ATLAS Highlights and LHC Computing Status

98th PRC meeting

Oliver Majerský on behalf of the DESY ATLAS group

Hamburg, November 5, 2024

HELMHOLTZ

DESY.

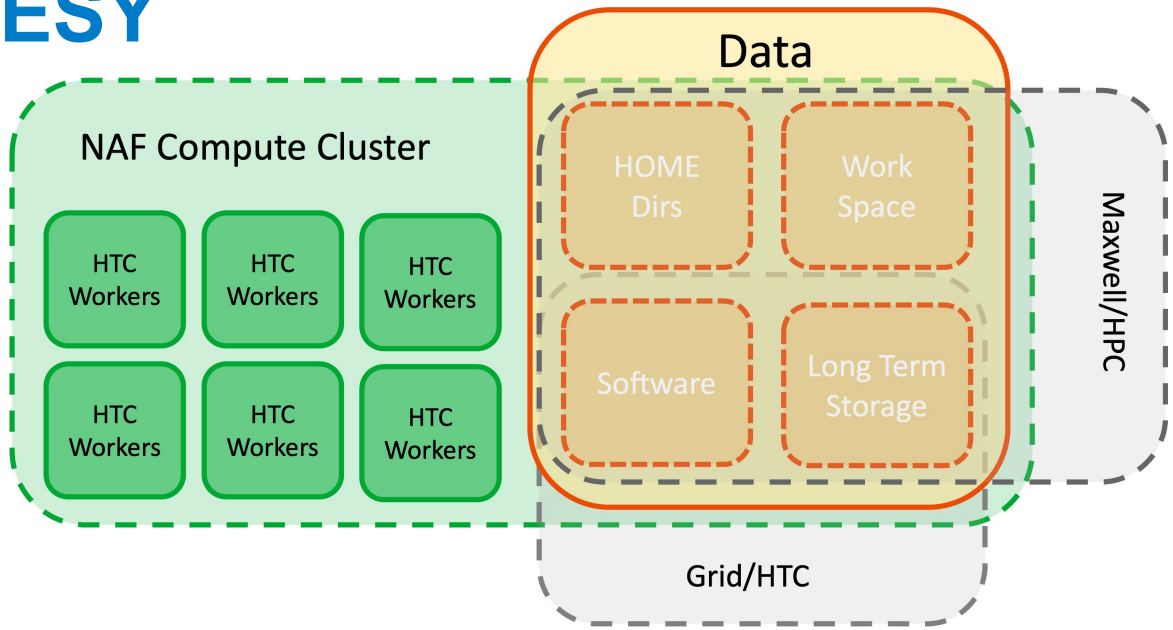
LHC Computing at DESY

Overview of LHC computing at DESY

Available resources & recent major news

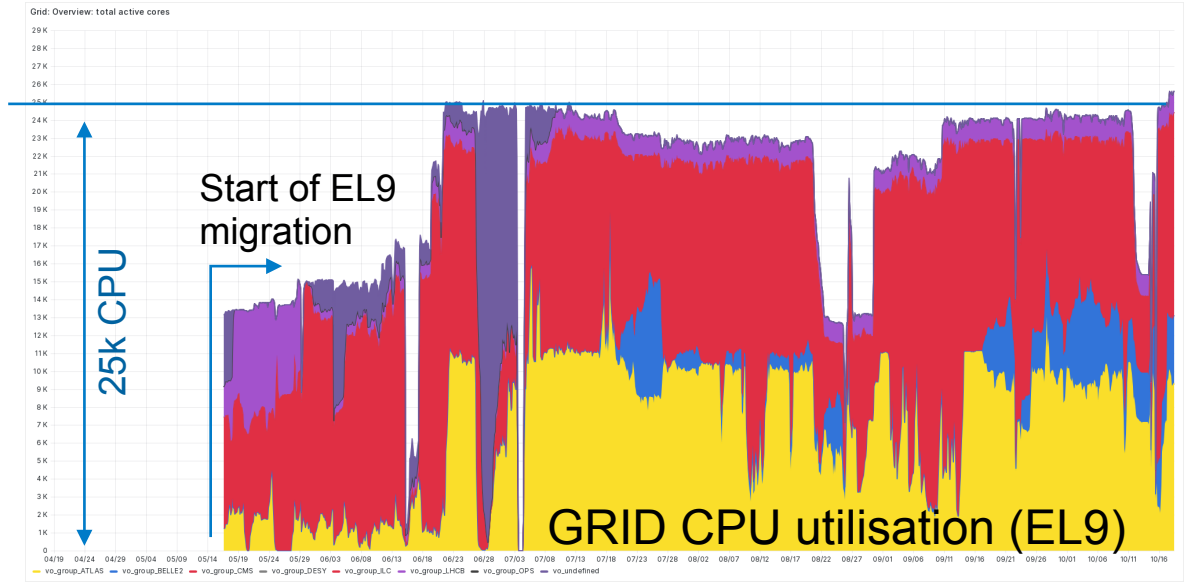
National Analysis Facility (NAF)

- HTCondor-based batch farm for small, low latency jobs
- 9k CPU cores
- Local DUST storage (~2.6 PB)



GRID computing — DESY is a Tier-2 WLCG site

- ~20k CPU cores in HH, 3k CPU cores in ZN
- Storage: dCache
  - 20PB of data in HH, ~3PB in ZN
  - Easily accessible on NAF
    - Important for efficient analysis of large datasets and simulations!



Migration to RHEL 9 linux (EL9)

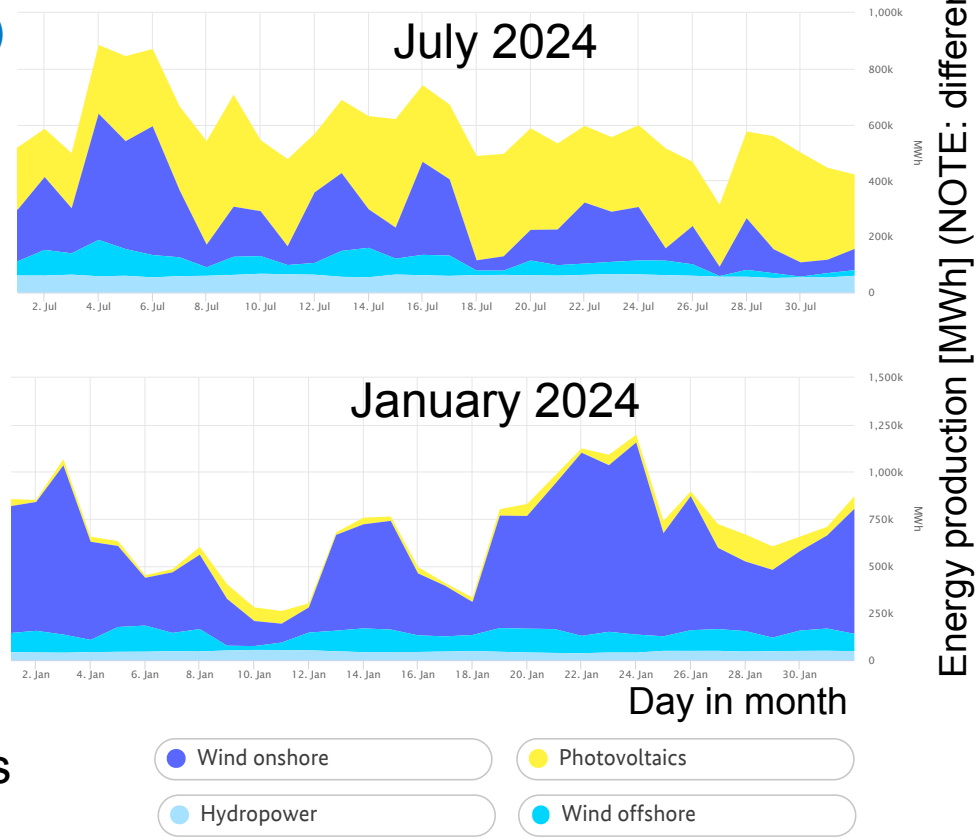
- Previously deployed CentOS 7 (EL7) reached end-of-support in June'24

Sustainability efforts

- **Why ?**
  - **One of main issues: electricity consumption from non-renewable energy sources**

- DESY member in the Research Facility 2.0 effort (Horizon Europe)
  - Major topics: accelerators and data centers
    - In Germany, only DESY involved in data center topics
- **Efforts to improve energy efficiency**
  - Upgrade older machines to newer, new architectures (ARM)
  - Utilizing GPUs, FPGAs
  - Cluster shaping based on green energy availability
    - Dynamic power-off of worker nodes, CPU throttling
- **Teach users good coding practices and best use of resources**
  - Reduce energy overhead by reducing # of failed jobs and thanks to more efficient code
  - Sustainability workshop (4th workshop Oct 7-8) addressing this

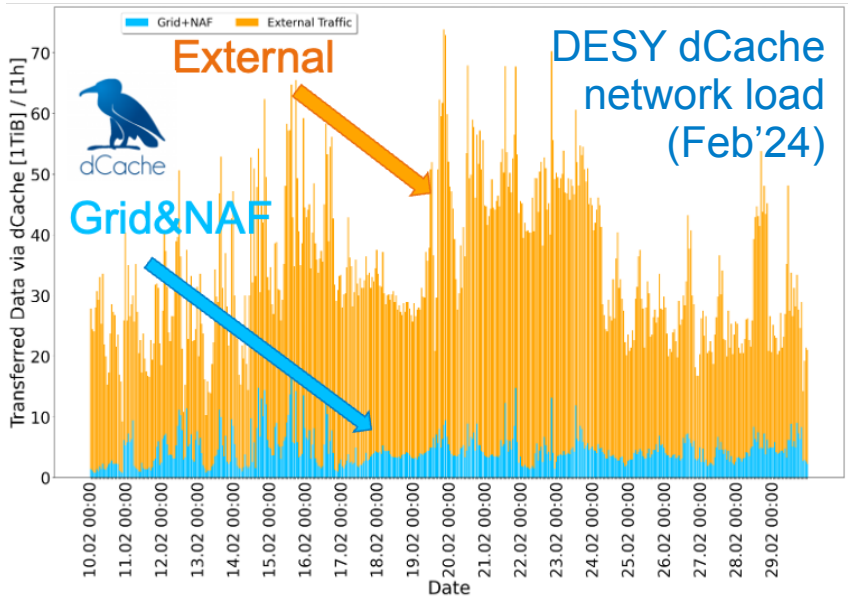
RF 2.0 RESEARCH FACILITY
TOWARDS A MORE ENERGY-EFFICIENT AND SUSTAINABLE PATH

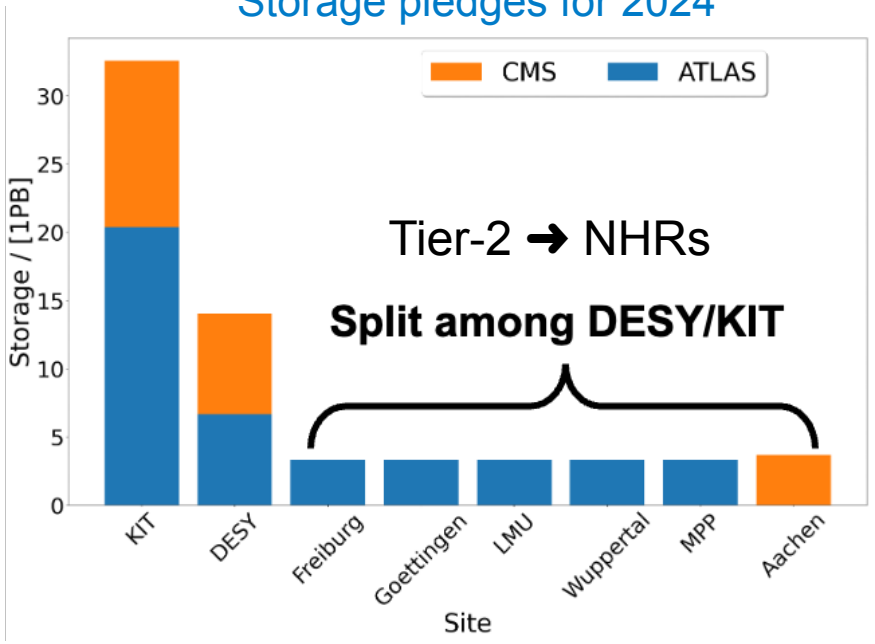


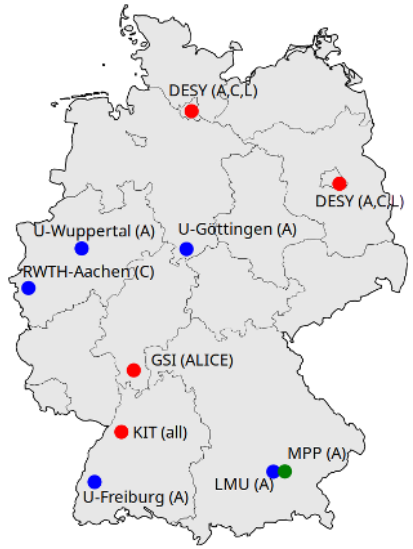
Changes in German HEP computing landscape

