Higgs and the Energy Frontier

Jim Hirschauer
Fermilab

on behalf of Gabriella Sciolla [co-Convener],
Michael Begel, and Meenakshi Narain

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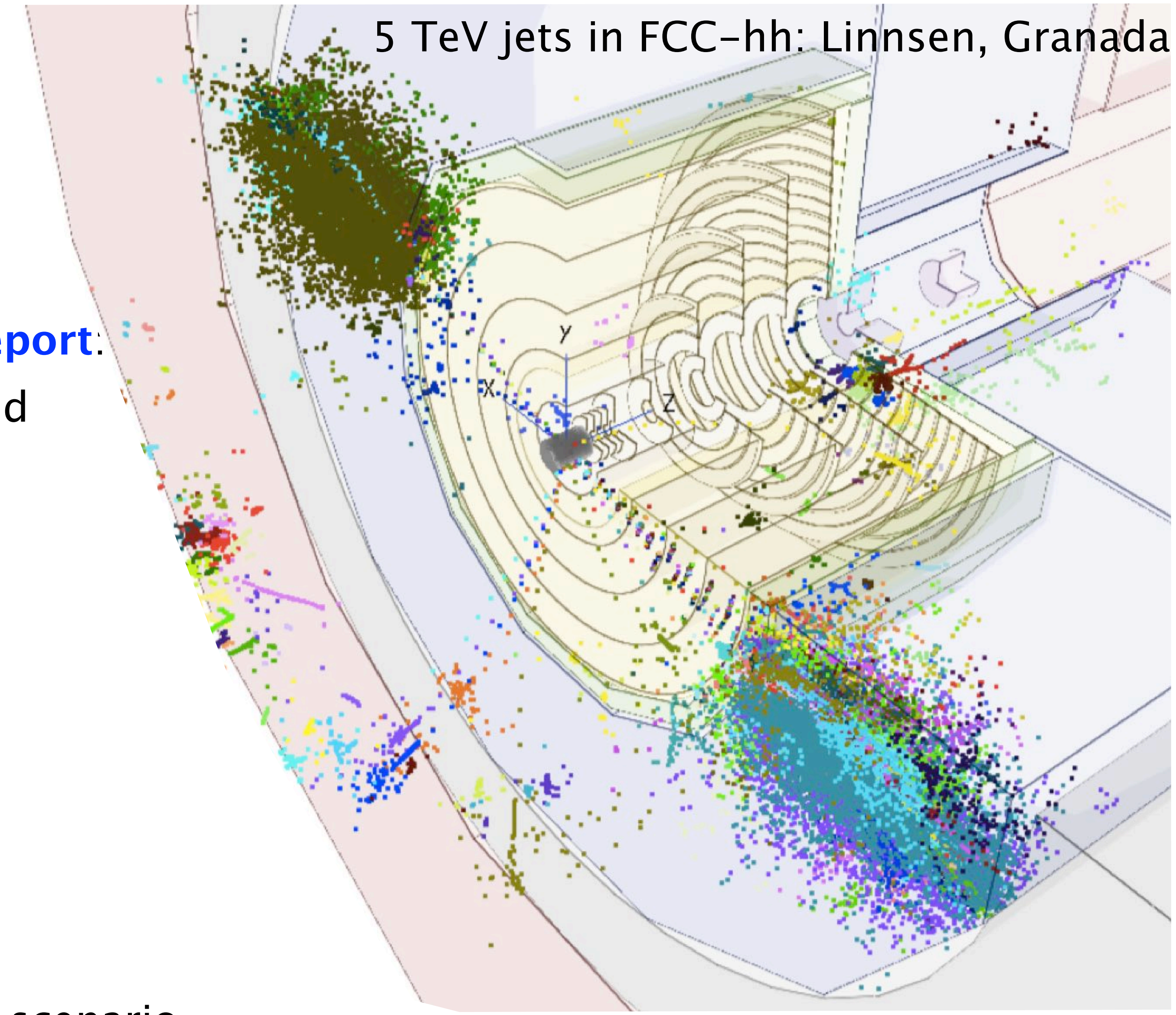
Introduction

Goal of this presentation:

- Convey approach and main ideas of Energy Frontier section of BRN report in ~12 minutes



Goals for Higgs & Energy Frontier section of BRN report:

- Describe **transformative physics opportunities** and **detector requirements** at future colliders
- **Be accessible** to non-experts and **inspirational**!
- **High-level Priority Research Directions:**
  1. **Tracking**
  2. **Calorimetry**
  3. **Precision timing**
  4. **Trigger and readout**
- No attempt to motivate specific collider or detector scenario
- Focus on **most exigent detector requirements** from all scenarios

Primary references during BRN process : European Strategy process and Briefing Book, Future detector CDRs, CPAD reports

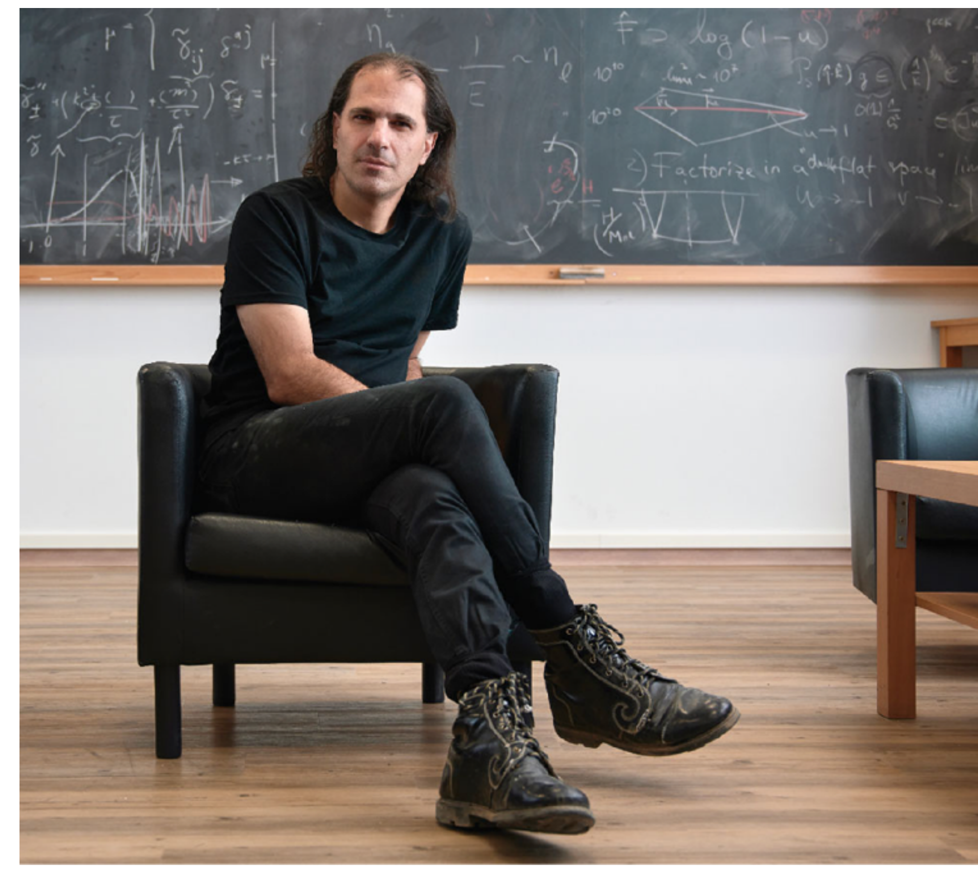
"... the path forward is completely clear ..."

