Exploring the scalar sector: challenges & opportunities for Run 3 and HL-LHC

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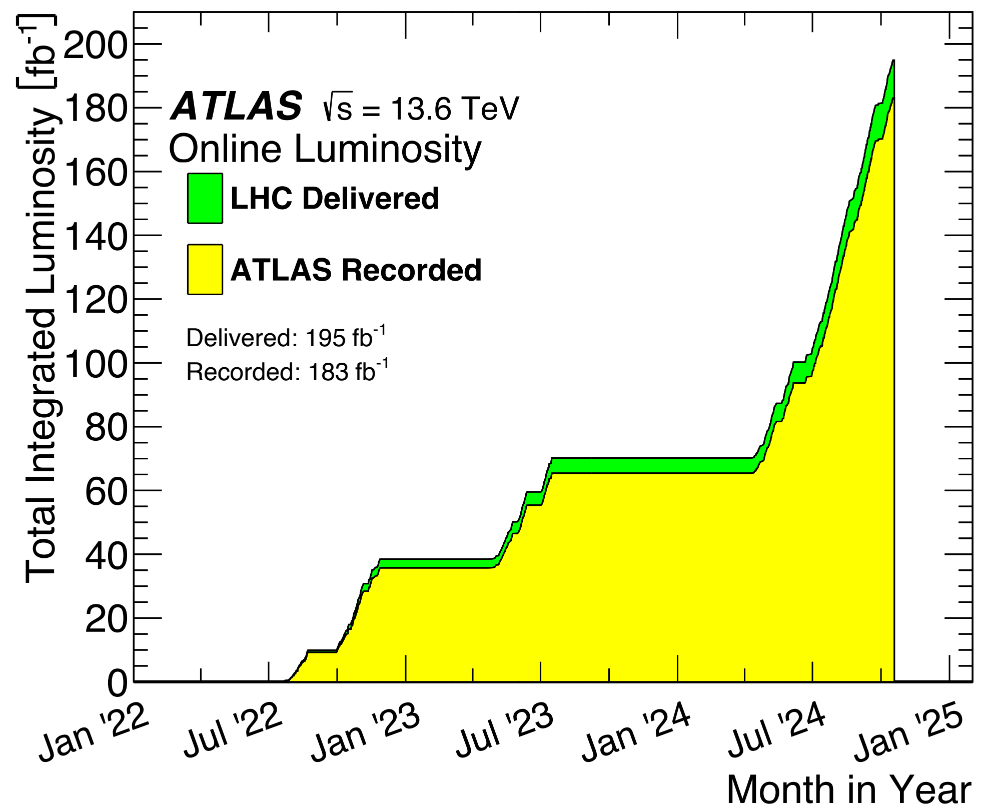
LHC Run 3 at large

Run 3 differs from its preceding Run 2 in two respects:

- CM energy: increase from 13 TeV to 13.6 TeV
- integrated luminosity: ~ 140 fb^{-1} ➠ > 450 fb^{-1} (Run 2 + Run 3 combined)

Especially the increased amount of data available for physics analysis is important



To make optimal use of it, ATLAS & CMS are pursuing two complementary approaches:

- improve online and offline selection, reconstruction and analysis
- continued focus on rarer final states (notably Higgs boson pair production), but also (very-) high-p_T physics (high-p_T tails of distributions sensitive to BSM physics)

Rise of the Machine Learning

We have moved on from the early days of Boosted Decision Trees and (single-hidden-layer) Neural Networks!

- greatly improved computing resources (often allowing for millions of parameters) + novel architectures
  ➠ significant performance improvements
- Example from b-tagging (long development line)

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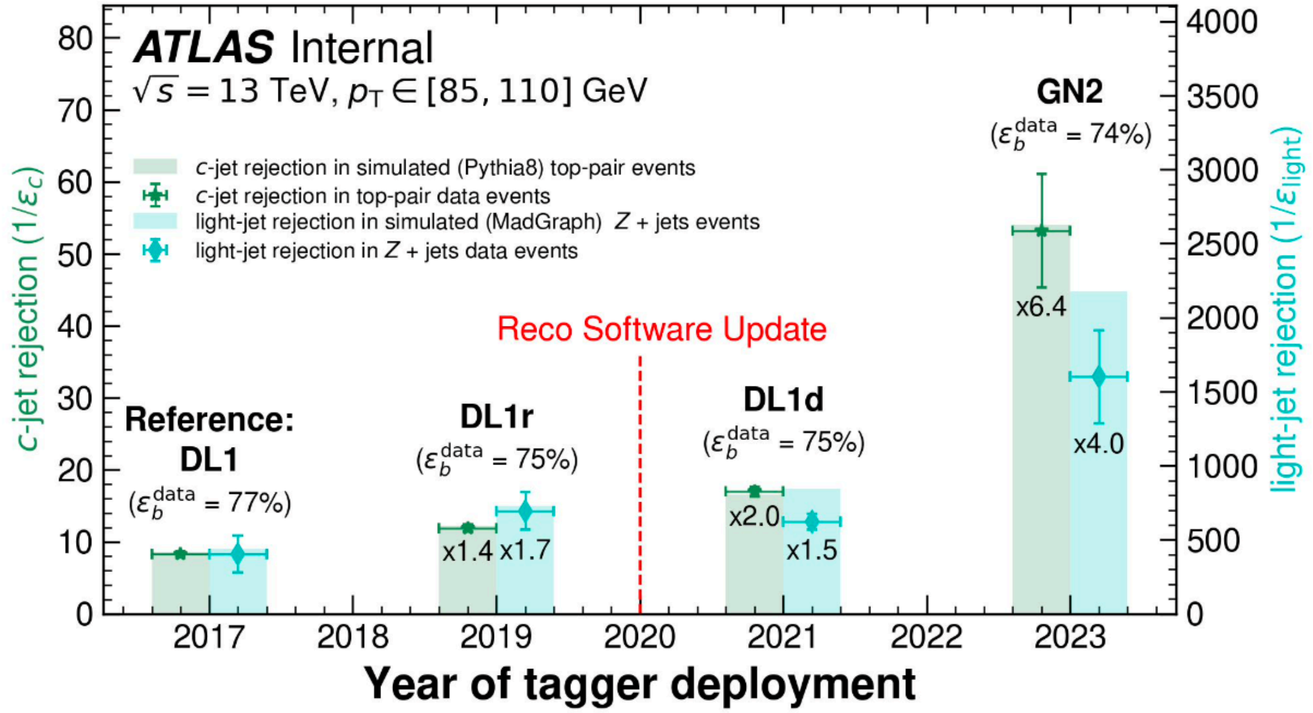

Note the (manageable but growing) differences between data and simulation ➠
precise calibrations remain essential!

- commensurate with growing uncertainties from known effects [link]

$\mathcal{O}(10^6)$ parameters ➠ need huge training datasets; typically not done for specific final states

Rise of the Machine Learning

CMS DeepTau algorithm: Deep Neural Network

- employing both low- and high-level inputs to improve reconstruction of notably 3-prong τ_{had} decays
  - ➠ benefiting both classification and $E(\tau_{\text{had}})$ reconstruction

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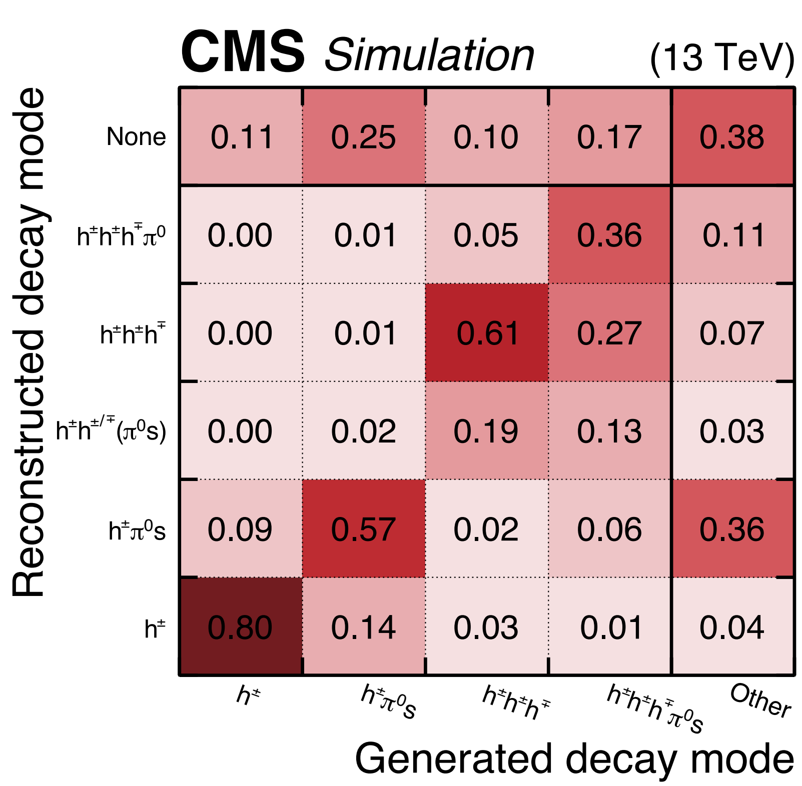

