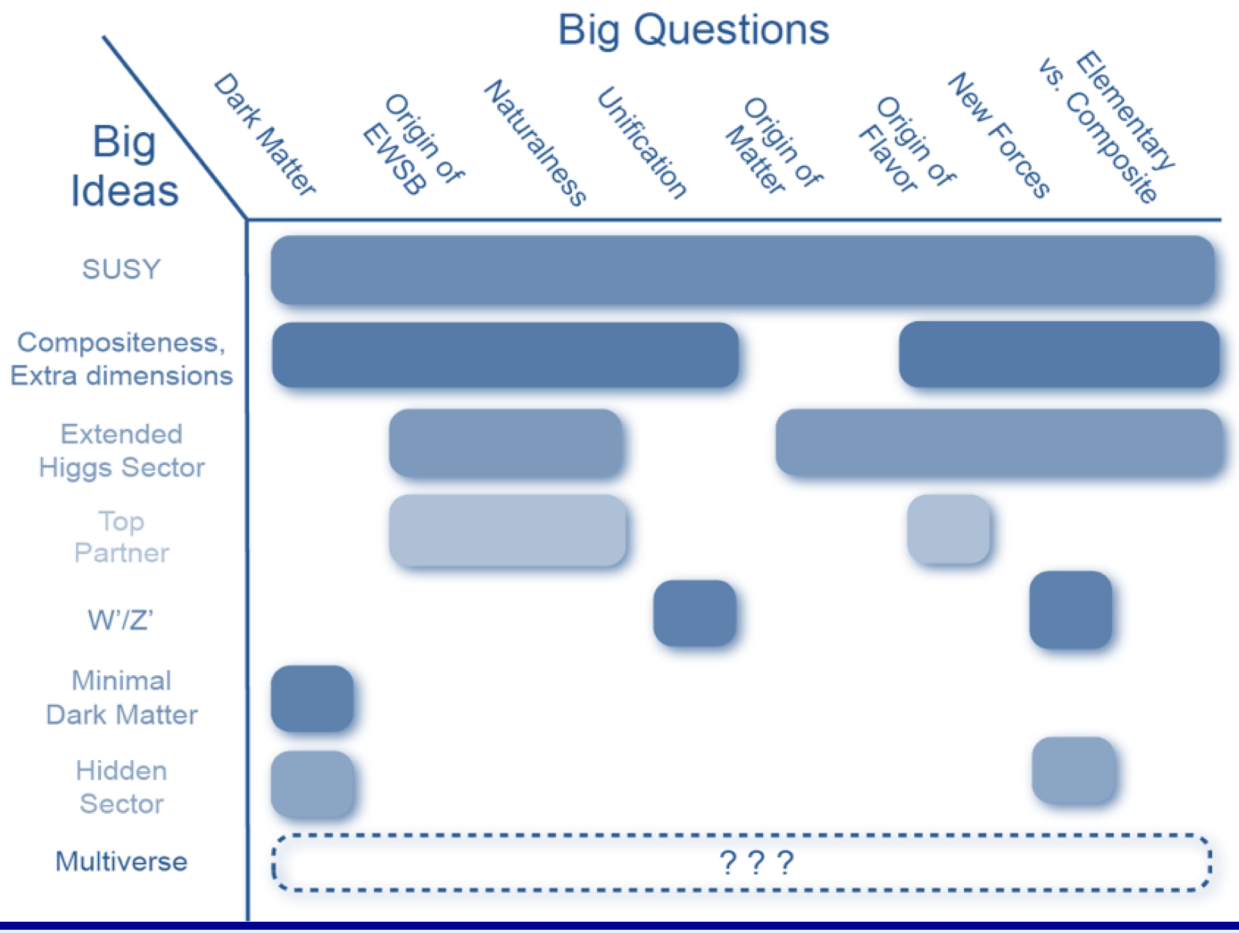
Mass: Run-1 (ATLAS & CMS): 125.09 ± 0.24 GeV | confirmed by ATLAS and CMS with Run-2 data

Spin / CP: Spin 1, 2 excluded with high significance | CP-even, but CP-odd admixtures possible

BR(H → invisible): < 26% (assuming SM production)

Differential cross section measurements ($p_T(H)$, $y(H)$, N_{jets}, …)**:** performed in most channels

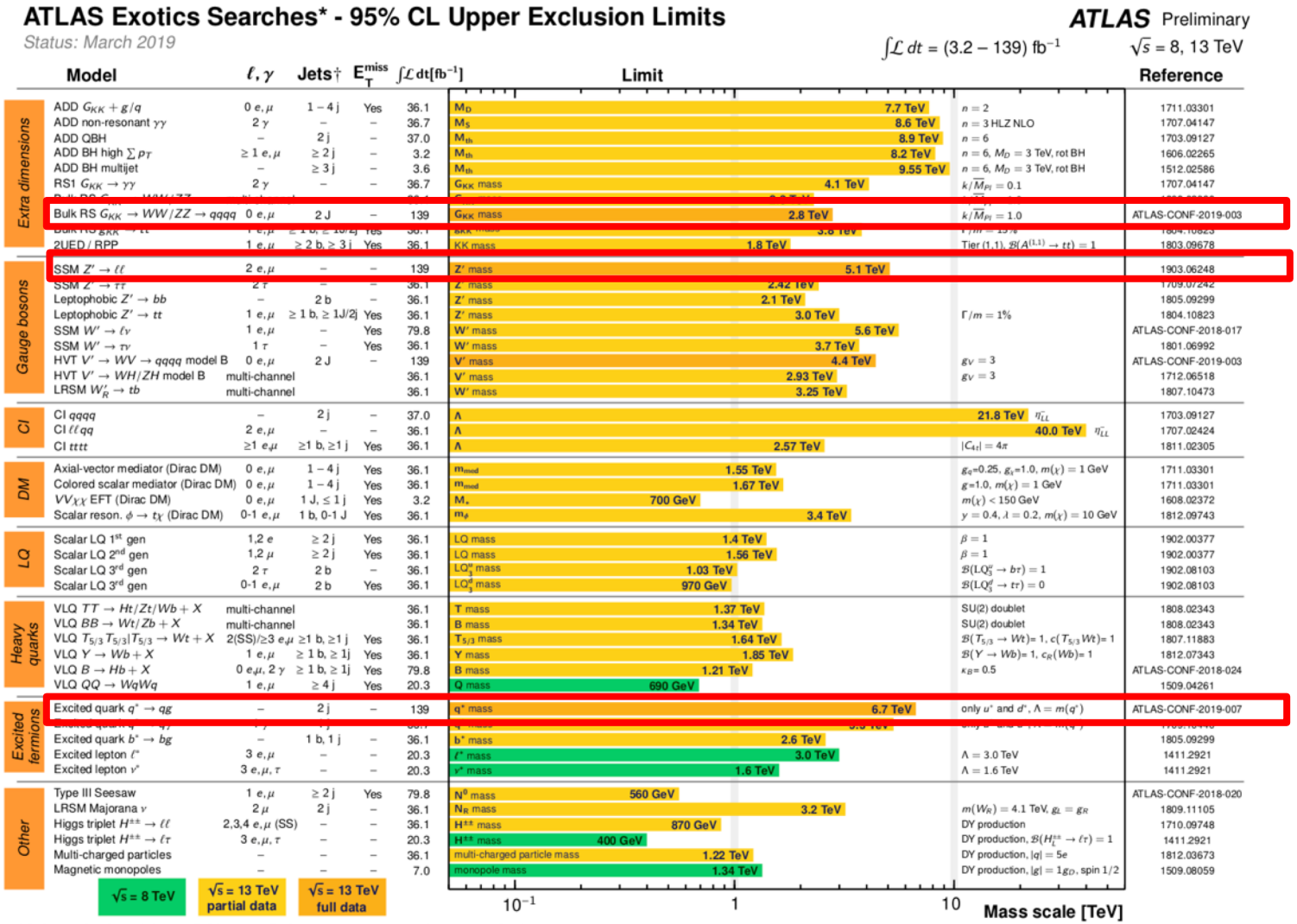
Searches for New Phenomena



arxiv:1311.0299
Snowmass Study

- There are many big questions beyond the SM to be answered at TeV scale
- Big Ideas are constrained from theory and observed phenomena

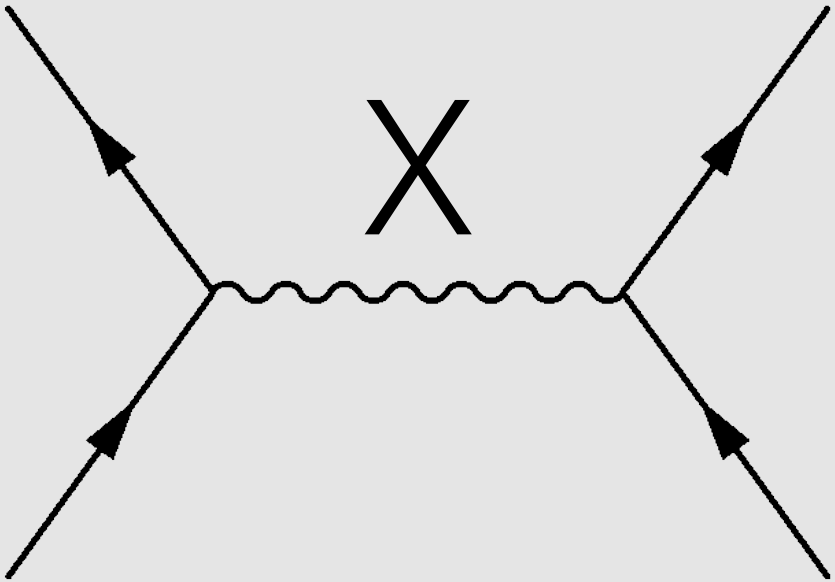
Searches for New Phenomena (Exotics)



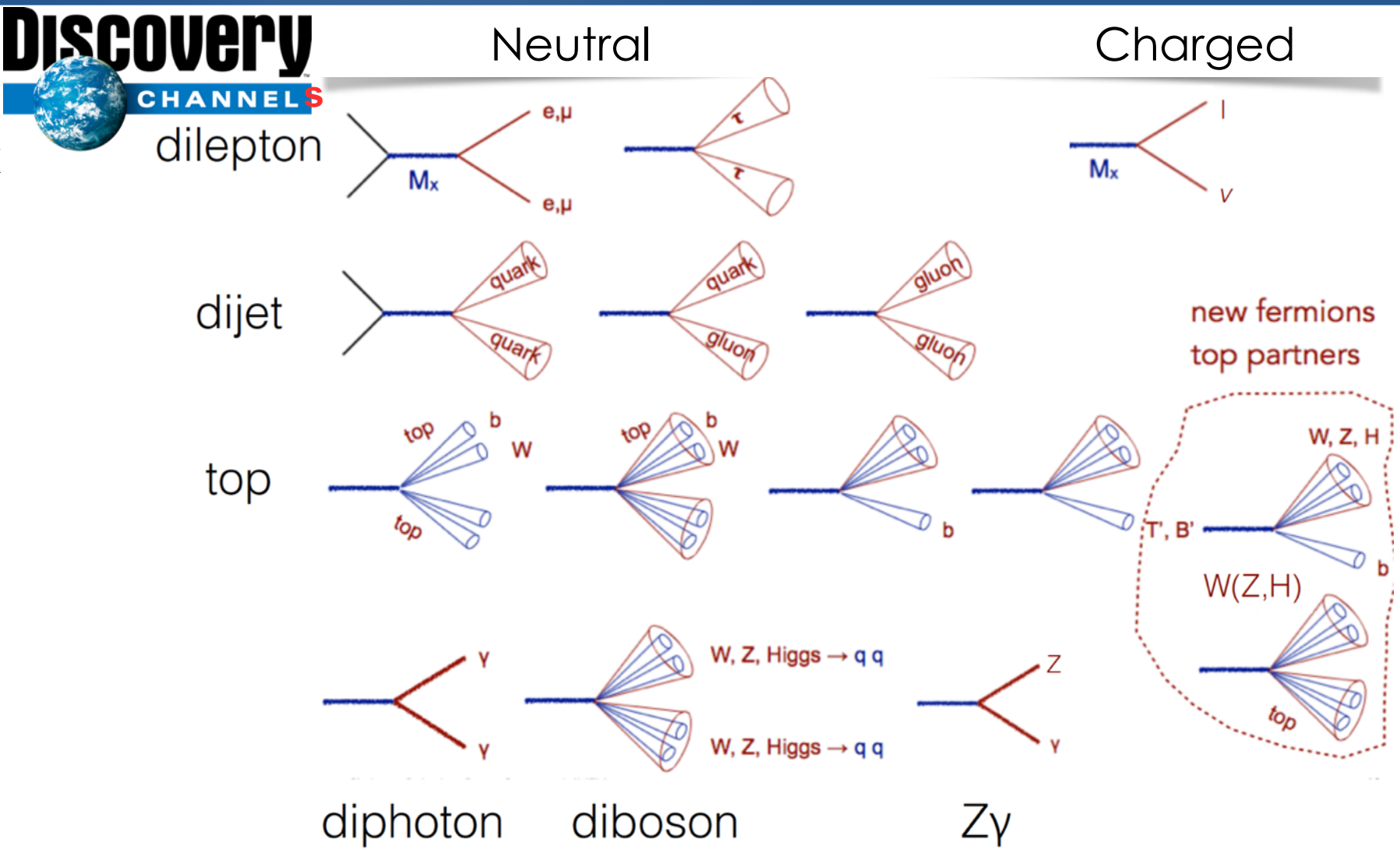
3 Searches with full Run-2 dataset

I.e.
You get to see the *"Final word"* on those (until 2021)

