Higgs Physics at future e+e- colliders

Physics Potential of Future Colliders
TRIUMF

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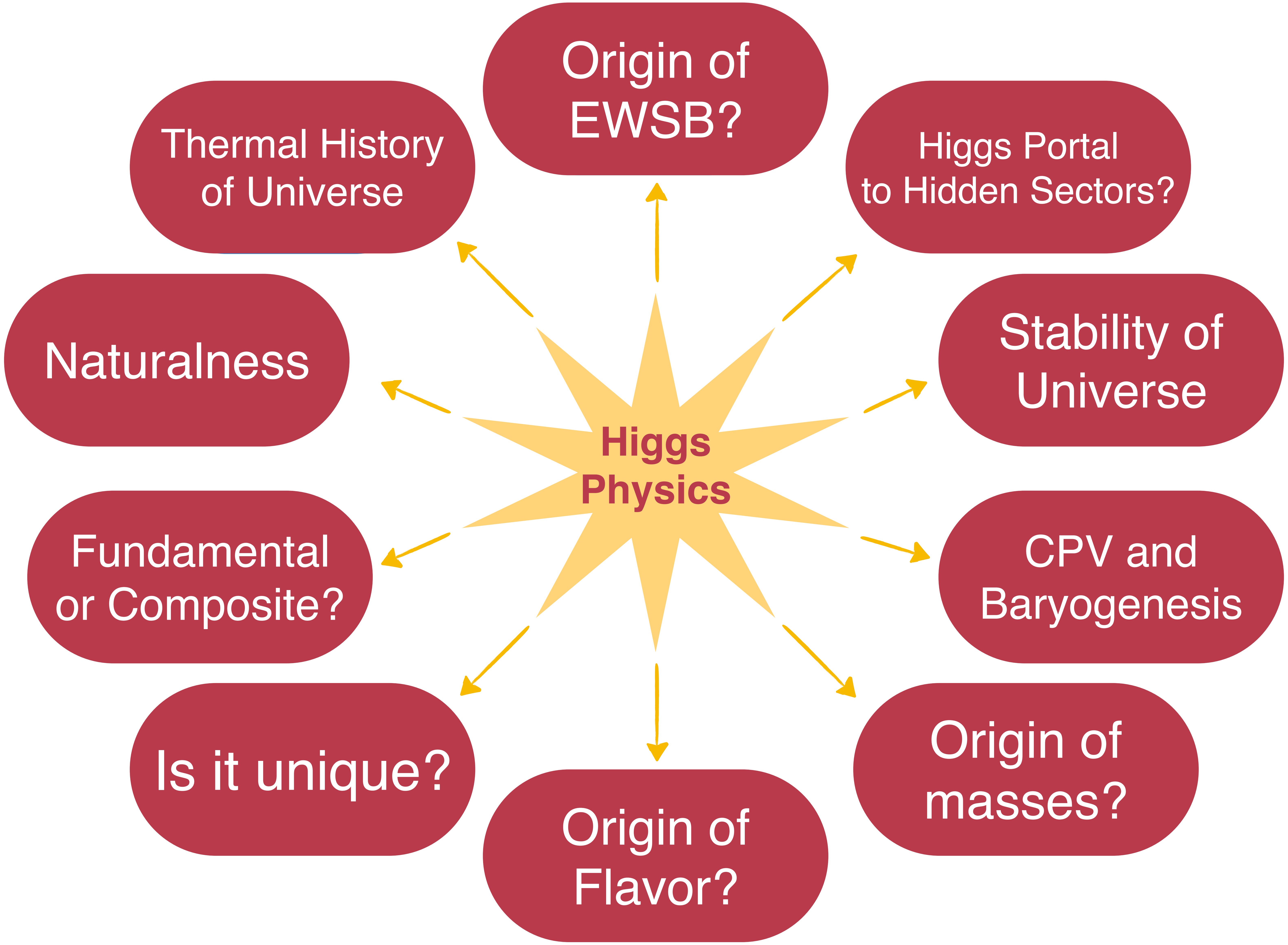
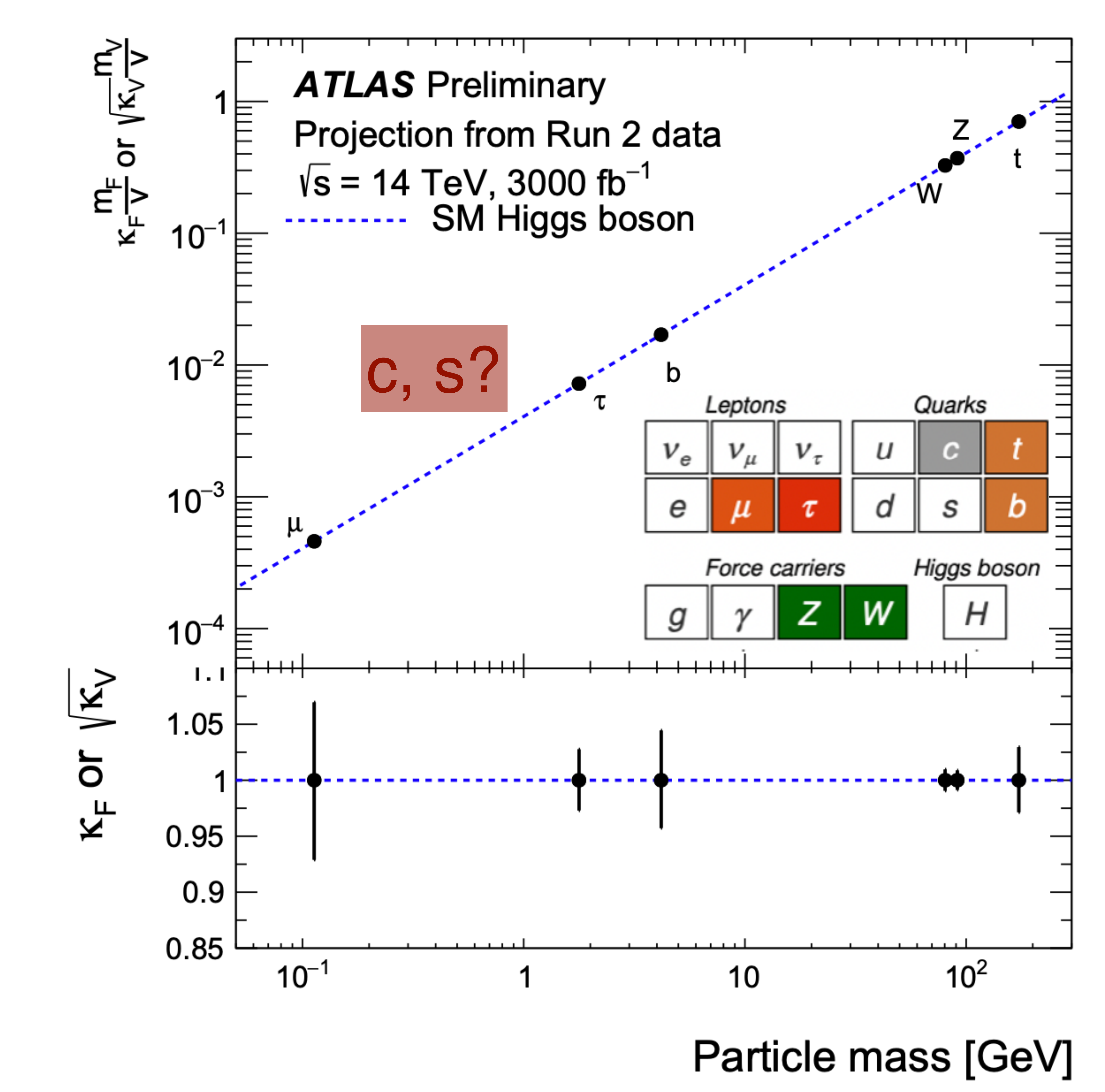
September 18, 2024

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY


Origin of EWSB?
Thermal History of Universe
Higgs Portal to Hidden Sectors?
Naturalness
Stability of Universe
Higgs Physics
Fundamental or Composite?
CPV and Baryogenesis
Is it unique?
Origin of masses?
Origin of Flavor?

Higgs at HL-LHC

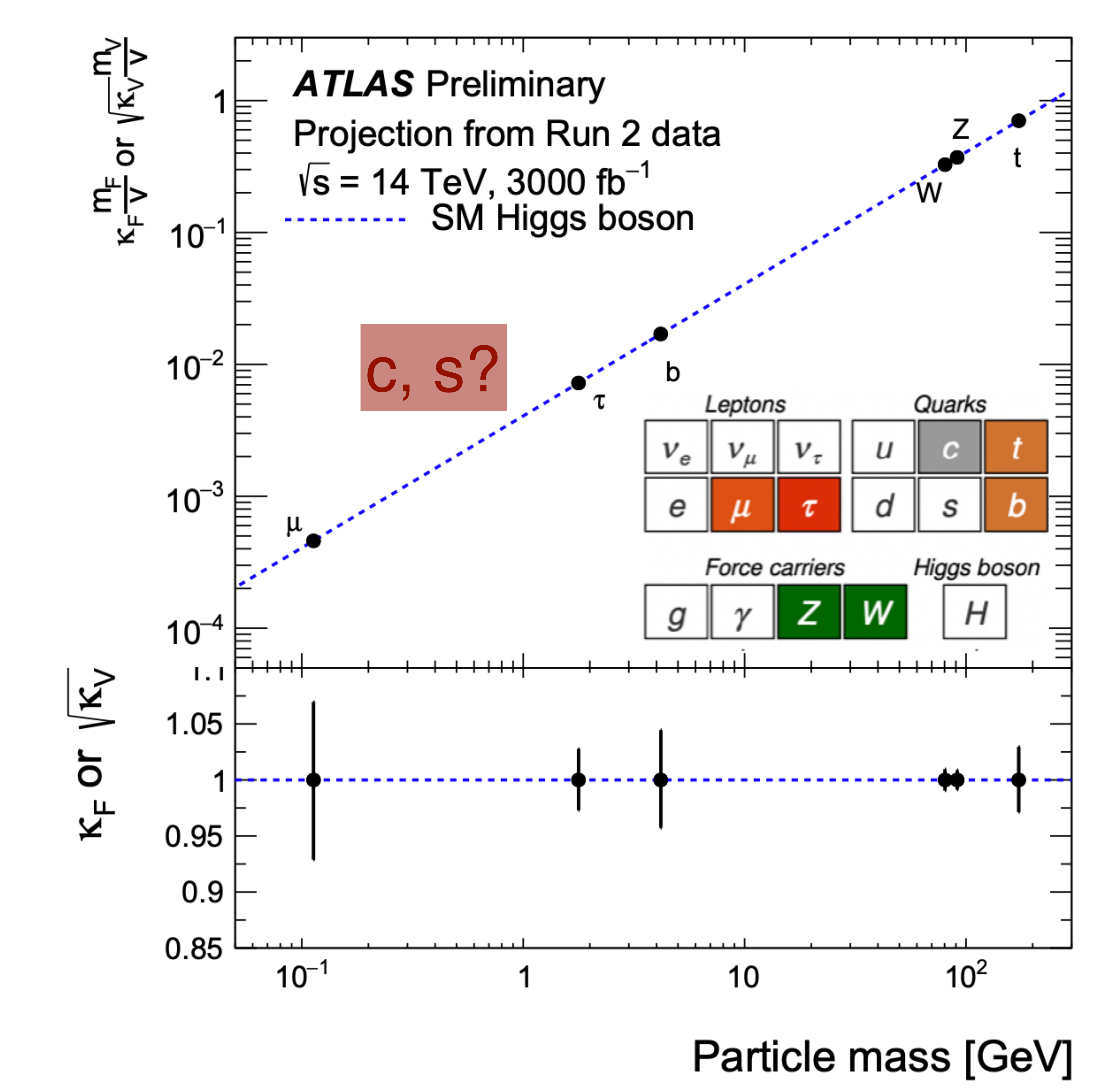


The High Luminosity era of LHC will dramatically expand the physics reach for Higgs physics:

- **2-5% precision for many of the Higgs couplings**
- **BUT much larger uncertainties on $Z\gamma$ and charm and ~50% on the self-coupling**

[1902.10229](1902.10229)
CERN-LPCC-2018-04

Higgs at HL-LHC



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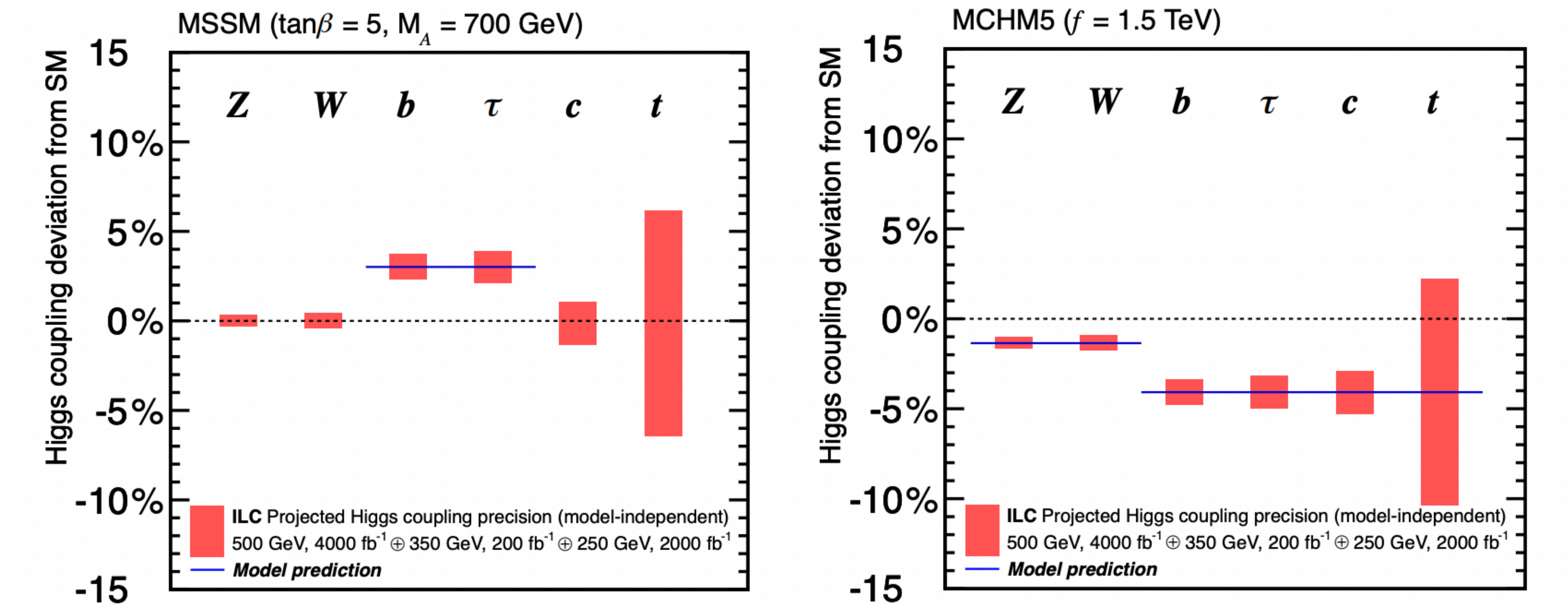
Light Yukawa out of reach in the LHC environment

ArXiv:2209.07510
ArXiv:2203.07622

No new particles discovered at the LHC so far…

What's next?
How can we use the Higgs to find new physics?



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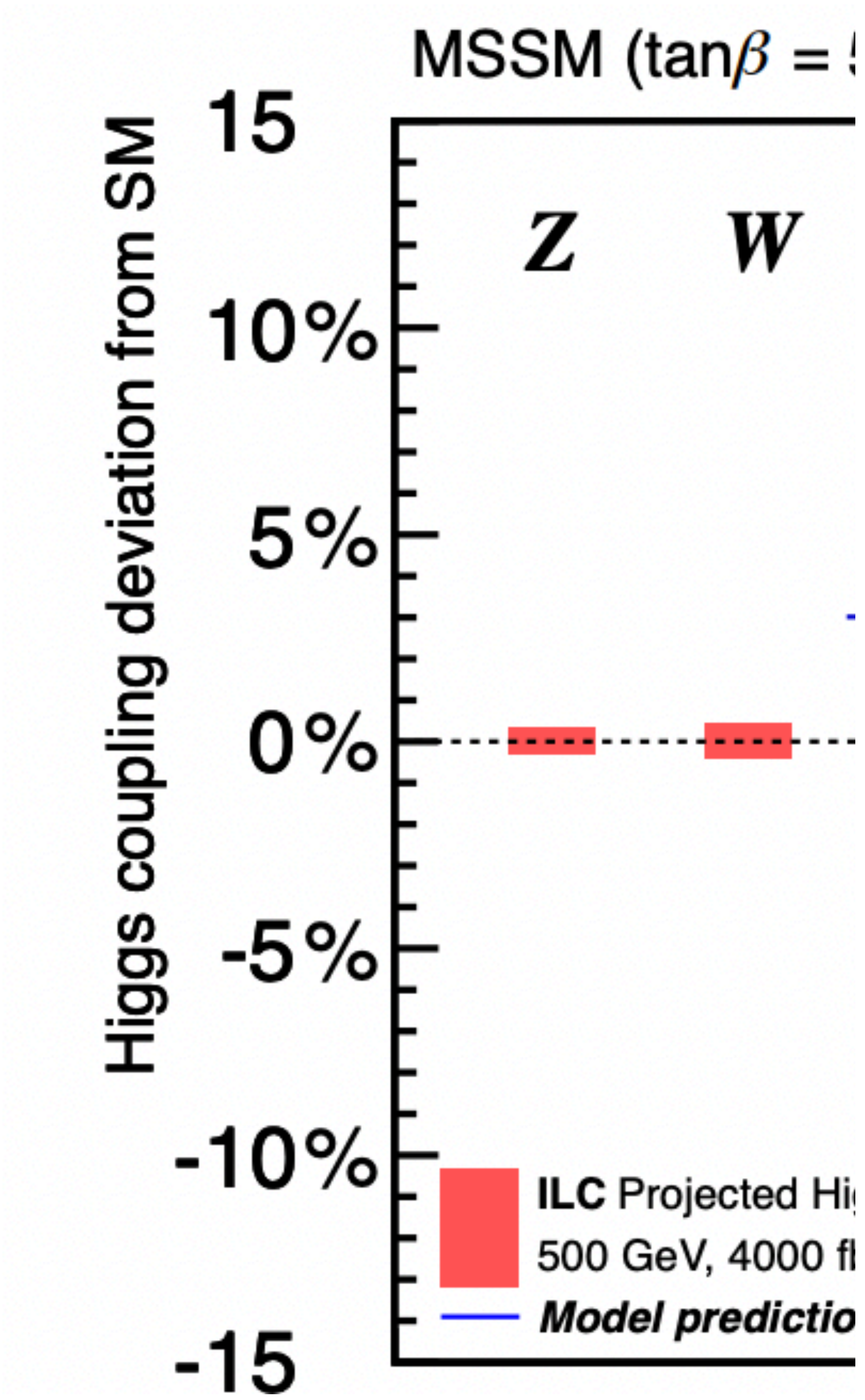
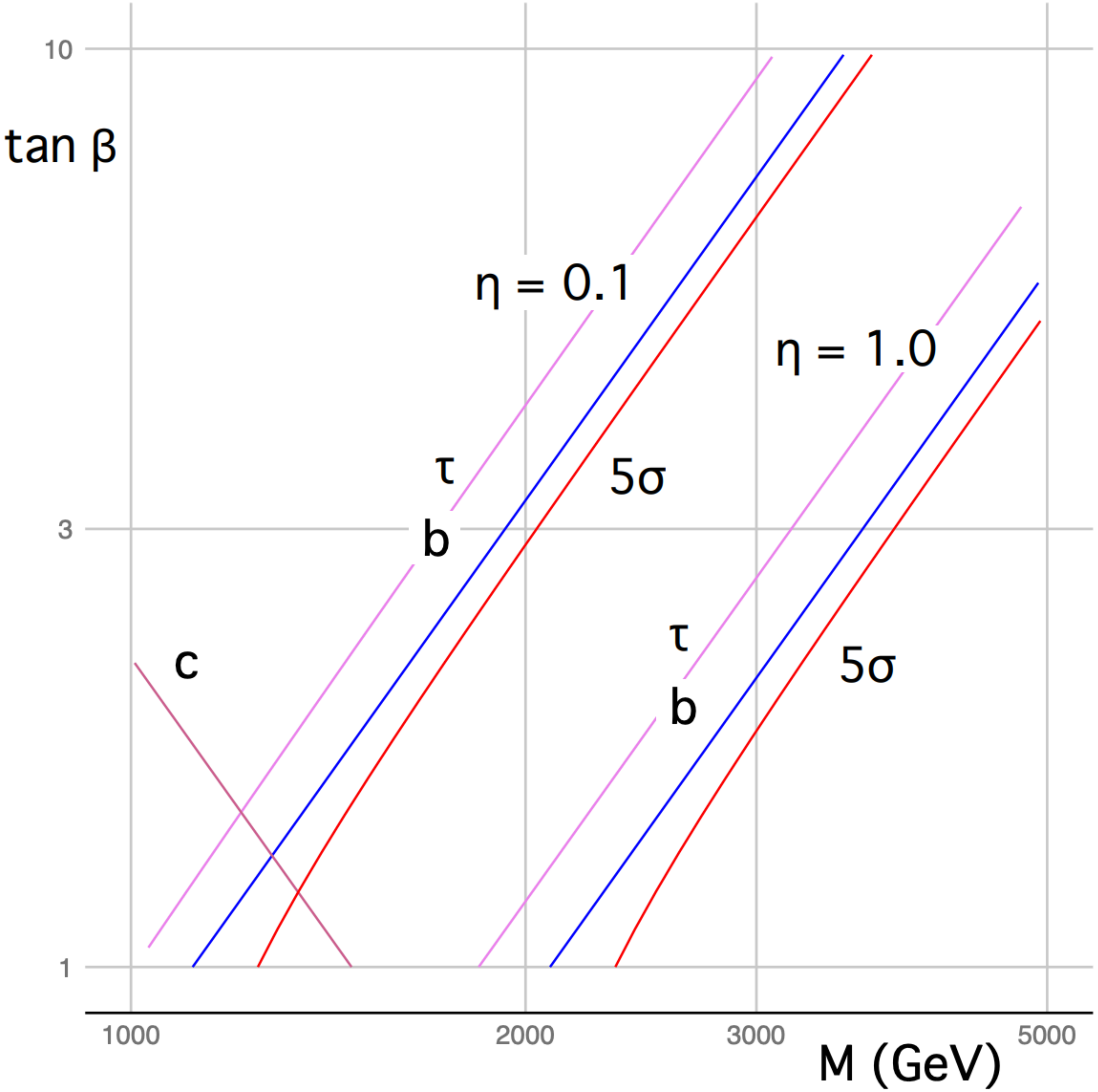
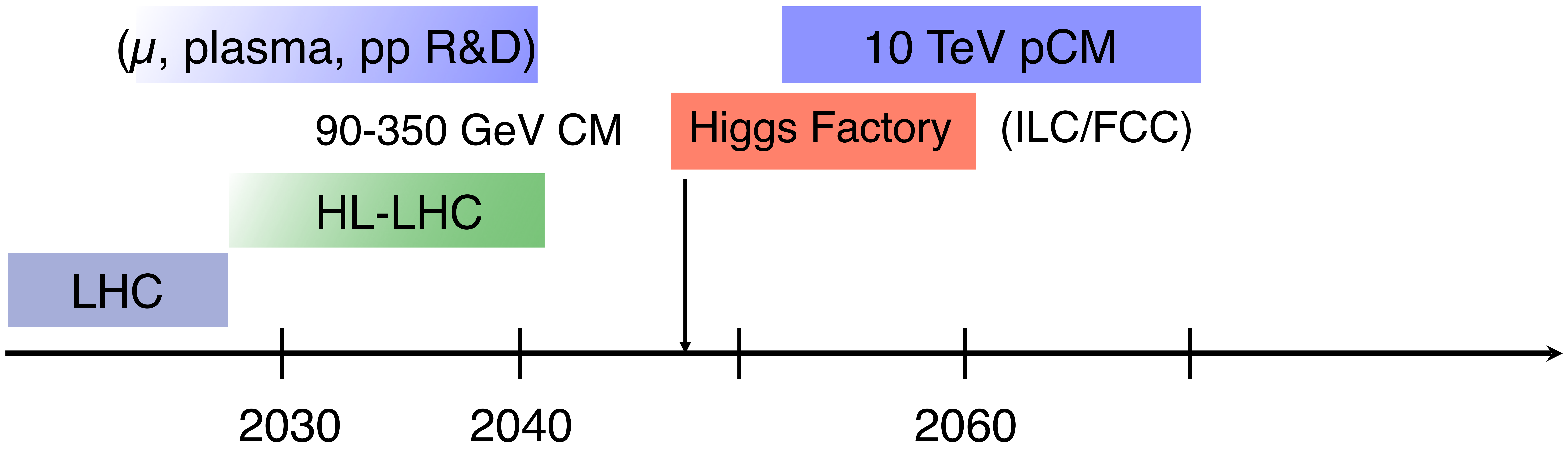