CERNCOURIER | Reporting on international high-energy physics

Nima Arkani-Hamed, 11 March 2019:

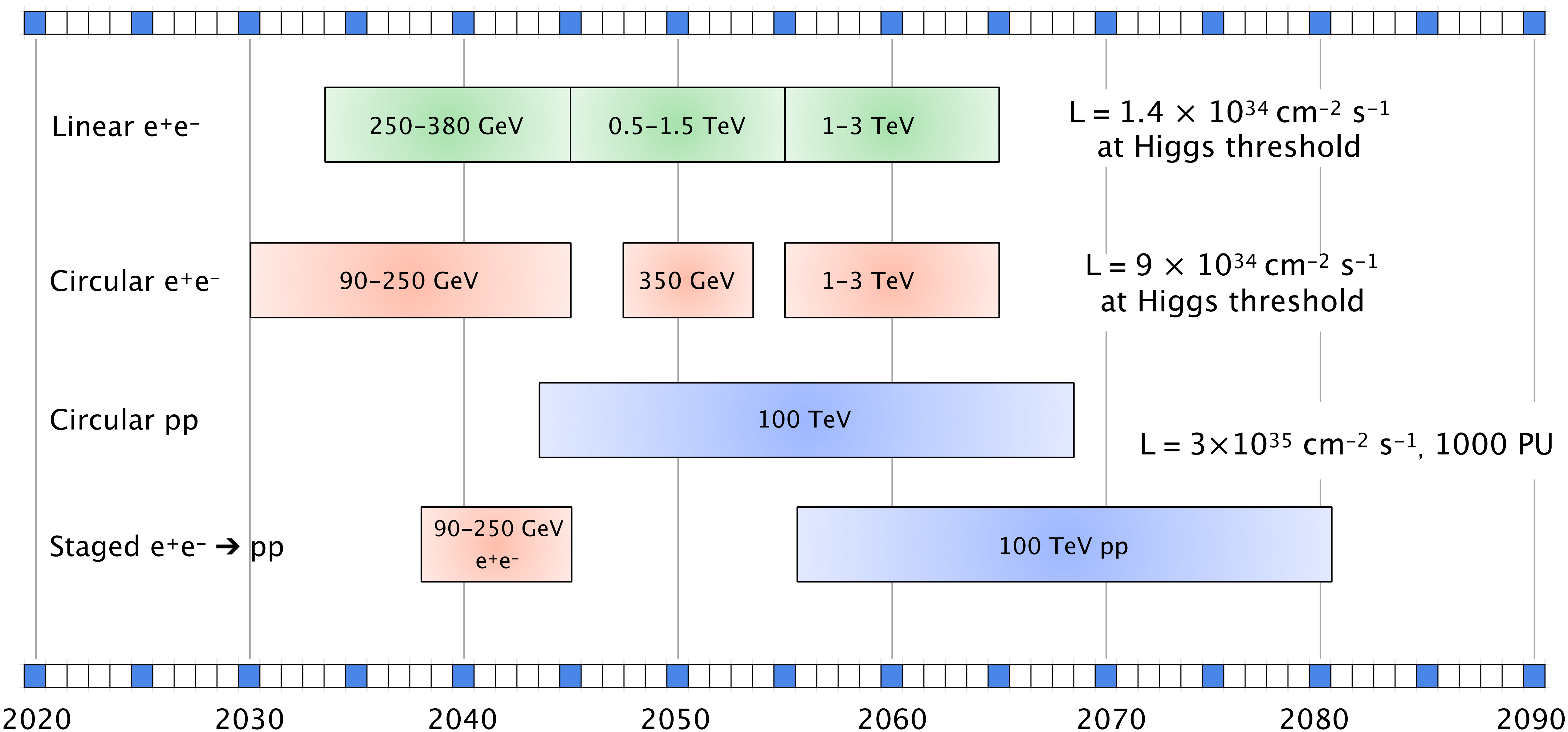
The discovery of the Higgs particle – especially with nothing else accompanying it so far – is unlike anything we have seen in any state of nature, and is profoundly “new physics” in this sense.
...

While we continue to scratch our heads as theorists, the most important path forward for experimentalists is completely clear: **measure the hell out of these crazy phenomena**!



Collider scenarios beyond HL-LHC

- Simplified collider timeline with focus on motivating detector R&D
- Based on Ursula Bassler's timeline presented at Granada Symposium.



Transformative physics goals beyond HL-LHC

- Elucidate theoretical mysteries of SM : **Measure properties of Higgs** [and top, W, etc.]
- Elucidate extant experimental mysteries : **Produce and study dark matter** [and other new phenomena]

Dual roles for future colliders : **ultimate discovery & precision measurement machines**

Higgs physics with FCC-comb* (e.g.)

- 0.2–1% precision on **all** Higgs couplings

  Up to 10× improvement over HL-LHC!
- Measure BR (H→inv) to 0.024%

  80× improvement over HL-LHC! Current limit <20%
- Measure self-coupling with 5% precision

  10× improvement over HL-LHC!
- Model independent Higgs total width measurement

Searching for new phenomena at 100 TeV pp

- 7× increase in mass reach beyond HL-LHC!
- Probe new structures at $\frac{1}{1{,}000{,}000}$ × proton radius!

