Physics at the Energy Frontier post HL-LHC: opportunities and challenges

Gabriella Sciolla
Brandeis University

Higgs Physics Working Group of the BRN for HEP R&D Study
Co-Conveners: J. Hirschauer and G. Sciolla
Members: M. Begel, M. Narain

2021 CPAD Workshop
March 18, 2021

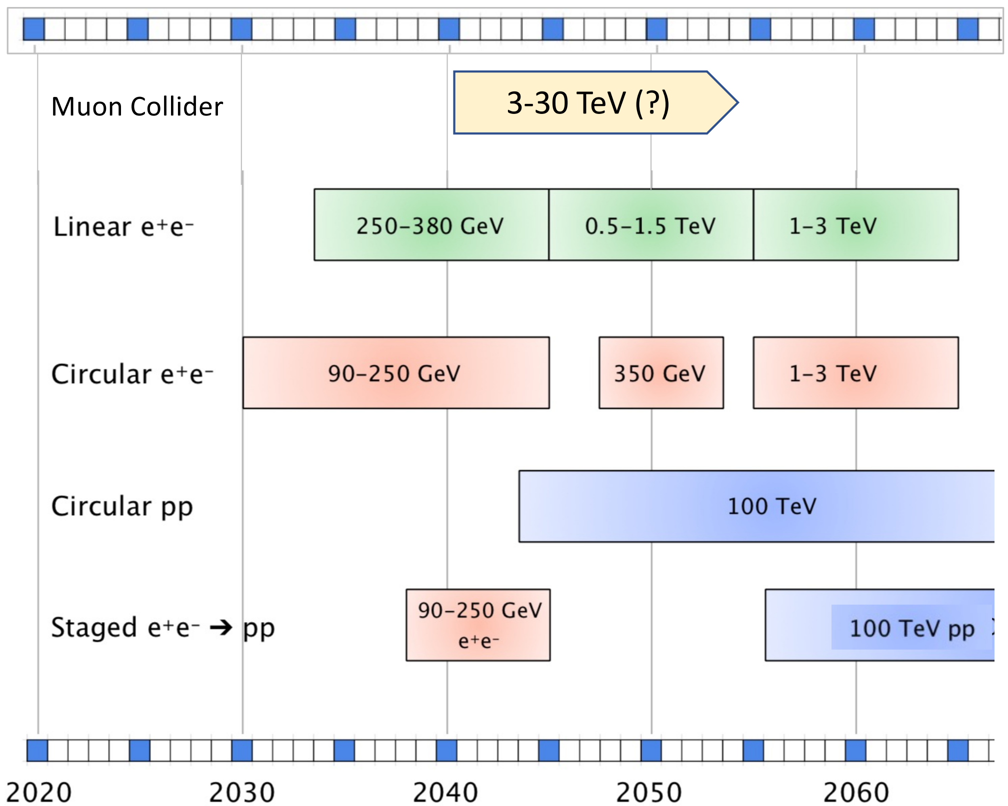
Introduction

- Goal of this presentation
  - Summarize physics opportunities at collider post HL-LHC
    - What are the measurements that will enhance our understanding of Particle Physics
    - Where: collider and experiments
    - When: very tentative timescale
  - Summarize experimental challenges that we need to overcome
    - Tracking
    - Calorimetry
    - Precision timing
    - Trigger and readout
- References
  - European Strategy Physics Briefing Book, CDRs for future Detectors, CPAD reports
  - Snowmass 2021

The need for future colliders

- SM has been extremely successful but we know it is incomplete
  - Naturalness problem
    - Higgs mass and its quantum correction indicate extreme fine tuning in the theory
  - Missing particles
    - e.g.: DM candidate
- Two complementary approaches to discover New Physics
  - Search for new particles/phenomena beyond SM
    - “Classic” BSM searches (e.g.: di-jet or di-lepton resonances, SUSY.,…)
    - Long-Lived particles
    - DM (pair) production
  - Precision measurement of properties of Higgs and other SM particles (top, W, Z,…)
    - Measurement of couplings of H to other particles (fermions/bosons, DM, …)
      - These measurements will see a **qualitative improvement**, not just incremental
        - Example: limits of Higgs to DM particles are now 20% and will be <0.02%
    - Measurement of Higgs self couplings
      - Hard to measure at (HL-)LHC, will be measured within a few % at future colliders