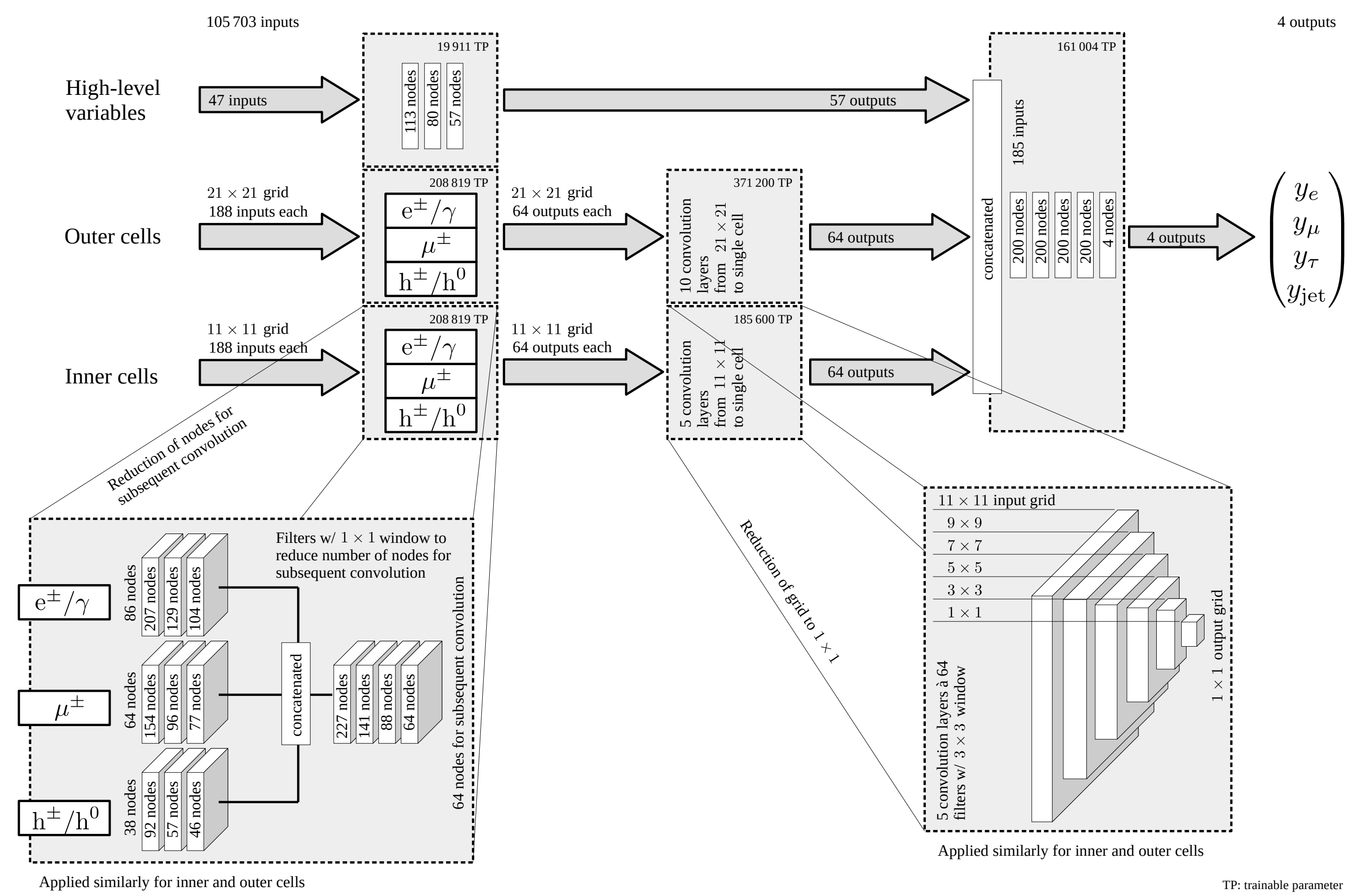

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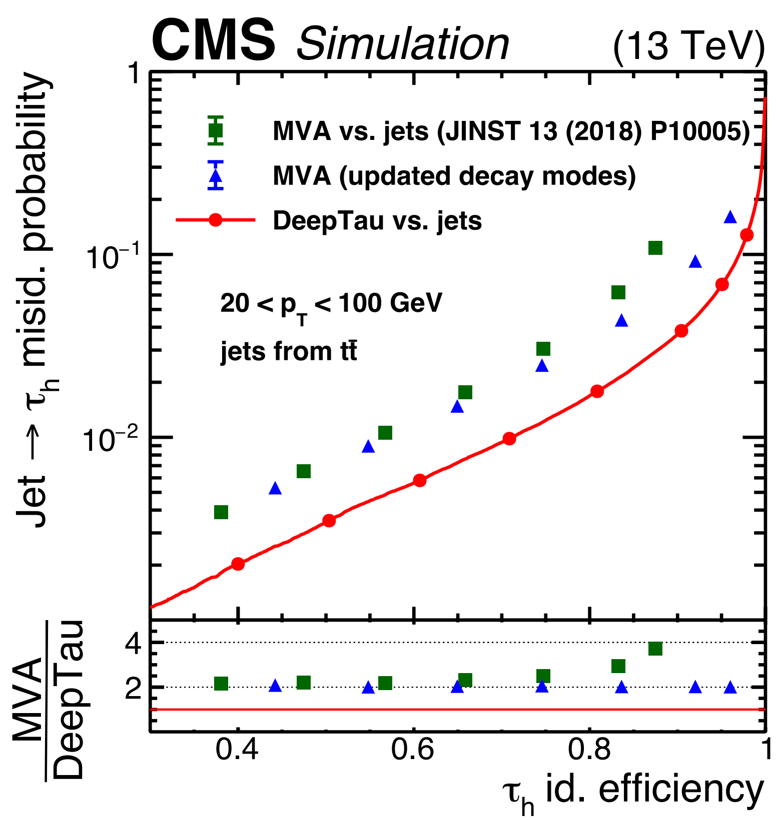
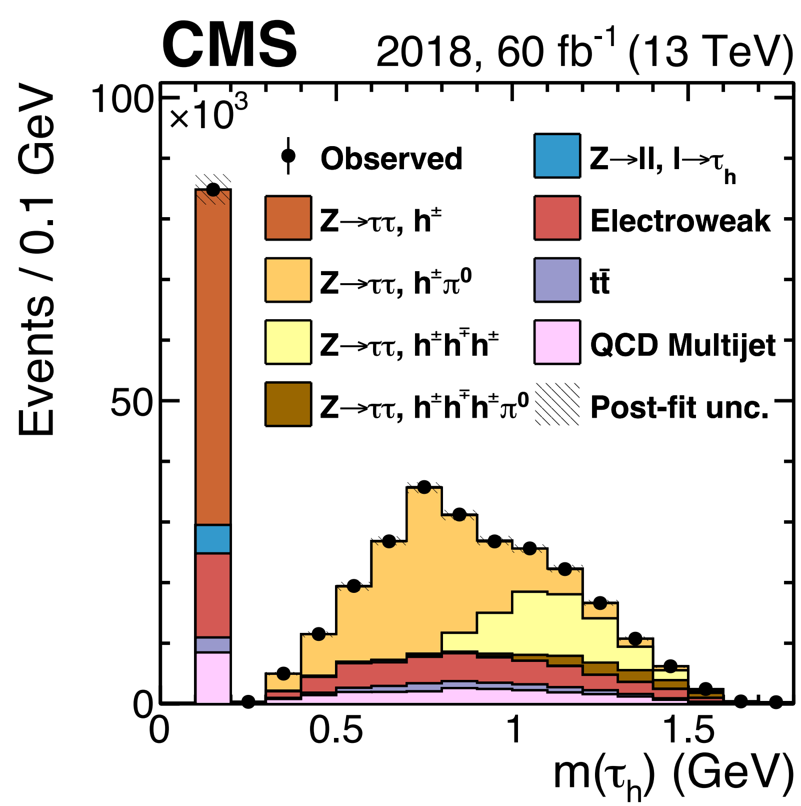
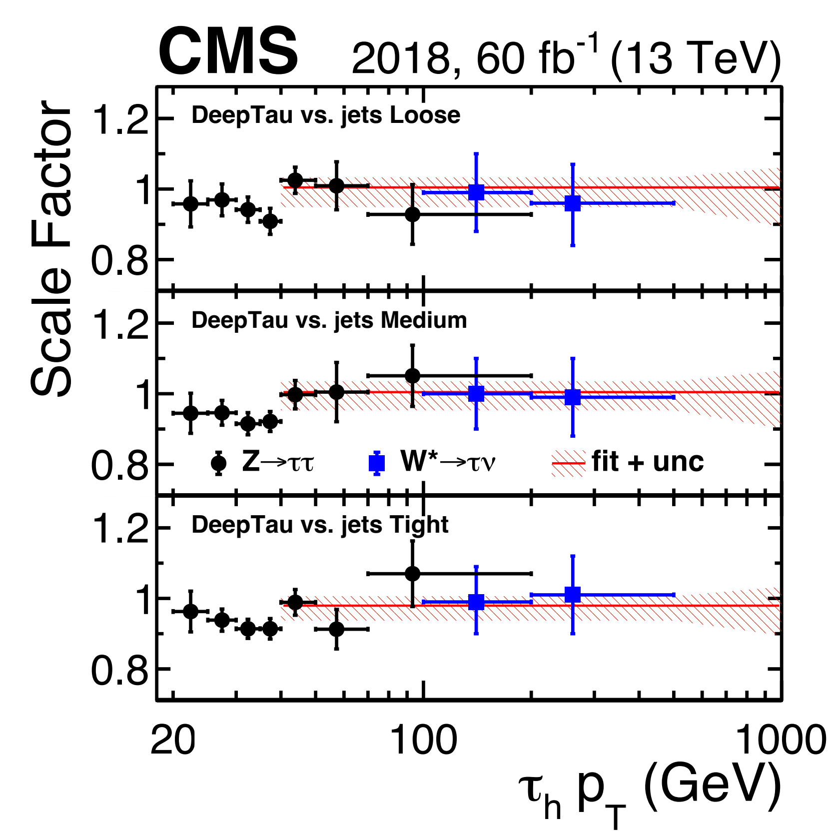
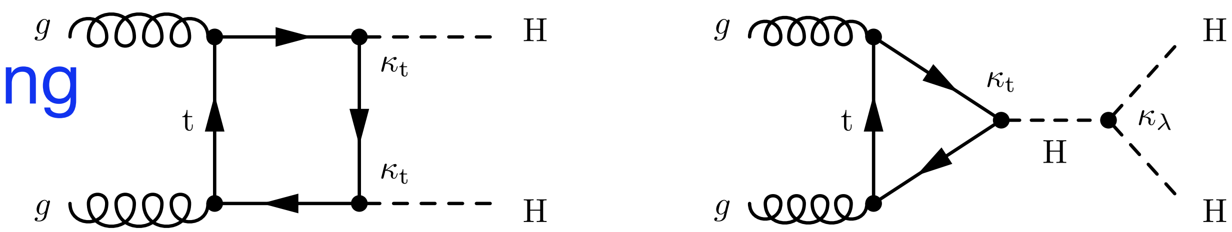






Putting Machine Learning to use

Investigation of Higgs boson self-coupling through investigation of HH production is among the most prominent LHC goals



- but cross section of ~ 30 fb and many decay modes make this very challenging
- I will focus on most "promising" decay modes: $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$

Example: Run-2 CMS search for $HH \to b\bar{b}\tau^+\tau^-$

- use of DeepTau + DeepJet for τ and b identification, respectively, followed by Deep Neural Network based event selection (72 event categories)
- in Run 3, expect many more analyses exploiting ML in various ways

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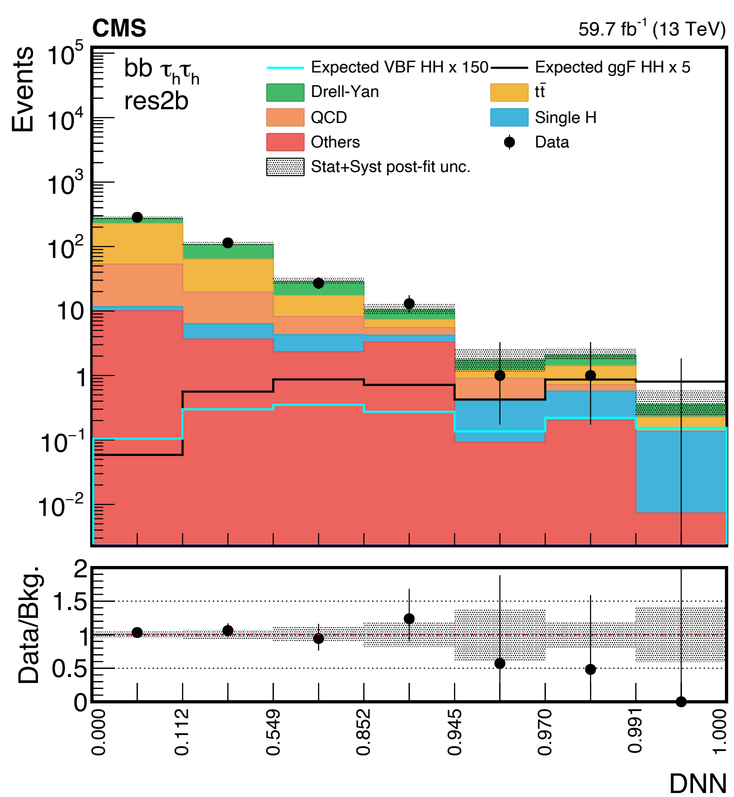
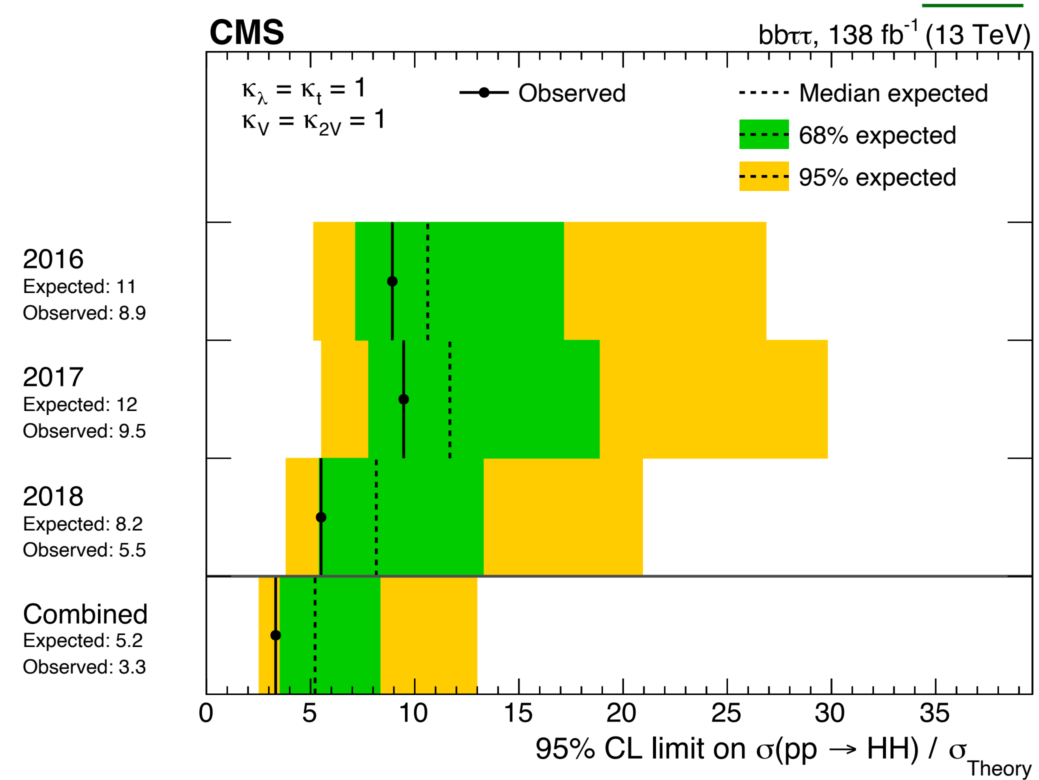




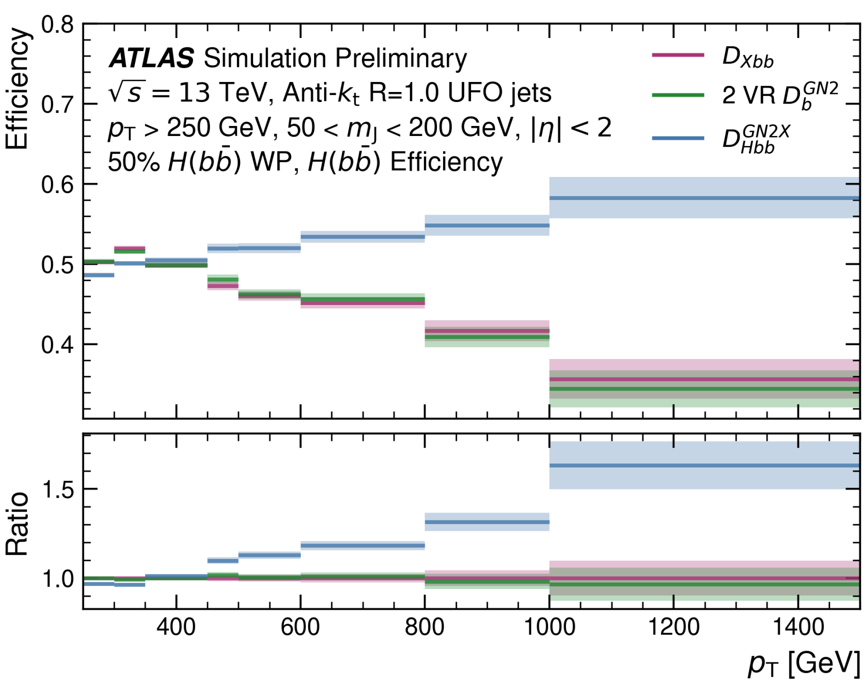
High-p_T Higgs bosons

Important in many specific models (e.g. as decay products of heavy Higgs bosons) and in context of EFT models

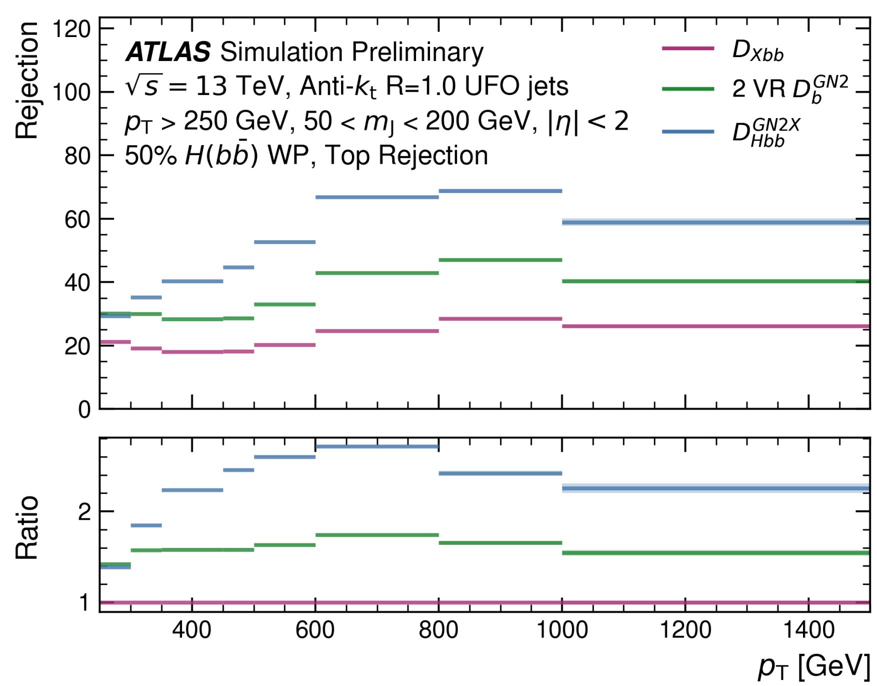
ATLAS (GN2X): identification of $p_T > 250$ GeV $H \to b\bar{b}/c\bar{c}$ using a Transformer based network, based on $R = 1$ jets

- shown: performance for $H \to b\bar{b}$

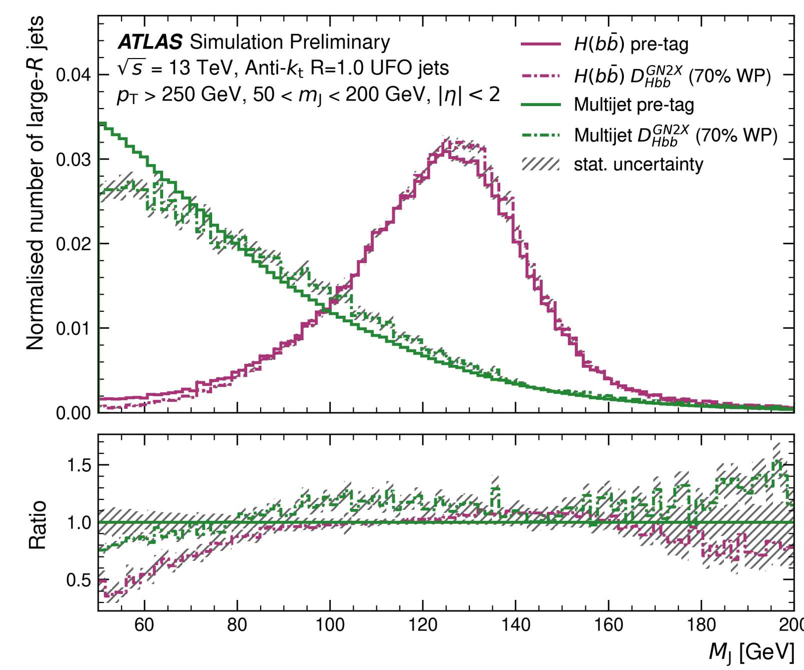
significant efficiency gain



significant rejection gain



residual mass dependence to be addressed by using mass-dependent working point



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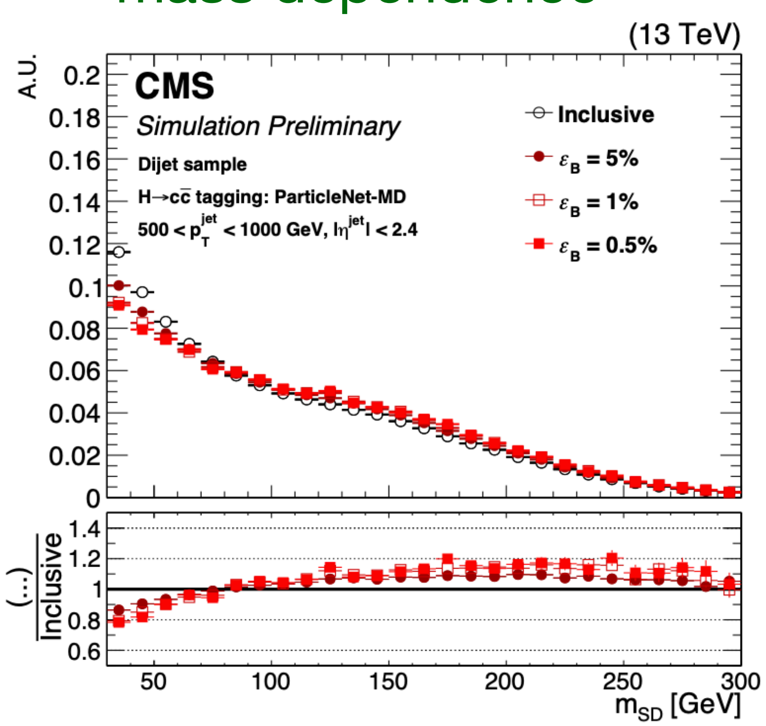
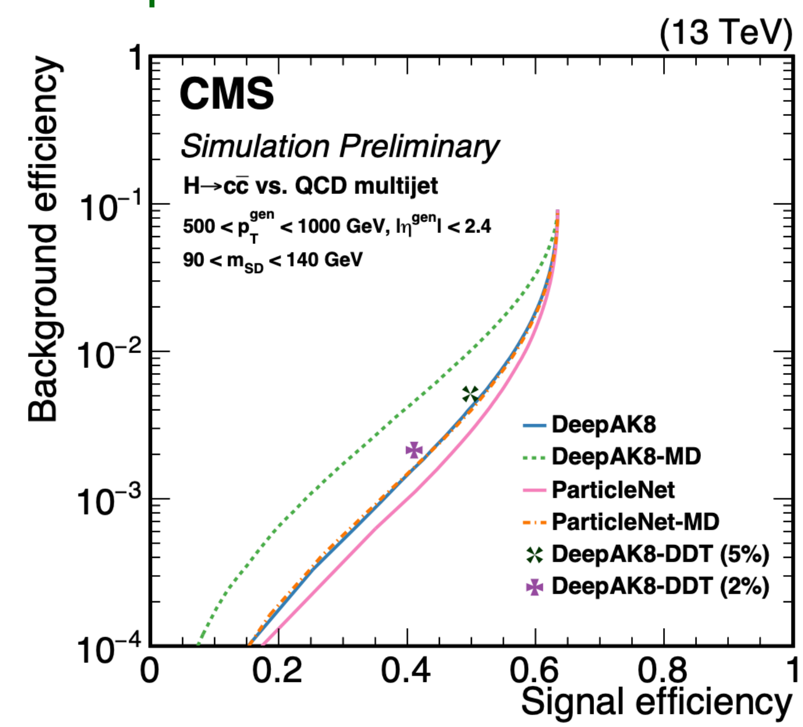
CMS (ParticleNet): graph neural network identifying hadronic decays of W, Z, H, based on $R = 0.8$ jets