Upcoming challenges for DESY

- Currently several universities operate Tier-2 (T2) sites
- Due to the federal funding ➜ universities moving to National HPC Centers (NHRs) ➜ incentive to retire the university T2s
  - Larger focus on computing power, less on storage
- **Consequence: more network and storage load on DESY**
  - Also more load on DESY IT person-power



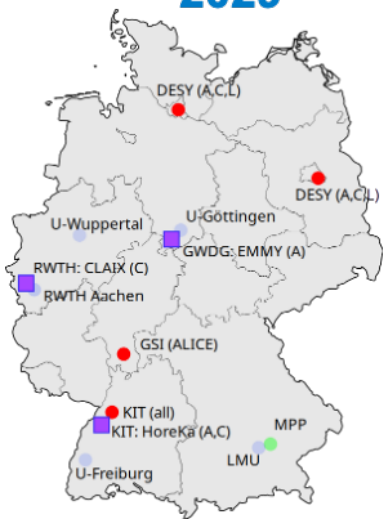




2023

Helmholtz Centers
Max-Planck-Institute
Universities
NHRs

2029



DESY ATLAS group activities

DESY ATLAS group-outing, July 11, 2024

ATLAS group activities

Strong involvement in many areas & several leadership roles

Data analysis

- From SM precision measurements to searches for new phenomena

Physics Objects performance & reconstruction

- Jets, b-jet identification
- Electrons + photons
- Forward protons
- Tracking for current and upgraded detector

Software and Computing

- Computing and software coordination
- Monte Carlo software and production

Detector operation, tools and software

- Semiconductor tracker (SCT) operation & monitoring
- Luminosity measurement

Detector upgrade - Inner Tracker (ITk)

- Design, test and assembly

Detector R&D

- CMOS sensor development (pixels and strips)
- SW development (Allpix Squared, Corryvreckan, Constellation)
- Medical applications

Leadership roles

- Physics (Deputy) coordinator
- ITk (Deputy) Strips project leader
- Computing coordinator
- and more…

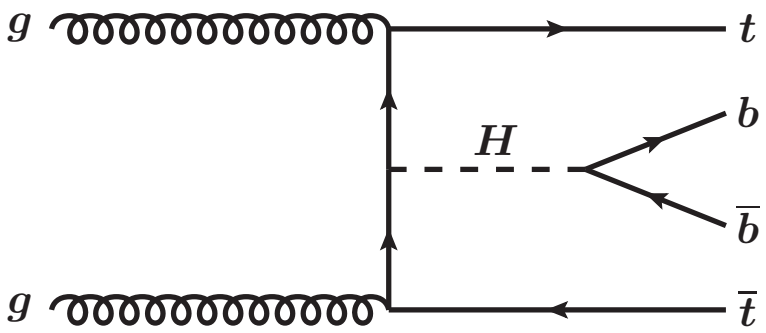
ATLAS highlights

With strong involvement of DESY

Since May 1st 2024:
- 17 papers published
- 3 papers submitted
- 6 CONF&PUB notes
- 10 non-ATLAS papers

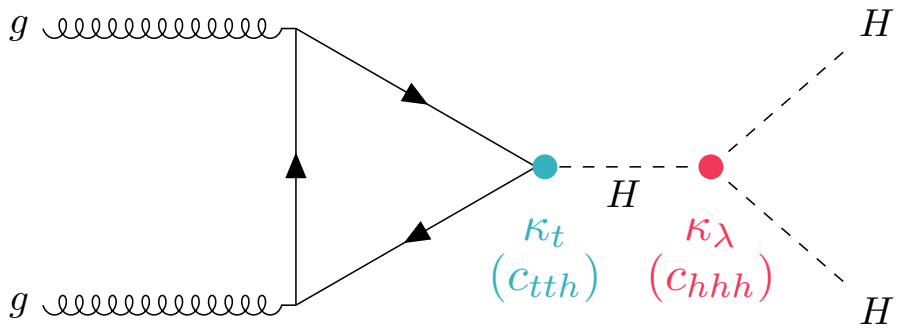
Legacy measurement of $t\bar{t}H(b\bar{b})$ production using full Run 2 dataset

[arXiv:2407.10904]



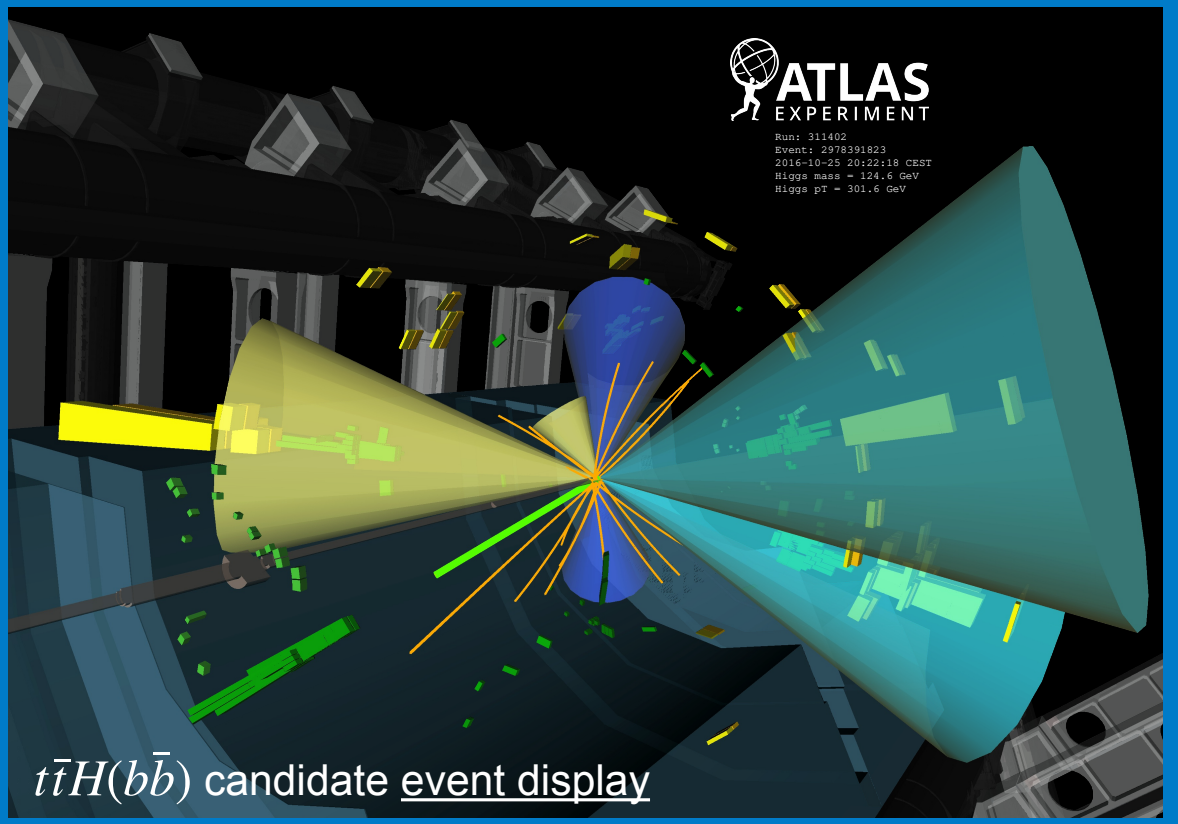
Combination of searches for non-resonant HH production using full Run 2 dataset

[PRL 133 (2024) 101801]



Measurement of the $t\bar{t}H(b\bar{b})$ production in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector at the LHC

arXiv:2407.10904

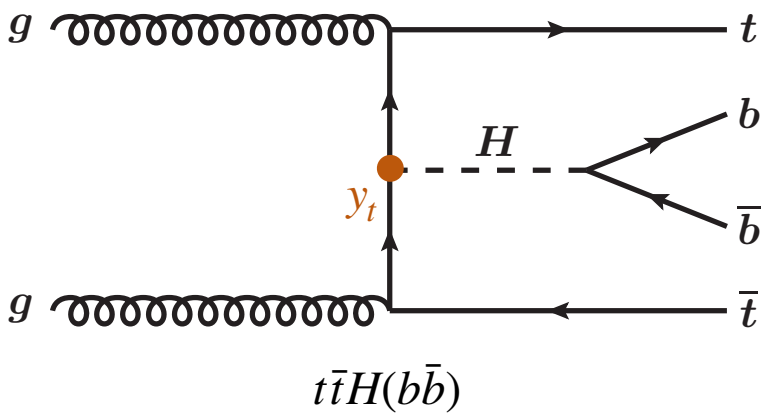


$t\bar{t}H(b\bar{b})$ candidate event display

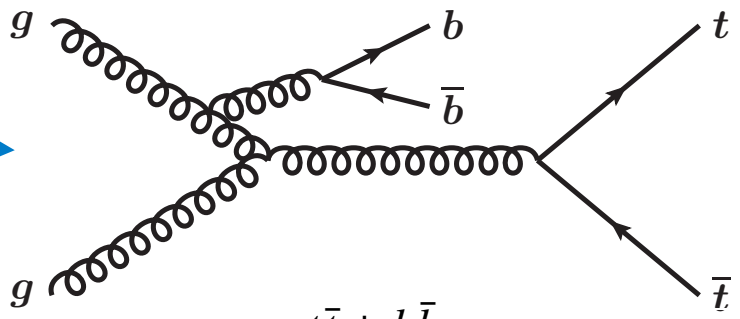
Measurement of the $t\bar{t}H(b\bar{b})$ production at $\sqrt{s}$ = 13 TeV

Motivation

- Top-Yukawa coupling $y_t \sim 1$
  - Important role in EW symmetry breaking
- $t\bar{t}H$ and tH only processes directly sensitive to y_t
  - $\sigma_{t\bar{t}H} \sim |y_t|^2$
- $H(b\bar{b})$ largest BR (~57%)
- Large irreducible $t\bar{t} + b\bar{b}$ background
  - Challenging to model — different scales in the process