post-P5 roadmap

P5 report



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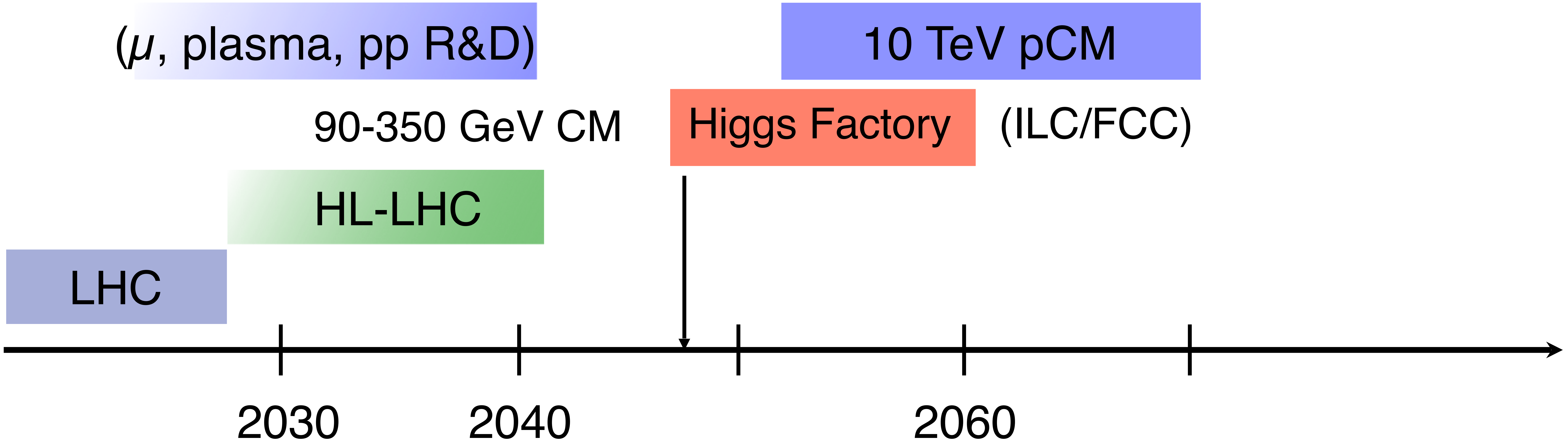

H couplings to:	**O(5-10)%**	**O(0.1-1)%**	
H self-coupling to:	**O(50)%**	**O(20)%**	**O(1)%**

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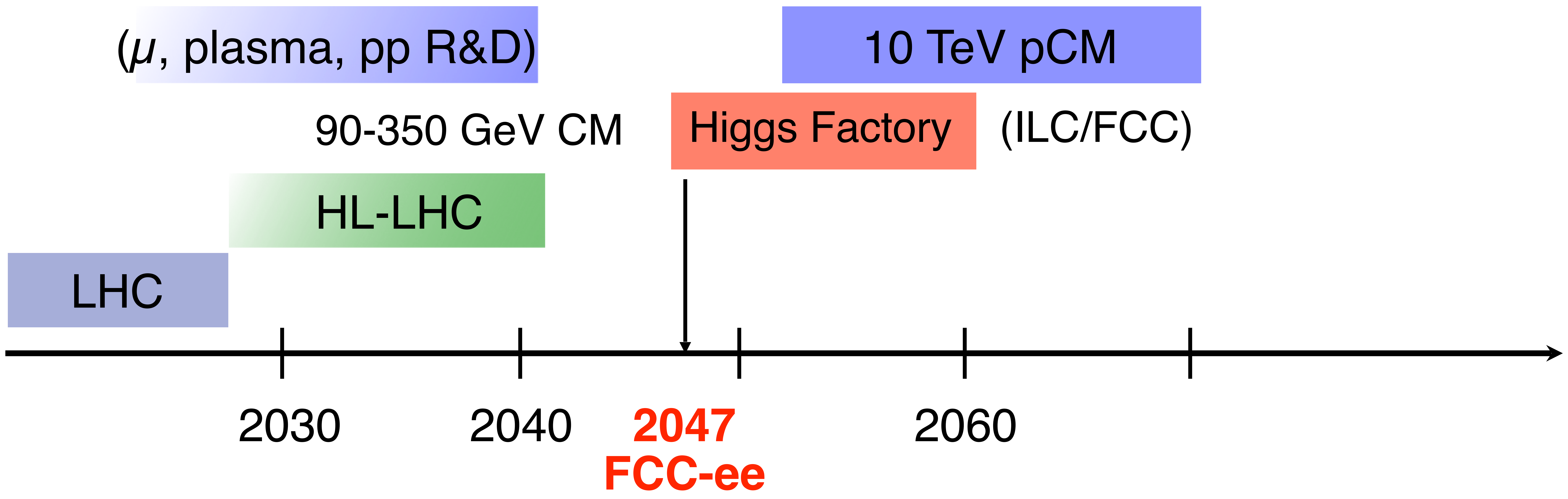
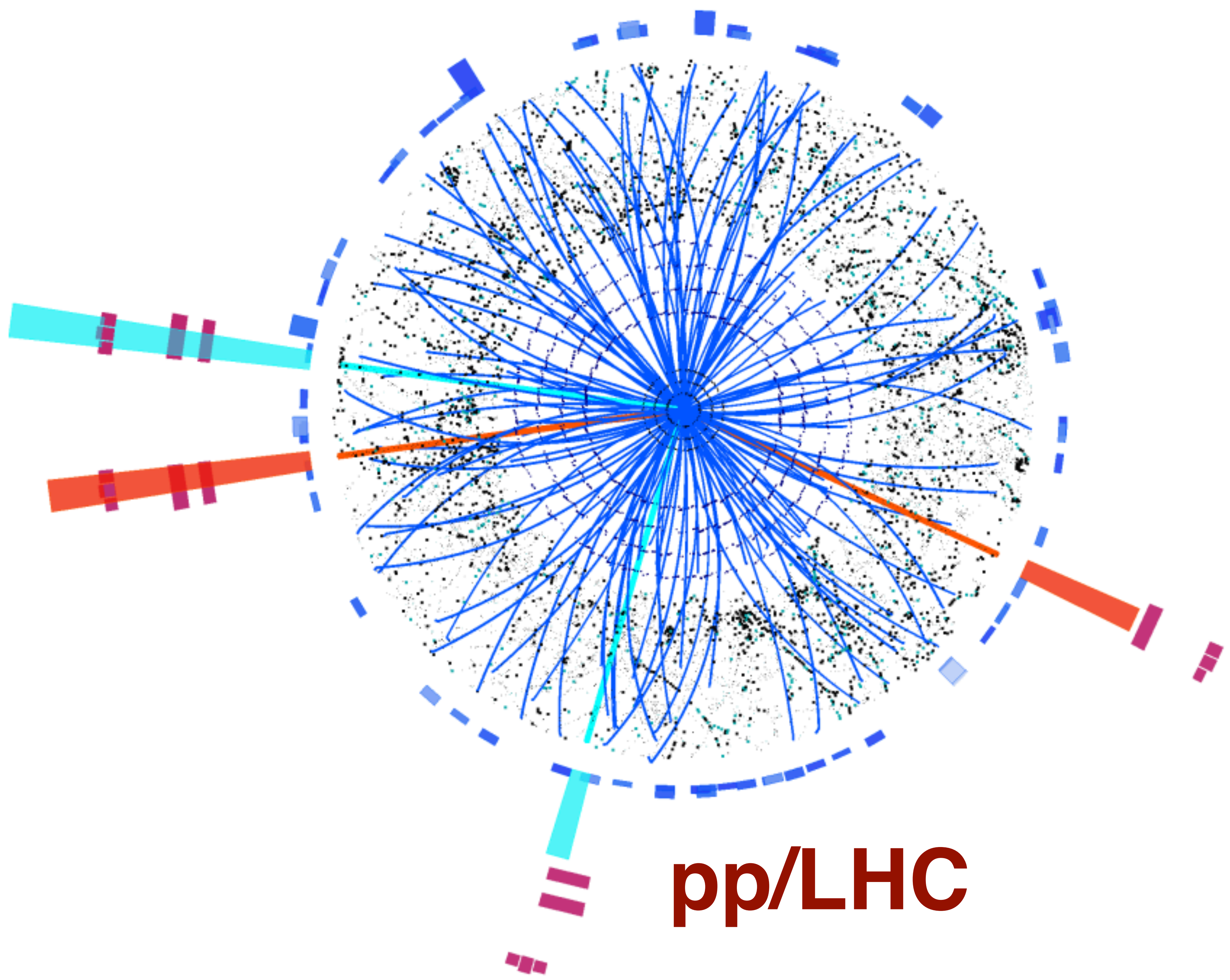