Searches for New Resonances

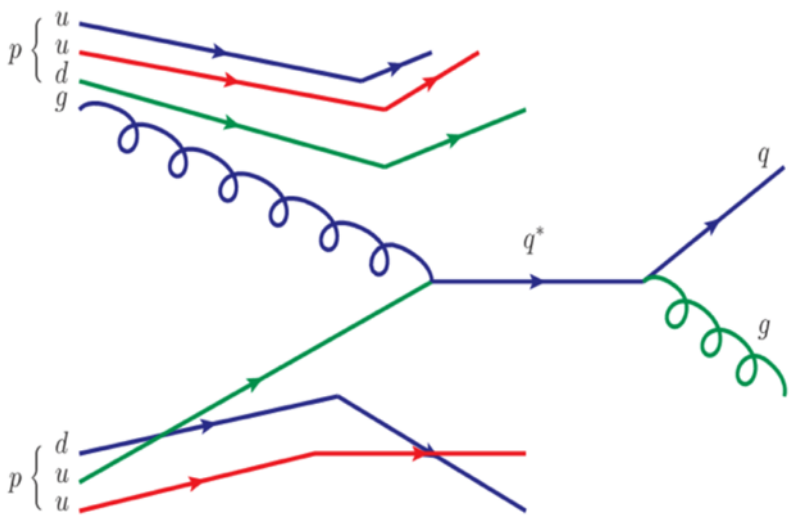


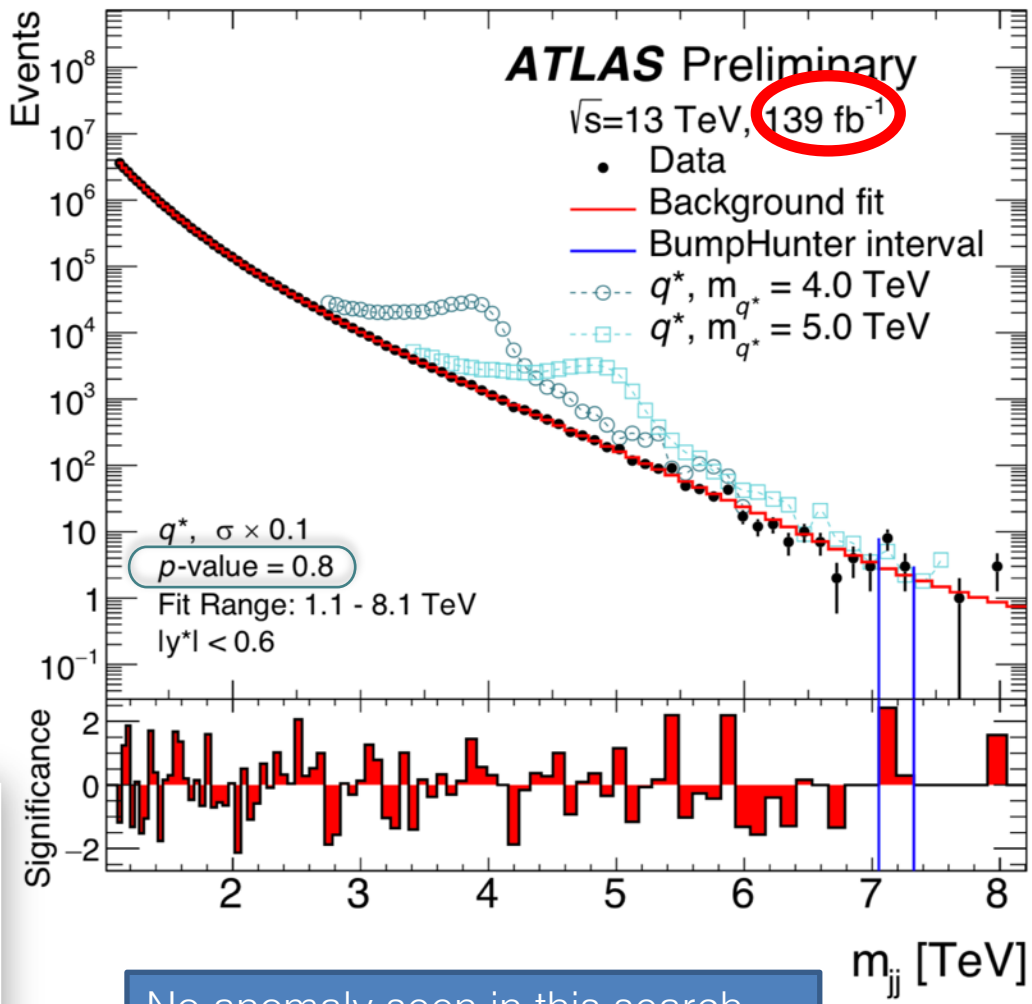
Searches for New Resonances

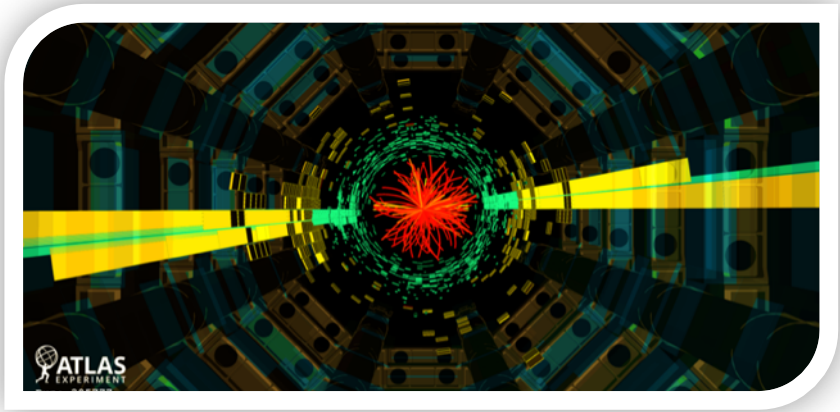


Searches for Di-Jet Resonances (Full Run-2 dataset)

Hadronic resonances are sensitivity to highest energy scales at the LHC
Benchmark: Excited quarks q*