	HL-LHC	FCC-comb*
κ_W [%]	0.985**	0.19
κ_Z [%]	0.987**	0.16
κ_g [%]	2	0.5
κ_γ [%]	1.6	0.31
$\kappa_{Z\gamma}$ [%]	10	0.7
κ_c [%]	--	0.96
κ_t [%]	3.2	0.96
κ_b [%]	2.5	0.48
κ_μ [%]	4.4	0.43
κ_τ [%]	1.6	0.46
BR_{inv}	<1.9%	< 0.024%
BR_{unt}	<4%**	<1%
κ_3	50%	5%

ESG Briefing Book; arXiv: 1905.03764

** Assume κ_V<1

* FCC-ee$_{240GeV}$ +FCC-ee$_{365GeV}$ + FCC-eh$_{3.5TeV}$ + FCC-hh$_{100TeV}$

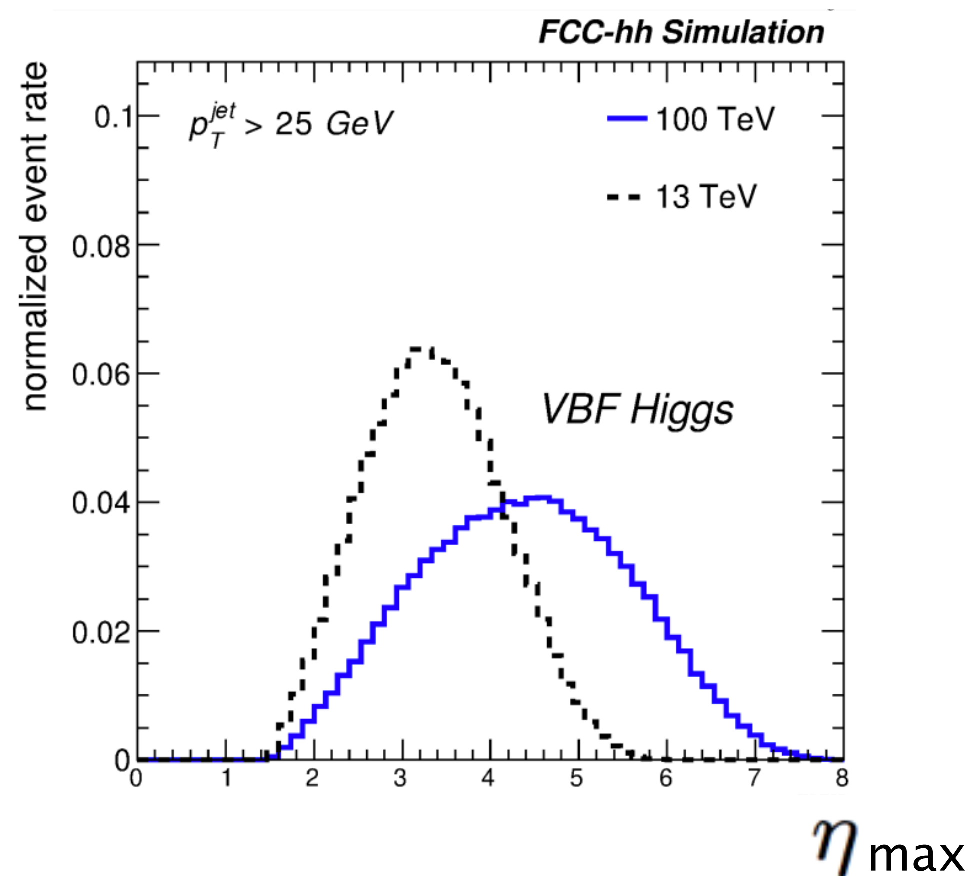
Extreme conditions at 100 TeV pp collider

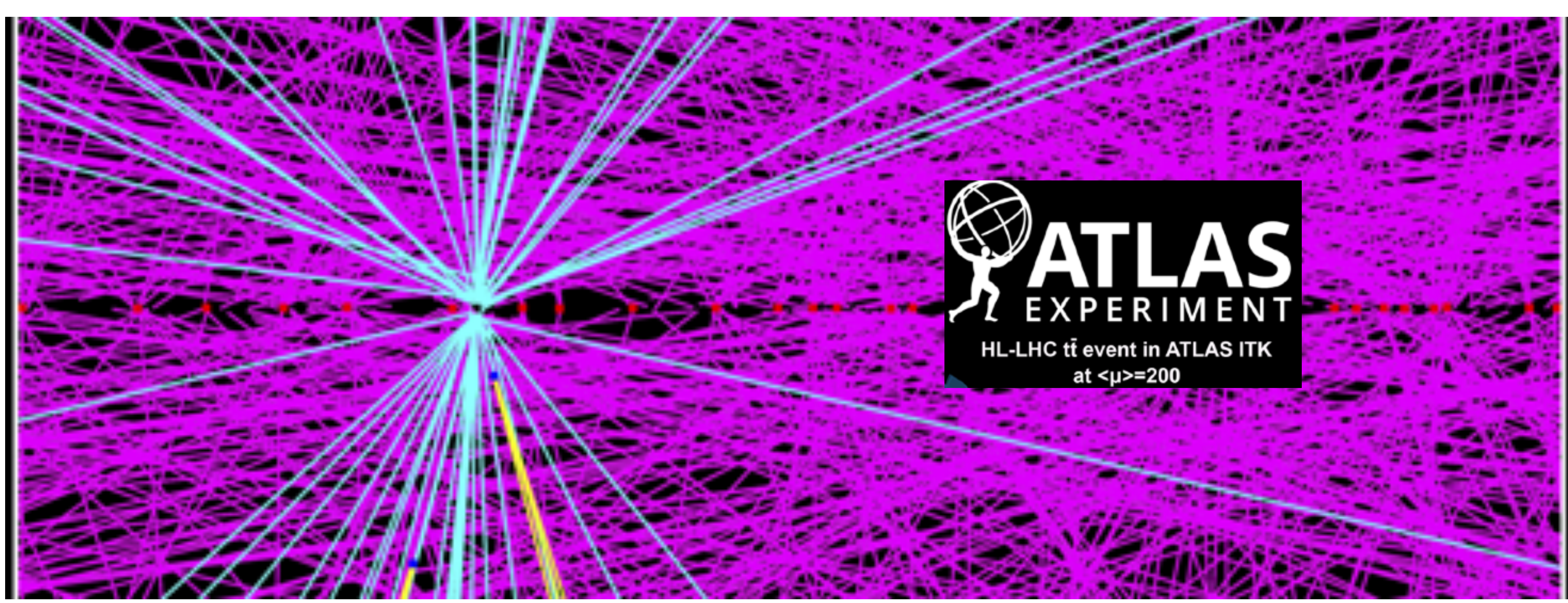
Conditions

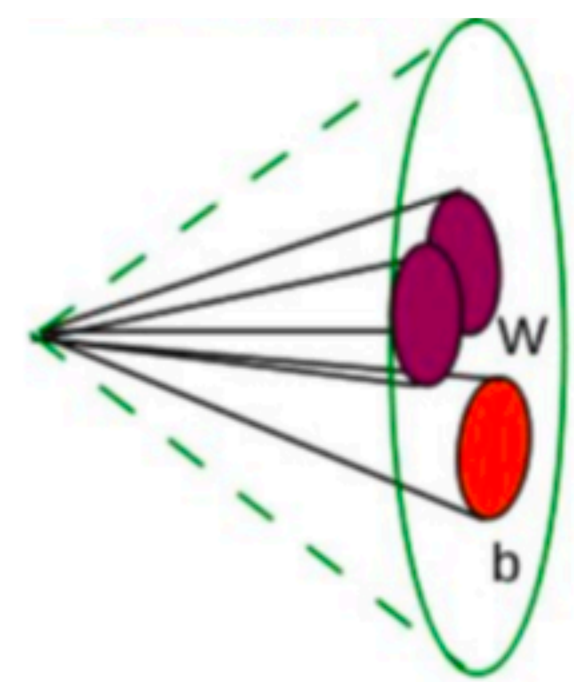
- 1000 **pile-up** *5-7× HL-LHC*
- **Radiation** : 1×10^{18} neutrons/cm^2, 300 MGy for inner detectors *100× HL-LHC*
- **Occupancy**: 20 GHz/cm^2 in first tracking layer *10× HL-LHC*

