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U.S. DEPARTMENT OF ENERGY

Study of CP properties of top Yukawa coupling with ATLAS experiment
and
Testing of ATLAS HL-LHC Pixel detector readout chip

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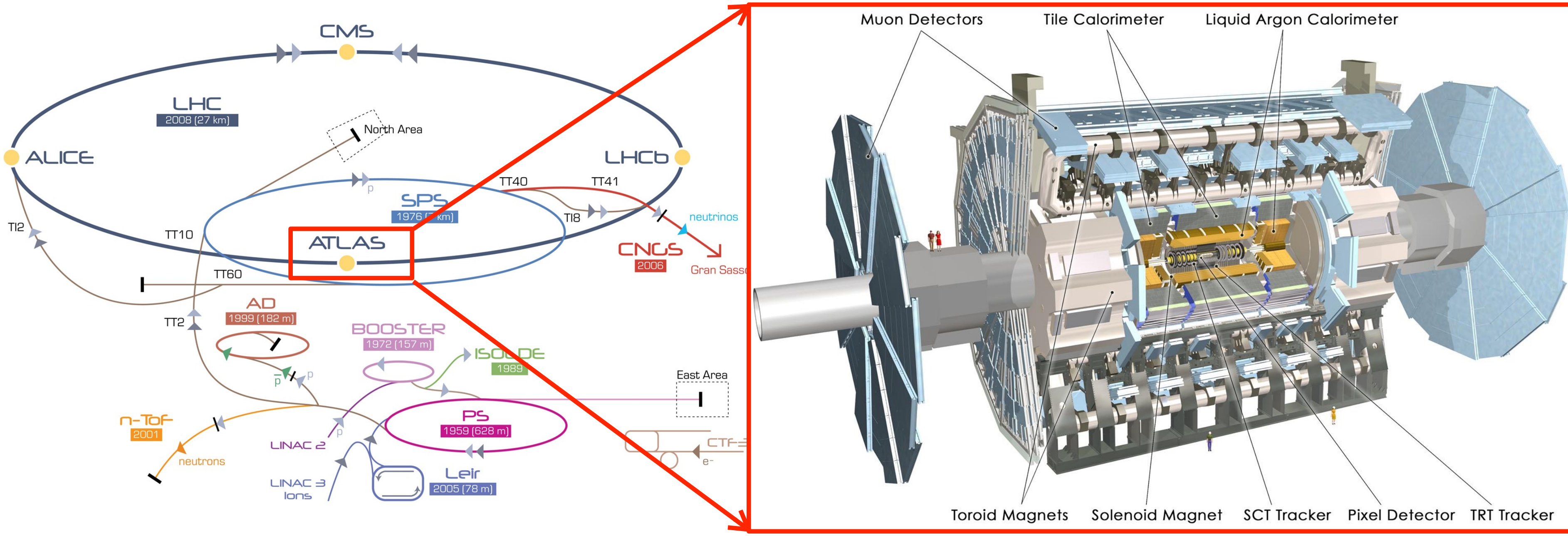
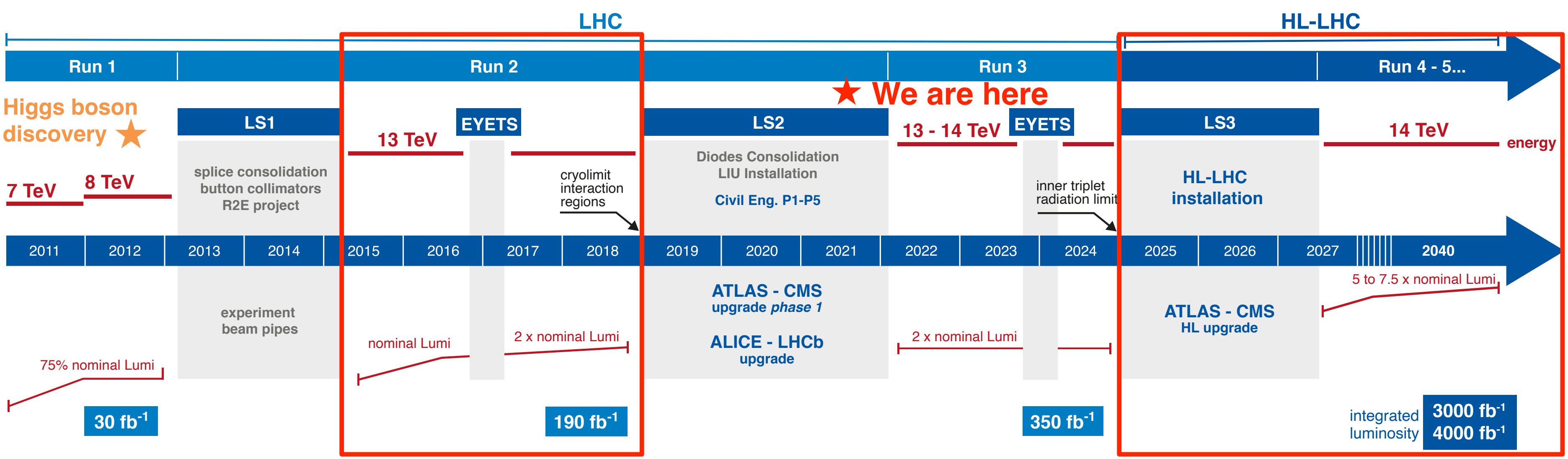
IHEP Seminar

July 7, 2021

ATLAS EXPERIMENT

The ATLAS experiment



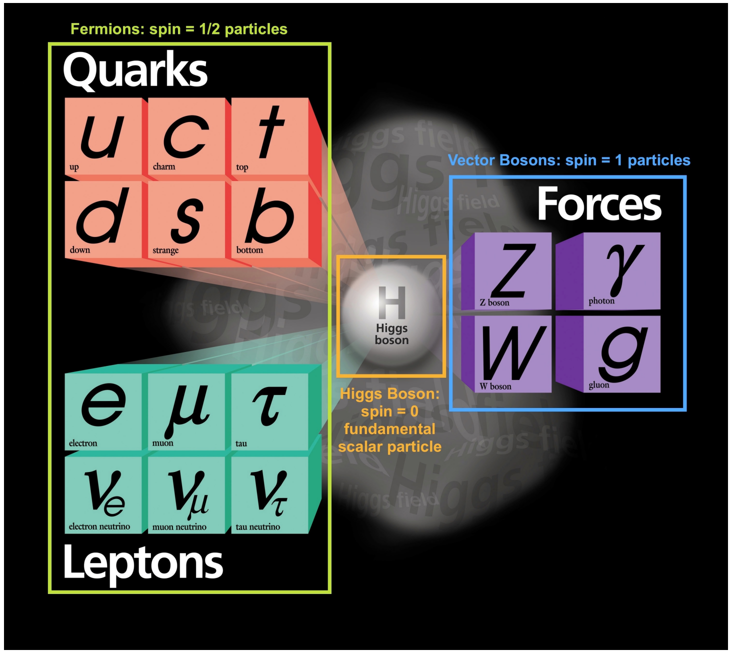


Study of CP properties of top-Higgs interaction in ttH/tH, H→γγ channel

PRL 125 (2020) 061802, CERN news

The Higgs boson

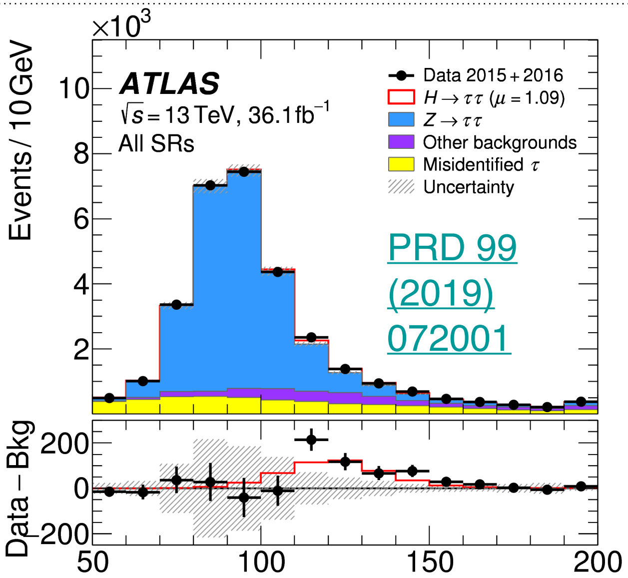
- In the Standard Model (SM), the Brout-Englert-Higgs mechanism is responsible for providing masses to elementary particles
- Higgs boson coupling measurements serve as golden test bench of SM and portal to probe potential new physics



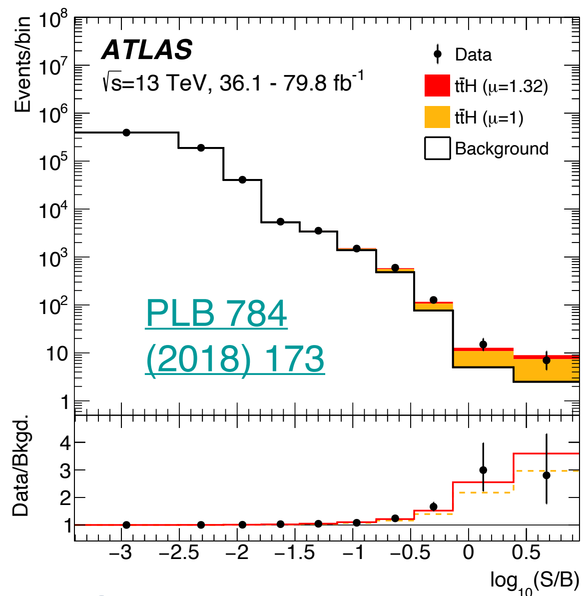
Fish discovered water

F. Wilczek

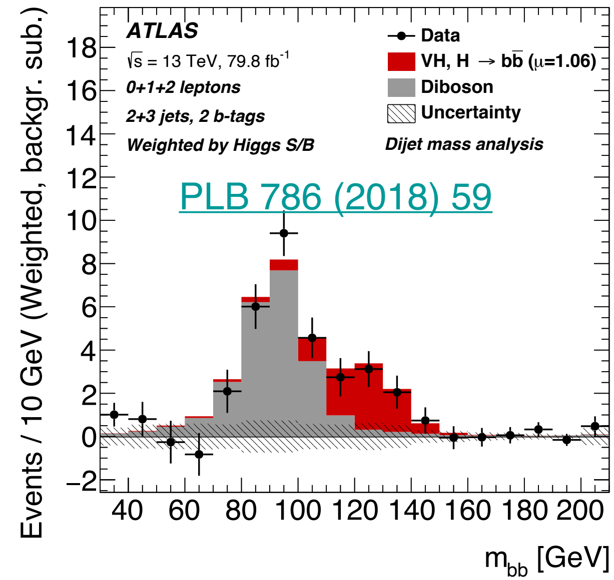
Big news in Run 2: Yukawa couplings



Single experiment observation of H→ττ

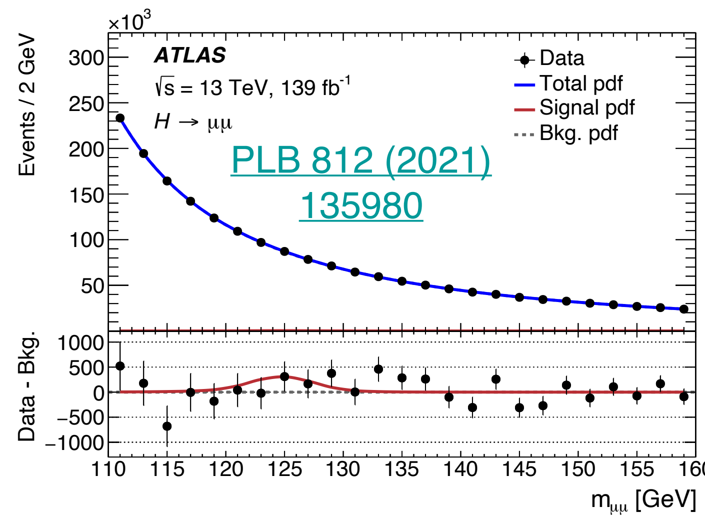


Observation of ttH

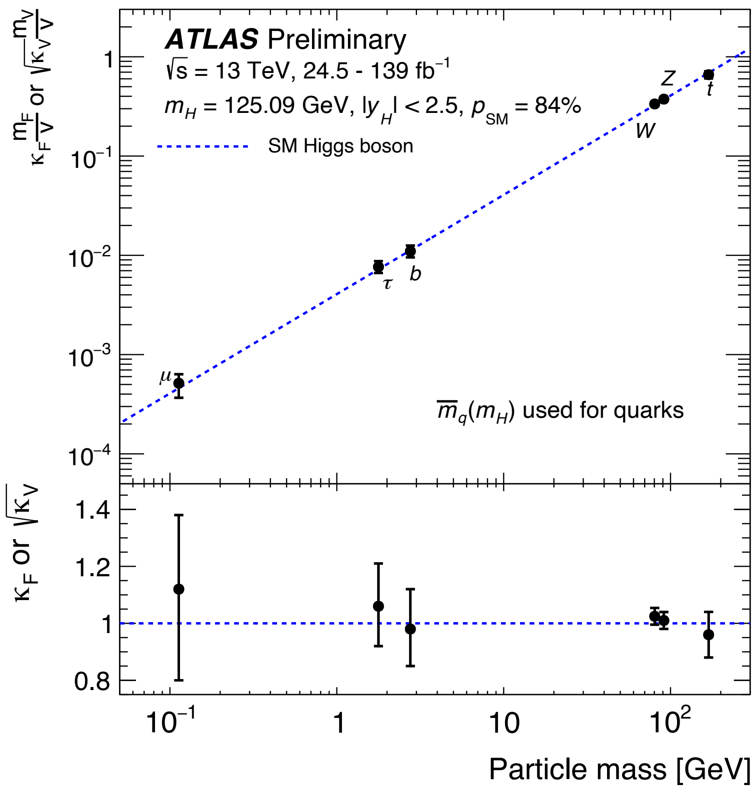


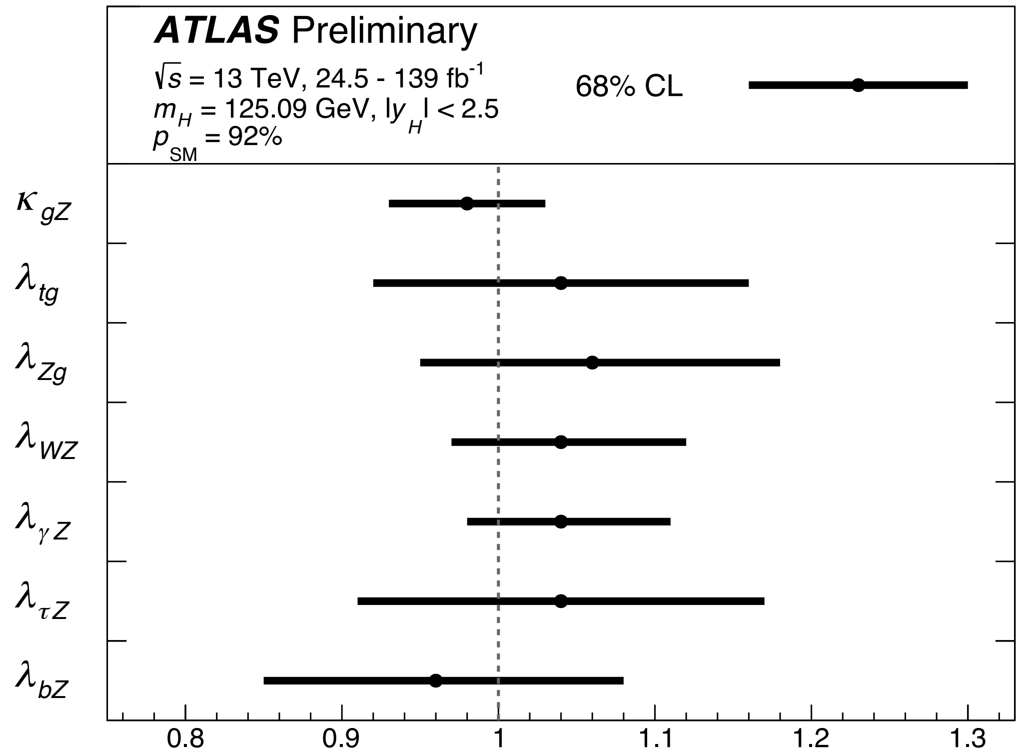
Observation of H→bb+VH

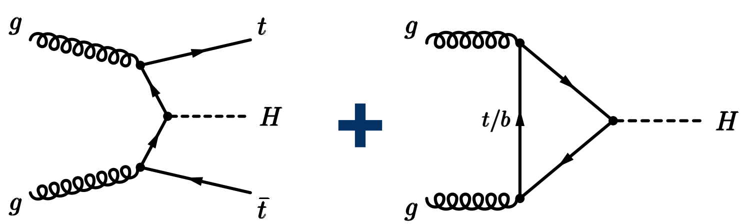
- **Direct observation of 3rd generation fermion Yukawa couplings all established**. Among them, **top Yukawa coupling** is particularly interesting
  - Largest (O(1)) Yukawa coupling in SMs
  - Rich phenomenology at LHC
- First evidence of 2nd generation Yukawa coupling

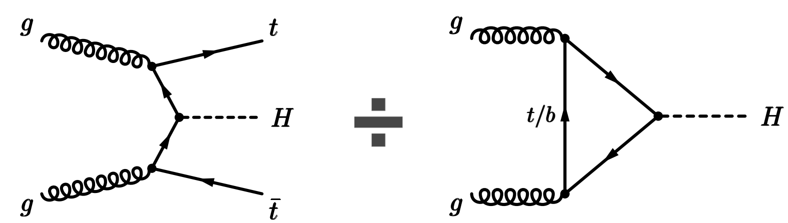


Measurement of top Yukawa coupling strength







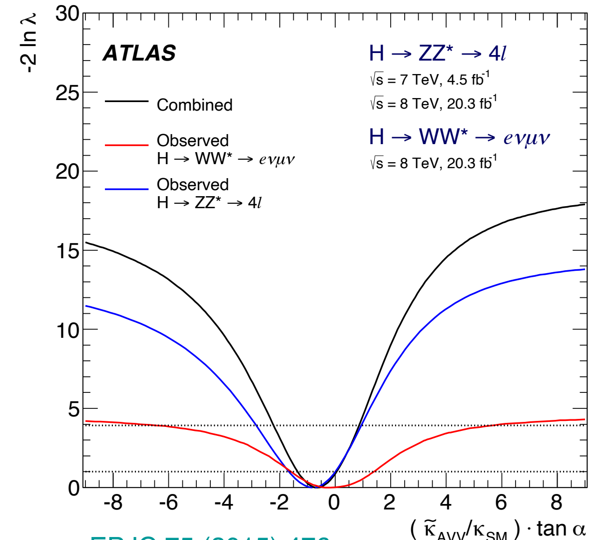


$\kappa_t = 0.96 \pm 0.08$

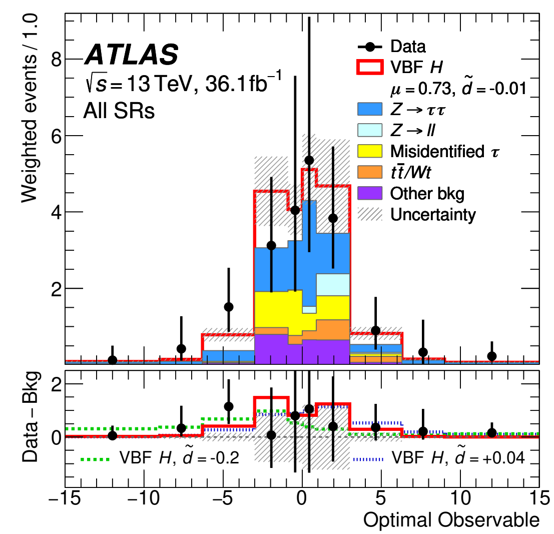
$$\lambda_{tg} = \frac{\kappa_t}{\kappa_g} = 1.04 \pm 0.12$$

Probe CP mixing in Higgs sector

- Large matter-antimatter asymmetry in Universe cannot be explained by known CP violation mechanism in SM
  - Well motivated to look for additional CP violation sources
- Study of CP properties in Higgs sector started with V-H interactions in VBF production or H→VV decay since Run 1
- CP properties of fermion Yukawa coupling, on the other hand, were not **directly** studied until quite recently



EPJC 75 (2015) 476



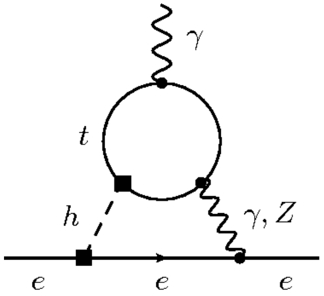
PLB 805 (2020) 135426

CP properties of top Yukawa coupling

- The Lagrangian for t-H interaction including CP mixing is

$$\mathscr{L}_t = -\frac{m}{v}\kappa_t(\cos(\alpha)\bar{t}t + i\sin(\alpha)\bar{t}\gamma_5 t)H,\ \kappa_t > 0,\ \alpha \in [-\pi, \pi]$$

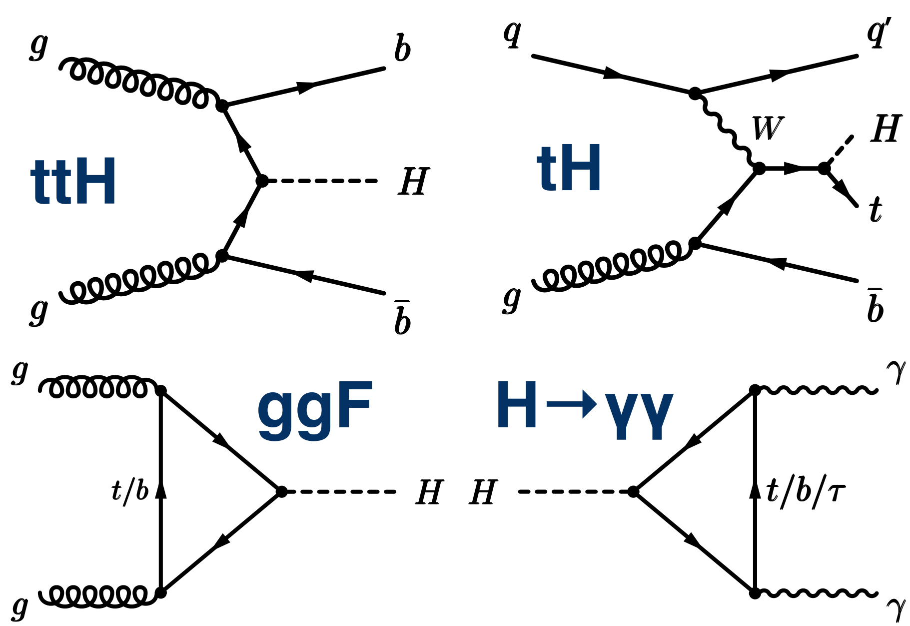
SM corresponds to **α = 0, κ_t = 1**, full CP odd is **α = 90°**

