Detector Overview

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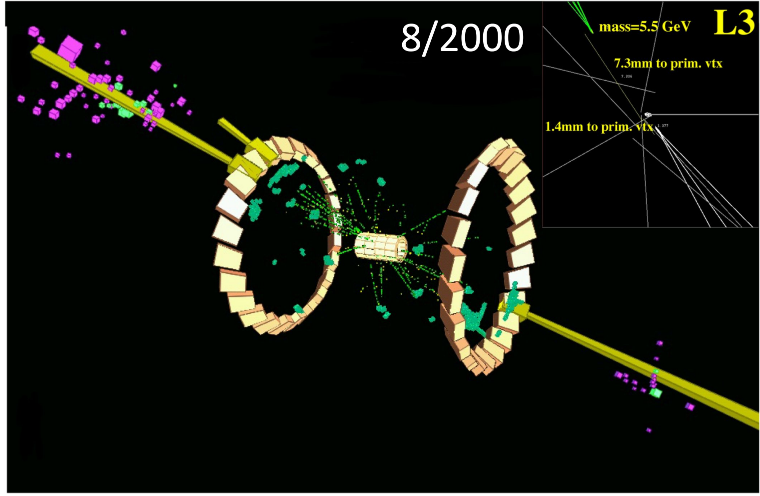
Princeton University

Horizons In Accelerators, Particle/Nuclear Physics and Laboratory-Based Quantum Sensors for HEP/NP

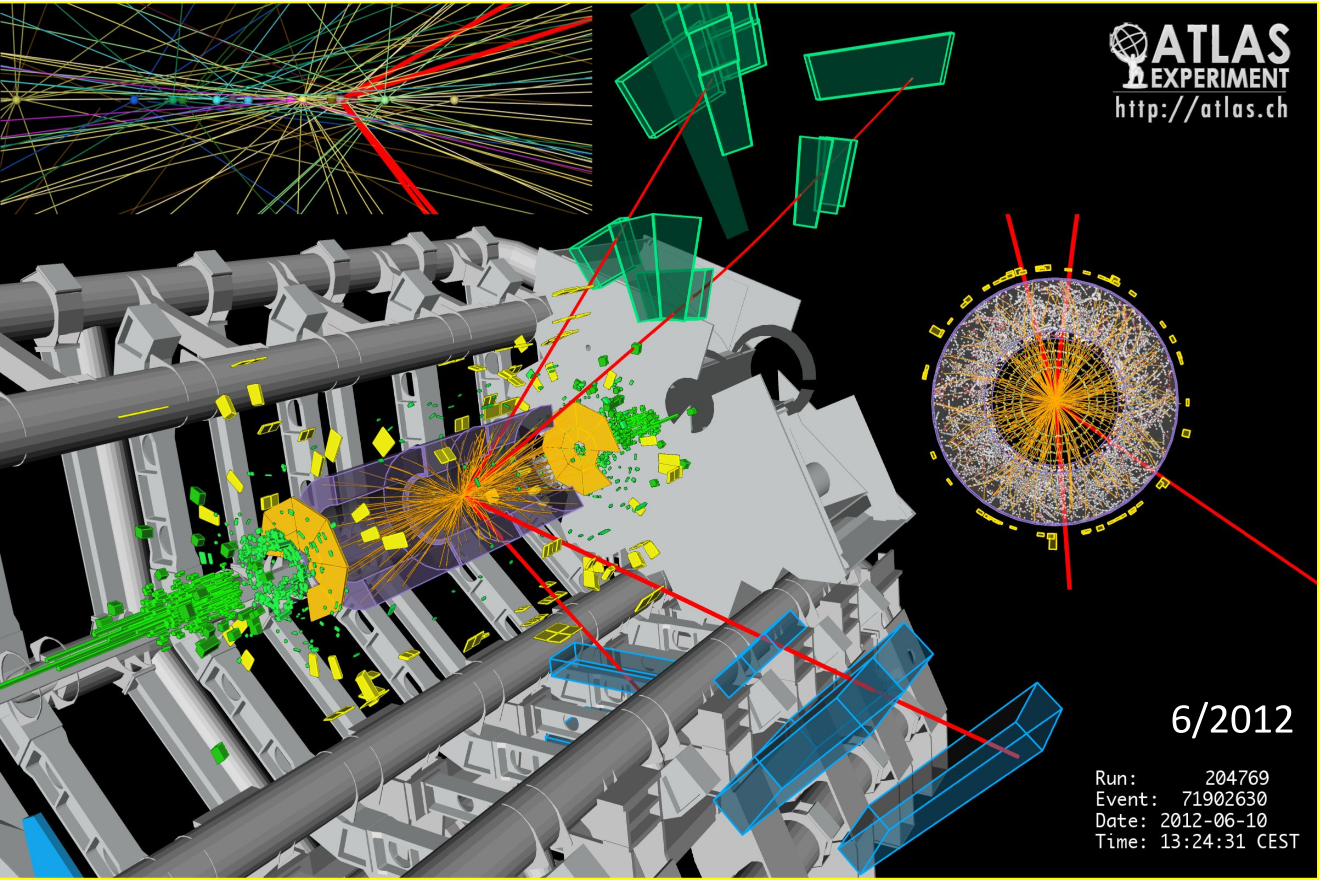
ICTS-TIFR, Bengaluru, India

14 November 2022

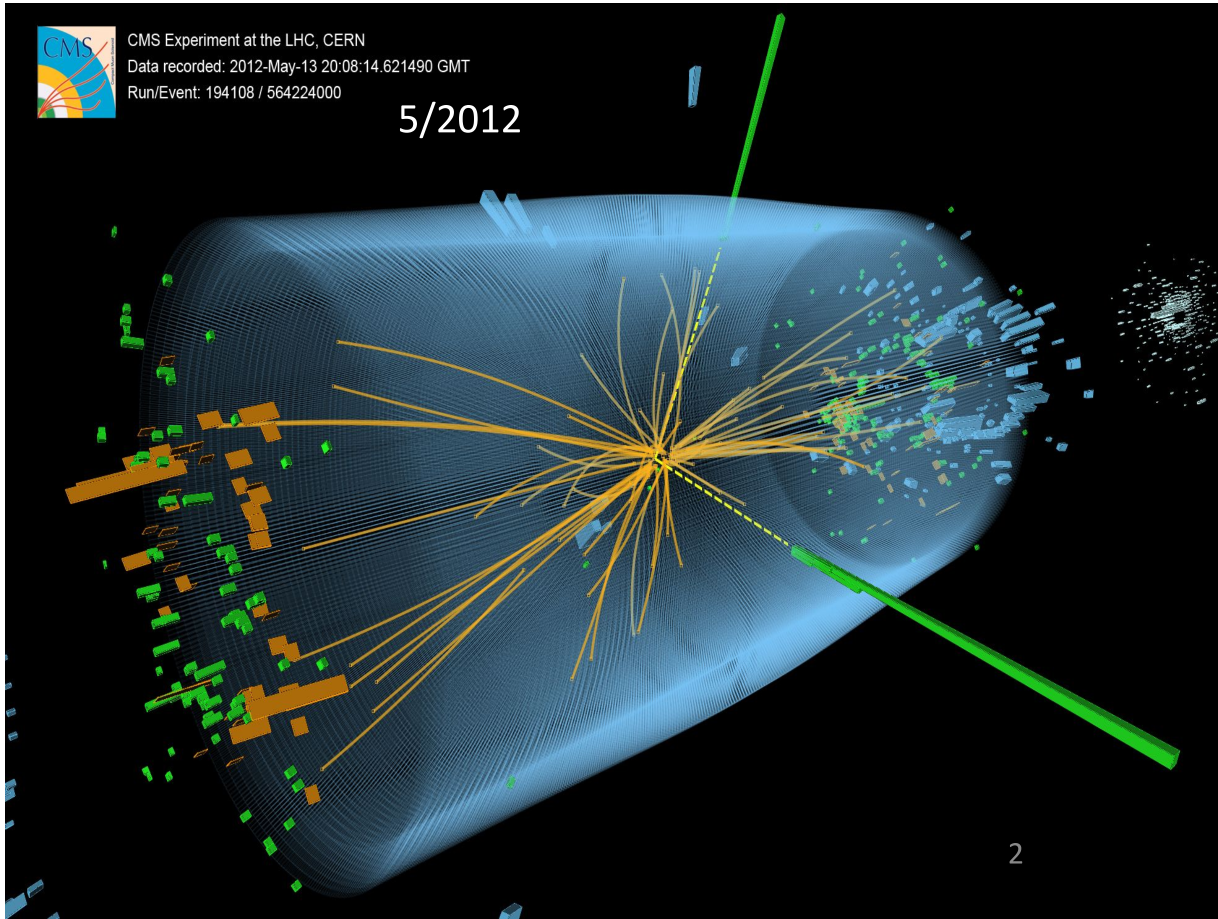
Revisiting the Collider Detector



8/2000

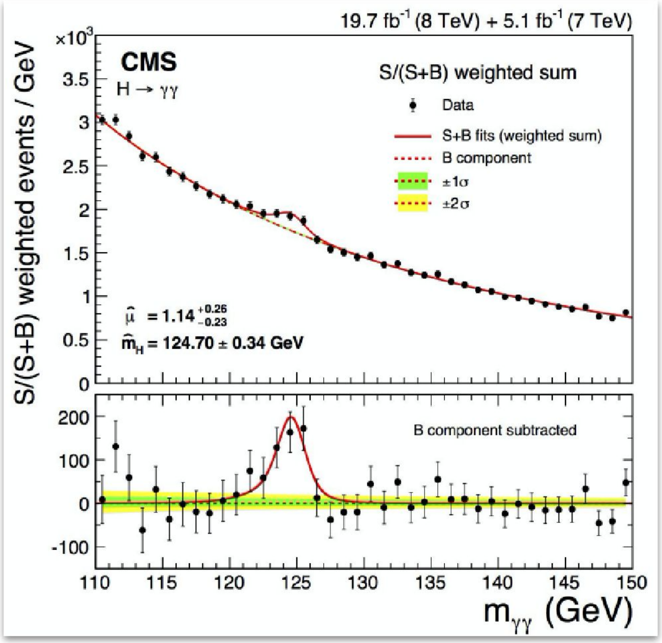


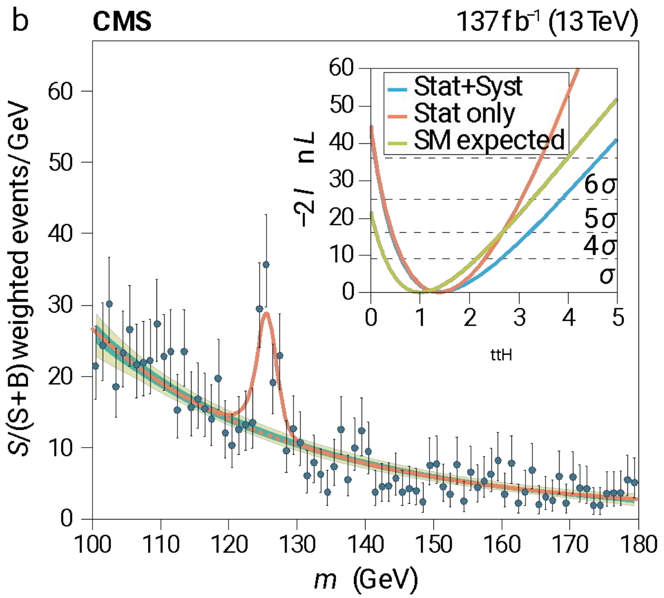
6/2012

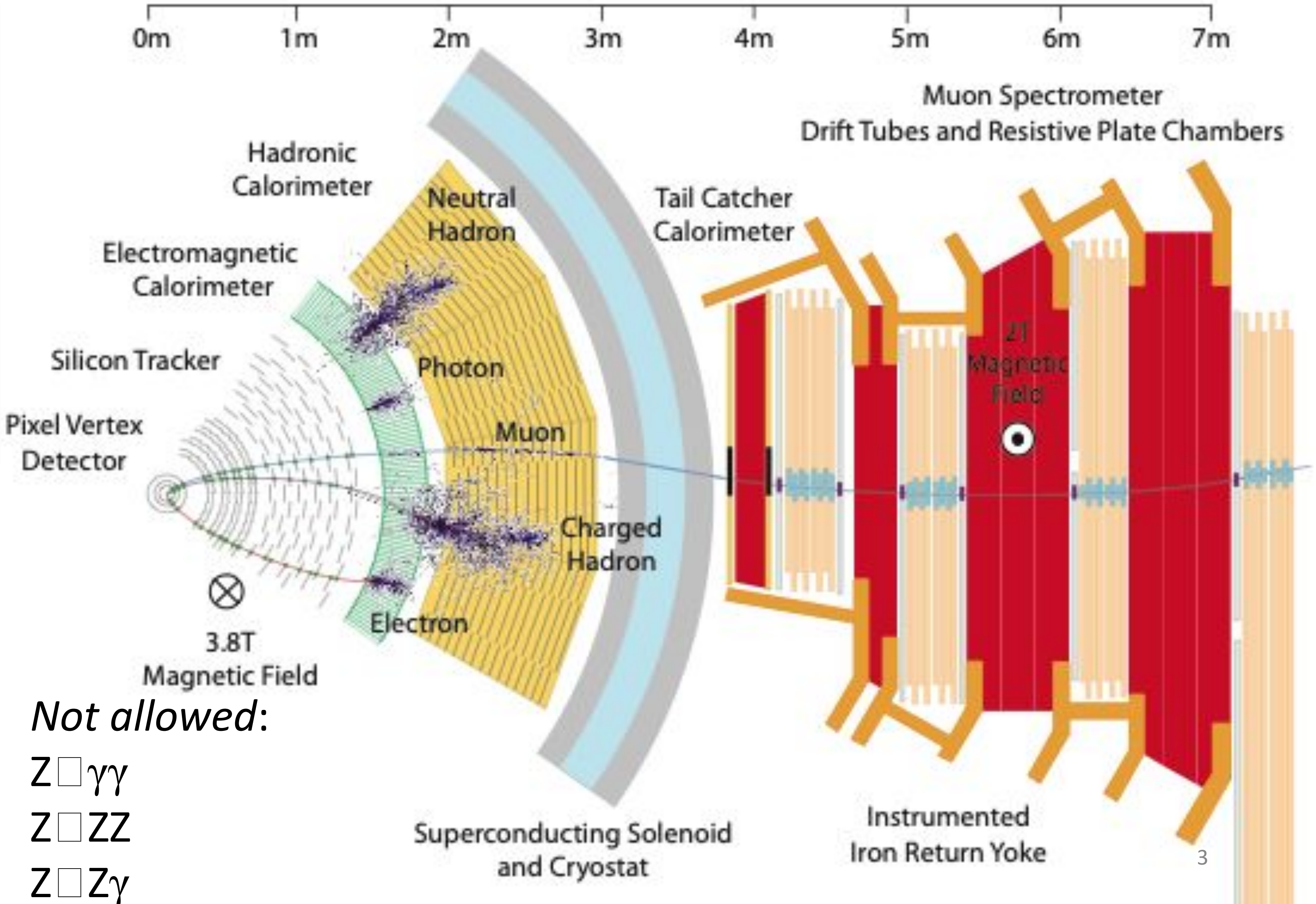


5/2012

Atlas/CMS: Designed for Higgs Boson Discovery







Not allowed:

Z□γγ

Z□ZZ

Z□Zγ

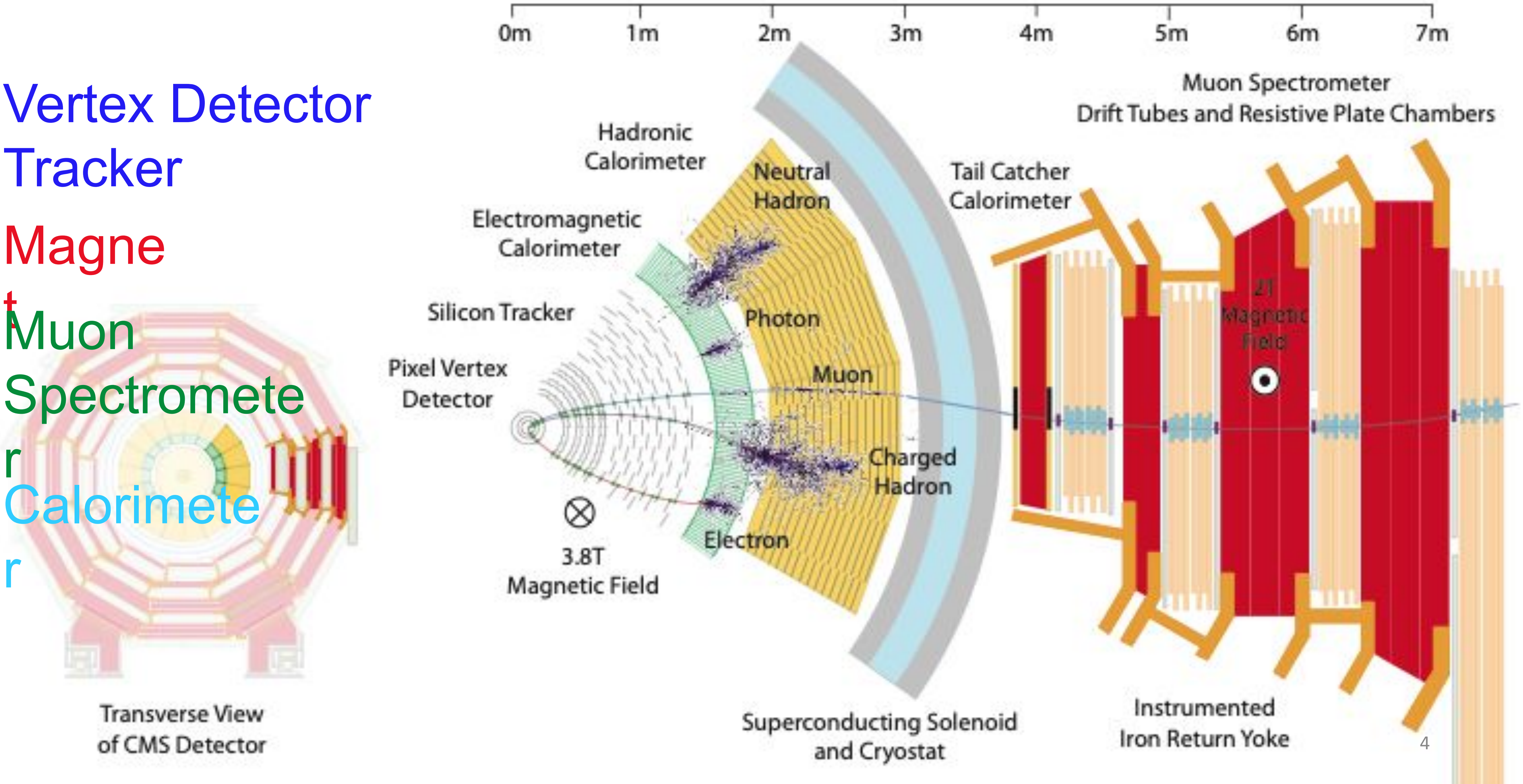
Atlas/CMS: Designed for Higgs Boson Discovery

Vertex Detector
Tracker

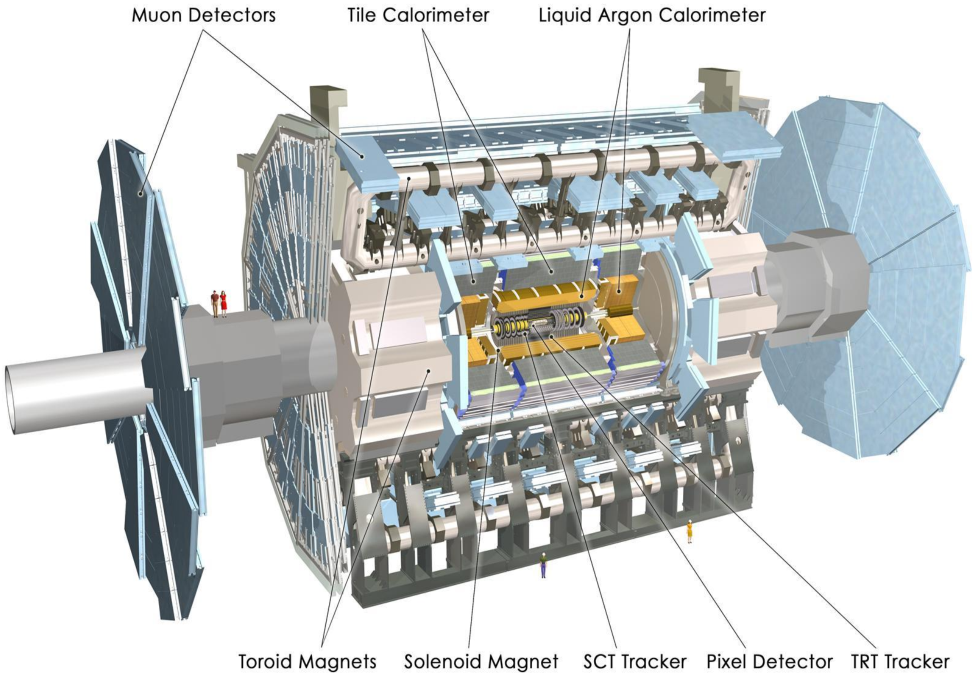
Magnet

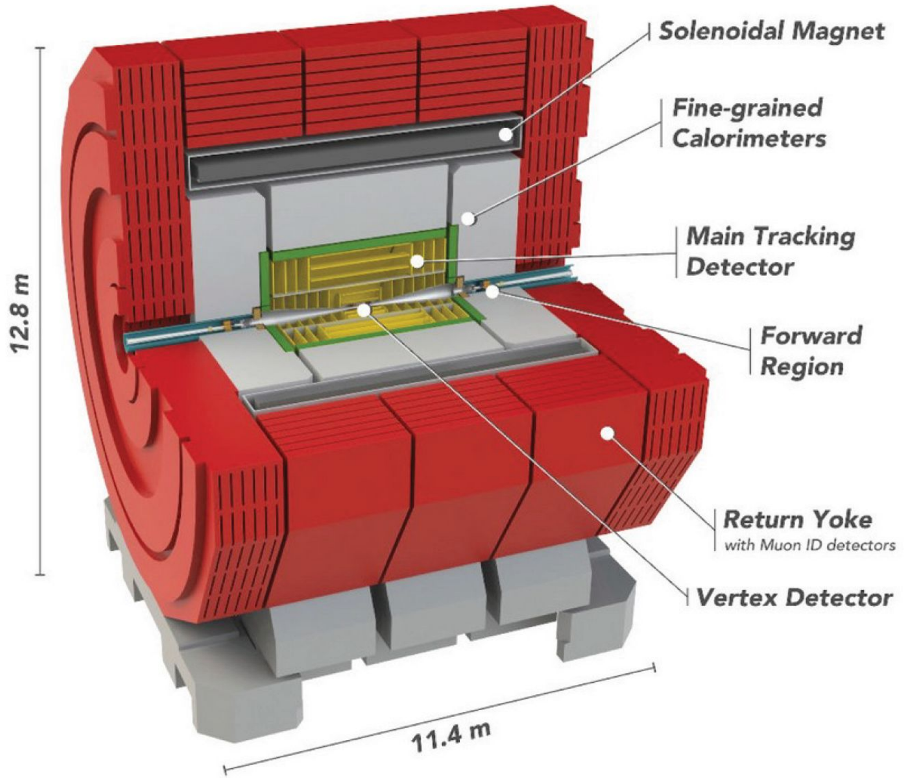
Muon Spectrometer

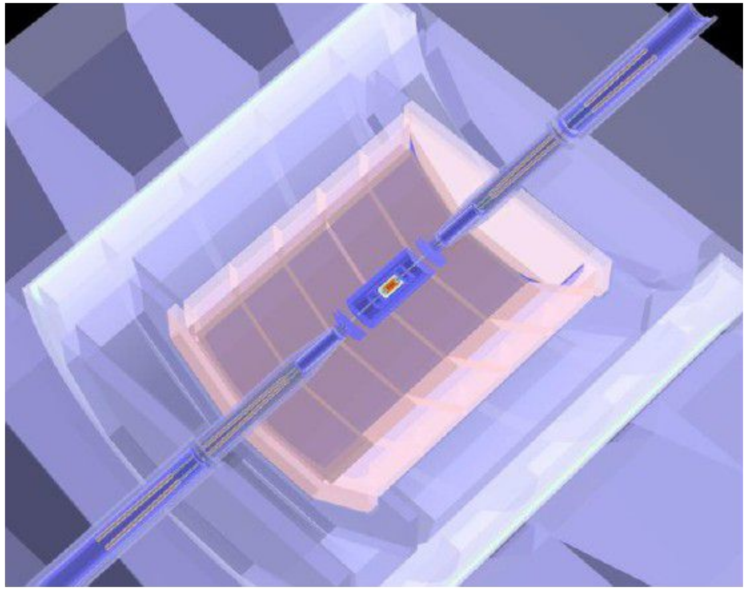
Calorimeter



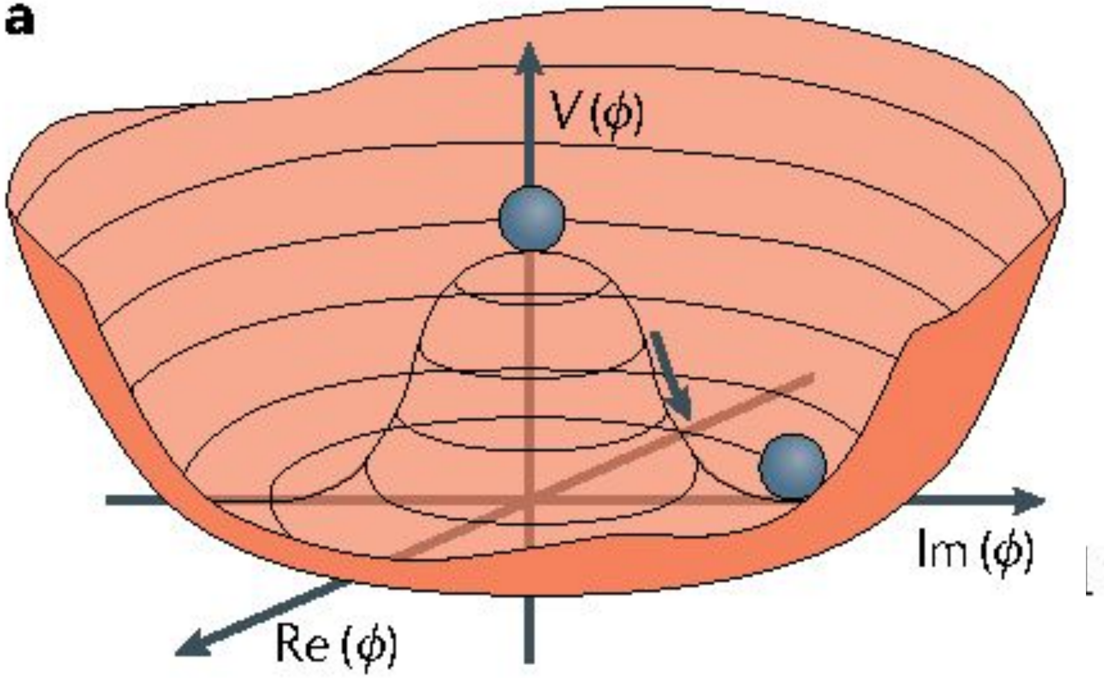
What tells us it's the right choice??