• shown: performance for $H \to c\bar{c}$

again, only modest mass dependence

relative mass independence at expense of some performance loss



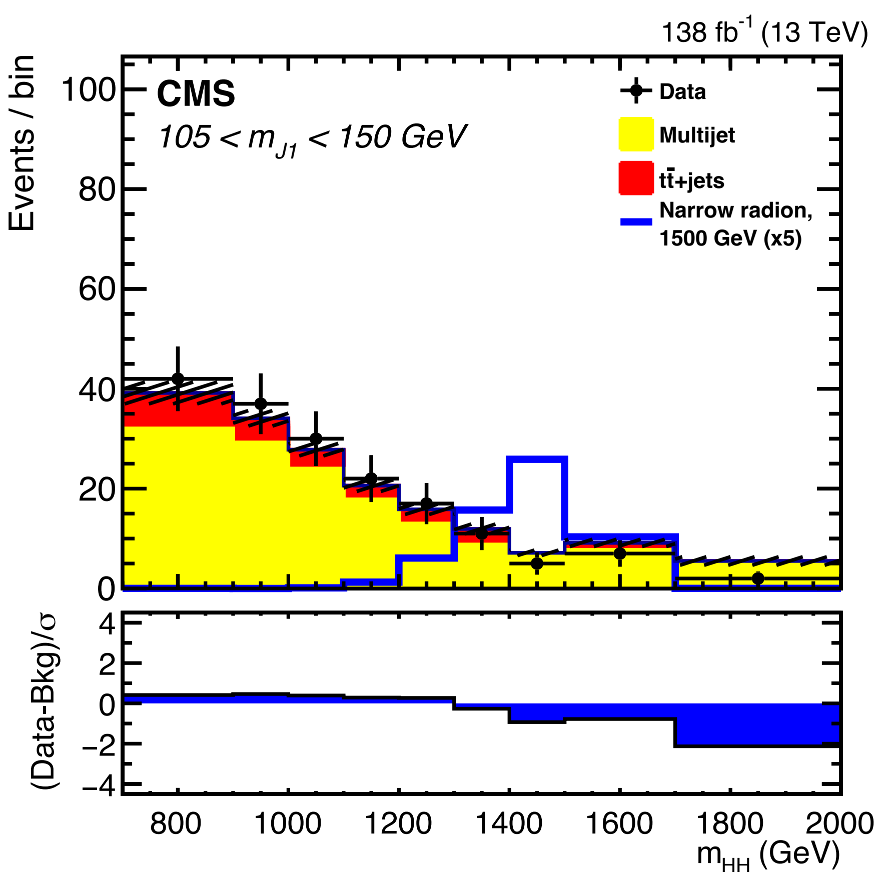


Use in resonant $HH \to b\bar{b}b\bar{b}$

CMS has used DeepAK8 (preceding ParticleNet) to identify high-p_{T} $H \to b\bar{b}$ decays

- background estimation aided by (nearly) m_{J_1} and m_{HH} independent DeepAK8 efficiency for multijet events

m_{HH} in semi-resolved SR



interpretation as narrow Radion exclusion limit

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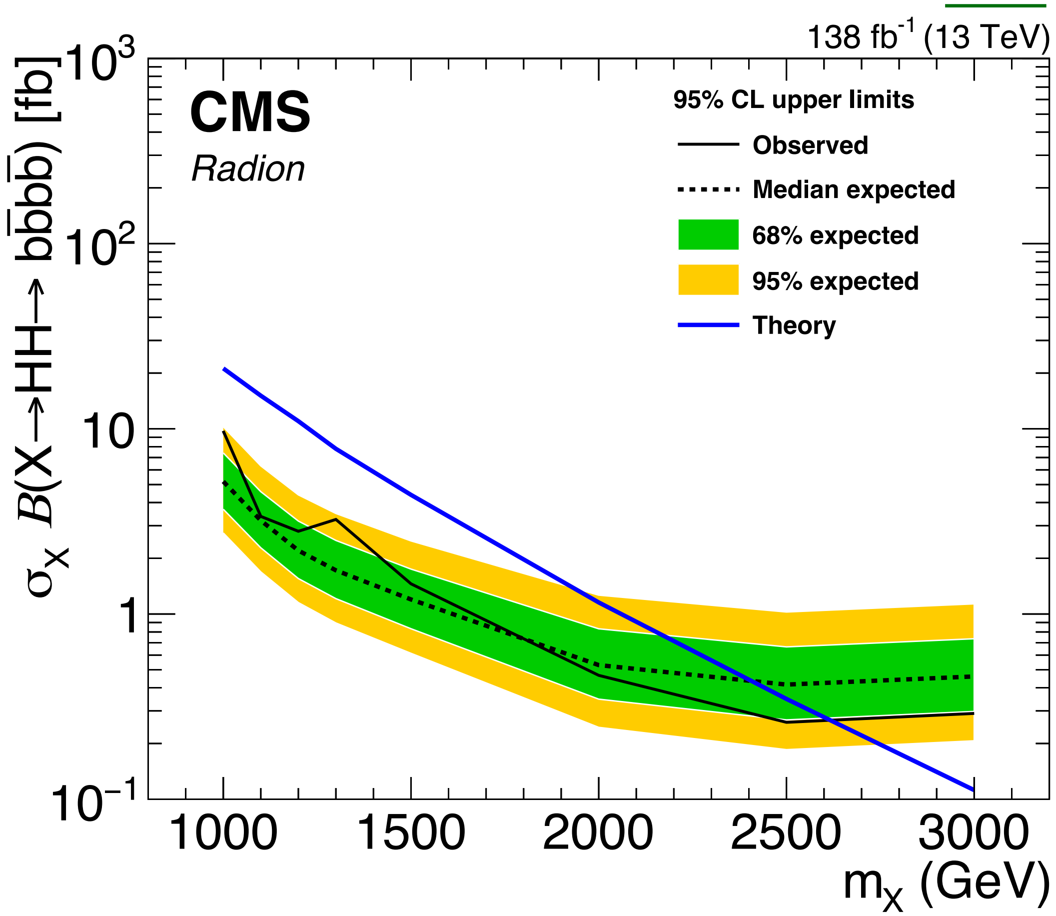
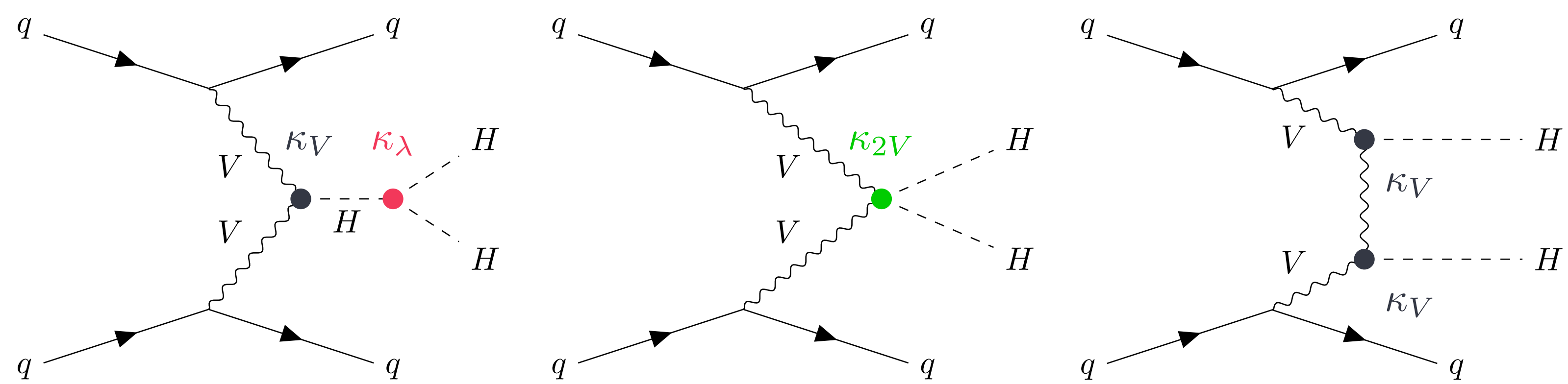


Vector Boson Fusion

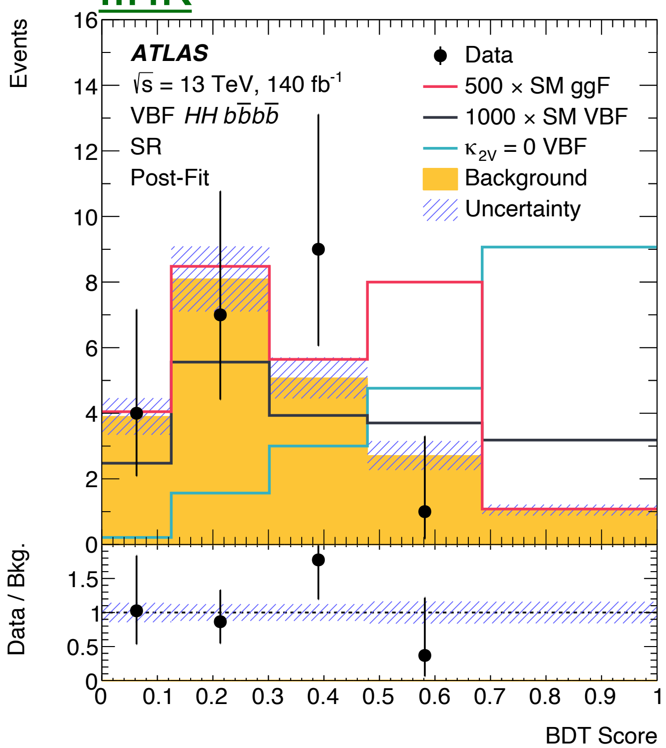
VBF: sensitive to κ_{2V} in addition to κ_λ (and κ_V)

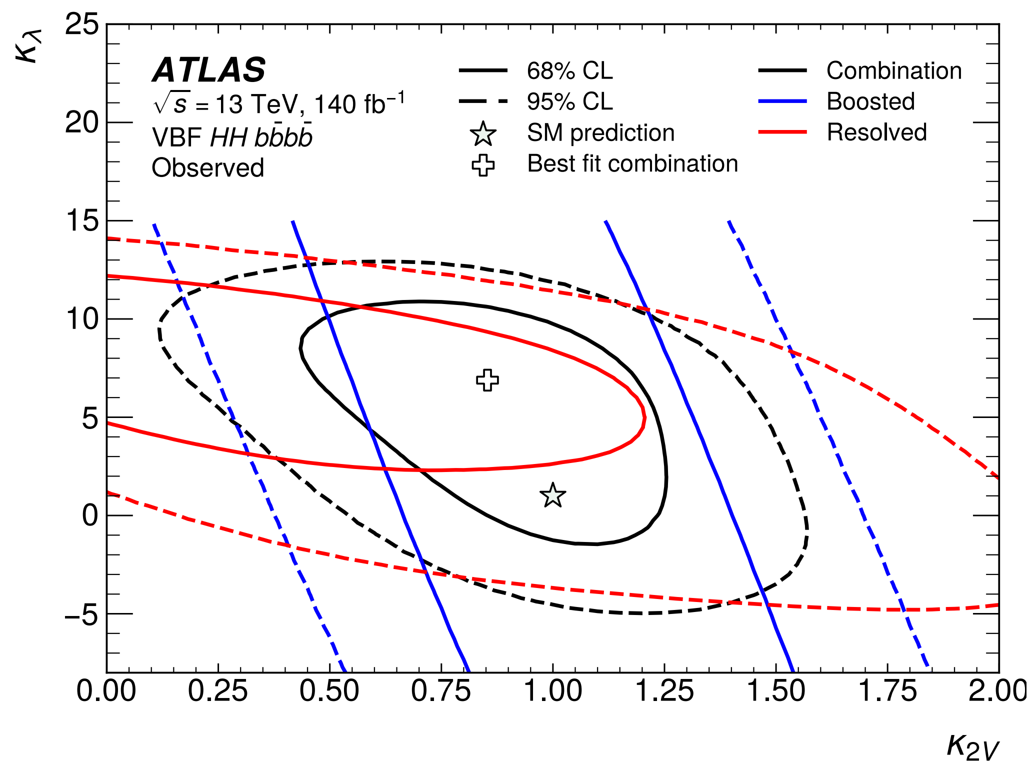


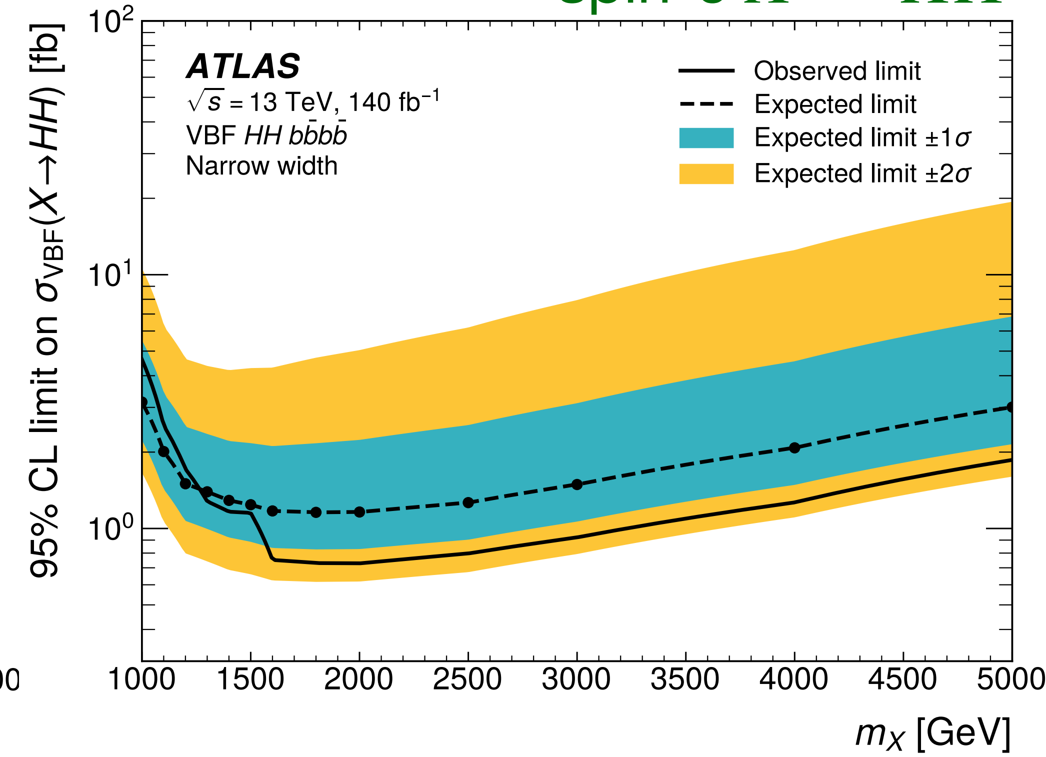
Exploited in ATLAS search for $HH \to b\bar{b}b\bar{b}$ with $R = 1$, $p_{\mathrm{T}} > 250$ GeV Higgs candidates to enhance sensitivity to κ_{2V}