$t\bar{t}H(b\bar{b})$



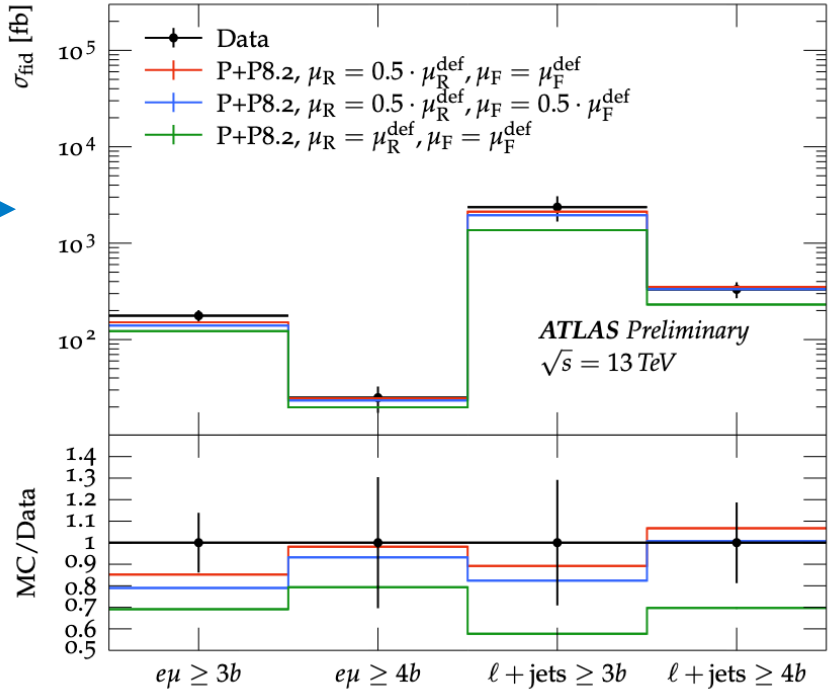
$t\bar{t} + b\bar{b}$

- Re-analysis of the Run 2 dataset with many improvements
- Using data with 1 or 2 leptons in final state
  - One or both tops decay semi-leptonically
- Single-lepton both resolved and boosted

Measurement of the $t\bar{t}H(b\bar{b})$ production at $\sqrt{s}$ = 13 TeV

Improvements compared to previous analysis

- $t\bar{t} + b\bar{b}$ modelling
  - Re-tuned MC and improved set of modeling uncertainties
  - Data-driven corrections
- Improved object reconstruction:
  - Particle flow (PFlow) jets
  - *DL1r* b-tagging
- Improved signal reconstruction and background discrimination using ML
  - Attention-based transformer NNs

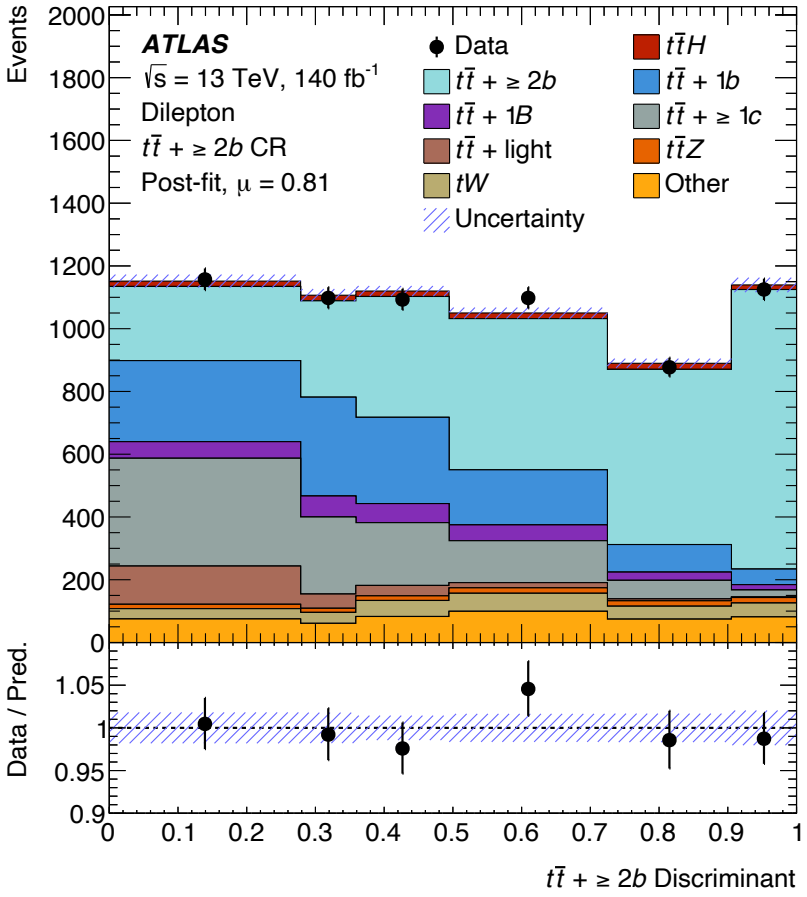


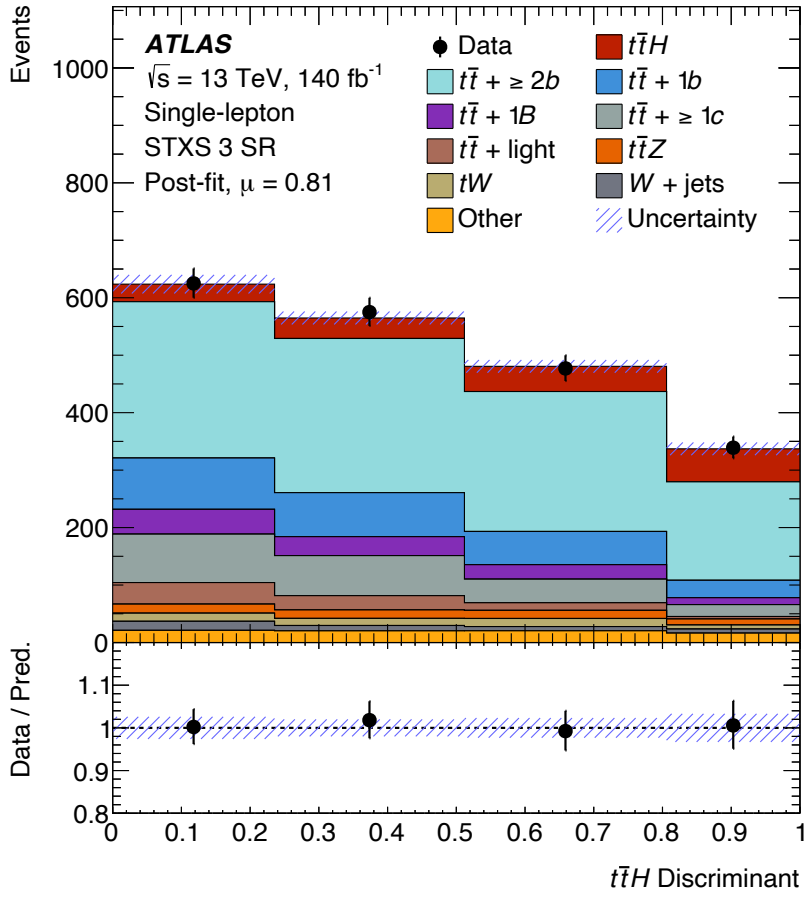
- DESY ATLAS group involved in the analysis on multiple fronts
  - $t\bar{t} + b\bar{b}$ modeling studies
  - ML reconstruction and classification
  - b-tagging

Measurement of the $t\bar{t}H(b\bar{b})$ production at $\sqrt{s}$ = 13 TeV

Statistical analysis

- Profile likelihood fit
  - NN discriminant per region
- 8 major $t\bar{t}$ + jets components fitted from dedicated CRs
  - Much improved control of the bkg
- Fit inclusive $\sigma_{t\bar{t}H}$ & differentially as a function of p_T^H





Measurement of the $t\bar{t}H(b\bar{b})$ production at $\sqrt{s}$ = 13 TeV

Results

Inclusive cross-section

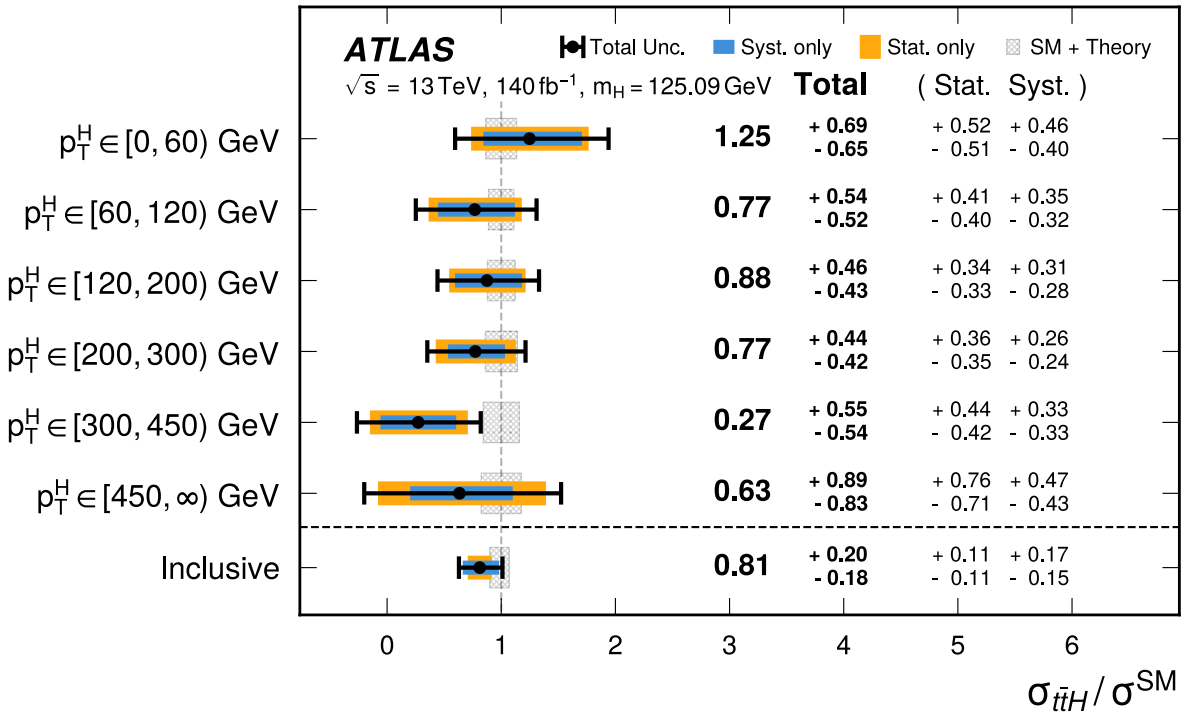
$$\sigma_{t\bar{t}H} = 411^{+109}_{-\ 92}\text{fb} = 411 \pm 54(\text{stat.})^{+85}_{-75}(\text{syst.})\text{fb}$$

- Most-precise $\sigma_{t\bar{t}H}$ measurement in a single decay channel
- Massive improvement in observed (expected) significance compared to previous ATLAS result with the same Run 2 dataset!