Kinematics

- **Dynamic range**: 20 GeV – 20 TeV *10× HL-LHC*
- **Pseudorapidity coverage**: $|\eta| < 6$ *$|\eta| < 3$-4 at HL-LHC*
- **Angular resolution** : 10 mrad separation between constituents in highly collimated jets; e.g. 10 TeV W→hh *0.1× HL-LHC*
- **Secondary vertices** : $\beta\gamma c\tau \sim 50$ cm for 5 TeV B mesons



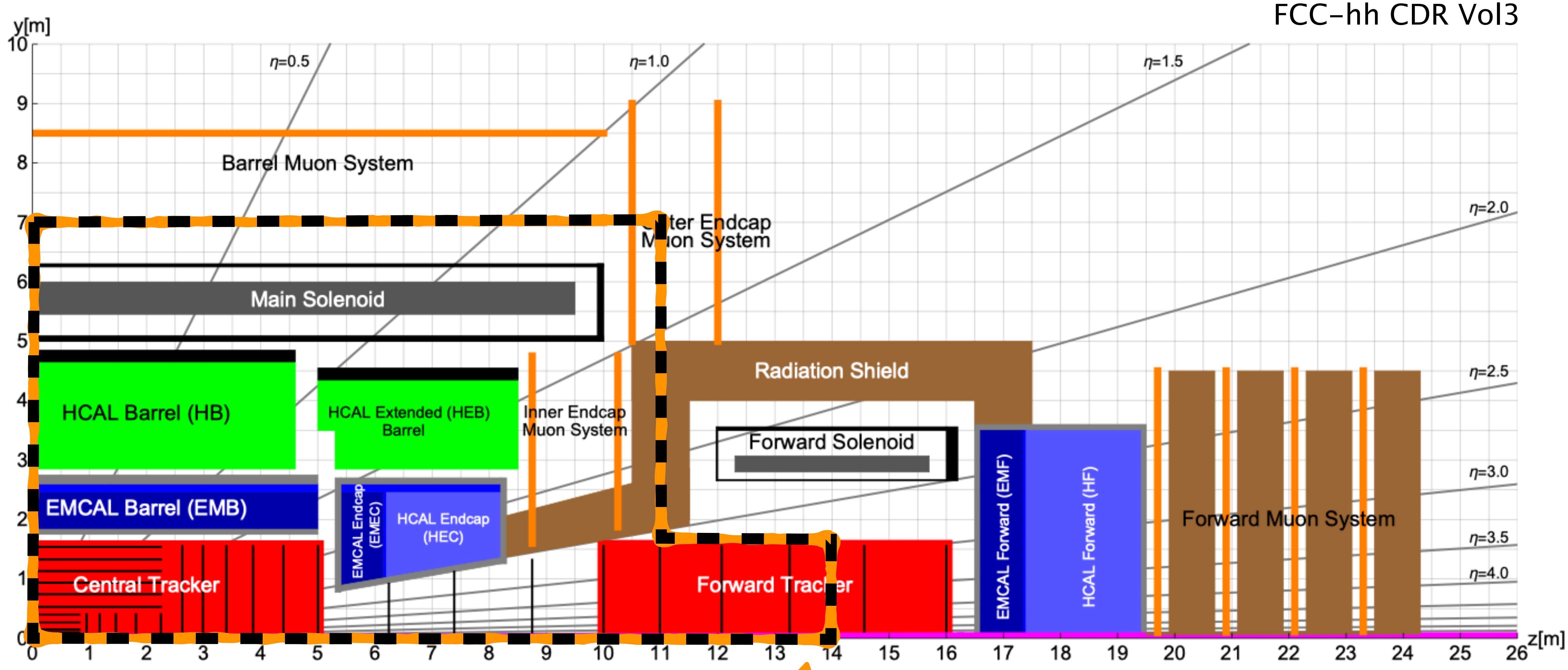




FCC-hh reference detector

- Future detectors will be designed for **"particle flow" reconstruction** algorithms in which each final state particle is reconstructed from the combination of corresponding information from all tracking detectors and calorimeters
    - requires high granularity for separating energy deposits

FCC-hh CDR Vol3



CMS profile for reference

Greatly enhanced forward coverage w.r.t. HL-LHC

PRD #1 : Integrated precision timing

- Extreme **pile-up** and **occupancy** must be mitigated with **high-granularity** tracking detectors and calorimeters capable of precise measurements of **particle time-of-arrival** (ToA).

