

Does the Higgs boson wear a Mexican-hat?

Brian Moser (University of Freiburg)

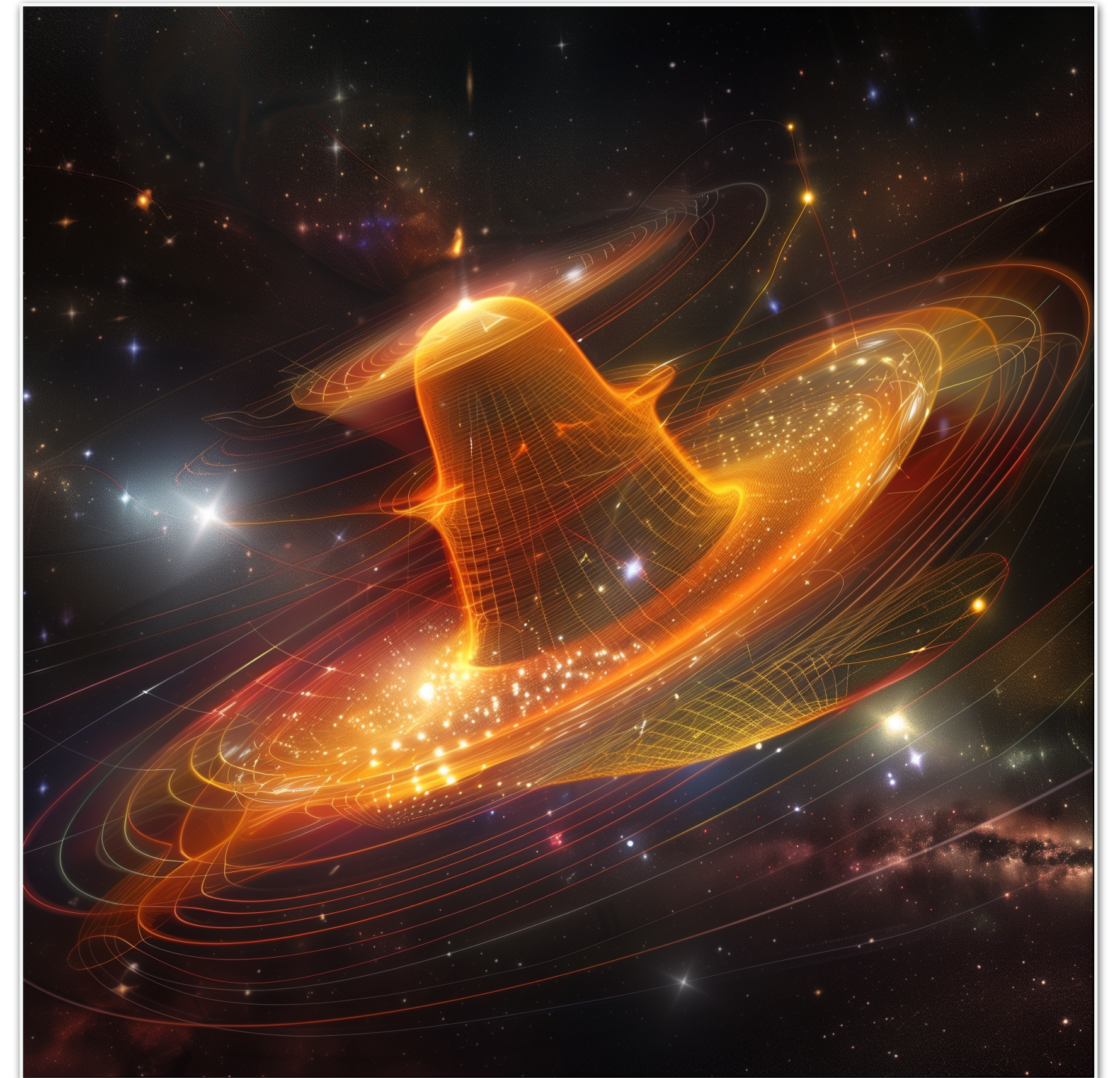
Oxford Particle Physics Seminar

14/05/2026



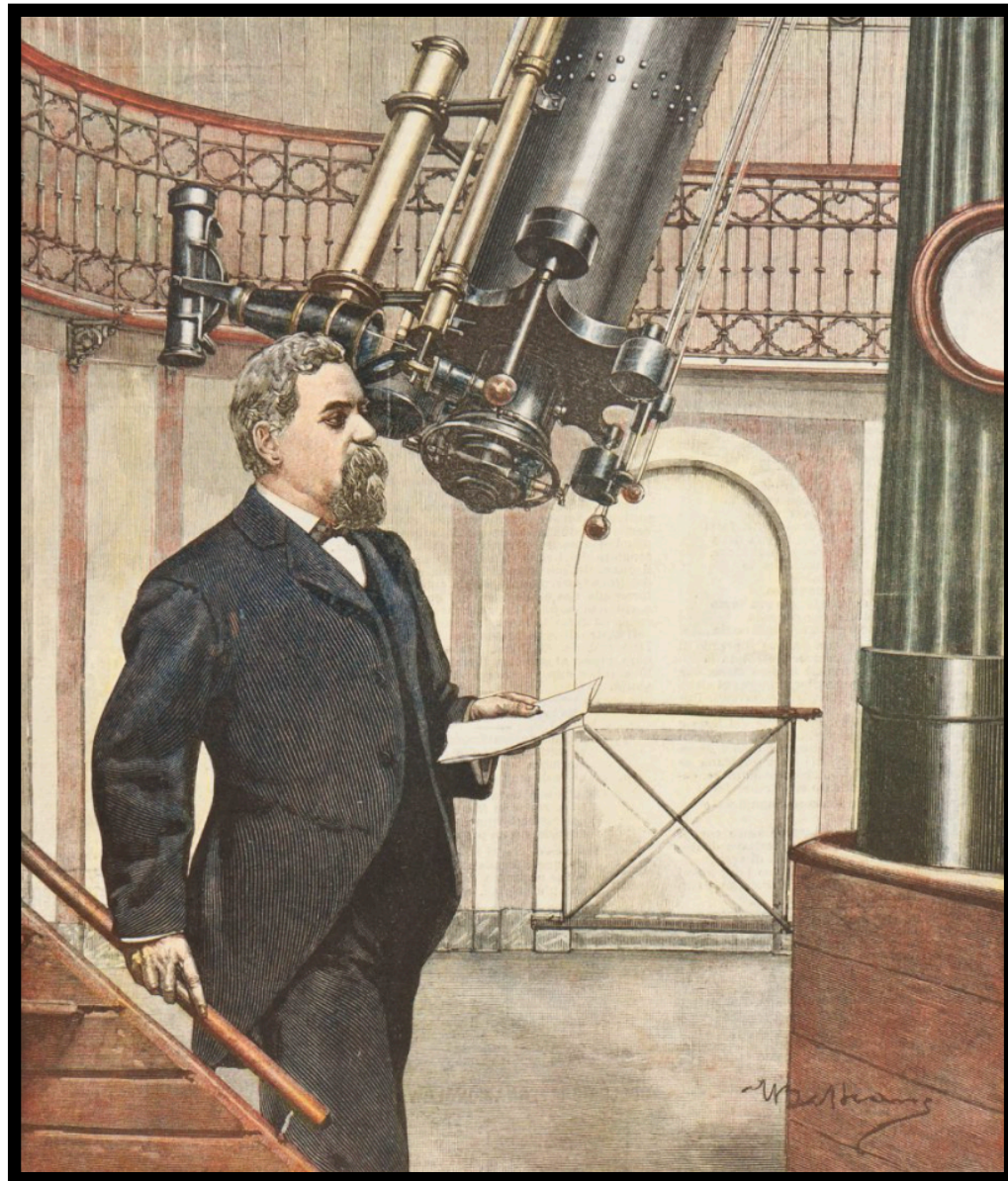
universität freiburg

Image created with Midjourney

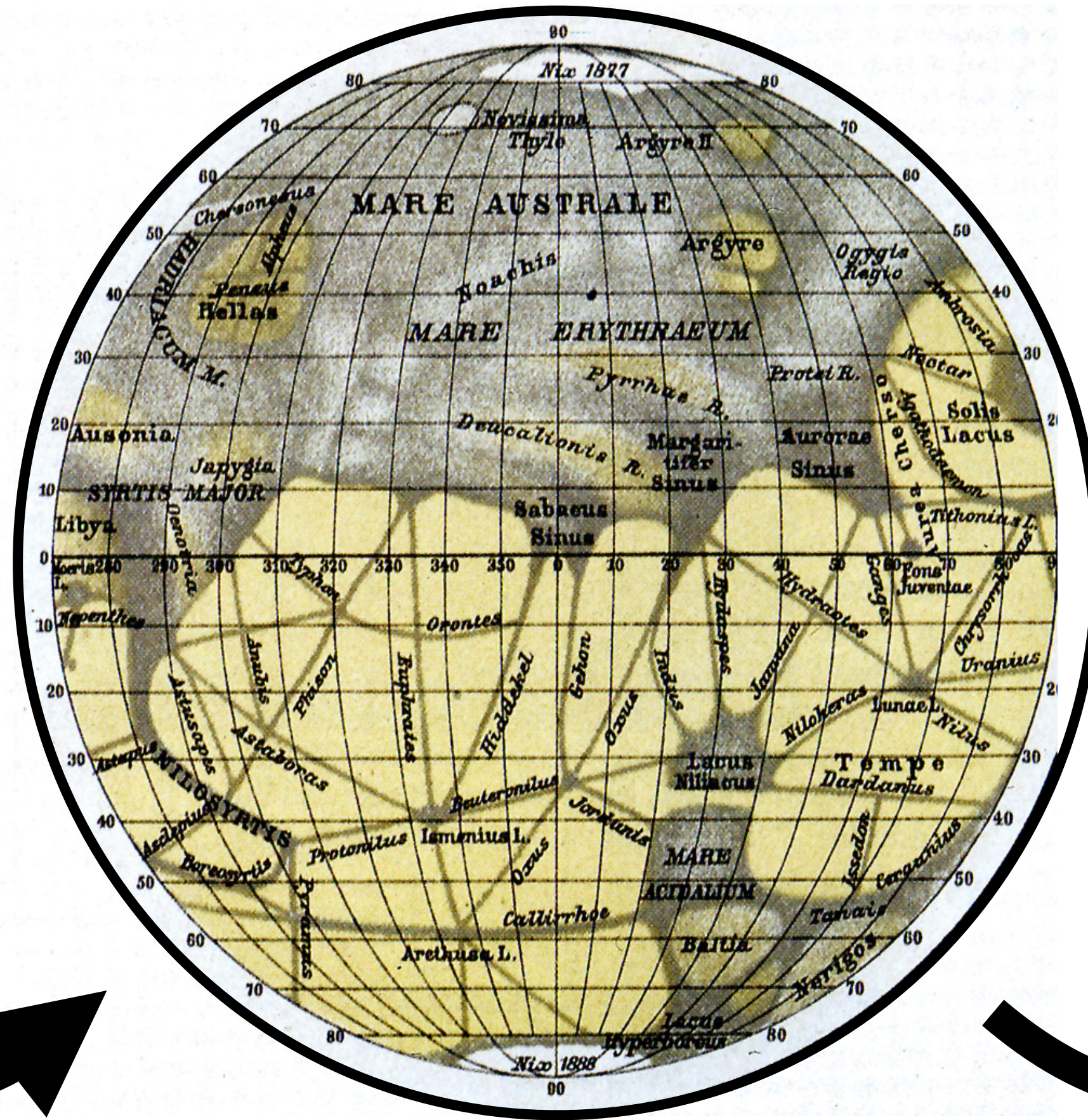


A cautionary tale about insufficient resolution

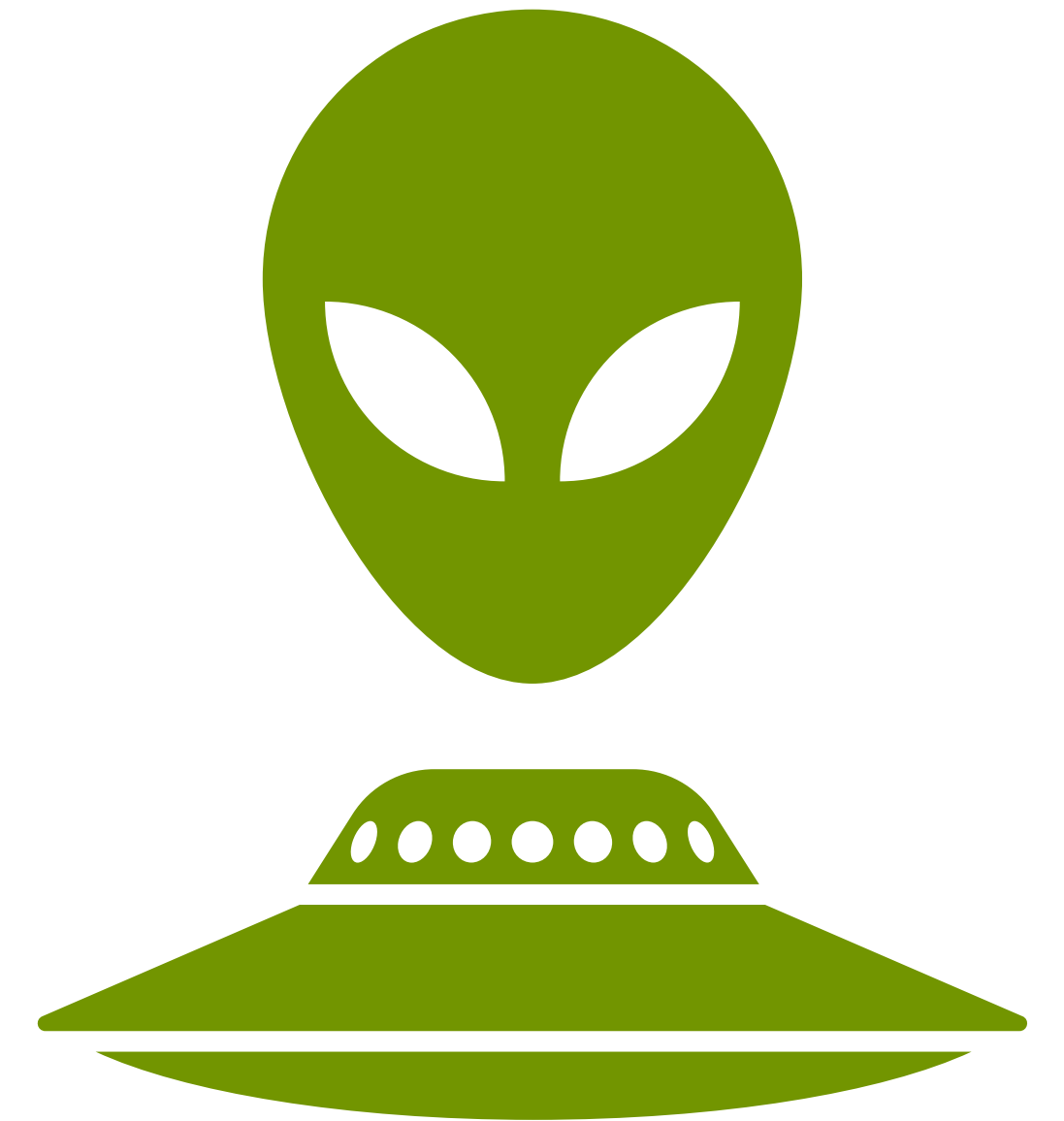
Giovanni Schiaparelli



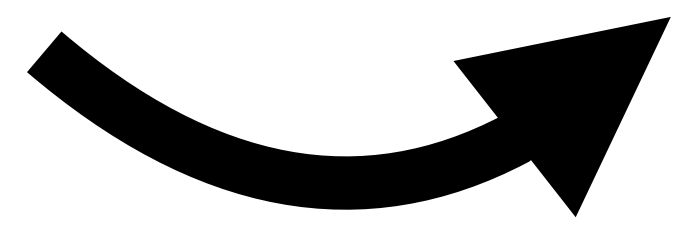
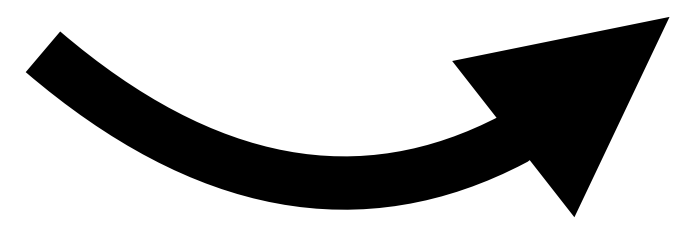
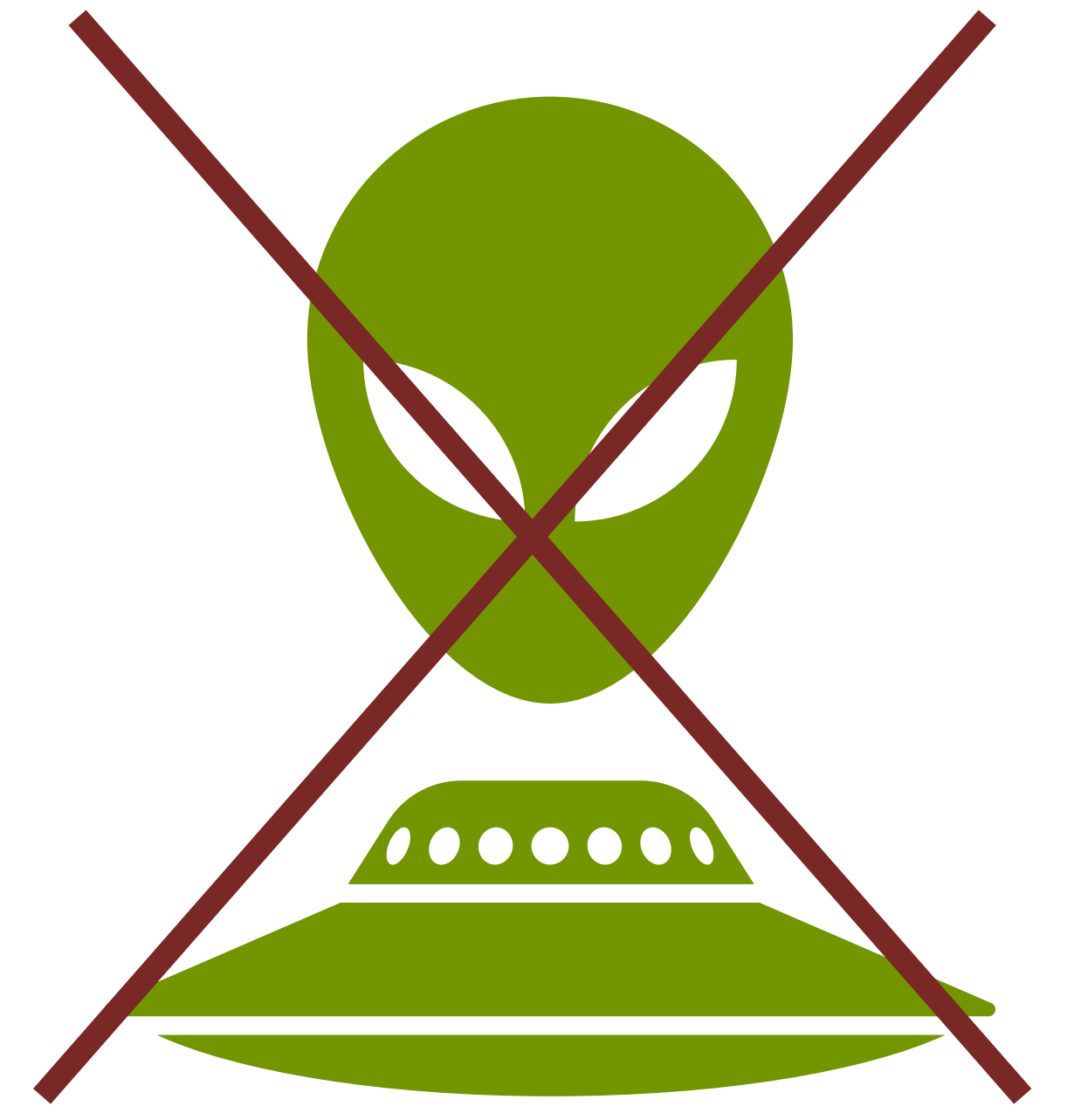
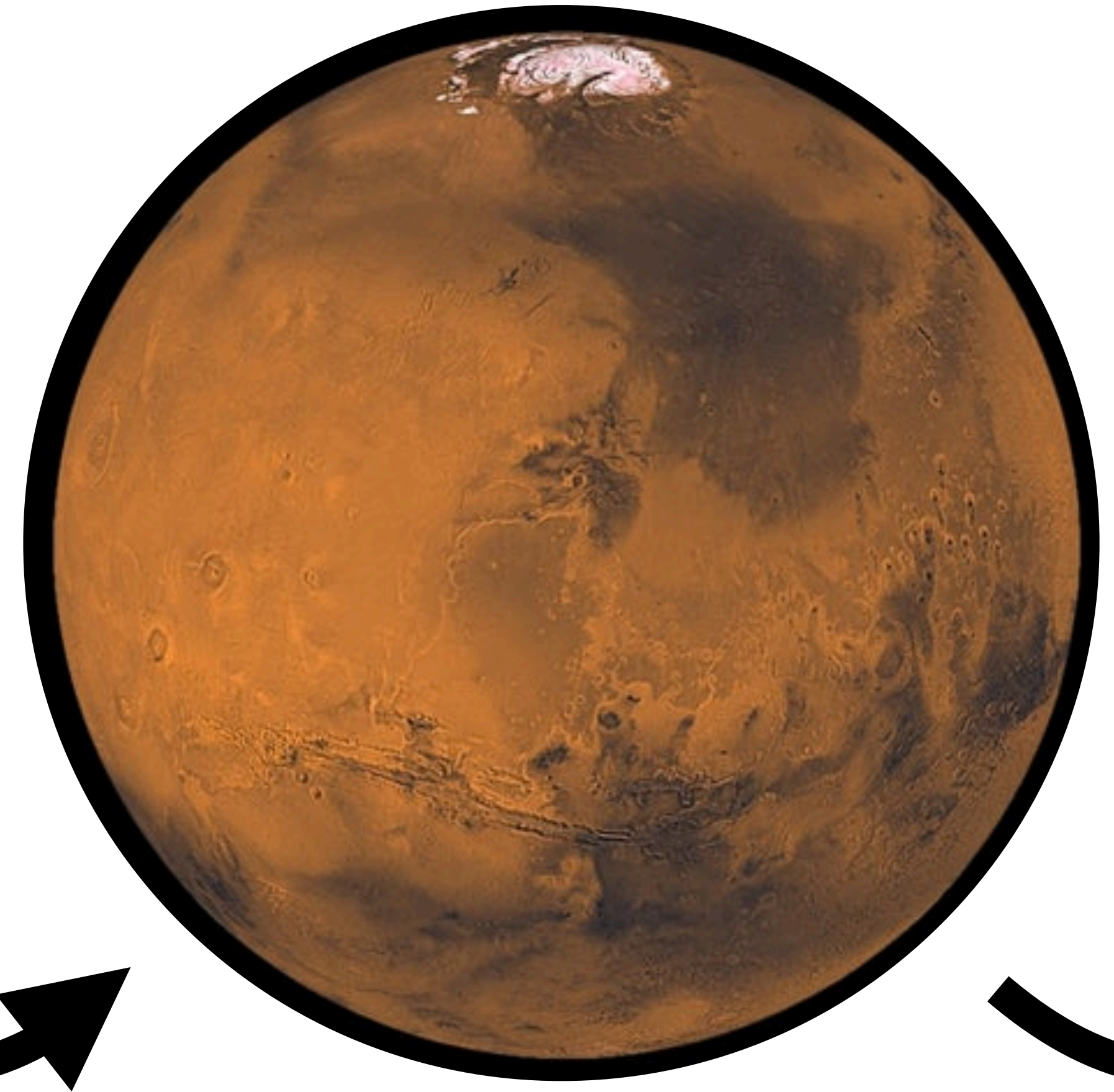
Late 19th century



Canals on Mars?

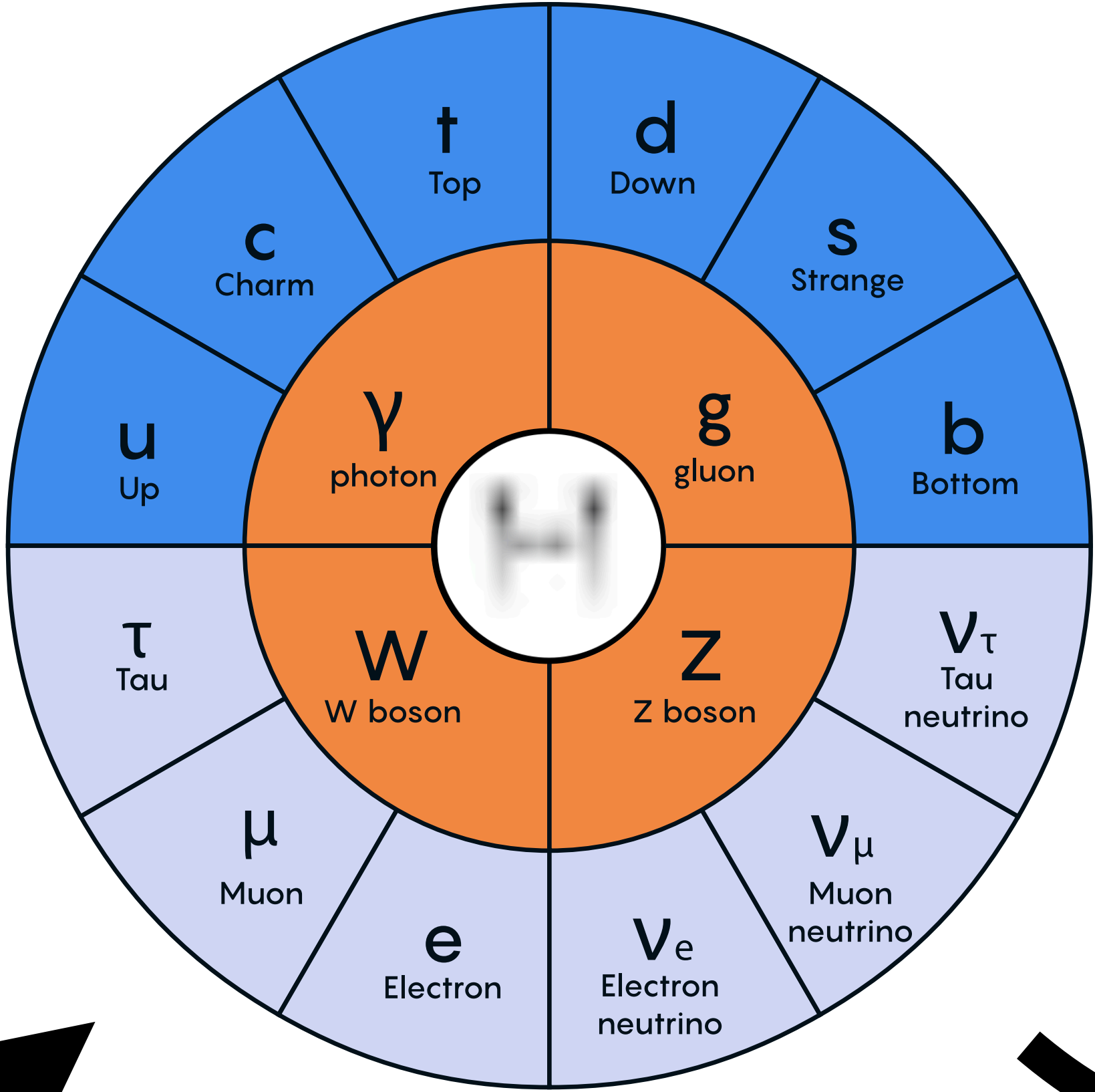


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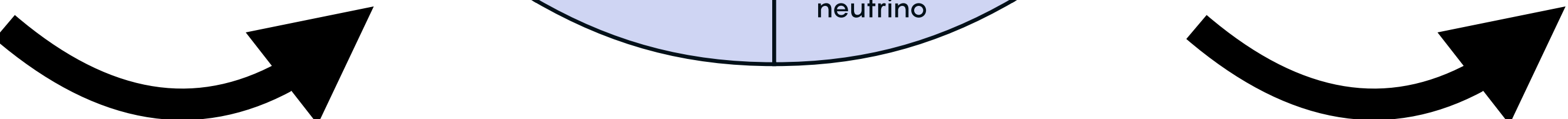
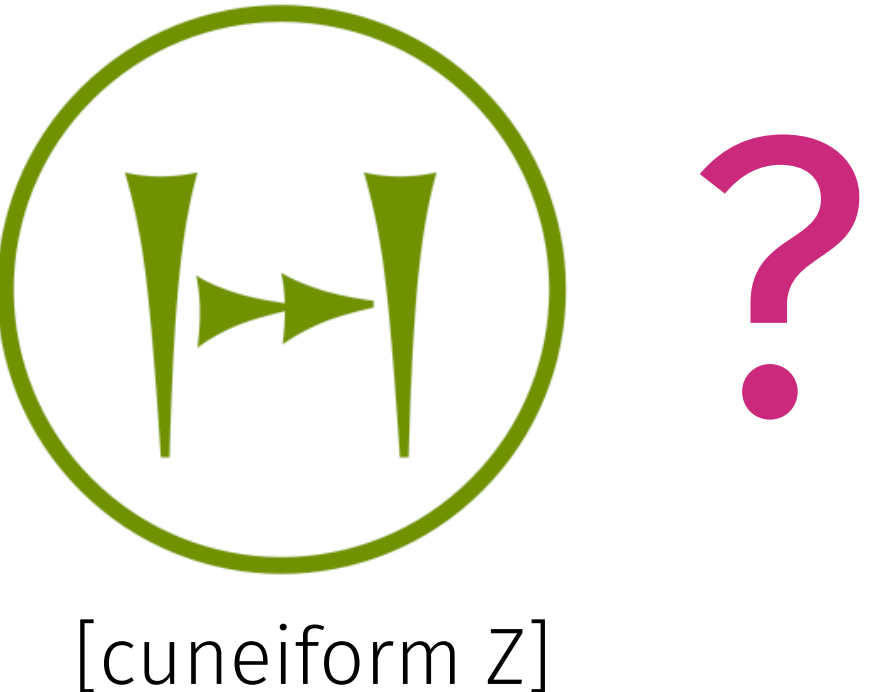


No canals on Mars!

Back to particles: looking at the Standard Model



new physics

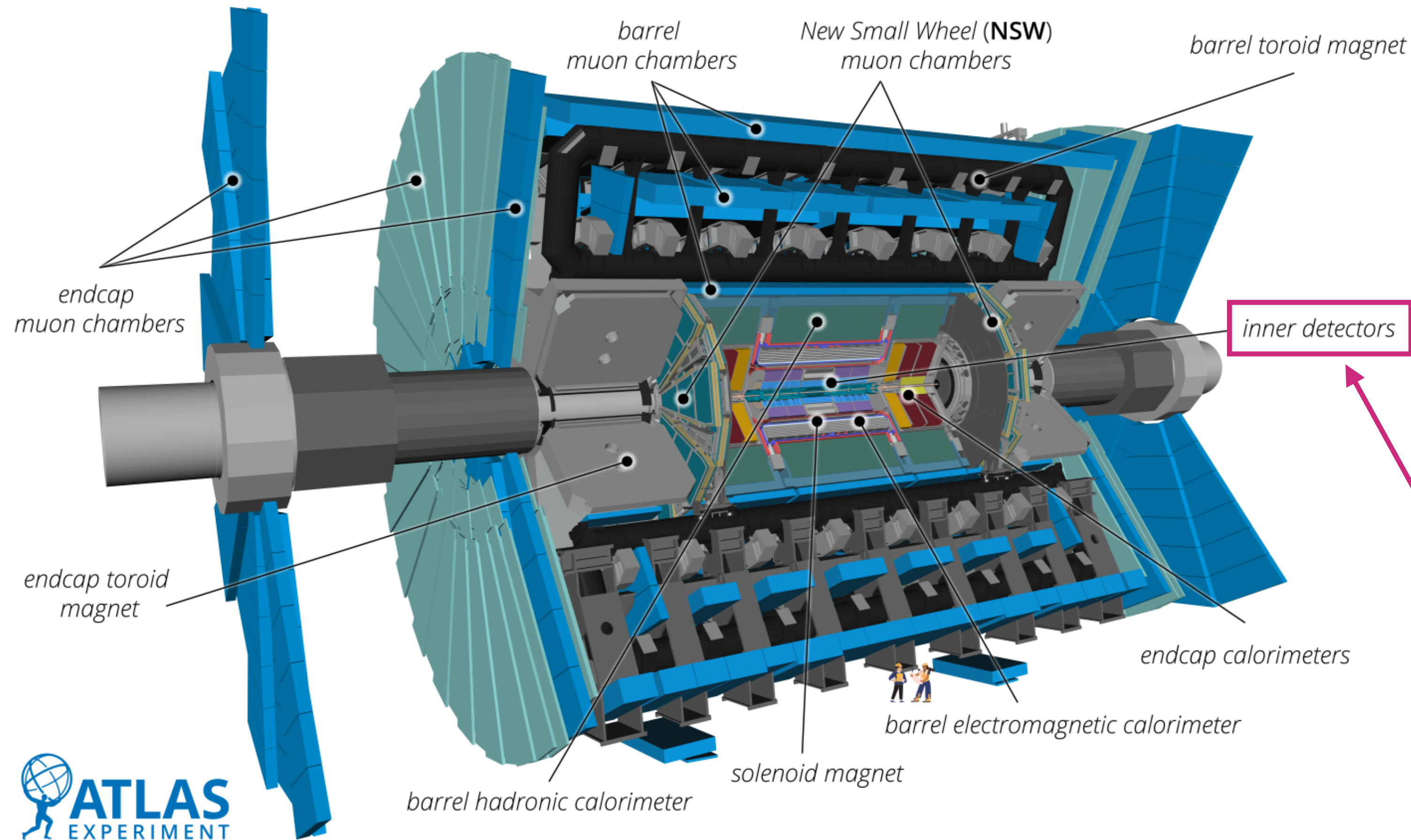


Our „picture“ of the Standard Model of Particle Physics



Our „telescope“: the ATLAS detector

- ▶ Layered LHC detector encapsulating interaction point: central tracker inside of a solenoid, calorimeters and an independent muon spectrometer with superconducting toroids



- ▶ Fast triggering on interesting signatures [**leptons, jets, ...**]
- ▶ Precise reconstruction of:
 - collision vertices
 - photons and **electrons**
 - **muons**
 - τ -leptons
 - jets
 - missing transverse momentum (MET)
- ▶ Identification of **heavy flavor jets and hadronic τ decays**

The Standard Model of Particle Physics ...

The Beauty

- Interactions among force particles, and between matter and force particles
- They arise from internal **symmetries** (requiring local gauge invariance)
- 3 free parameters

$$\mathcal{L}_{\text{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi$$

The Beast

- The “Higgs sector”
- Introduced **ad-hoc**
- **15** free parameters
- **Descriptive**, but lacking a deeper understanding
- Couplings with vastly different values spanning orders of magnitude

$$+ |D_{\mu}\phi|^2 - \mu^2(\phi^{\dagger}\phi) - \lambda(\phi^{\dagger}\phi)^2 + y_{ij}\psi_i\phi\psi_j + \text{h.c.}$$



The Standard Model of Particle Physics ...