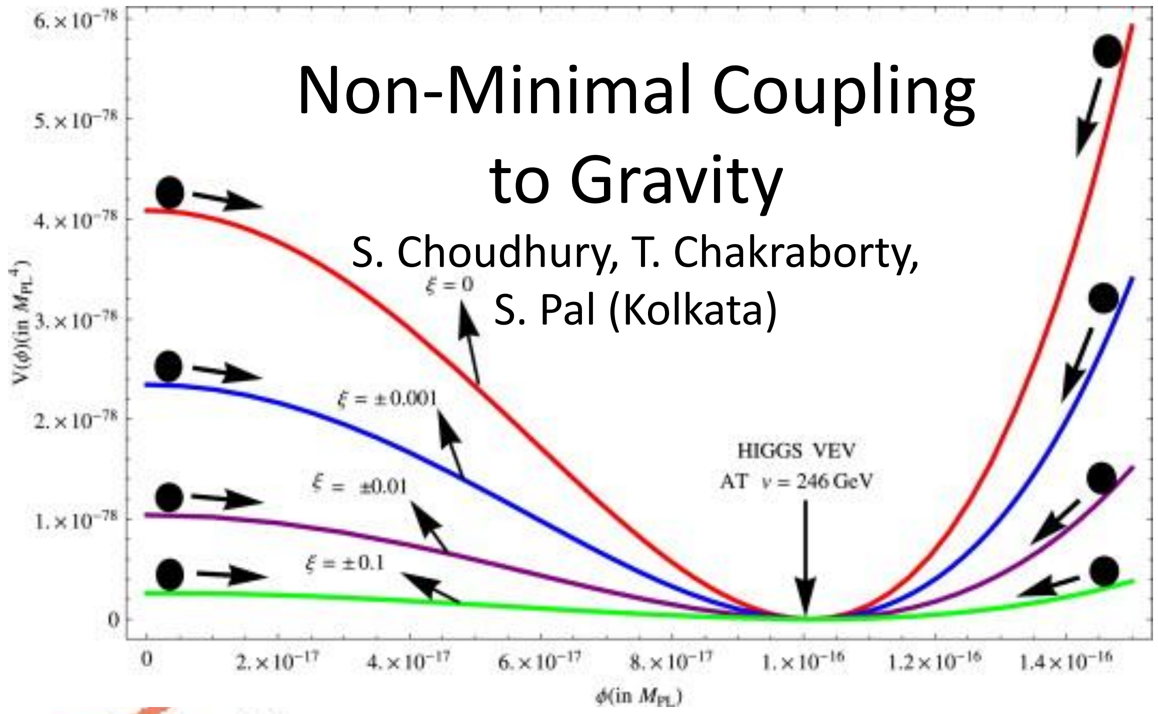




Higgs Potential/Self-Coupling/Non-Minimal Coupling

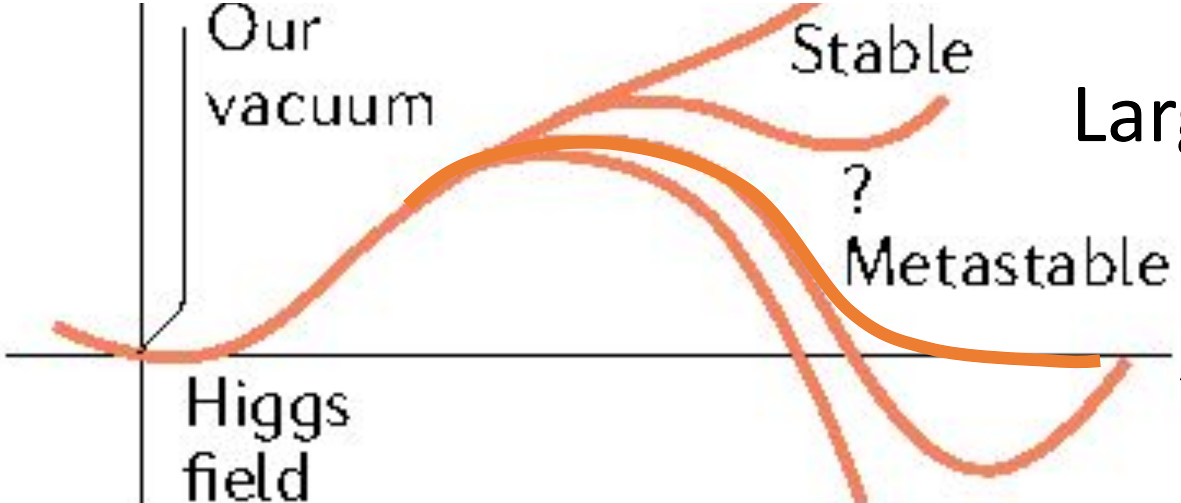


EW symmetry breaking



Non-Minimal Coupling to Gravity

S. Choudhury, T. Chakraborty, S. Pal (Kolkata)

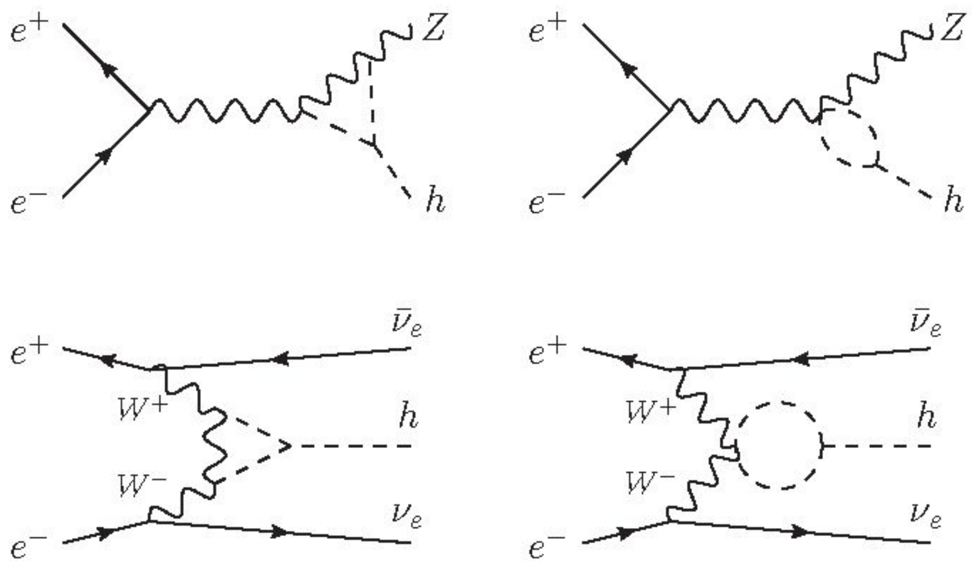


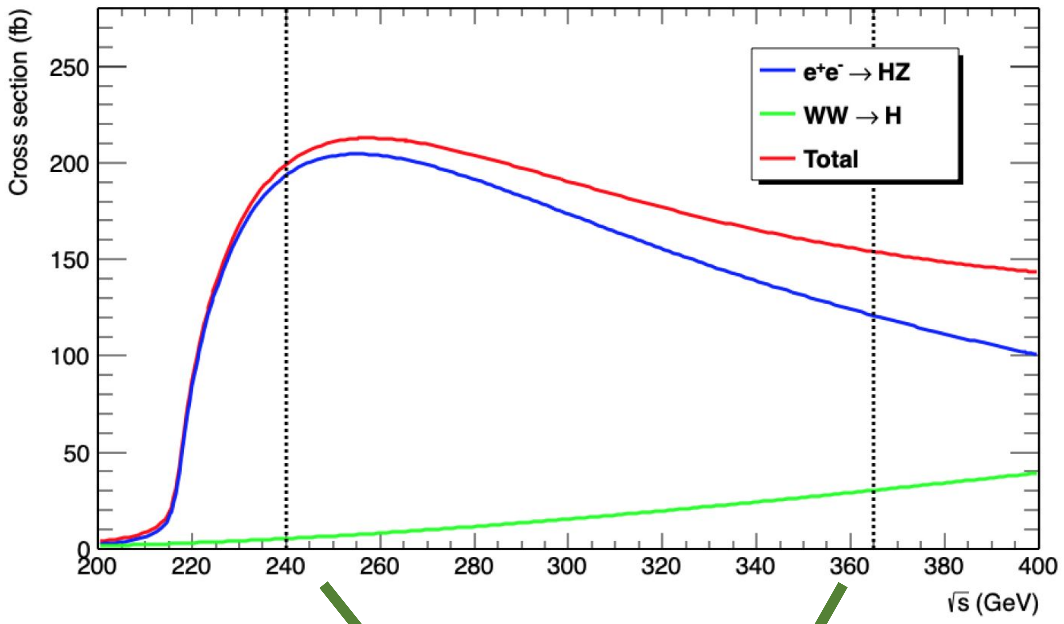
Large-Field Stability?

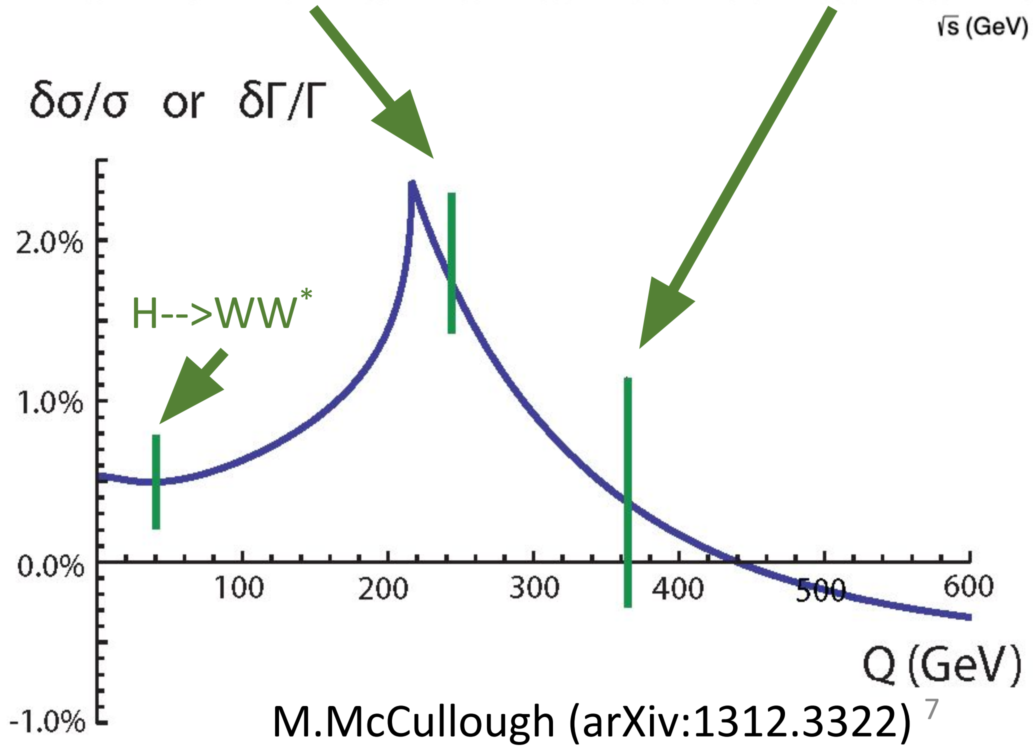
$\lambda(m_{GUT}) \sim \lambda'(m_{GUT}) \sim 0$

P. Azzurri et al. Special Study FCC-ee (arXiv:2106.15438)

Probing Higgs at Loop-Level



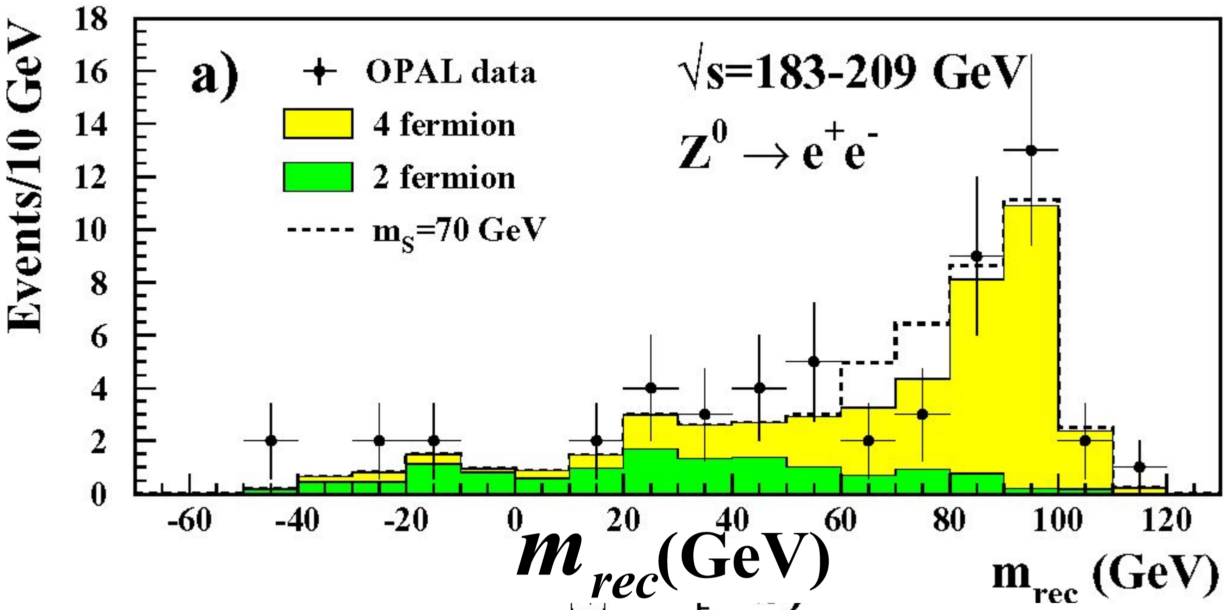


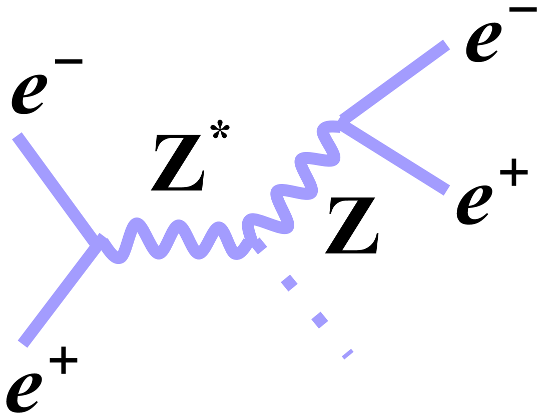


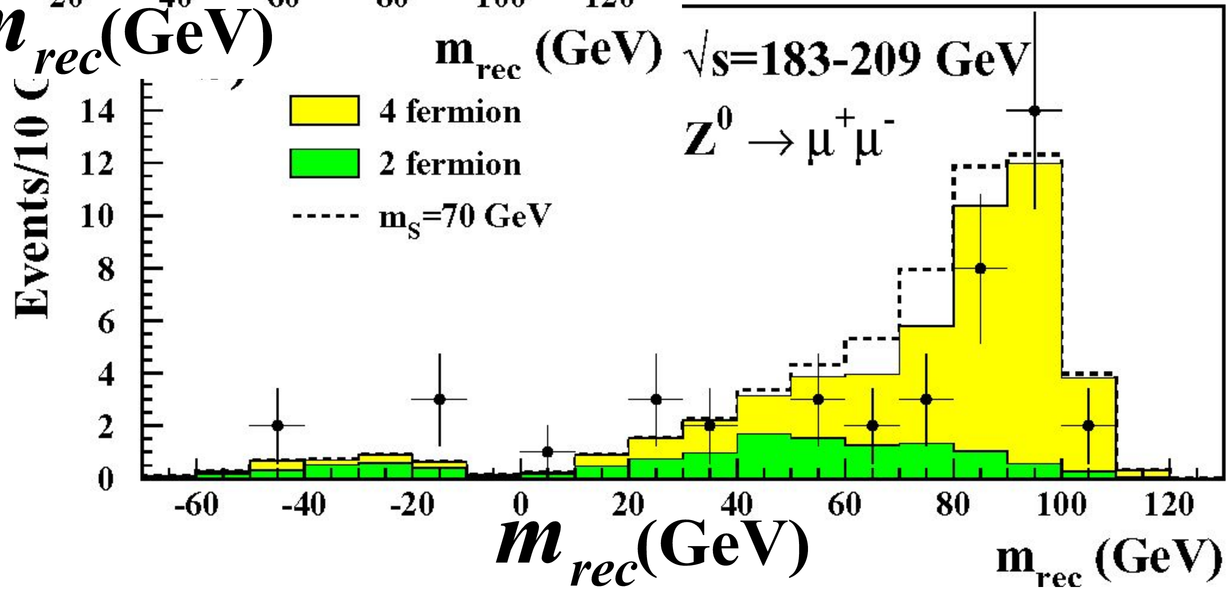
<u>Design detector</u>/physics program to achieve/exceed ~0.2% on HZ production at 240 GeV for >5 σ HHH self-coupling evidence (compare to $\Delta\rho$ measurement at LEP1)

