



# Building the Future of Higgs Boson Physics

Heavy-Flavour Higgs Decays, Novel Signatures and Detector Innovation

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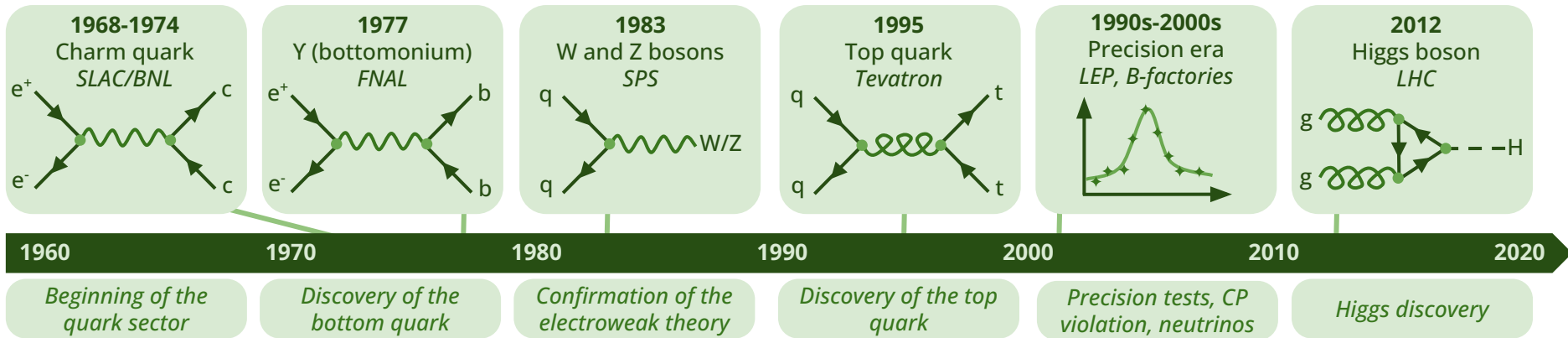


# High energy particle colliders

Colliders have been at the core of fundamental physics discoveries over the past decades

Produce new particles and access a variety of processes at the highest energies possible:

- **Discovery of new particles** through e.g. resonances
- **Constraining new physics** through precision measurements



# Standard Model of Particle Physics

		Fermions			Bosons	
		I	II	III		
Quarks	u	c	t	g	H	
	d	s	b	γ		
	e	μ	τ	Z		
Leptons	ν <sub>e</sub>	ν <sub>μ</sub>	ν <sub>τ</sub>	W		

- **Standard Model of Particle Physics (SM)**
  - Quantum field theory based on invariance under local  $SU(3)_{\text{QCD}} \times SU(2)_L \times U(1)_Y$
  - Current best description of fundamental interactions and particles
- **SU(2) symmetry spontaneously broken by Brout-Englert-Higgs mechanism**
  - Generates **W/Z boson** & **fermion** masses and **new scalar H (Higgs)**
  - Well-behaved renormalizable theory, which allows to compute precise predictions to be tested experimentally

# Standard Model of Particle Physics

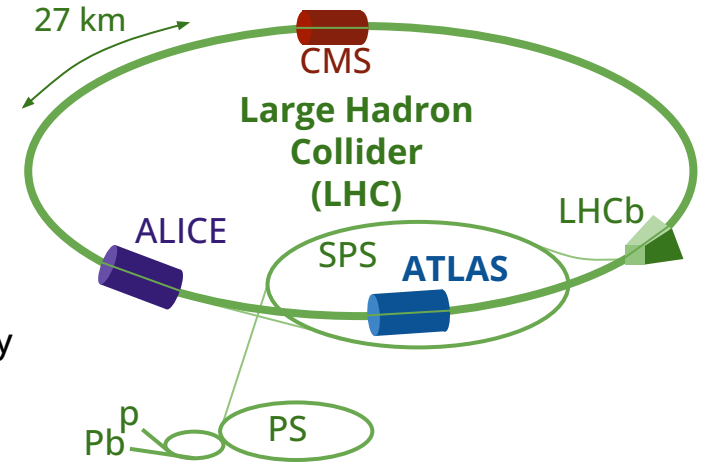
		Fermions			Bosons	
		I	II	III		
Quarks		u	c	t	g	H
		d	s	b	$\gamma$	
Leptons		e	$\mu$	$\tau$	Z	
		$\nu_e$	$\nu_\mu$	$\nu_\tau$	W	

- Predicted SM particle content completed with discovery of Higgs boson in 2012
  - **SM has been remarkably successful in describing processes at collider experiments**
  - Plenty of indications that there must be physics beyond the SM:
    - Dark matter (and dark energy)
    - Matter-antimatter asymmetry
    - Hierarchy problem
    - Neutrino mass hierarchy
- Need tools to continue **probing the SM** and **search for phenomena beyond it**

# Large Hadron Collider (LHC)

**Large Hadron Collider (LHC)** at CERN is our current best tool for probing SM at the highest possible energies:

- Proton-proton and heavy ion collisions with four major experiments: **ATLAS**, **CMS**, **LHCb** and **ALICE**
- Currently finishing Run 3 of the LHC at  $\sqrt{s}=13.6$  TeV
- Followed by upgrade of accelerator complex to High-Luminosity LHC  $\rightarrow$  collect 10 x larger dataset at  $\sqrt{s}=14$  TeV



Upgrade to  
HL-LHC

2010

2020

2030

2040

2050

2060

2070

LHC

Run 1

Run 2

Run 3

Run 4

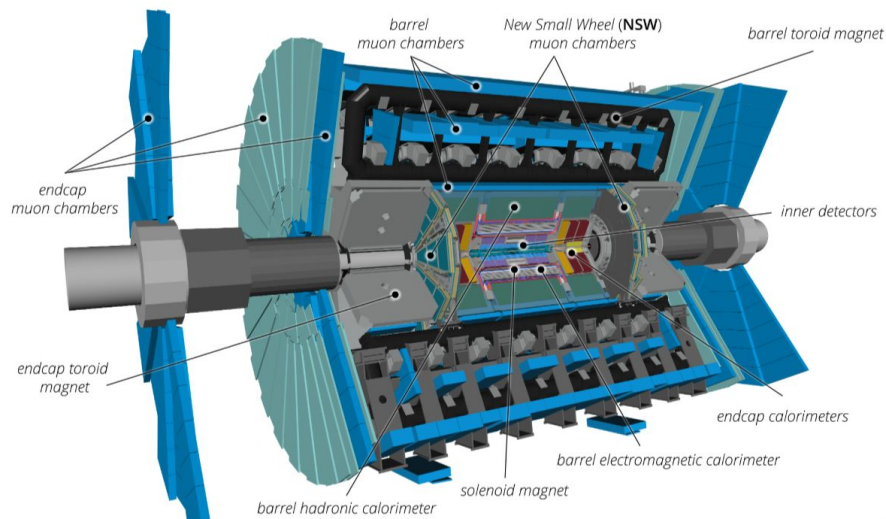
Run 5

# ATLAS experiment

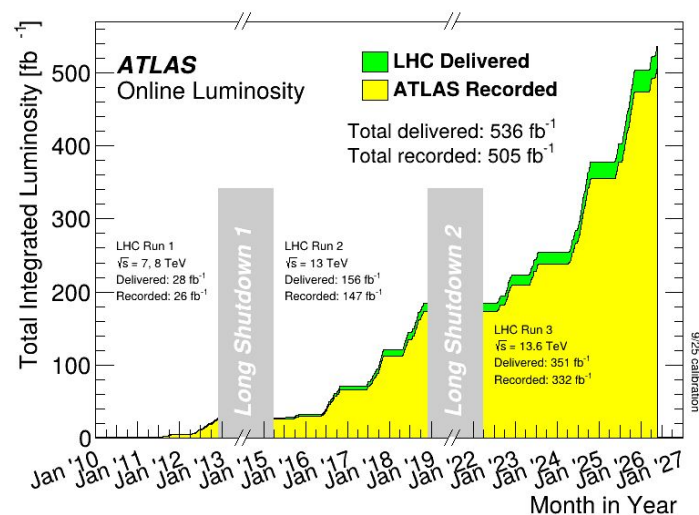
**ATLAS:** general purpose detectors at the LHC with excellent reconstruction, identification and energy-momentum measurement of electrons, photons, muons, taus, jets (including flavour-tagging)

- Collected a total of **500 fb<sup>-1</sup> of proton-proton collision data** at  $\sqrt{s}=7,8, 13$  and 13.6 TeV
- **Major upgrades** planned for the HL-LHC era, including all-silicon inner tracker (ITk)

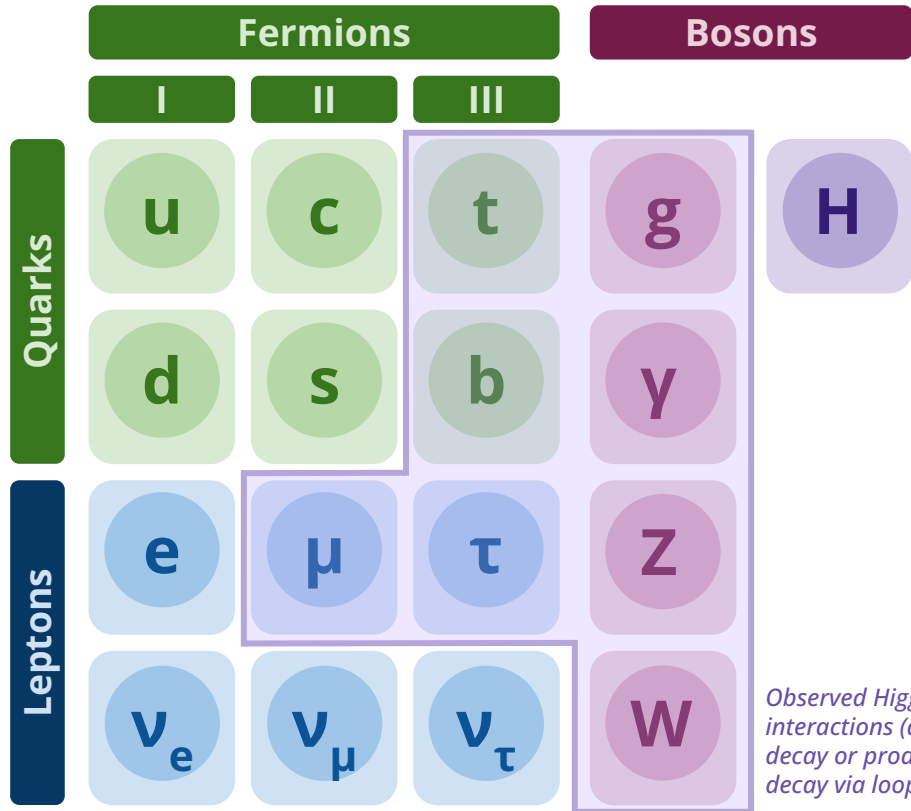
## ATLAS detector configuration for Run 3



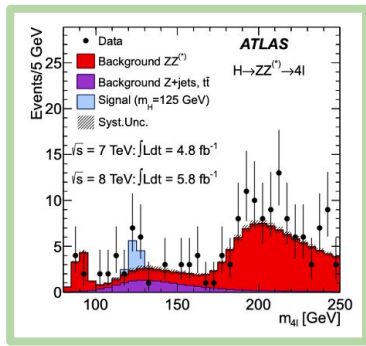
## Integrated luminosity collected by ATLAS



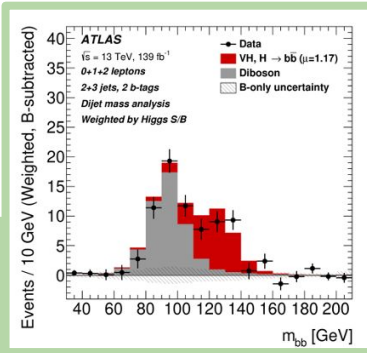
# Higgs boson measurements @ ATLAS



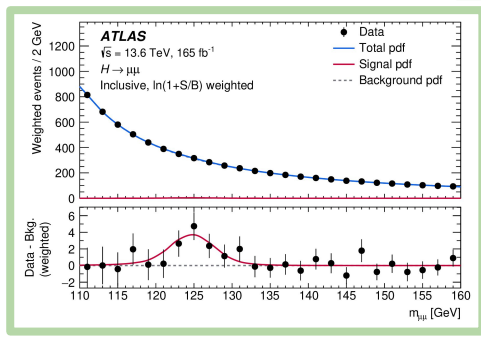
Observed Higgs interactions (direct decay or production/decay via loops)



**Run 1 (Higgs discovery)**  
 Coupling to bosons  
 ( $H \rightarrow ZZ^*$ ,  $H \rightarrow WW$ ,  $H \rightarrow \gamma\gamma$ )



**Run 2**  
 Coupling heavy fermions  
 ( $H \rightarrow bb$ ,  $H \rightarrow \tau\tau$ ,  $t\bar{t}H$ )



**Run 3**  
 Coupling to lighter fermions  
 ( $H \rightarrow \mu\mu$ )

# Higgs as a discovery tool

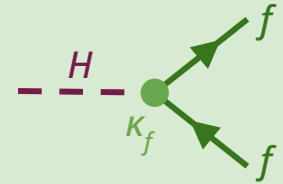
Moving from Higgs discovery to using it as a **tool to probe for new physics**:

- Only fundamental scalar that we know of
- Central to the **mechanism of mass generation**
  - Couplings to fermions predicted to be proportional to mass
    - Deviations might give hints of new physics
  - Search for couplings to other massive particles (that could constitute e.g. dark matter)
- Broad Higgs physics program pursued with ATLAS
- Higgs precision measurements as a **core priority for future collider** machine (e.g. FCC-ee)

## Higgs couplings (two-body decays)

Probe Higgs couplings to fermions/bosons

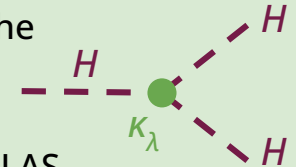
New physics can show up as modifications to decay rates



## Tri-linear Higgs self-coupling

Higgs self-coupling  $\kappa_\lambda$  one of the main SM parameters not measured yet

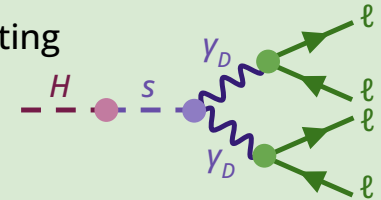
Strong di-Higgs program in ATLAS



## New physics searches using the Higgs

Dedicated analysis targeting specific rare processes

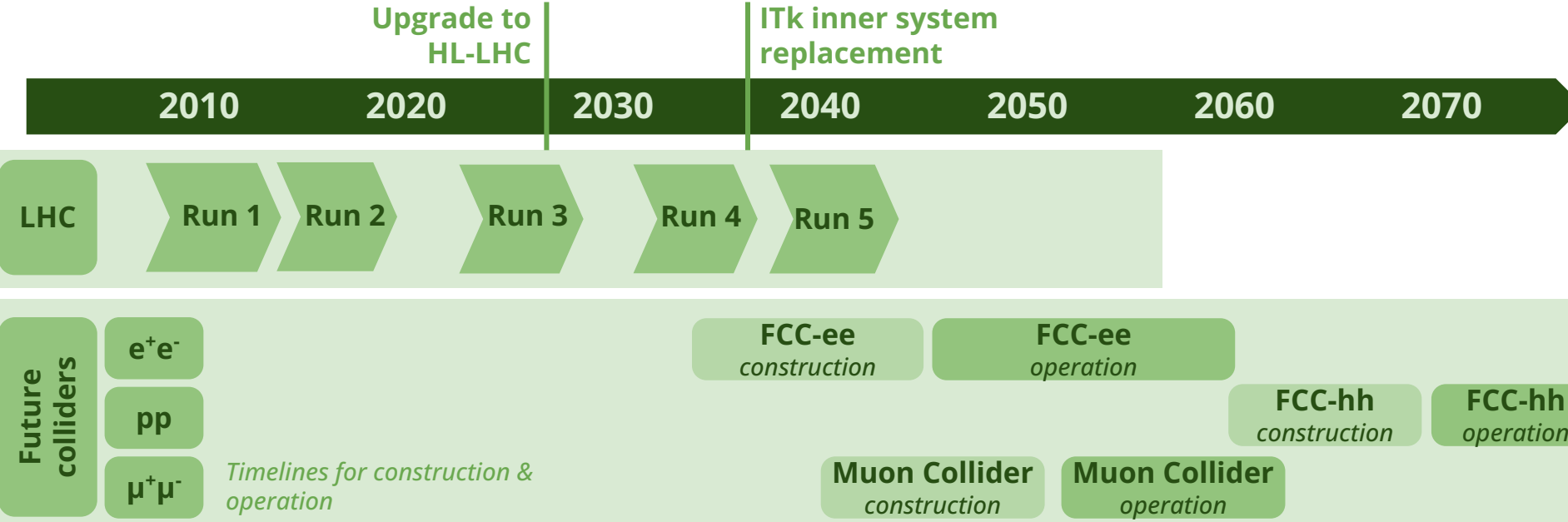
or new physics models including the Higgs



# Detector upgrades & future colliders

Need to ensure we will be able to collect the data necessary for this physics program: Both HL-LHC and future Higgs factory pose **significant challenges for our detectors**

→ need to finish upgrading our detectors for HL-LHC and start R&D efforts for a future collider!