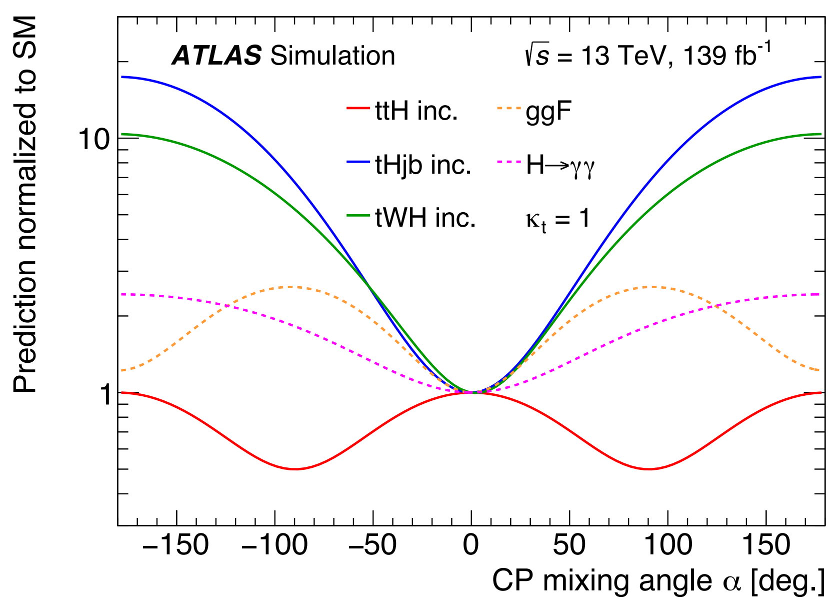


- Only **indirect** constraints on CP mixing in **t-H** interaction existed before ttH observation
  - Stringent limits from **EDMs (e, n, …)**: $\kappa_t \sin(\alpha) < 10^{-3}$
  - Also from loop-induced **H→γγ** and **ggF** rates: $\kappa_t \sin(\alpha) < \sim 0.5$
- **The ttH/tH production mode** opens a new possibility to **probe CP mixing** **directly in the top Yukawa coupling at tree-level**
- **The H→γγ channel** is ideal for this study due to excellent sensitivity and clean signature

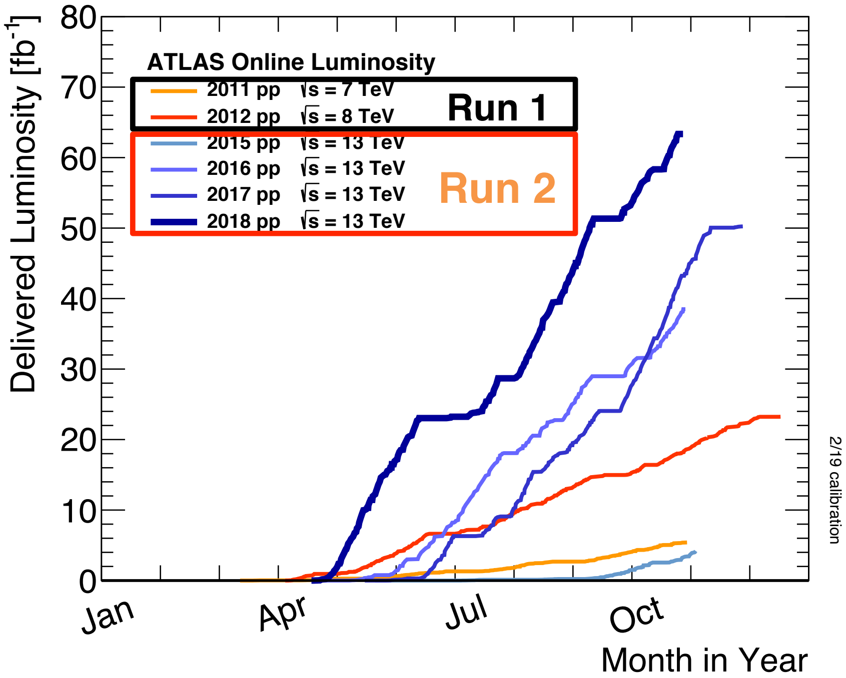
What if there is CP mixing?

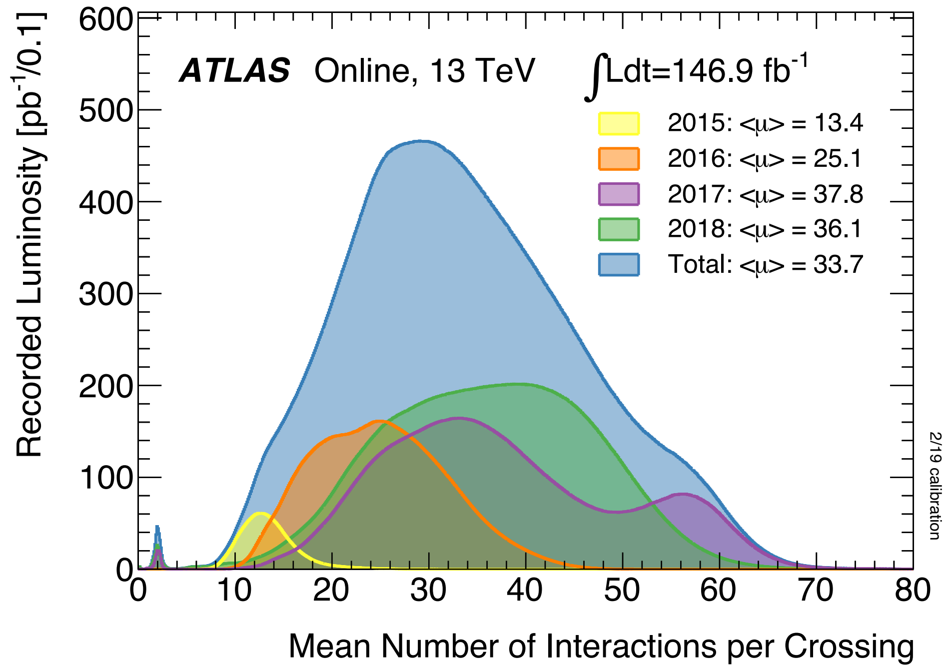
- The presence of a CP odd component in t-H coupling alters:
  - Cross sections as well as kinematics of **ttH & tH processes**: provide **direct constraint** of CP mixing in top Yukawa coupling (focus of this analysis)
  - H→γγ BR and ggF cross-sections: indirect constraint, also sensitive to other new physics scenarios





Data and Higgs boson MC samples

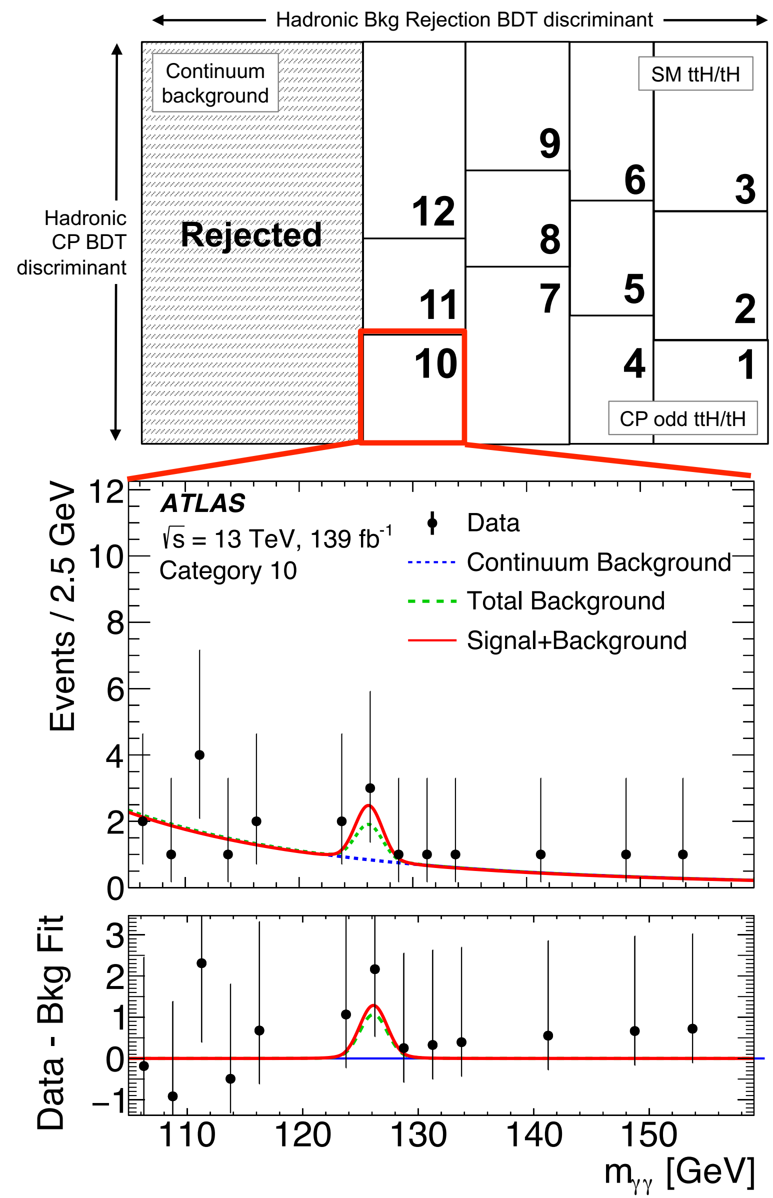




- **Full Run 2 data**: **139 fb^{-1}** of **13 TeV** proton-proton collisions collected for physics by ATLAS detector
  - Average 34 interactions per bunch crossing
- **ttH/tH MC**: MG_aMC with **Higgs Characterization** model
- Other Higgs boson production modes use standard PowHeg MC samples

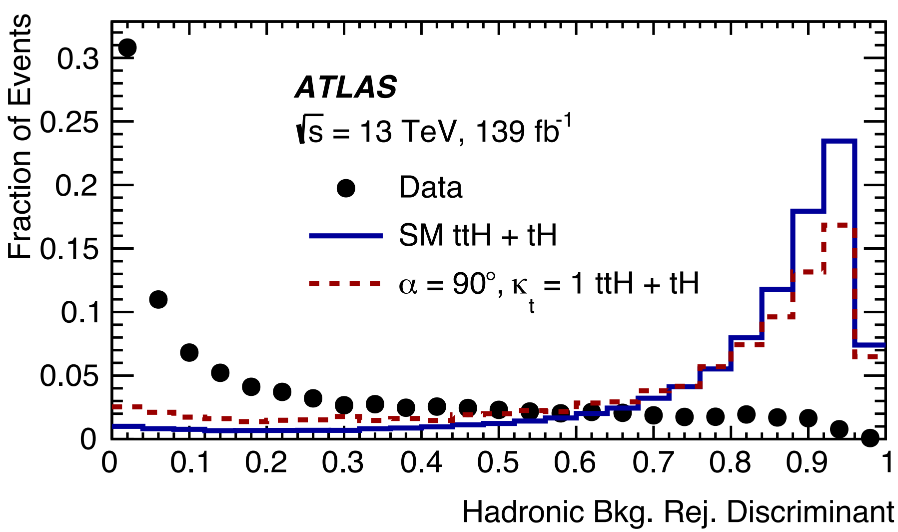
Analysis strategy

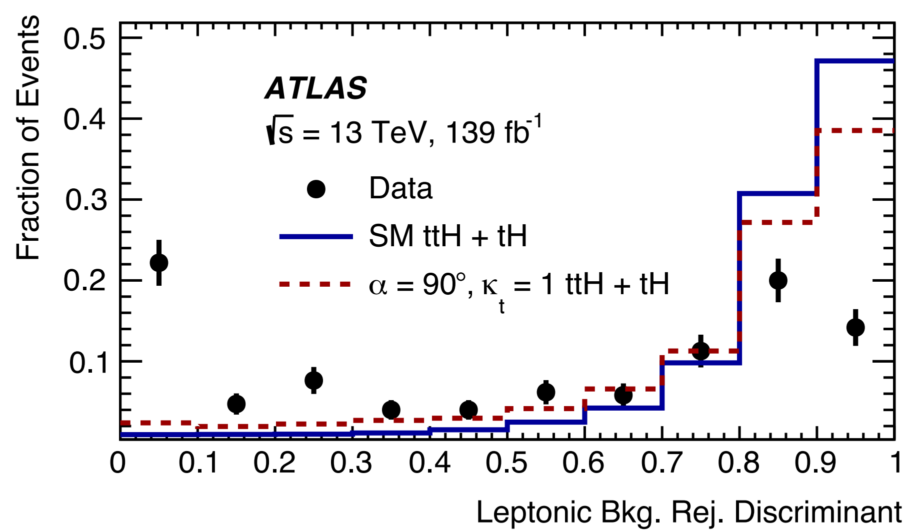
- Divide diphoton sample into two regions
  - **Hadronic** (**≥3 jets, ≥1 b-jet, 0 lep**)
  - **Leptonic** (**≥1 b-jet, ≥1 lep**)
- In each region, train following two BDTs (using XGBoost package)
  - **Bkg. rejection BDT**: separate ttH-like events from continuum background
  - **CP BDT**: separate CP-even ttH/tH events from CP-odd
- Divide categories on 2D plane of bkg. rejection vs. CP BDTs
- Fit the $m_{\gamma\gamma}$ spectrum in all categories simultaneously to extract signal



Background rejection BDT

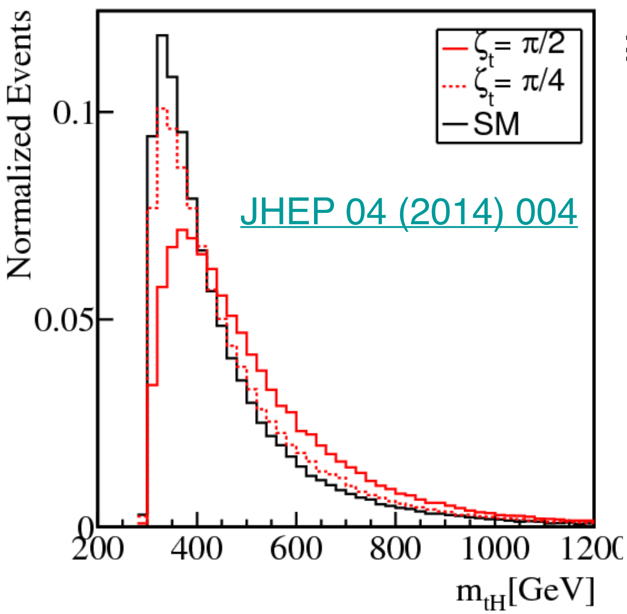
- Use the same BDT discriminant (but not categories!) from ttH search, which is trained using **low-level inputs** such as 4-vec. of γ, j, l, and MET
- Serves the purpose of CP analysis very well
  - Good rejection of background; good acceptance of ttH/tH signal
  - Weak dependence on CP mixing angle

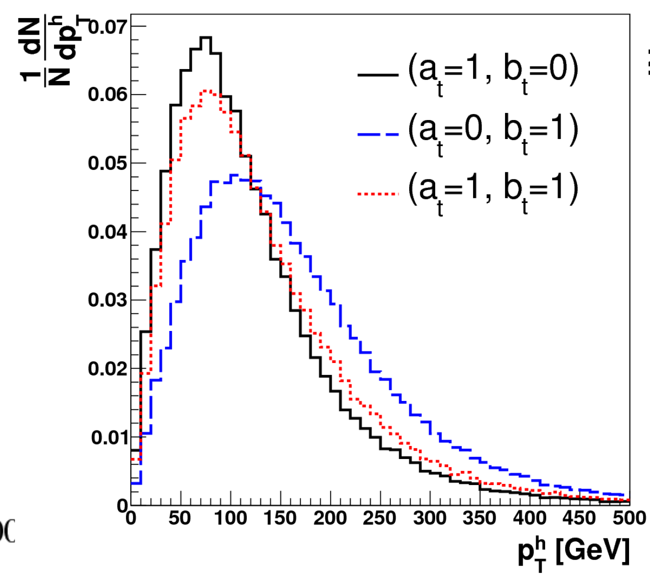


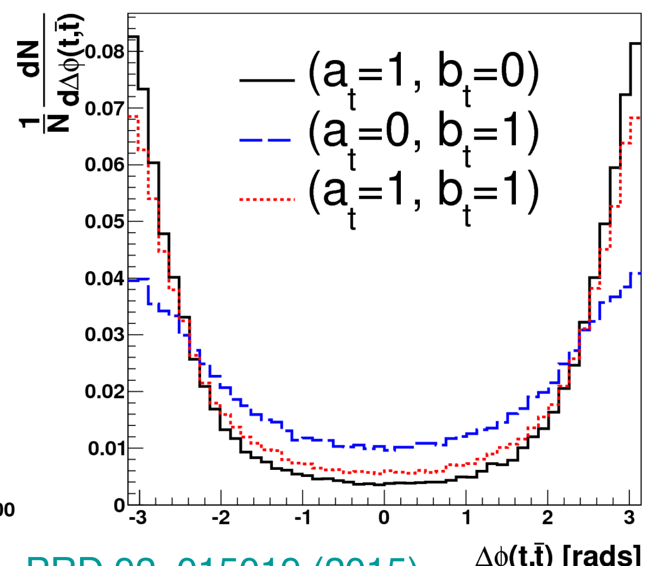


CP sensitive observables

- Compared with SM (CP even), CP odd ttH/tH gives
  - Larger m_{tH} and $m_{t\bar{t}}$; more boosted $p_T(H)$
  - Less back-to-back $\phi(t\bar{t})$; larger opening $\eta(t\bar{t})$
- Exploit shape information in this analysis. Avoid relying on normalization dependence

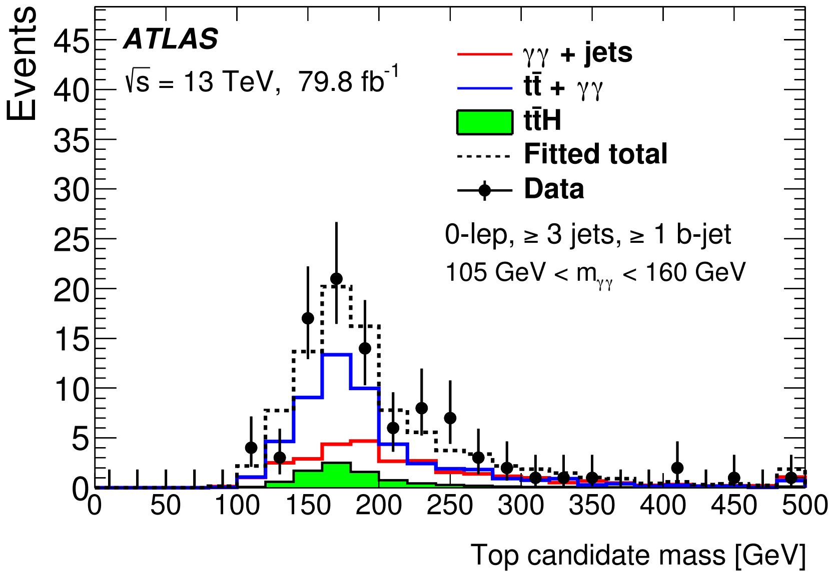


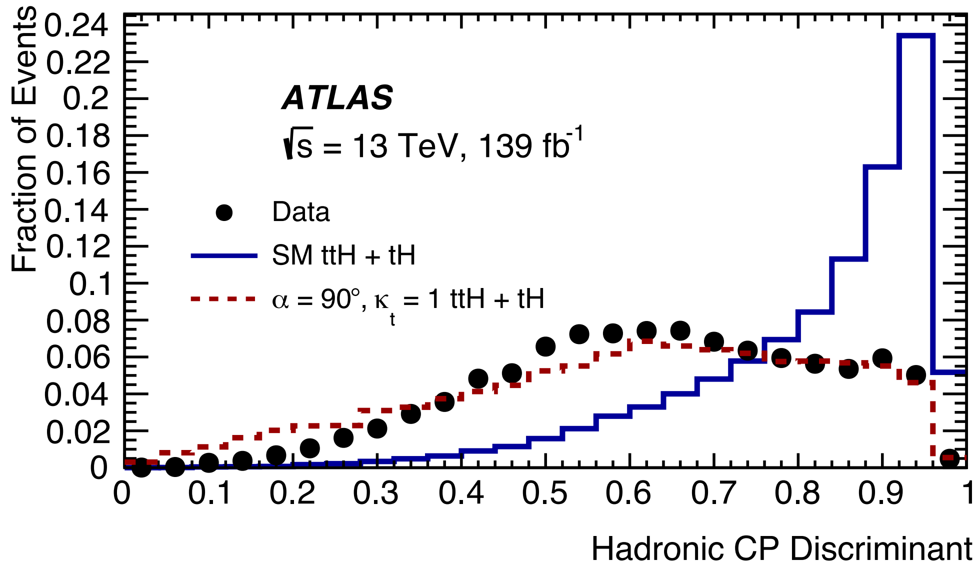




PRD 92, 015019 (2015)