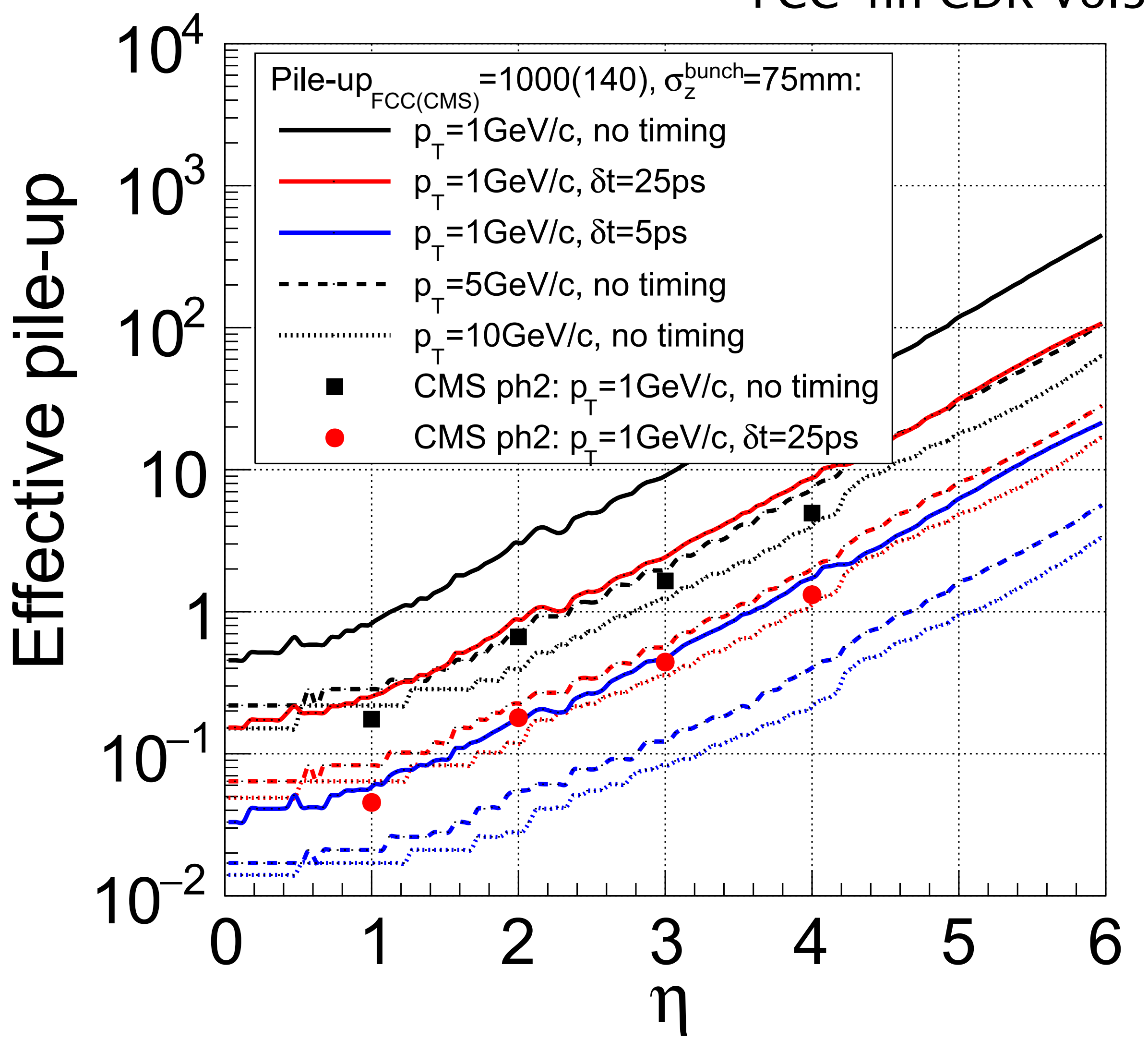
Per particle timing resolution requirement:

- **Effective pile-up** = number of vertices compatible with track (η, p_T)
- **CMS at HL-LHC** : effective PU = 1 for 1 GeV track at η=4 with 25ps resolution.
- 100 TeV pp requires **5 ps per particle resolution** for comparable performance.

FCC-hh CDR Vol3

Requirements for detectors:

- Multiple measurements of each charged particle ToA with **trackers with per pixel precision timing**.
- Multiple time measurements of neutral particle showers with **granular calorimeters with per cell precision timing**.
- **Precise clock distribution**



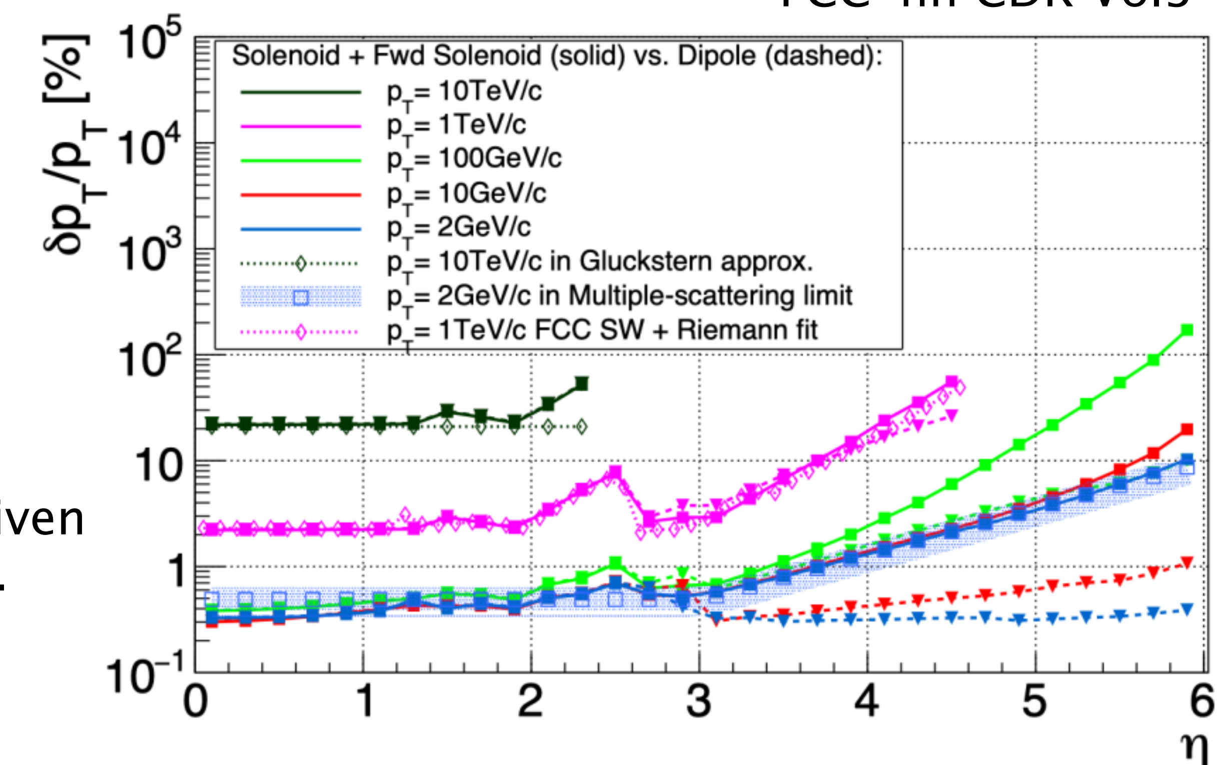
PRD #2 : Low-mass, 4D tracking detectors

- Excellent p_T resolution over large p_T range requires **large, low-mass trackers**
  - The beam structure at an ILC-like collider allows **power pulsing** ➔ air cooling ➔ low mass
  - **Monolithic active pixel sensors** provide another path low mass

FCC-hh CDR Vol3

- Resolution driven by e^+e^- collider requirements :
  - $\sigma_{p_T}/p_T^2 \approx 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$ *10x better than LHC*
  - $\sigma_{r\phi} \approx 5 \oplus 15\ (p\ [\mathrm{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\mathrm{m}.$

σ/pT ~ 0.5% at low pT driven by multiple scattering.