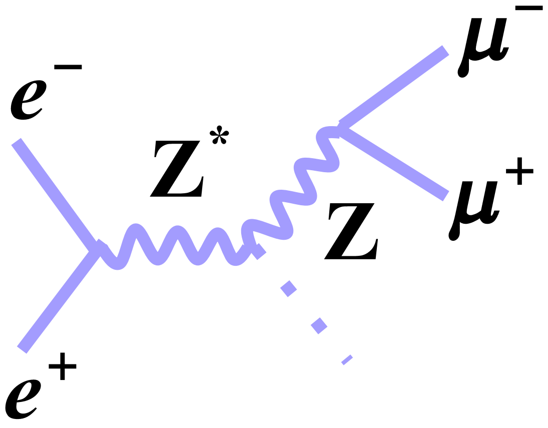
M.McCullough (arXiv:1312.3322)

Recoil Mass Analysis from LEP

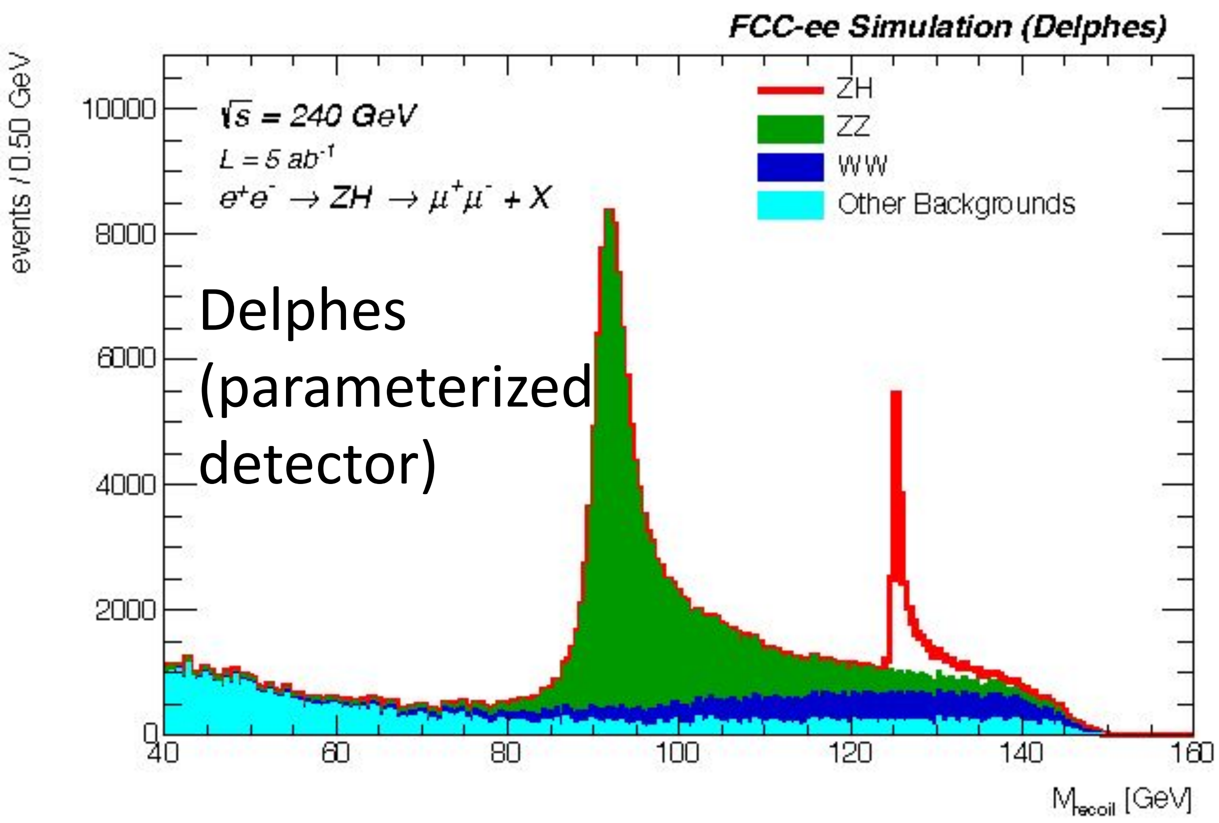




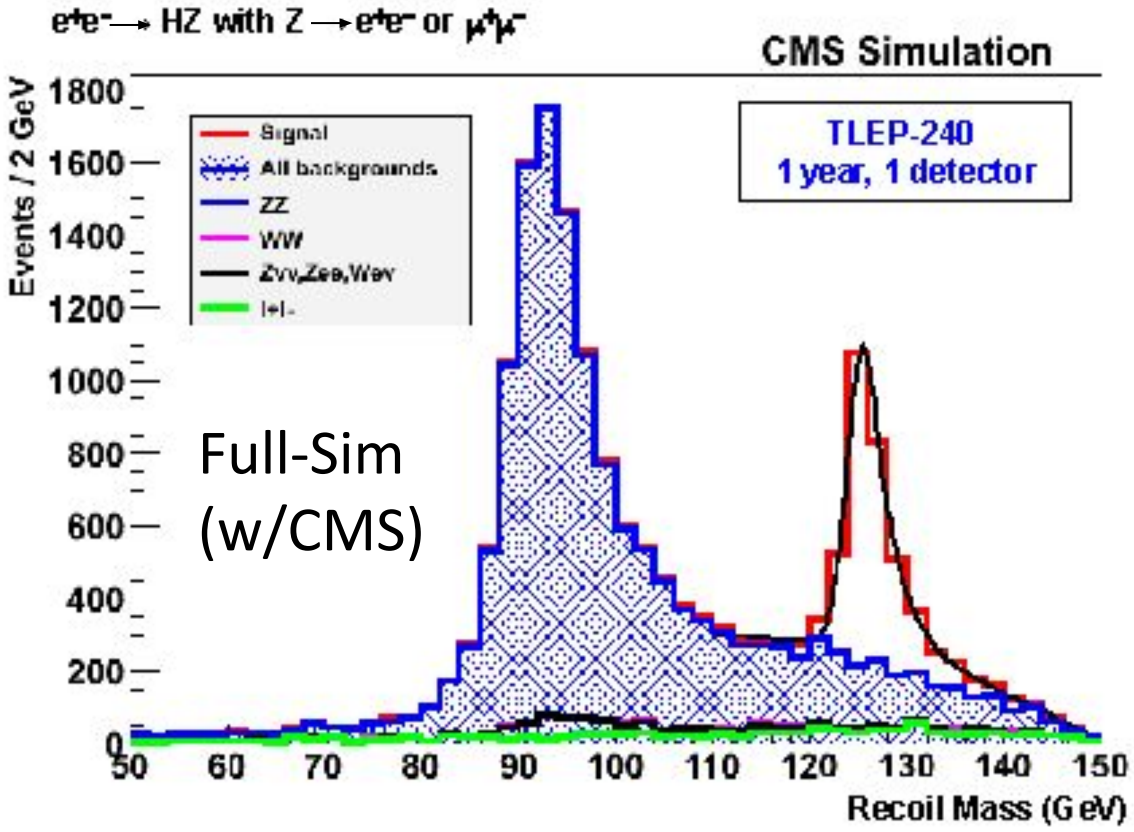




Studies on Z□ℓℓ Recoil Mass



P. Azzurri et al. Special Study FCC-ee (arXiv:2106.15438)



First Look Study TLEP (arXiv:1308.6176)

Detector Limitation:

Lack of separation of Z from ZZ with H from ZH, even when computing recoil from Z□ll

Statistical power/Systematics: L_{int} and Z□jj recoil and lumi systematics

Summary Table of Energy Resolutions

https://arxiv.org/abs/2109.00391

Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12,20]	1 % [12,20]	45 – 50 % [45,20]	≈ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8 10 % [24,27,46]	< 1 % [24,27,47	≈ 40 % [27,28]	≈ 6 % ?	3 4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	≈ 30 % [48]	4 – 5 % [49]	3 – 4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	≈ 26 % [30]	5 – 6 % [30,50]	3 – 4 % [50]

If the focus is mainly jets, then high-granularity with PFA delivers 4% at 50 GeV – often called “PFA calorimetry”

Noble Liquid is a better calorimeter across the board, but needs PFA studies

Higher EM performance with Noble Liquid or Fibers – Highest with Crystals

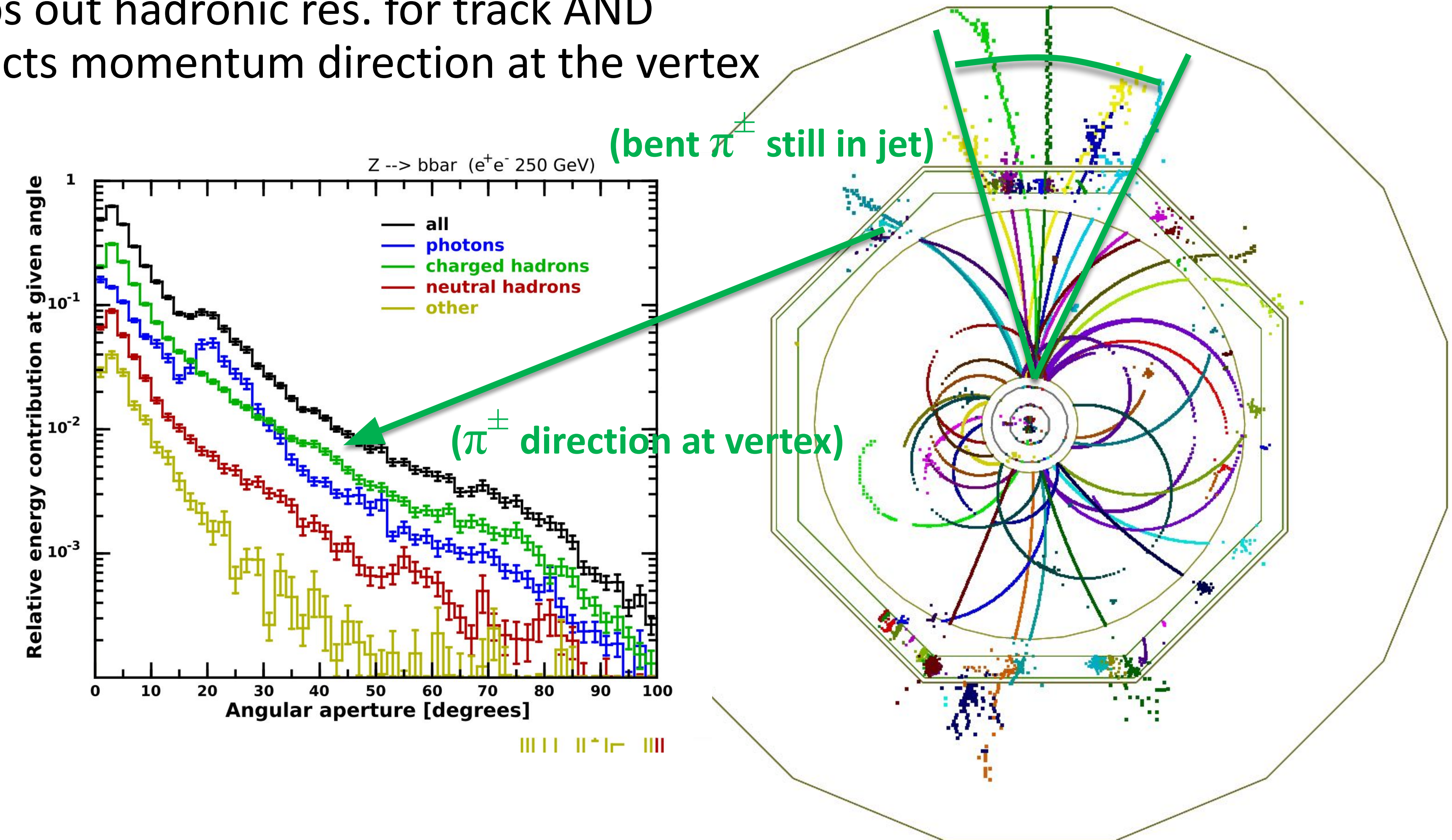
Best Intrinsic Hadron Performance with Dual-Readout Fibers

Hybrid Dual-Readout Crystals+Fibers attempts to maximize all performances

Why PFA helps

- Review of Principles of Jet Performance:
  - Swaps out hadronic res. for track AND corrects momentum direction at the vertex