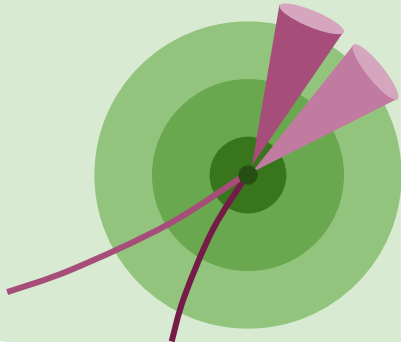


# Outline

**Objective:** Make the most of the existing dataset we collect with the LHC, while we prepare for the future of LHC and future colliders

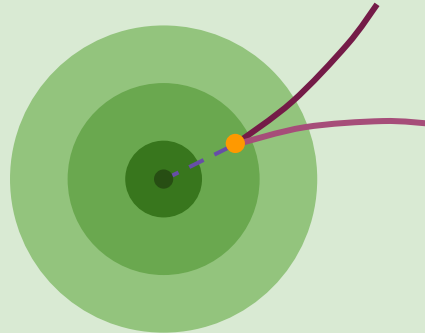
## **1. Measurements of known Standard Model processes**

*Higgs boson decays to heavy flavour final states ( $bb, cc$ )*



## **2. Exploration of new physics models & unconventional signatures**

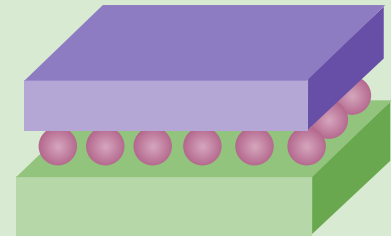
*Long-lived dark photon decays to pairs of displaced muons*



## **3. Detector development for ATLAS and future colliders**

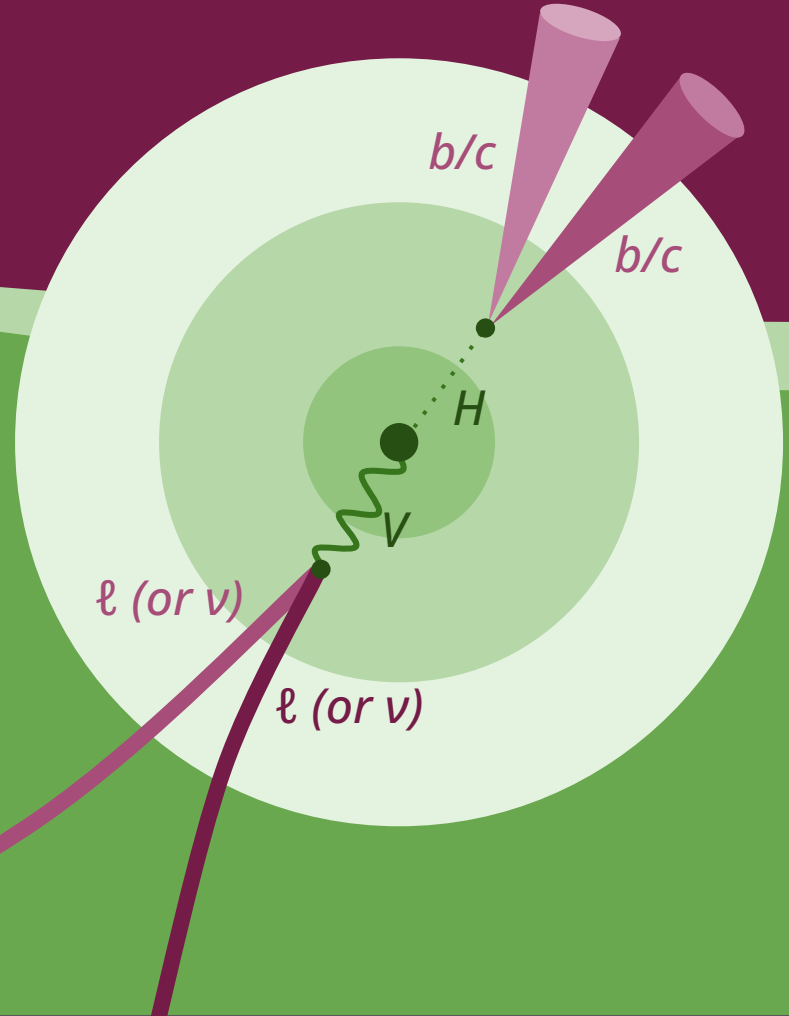
*Building the ATLAS ITk Pixel detector*

*Thin film sensor R&D for future colliders*



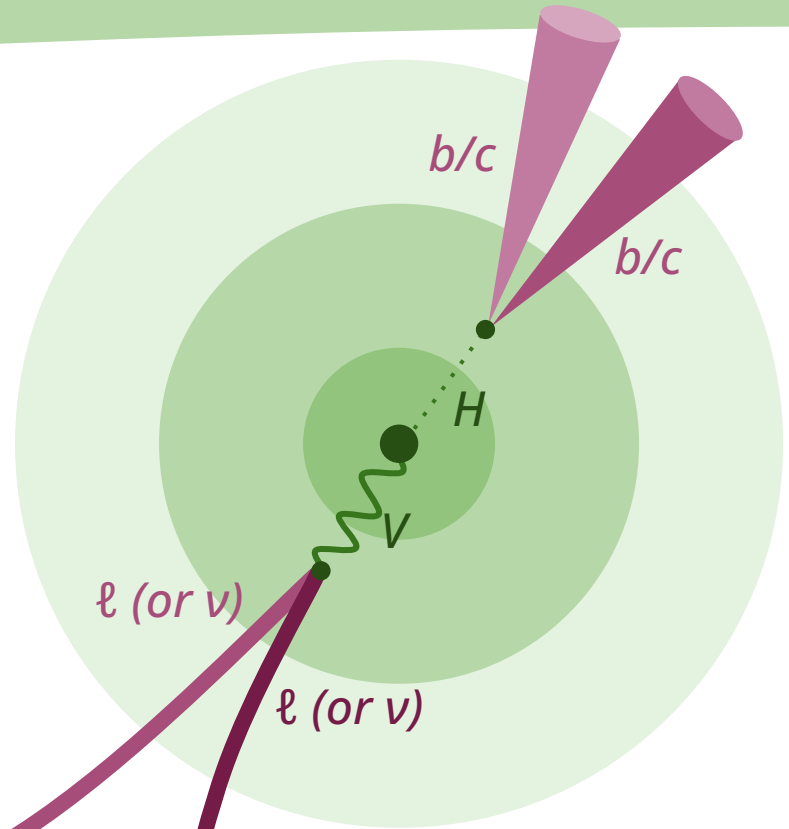
# Heavy-flavour Higgs decays

Measurements of  $VH$ ,  $H \rightarrow bb, cc$



# H → bb, cc decays

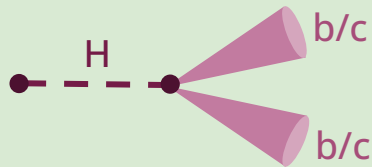
- Higgs coupling to **b-quarks** (BR=58%) well-established  
→ moving to more precise and granular measurements
- Higgs coupling to **c-quarks** (BR=2.7%) not observed yet  
→ most common decay mode still to be observed
- New physics can manifest as:
  - **Precision corrections to H → bb** decay rate or
  - **Significant modifications to H → cc rate** (e.g arXiv [1804.02400](#), [1508.01501](#))
- Target **VH production mode**: use leptonic decays of the W/Z boson to suppress QCD background
- H → bb/cc decays have very similar signatures:  
→ perform **simultaneous analysis of both decays** with common jet flavour tagging strategies



# Topologies and channels

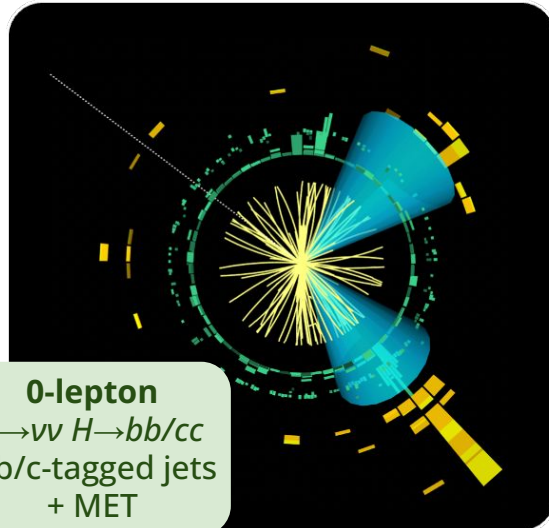
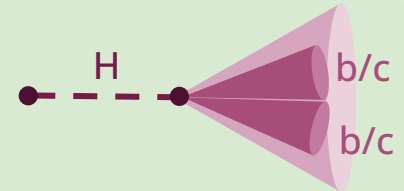
## Resolved (low Higgs $p_T$ )

Higgs candidate reconstructed from two small-radius ( $R=0.4$ ) jets



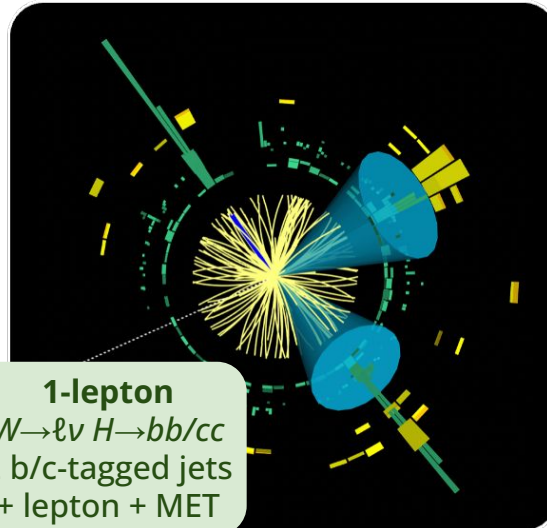
## Boosted (high Higgs $p_T$ )

Higgs candidate reconstructed from one large radius ( $R=1.0$ ) jets



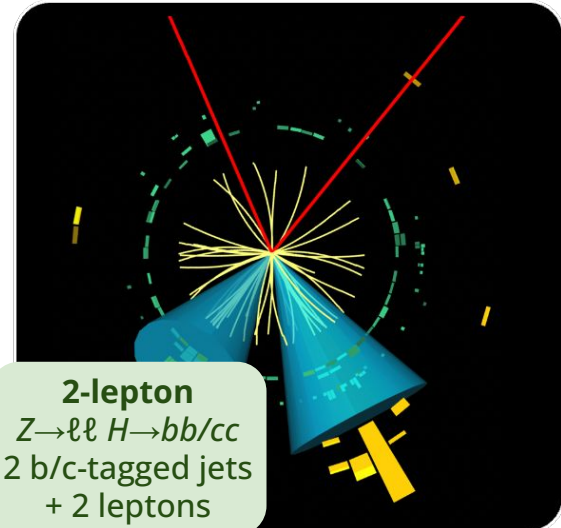
### 0-lepton

$Z \rightarrow \nu\nu$   $H \rightarrow bb/cc$   
2 b/c-tagged jets  
+ MET



### 1-lepton

$W \rightarrow \ell\nu$   $H \rightarrow bb/cc$   
2 b/c-tagged jets  
+ lepton + MET



### 2-lepton

$Z \rightarrow \ell\ell$   $H \rightarrow bb/cc$   
2 b/c-tagged jets  
+ 2 leptons

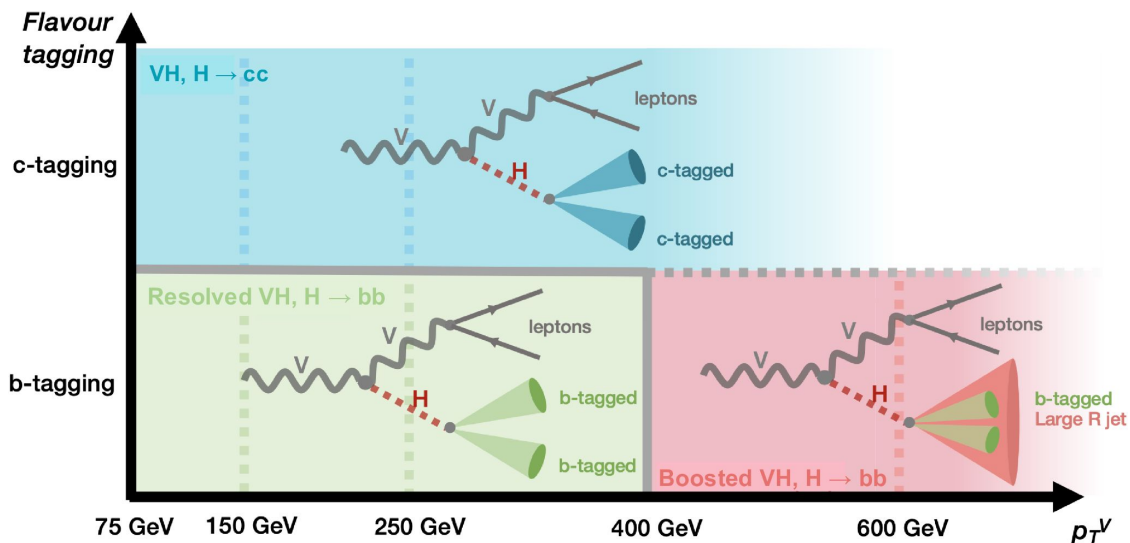
# VH, H→bb,cc analysis

Second iteration of analysing ATLAS Full Run 2 dataset, aiming for:

- Coherent treatment of **resolved VH, H→bb**, **boosted VH, H→bb** and **VH, H→cc** events
- Improved sensitivity with respect to previously published results in standalone analyses

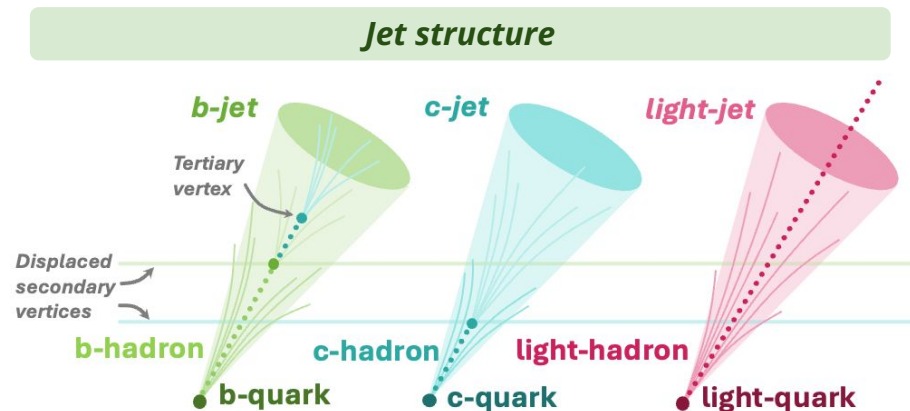
Phase space separation:

- Separation of H→bb and H→cc through **jet flavour tagging**
- Separation of boosted and resolved regime through **transverse momentum of vector boson ( $p_T^V$ )**

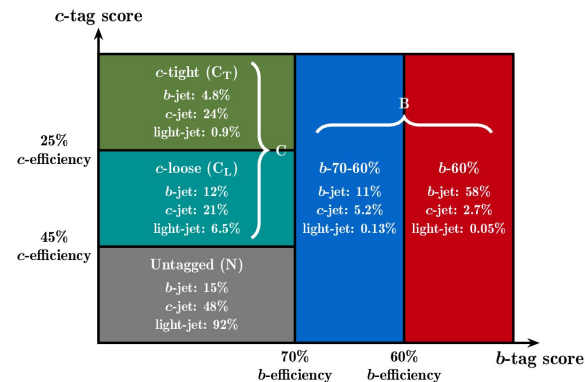


# Analysis highlights: jet flavour tagging

- **Jet flavour tagging** used to distinguish jets originating from b-, c- and light-quarks
- ML-based algorithms trained on jet kinematics and secondary vertex information
- New flavour tagger used in this analysis, with simultaneous b- and c-tagging working point  
→ **40% improvement** in sensitivity to VH,  $H \rightarrow cc$  process
- Jet flavour tagging rapidly developing with transformer-based taggers promising even better performance ([arXiv: 2505.19689](https://arxiv.org/abs/2505.19689))



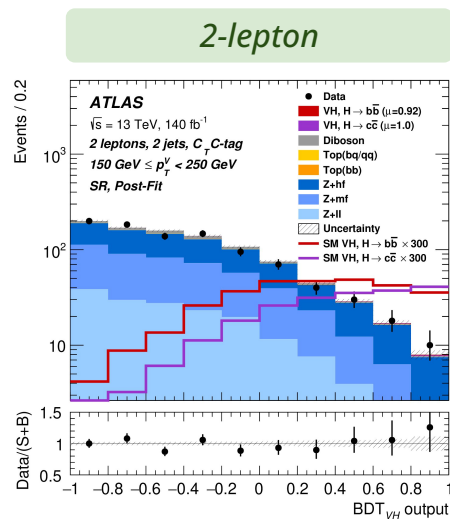
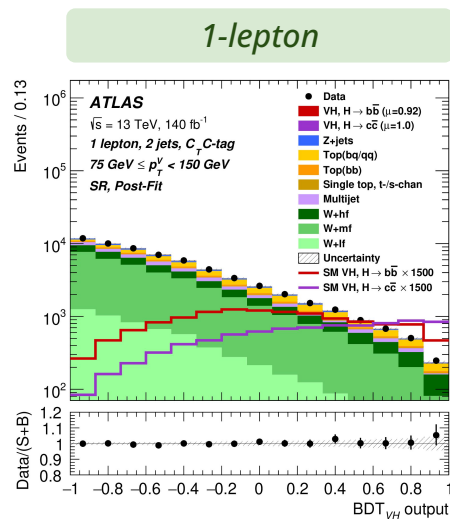
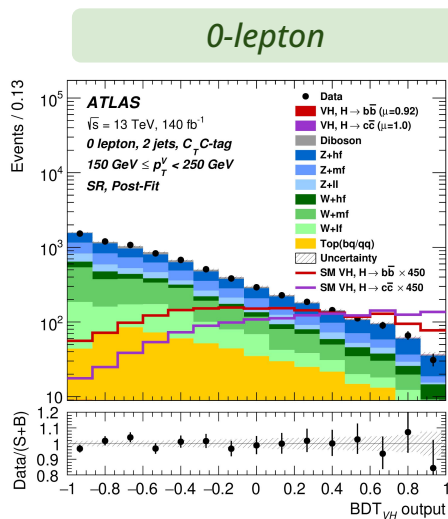
**2D jet flavour tagging scheme**



# Analysis highlights: BDT discriminant

- **Boosted decision tree (BDT)** discriminant used as the fit variable in all analysis signal regions
- Trained to distinguish  $VH, H \rightarrow bb, cc$  against backgrounds using kinematic and flavour tagging variables  
→ **50% improvement** in sensitivity for  $VH, H \rightarrow cc$

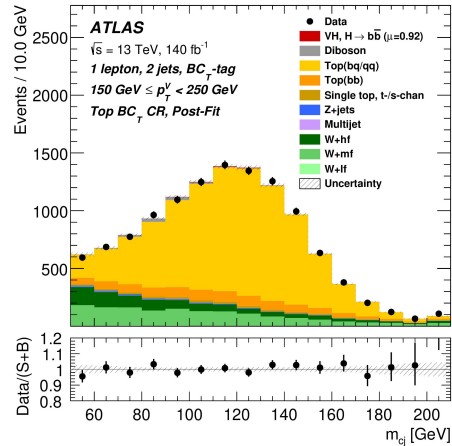
Example  
signal region  
BDT  
distributions



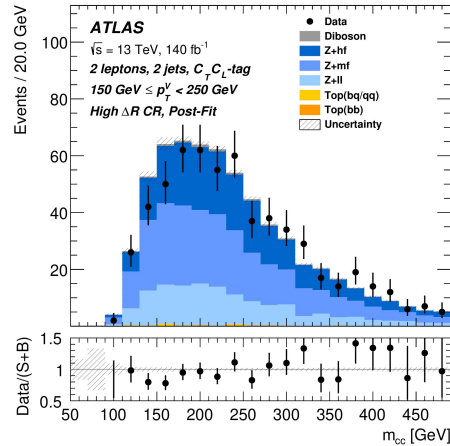
# Analysis highlights: Background modelling

- Analysis characterized by complex background composition: **W+jets**, **Z+jets** and **Top** (ttbar + single top)
  - Constrained in dedicated control regions by fitting specific variables to constrain kinematic shapes
- CARL: ML-based method for assessing modelling uncertainties to improve simulated sample statistics
  - **~20% improvement** in sensitivity for VH, H→cc

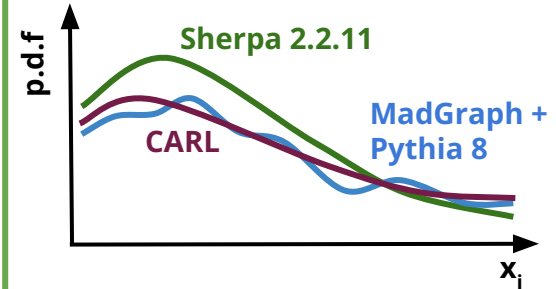
**Top control region**  
Common for H→bb and H→cc regions



**Z+jets (heavy flavour) CR**  
Using  $\Delta R$  sidebands, fitting  $m_{cc}$



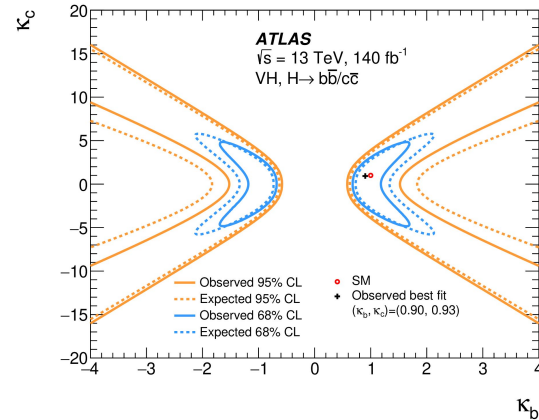
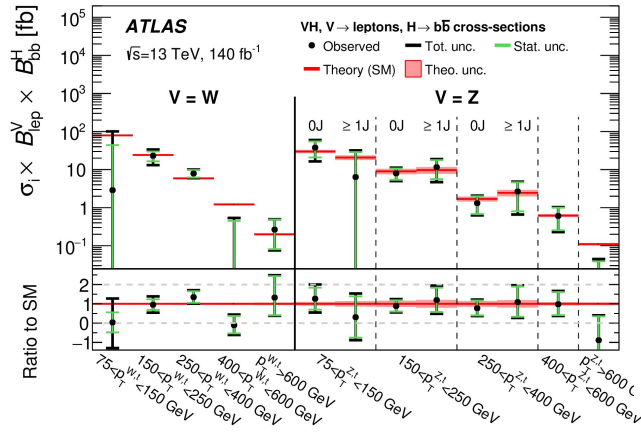
**CARL shape uncertainties**  
Reweighting of samples to assess  
shape modelling uncertainties