CP BDT

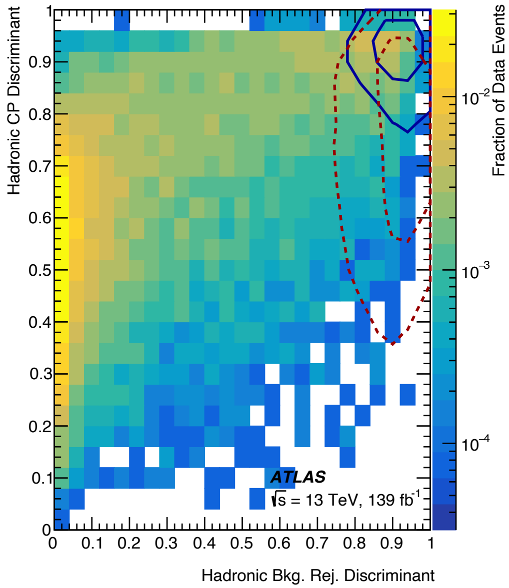


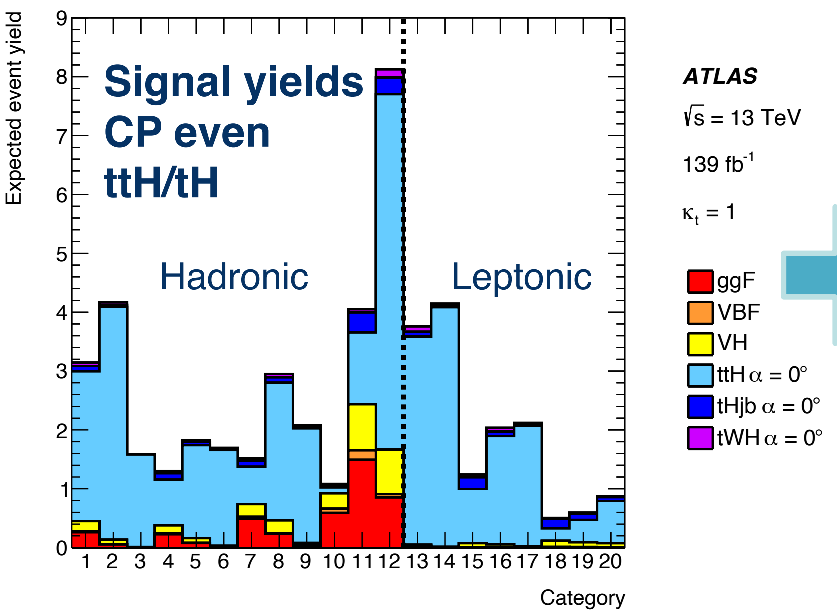


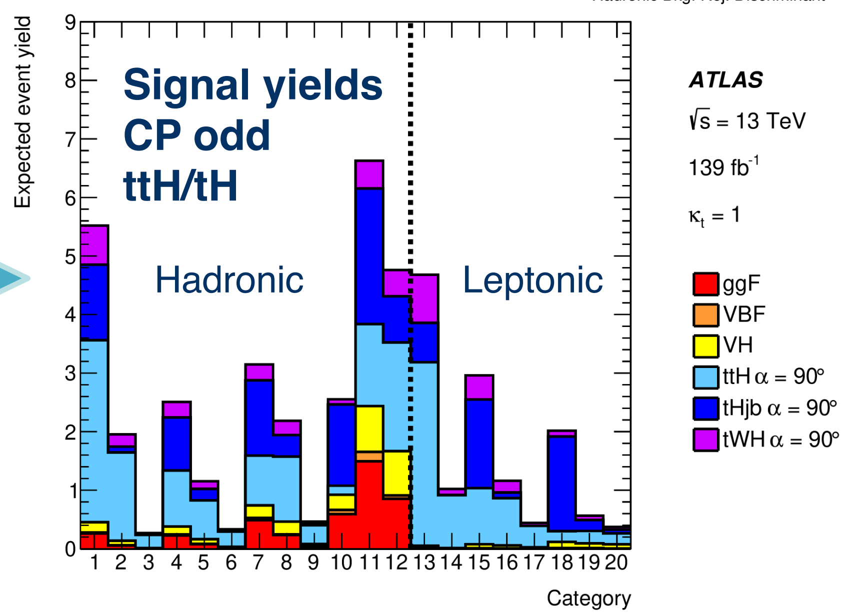
- Train **top reconstruction BDT** to reconstruct two top quarks t_1, t_2
  - Trained using ttH sample: correct pairing vs. wrong paring
  - In case t_2 cannot be built, sum up all remaining objects as t_2
- Train **CP BDT** to separate between **CP even** and **CP odd** ttH+tH
  - p_T / η of diphoton system; H_T, n_{jets}, n_{bjets}, $\Delta R(\gamma, j)$
  - p_T / η / ϕ / **top reco. BDT** score of t_1 and t_2, $m_{t_1 H}$, $m_{t_1 t_2}$, $\phi(t_1 t_2)$, $\eta(t_1 t_2)$

Categorization

- Scan category boundaries on 2D bkg. rejection BDT vs. CP BDT plane to optimize both SM ttH significance and CP separation
- **20 analysis categories** defined in total
  - 12 categories in hadronic region, 8 in leptonic



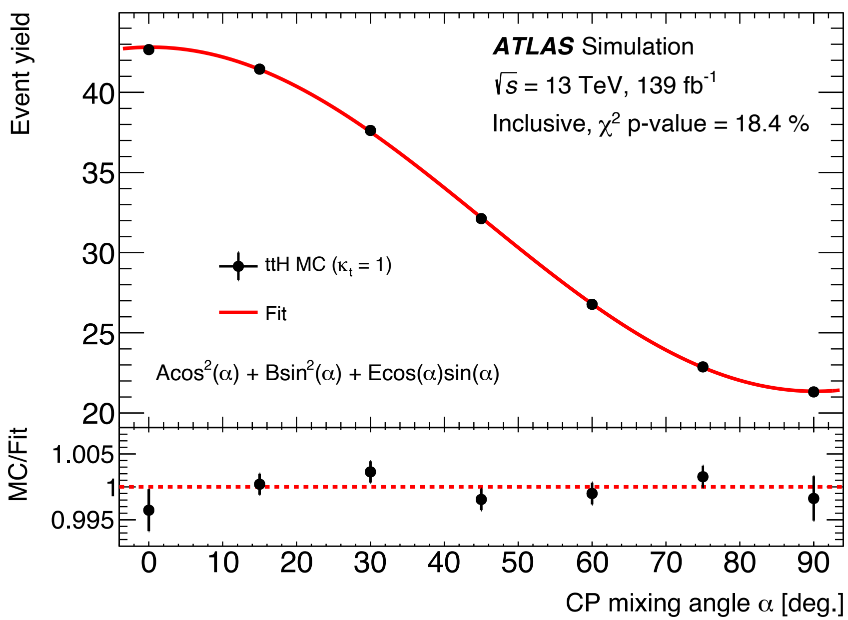




ttH signal yield parameterization

- Parameterize **ttH** and **tH** signal yields in each category as **mixing angle** α and **top Yukawa coupling strength** κ_t
- For ttH process, use

$$A\kappa_t^2\cos^2(\alpha) + B\kappa_t^2\sin^2(\alpha) + E\kappa_t^2\sin(\alpha)\cos(\alpha)$$



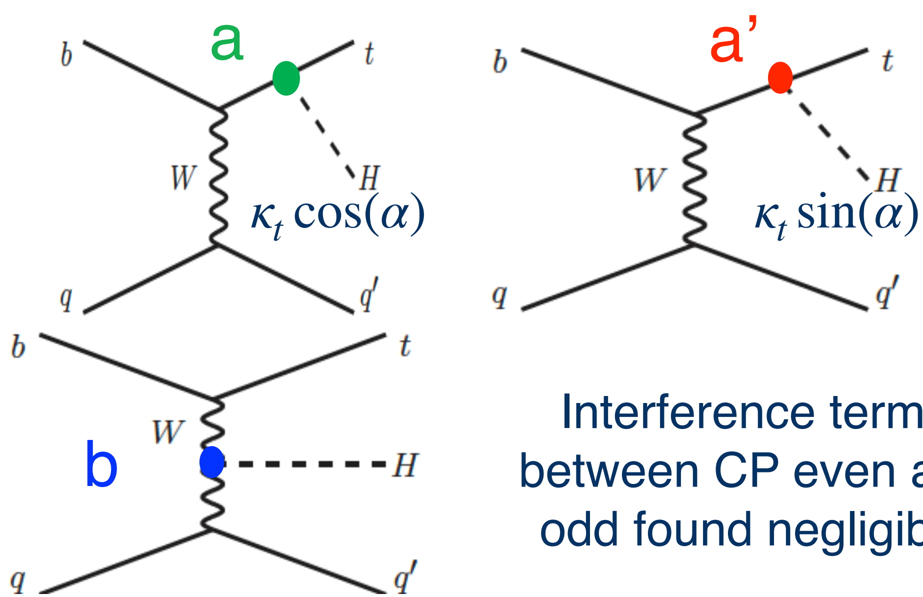
- Parameterization describe MC predictions well in all categories
- Coefficient E for interference term found to be negligible as expected

tH signal yield parameterization

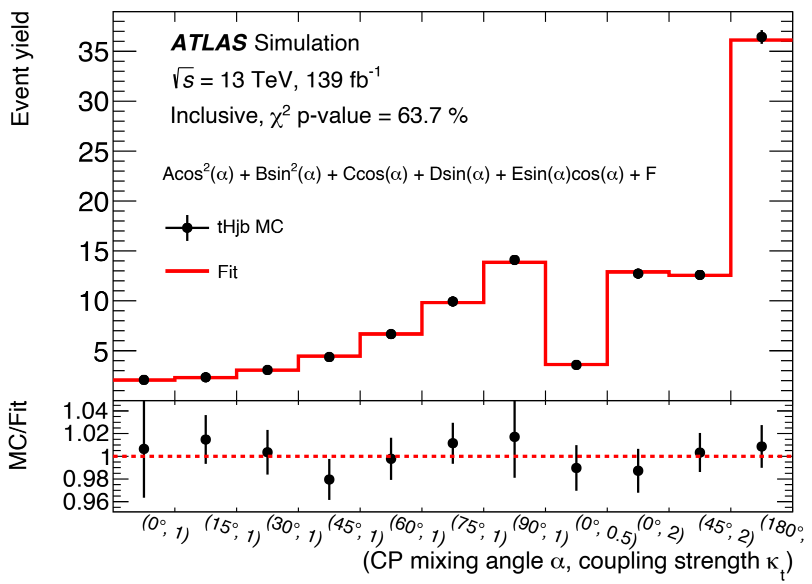
- For tHW and tHjb processes, need to use more complicated parameterizations considering interference between t-H and W-H

$$A\kappa_t^2\cos^2(\alpha) + B\kappa_t^2\sin^2(\alpha) + C\kappa_t\cos(\alpha) + D\kappa_t\sin(\alpha) + E\kappa_t^2\sin(\alpha)\cos(\alpha) + F$$

a² — a'² — 2 Re(a b) — 2 Re(a' b) — 2Re(a a') — b²



Interference terms between CP even and odd found negligible

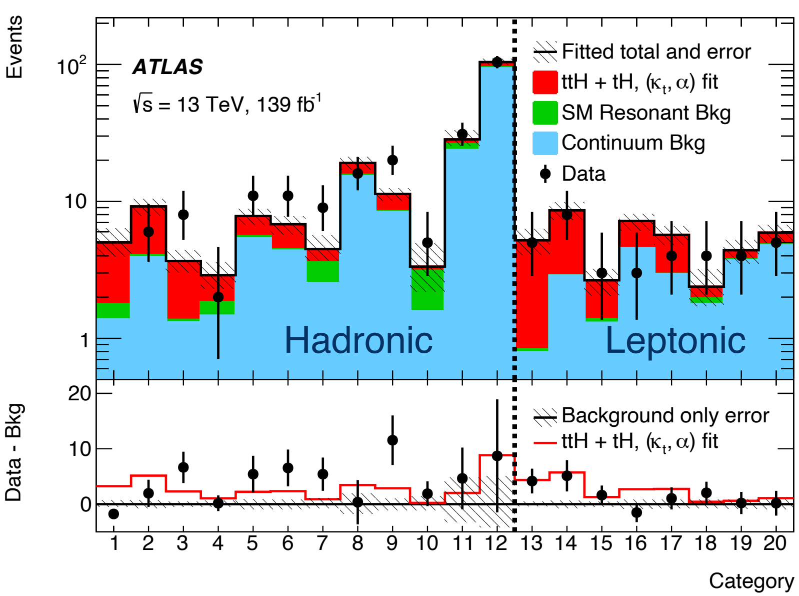


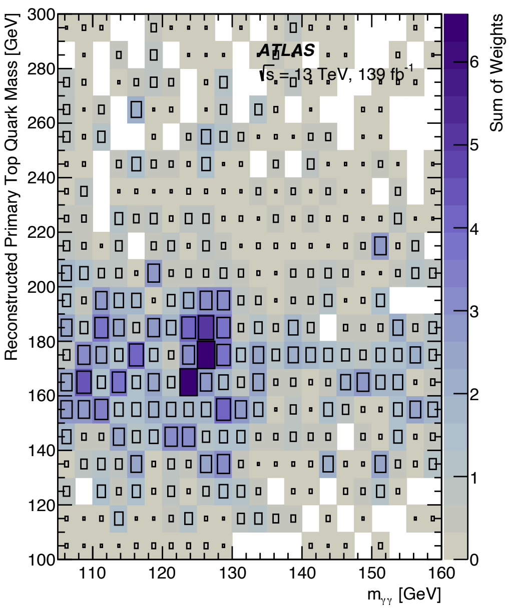
ttH and tH cross-section measurements

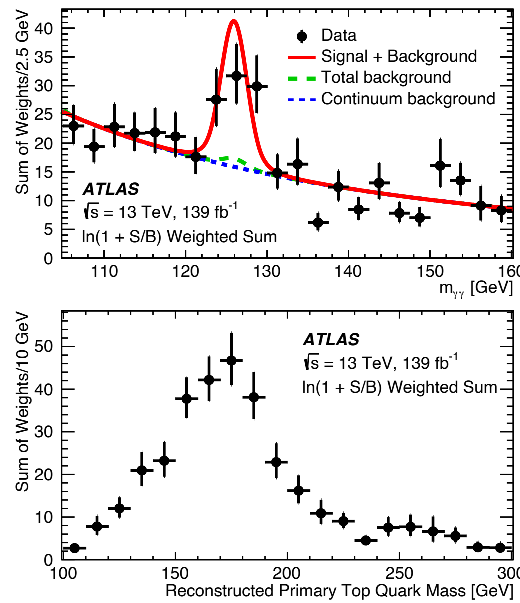
- **Single-channel ttH observation at 5.2σ,** assuming SM for other prod. modes

$$\mu = 1.43^{+0.33}_{-0.31}(\text{stat.})^{+0.21}_{-0.15}(\text{syst.})$$

- tH cross-section < 12×SM @95% CL

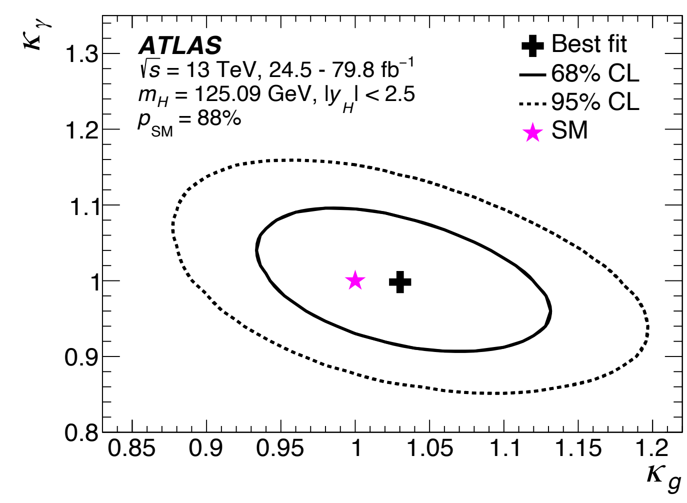


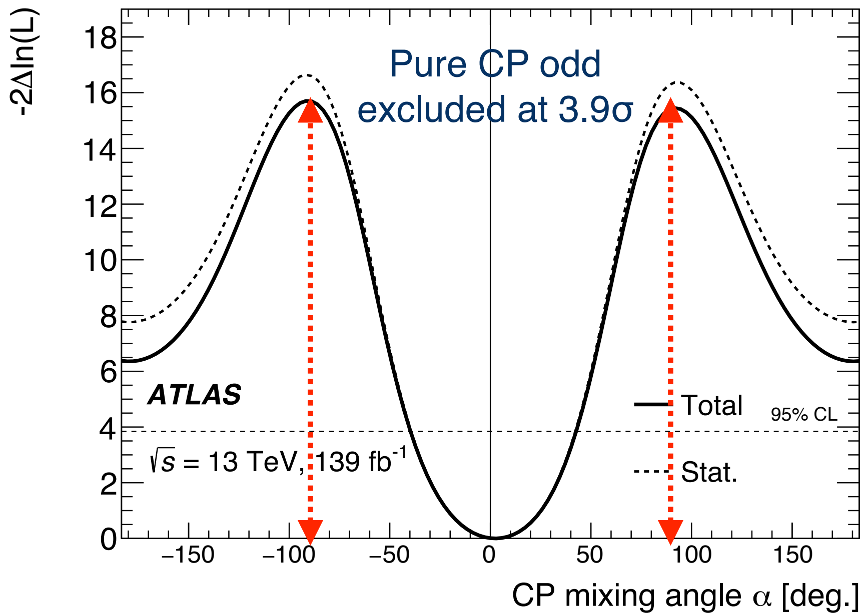


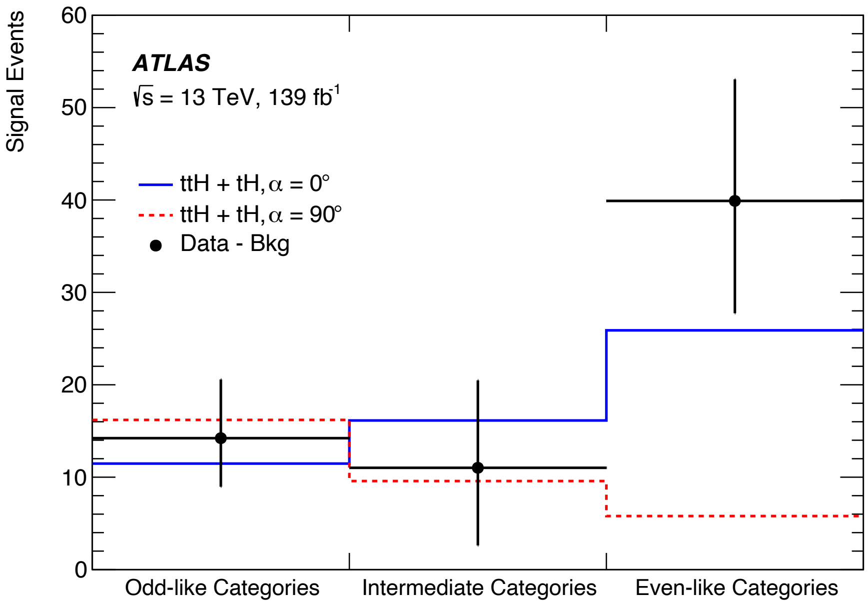


CP constraint: not resolve H→γγ/ggF loops

- Provide **direct** constrain mixing angle α using **only ttH and tH info**
  - Use κ_γ **vs** κ_g **contour (80 fb^{-1})** to constrain H→γγ and ggF rates
- **|α| > 43°** excluded @95% CL **without assumption on κ_t**





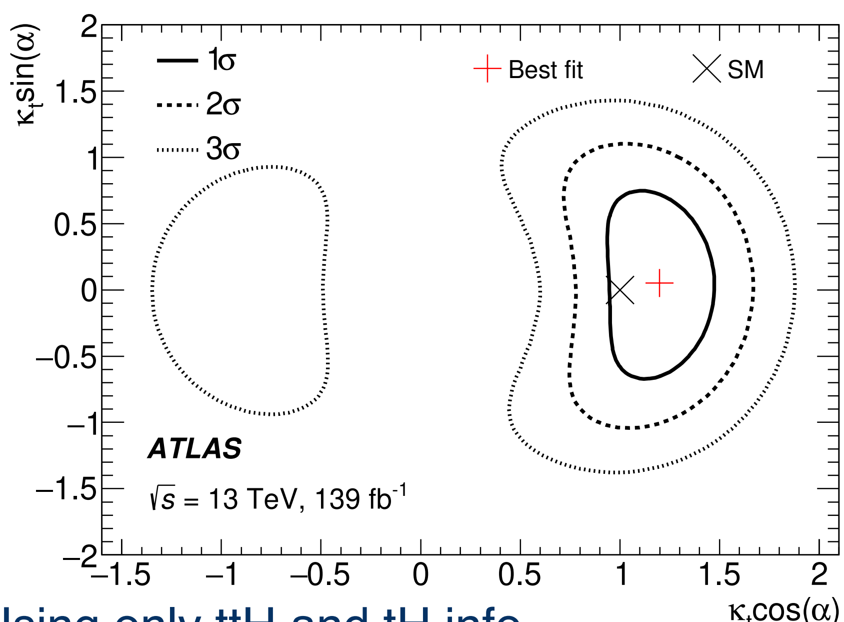


CP constraint: resolve H→γγ/ggF loops

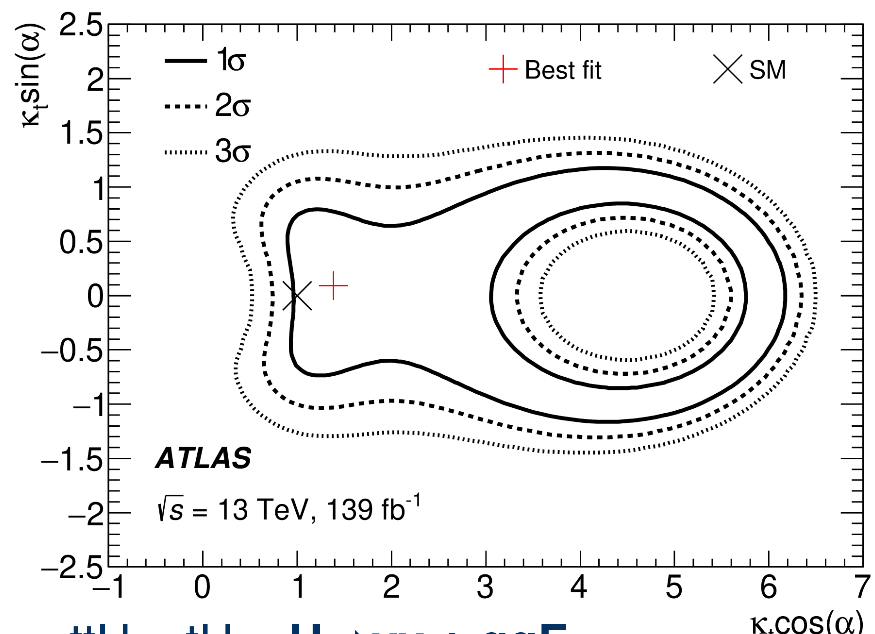
- Assume potential new physics in H→γγ/ggF is only in t-H coupling, and can be parameterized as function of α and κ_t (Ellis et. al. JHEP 04 (2014) 004)

$$\kappa_g^2 = \kappa_t^2 \cos^2(\alpha) + 2.6\kappa_t^2 \sin^2(\alpha) + 0.11\kappa_t \cos(\alpha)(\kappa_t \cos(\alpha) - 1)$$
$$\kappa_\gamma^2 = (1.28 - 0.28\kappa_t \cos(\alpha))^2 + (0.43\kappa_t \sin(\alpha))^2$$