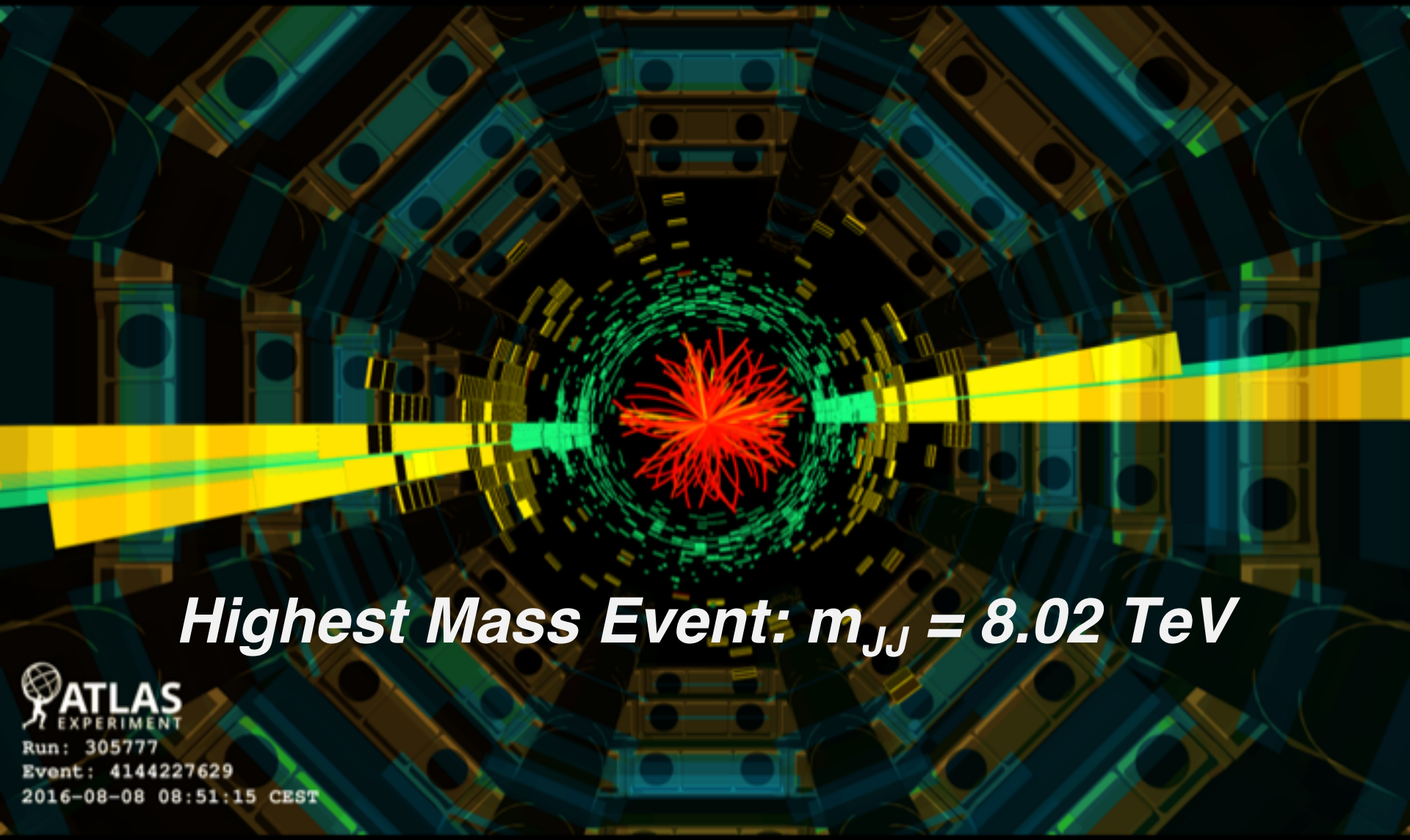




No anomaly seen in this search
Limit on M_{q^*} > 6.7 TeV at 95% CL

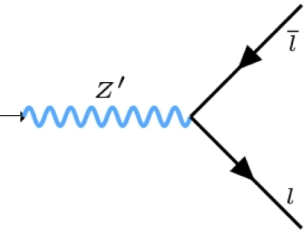
ATLAS-CONF-2019-007

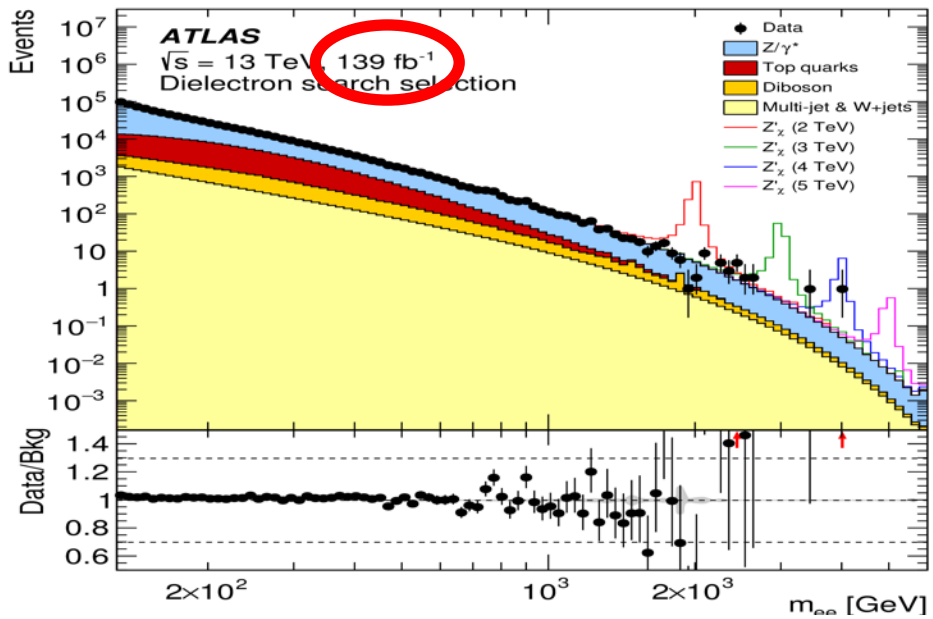
Searches for New Resonances

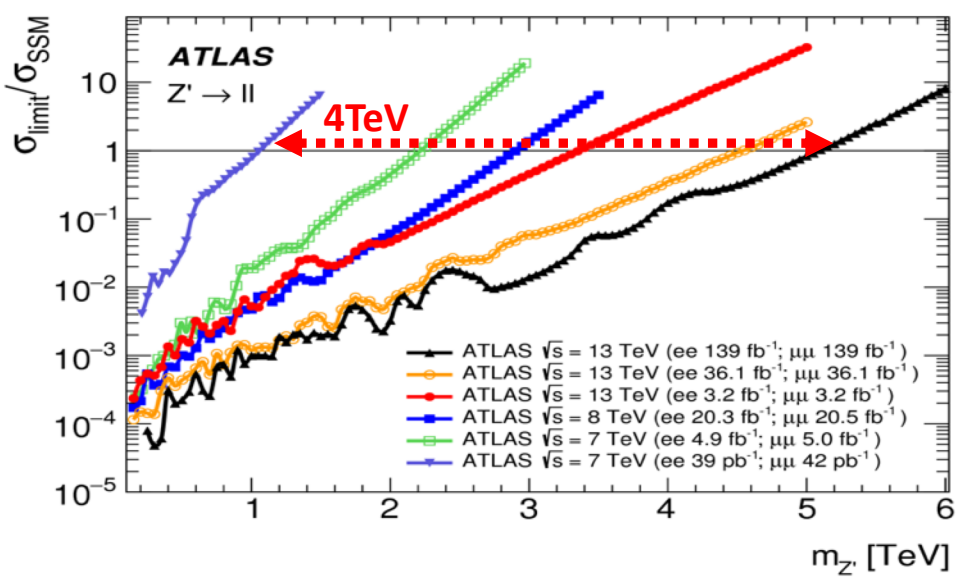


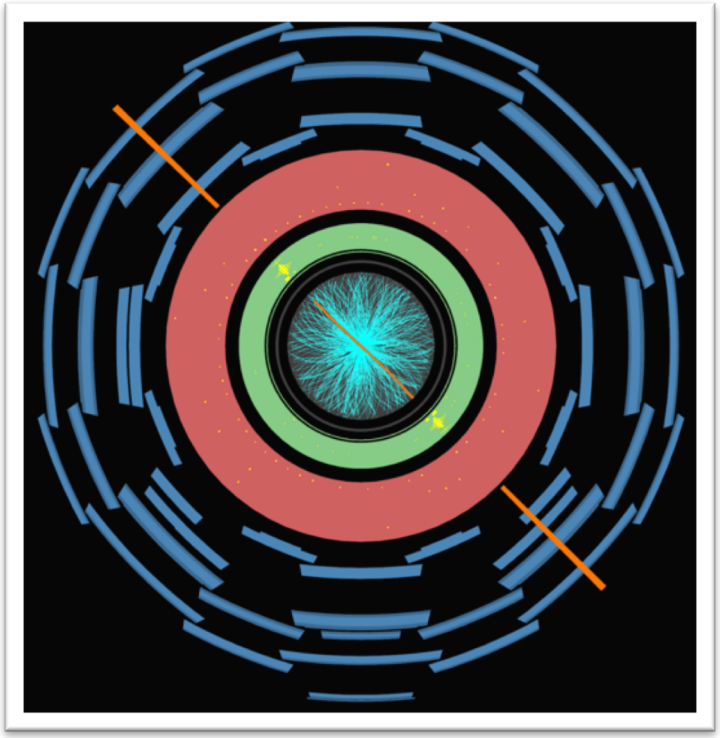
Highest Mass Event: m_{JJ} = 8.02 TeV

Dilepton Resonance Searches (Full Run-2 dataset)









arXiv:1903.06248

Highest mass dilepton candidate:
m_{ee} = 4.06 TeV

ATLAS has excluded Z' bosons with SM couplings up to 5.1 TeV at 95% CL

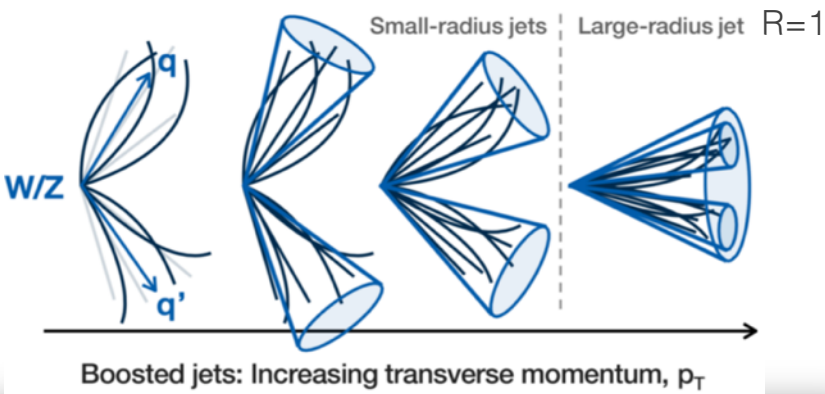
See Etienne Dreyer's talk

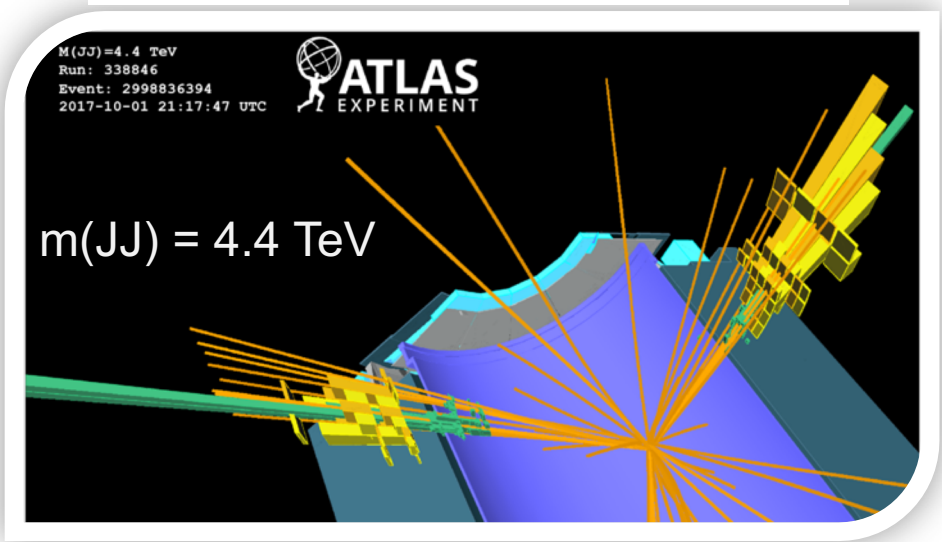
Di-Boson Resonance Search

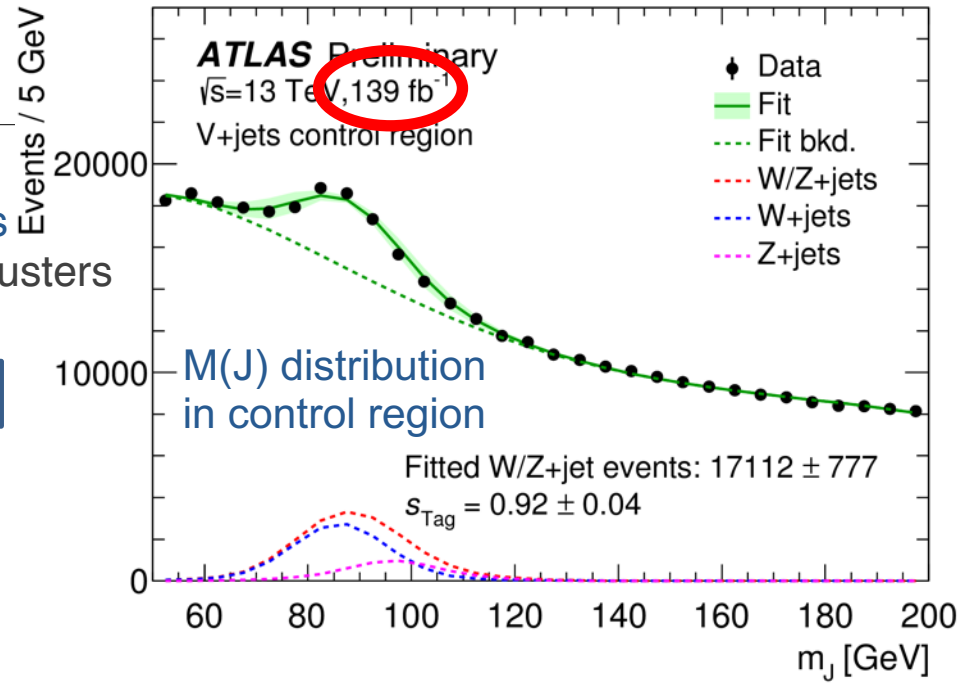
Use large radius R=1.0 jets as input to *W/Z Tagger* to reconstruct boosted W/Z bosons

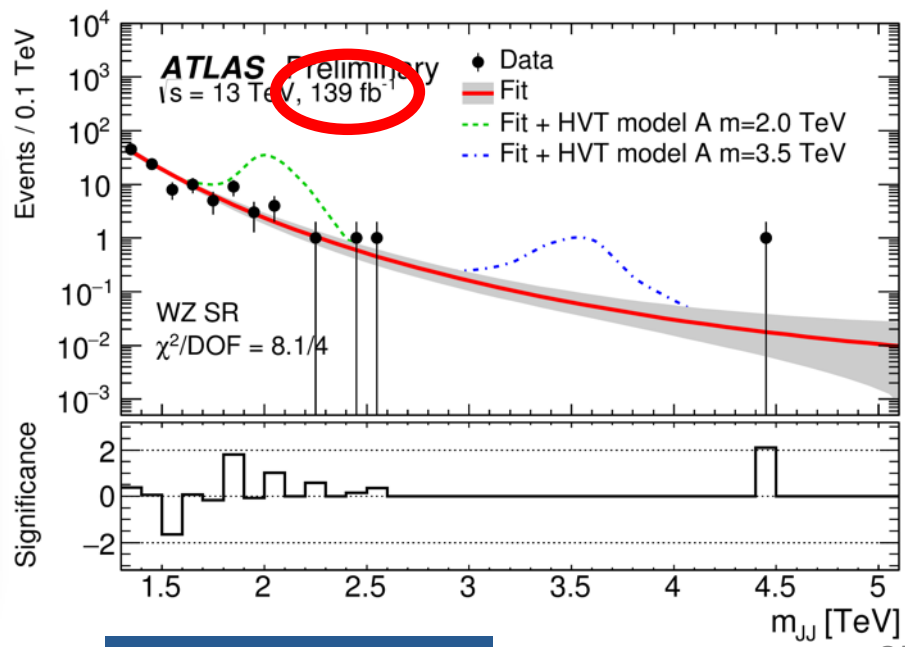
- Substructure analysis based on Track-CaloClusters
- Consider spin-0, 1, 2 benchmark models

