ATLAS Upgrades

June 11, 2021

Physics

LHC Upgrade

ATLAS

LHCP 2021

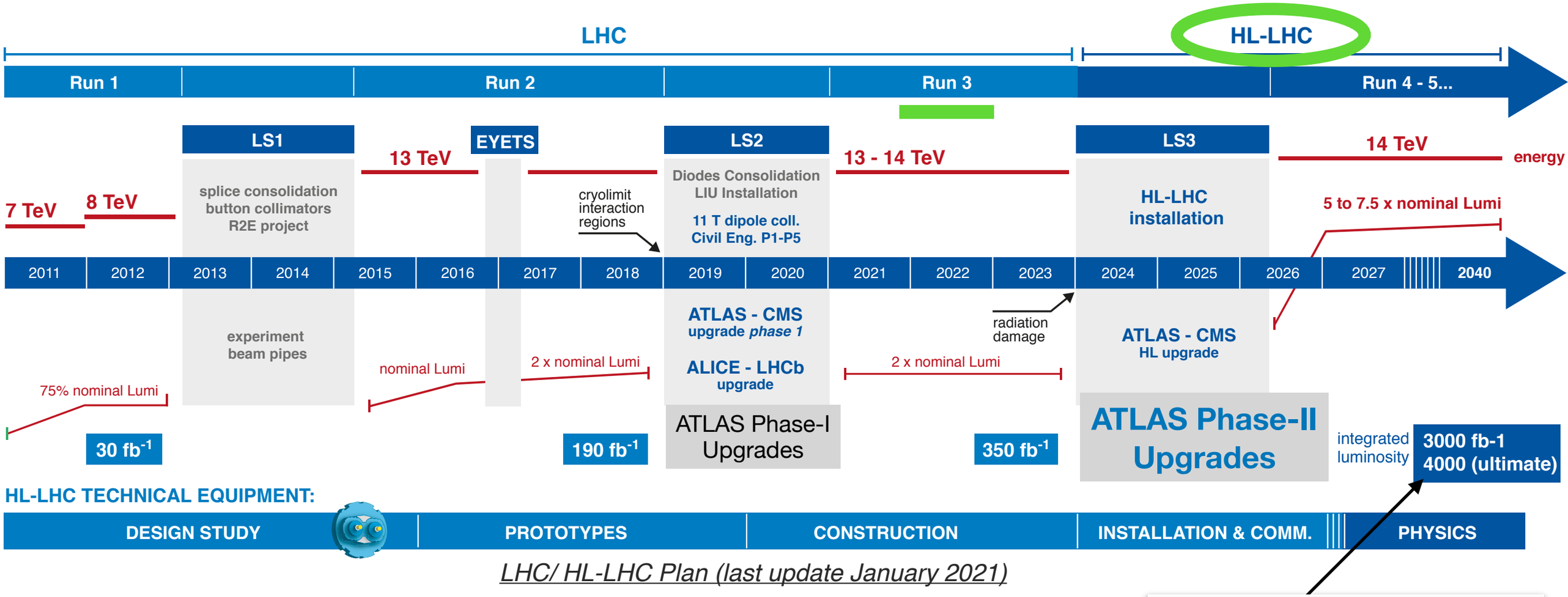
ATLAS EXPERIMENT

Richard Teuscher (IPP/Toronto)

INSTITUTE OF PARTICLE PHYSICS

UNIVERSITY OF TORONTO

LHC / HL-LHC Plan



LHC/ HL-LHC Plan (last update January 2021)

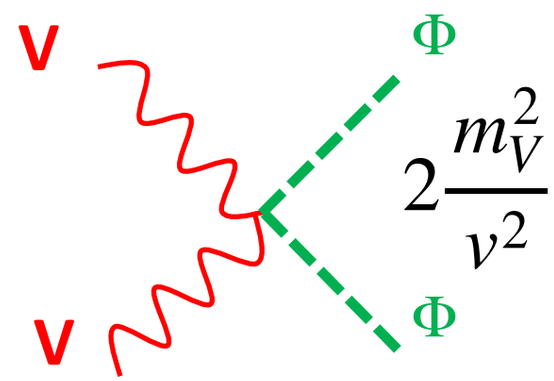
4000 fb-1 ultimate

- High-Luminosity LHC formally approved by CERN Council in June 2016
- High priority of worldwide subatomic physics community
- -> Significant **detector challenges** in this environment with up to 200 separate proton-proton collisions per 25 ns bunch-crossing (pileup) … see slides ahead…
- **First**: physics prospects —>

1. Prospects for Higgs Couplings

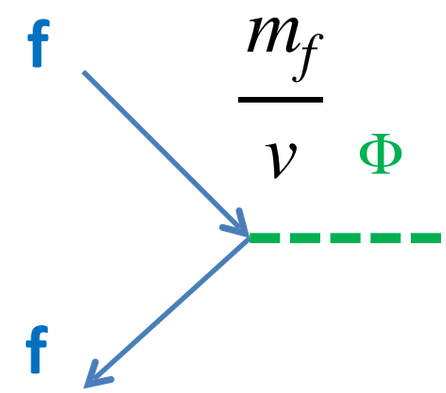
Gauge interaction

Vector Bosons V=W,Z

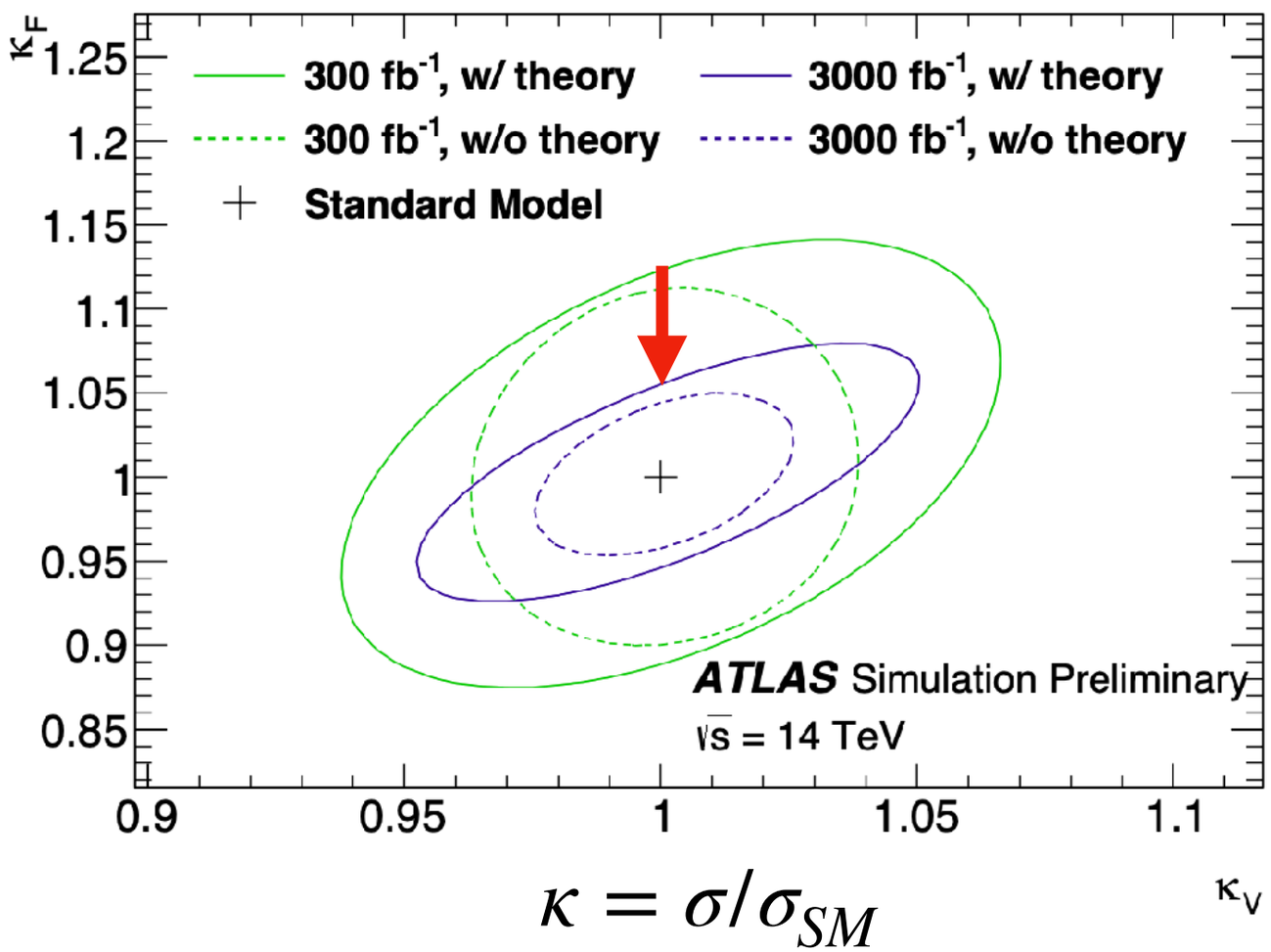


Yukawa interaction

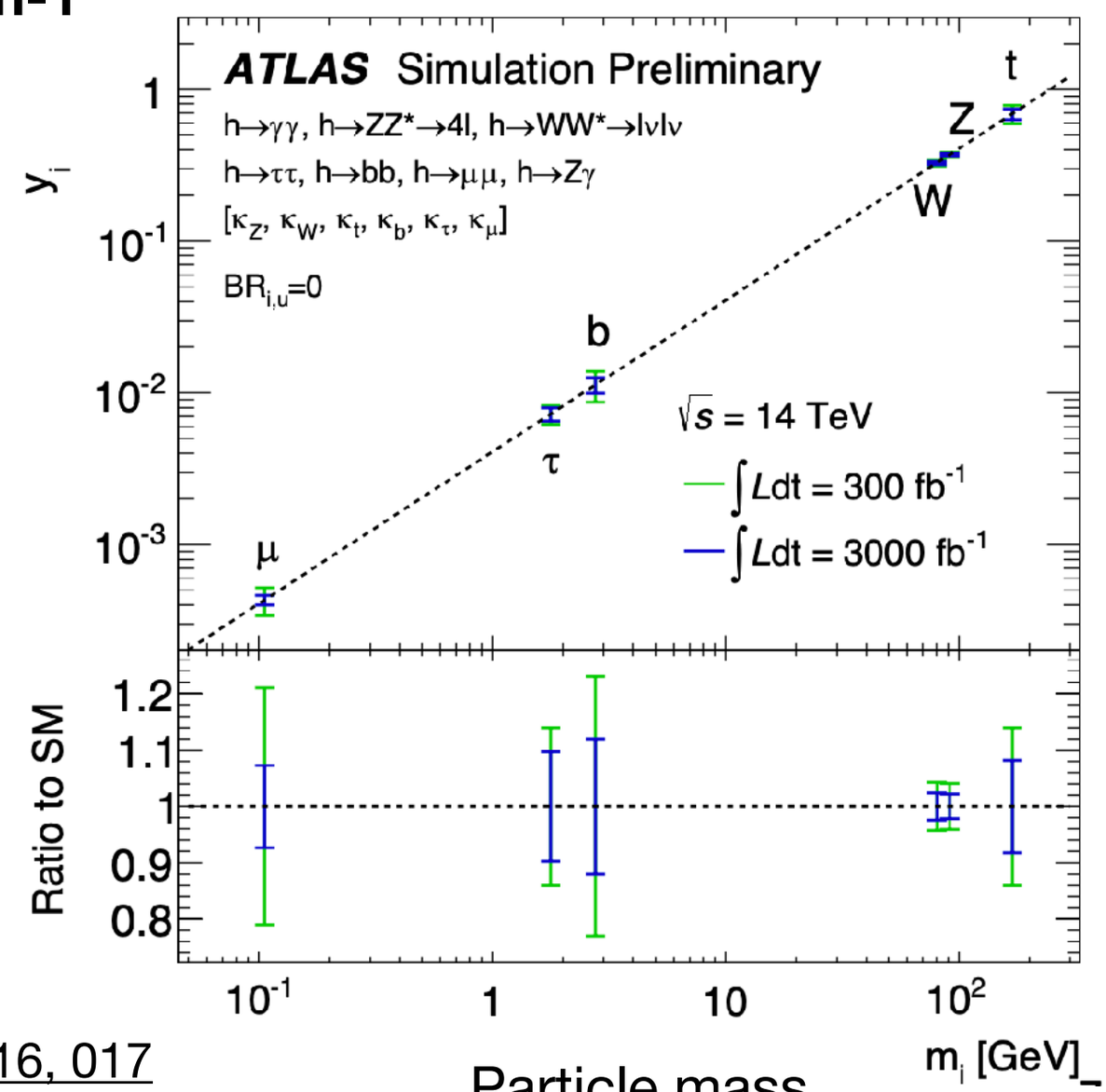
f = fermions



Estimates for Run 3 and HL-LHC based on Run-1



$\kappa = \sigma/\sigma_{SM}$



Particle mass

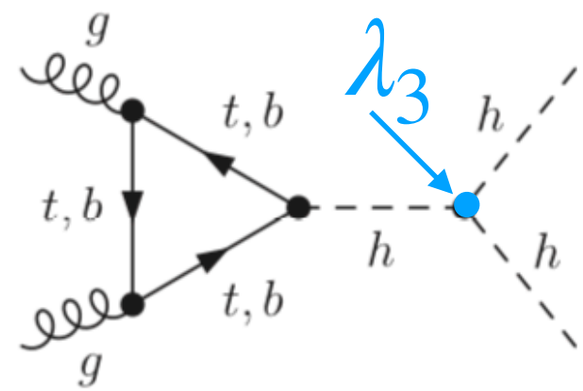
ATL-PHYS-PUB-2018-054 ATL-PHYS-PUB-2014-016, 017

Updates planned for SNOMASS, see also European Strategy Update

2. Probe Higgs Self Coupling

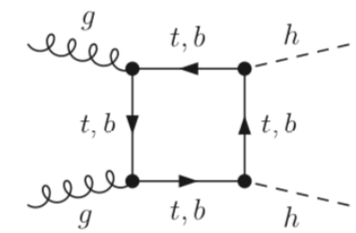
$$V = \frac{m_h^2}{2}h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4}h^4$$

$$\lambda_3 = \lambda_4 = m_h^2/(2v^2)$$



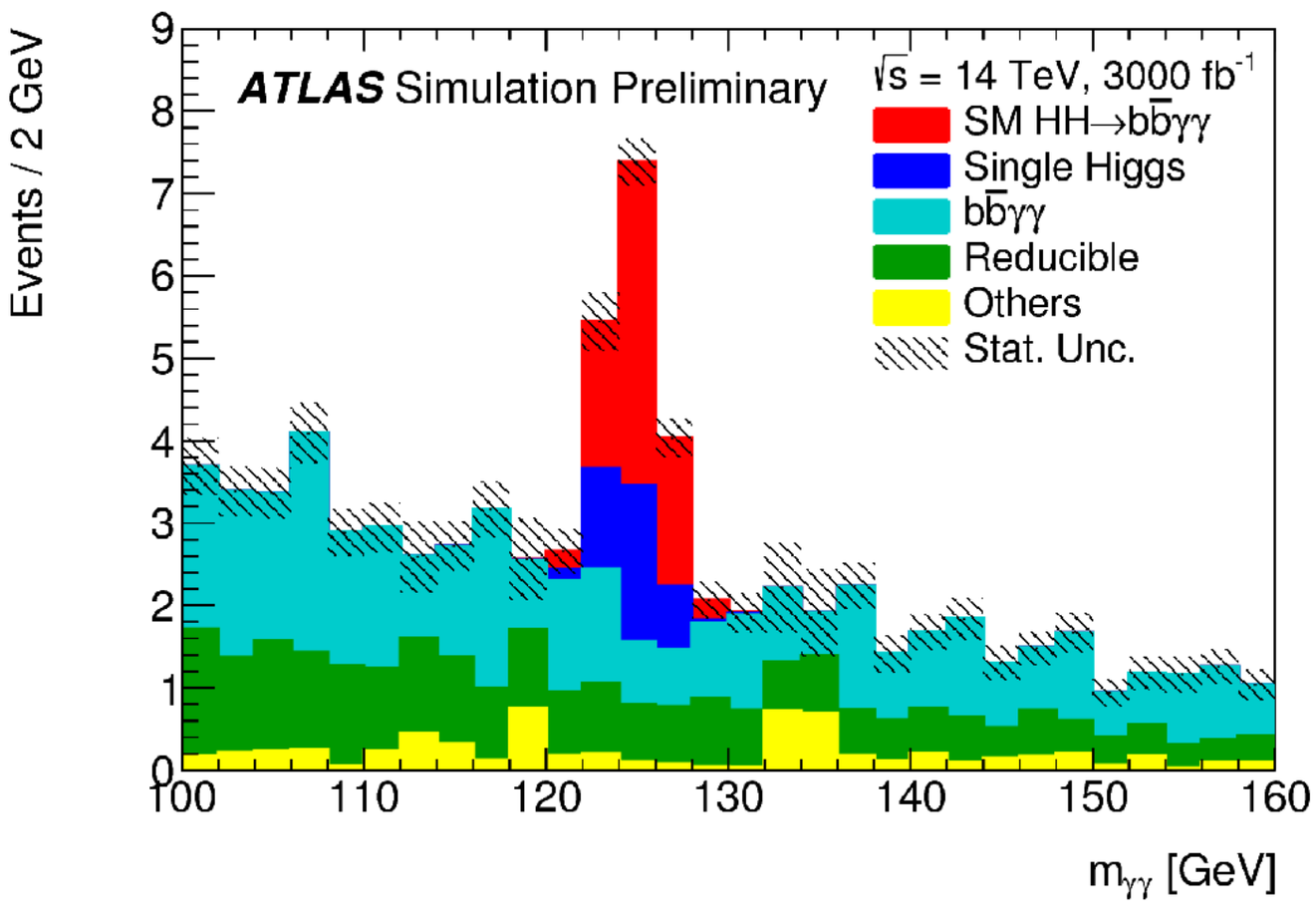
Di-Higgs

σ~ 40 fb @ 14TeV
O(100k) HH
produced

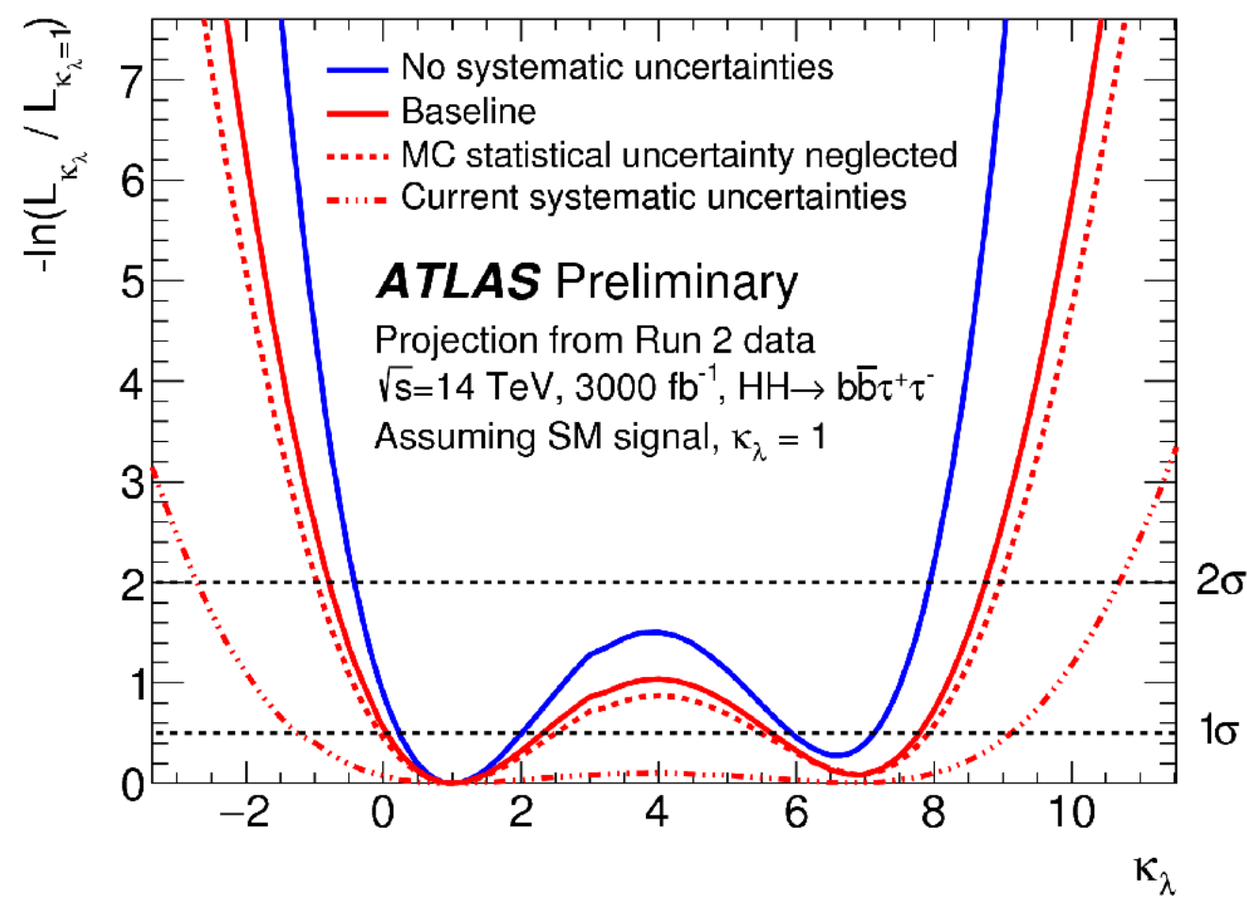


destructive
interference

- Channel bb$\gamma\gamma$



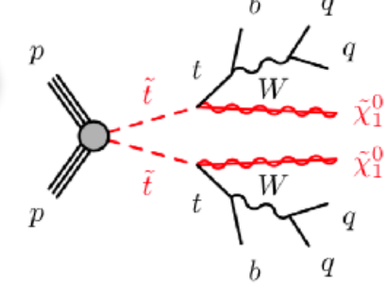
- Channel bb$\tau\tau$. Most sensitive



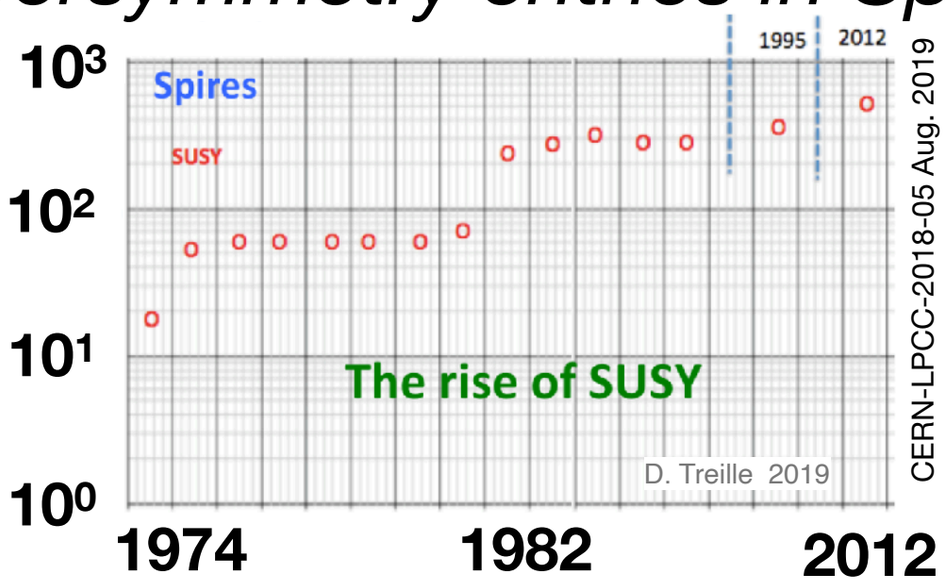
$$\kappa_\lambda = \lambda_3/\lambda_3^{SM}$$

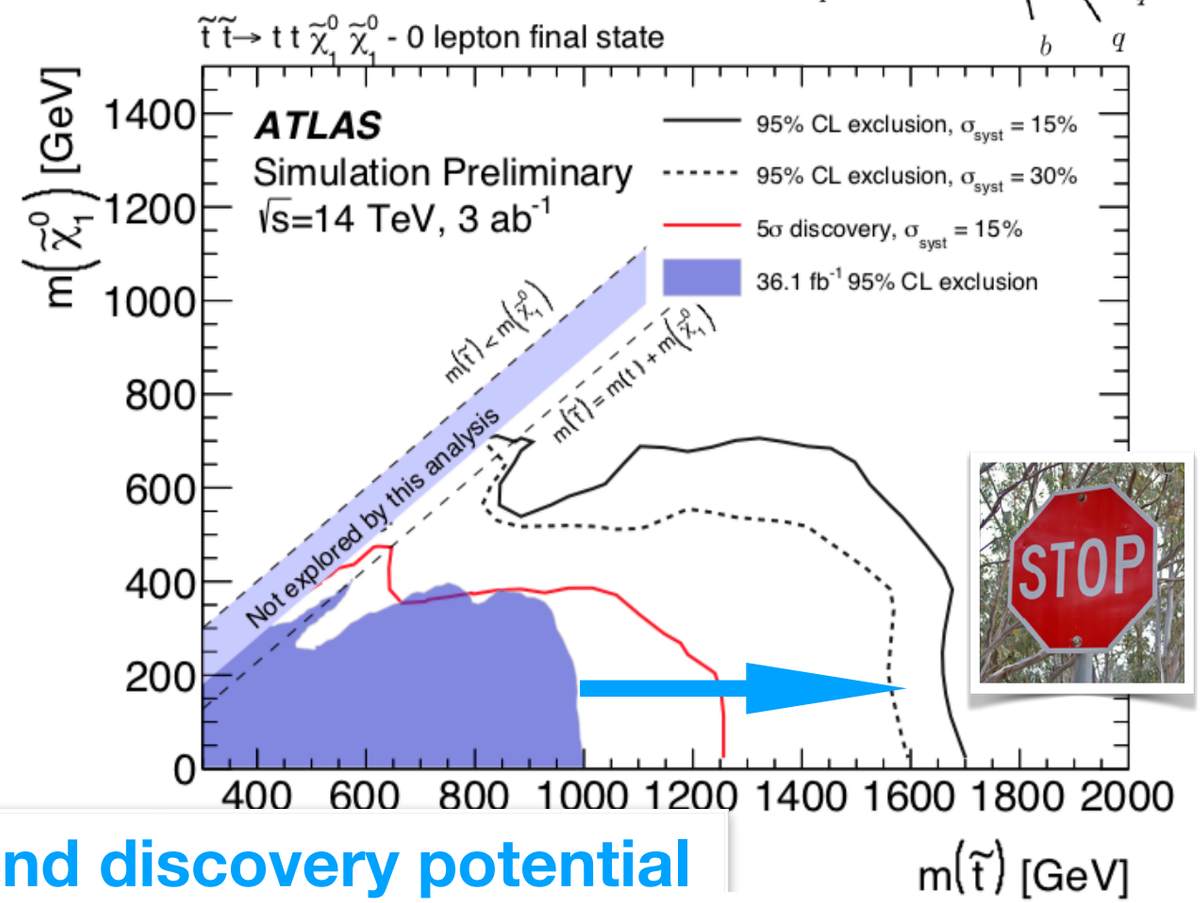
ATL-PHYS-PUB-2018-053

3. Find Supersymmetry?



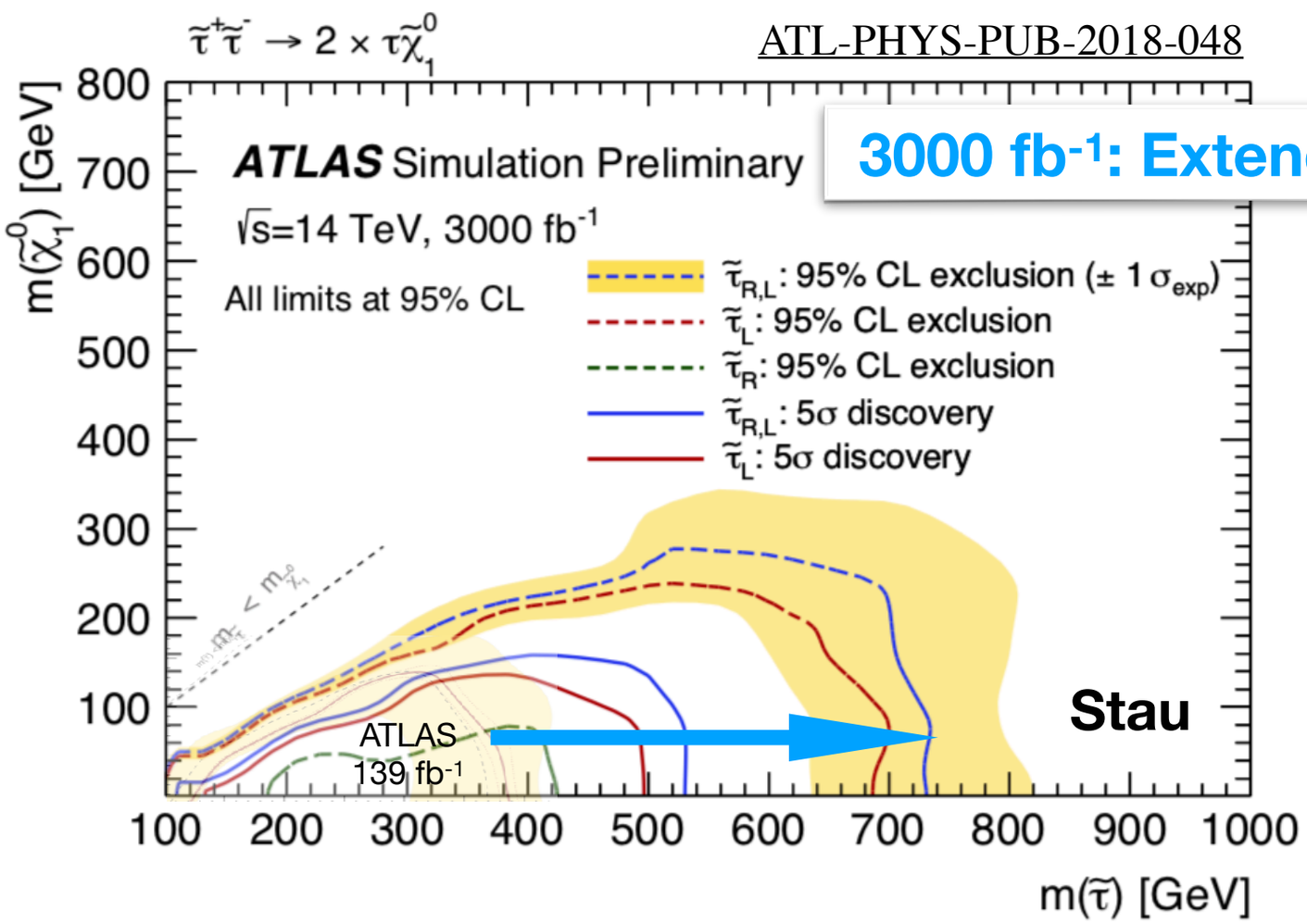
Supersymmetry entries in Spires:

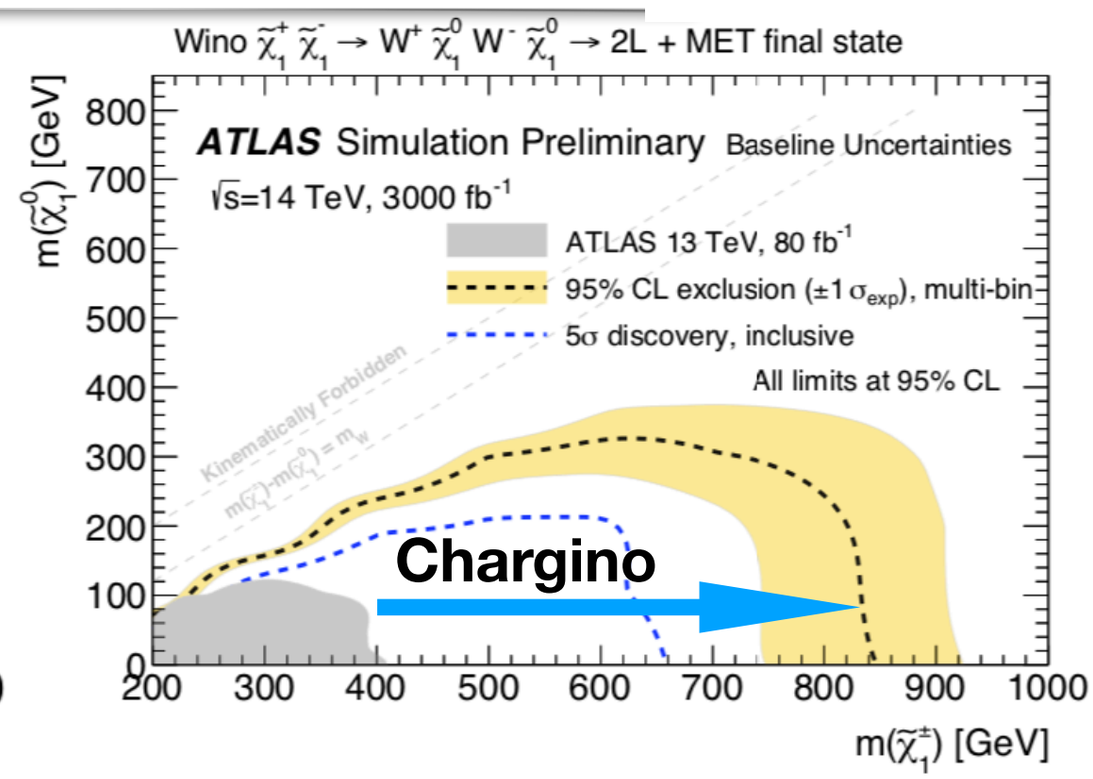




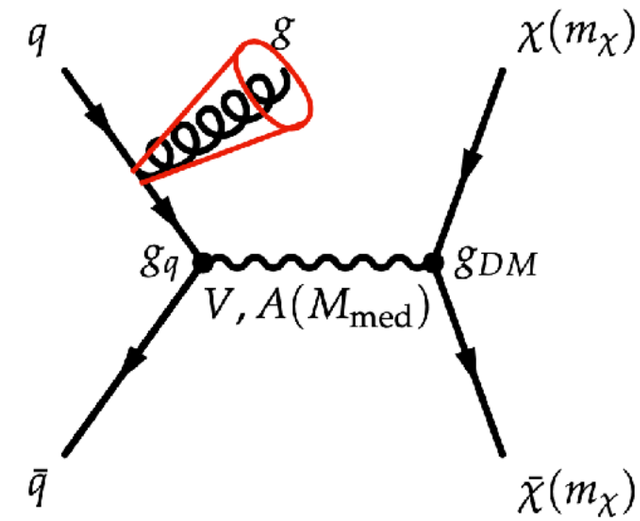
ATL-PHYS-PUB-2018-048

3000 fb^{-1}: Extend discovery potential



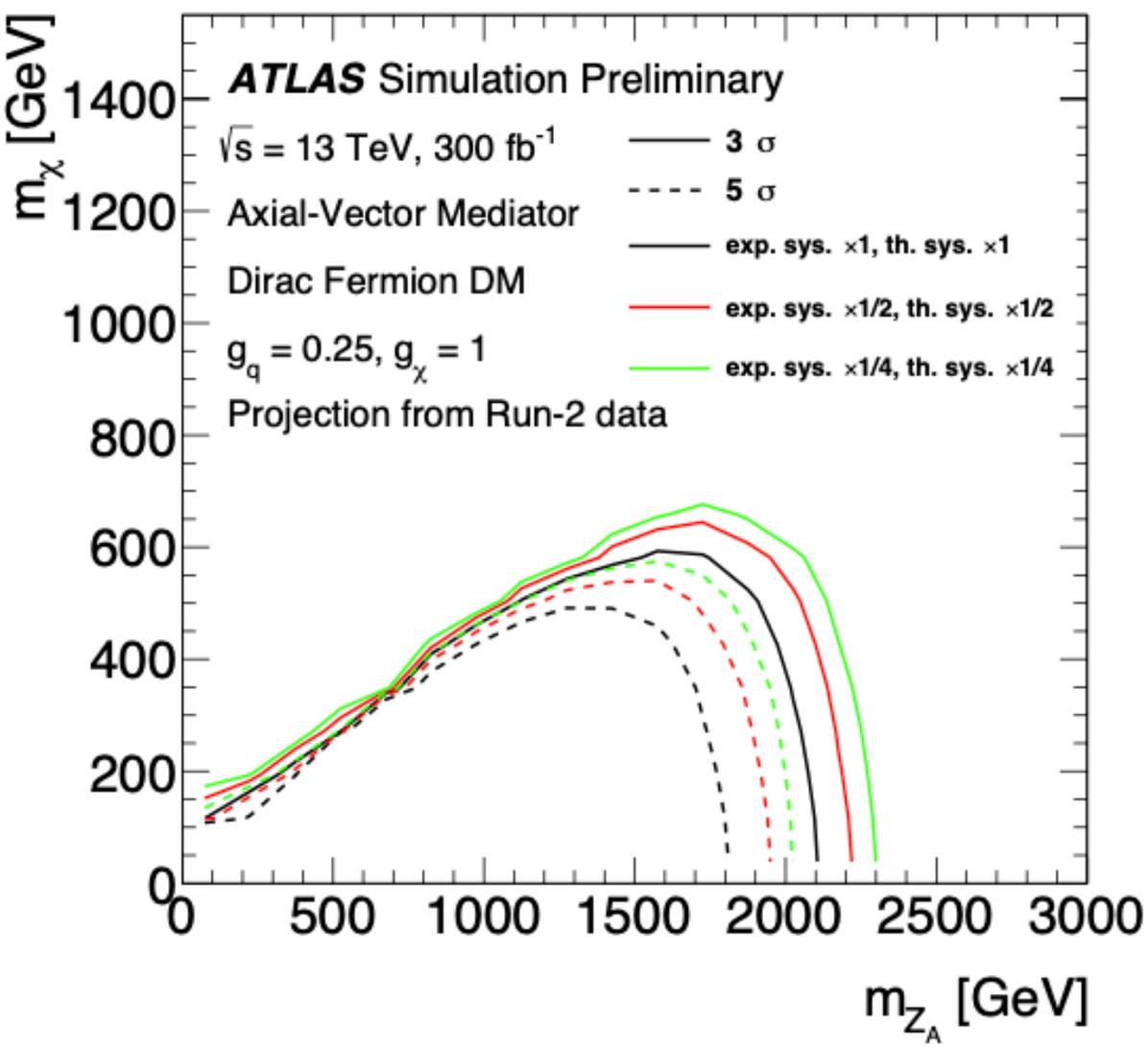


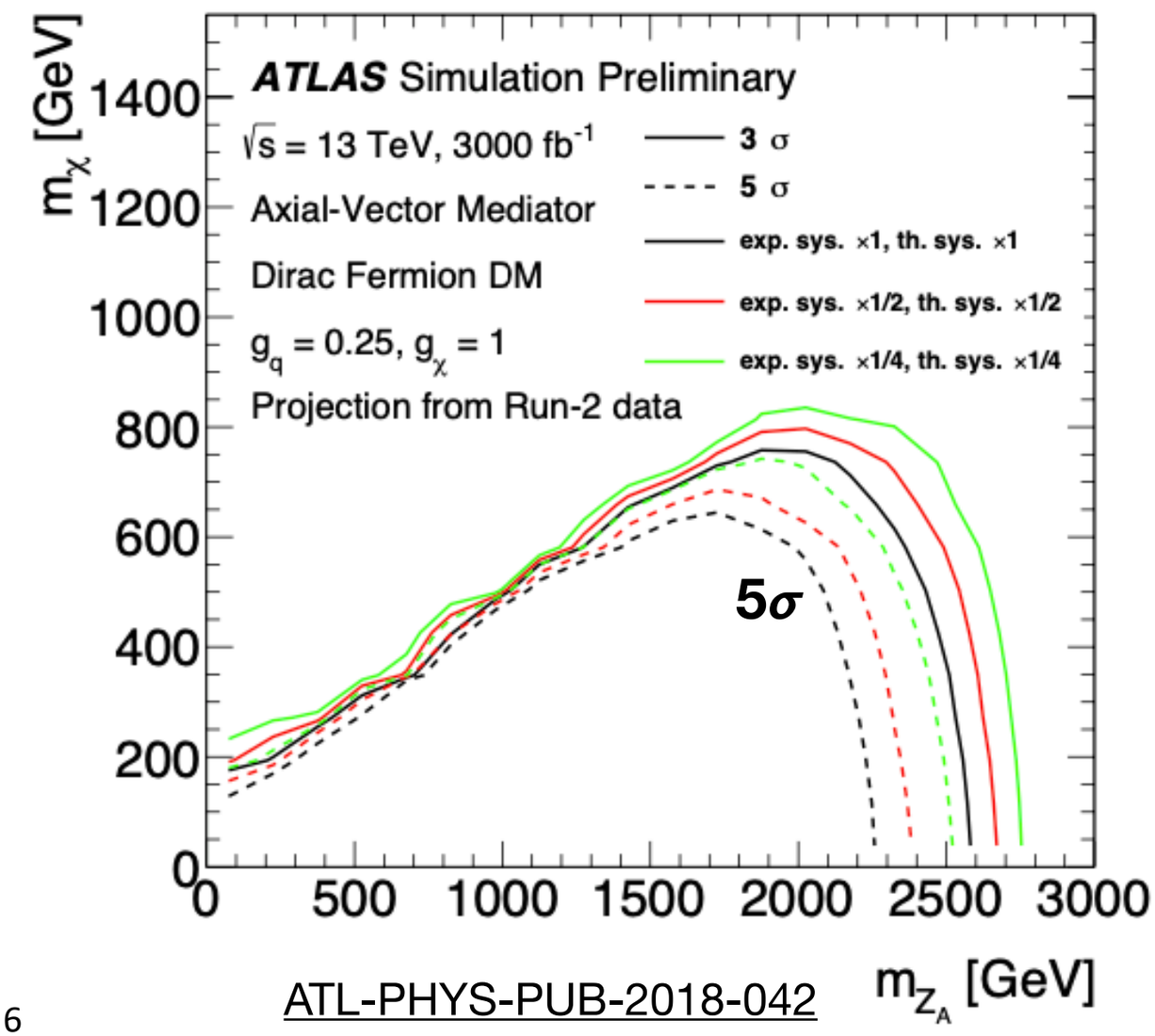
4. Detect Dark Matter?



- **Mono-jet searches projected to end of Run 3 & HL-LHC**
- **Systematic uncertainties extrapolated from current analyses under different scenarios**

Run 3 → **HL-LHC**

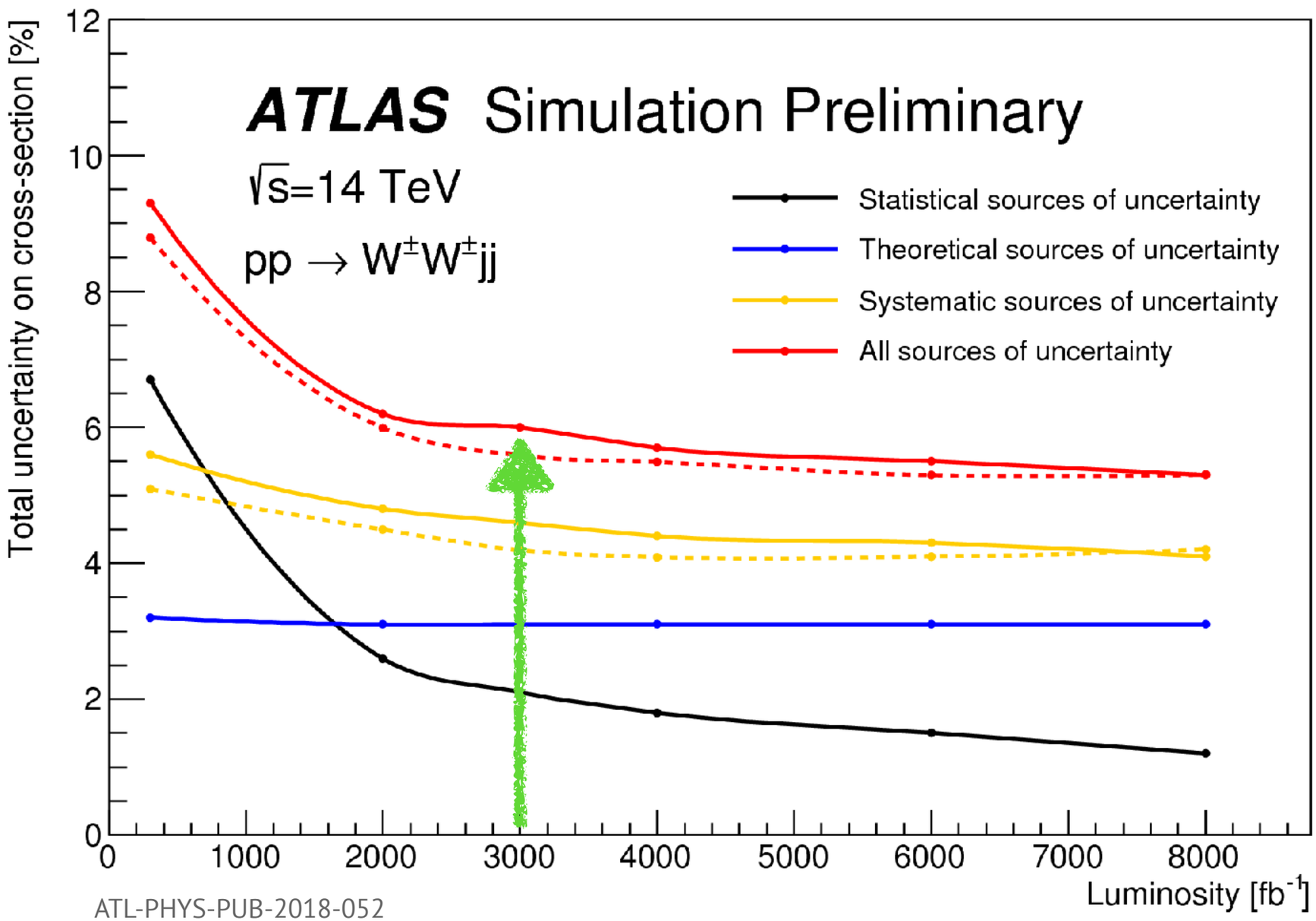




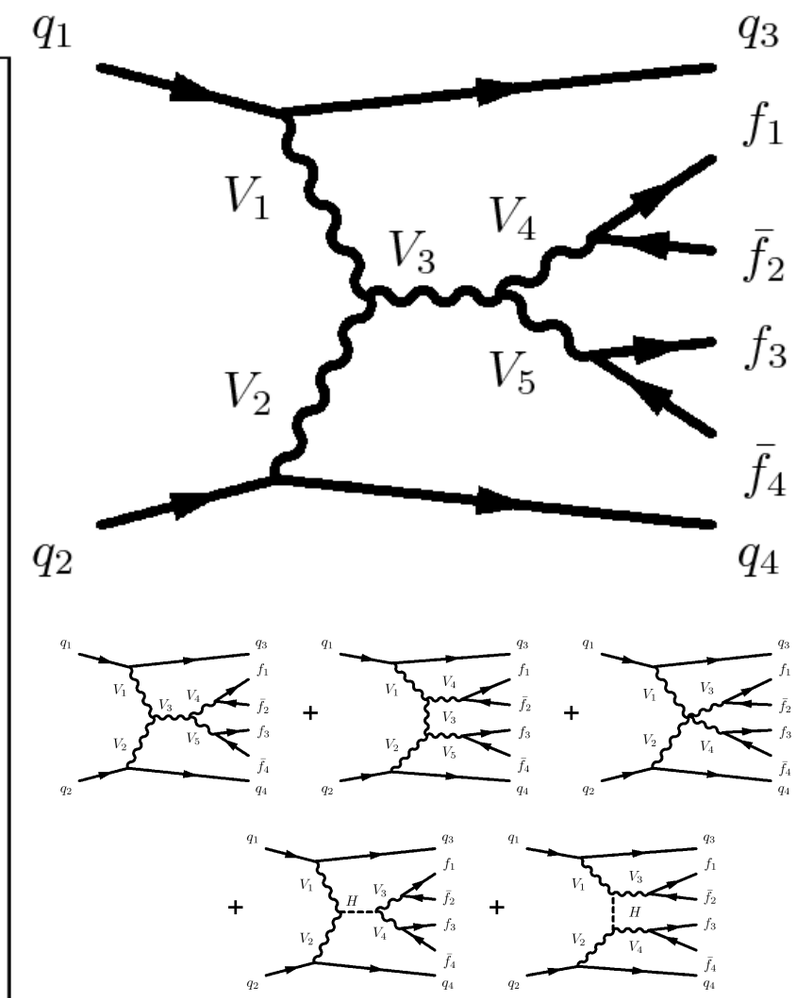
ATL-PHYS-PUB-2018-042

5. Measure Vector Boson Scattering

The study of the scattering of two massive vector bosons V = W, Z (vector boson scattering, VBS) provides a key opportunity to probe the nature of the electroweak symmetry breaking (EWSB) mechanism as well as physics beyond the Standard Model. It is still unknown whether the Higgs boson preserves unitarity of the longitudinal VV scattering amplitude at all energies, or if other new physics processes are involved.

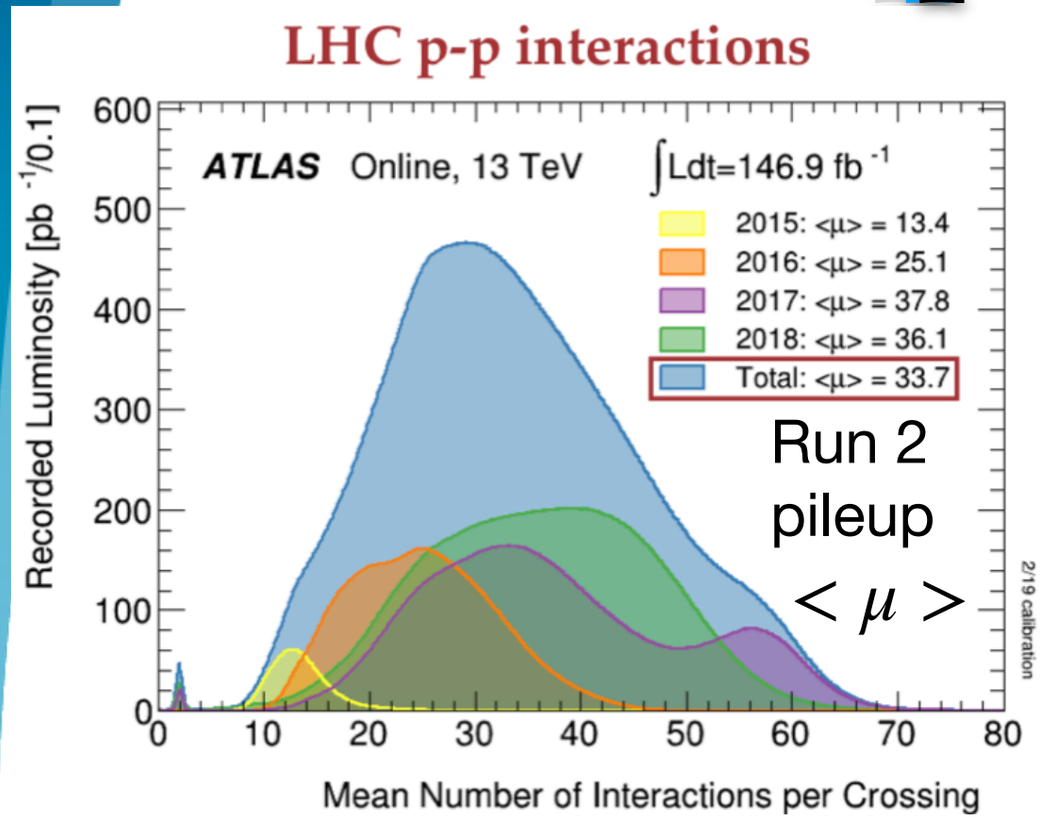


ATL-PHYS-PUB-2018-052

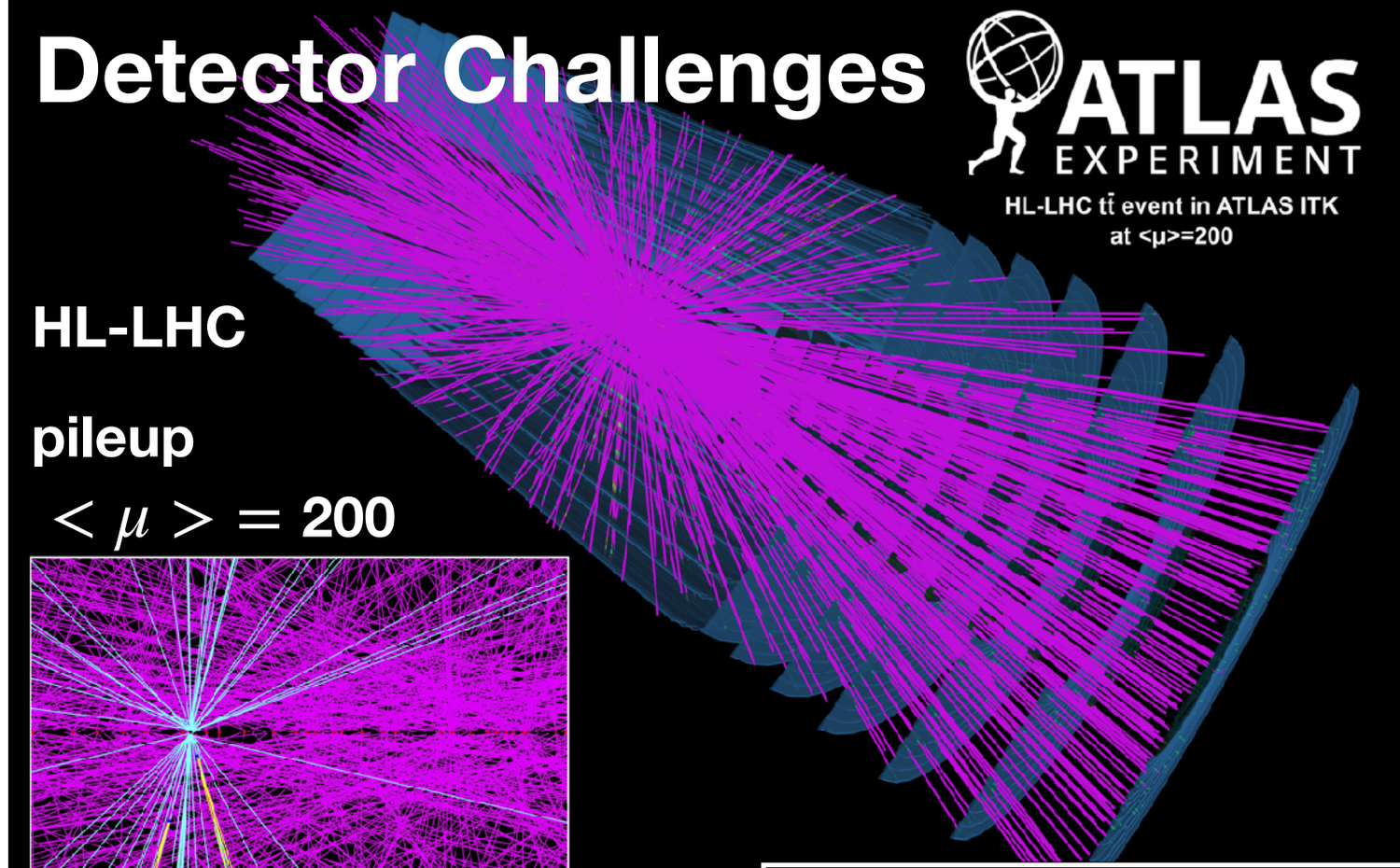


expected total uncertainty of 6% is achieved @ HL-LHC

⟶ Pileup



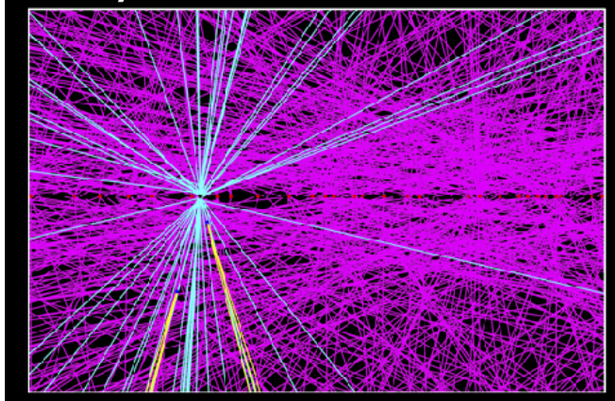
Detector Challenges



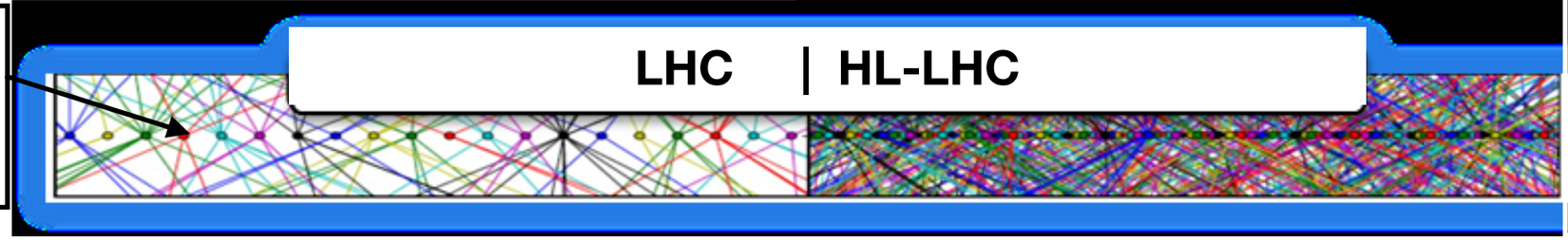
HL-LHC

pileup

$< \mu > = 200$



collision vertices 1 event



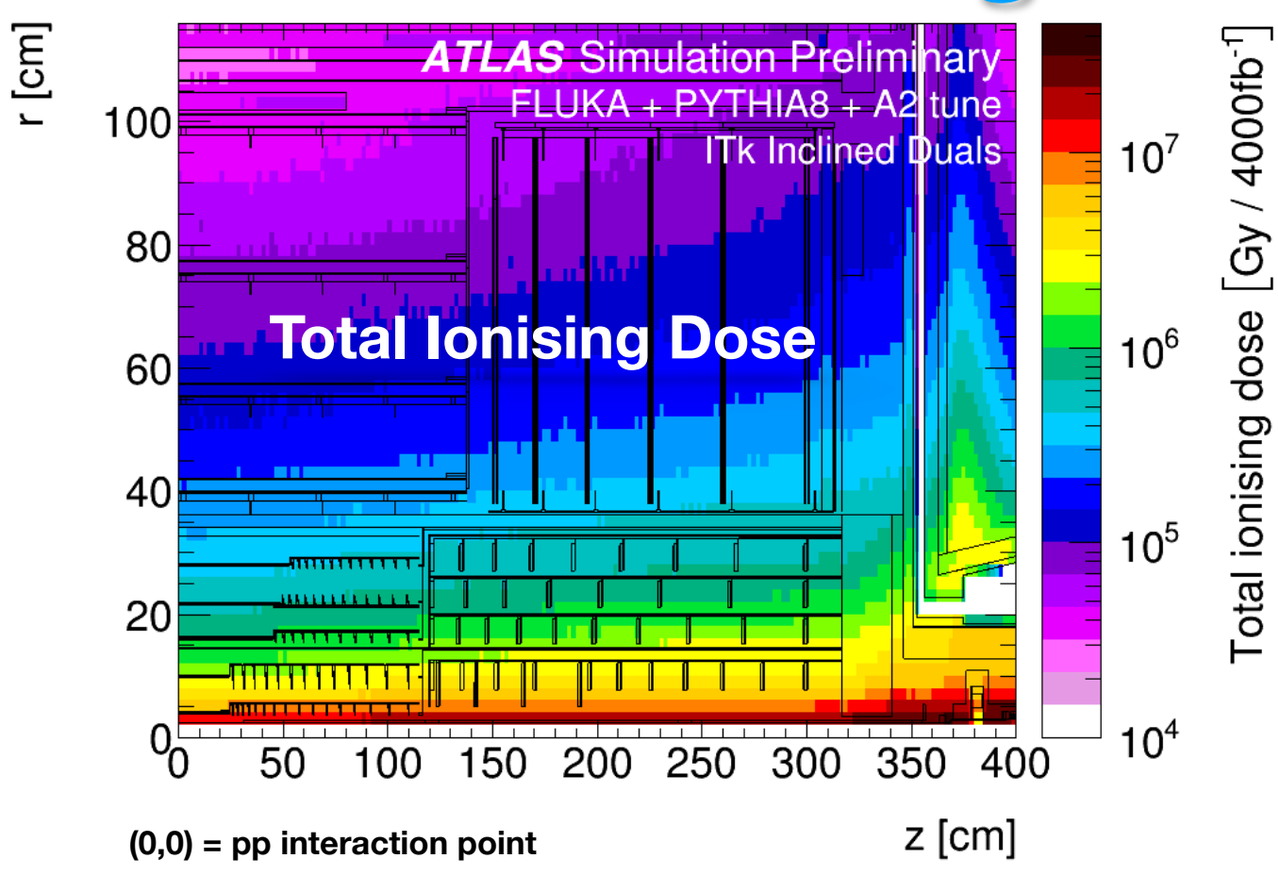
	<μ>	pileup jets pT>30GeV
Run-1	20	0.04 @ 7 TeV
HL-LHC	200	**7.4** @ 14 TeV

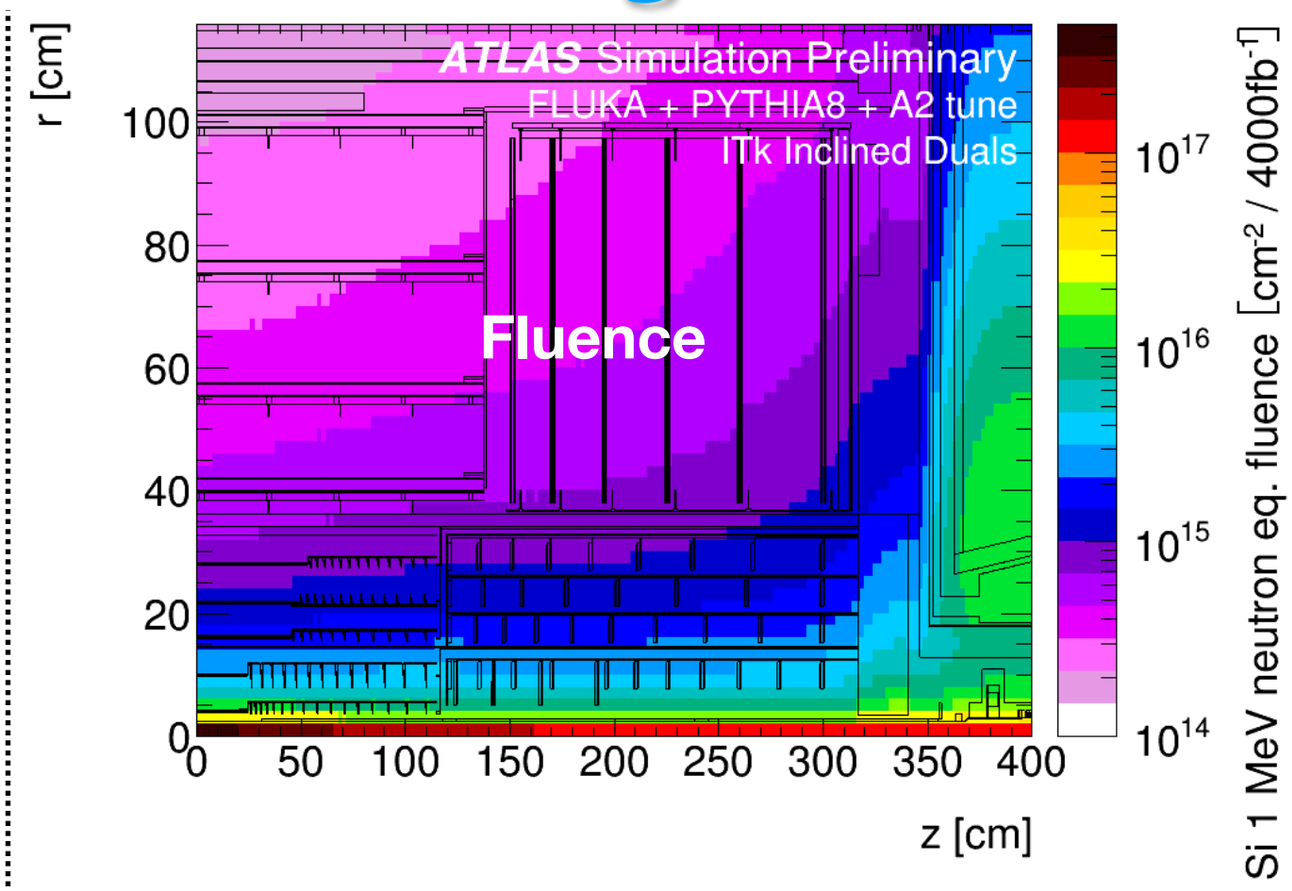
➔ 10x the luminosity reach of first 10 years of LHC operation

	Energy	Instantaneous $\mathcal{L}$	Integrated $\mathcal{L}$	Pileup
Run 2 LHC	13 TeV	2×10^{34} cm^{-2}s^{-1}	300 fb^{-1}	37
HL-LHC (Nominal)	14 TeV	5×10^{34} cm^{-2}s^{-1}	3000 fb^{-1}	140
HL-LHC (Ultimate)	14 TeV	7.5×10^{34} cm^{-2}s^{-1}	4000 fb^{-1}	200

Integrated $\mathscr{L}$ per year: 250 fb^{-1} (baseline), > 300 fb^{-1} (ultimate)

Challenge: Radiation Damage





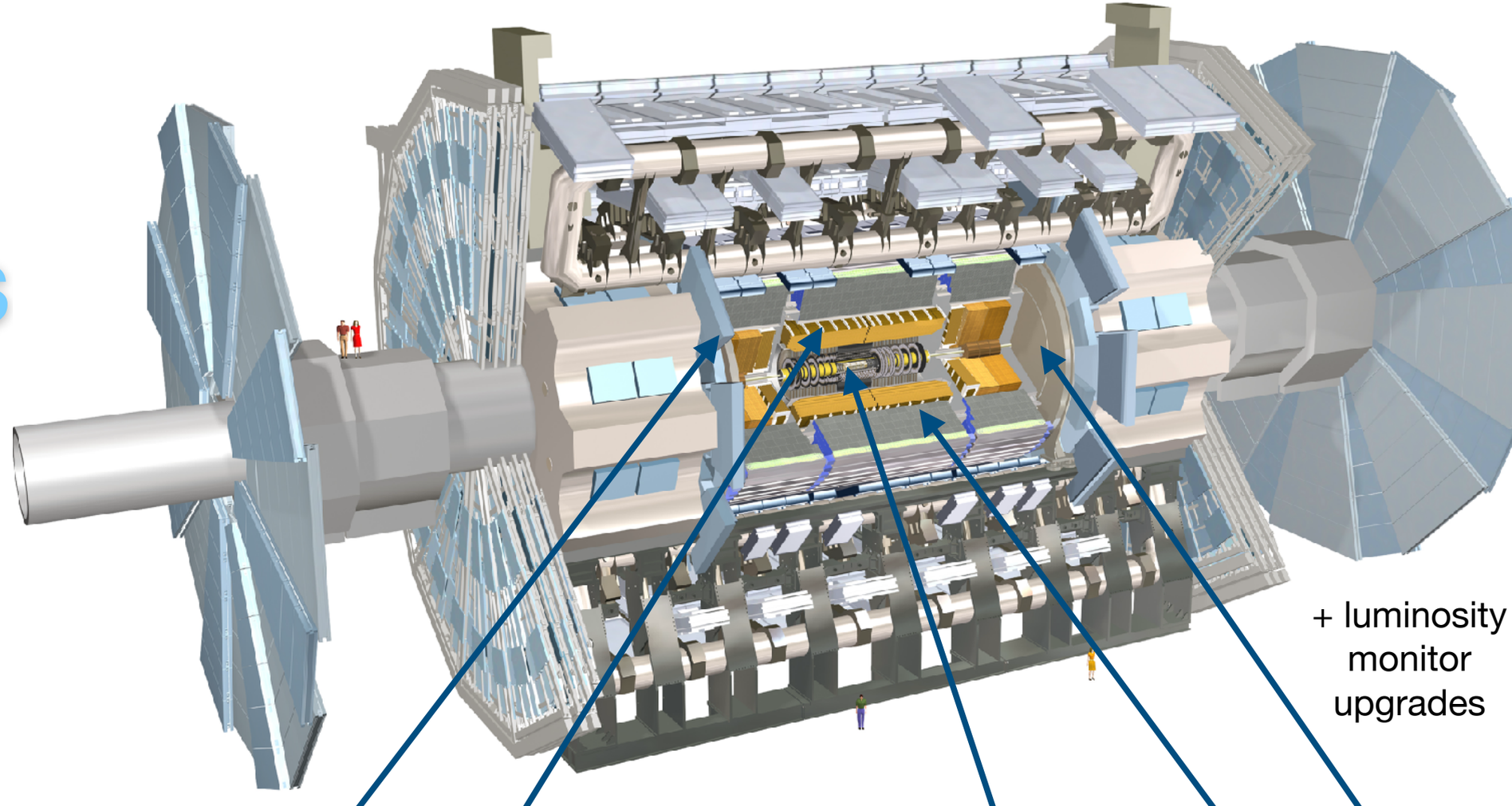
The inner **tracker** must continue to perform up to 4000 fb^{-1} (except Pixel Inner System replaced @ 2000 fb^{-1}.):