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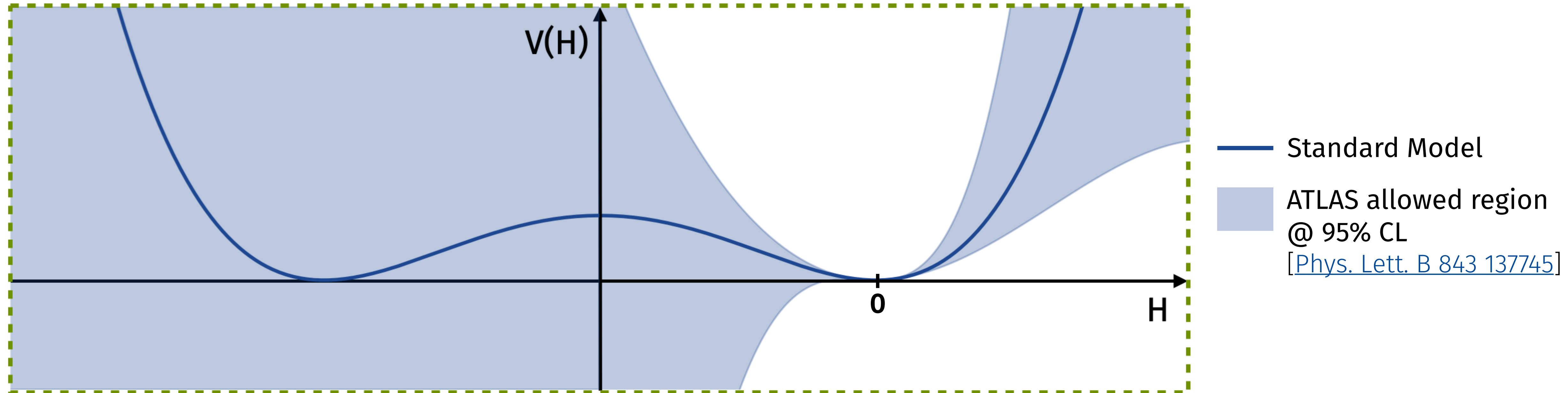
$$+ |D_{\mu}\phi|^2 - \mu^2(\phi^{\dagger}\phi) - \lambda(\phi^{\dagger}\phi)^2 + y_{ij}\psi_i\phi\psi_j + \text{h.c.}$$



... and the famous Higgs potential $V(H)$

arbitrary \uparrow > 0 \uparrow highest term even, else any polynom. would do

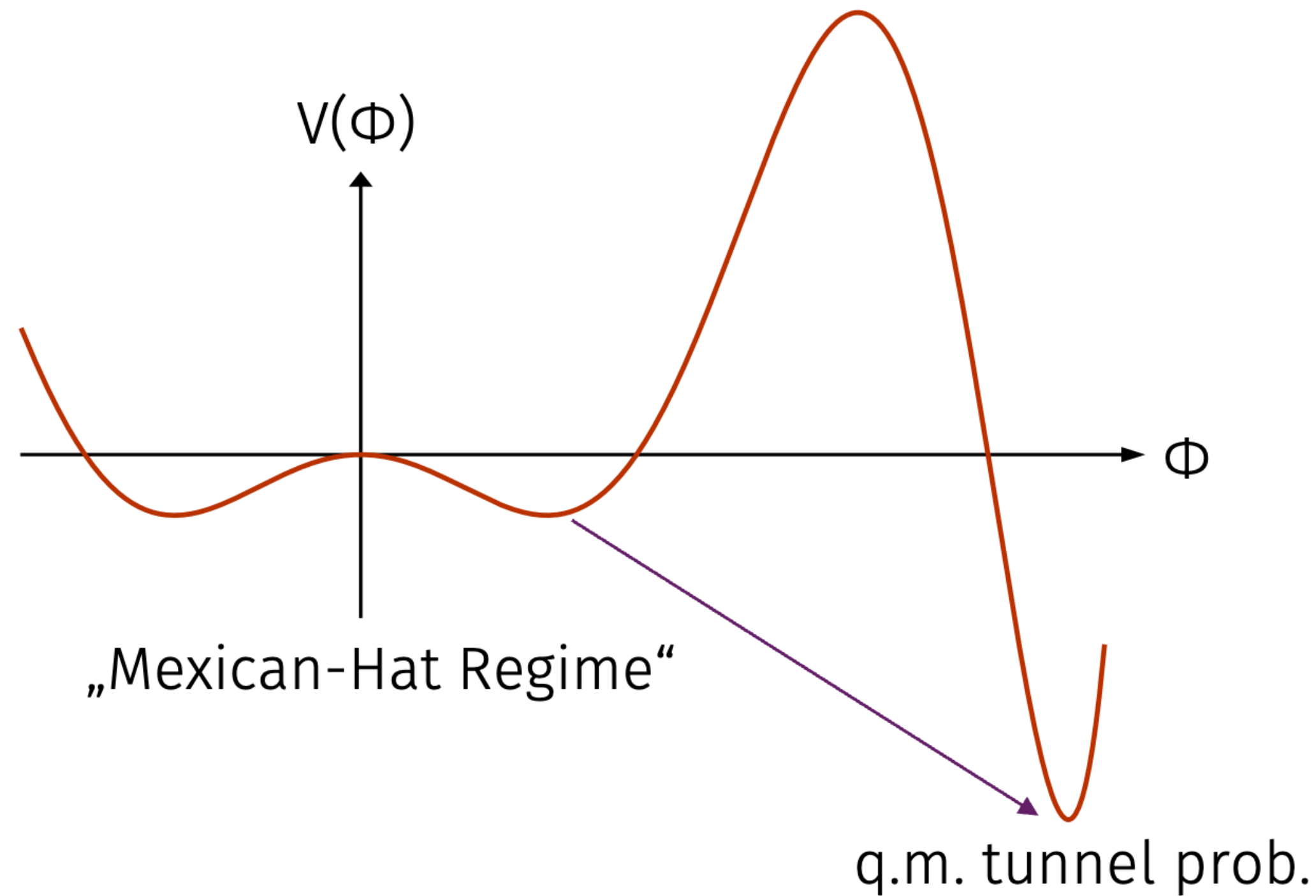
$$V(\phi) = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2 \longrightarrow V(H) = \frac{1}{2}m_H^2 H^2 + \lambda \text{ vev } H^3 + \frac{1}{4}\lambda H^4$$



Why **is the Higgs potential Mexican-hat shaped?**

The Higgs potential and the big open questions

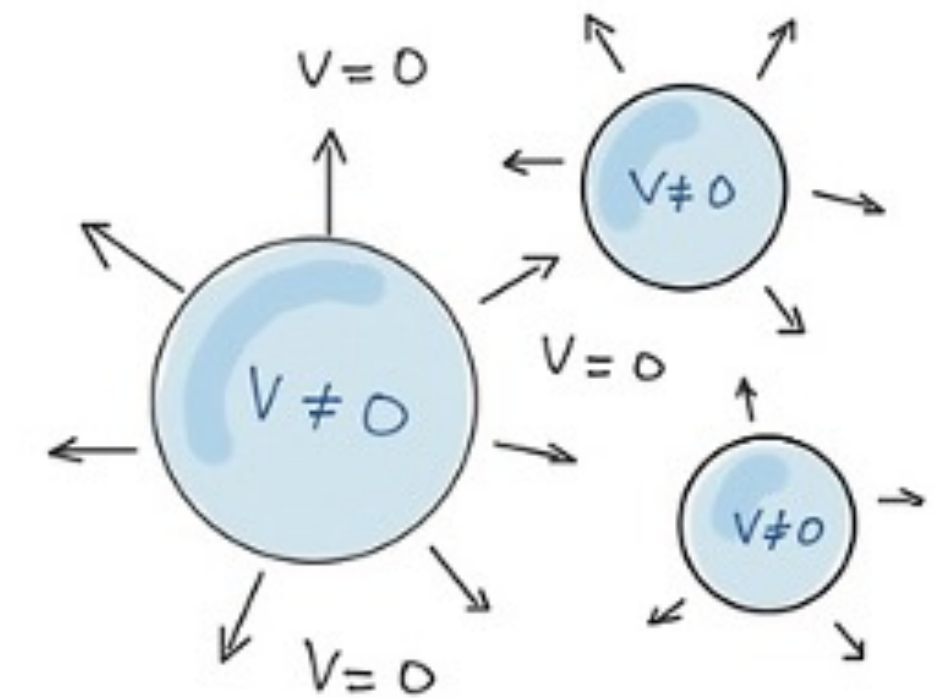
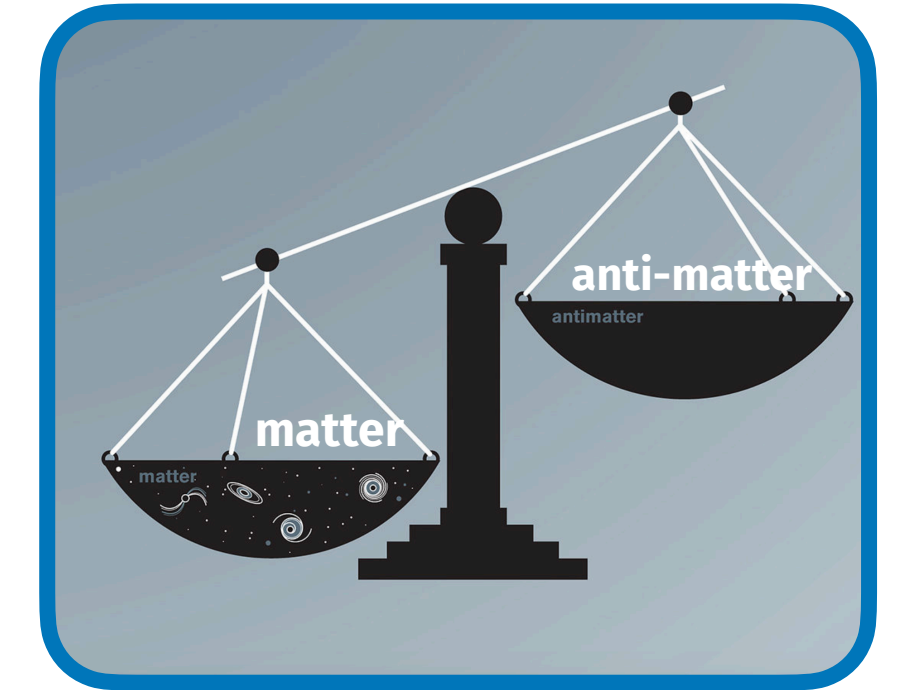
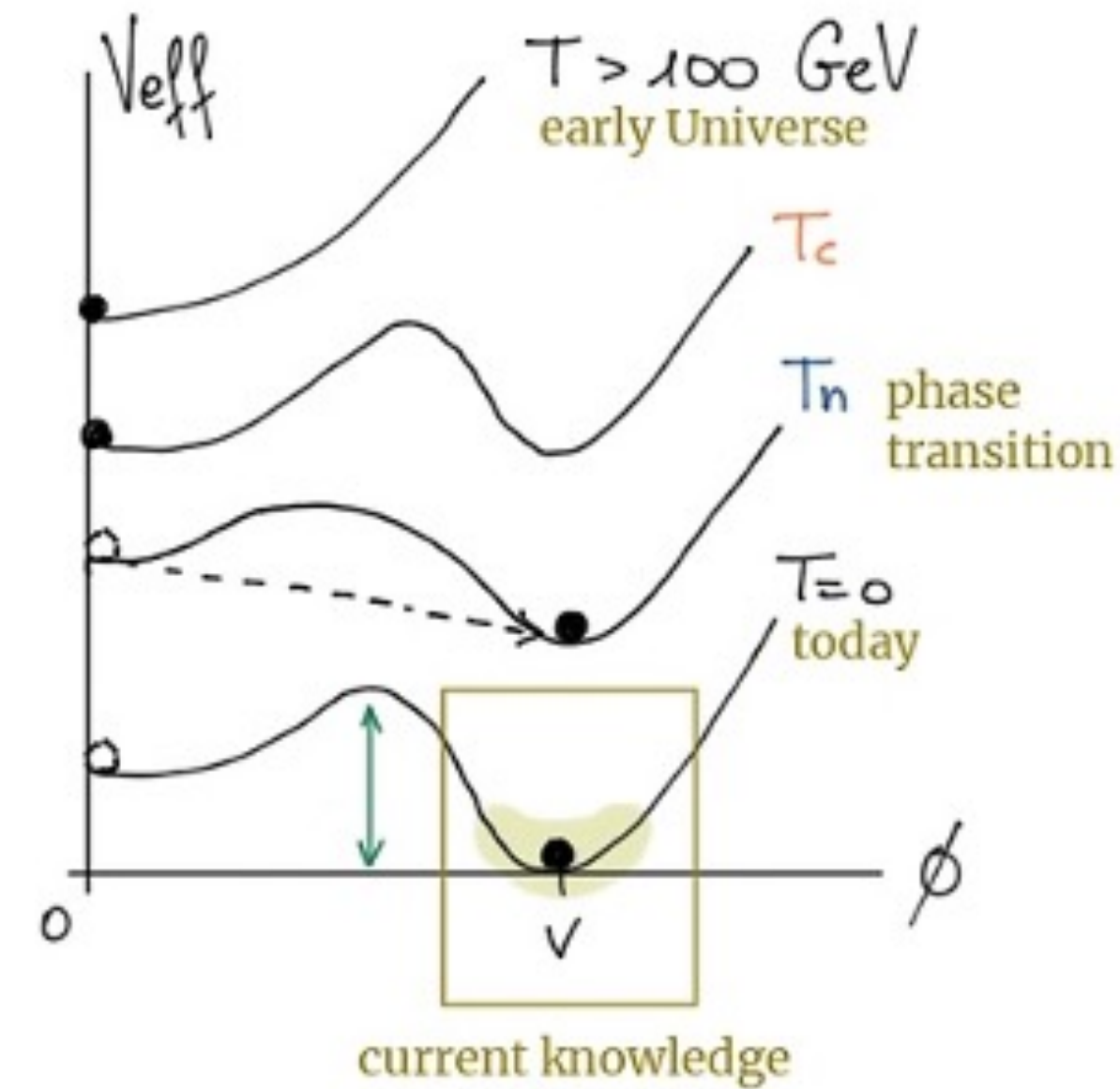
From the stability of the vacuum ...



Stable?

Meta-stable?

... to explaining the matter-antimatter asymmetry

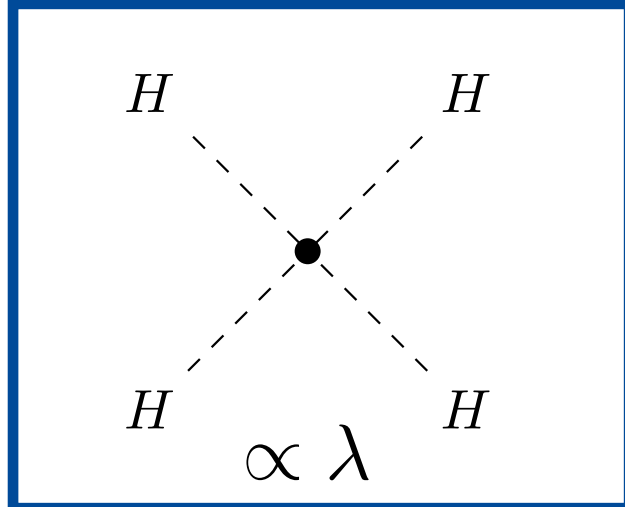
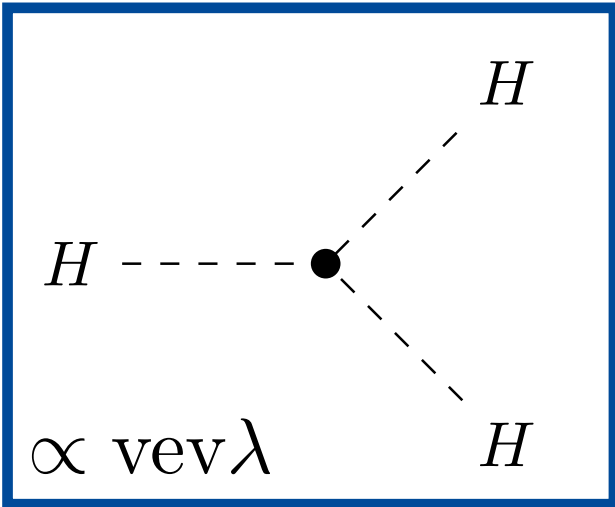
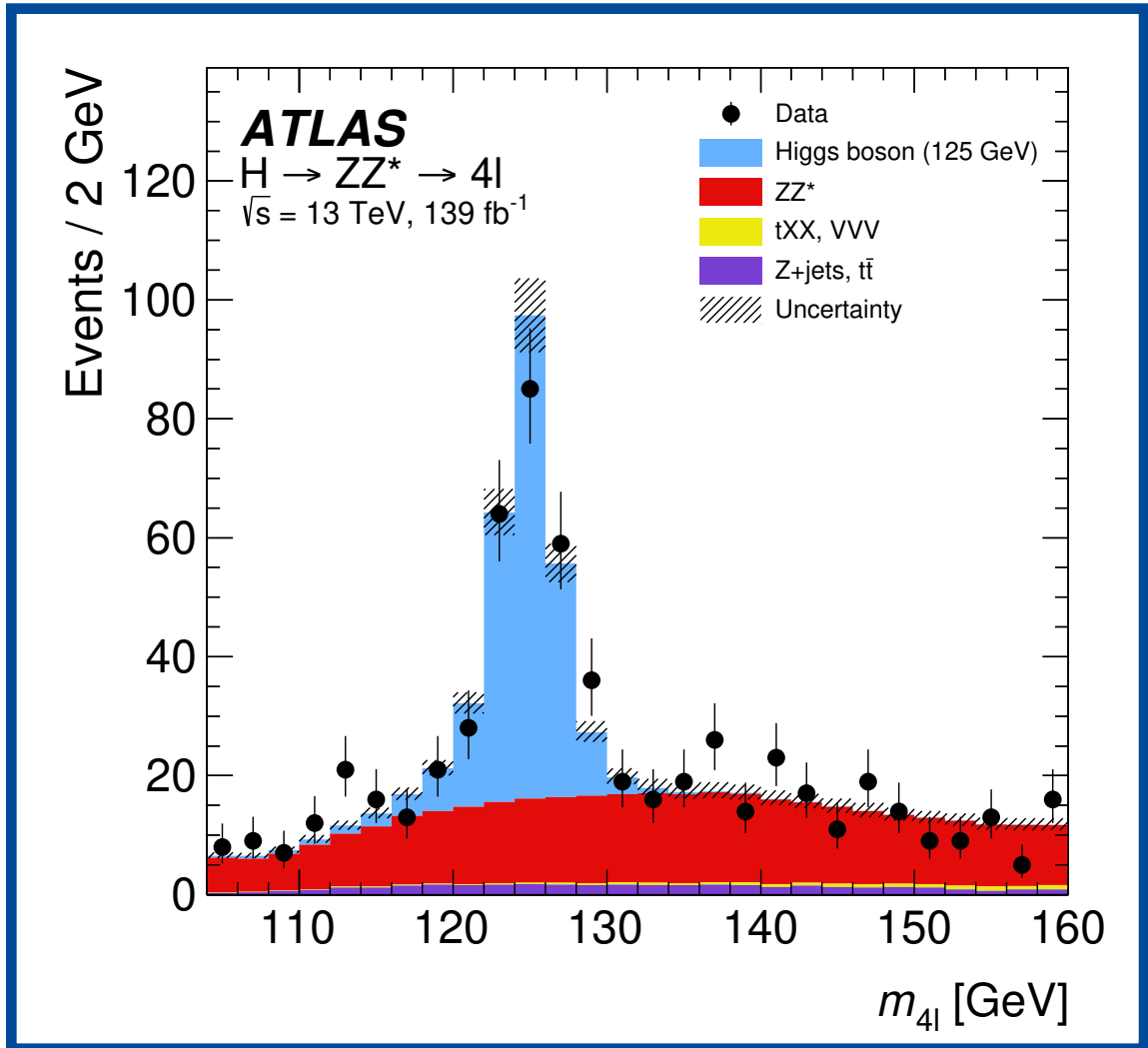


Non-SM Higgs potential needed for electroweak baryogenesis

How to measure the Higgs potential?

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda \text{vev} H^3 + \frac{1}{4} \lambda H^4$$

(vev known with sub-% precision from muon lifetime)

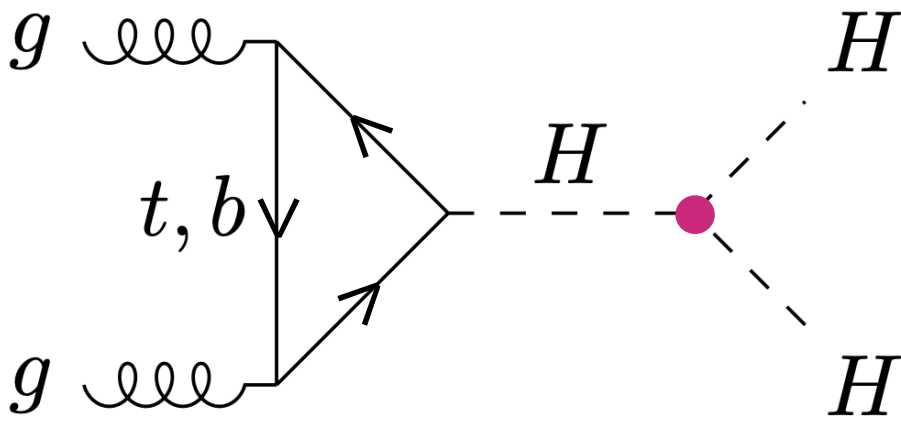


In the SM:

$$\lambda = \frac{m_H^2}{2\text{vev}^2} \approx \frac{125^2}{2 \cdot 246^2} \approx \frac{1}{8}$$

Any deviation would be a clear sign of new physics!

Measure $pp \rightarrow HH$ to determine λ :



ATLAS $H \rightarrow ZZ^* \rightarrow 4\ell + H \rightarrow \gamma\gamma$ Run 1 + Run 2

$m_H = 125.11 \pm 0.09 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$
 [0.09% relative uncertainty]

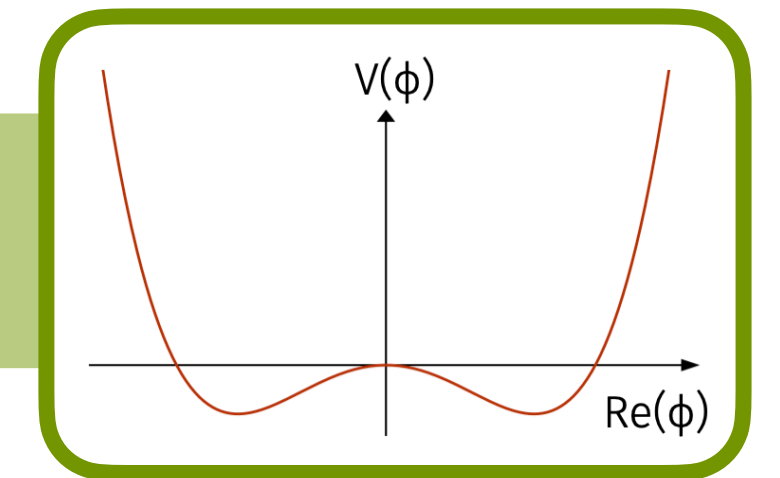
[Phys. Rev. Lett. 131 (2023) 251802]



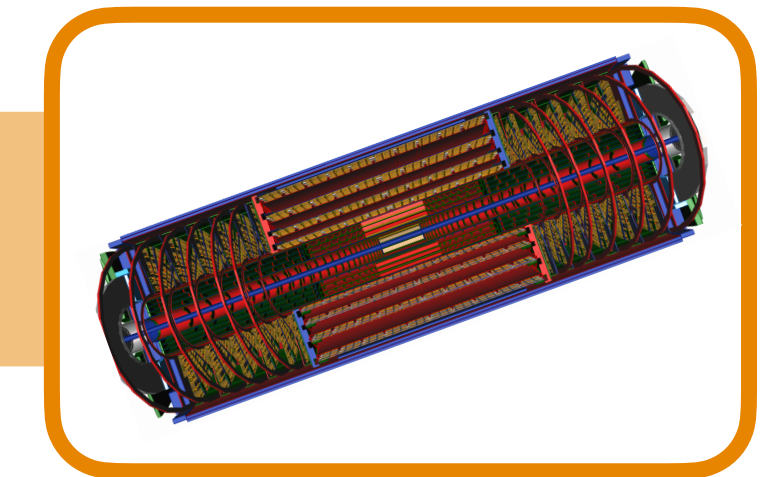
This seminar: 2 snapshots of my work ...

... all aimed to increase resolution

1. Measuring the shape of the Higgs potential



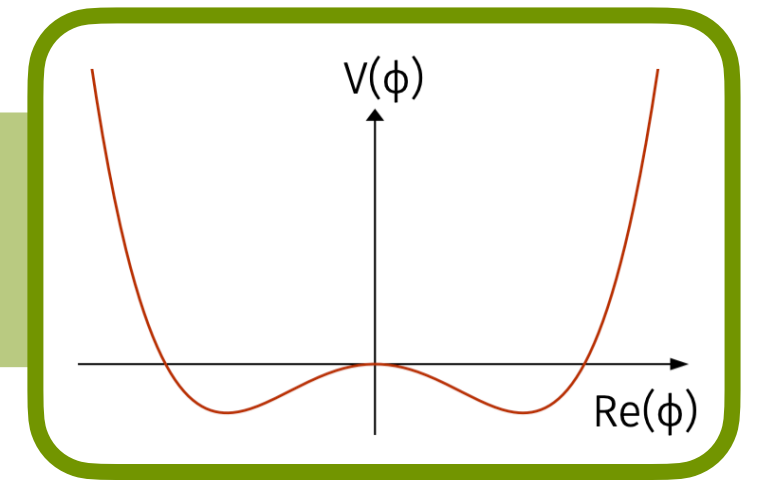
2. Building the new ATLAS pixel detector



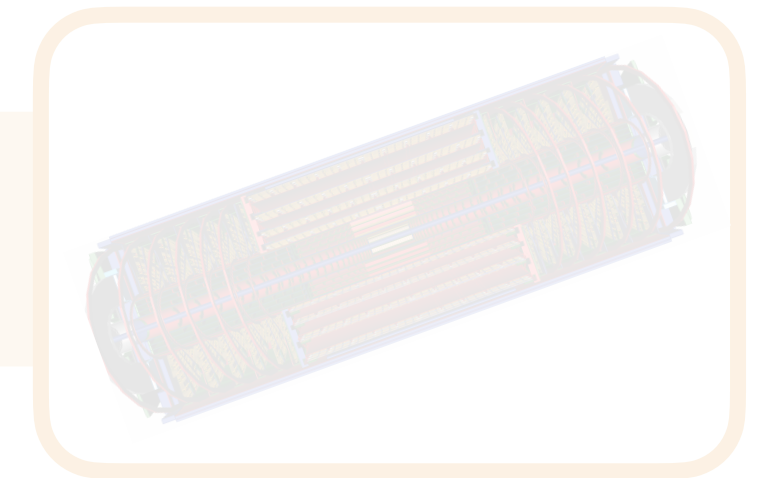
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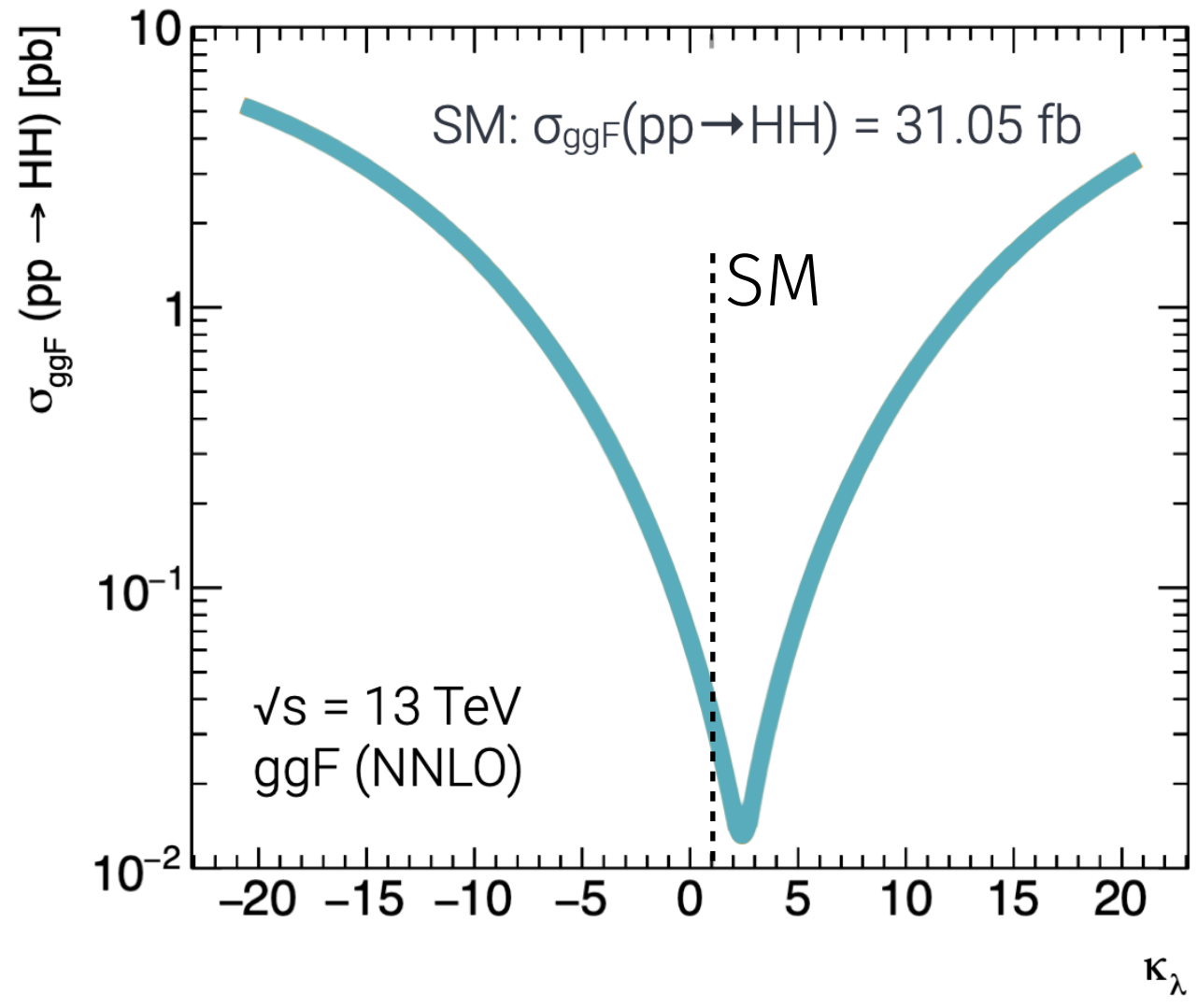
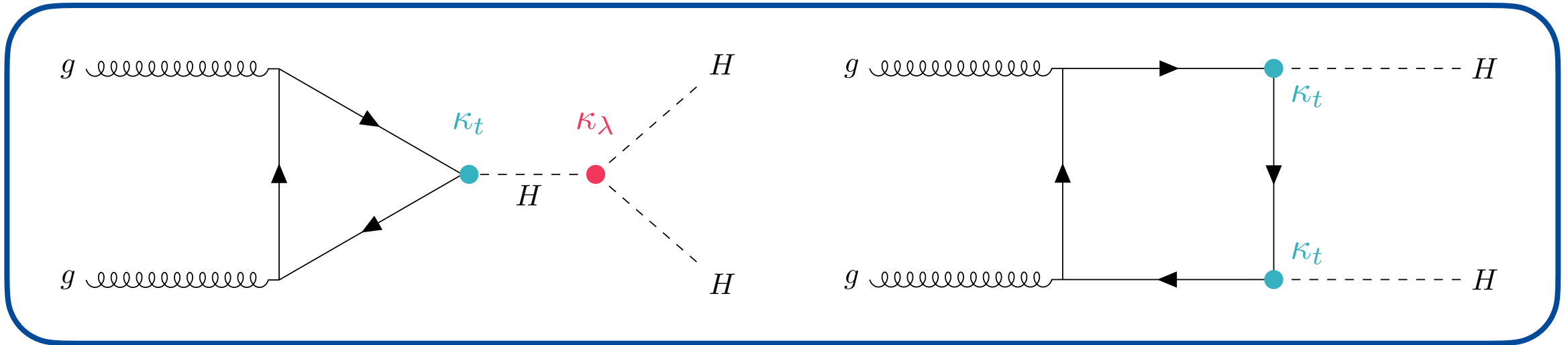
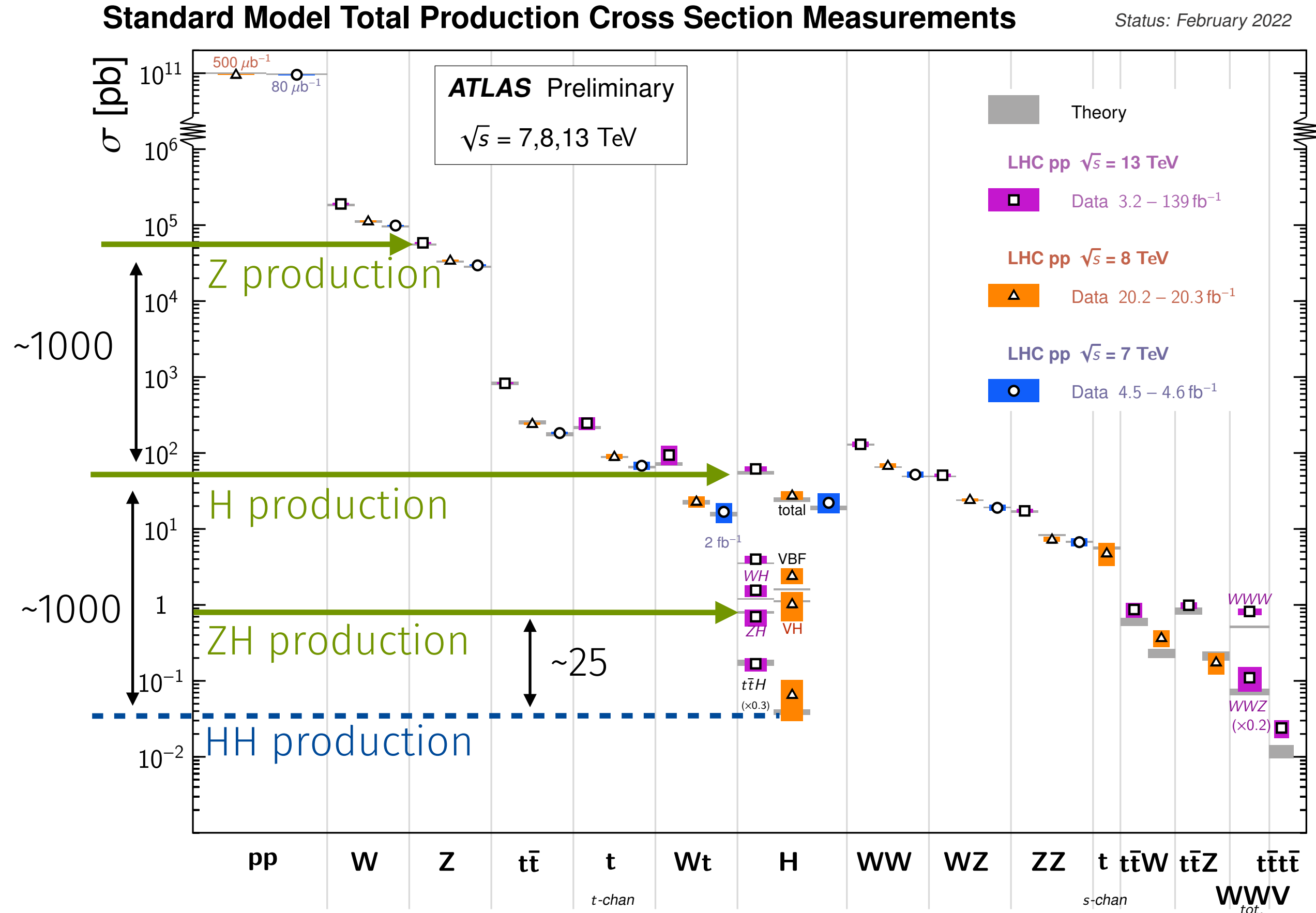
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How to look for HH production?

- ▶ Same production modes as for single Higgs production: ggF, VBF, VH, ttH, ...
- ▶ Small cross-section → **only ~ 4000 HH pairs** produced during LHC Run 2

ggF: $\sigma = 31^{+2.7}_{-7}$ fb @ NNLO FT approx. [13 TeV]



$$\kappa_\lambda = \frac{\text{measured self-coupling}}{\text{SM prediction}}$$

Larger values of $|\kappa_\lambda|$ enhance the HH production cross-section significantly



Which decay channel to pick?