1.3 TeV < M_{G^*} <1.6 TeV at 95% CL (bulk RS model)



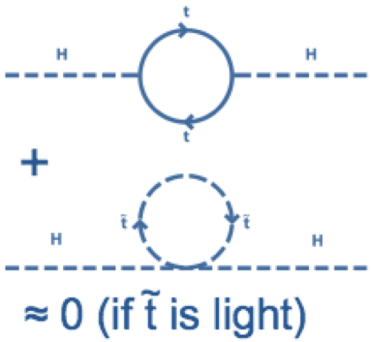




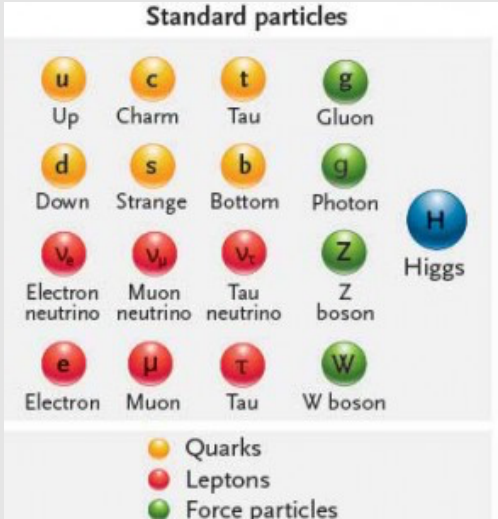


ATLAS-CONF-2019-003

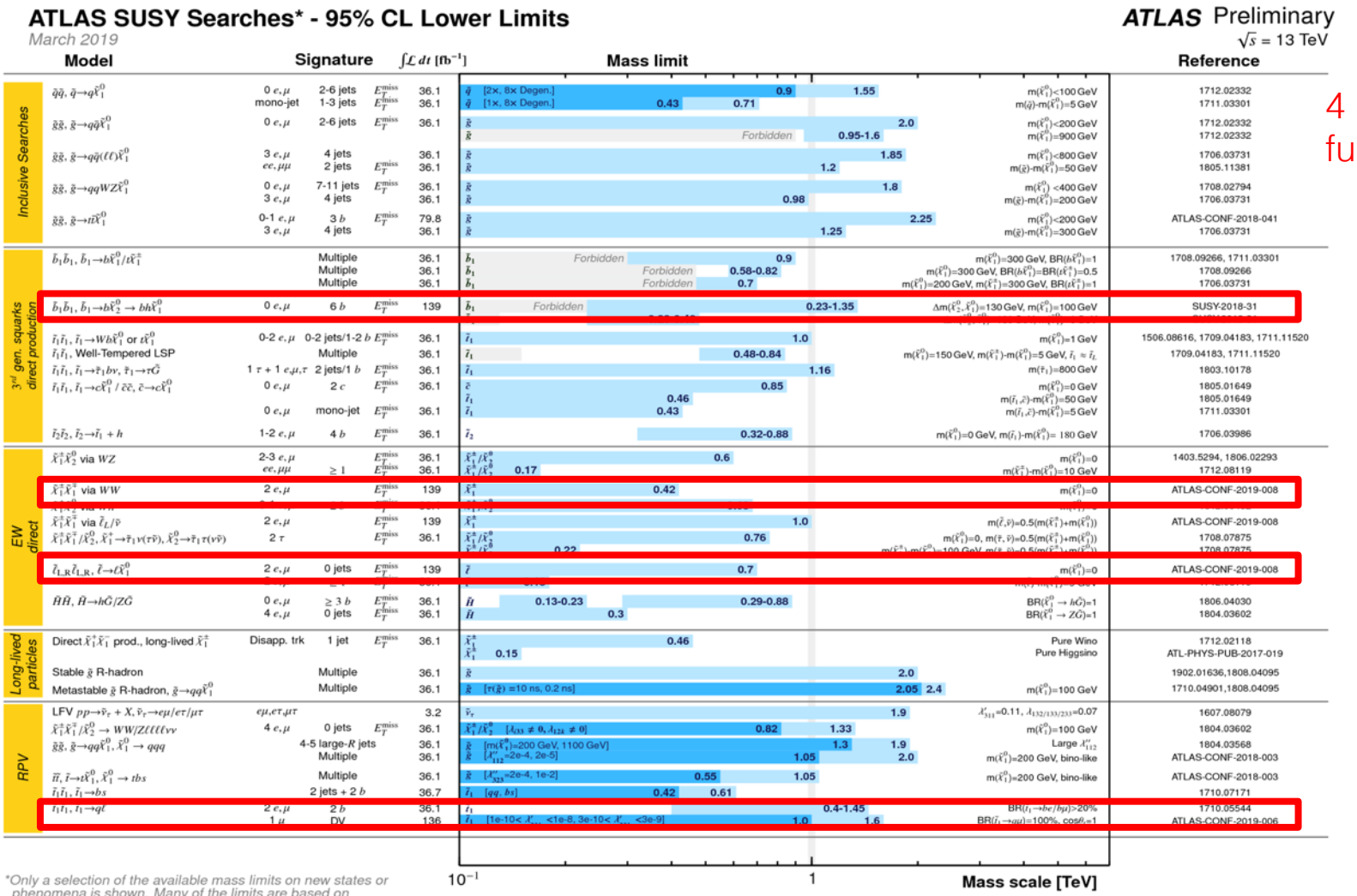
Search for Supersymmetry



"naturalness"



Searches for New Phenomena (SuperSymmetry)



4 Searches with full Run-2 dataset

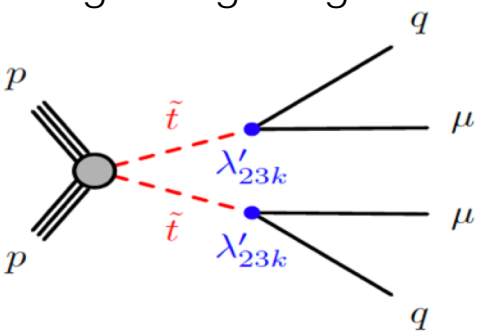
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Search for long lived Top Squarks (Full Run-2 dataset)

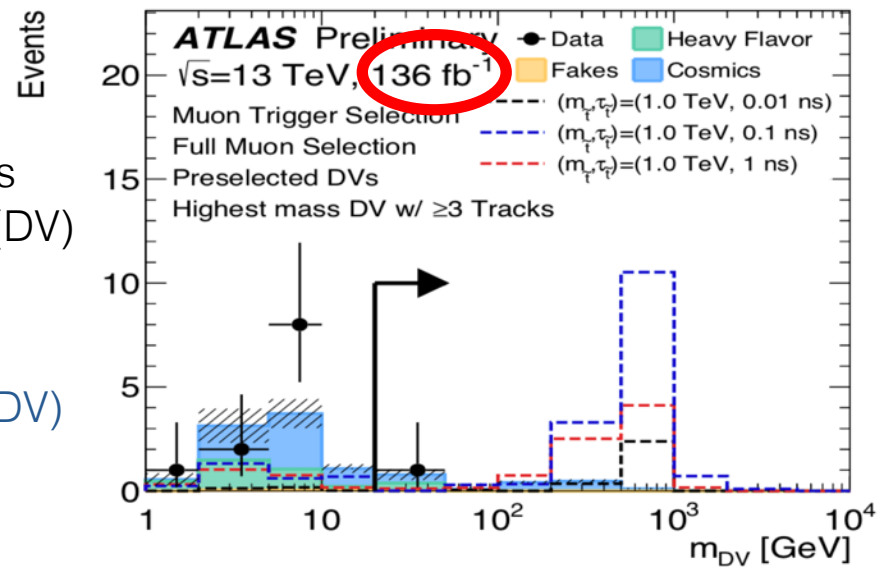
ATLAS-CONF-2019-006

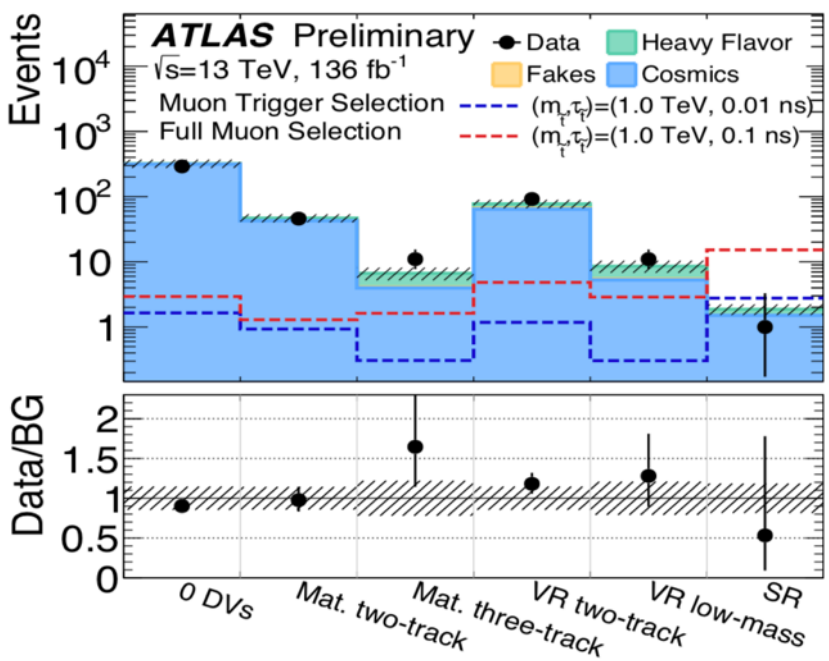
What if SUSY particles are long lived?