Opportunities on the horizon



Muon colliders are regaining momentum

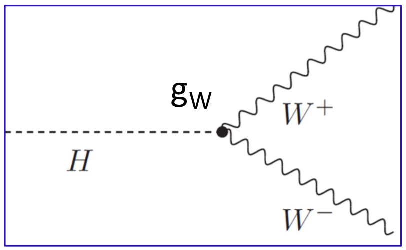
$L = 1.4 \times 10^{34}$ cm^{-2} s^{-1} at Higgs threshold

$L = 9 \times 10^{34}$ cm^{-2} s^{-1} at Higgs threshold

$L = 3\times10^{35}$ cm^{-2} s^{-1}, 1000 PU

Main focus for BRN report

Higgs #1: H couplings to fermions and bosons



$\kappa = (g_W)^{obs}/(g_W)^{SM}$

- HL-LHC will achieve %-level precision on the measurement of the Higgs coupling to most particles in the SM
  - Even on coupling to μ and top
- Next generation colliders will drastically improve
  - Sub-percent precision in all channels
  - Measure last coupling (κ_c)

→ Improvement up to x10!

Uncertainty in % on κ

	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

New!

x10!

** Assume κ_V<1

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

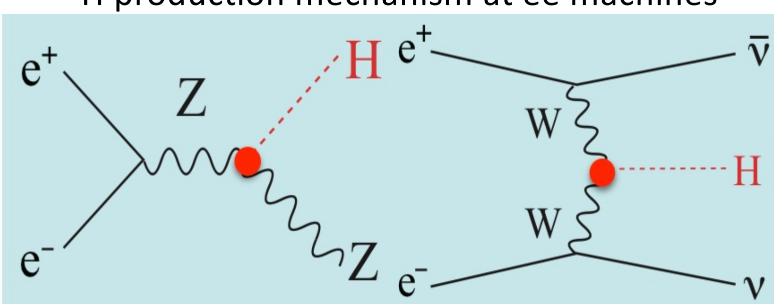
Higgs #2: search for H→dark matter

- Drastic improvement expected at future machines
- Lepton colliders
  - Exploit clean production mode in HZ and Hνν
    - → inclusive reconstruction
- Hadron colliders
  - H produced in VBF or ttH

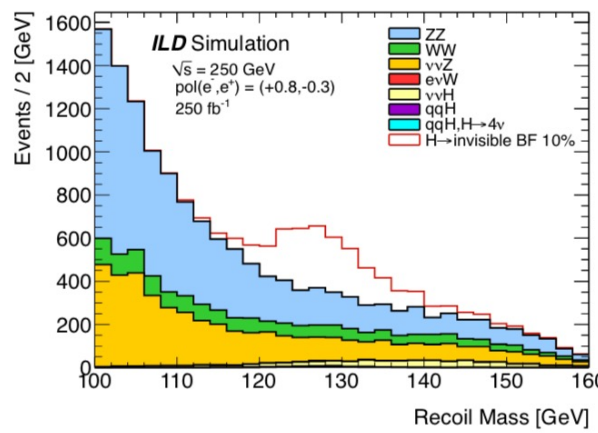
Limits on Higgs BR to DM (invisible) particles				
	LHC 2020	HL-LHC	ILD 250	FCC-comb
BR_{inv}	<20%	<1.9%	0.28%	<0.024%

3 orders of magnitude improvement w.r.t. current knowledge !