- ▶ Same production modes as for single Higgs production: ggF, VBF, VH, ttH, ...
- ▶ Small cross-section → **only ~ 4000 HH pairs** produced during LHC Run 2
- ▶ Balance needed between high signal yield and high background rejection

BRs	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

The “golden” channels:

$H(\rightarrow bb)H(\rightarrow bb)$:
largest BR, but huge QCD multi-jet background

$H(\rightarrow bb)H(\rightarrow \tau\tau)$:
moderate BR, multi-jet rejection due to presence of τ

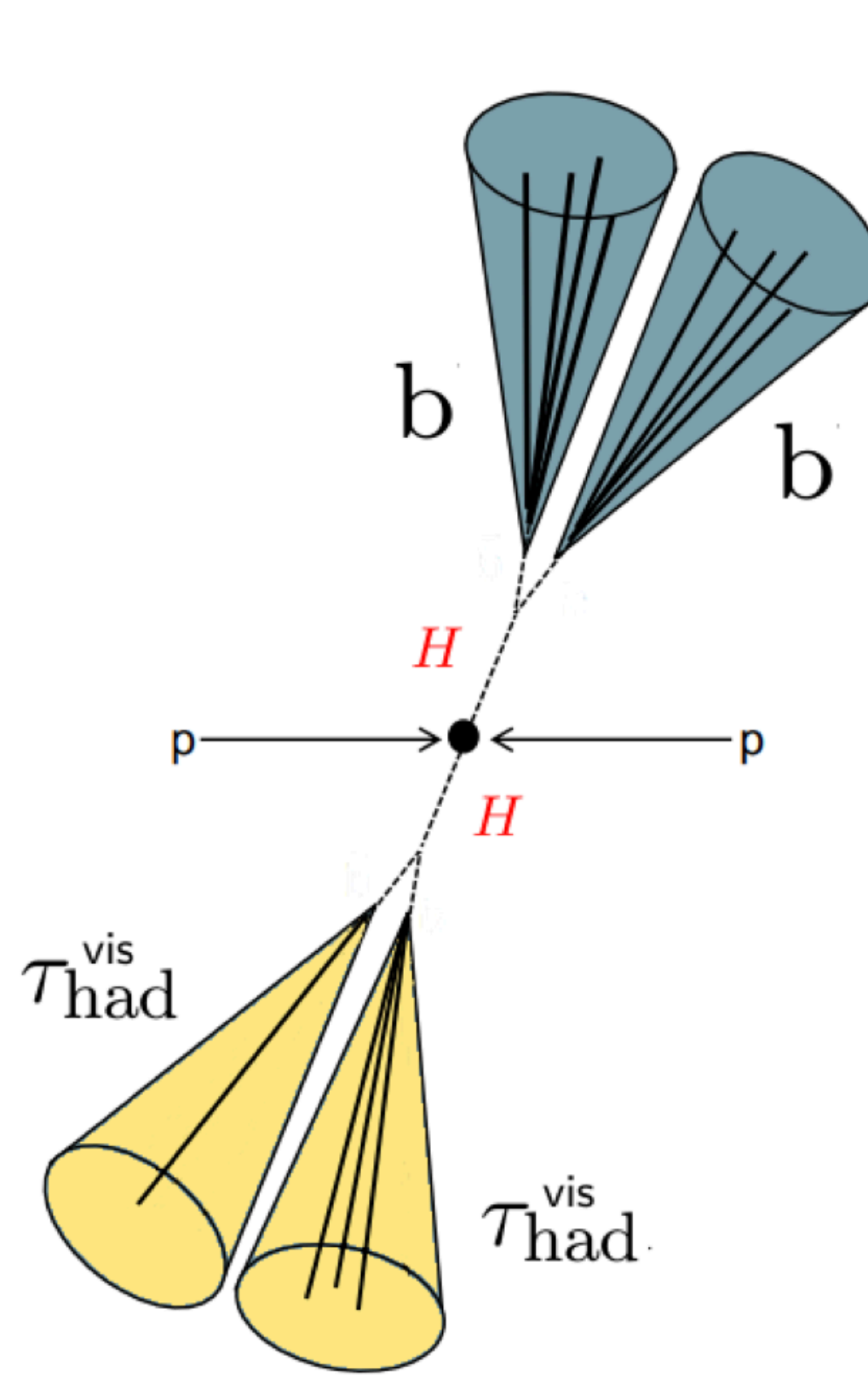
$H(\rightarrow bb)H(\rightarrow \gamma\gamma)$:
small BR, but very clean signature + benefits from $m_{\gamma\gamma}$ resolution

Most sensitive channels all require at least one $H \rightarrow bb$

The search for $pp \rightarrow HH \rightarrow bb\tau\tau$

My role:
 Main analyser $\tau_{had}\tau_{had}$, 2022-2024
 Analysis coordination since 2023

- Two analysis channels, depending on the τ decays: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$
 [$\tau_{lep}\tau_{lep}$ is included in the $pp \rightarrow HH \rightarrow bbl\ell$ analysis]



$\tau_{had}\tau_{had}$

$\tau_{had}\tau_{had}$

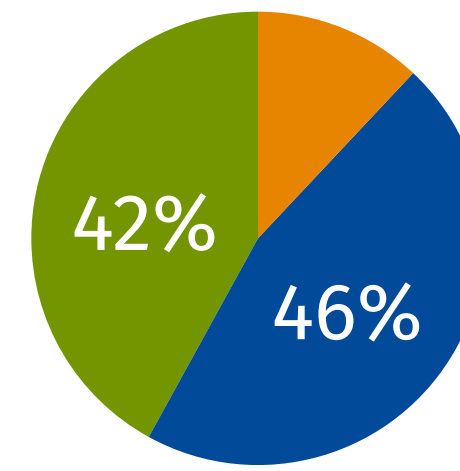
single and di- τ_{had} triggers

exactly two τ_{had}

0 electrons/muons

exactly two b-tagged jets

👎 difficult trigger strategy
 👍 lower backgrounds
 👍 better di- τ resolution



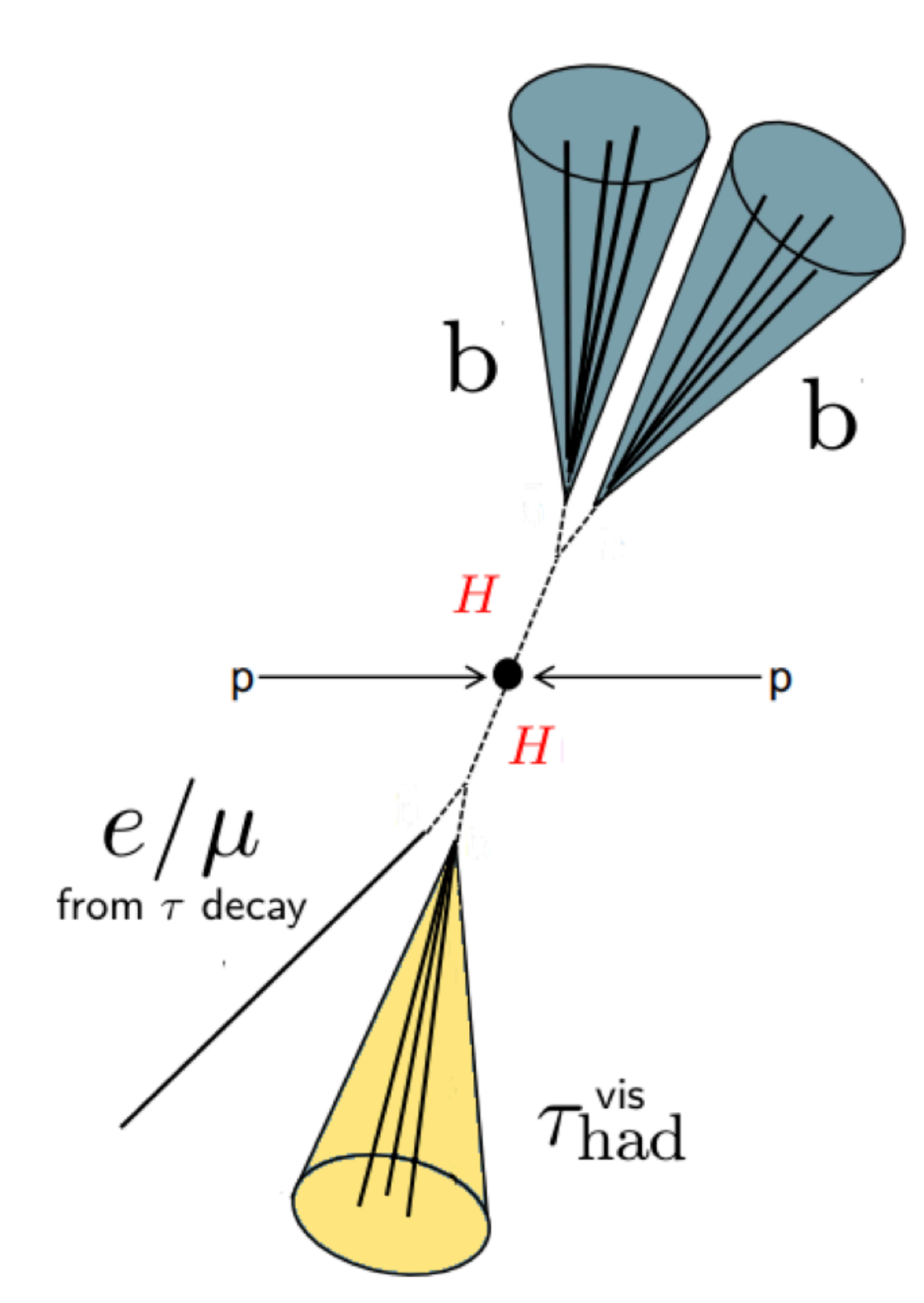
$\tau_{lep}\tau_{had}$

single e/μ triggers

exactly one τ_{had}

1 electron or 1 muon

👍 better to trigger on
 👎 larger backgrounds



$\tau_{lep}\tau_{had}$

[[Phys. Rev. D 110 \(2024\) 032012](#)]

with F. Haslbeck (then Oxford, now CERN)

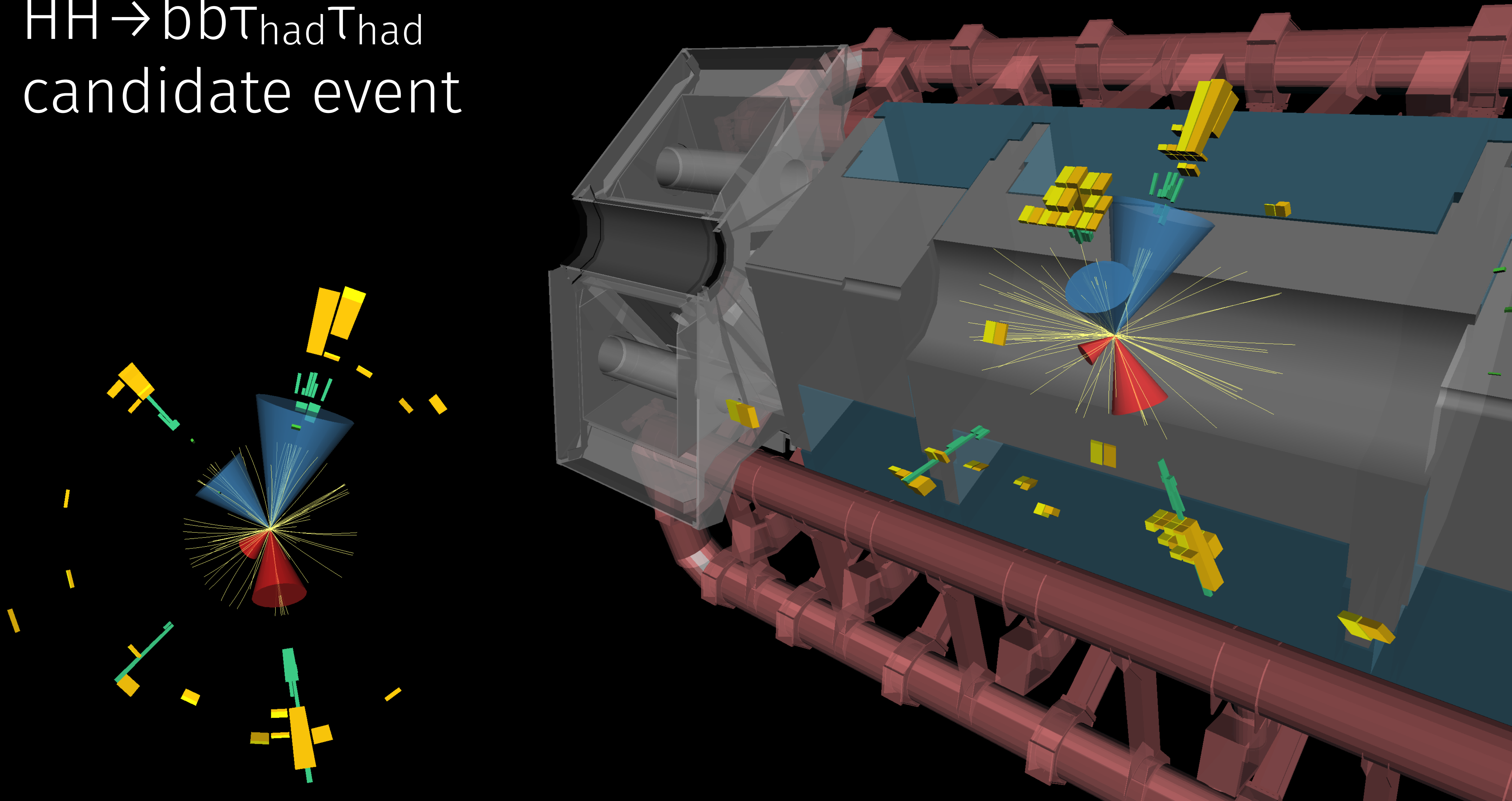
Brian Moser

Does the Higgs boson wear a Mexican-hat?

14/05/2026



$HH \rightarrow bb\tau_{\text{had}}\tau_{\text{had}}$
candidate event



Main backgrounds and how to control them

Main backgrounds:

- ttbar
- Z+ heavy flavour jets

dedicated control region

- single top
- single Higgs
- diboson

from simulation

- ttbar with jet $\rightarrow \tau_{\text{had}}$ fakes
- QCD multijet with jet $\rightarrow \tau_{\text{had}}$ fakes

data-driven

Example regions:

had-had high- m_{HH} SR

$\sim 450 \times \text{HH}$

$\sim 160 \times \text{HH}$

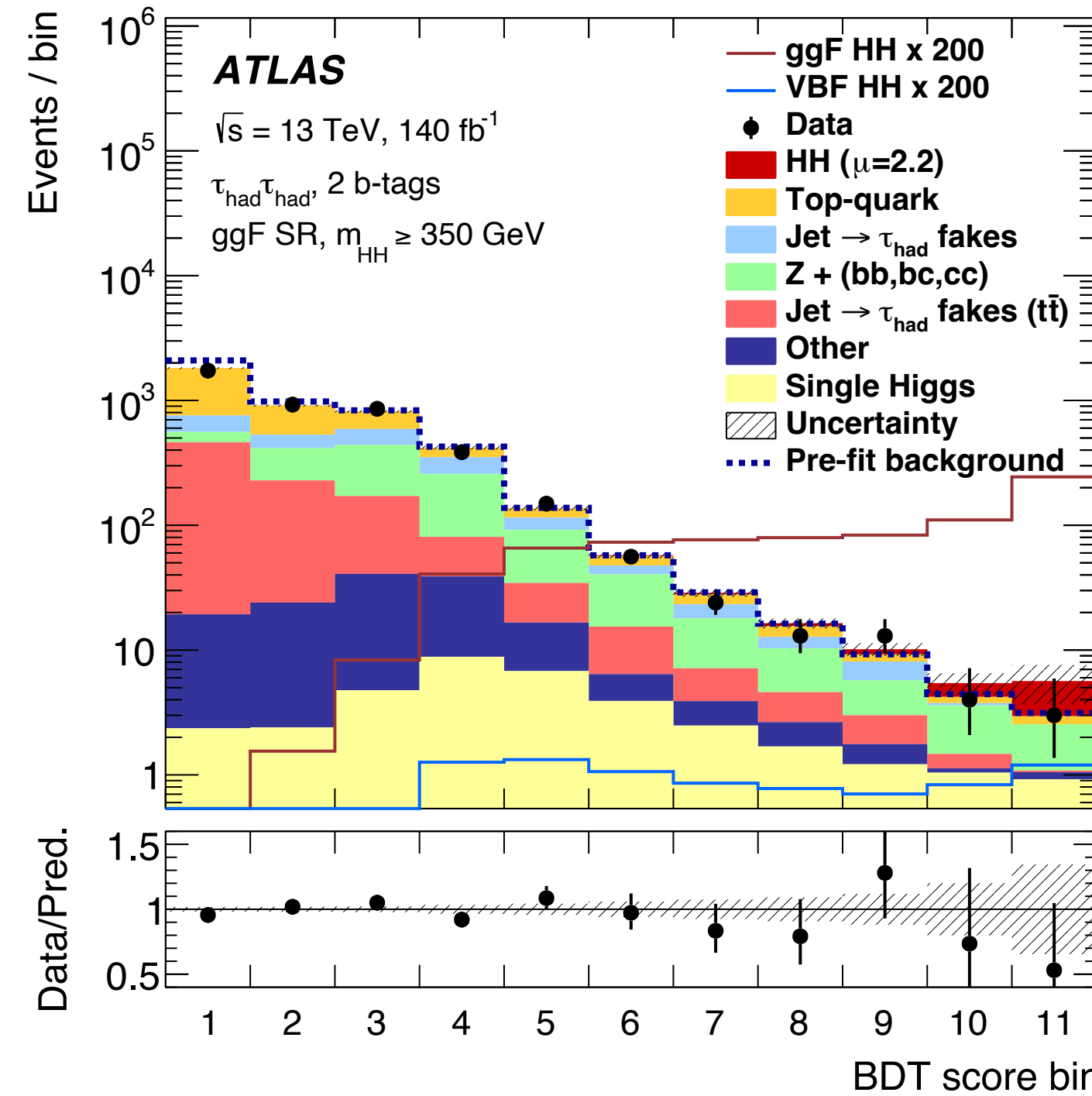
$\sim 40 \times \text{HH}$

$\sim 10 \times \text{HH}$

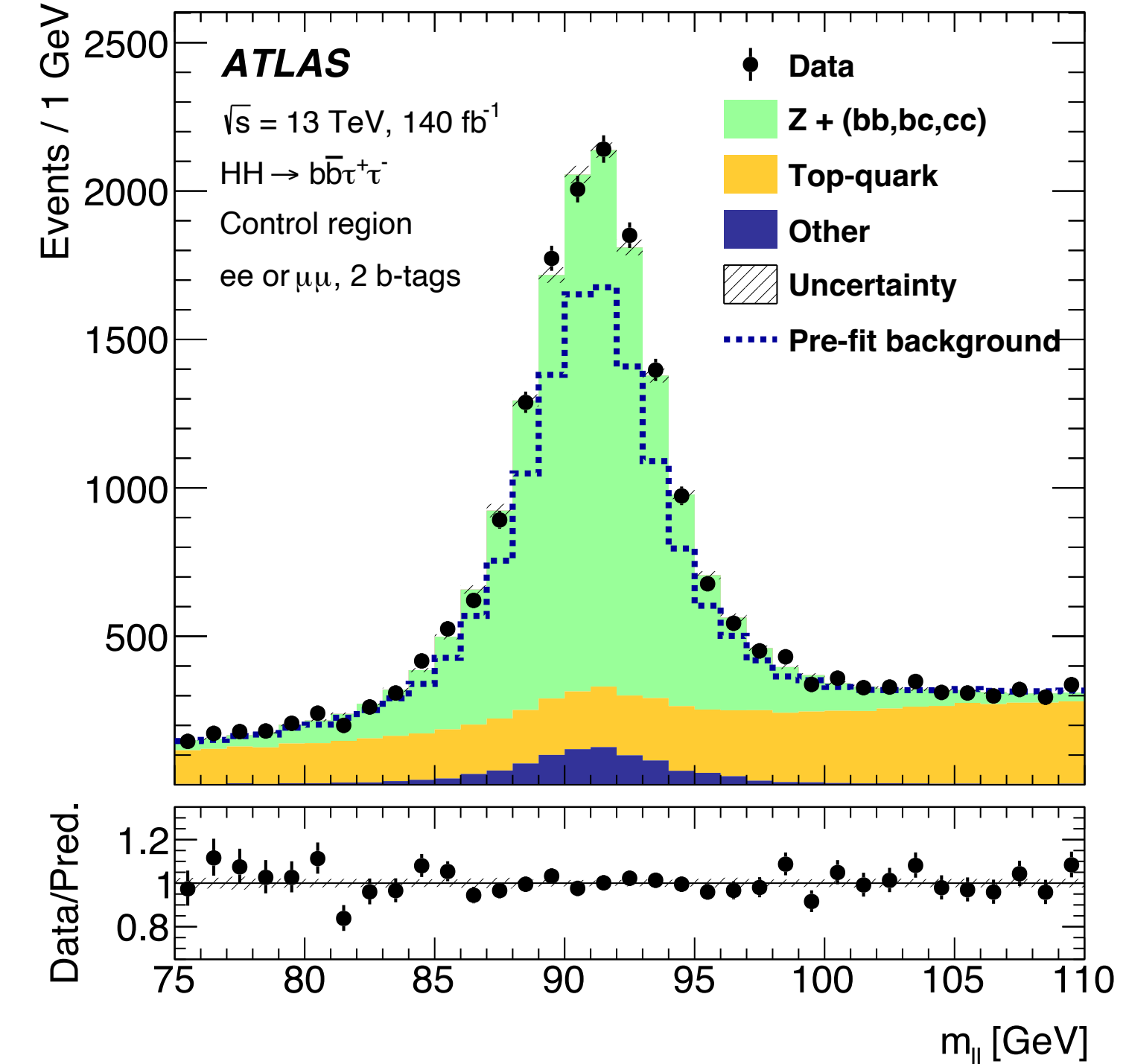
$\sim 5 \times \text{HH}$

$\sim 250 \times \text{HH}$

$\sim 150 \times \text{HH}$



Z+hf region



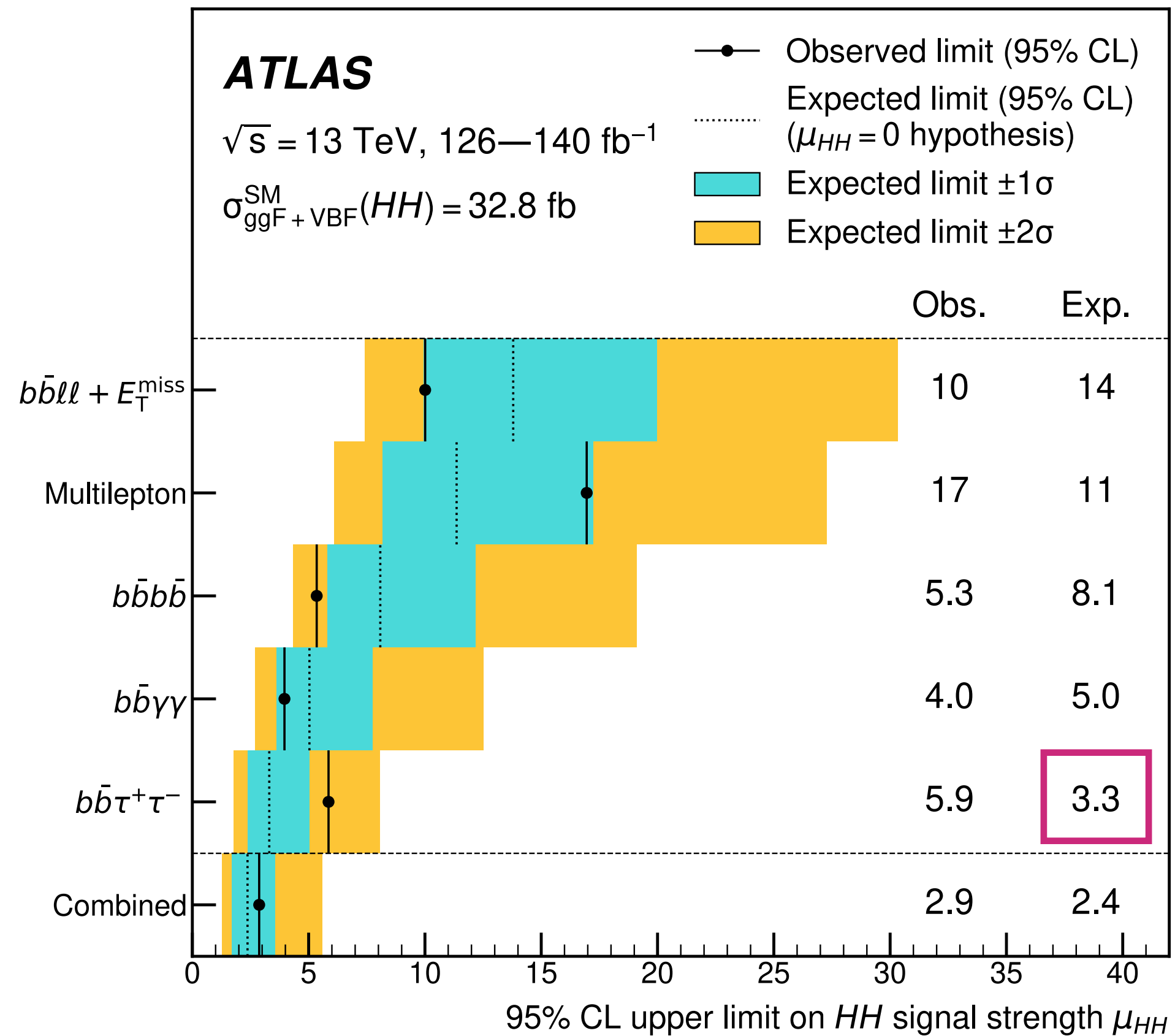
Name of the game:

Signal vs. background discrimination
 \rightarrow multivariate analysis methods

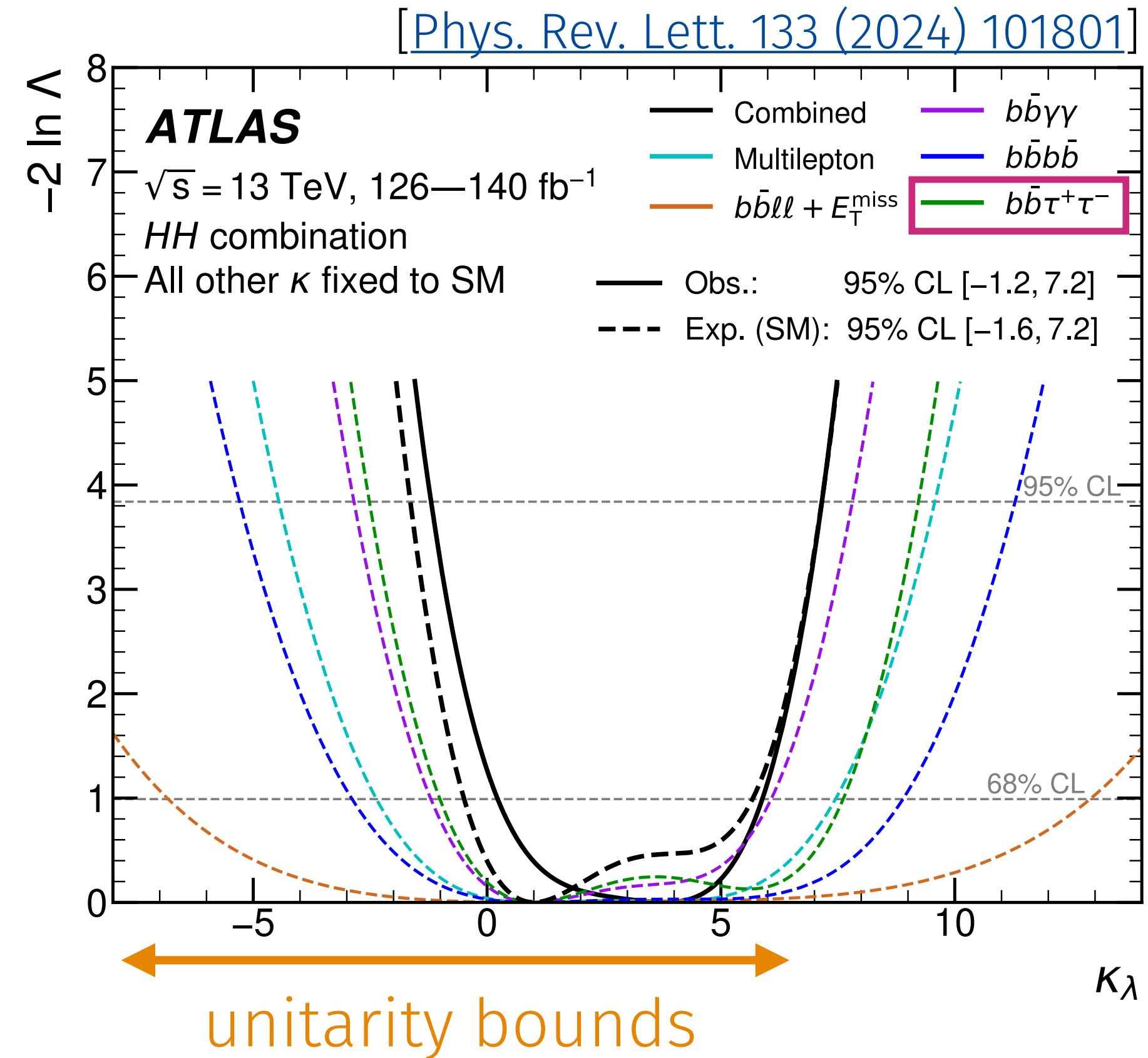


The results at one glance

$pp \rightarrow HH \rightarrow bb\tau\tau$ signal strength $< 5.9 \times \text{SM}$ @ 95% CL [3.3 expected]

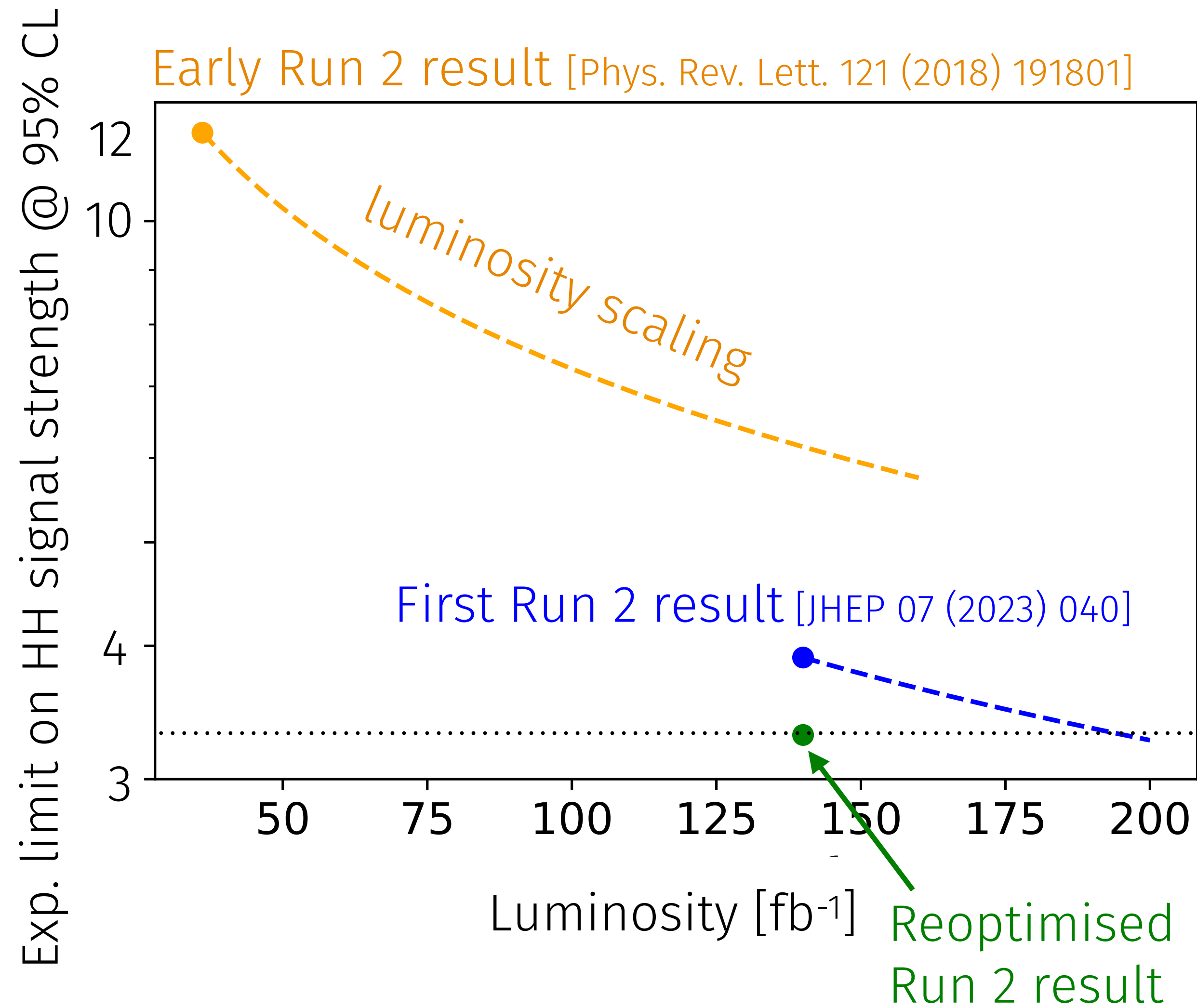


$HH \rightarrow bb\tau\tau$ leading expected limit on HH signal strength



$HH \rightarrow bb\tau\tau$ best limits on lower κ_λ side

How did we get there?



First Run 2 result was a compromise between a resonant search for $X \rightarrow \text{HH}$ and the non-resonant (SM) search

Re-analysis of Run 2 with focus on the non-resonant part

- more granular event categorization
- improved bkg simulation
- improved MVA

15% improvement → equivalent of adding 30% more data (half a year of data taking)

We are constantly beating the simple luminosity-based scaling → Creativity paired with hard work is certainly worth it

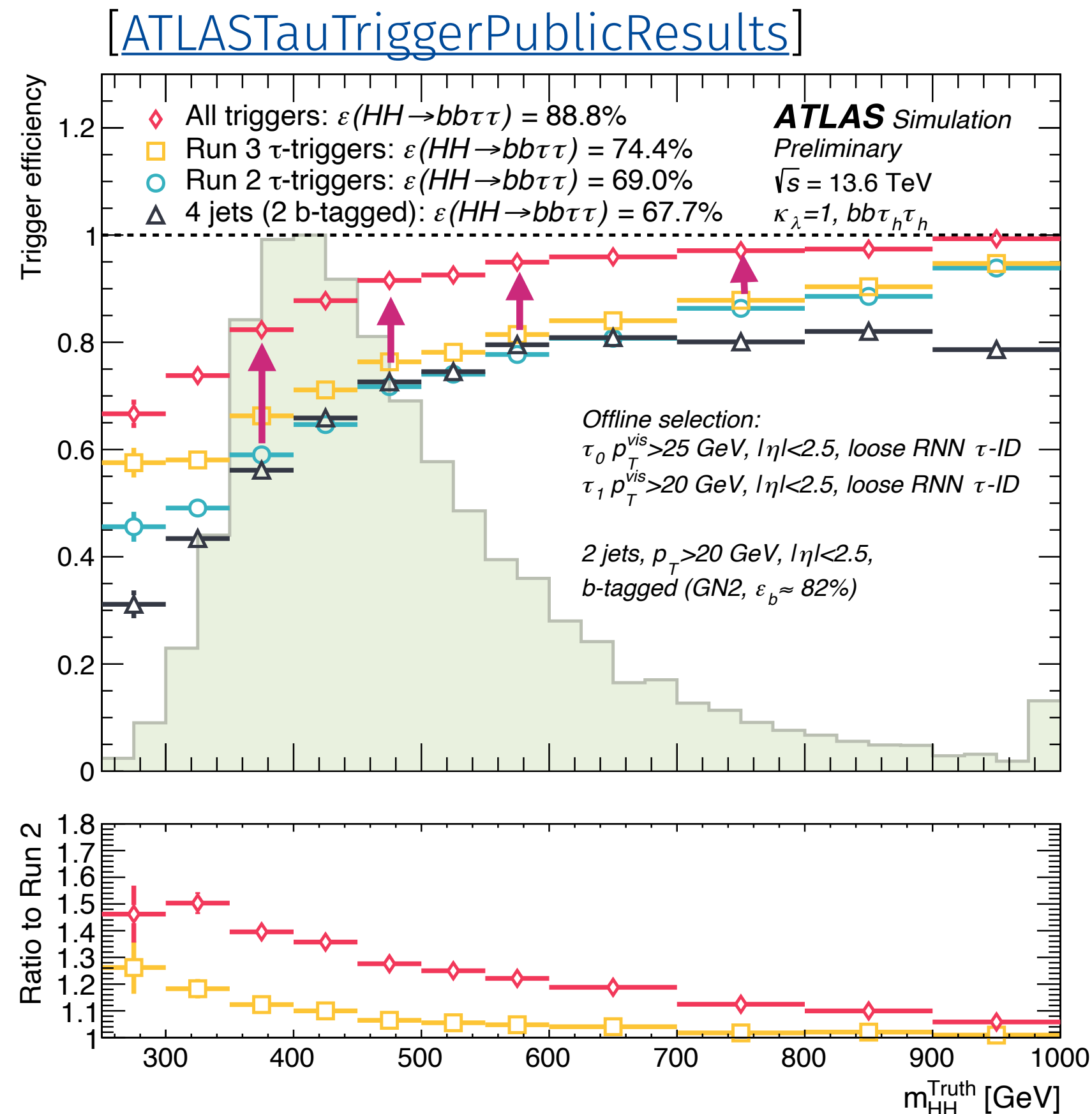
Where do we go from here?

- ▶ Run 3 of the LHC ongoing since 2022 (until mid-2026): will triple the available pp collision data set
- ▶ Comes hand-in-hand with analysis improvements [unfortunately, nothing public yet]

New **triggers** to improve the overall signal efficiency

40% higher efficiency at low m_{HH}

20% higher efficiency at high m_{HH}



[G. Rupnik [master thesis](#)]

ALMA MATER STUDIORUM · UNIVERSITY OF BOLOGNA

School of Science
 Department of Physics and Astronomy
 Master Degree in Physics

**A Transformer and Novel Triggers
 for the Search for Higgs Boson Pair
 Production in the $b\bar{b}\tau^+\tau^-$ Final State
 with the ATLAS Detector**

Supervisor:
 Prof. Maximiliano Sioli

Submitted by:
 Giovanni Rupnik Boero

Co-supervisors:
 Dr. Brian Moser
 Prof. Valerio Dao

CERN-THESIS-2024-328
 / 2024

Terminal



Where do we go from here?

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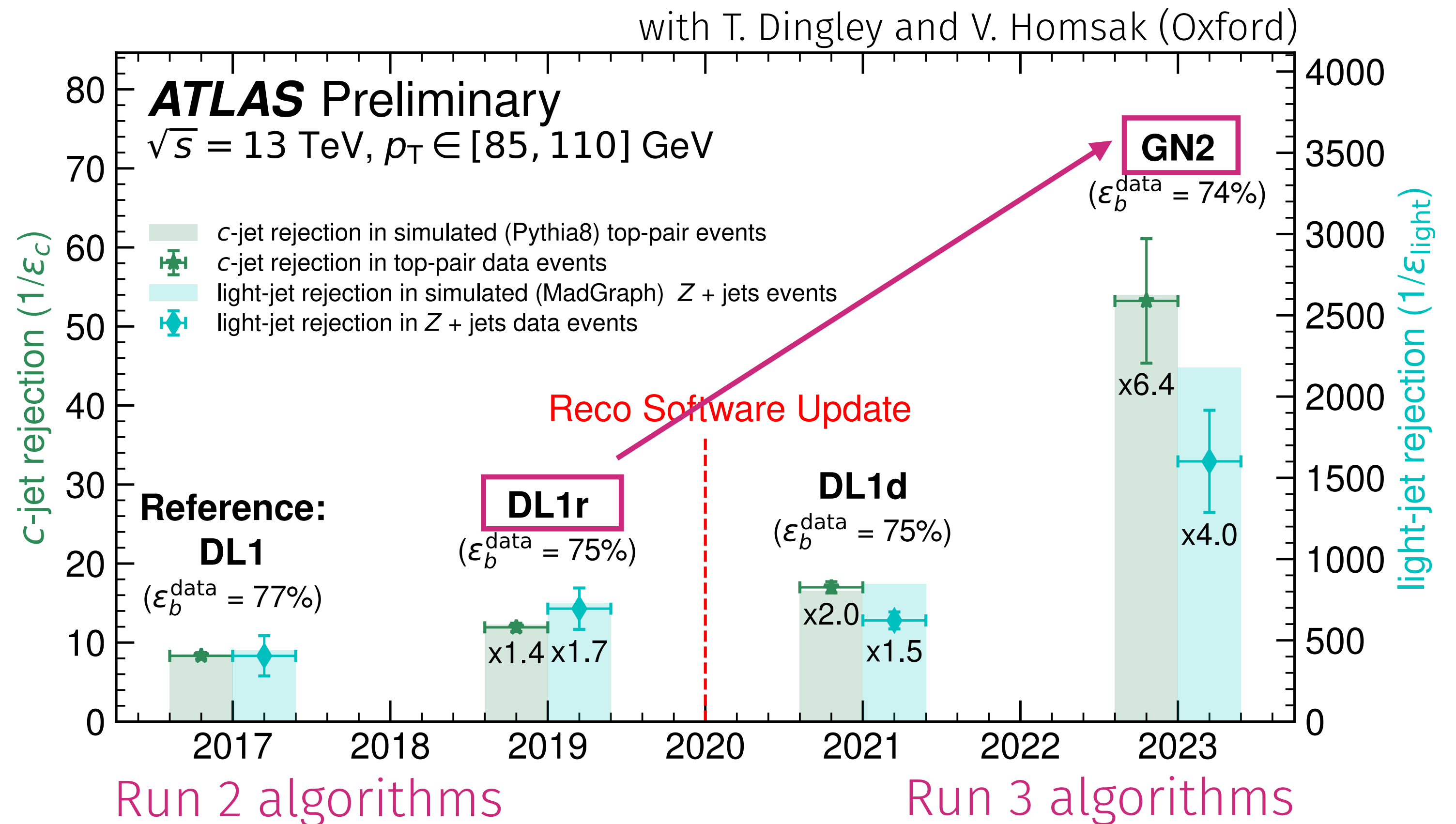
Transformer-based networks are revolutionizing **b-tagging**

What is the rate of c-jets that will be mistakenly identified as b-jets?