Slide borrowed from Marcel Vos

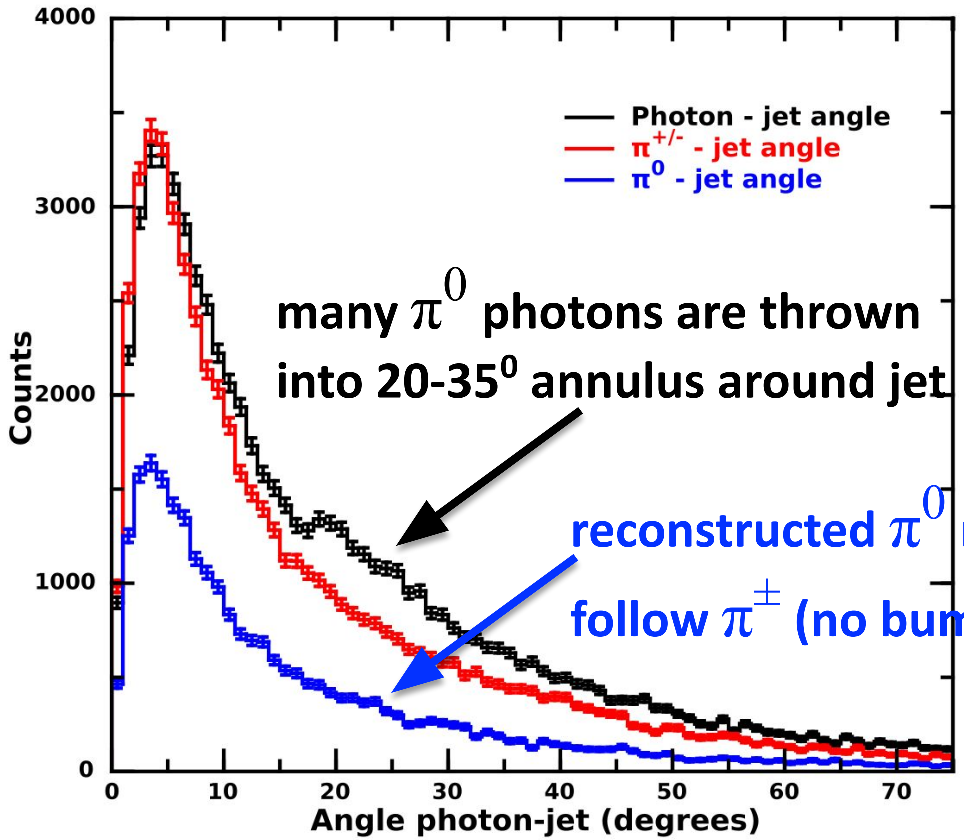


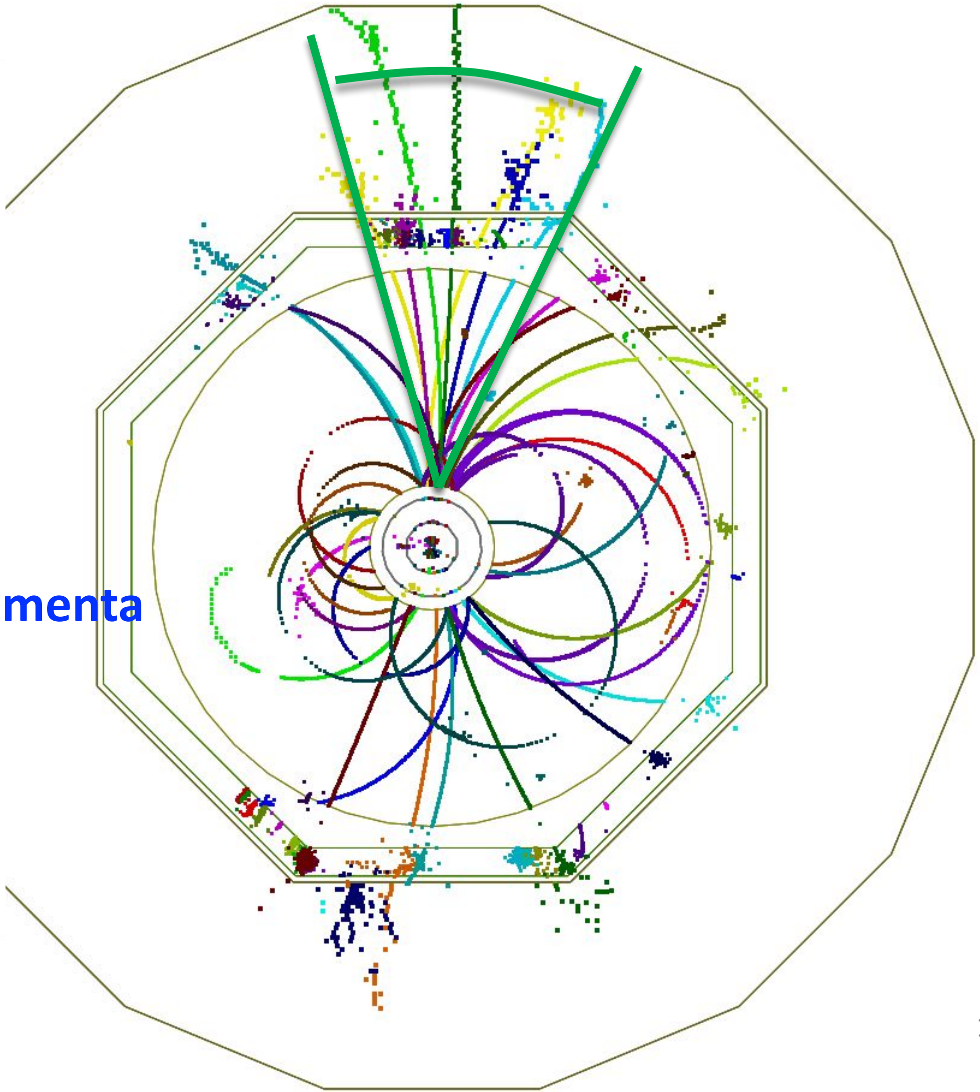
Marco
Lucchini

PFA can help even more (π^0 pre-clustering)

- Review of Principles of Jet Performance:
  - How about photons?

Slide borrowed from Marcel Vos



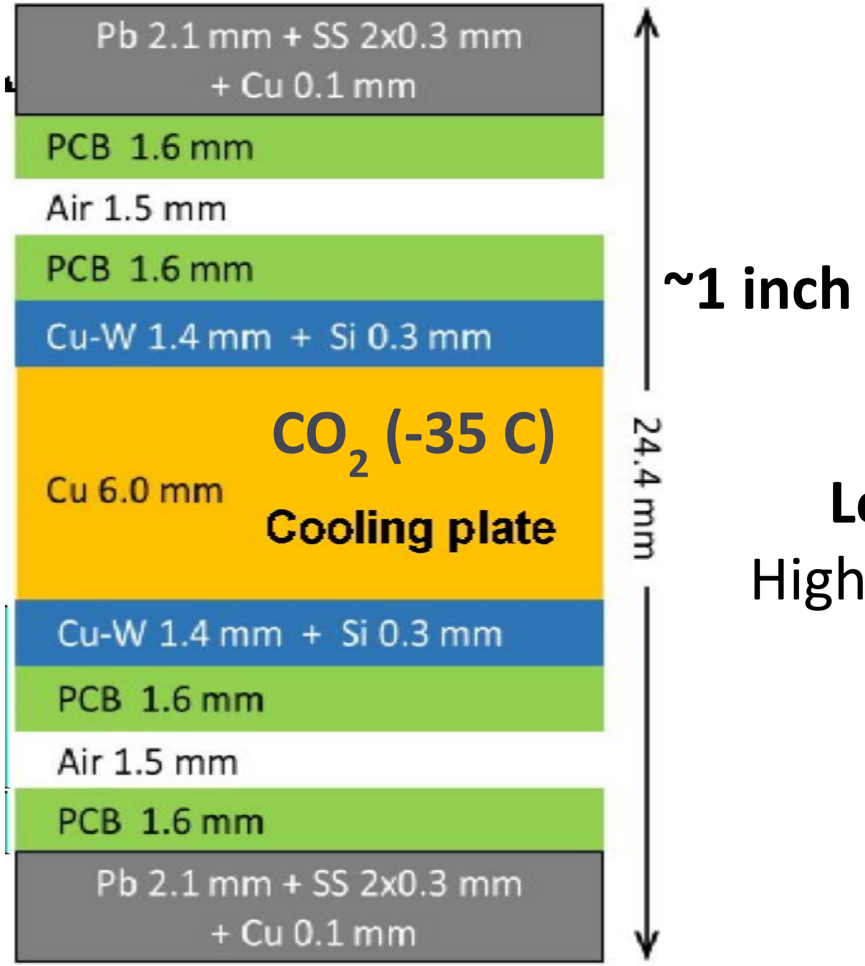


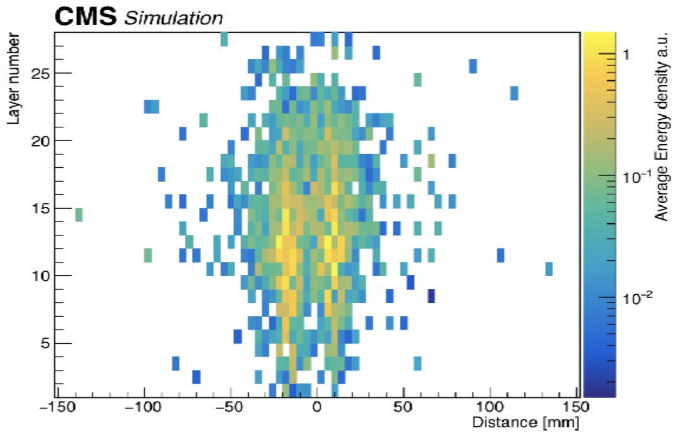
Marco Lucchini

Tracking/Imaging Capabilities of Silicon (SF~1/300)

“Si-W”

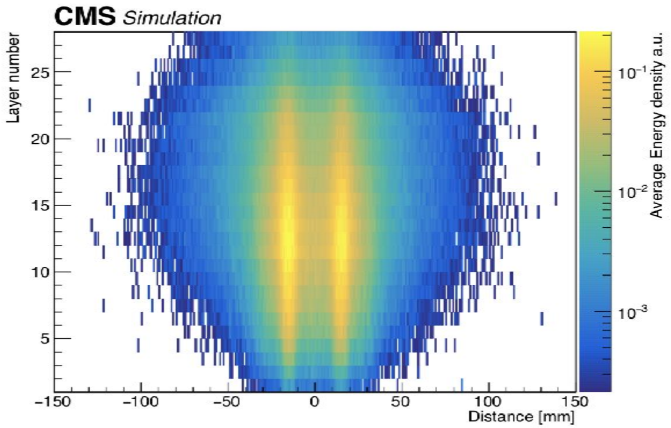
Implemented for HGCal CMS Phase-2





One event

Fluctuations driven by
Low Sampling Fraction(~1/300)
High SF □ one shower looks like many



Several thousand events

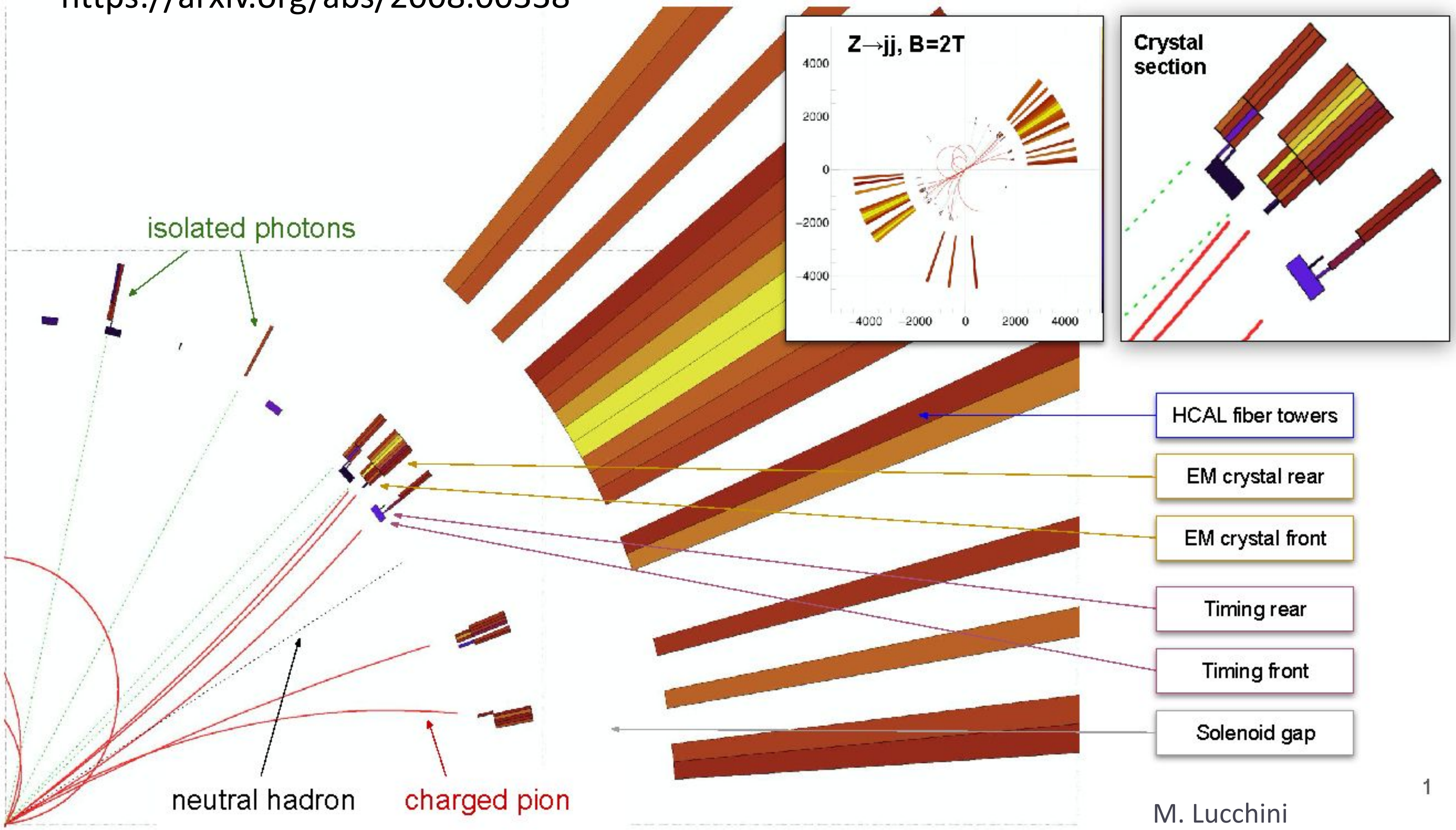
Balancing
# of Layers of Si

versus
(equiv. of)