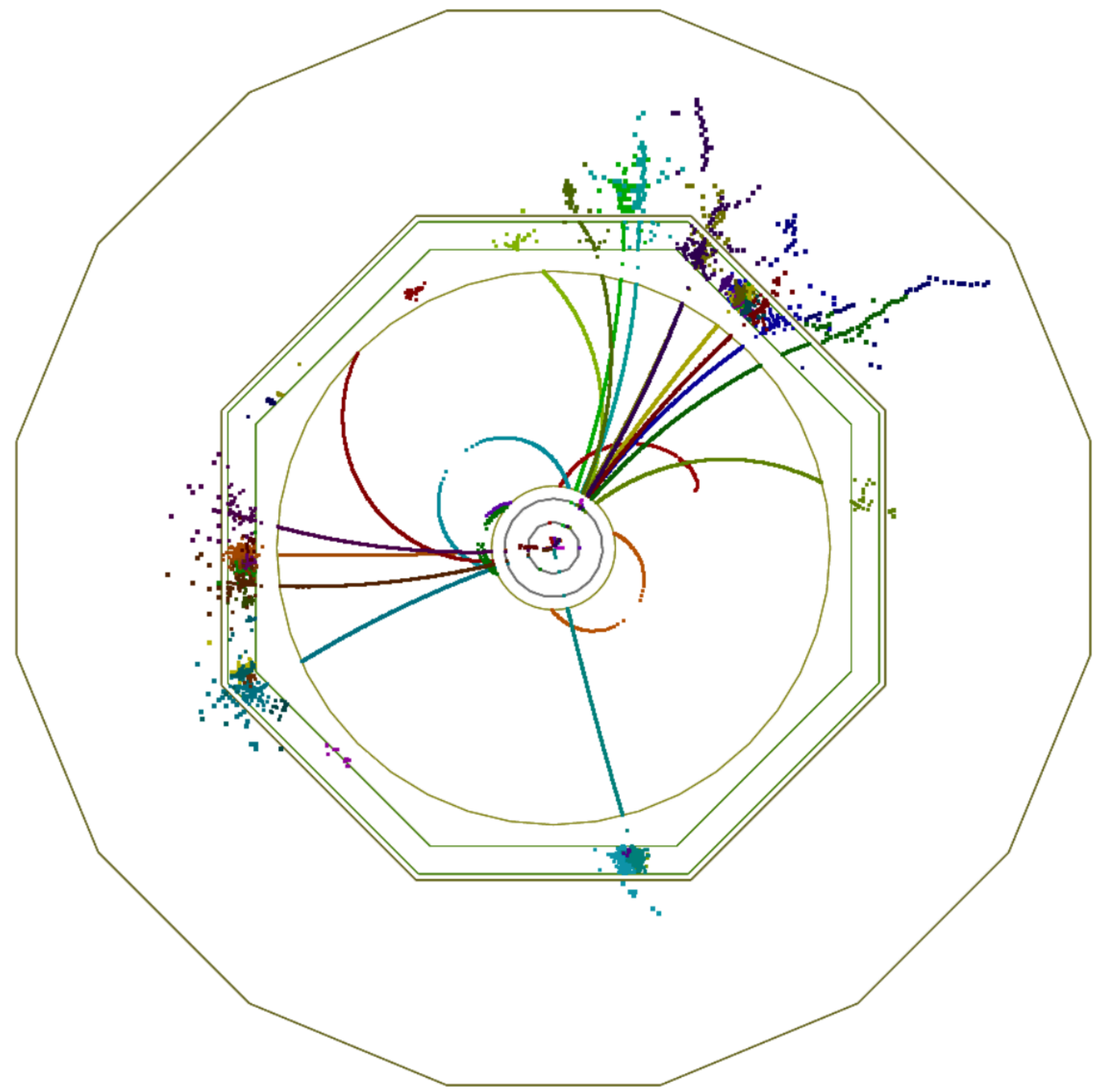
Why e^+e^-?

Initial state well defined & polarization $\Longrightarrow$ High-precision measurements

Higgs bosons appear in 1 in 100 events $\Longrightarrow$ Clean experimental environment and trigger-less readout



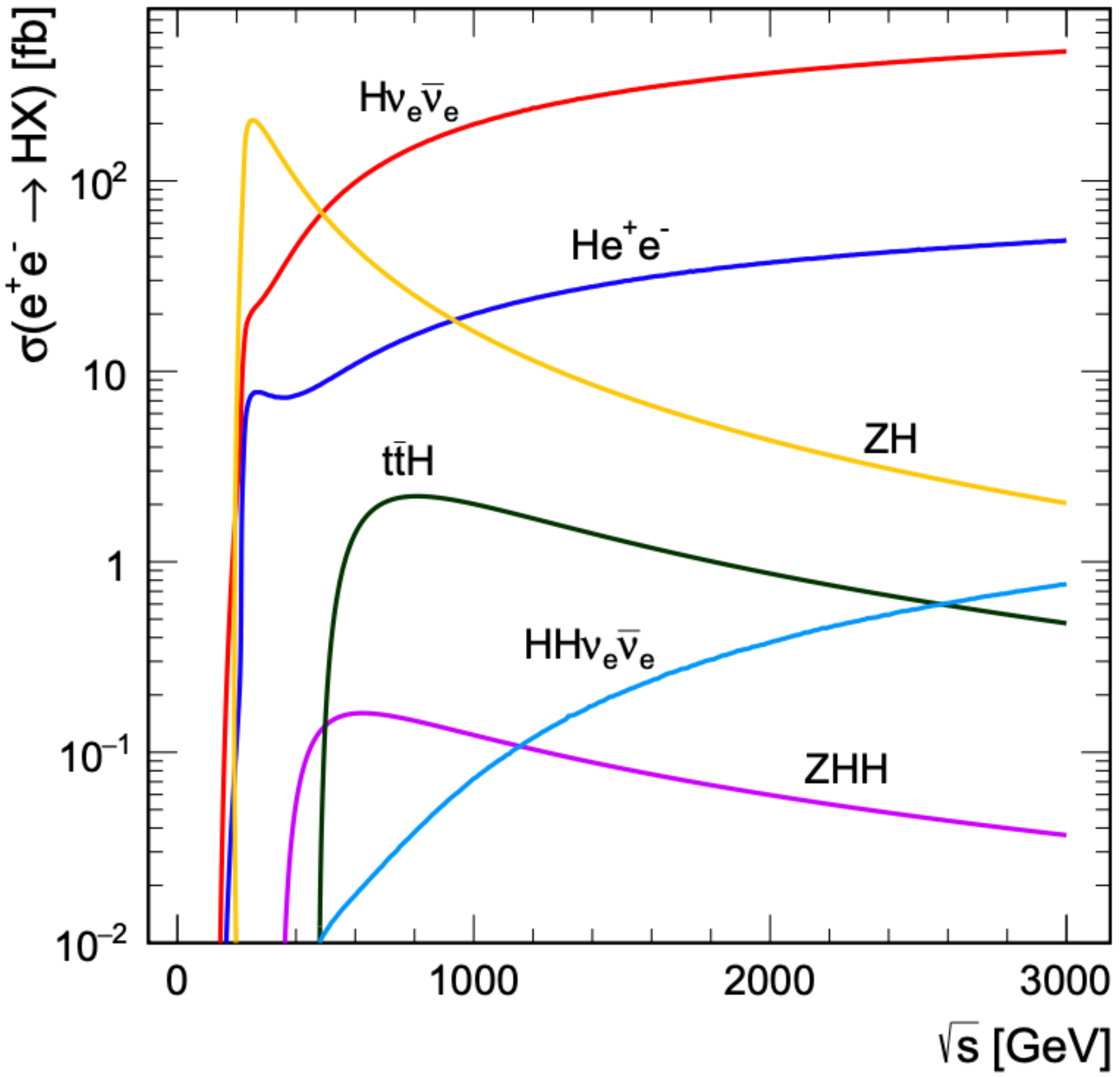
pp/LHC



e^+e^-

Higgs at e^+e^-

[The Energy Frontier 2021 Snowmass Report]



- ZH is dominant at 250 GeV
- Above 500 GeV
  - Hvv dominates
  - ttH opens up
  - **HH accessible with ZHH**