# Results

- Measurement of **WH,  $H \rightarrow bb$  with 5.3 (5.5)  $\sigma$**  and **ZH,  $H \rightarrow bb$  with 4.9 (5.6)  $\sigma$**  observed (expected)
  - First observation of WH production with heavy flavour final states
- 95% CL upper limit on **VH,  $H \rightarrow cc$  of 11.5 (10.6) x SM** observed (expected)
  - **3 x better limit compared to previous analysis on same dataset**
- Limited by data statistics and systematic uncertainties (V+jets and top modelling, jet and flavour tagging)

**VH,  $H \rightarrow bb$  STXS cross-sections**  
 → most granular VH,  $H \rightarrow bb$  STXS measurement to date

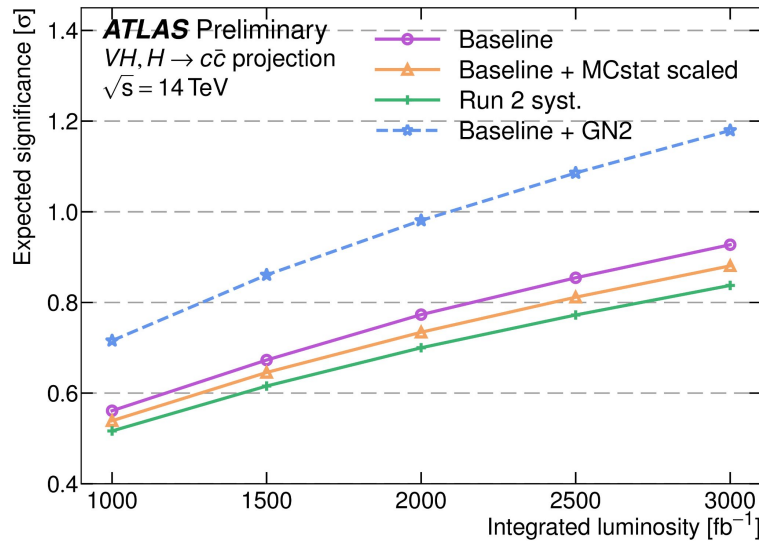


**Constraints on couplings  $\kappa_c$  vs  $\kappa_b$**   
 → direct probe of Higgs-charm and Higgs-bottom couplings

# VH, H→cc at HL-LHC

- VH, H→cc will benefit significantly from the increased dataset at the High-Luminosity LHC (HL-LHC)
- Extrapolation of the expected sensitivity to **VH, H→bb and VH, H→cc for 3000 fb<sup>-1</sup> at √s=14 TeV**
  - Assuming improvements in systematic uncertainties & improved jet flavour tagging performance
- Expected to reach around **~1σ sensitivity for VH, H→cc**
  - Significant analysis improvements needed for observation at HL-LHC

*Expected VH, H→cc significance as a function of collected luminosity*



# Outlook

Promising directions for  $H \rightarrow cc$ :

- **Boosted VH,  $H \rightarrow cc$ :** Promising results in CMS, now under investigation in ATLAS with new boosted jet tagger
- **VBF,  $H \rightarrow cc$ :** Recent ATLAS results in VBF  $H$ ,  $H \rightarrow cc$  measures a limit of 41 (28)  $\times$  SM
- **$ttH$ ,  $H \rightarrow cc$ :** Comparable sensitivity to VH channel in CMS (8  $\times$  SM)

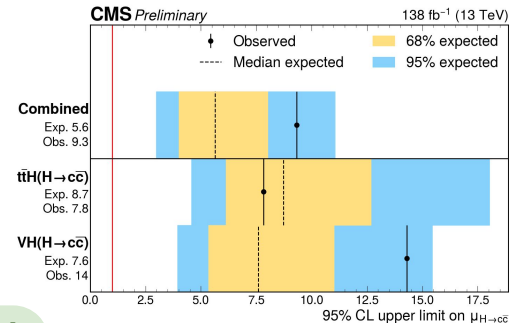
→ Observation at HL-LHC will require a **combination of all of these channels**, and a coherent (common) analysis strategy

- HL-LHC will allow us to map out the **predicted SM Higgs properties** with high precision
  - Mass, spin, couplings to fermions & bosons, Higgs self-coupling and even challenging decay modes like  $H \rightarrow cc$

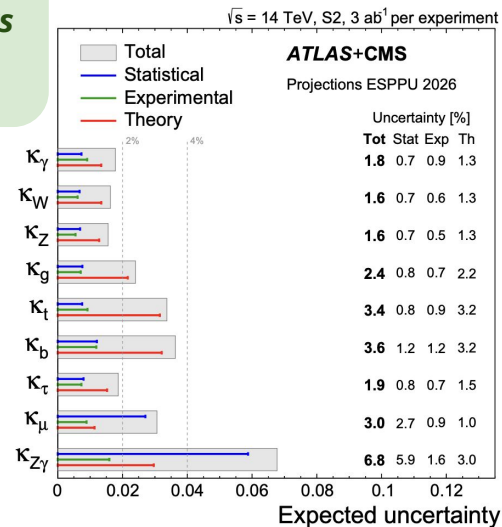
→ but what about **properties of the Higgs that go beyond what the Standard Model predicts?**

**CMS VH and  $ttH$ ,  $H \rightarrow cc$  limits**

[Phys. Rev. Lett. 136 \(2026\) 011801](#)

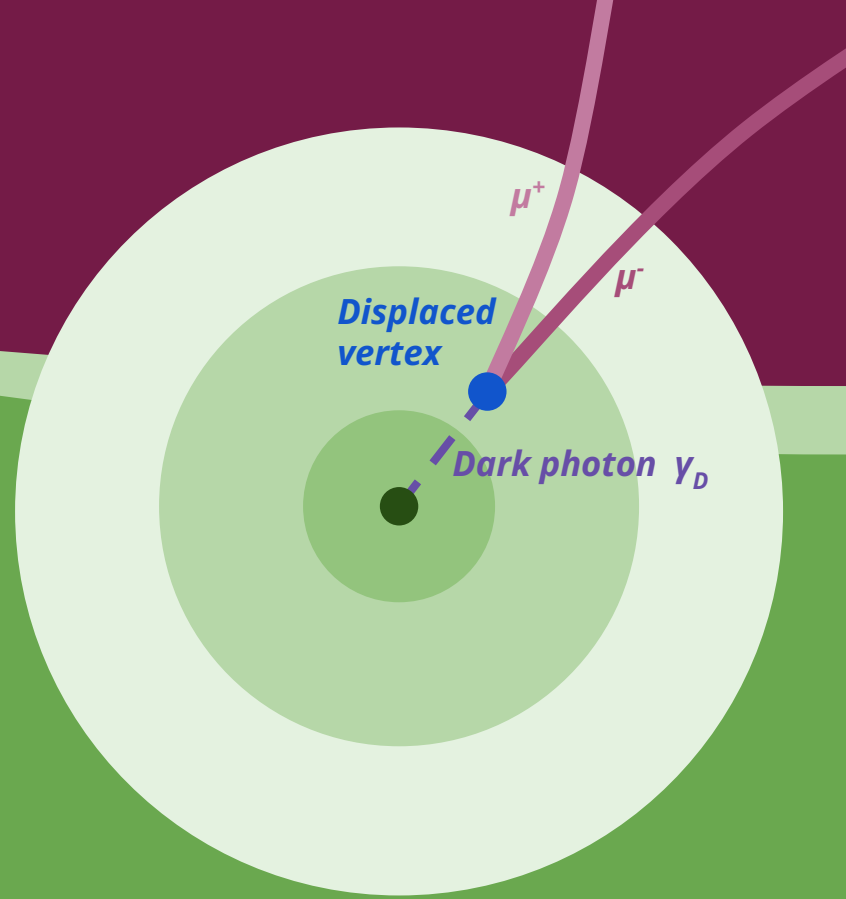


**Projected Higgs couplings at the HL-LHC**



# Novel Higgs Signatures

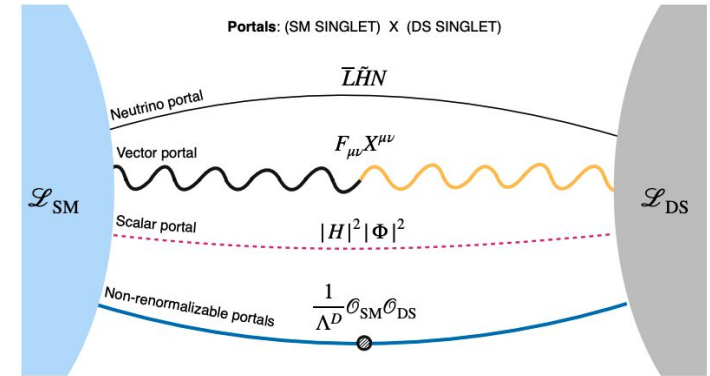
Searching for displaced di-muon decays from Higgs-produced dark photons



# Dark sector models

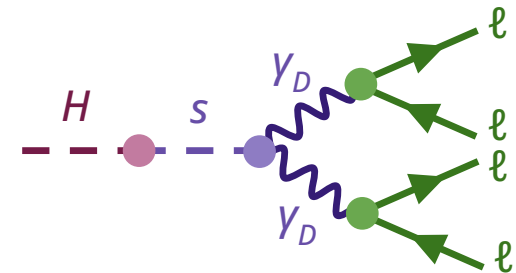
- Dark Matter could be viewed as a **dark sector** of particles, which does not directly interact with SM particles
  - DM could couple to SM though mediator particles (**portals**)
- Example: **Hidden Abelian Higgs Model (HAHM)**
  - Introduce additional  $U(1)_X$  symmetry
    - **dark scalar (s)**
    - **dark photon ( $\gamma_D$ )**
    - interact with the SM through kinetic mixing
  - Model parameterized by **mixing strength ( $\epsilon$ )** and **dark photons mass  $m_{\gamma_D}$**
  - Dark photon can have a measurable lifetime and decay at a displacement from where it was produced
  - Could be observed in ATLAS through decays of the dark photon into leptonic final states

## Illustration of dark sector portals



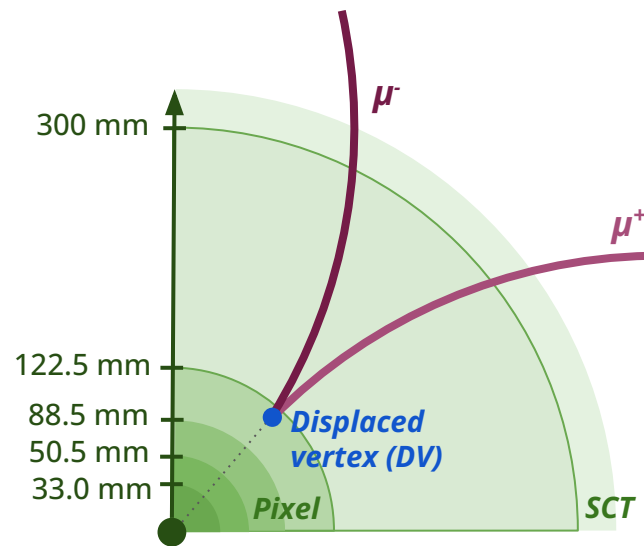
[Link to diagram](#)

## Hidden Abelian Higgs Model (HAHM)



# Low-mass dark photon search

- Search for a dark photon resonance
  - **Low-mass** (400 MeV - 10 GeV)
  - Decaying into a **displaced pair of muons**
  - Inside of the inner detector pixel volume (radius  $L_{xy}$  [1,300] mm)
- Targeting **new phase space** in HAHM model searches
- **Signal characteristics:**
  - Highly boosted displaced muon vertex
  - Collimated muons at vertex
  - With small transverse impact parameter  $d_0$



# Reconstruction

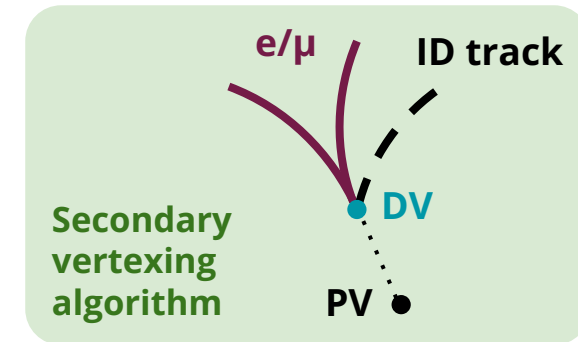
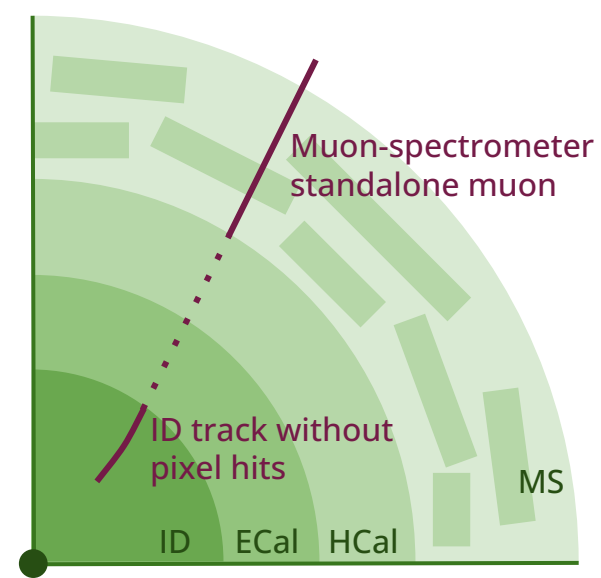
Displaced nature of final state requires careful development of reconstruction techniques:

## Muon reconstruction:

- Muons in the analysis are produced displaced from the primary interaction
- Standard reconstruction algorithms in Run 3 look for promptly produced muons
- Extended standard prompt muon reconstruction (which requires  $\geq 1$  ID Pixel hit) to also include tracks w/o pixel hits  
→ dedicated processing and calibration

## Vertexing:

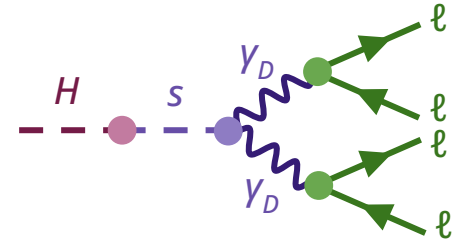
- Reconstructed muons then combined into displaced vertices
- Secondary vertexing algorithms reconstructs vertices from muon pairs, with vertexing selection optimized for this analysis



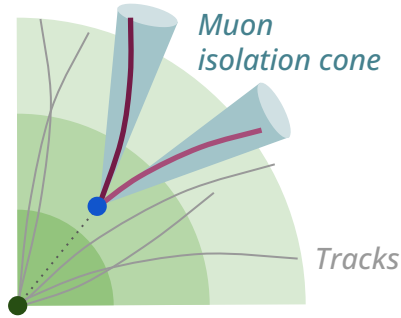
# Event selection

- Select events with at least one reconstructed displaced di-muon vertex
- Event selection with requirements on displaced vertices, vertexed muons and kinematics to reduce background:
  - **Isolated muons** with high muon quality
  - High  **$L_{xy}$  significance** ( $L_{xy}/\sigma(L_{xy})$ )
  - Di-muon  $p_T$  pointing back to the primary vertex
- Control/validation regions defined by inverting one or multiple cuts

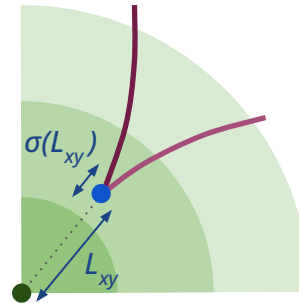
## Target signal (HAHM)



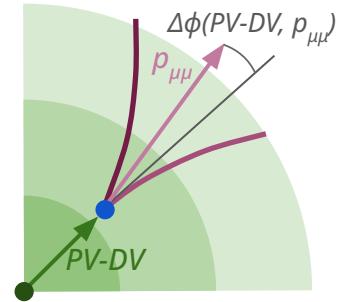
## Muon isolation



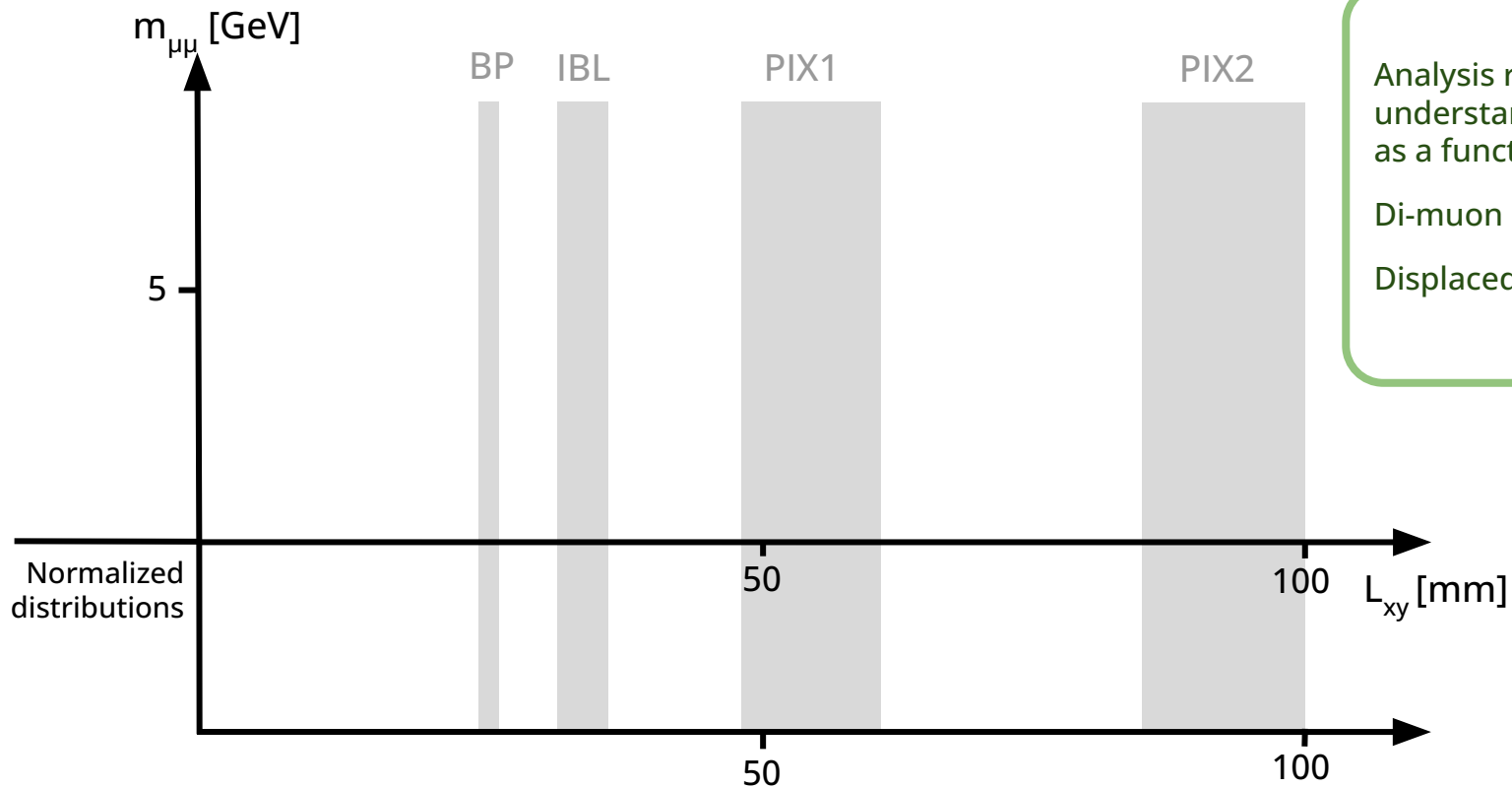
## $L_{xy}$ and $L_{xy}$ significance $L_{xy}/\sigma(L_{xy})$



## Dimuon pointing angle cut



# Background composition



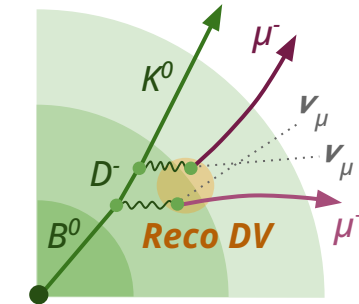
Analysis requires detailed understanding of backgrounds as a function of:

Di-muon invariant mass ( $m_{\mu\mu}$ )

Displaced vertex location ( $L_{xy}$ )