- Higgs candidates tagged with algorithm pre-dating GN2X
  - combined with "resolved" search (lower $p_{\mathrm{T}}(H)$) for optimal sensitivity
- also CMS have analysed this final state, excluding $\kappa_{2V} = 0$ at 6.3 σ link

Limits on heavy spin-0 $X \to HH$







Searches for other Higgs bosons

It is a small step to widen the search from resonant HH to $X \to YH$, with both X, Y new Higgs bosons

- e.g. NMSSM with suppressed couplings to fermions

ParticleNet used by CMS to search for X with 900 GeV < m_X < 4 TeV, with $Y \to b\bar{b}$, $H \to b\bar{b}$

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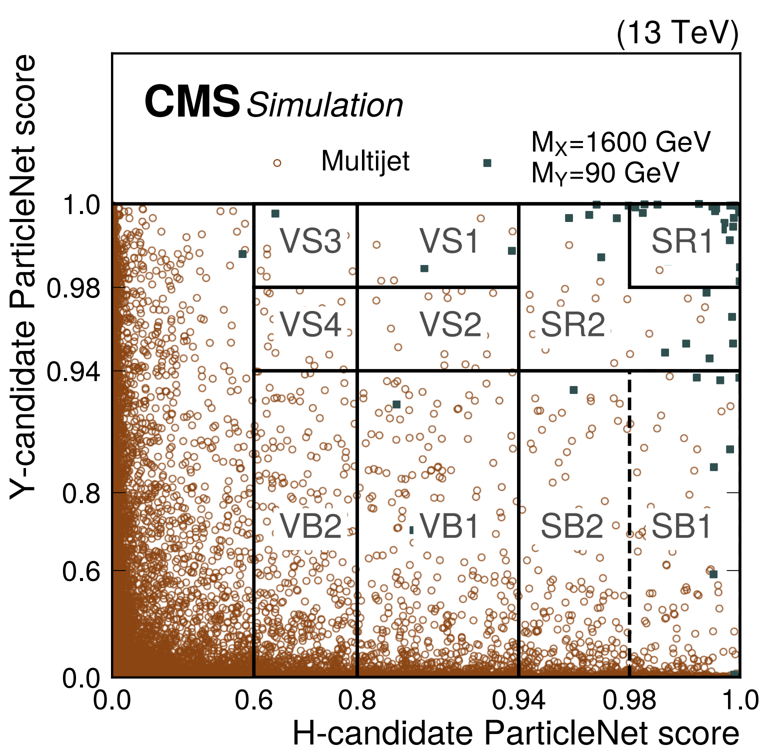

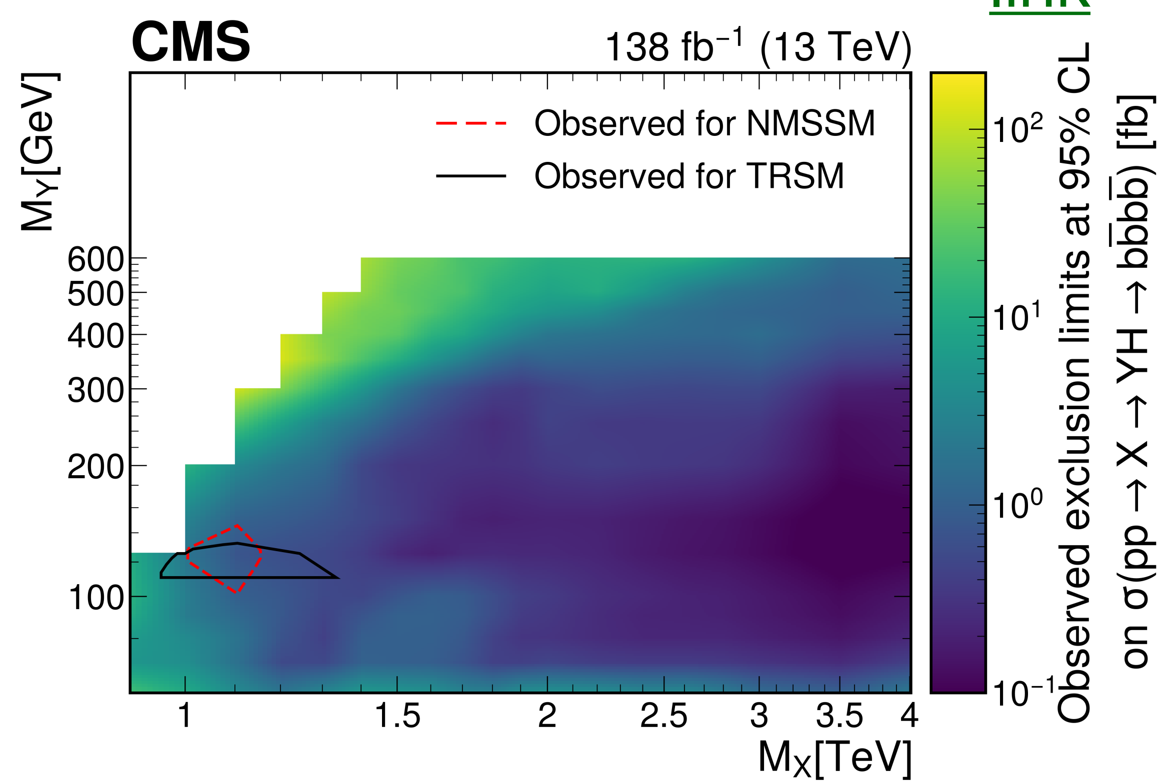

- lower m_X probed by "resolved" final states, e.g. ATLAS $Y(b\bar{b})H(\gamma\gamma)$ [link]
- room for probing other Y decay modes $(WW, ZZ, t\bar{t})$ for higher m_Y

Improved triggers

Back to non-resonant $HH \to b\bar{b}b\bar{b}$: most ubiquitous HH decay mode, but with important trigger limitations

- bandwidth (data rate to “tape”): 1.7 kHz × ~ 2 MB/event (ATLAS)
- computing resources: ~ 60k CPU cores for High-Level Trigger (ATLAS)

Aided by refactoring of HLT tracking & b-tagging: rate reduction for HLT requiring 4 PFlow jets with $p_T > \{88,55,28,20\}$ GeV by a factor 5-10, with efficiency ≥ 96%

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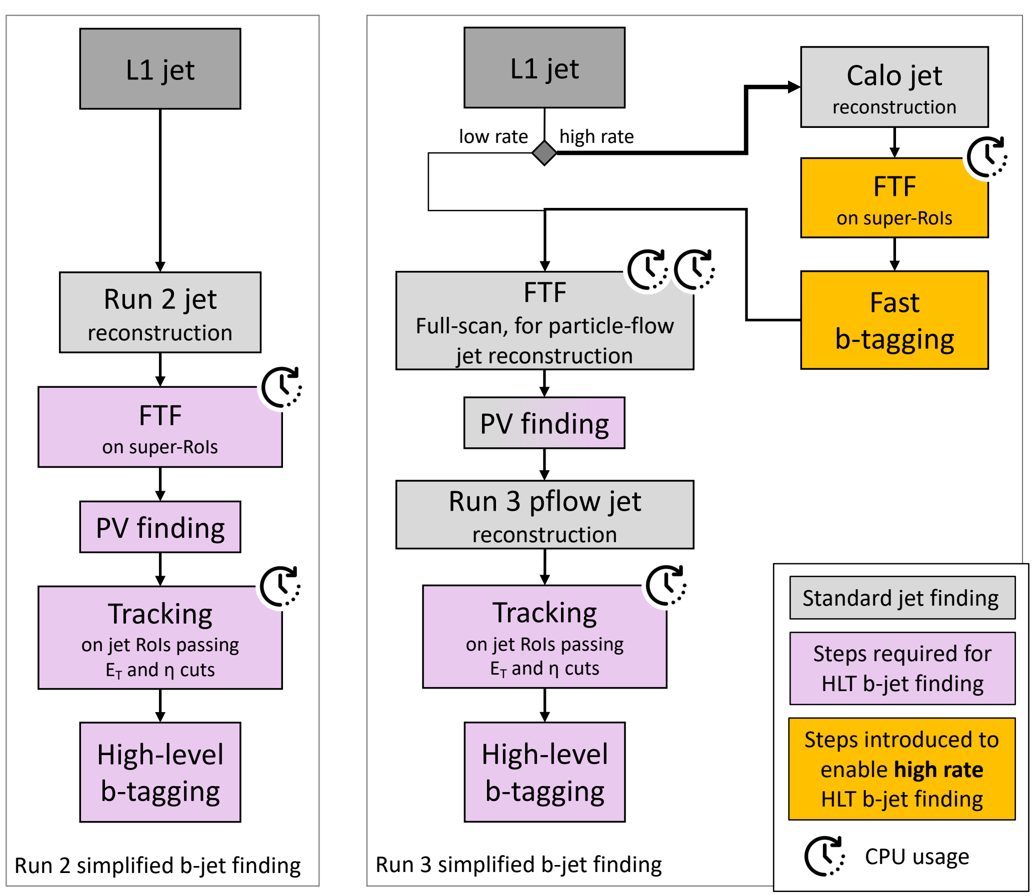
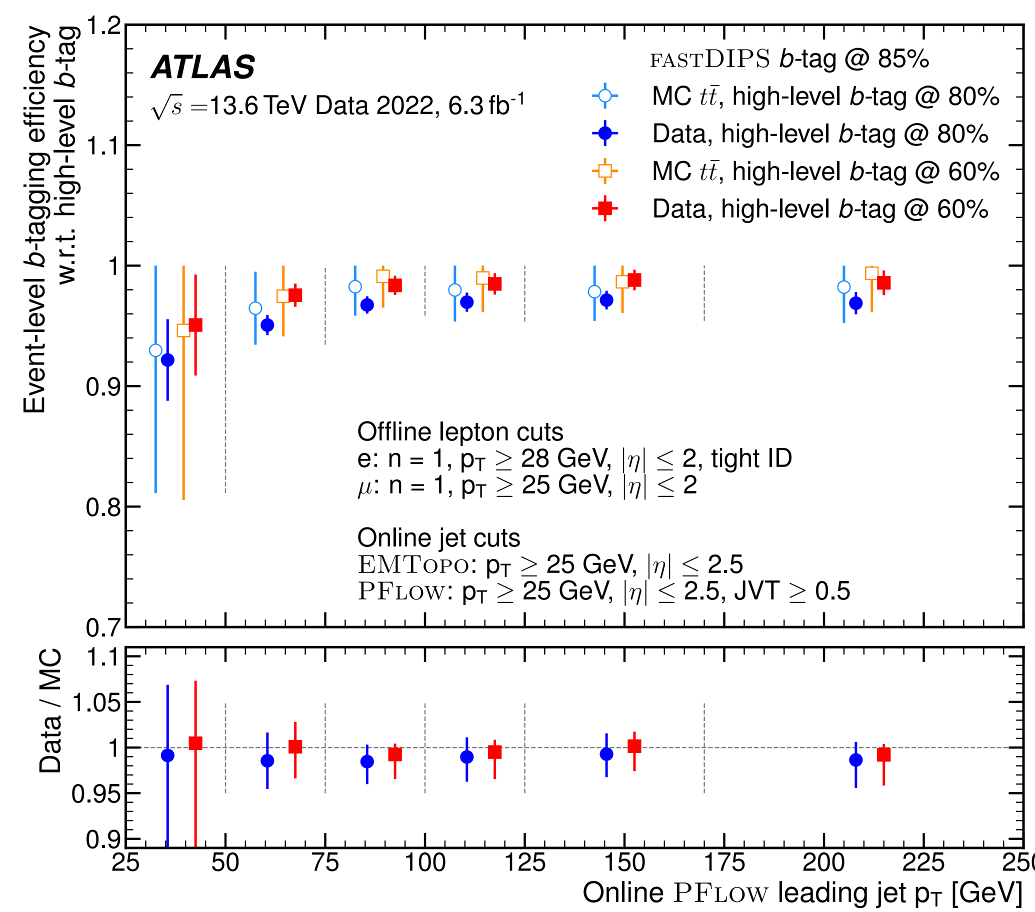


Validation with $t\bar{t}$ candidates in data



Improved triggers

Also CMS trigger strategy for $HH \to b\bar{b}b\bar{b}$ selection has been revisited

- HLT: $H_T > 280$ GeV, 4 jets with $p_T > 30$ GeV and 2 jets b-tagged using online ParticleNet tagger