- Exclude **$|\alpha| > 43°$ @95% CL without assumption on κ_t**



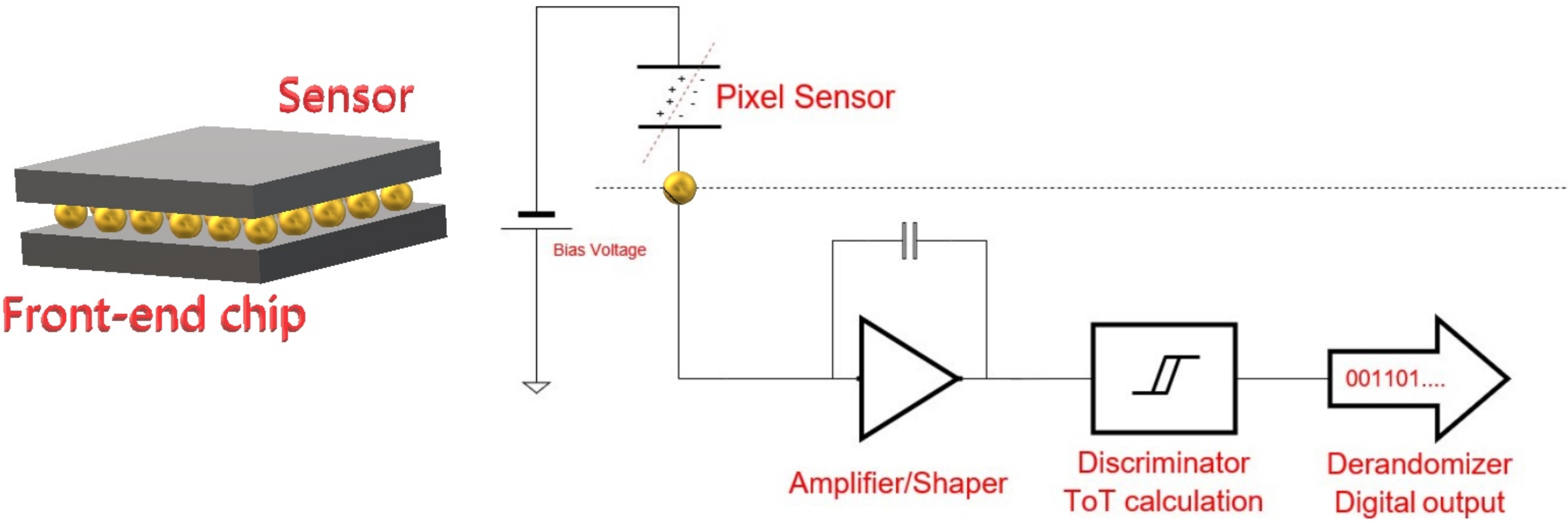
Using only ttH and tH info



ttH + tH + **H→γγ + ggF**

Testing of ATLAS HL-LHC Pixel detector readout chip

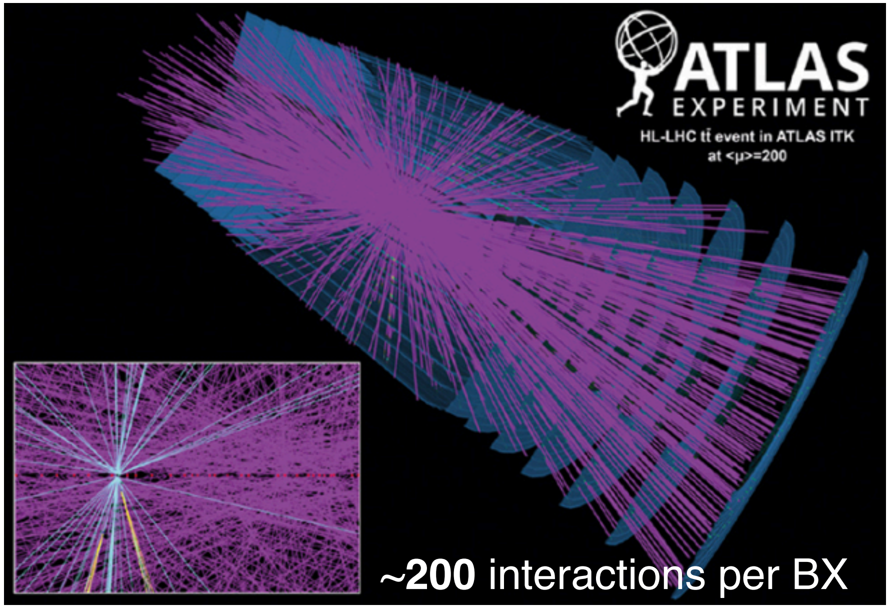
Schematic of pixel module



- Our focus today will be on the front-end readout chip

ATLAS Pixel detector at HL-LHC

- Pixel detector is at the center of ATLAS detector. It is essential for vertex reconstruction and tracking of charged particles
- At High-Luminosity LHC (HL-LHC), Pixel detector will be upgraded to cope with **extreme data rate and irradiation**
  - Designing a readout front-end chip that meets the requirements is one of the greatest challenges of the upgrade project



Requirements for readout chip

- Reduced pixel size
- Analog FE operates at low threshold and has low power consumption
- Large enough output bandwidth + highly compressed data stream
- Large module size; serial powering
- Radiation hard…

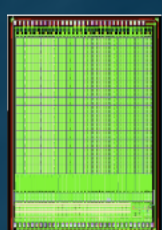
RD53 Timeline

RD53 Collaboration LOI

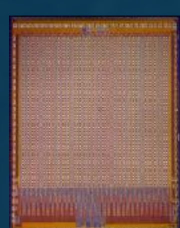
02/2013

12/2015

FE65-P2 and CHIPIX prototype chips



CHIPIX (64x64)



FE65-P2 (64x64)

RD53A chip submission

11/2017

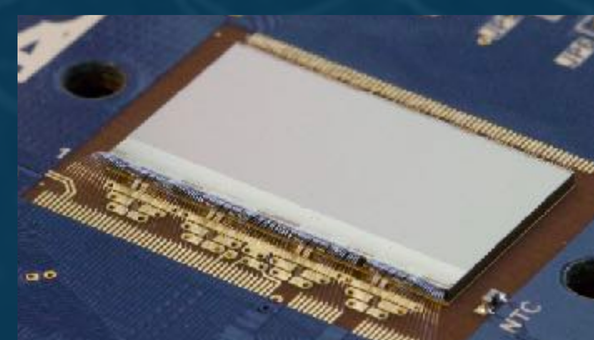
12/2018

RD53A AFE review & design validation finished

RD53 Collaboration

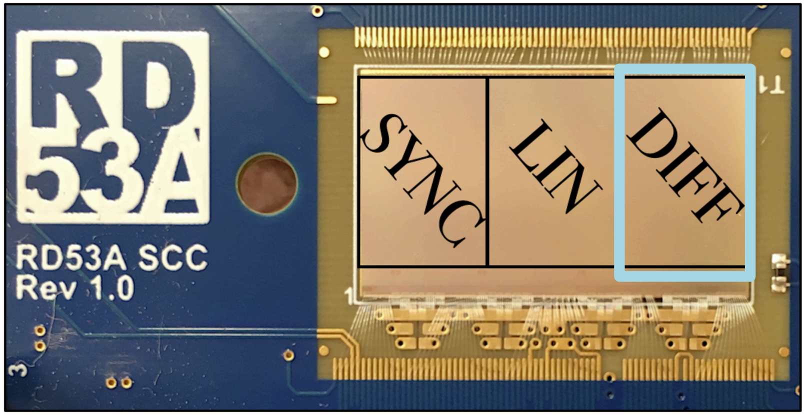
22 collaborating institutes

RD53A (400x192)

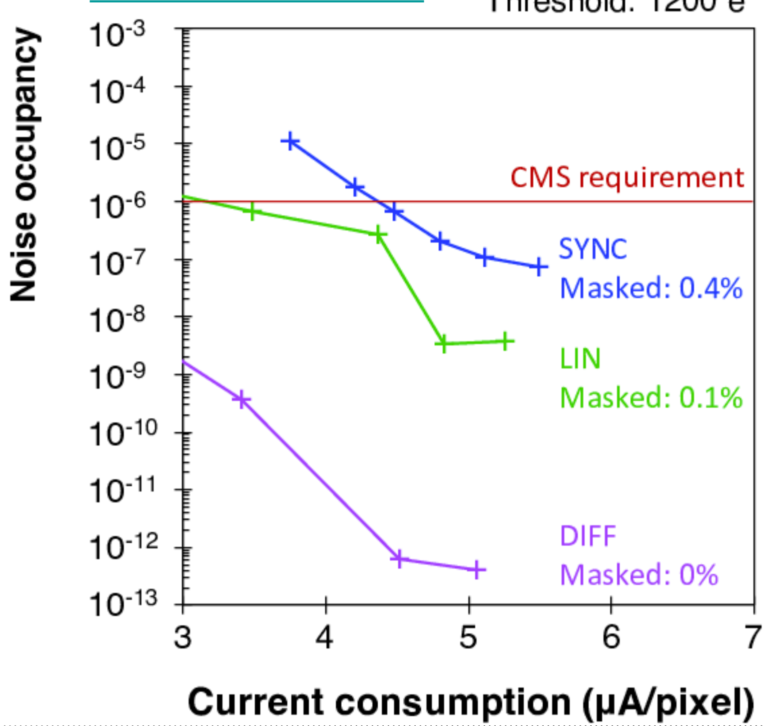


Analog FE technologies tested on RD53A

- Three analog FE technologies tested on the pre-ITkPix-V1 demonstrator chip **RD53A**
- ATLAS experiment decided to choose **differential FE** for Phase 2 Inner Tracker (ITk) Pixel upgrade
  - Main advantage: **able to operate at low current without noise issues**
  - Known caveats in RD53A differential analog FE design
    - **Timing precision problem**
    - **Not radiation hard**

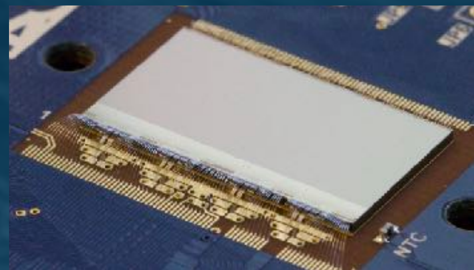


arXiv:2105.00070



RD53 Timeline

RD53A (400x192)



RD53 Collaboration LOI

02/2013

RD53A chip submission

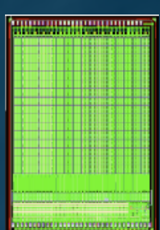
11/2017

RD53B design finished

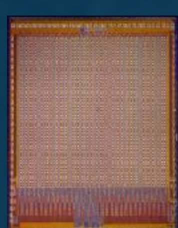
11/2019

12/2015

FE65-P2 and CHIPIX prototype chips



CHIPIX (64x64)



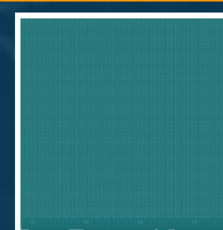
FE65-P2 (64x64)

12/2018

RD53A AFE review & design validation finished

03/2020

ITkPixV1 submission



ITkPixV1 (400x384)

ITkPix-V1 pixel readout chip

- ITkPix-V1 is supposed to be the pre-production chip for ATLAS Phase 2 ITk Pixel
  - **Great advantage over FE-I4 chip used on current ATLAS Insertable B-Layer (IBL)**
  - Improved from RD53A in almost every aspect

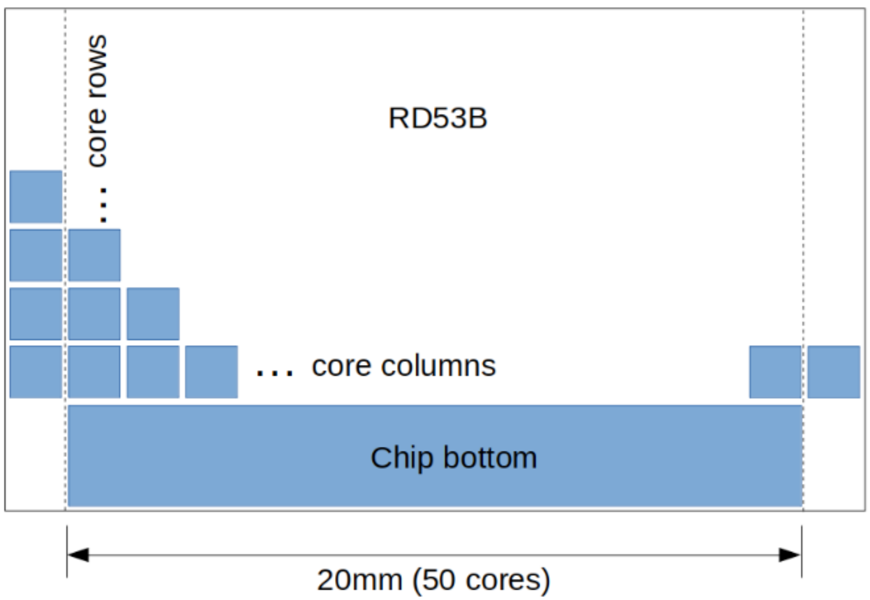
Readout chip	Number of pixels	Pixel size	Pixel hit rate	Trigger rate
ITkPix-V1	153600 (in 2×2 cm^2)	50×50 μm^2	3 GHz/cm^2	4/1 MHz
FE-I4	26880 (in 2×2 cm^2)	50×250 μm^2	400 MHz/cm^2	100 kHz

Readout chip	Trigger latency	Current consumption	Radiation tolerance	Min. stable threshold
ITkPix-V1	12.8/51.2 µs	< 8 µA/pixel	0.5 Grad	1000 e
FE-I4	6.4 µs	20 µA/pixel	300 Mrad	1500 e

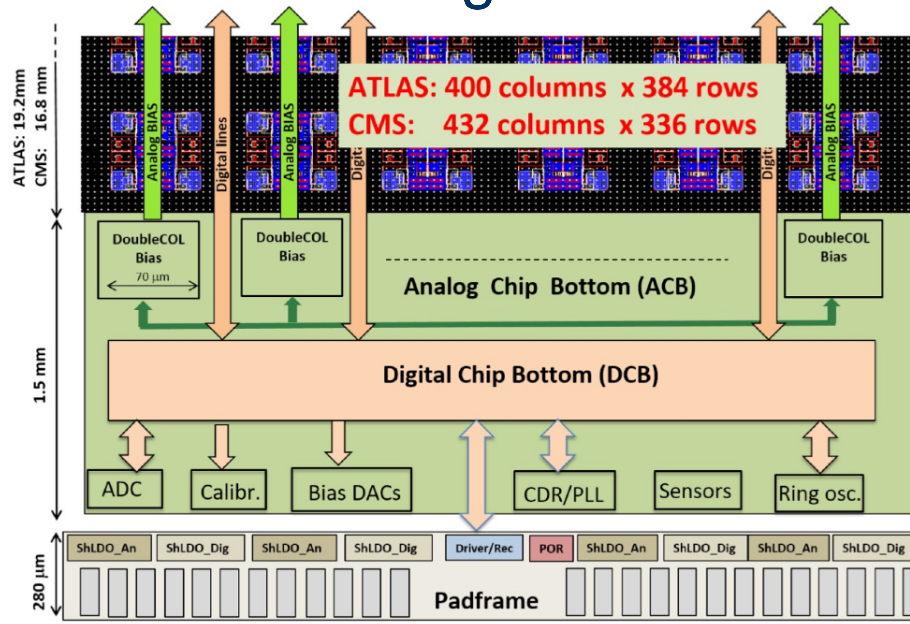
ITkPix-V1 vs. FE-I4 (used in current ATLAS Insertable B-Layer) specifics

ITkPix-V1 overview

Digital view



Analog view

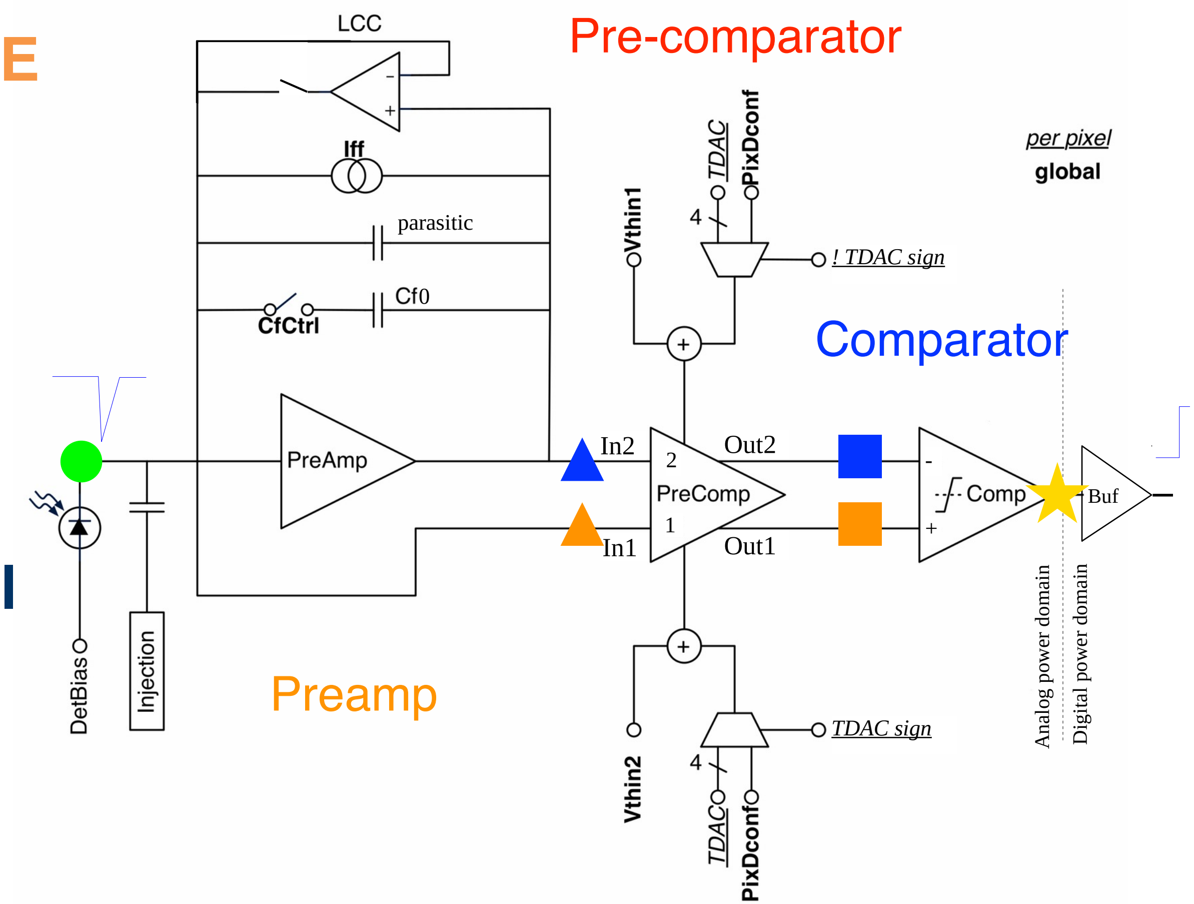


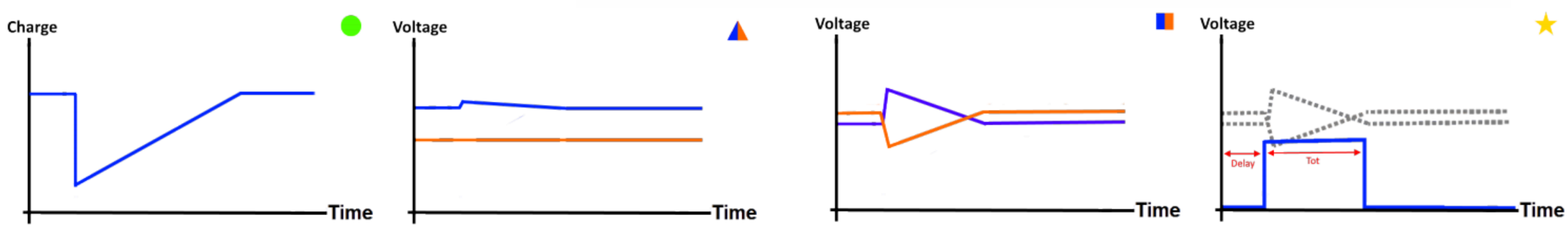
- Organized in **8×8 digital cores**
- Cores are stepped & repeated to create pixel matrix
- Cores are interconnected for configuration & readout

- Analog islands organized in 2×2 pixels on digital sea
- Multiple blocks integrated in analog chip bottom