# Background composition

## Heavy flavour background



B-hadron background from semileptonic decays reconstructed with displaced DVs

Studied in dedicated simulated samples

**Main background (especially for  $m_{\mu\mu} < 5$  GeV)**

$m_{\mu\mu}$  [GeV]

BP

IBL

PIX1

5

Heavy flavour background

Normalized distributions

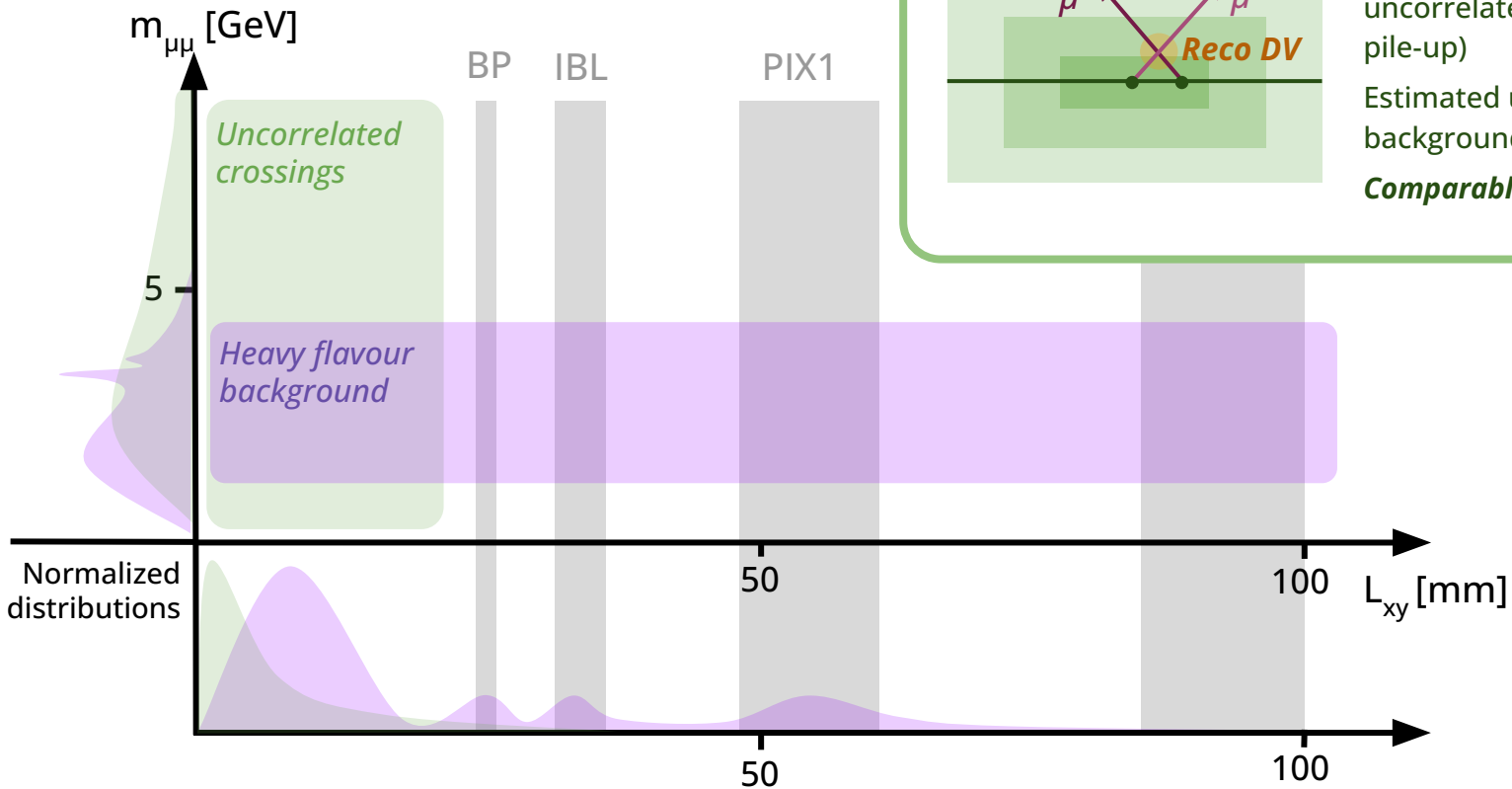
50

100  $L_{xy}$  [mm]

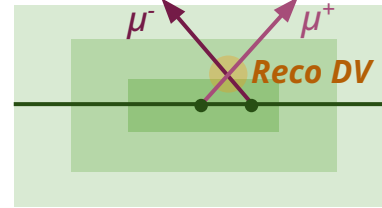
50

100

# Background composition



## Uncorrelated crossings



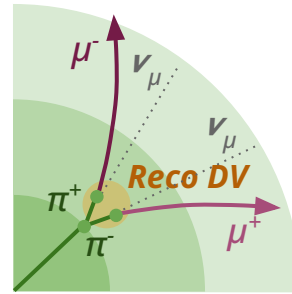
Fake DVs from muons from uncorrelated sources (e.g. pile-up)

Estimated using combinatorial background estimation

**Comparable to HF at high  $m_{\mu\mu}$**

# Background composition

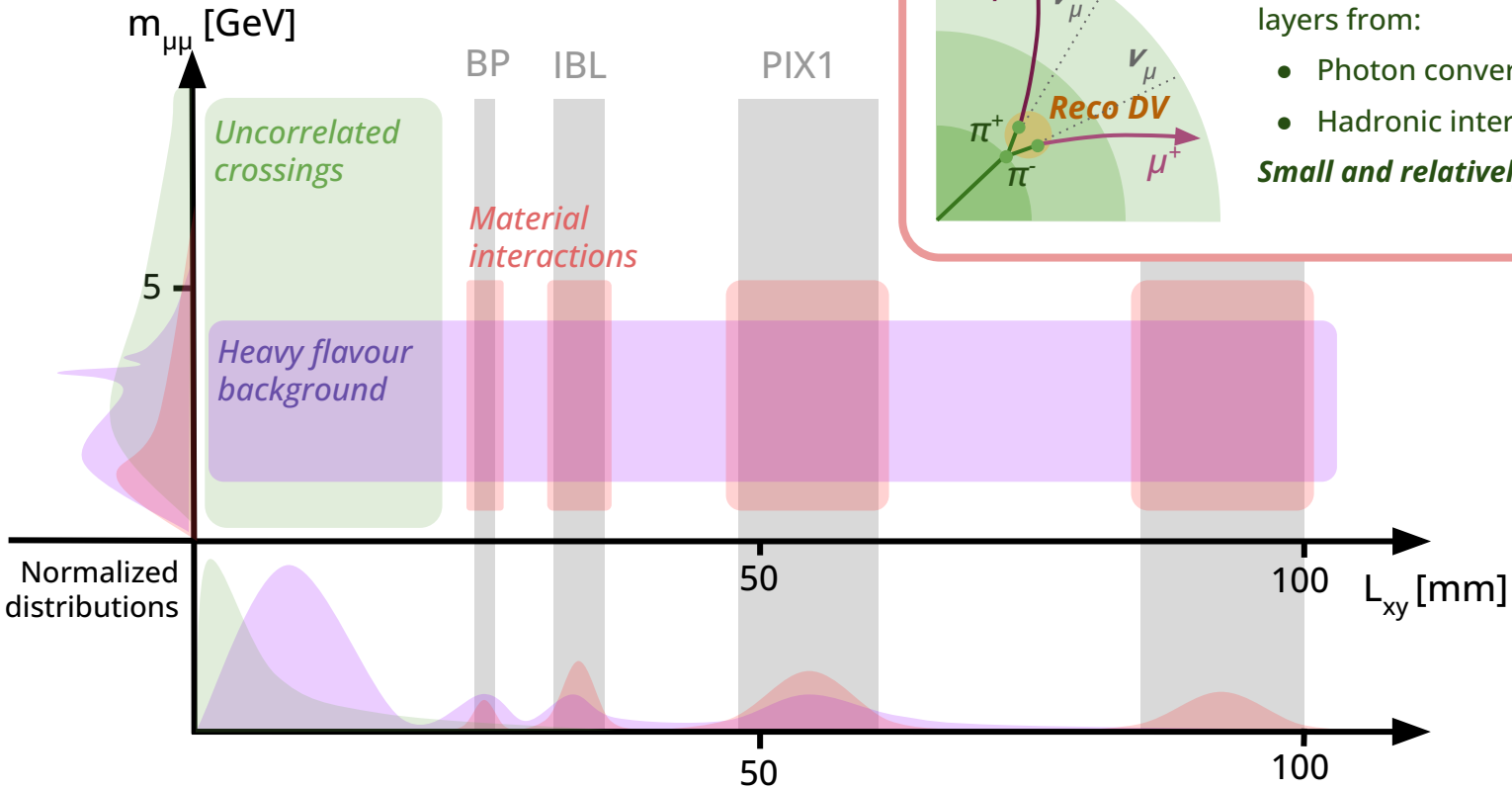
## Material interactions



Background produced in material layers from:

- Photon conversions
- Hadronic interactions

**Small and relatively smooth in  $m_{\mu\mu}$**



# Background & statistical analysis strategy

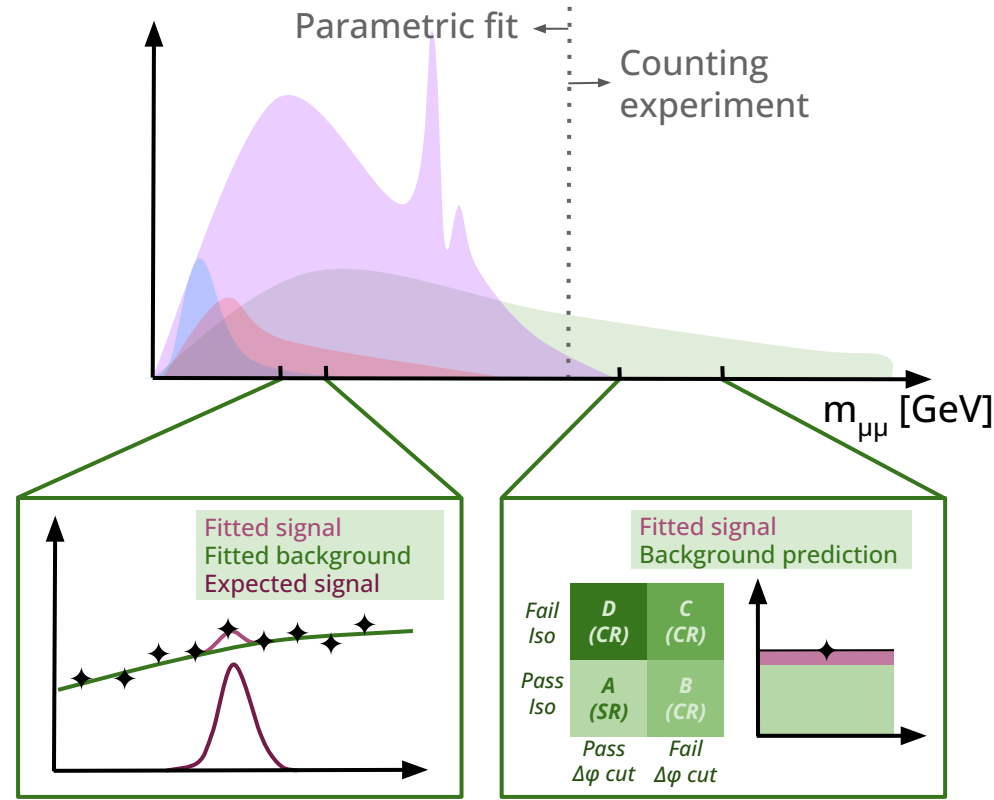
Background estimation and statistical analysis separated into:

**Low-mass region** ( $m_{\mu\mu} < 5.5$  GeV):

- Large smooth background dominated by heavy-flavour decays
- Parametric fits in sliding mass windows

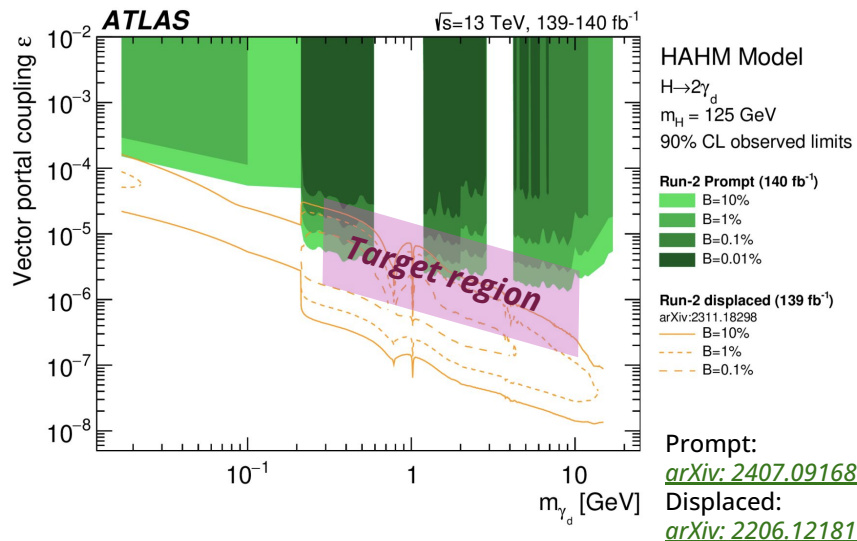
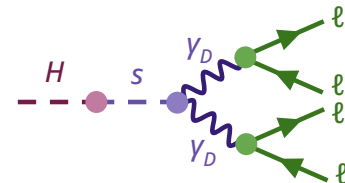
**High-mass region** ( $m_{\mu\mu} > 5.5$  GeV):

- Low background from heavy-flavour decays and uncorrelated crossings
- Data-driven estimate of residual background
- Cut-and count analysis



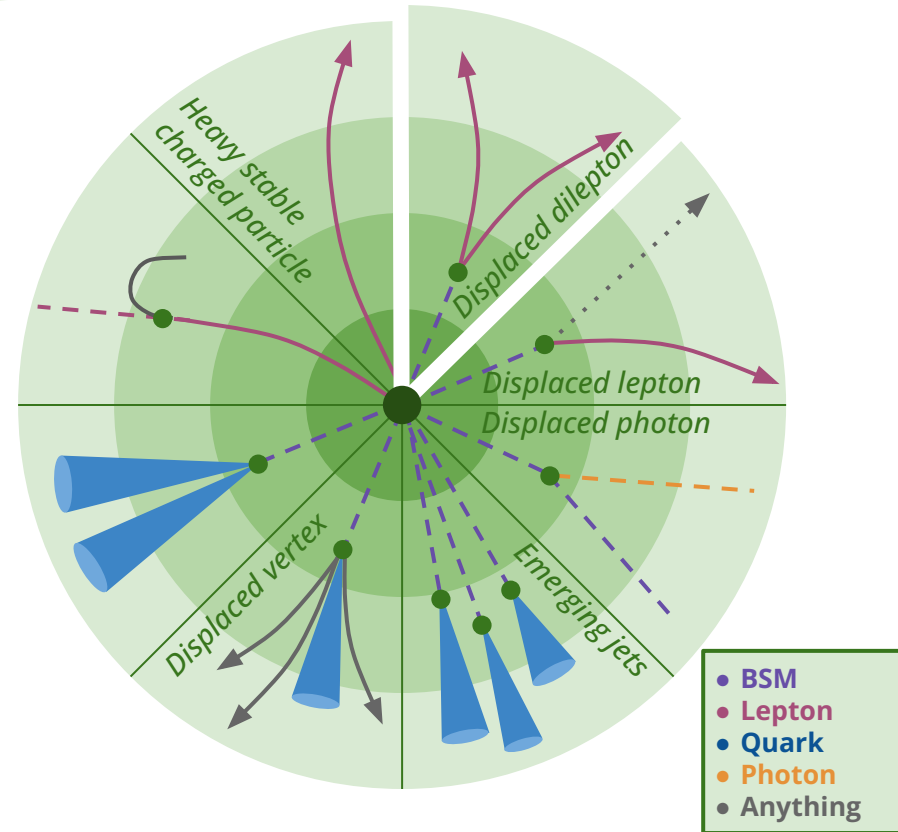
# Target phase space region

- Expect to have sensitivity in regions not explored yet
  - Dark photon masses **0.4 - 10 GeV**
  - Dark photon **mixing strengths  $\epsilon$   $10^{-4} - 10^{-6}$**
- Complementary to existing analyses in ATLAS looking for
  - prompt ([arXiv: 2407.09168](https://arxiv.org/abs/2407.09168))
  - or displaced fermions using calorimeter or muon spectrometer information ([arXiv: 2206.12181](https://arxiv.org/abs/2206.12181))
- Competitive with CMS search ([JHEP04 \(2022\) 062](https://arxiv.org/abs/2206.12181)) which uses a dedicated low-momentum di-muon trigger stream



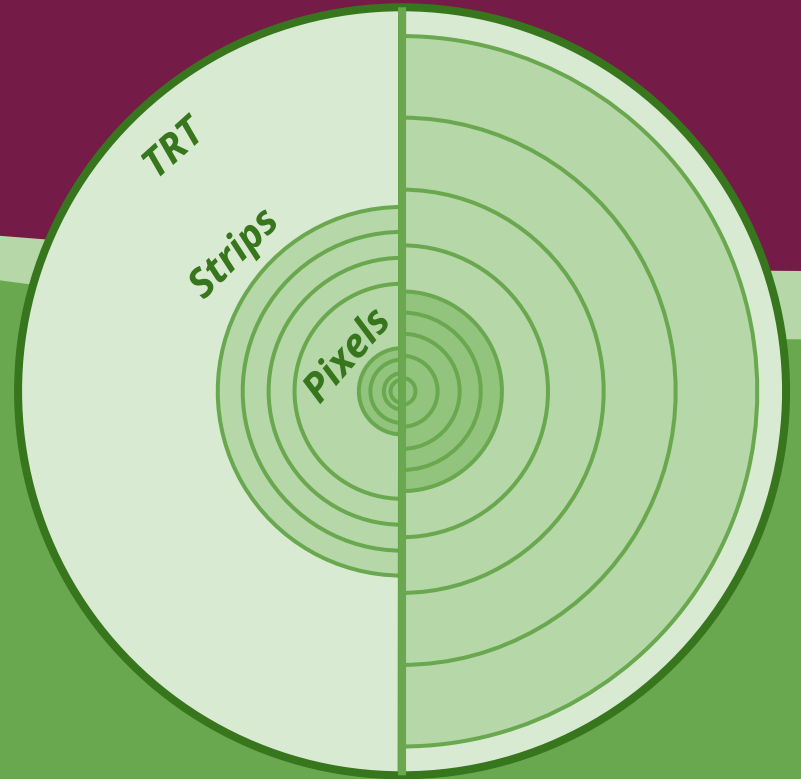
# Long-lived particles & displaced signatures

- Displaced di-muon analysis is an example of **Long-Lived Particle (LLP)** search
- LLPs can result in a wide array of **unconventional final states**
  - **trying to use unexplored signatures to discover new physics**
- Dark sector interactions are theoretically only very **loosely constrained**
  - **Higgs-mediated dark sector** can manifest as a many possible signatures
  - Interesting possibilities to explore in the coming years!