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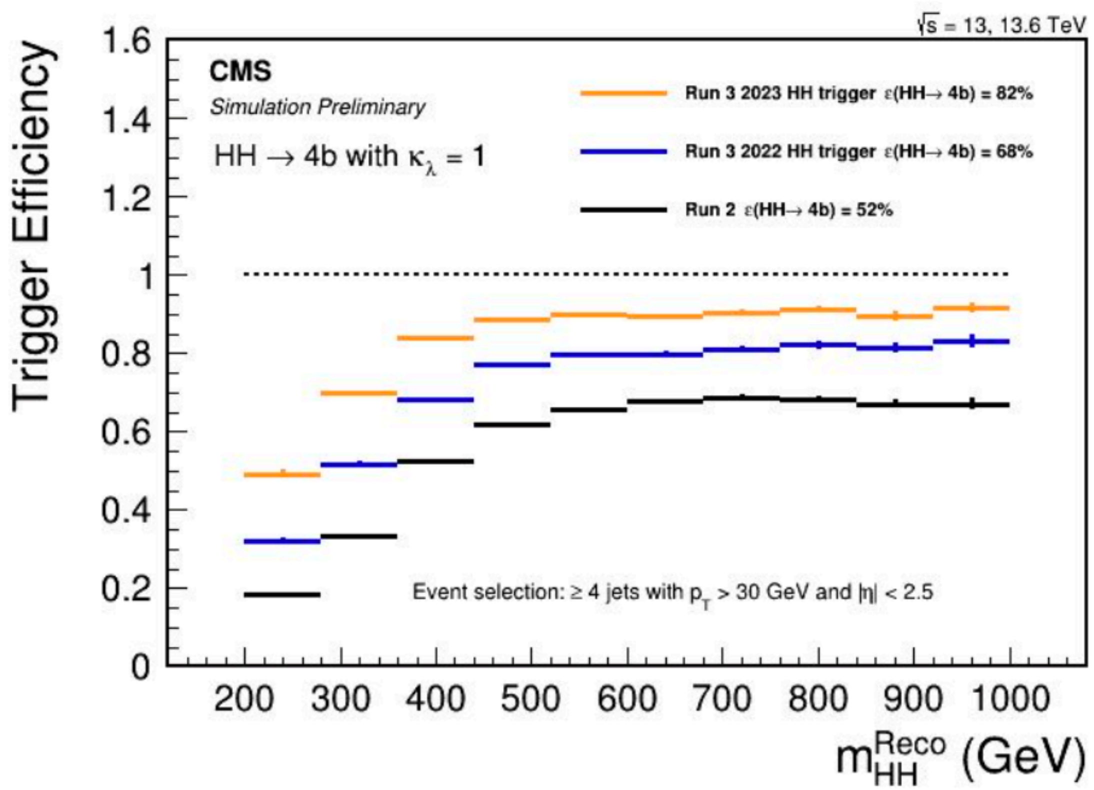
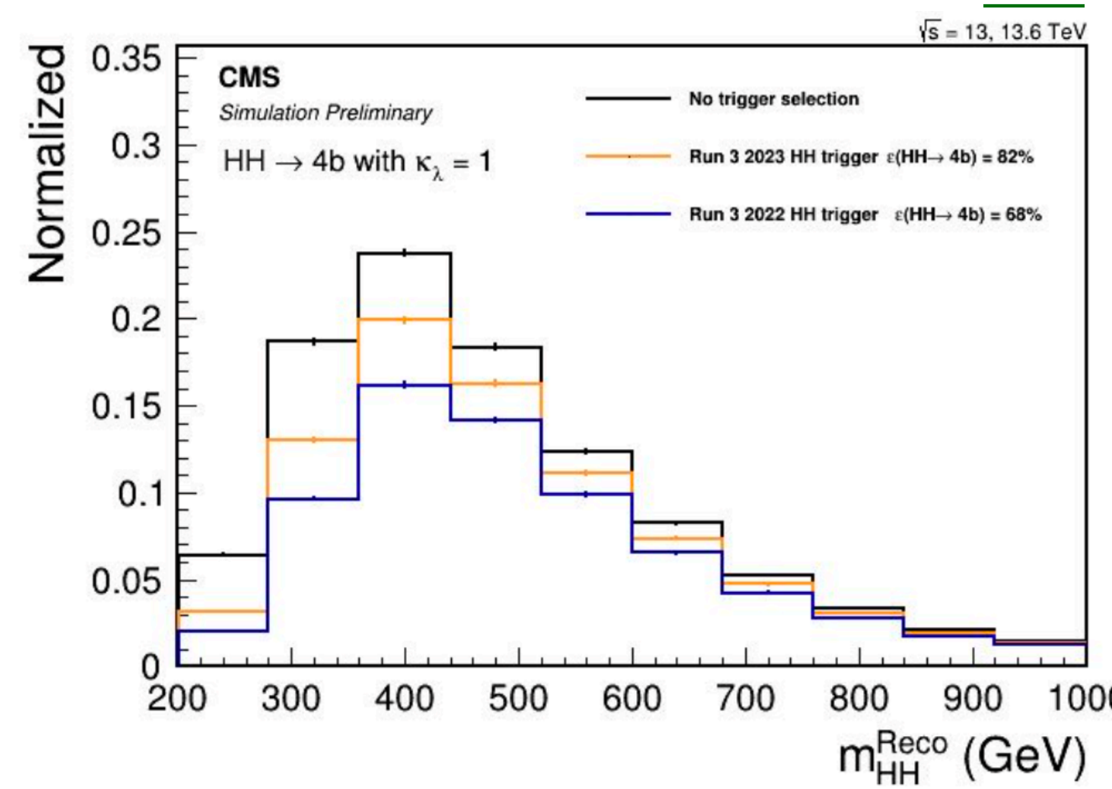
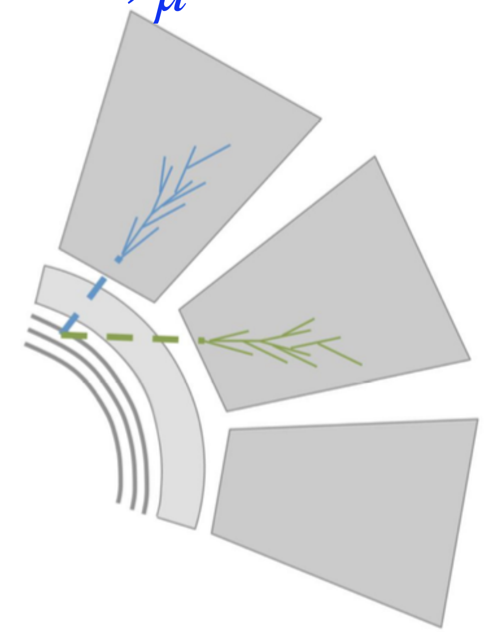




- resulting HLT rate of 180 Hz too large to be processed immediately ➠ "parking" (delayed offline reconstruction)
- similar strategy for $HH \to b\bar{b}\tau^+\tau^-, HHH \to 6b, HHH \to 4b\tau^+\tau^-$
- note: ATLAS uses parking ("delayed stream") too

Long-lived particles

ATLAS search for ALPs in $H \rightarrow a(\gamma\gamma)a(\gamma\gamma)$: inspired by $(g-2)_\mu$ anomaly



- exploiting fine segmentation of electromagnetic calorimeter to detect decays of long-lived a for small $a\gamma\gamma$ couplings (in addition to studying collimated $\gamma\gamma$)
- results (exclusion limits) as function of m_a, coupling $C_{a\gamma\gamma}$
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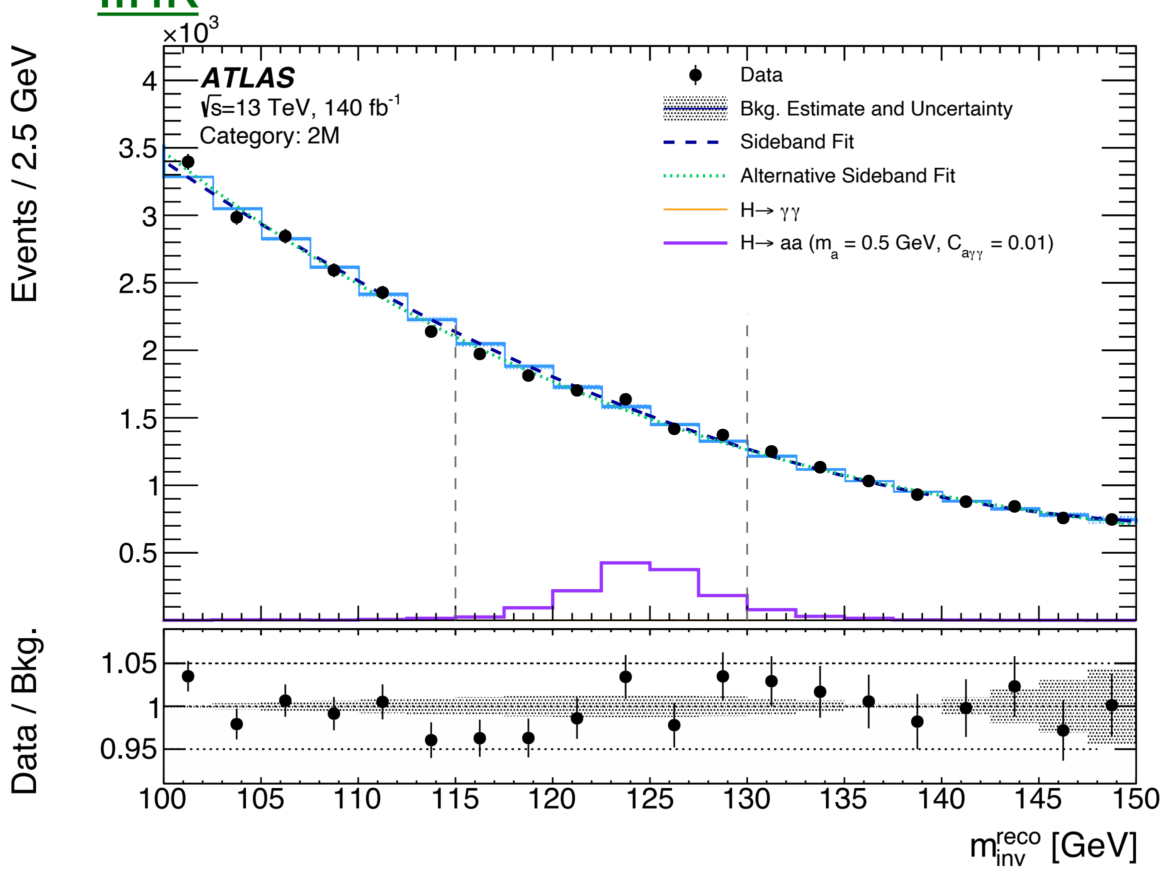

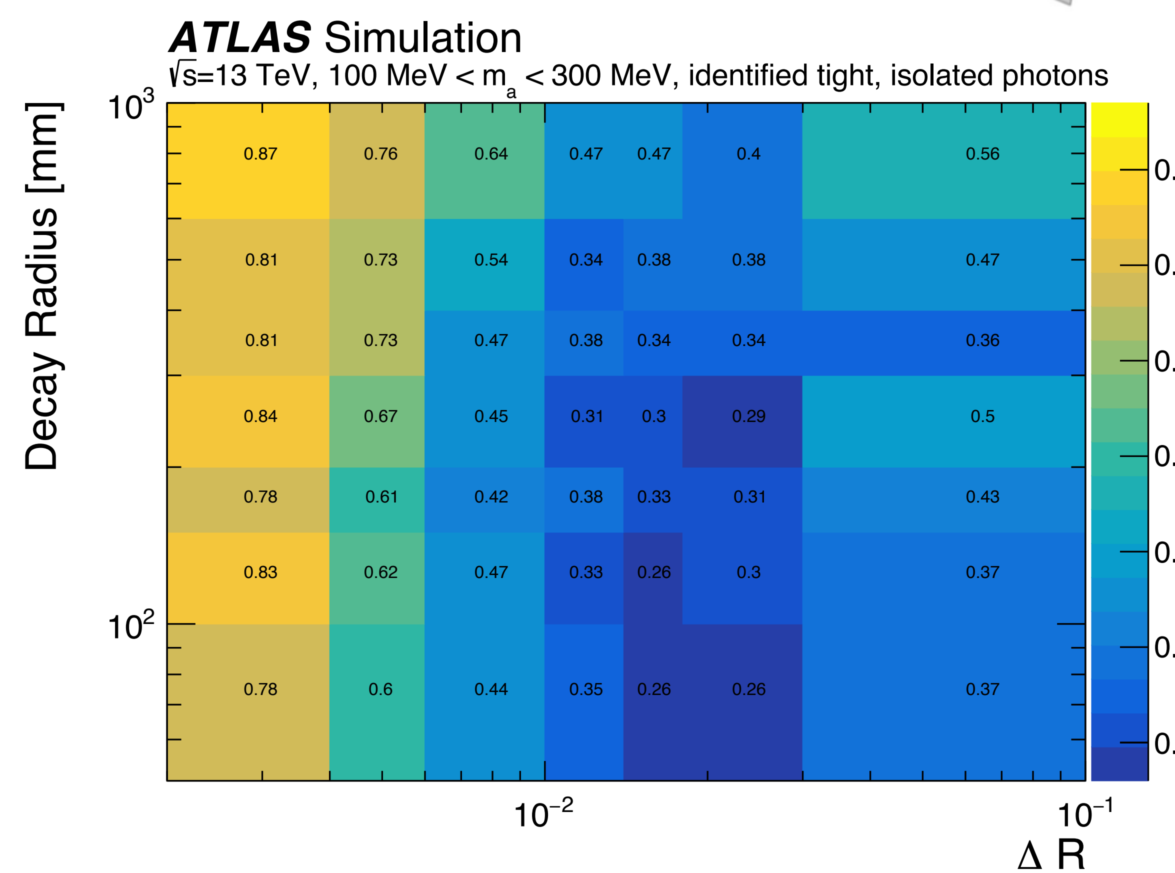

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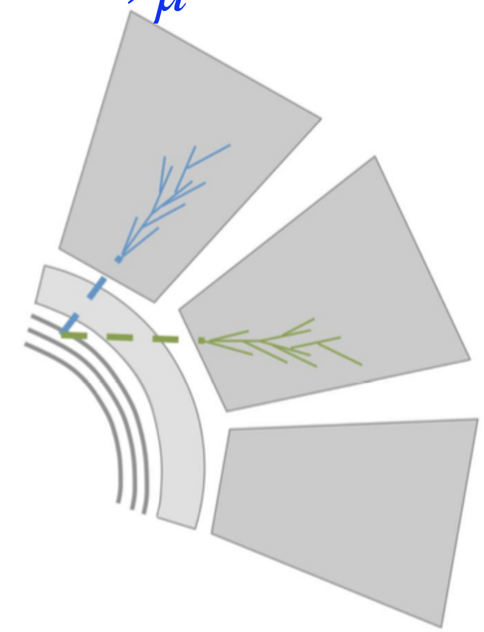