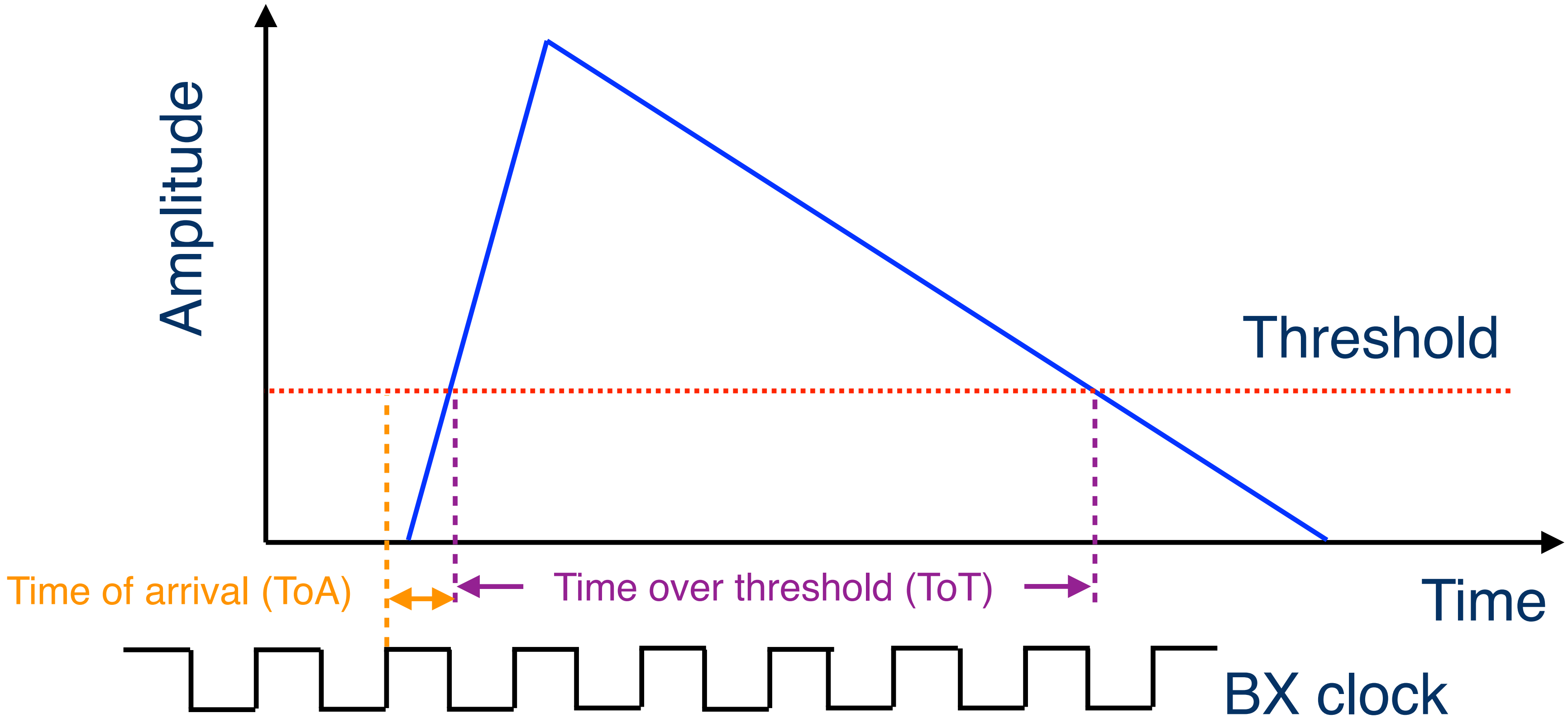
Differential analog FE in ITkPix-V1

- **Differential analog FE in ITkPix-V1** is significantly improved from RD53A
- It features **low noise** and **fast time-walk**, optimized for **minimal power consumption** and **radiation hardness**





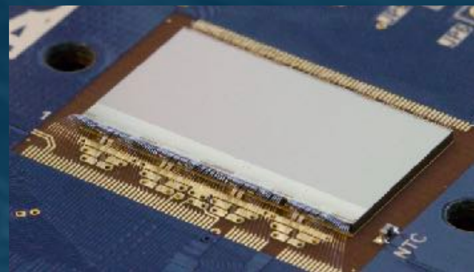
Data from ITkPix-V1



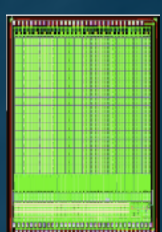
- Data stream from ITkPix-V1 is highly compressed to cope with high occupancy at HL-LHC. Decoding becomes a great challenge!
  - Hit map compressed with binary tree + Huffman coding
  - Pixel address compressed when it is close to other firing pixels

RD53 Timeline

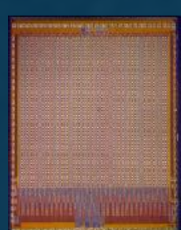
RD53A (400x192)



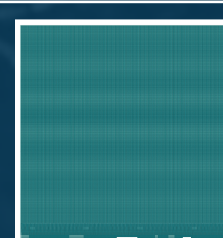
- 02/2013 — RD53 Collaboration LOI
- 12/2015 — FE65-P2 and CHIPIX prototype chips
- 11/2017 — RD53A chip submission
- 12/2018 — RD53A AFE review & design validation finished
- 11/2019 — RD53B design finished
- 03/2020 — **ITkPixV1 submission**
- 06/2020 — **ITkPix-V1 delivered to testing sites**



CHIPIX
(64x64)

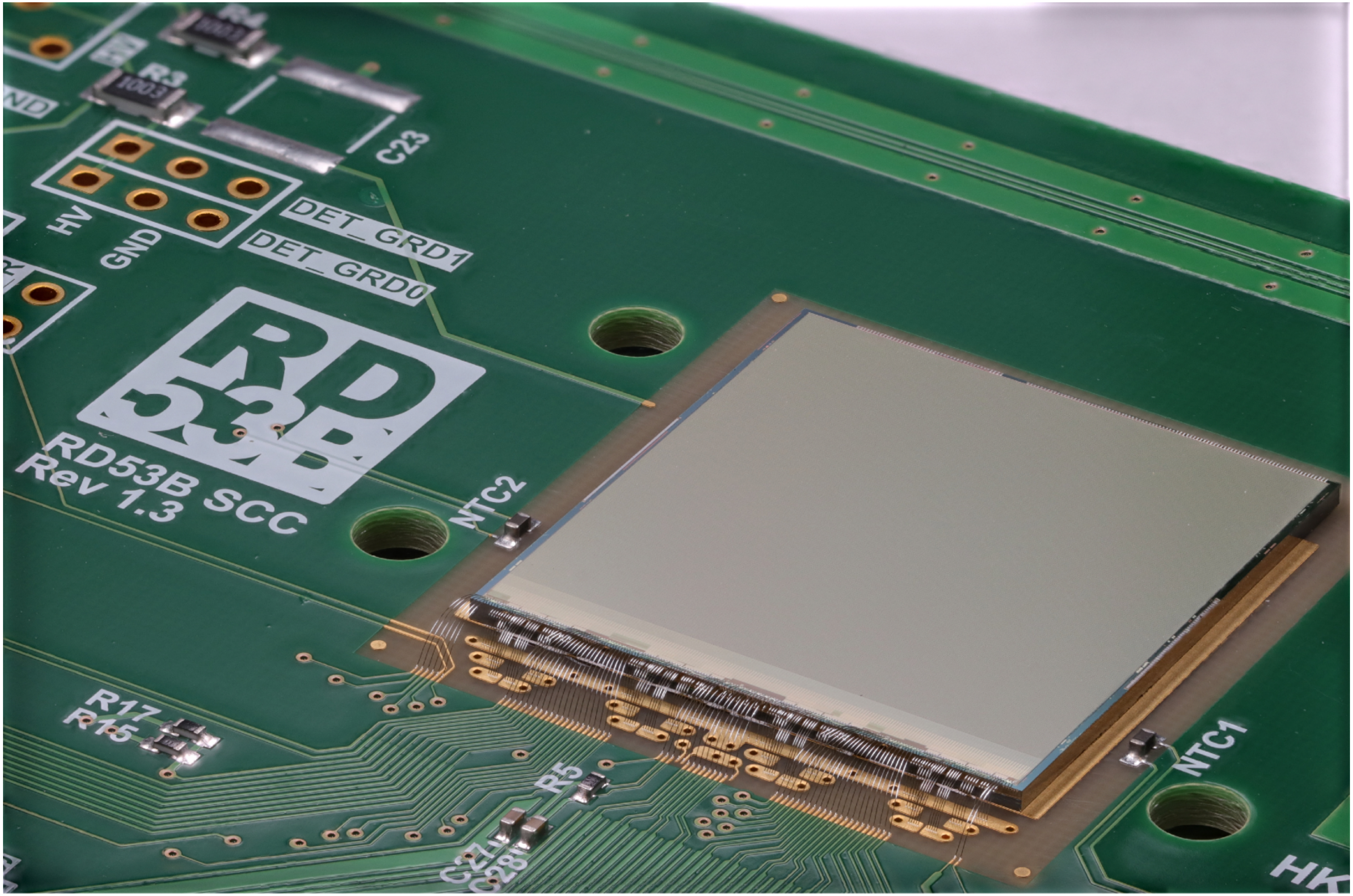


FE65-P2
(64x64)



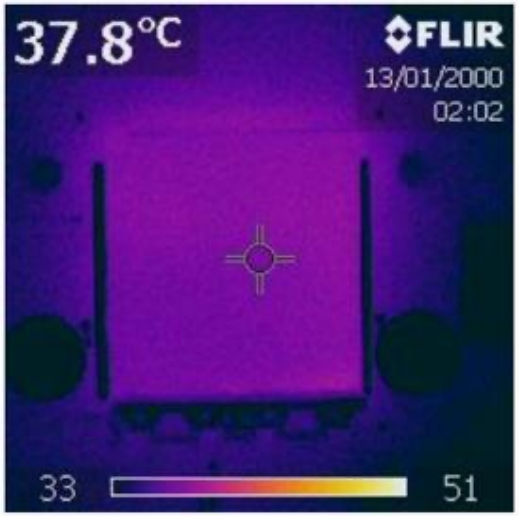
ITkPixV1
(400x384)

ITkPix-V1 on Single Chip Card



Unexpected high digital current

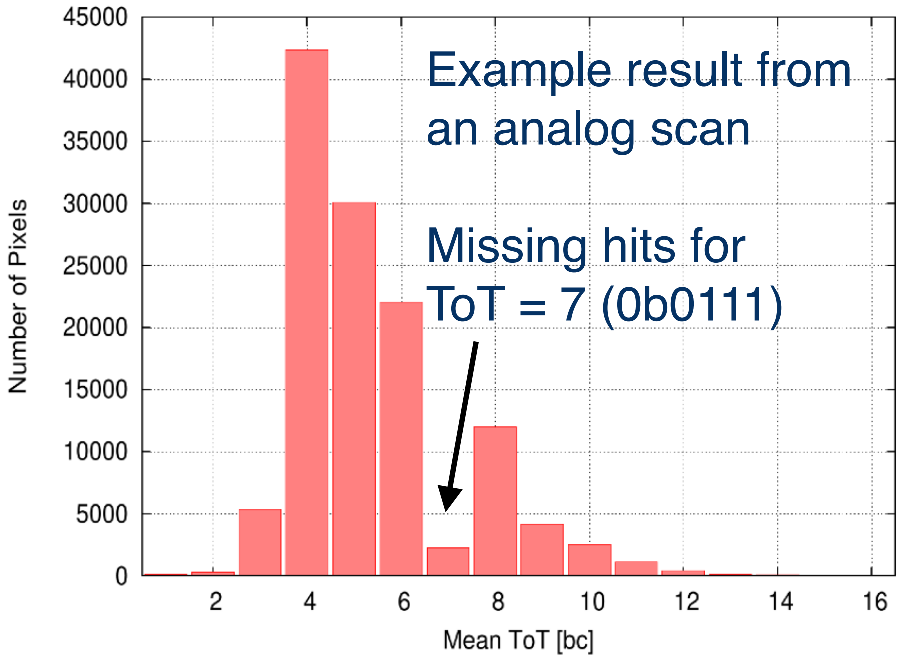
- First chips showed **large current on digital rail**. Also significant **hit losses** were observed
  - Not a simple short, current is not ohmic but depends heavily on voltage. Independent of clock
  - Behavior consistent over all chips tested (~20), multiple testing sites, and wafer batches
- Analysis of Process Control Monitoring shows no anomalies
- Thermal imaging suggests the culprit could be in the pixel matrix



- All the observations point to a design bug

Multi-bit latch for ToT memory

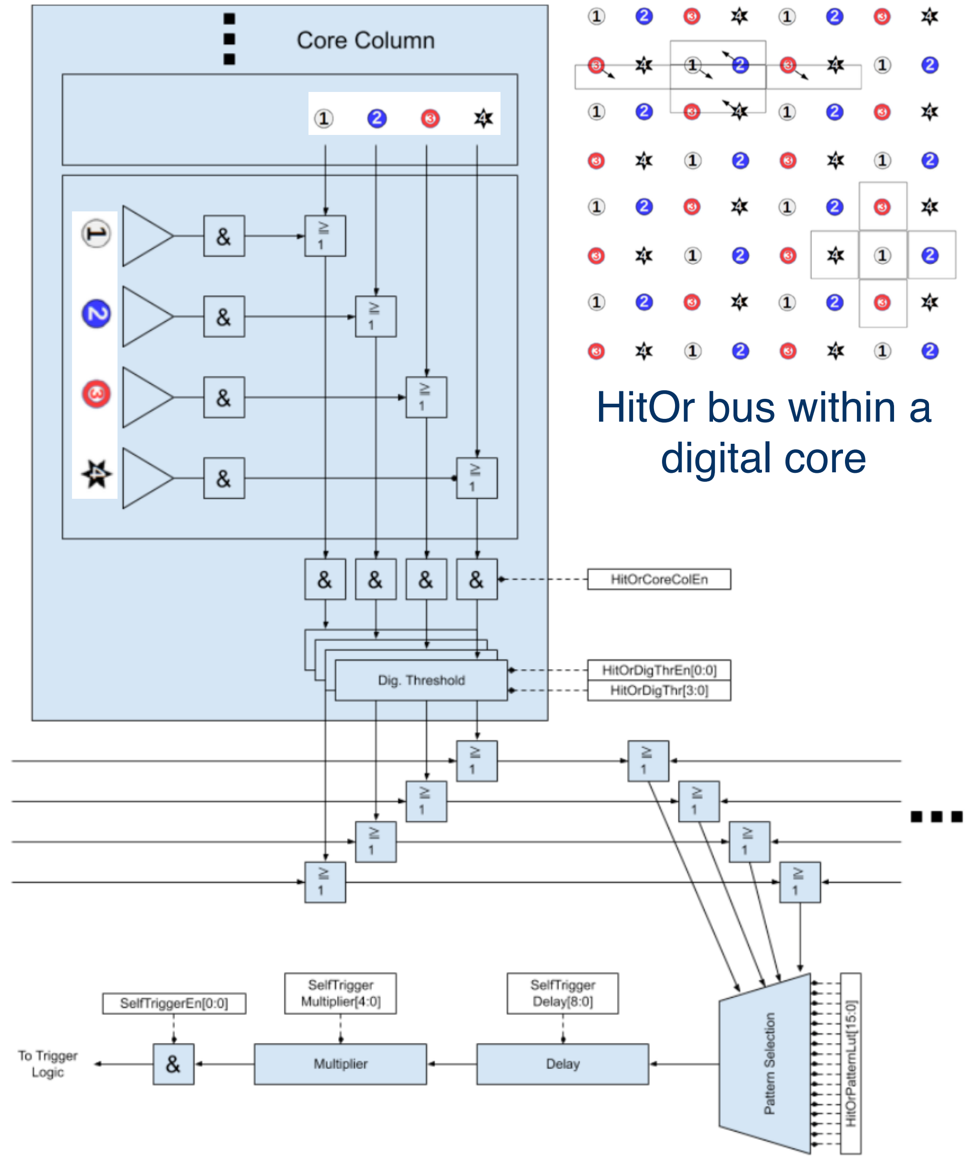
- Each pixel has a 4-bit time-over-threshold (ToT) memory
  - Made from **custom multi-bit latches** used for the first time in ITkPix-V1 (RD53A used a standard latch)
- Notice loss of hits associated with 4-bit ToT value contains more than one bit of "1" → points to problem in ToT memory



- Found a bug in multi-bit latch that allows a direct path from VDDD to ground under specific circumstances
- It also leads to some internal nodes not being on a well defined potential, and appearing as "1" on the output
  - "1111" means no hit

HitOR bus and precision ToT

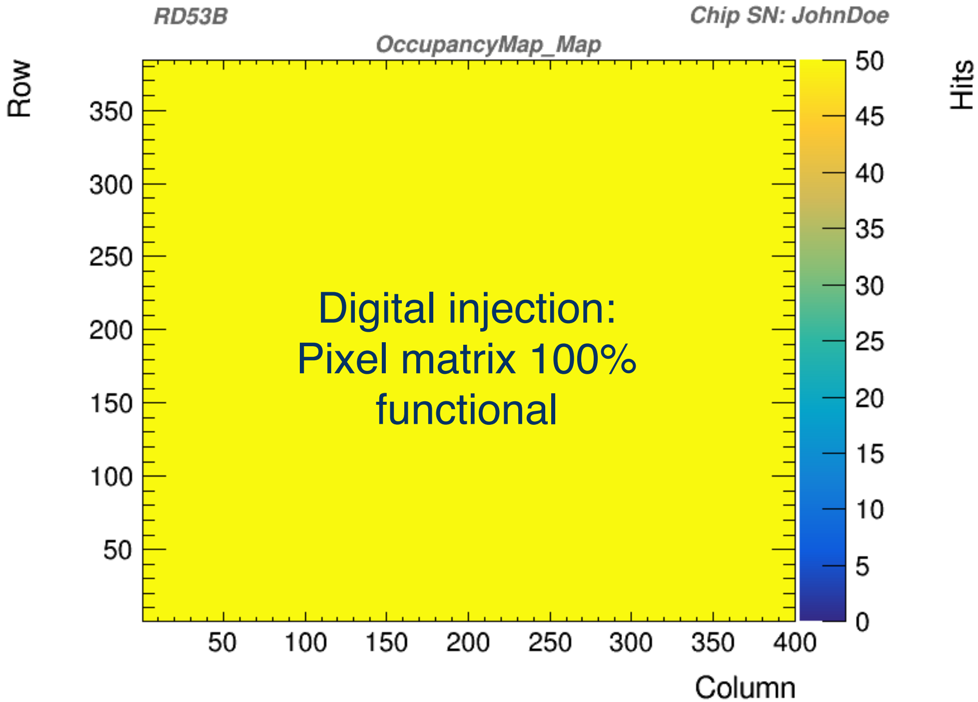
- There are **four HitOR nets** serial-chaining all pixels in each **core column** (8-pixel wide)
- HitOR bus is used to
  - Generate self-trigger: used for source scans
  - Provide **precision time-over-threshold (ToT) / time-of-arrival (ToA)** counted in **640 MHz** clock (new feature!)
    - By only enabling one pixel on one HitOR bus at one time, **we can use precision ToT data for calibration scans**!