# Detector Innovation

Upgrade of the ATLAS inner pixel detector for HL-LHC & detector development for future colliders



*ATLAS Run 2 Inner  
Detector*

*ATLAS Inner Tracker  
(ITk)*

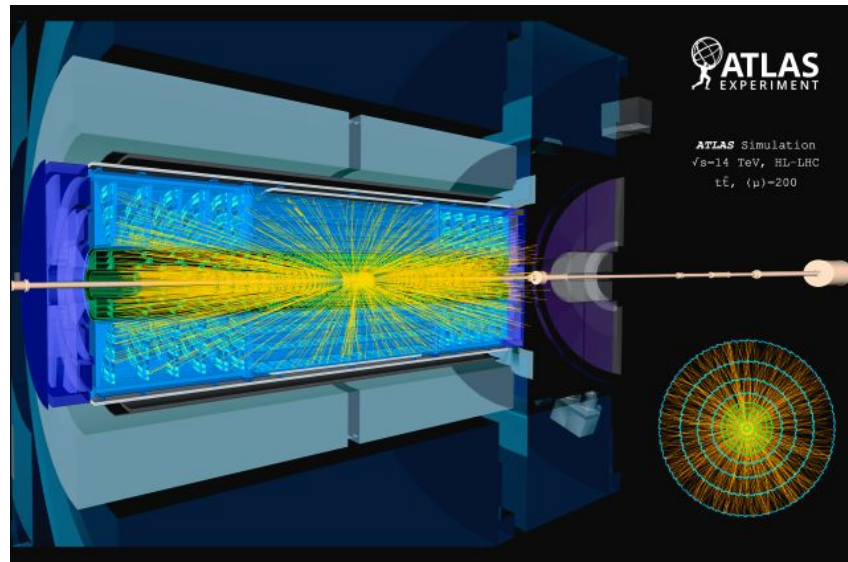
# Detectors for HL-LHC

Upgrade to **HL-LHC** (around 2030):

- Requires significant detector upgrades to collect the **10 x larger dataset**
- Factor 4 increased number of interactions per collision

**Inner tracker requirements** at HL-LHC:

- **Radiation tolerance:** 10 x more radiation tolerant technology needed
- Better **granularity** needed to keep low occupancy and current tracking performance
- **Trigger** needs high-speed and memory electronics



Need a new inner tracker to meet the requirements of HL-LHC

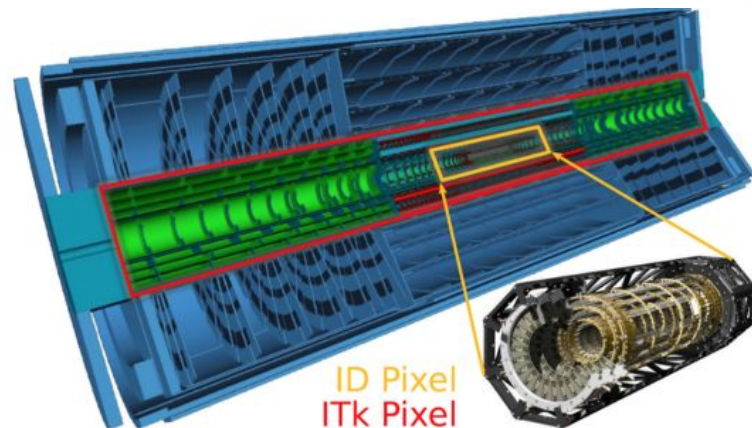
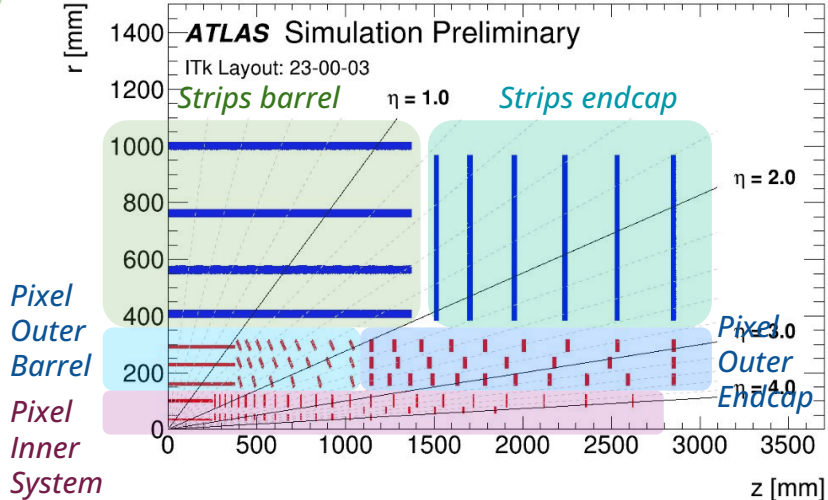
Using new technology for all detector components (e.g chip & sensor)

→ Upgraded **ATLAS Inner Tracker (ITk)**

# ATLAS ITk Upgrade

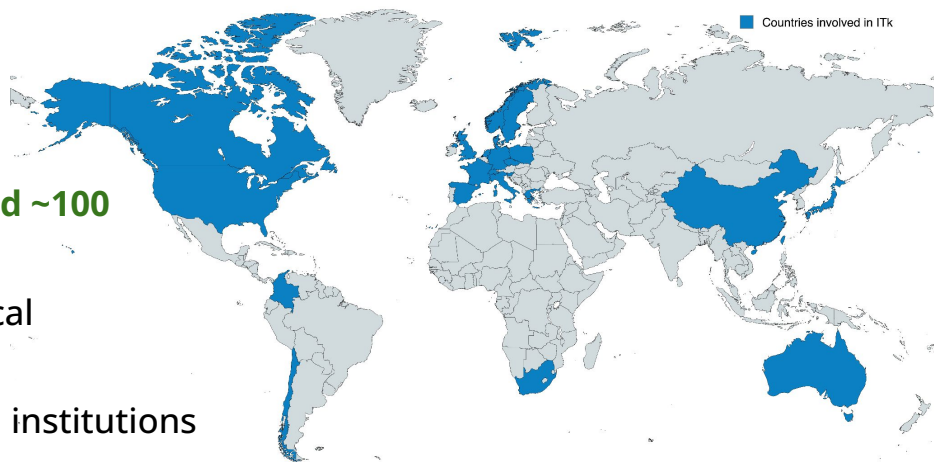
Upgraded all-silicon **ATLAS Inner Tracker (ITk)**:

- **ITk Strips detector** with 4 barrel and 6 endcap disks
- **ITk Pixel detector** consisting of 5 barrel layers & many endcap rings
  - 6x larger silicon area than current tracking detector ( **$\sim 13 \text{ m}^2$  of active area**)
  - **O(10k) pixel modules**, 5.1 billion pixels
  - Extended coverage to  **$|\eta| \leq 4$**
  - Smaller pixel pitch  $400 \times 50 \mu\text{m}^2 \rightarrow$   **$50 \times 50 \mu\text{m}^2$**
  - **New readout chip** designed to cope with increased data rates and radiation



# ATLAS ITk Collaboration

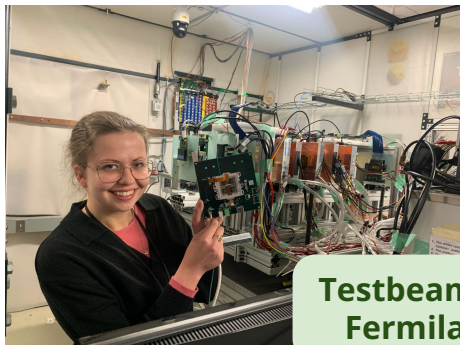
- ATLAS ITk project is a large collaboration with **around ~100 collaborating institutions**
  - close collaboration between electrical & mechanical engineers, physicists, management and industry
- Production and testing of components split between institutions
  - LBL involved in ITk Strips Module production and testing, ITk Pixel ASIC design, DAQ and module testing



*Countries involved in ITk*



**Sensor testing  
@ Oxford**

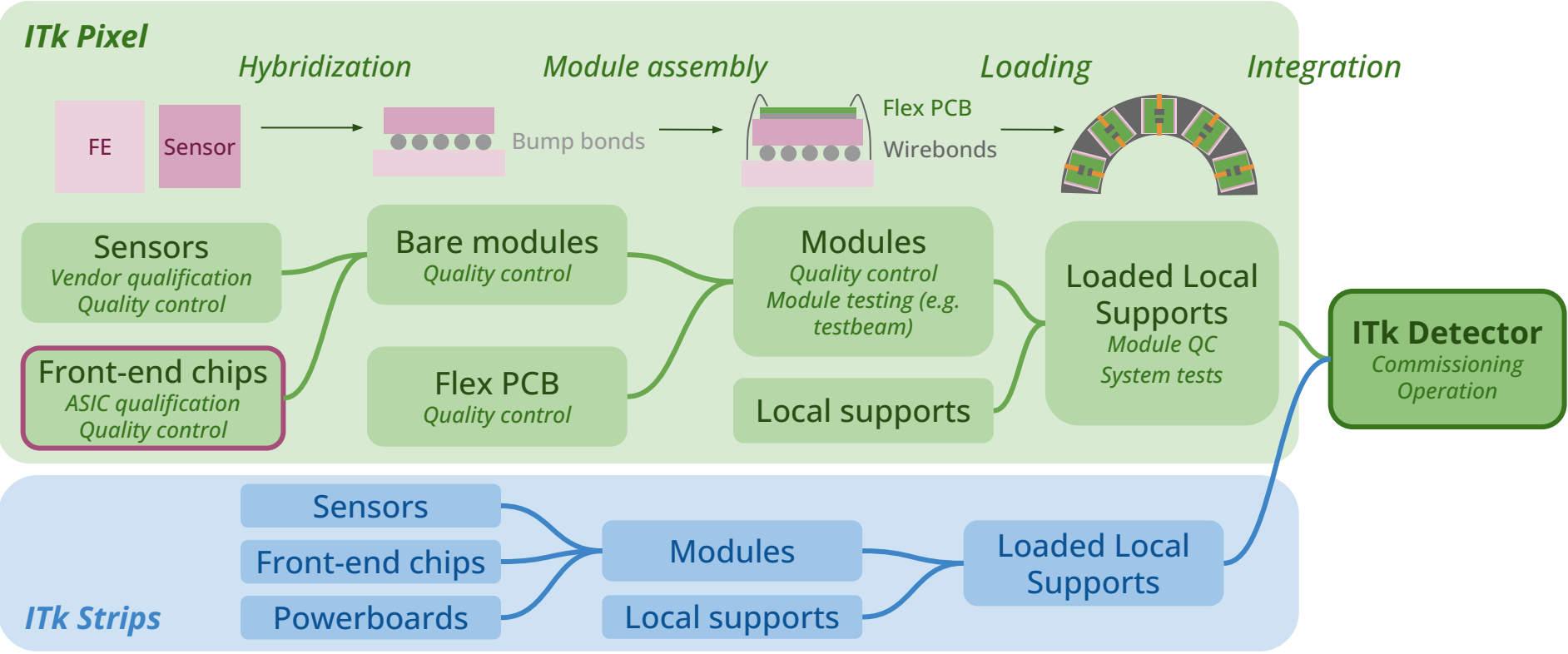


**Testbeam @  
Fermilab**

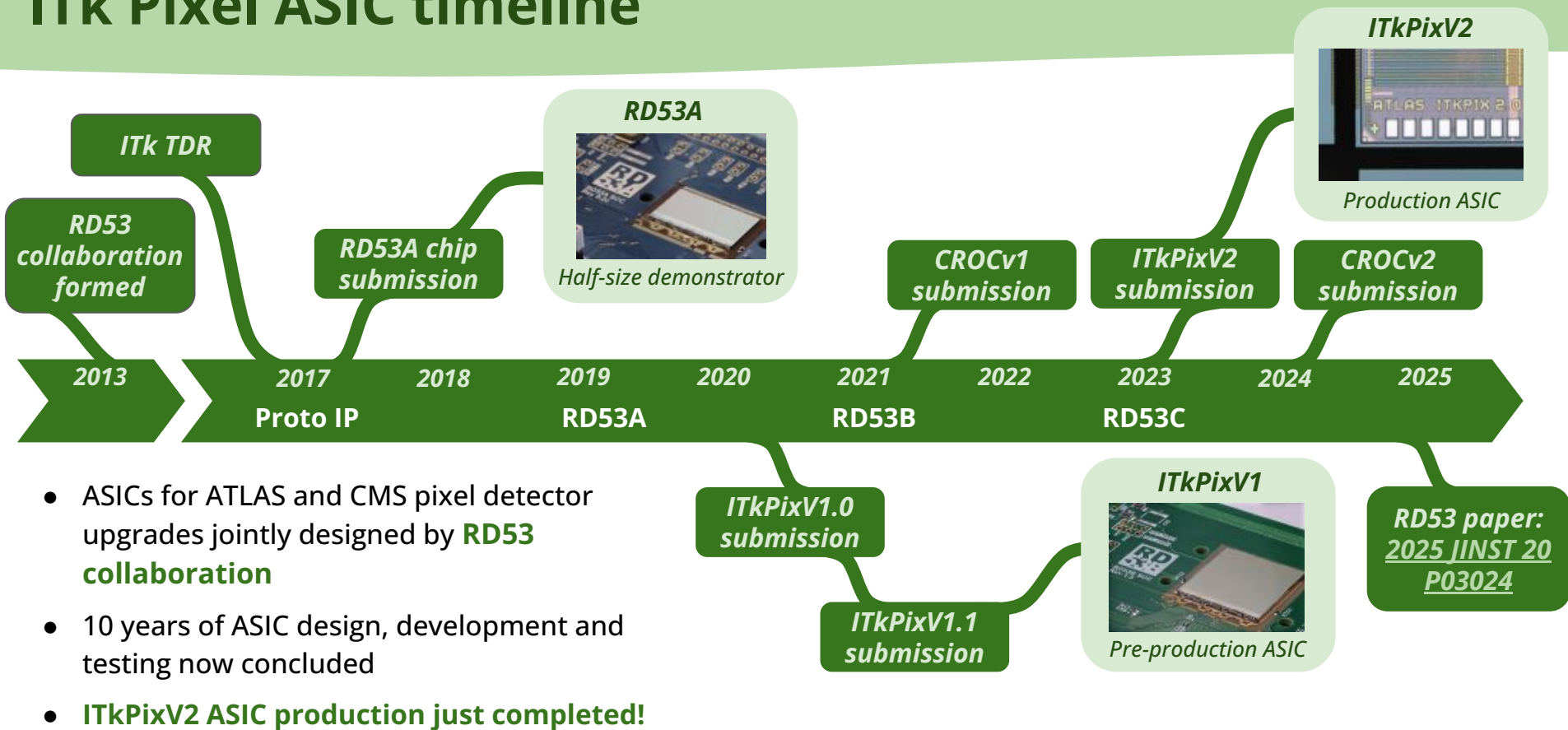


**Testbeam @  
KEK**

# From components to the ITk detector



# ITk Pixel ASIC timeline

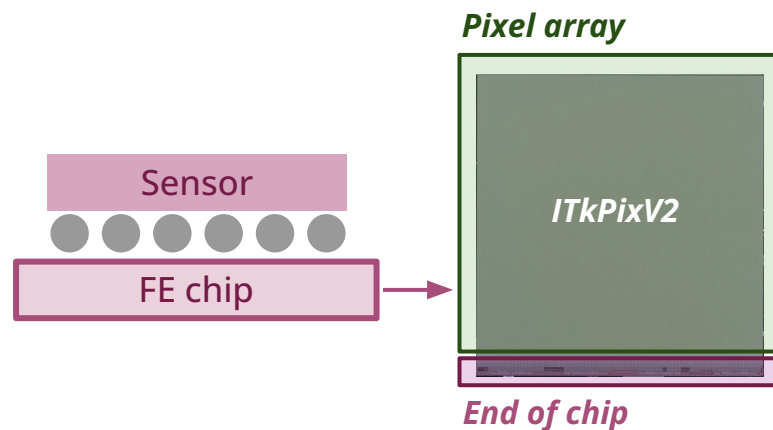


- ASICs for ATLAS and CMS pixel detector upgrades jointly designed by **RD53 collaboration**
- 10 years of ASIC design, development and testing now concluded
- **ITkPixV2 ASIC production just completed!**

# ITkPixV2 chip

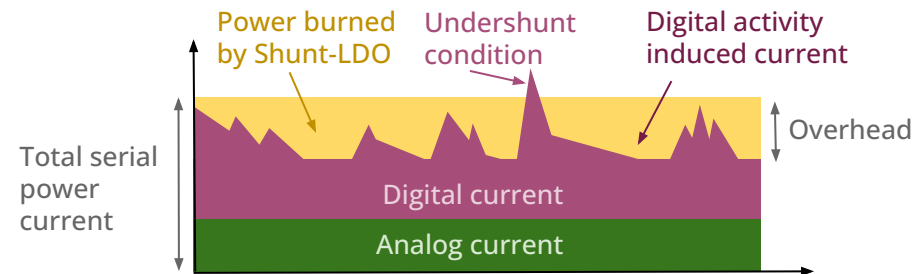
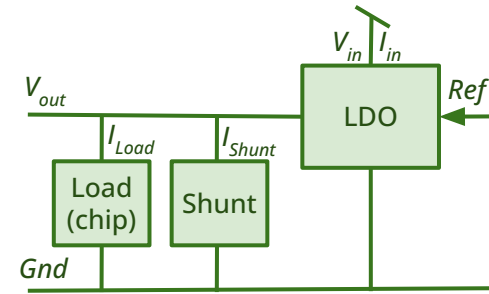
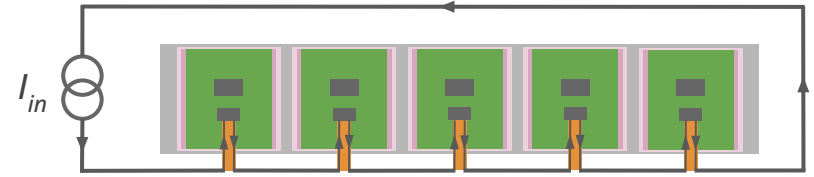
- **ITkPixV2**: ATLAS ITk production on-detector readout ASIC, bump-bonded to the sensors
- **Processes** raw signal of particles passing through sensor, **digitises them** and **sends out data** for further processing
- For our purposes we can identify 3 main components
  - **Powering (Shunt-LDO circuit)**
  - **Analog Front-End**
  - **Digital logic**
- Detailed characterisation and validation campaign of ITkPixV2 chip needed to ensure all ASIC components meet the detector requirements

CMOS technology	65 nm
Max. hit rate	3.5 GHz/cm <sup>2</sup>
Pixel size	50 x 50 μm <sup>2</sup>
Pixel array	400 x 384
Chip dimensions	20 x 21 mm <sup>2</sup>
Power	< 0.5 W/cm <sup>2</sup>
Radiation tolerance	1 Grad @ -10 C



# ITkPixV2 Powering

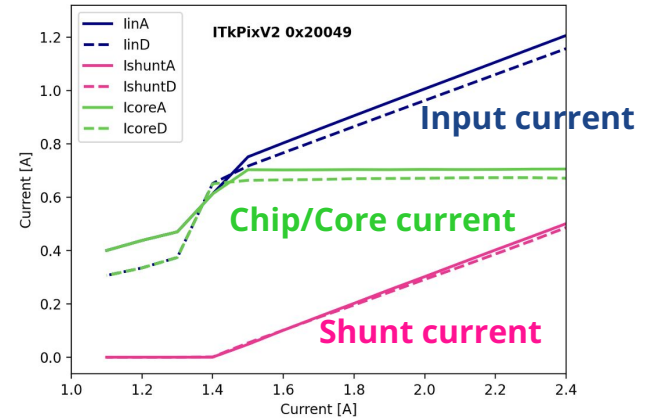
- Pixel modules will operate in **serial powering configuration**
    - Constant current supplied to chain of modules
    - Reduce cables (i.e. passive material) in detector
  - Current consumed by chip **varies throughout operation**, e.g. with particles hits & digital activity
  - To account for this in serial powering, the chip has a SLDO circuit, which powers:
    - main load (**chip**)
    - internal load (**shunt element**)
- Shunt element designed to use up any excess current not needed by the chip



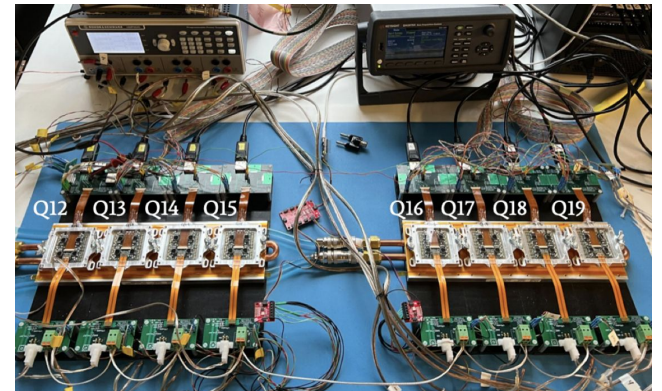
# ITkPixV2 Powering

- Use SLDO start-up curves to validate chip start-up and powering behaviour
  - **Validated SLDO circuit functions as expected, even at low temperatures of -50 C**
- Tested serial power chain with 8 modules to validate realistic multi-module operation
- Performed similar tests for all chip features:
  - Analog Front-End
  - Data transmission
  - Radiation tolerance
  - Single Event Upset
- **Fully qualified ASIC as ready for production in mid-2024**