➢ **Detector Sensor technologies** (Si planar, 3D, diamond) qualified for: (3-19x10^{15} n_{eq}/cm^2, 2-10 MGy)
- NIEL (Non-Ionizing Energy Loss)
  —> bulk damage (trapping centres), depletion voltage and leakage current increase

➢ **Front-End Readout ASICs** (Application Specific Integrated Circuits) qualified for:
- TID (Total Ionising Dose) —> surface effects, transistor damage and ageing effects
- SEE (Single Event Effects) induced by heavy ions and hadrons —> either soft errors (no permanent damage: Single Event Upsets,…) or hard errors (permanent damage: Single Event Latchup)

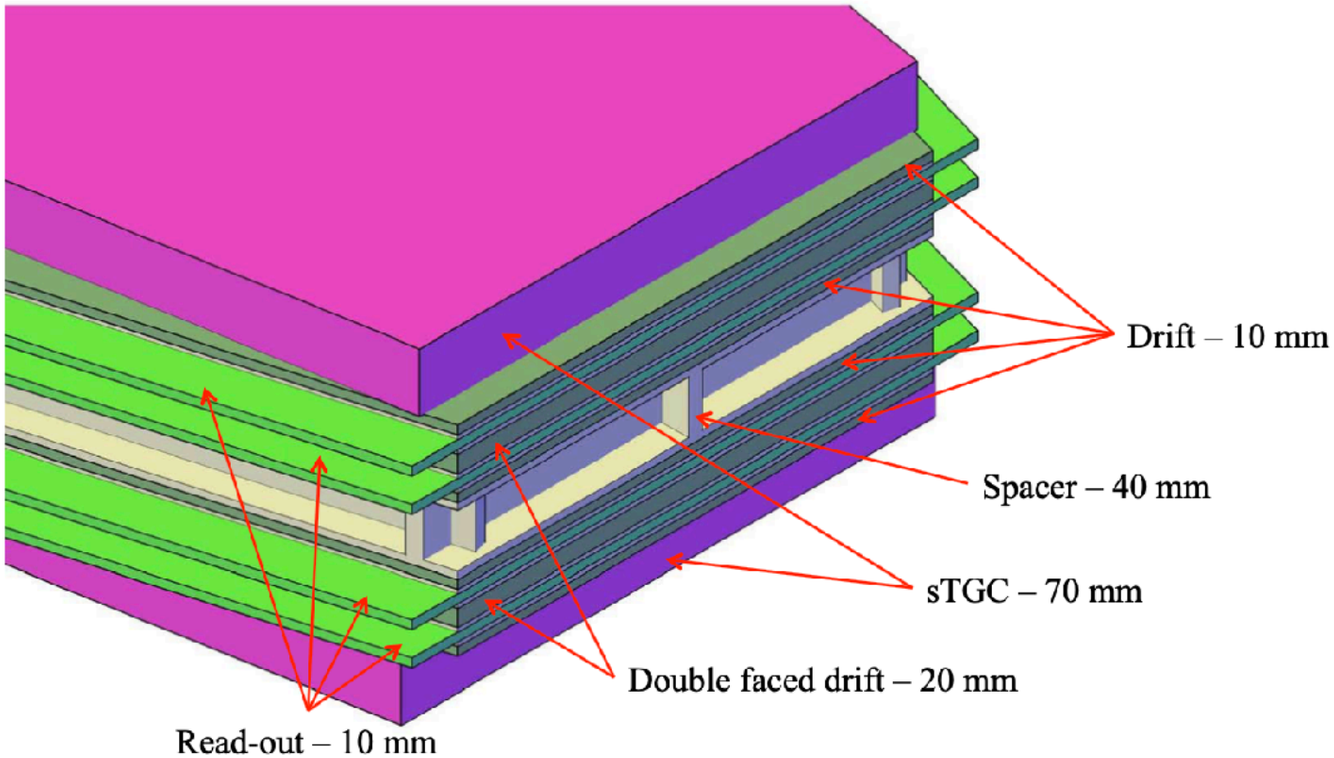
➢ **Material (cable, glue, composite…) must be qualified**
- TID can compromise chemical/mechanical integrity

ATLAS Upgrades

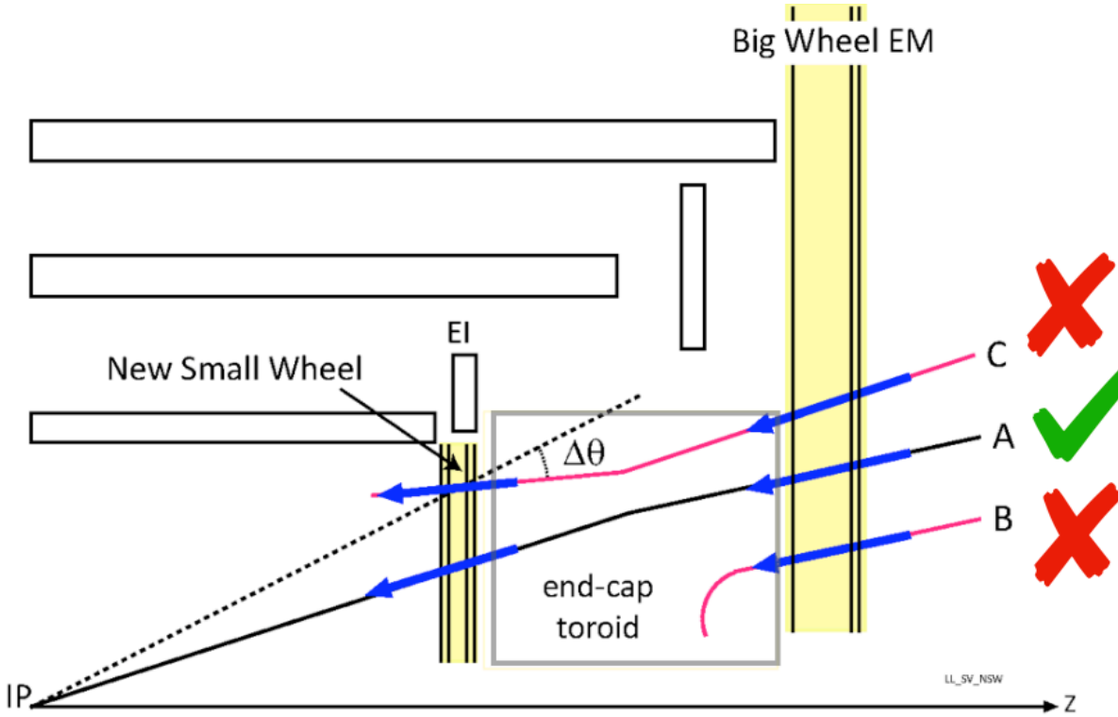


System	Phase-I	Phase-II
Muon	New Small Wheels (NSW)	Muon chambers for inner barrel Continuous readout.
Tracking		All-silicon Inner Tracker (ITk) w. $\lvert\eta\rvert < 4$
Calorimeters	Level-1 (L1) trigger electronics Liquid Argon (LAr):	LAr: Continuous readout Tile Calorimeter (TileCal): Continuous readout
Timing		High-Granularity Timing Detector (HGTD)
Trigger / DAQ	Trigger hardware – Higher purity e/γ triggers – Lower forward muon fake rate	L1 rate increased: 1 MHz High Level Trigger increased: 10 kHz

Phase-1: Muon Upgrade

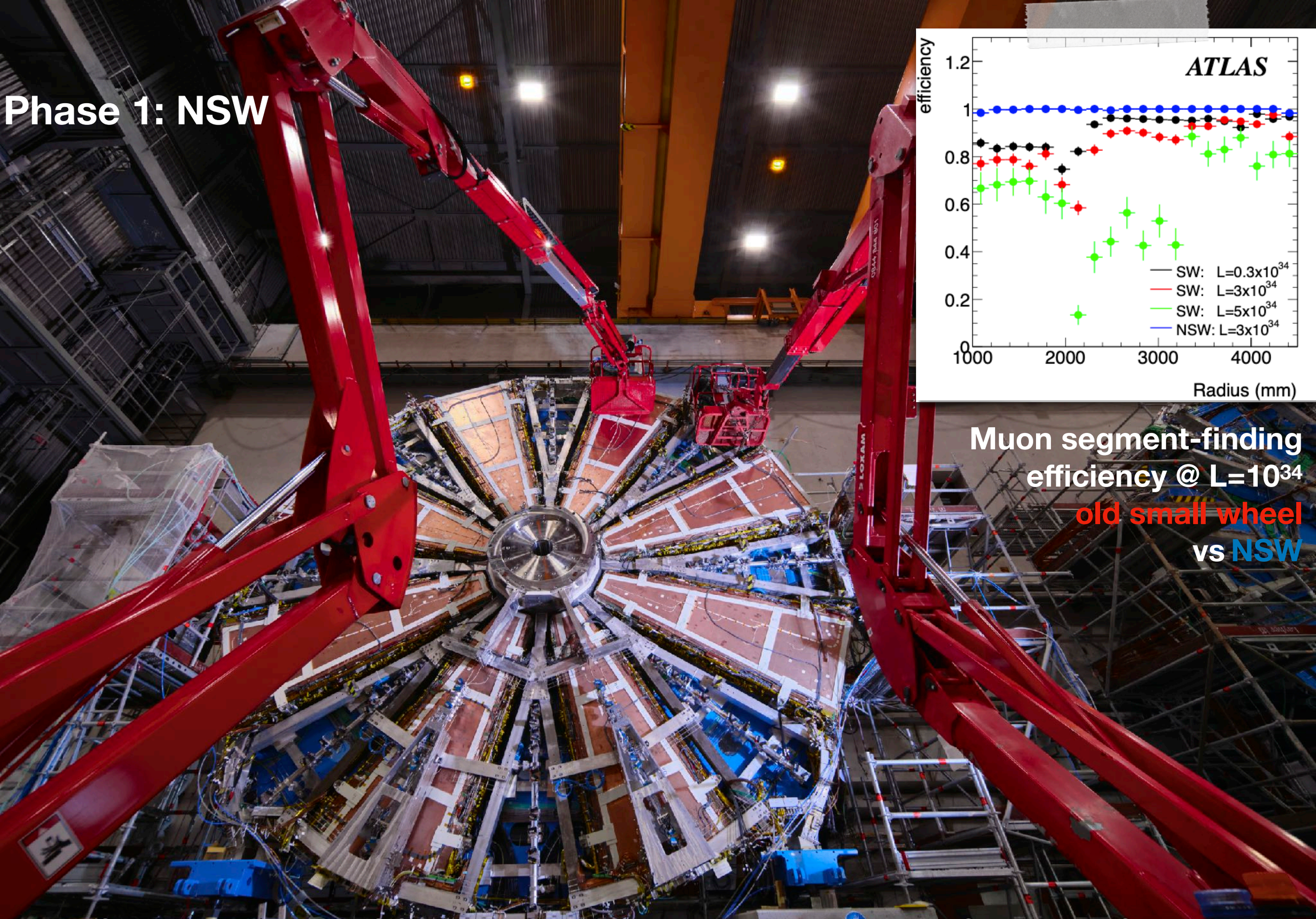


ATLAS-TDR-020



- New Small Wheels will replace current inner muon endcap wheels
- Thin-Gap Chambers, primary trigger, < 1 mrad resolution
- MicroMegas, primary tracking, resolution < 100 microns
- Now commissioning at CERN —>

Phase 1: NSW

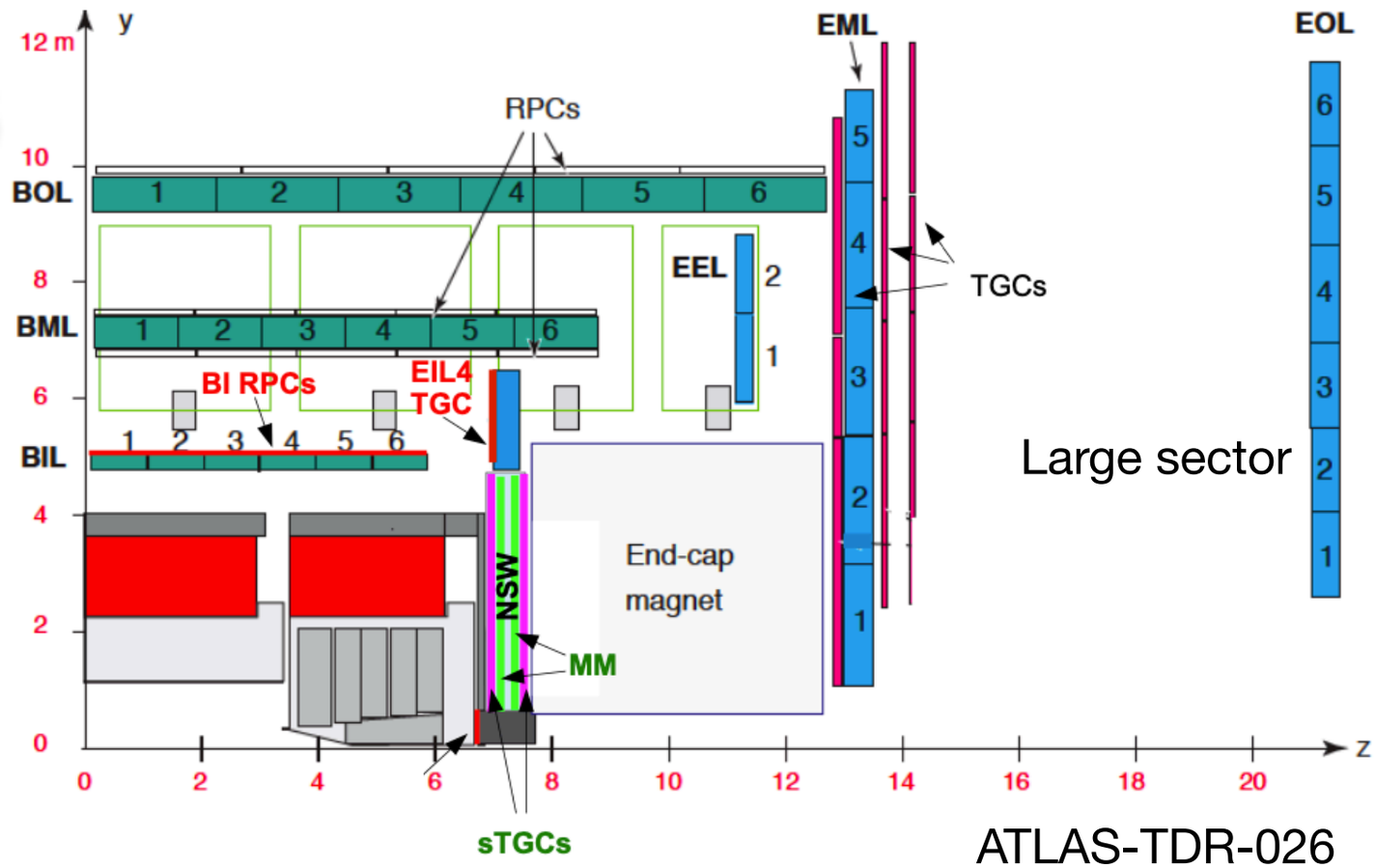


Muon segment-finding efficiency @ L=10^{34}
old small wheel vs NSW

Construction of sTGC and Micromegas modules for both NSW-A and C is nearing completion. Sector installation and commissioning well underway.

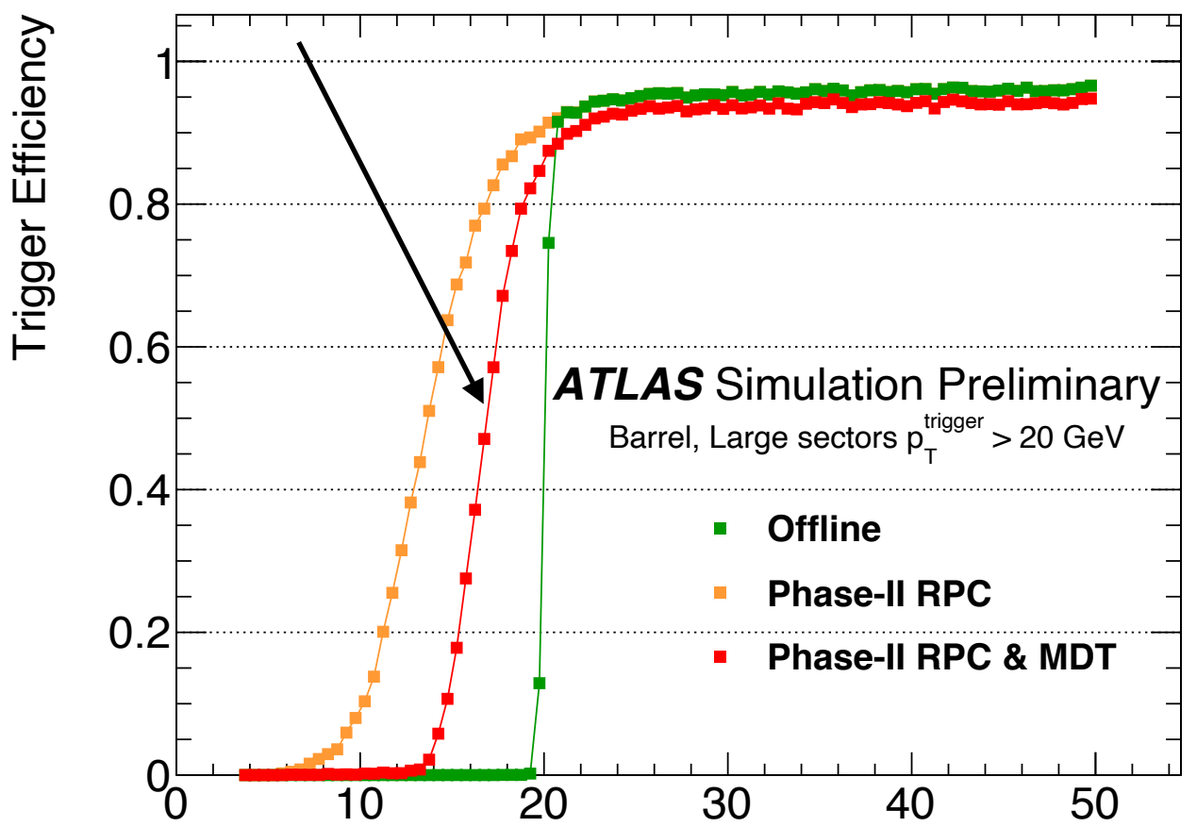
Phase 2: Muons

- New readout + trigger electronics
- Inner barrel RPC new layer
- New TGC triplet module EIL4
- Combine trigger NSW-TGC
- MDT data at L1: better resolution

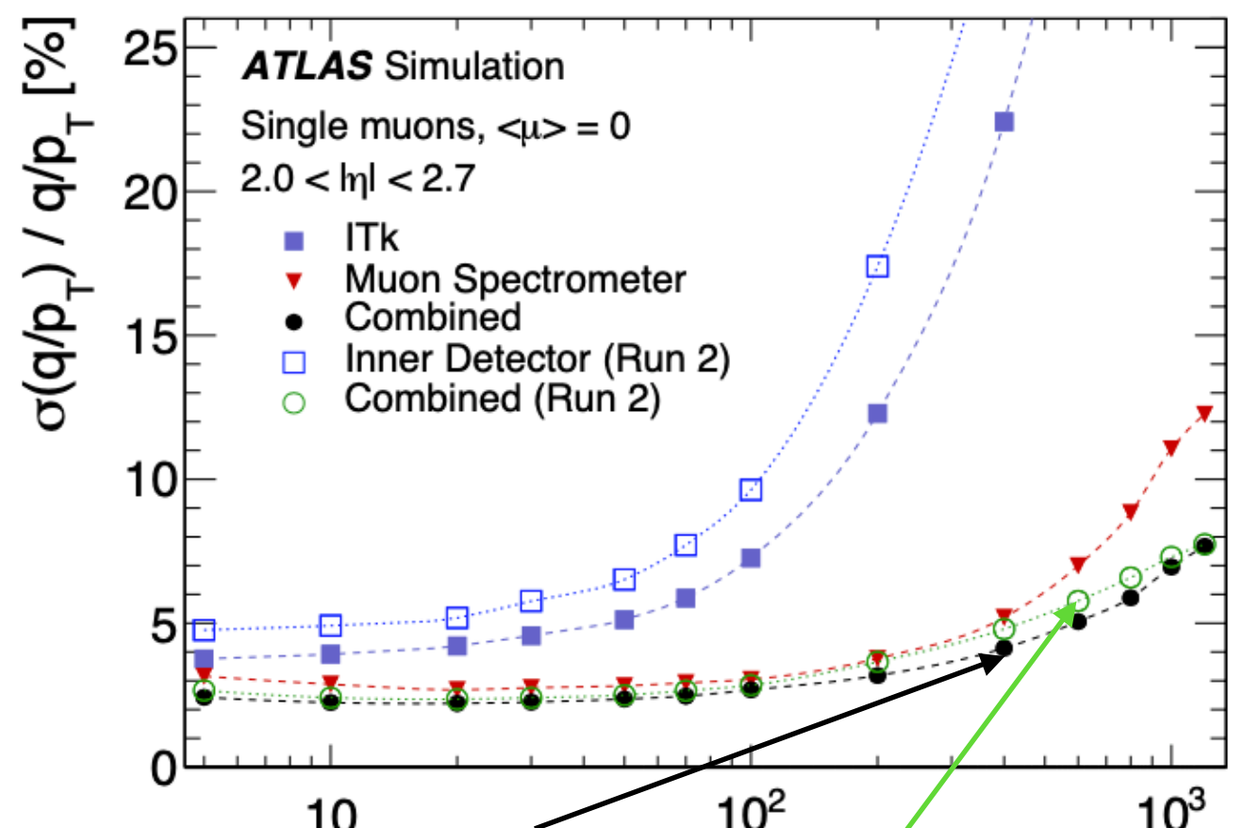


ATLAS-TDR-026

MDT = Monitored Drift Tubes

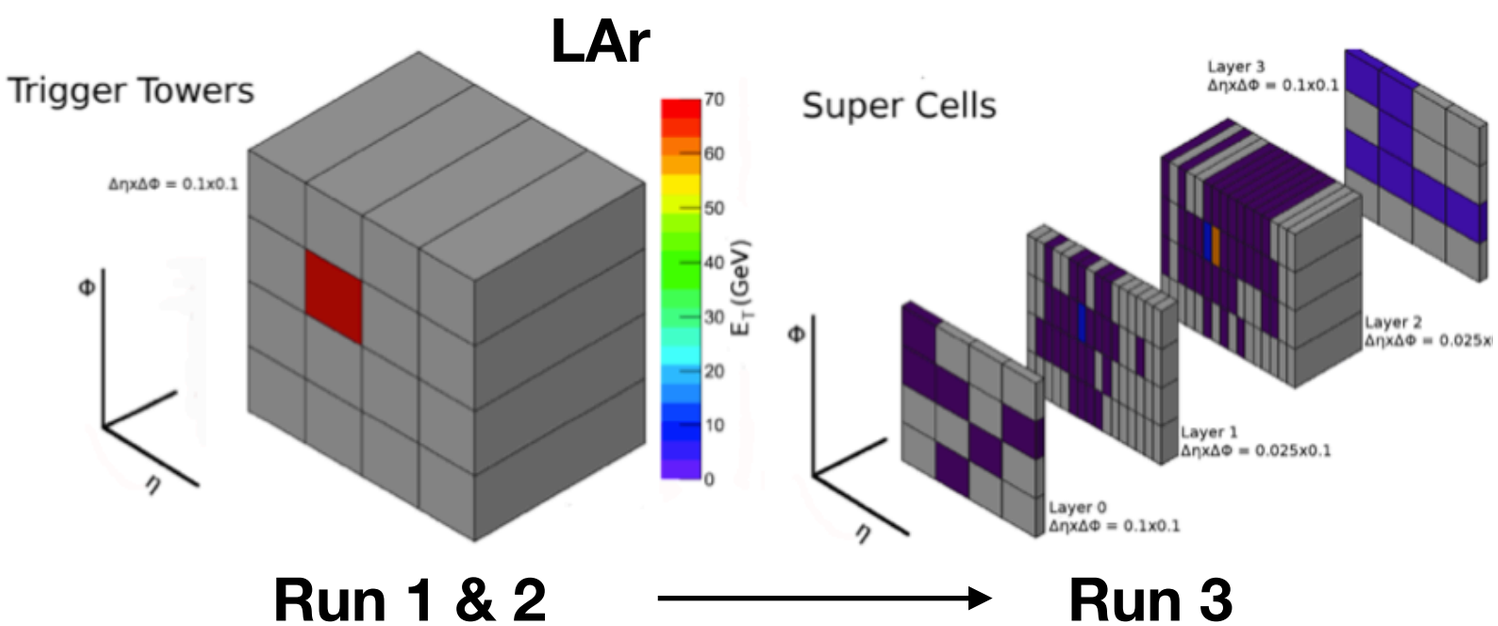


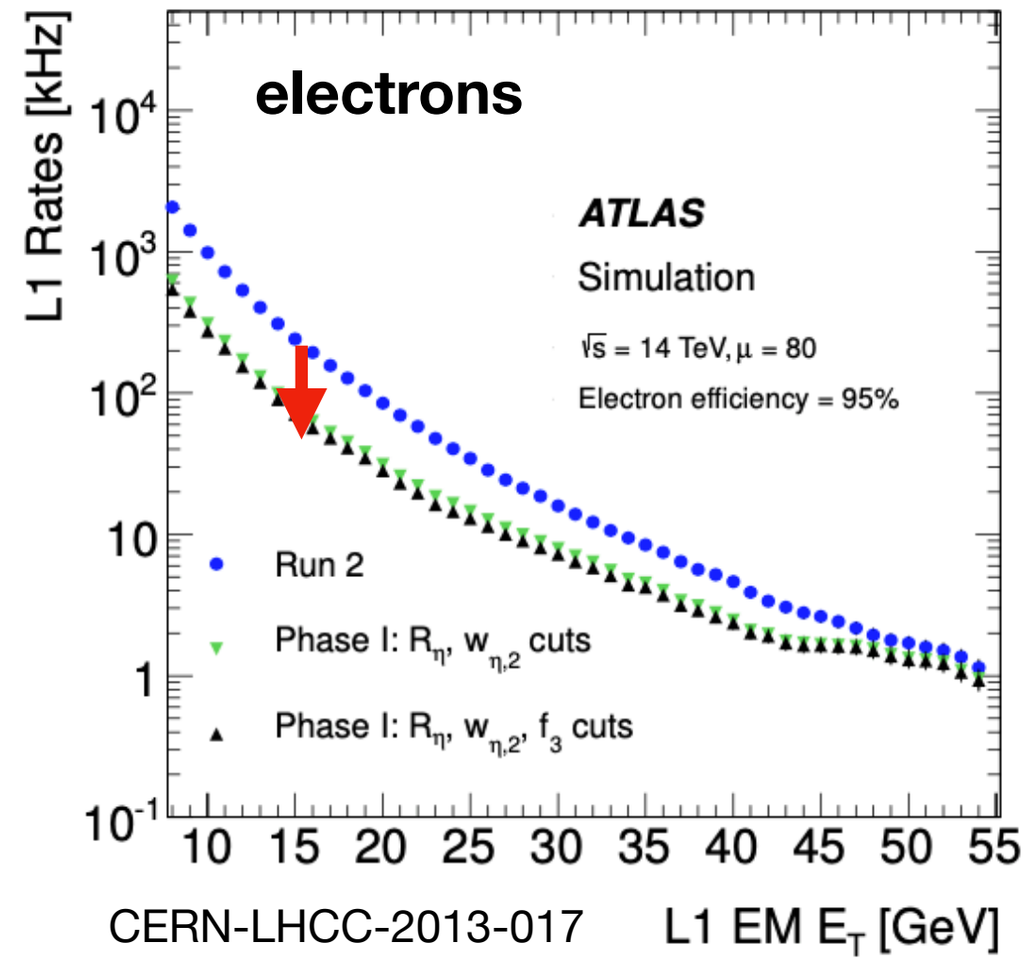
ATL-COM-DAQ-2019-128



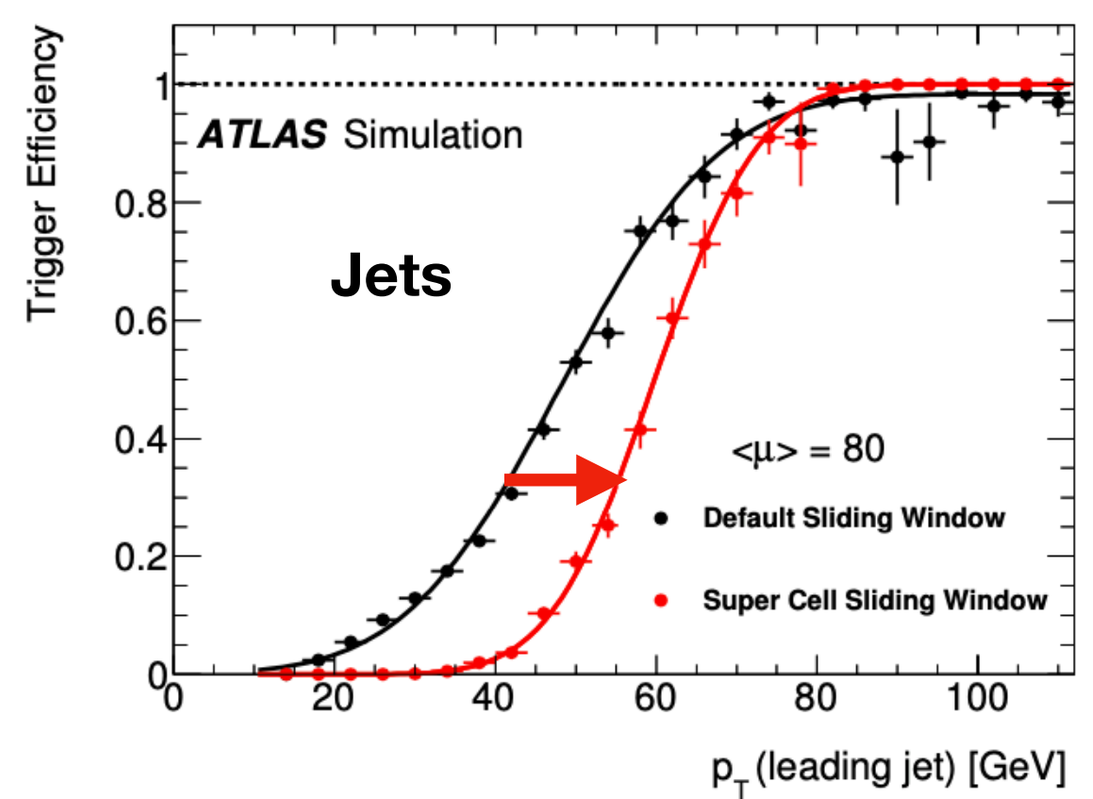
Combined performance >= Run 2

Upgrades to Calorimeters



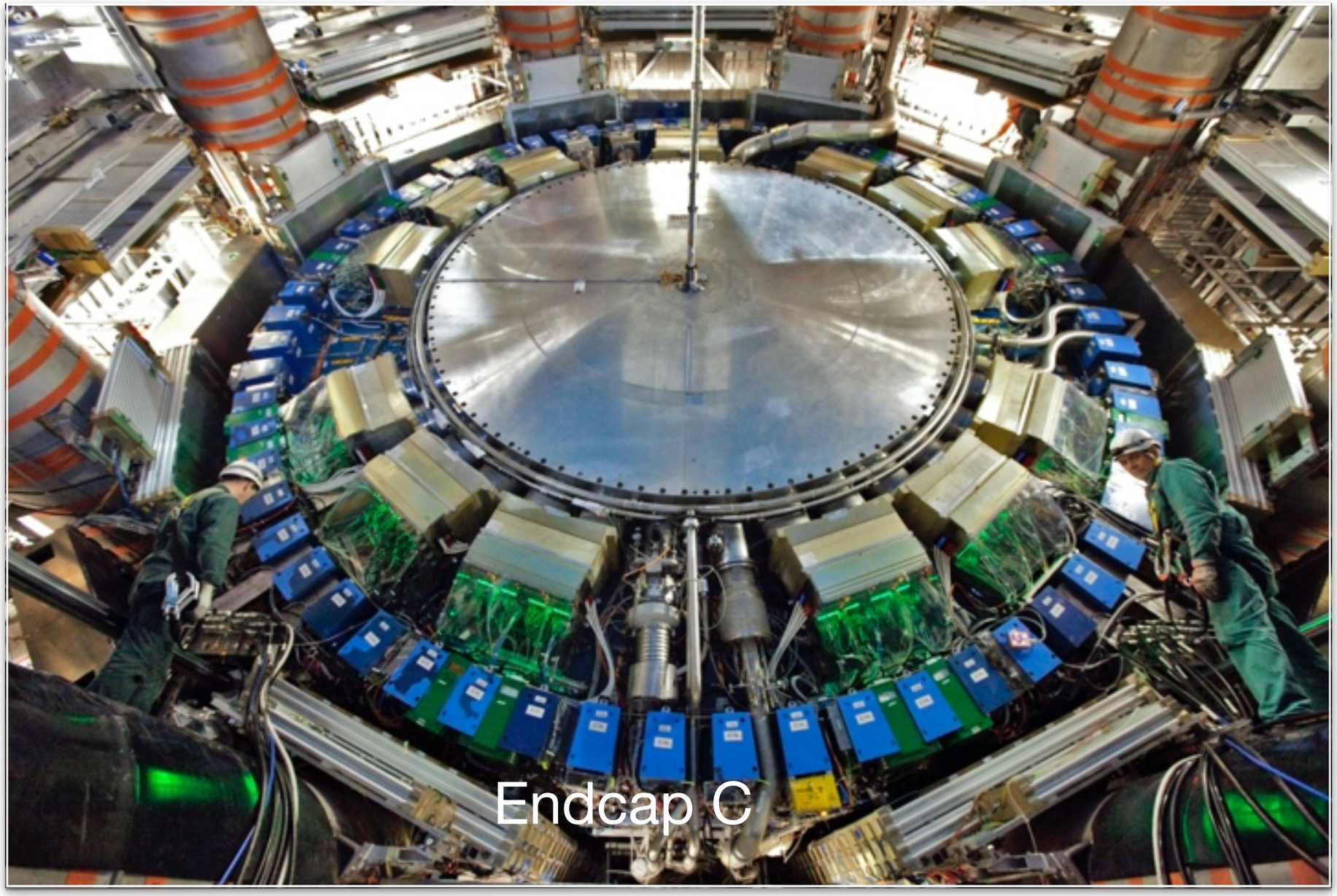


CERN-LHCC-2013-017



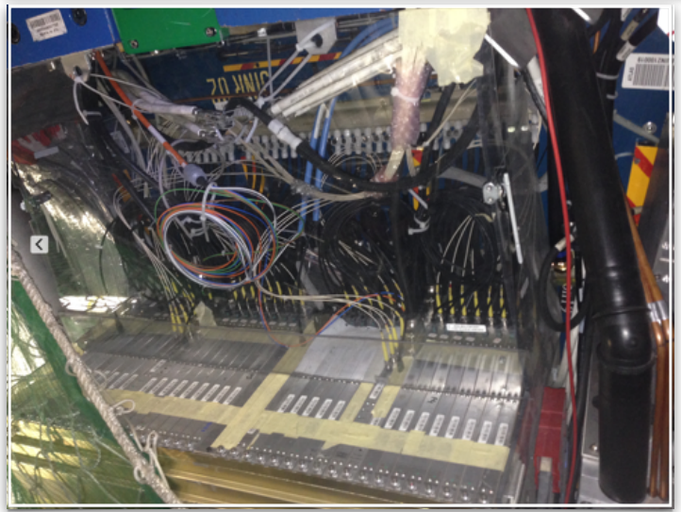
- **Phase-1**: LAr trigger electronics with higher granularity "Super Cells", longitudinal shower information
  - Electrons: high efficiency & reduced trigger rate
  - Jets: Improved resolution
- **Phase 2**: LAr and TileCal data streaming at 40 MHz, radiation-tolerant electronics