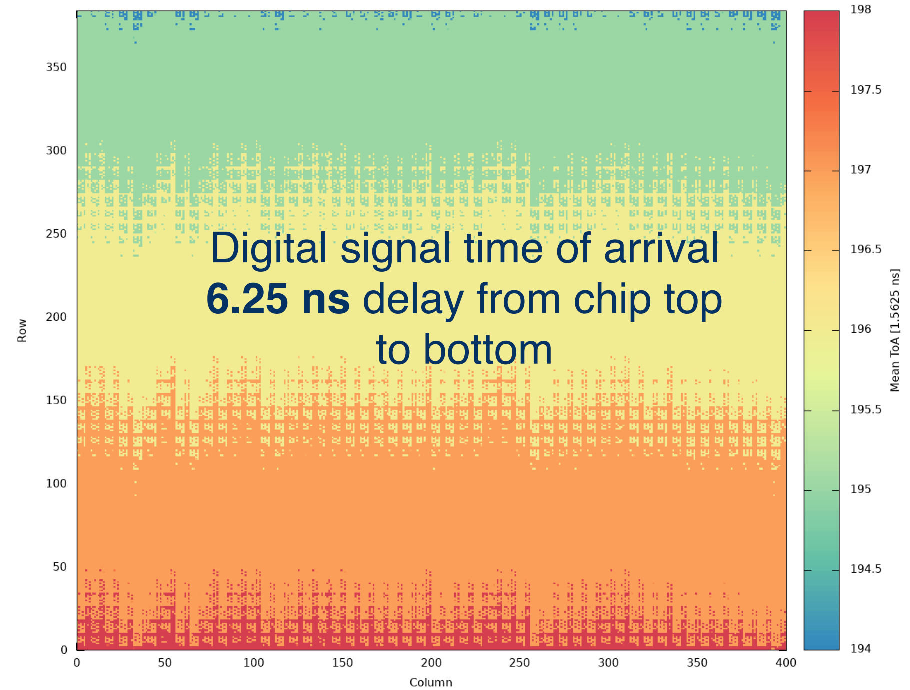


HitOr bus within a digital core

Circumvent ToT memory issue in ITkPix-V1

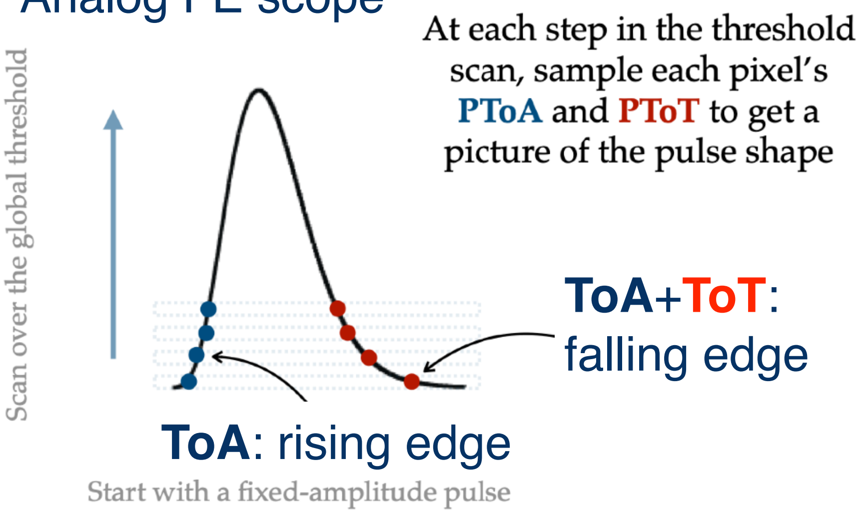
- **Hit loss:** recovered using precision ToT data
- **Large digital current:** managed by resetting ToT memory to **0000**
  - Can reach **normal current** with this mitigation
- **Above two mitigations enable ITkPix-V1 for most single chip tests, including irradiation and single-event-upset!**

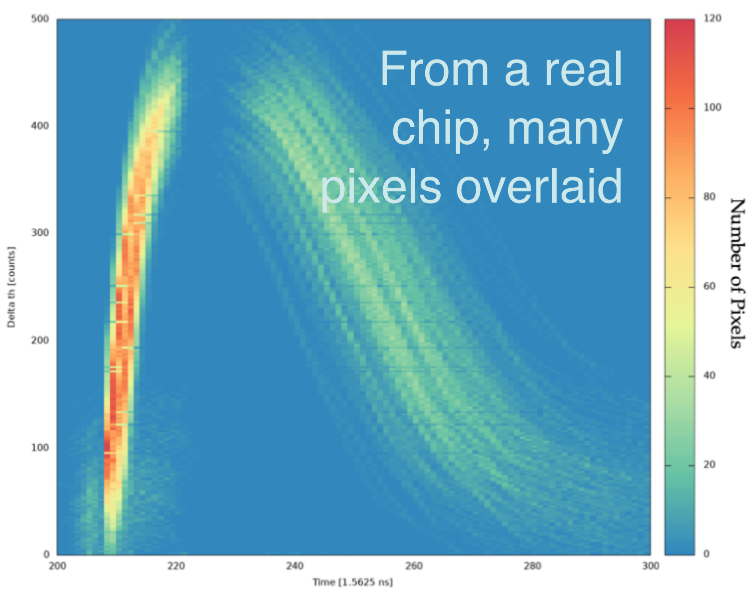


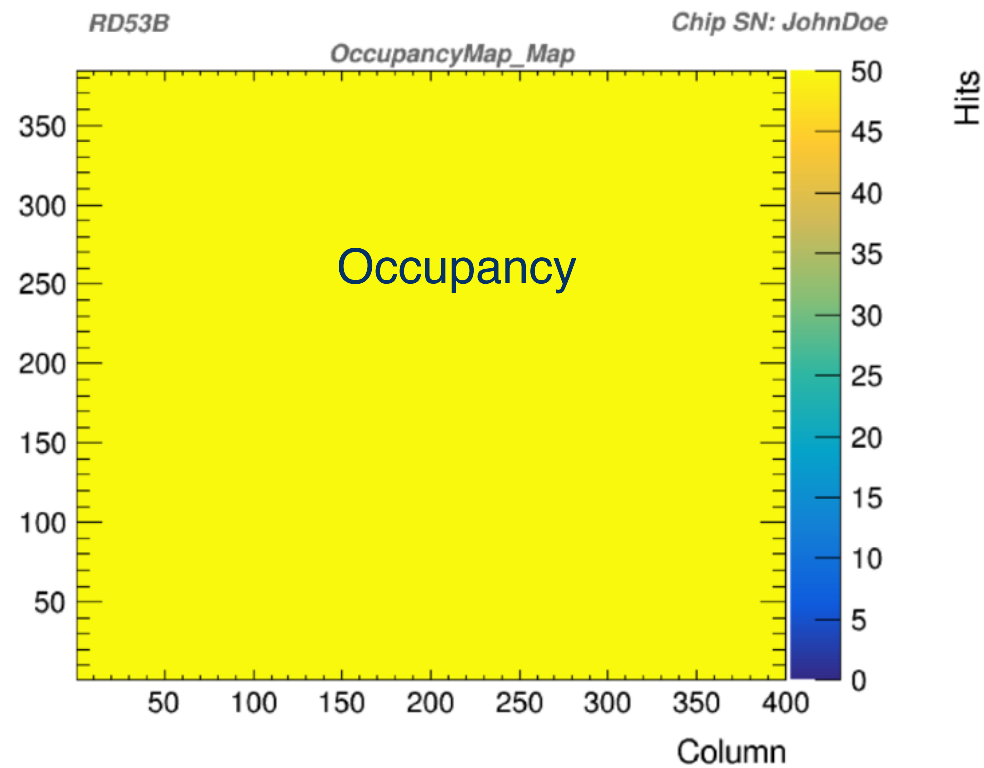


Analog test (bare chip)

Analog FE scope

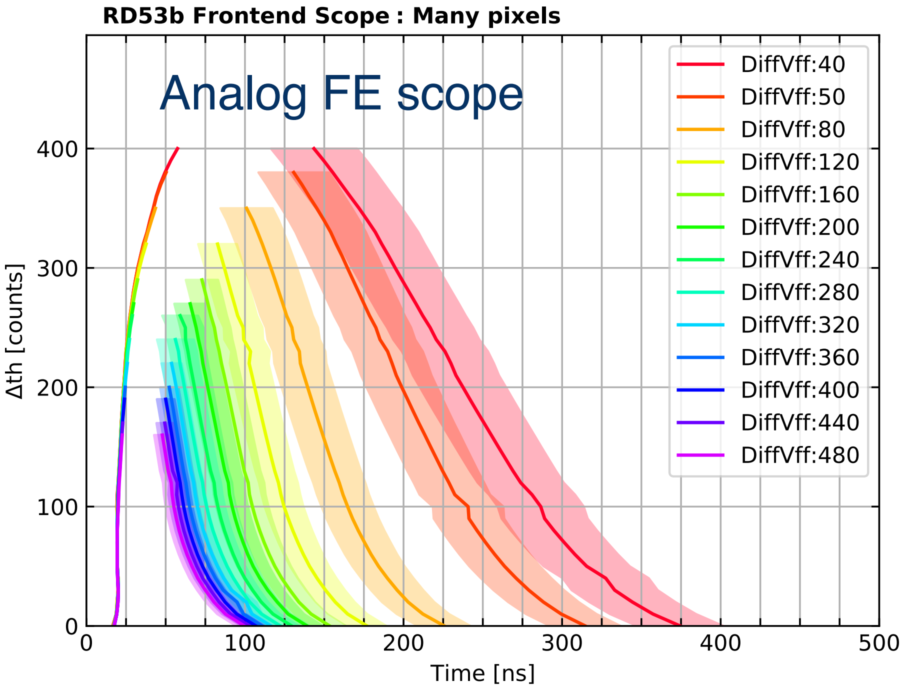


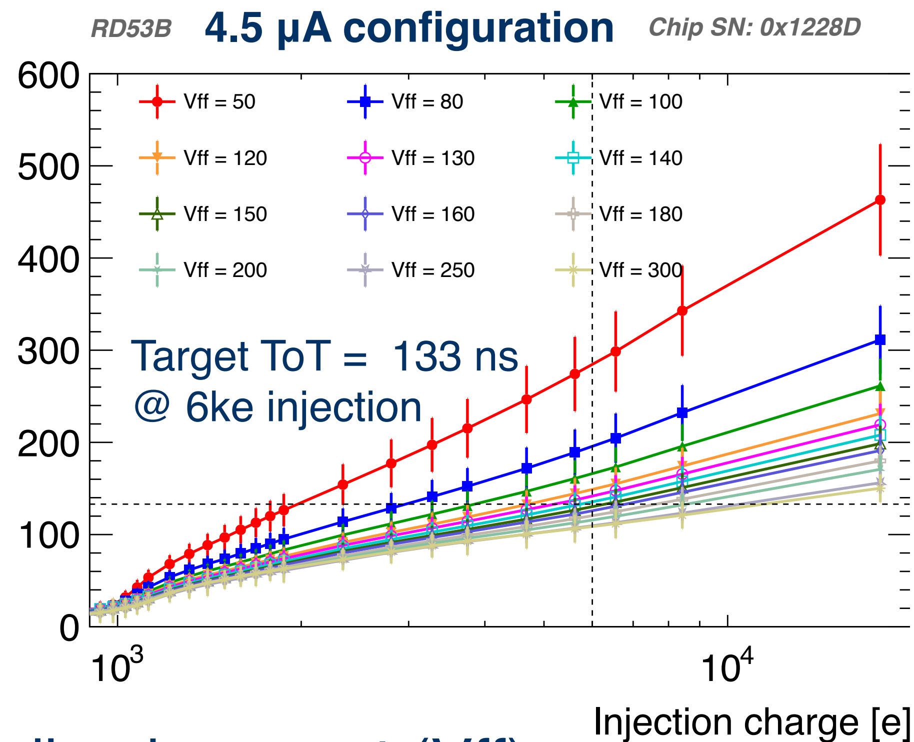




- Analog injections show uniform 100% occupancy across pixel matrix
- Can use new feature in ITkPix-V1, precision time-over-threshold and time-of-arrival, to visualize the signal profile

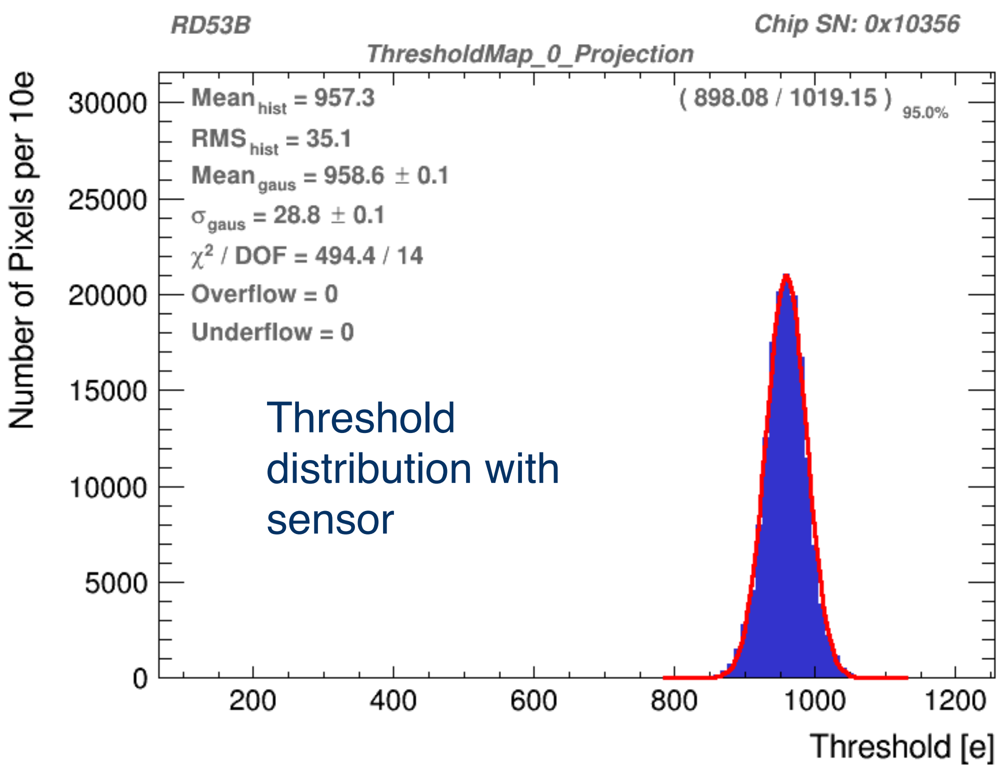
ToT tuning (bare chip)

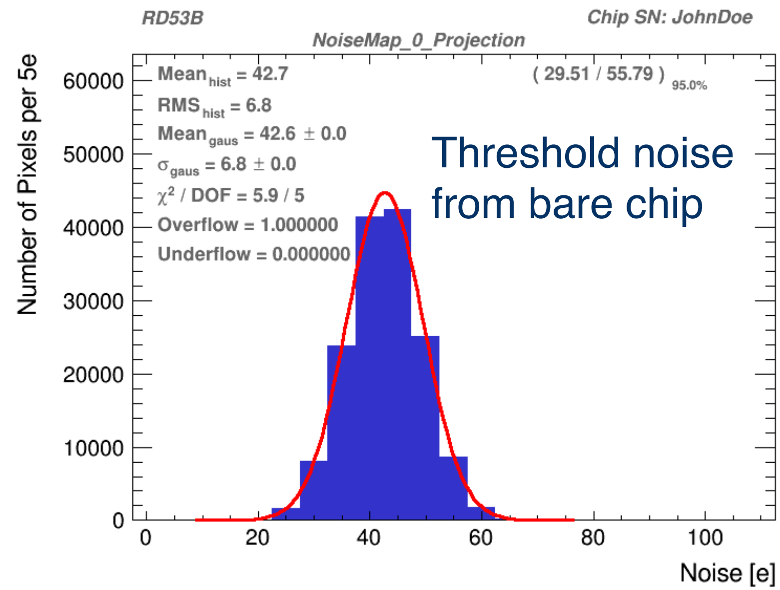


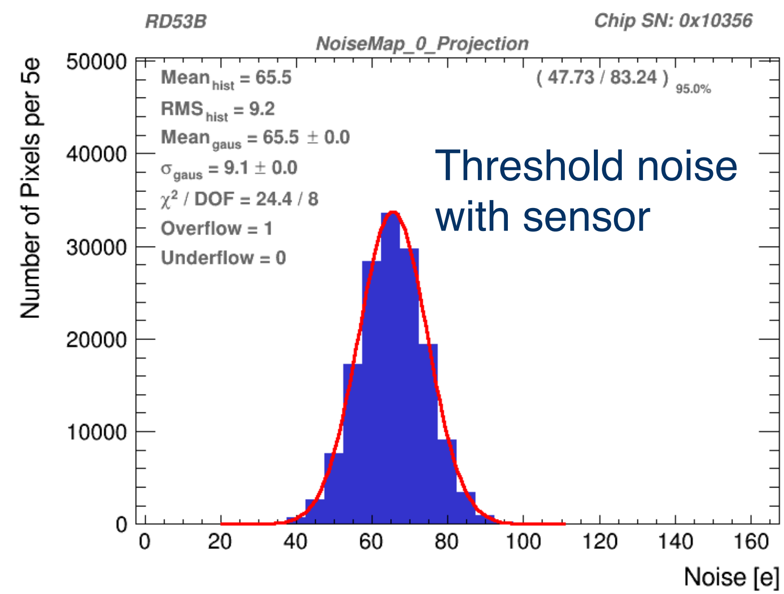


- ToT is tuned globally via the feedback current (Vff)
  - No per-pixel ToT tuning available; can be solved by translating ToT to charge with per-pixel look-up table in software
- Recommended DAC values available for different configurations to be used in inner/outer layers of ITk Pixel detector

Threshold tuning with sensor



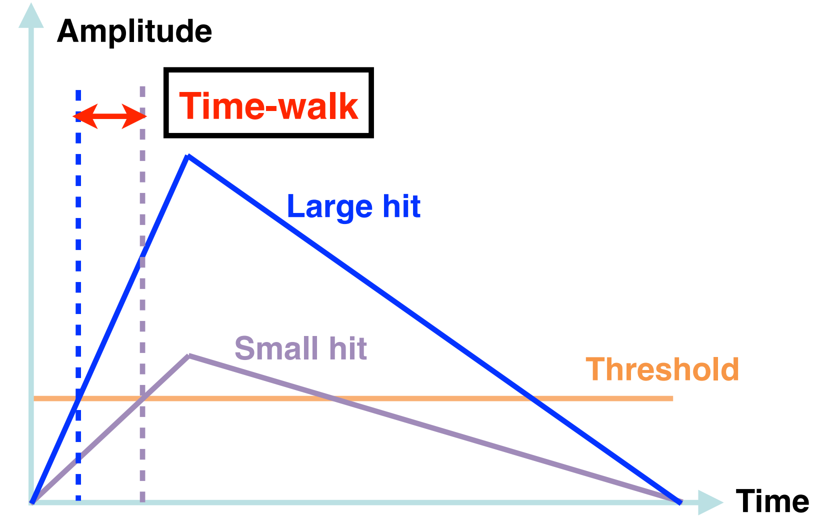


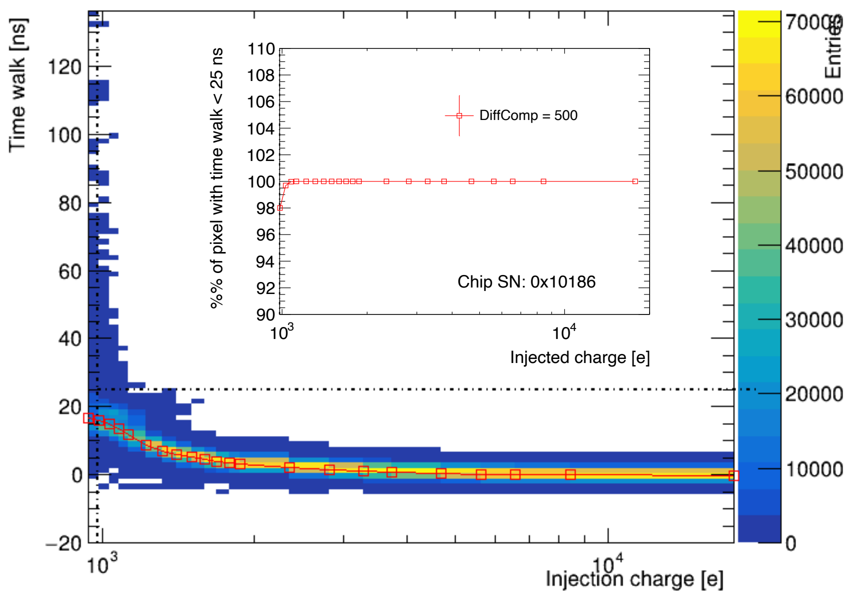


- Able to tune a sharp threshold distribution from ITkPix-V1 chip: **~25e dispersion** at 1000e threshold
- **Very low noise**: ~45e from bare chip, ~65e with sensor attached

Time-walk measurement (bare chip)

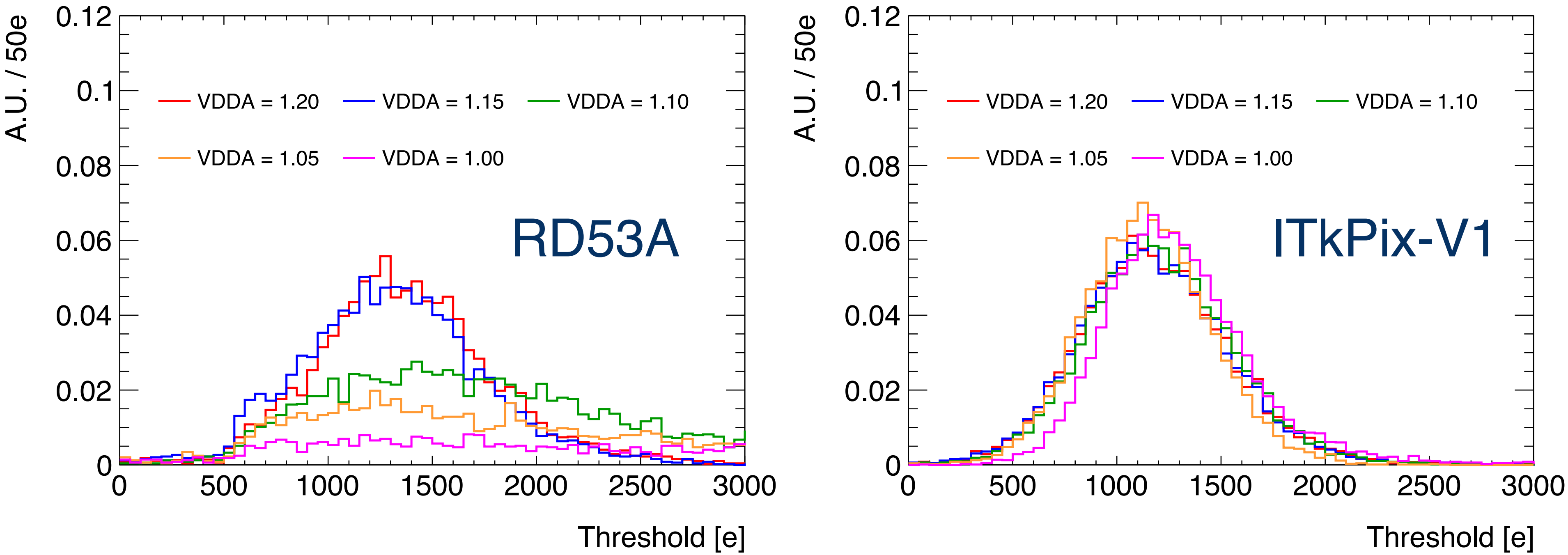
- Time-walk: time-of-arrival difference between a small and a very large signal injection
  - LHC bunch crossing frequency is 40 MHz, so there are **25 ns** before the signal gets a wrong bunch crossing stamp
- ITkPix-V1 differential analog FE time-walk is **well below 25 ns** on bare chip (to be revisited with sensor attached)





Pixel threshold tuned to 1000e, bare chip

Operating margin needed for radiation tolerance: ITkPix-V1 vs. RD53A (bare chip)