## SLDO current curves

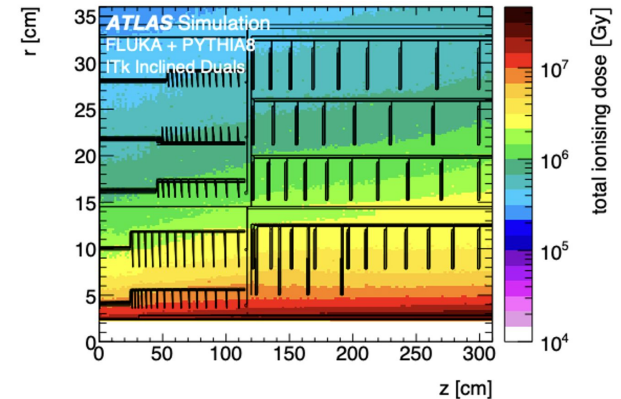
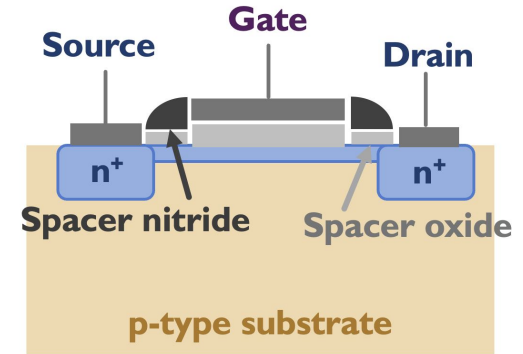


## Serial power chain at LBL



# TID damage and ASICs

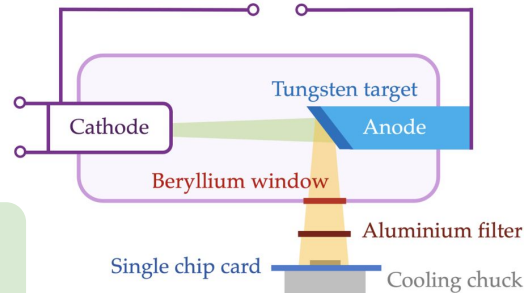
- ATLAS ITk detector will face unprecedented levels of radiation
  - up to **1 Grad Total Ionizing Dose (TID)** at dose rate of 20 krad/h
- Radiation damage in transistors dominated by damage in  $\text{SiO}_2$  and  $\text{Si-SiO}_2$  interfaces
- Damage dependent on device parameters: technology (e.g. 65 nm CMOS), transistor size and layout
- Environmental parameters:
  - Temperature & supplied voltage
  - Dose rate → more damage observed at low dose rates
- **Detailed irradiation studies needed for ITk Pixel ASIC**
- Most damage expected for digital logic (made of small transistors)
  - chip includes dedicated **ring oscillator** test circuits to measure **transistor delay increase**



# Short-term irradiations - X-rays

- **X-ray setups** used for performing ~20 irradiation campaigns at Oxford and LBNL on ITkPixV1 and ITkPixV2
- Convenient to deliver precise (and large) amount of dose over a few weeks
- Using consistent irradiation configurations and calibrations
  - 40kV tube voltage, 150  $\mu\text{m}$  Al layer
  - Chip temperature of -10 C
  - Monitoring chip voltages and **ring oscillators**

*X-ray  
irradiation  
configuration*



*Oxford  
X-ray  
irradiation  
setup*

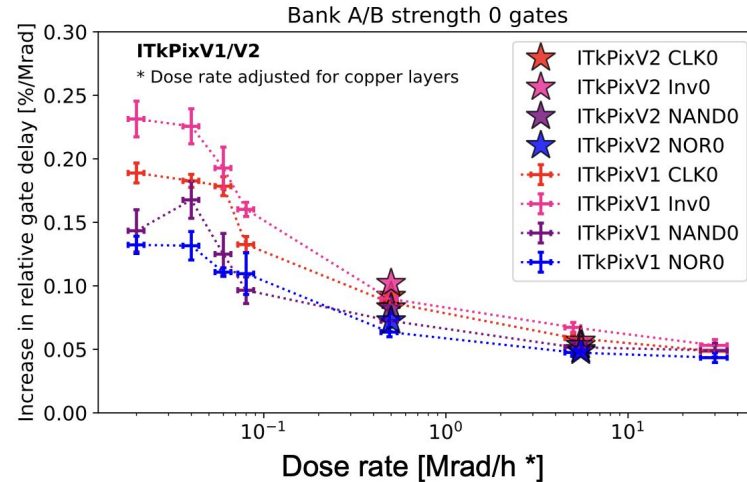
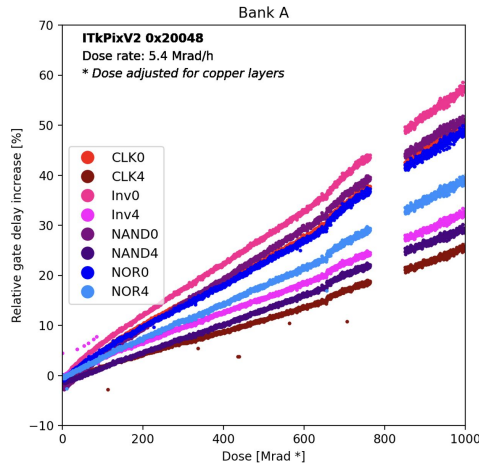


*LBL X-ray  
irradiation  
setup*

# X-ray irradiations - Dose rate dependence

- Measured gate delay increase of ring oscillators as a function of total delivered dose
  - Relative gate **delay increase should stay below 200%** to meet readout speed requirement for ITk
- Measured dose rate dependence in X-ray irradiations to low total dose (~10 Mrad)
  - Radiation damage is heavily dependent on dose rate, **2 times more damage observed at low dose rate**

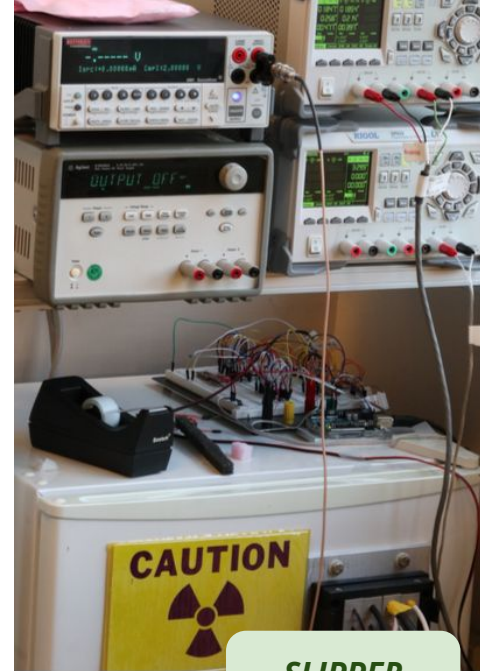
*Gate delay increase vs total dose*



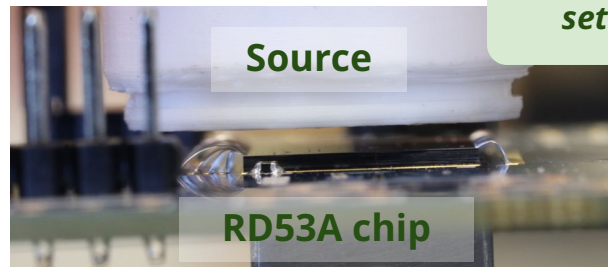
*Gate delay increase @ different dose rates*

# Long-term irradiations - Kr-85

- For more realistic irradiations at low dose rates, need setups that can continuously operate for years
- **SLIPPER** of Phase-2 Pixel Readout (SLIPPER) setup at LBNL:
  - Long-term irradiation of **RD53A chip using Kr-85 source**
  - Source mounted on top of a chip in commercial freezer
  - Collected ~700 Mrad of TID over 4 years at dose rate expected for innermost pixel layers (20 krad/h)
  - Stopped after operational issues were observed (expected from the types of gates used in RD53A)
- **SLIPPERv2** using two ITkPixV2 chips commissioned last year at LBL (w/ several improvements to setup)
  - Will provide expectation for behaviour of ASIC in ITk



**SLIPPER  
setup**



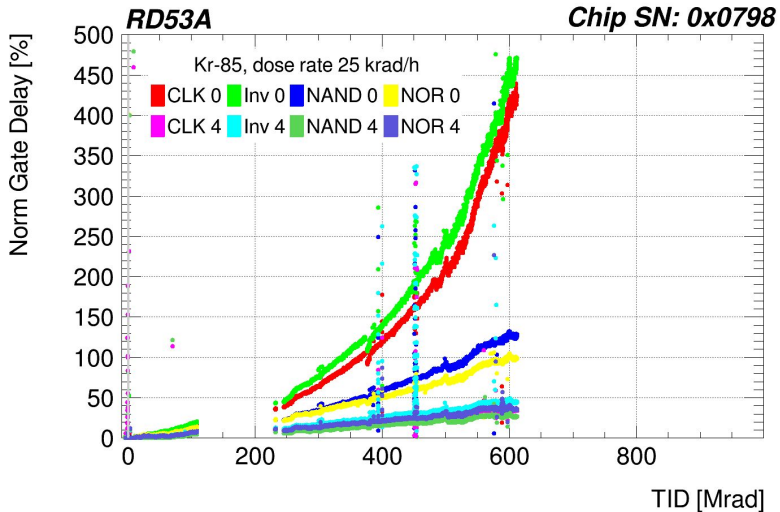
**Source**

**RD53A chip**

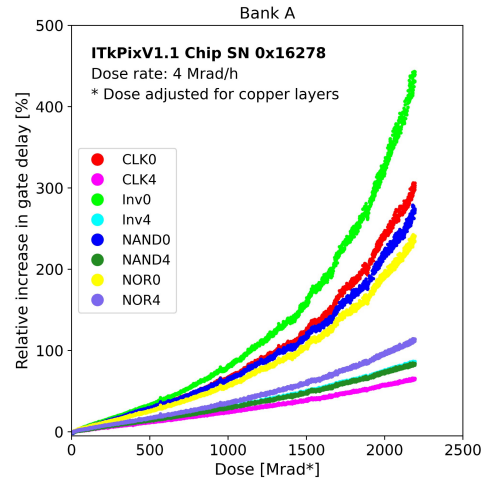
# Long-term irradiations - Kr-85

- SLIPPER measured gate delay increase of ring oscillators at low dose rate to high TID
- Observed **> 200% gate delay increase** for smaller (strength 0) gates → not used in final ASIC design
- Observed **non-linear behaviour** of gate delay increase at high TID  
→ can derive **gate-dependent correction factors** between damage at low and high dose rates

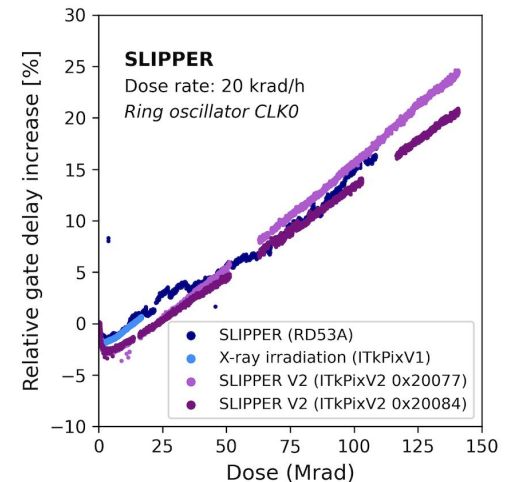
**SLIPPER: Gate delay increase vs. total dose**



**High dose rate X-ray: Gate delay increase vs. total dose**



**SLIPPERv2 progress**

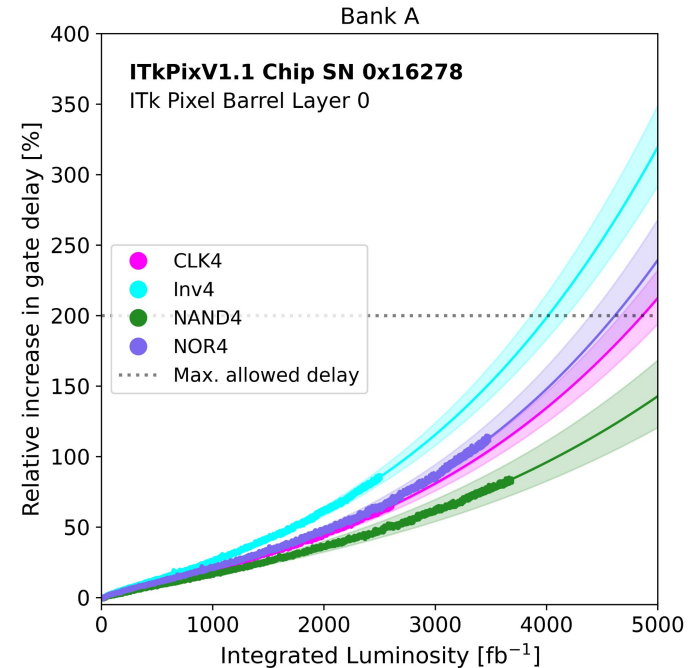


# Expected failure point of ASIC in ITk

- Convert to expected integrated luminosity in ITk Pixel Barrel Layer 0 to estimate when operational issues in digital logic are expected
- Expect digital logic to fail with > 200% gate delay increase  
→ expect to reach this point **after around 4000 fb<sup>-1</sup>** collected data in the innermost barrel layer (well above requirement)

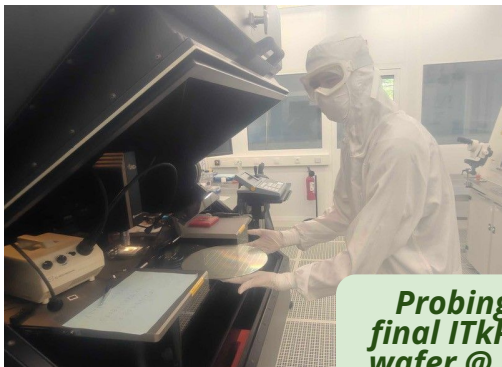
Gate type	Expected failure point [fb <sup>-1</sup> ]
Clock	4700
Inverter	3700
NAND	6000
NOR	4200

## Gate delay increase vs integrated luminosity



# ITk Pixel towards Production

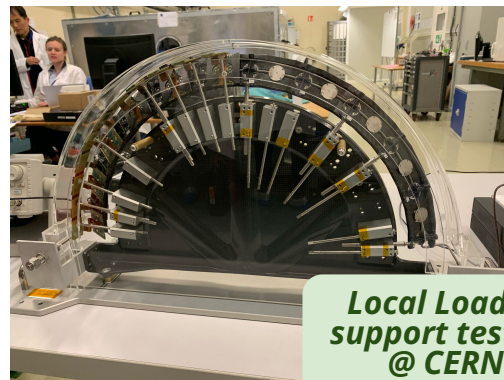
- Highlighted some of the work done for the ITk Pixel ASIC to validate and ensure the chip meets our detector requirement → one of the **first step towards the detector!**
- ITk Pixel ASIC production (i.e. chip wafer probing) has now finished
- **ITk Pixel modules are now in production** with assembly and quality control ongoing at many sites
- Tests of **larger local loaded support structures are ongoing** at CERN and SLAC → moving towards integration and commissioning of ITk detector in 2029!



*Probing of  
final ITkPixV2  
wafer @ Bonn*



*Module QC  
test box @  
LBL*



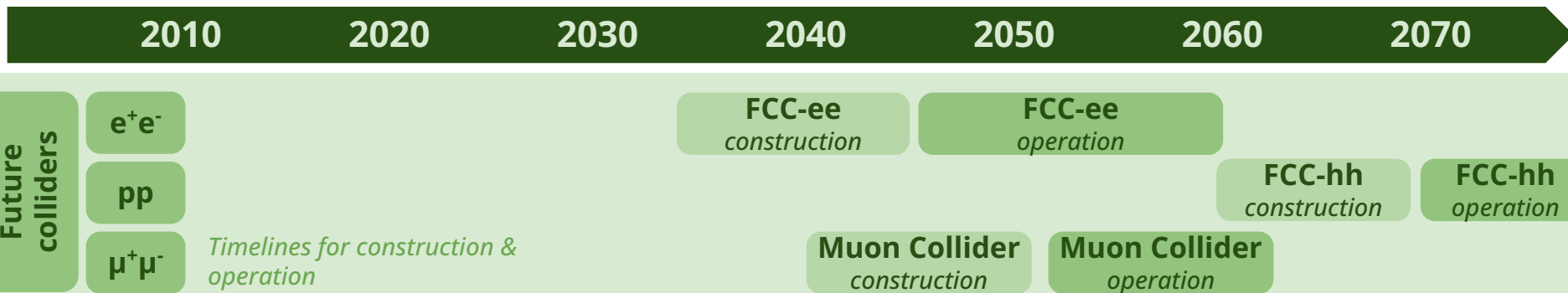
*Local Loaded  
support testing  
@ CERN*

# Detector R&D for future colliders

Future colliders will require novel technologies and each potential future collider will face unique challenges:

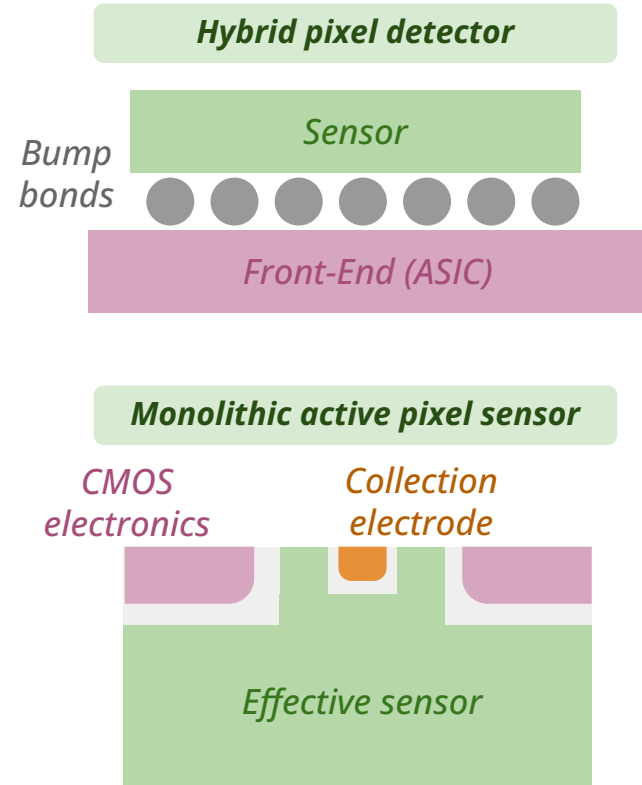
- **FCC-ee**: High spatial precision and very low mass
- **FCC-hh**: Extreme radiation hardness & fast timing / on-chip intelligence for pile-up rejection
- **Muon collider**: fast timing/on-chip intelligence for beam-induced background rejection, radiation tolerance

→ Develop detectors with the lessons learned from ITk production, and while incorporating new technologies (e.g. AI/ML) for design and study



# Future pixel detectors

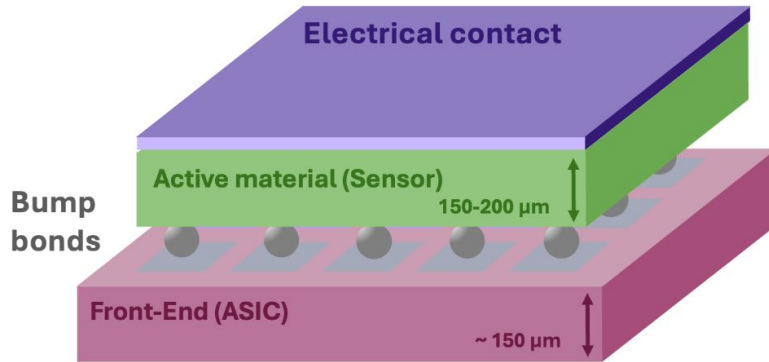
- Current pixel detectors constructed as **hybrid detectors**
  - Active sensor material & ASIC in different pieces of silicon
    - allows for optimization of silicon properties
  - Attached pixel-by-pixel through bump bonds (hybridization)
- As seen in ITk, **hybridization is complex, expensive and time consuming**
- Alternative are **Monolithic Active Pixel Sensors (MAPS)**, with active area and electronics in one piece of silicon
  - Require significant process modification to meet hit radiation & hit rate requirements for future collider application