Upgrades to LAr Calorimeter



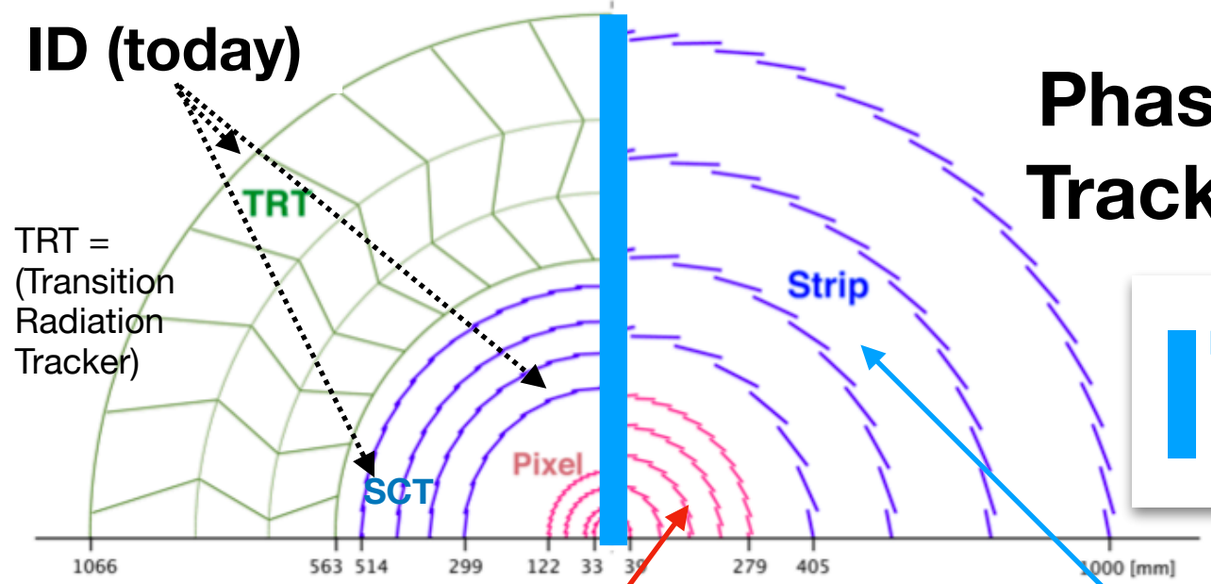
Back-end crates

See poster by Marcos Oliveira

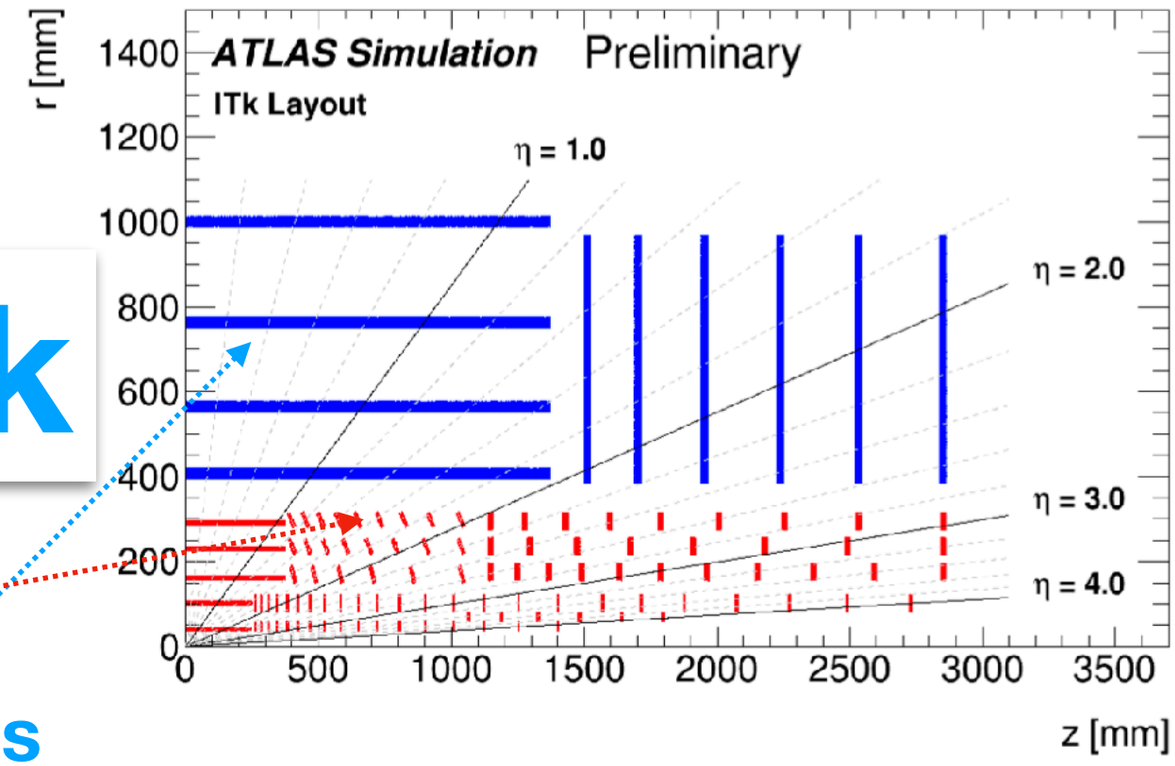


Front-end crates

Phase 2 Tracking



ITk

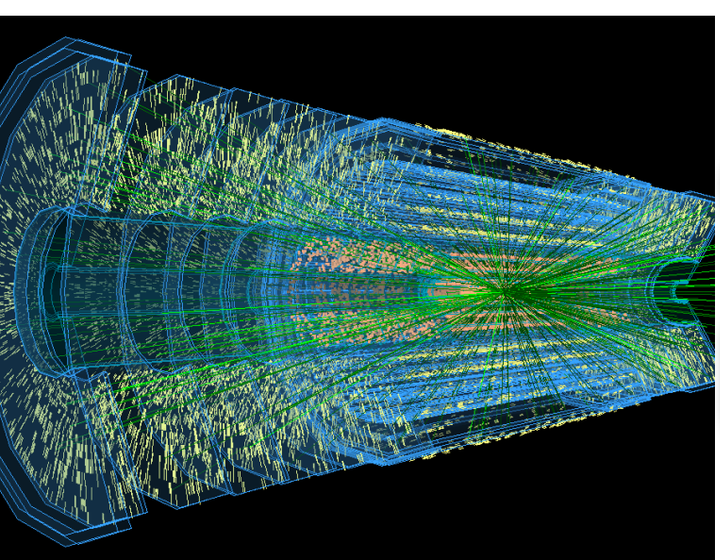


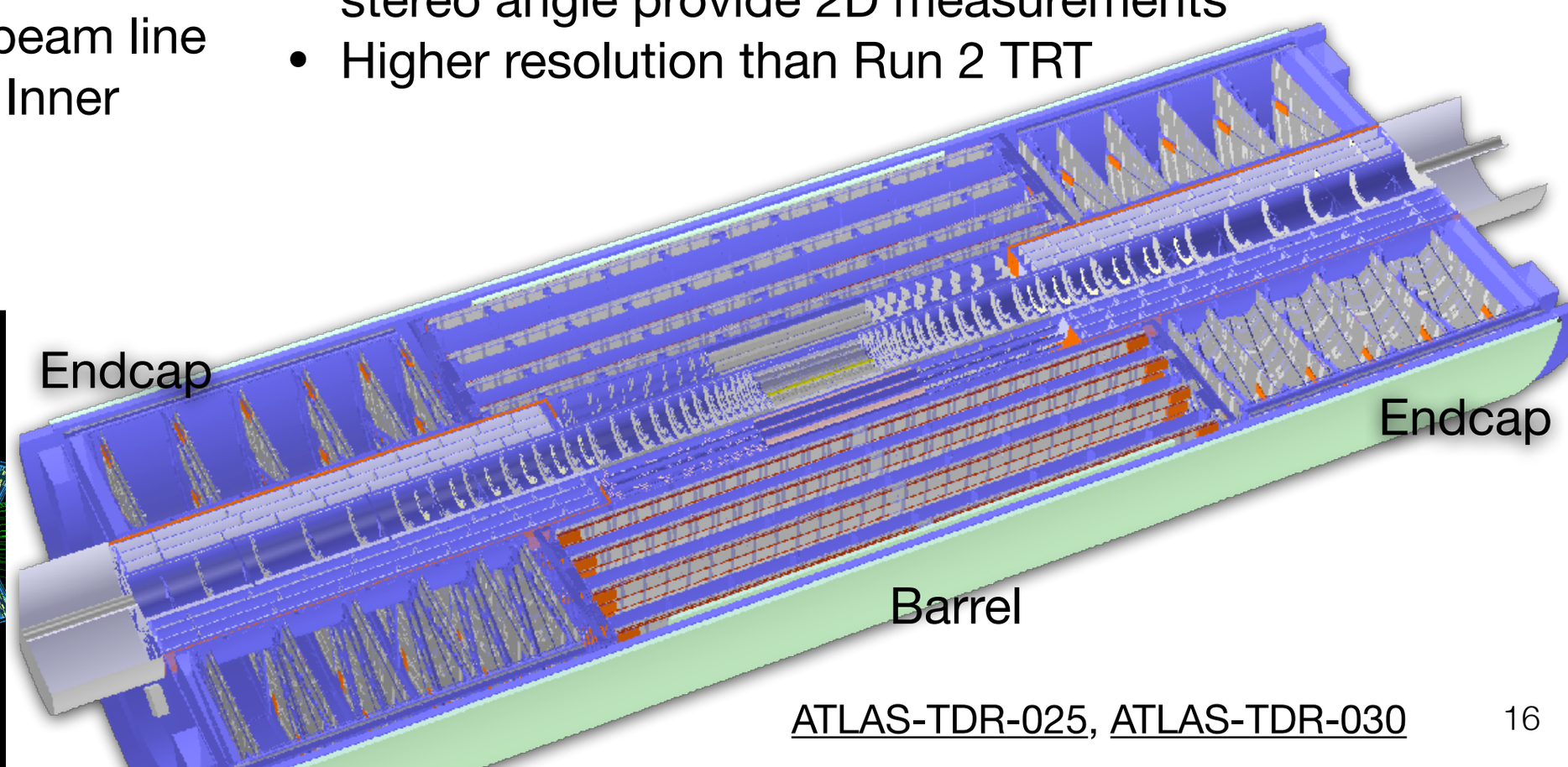
ITk Pixels

- **5** barrel layers + **5** EC (EndCap)
- Inclined sensors
- Covers $|\eta| < 4$ (was 2.5)
- 1st layer 35 mm from beam line
- Higher resolution than Inner Detector (ID) pixels

ITk Strips

- **4** barrel layers + **6** EC (Endcap) rings
- Silicon microstrip modules with small stereo angle provide 2D measurements
- Higher resolution than Run 2 TRT



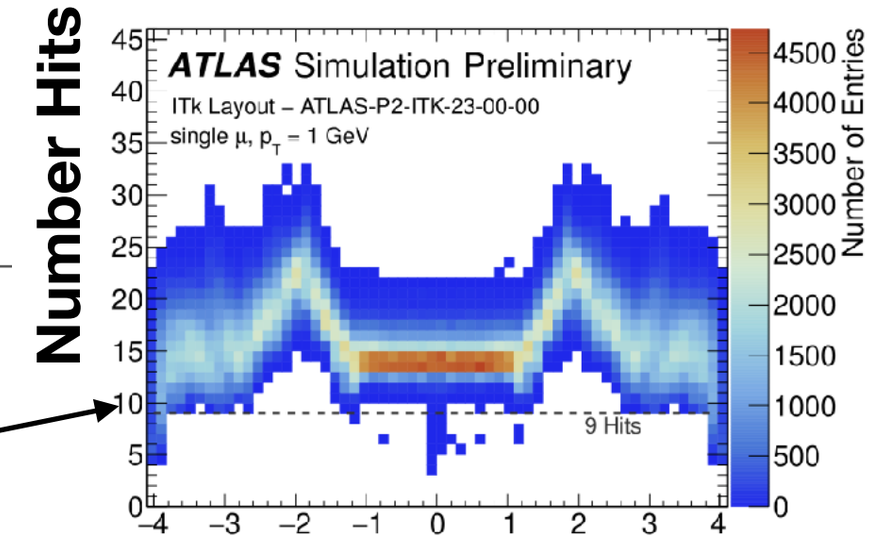


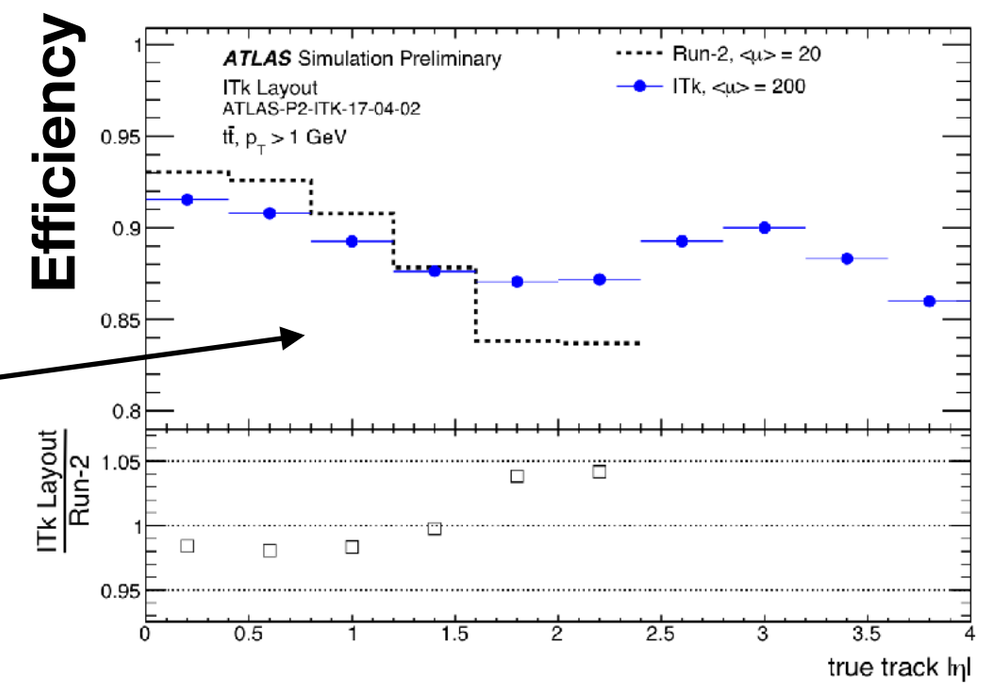
ATLAS-TDR-025, ATLAS-TDR-030

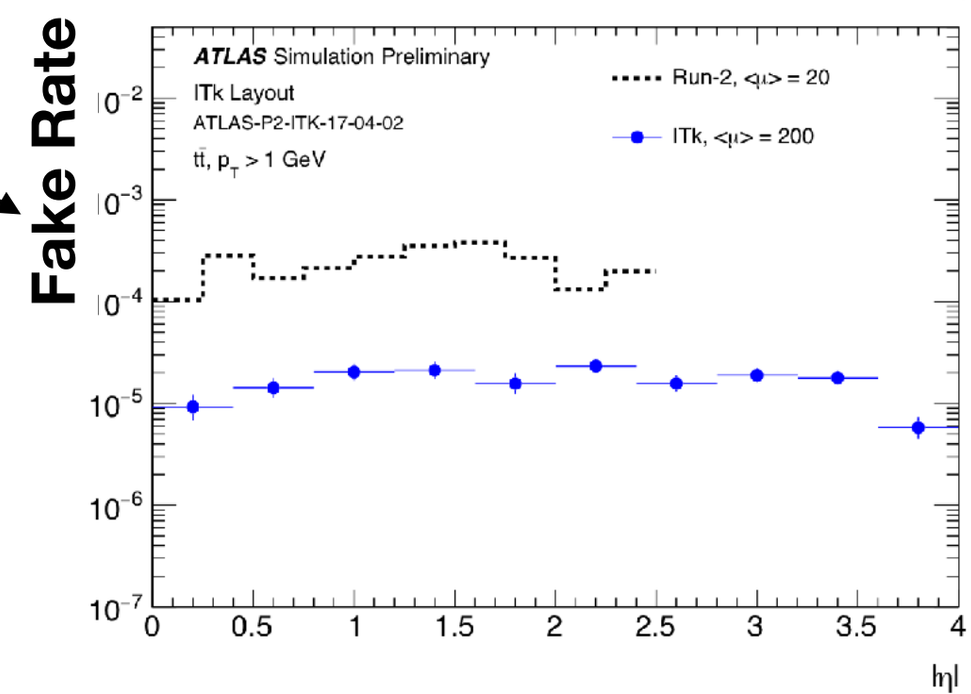
ITk Tracking Performance

✓ ITk layout designed to guarantee **hermetic** coverage within $|\eta| < 4$

- Provides at least **9 hits** for all particles with $p_T > 1$ GeV within $|z_{vertex}| < 150$ mm
  - Allows for **tighter track selection** without compromising reconstruction efficiency
- Maintain **efficiency over 85%** up to $|\eta| < 4$, comparable to Run2 ID at $\langle\mu\rangle = 20$
- Improves the **fake rate over Run2 ID,** <u>even with a 10x increase in pile-up</u>.



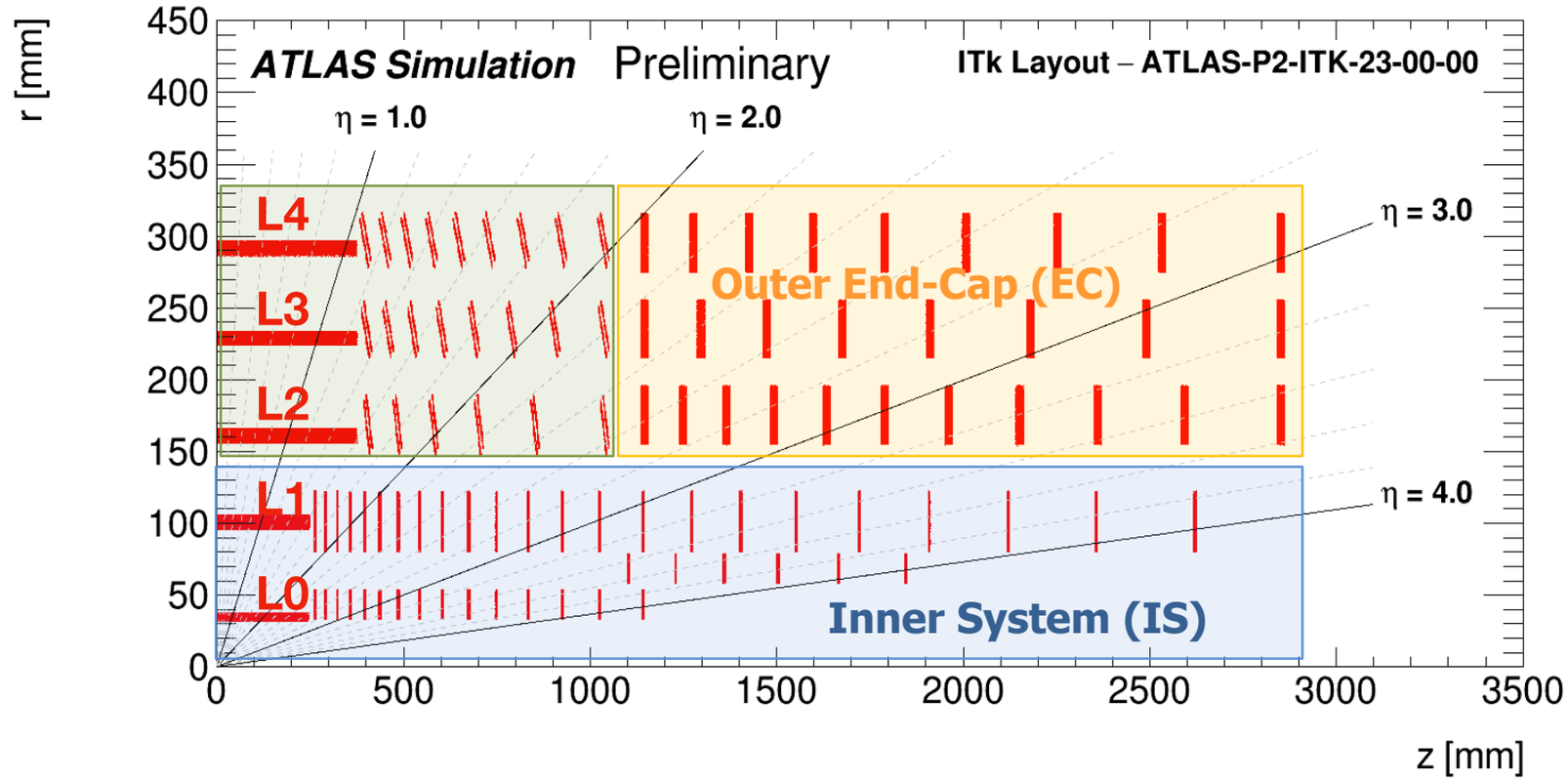




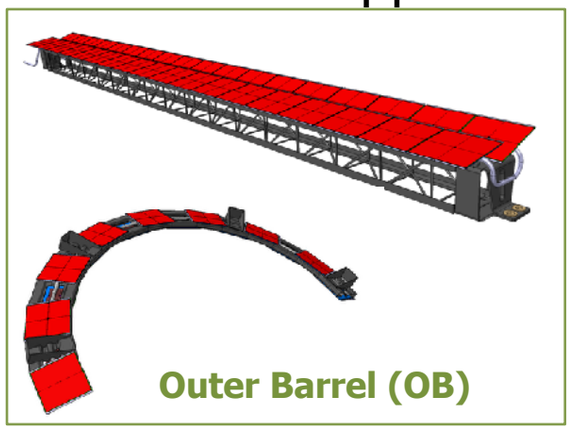
Overall significant improvement thanks to

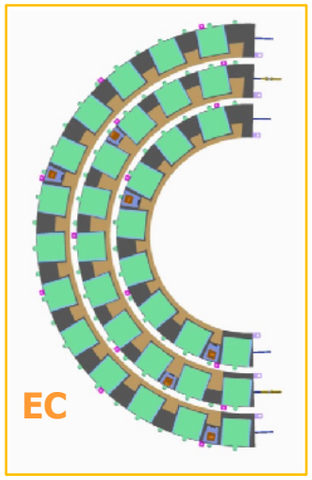
- Reduced material budget → minimize material interactions
- Increase in overall hit counts → tighter track selection
- Improved hermeticity ➔ more hits, fewer holes

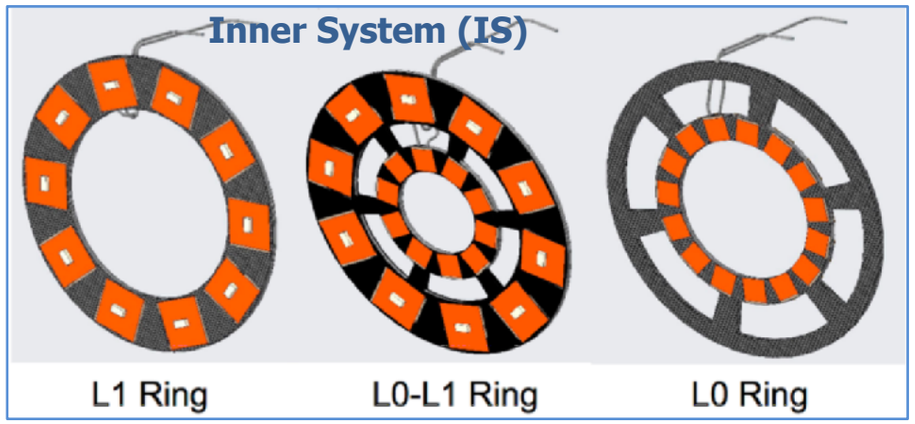
ITk Pixel Overview



Local supports:

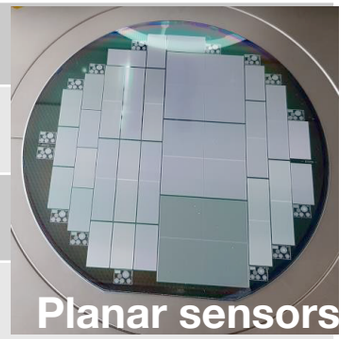


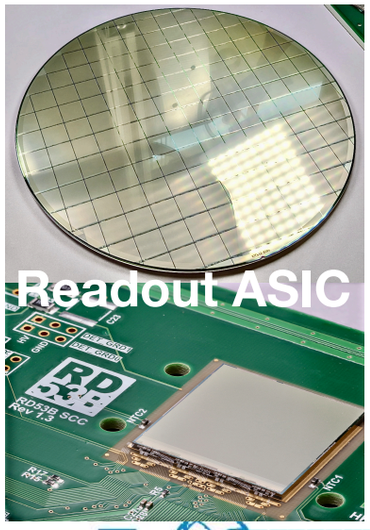




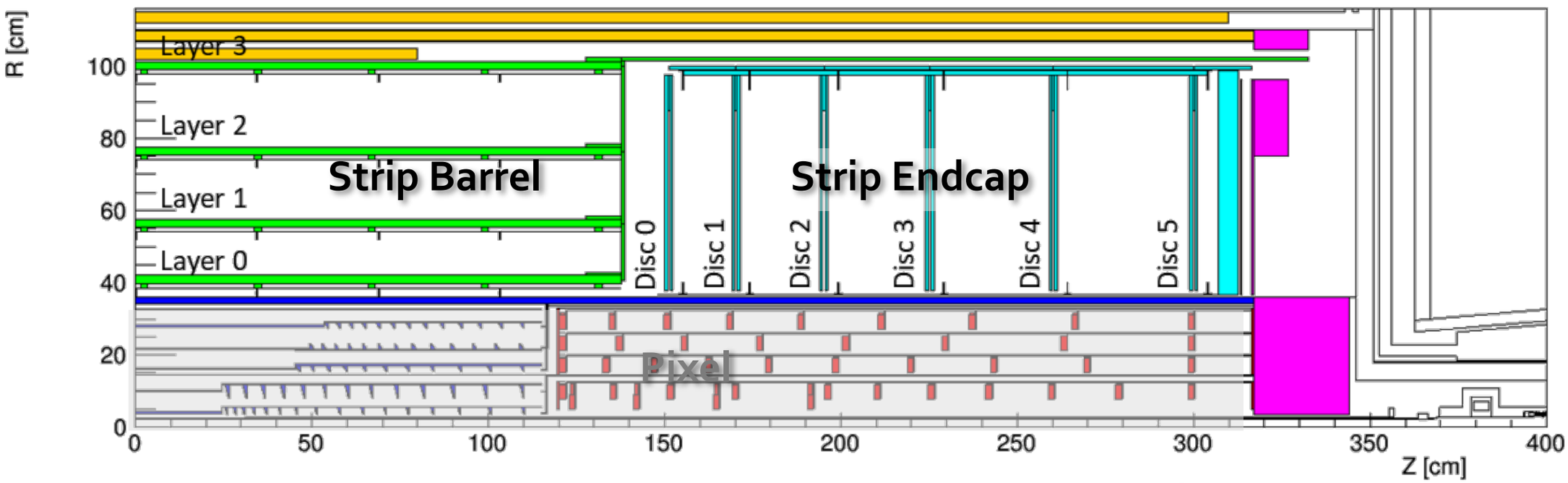
Pixels: transition from R&D to pre-production

Layer	Sensor Type	Thickn. [µm]	Sensor Size [µm²]	Module Type	Modules installed	Replacement (2000 fb⁻¹)	Fluence w/ SF [1e15 n_{eq}/cm²]
L0 barrel	3D n-in-p	150	25x100 1E	Triplet	288	Yes	18
L0 rings	3D n-in-p	150	50x50 1E	Triplet	900	Yes	18
L1	Planar n-in-p	100	50x50	Quad	1160	Yes	4
L2-4	Planar n-in-p	150	50x50	Quad	6816	No	4-1

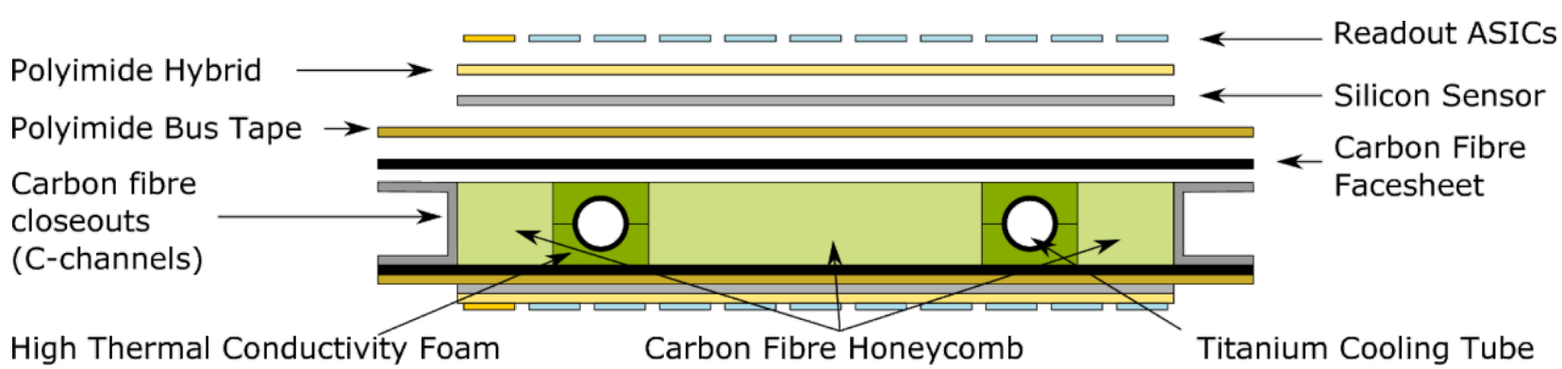




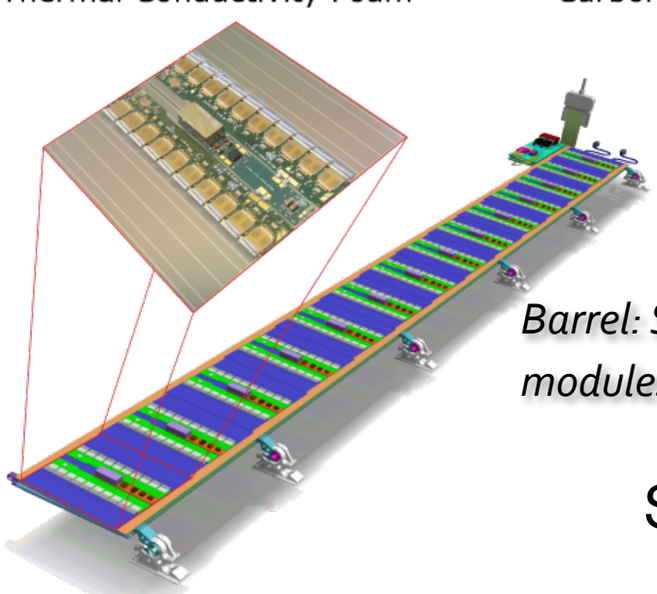
ITk Strip Overview



Barrel: 4 barrel layers instrumented with modules on the two sides of the stave local support
Endcap: 6 disks instrumented with modules on the two sides of the petal local support

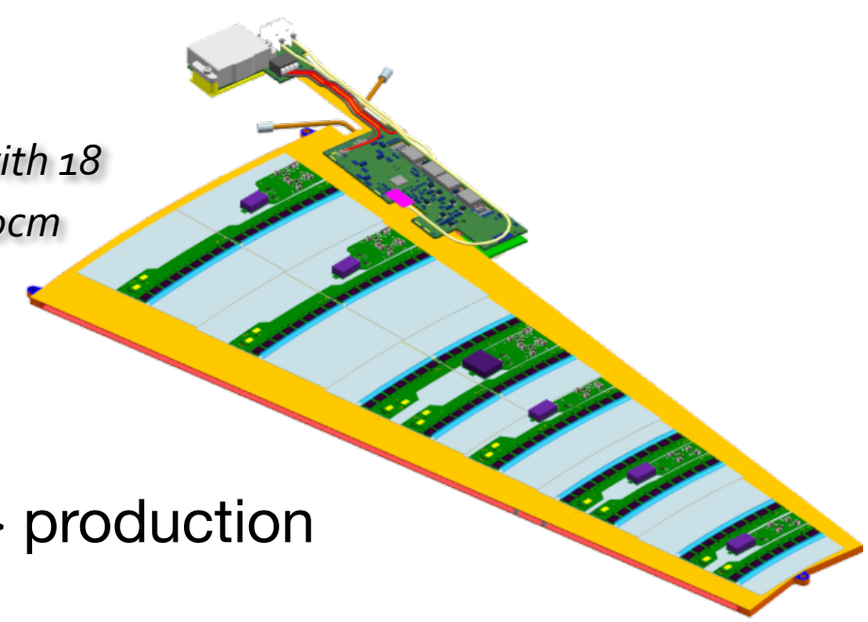


	Barrel	Endcap
# of modules	10976	6912
# of Local Support	392	384
Surface [m²]	104.8	60.4