Fewer
Homogenous
Crystal Depths
(w/Dual-Readout)

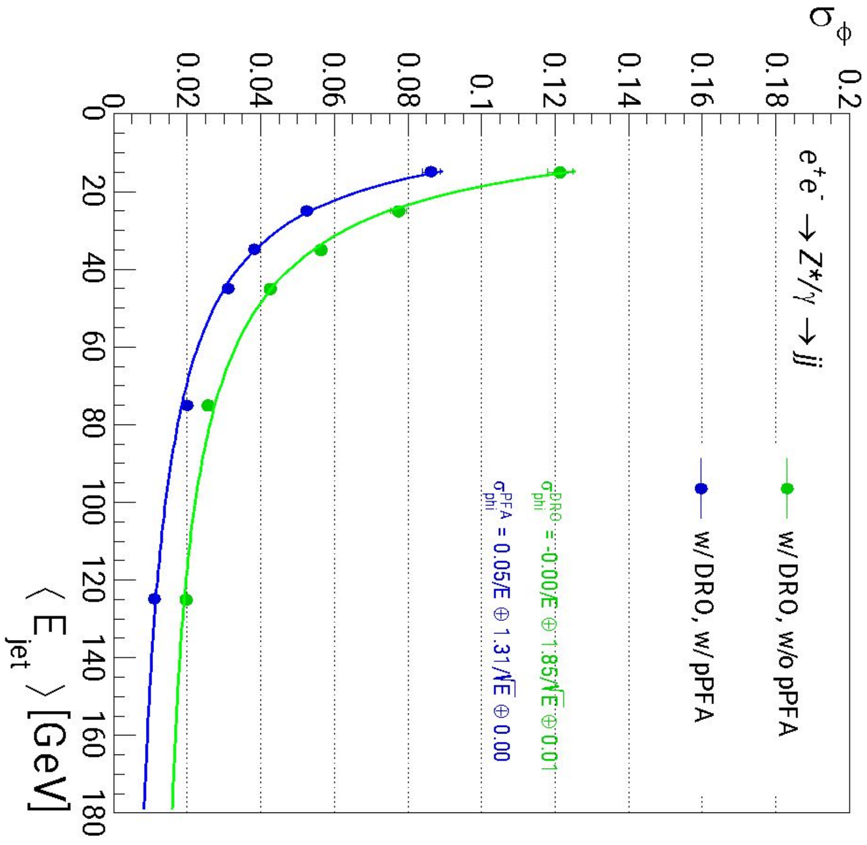
Hybrid Dual-Readout Crystals+Fibers

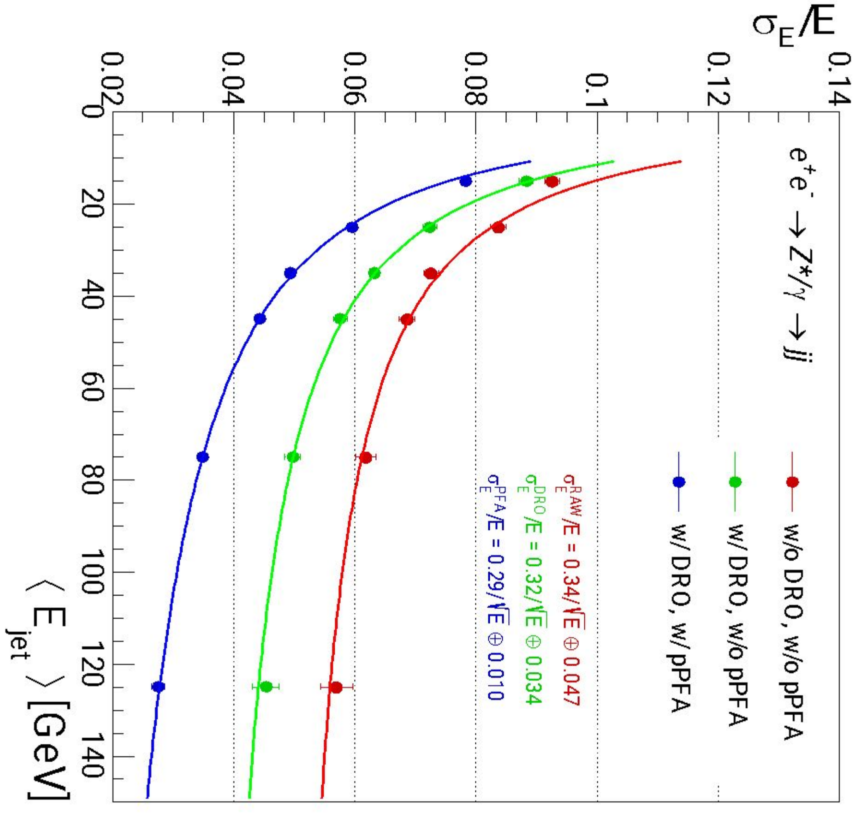
https://arxiv.org/abs/2008.00338



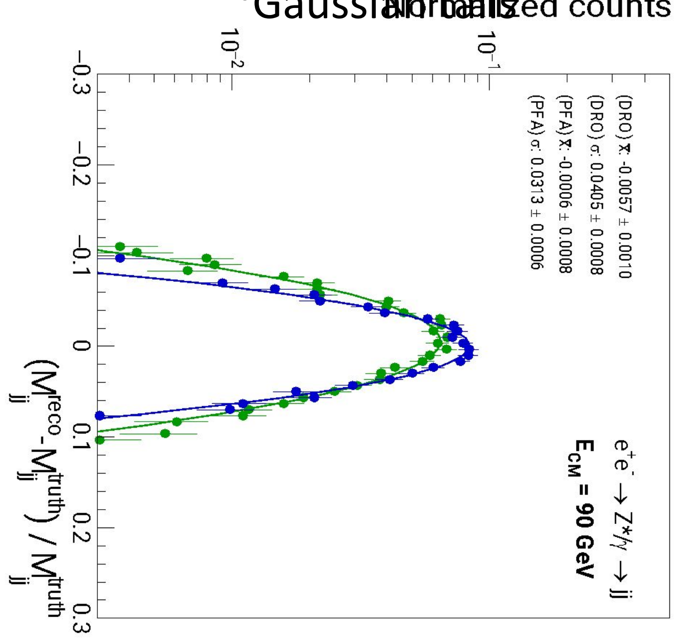
M. Lucchini

Dual-Readout Particle-Flow Jets





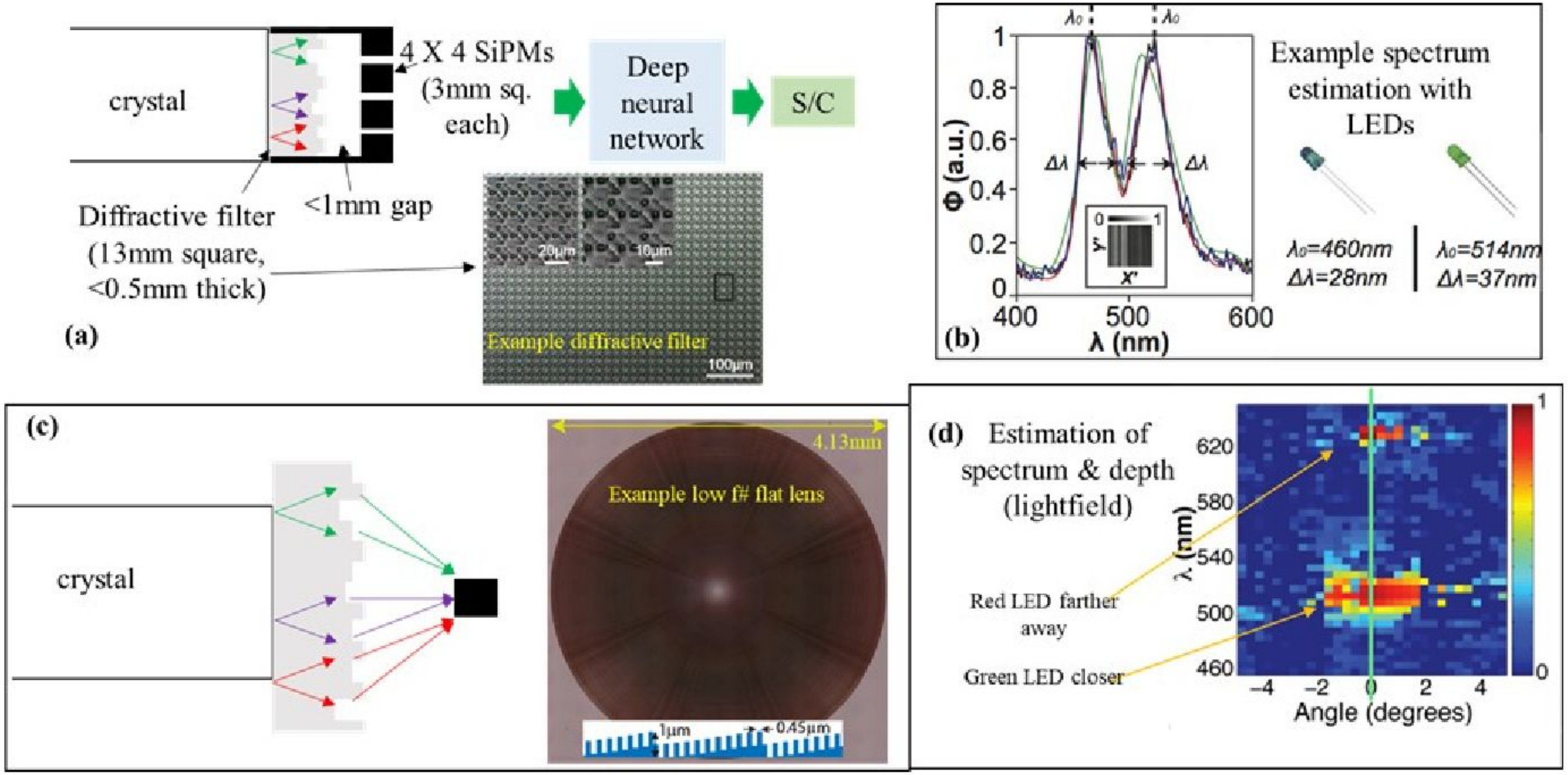
Hallmark of good PFA
~Gaussian tails



Marco T. Lucchini, Lorenzo Pezzotti, Giacomo Polesello, Christopher G. Tully
“Particle Flow with a Hybrid Segmented Crystal and Fiber Dual-Readout Calorimeter,”
https://arxiv.org/abs/2202.01474

Dual-Readout Blue Sky R&D

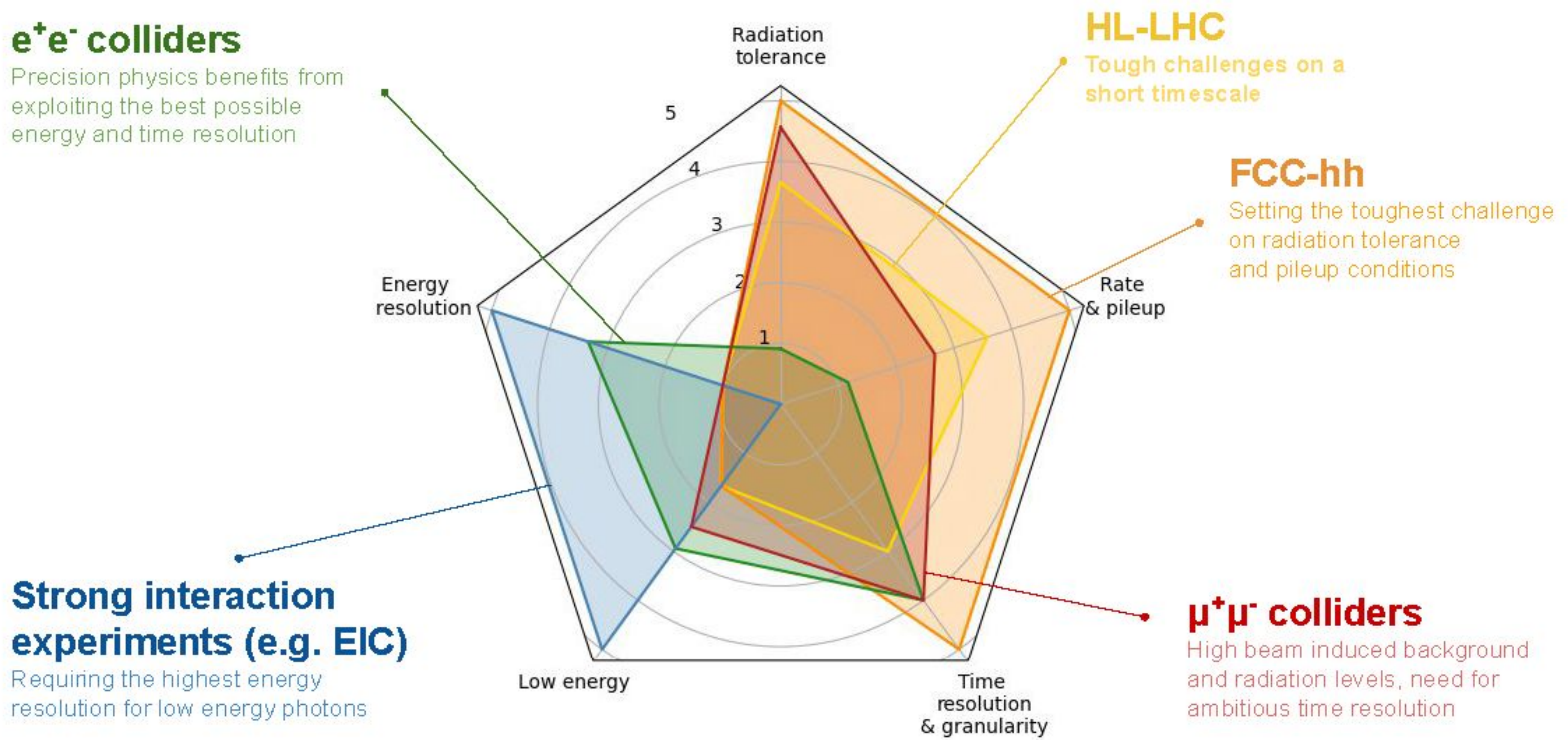
(CalVision Proposal, H. Newman)