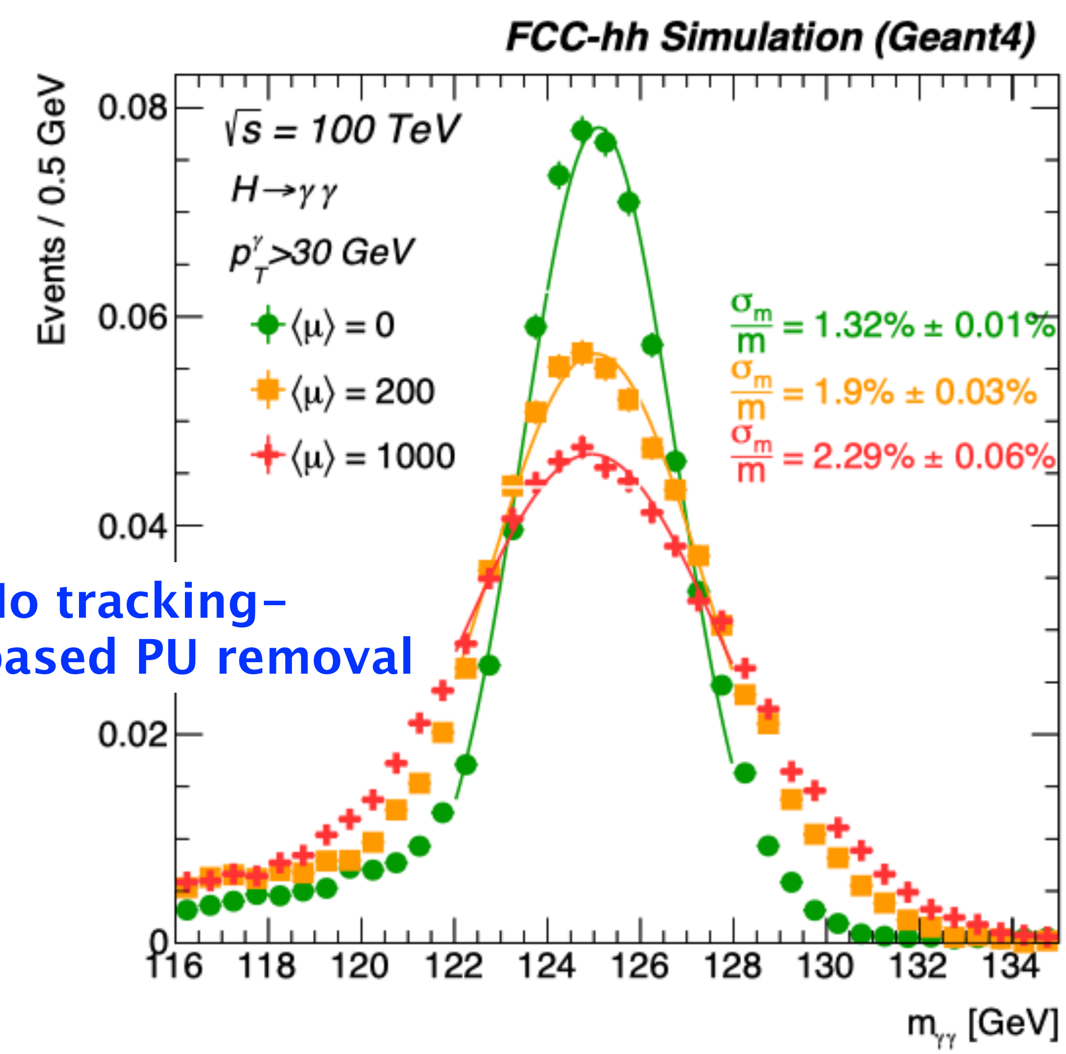


- **Additional requirements at 100 TeV pp collider**:
  - 4D tracking detector with 5 ps per particle resolution ➔ per **pixel time resolution of ~10 ps**
  - **small pixels** (~25μm) to cope with high occupancy
  - **<5 μm single hit resolution** to allow two-track separation in highly collimated jets.
  - **Radiation tolerant** sensors and readout electronics

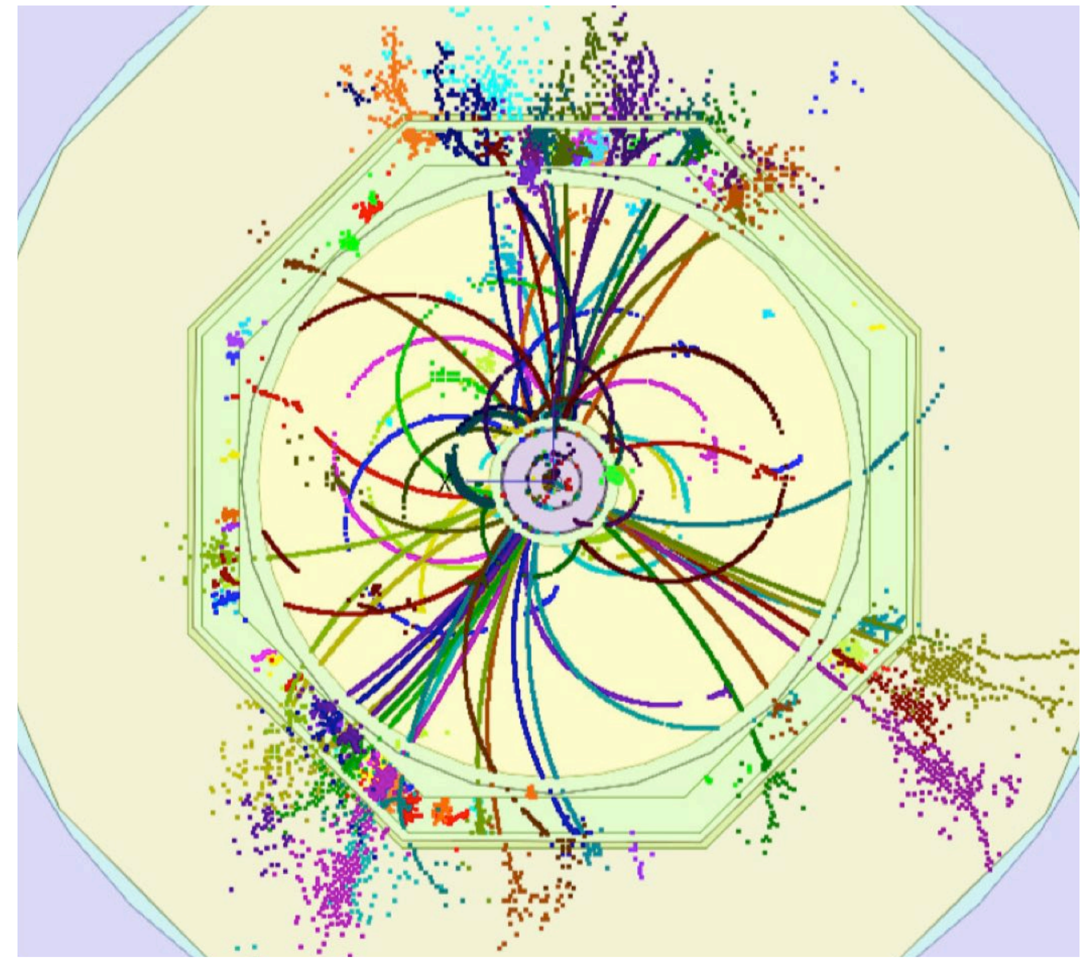
PRD #3 : high-granularity, 5D calorimeters