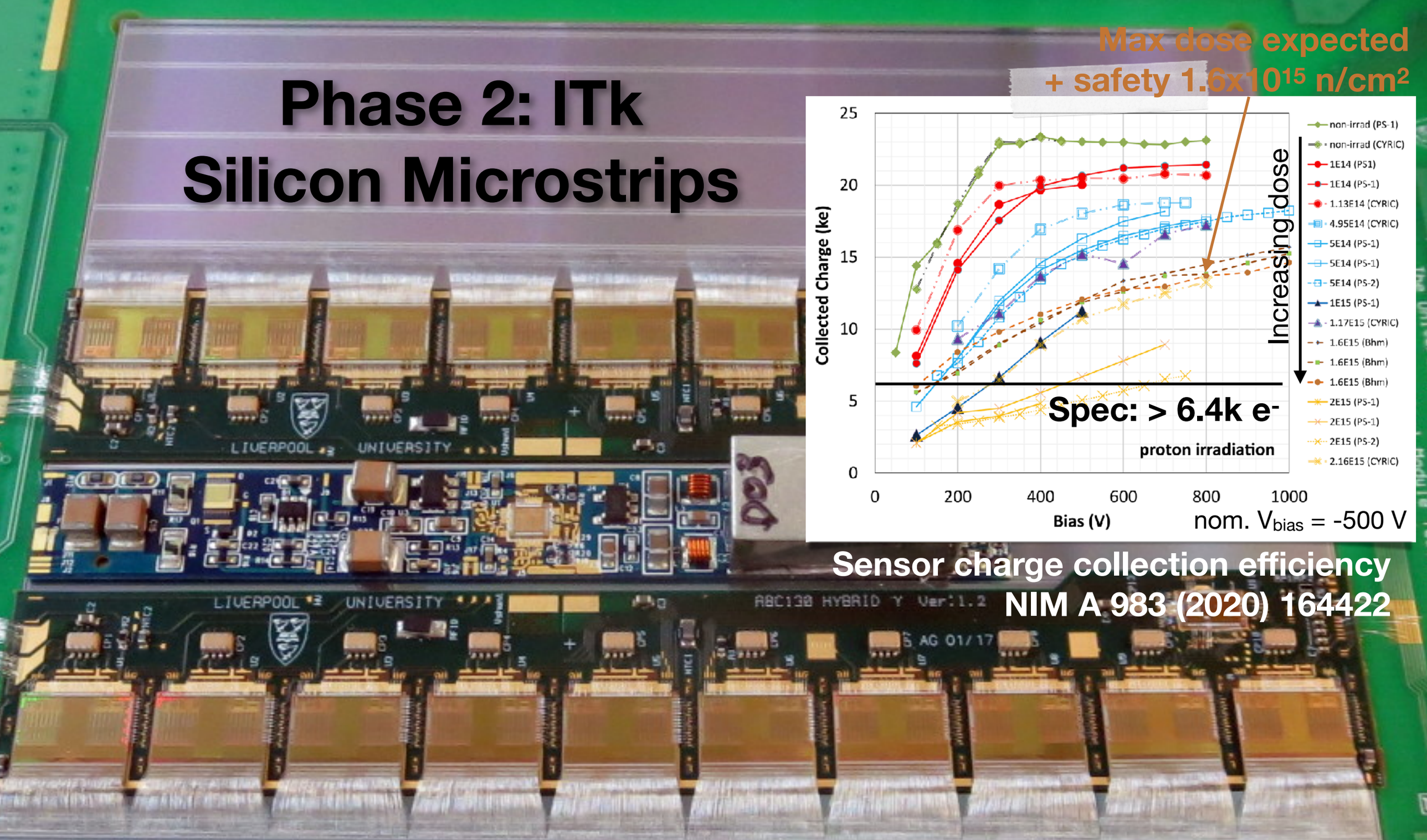
Barrel: Stave is loaded with 28 modules → Length ~ 140 cm

Endcap: Petal is loaded with 18 modules → Length ~ 60cm



Strips: transition pre-production -> production

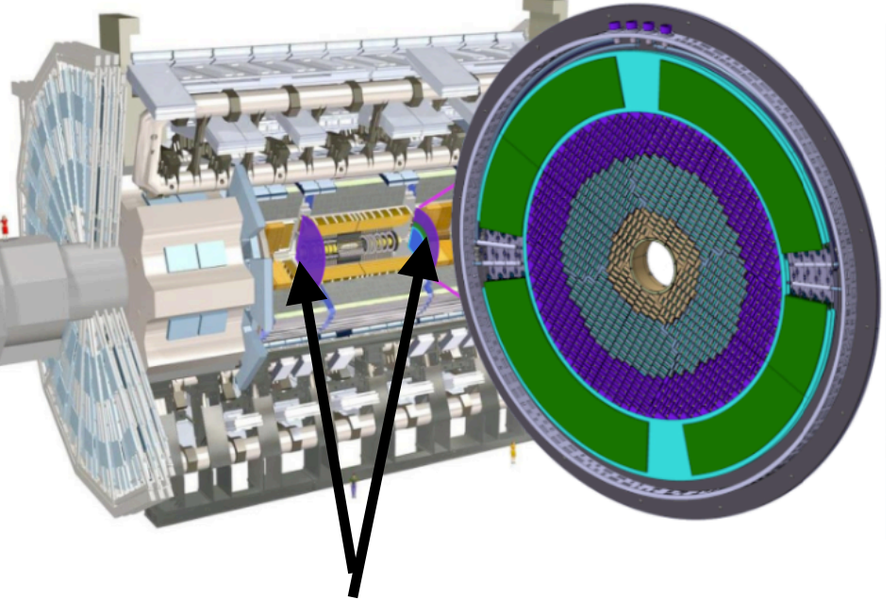
Phase 2: ITk Silicon Microstrips

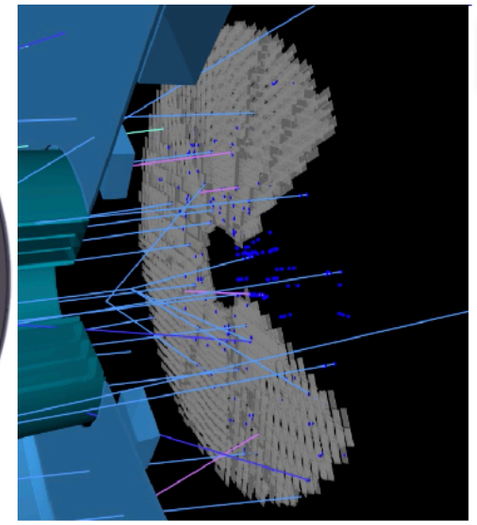


Max dose expected
+ safety 1.6×10^{15} n/cm^2

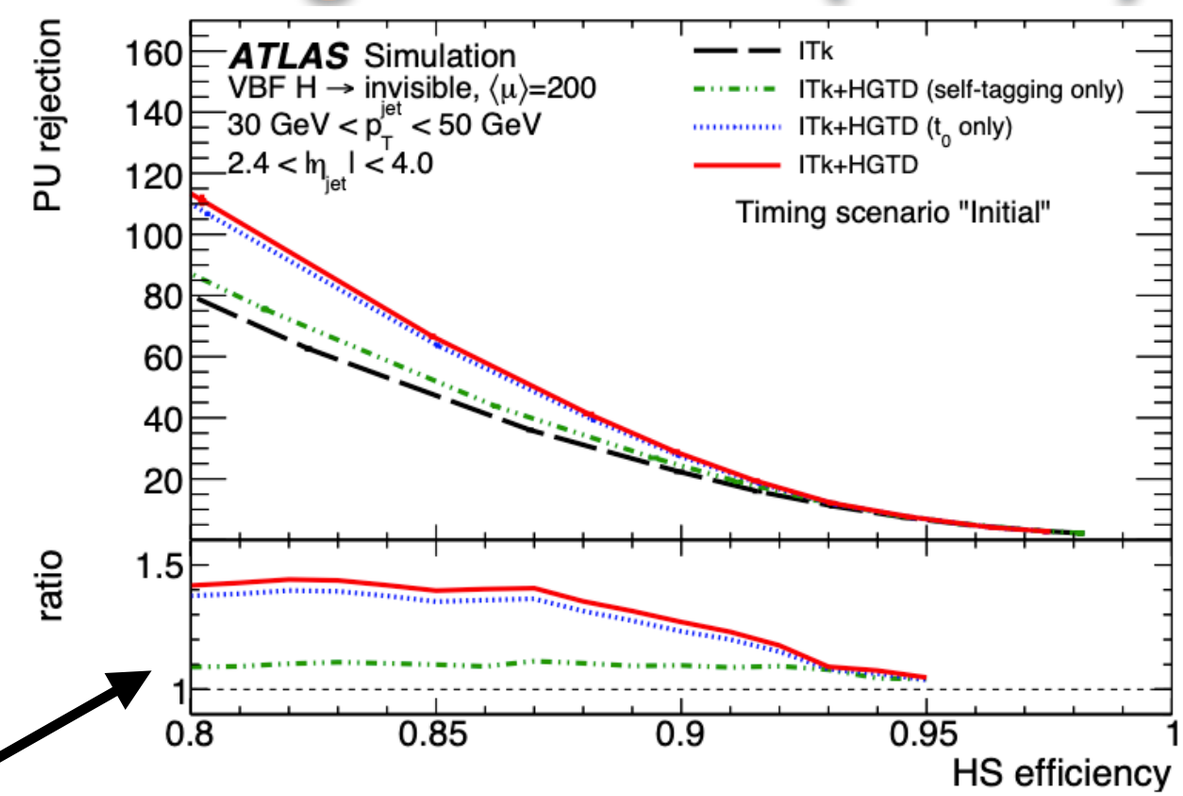
Sensor charge collection efficiency
NIM A 983 (2020) 164422

Phase-2: High Granularity Timing Detector (HGTD)



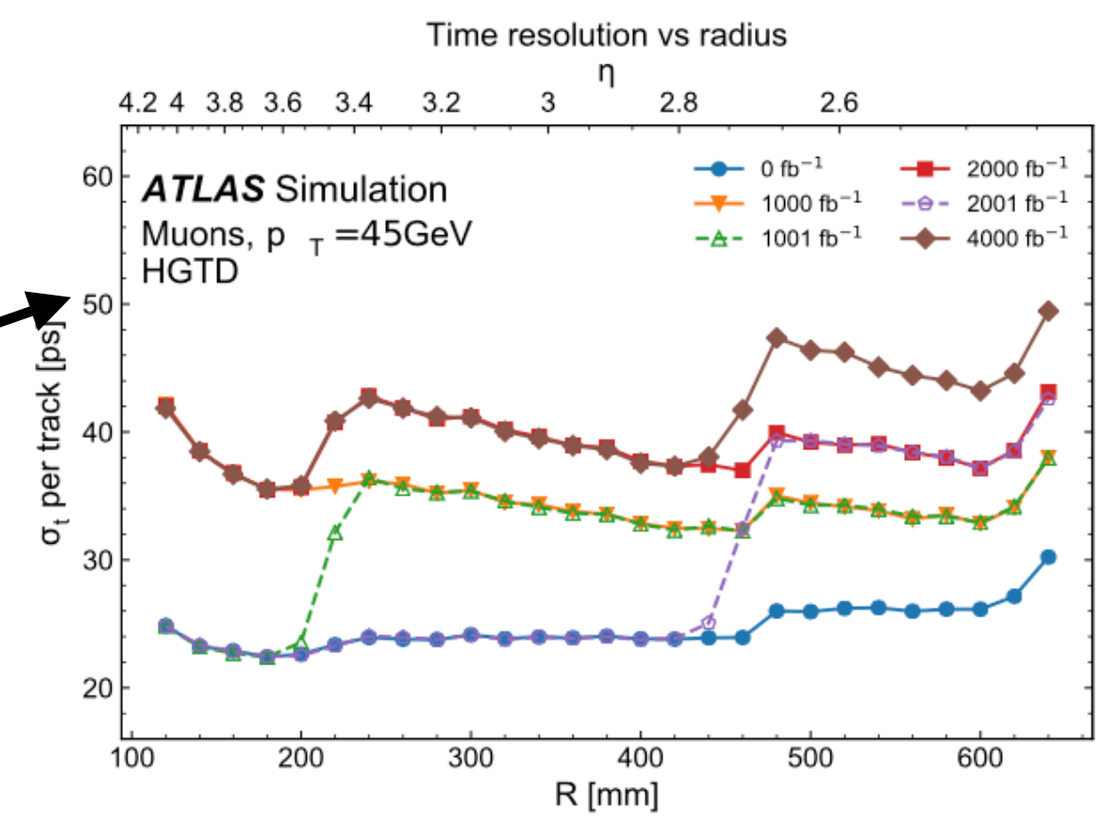


- LGADS (Low-Gain Avalanche Detectors) located on cryostat wall between barrel and endcap calorimeters $2.4 < |\eta| < 4.0$



ATLAS-TDR-031

- Timing information enhances pileup jet rejection combined with ITk

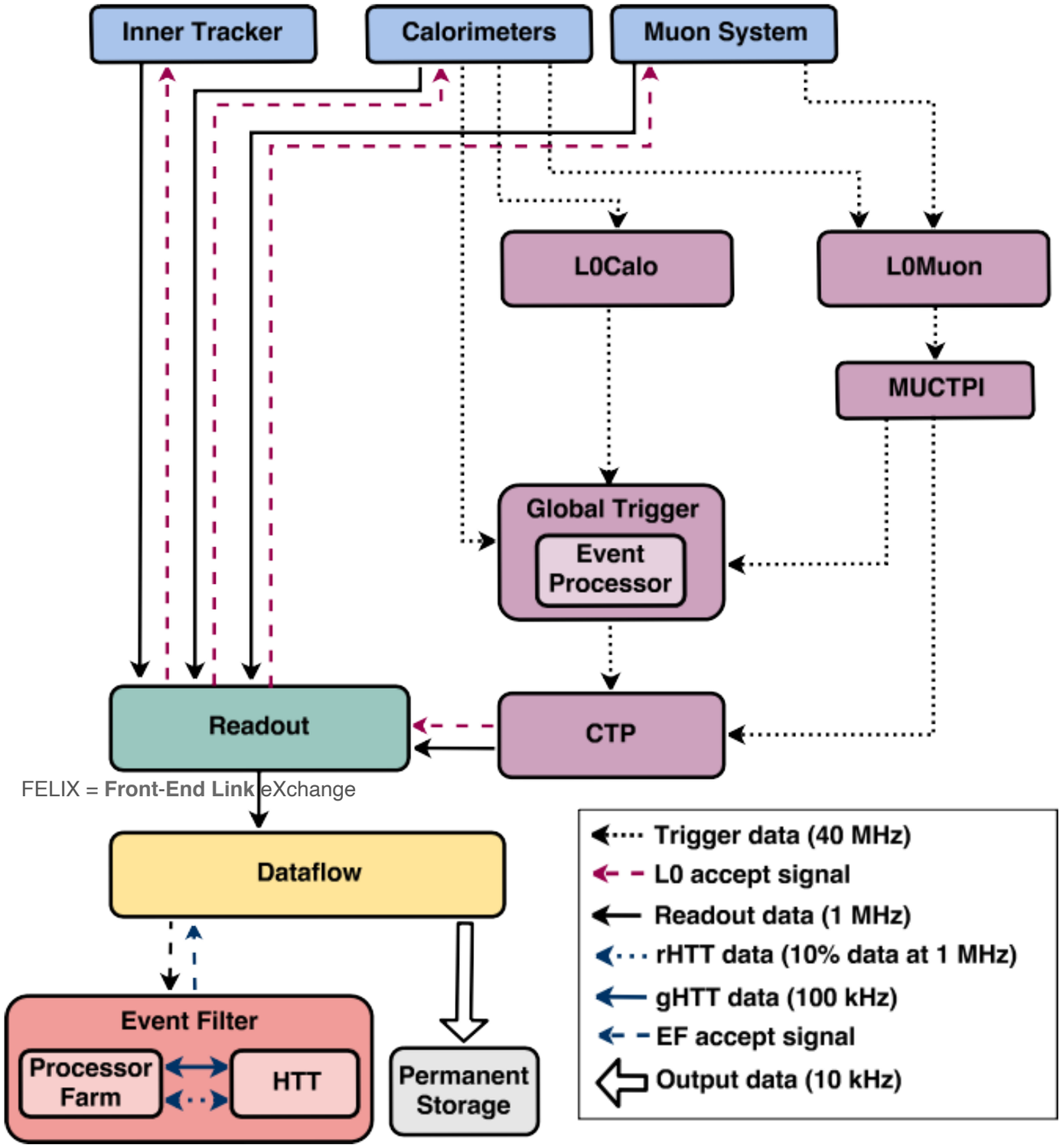


- Req. resolution: 30-50 ps/track

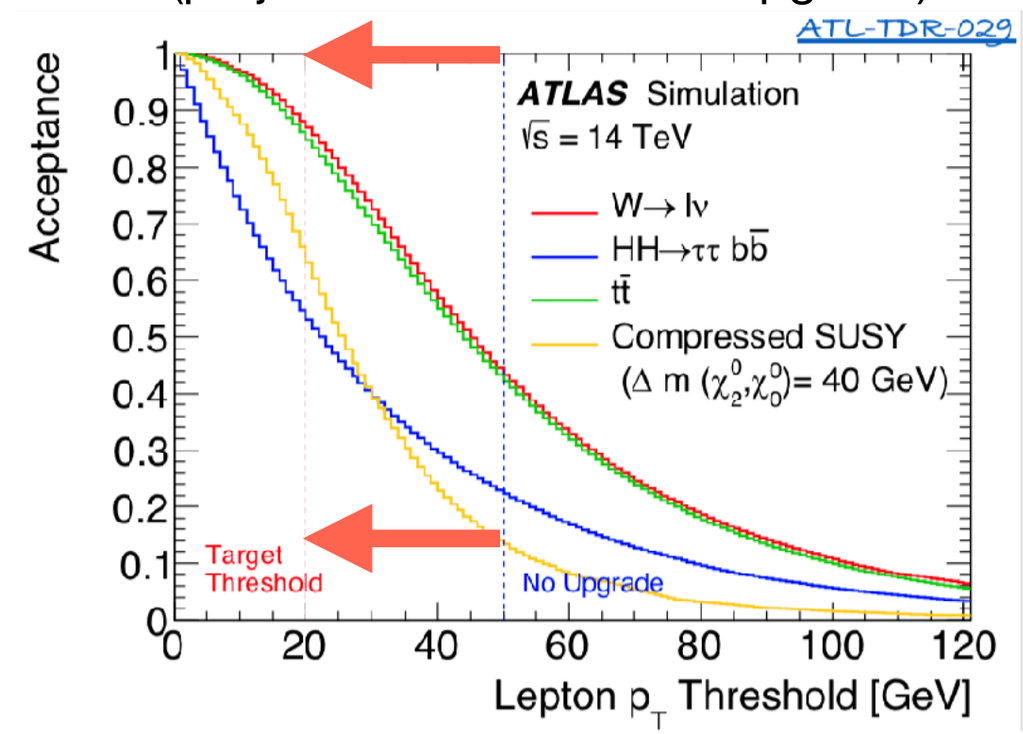
- Constraints: thickness < 12.5 cm, Fluence 2.5+15n/cm2, TID 2 MGy

See talk by C. Ohm

Phase-2 Trigger Upgrade



The Phase-II TDAQ upgrade enables lowering the single lepton Level-0 threshold to 20 GeV from 50 GeV, (projected threshold w/o upgrade).



Trigger in 3 systems:

1) **Level-0 Trigger**
2) **Readout & Dataflow**
3) **Event Filter**

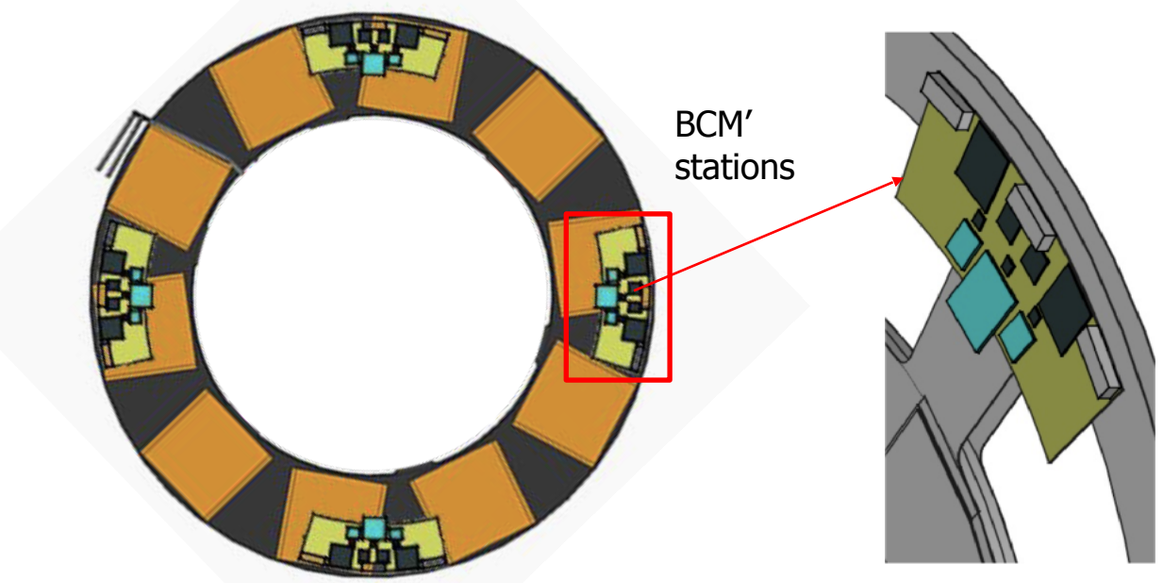
1) L0Trigger Data from the detectors @ 40 MHz
Latency: within **10 μs** (2.5 μs today)

2) Complete event-data then transmitted through Readout & Dataflow into Event-Filter @ **1 MHz** (100 kHz today)

3) Event Filter performs event reconstruction & selection + info from HW-based tracking (HTT).
Final selected events (5 vs 2 MB today) then transferred to permanent storage @ **10 kHz**
(1 kHz today)

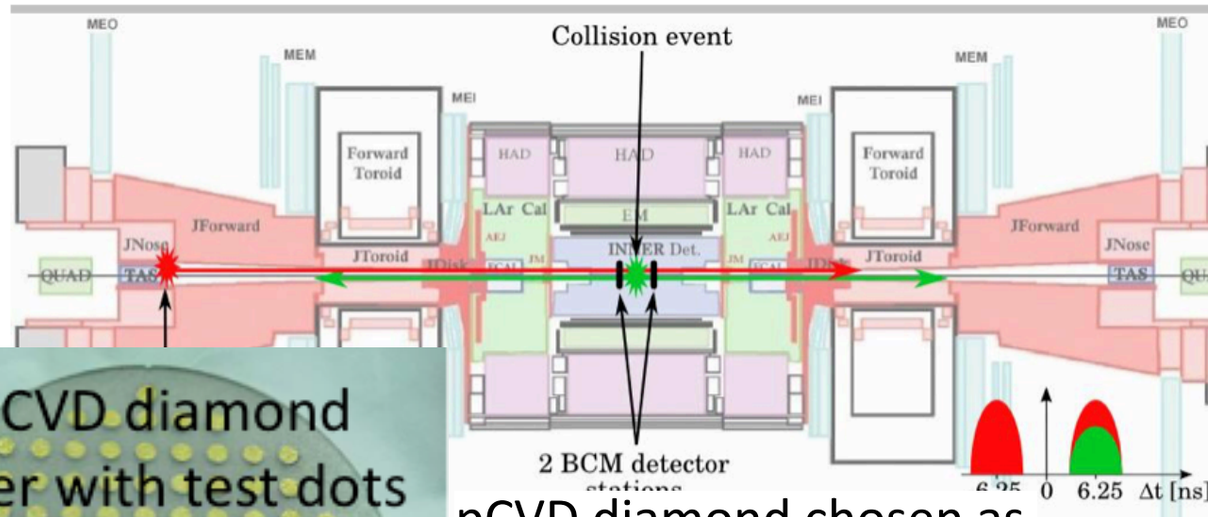
Luminosity and Beam Protection

- ✓ **1. Beam Conditions Monitor Upgrade (BCM')**
- ✓ Provides Fast (bunch-by-bunch) safety system for ATLAS, Luminosity measurement and Background monitoring
- ✓ Inner Pixel system: Separate ring; 4 stations per side with abort, lumi BCM' and BLM.



BCM TOF concept

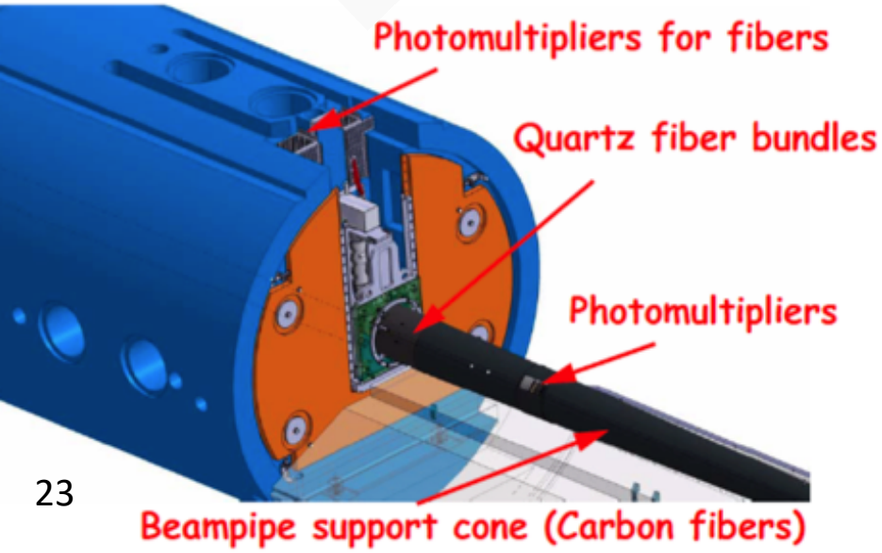
- Collisions: in-time
- Background: out-of-time



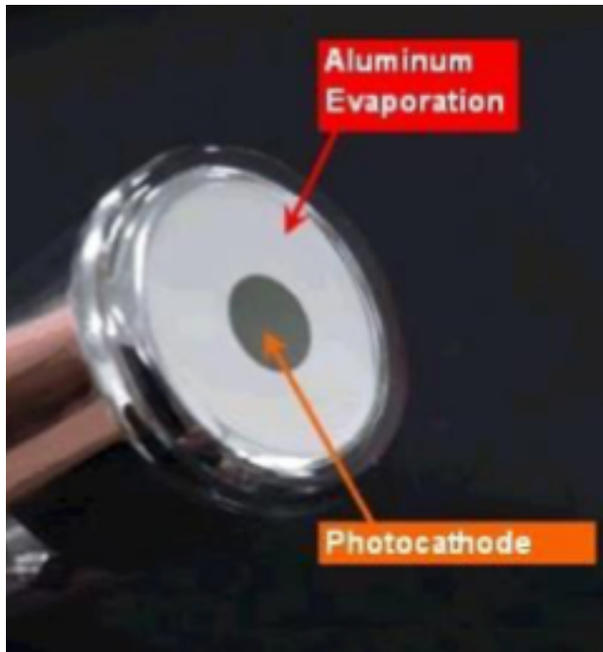
pCVD diamond chosen as sensor material

- robustness (no cooling), low *C*, negligible *I*, fast signal, radiation hard

2. LUCID (LUminosity Cherenkov Integrating Detector) Upgrade

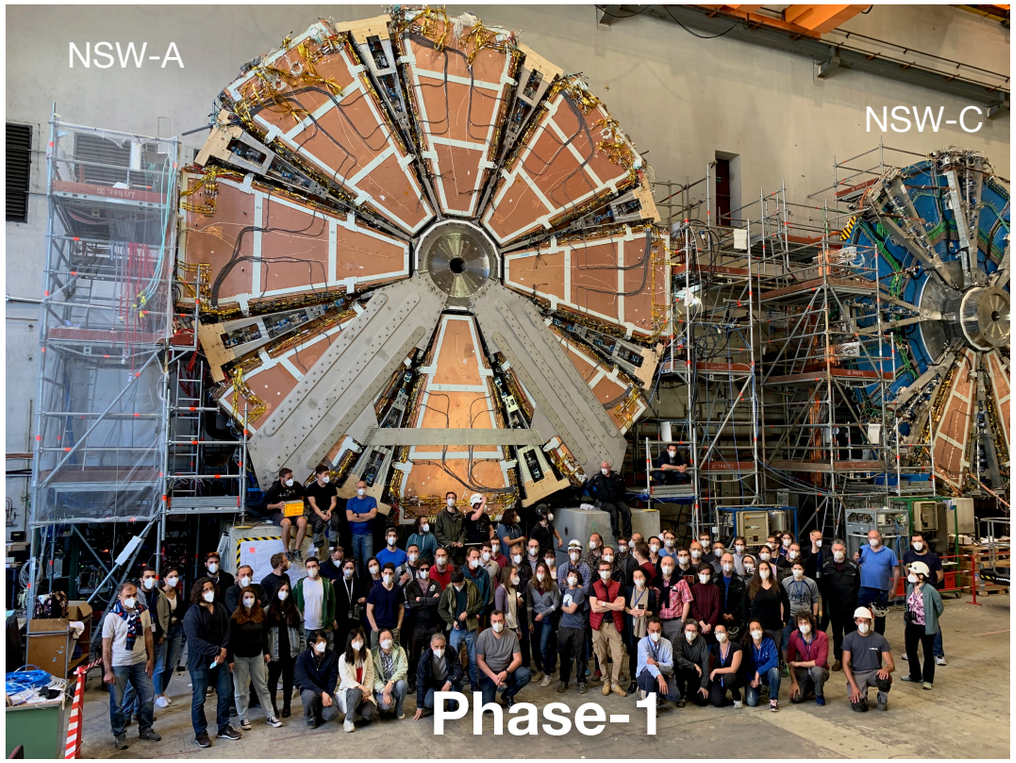


- Replace all PMTs with MOD-PMTs (modified: Aluminum ring deposited on inside of windows)
- Reduce PMT acceptance
  -> avoid saturation @ high μ
- Move detectors to region w. lower flux



Conclusion and Outlook

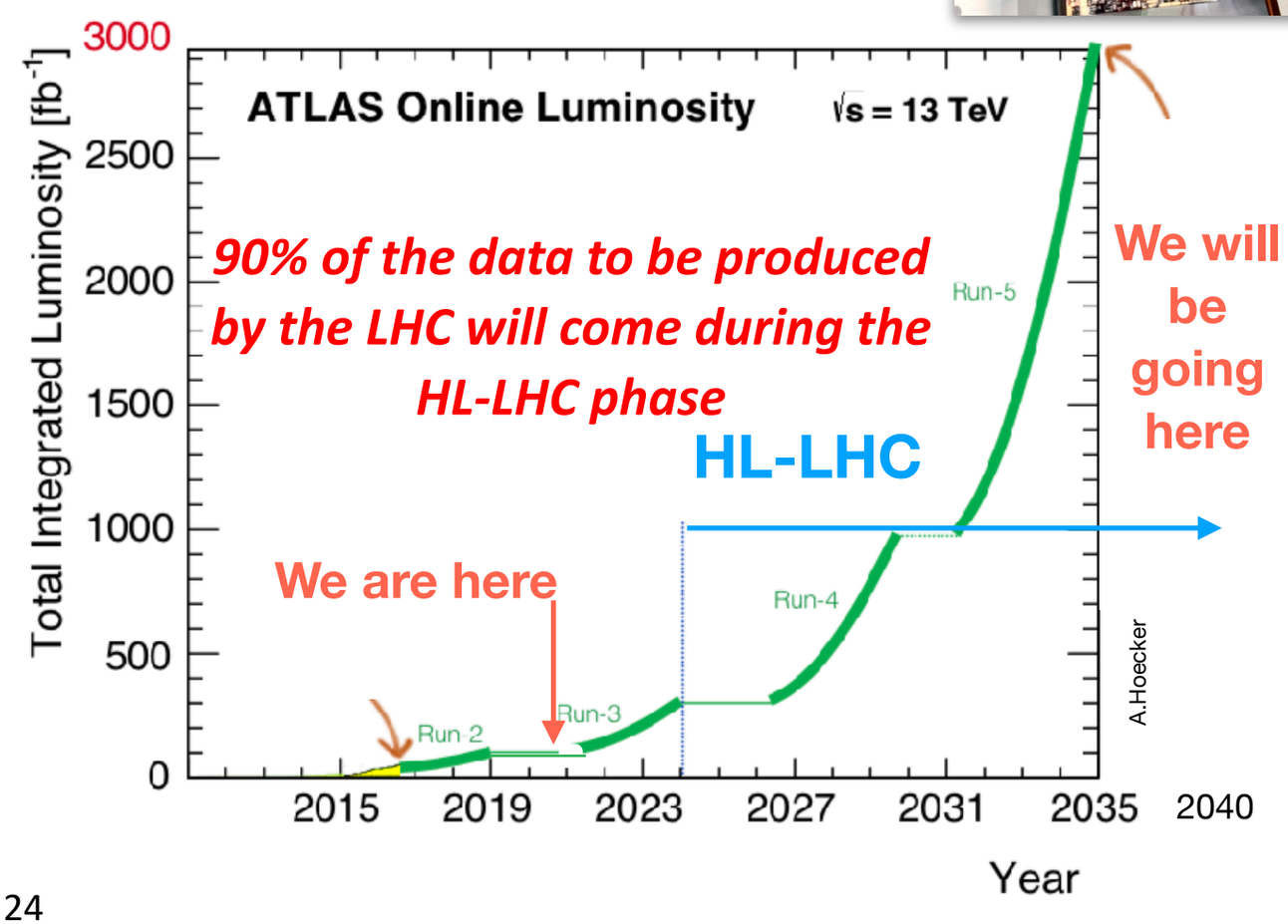
See presentations M. Donadelli, O. Solovyanov