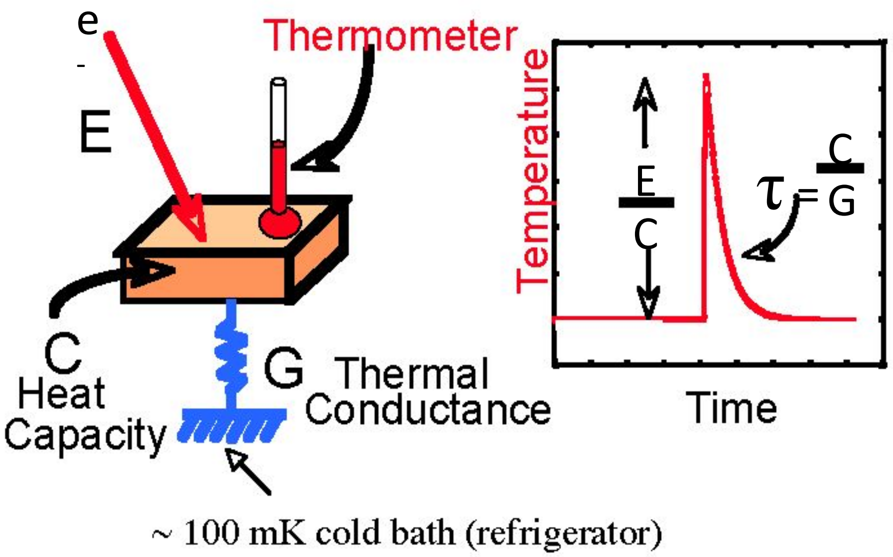
Customized SiPMs also a major development area

Dimensionality of Future Detectors

M. Lucchini (SCINT22)

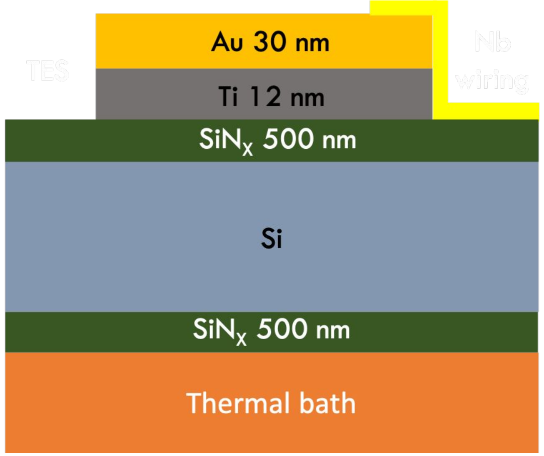


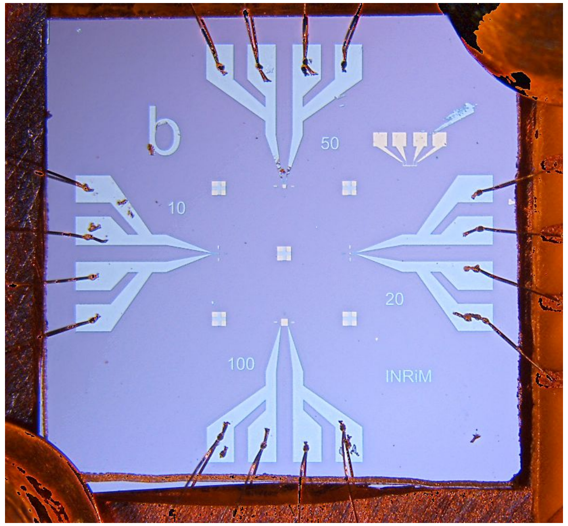
New Perspectives: Calorimetry at the Quantum Frontier

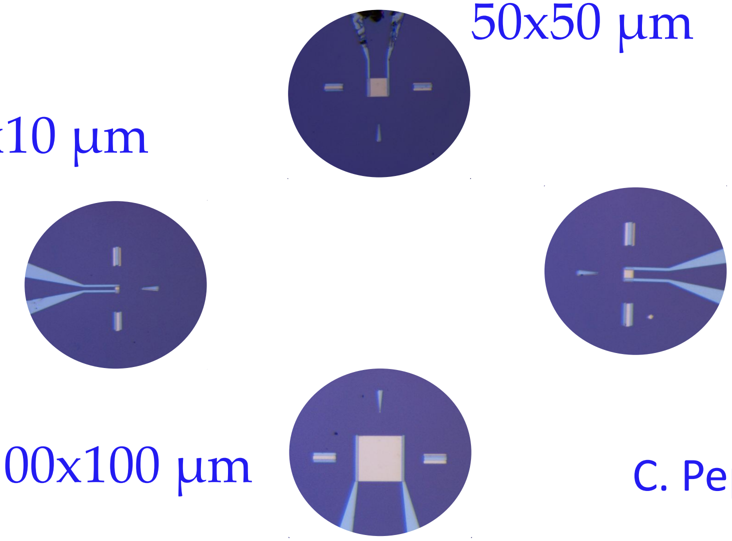


Thin sensors:

~1 eV electron can be stopped with very small C







50x50 μm

10x10 μm

20x20 μm

100x100 μm

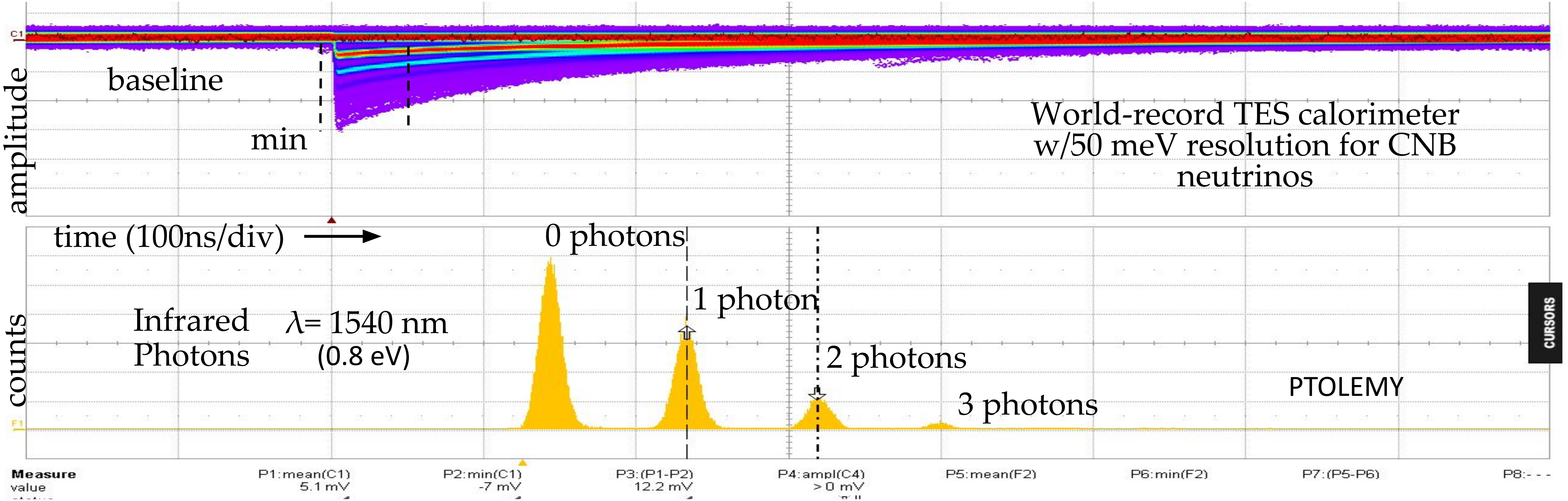
C. Pepe, E. Monticone, M. Rajteri

Mauro Rajteri, Eugenio Monticone and others, https://doi.org/10.1007/s10909-019-02271-x
“TES Microcalorimeter for PTOLEMY”, J. Low Temp. Phys. 199 (2020) 138-142.

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Highest Absolute Energy Resolution EM Calo ($\sigma \approx m_\nu$)

1% energy resolution at optical photon energies, i.e.
measures the wavelength of a 500nm photon to a few nm



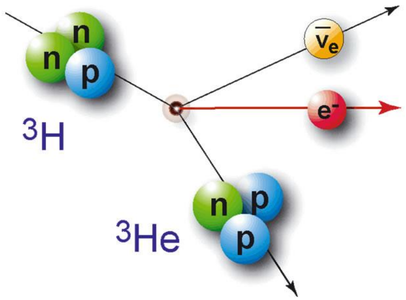
C. Pepe, E. Monticone, M. Rajteri

JOHN TEMPLETON FOUNDATION
Inspiring Awe & Wonder

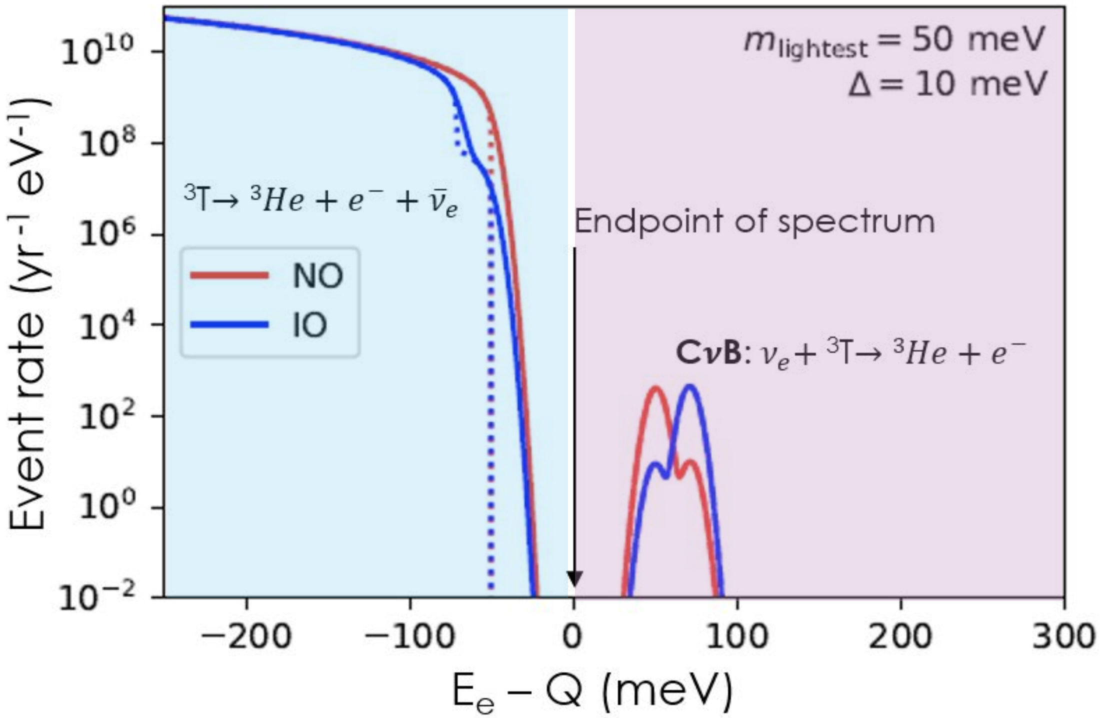
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Detection Concept: Neutrino Capture

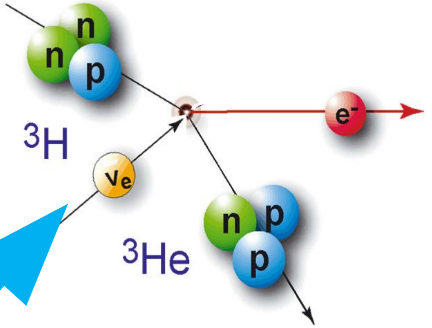
- Basic concepts for relic neutrino detection were laid out in a paper by Steven Weinberg in **1962** [*Phys. Rev*. 128:3, 1457] applied for the first time to massive neutrinos in **2007** by Cocco, Mangano, Messina [ ] and revisited in **2021** by Cheipesh, Cheianov, Boyarsky

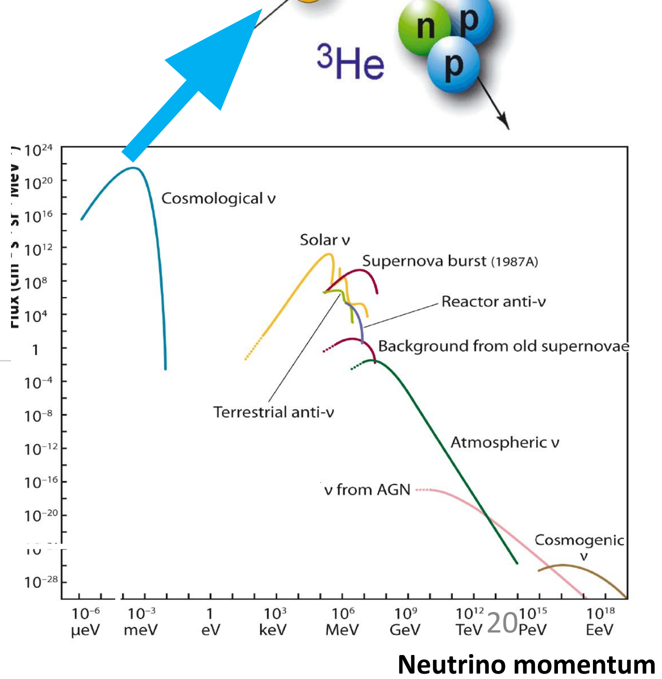


Tritium β-decay



Big Bang Neutrino capture on Tritium





What do we know?