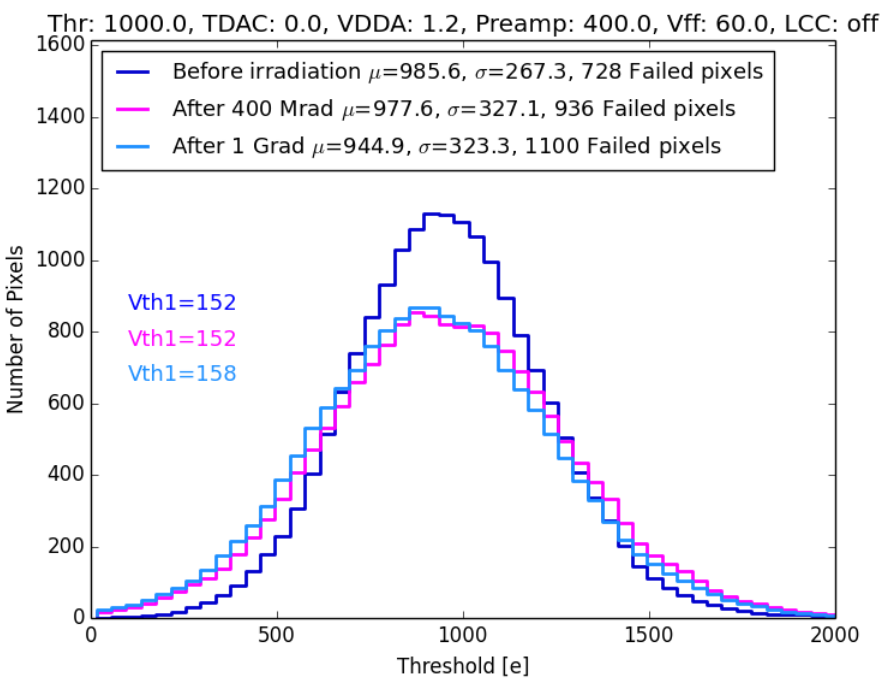


Untuned threshold distributions normalized to total number of good pixels

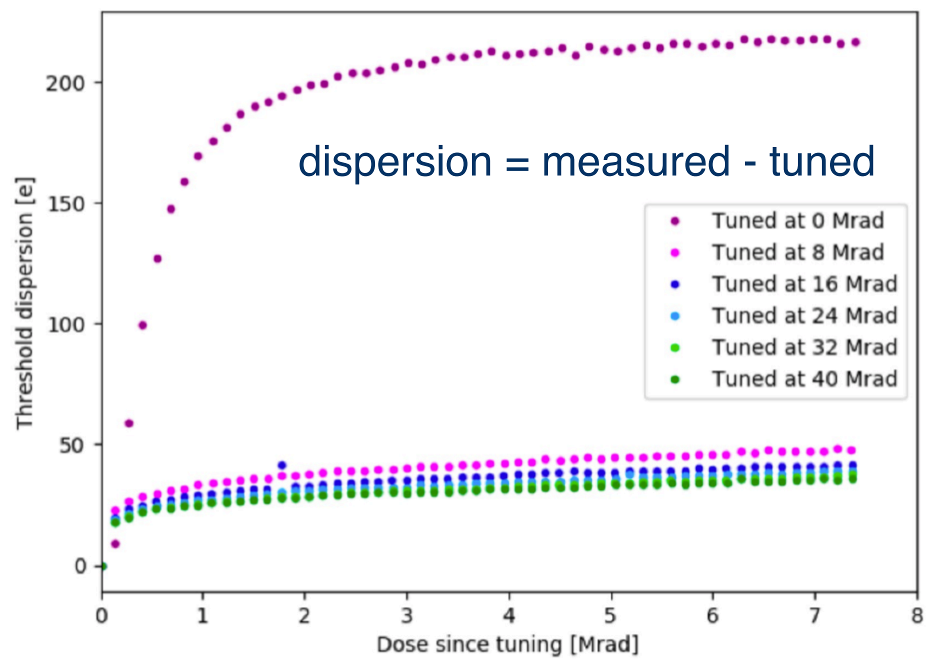
- Use **low temperate** (-40°C) and **low VDDA** to emulate radiation effect
- When RD53A stops working, ITkPix-V1 threshold distribution remains sharp at reduced VDDA
  - **ITkPix-V1 analog FE is more radiation-hard than RD53A!**

X-ray irradiation studies (bare chip)

- Various testing sites now use X-ray machines to perform irradiation tests
- Measurements suggest ITkPix-V1 is radiation hard up to **1 Grad!**
- Threshold de-tune rapidly at low radiation dose, then become stable
  - Need to monitor chip tuning closely at the beginning of HL-LHC data taking



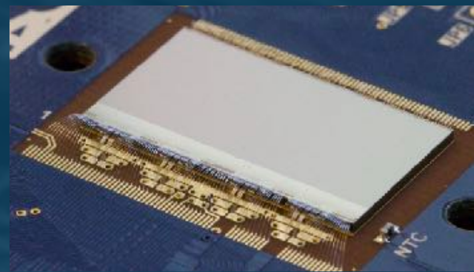
Untuned threshold distribution



Tuned threshold dispersion

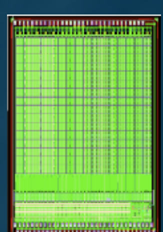
RD53 Timeline

RD53A (400x192)

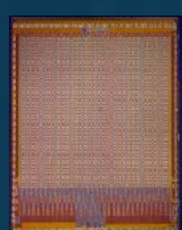


02/2013 — RD53 Collaboration LOI

12/2015 — FE65-P2 and CHIPIX prototype chips



CHIPIX (64x64)



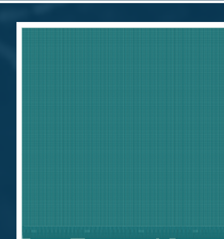
FE65-P2 (64x64)

11/2017 — RD53A chip submission

12/2018 — RD53A AFE review & design validation finished

11/2019 — RD53B design finished

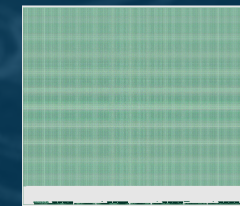
03/2020 — ITkPixV1 submission



ITkPixV1 (400x384)

***10/2020** — **ITkPixV1.1 submission with patch for ToT memory issue in V1**

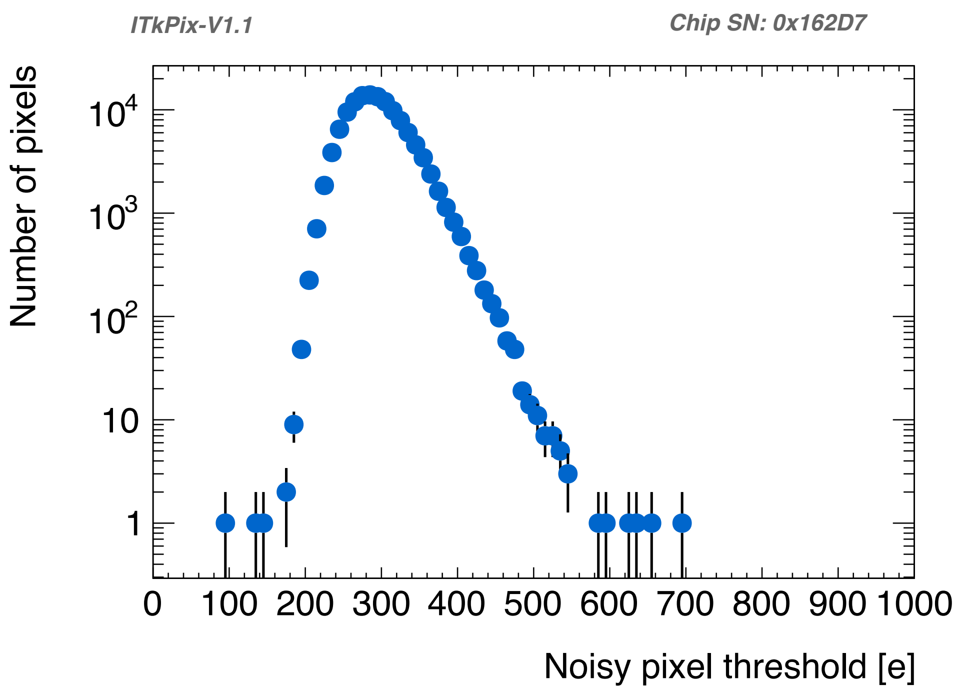
CROC submission

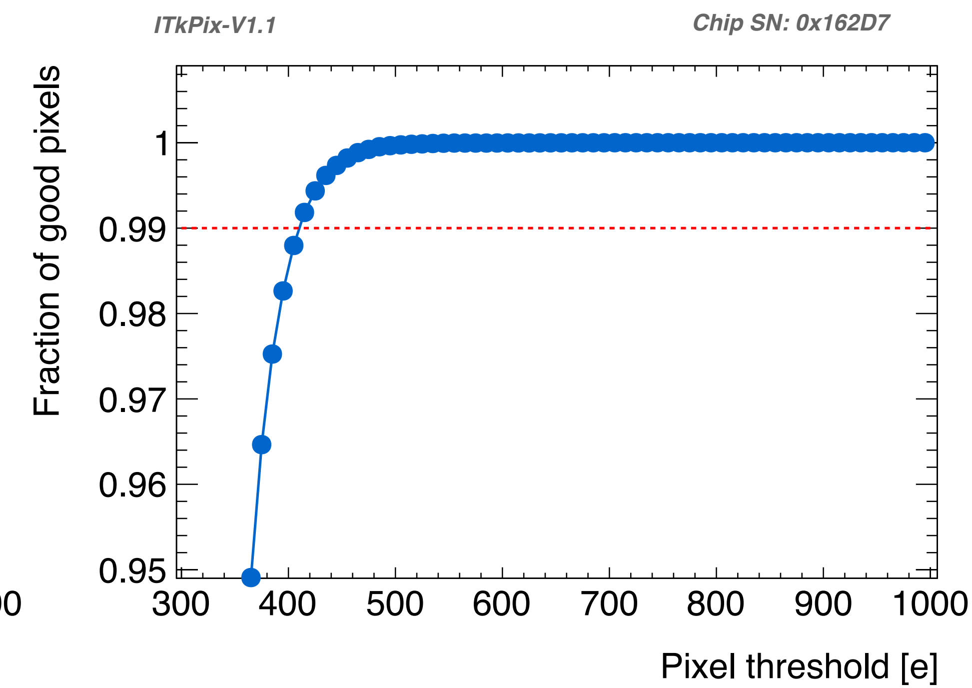


CROC (432x336)

ITkPixV2 submission

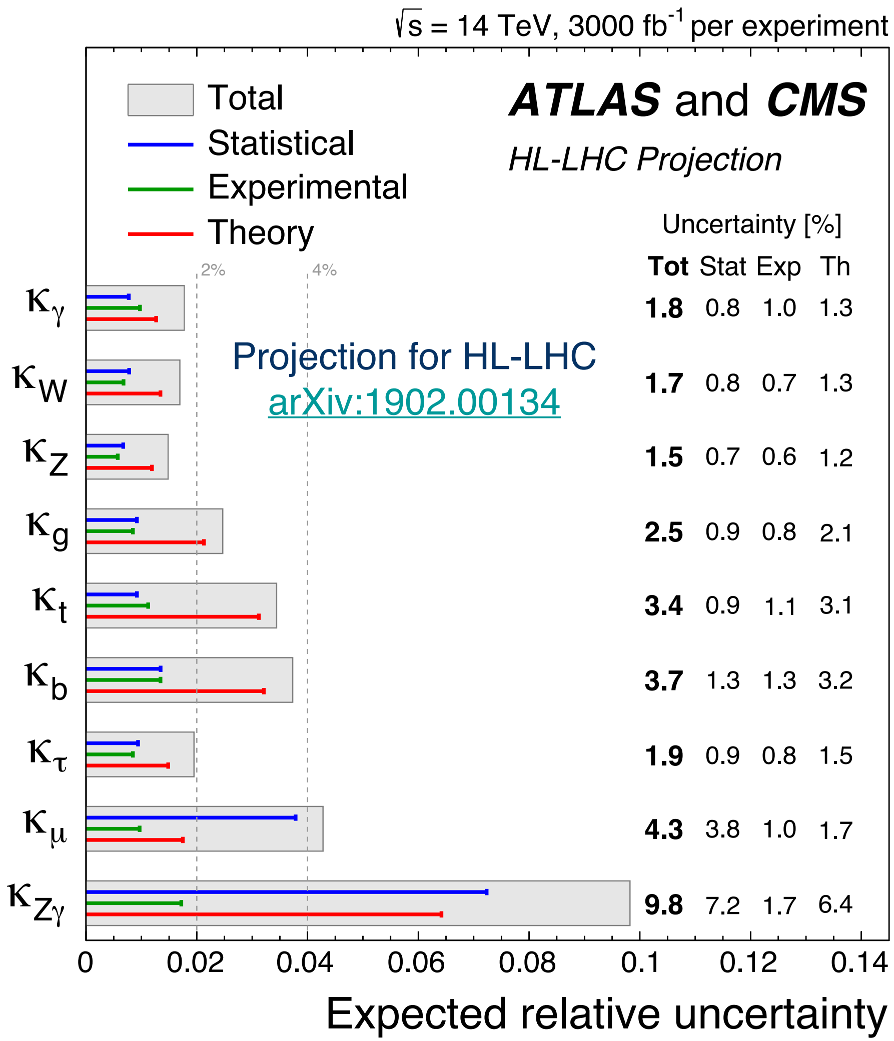
Noise occupancy study on ITkPix-V1.1 (bare chip)



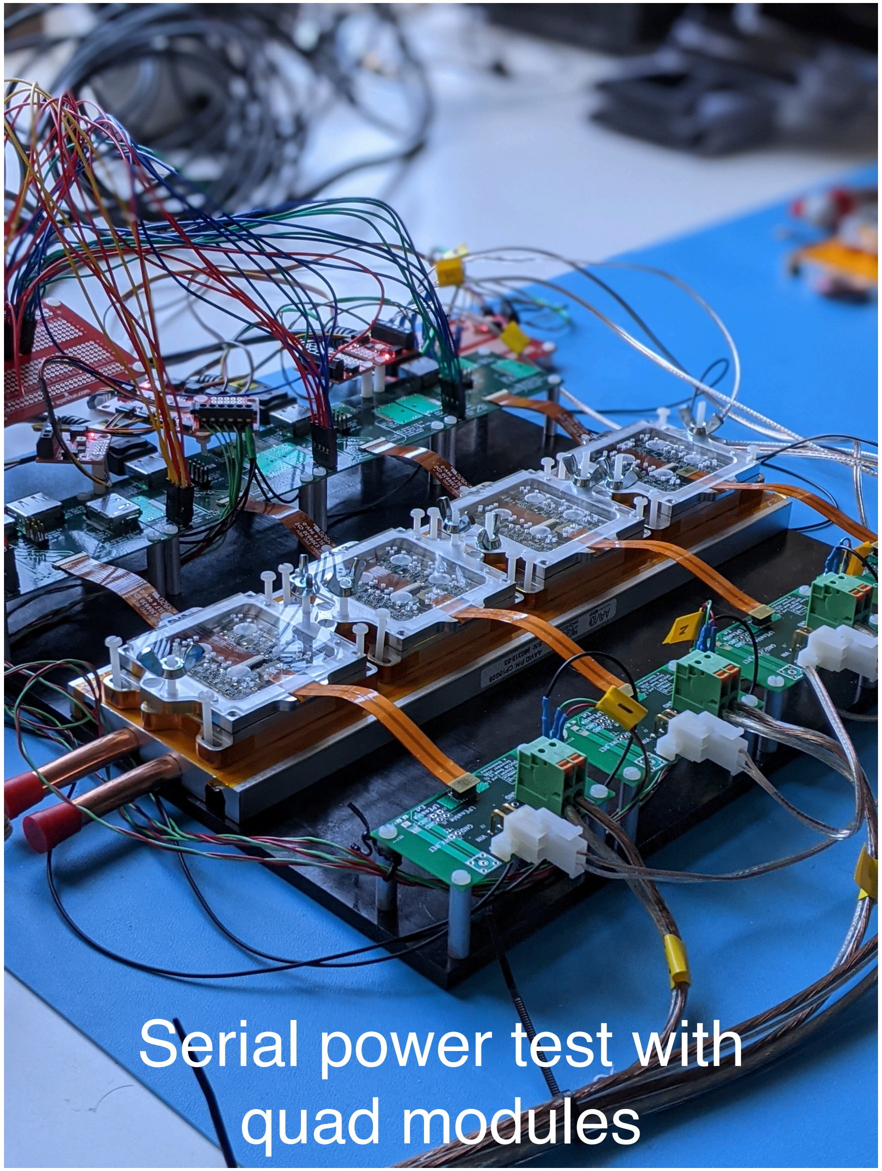


- Gradually lower the threshold in small steps, and record the number of pixels with noise occupancy **>10^{-6} hits per trigger** at each step
  - >99% pixel working when threshold is above 400e

Conclusions



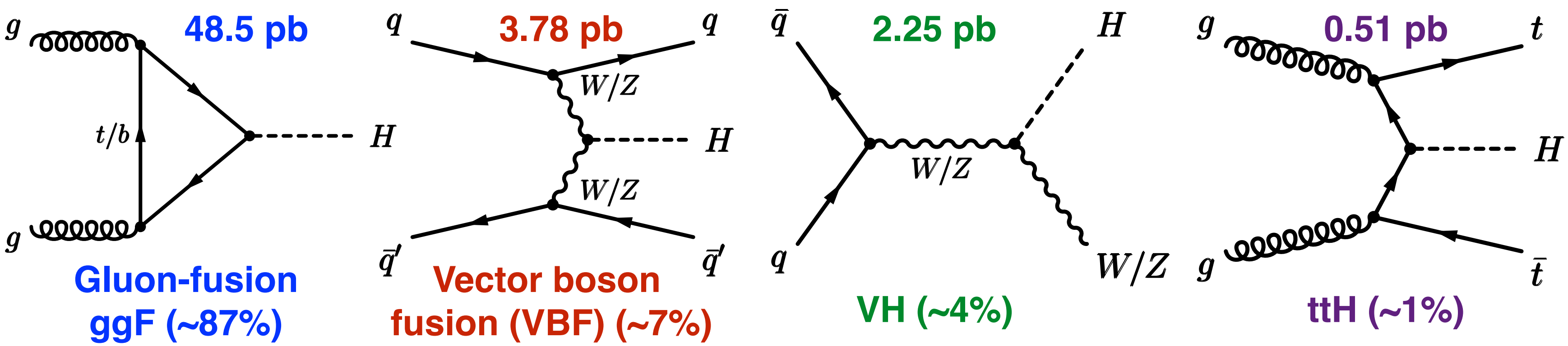
Current dataset only 5% of expected LHC total!



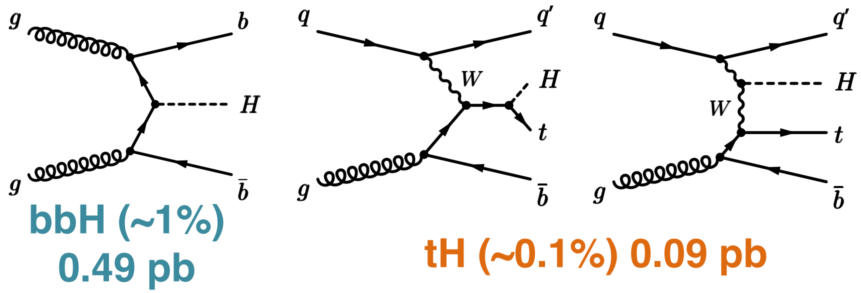
Backup

SM Higgs boson production at LHC

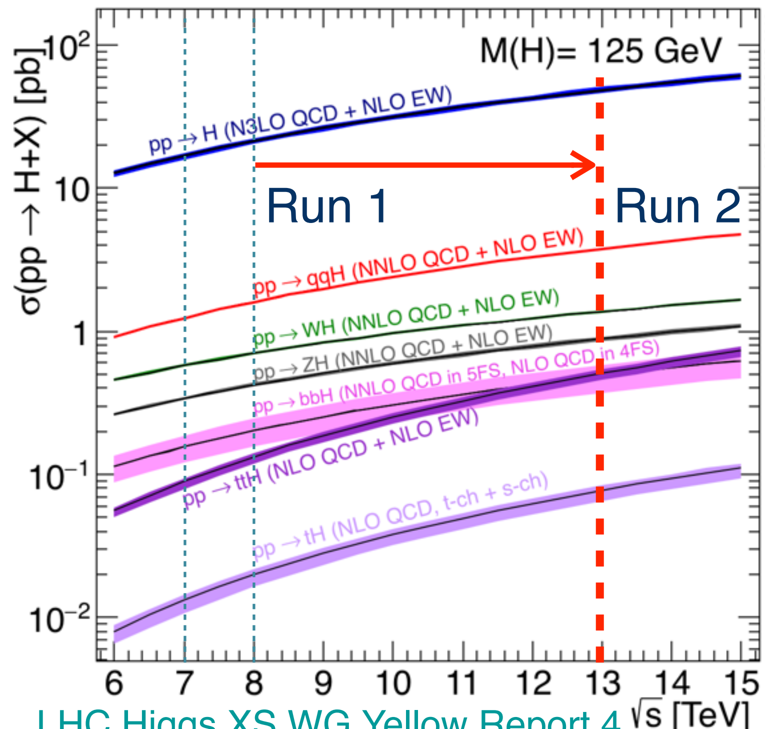
Main



Rare



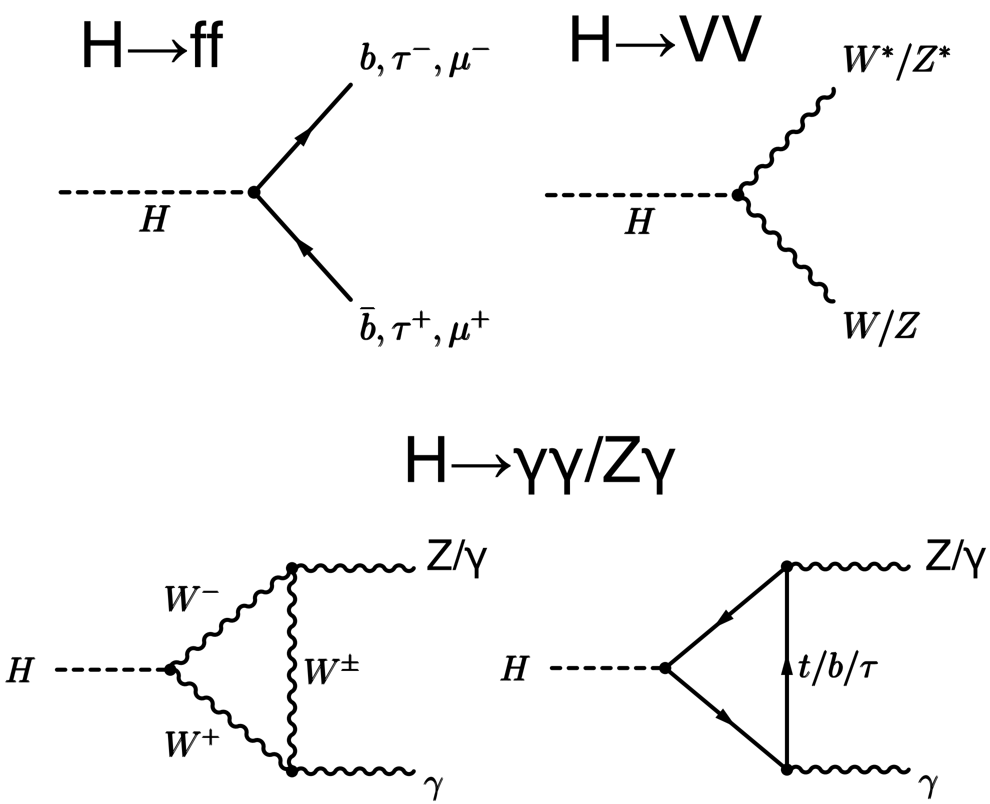
- Distinct topology from each production mode
- Cross section of main production modes calculated with relatively high accuracy
- Rare production modes difficult to probe, but important for beyond the SM (BSM) scenarios