Phase-2

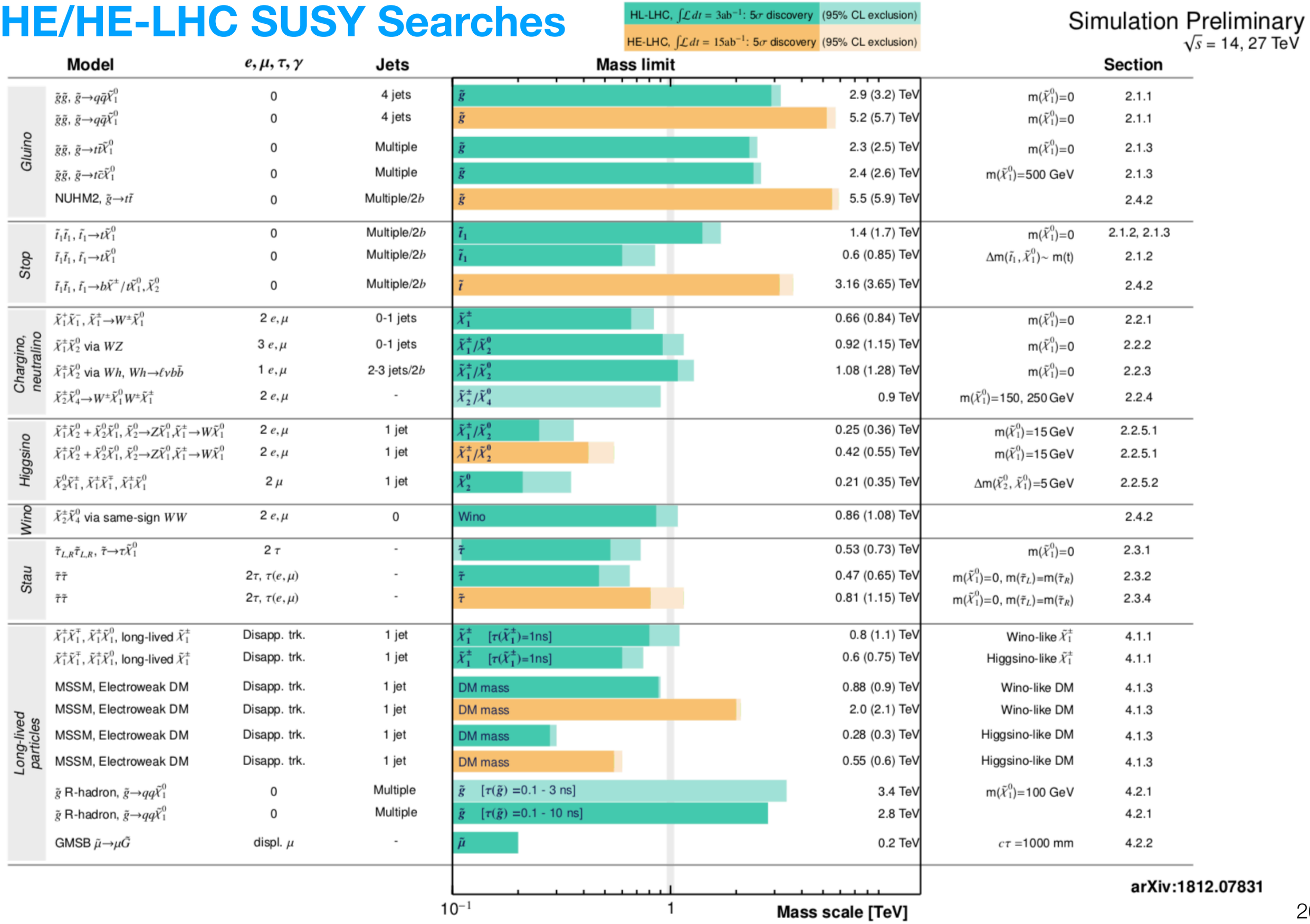
ITk Barrel stave

- **ATLAS Upgrades well underway (despite many challenges of covid)**
- **Phase 1 - Installation & Commissioning**
- **Phase 2 - Prototypes**
  —> Preproduction
  —> Construction
- **Will meet challenges of HL-LHC**
- **Open range of physics possibilities**



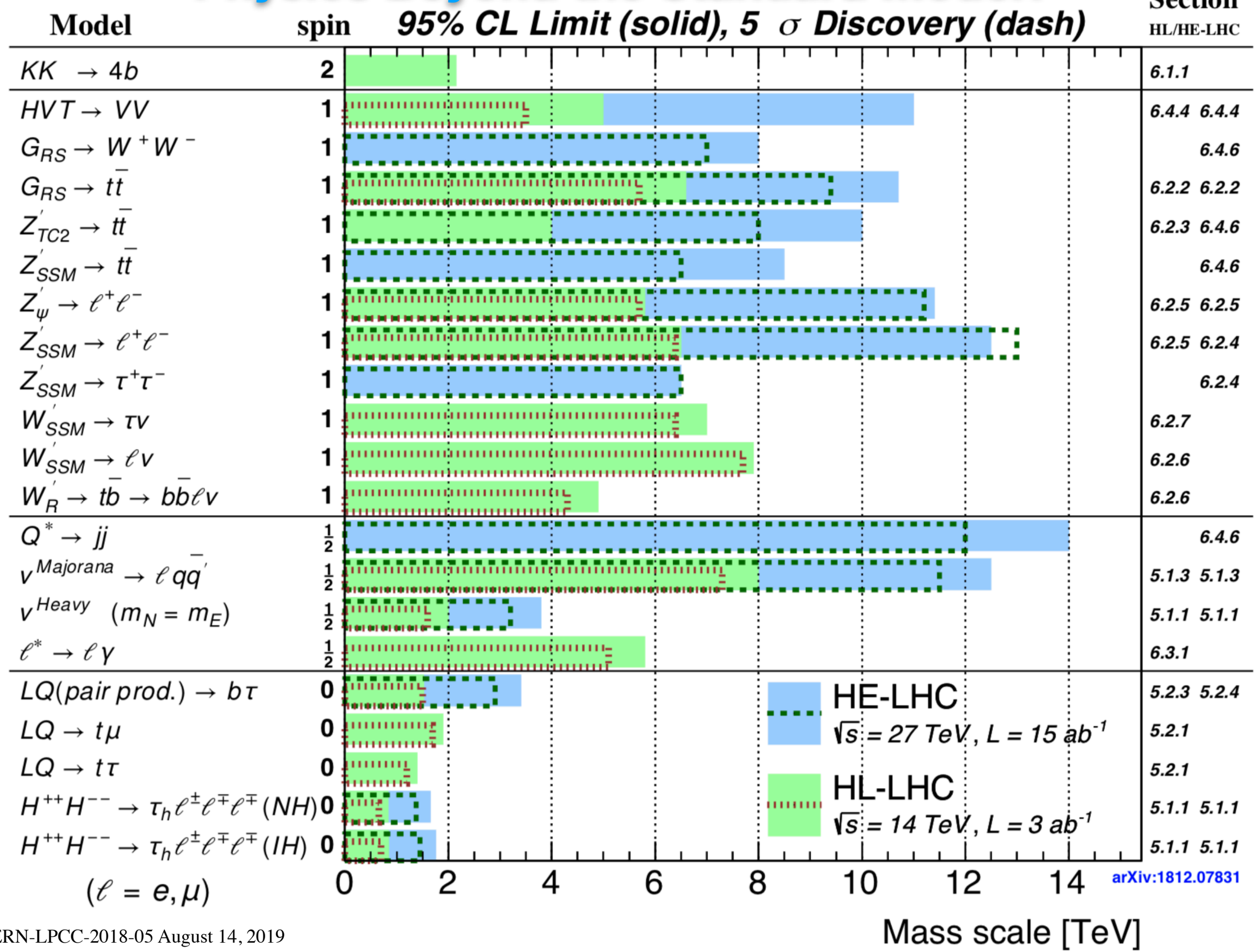
See ATLAS Upgrade Presentations at LHCP’21: M. Donadelli, G. Myers, O.Solovyanov, A. Aboulhorma, R.P, Mckenzie, P.M. Suarez, P. Atmasiddha, A.E. Moussaouy, S. Tzanos, E.K. Nkadimeng, M. Perganti

HE/HE-LHC SUSY Searches

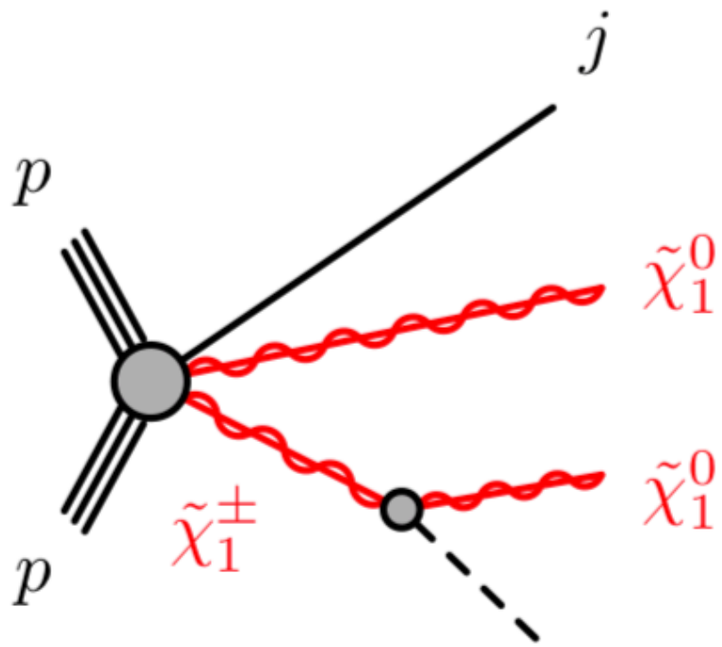


HL-LHC will probe gluino masses up to 3.2 TeV, R-parity conserving scenarios. This is about 0.8 – 1 TeV above the Run-2 $\tilde{g}$ mass reach for 80 fb^{-1}. Top squarks can be discovered (excluded) up to masses of 1.25 (1.7) TeV for massless neutralinos, *i.e.* $\Delta m(\tilde{t}, \tilde{\chi}^0) \gg m_t$, under realistic uncertainty assumptions. This extends by about 700 GeV the reach of Run-2 for 80 fb^{-1}. The reach in m degrades for larger $\tilde{\chi}^0$ masses. If $\Delta m(\tilde{t}, \tilde{\chi}^0) \sim m_t$, the discovery (exclusion) reach is 650 (850) GeV.

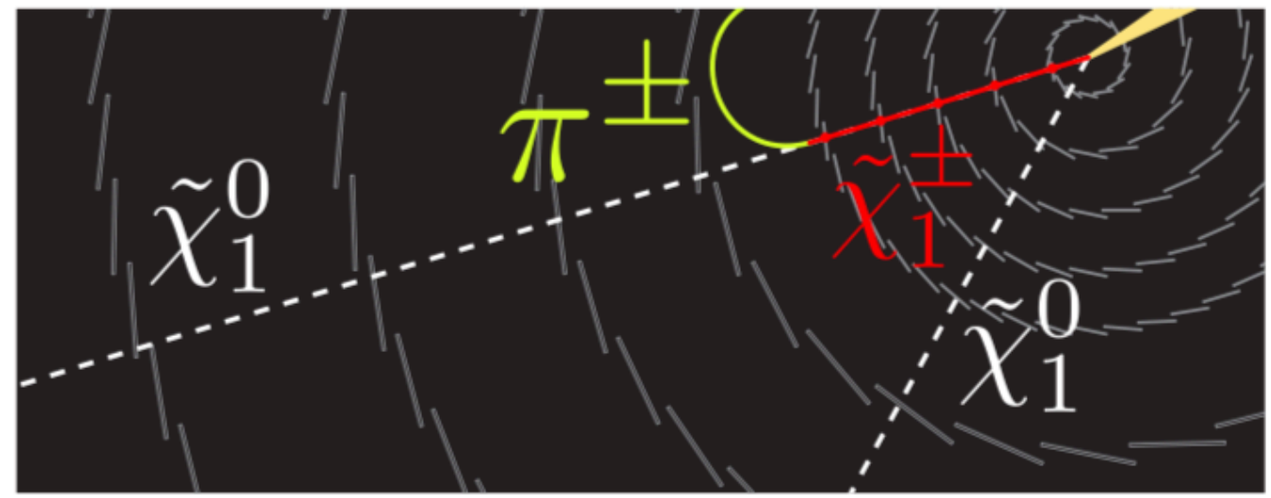
Physics Beyond the Standard Model?

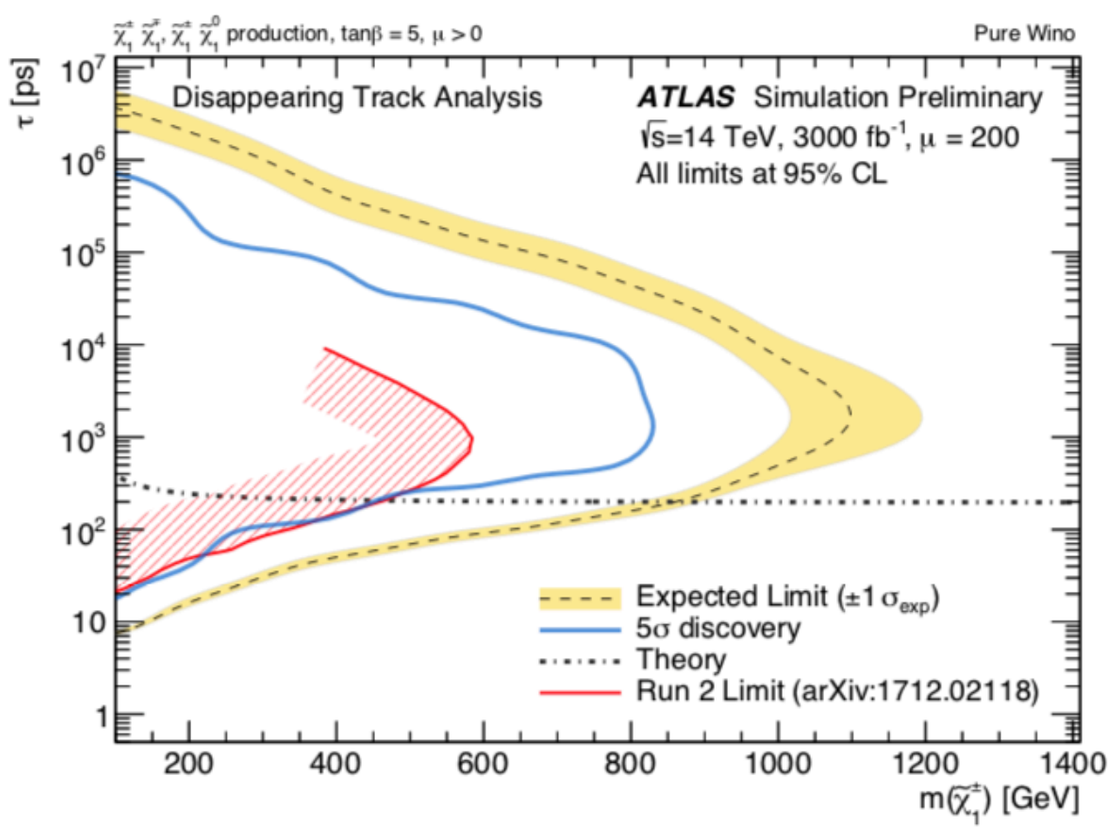


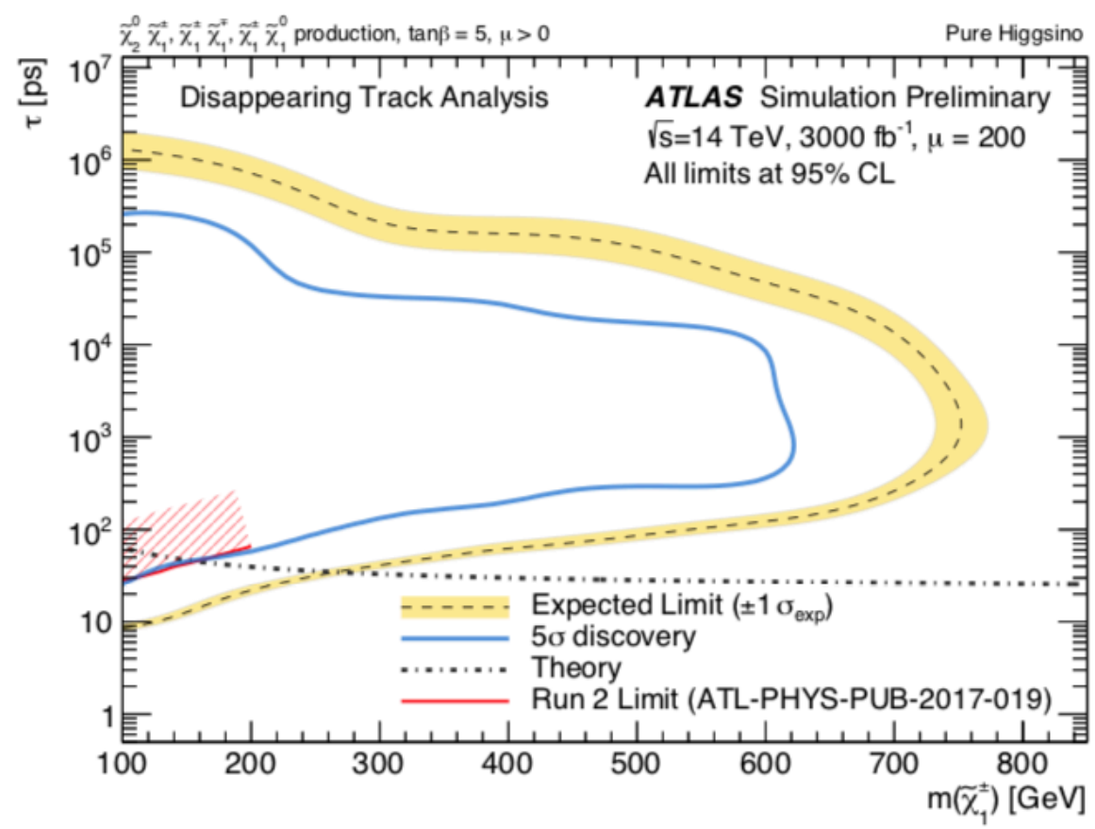
Long-Lived Particles?



“Disappearing track"

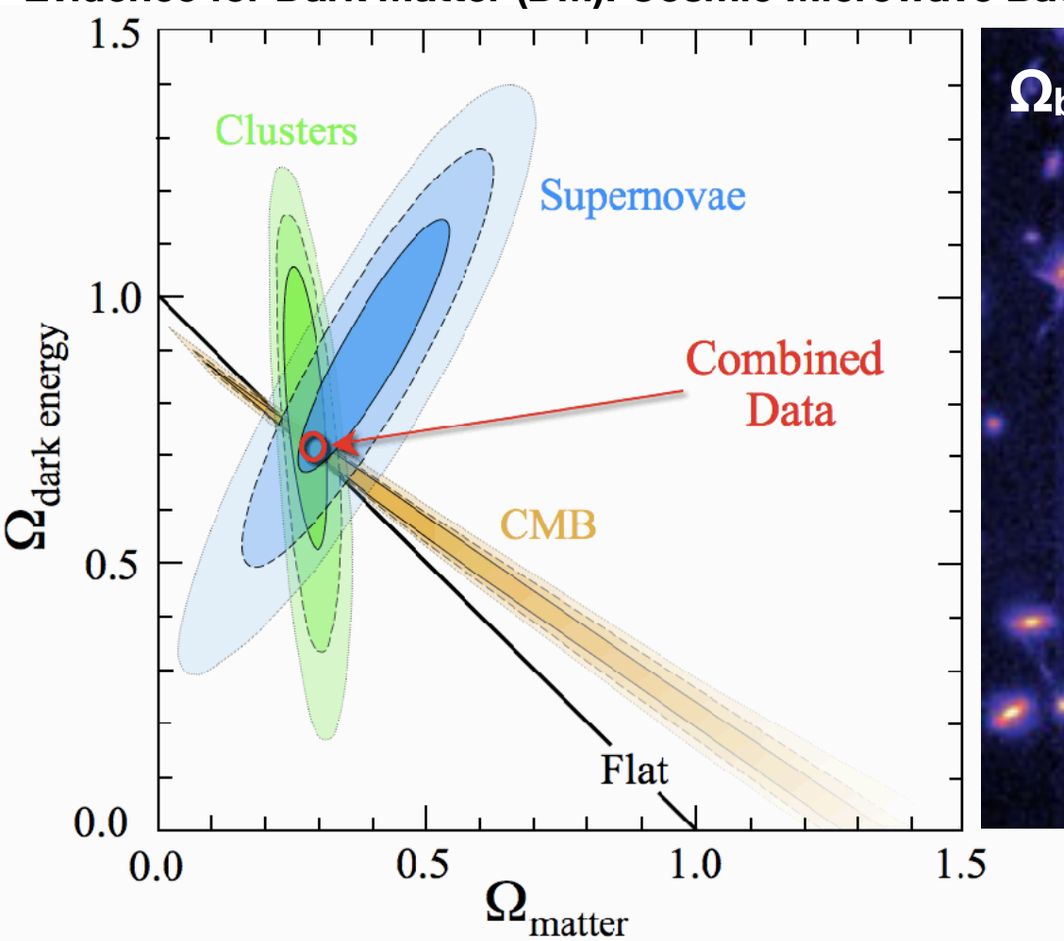


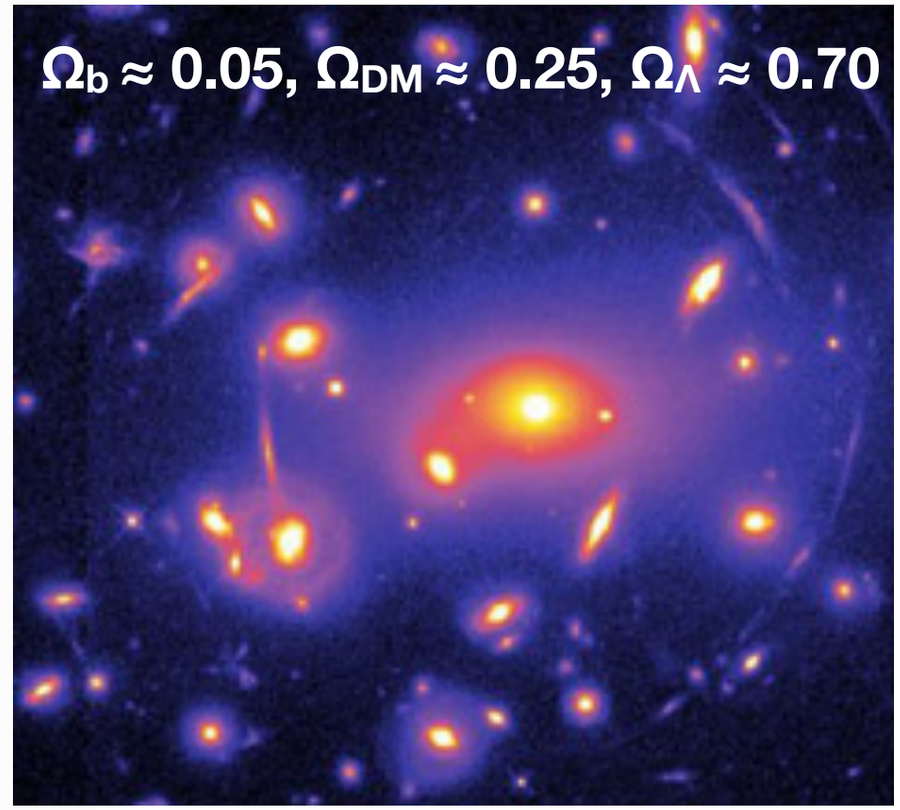


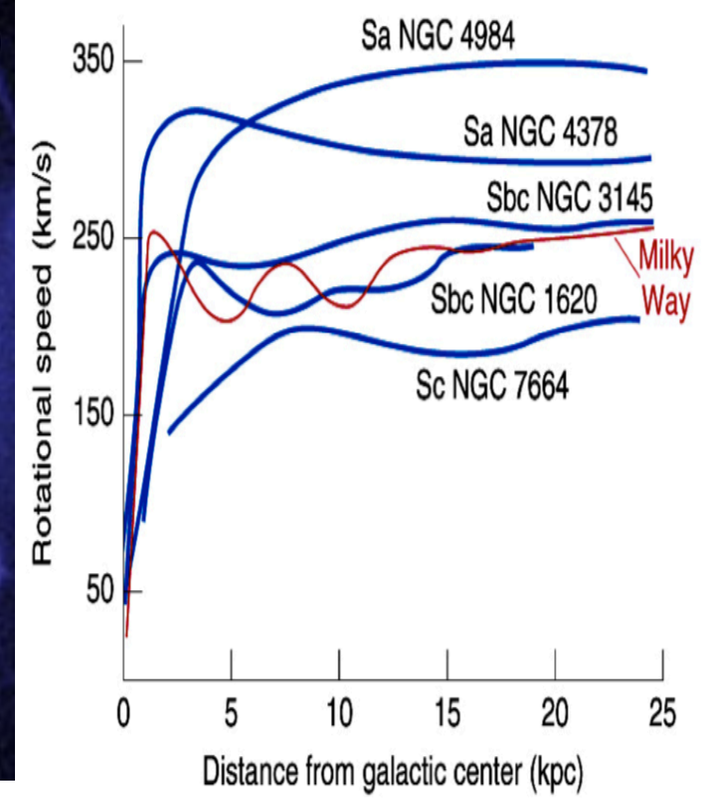


Detect Dark Matter?

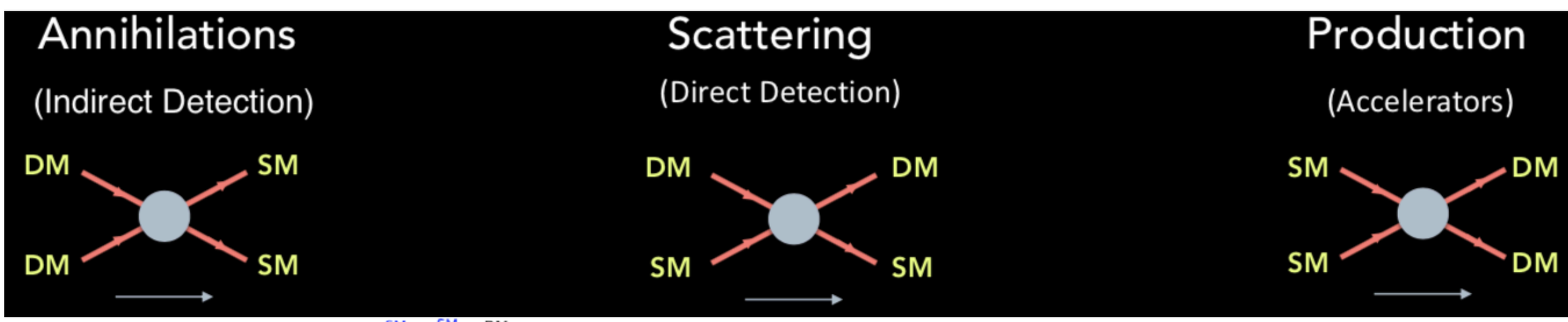
Evidence for Dark Matter (DM): Cosmic Microwave Background, gravitational lensing, galaxy rotation curves, large scale structure…

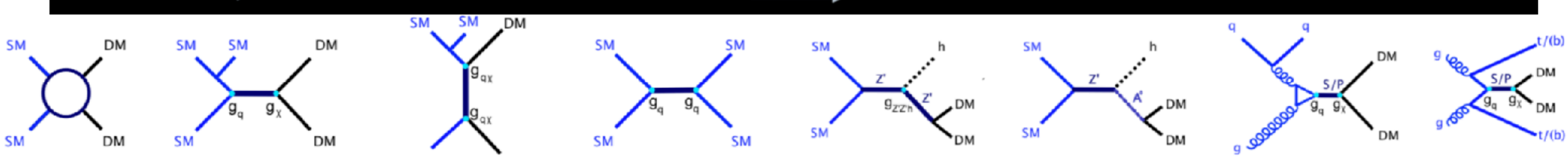






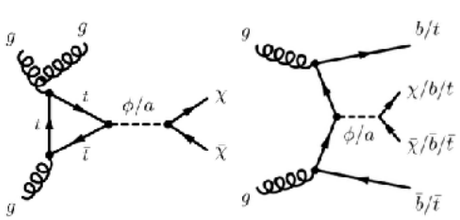
Methods of Detection:





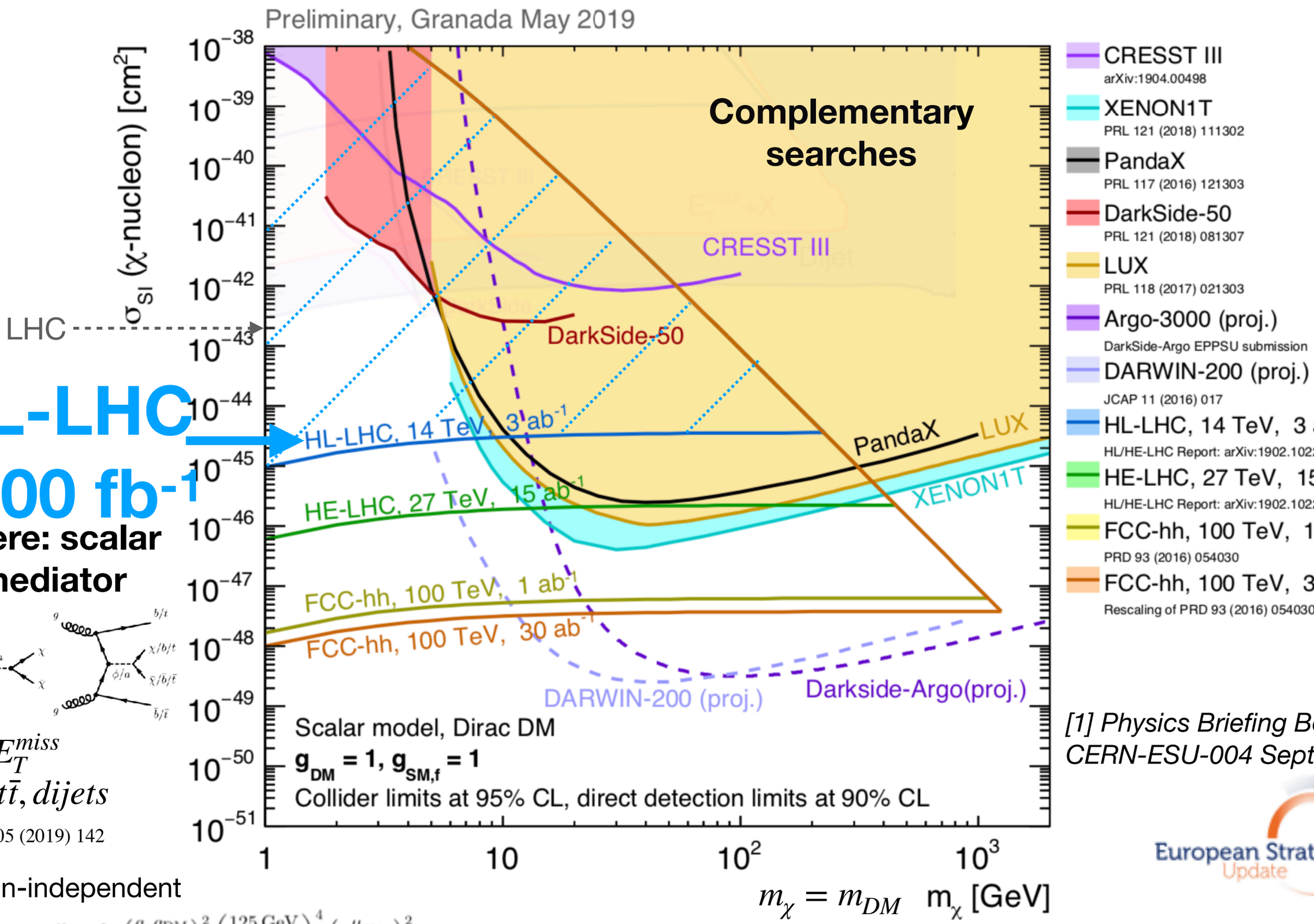
Dark Matter Prospects

HL-LHC
3000 fb^{-1}
- here: scalar mediator



$X + E_T^{miss}$
$X = t\bar{t}, dijets$

JHEP 1905 (2019) 142



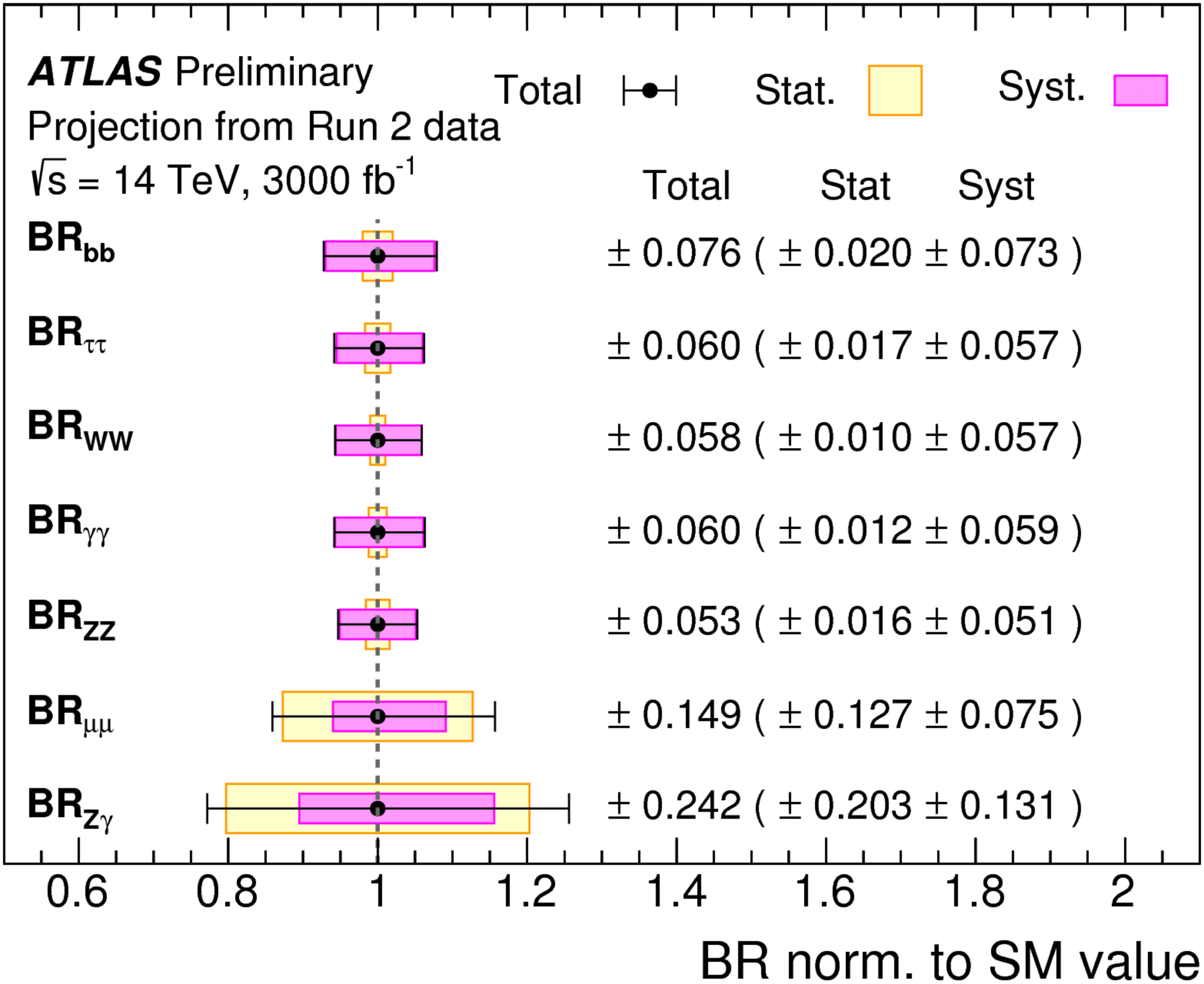
[1] Physics Briefing Book CERN-ESU-004 Sept.2019