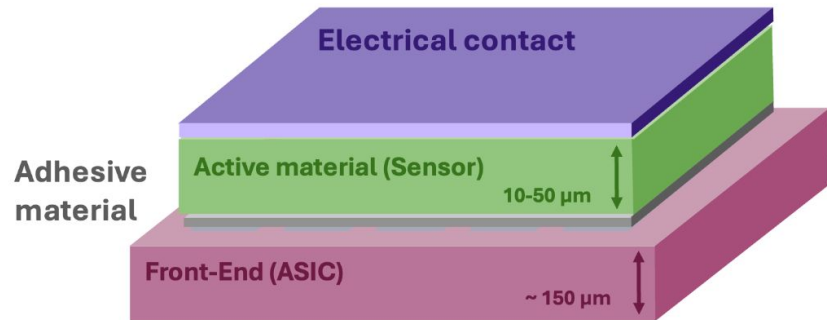
# FORC: Film on Readout Chip

- Instead of bump-bonding, deposit thin layer of **sensor material directly on top of ASIC**, e.g. using plasma enhanced chemical vapour deposition (PECVD) or sputtering
  - Optimize sensor materials separately and **investigate materials beyond silicon**
- Ongoing R&D work as part of LDRD grant at LBNL (FORC: Film on Readout Chip)
  - Exploring possible sensor materials: amorphous **Silicon**, **Indium Gallium Zinc Oxide**, amorphous **Selenium** (w/ UC Santa Cruz)

*Hybrid pixel detector*

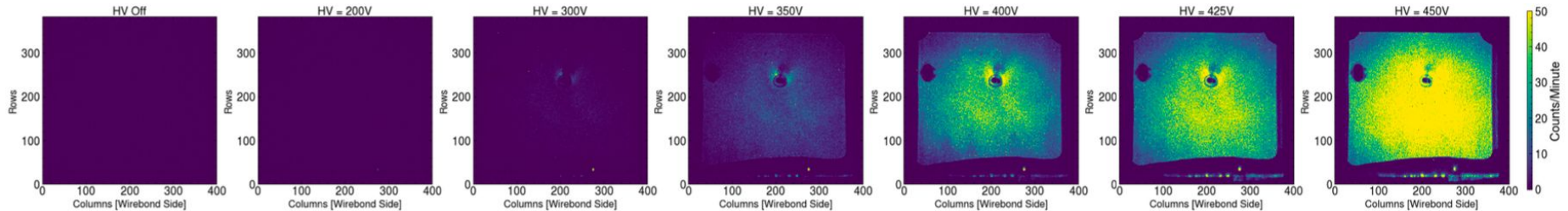
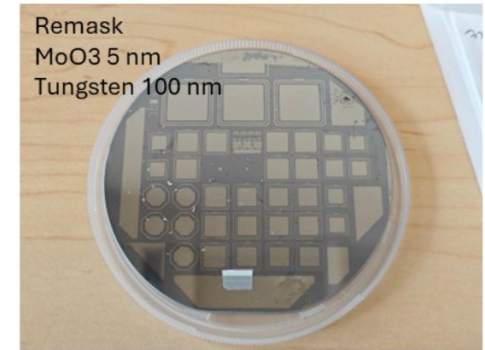


*Thin film detector*



# FORC: Film on Readout Chip

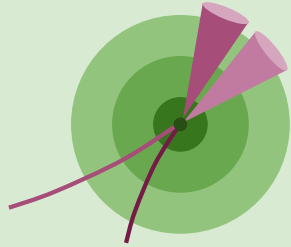
- Developing in-house **deposition on wafer**, electrically characterizing behaviour of different material stackup
- Successfully deposited **amorphous Selenium on an ITkPixV2 chip** (collaboration with UC Santa Cruz)  
→ **Were able to successfully see hits from a Kr-85 source in a thin film sensor!**



*Bias voltage*

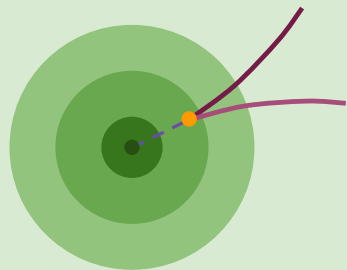
# Conclusion

**Objective: Make the most of the existing dataset we collect with the LHC, while we prepare for the future of LHC and future colliders**



## ***1. Measurements of known Standard Model processes***

- Measurement of Higgs boson decays to heavy flavour final states (bb,cc) sets **upper limit on  $H \rightarrow cc$  of 12 x SM expectation**
- HL-LHC era will provide a comprehensive picture of Higgs boson properties (including possible sensitivity to Higgs-charm coupling)

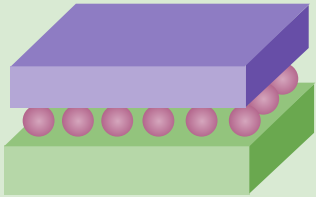


## ***2. Exploration of new physics models & unconventional signatures***

- Higgs portal to a potential dark sector provides many possible interesting & unconventional signatures
- **Search for displaced di-muon pairs** from a dark photon expected to provide new limits on the Hidden Abelian Higgs Model (HAHM) in ATLAS

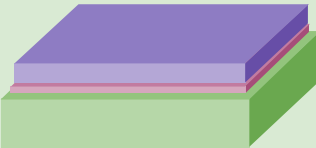
# Conclusion

**Objective: Make the most of the existing dataset we collect with the LHC, while we prepare for the future of LHC and future colliders**



### ***3. Detector development for ATLAS and future colliders***

- **ITk Pixel Front-End chip** design & characterization concluded successfully
- Detailed X-ray and Kr-85 irradiation studies allow to predict the expected failure point of ASIC in ITk around  $4000 \text{ fb}^{-1}$  (well above requirement)
- ITk Pixel project project now in production and moving towards integration & commissioning
- **Thin film sensors** provide an exciting option for **pixel detectors w/o hybridization** for a future collider detector



*Whats next?*

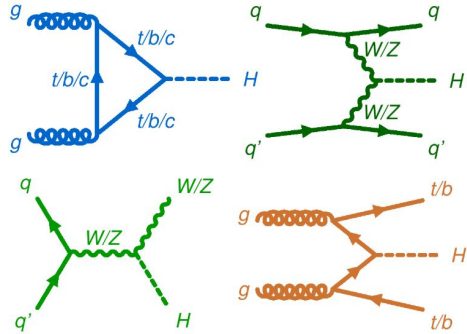
- **Many interesting signatures to explore in physics analysis (in the SM and beyond)**
- **An exciting collision dataset to be collected in the next decade**
- **And new detectors to build for the future collider challenges to come!**



**Thank you! Questions?**

# Anatomy of the Higgs boson

## Higgs production modes:

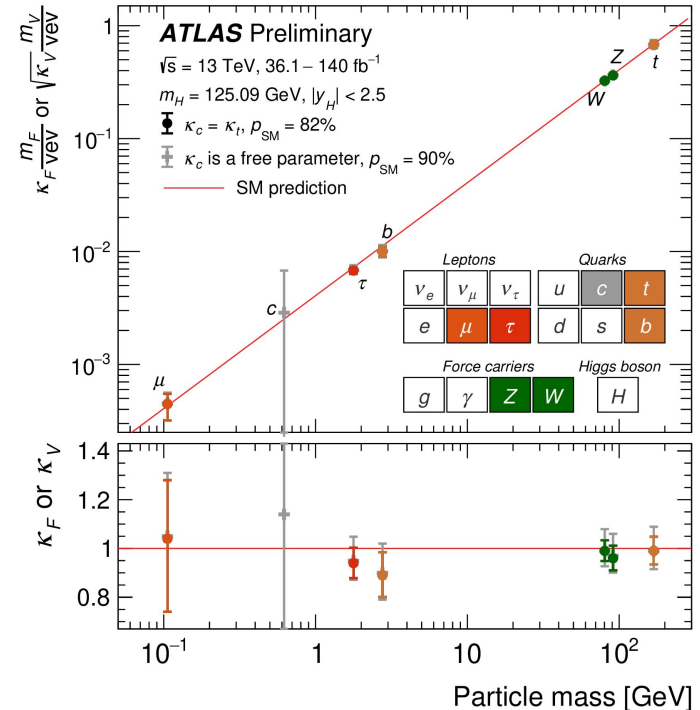


H

## Properties:

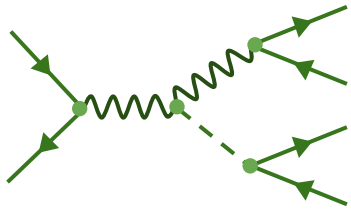
- **Higgs mass** has to be measured experimentally  
→  $m_H = 125.09 \pm 0.14$  GeV
- Only elementary particle with **spin 0 (scalar)**
- **Couplings** to SM particles predicted to be proportional to mass  
→ Couplings to bosons and heavy fermions in good agreement with predictions

## Measured Higgs couplings

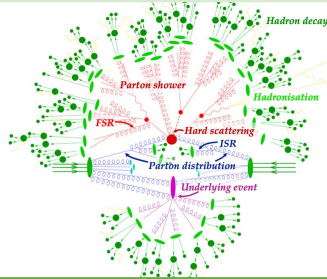


# How are we doing collider physics?

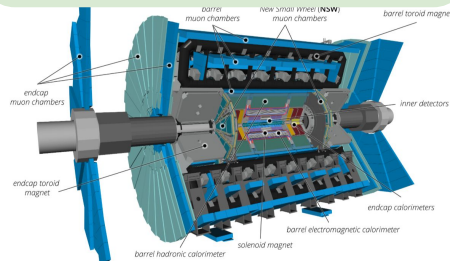
## Simulation of high energy physics processes



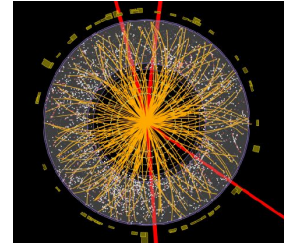
## Simulation of soft physics processes & pile-up



## Simulation of the ATLAS detector

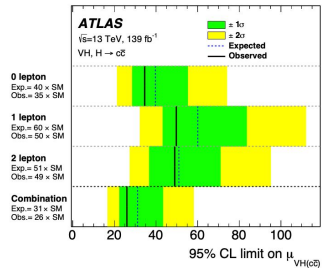


## Collision data



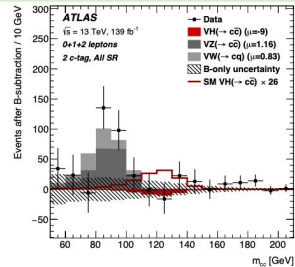
## Results

Observation of or upper limit on specific process



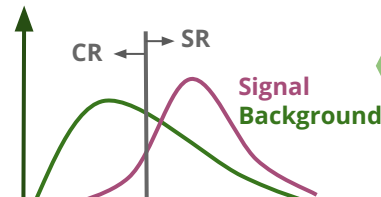
## Statistical analysis

Quantifying agreement of data and prediction

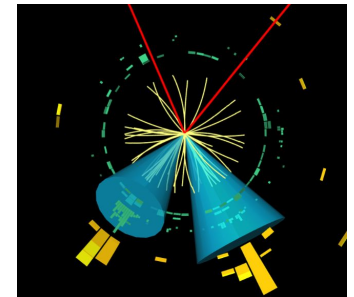


## Analysis event selection

Define regions enhanced in signal & background

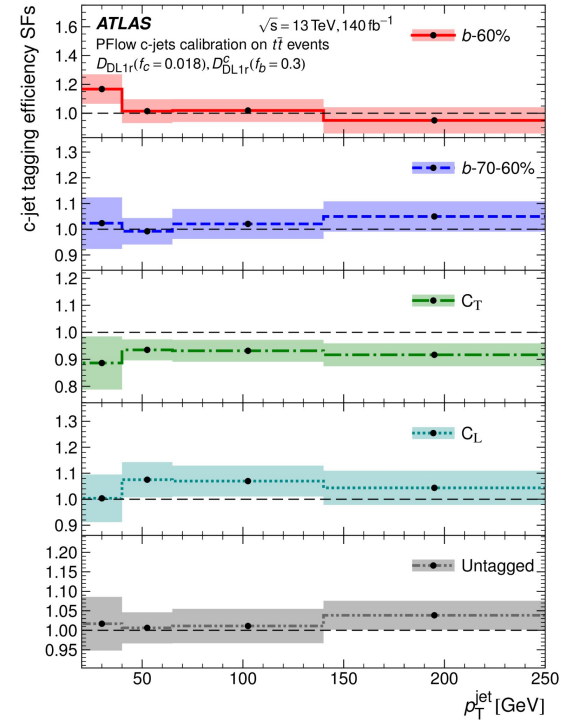
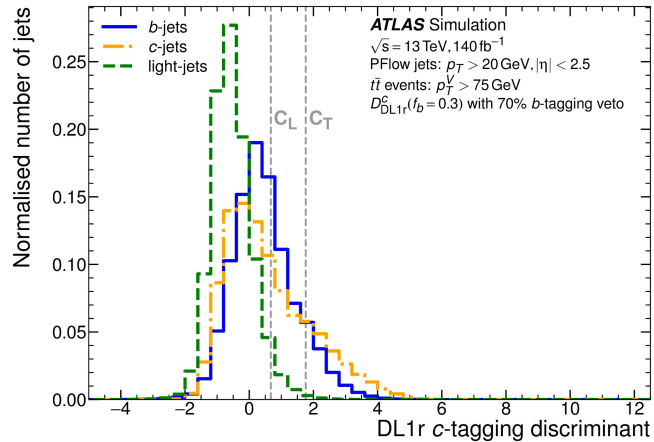
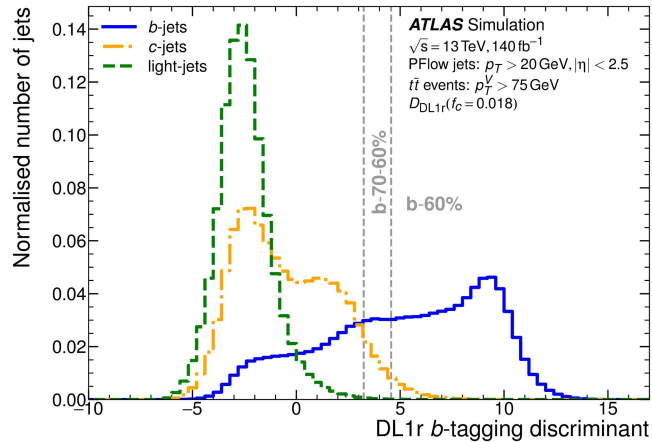


## Reconstruction in ATLAS



# Flavour tagging

$$D_{DL1r} = \ln \left( \frac{p_b}{f_c \cdot p_c + (1 - f_c) \cdot p_{\text{light}}} \right),$$



# From standalone analysis to combination

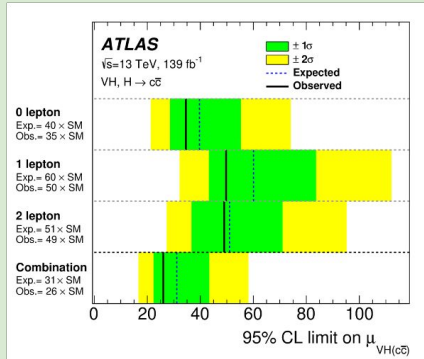
Initially explored  $VH$ ,  $H \rightarrow bb, cc$  phase space through standalone analyses

## $VH(cc)$ (resolved regime)

Cut-based analysis using Full Run 2 dataset

Upper limit of  $26 \times \text{SM}$ , first direct constraint on  $|\kappa_c| < 8.5$

$VH$ ,  
 $H \rightarrow cc$   
limits



[Eur. Phys. J. C 82 \(2022\) 717](#)

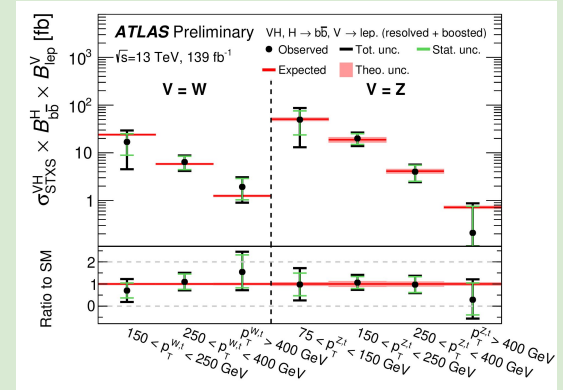
## Resolved $VH, H \rightarrow bb$

$H \rightarrow bb$  discovery channel

Sensitivity improvements through usage of ML discriminants

Total  $H \rightarrow bb$  significance of  $6.7\sigma$ , fiducial cross-section measurement and EFT interpretation

[Eur. Phys. J. C 81 \(2021\) 178](#)



Resolved  $VH, H \rightarrow bb$  cross-sections

## Boosted $VH, H \rightarrow bb$

Cut-based analysis, first  $H \rightarrow bb$  analysis using boosted reconstruction

Total observed significance of  $2.1\sigma$ , fiducial cross-section measurement and EFT interpretation

[Phys. Lett. B 816 \(2021\) 136204](#)

# V+jets modelling

- **V+jets** processes simulated using **Sherpa 2.2.11** generator
- Normalizations floating in fit to SR and CRs with as much granularity as data allows (in bins of jet multiplicity,  $p_T^V$ )
- Systematic uncertainties derived from comparison with:
  - **MadGraph AMC@NLO** alternative samples
  - **Renormalization/factorization scale** ( $\mu_R, \mu_F$ ) variations
  - **Sherpa 2.2.1** → dedicated pTV modelling uncertainty
- Assess **normalization, acceptance** and **shape** uncertainties
- ML-based approach for shape uncertainties (**CARL**) → reweighting to ensure sufficient statistics in of alternative setups
- $VH, H \rightarrow bb, cc$  one of the driving analyses in ATLAS for informing V+jets MC generation decisions
  - close collaboration with the **weak boson physics modelling group**
  - **several generator improvements already planned for Run 3/4 MC!**

$p_T^V$  in different MC generators

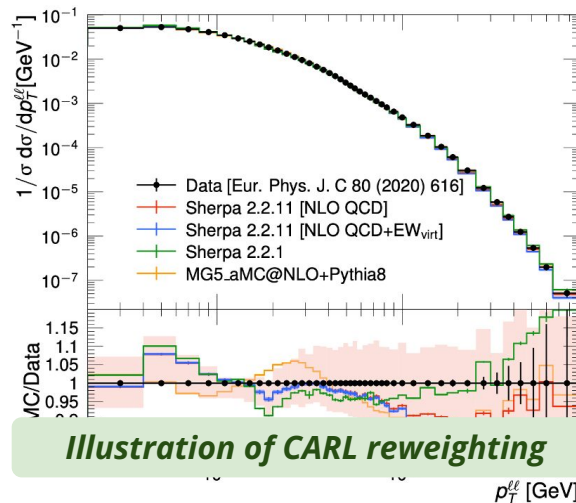
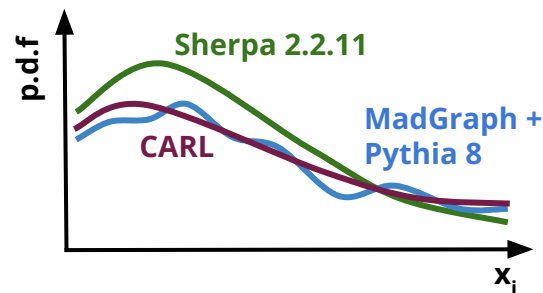