Significant improvement in background rejection at the same signal efficiency

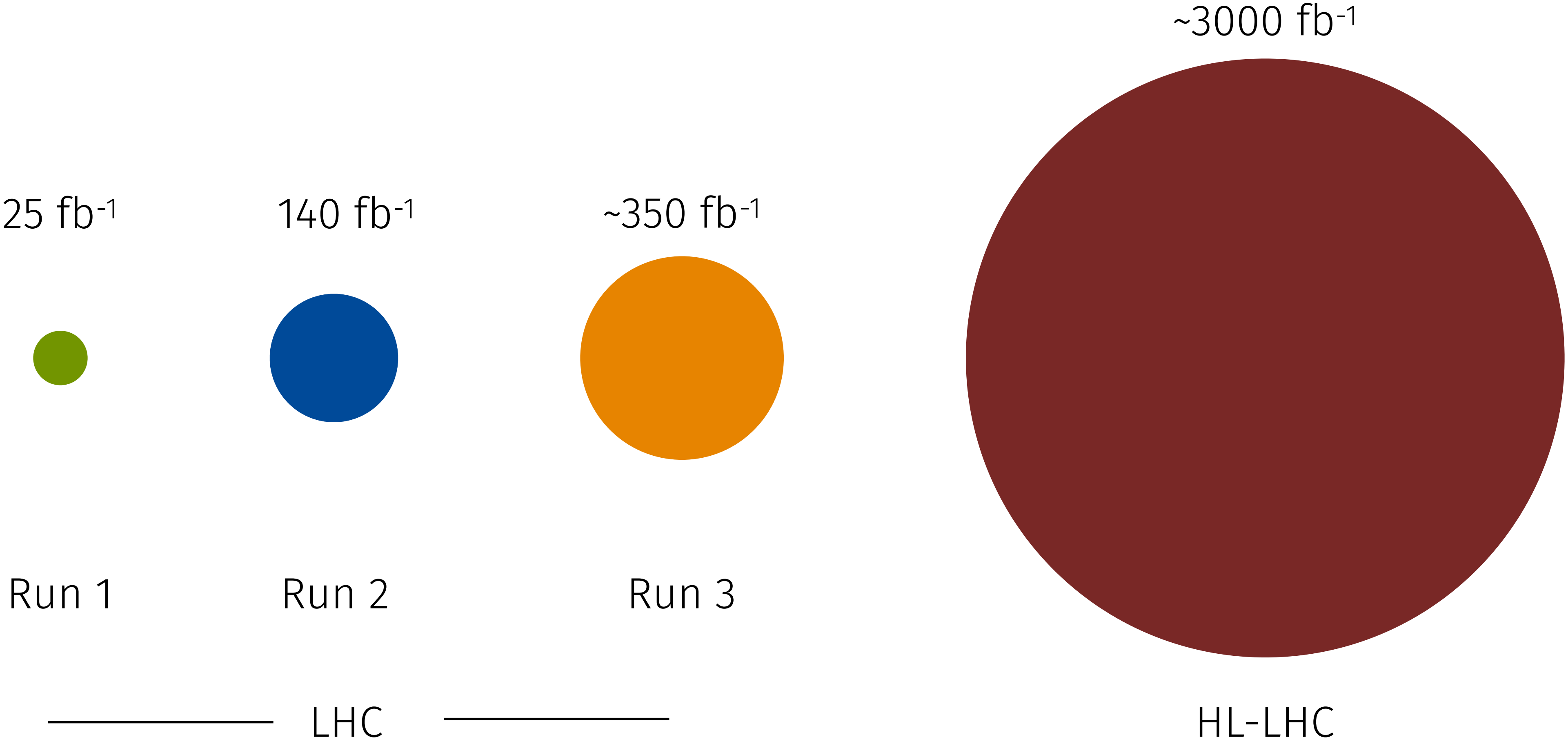
Seen in actual data (= calibrated)!

My role:
calibration convener, 2023-2025



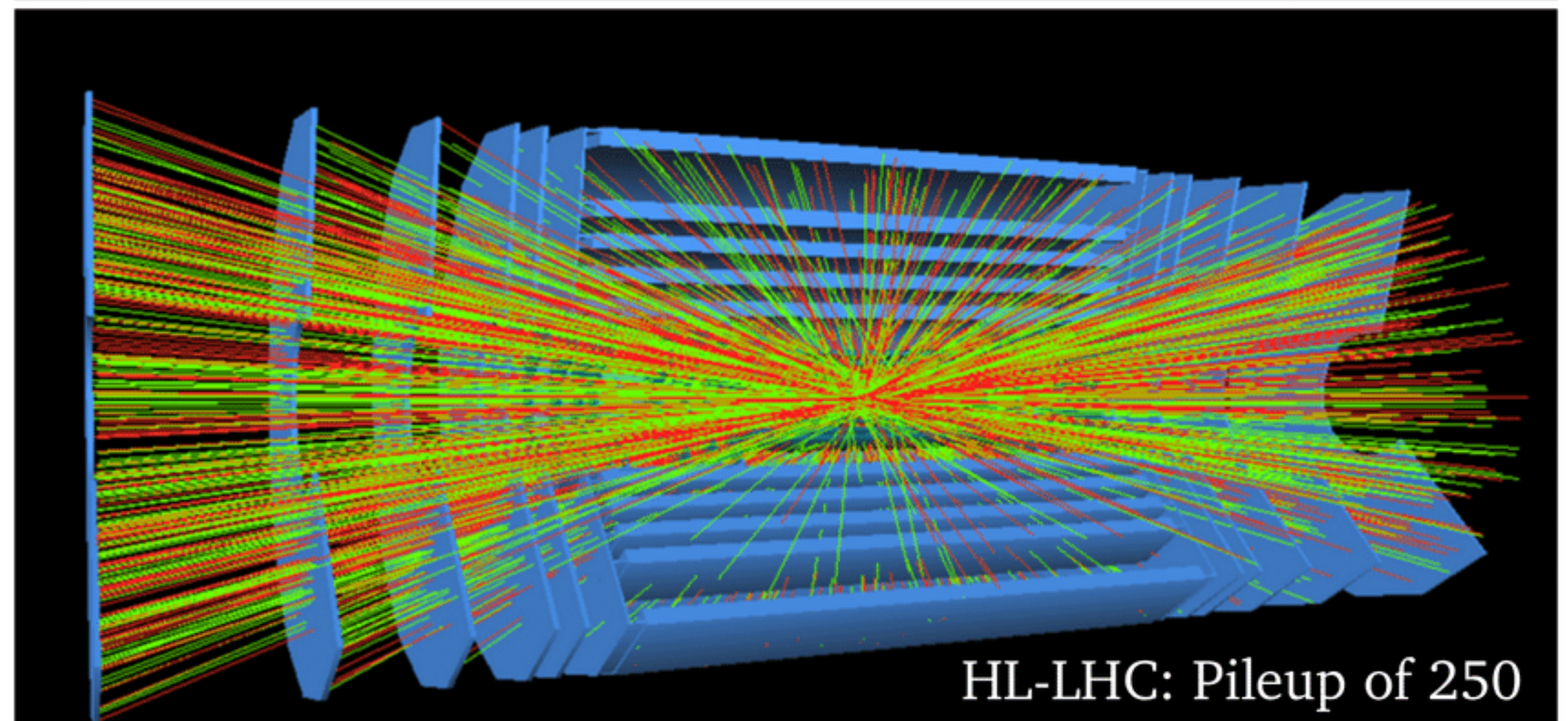
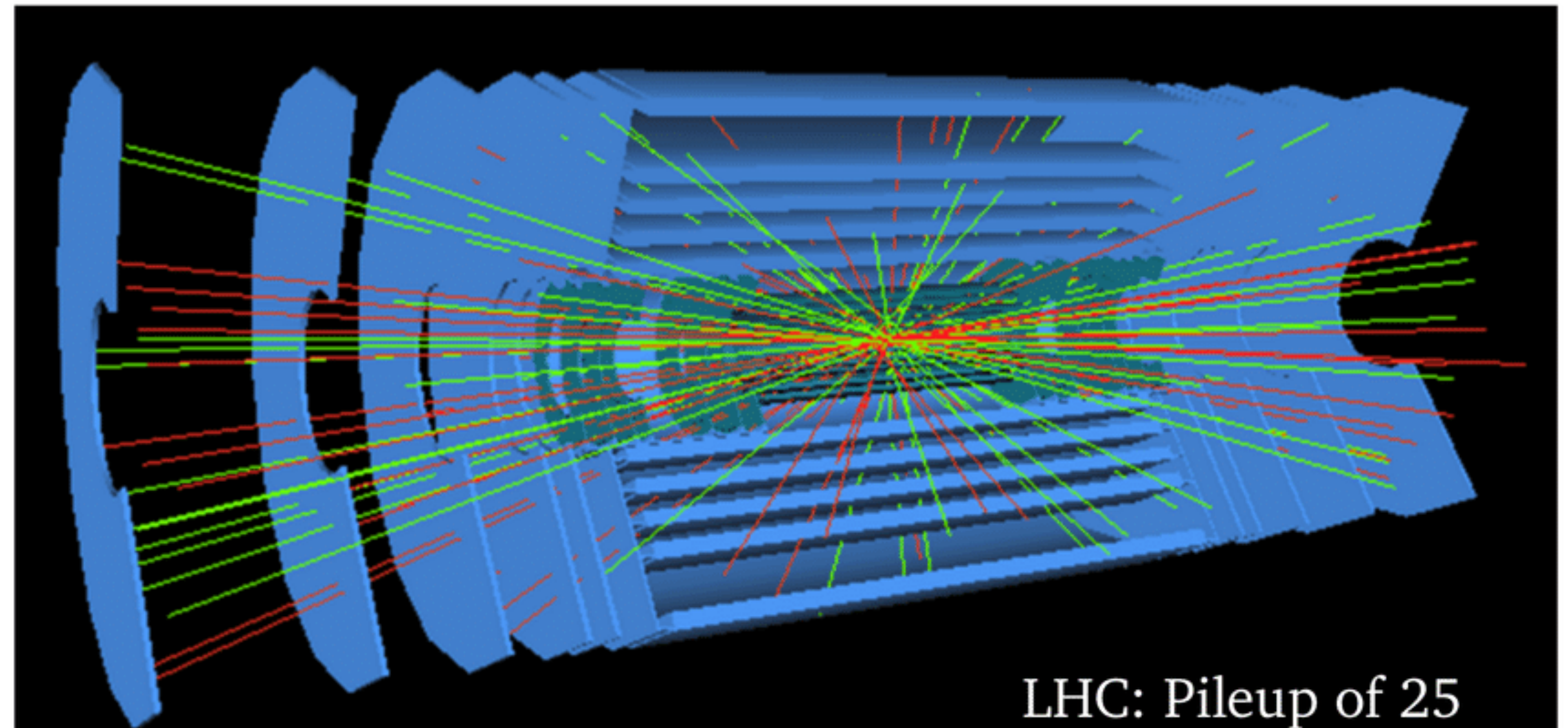
Ultimate HH precision with the HL-LHC dataset

Current searches for HH production are all **limited by the size of the pp collision dataset**
→ large improvements expected from the high luminosity upgrade of the LHC (HL-LHC)



The ATLAS Inner Tracker Upgrade (ITk)

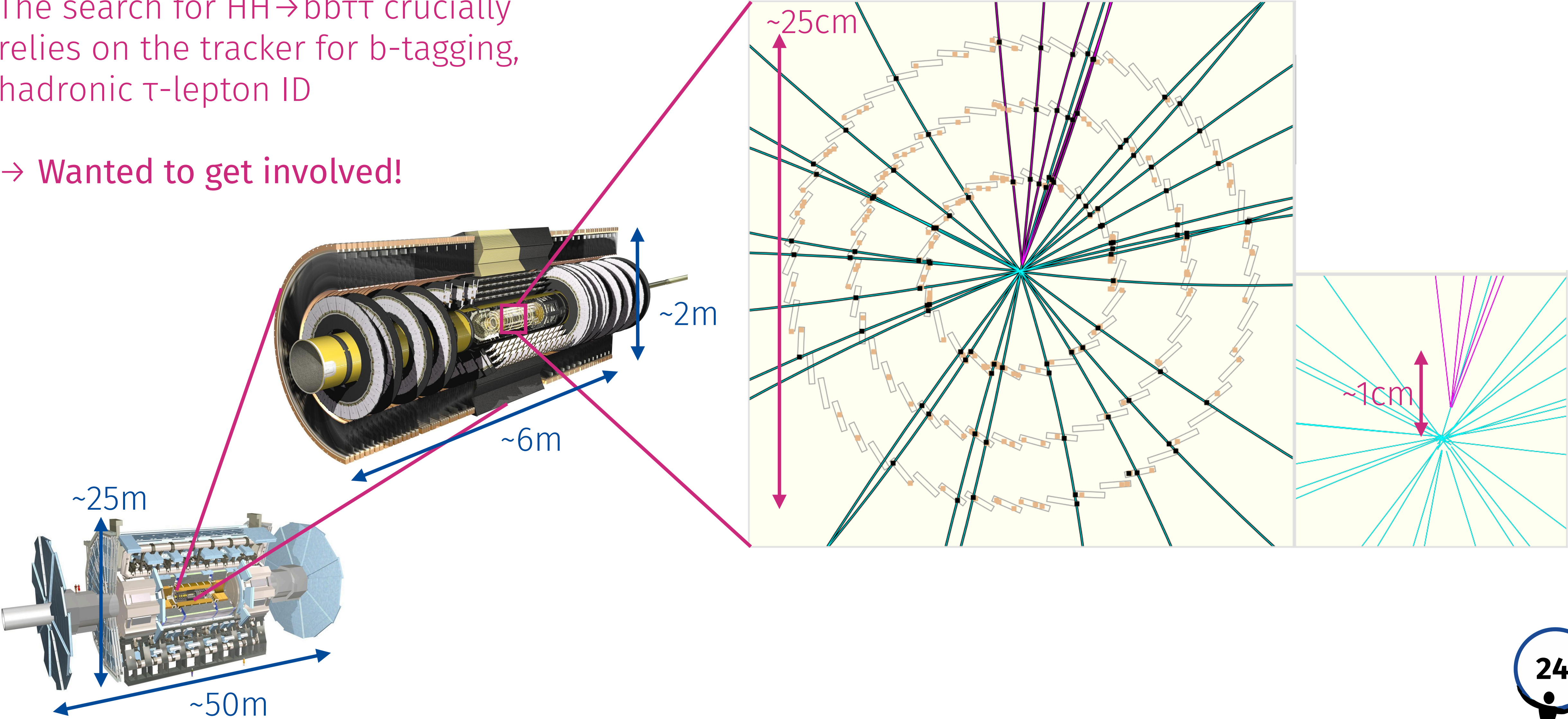
- ▶ LHC will increase the average number of collisions per bunch crossing from ~ 60 (Run 3) to ~ 200 (HL-LHC) to be able to deliver the 3000 fb^{-1}
- ▶ The current inner detector can not withstand these environments
- Novel **all-silicon tracker** to replace the full ATLAS inner detector
 - Radiation harder, more granular, increased coverage up to $|\eta| \leq 4$
 - Lower material budget to minimize multiple scattering
 - 5 innermost layers = pixel detectors
 - Novel serial powering scheme, bi-phase CO_2 cooling, ...



No ITk = no search for $HH \rightarrow bb\tau\tau$

The search for $HH \rightarrow bb\tau\tau$ crucially relies on the tracker for b-tagging, hadronic τ -lepton ID

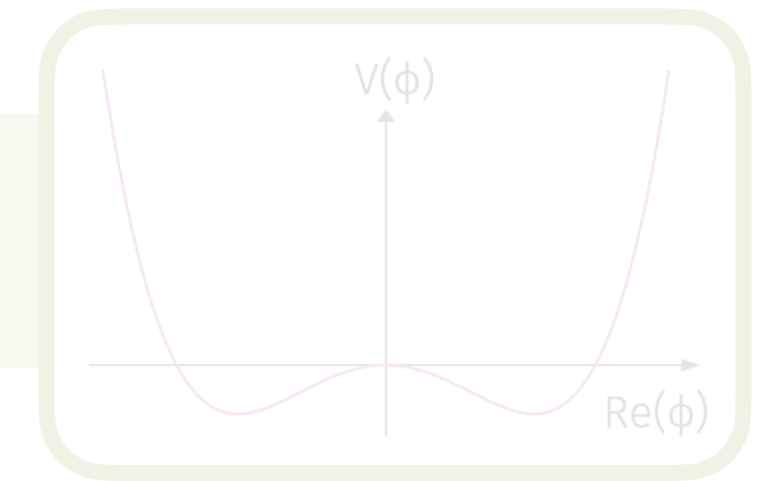
→ Wanted to get involved!



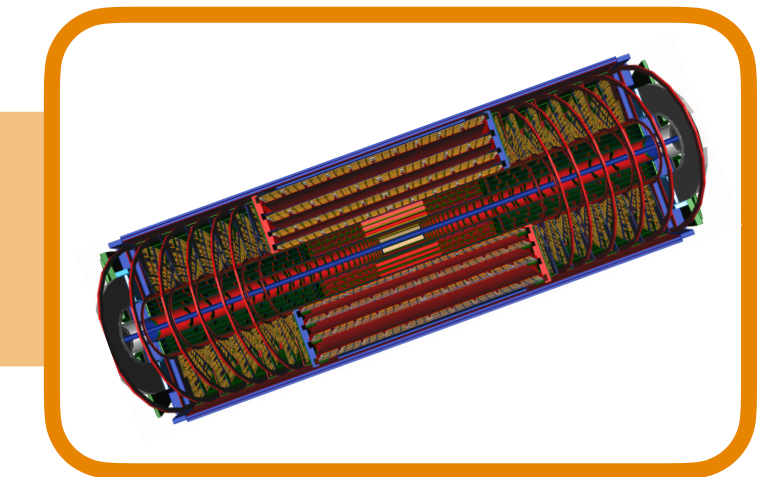
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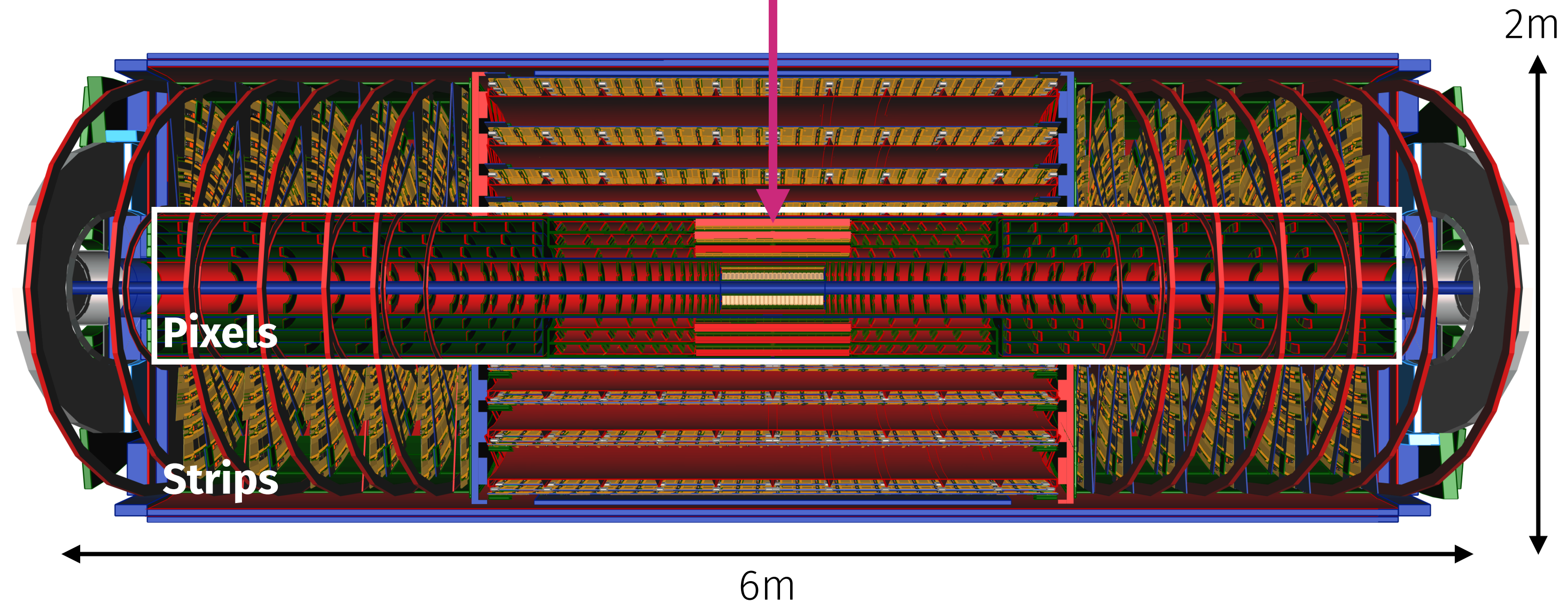
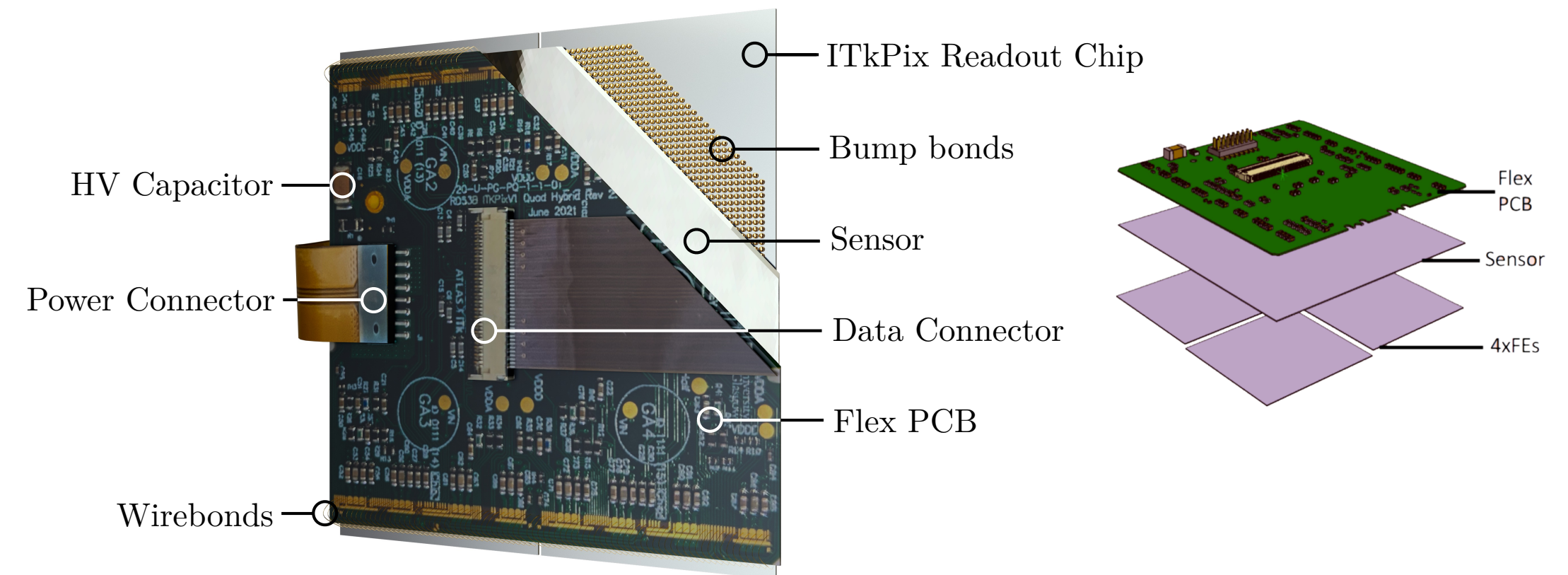


2. Building the new ATLAS pixel detector



From modules to the detector

- ▶ Need an intermediate step between individual module testing and building a full detector → **prototypes**

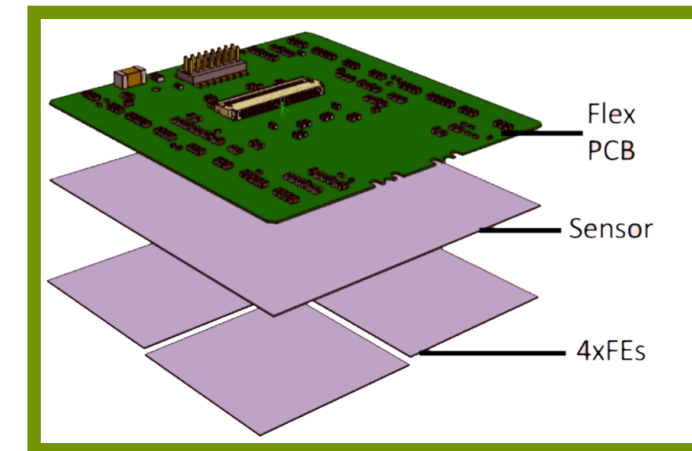


From modules to the detector via prototypes

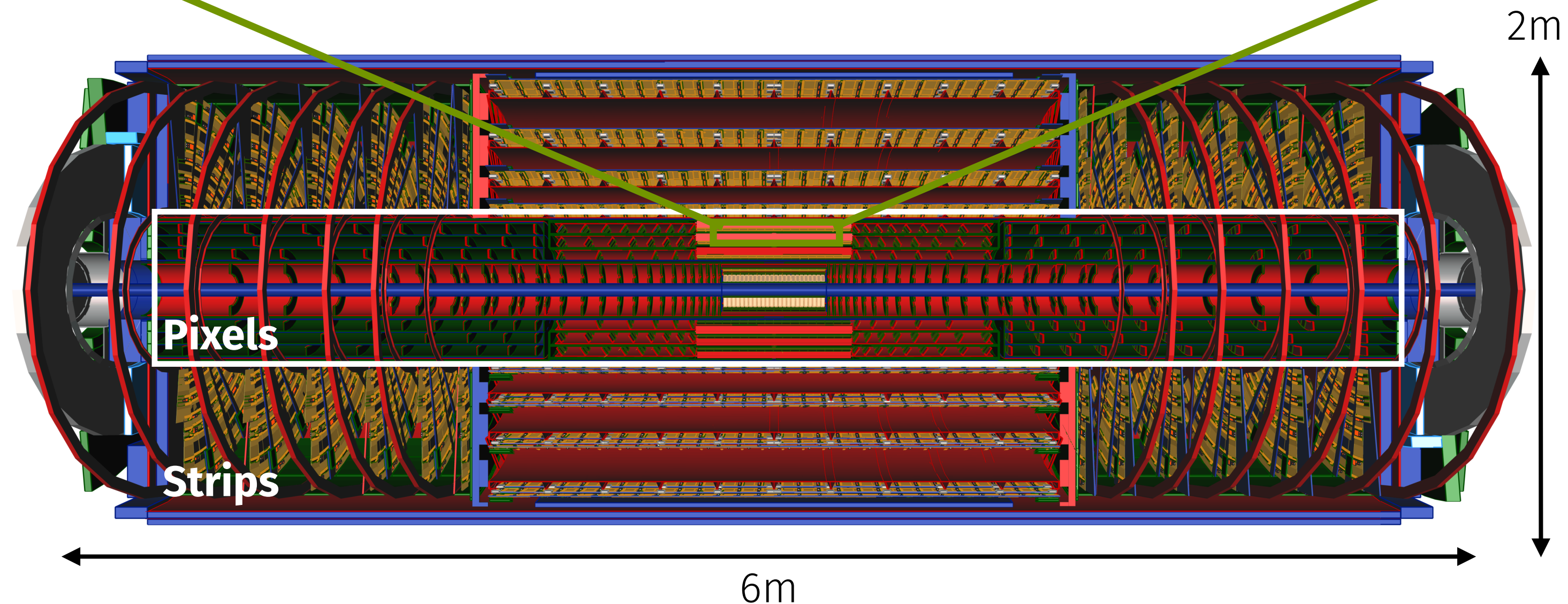
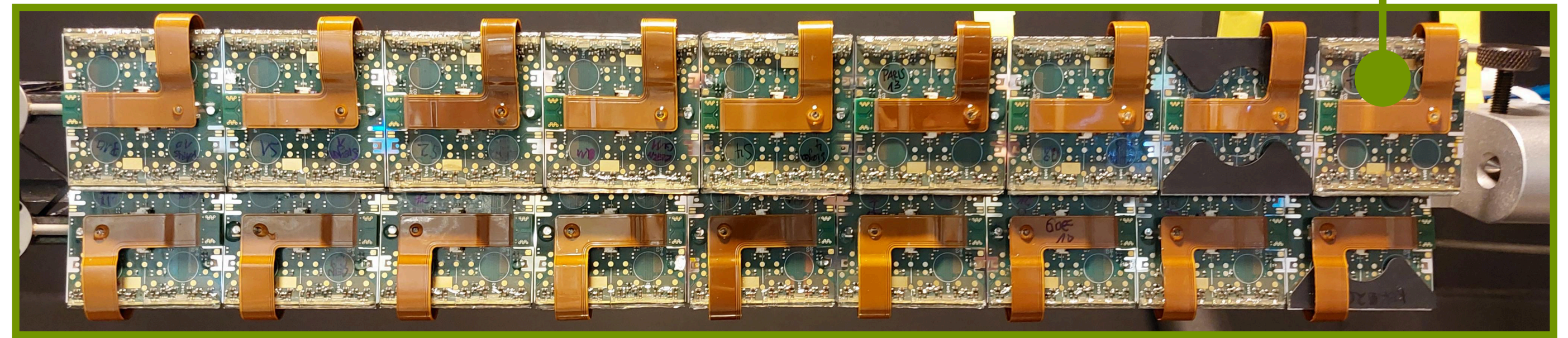
- ▶ Need an intermediate step between individual module testing and building a full detector → **prototypes**
- ▶ **Largest structure of ITk pixels that we could operate back then**
 - 18 quad modules
 - ~3% of the third pixel barrel layer, ~0.1% of the total detector

Many testing opportunities:

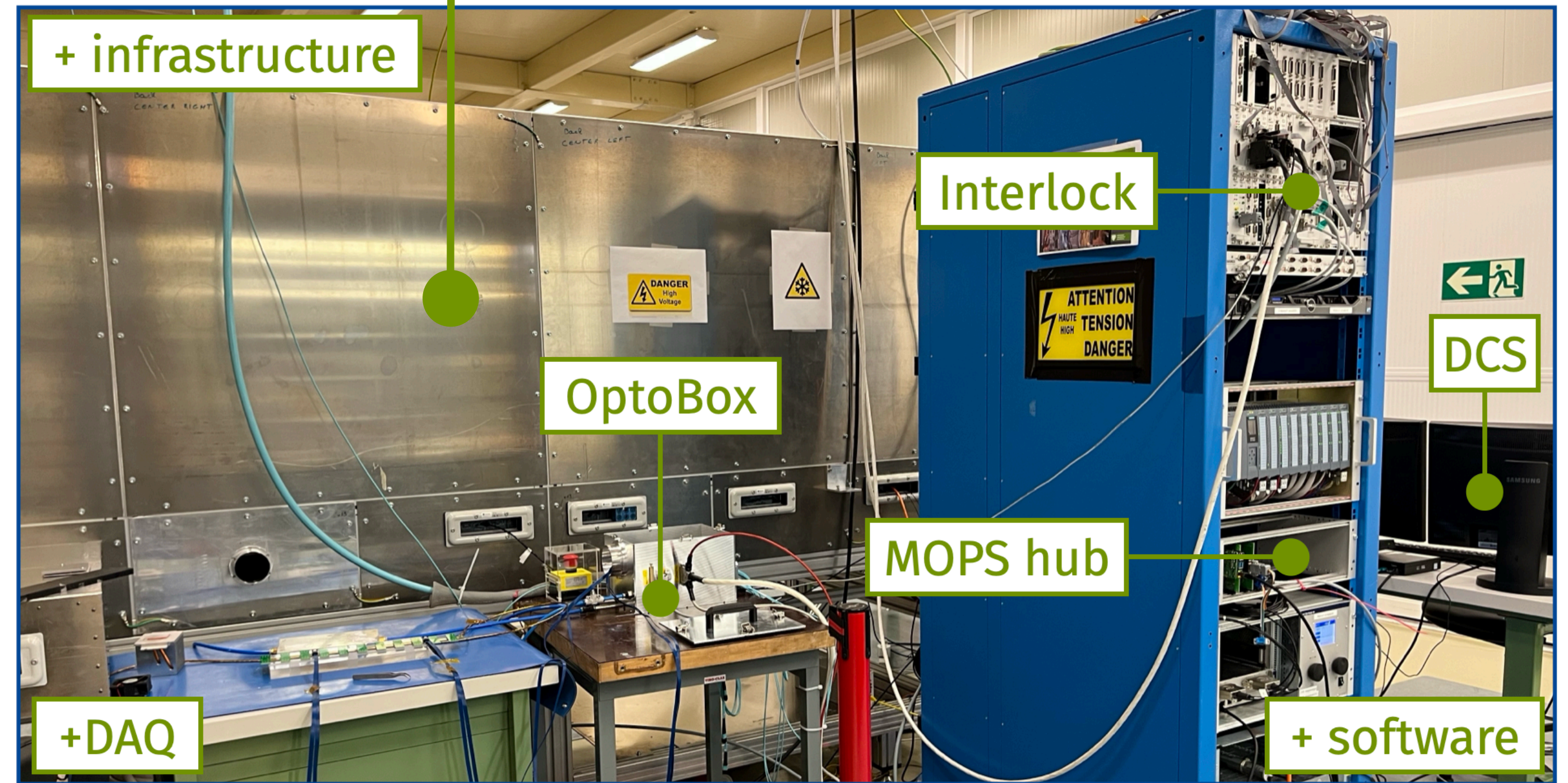
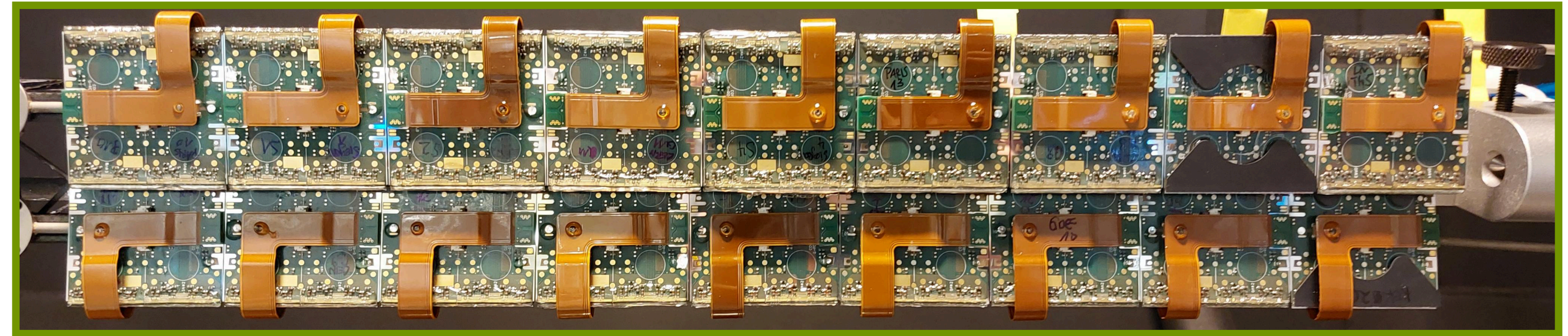
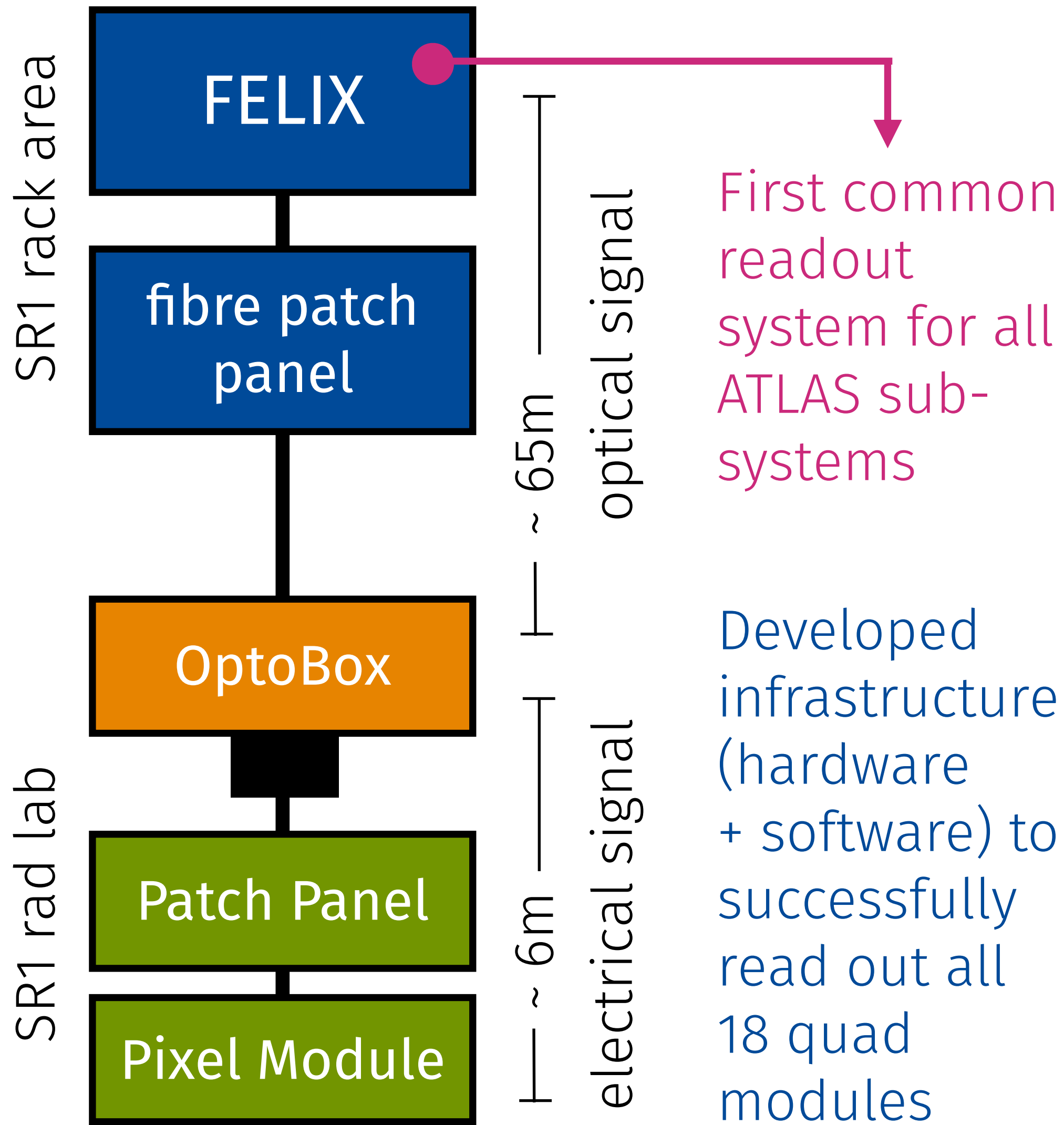
- Detect damages during loading procedure
- Test in realistic environment [services, readout system, interlock, detector control system, ...]