H production mechanism at ee machines



Lower energies   Higher energies

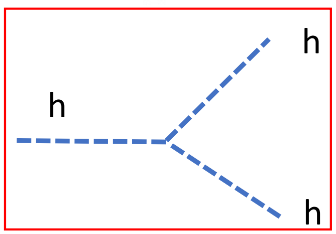


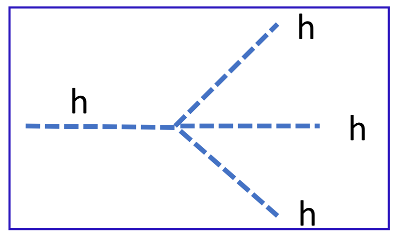
arXiv:1909.07537

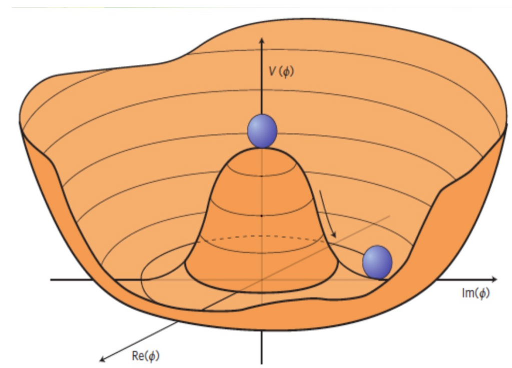
Higgs #3: Measure shape of Higgs potential

- To understand EW symmetry breaking we need to understand the Higgs potential

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





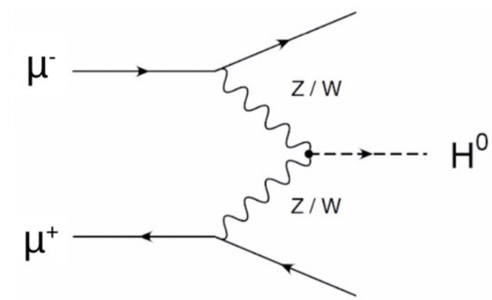


- Future colliders will improve tremendously on the HL-LHC
  - FCC-comb can measure κ_3 to 5%
    - 10x improvements over HL-LHC from FCC!
  - Muon colliders can measure κ_3 to 2%
    - 25% @ 3 TeV, 5% @ 10 TeV, 2% @ 30 TeV