Expected $2.7\sigma \rightarrow 5.4\sigma$

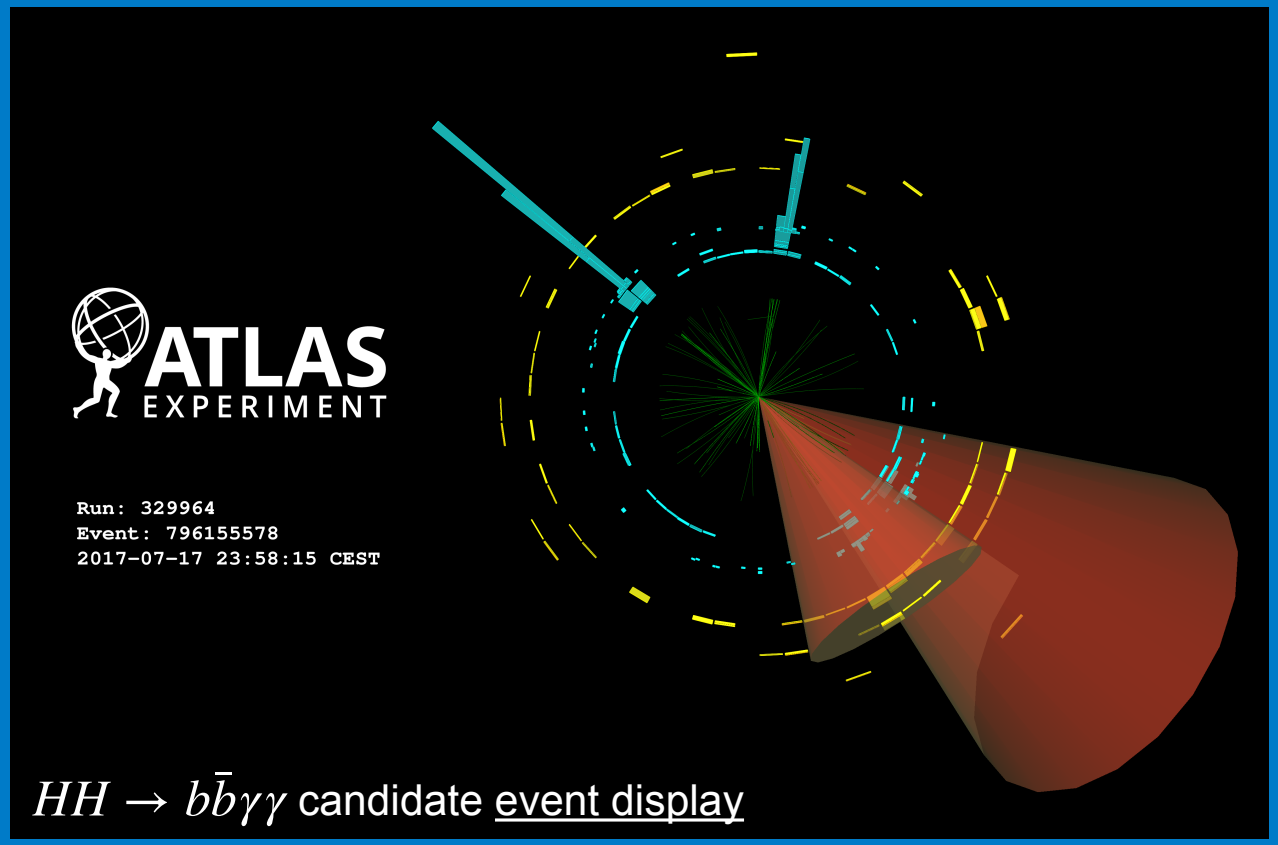
Observed $1.0\sigma \rightarrow 4.6\sigma$

$\sigma_{t\bar{t}H}$ vs p_T^H limited statistically



Combination of searches for Higgs boson pair production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

PRL 133 (2024) 101801



$HH \to b\bar{b}\gamma\gamma$ candidate event display

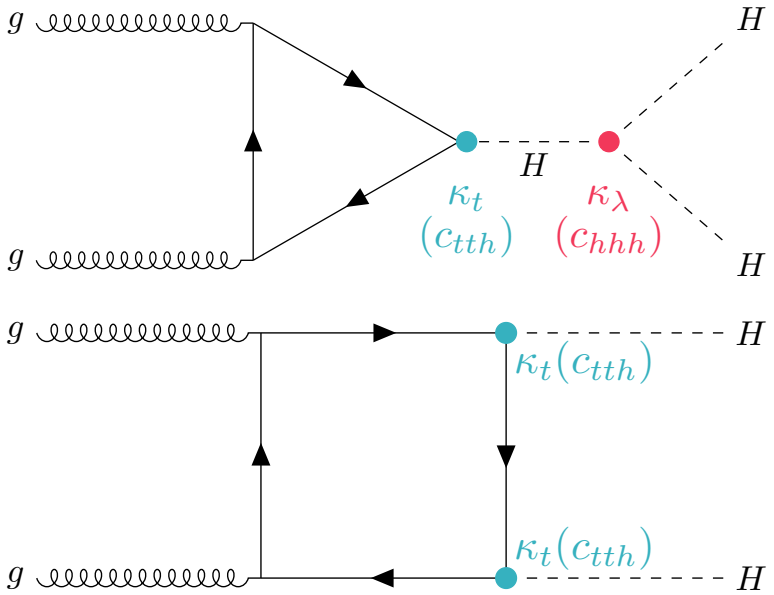
ATLAS HH searches combination at $\sqrt{s} = 13$ TeV

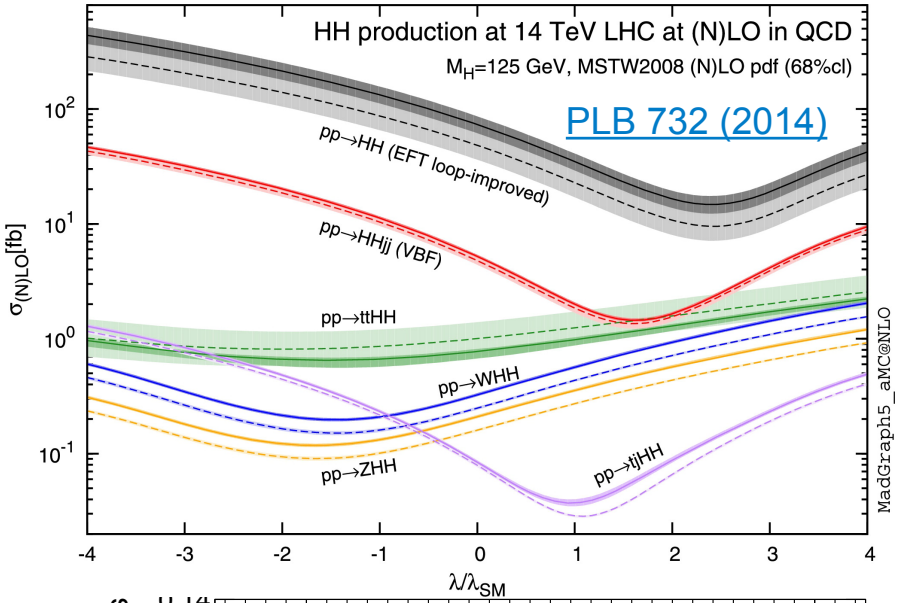
Motivation

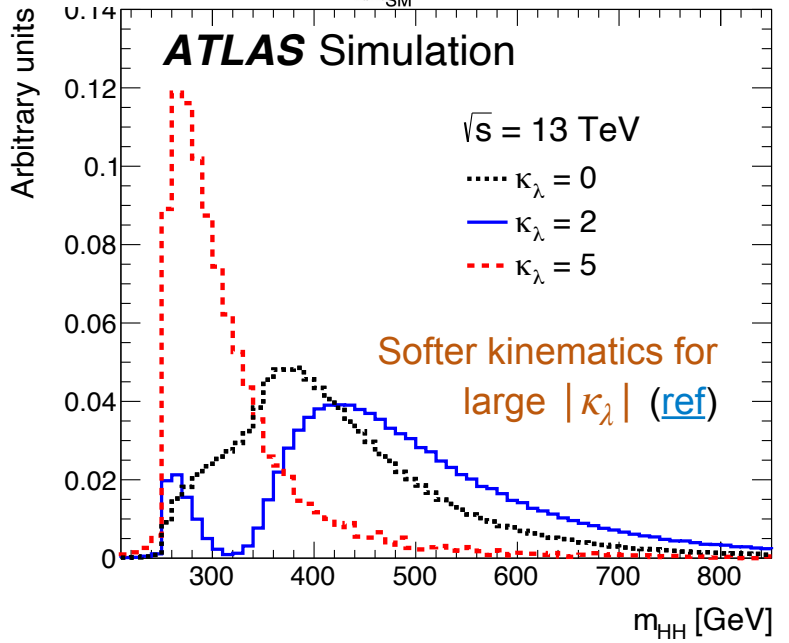
- Large amount of research on Higgs boson properties
- Little experimental constraints on Higgs potential shape

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4, \qquad \mu^2 < 0$$

  - Need to measure $\kappa_\lambda = \lambda/\lambda_{SM}$
- At the LHC, HH produced dominantly via gg fusion: $\sigma^{SM}_{ggF} \sim 31$ fb
- Challenge: destructive interference







ATLAS HH searches combination at $\sqrt{s} = 13$ TeV

Channels combined — covering > 50% of HH decays

- Sensitivity is a compromise between HH branching ratio and background contamination
  - $b\bar{b}\gamma\gamma$ — low BR, excellent m_{HH} resolution
    - Possible to study m_{HH} threshold
    - Best sensitivity to κ_λ
  - $b\bar{b}b\bar{b}$ — highest BR, challenging multijet bkg
    - Best sensitivity to κ_{2V}
  - $b\bar{b}\tau^+\tau^-$ — middle ground
  - $b\bar{b}$ + neutrinos (E_T^{miss}) (2.9%)
  - Multileptons (6.5%)