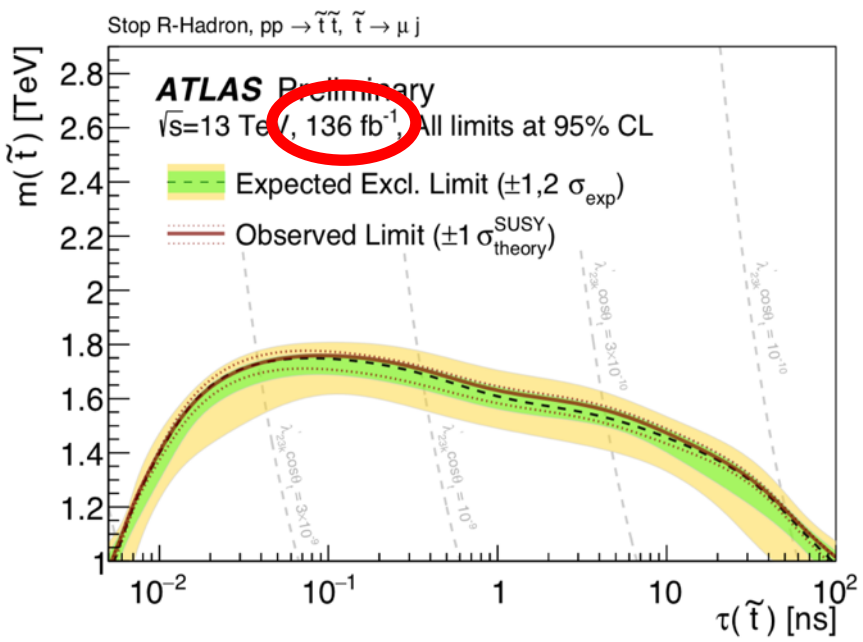
- New search for long-lived top squarks
- For small couplings λ, lifetime of top squark is long enough to give rise to displaced vertex (DV)

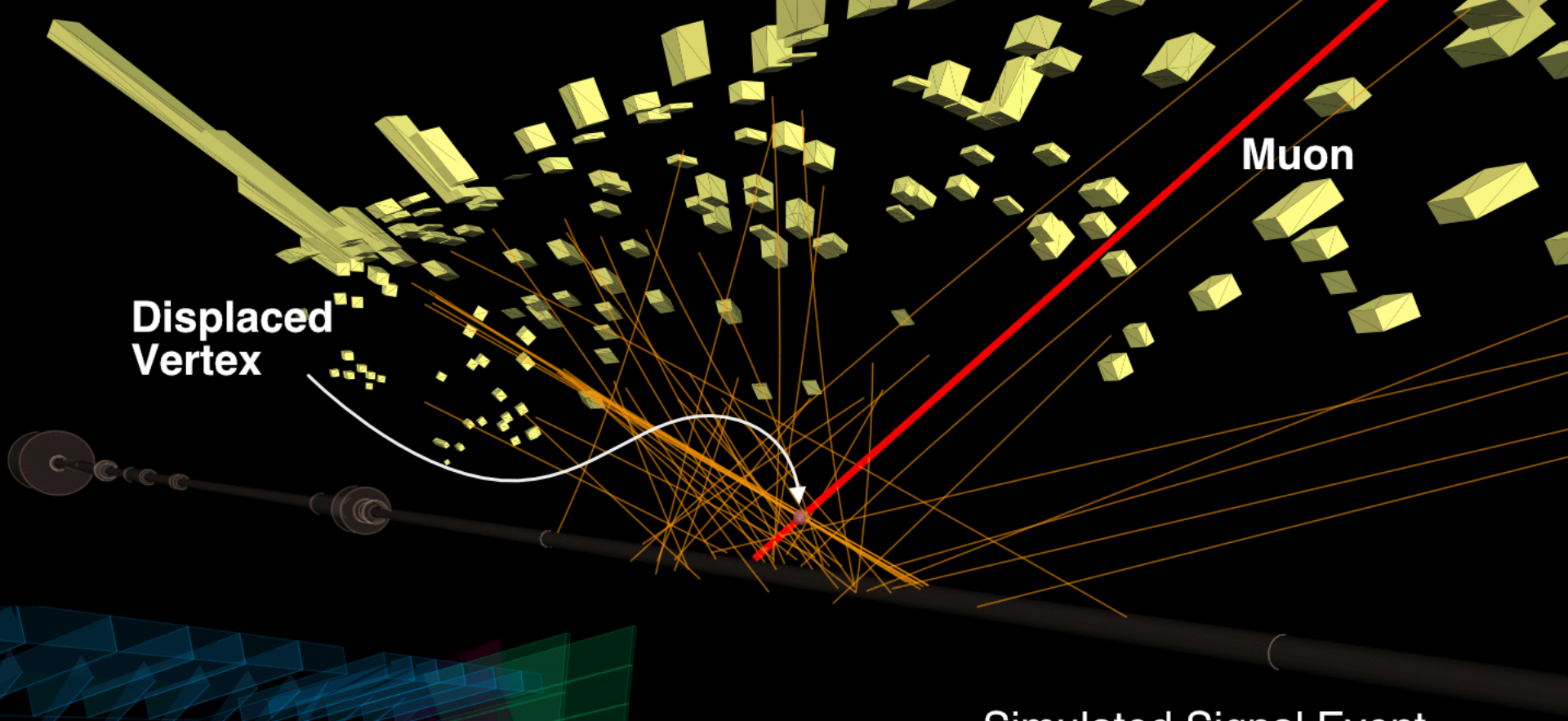


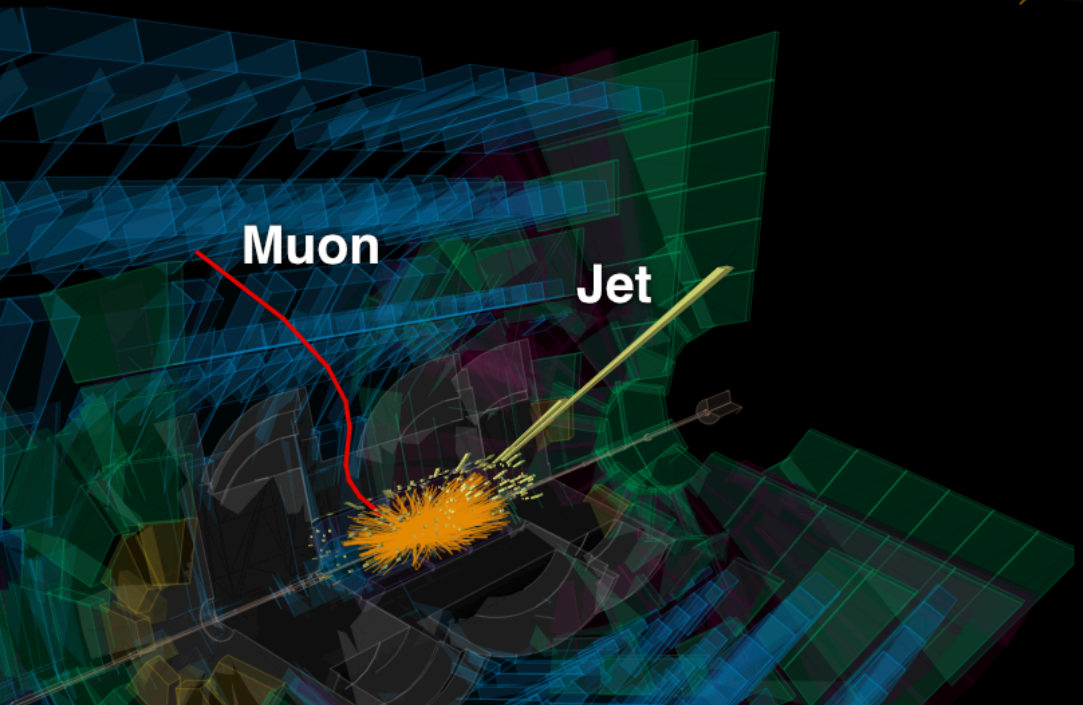
Search for heavy displaced vertex (DV) + muon











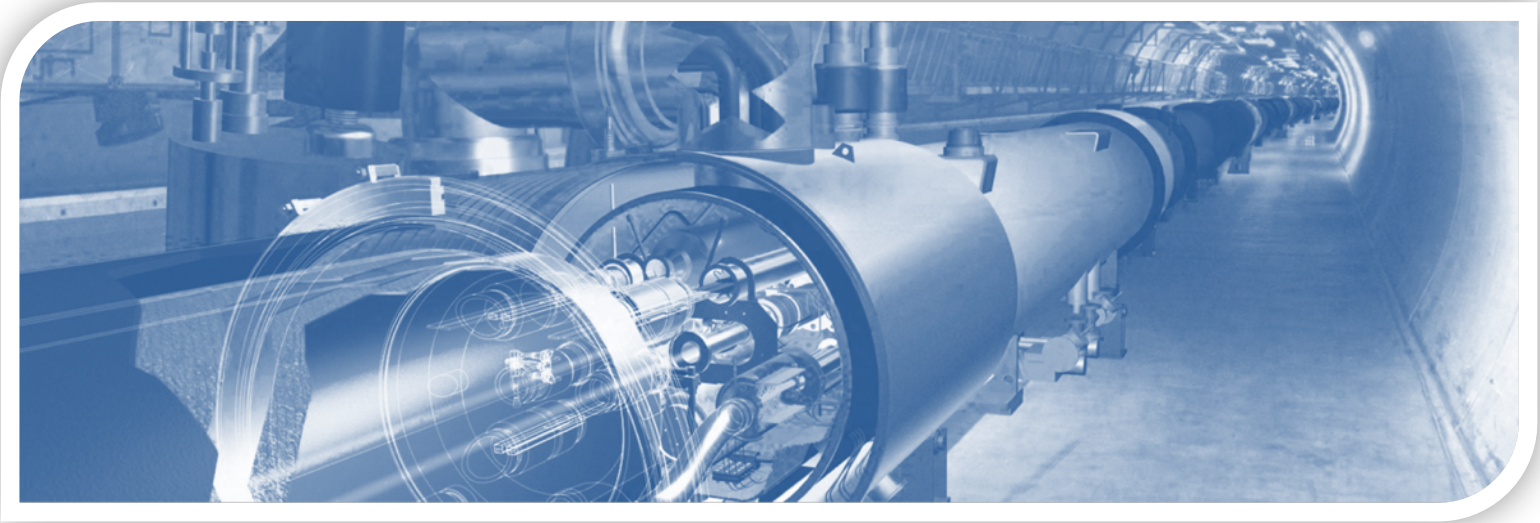
Simulated Signal Event
Top Squark Pair Production

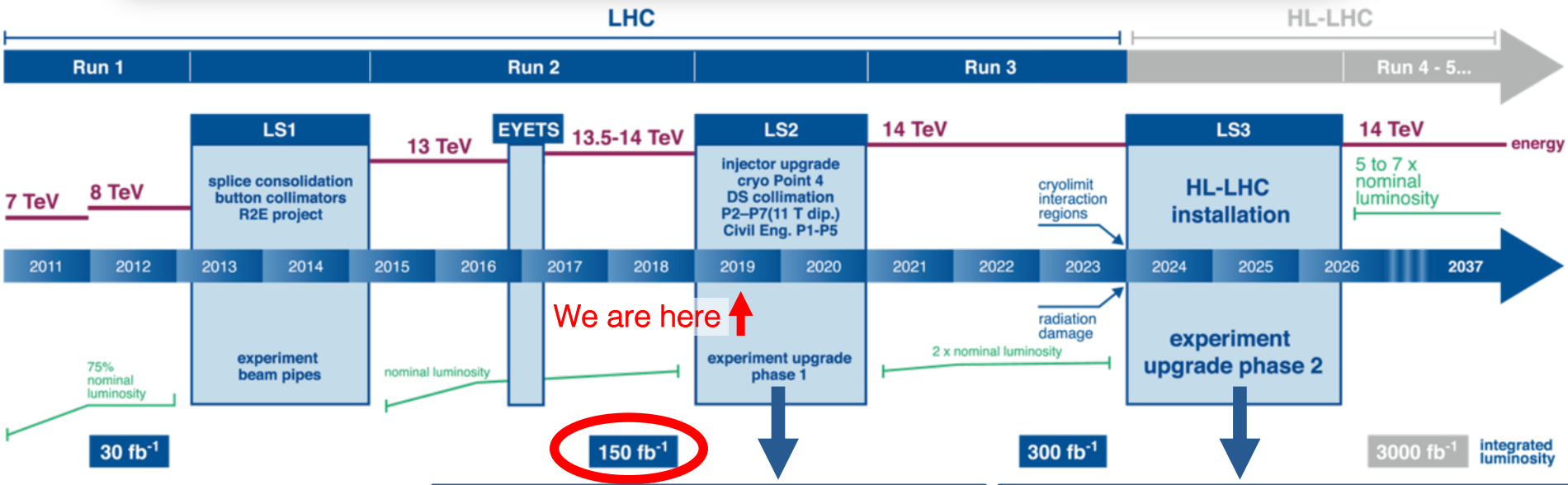
$m(\tilde{t}) = 1.5 \text{ TeV}, \ \tau(\tilde{t}) = 1 \text{ ns}$