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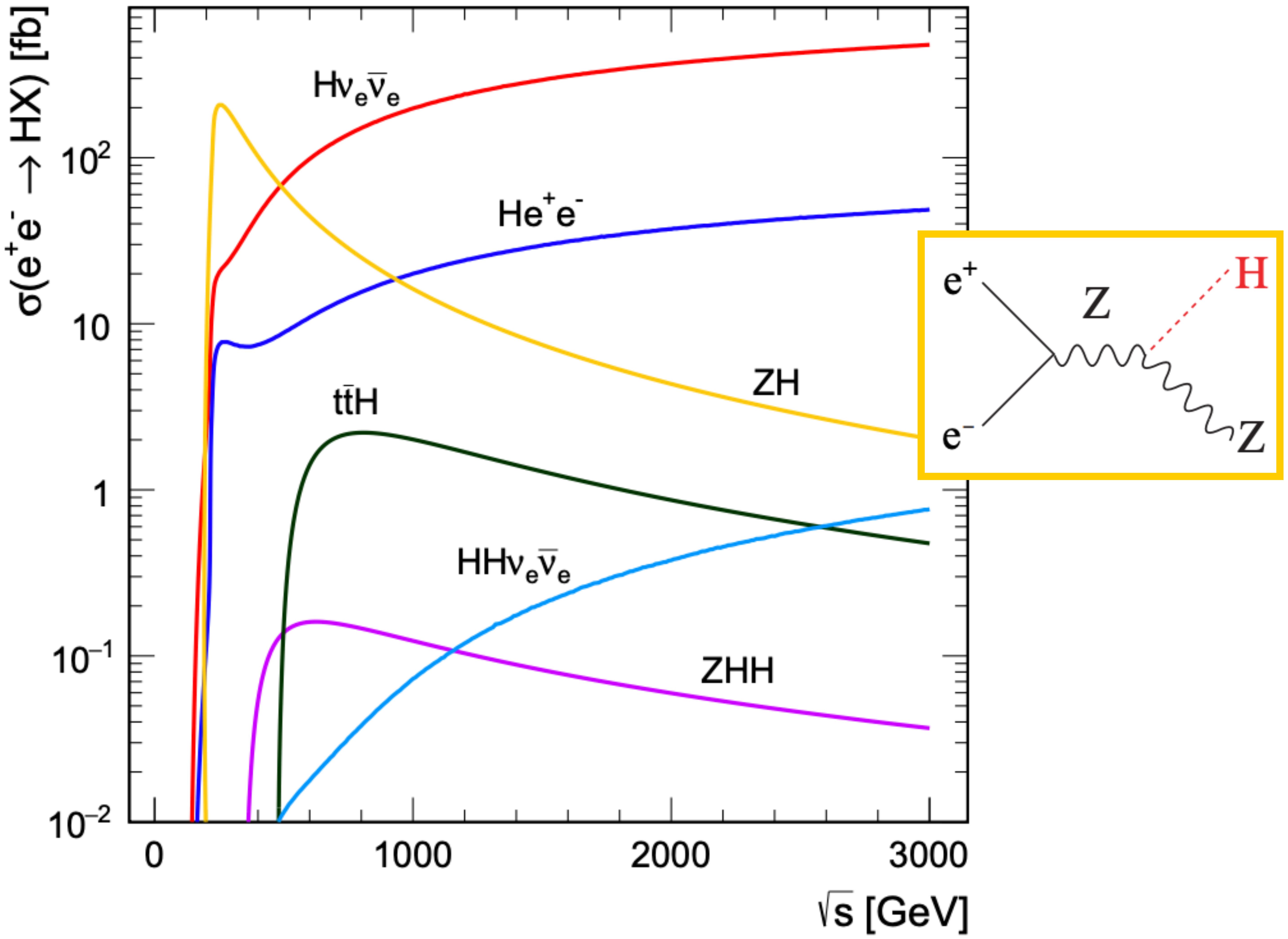

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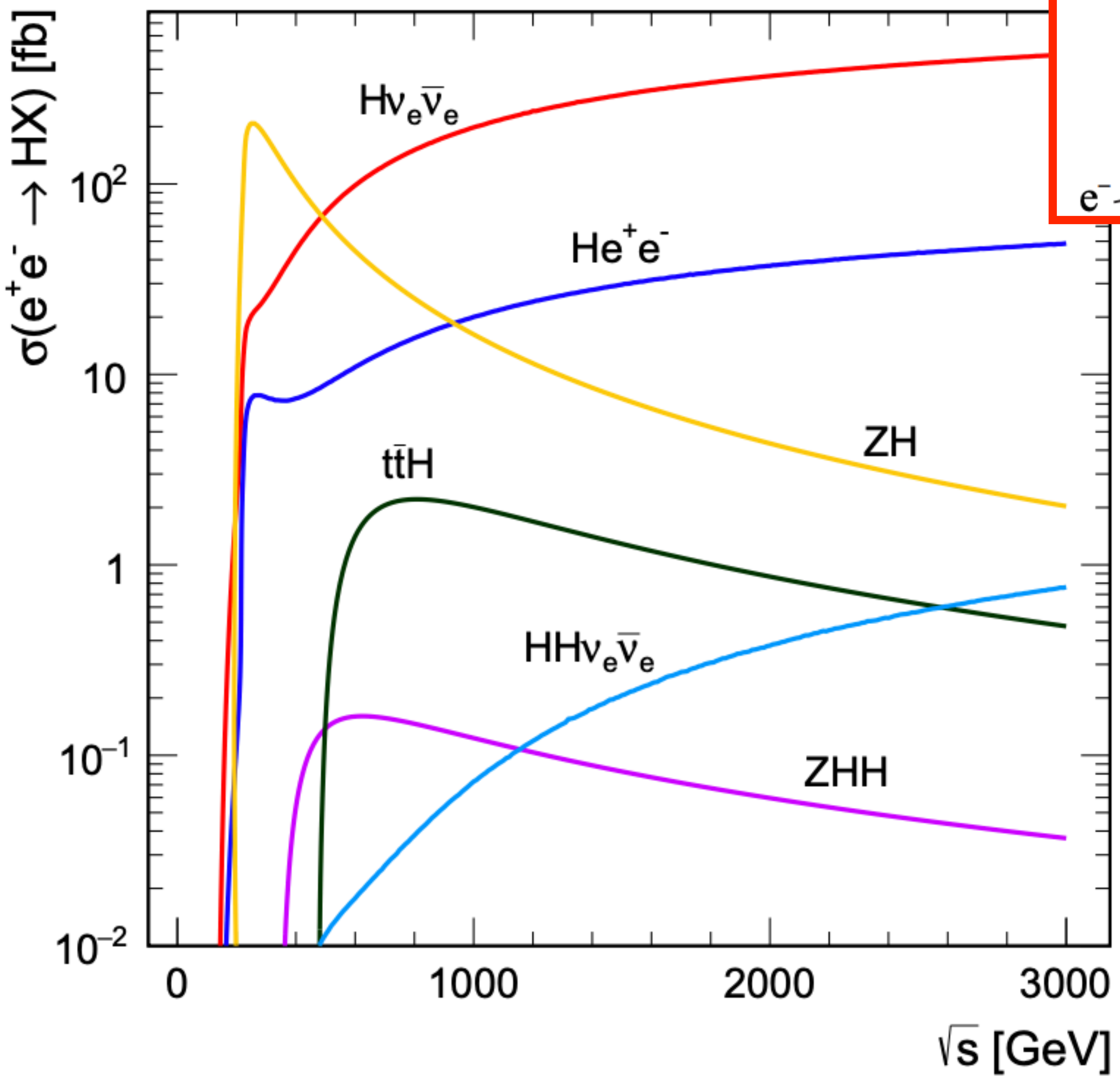

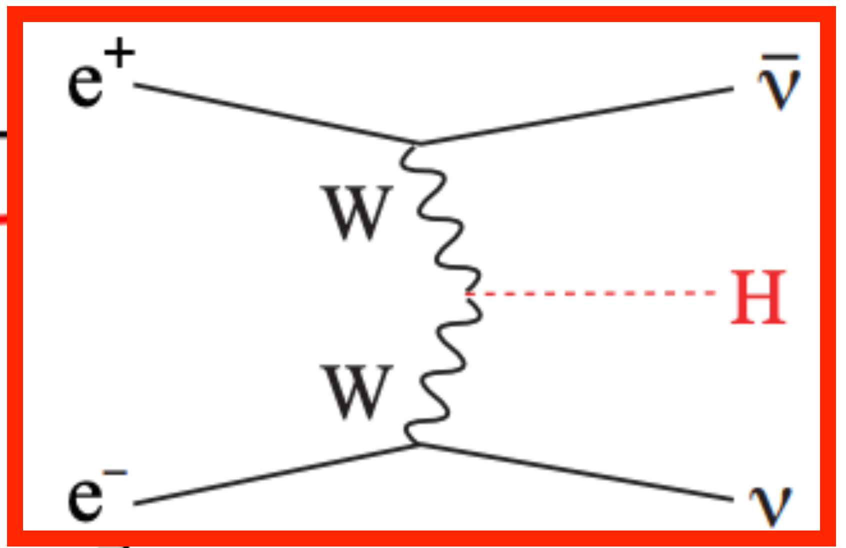

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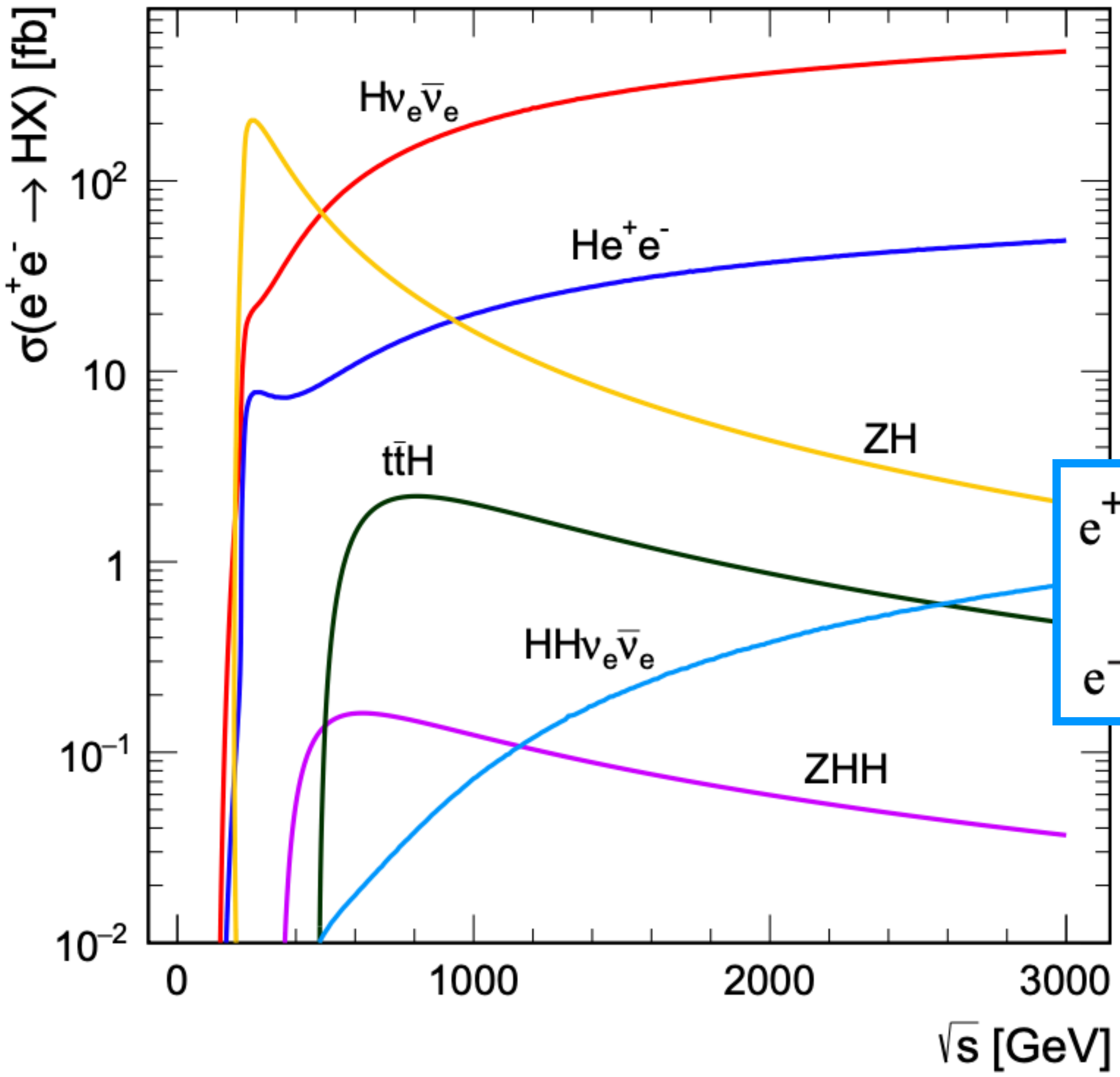