Local support prototype in the SR1 RadLab at Point 1, CERN

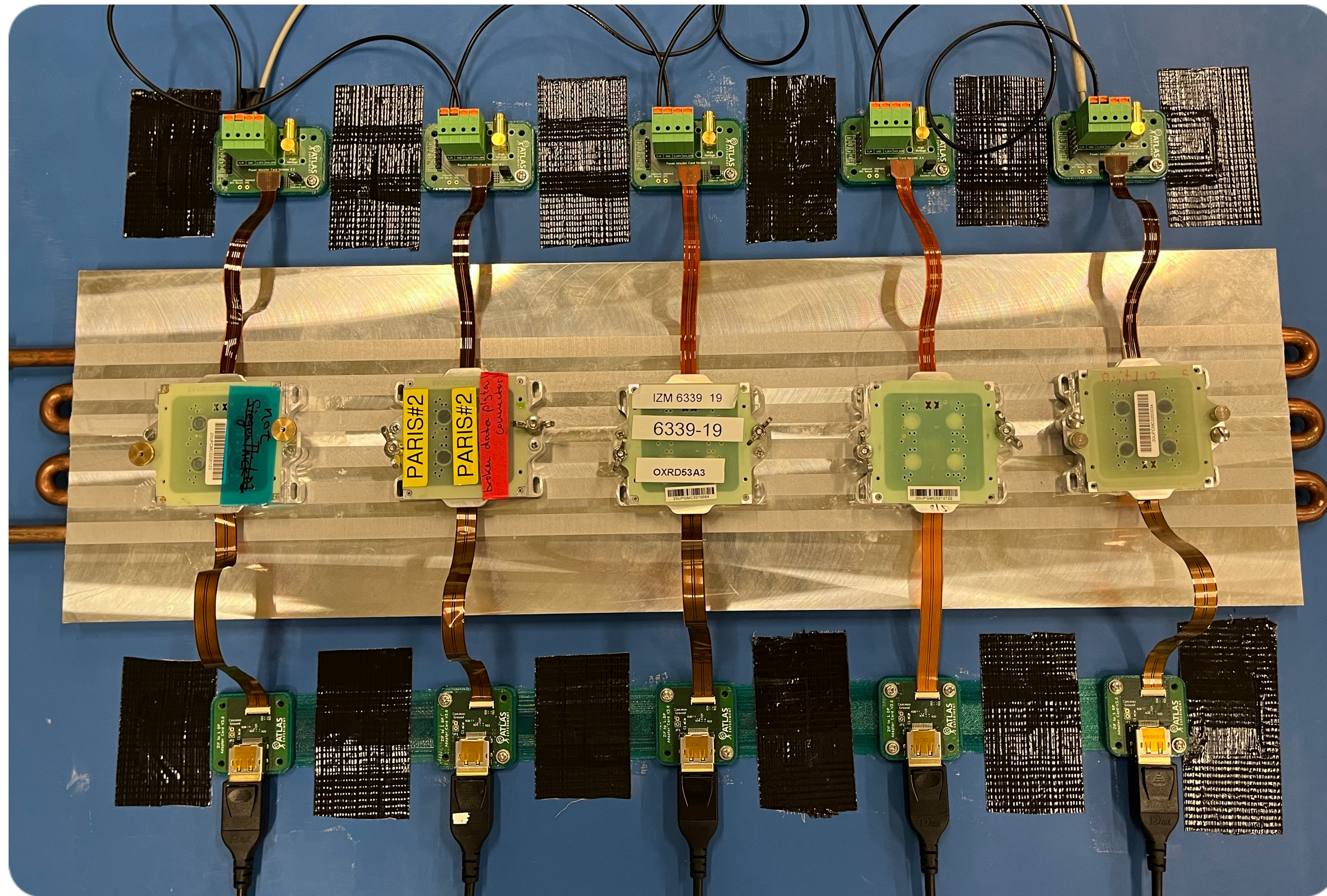


The SR1 pixel demonstrator at CERN

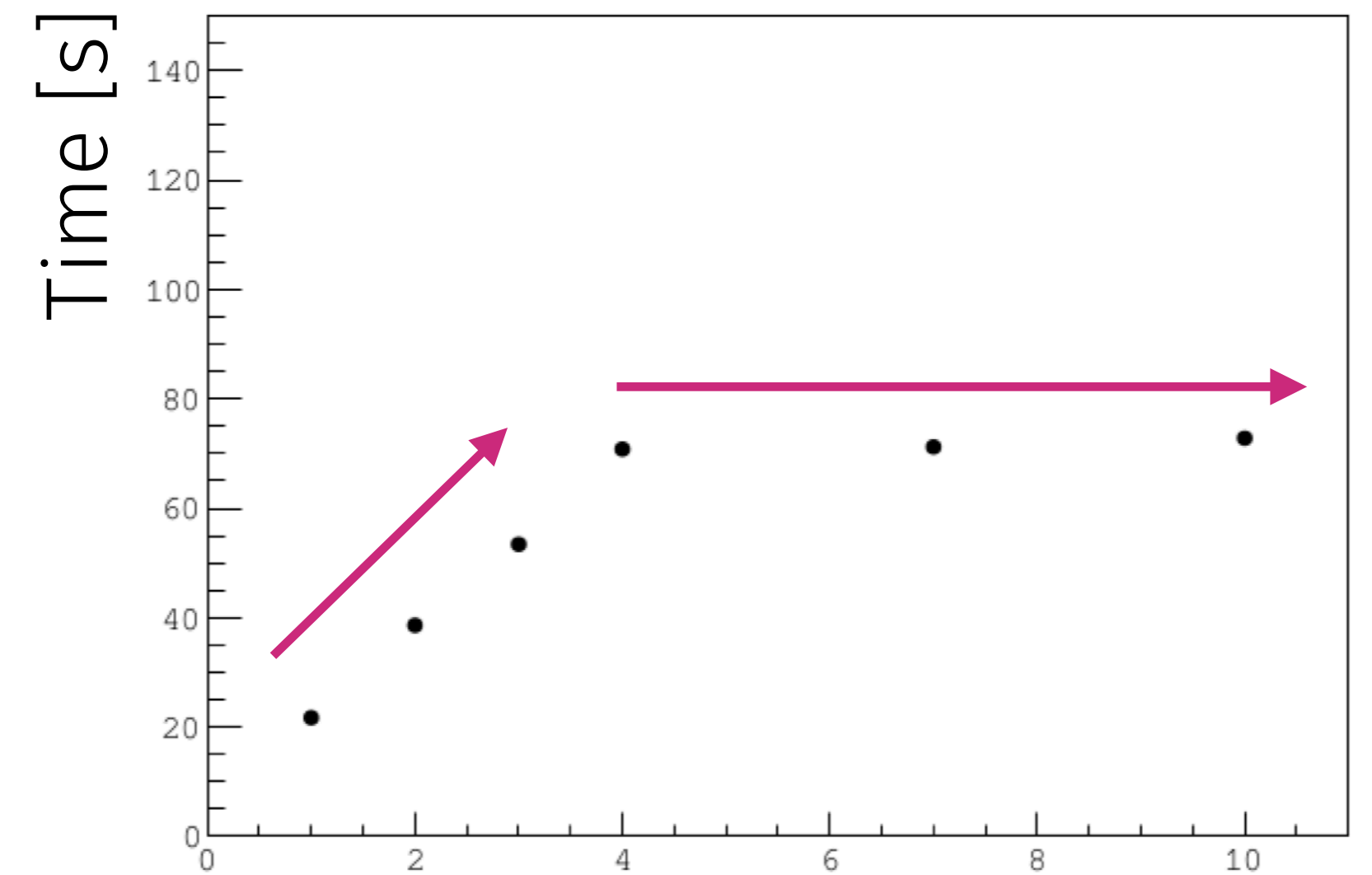


Further developments: multi-module DAQ setup

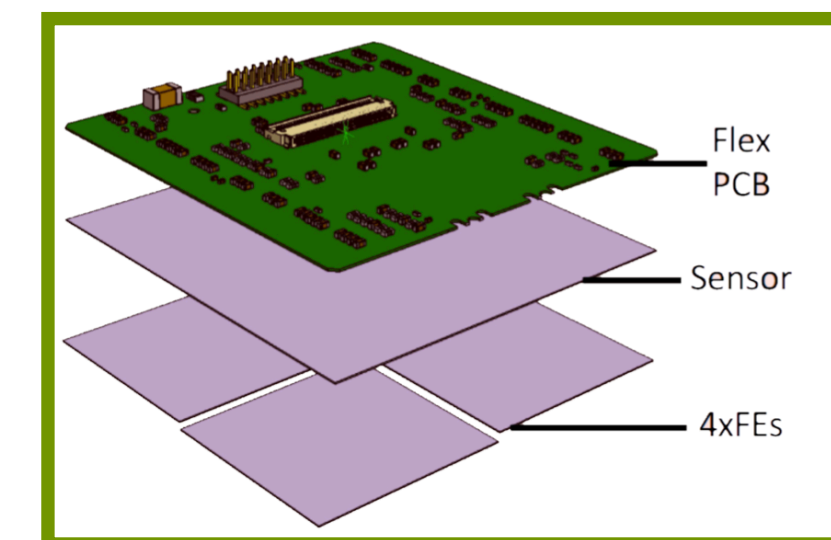
- ▶ **Aim:** build an additional test bench for development of the data acquisition software



Benchmarking electrical testing time



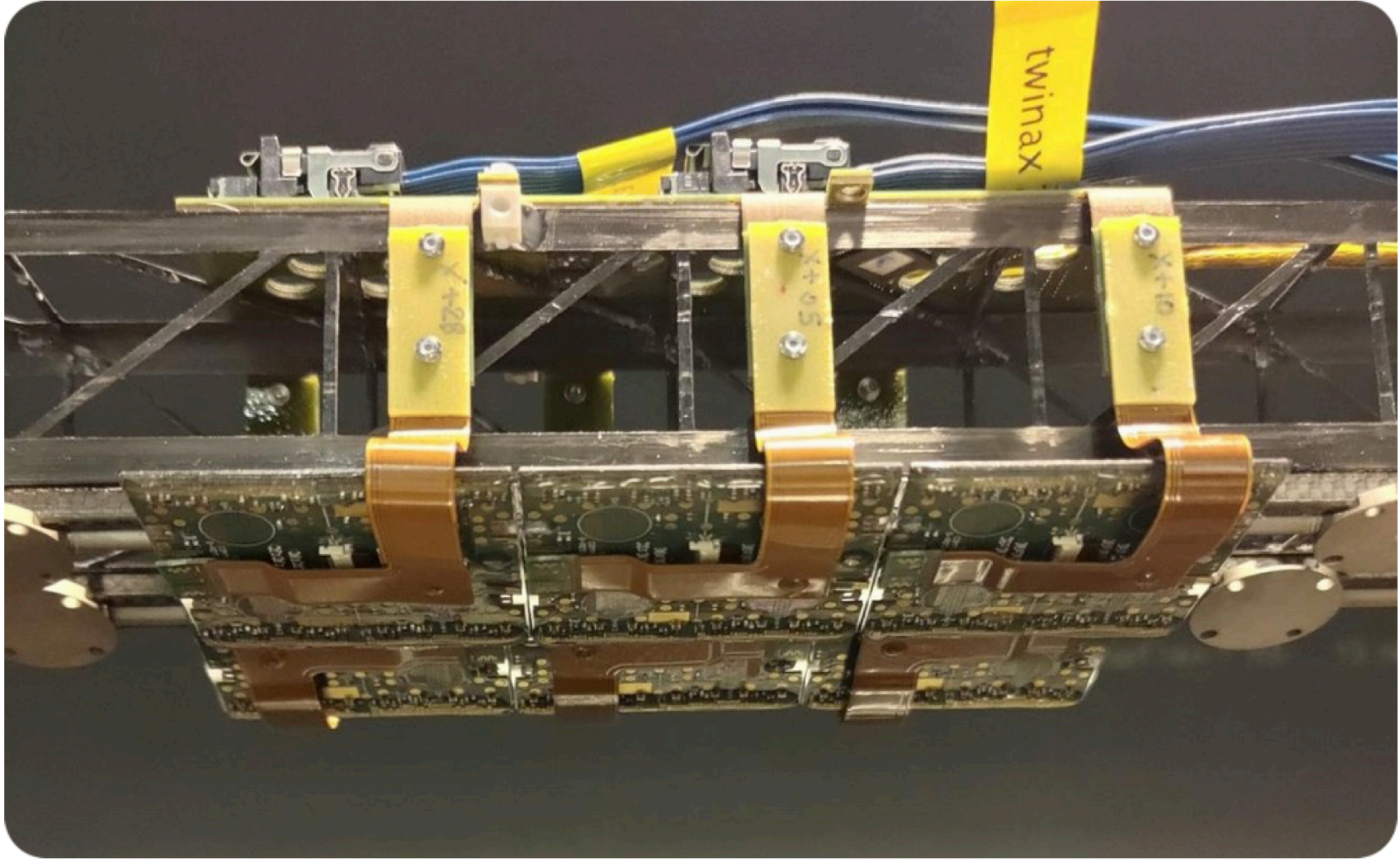
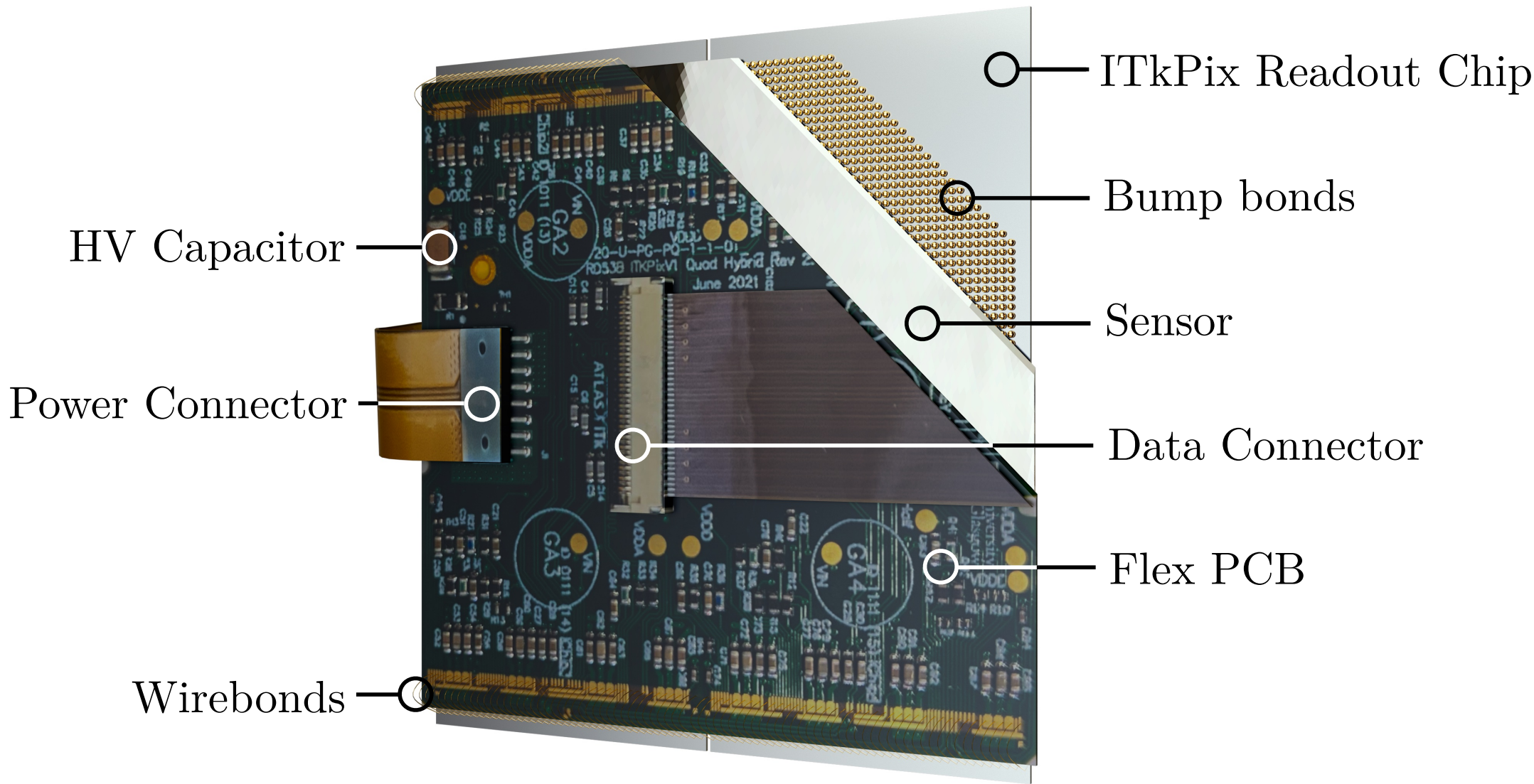
Number of read-out chips



- ▶ Setup still in use at CERN today!

Modules, patch panels, cables, supports, ...

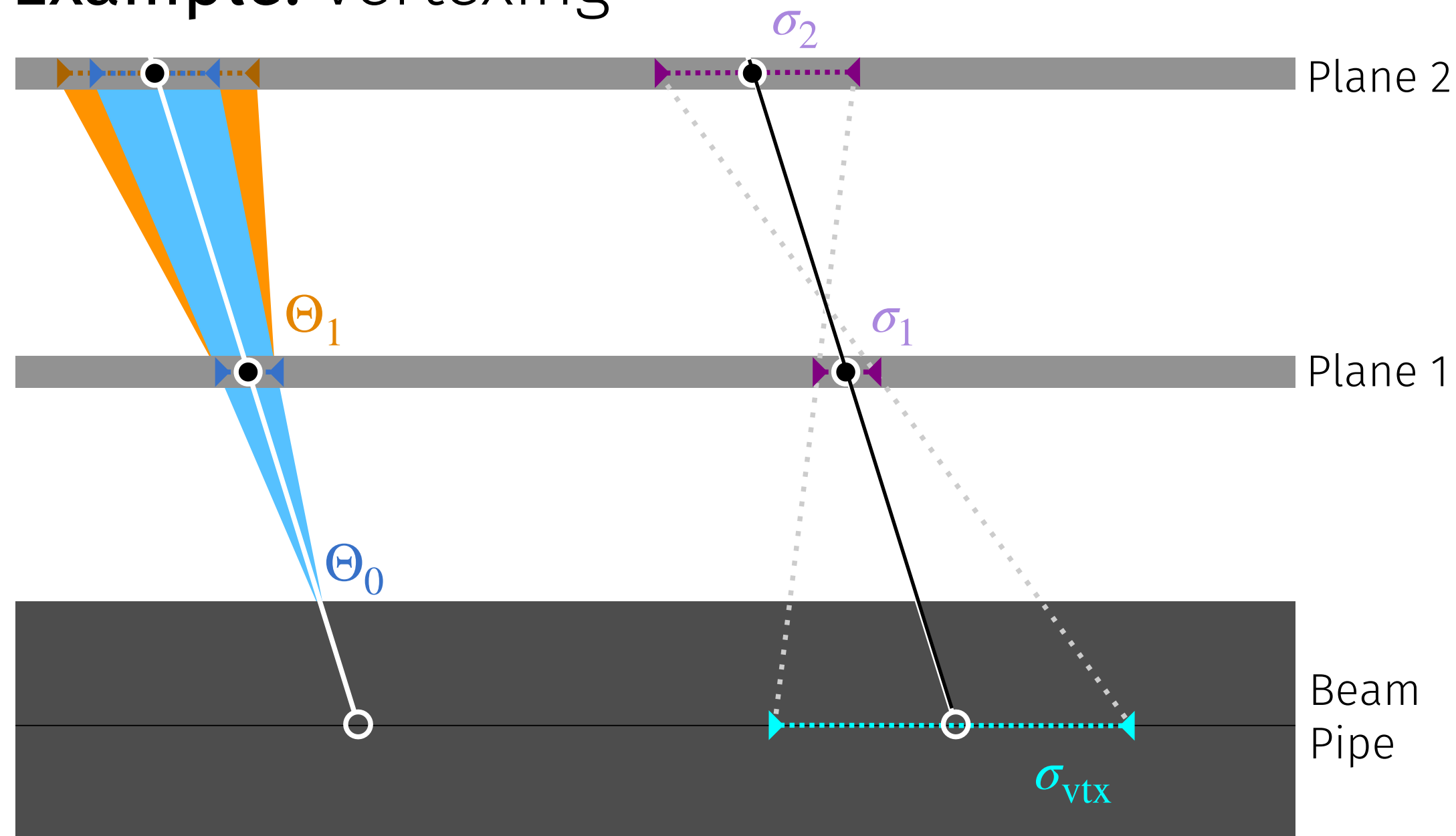
... there's a lot of **material** going in a detector



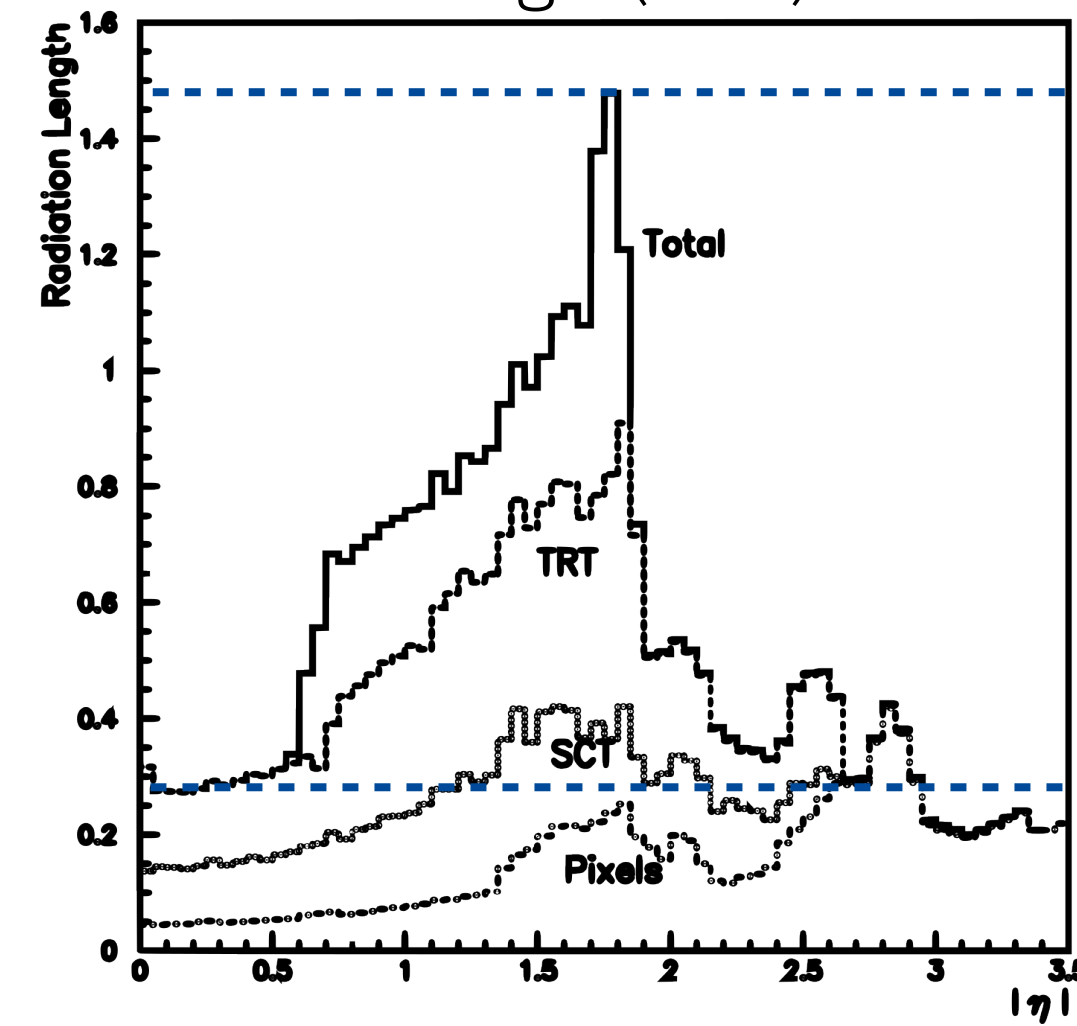
Keep your material budget low!

- ▶ Detector material impacts our physics performance: **minimisation of material** and **precise knowledge** of the detector makeup are critical for success
→ not an easy task

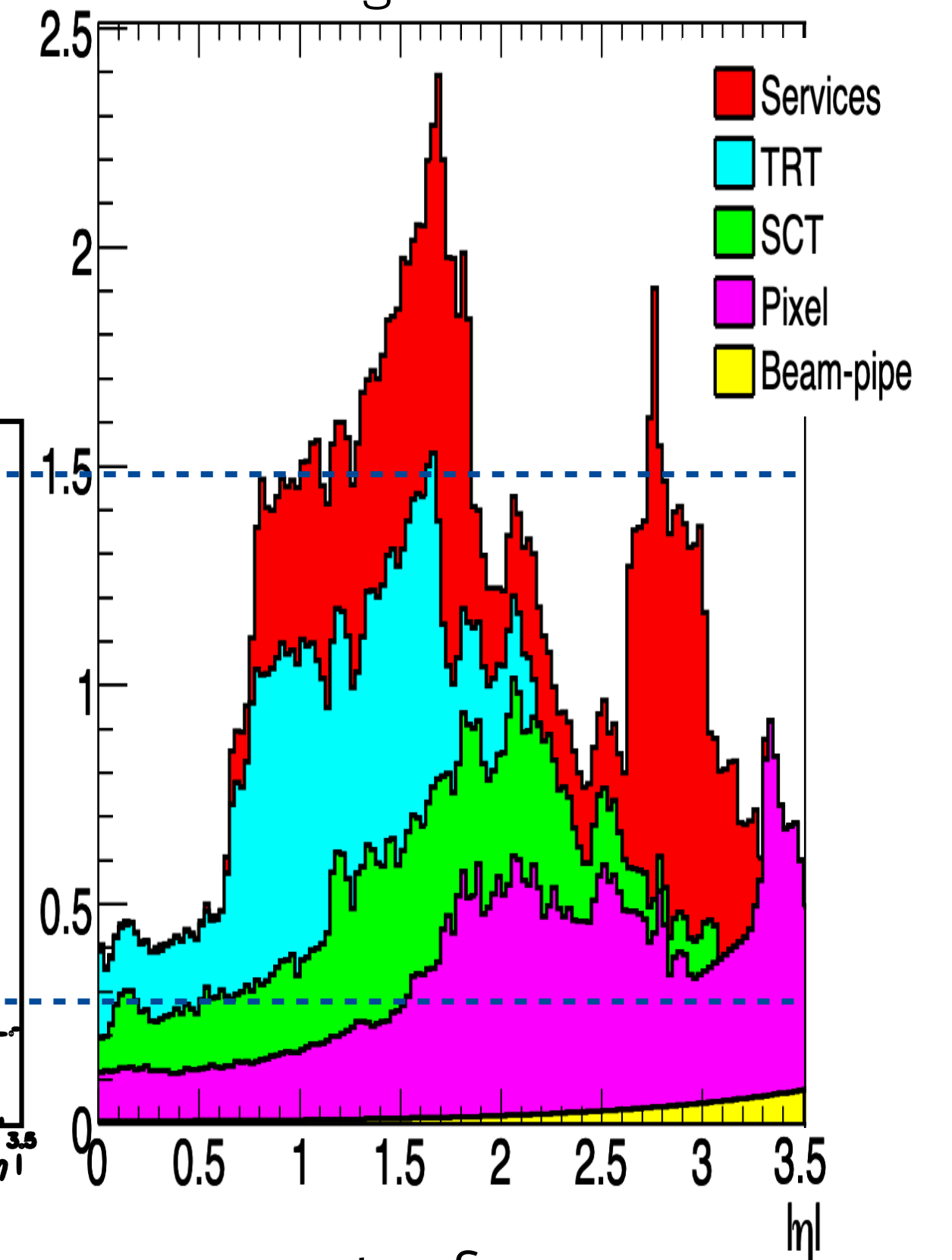
Example: vertexing



Initial design (TDR)



Final design

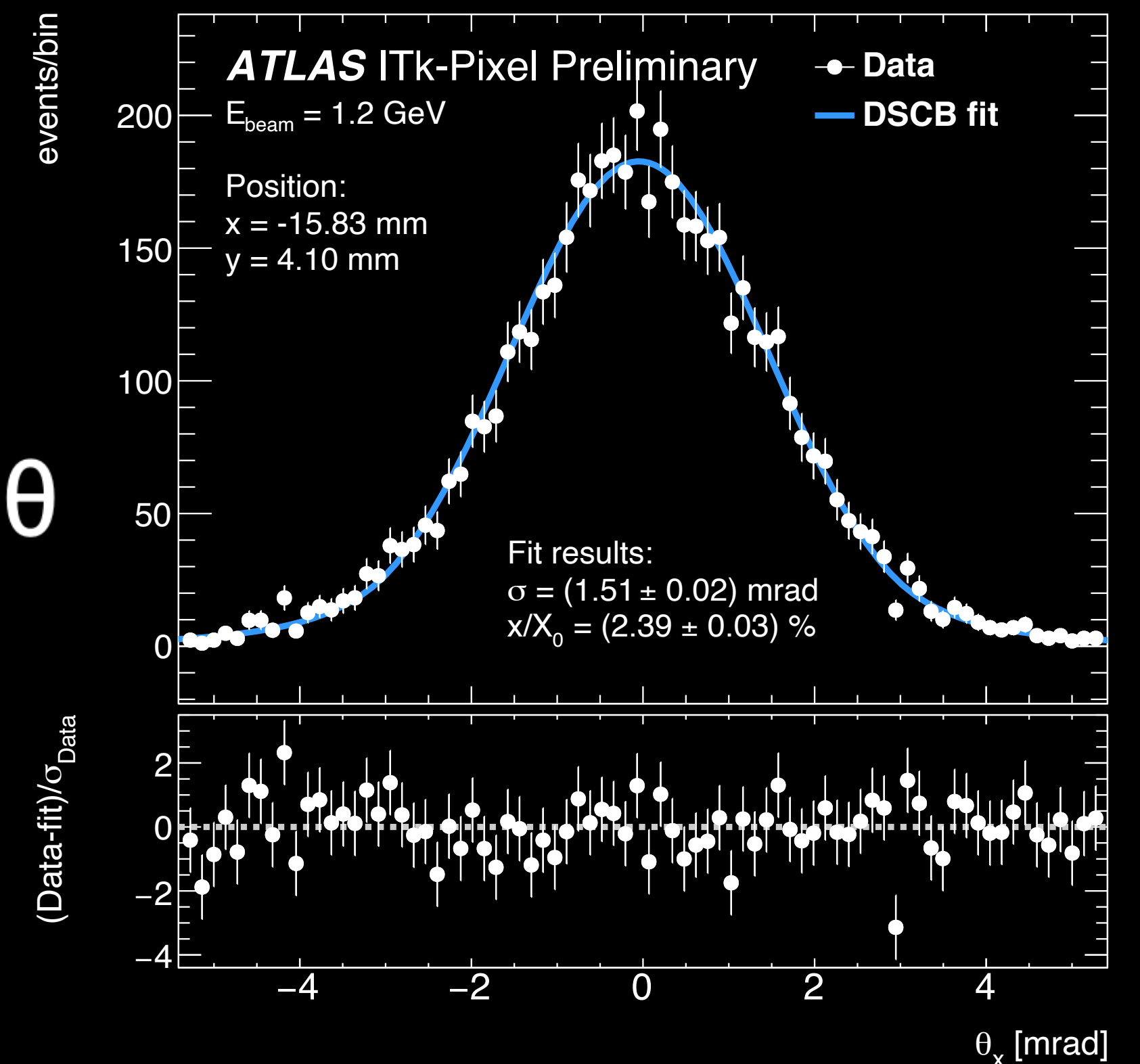
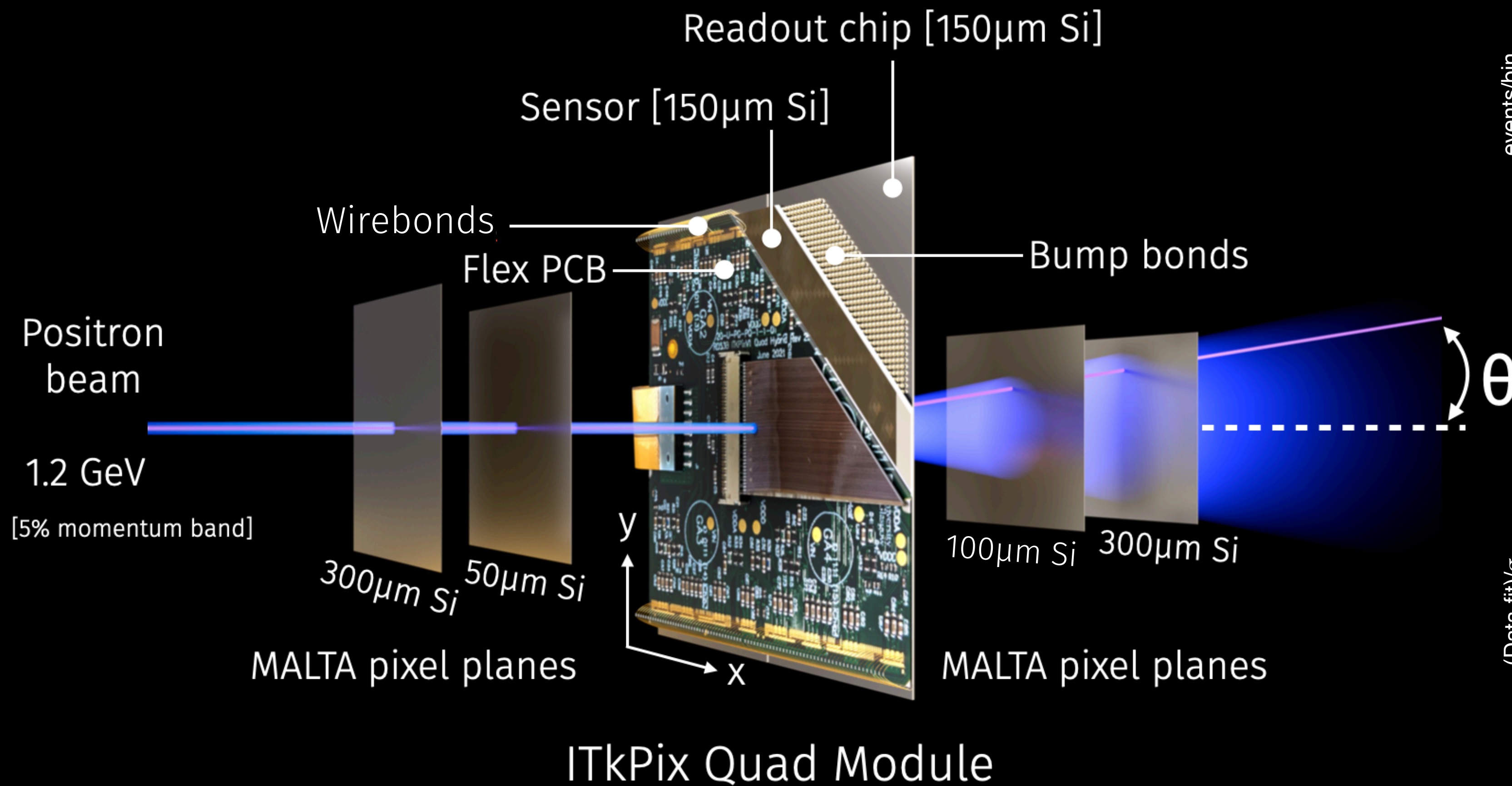


- ▶ **Idea:** infer the material content (the fractional radiation length x/X_0) via the amount of multiple scattering → started as a summer student project with S. Koch (then Oxford, now CERN)

Measuring x/X_0 using multiple scattering!