$\tilde{t} \rightarrow \mu j$

ATLAS
EXPERIMENT

Looking to the Future



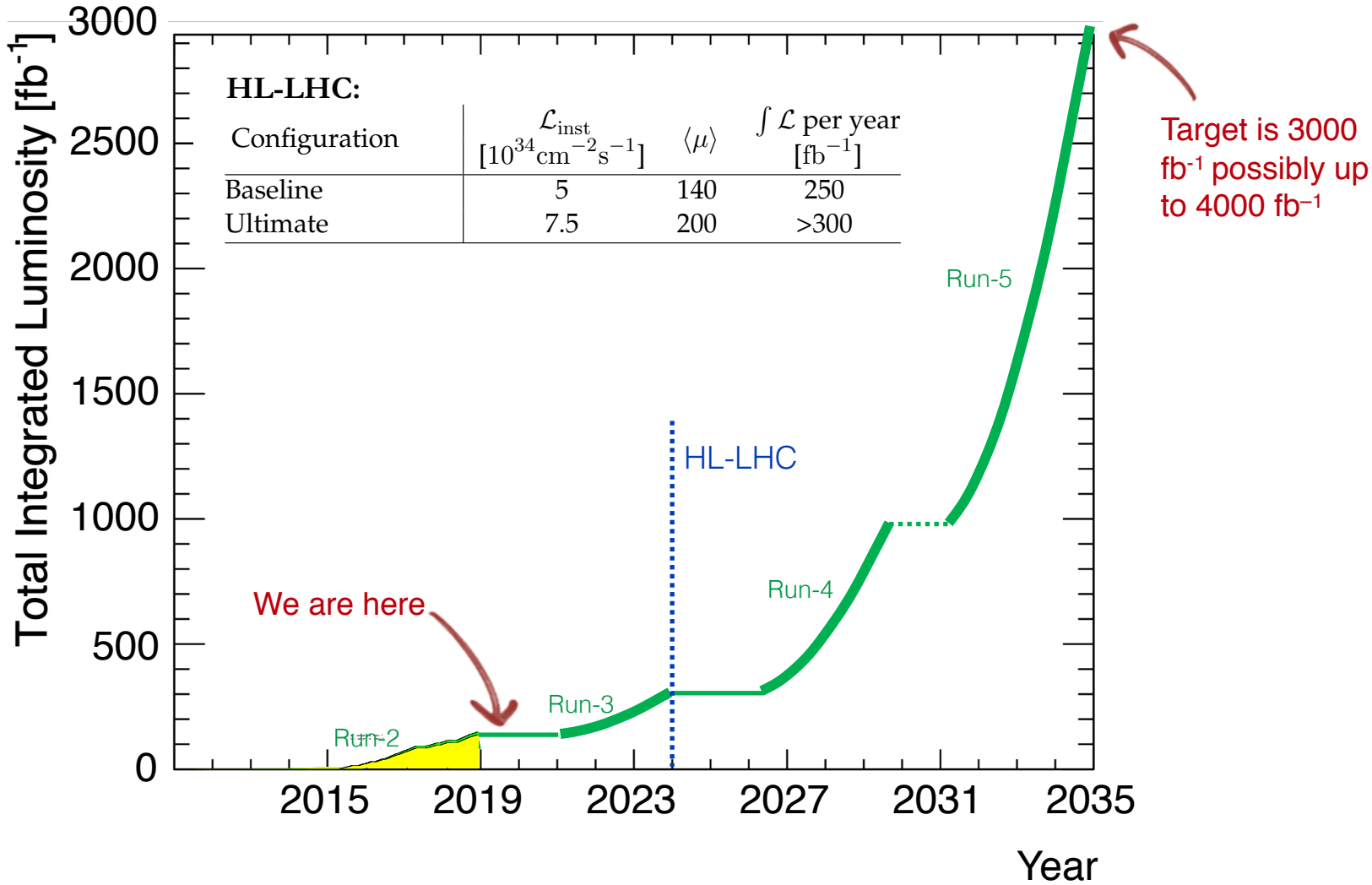


- sTGC for Muon New Small Wheel
- LAr Calorimeter trigger electronics

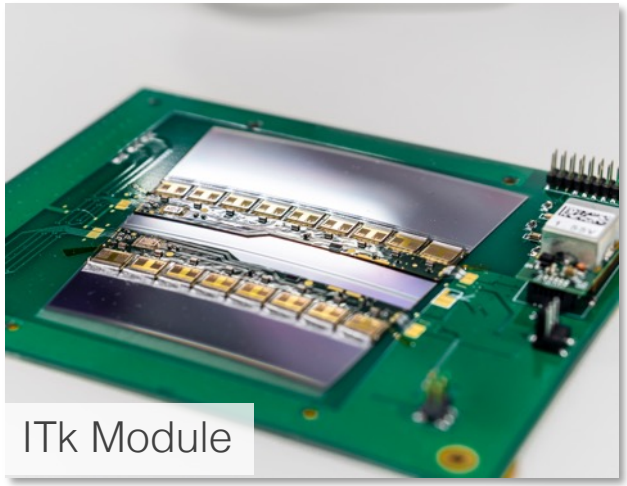
- New ATLAS Inner Tracker (ITk)
- LAr Calorimeter readout electronics

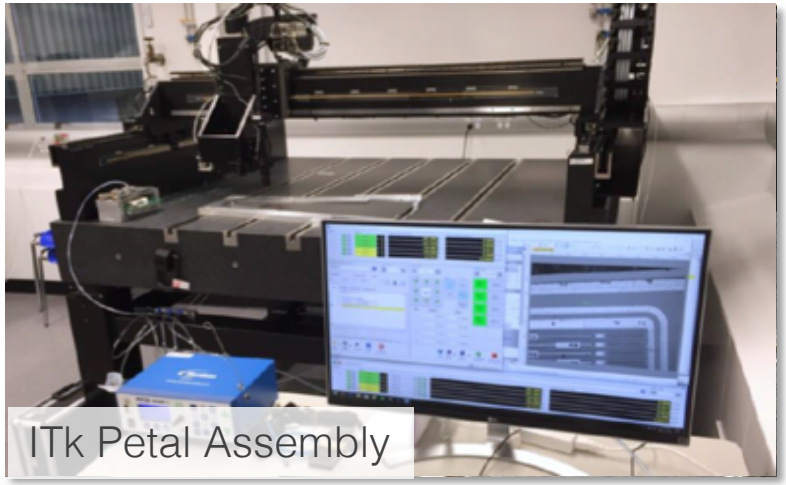
See Jesse Heilman's talk

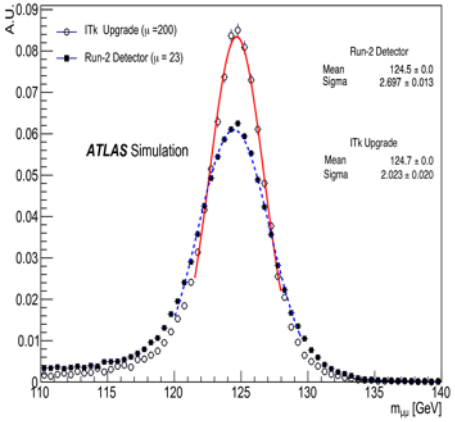
Expected integrated luminosity of LHC and HL-LHC

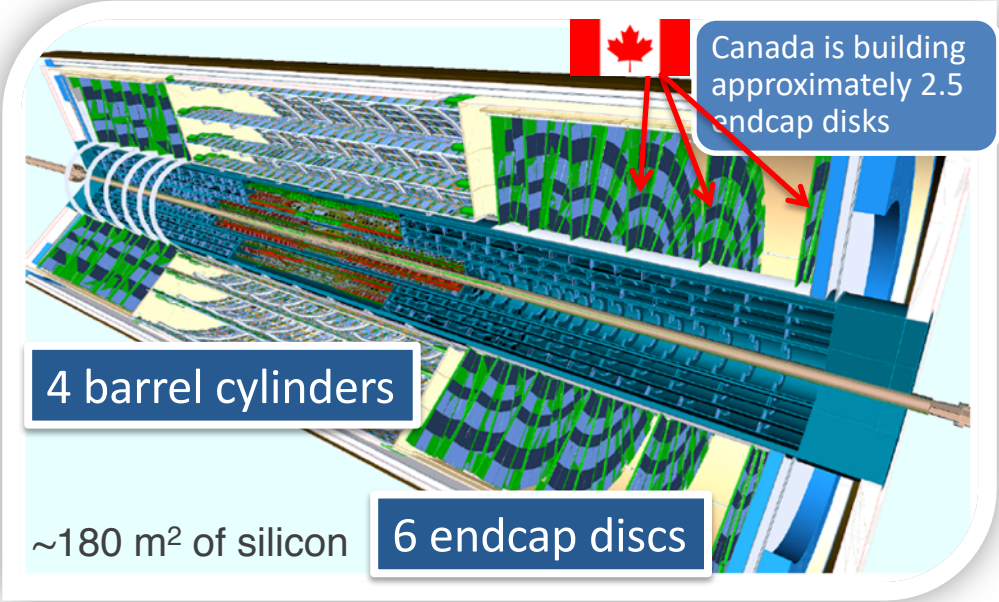


New ATLAS Inner Tracker (ITk) for the HL-LHC







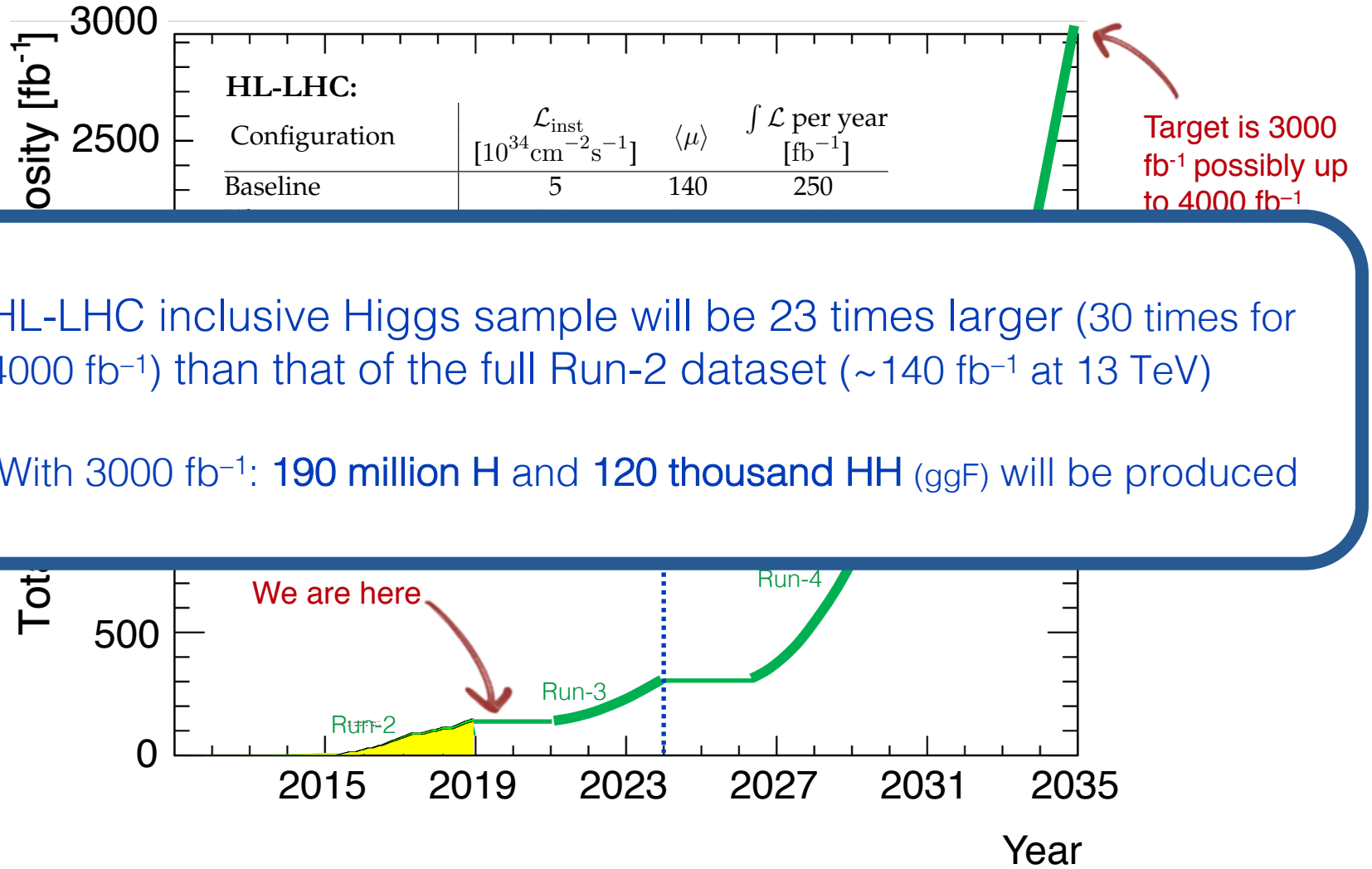


Challenges for the ITk upgrade:

- Higher occupancies and pile-up
  →Finer segmentation
- Higher particle fluences
  →Increase radiation tolerance

New Inner Tracker: 80M → ~5G channels
Rapidity coverage: $|\eta| < 2.5$ → $|\eta| < 4$

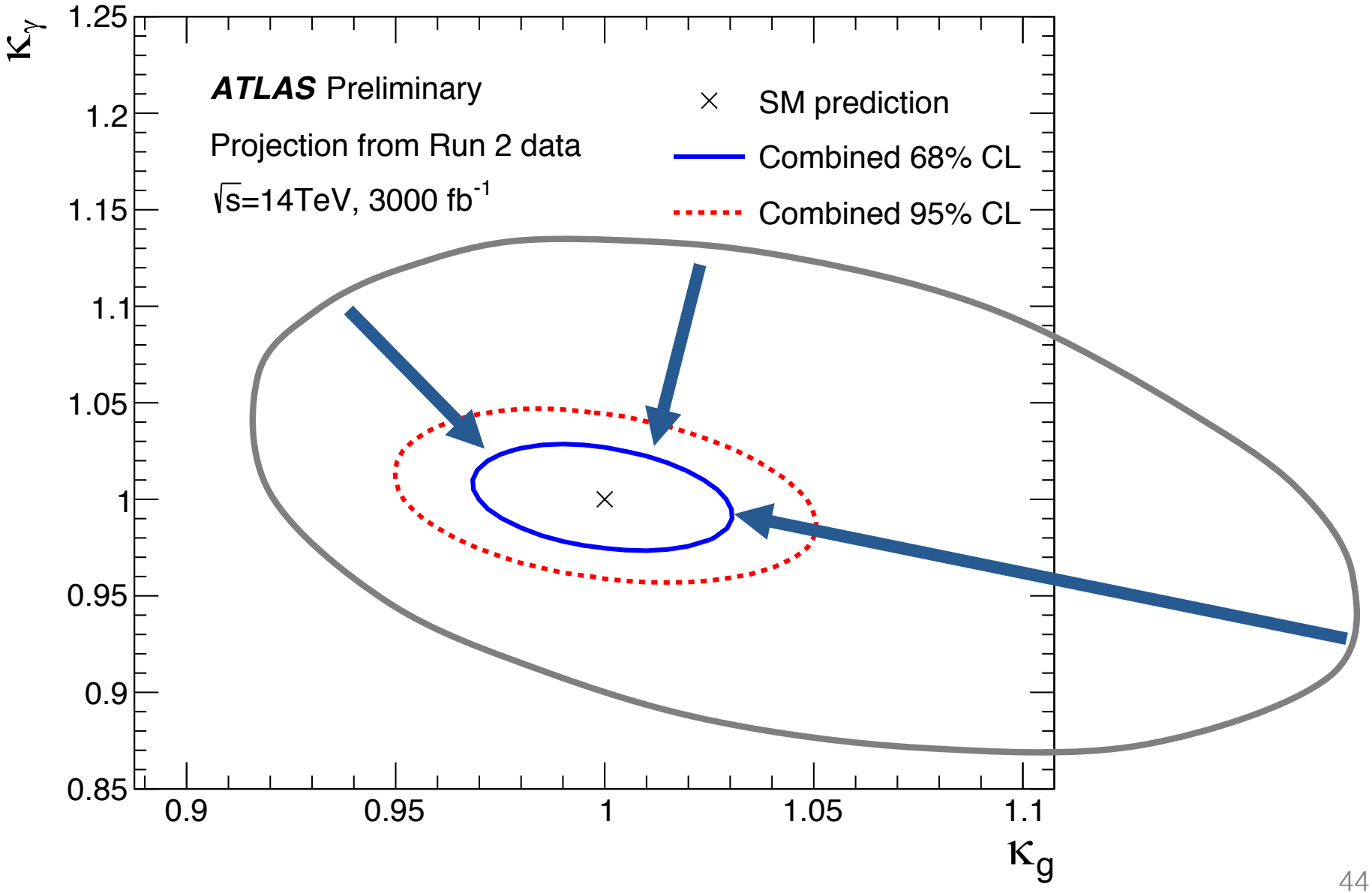
Expected integrated luminosity of LHC and HL-LHC



HL-LHC inclusive Higgs sample will be 23 times larger (30 times for 4000 fb^{-1}) than that of the full Run-2 dataset (~140 fb^{-1} at 13 TeV)

With 3000 fb^{-1}: **190 million H** and **120 thousand HH** (ggF) will be produced

Higgs Boson Coupling Measurements at the HL-LHC



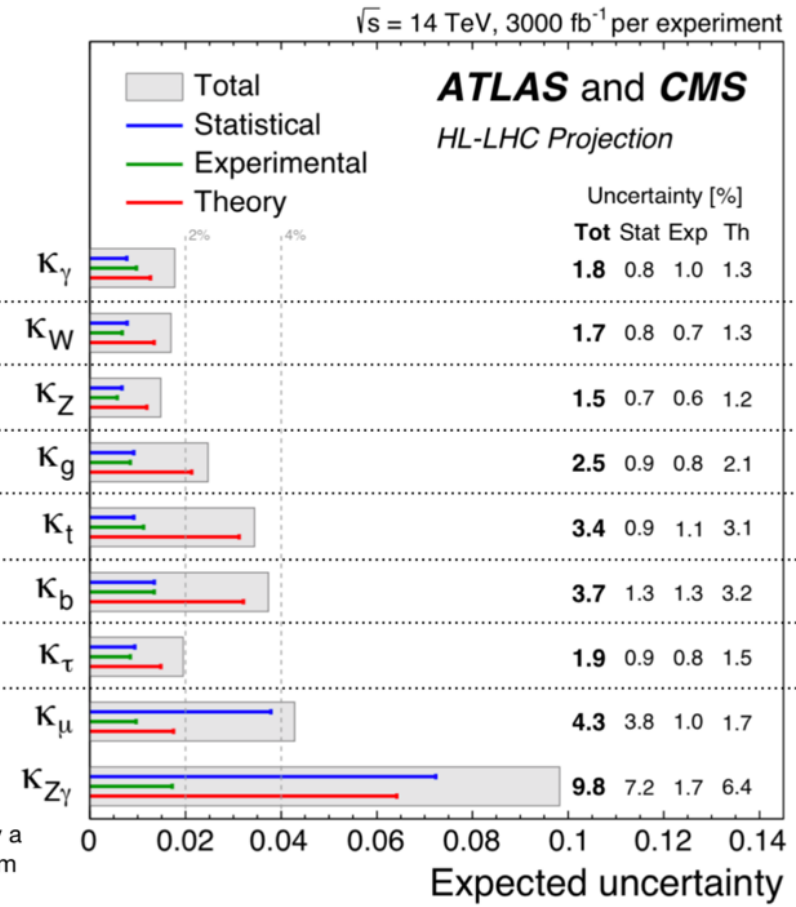
Higgs Boson Coupling Measurements at the HL-LHC

NEW Measurement of the couplings properties of the Higgs boson - in this case assuming no BSM in the Higgs width

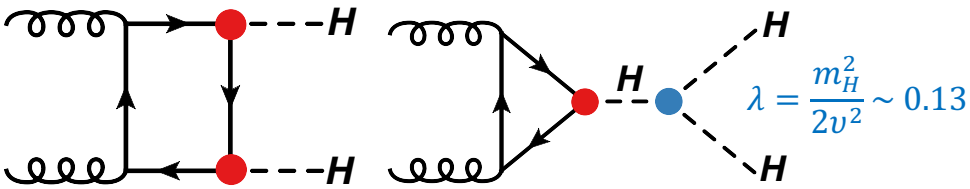
YR2018 1902.00134

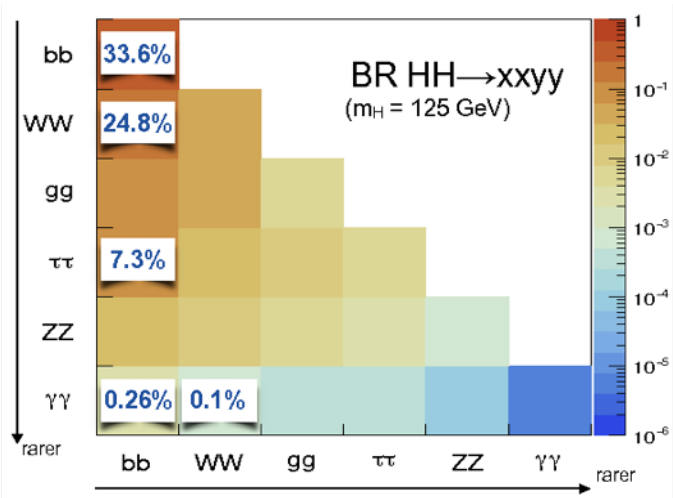
	ATLAS - CMS Run 1 combination	ATLAS Run 2	HL-LHC
κ_γ	13%	9%	1.8%
κ_W	11%	8.6%	1.7%
κ_Z	11%	7.2%	1.5%
κ_g	14%	11%	2.5%
κ_t	30%	14%	3.4%
κ_b	26%	18%	3.7%
κ_τ	15%	14%	1.9%
	JHEP 08 (2016) 045	ATLAS-CONF-2019-04	HL-LHC YR 1902.00134

Improved TH and PDF uncertainties by a factor of 2 w.r.t. current (motivated from current PDF studies and current TH uncertainties assumptions)



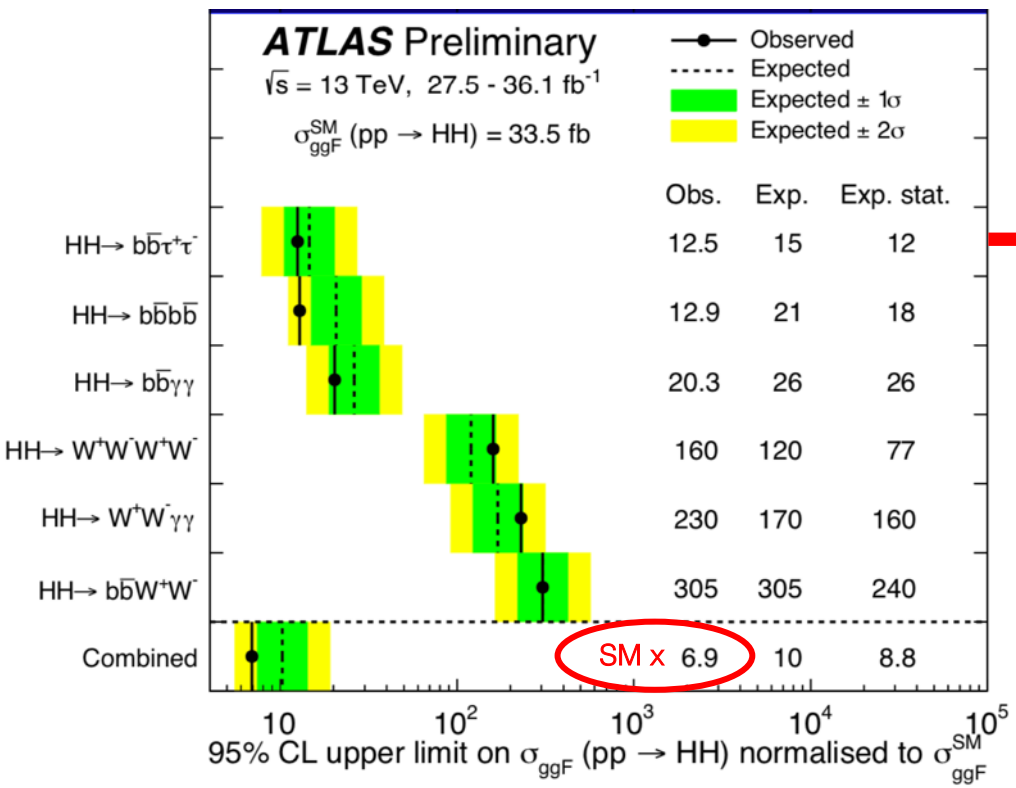
Higgs Boson Pair Production (Di-Higgs)