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

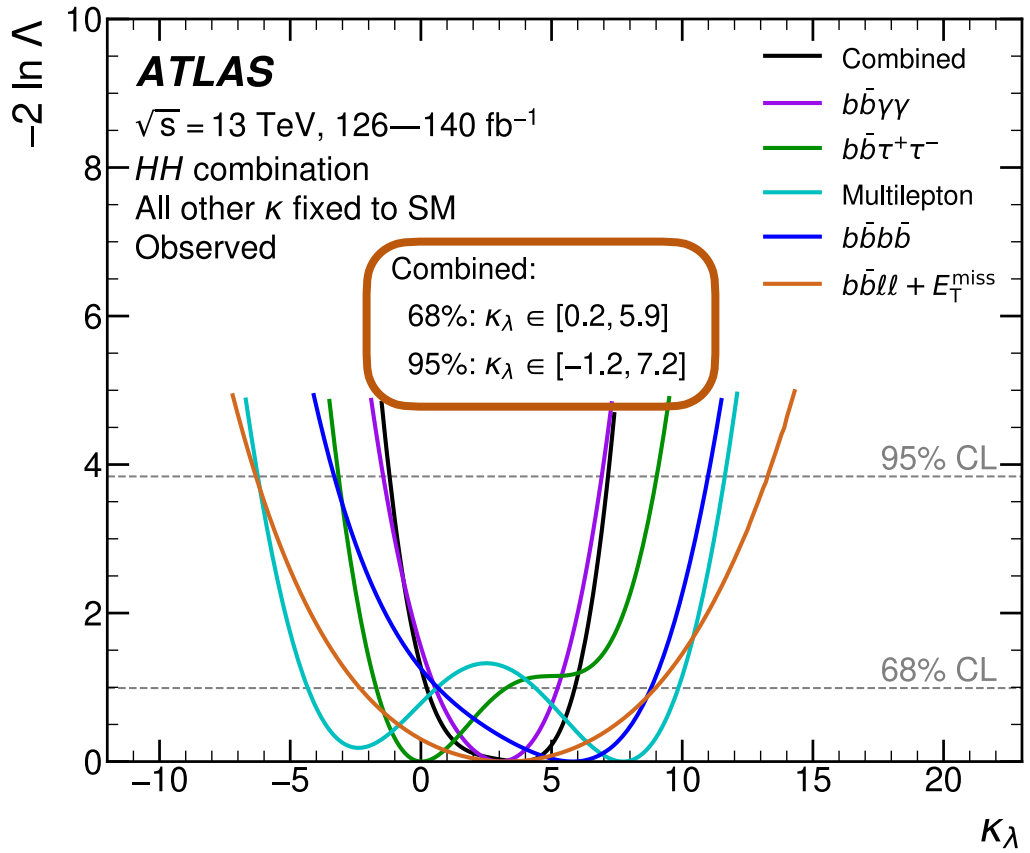
HH branching ratio

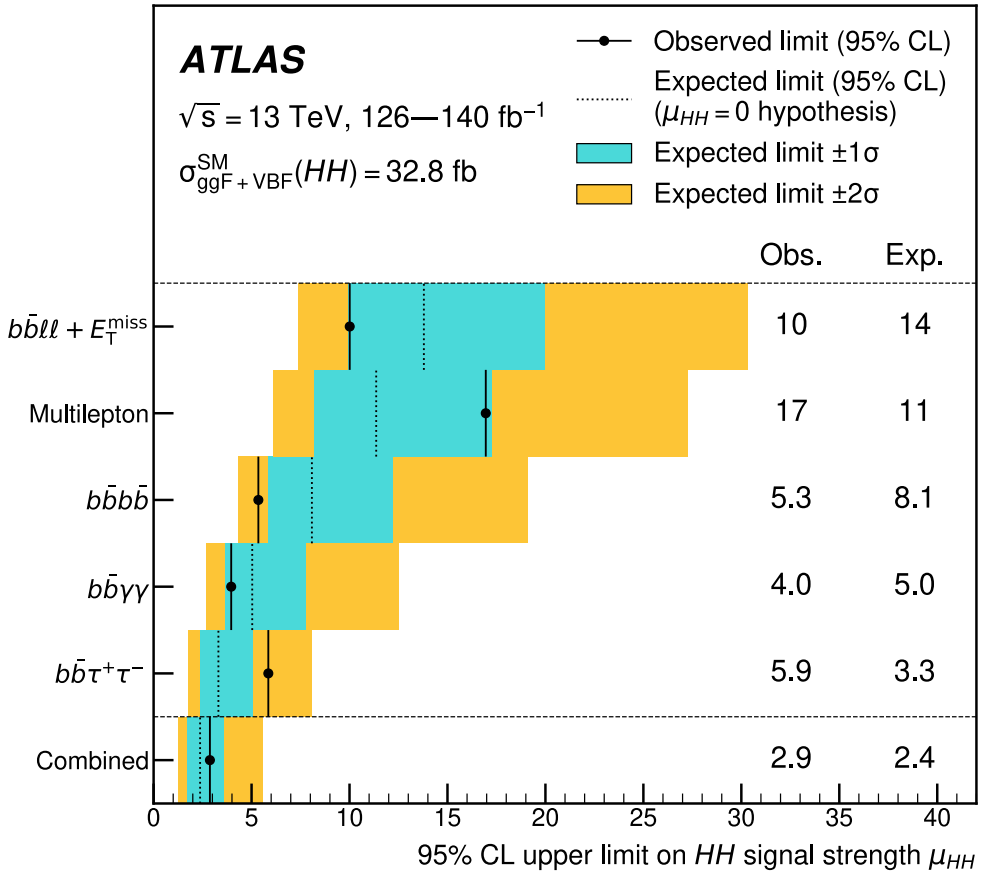
- DESY ATLAS group directly involved in $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ channels and combination itself
- Important contributions to object reconstruction performance
  - Jet calibration and b-tagging
  - Electron and photon reconstruction

ATLAS HH searches combination at $\sqrt{s} = 13$ TeV

Results — HH production

- Most stringent constraints on HH production and κ_λ
- Limit on κ_λ driven by $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ channels

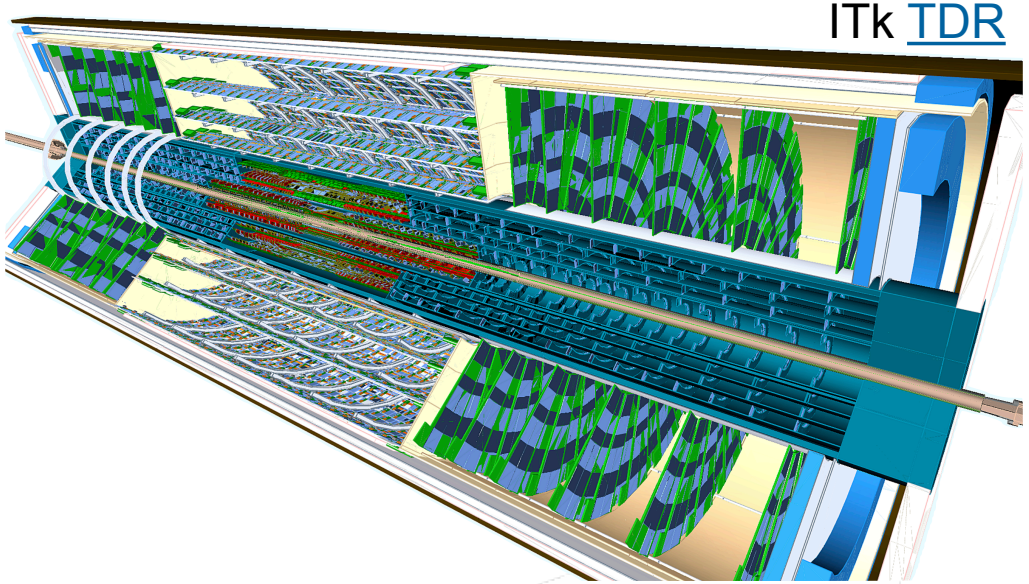




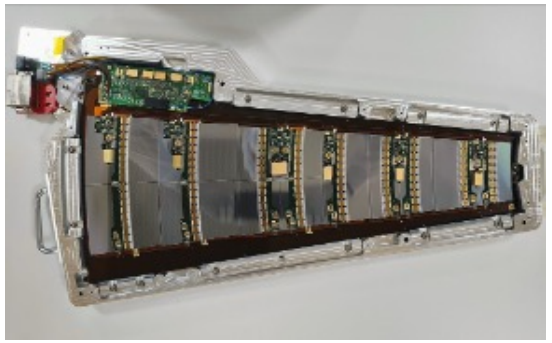
ATLAS Detector Upgrade: Inner Tracker (ITk) end-cap

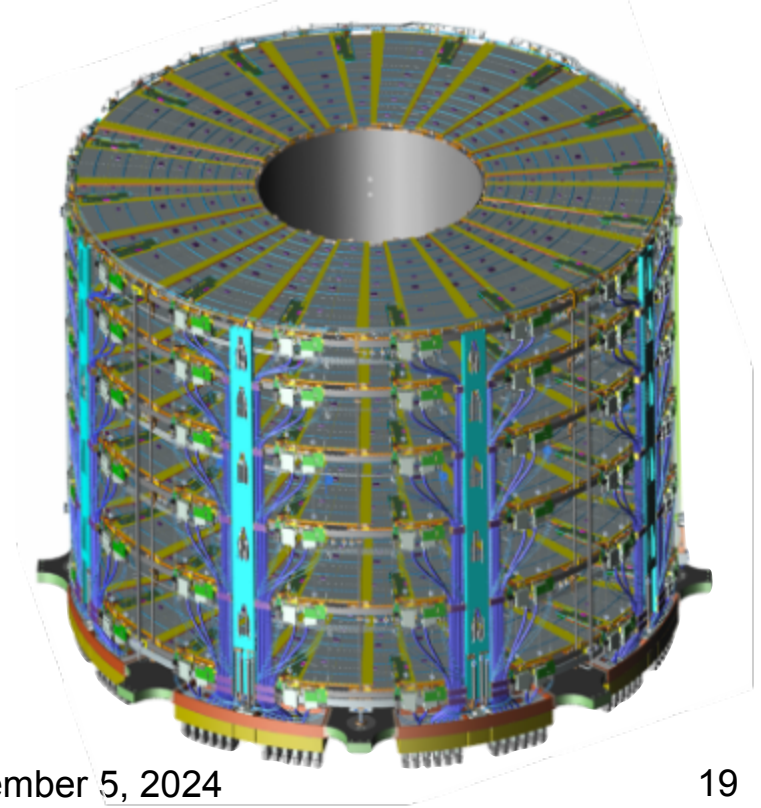
Overview of ITk-related activities

Tracker upgrade for the HL-LHC



- **DESY building one full end-cap of the ITk strip**
  - Sensor studies
  - Quality control of sensors & hybrids
  - Module development, building and testing
  - Petal core development, production and testing
  - Module loading onto petal cores
  - End of substructure (EoS) card
  - Endcap integration at DESY and CERN
  - CO_2 cooling
  - ITk Strip testbeam
  - and more…





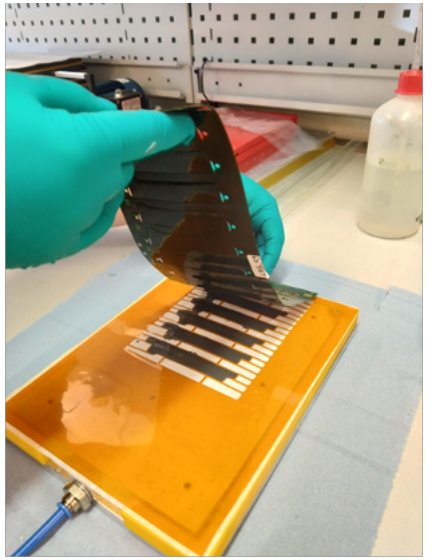
Major technical challenges

- Sensor cracking due to thermal cycling → Addition of interposer
- Newly found problems in readout electronics (lpGBT chip issues)

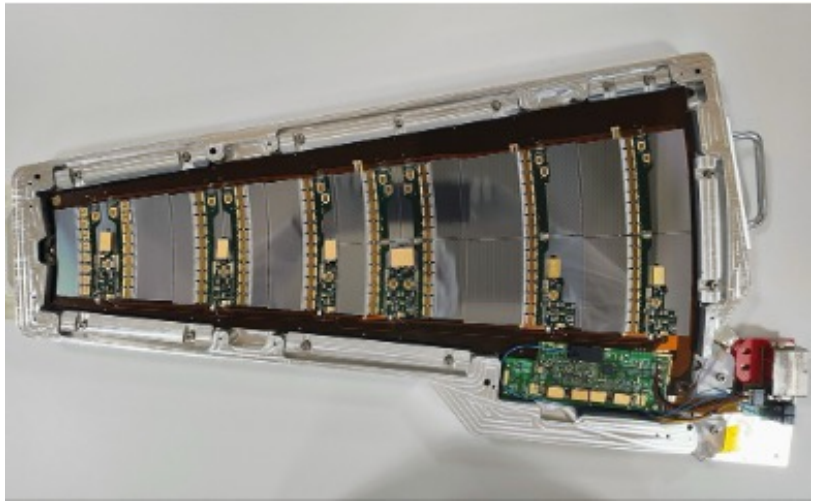
ITk Modules

Pre-production and production preparation

- **Production start planned early 2025**
  - Produced 63 hybrids & 41 modules as part of pre-production
- **Mitigating module cracking**
  - Discovered during pre-production
  - Cracking caused by differences in material thermal expansion
  - Addition of interposed layer reduces expansion-induced material stress
    - DESY building the interposed modules
    - First interposed modules finished and under extensive tests
  - Goal: Start interposing hybrids at DESY in Nov
- **Module loading**
  - Gluing and placement of silicon modules and EoS cards on the petal cores using gantry robot
  - DESY now qualified as a loading site beginning of Oct