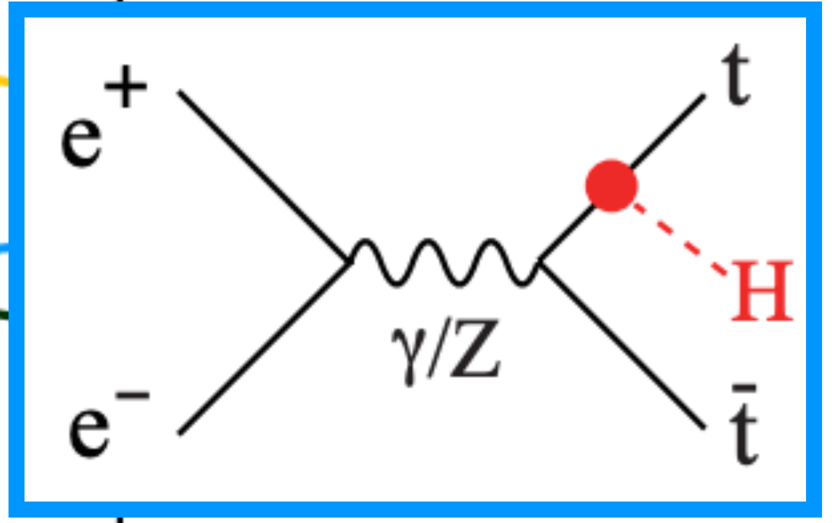

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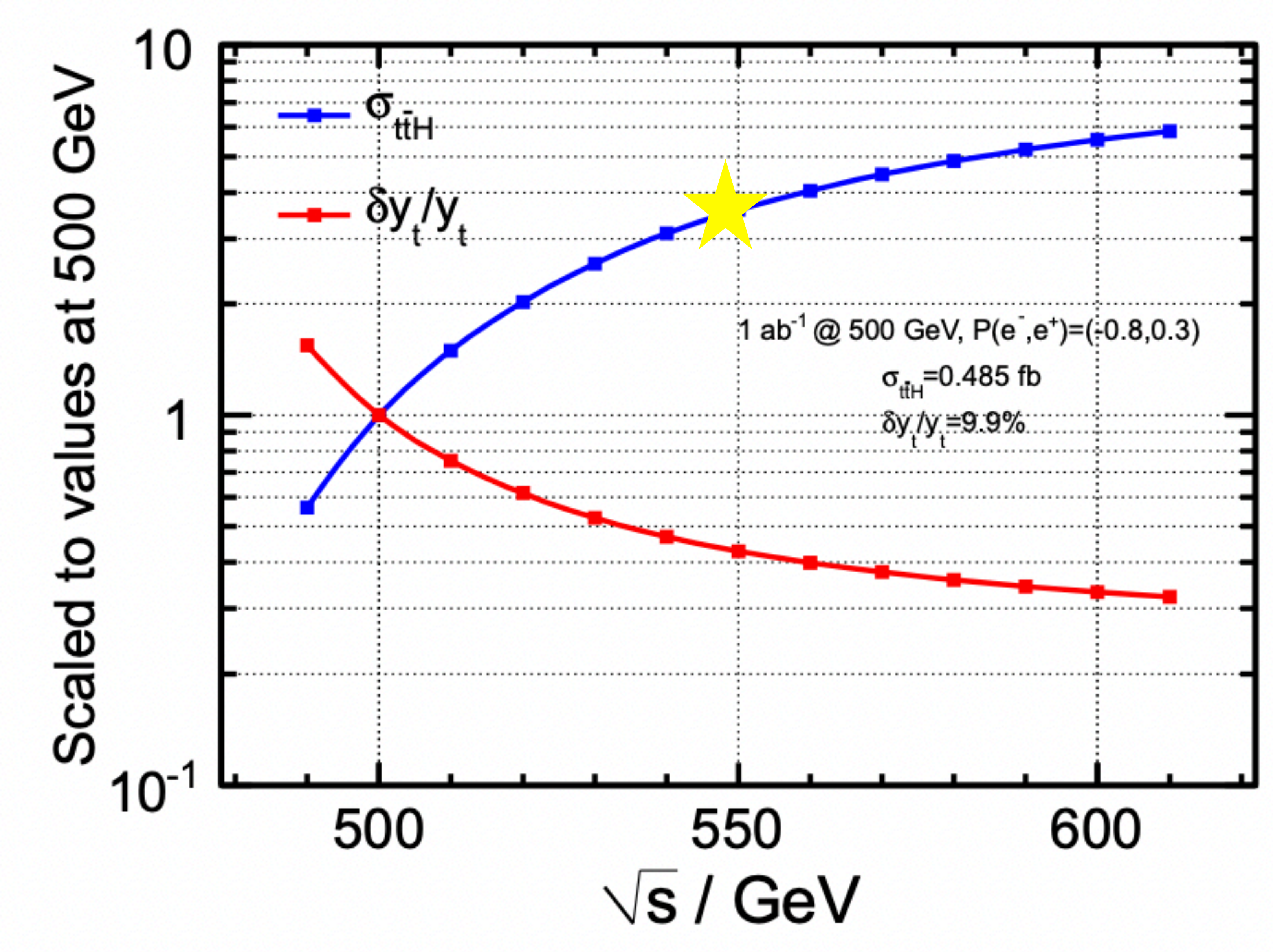

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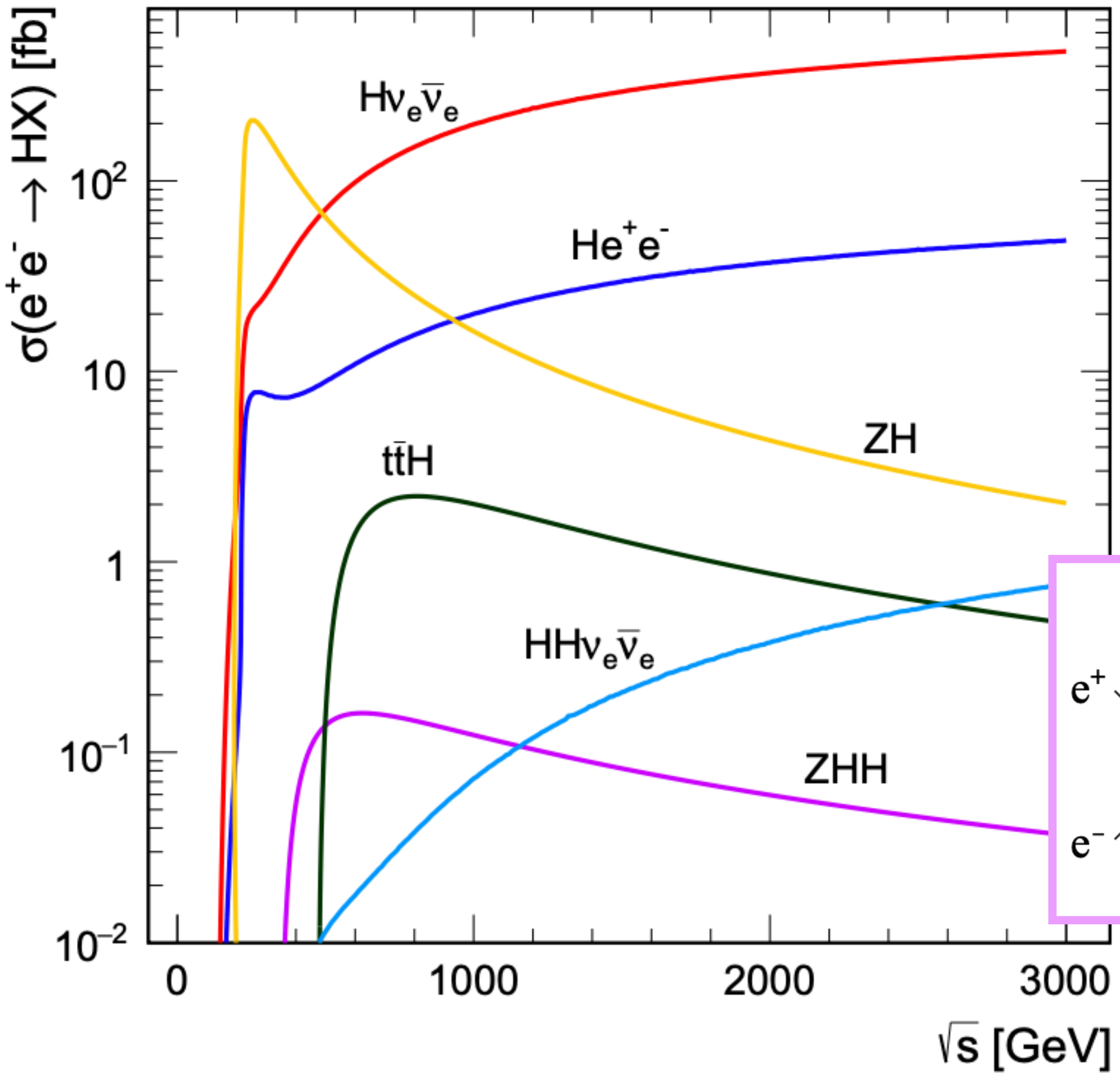