Starting point: operational ITkPix quad module mounted on a movable x-y stage

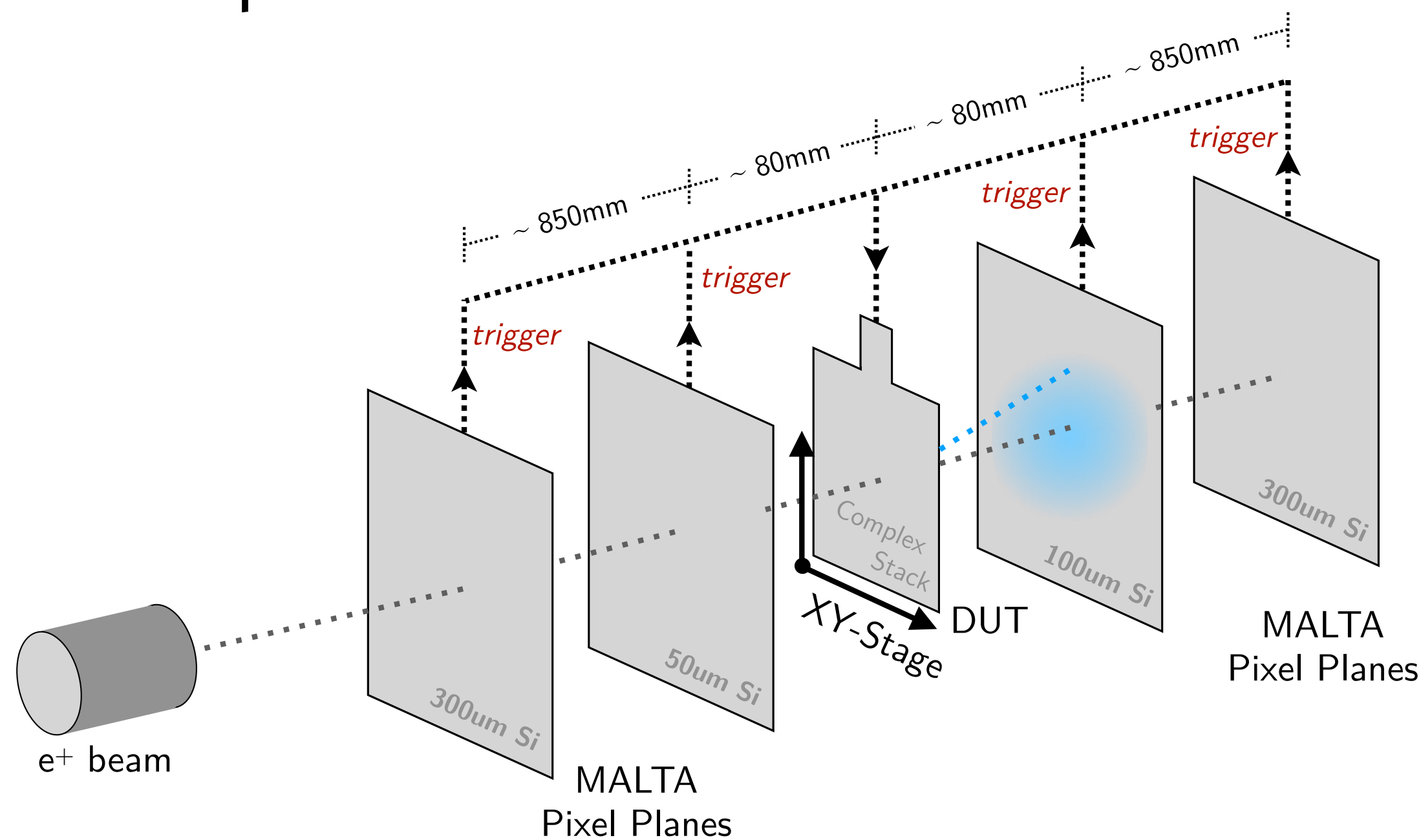
→ built a beam telescope with low material reference planes around it



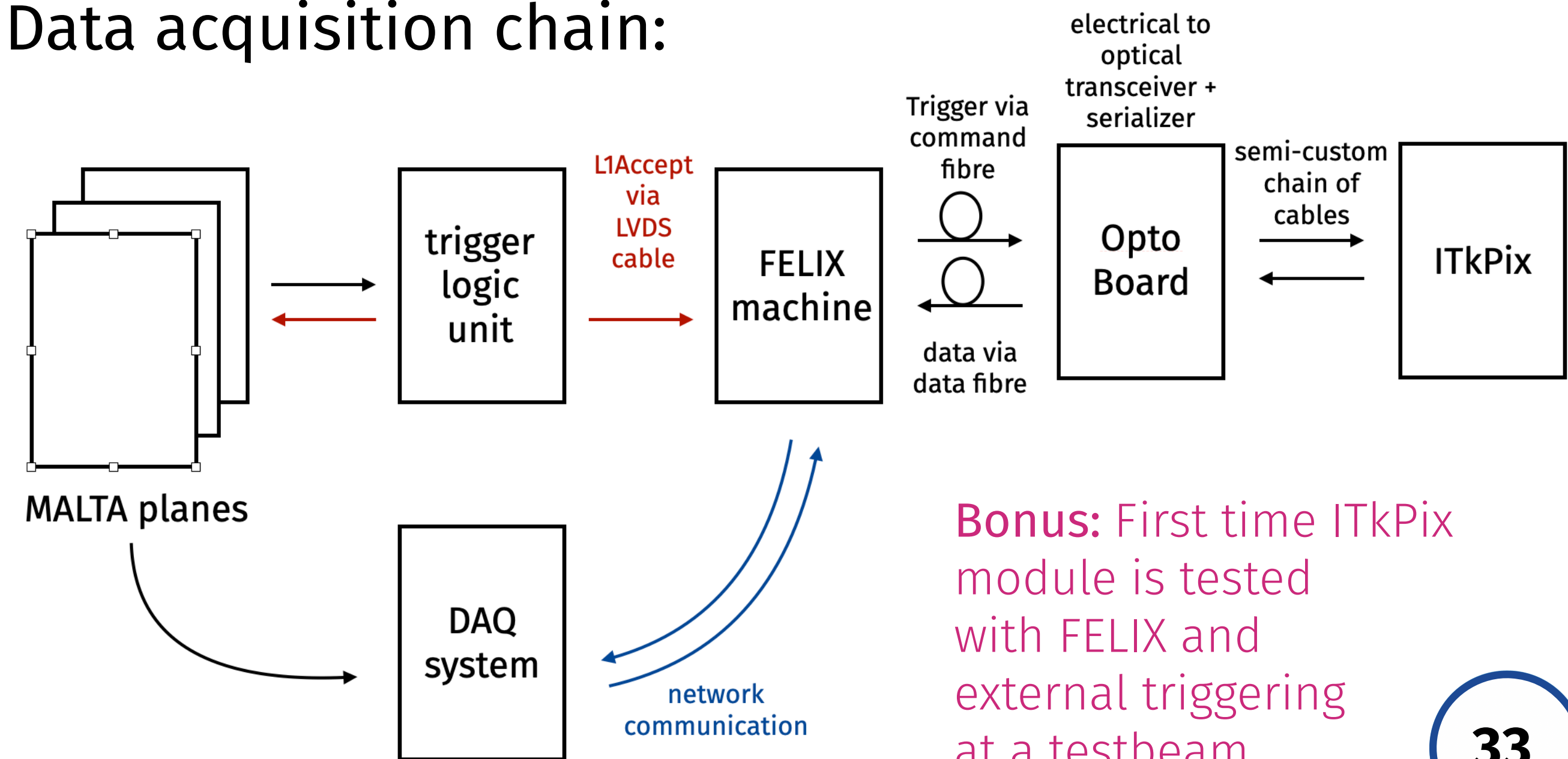
The MONSTAR telescope

- ▶ The beam telescope needed to have low material content itself, to minimize multiple scattering in the reference planes → MALTA monolithic pixel sensors (down to 50μm thick)
- ▶ Long enough to resolve the scatter angles → 2m
- ▶ Triggering on reference plane coincidence
- ▶ Active DUT mounted on a linear stage to be able to scan large areas

Telescope:

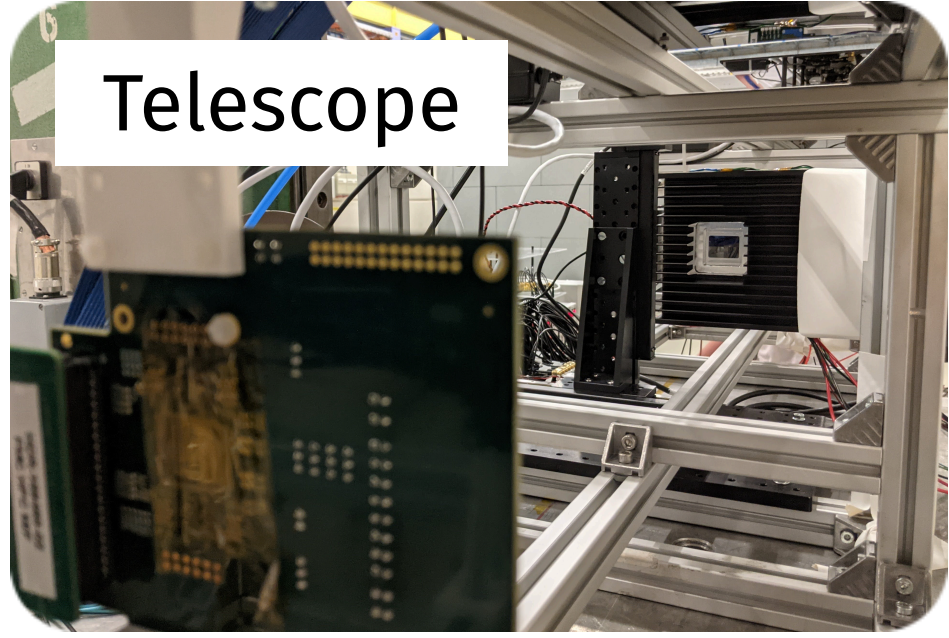
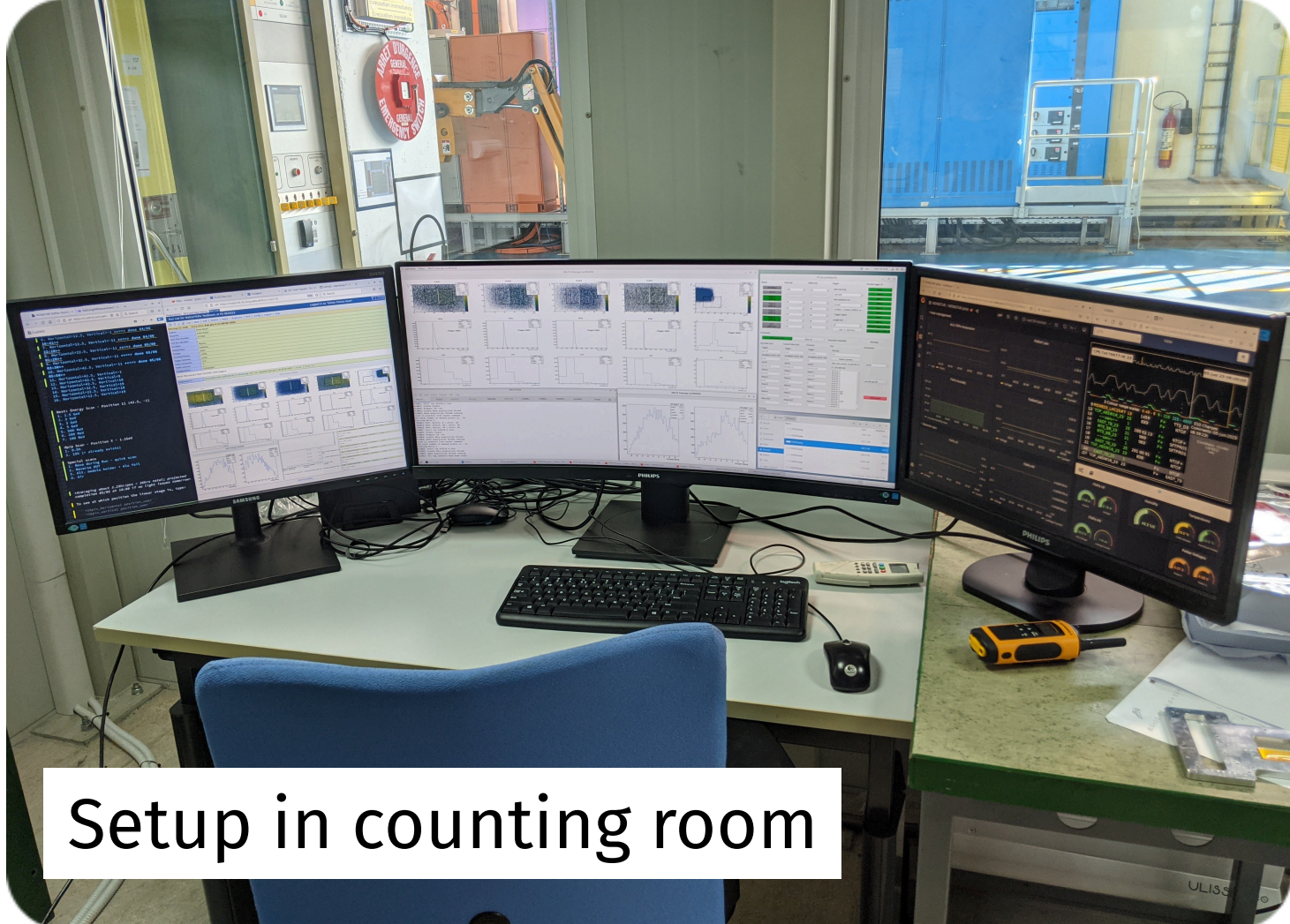
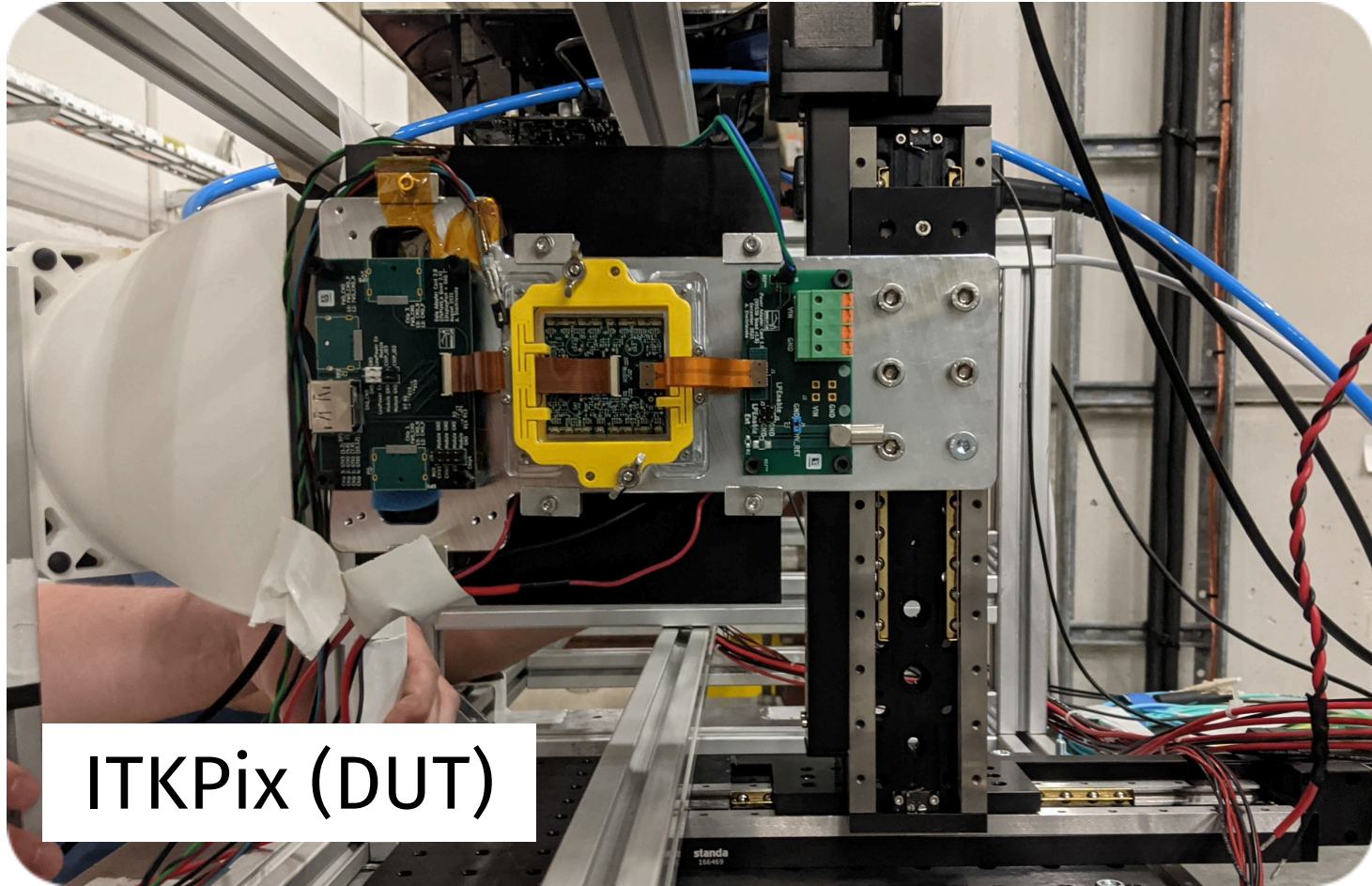
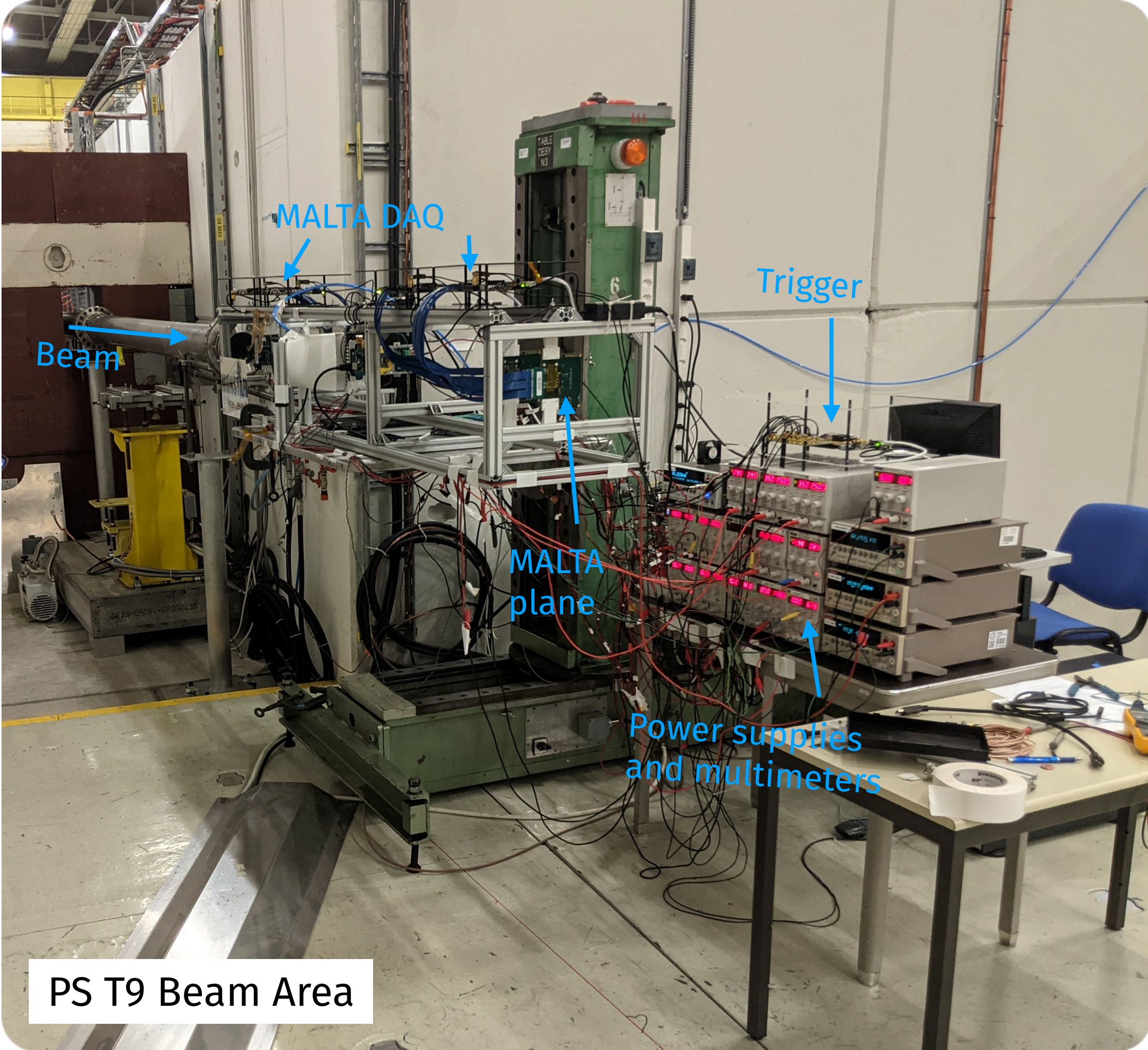


Data acquisition chain:



Bonus: First time ITkPix module is tested with FELIX and external triggering at a testbeam

Our setup at the CERN Proton Synchrotron



► A huge effort done by a small dedicated team of people!

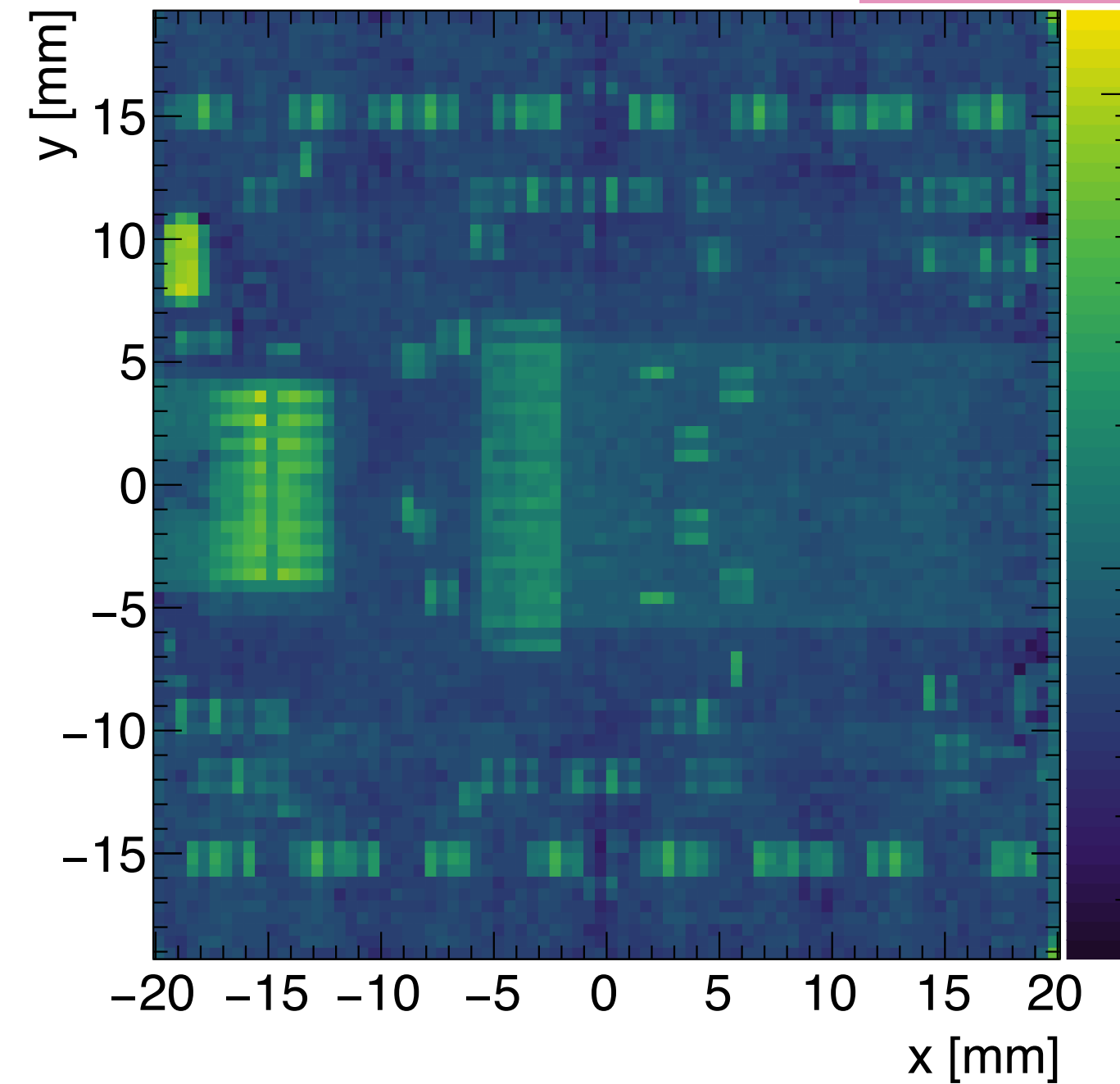
The measurement results

- The result shows **good agreement** with estimate, mean agrees within uncertainties

Measurement:

ATLAS ITk-Pixel Preliminary

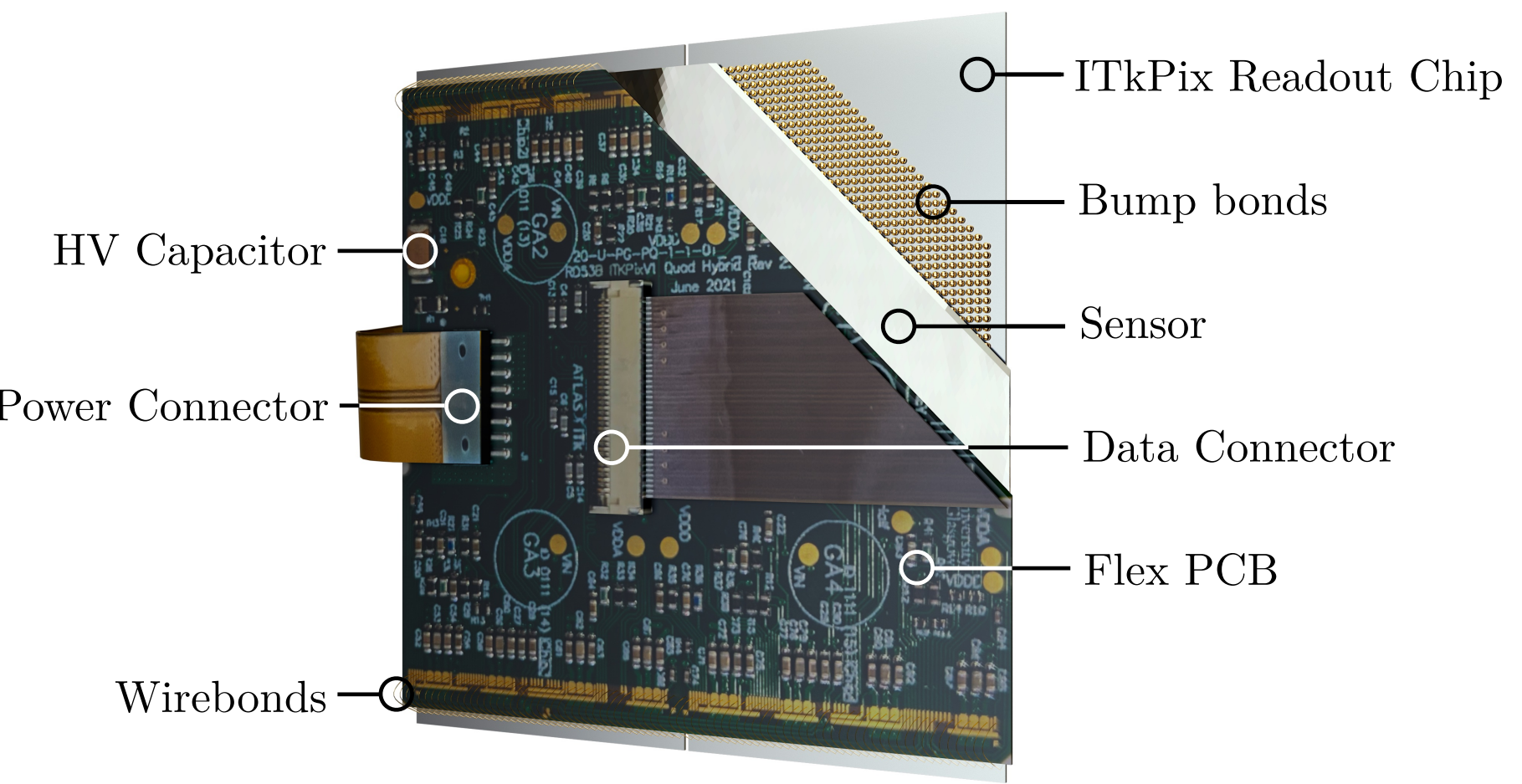
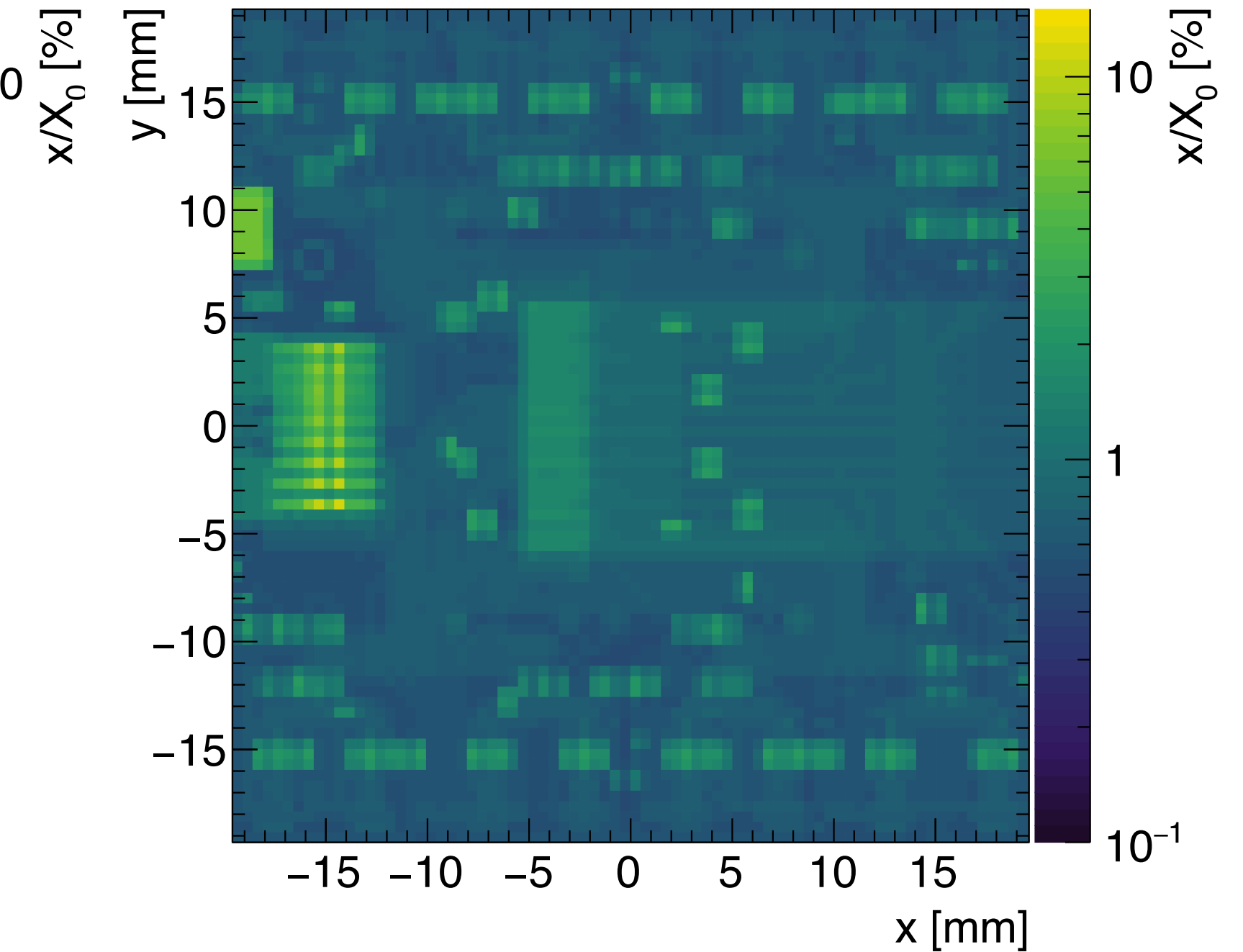
Combined measurement, $E_{\text{beam}} = 1.2 \text{ GeV}$
 $\langle x/X_0 \rangle [\%] = 0.84 \pm 0.01 \text{ (reso.)} \pm 0.11 (E_{\text{beam}})$



Estimate:

ATLAS ITk-Pixel Preliminary

Material budget estimate
 $\langle x/X_0 \rangle [\%] = 0.87$



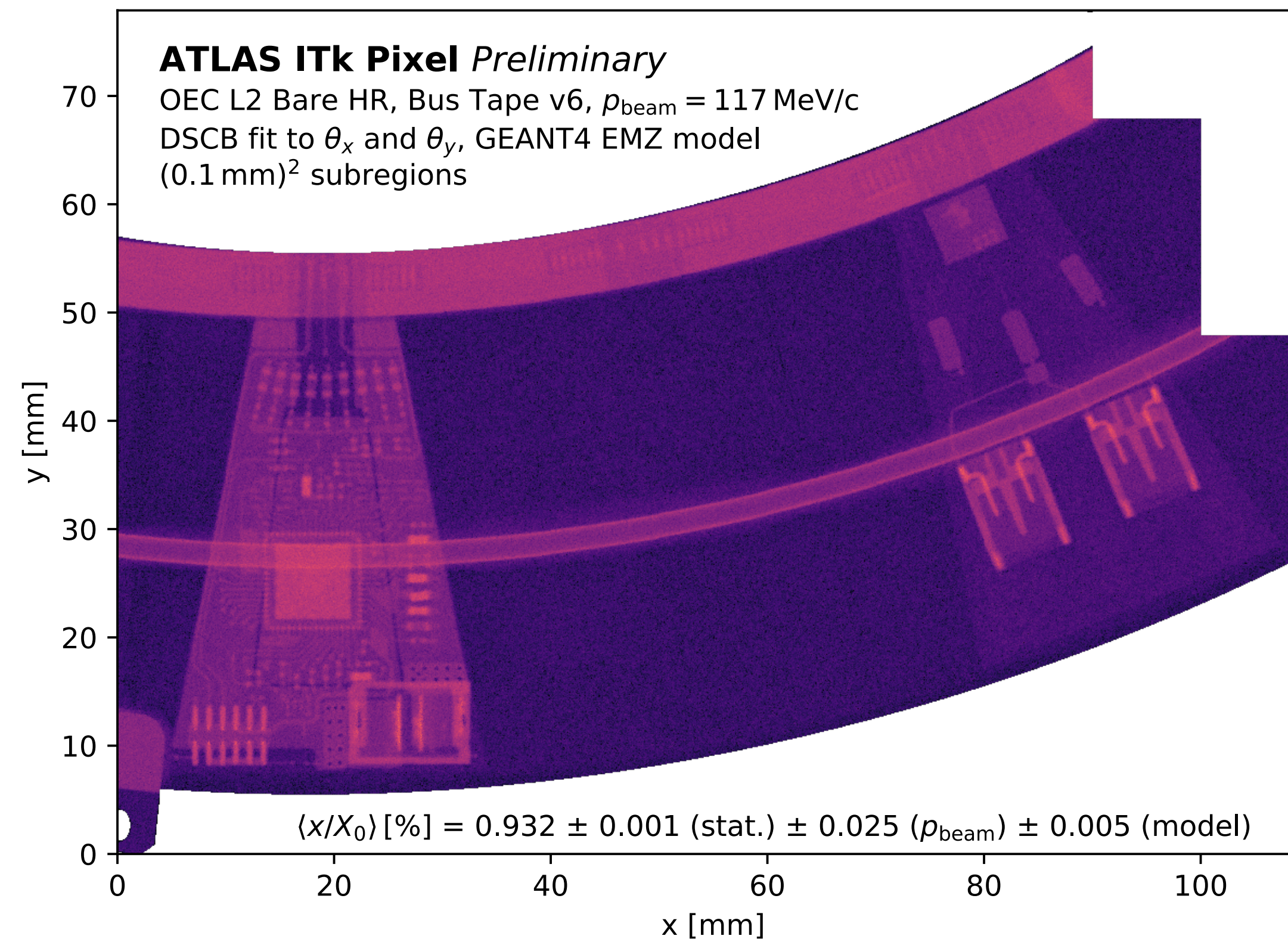
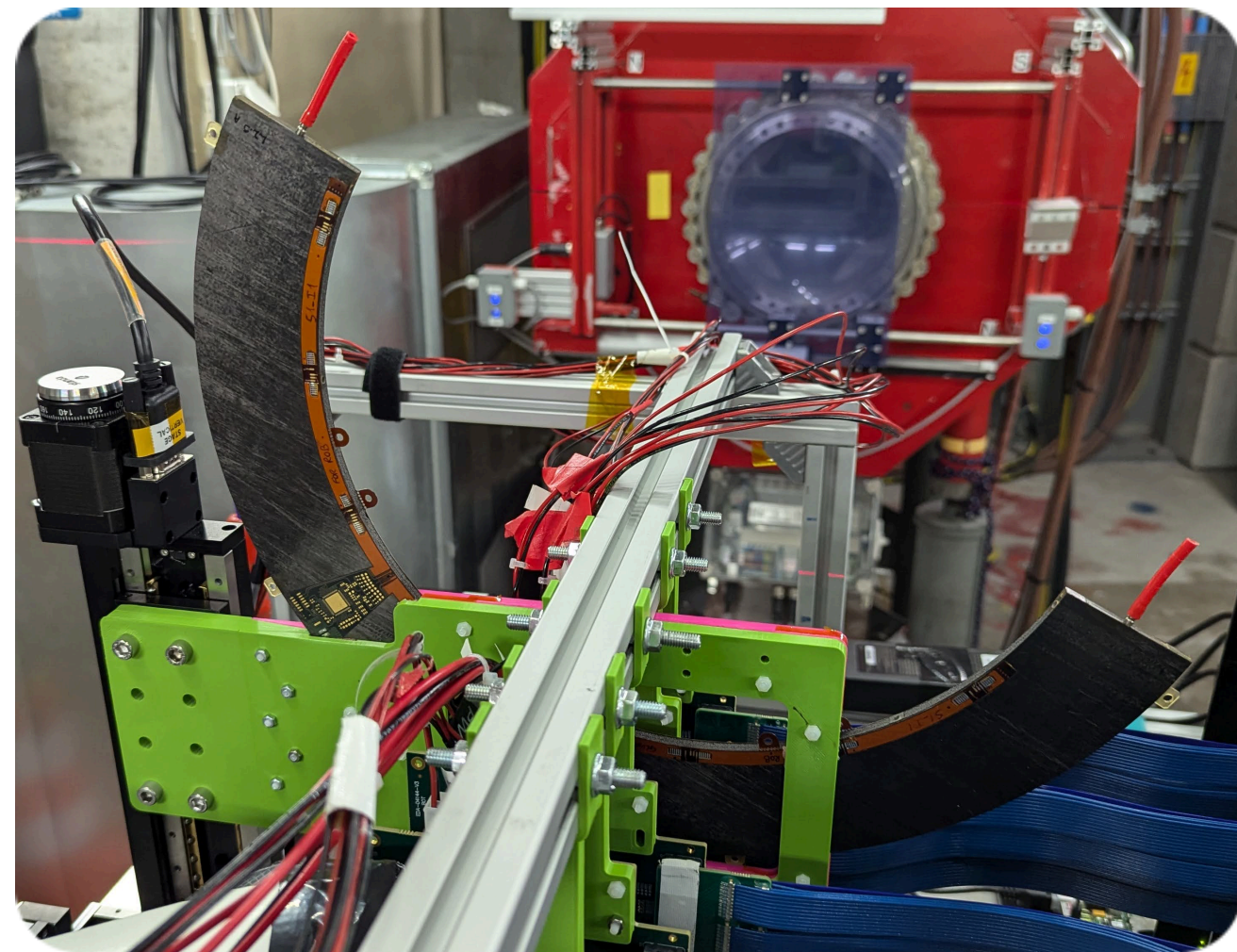
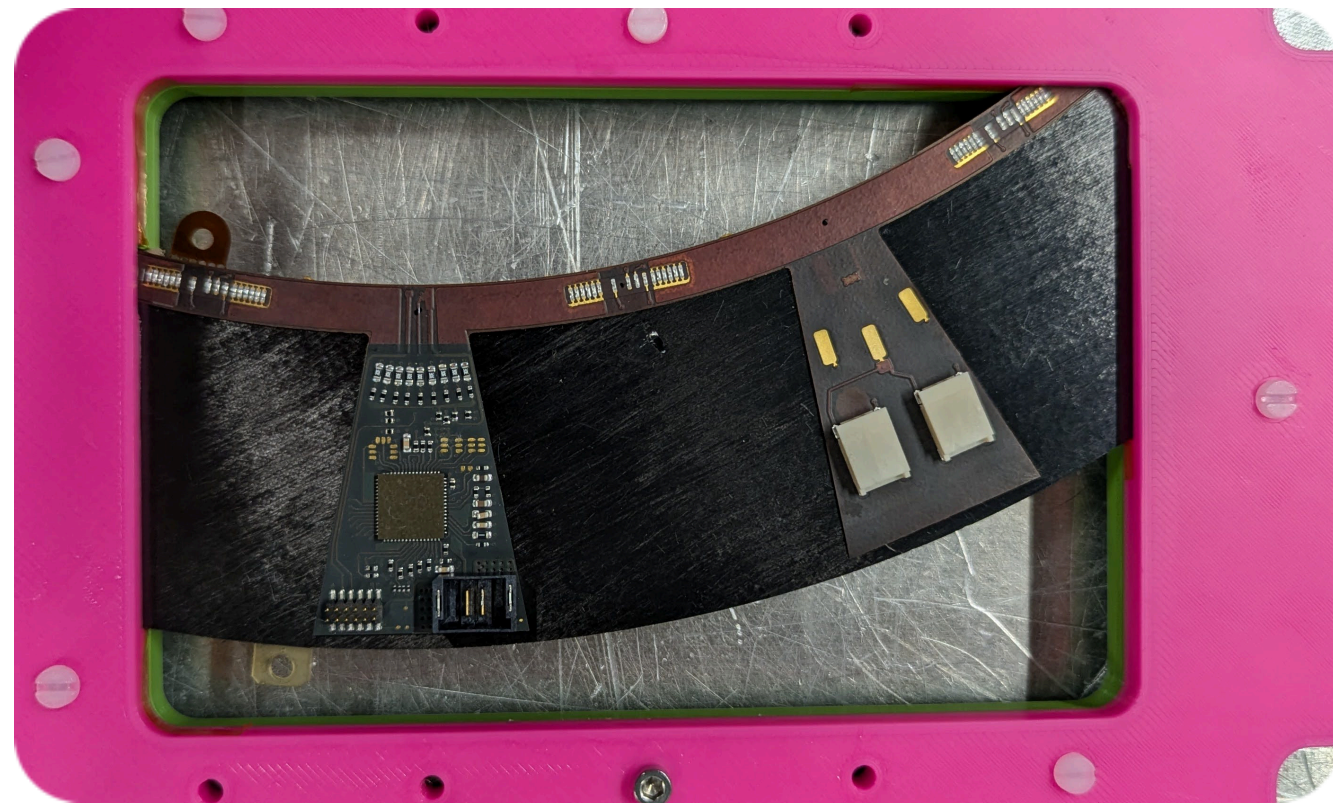
- Dominant uncertainty: **beam momentum band**
 (optimized to 5%, otherwise too low rate → limiting factor)



Scaling things up at the PSI

with S. Koch, R. Li, N. Dimova, A. McDougall, A. Ruggiero, B. Tuncay (Oxford)

- ▶ Partnered up with CMS and Mu3e for a follow-up measurement at the PiM1 beam line of the Paul-Scherrer-Institute, Switzerland

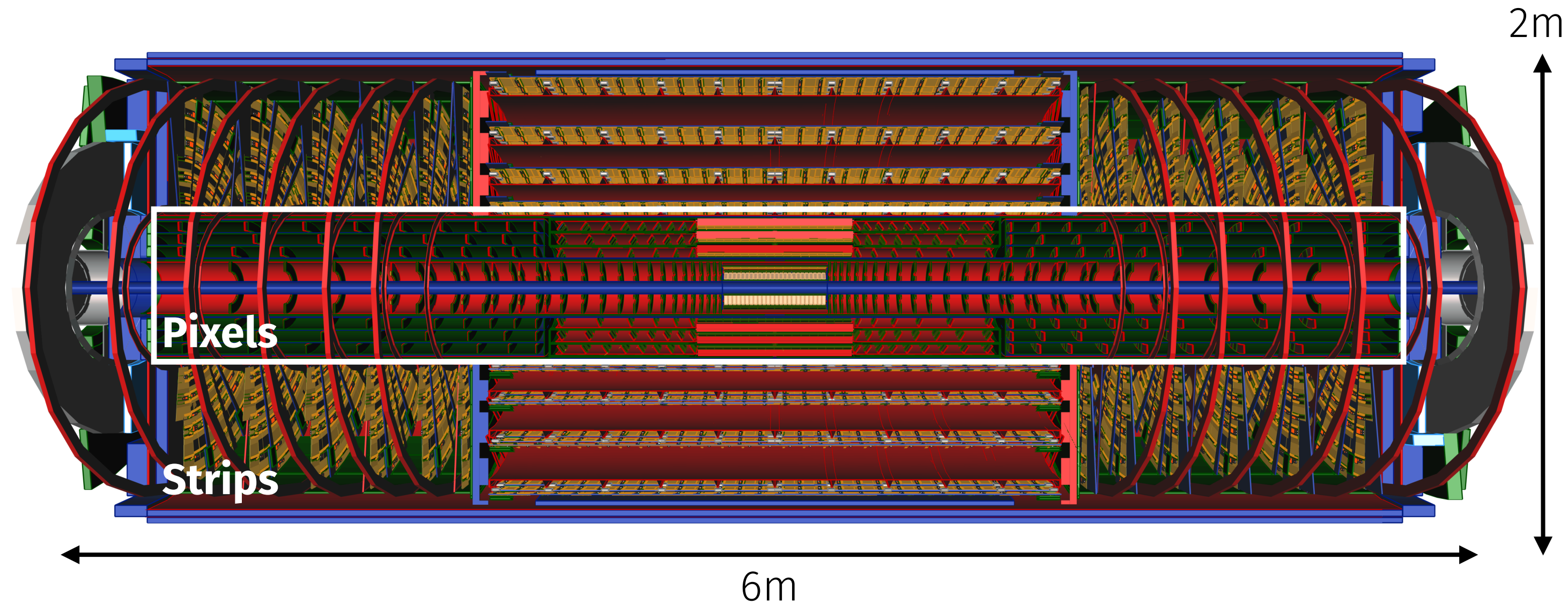


[Public plots]

Successfully measured over 500 cm^2 of detector components

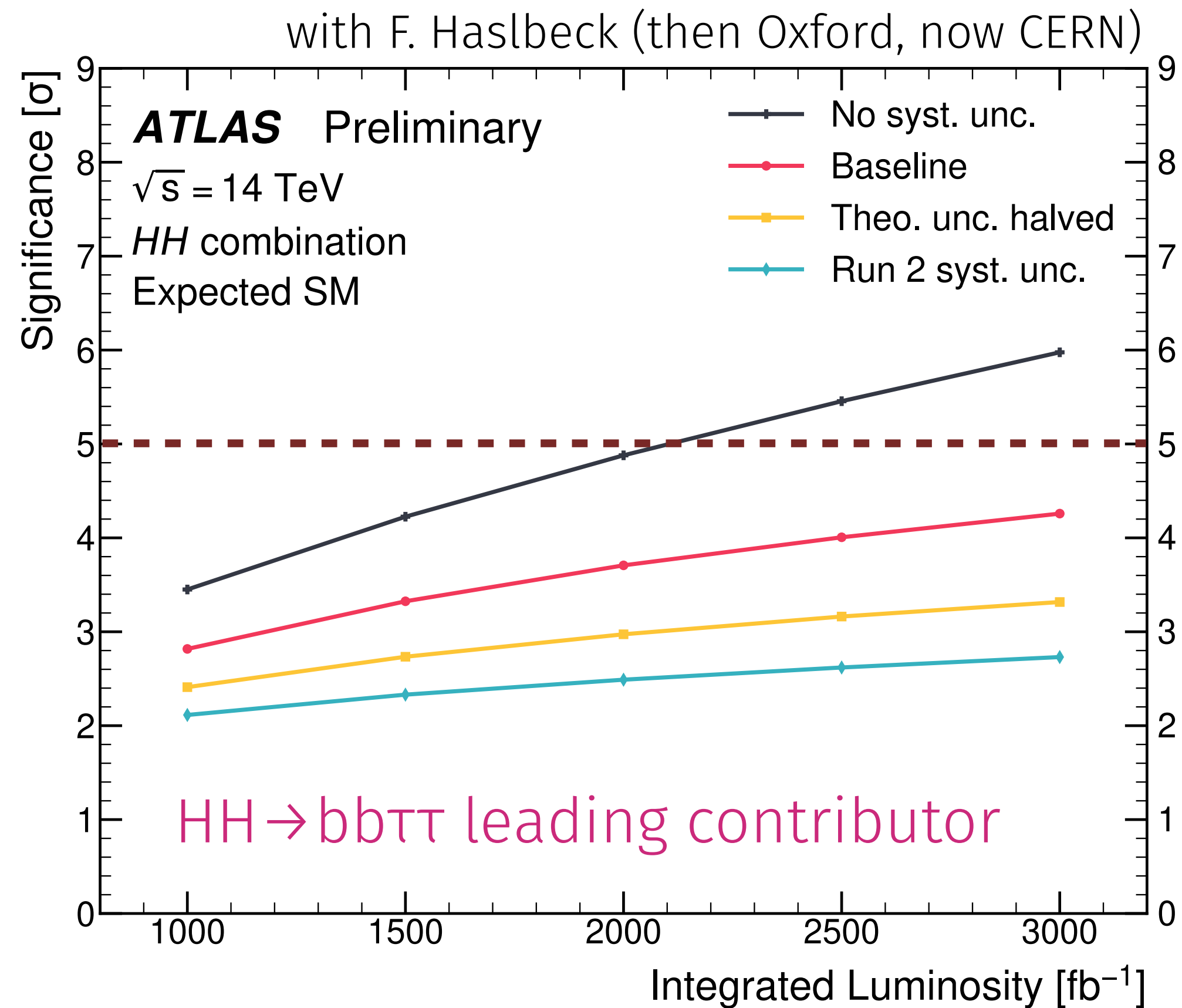
Let's imagine we built the detector, know its material content very precisely ...

... what physics can we do with it?



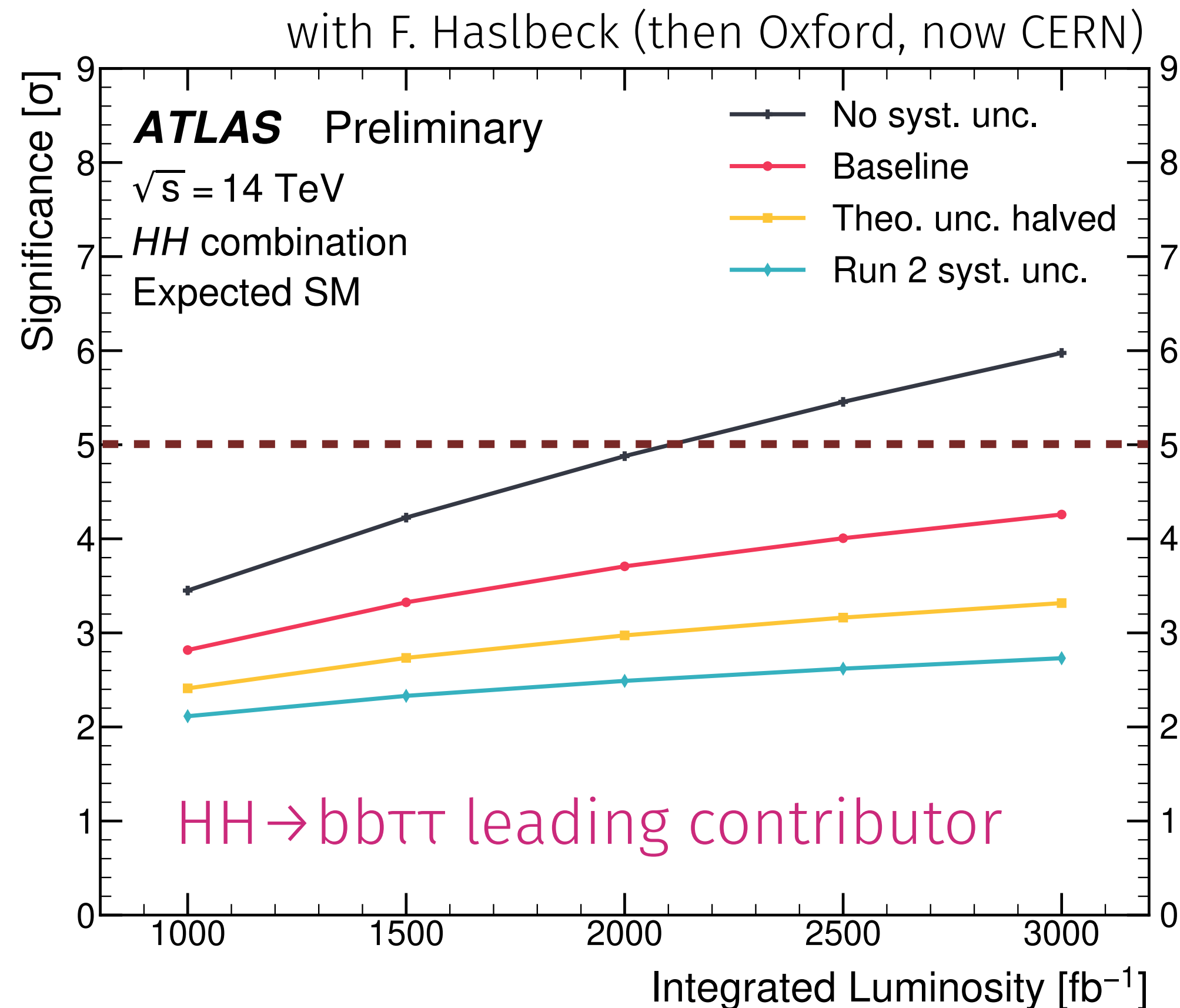
The physics potential of the HL-LHC: HH searches

- **Observation of HH production** (if SM-like) seems possible with the HL-LHC data set



The physics potential of the HL-LHC: HH searches

- **Observation of HH production** (if SM-like) seems possible with the HL-LHC data set



Caution with extrapolations!

[ATL-PHYS-PUB-2015-046]

Higgs Pair Production in the $H(\rightarrow \tau\tau)H(\rightarrow b\bar{b})$ channel at the High-Luminosity LHC

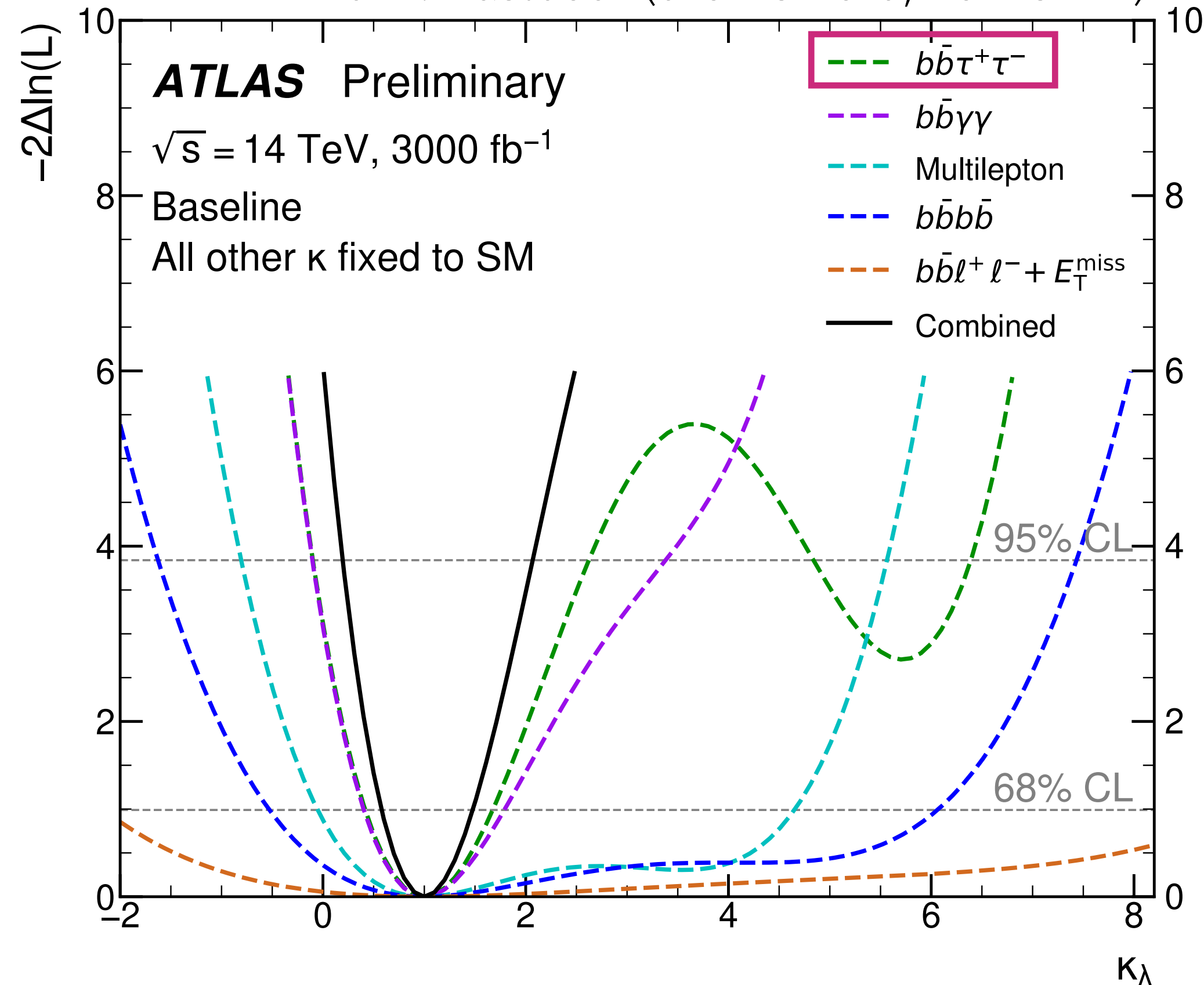
performed under different assumptions for the Higgs trilinear self-coupling values. Assuming SM background and SM signal, we expect to set an upper limit of the cross section for the di-Higgs production of $4.3 \times \sigma(HH \rightarrow b\bar{b}\tau^+\tau^-)$ at 95% Confidence Level. Using an

2015 extrapolation for the end of HL-LHC
 We are already doing better than this with Run 2 alone
 [5% of the dataset]

The physics potential of the HL-LHC: HH searches

- **Observation of HH production** (if SM-like) seems possible with the HL-LHC data set

with F. Haslbeck (then Oxford, now CERN)



Caution with extrapolations!

[ATL-PHYS-PUB-2015-046]

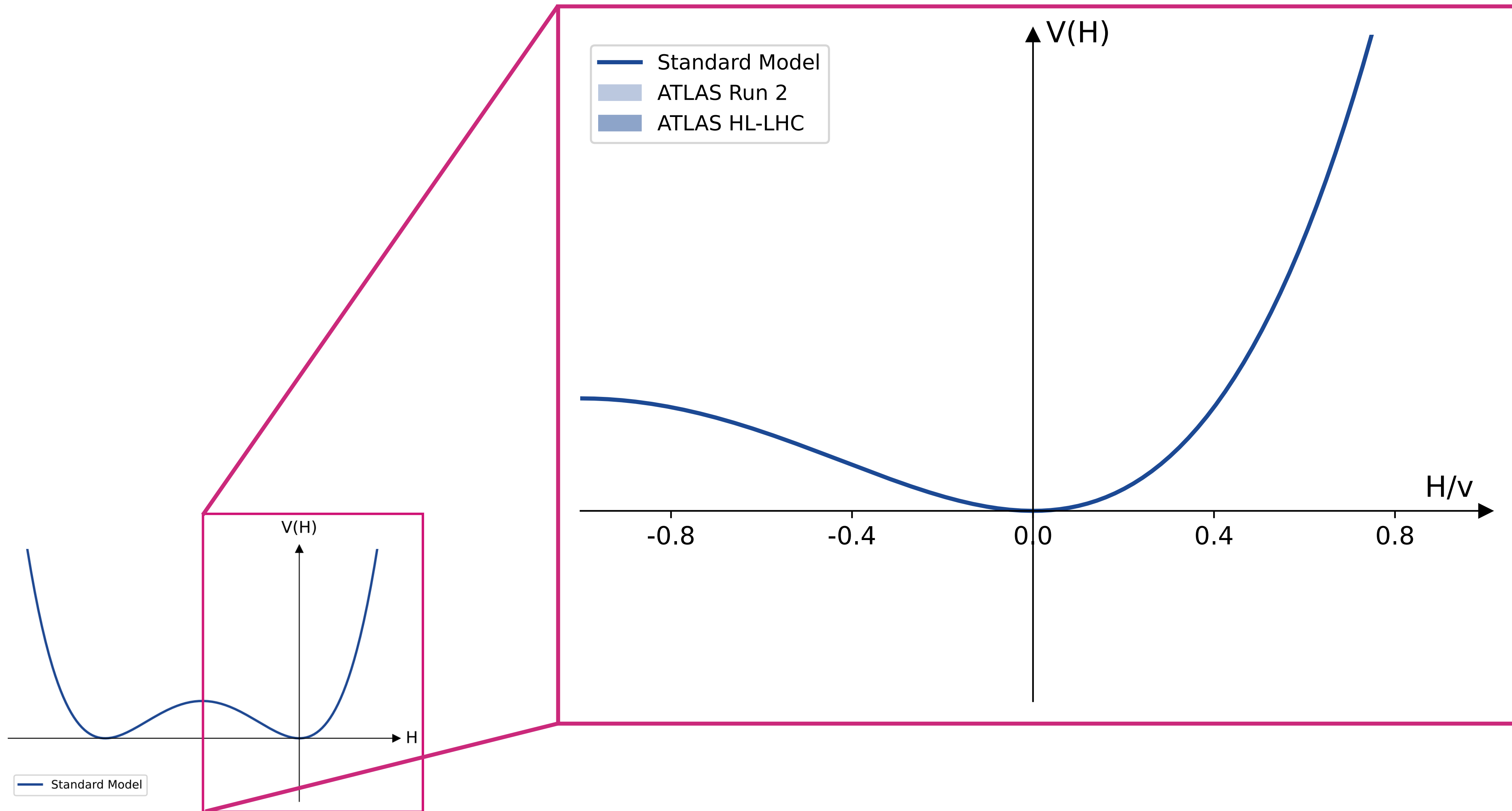
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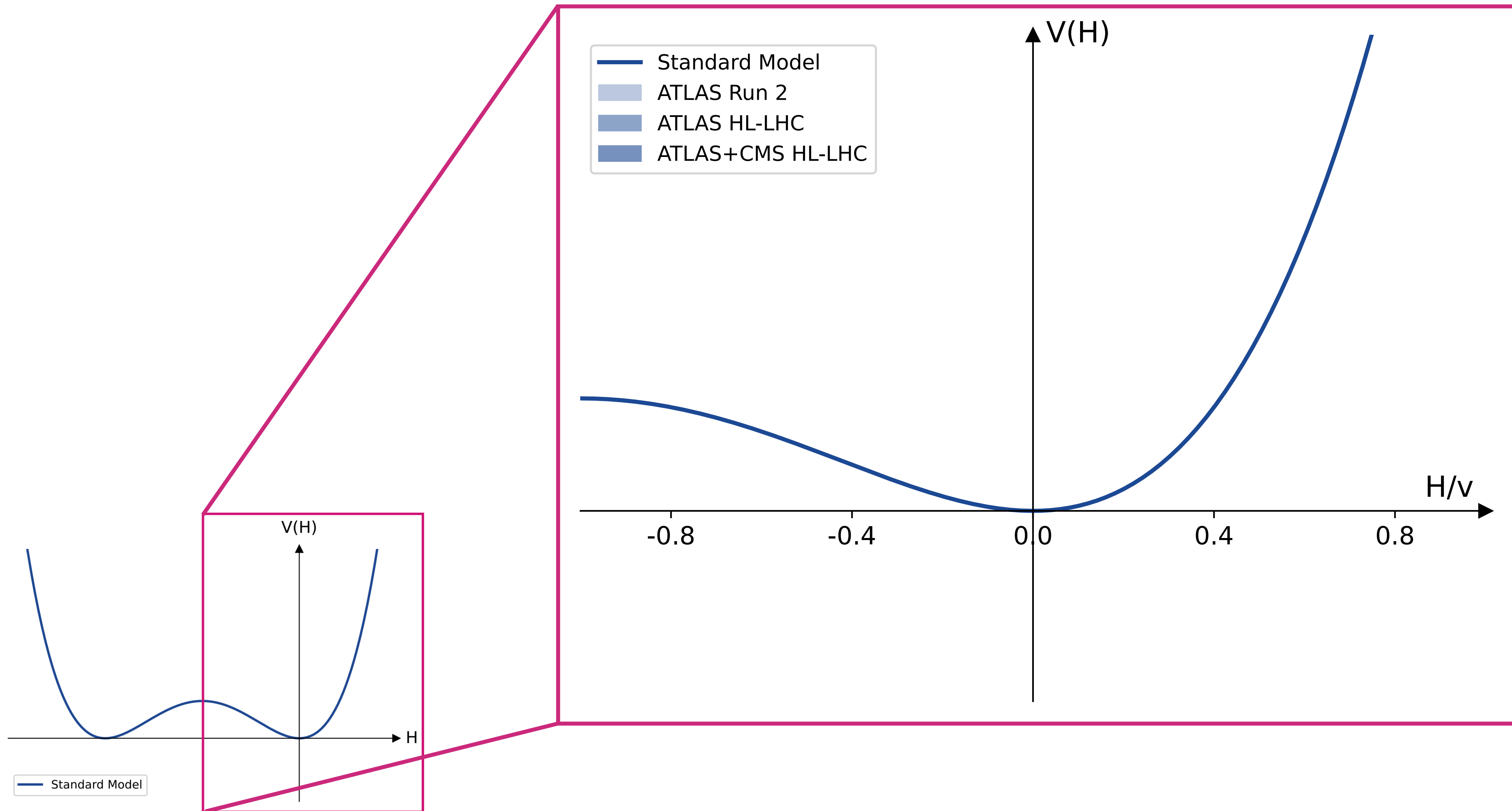
2015 extrapolation for the end of HL-LHC
 We are already doing better than this with Run 2 alone
 [5% of the dataset]

- This would translate into a **O(50%) precision** on the **Higgs boson self-coupling**

So, does the Higgs boson wear a Mexican-hat?



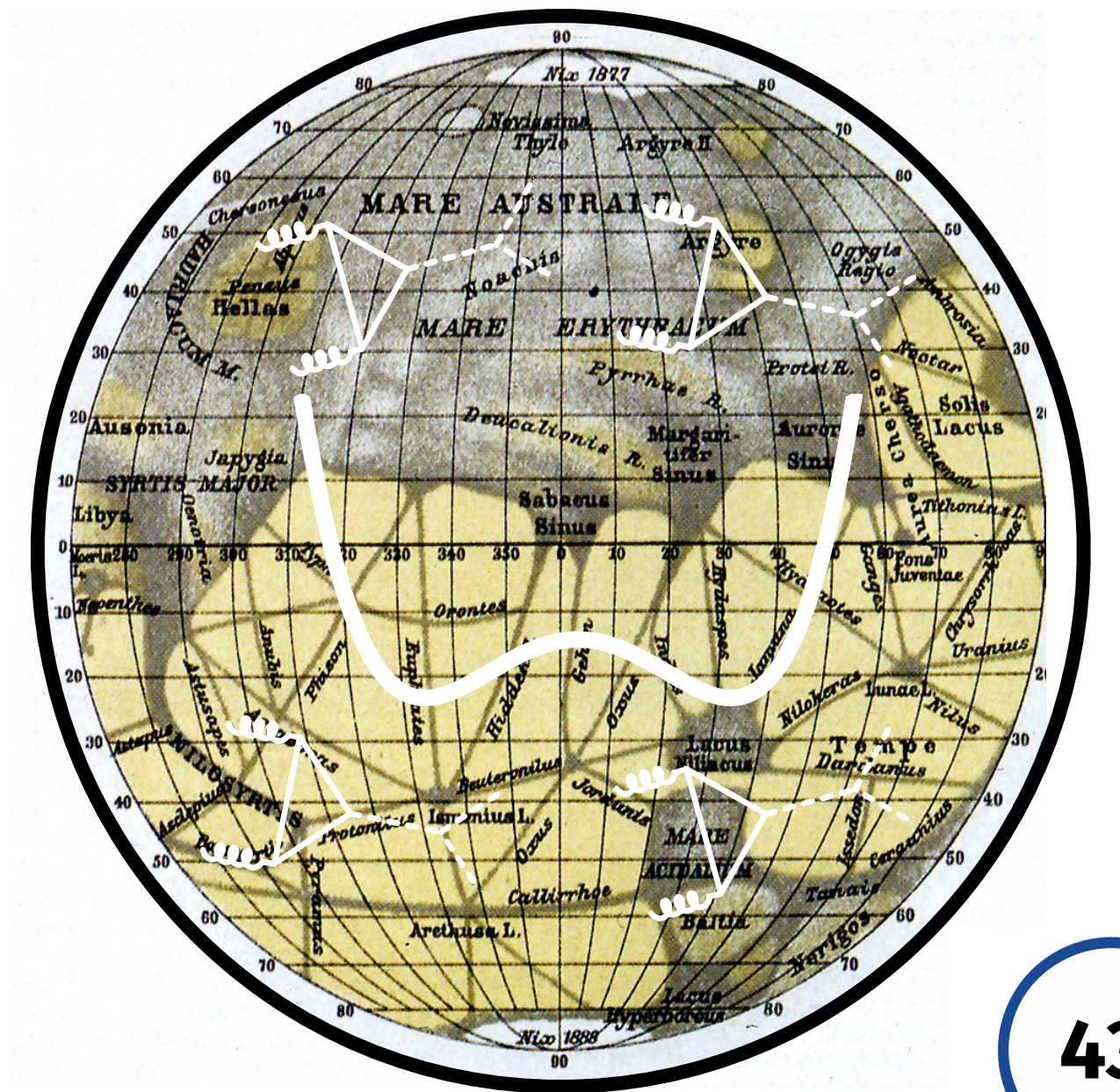
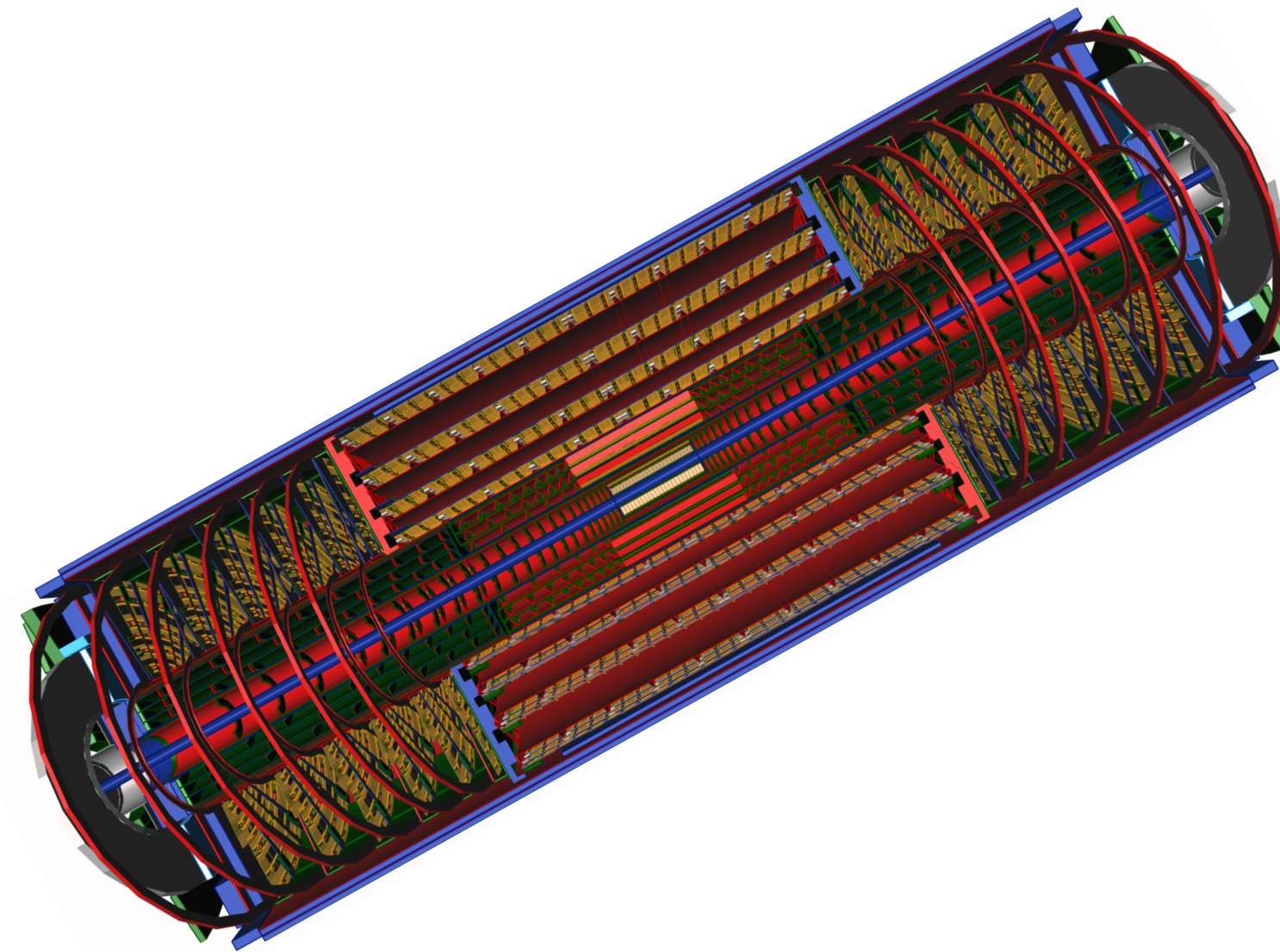
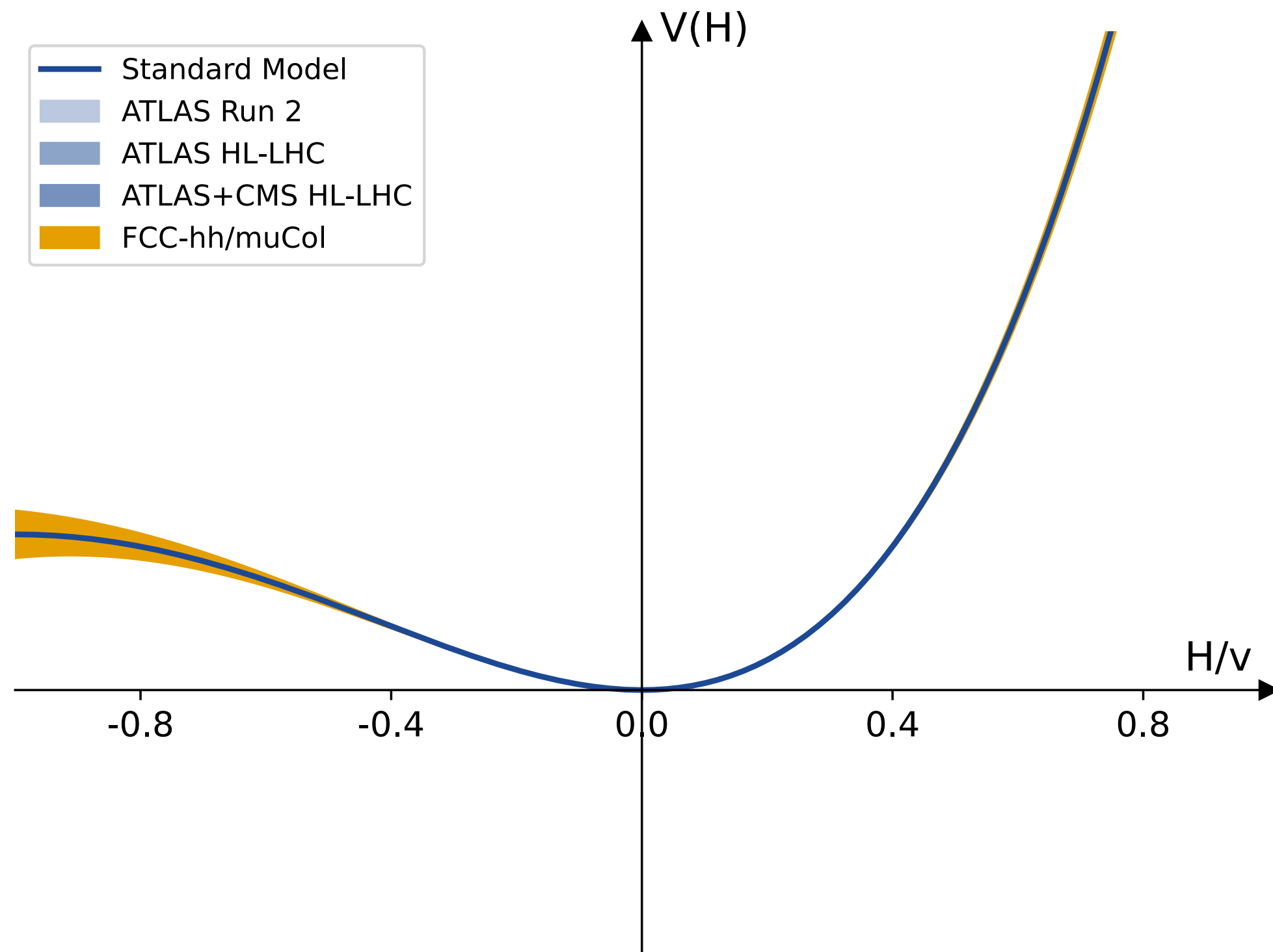
So, does the Higgs boson wear a Mexican-hat?