European Strategy Update

SI=spin-independent

$$\sigma_{SI} \simeq 6.9 \times 10^{-43}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{DM}}{1}\right)^2 \left(\frac{125\ \mathrm{GeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2 .$$

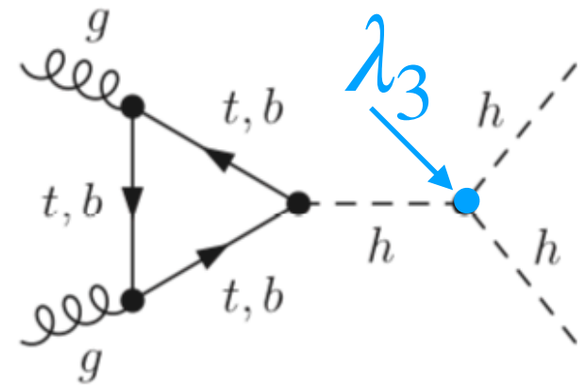
Higgs Branching Ratio Projections



Probe Higgs Self Coupling with 3000 fb^{-1}

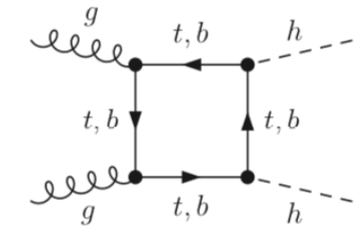
$$V = \frac{m_h^2}{2}h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4}h^4$$

$$\lambda_3 = \lambda_4 = m_h^2/(2v^2)$$

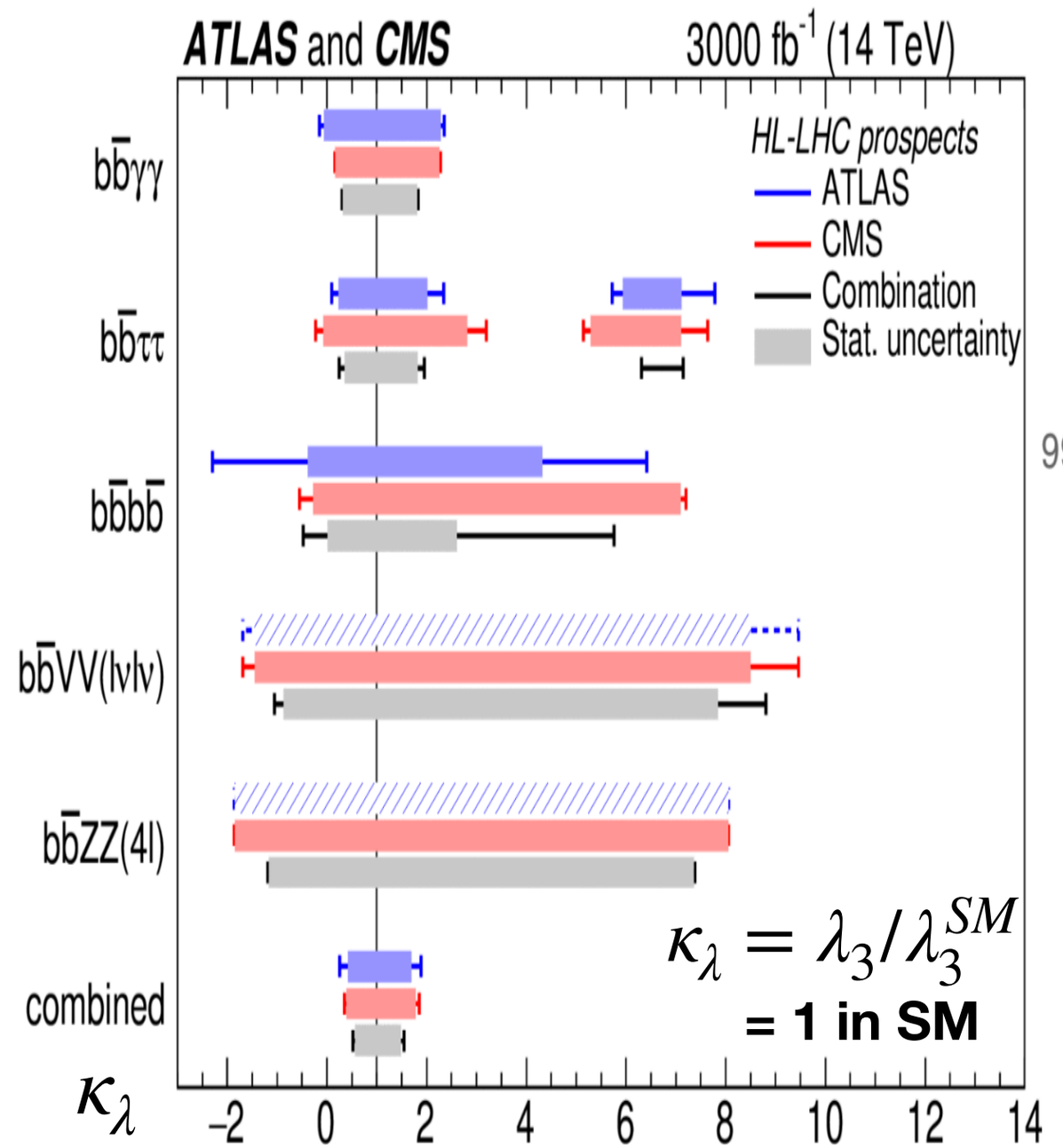


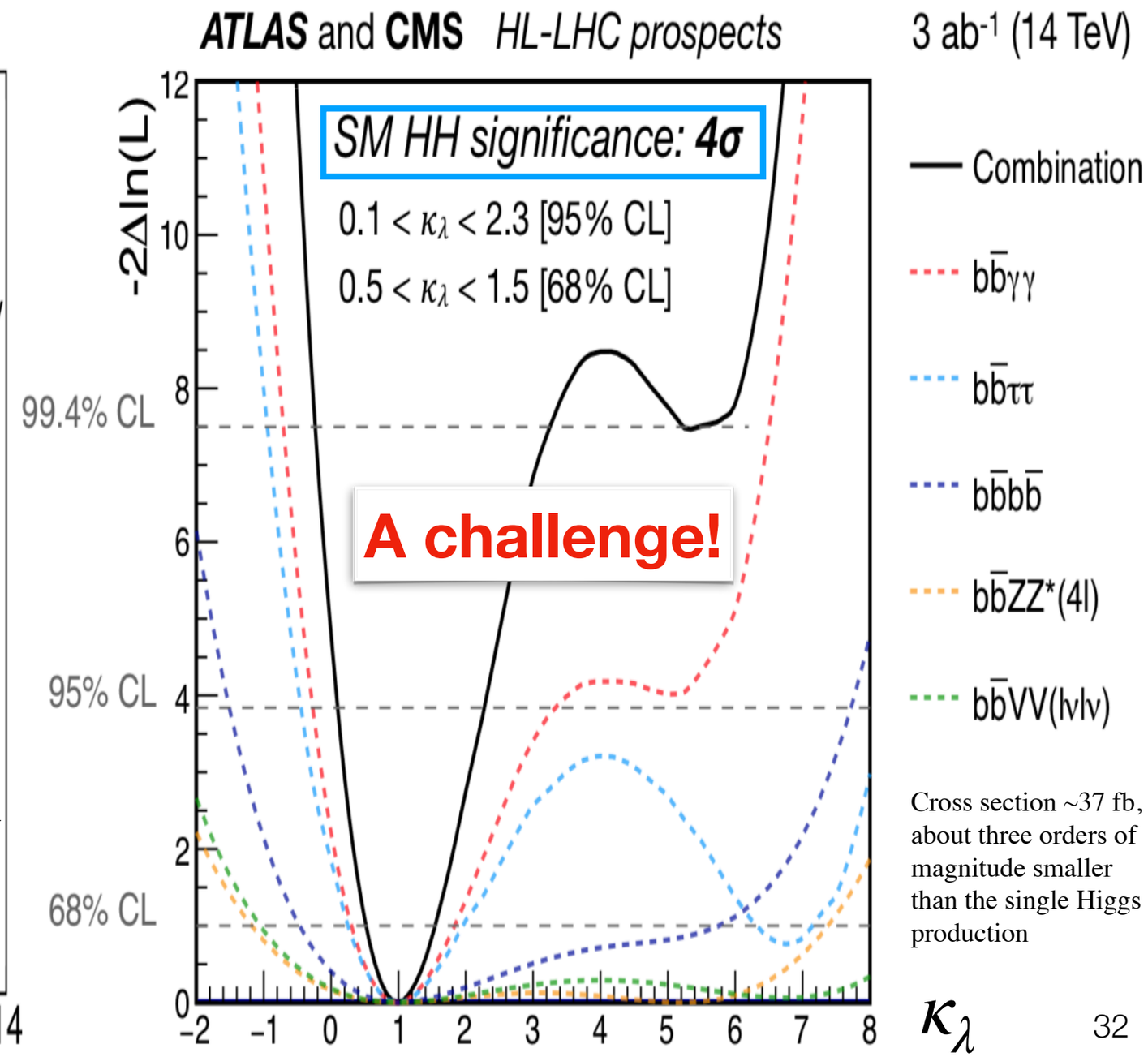
Di-Higgs

σ~ 40 fb @ 14TeV
O(100k) HH produced



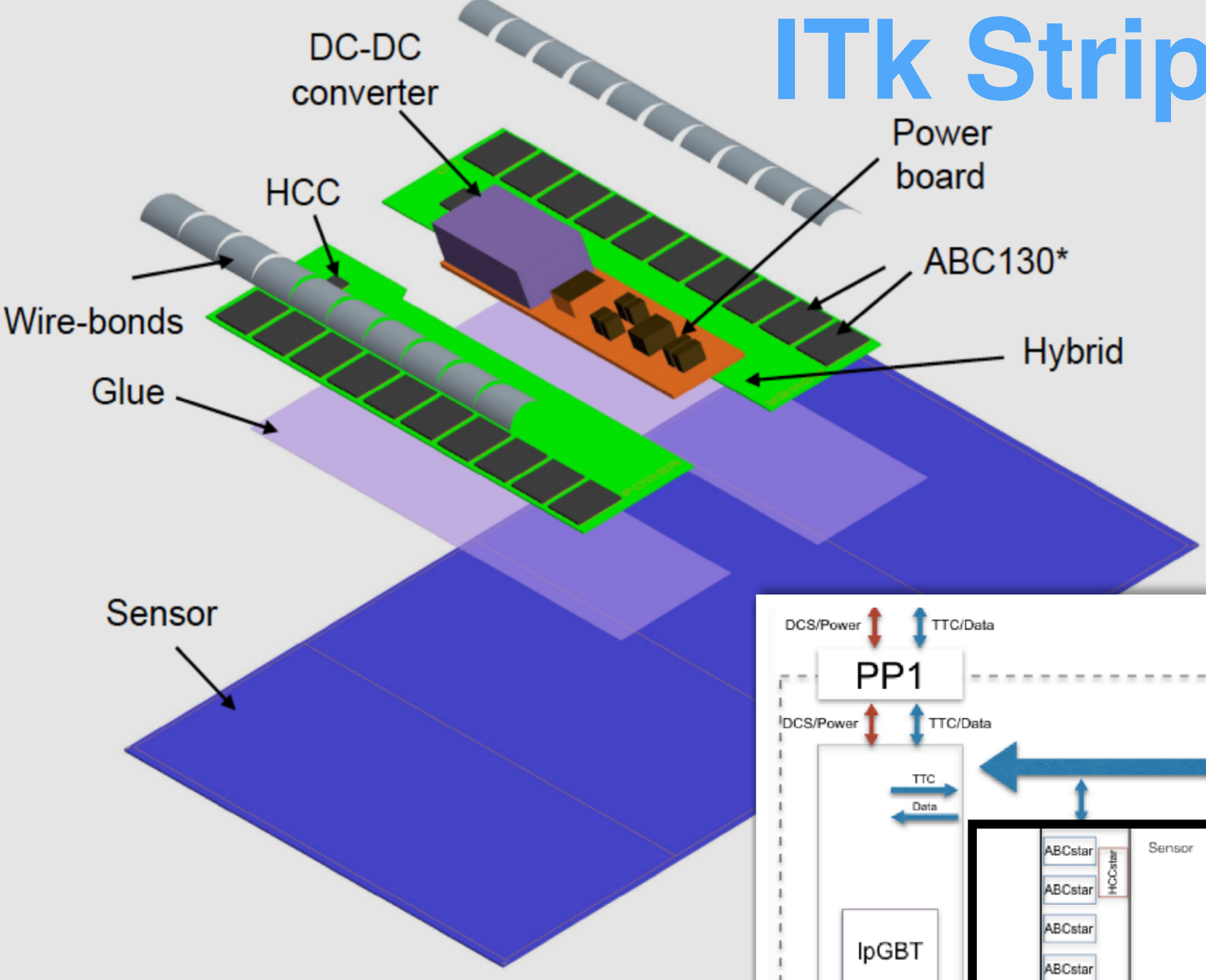
destructive interference





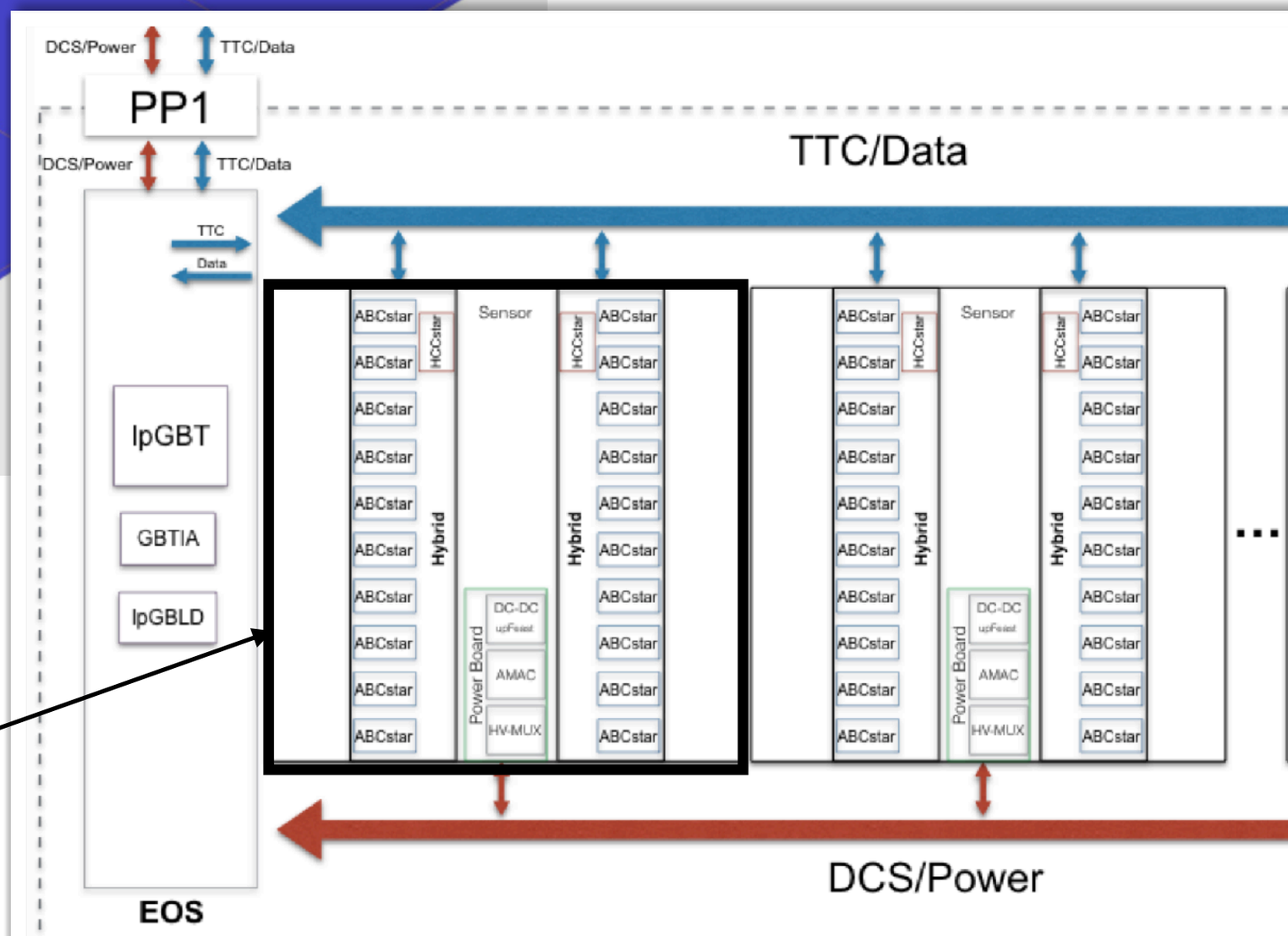
Cross section ~37 fb, about three orders of magnitude smaller than the single Higgs production

ITk Strips Module



Front-End (FE) **ASICs:** ABC + HCC

Hybrid: PCB containing ASICs reading out silicon microstrip sensor



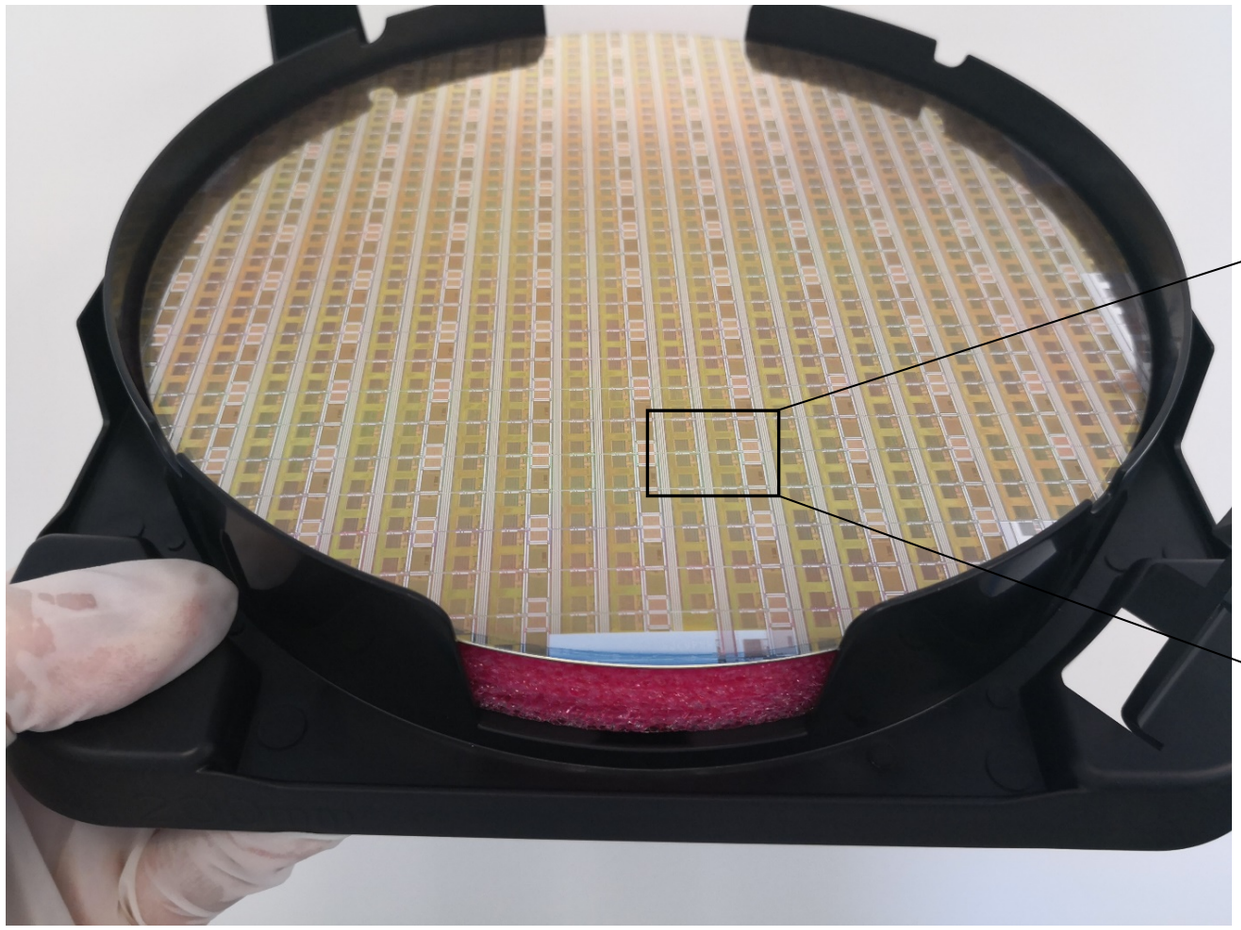
Sensors: Silicon microstrip sensors, 10x10cm, ~300 μm thick, 75 μm pitch

Module = hybrid + sensor

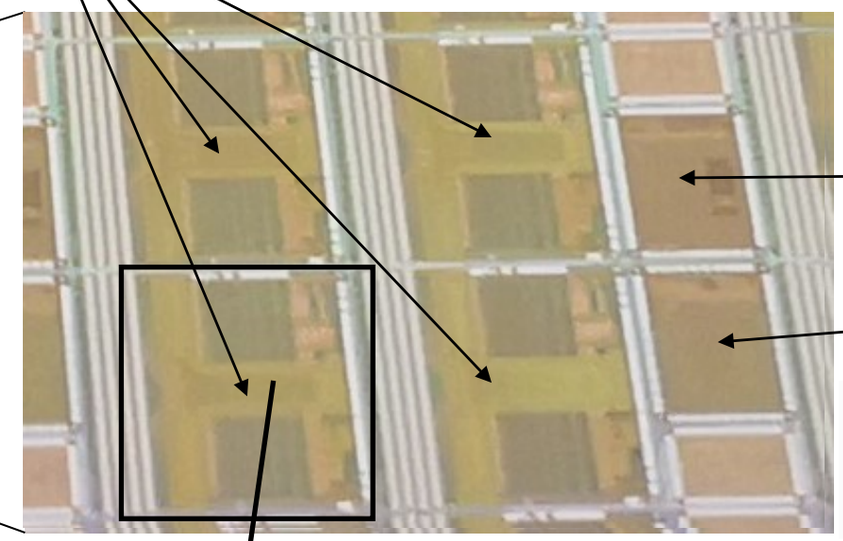
groups of modules -> barrel stave or EC "petal"

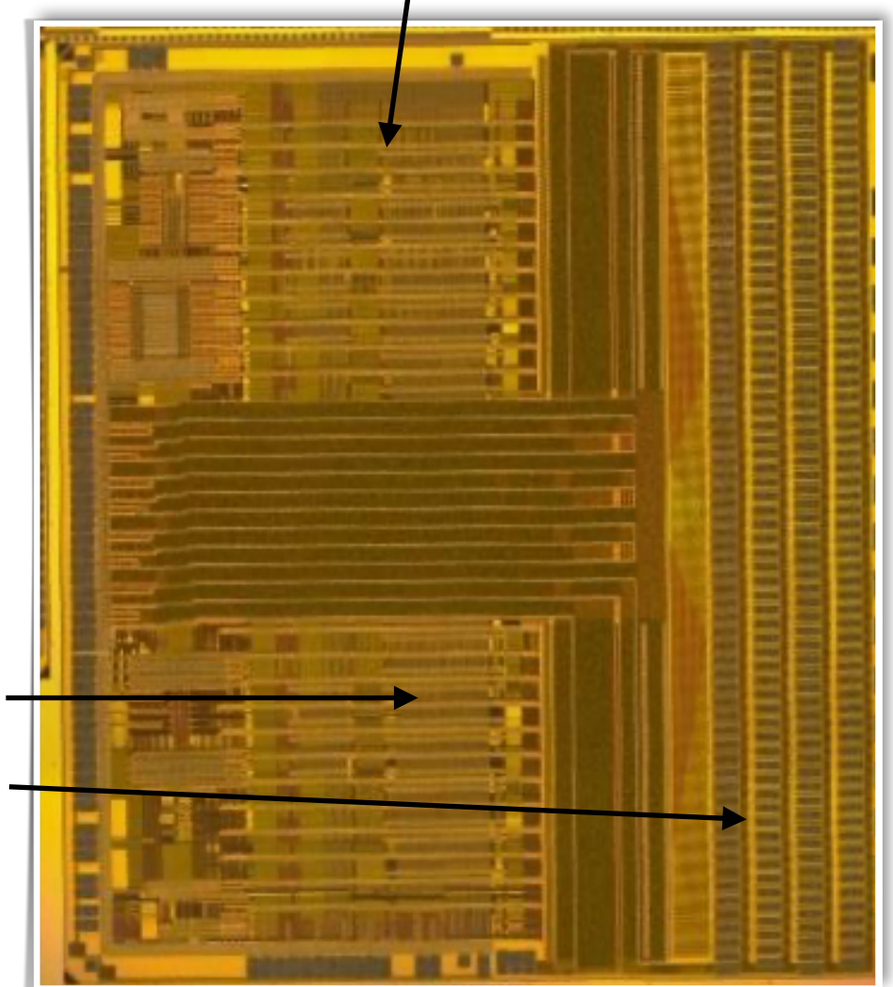
ITk Strips Front-End ASICs

Technology: GF (ex IBM) 130nm CMOS8RF technology

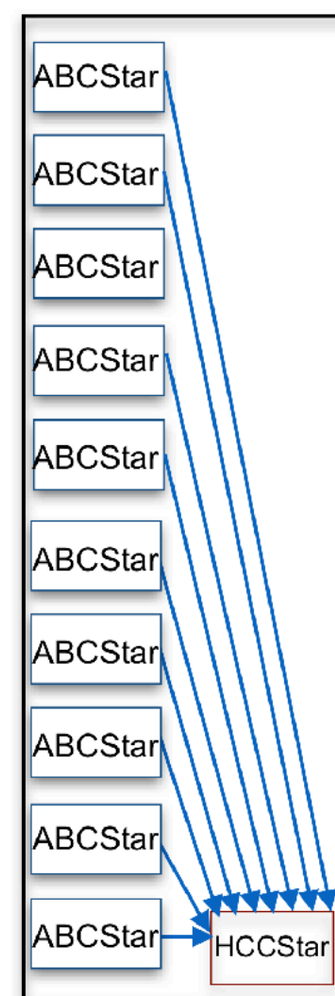


Wafer with pre-production ASICs



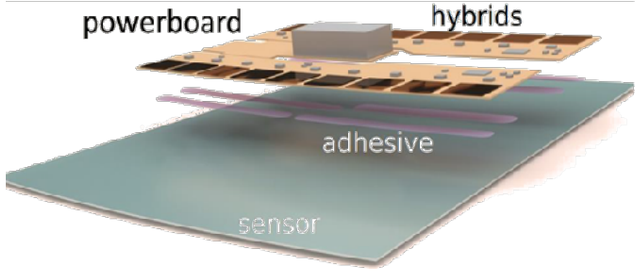


ABCStar (ATLAS Binary Chip) die showing I/O and 4 rows of front-end pads



Star architecture

Strip Sensors



- n-in-p float-zone sensors with p-stop isolation, ~320 µm thickness
- 8 different sensor types (2 barrel, 6 EC)

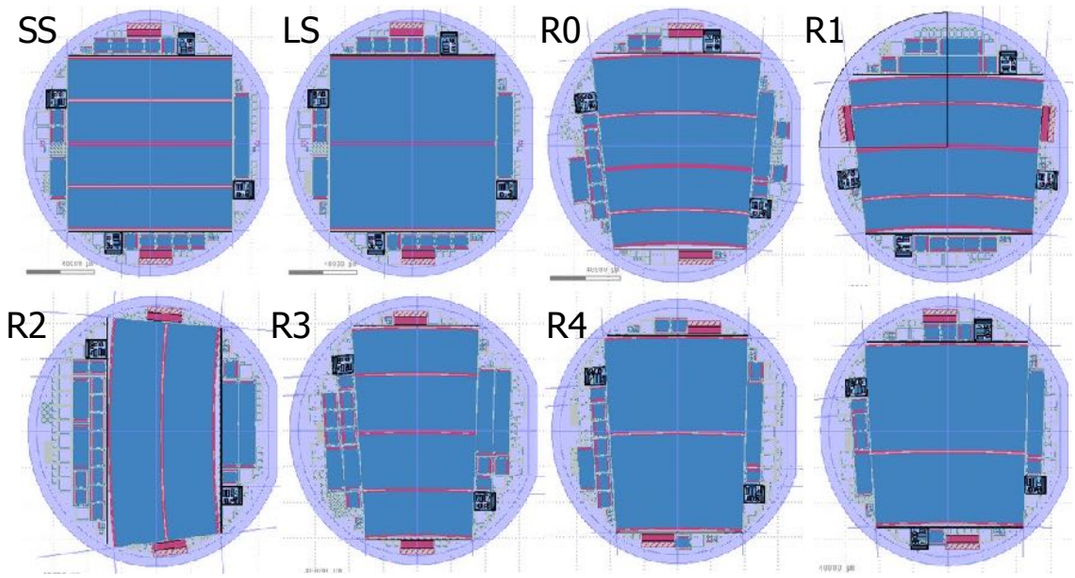
✓ Sensor produced by Hamamatsu.

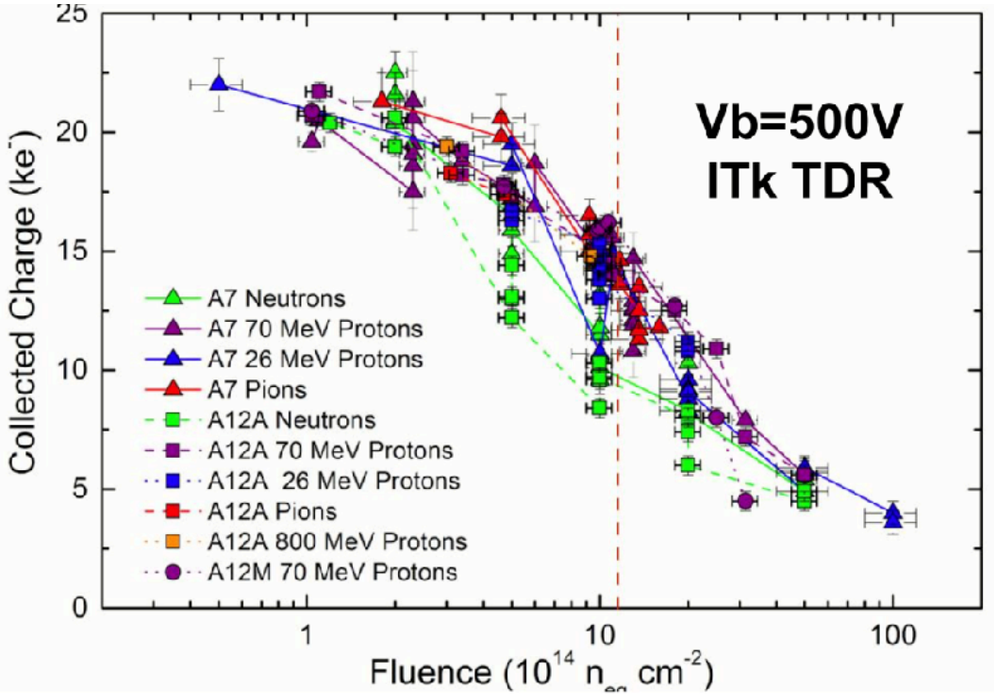
✓ All pre-production has been delivered including all EC sensors.

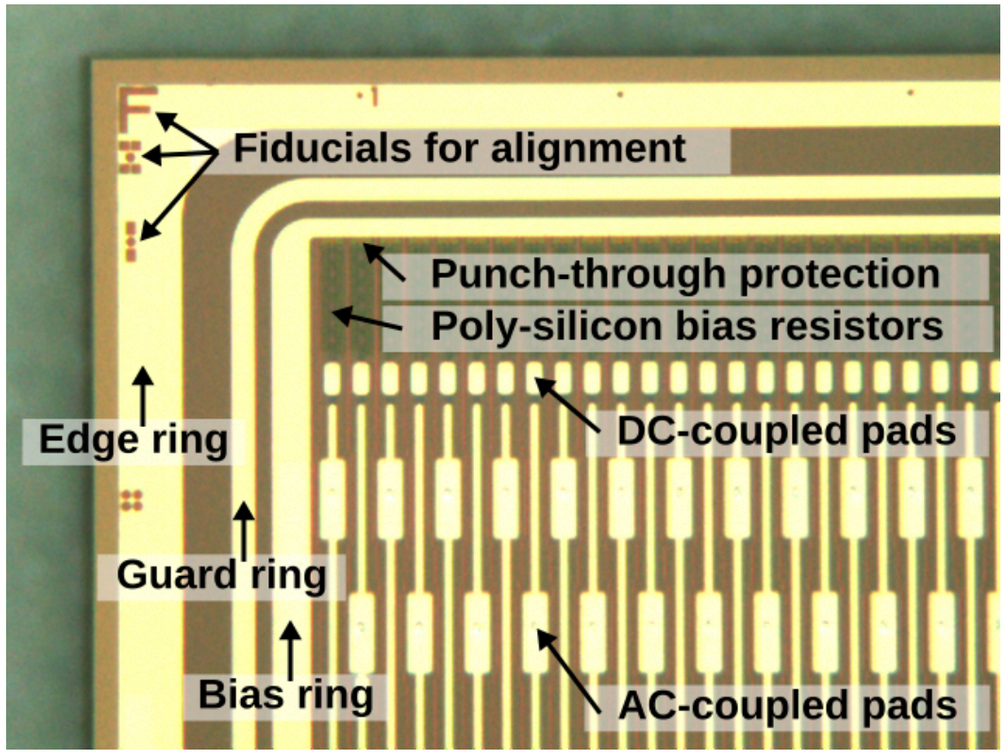
- Mini sensors and other test structures on each wafer. First test results are as expected from new Test Chip structures

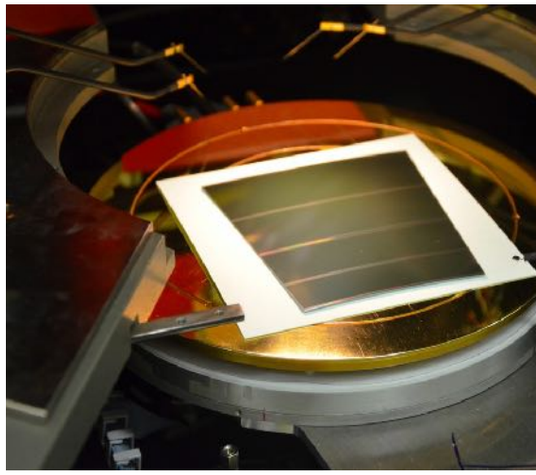
✓ Qualification of sites on going.