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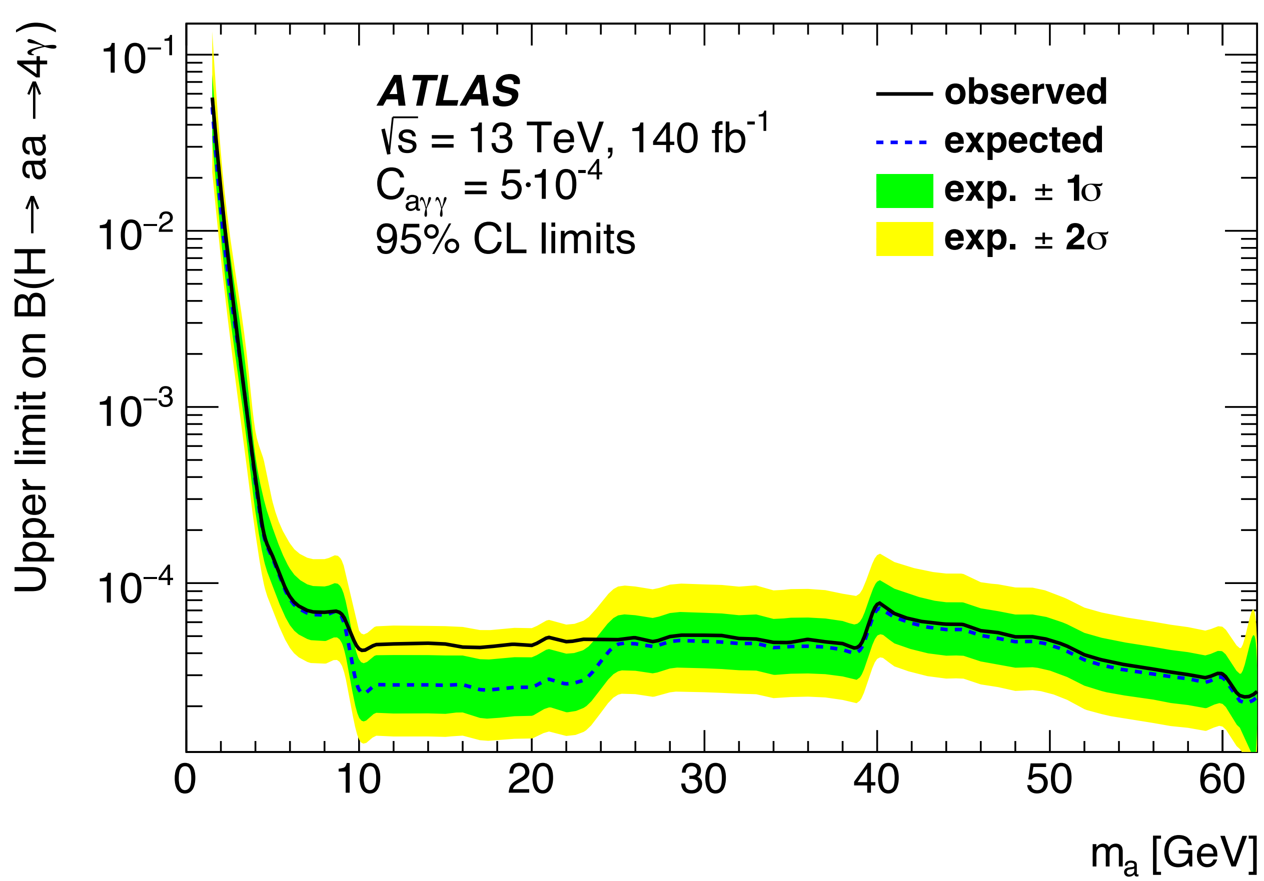
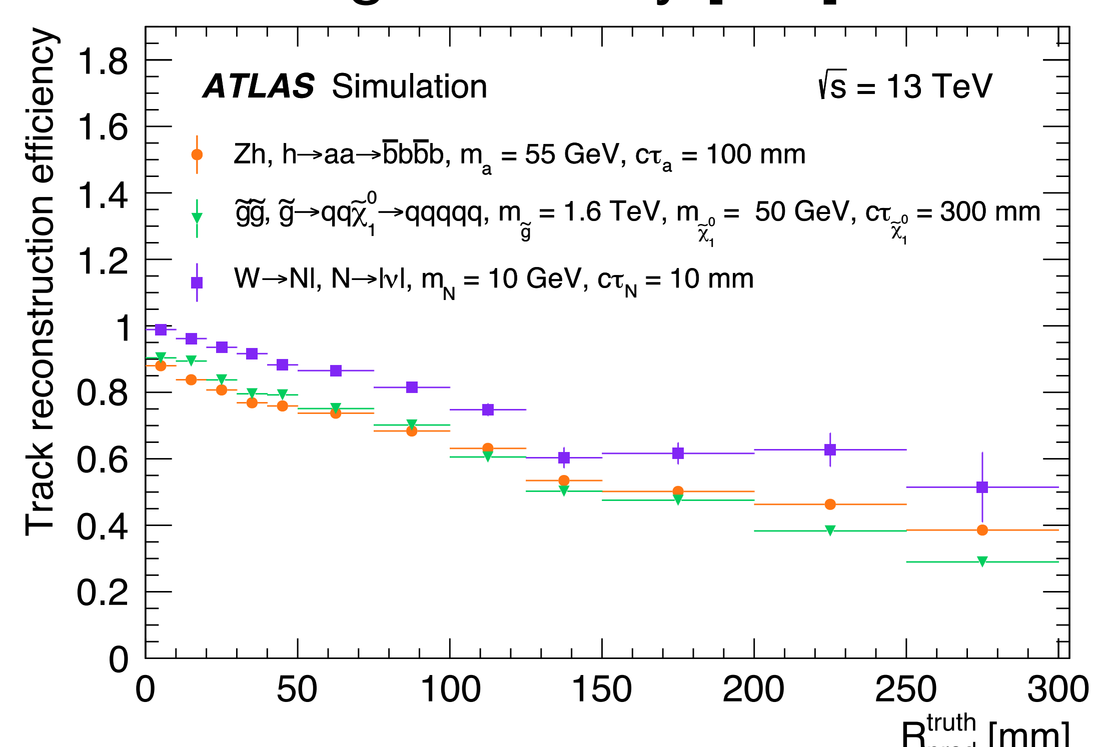
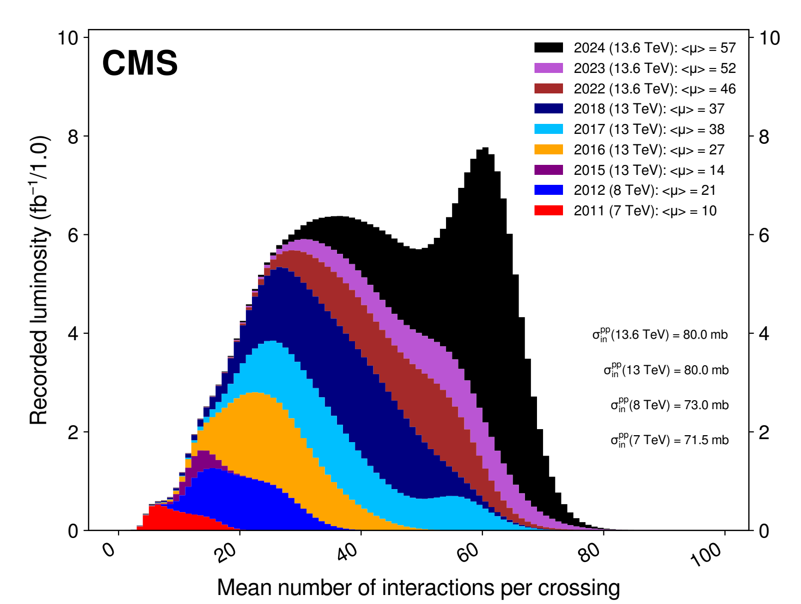
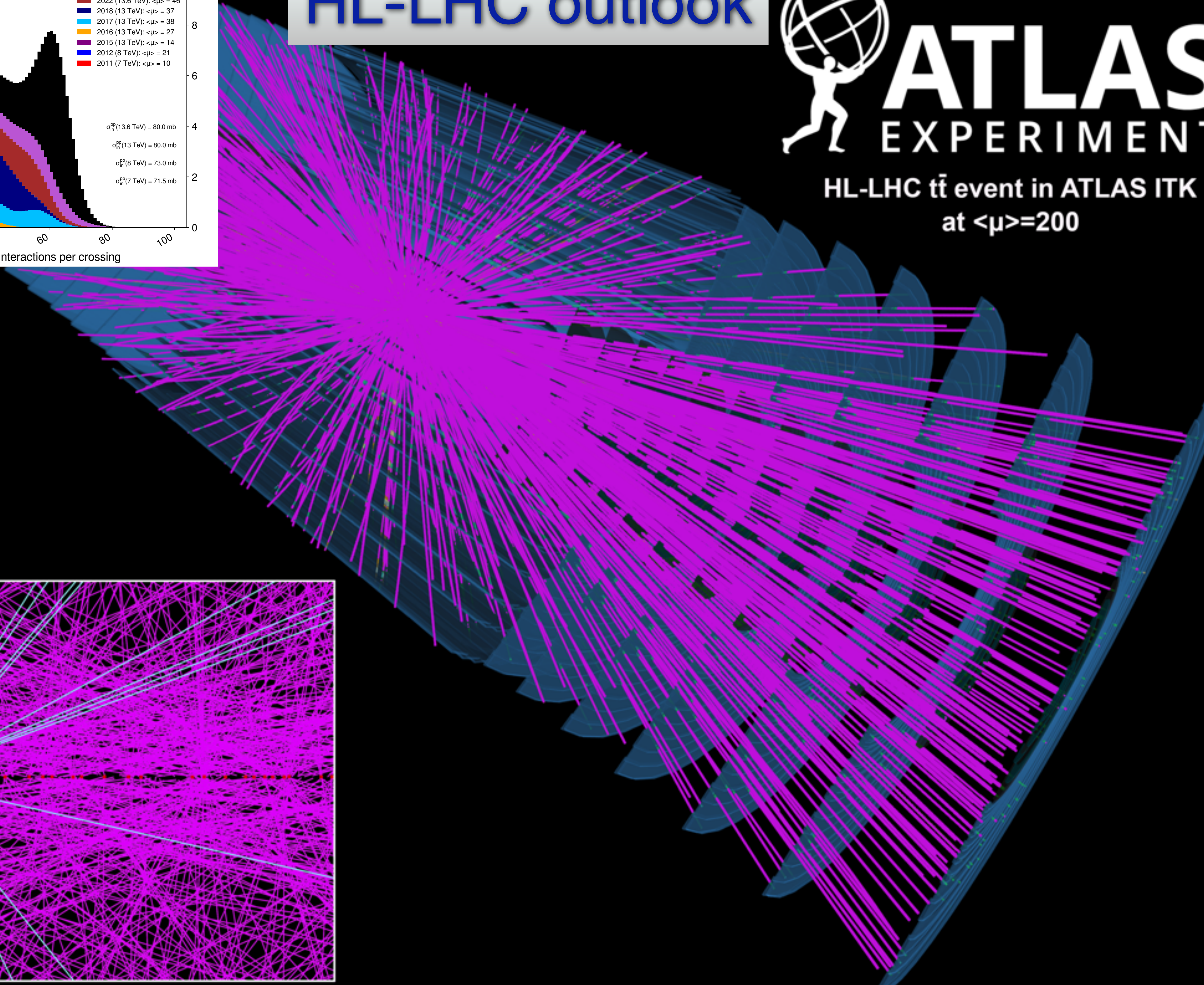


More to come: improved tracking efficiency [link]



HL-LHC outlook

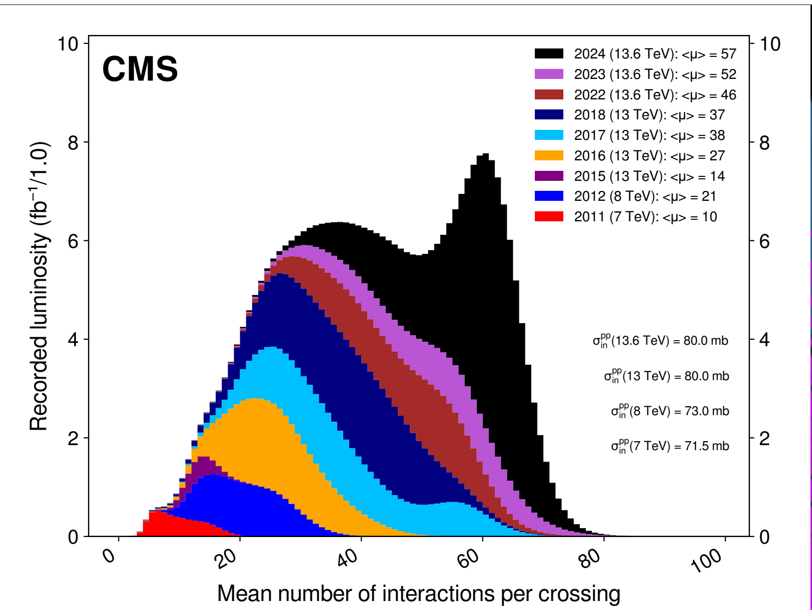


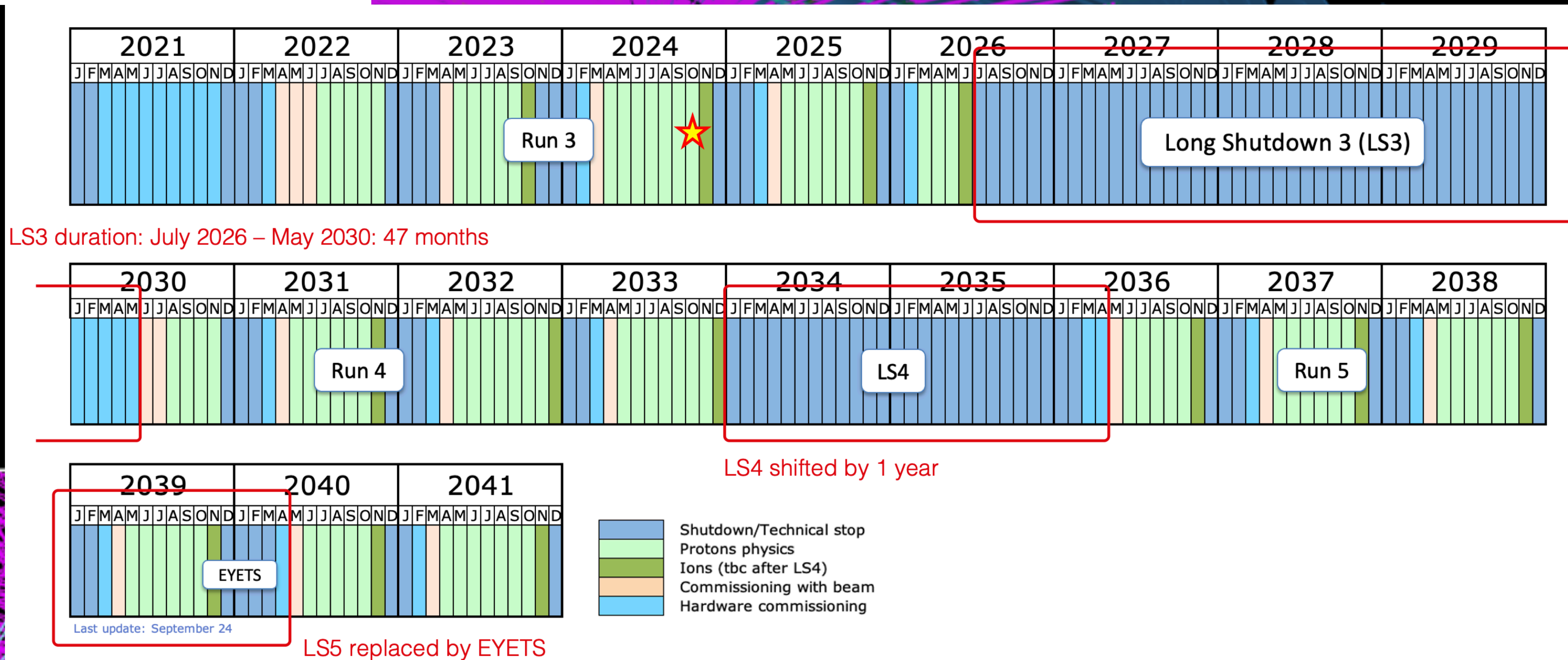


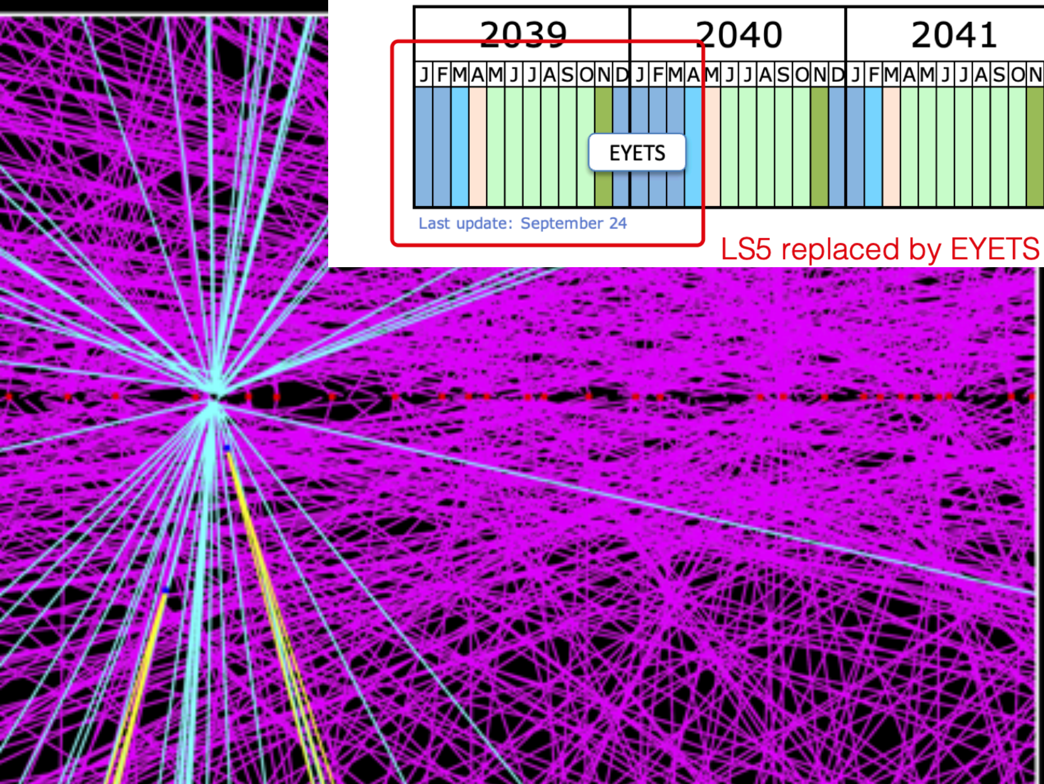
ATLAS EXPERIMENT

HL-LHC $t\bar{t}$ event in ATLAS ITK at <μ>=200

HL-LHC outlook







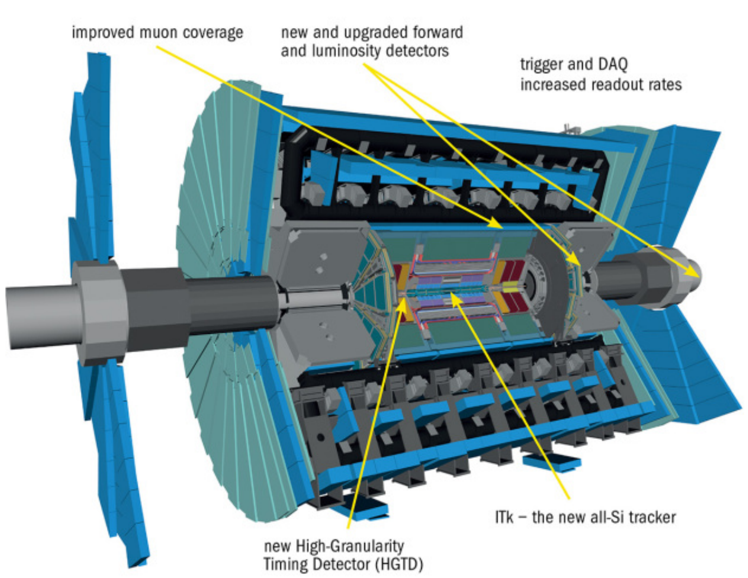
HL-LHC environment

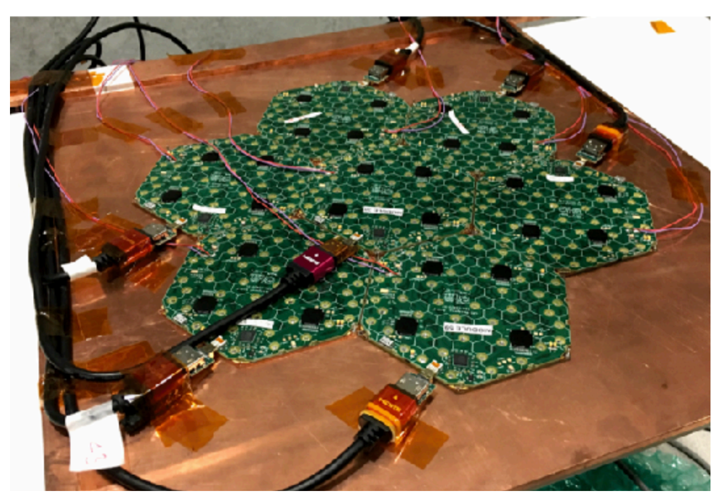
Further increased instantaneous luminosity in HL-LHC phase ($\gtrsim$ 2030):