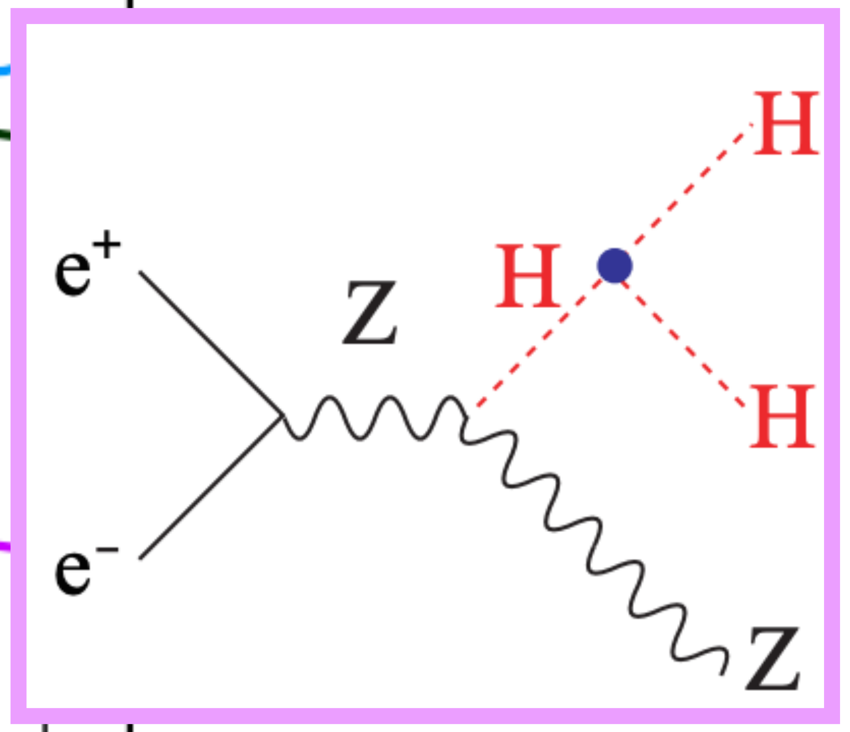

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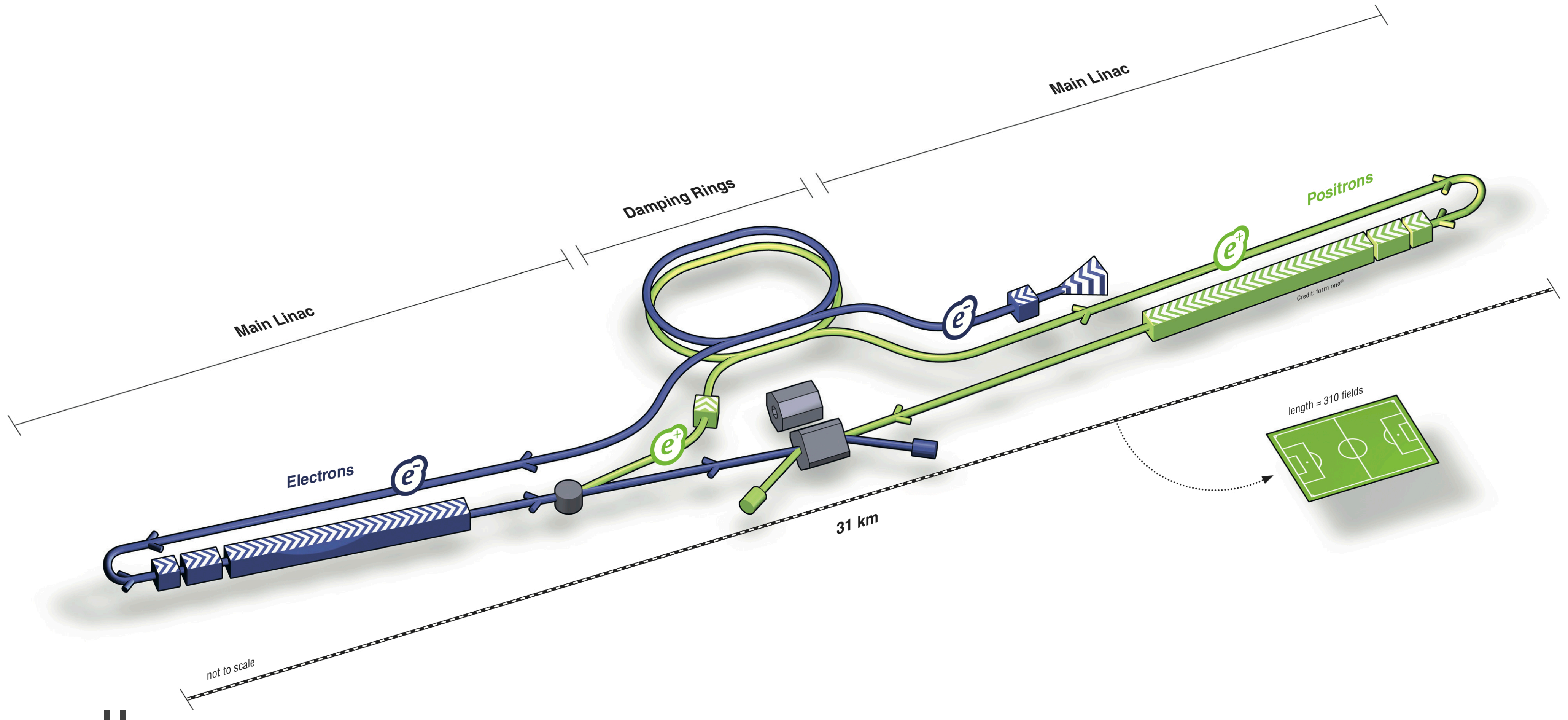
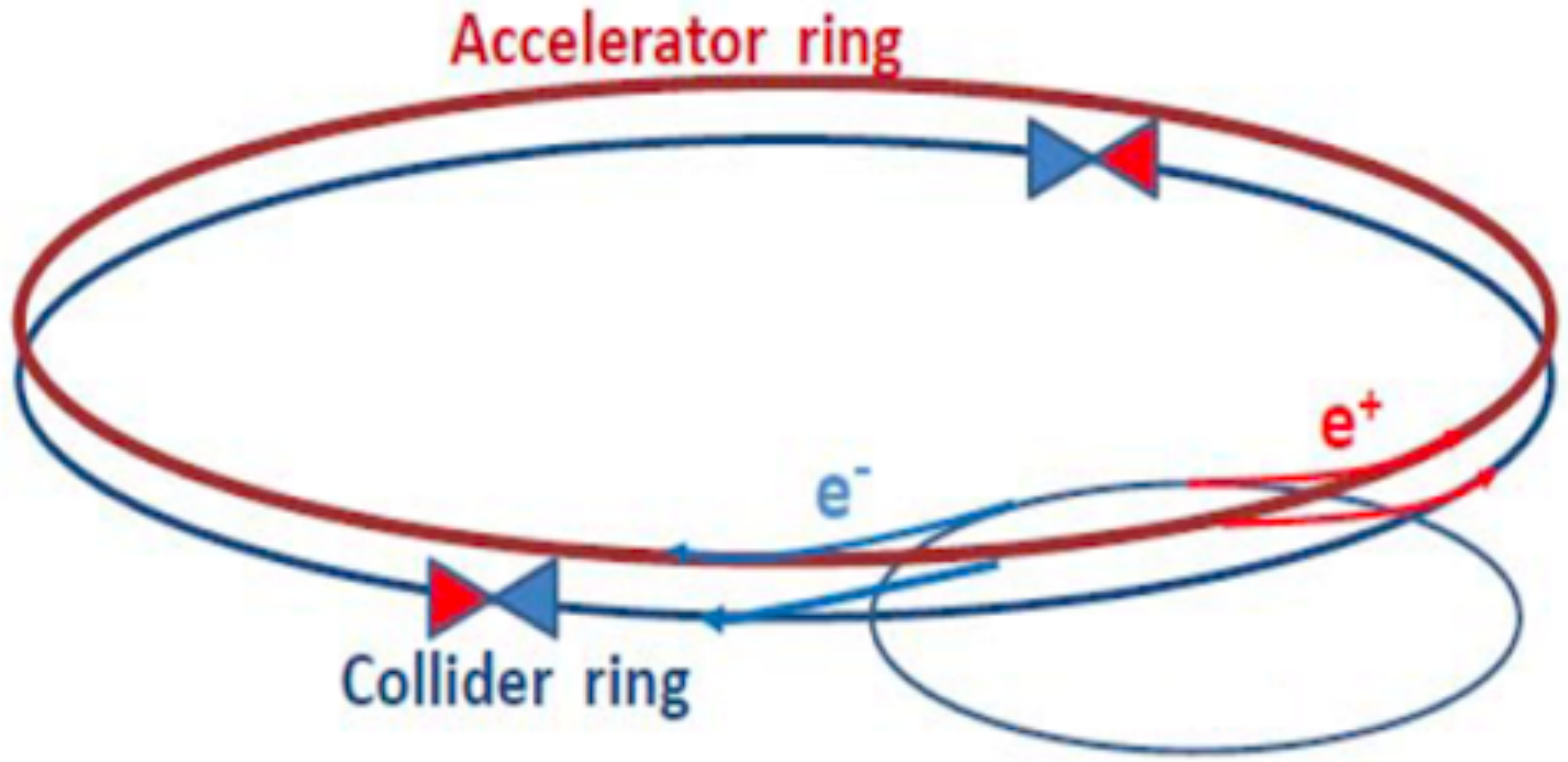
Linear or Circular

Linear e^+e^- colliders: **higher energies** (~ TeV)

- Can use **polarized** beams
- Collisions in bunch trains (~0.5% duty cycle)
  - Trigger-less readout
  - Power pulsing → Significant power (& material) saving for detectors
- <u>**One interaction point**</u> with two detectors alternating with push-pull
  - Or possible to share luminosity with two BDS systems