Snowmass 2021

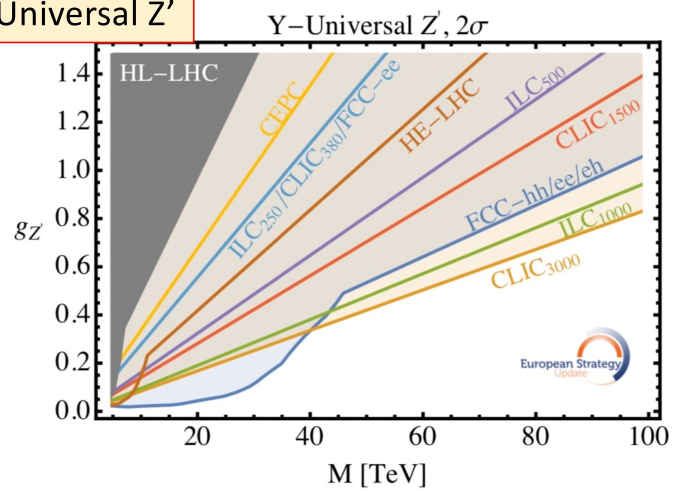
Precision on Higgs self coupling κ_3

	HL-LHC	FCC-comb	μ collider
κ_3	50%	5%	2%

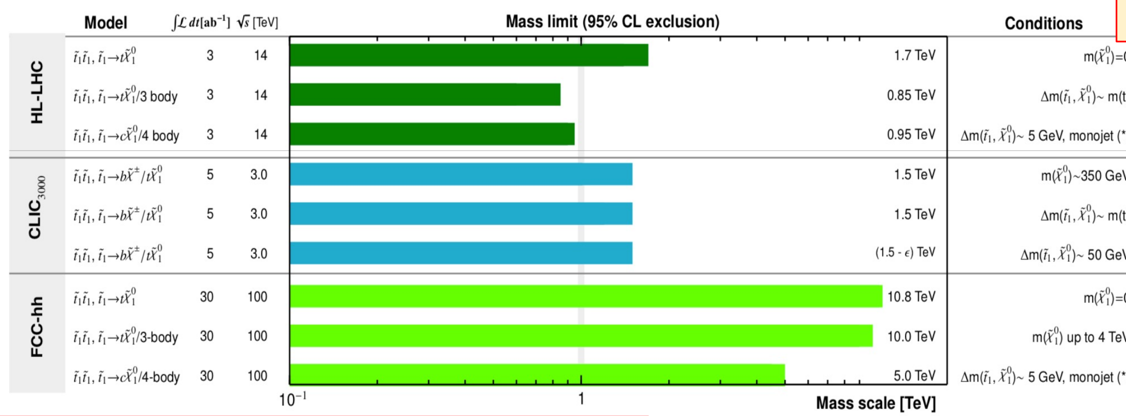


Direct searches for new particles

Y-Universal Z’



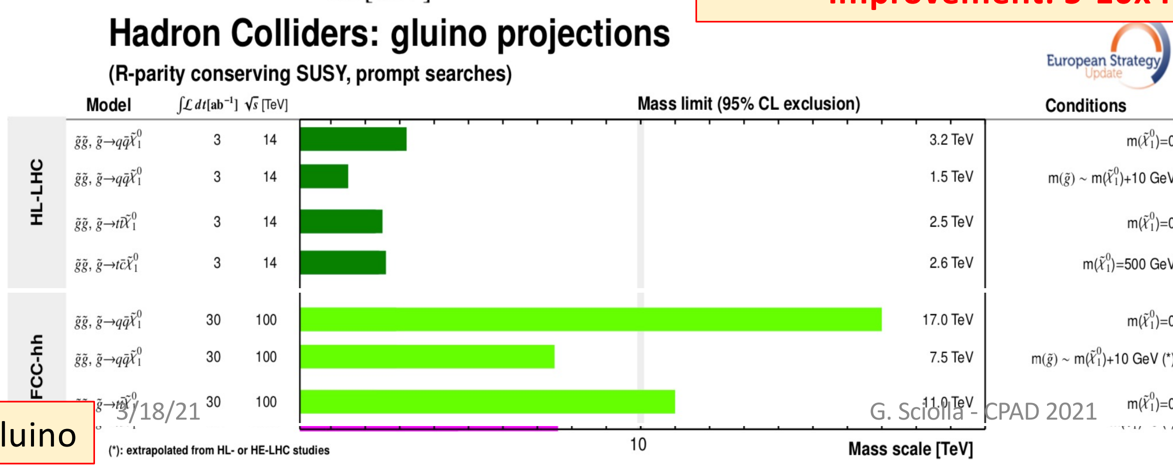
stop



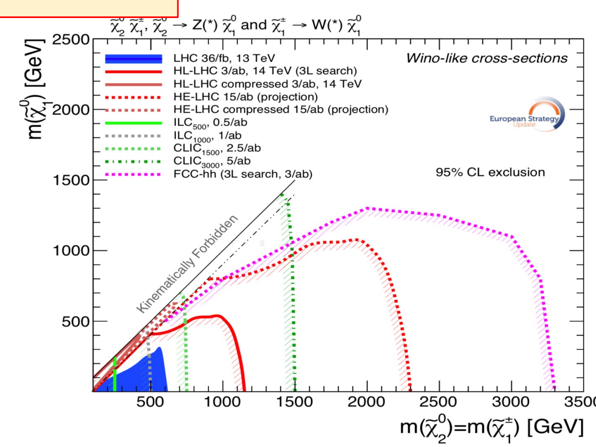
pp colliders have an advantage in searches