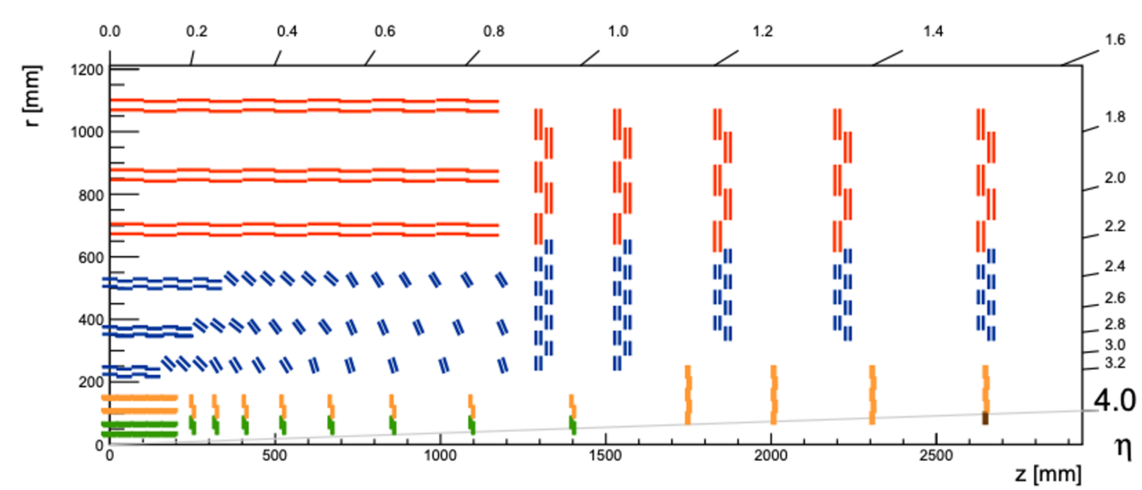
$2 \rightarrow \lesssim 7.5 \times 10^{34}$ cm^{-2} s^{-1}: ~ 60 → ~ 200 p-p interactions / bunch crossing

Notable planned upgrades:

- all-Si inner tracking detectors with extended coverage: $|\eta| < 4$
  - complemented by addition of detectors providing precise timing information
- increase of L1 trigger rate from ~ 100 kHz to ~ 1 MHz
  - increase of rate to tape to multiple kHz (but confounded by parking & events with no or only partial offline reconstruction)
- extended muon system acceptance ($|\eta| < 2.8$), better momentum resolution
- their detailed effects are only partially represented in the following studies





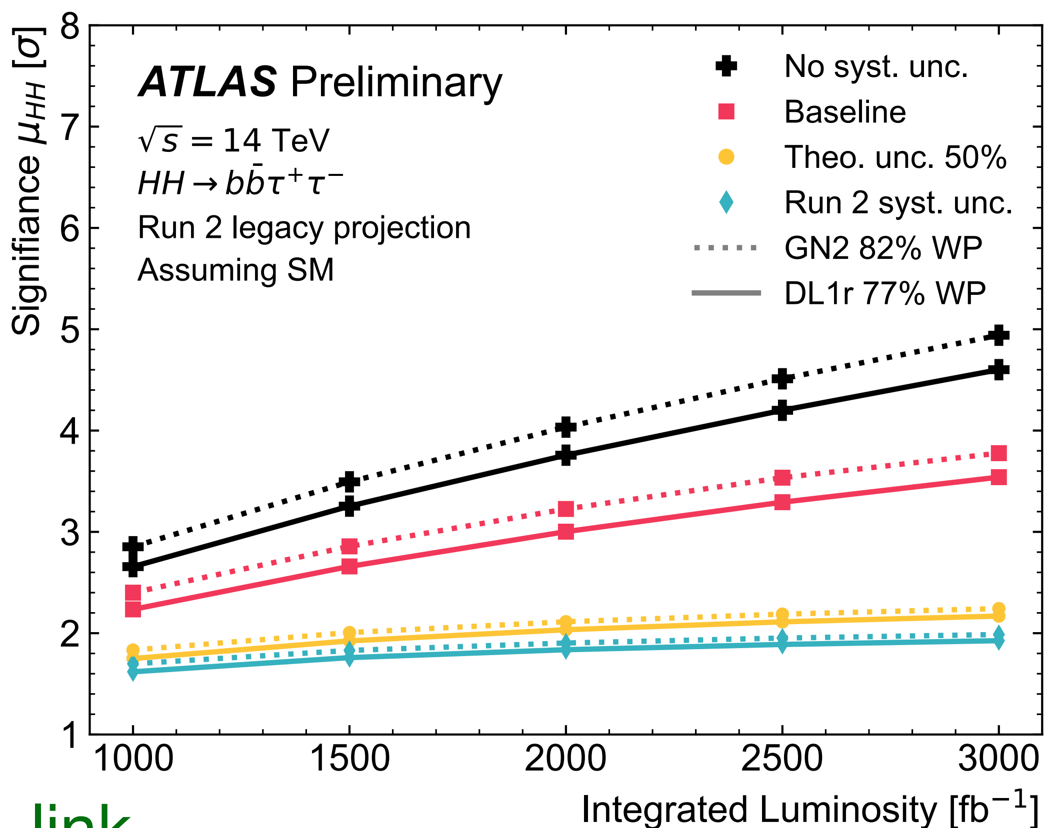


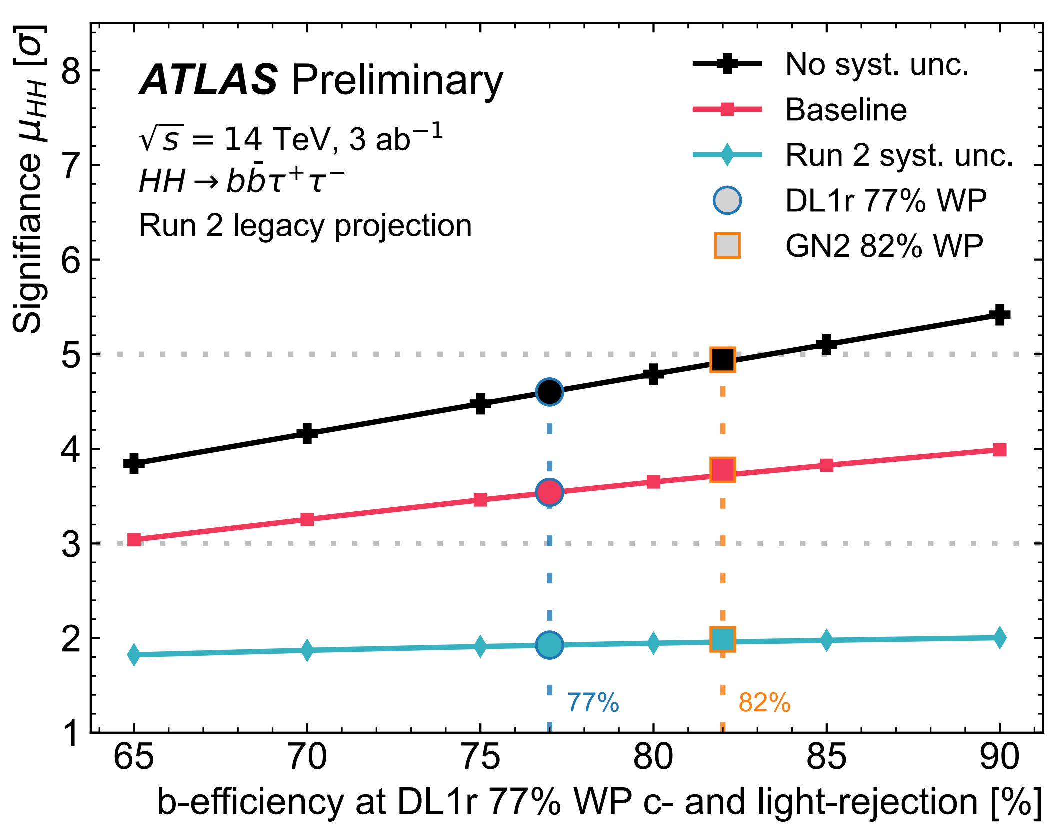
Prospects for Higgs pair production studies

This remains one of the most prominent objectives of the HL-LHC

Example: ATLAS $HH \to b\bar{b}\tau^+\tau^-$ analysis

- extrapolating from published Run-2 analysis, but emulating effects of improved b-tagging (GN2) and possibly improved (hadronic) $\tau^\pm$-tagging
- up to 4σ significance possible with this channel alone





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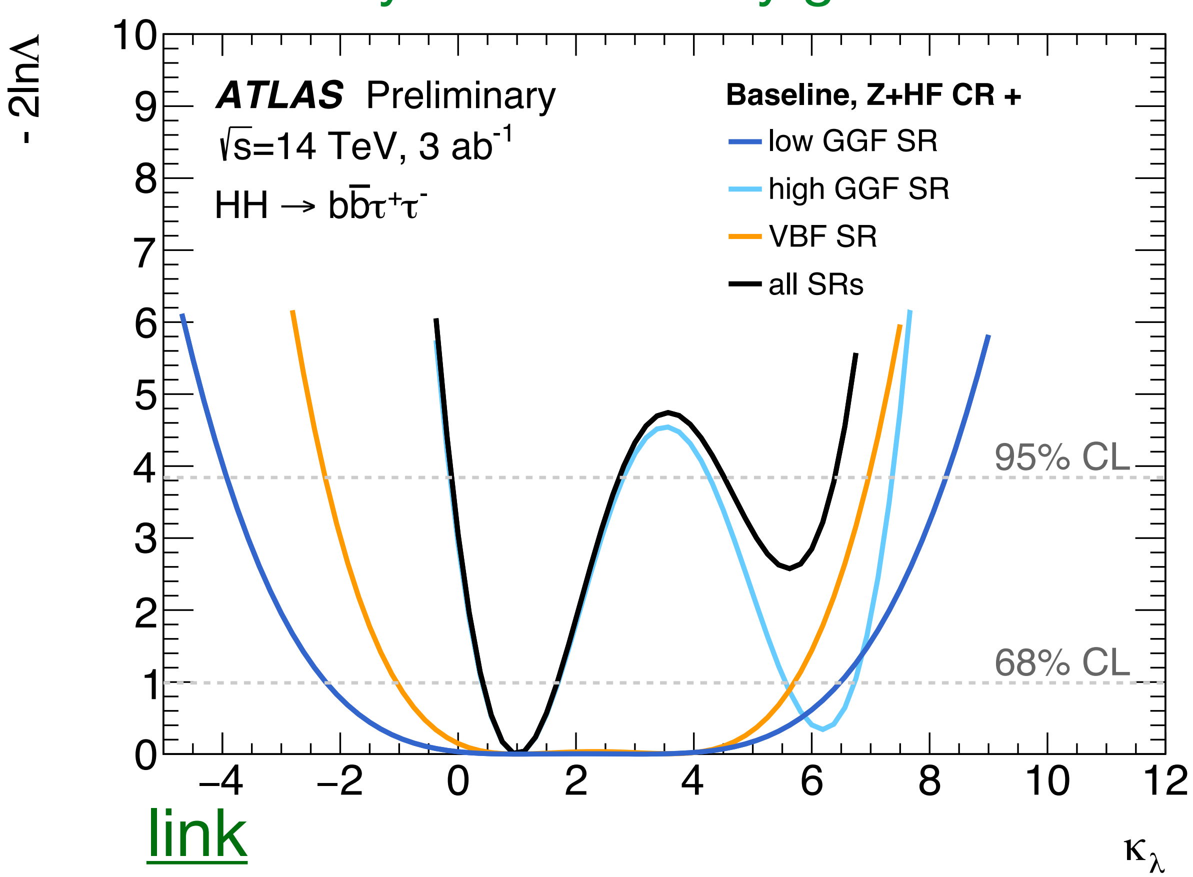
- up to 4σ significance possible with this channel alone
- ~ entirely dominated by gluon fusion



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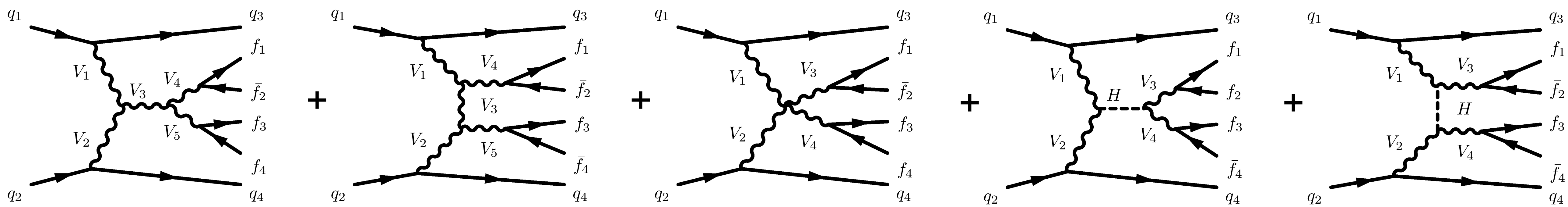
Source of uncertainty	Baseline $\Delta\mu_{HH}$		Run 2 Syst. $\Delta\mu_{HH}$	
Total	+0.35	-0.31	+0.65	-0.51
Statistical	+0.24	-0.23	+0.24	-0.23
↪ Data stat only	+0.24	-0.23	+0.24	-0.23
↪ Floating normalisations	+0.02	-0.02	+0.04	-0.02
Systematic	+0.25	-0.20	+0.61	-0.46
Experimental uncertainties				
Electrons and muons	< 0.01		< 0.01	
τ-leptons	+0.03	-0.03	+0.06	-0.05
Jets	+0.06	-0.06	+0.06	-0.07
b-tagging	+0.02	-0.02	+0.04	-0.03
E_T^{miss}	+0.03	-0.02	+0.04	-0.02
Pile-up	+0.01	-0.01	+0.01	-0.01
Luminosity	+0.02	-0.01	+0.02	-0.01
Theoretical and modelling uncertainties				
Signal	+0.12	-0.05	+0.39	-0.07
Backgrounds	+0.19	-0.17	+0.37	-0.30
↪ Single Higgs boson	+0.17	-0.15	+0.34	-0.27
↪ Z + jets	+0.06	-0.05	+0.10	-0.09
↪ W + jets	< 0.01		< 0.01	
↪ $t\bar{t}$	+0.02	-0.02	+0.03	-0.02
↪ Single top quark	+0.01	-0.01	+0.03	-0.04
↪ Diboson	< 0.01		< 0.01	
↪ Jet → τ_{had} fakes	+0.05	-0.05	+0.09	-0.08
MC statistical	< 0.01		+0.38	-0.36

Vector Boson Scattering

Unitaritisation — bottom-up raison d'être for the Higgs boson!