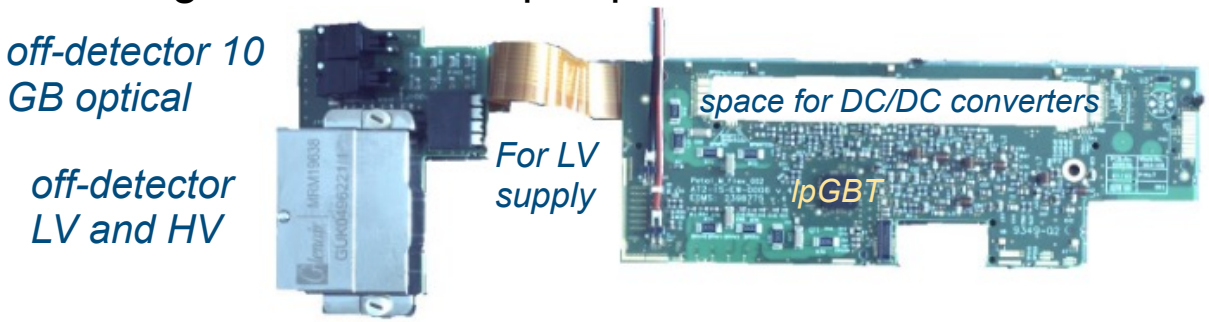
Mitigate cracking by Interposing hybrid panel



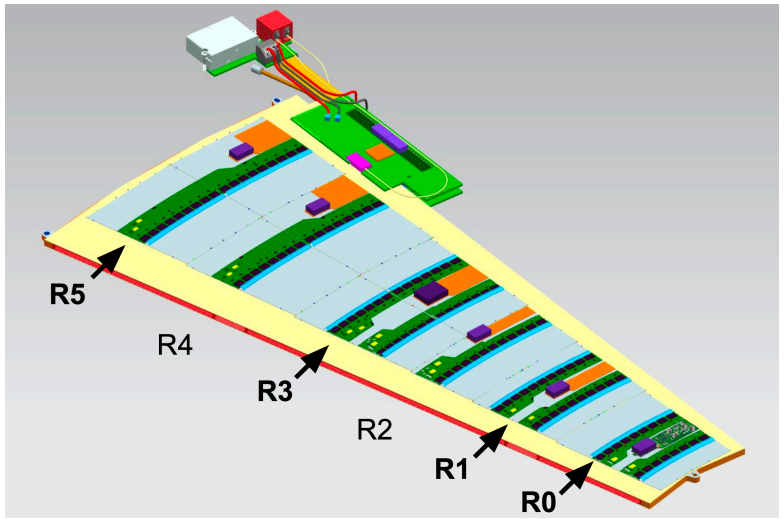
End of Substructure (EoS) Card

Gateway between on- and off-detector systems – data, communication, power

- DESY is building EoS cards for ITk strips
- Designed at DESY around the CERN-based integrated circuit chips: lpGBT and VTRx+

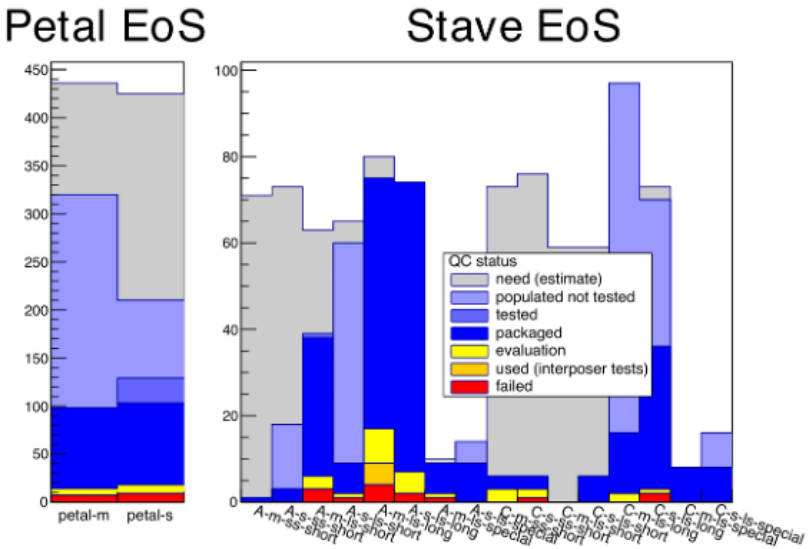


Main EoS card for petal



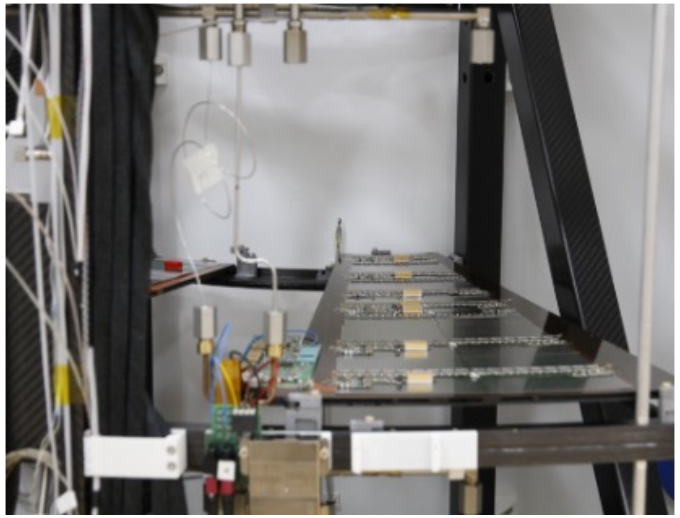
Production on hold due to major issue with lpGBT chips

- Discovered at DESY
- Impacts every detector at HL-LHC
- Under investigation, waiting for radiation damage studies at CERN



90% of bare PCBs produced, ⅔ populated, ⅓ tested & packaged

End-cap system tests and integration

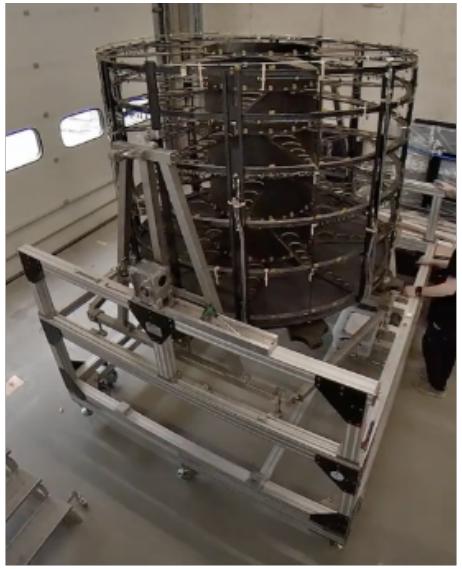


Emulation of full system

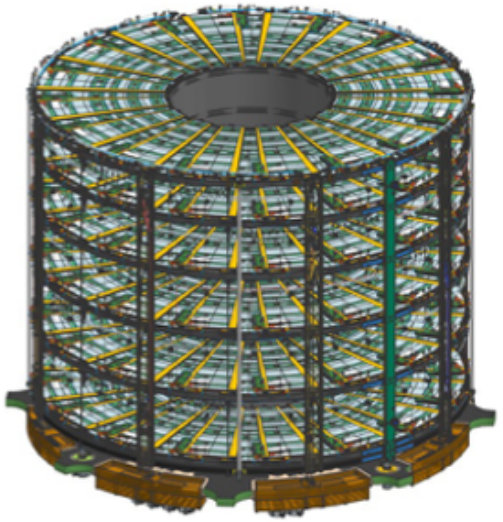
- **Goal: test up to 12 petals in a realistic detector setting**
- Powering, cooling and readout tested
- Currently one petal inserted and fully tested
- First cosmics data recorded
- **Next steps:**
  - Further petals ready on site, to be inserted
  - Goal: demonstrate readout of multiple petals and measure noise cross-talk

Petal installation

- The **skeleton** for the DESY end-cap (EC1) is ready at Nikhef
  - Arrival ~ November 25th 2024



EC1 mounted on the super-frame



CAD of fully-loaded EC

Summary

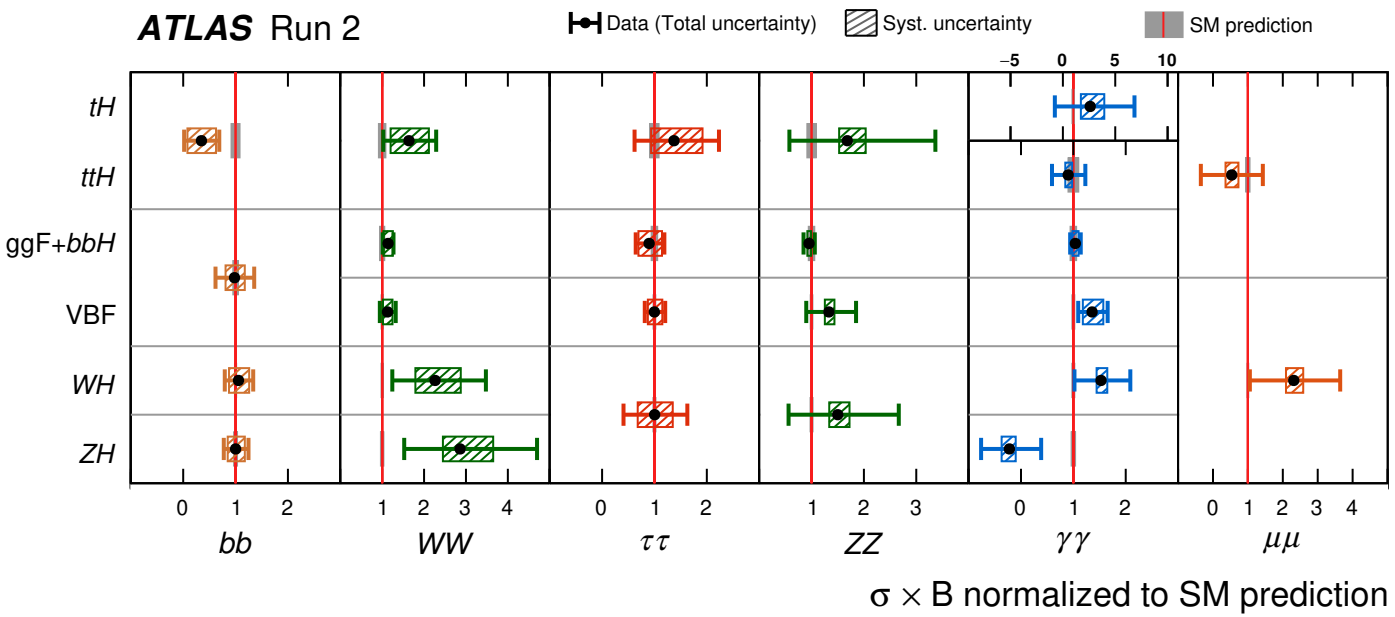
- DESY continues it's strong involvement in multiple areas in ATLAS operation and physics
  - Detector operations, performance, software & computing
  - Leading efforts and significant contributions to new physics results with significant impact
- Fully committed team to the delivery of an end-cap to the ITk detector
  - Strong dedication ensures steady progress despite the significant challenges