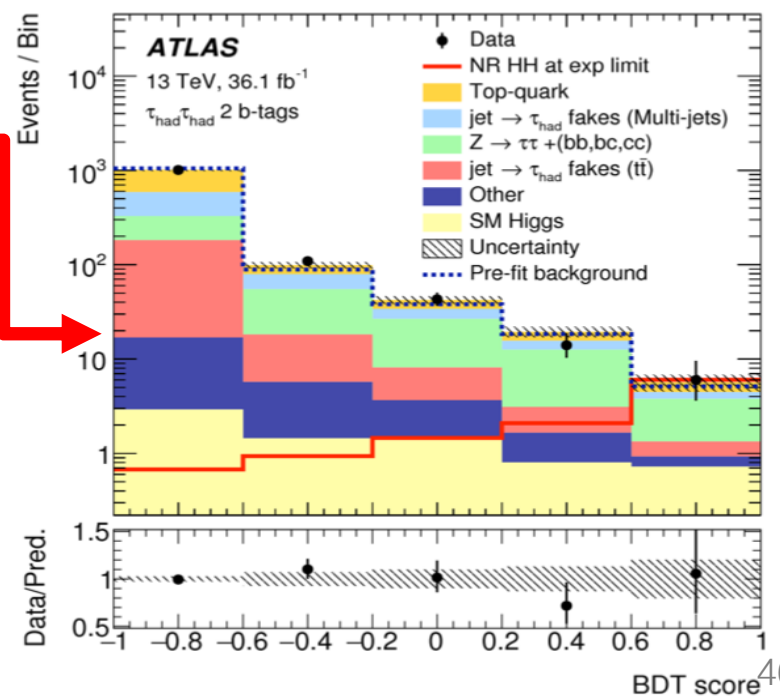




SM Higgs pair production is small (33.5 fb at 13 TeV)

- Destructive interference between two diagrams
- Allows to directly probe **Higgs self-coupling** λ
- Combination of several channels and lots of data (+MVAs)





Higgs Boson Pair Production (Di-Higgs) → HL-LHC Prospects

Combination of ATLAS and CMS data (projection)

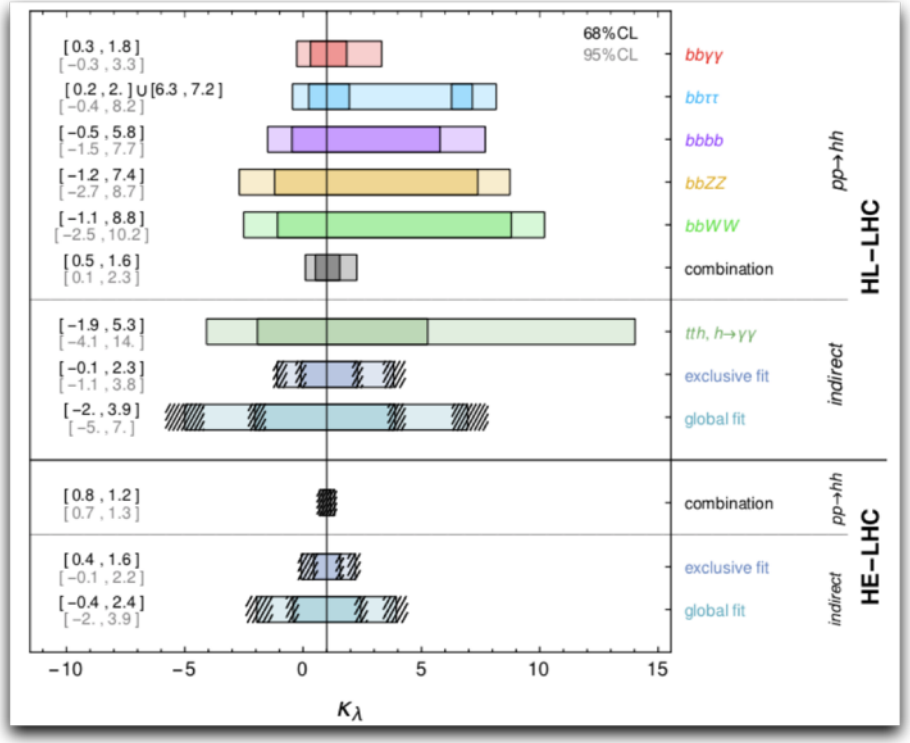
- ATLAS includes bbbb, bbττ and bbγγ
- CMS includes bbbb, bbττ, bbγγ, bbVV (2-lepton) and bbZZ (4-lepton)

Scale HL-LHC (14 TeV) to HE-LHC (27 TeV)

- Cross section x4
- Dataset size 15 ab^{-1}

HL-LHC

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



- Expected **HH signal significance 4σ**
- Expected precision on signal strength μ_{HH} is estimate to be $\Delta\mu_{HH}$=25%

Note: Not all projected channels optimized yet to measure κ_λ

$0.5 < \kappa_\lambda < 1.5$ (incl sys) at HL-LHC (50%)

$0.8 < \kappa_\lambda < 1.2$ (incl sys) at HE-LHC (20%)

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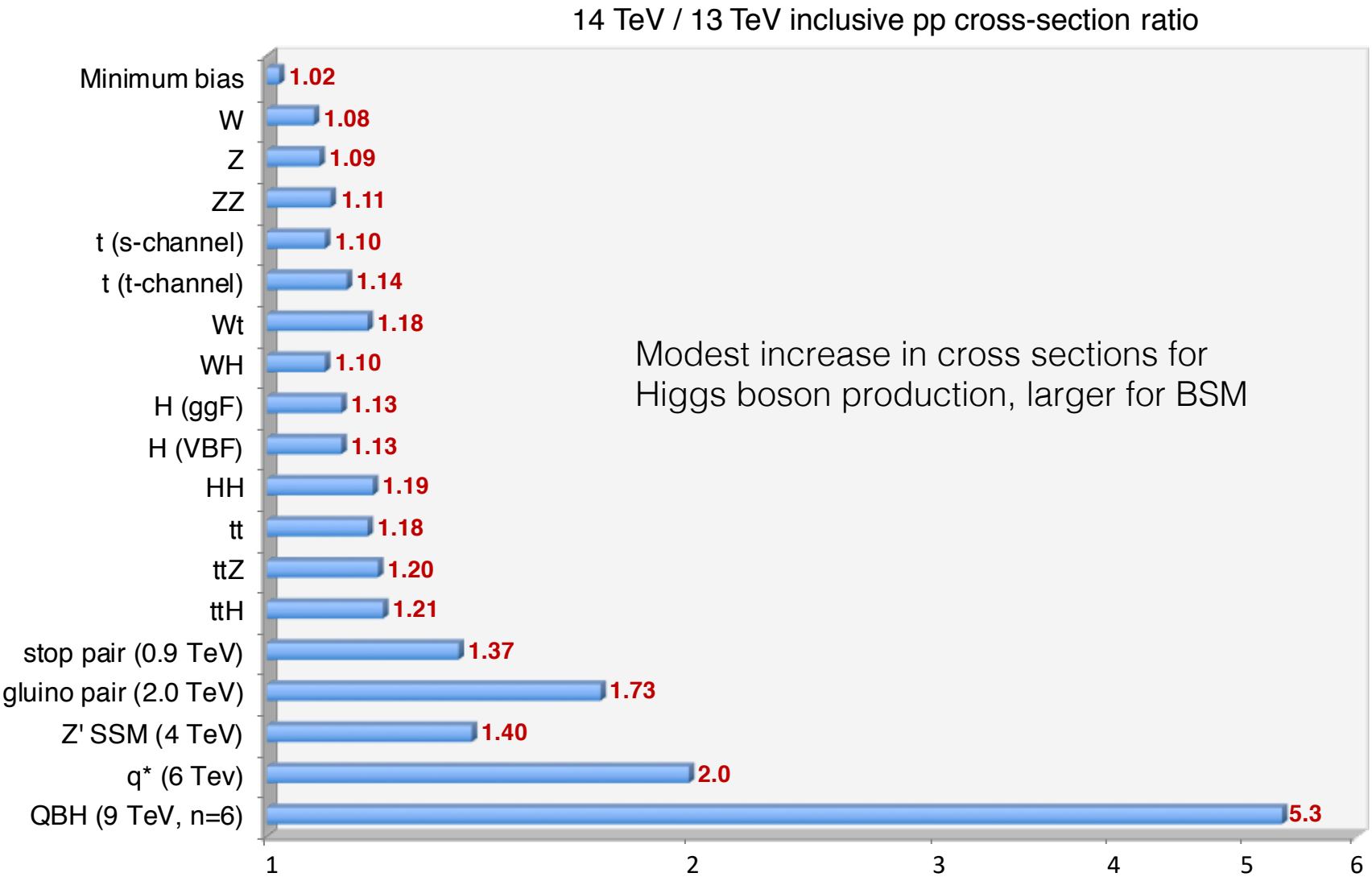
Going to 14 TeV proton–proton centre-of-mass energy

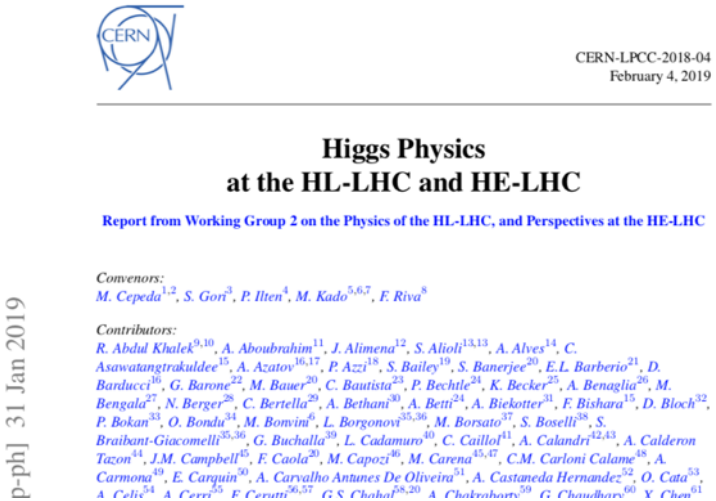


Conclusions

- Particle physics at the energy frontier is extensively probing TeV scale physics
- Contrary to the Fermi (electroweak) scale, we do not know the next new physics scale. Naturalness suggests O(TeV) but it is challenged by LHC results
- We have observed the Higgs boson – none of its properties can be taken for granted
- Nice progress during Run-2 – detailed measurements is the responsibility of the LHC
- Run-3 promises more interesting advances (2nd generation Yukawas, BSM, etc)

Looking into the future

- Upgrades for the HL-LHC are underway
- HL-LHC Higgs physics shows impressive goals
- Leave no stone unturned (e.g. lifetime frontier, unconventional signatures, etc)
- More new ideas are needed to further push the frontiers of particle physics at LHC.



CERN-LPCC-2018-04
February 4, 2019

Higgs Physics at the HL-LHC and HE-LHC

Report from Working Group 2 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

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p-ph] 31 Jan 2019

https://arxiv.org/pdf/1902.00134.pdf

Thank you!

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