Older study of (cleanest) same-sign EW WW production

- but a small signal on top of irreducible background
- significance will depend sensitively on both experimental & theoretical uncertainties

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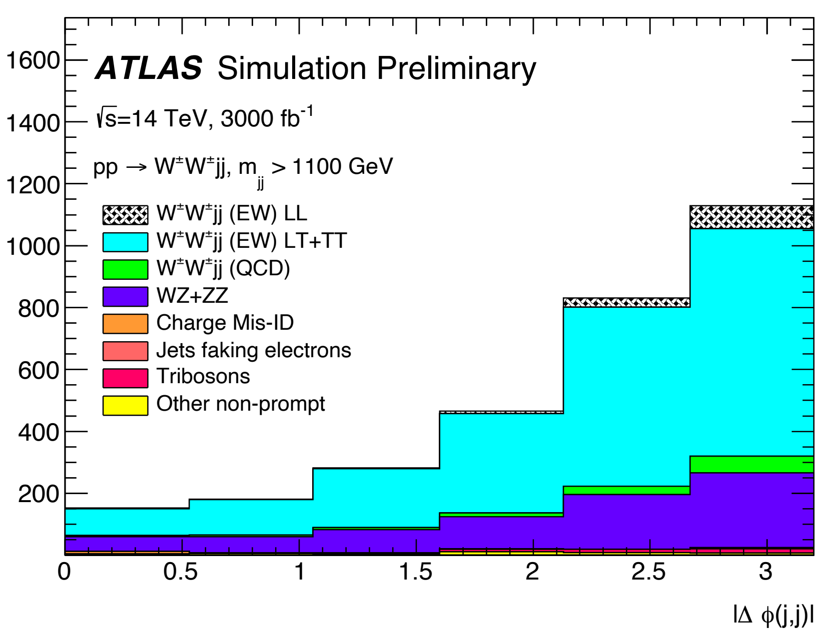
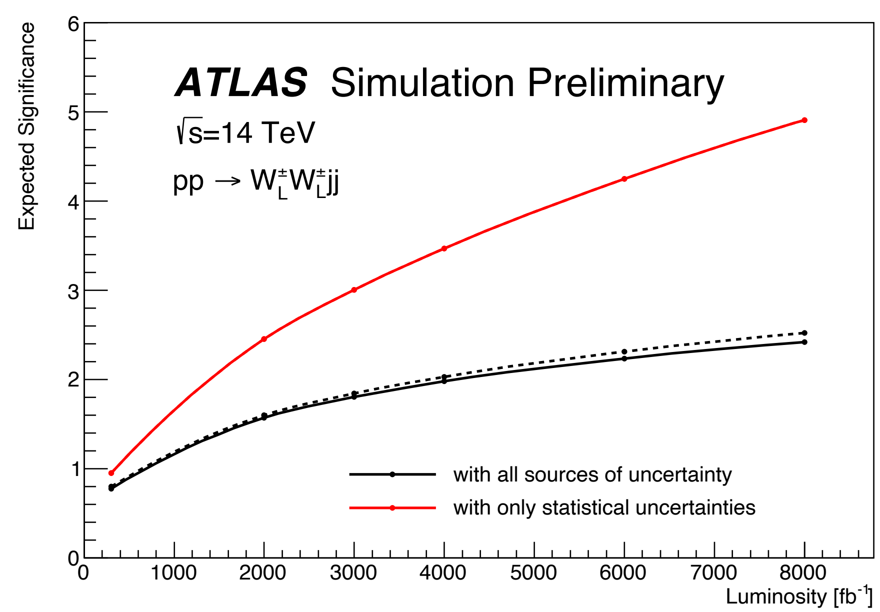
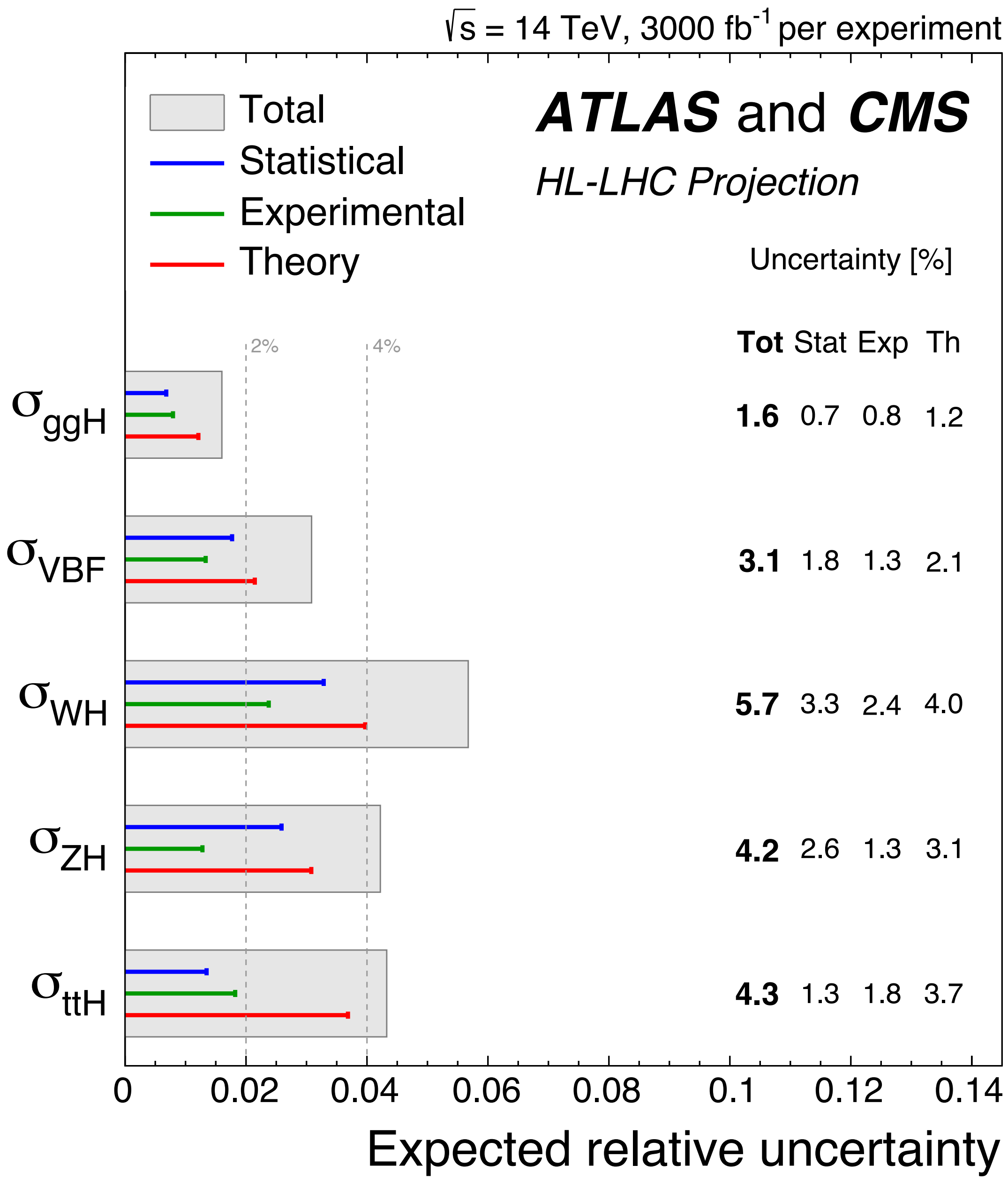


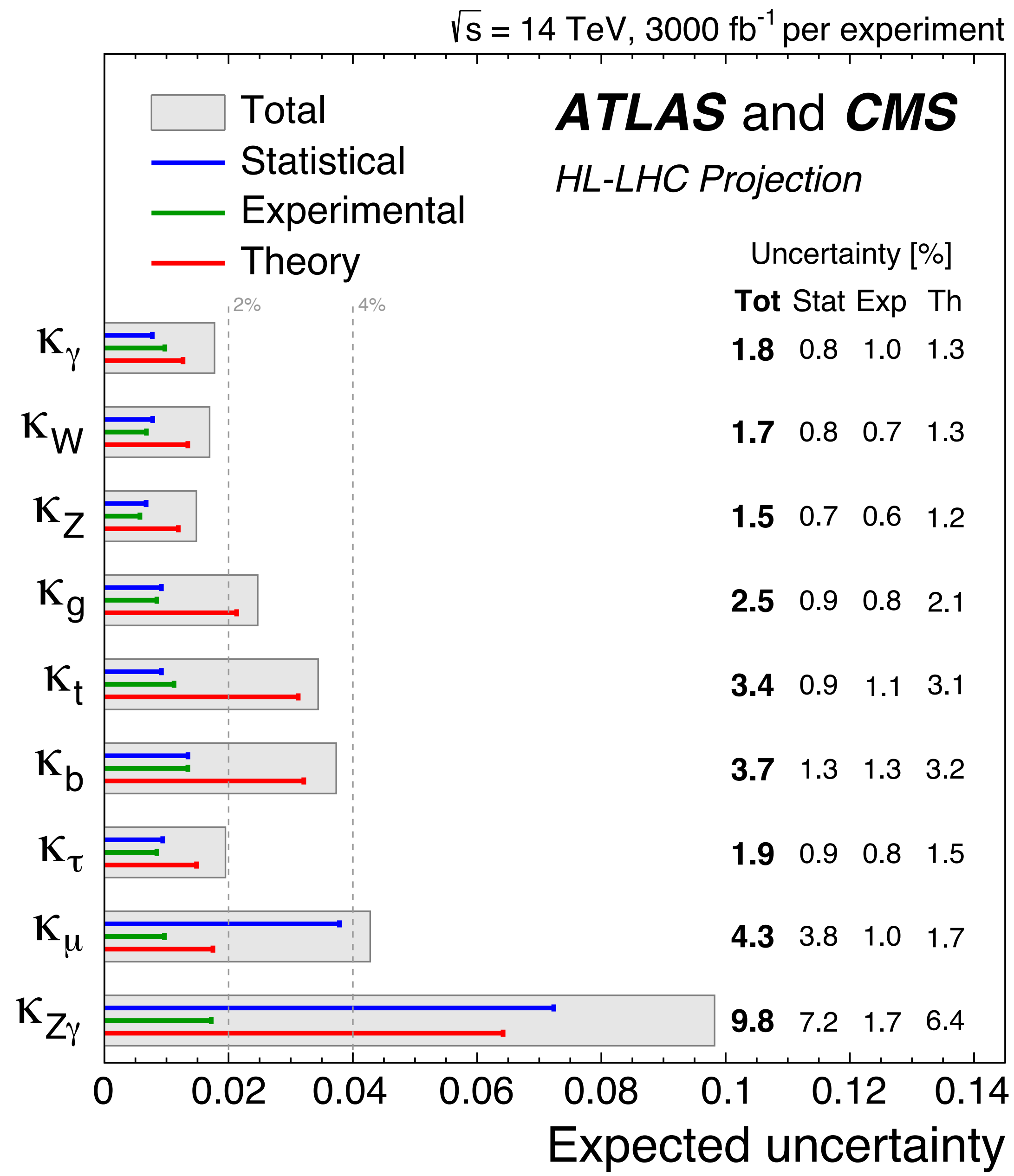


Source	Uncertainty (%) Baseline	Optimistic
$W^{\pm}W^{\pm}jj$ (EW)	3	
Luminosity	1	
Trigger efficiency	0.5	
Lepton reconstruction and identification	1.8	
Jets	2.3	
Flavour tagging	1.8	
Jets faking electrons	20	
Charge mis-ID	25	
$W^{\pm}W^{\pm}jj$ (QCD)	20	5
Top	15	10
Diboson	10	5
Triboson	15	10

Single-Higgs studies

link





Precision on many coupling constants will become exciting!

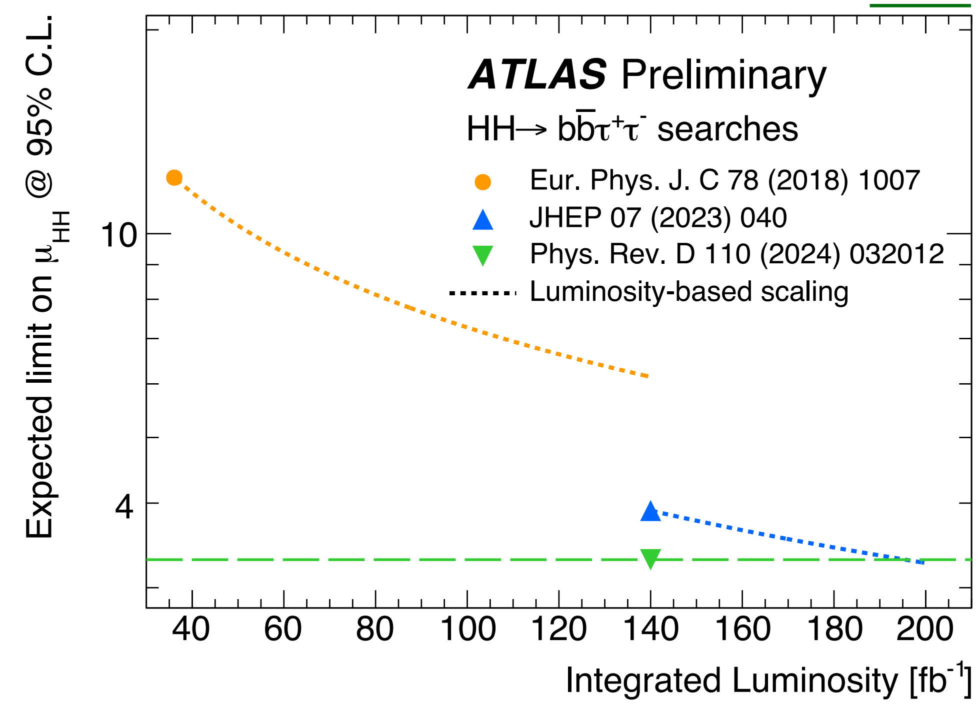
- theoretical uncertainties (assumed to be reduced by a factor of 2) leading for most couplings

Summary of prospects

link

In the shorter run (~ Run 3), expect a substantial flow of publications exploiting recent improvements to Higgs boson identification

- analyses that are limited by systematic uncertainties can still make significant performance leaps!



- challenge: long timeline before object-level improvements make their way to (published) analyses

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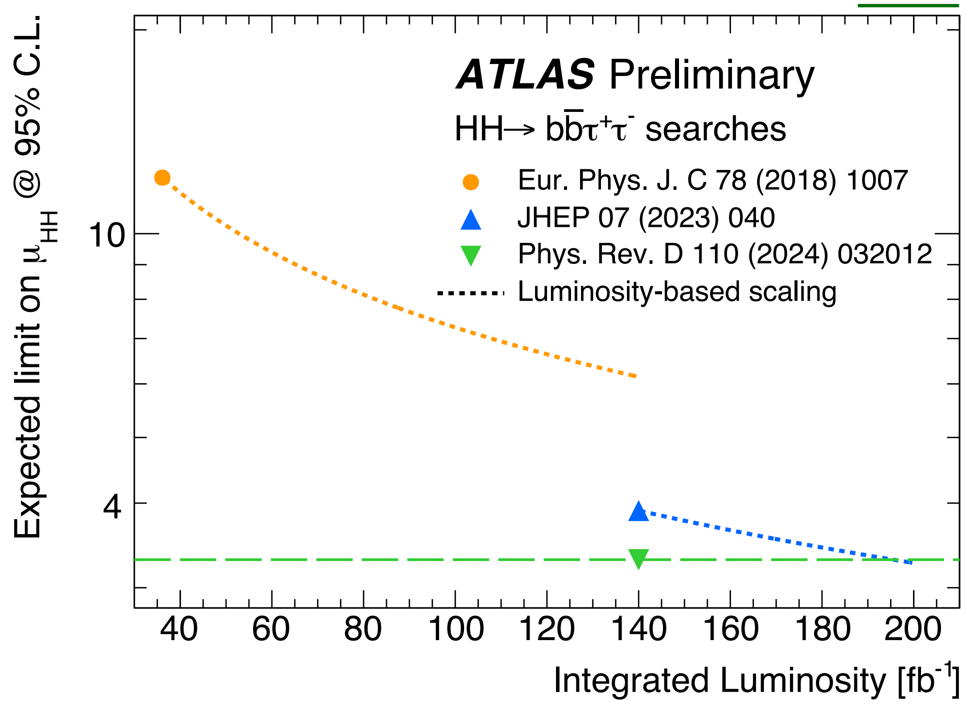

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The HL-LHC promises a host of sensitive probes of both the SM and the BSM scalar sector (through precision measurements as well as direct searches)

- but reaching the sensitivity will require hard work on the experimental as well as on the theoretical side
- We are looking forward to many more innovations, from trigger to reconstruction to analysis