Backup

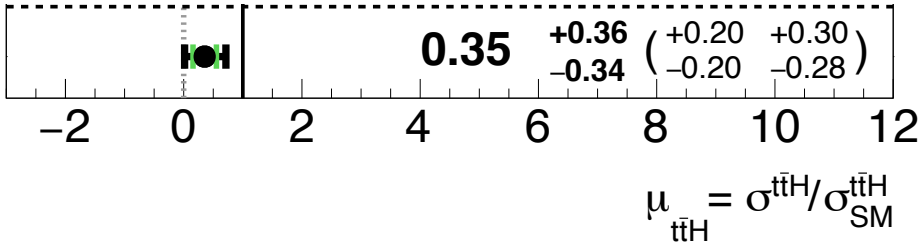
Measurement of the $t\bar{t}H(b\bar{b})$ production at $\sqrt{s}$ = 13 TeV

Previous results

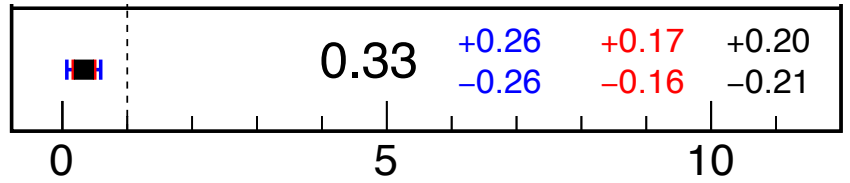
- Previous ATLAS & CMS measurements
  - Slight tension w.r.t. SM prediction in $H(b\bar{b})$
  - Good compatibility in other H decay channels
  - Good compatibility in other production modes



ATLAS $t\bar{t}H(b\bar{b})$ JHEP 06 (2022) 097



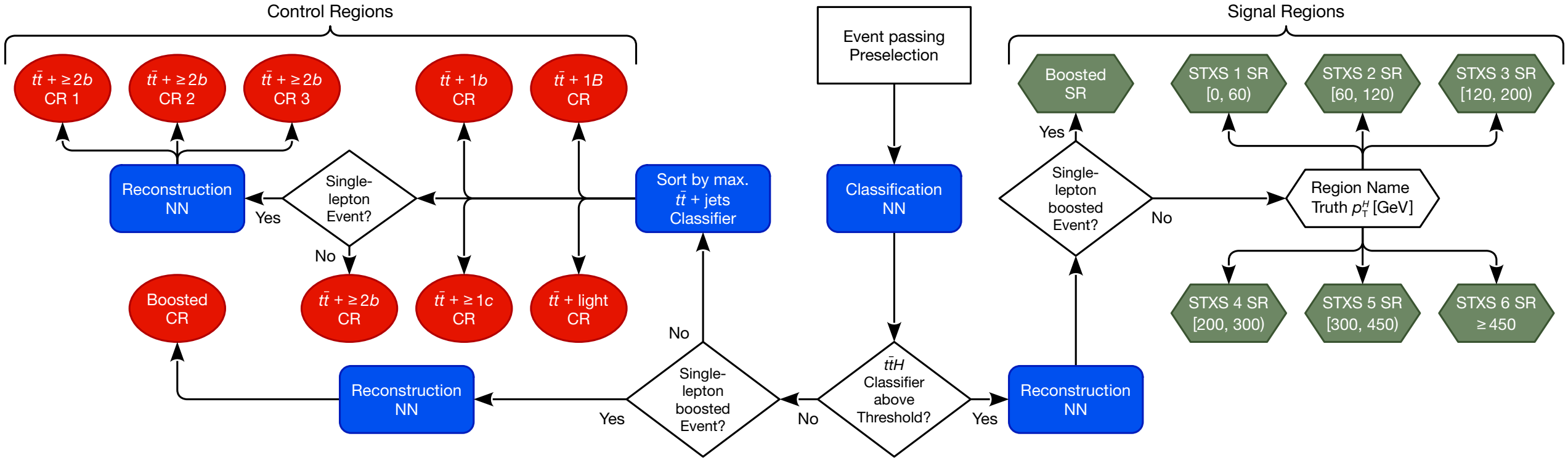
CMS $t\bar{t}H(b\bar{b})$ arXiv:2407.10896



ATLAS Higgs cross-section measurements Nature 607, 52 (2022)

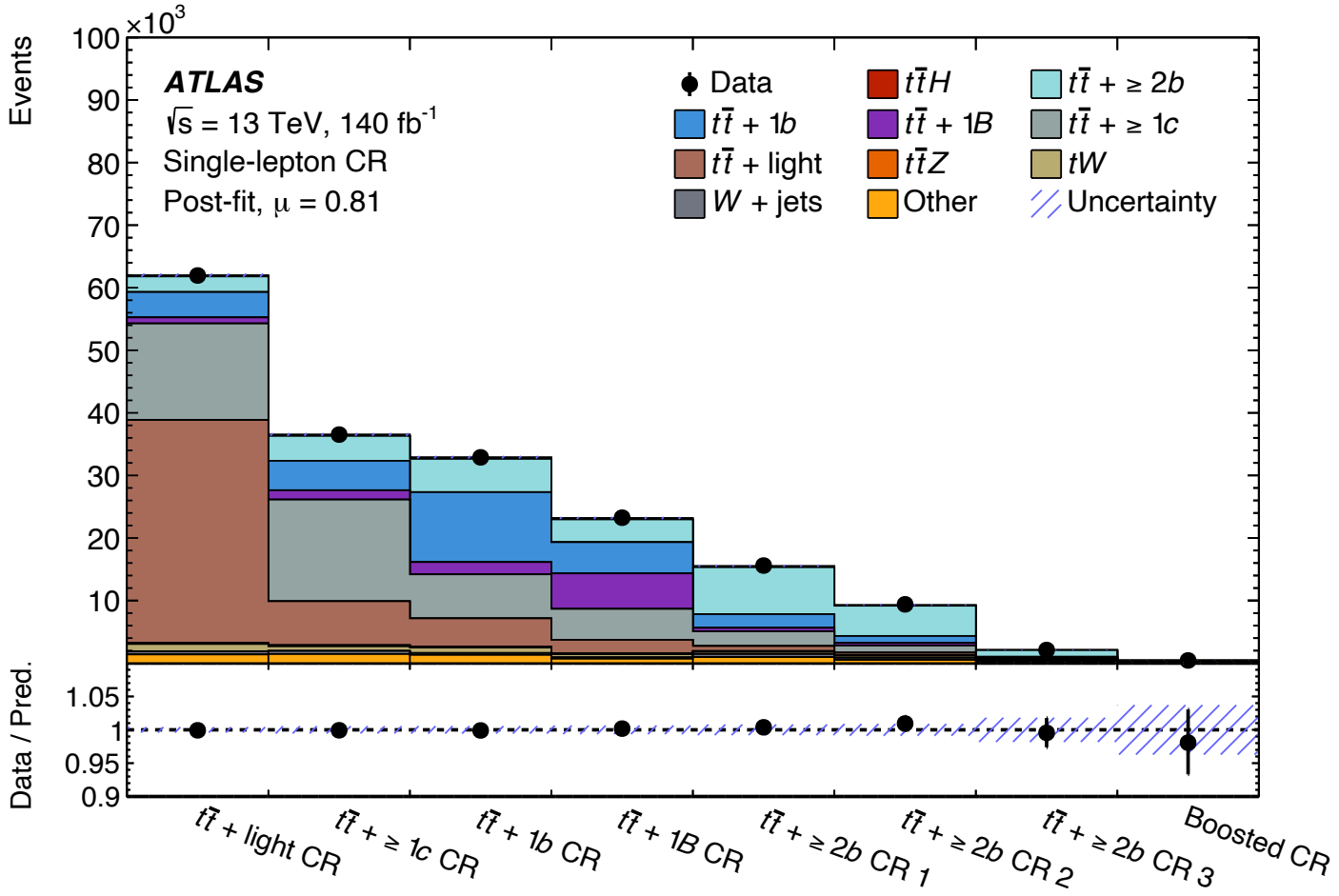
Measurement of the $t\bar{t}H(b\bar{b})$ production at $\sqrt{s}$ = 13 TeV

Event classification & reconstruction approach



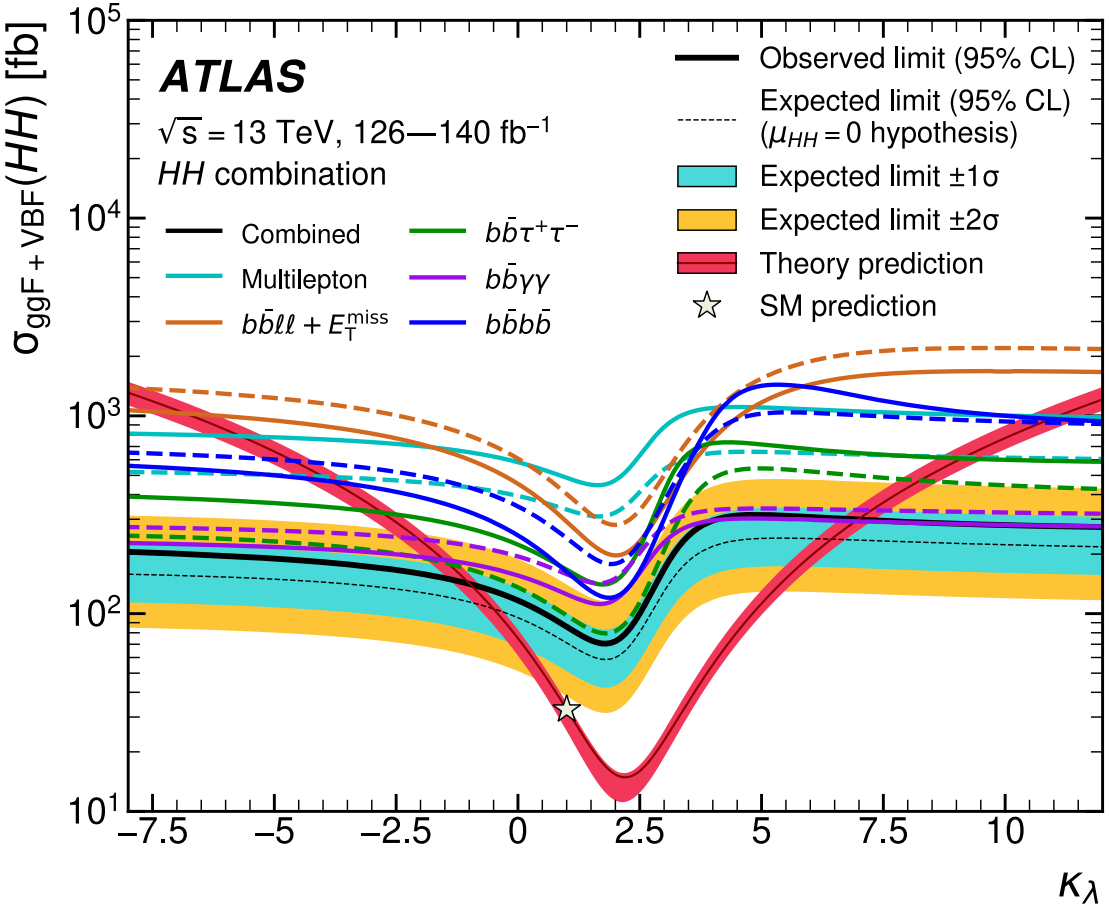
Measurement of the $t\bar{t}H(b\bar{b})$ production at $\sqrt{s}$ = 13 TeV