Improvement: 5-10x HL-LHC

ILC 500: discovery in all scenarios up to kinematic limit $\sqrt{s}/2$



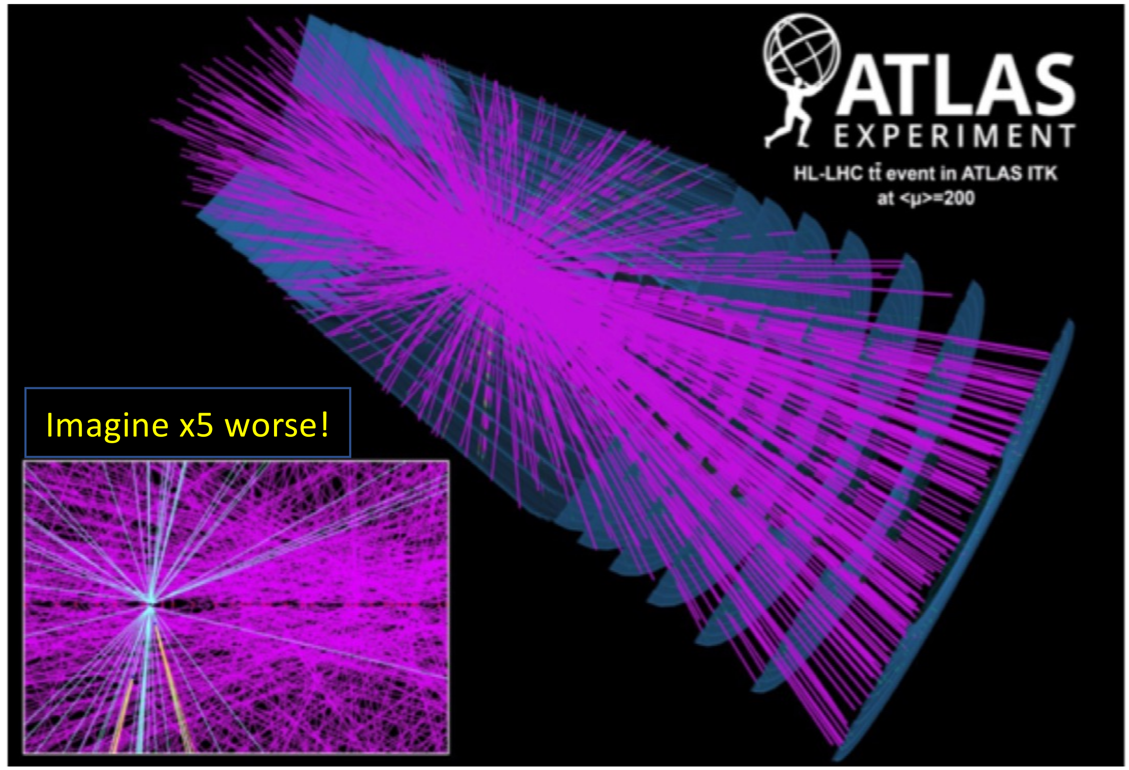
Gluino



chargino

Experimental challenges @ 100 TeV pp colliders

- Extremely harsh environment
  - Pileup: ~1,000 — 5x HL-LHC
  - Radiation: — 100x HL-LHC
    - 1×10^{18} n/cm^2 for innermost tracking layer
    - 300 MGy for innermost tracking layer
  - Occupancy: — 10x HL-LHC
    - 20 GHz/cm^2 in innermost tracking layer
- Kinematics
  - Dynamic range: — 10x HL-LHC
    - From few GeV (Higgs) to 20 TeV (searches)
  - |eta|<6 — 2x HL-LHC
    - More energy, more forward particles
  - Angular resolution: — 10x HL-LHC
    - 10 mrad separation in highly collimated jets
  - Calorimeter thickness — 2× HL-LHC



Detectors designed for **"particle flow" reconstruction** → high granularity for separating tracks and energy deposits

Technical requirement #1:

Tracking: low-mass, high-granularity, 4D Si detectors

Measurement	Technical Requirement (TR)
TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_\mathrm{T}}/p_\mathrm{T} = 0.2\%$ for central tracks with $p_\mathrm{T} < 100$ GeV, $\sigma_{p_\mathrm{T}}/p_\mathrm{T}^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_\mathrm{T} > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\mathrm{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\mathrm{m}$ TR 1.1.3: Granularity : $25 \times 50\ \mu\mathrm{m}^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps
TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8 \times 10^{17}\ \mathrm{n_{eq}/cm^2}$ TR 1.2.2: $\sigma_{p_\mathrm{T}}/p_\mathrm{T} = 0.5\%$ for tracks with $p_\mathrm{T} < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification

1) Excellent p_T resolution at low p_T
→ Very low-mass detectors
LC: no active cooling

2) Impact parameter resolution

3) Good granularity

DOE BRN Study on HEP Detector R&D Report

Technical requirement #1:

Tracking: low-mass, high-granularity, 4D Si detectors

Measurement	Technical Requirement (TR)
TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\text{GeV}] \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\text{m}$ TR 1.1.3: Granularity : $25 \times 50\ \mu\text{m}^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps
TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8 \times 10^{17}\ \text{n}_{\text{eq}}/\text{cm}^2$ TR 1.2.2: $\sigma_{p_T}/p_T = 0.5\%$ for tracks with $p_T < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification

Similar to ee detectors except for:

1) Harsher environment → Radiation hard detectors and electronics
2) Less stringent requirements on p_T resolution at low p_T
3) Timing is more crucial (pileup)
4) 5μm resolution needed for 2-track separation in collimated jets and high pileup

DOE BRN Study on HEP Detector R&D Report

Detector requirement #2:

Calorimeters: high-granularity, 5D with 10^6 dynamic range

TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of 0.5×0.5 cm^2, hadronic cells of 1×1 cm^2 TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps
TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and 3×10^{16} (5×10^{18}) n_{eq}/cm^2 in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps

1) 4% jet energy resolution for Higgs total width (in ZH)

2) High granularity → High position resolution

3) Necessary for H/Z decays → e/γ

4) Timing for particle ID, long-lived particles

- Particle flow will be necessary to deliver the resolutions necessary
- Particle flow needs excellent energy and position resolution

DOE BRN Study on HEP Detector R&D Report

Detector requirement #2:

Calorimeters: high-granularity, 5D with 10^6 dynamic range

TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of 0.5×0.5 cm^2, hadronic cells of 1×1 cm^2 TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps
TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and 3×10^{16} (5×10^{18}) n_{eq}/cm^2 in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps

Similar to ee detectors except for:

1) Radiation tolerance requirement much more stringent (exp. Forward)

2) More stringent timing requirements due to pileup

- Particle flow will be necessary to deliver the resolutions necessary
- Particle flow needs excellent energy and position resolution

DOE BRN Study on HEP Detector R&D Report

Detector requirement #3:

High-bandwidth, low-latency trigger and readout

TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and $8 \times 10^{17}\ n_{eq}/cm^2$
	TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider

1) Electronics needs to be rad-hard, especially at pp colliders

2) 10 TeV pp detector: High granularity (particle flow) → 20 billion channels → 1 exabyte/s of raw data w/o localized processing and on-detector reconstruction: 1,000x HL-LHC!
To reduce this data to something manageable, we need low-latency and low-power processing using rad-hard ASICS, FPGAs, RISC processors using Artificial Intelligence/Machine Learning technologies.