Illustration of CARL reweighting



# Analysis regions

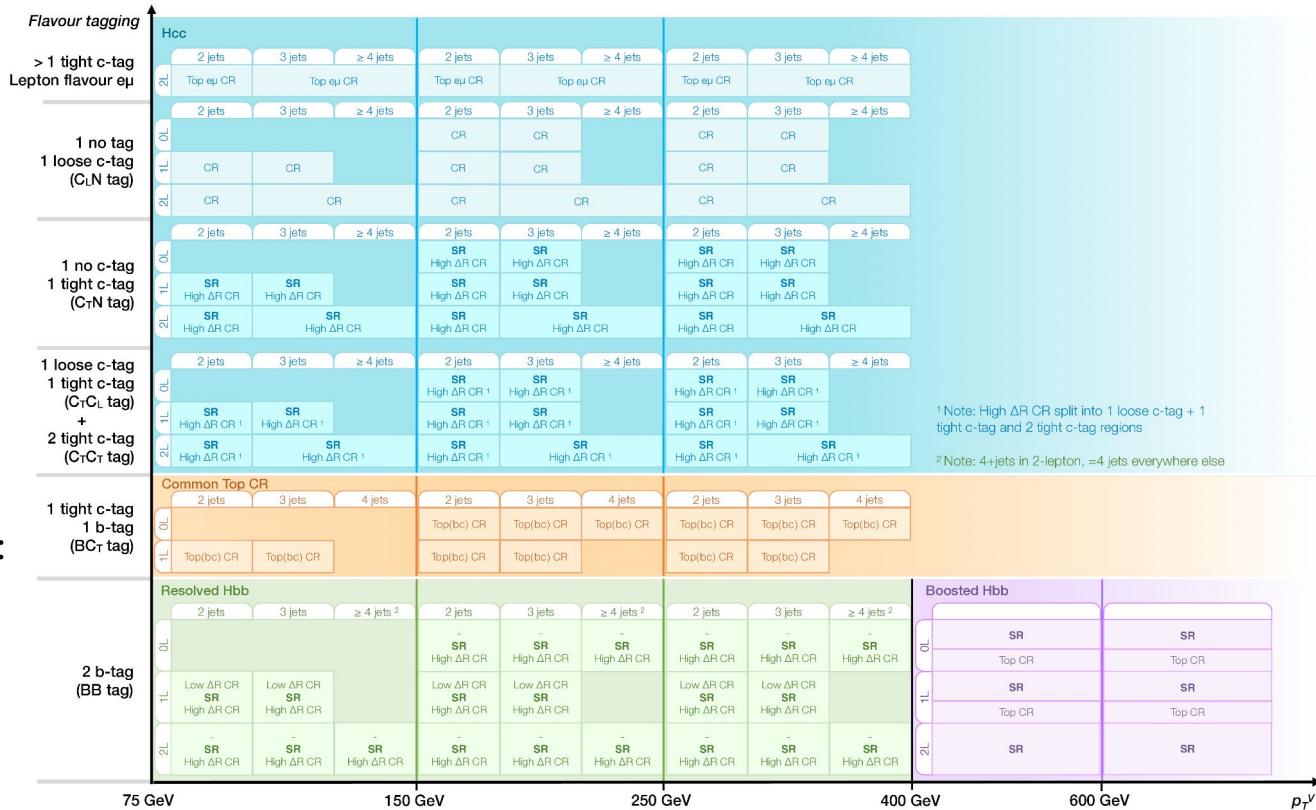
Complex analysis with large number of signal and control regions

Signal regions separated by:

- b-/c-tagging categories
- $p_T$  of the vector boson ( $p_T^V$ )
- Jet multiplicity (2 and 3(+ jets))

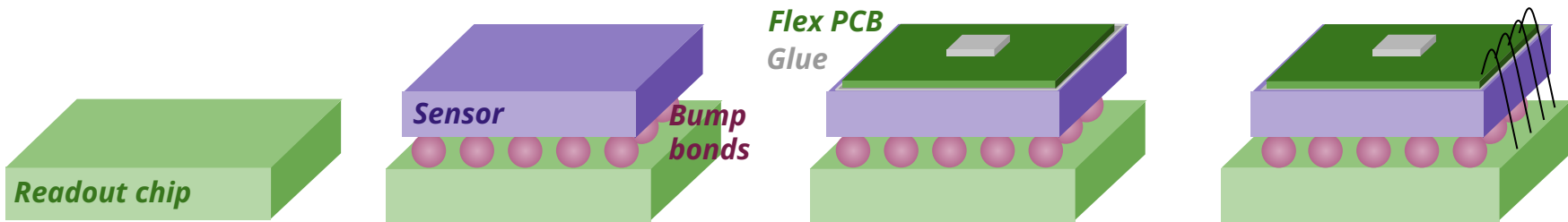
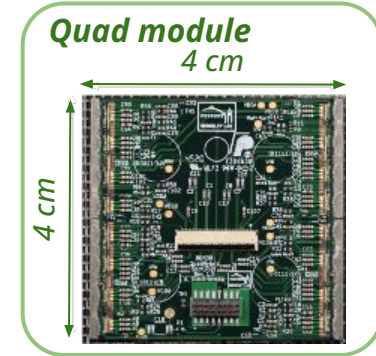
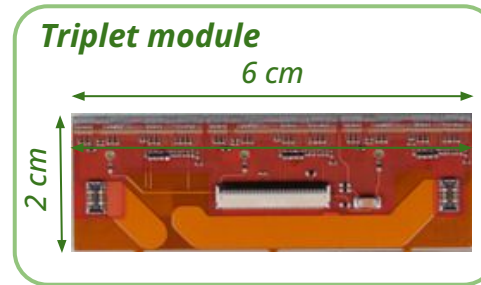
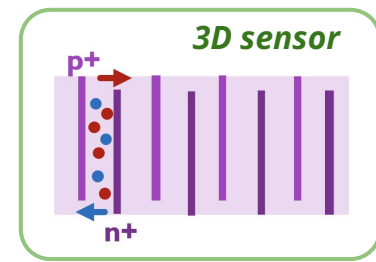
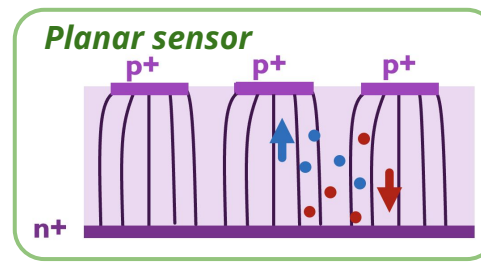
Control regions defined through:

- Intermediate/loose flavour tagging categories
- $\Delta R(\text{jet1}, \text{jet2})$  sidebands



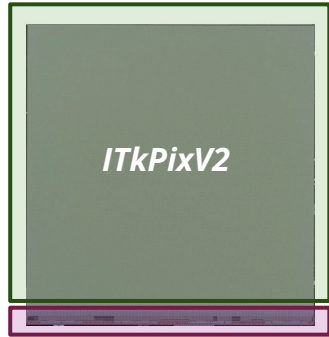
# Pixel modules

- Pixel modules consist of sensor and front-end chip (attached through bump bonding) and flex PCB
- Assembled into staves and rings to build ITk
- **Planar** and **3D-sensors** used for ITk
- Different kinds of modules used in different layers:
  - **Triplet modules** used in innermost layers (3D sensors attached to 3 FE chips)
  - **Quad modules** in outer layers (planar sensors attached to 2x2 FE chips)



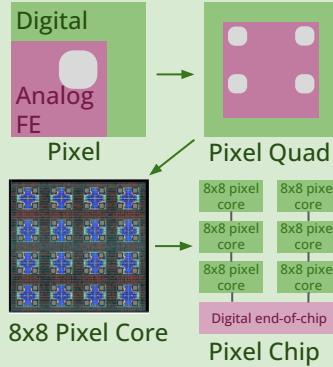
# ITkPixV2 qualification - Digital & Analog

Pixel array

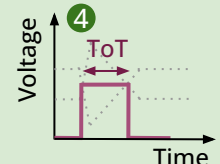
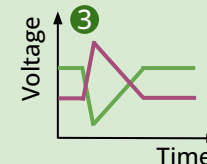
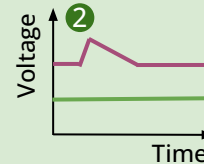
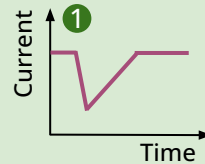
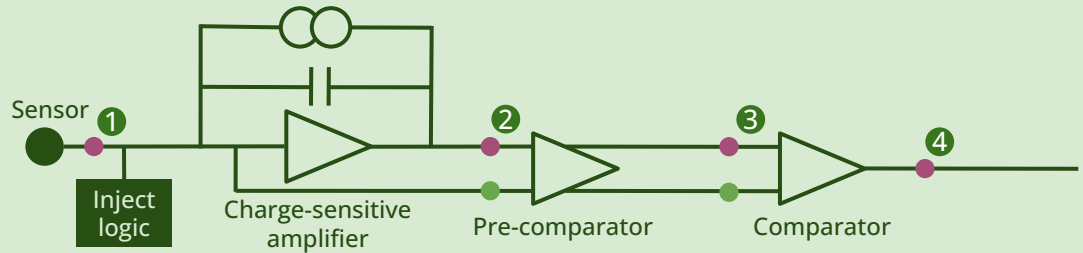


End of chip

## Pixel array



- 50 x 50  $\mu\text{m}^2$  pixels, roughly half analog/digital
- Digital logic synthesized or 8x8 pixels to form pixel core, stepped up in rows and columns (core columns)
- Analog front-end translates charge pulse signal produced in the sensor and translates to time-over-threshold (ToT)

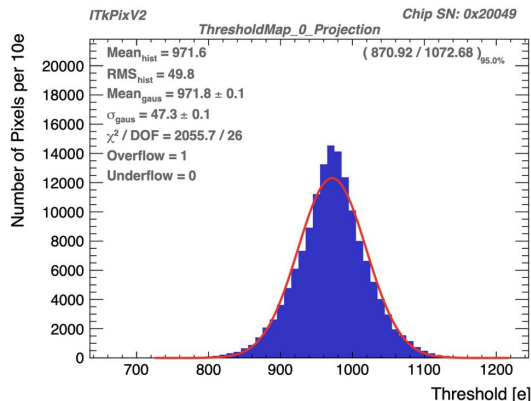


# ITkPixV2 qualification - Analog

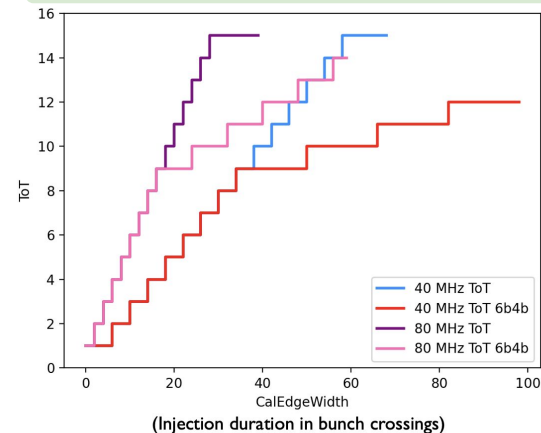
## Analog Front-End:

- Characterized various time-over-threshold (ToT) modes using digital charge injection → validating **ToT bug-fix** in ITkPixV2
- Studied capabilities of tuning of global and pixel thresholds & characterized noise of analog-front end, also across temperatures
- Performed similar tests for all chip features: data transmission, irradiations, Single Event Upset...  
→ **Fully qualified ASIC ready for production in mid-2023**

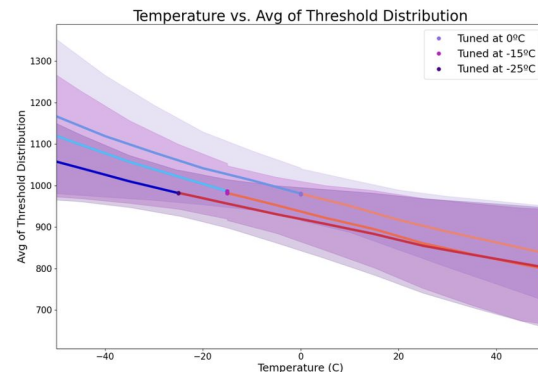
## Distribution of thresholds



## ToT vs digital injections



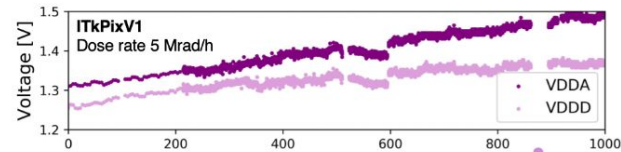
## Threshold vs temperature



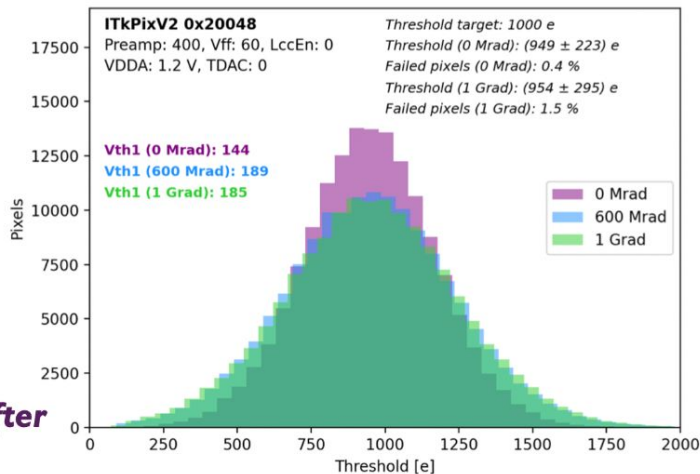
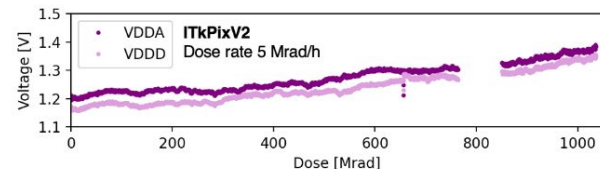
# SLDO/Analog Irradiations

- **Chip internal voltages:** Metallisation layers in ITkPixV2 were modified to try and ensure more uniform drift of analog and digital voltages  
→ seems to have desired effect, at least at high dose rates
- **Analog front-end:** No operational issues observed after irradiation to 1 Grad
- Most damage to AFE occurs in the first tens of Mrad of irradiation (consistent with ITkPixV1)

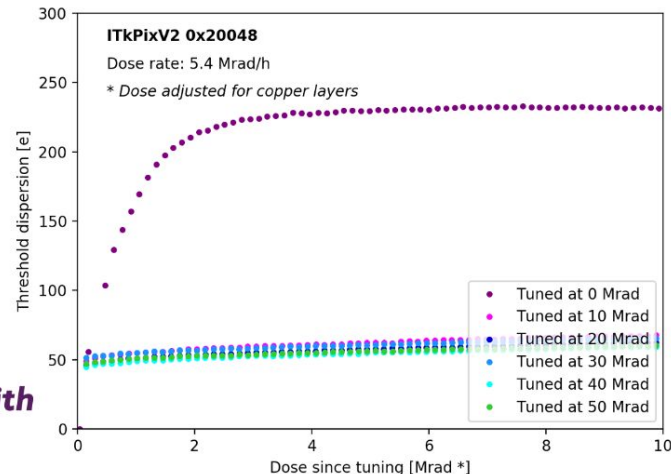
## VDDA/VDDD in ITkPixV1



## VDDA/VDDD in ITkPixV2

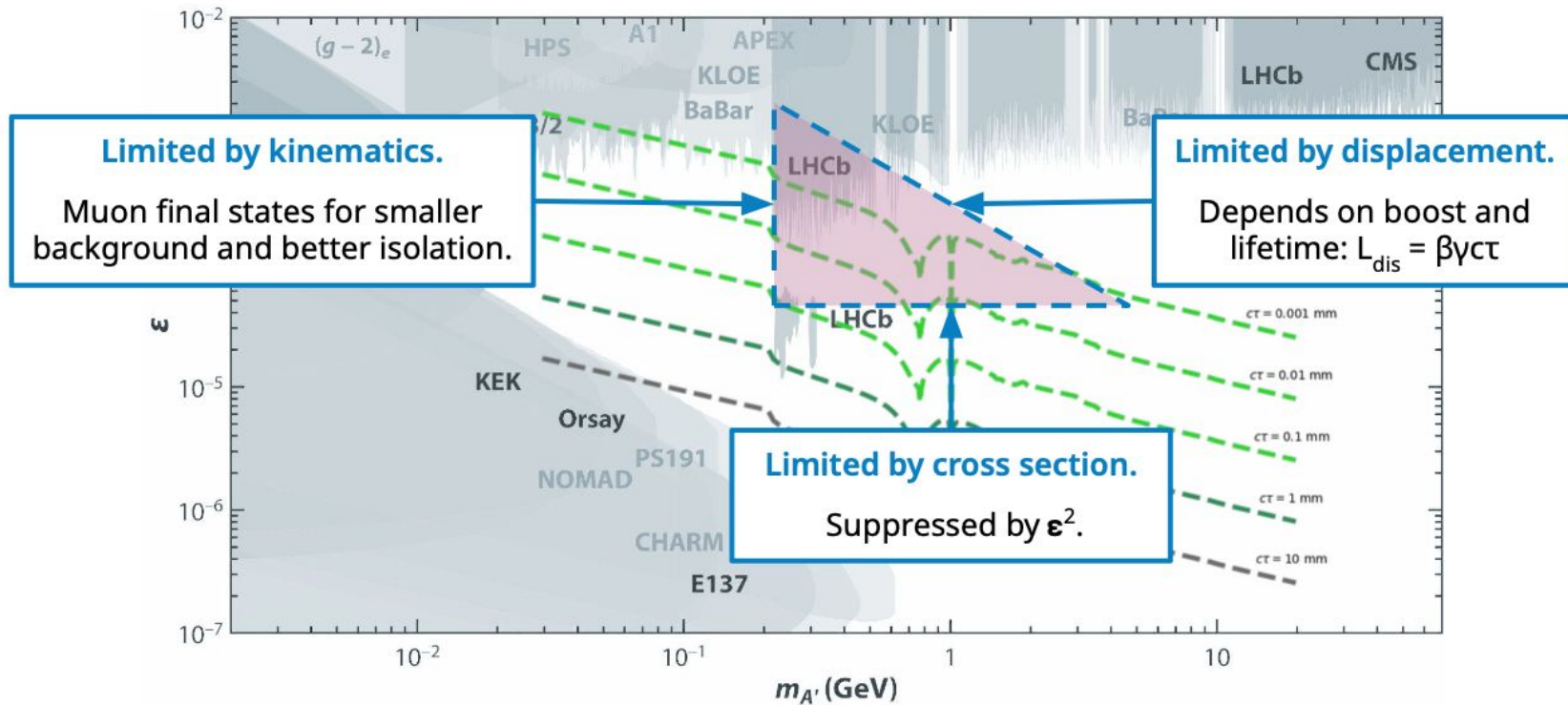


**Untuned threshold distributions before and after irradiation**



**Threshold detuning with irradiation**

# Minimal model

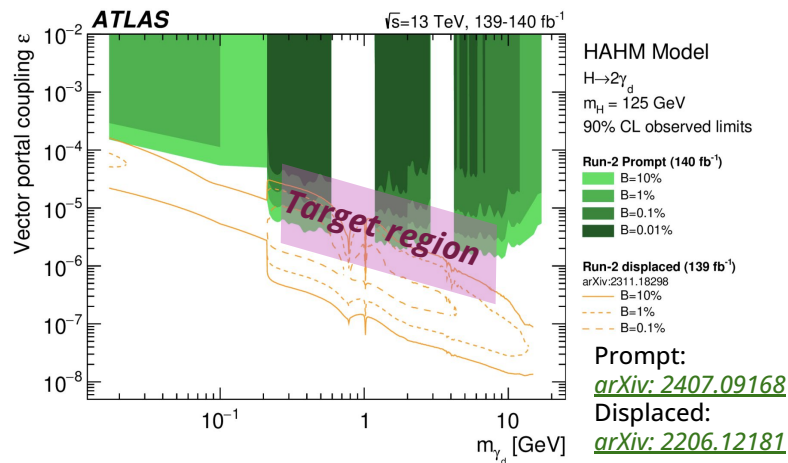
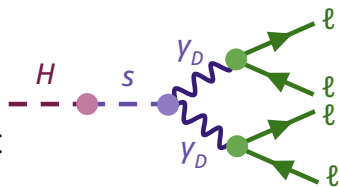


# Target phase space region

## HAHM model

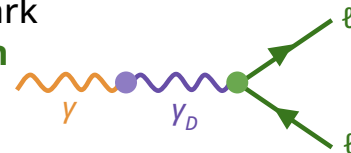
Expect to have sensitivity in regions not explored yet

(e.g. complimentary to prompt or displaced ATLAS searches using calorimeter/MS)



## Dark photon minimal model

Planned interpretation for dark photon **direction production** model



→ **first in ATLAS!**

Graham M. et al. 2021