8 pre-production masks









Charge collection efficiency vs fluence

Table 2.9: The maximal 1 MeV neutron equivalent fluences and total ionising dose for different parts of the Pixel Detector, for the baseline replacement scenario for the inner section. All values have been multiplied by a safety factor of 1.5.

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

*** Updated in 2020: 3.9 -> 3.4 cm, Fluence -> 188 E+14 neq/cm**2**

Pixel 3D sensors

3D sensor technology has matured in the last 20 years and is now becoming a standard choice where extreme radiation hardness is critical. In ATLAS, part of the Insertable B-Layer (IBL) relies on 3D pixel sensors.

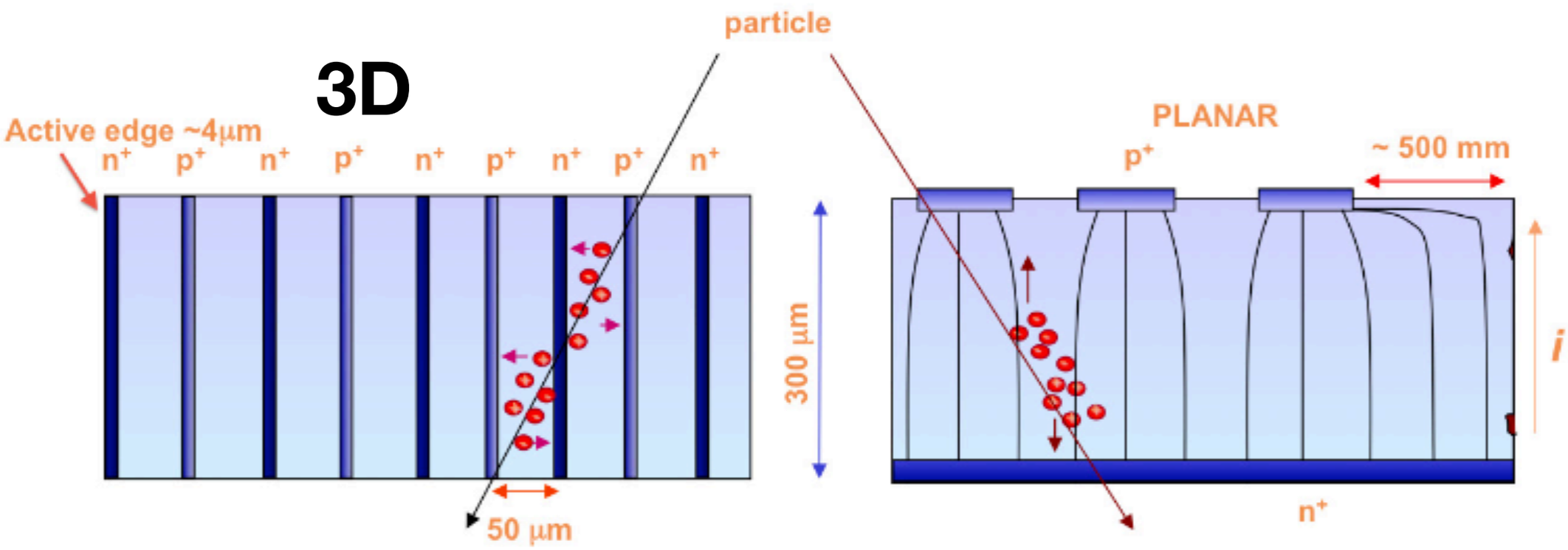
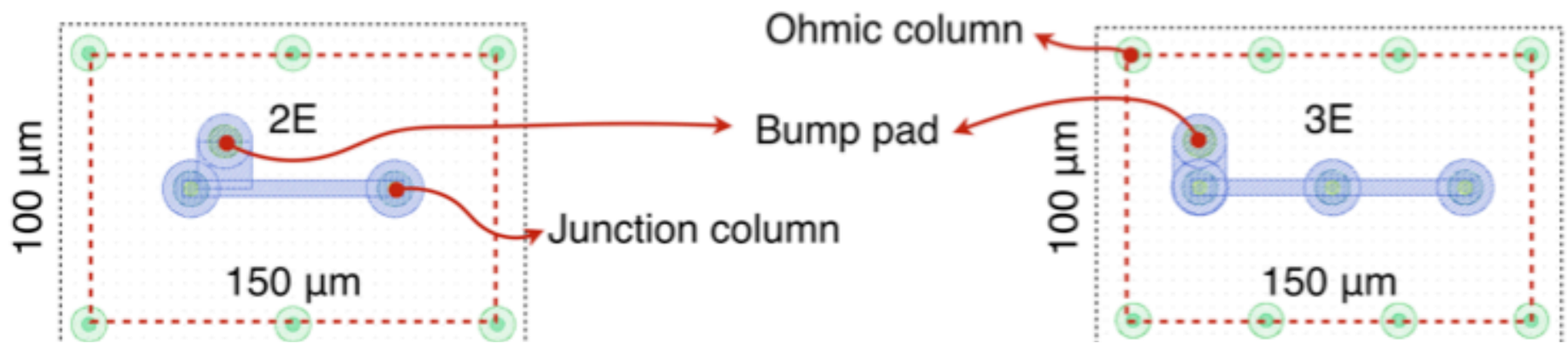
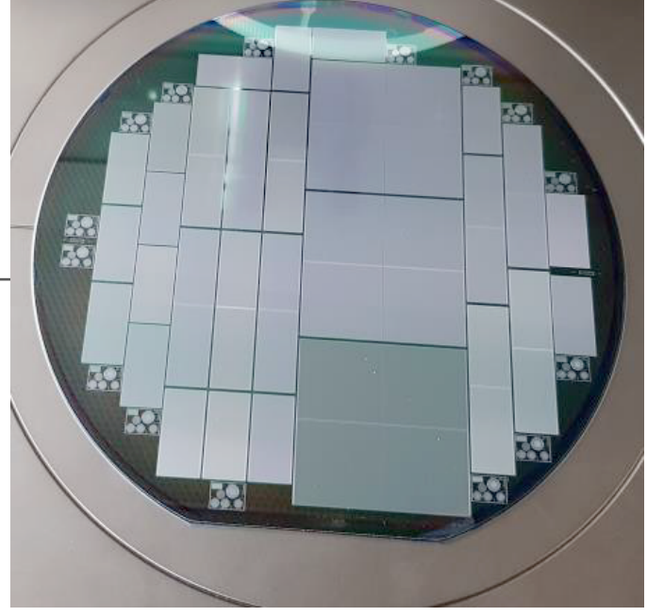


Figure 4.7: Schematic view of electrode arrangement and charge collection in planar and 3D pixel sensors.

1E: 1 electrode / pixel
2E: 2 electrodes / pixel
3E: 3 electrodes / pixel



Pixel Planar Si sensors

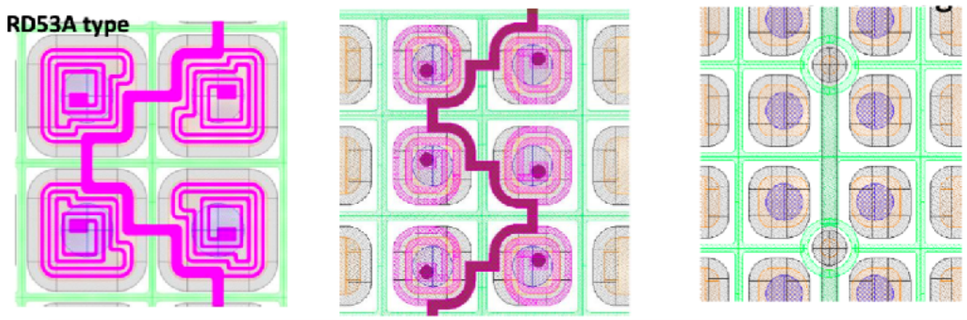


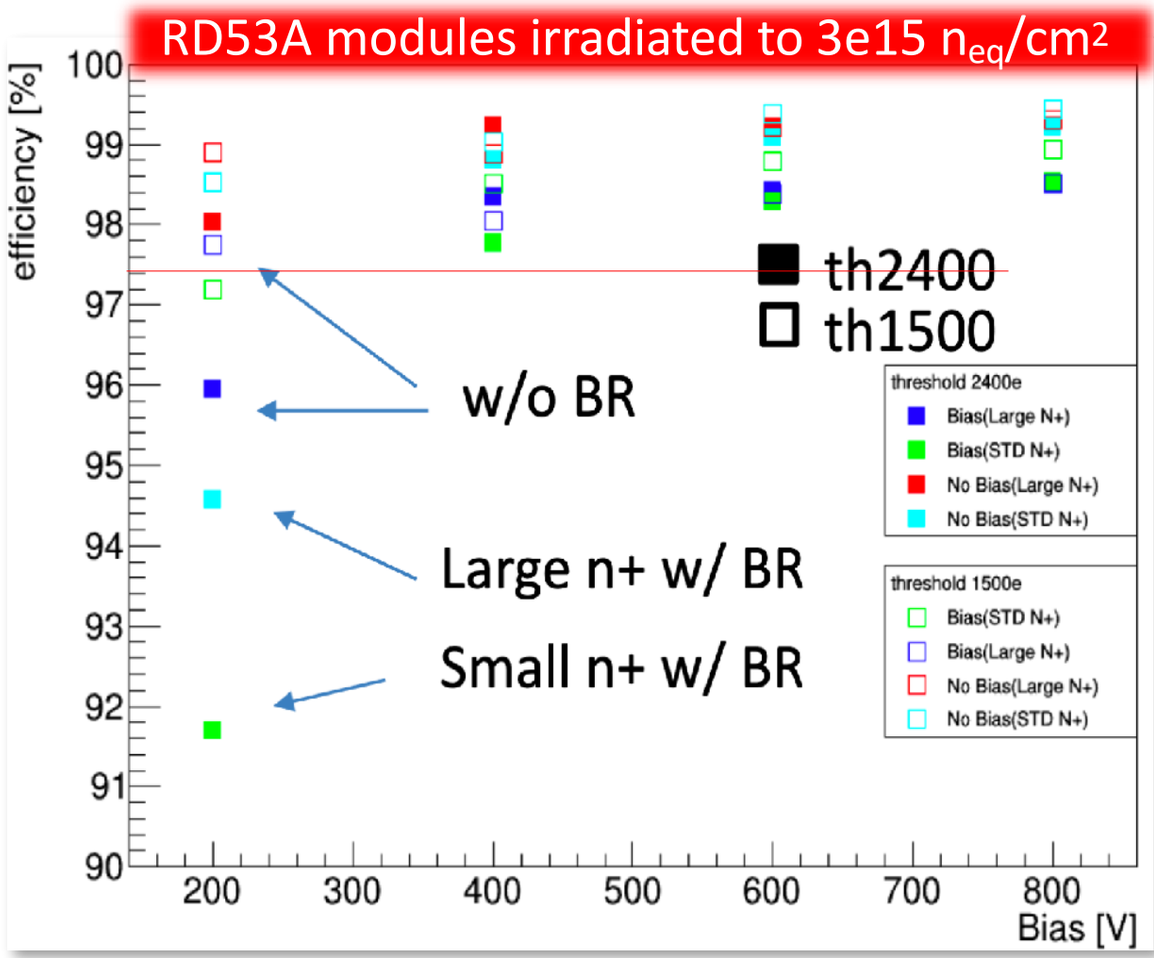
- Thin n-in-p planar sensors: **IBL (Insertible B-Layer)** in ID today uses 200 μm n-in-n planar sensors with 50x250 μm² pixel cells.
- **ITk** will use n-in-p technology (single side process) with 50x50 μm² pixel cells: 150 μm for the outer layers; 100 μm for the inner Layer-1

✓ Required performance
- First results show clear operating hit efficiency >97%
- Bias voltage at end of lifetime up to:
  - 600 V for 150 μm active thickness
  - 400 V for 100 μm active thickness

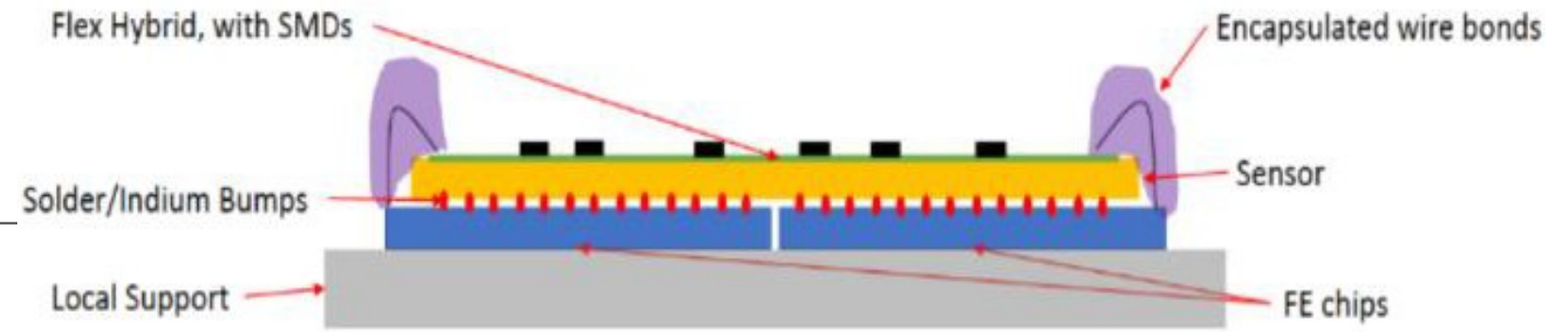
✓ Market Survey almost finalized
- Tender issued by the end of the year

✓ Vendors are optimizing the final design
- Different biasing solutions allowed
  - Punch through (PT)
  - Bias Rail (BR) and bias resistor
  - Temporary Metal (TM)
- Dimension of the n⁺ implant

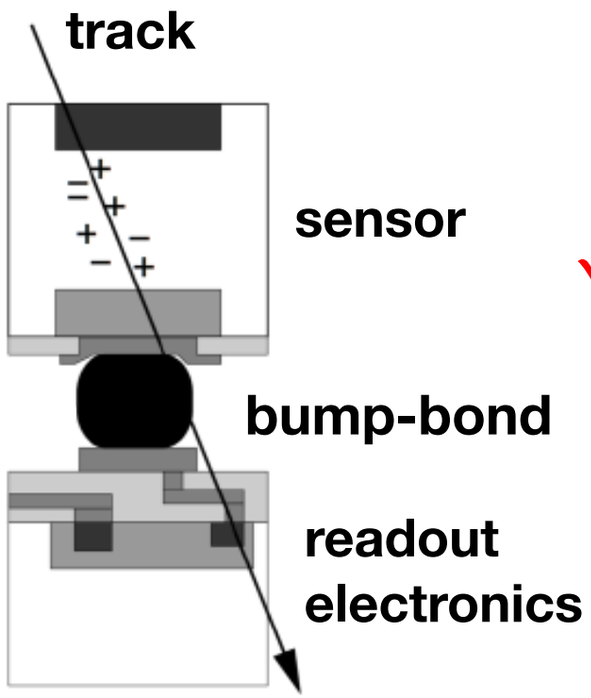




Pixel Modules



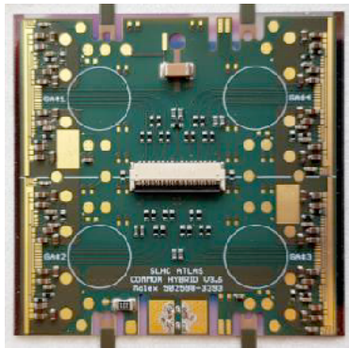
65 nm CMOS



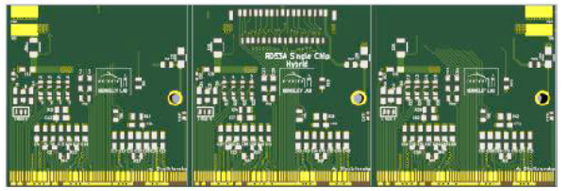
✓ Several module prototype stages have helped to reach maturity in several aspects:

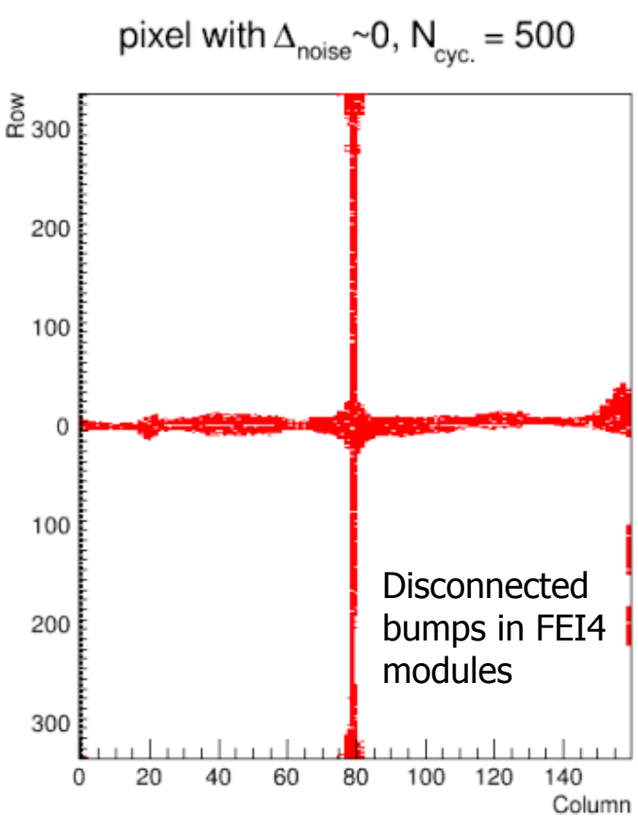
- General module design explored with FEI4 prototypes
- Extensive studies with ~ 250 RD53A module prototypes: thermal cycling, serial powering, new demonstrator to explore system aspects, …
- ITkPixV1 modules coming.

RD53A
Quad Dummy



RD53A Triplet Flex
for Layer 0





✓ Hybridization

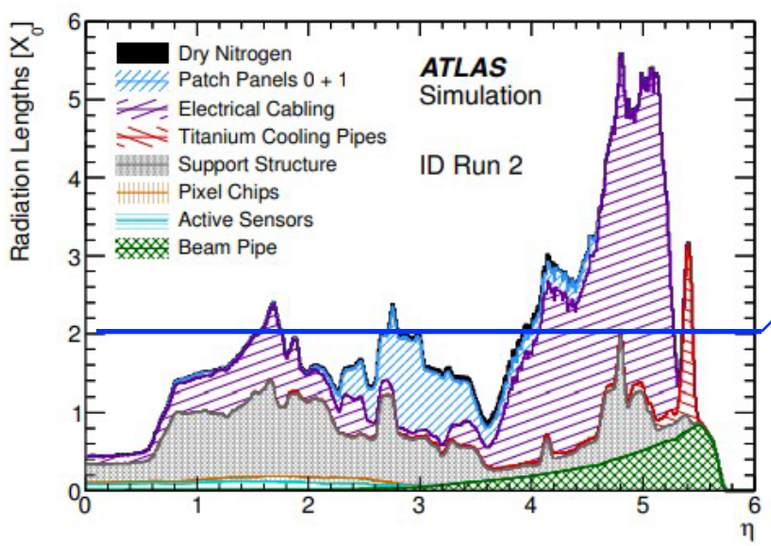
- Demonstration of fine-pitch bump-bonding on RD53A successful.
- Market survey of vendors running for different process steps: bump deposition, UBM, flip-chip.
- Concern: Thermal cycling causes bump stress, in case of large CTE mismatch between flex (Cu) and Si. Observed in inter-chip regions of FEI4 quads.
  - Improves with parylene coating of the assembled modules and mitigations in interfaces and flex design.

✓ Flex-Hybrid

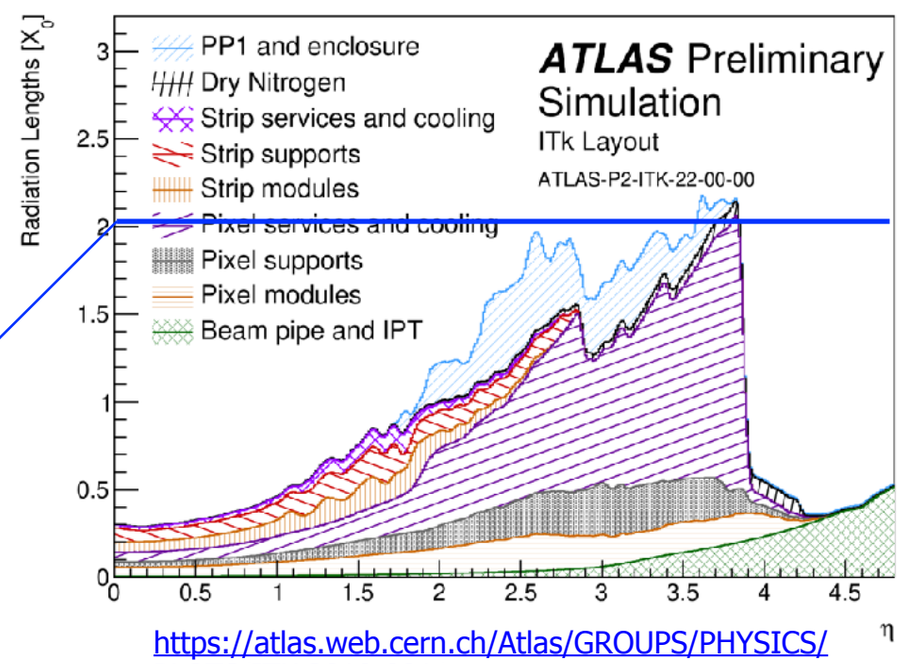
- Designs for common flex hybrids finished (RD53A)/ongoing (ITkPixV1).
- Reduced Cu content to mitigate CTE mismatch with Si

ITk Material Budget

- ✓ With the increased surface and granularity wrt ID, X_0 mitigation thanks to:
  - Strip: DC-DC powering and data transmission with optical links and lpGBT
  - Pixel: Thinned sensors and FE, Serial powering, inclined region in the Outer Barrel, increased readout speed
  - Common (ITK and Strip): Light structures, cooling designs optimized as well as material choice wrt the requirements (precision, stability, contain the thermal run away, …)
  - NB: Material budget is regularly updated as the engineering design evolves



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/CERN-LHCC-2017-021/

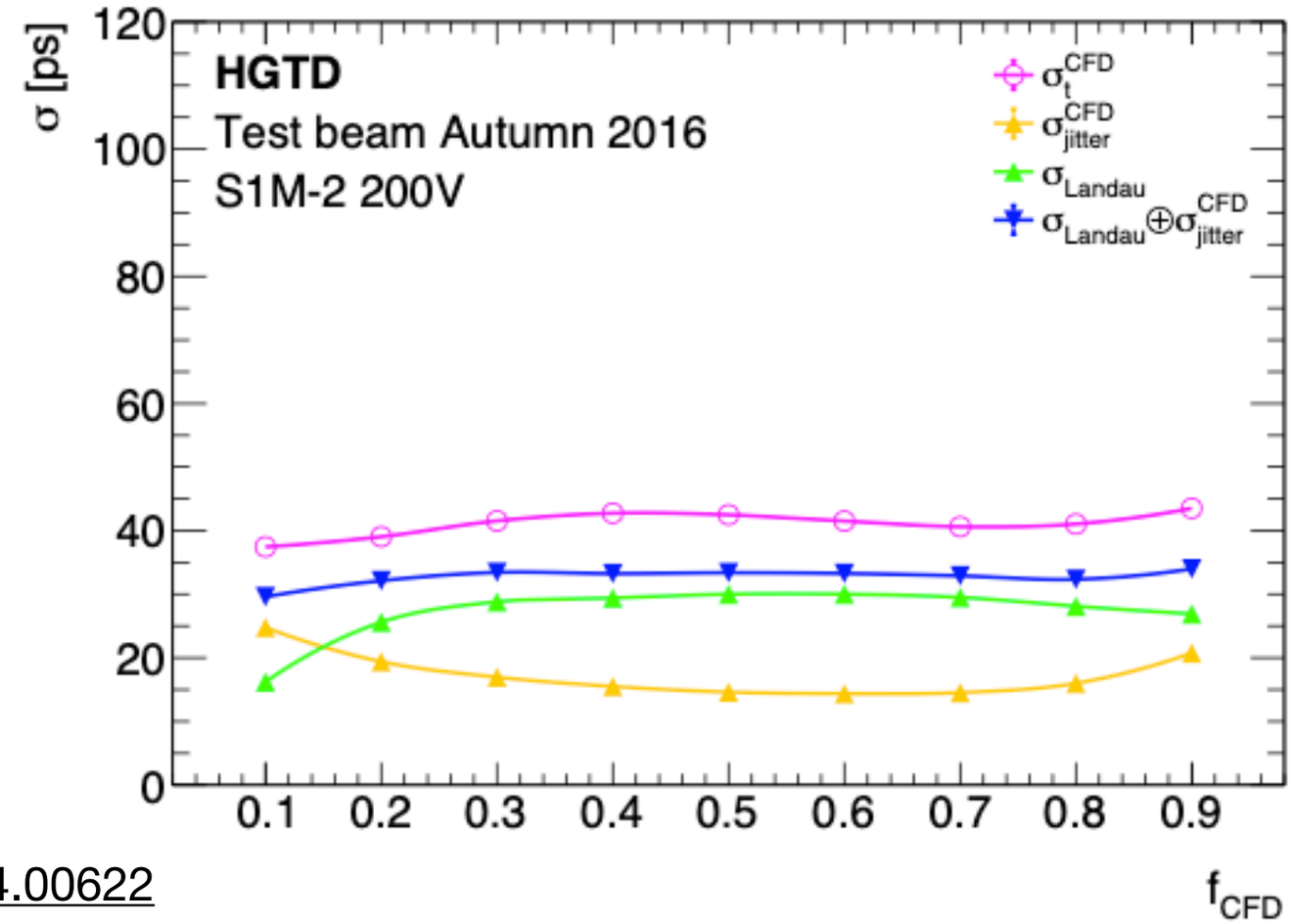


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2019-001/

Reduced material budget versus current ID in Run 2.

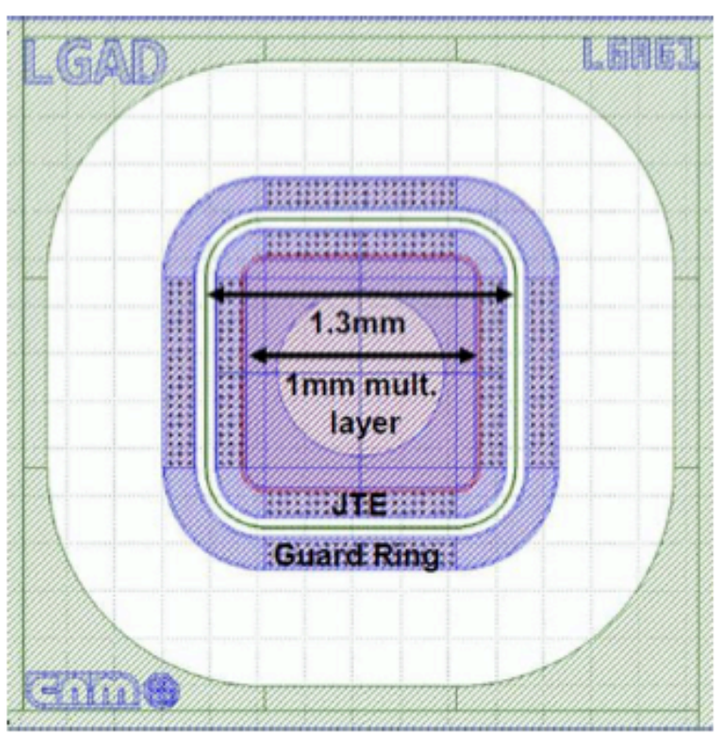
→ Minimize effects of multiple-scattering and energy losses before outer detectors.

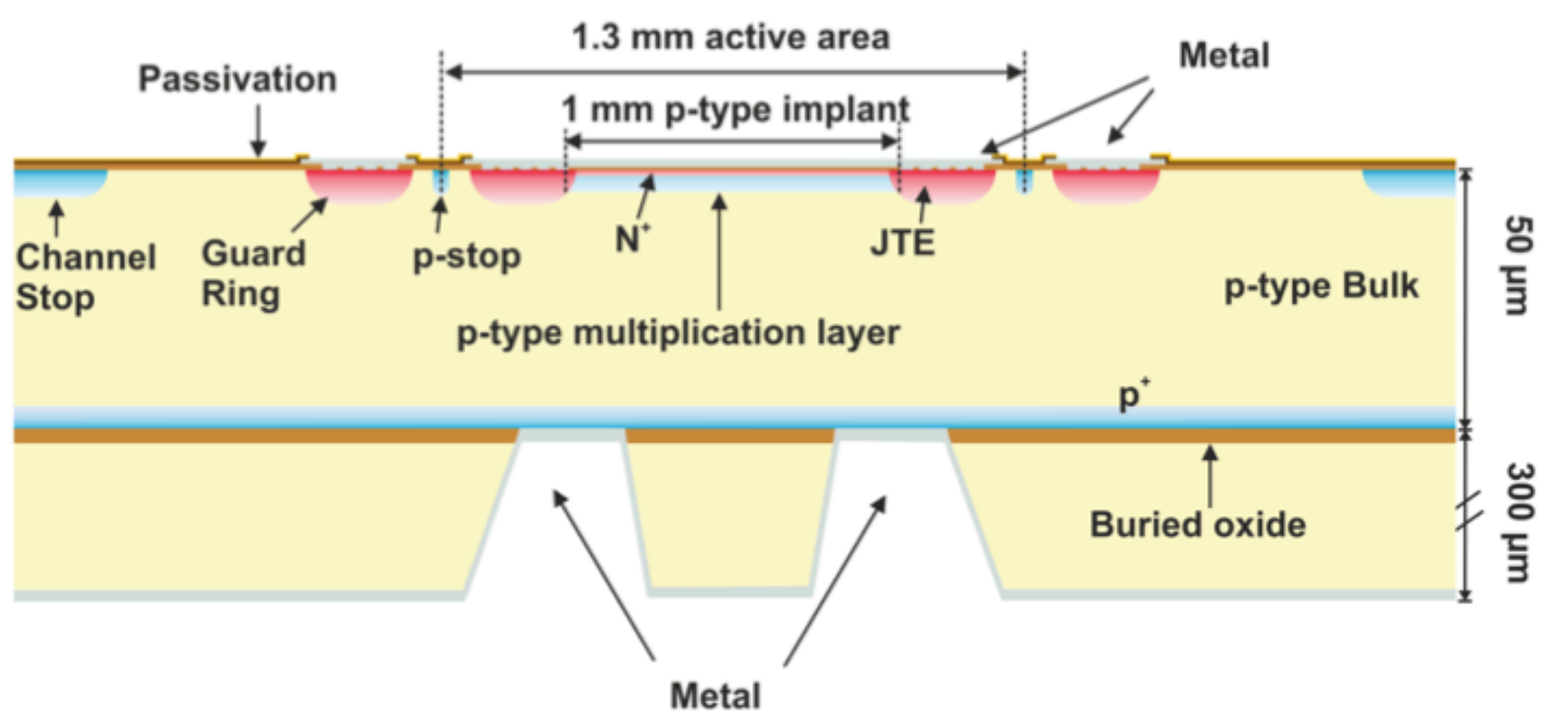
HGTD Time resolution



- Test beam results: https://arxiv.org/abs/1804.00622

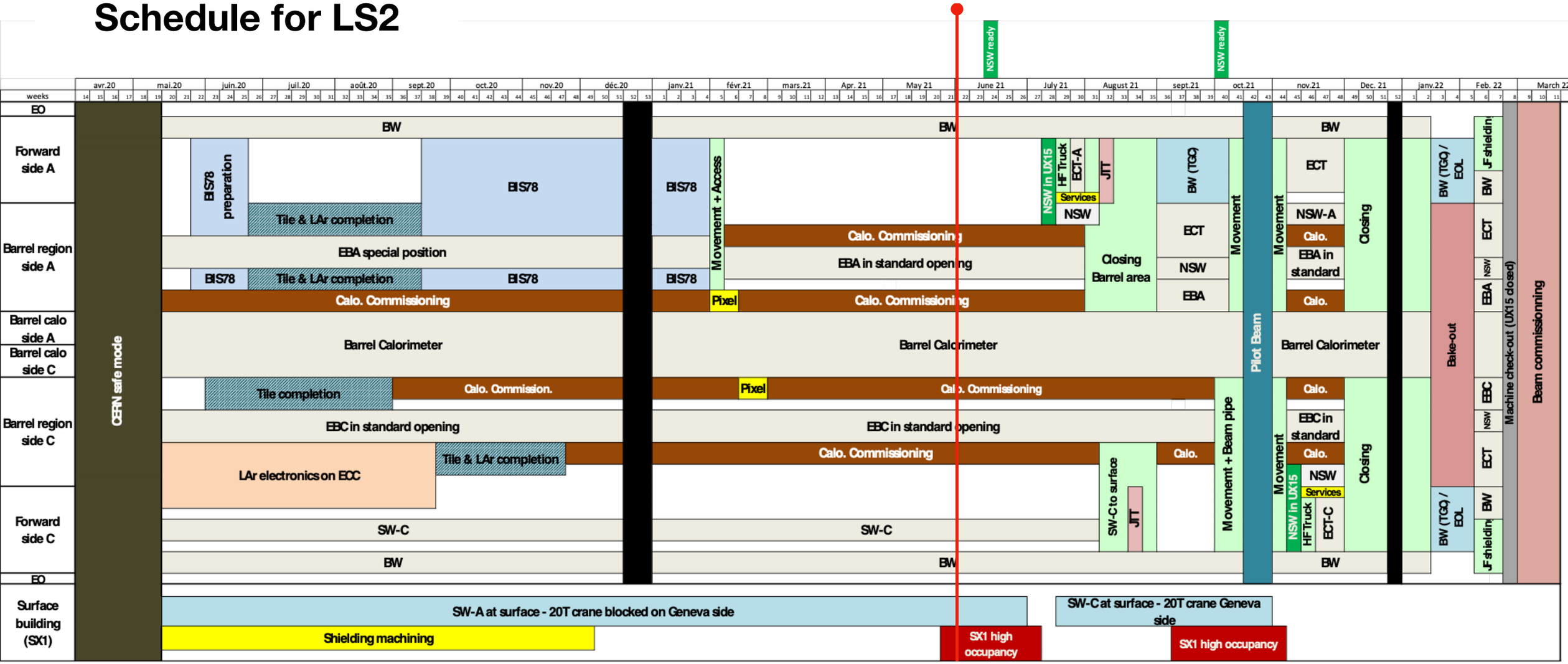
Single Pad LGA





Preparations for Run 3

Schedule for LS2



- **LHC pilot beam weeks 42/43 (preliminary schedule)**
- **Udates to ATLAS software in preparation including multi-threading, speed-up tracking**