- Lepton colliders require **particle flow jet energy resolution σ_E/E ~ 3.5-5%**
  - distinguish W/Z/H ➔ qq
  - measure Higgs total width in ee ➔ ZH
- Underlying calo energy resolution
  - a = 10% (50%) for ECAL (HCAL)
  - c = 0.7% (3%) for ECAL (HCAL)

$$\frac{\sigma_E}{E} \approx \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$



No tracking-based PU removal



- **Granularity** (Δη x Δφ): *4x more granular than LHC*
  - 100 TeV pp ECAL : 0.01 × 0.01 (2 cm² at 2m)
  - 100 TeV pp HCAL : 0.025 × 0.025
  - e^+e^- ECAL : 0.5 cm × 0.5 cm
  - e^+e^- HCAL : 1-3 cm²
- Per cell time measurement providing **5 ps resolution per shower**.
- **Radiation tolerant** sensors and readout electronics

PRD #4 : Trigger and DAQ

Requirements:

- High **data rate** + high **granularity** = **>1 Pb/s of data**
- Require **comprehensive trigger** incorporating calorimetry, tracking, and timing ... or triggerless readout
- Require low latency for trigger or selection decisions

FCC-hh CDR Vol3

	HL-LHC		100 TeV pp	
	σ [nb]	rate [kHz]	σ [nb]	rate [kHz]
jet (50 GeV)	21k	1100	300k	90k
bb (30 GeV)	1600	80	28k	8k
W → ℓν	200	10	1300	390
Z → ℓℓ	2	0.02	14	4.2
tt	1	0.05	35	11

Solution will involve

1. Initial data selection/compression/concentration **on-detector** with **radiation-tolerant**, low-power electronics → **currently ASICs**
2. High-bandwidth, **radiation-tolerant** transmitters → **currently VCSEL with custom ASIC driver**
3. Flexible, **off-detector** electronics → **currently FPGA + CPU**

Directions for R&D

- Improved ASIC rad tolerance and power dissipation
- Silicon photonics & high-bandwidth rad tolerant transmitters
- Flexible systems with hybrid hardware : FPGA + CPU + GPU ...
- Machine learning techniques for low-latency and high throughput

Summary

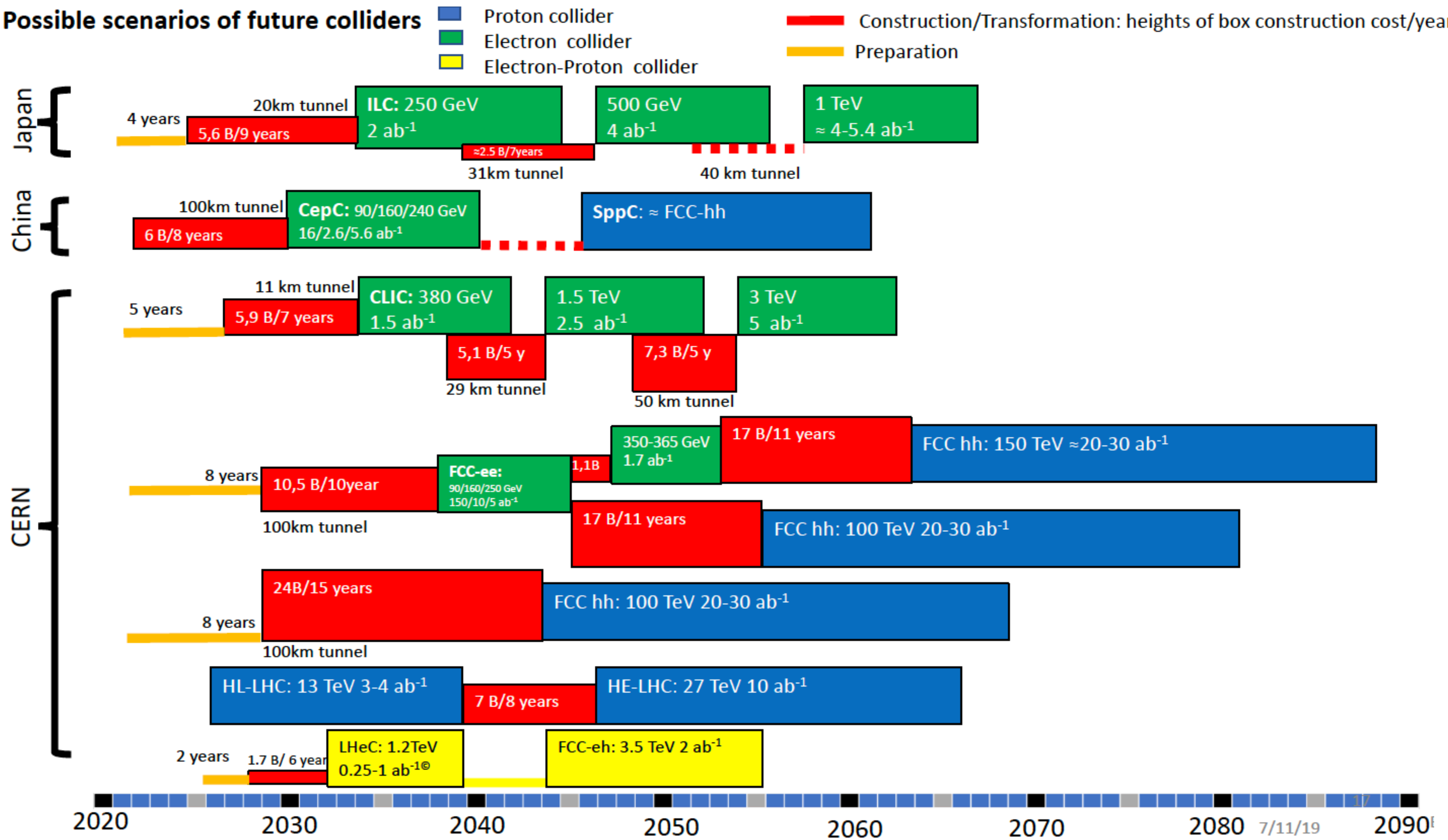
- The **physics opportunities** beyond HL-LHC are **transformative** ...
- ...but future colliders place similarly **transformative requirements on future detectors**.