DOE BRN Study on HEP Detector R&D Report

Common themes for detector requirements

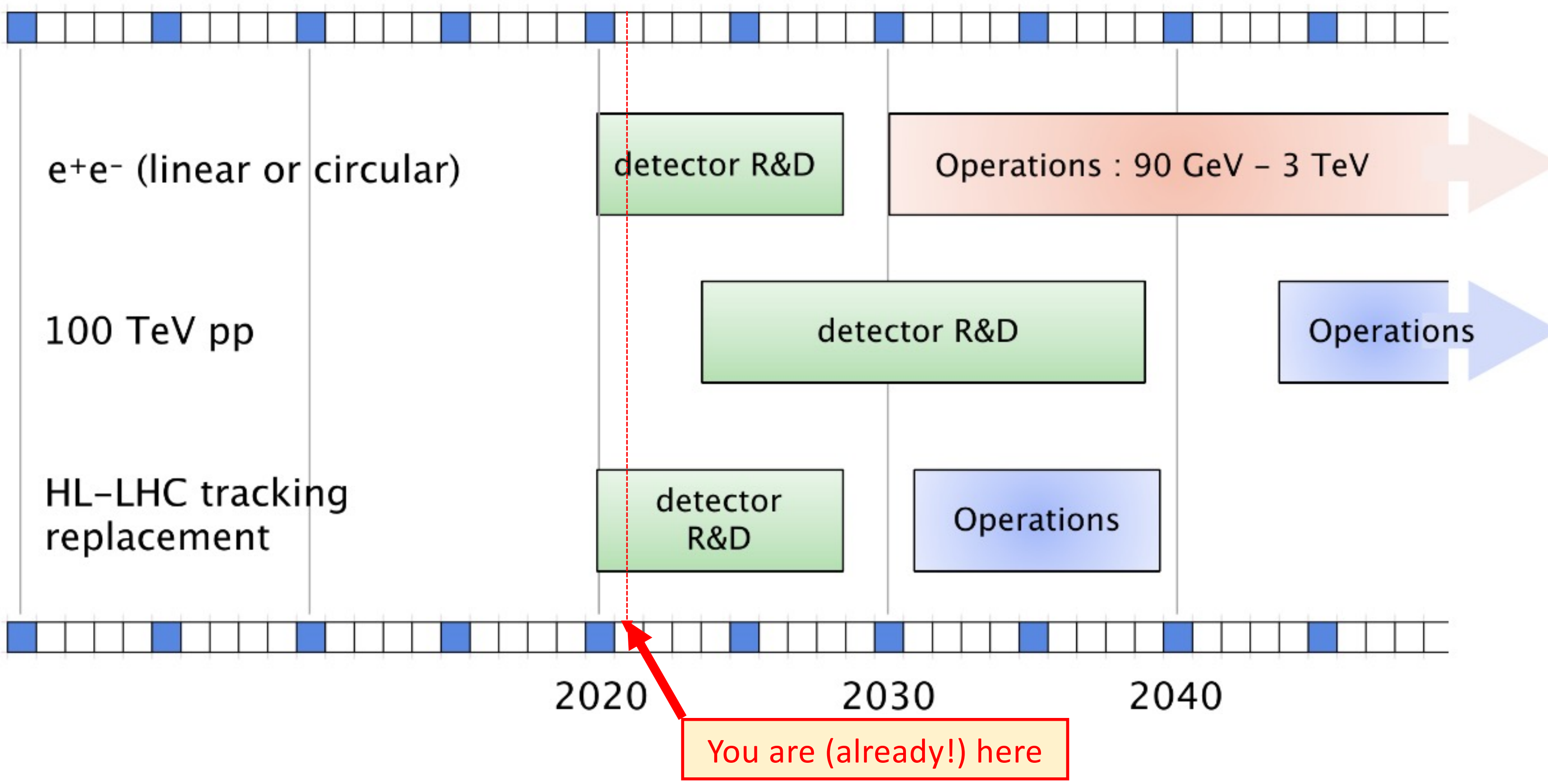
- Precision timing will be key
  - 5-10 ps per particle resolution needed for both charged and neutral particles
    - Lepton colliders: essential to reduce beam-induced background
    - Hadron colliders: essential to manage pileup effects and radiation effects, especially in forward region

- Detectors and electronics need to be very radiation-hard
  - Innermost layer of barrel tracker
    - Silicon lattice displacement damage: 1×10^{18} neq/cm^2
    - Total Ionizing Dose: 300 MGy
  - Forward Calorimeter $2.5|\eta|<6$
    - 5×10^{18} neq/cm^2, 5,000 MGy
  - Radiation levels are up to ~ 1,000x HL-LHC

Conclusion

- Many physics opportunities ahead will allow us to make major progress in our understanding of Particle Physics
  - Direct searches for new BSM particles
  - Indirect searches using precision tests of the Standard Model (e.g.: Higgs couplings)
- Many accelerators have being proposed for the decades to come
  - Lepton colliders: ee linear and circular colliders, muon colliders
  - Hadron colliders: post-LHC pp machines will allow us to explore higher energies
- While operation of (some of) these accelerators is far in the future, there is a lot of detector R&D that needs to take place
  - If we want a bright future for our students, R&D needs to ramp up now

Operations vs. R&D



Detector R&D needs to start ~ now if we want to have these opportunities in the future