So, does the Higgs boson wear a Mexican-hat?

- ▶ Studying the shape of the Higgs potential via HH searches is crucial
- ▶ Observation of Higgs boson pair production seems in reach at the HL-LHC, but in order to record and make use of the data ATLAS needs a new tracker
- ▶ Ultimate precision on the Higgs potential shape can be reached at future machines

Exciting times ahead!



The image features a dark blue background filled with a dense field of small, bright blue particles. These particles are arranged in a way that suggests a circular or spherical shape, with a brighter, more concentrated area on the right side. The overall effect is that of a glowing, ethereal sphere or a nebula. In the center of this particle field, the word "Backup" is written in a clean, white, sans-serif font. The text is centered horizontally and vertically, standing out prominently against the complex, textured background.

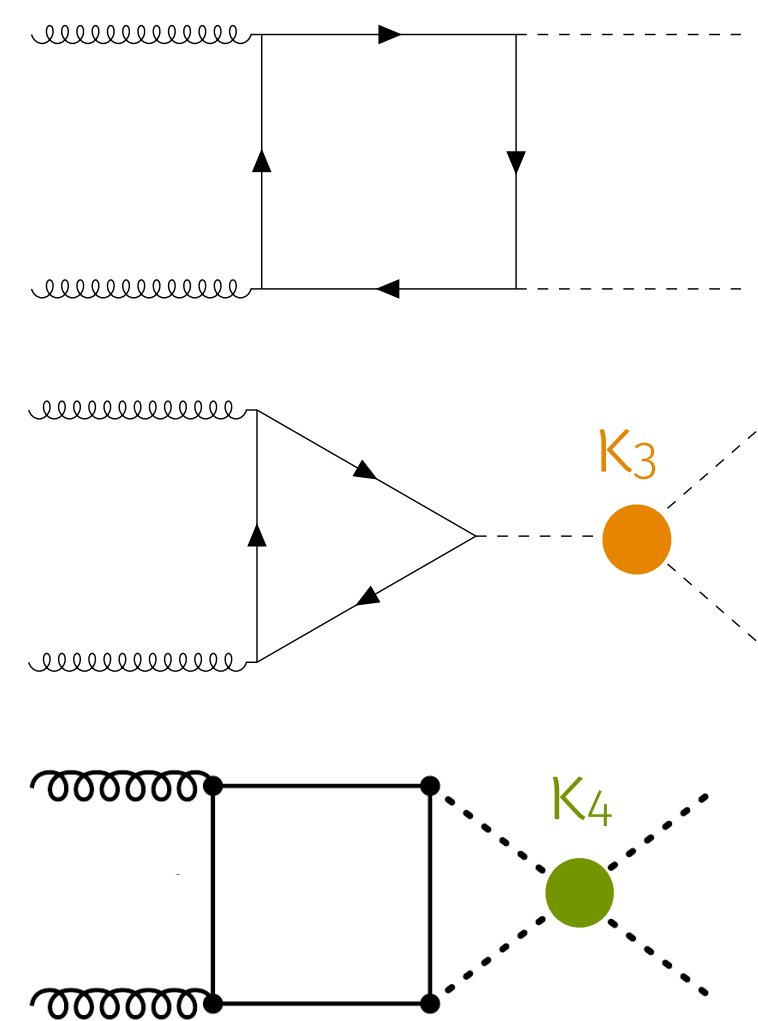
Backup

Bonus: One, two, three, Higgs

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 \text{vev } H^3 + \frac{1}{4}\lambda_4 H^4$$

- ▶ In the SM (and dim-6 SMEFT) the cubic and quartic Higgs self coupling are linked
- ▶ This does not need to be the case (e.g. in HEFT) → searches for HHH can complement the picture

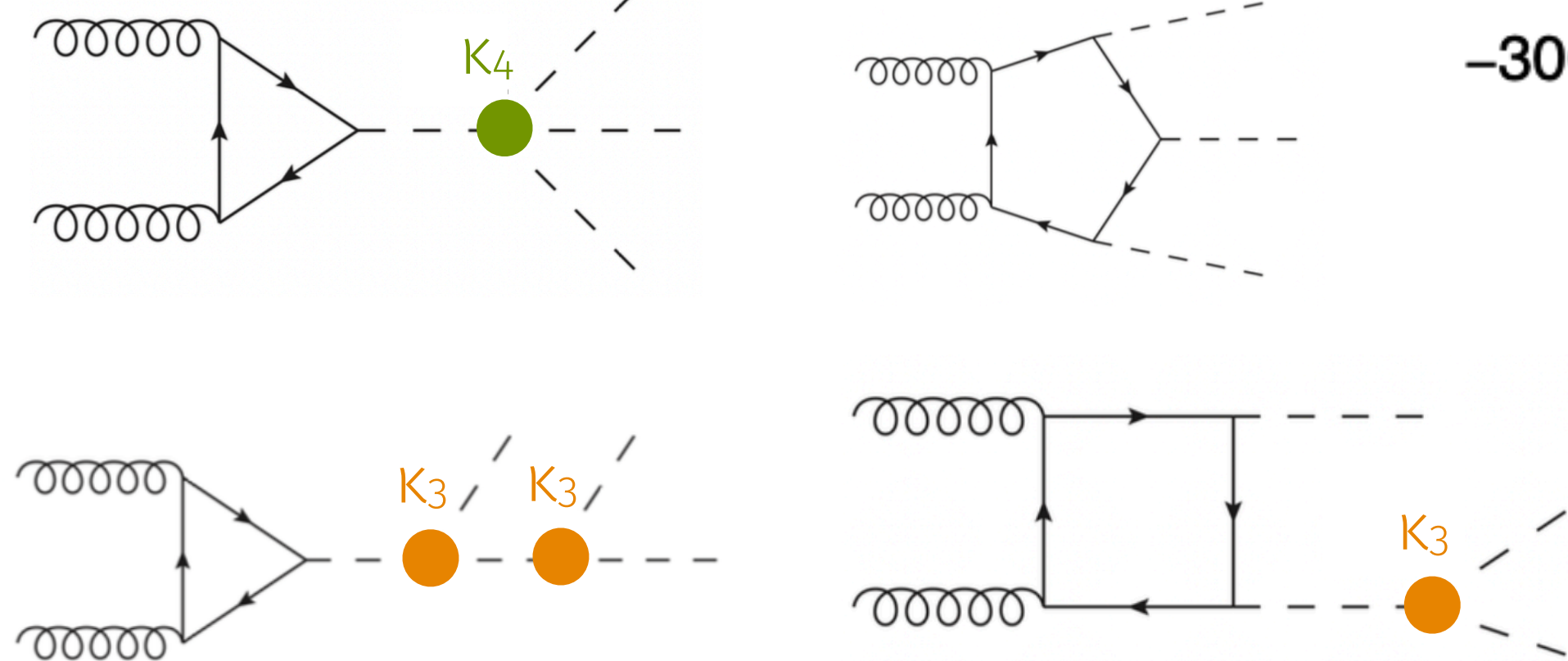
pp → HH:



[arXiv:2402.03463]

Brian Moser

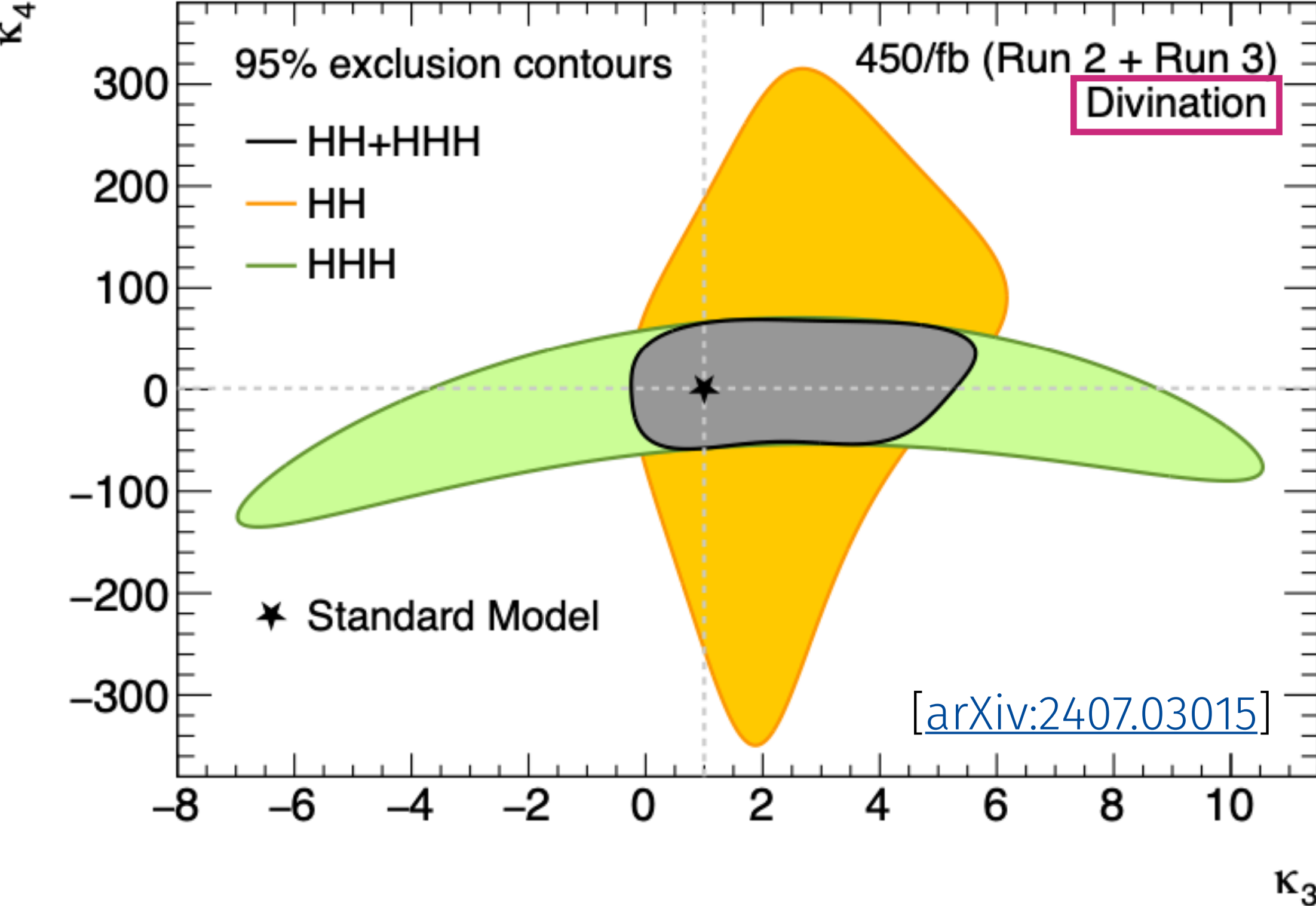
pp → HHH:



First exp. results become available, e.g. ATLAS search for HHH → 6b [Phys. Rev. D 111 (2025) 032006]

Does the Higgs boson wear a Mexican-hat?

Nice complementarity between HH and HHH searches



Run 2 expected yields:

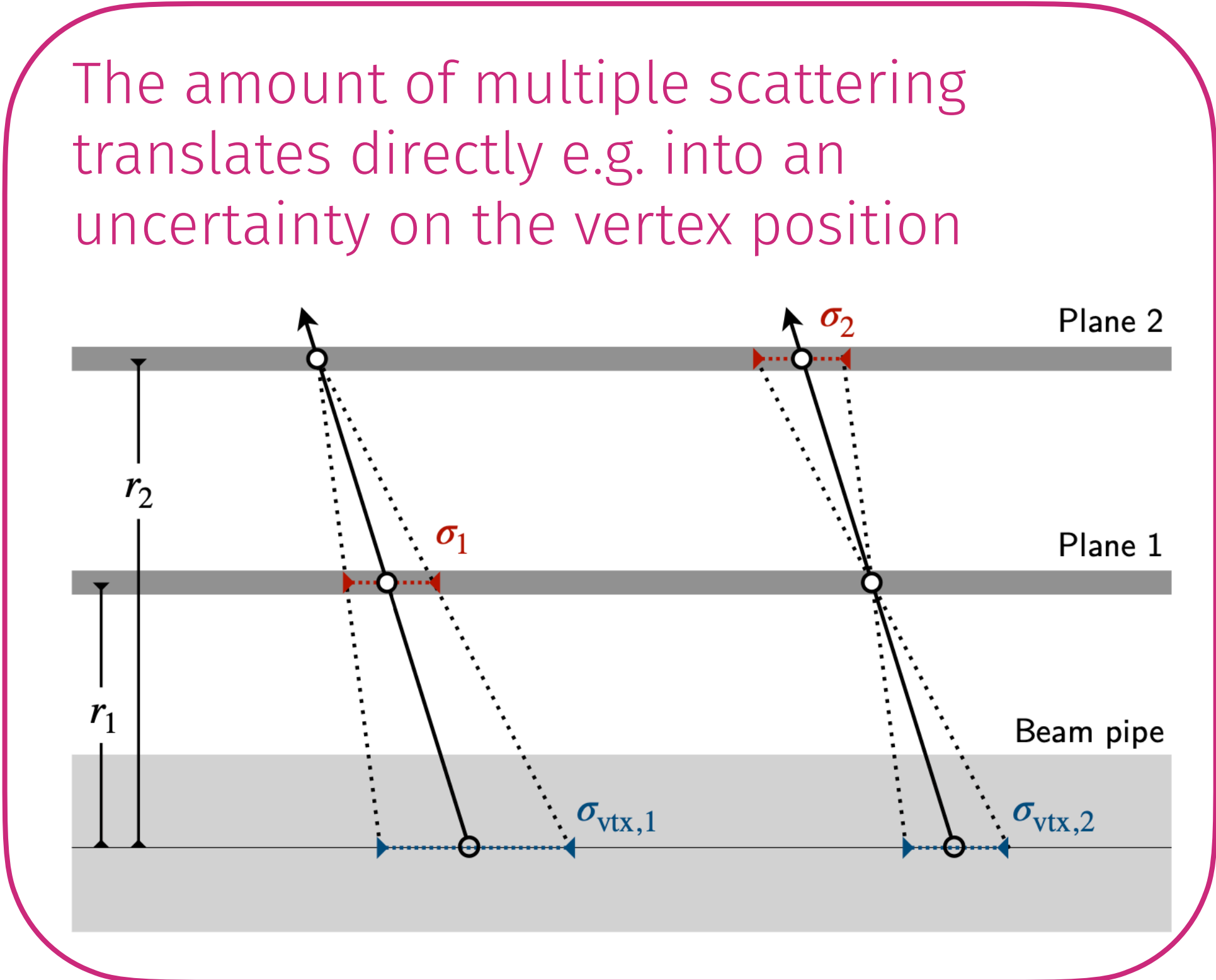
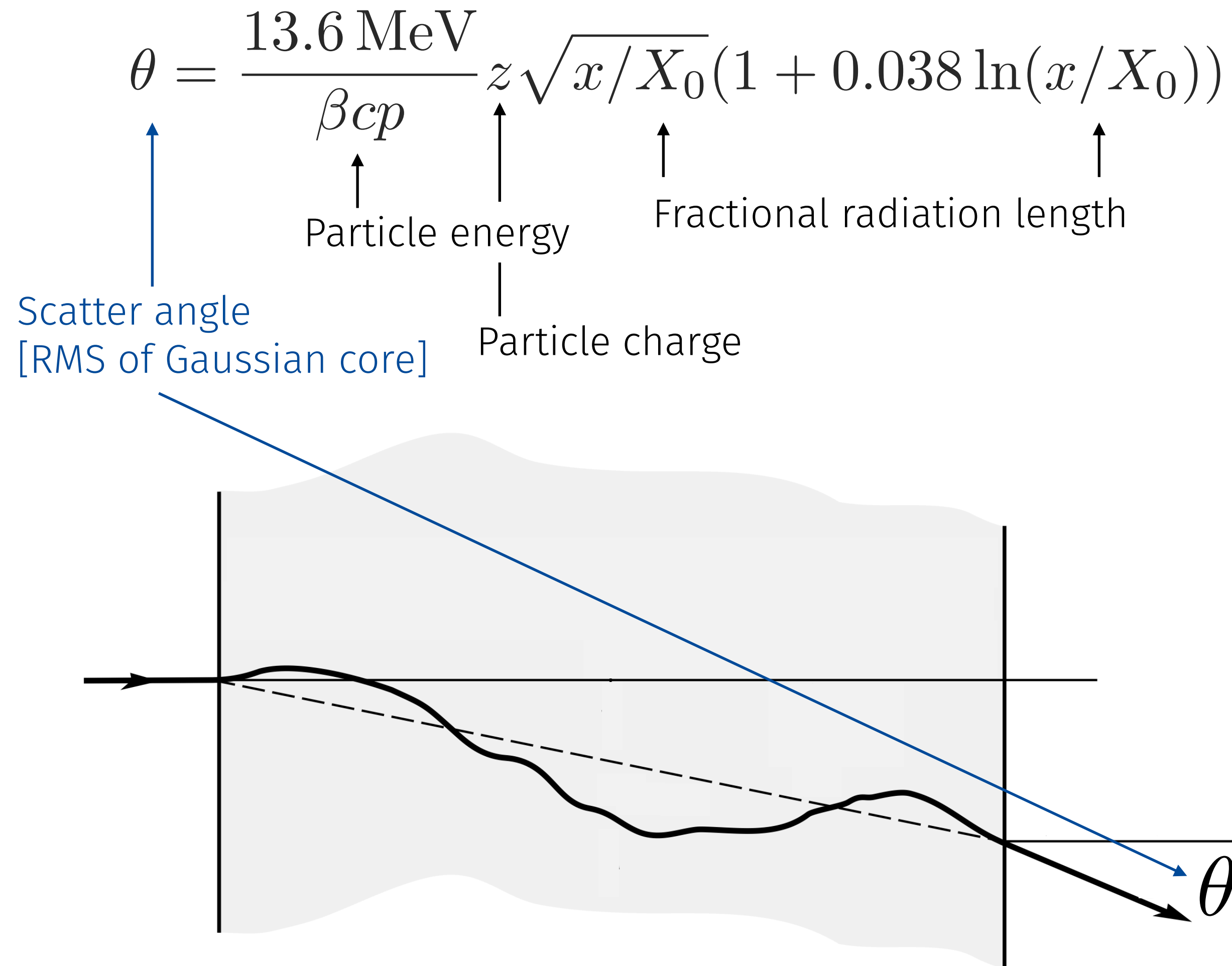
- pp → HH: ~ 4000 events
- pp → HHH: ~ 13 events



14/05/2026

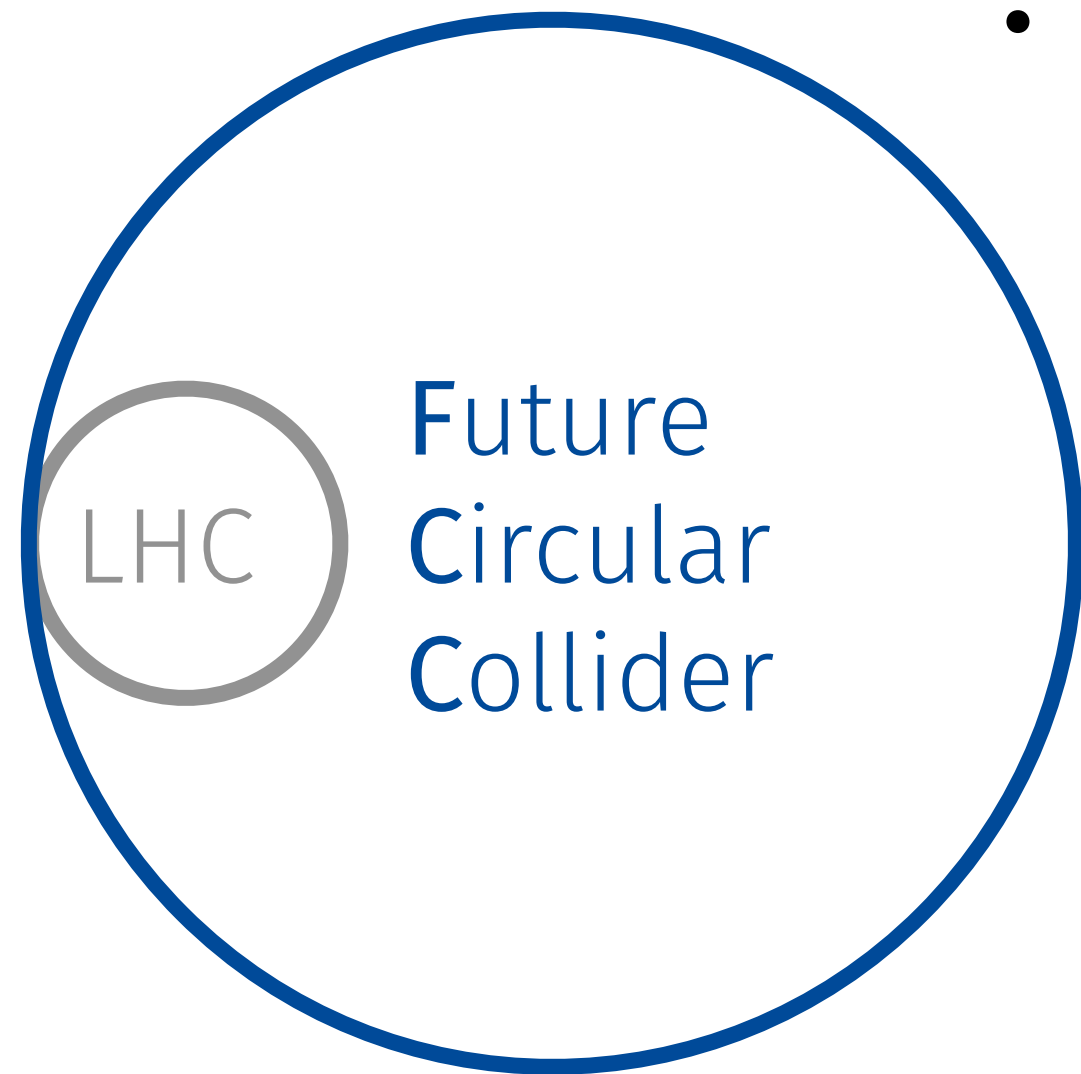
Keep your material budget low!

- Multiple Scattering described by a Gaussian core with $\sin(\theta)^{-4}$ Rutherford tails
 - can be described by a **double sided crystal ball** function



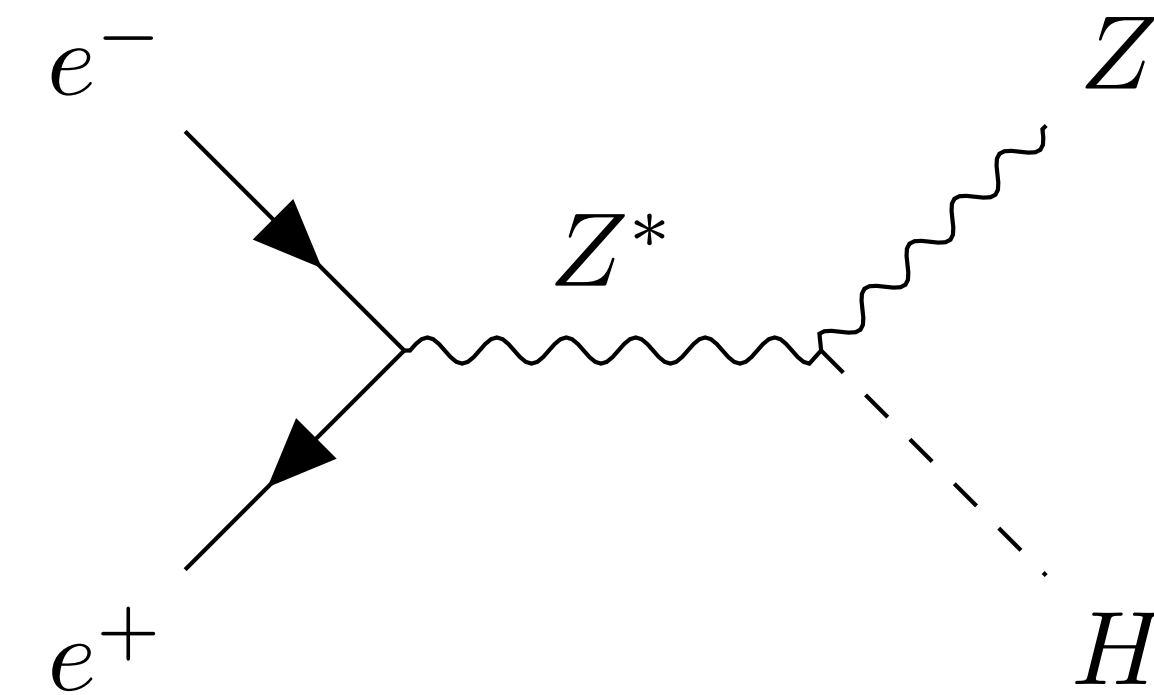
For particles with known energy we can measure the scatter angle to infer the fractional radiation length

Higgs physics at the Future Circular Collider (ee)

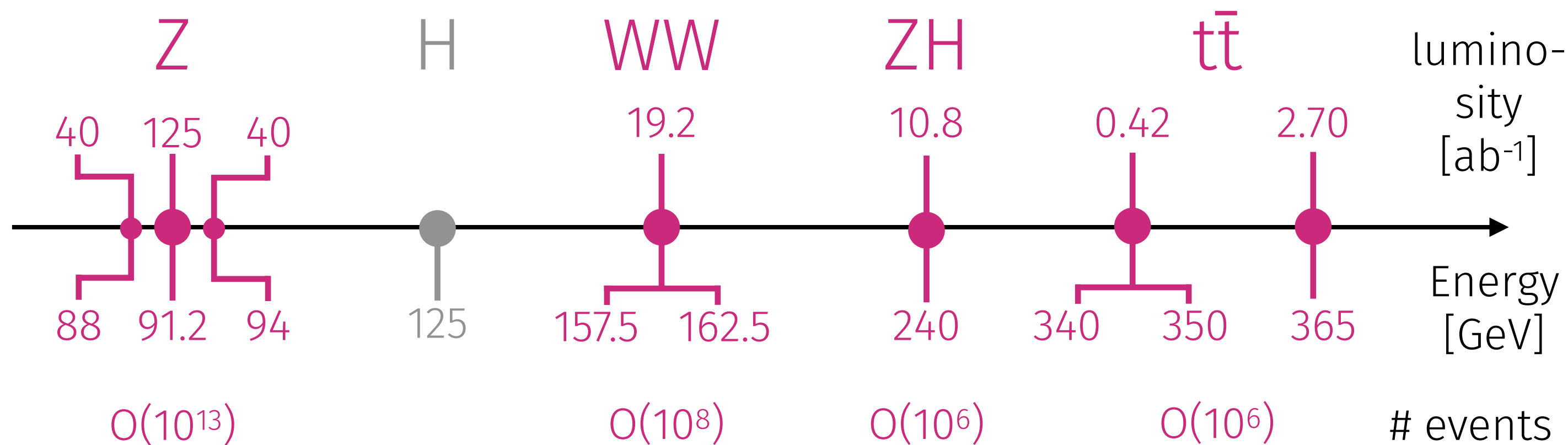


- 1st stage: e^+e^- collider (FCC-ee)
 - 91 km length
 - Multiple \sqrt{s} up to 365 GeV \rightarrow no HH 😞
- Followed up by a pp machine \rightarrow HH 😊

Main Higgs boson production mode at $\sqrt{s} = 240$ GeV



Planned FCC-ee programme:



Unique feature of e^+e^- : recoil mass

$$(P_{e^+}^\mu + P_{e^-}^\mu) = (P_H^\mu + P_Z^\mu)$$

$$m_H^2 = s + M_Z^2 - 2\sqrt{s} E_Z$$

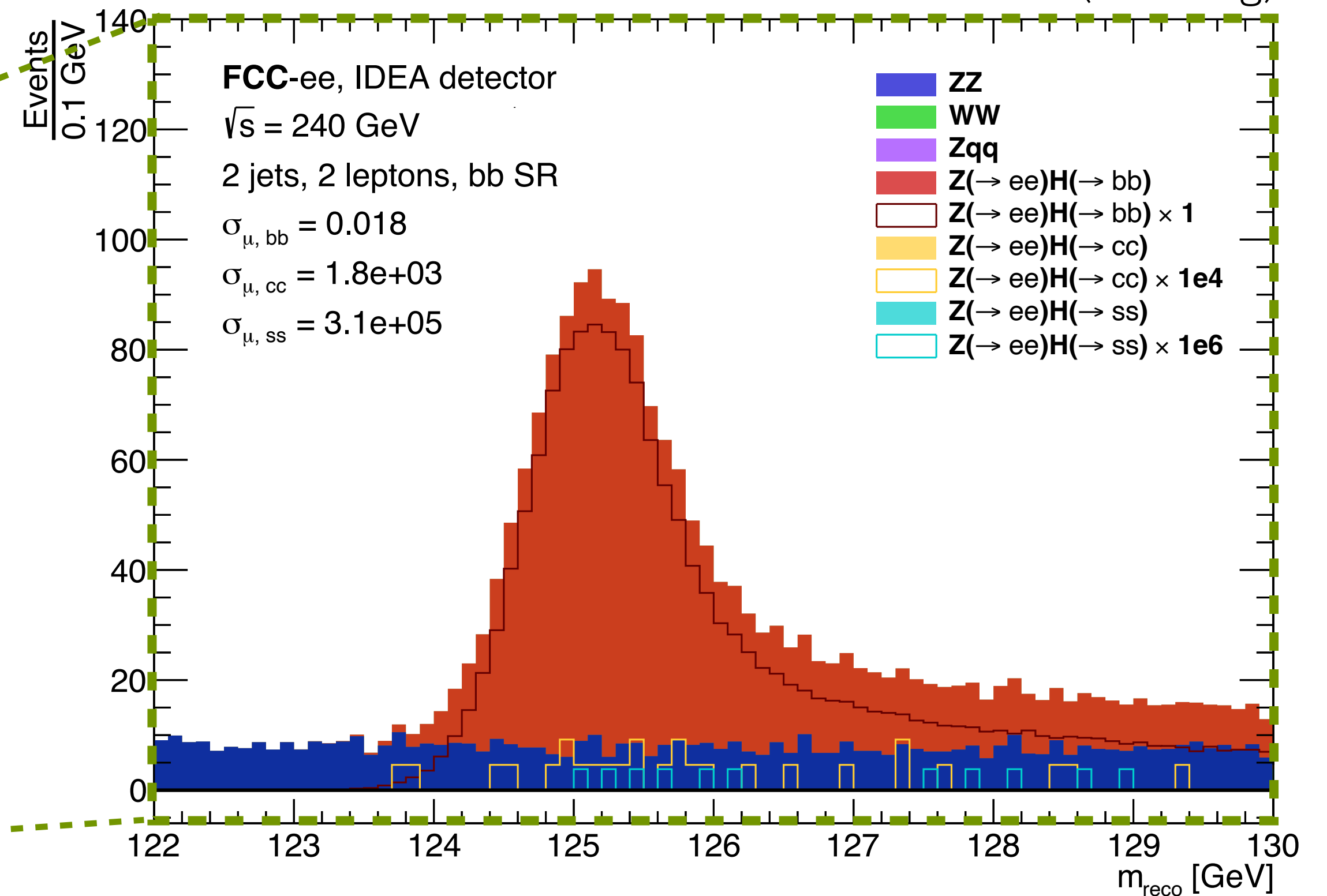
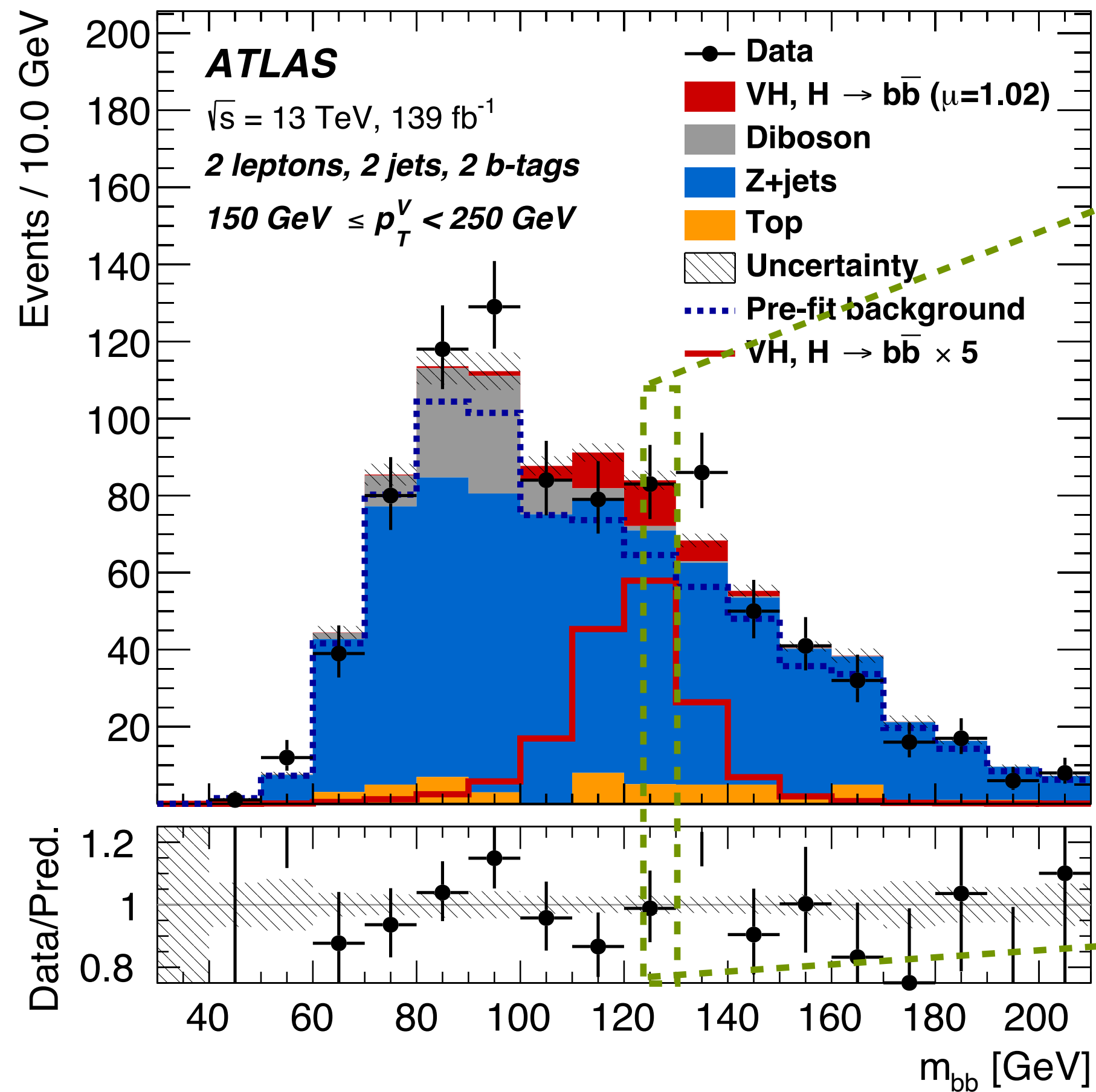
Example: $H \rightarrow bb$ at the LHC vs. FCC-ee

Resolution: ~ 10 GeV

e^+e^- : recoil mass

Resolution: $O(0.5$ GeV)

V. Halfman (Freiburg)



\rightarrow %-level, model independent determination of b-quark Yukawa coupling will be possible