- To meet the needs, we require **ambitious R&D in four areas:**
  1. Fully integrated **precision timing**
  2. Low-mass, 4D **tracking**
  3. High granularity, 5D **calorimeters**
  4. High bandwidth, low latency **trigger and DAQ**

Additional material

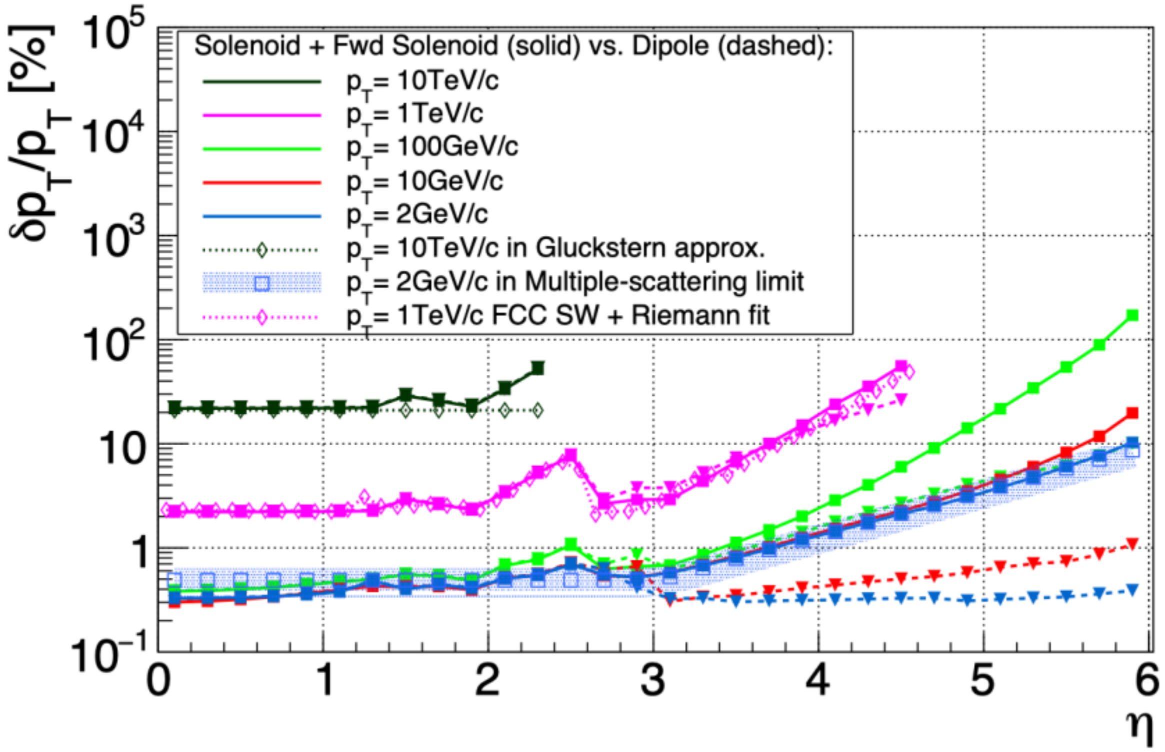
Beyond HL–LHC

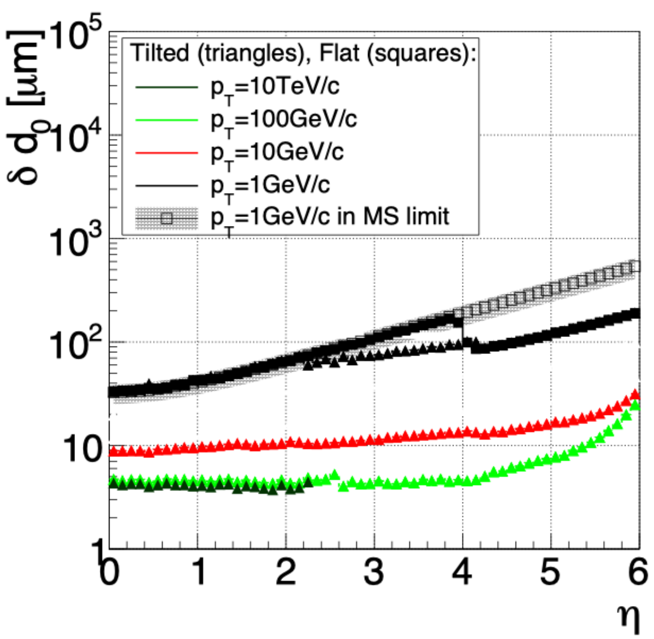
- Collider timeline with focus on motivating detector R&D



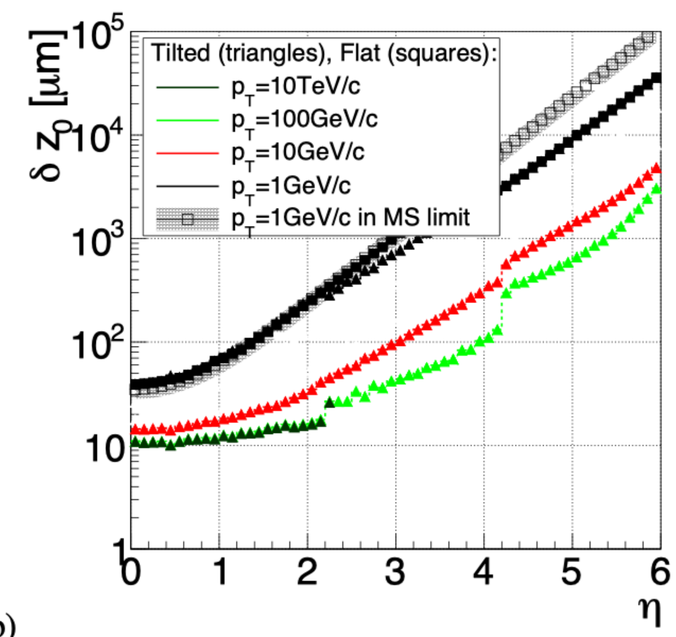
Ursula Bassler @ Granada meeting

FCC-hh tracker resolution





a)



b)

The momentum resolution is around 20% for p_T = 10TeV/c in the central region.

The resolution limit due to multiple scattering is around 0.5% in the central region.

The material dominates the resolution up to p_T = 250GeV/c.

In the forward region beyond η = 3.5 the momentum resolution deteriorates due to the 'loss of lever arm' in the solenoid field.

Using dipole magnets in the forward region the momentum resolution can be kept below 1% even up to η = 6.

The resolution curves for the solenoid field can be reproduced with the standard 'pocket' formulas.

d_0 and z_0 resolution of 30μm at η = 0 for p_T = 1GeV/c, limited by multiple scattering.

W Reigler, March 2019