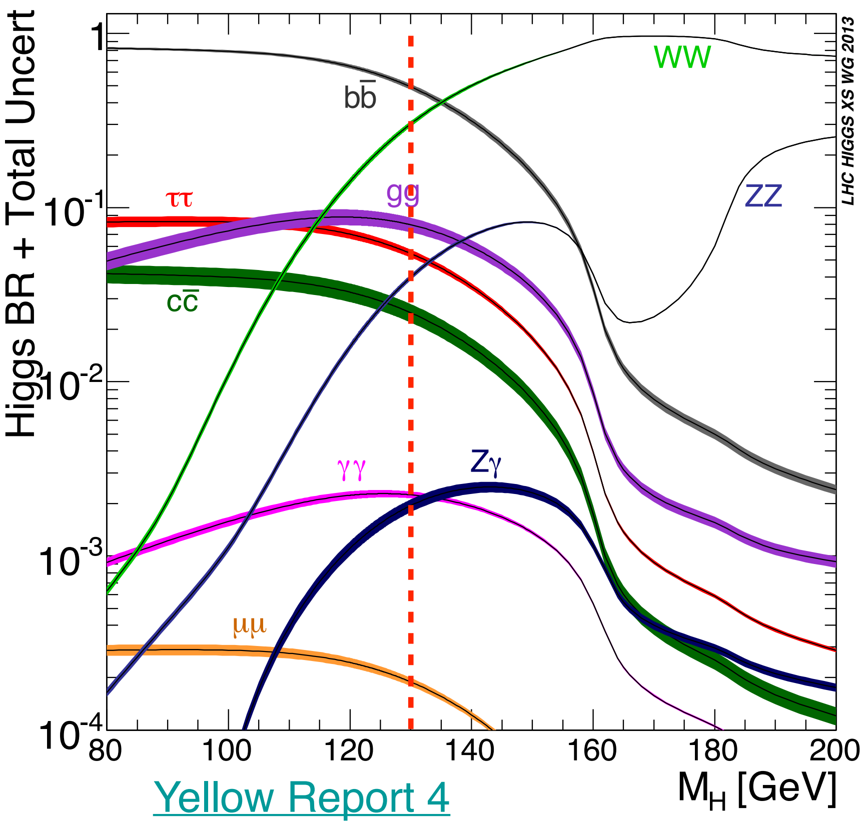


LHC Higgs XS WG Yellow Report 4

Higgs boson decays

- "Big five": **γγ** (0.23%), ZZ, WW, ττ, bb
- "Rare" channels: μμ, Zγ, cc, etc.



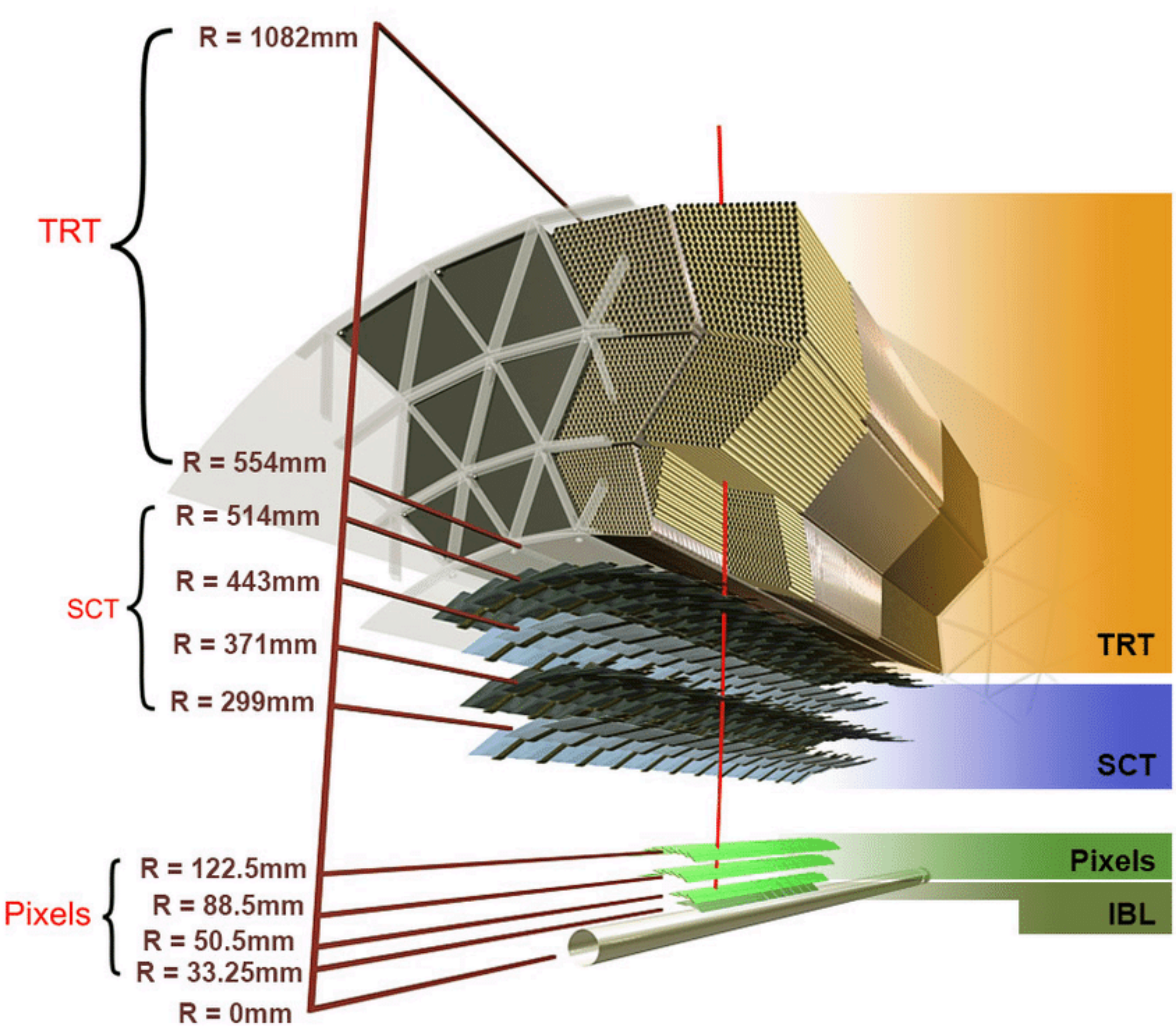


Yellow Report 4

Data & signal MC samples for ttH CP analysis

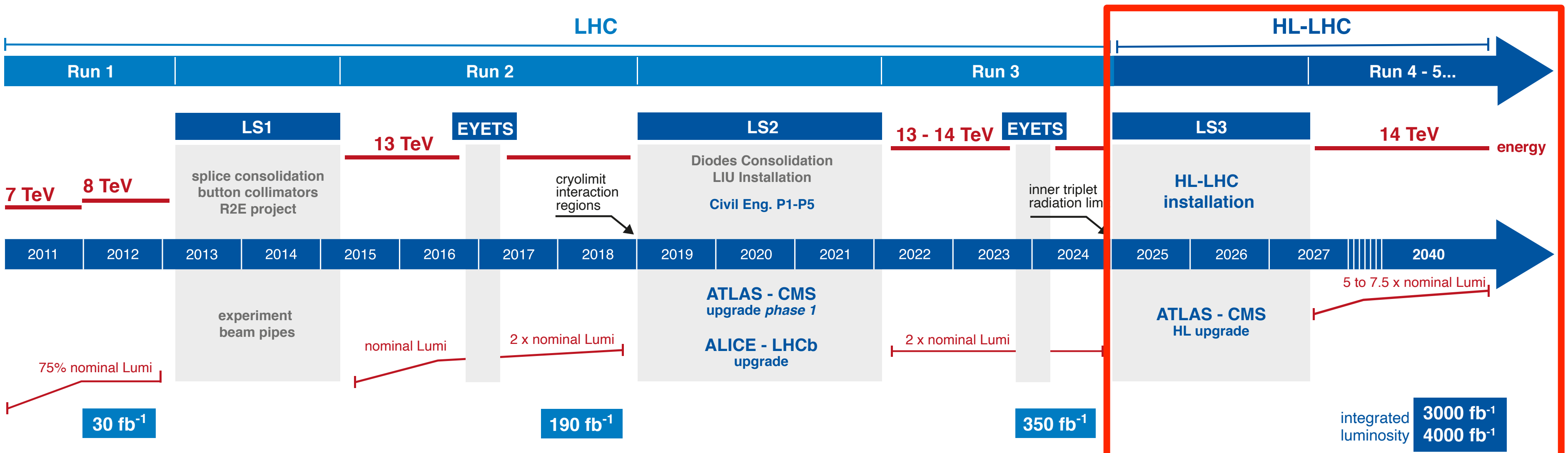
- **Data**: full Run 2 dataset of 139 fb^{-1}
- **ttH/tH signal**: **NLO MG5_aMC+Pythia8** using **Higgs Characterization (HC) model**
  - ttH: $\boldsymbol{\kappa_t = 1}$, $\alpha = 0°, 15°, 30°, \ldots, 90°$
  - tHjb/tWH: sample generated with both $\boldsymbol{\kappa_t = 1}$ **and ≠ 1** at different mixing angles. $\kappa_W = 1$
- **ggF signal**: PowHeg NNLOPS
  - Kinematic dependence on CP mixing checked to be well-covered by syst. using **MG_aMC HC model ggF+2j** samples
- **Other Higgs production modes**: same as typical ATLAS Run 2 Higgs analyses

Current ATLAS Inner Detector

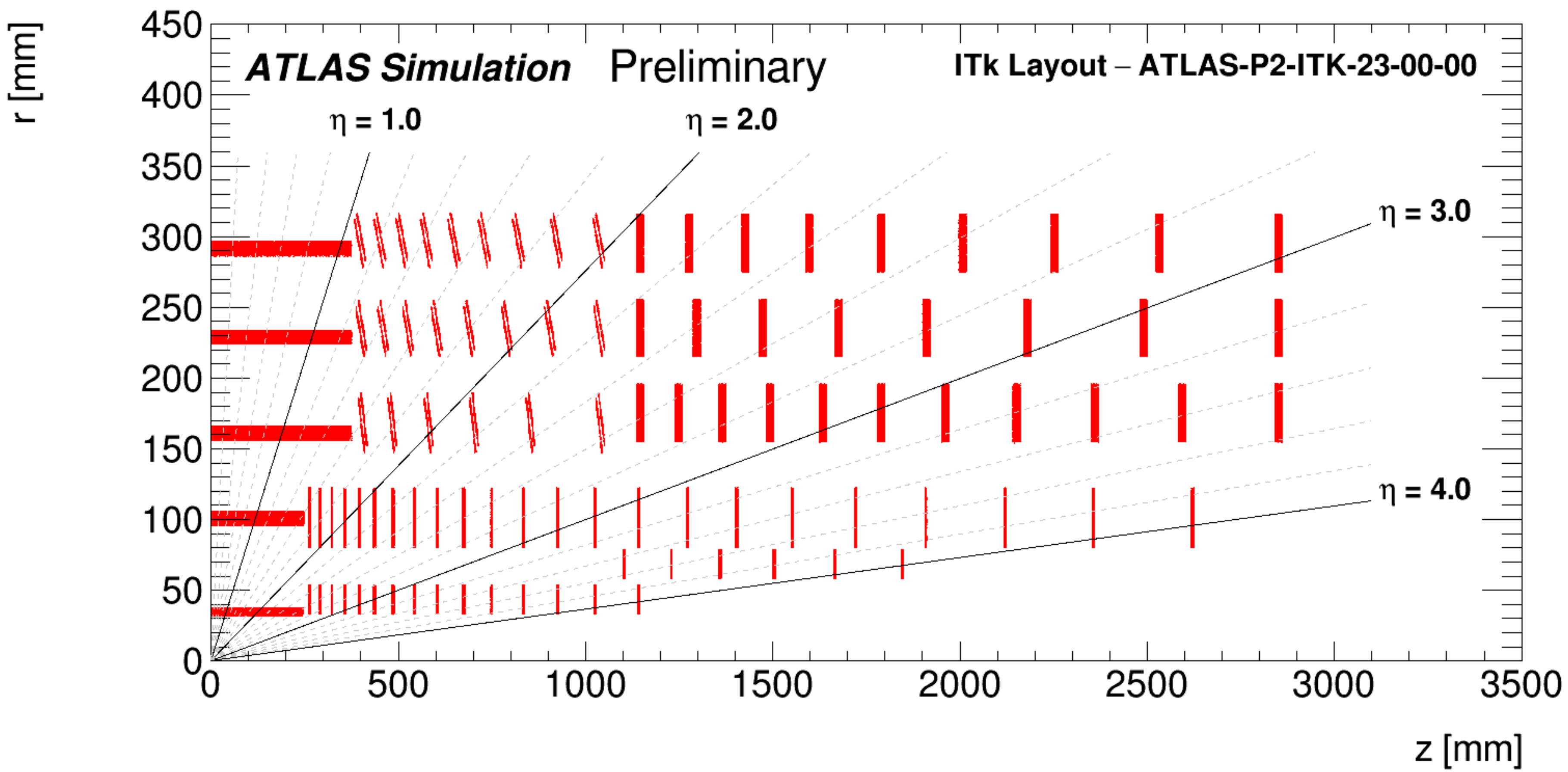


HL-LHC schedule

- HL-LHC will operate with instantaneous luminosity up to **7.5×10^{34} $cm^{-2}s^{-1}$** (~**200** interactions per bunch crossing). Aiming to deliver up to **4000 fb^{-1}** *pp* collision data
- Upgraded pixel detector is expected to deliver no worse performance compared with current one



ITk Pixel Detector layout

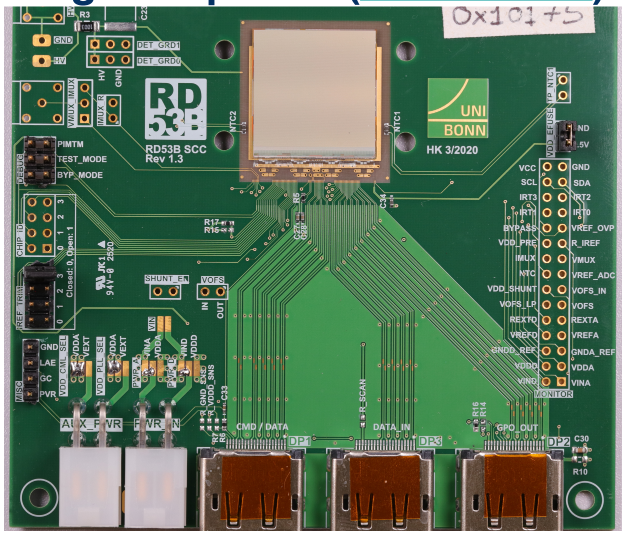


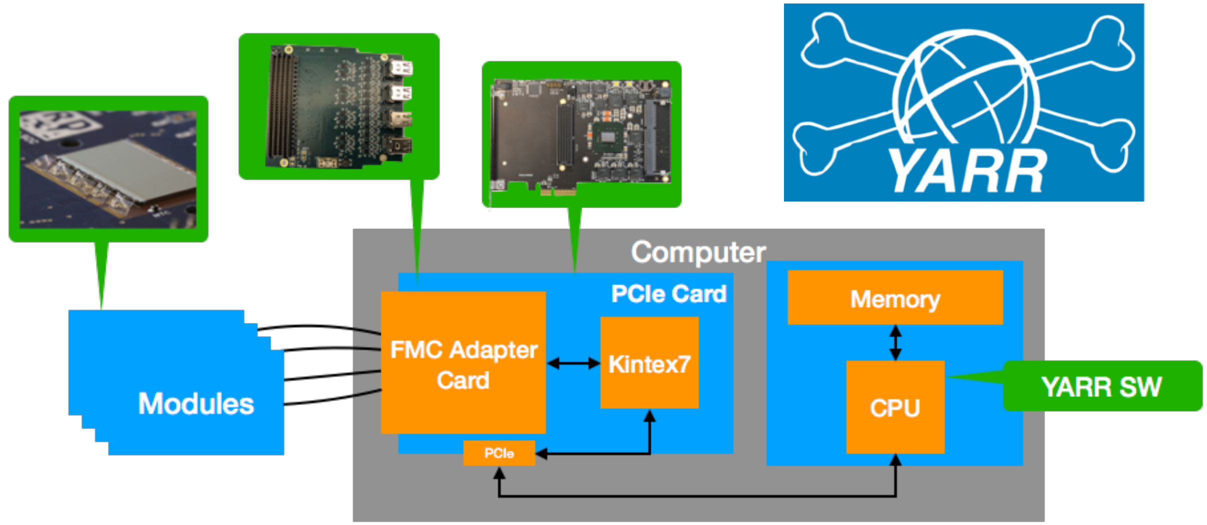
ITk Pixel Detector radiation tolerance

Luminosity	Layer	Location	R (cm)	z (cm)	Fluence (10^{14} n_{eq}/cm^2)	Dose (MGy)
2000 fb^{-1}	0	flat barrel	3.9	0.0	131	-
			4.0	24.3	-	7.2
		inclined barrel	3.7	25.9	123	-
			3.7	110.0	-	9.9
		end-cap	5.1	123.8	68	6.3
2000 fb^{-1}	1	flat barrel	9.9	24.3	27	1.5
		inclined barrel	8.1	110.0	35	2.9
		end-cap	7.9	299.2	38	3.2
4000 fb^{-1}	2-4	flat barrel	16.0	44.6	28	1.6
		inclined barrel	15.6	110.0	30	2.0
		end-cap	15.3	299.2	38	3.5

Test system

Single chip card (schematics)

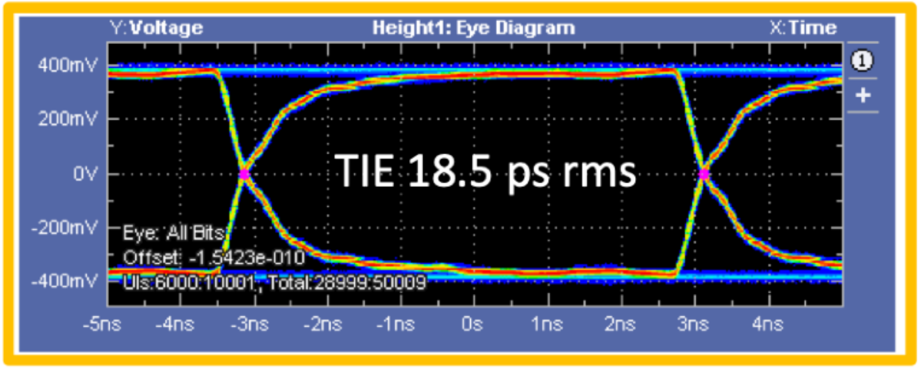


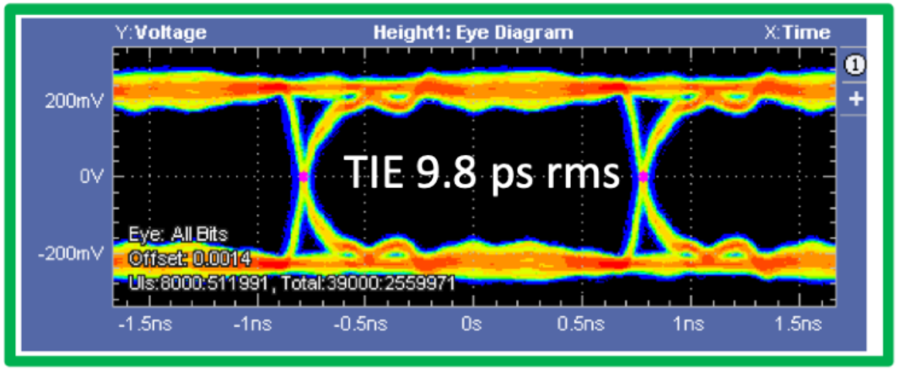


- ITkPix-V1 mounted on single chip card for testing
- Readout using YARR system (https://yarr.web.cern.ch/yarr/)
  - Commercial PCIe FPGA board with custom FMC adapter card
  - PCIe communication to PC
  - Hardware agnostic SW based on C++, aiming at growing from chip characterization all the way to detector operation
- Tests can also be performed with BDAQ53 system

ITkPix-V1 validation

- **Most ITkPix-V1 functionalities are working as expected**
- In particular, the CDR circuit is performing within requirements
  - 160 MHz clock recovered from custom DC balanced CMD protocol. 40 MHz bunch crossing clock derived via special sync frames
  - Internal PLL multiplies 160 MHz up to 1.28 GHz clock, which is used to drive four 1.28 Gbps data output
    - **Small jitter**: significant improvement compared with RD53A
    - Important for long distance (>6 m) data transmission





How did the ToT bug happen

- Custom multi-bit latch was designed during RD53A time as a potential alternative for the standard single-bit latches for space saving
  - **It was not used for RD53A** but remained in the design library
- Designer of the multi-bit latch left RD53 collaboration after submitting the design. It was assumed that the design was finished and verified, which is not the case
- The multi-bit latch was then used in ITkPix-V1 to reduce congestion in the digital core
- **The specialized commercial tool** used to build the electrical model, extracting timing, power, and signal integrity values from the physical design of digital cells **did not detect that the multi-bit latch had pattern dependent issues**
  - A more recent version of the same tool now reports a problem