Gap (2m) constrained to

m < ~200meV

from **precision cosmology**

Electron flavor expected with

m > ~50meV

from **neutrino oscillations**

CνB Detection Requires:

few x 10^{-6} energy resolution set by m_ν

KATRIN ~ 10^{-4} (current limitation)

PTOLEMY: **10^{-4} x 10^{-2}**

(compact filter) x (microcalorimeter)

Unexplored/Revisited Areas of Research expect to face new challenges and more unexpected outcomes

New Experimental Achievements:
World-Record Hydrogenation on Graphene Structures

Gap Opening in Double-Sided Highly Hydrogenated Free-Standing Graphene

Maria Grazia Betti,* Ernesto Placidi, Chiara Izzo, Elena Blundo, Antonio Polimeni, Marco Sbroscia, José Avila, Pavel Dudin, Kailong Hu, Yoshikazu Ito, Deborah Prezzi,* Miki Bonacci, Elisa Molinari, and Carlo Mariani

Cite This: Nano Lett. 2022, 22, 2971−2977 | Read Online

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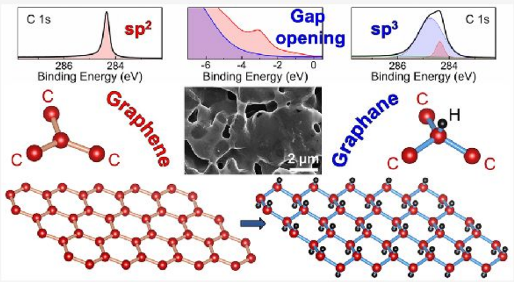
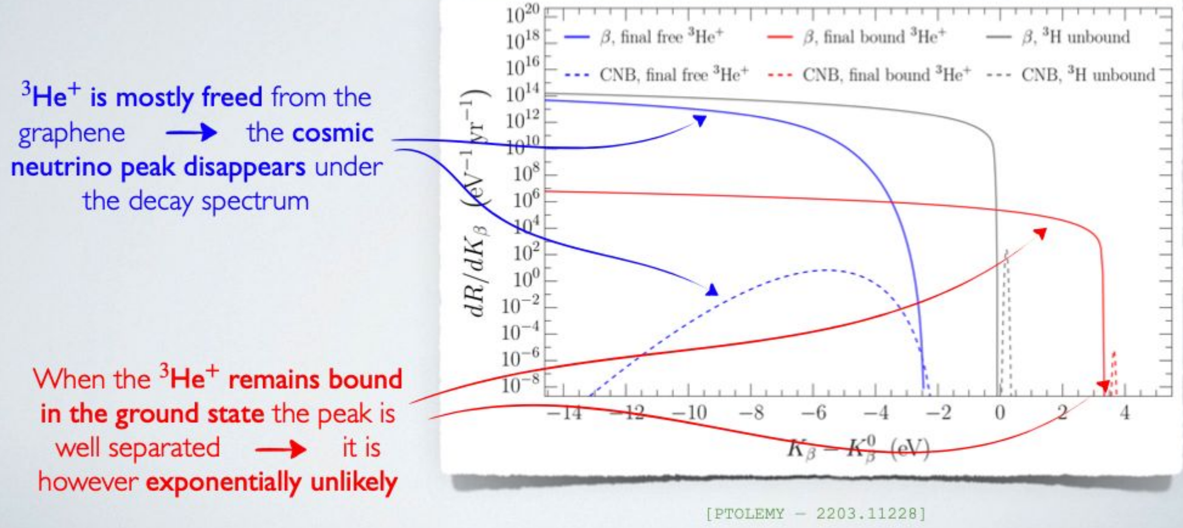
ABSTRACT: Conversion of free-standing graphene into pure graphane—where each C atom is sp^3 bound to a hydrogen atom—has not been achieved so far, in spite of numerous experimental attempts. Here, we obtain an unprecedented level of hydrogenation (≈90% of sp^3 bonds) by exposing fully free-standing nanoporous samples—constituted by a single to a few veils of smoothly rippled graphene—to atomic hydrogen in ultrahigh vacuum. Such a controlled hydrogenation of high-quality and high-specific-area samples converts the original conductive graphene into a wide gap semiconductor, with the valence band maximum (VBM) ∼ 3.5 eV below the Fermi level, as monitored by photoemission spectromicroscopy and confirmed by theoretical predictions. In fact, the calculated band structure unequivocally identifies the achievement of a stable, double-sided fully hydrogenated configuration, with gap opening and no trace of π states, in excellent agreement with the experimental results.



QUANTUM SPREAD

New Levels of Requires Quantum Engineering of Materials:
Localization of Tritium atoms a major factor
in neutrino mass sensitivity



Angelo Esposito — IAS | 11 | NuMass 2022

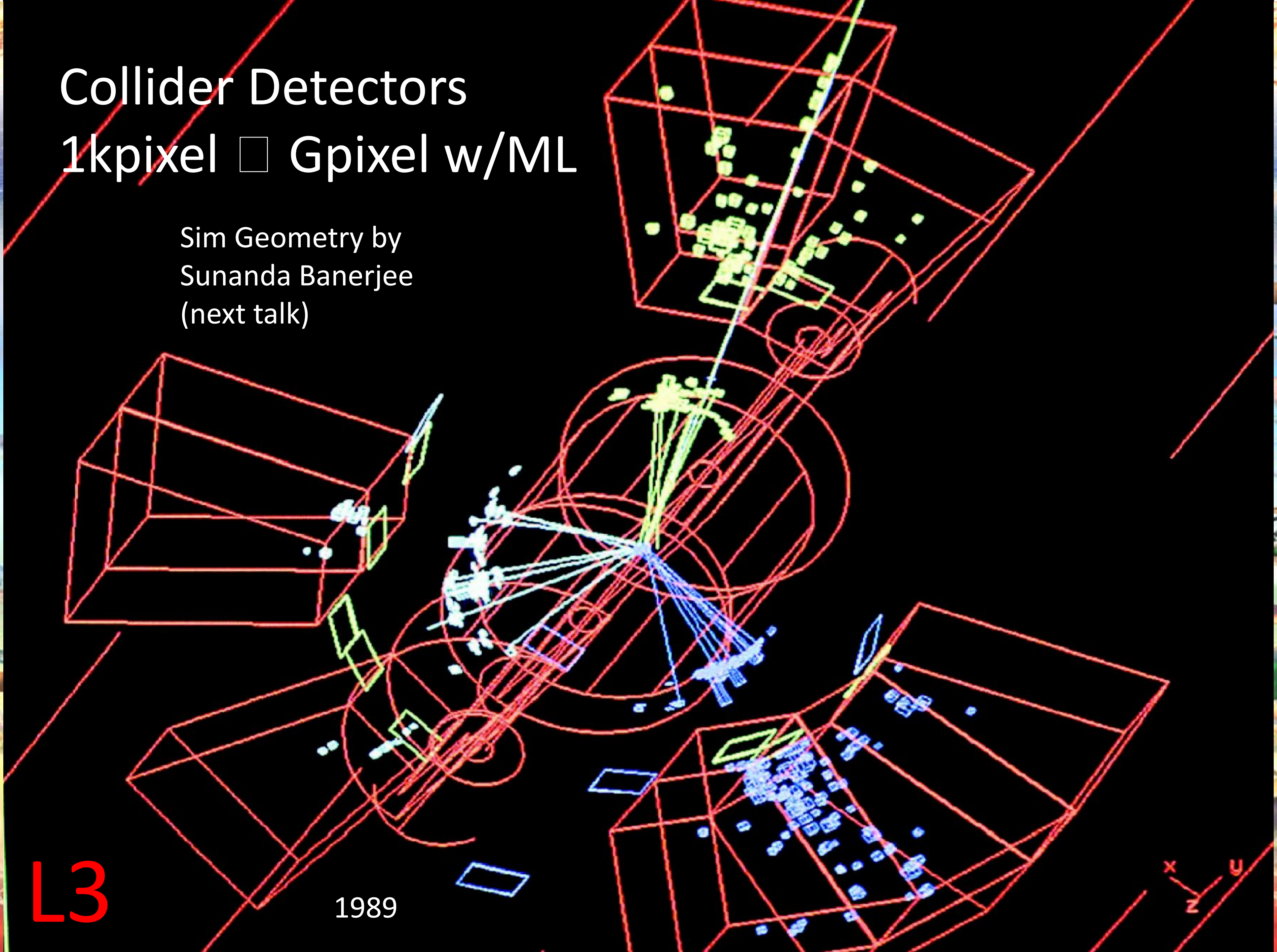
Many New Innovations to Come

- Precision timing throughout
    - Near vertex to measure t0 of collision
    - Throughout tracker/calo to reject beam-induced background
    - ToF for extended particle-ID and long-lived particles
- Trigger-Level Tracking
    - Double-layer momentum selection
    - High-bandwidth on-detector data movement
    - Ultra-low mass materials (2D structures)
- Low Mass Solenoids
- Muon System Long-Lived Particle Decay Volume
- Real-Time Machine Learning DAQ/Trigger
    - Full Blade ATCA Processing and Cross-Detector Particle-Flow w/ML
    - Parasitic Reconfigurable Trigger Slice for Trigger Learning and New Model/User Facility
    - Triggerless/Open readout operation
- Machine-Beam Interface
    - New approaches to Luminosity, Background, Fast-feedback systems
    - Muon beam optimized and forward muon neutral current taggers
- Quantum Sensor Technologies – across all experimental particle physics detectors

*Integrated Computational/Algorithmic Development w/Detector Design
Many strong drivers for ASIC development
Novel sensors based on new materials
ML embedded processing
User facility-like customized triggers
Broader integration with long-lived detectors
…lots of room for new ideas

Collider Detectors
1kpixel □ Gpixel w/ML

Sim Geometry by
Sunanda Banerjee
(next talk)

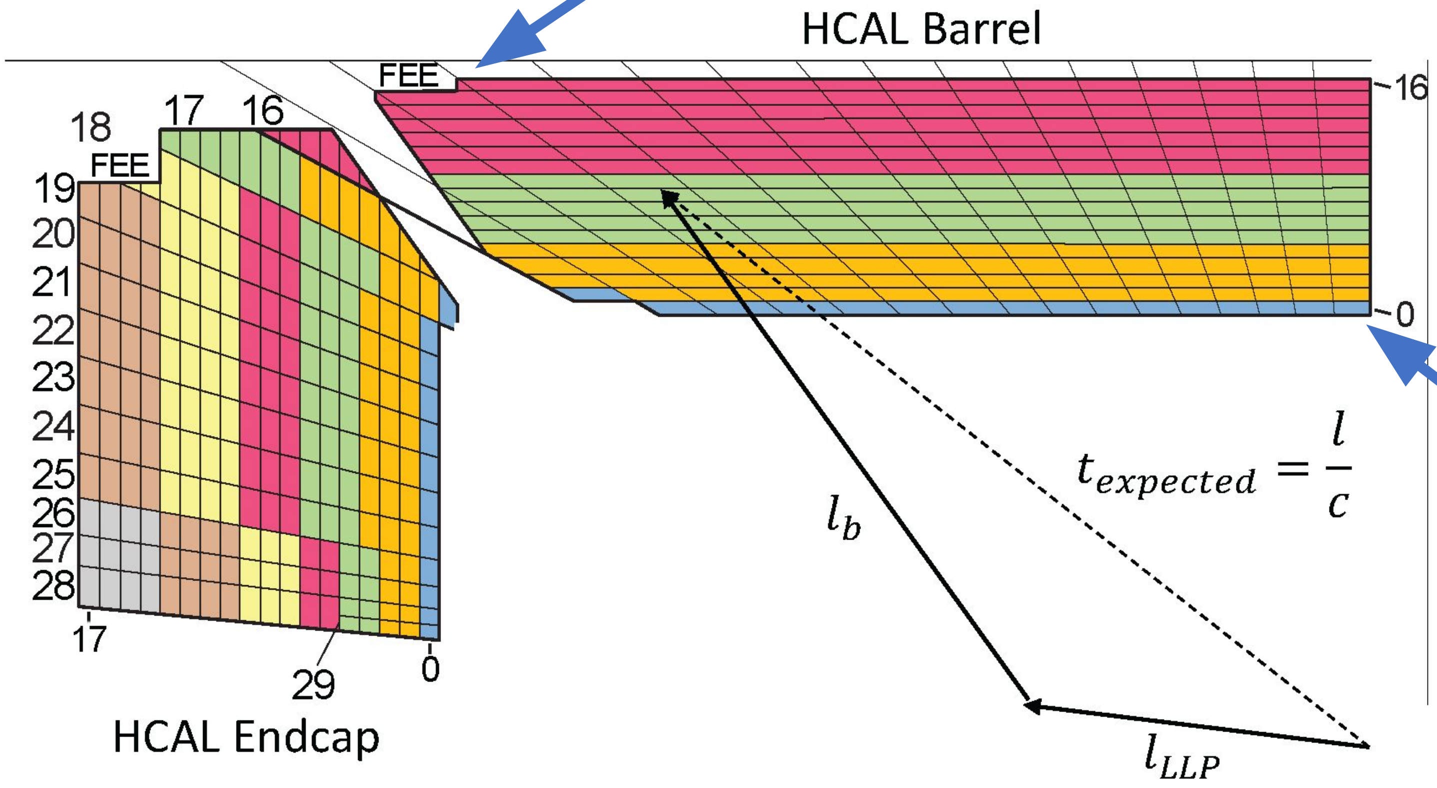


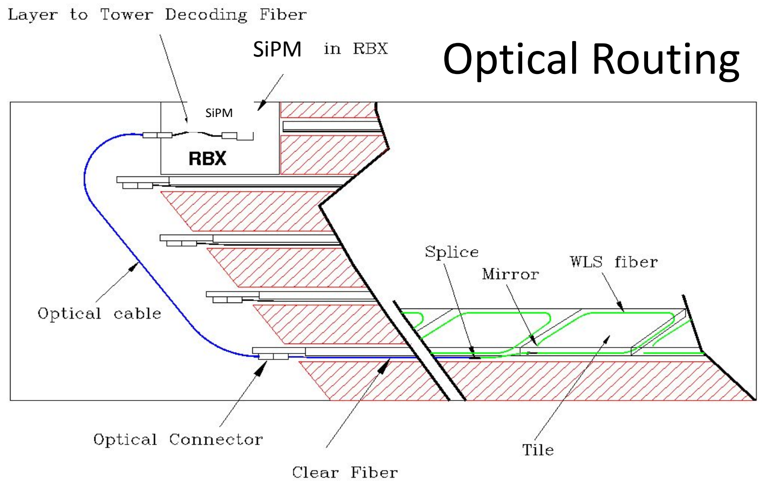
Backup

CMS HCAL

Timing Alignment (LHC Run-3)

Prompt pulse edge arrives ~14ns too early





Prompt pulse edge arrives ~6ns late

relative to what we thought was the correct alignment

$$\Delta t = \frac{l_{LLP}}{v_{LLP}} + \frac{l_b}{c} - t_{expected}$$

Long-Lived Particle (LLP) Trigger
New Run-3 Hardware-Level 1 Seed