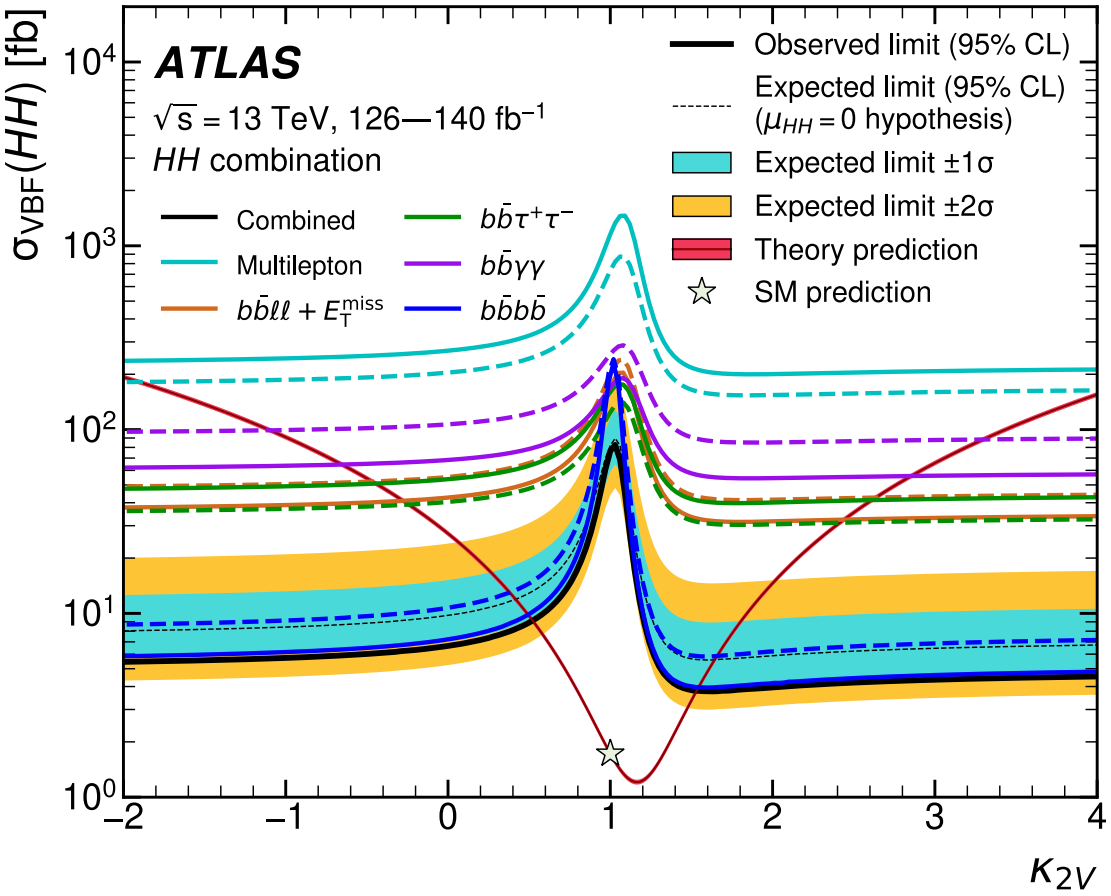
Control regions



ATLAS HH searches combination at $\sqrt{s} = 13$ TeV

Limits on σ_{HH} vs κ_λ and κ_{2V}

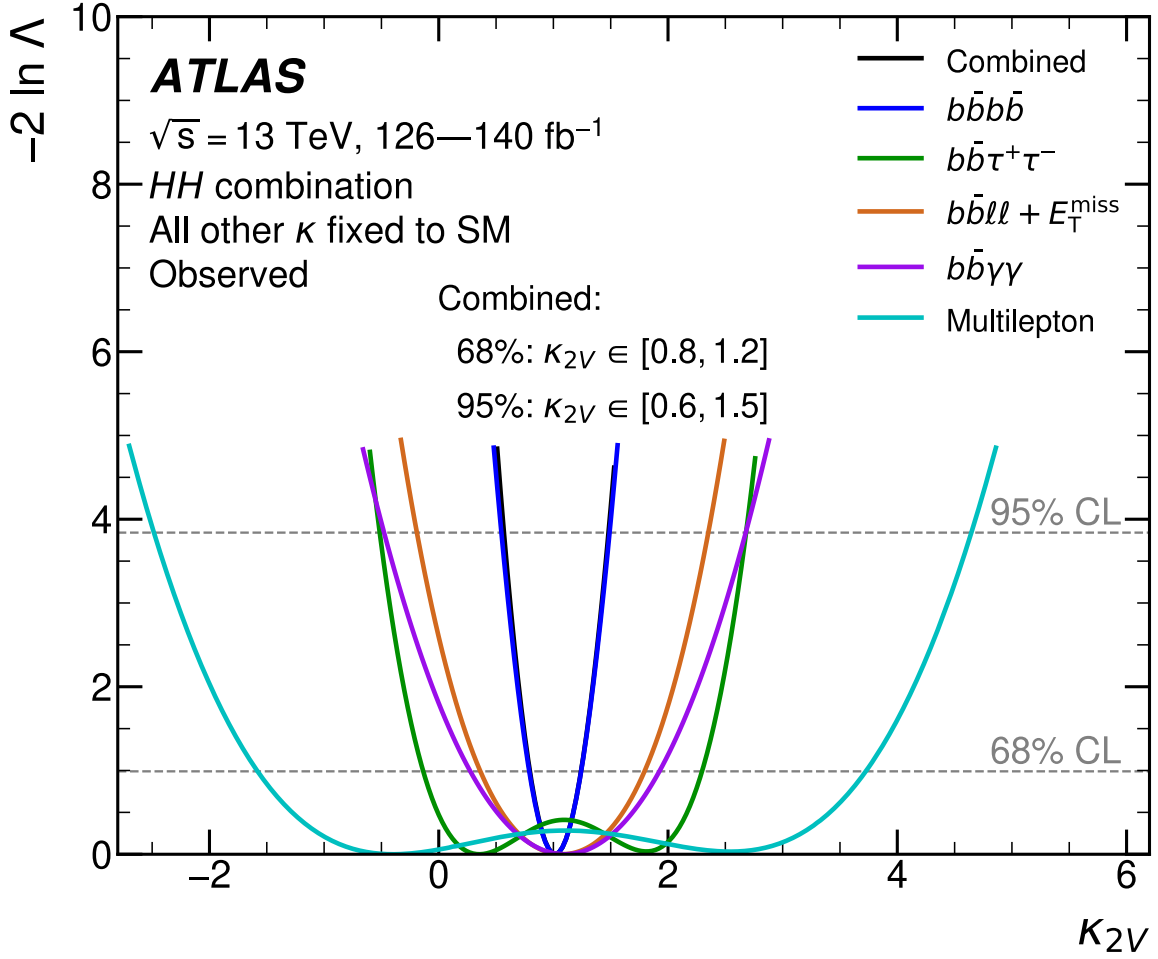




ATLAS HH searches combination at $\sqrt{s} = 13$ TeV

Limits on κ_{2V}

Limit on κ_{2V} driven by $b\bar{b}b\bar{b}$ channel



Role of DESY in the Shifting German WLCG Environment

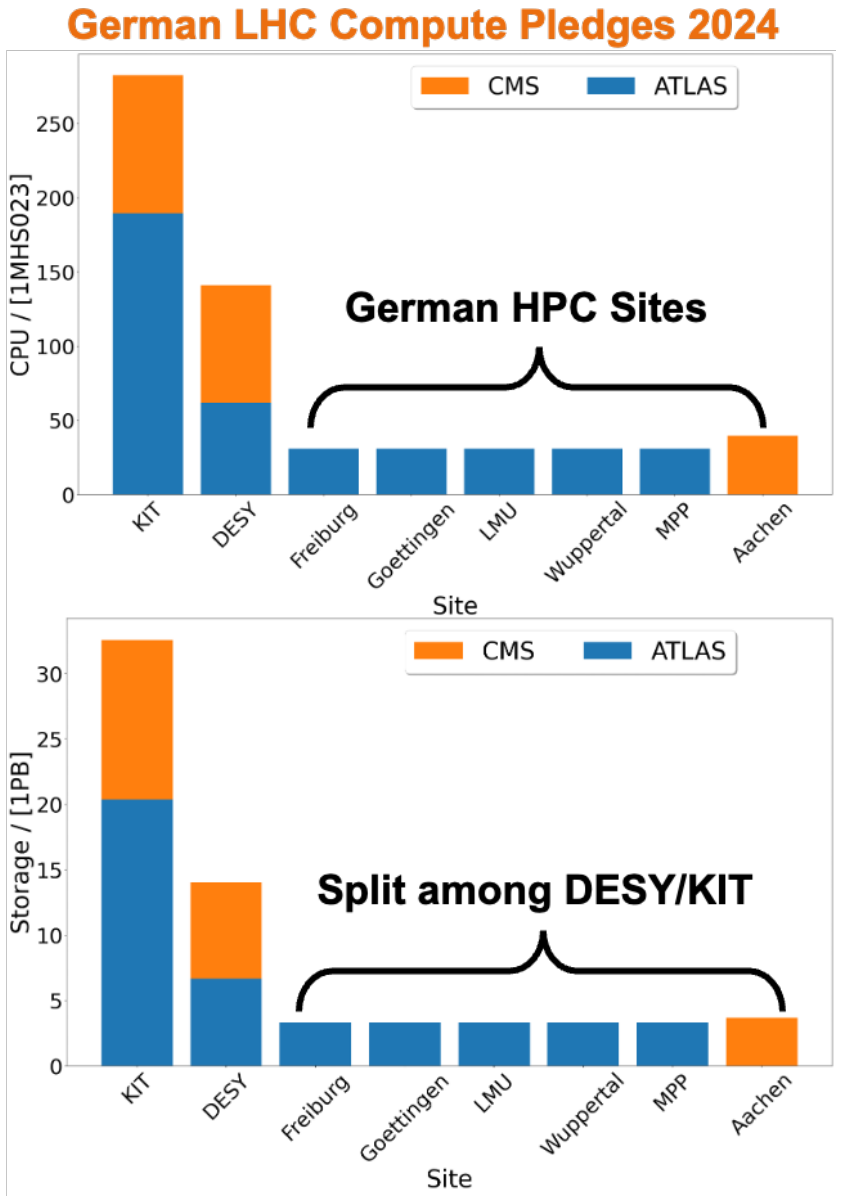
Overview of the Changes

Change in future for the LHC computing

- Next to DESY&GSI several German universities operate Tier-2s
- Compute for universities moving to National HPC centers (NHR)
- Due to the federal funding ➜ incentive to retire the Uni Tier-2s
- Gradual replacement towards the HL-LHC

How will the new computing look like

- Several large German HPC sites will take over the CPU share
- Helmholtz sites DESY/KIT will take over the storage shares
- Process will start in 2025
- Annual ramp down of 20% of the University shares
- Increase of the storage pledges taken over by DESY&KIT



Role of DESY in the Shifting German WLCG Environment

Risks and How DESY will Position Itself in the New Scheme

- Connecting between CPUs at HPC sites and storage at DESY not yet finalized ➜ most likely caching at the NHR
- Remote read will put further strain on our limited network connection (2x50Gb/s) ➜ network-limited during DC'24
- DESY willing to help develop and provide a caching solution taking a leading role in an upcoming project call
  - Utilize a dCache-based solution similar to Nordic Tier-1 ➜ treat the NHRs as satellite sites providing disk only, becoming a part of the hosting site, e.g. DESY
  - Goal is to make the deployment and configuration easier
  - Adapt existing tape workflows to 'warm-up' the caches at the NHR sites
  - Consider employing a similar idea to support Uni Tier-3s