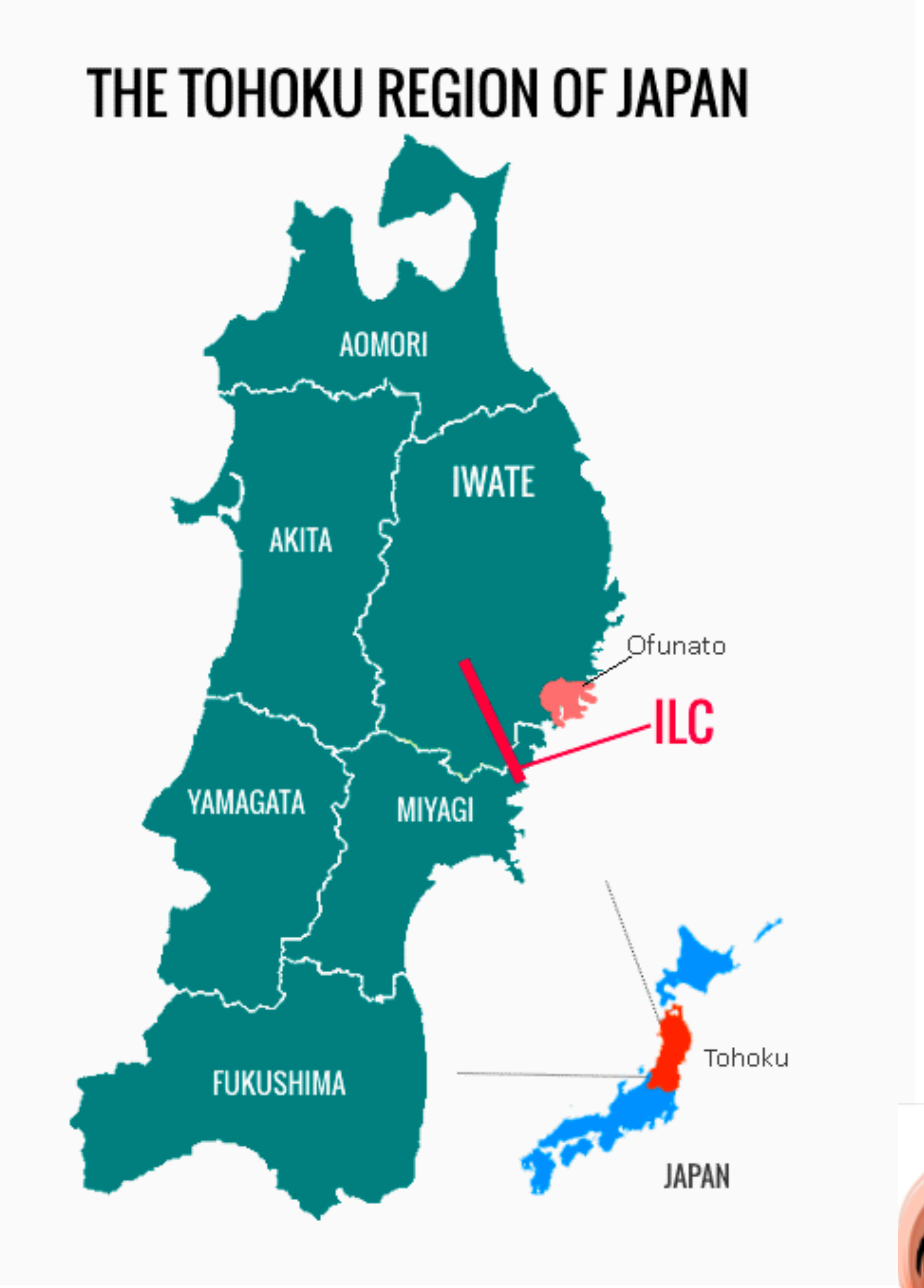


Circular e^+e^- colliders: **highest luminosity** at Z/WW/Zh

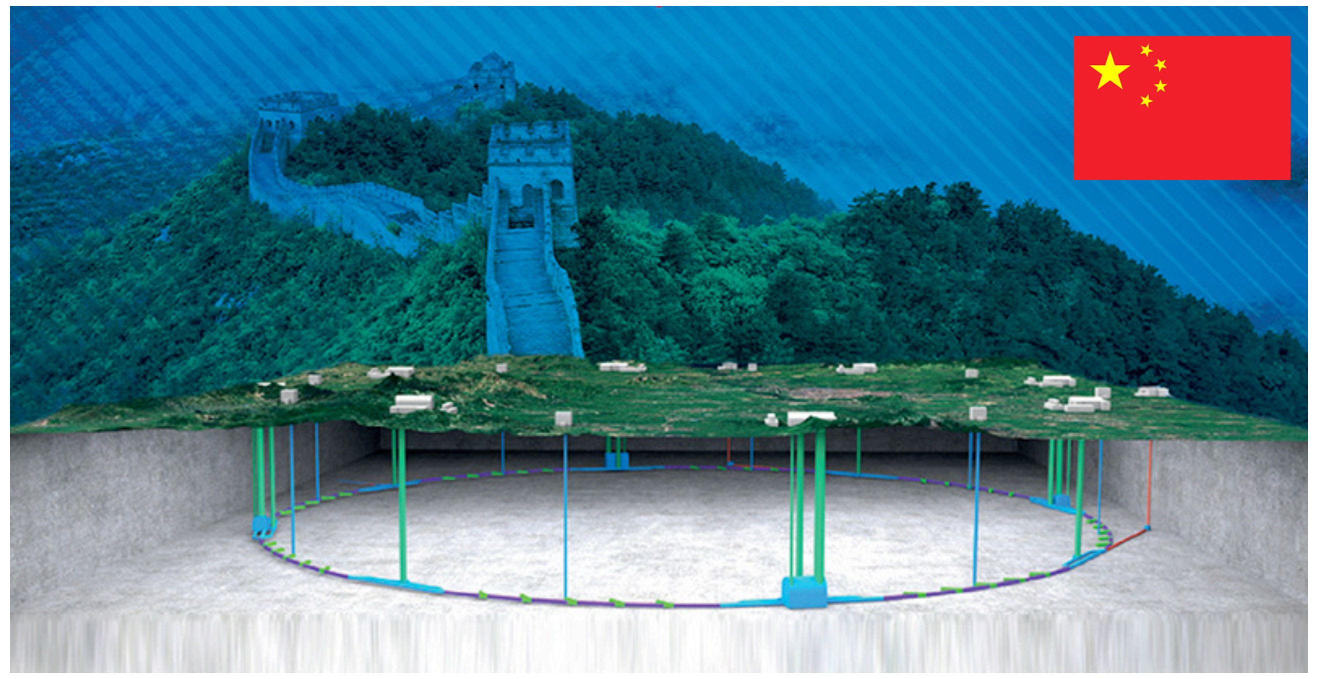
- Beam continues to circulate after collision
  - Detectors need active cooling (more material)
- Limited by synchrotron radiation above 350/400 GeV (~ γ^4/ρ^2)
  - <u>**Multiple interaction points**</u>

Various proposals during Snowmass

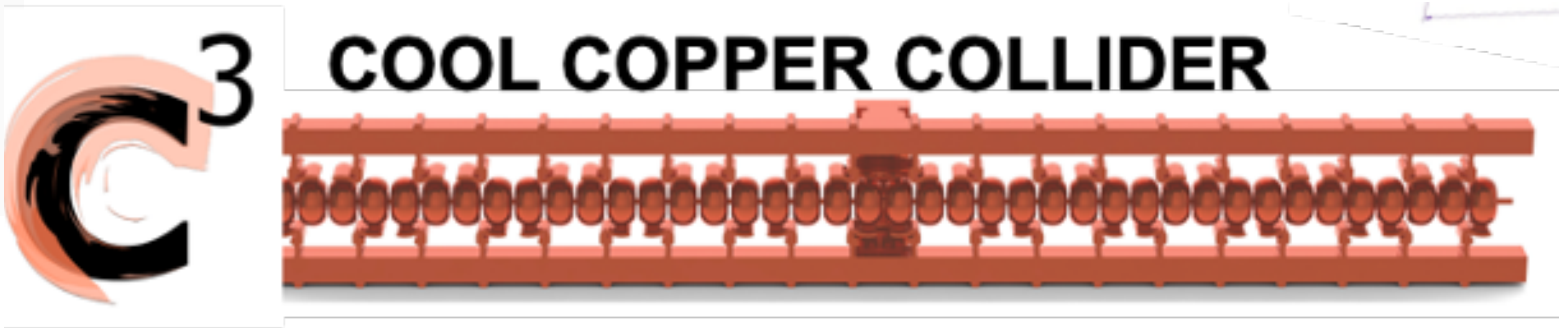
P5 report



250/500 GeV

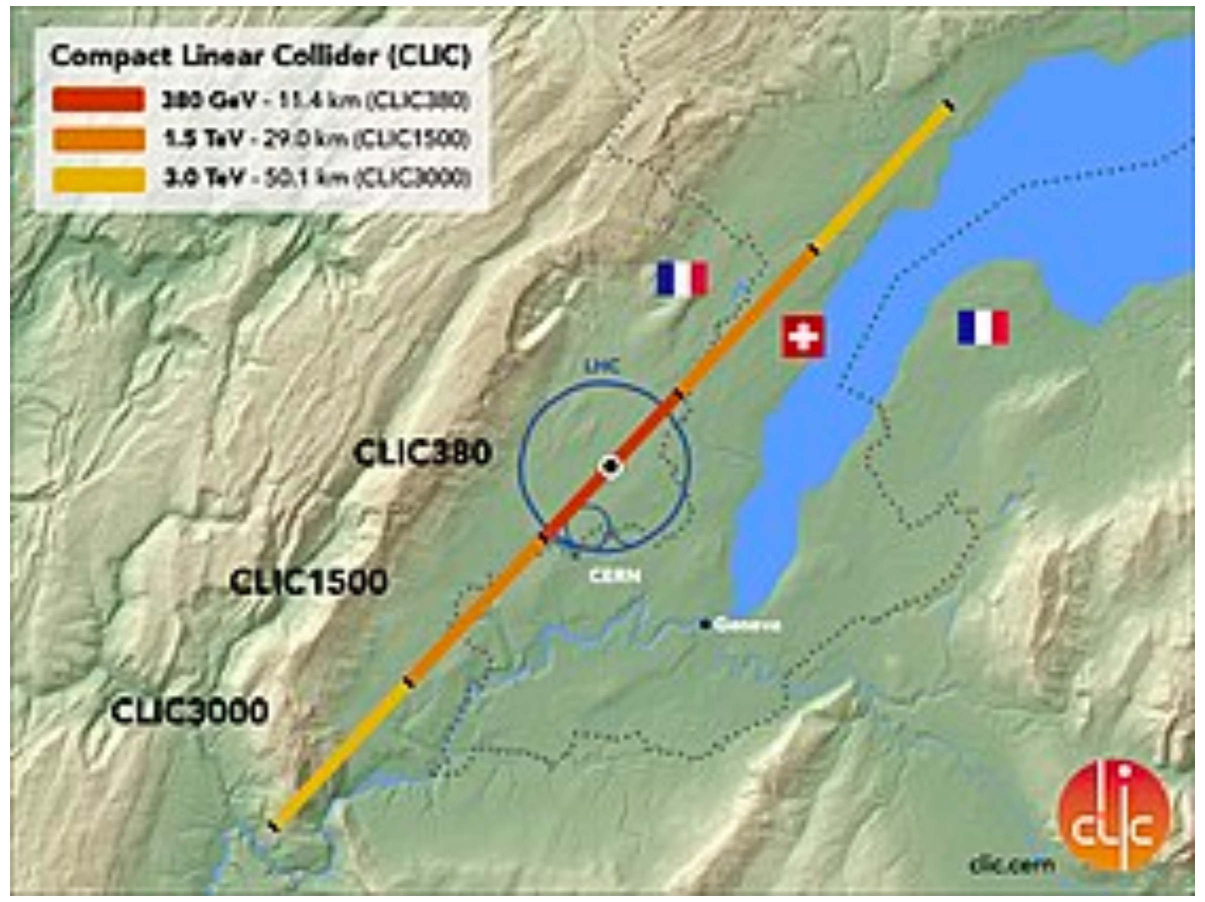


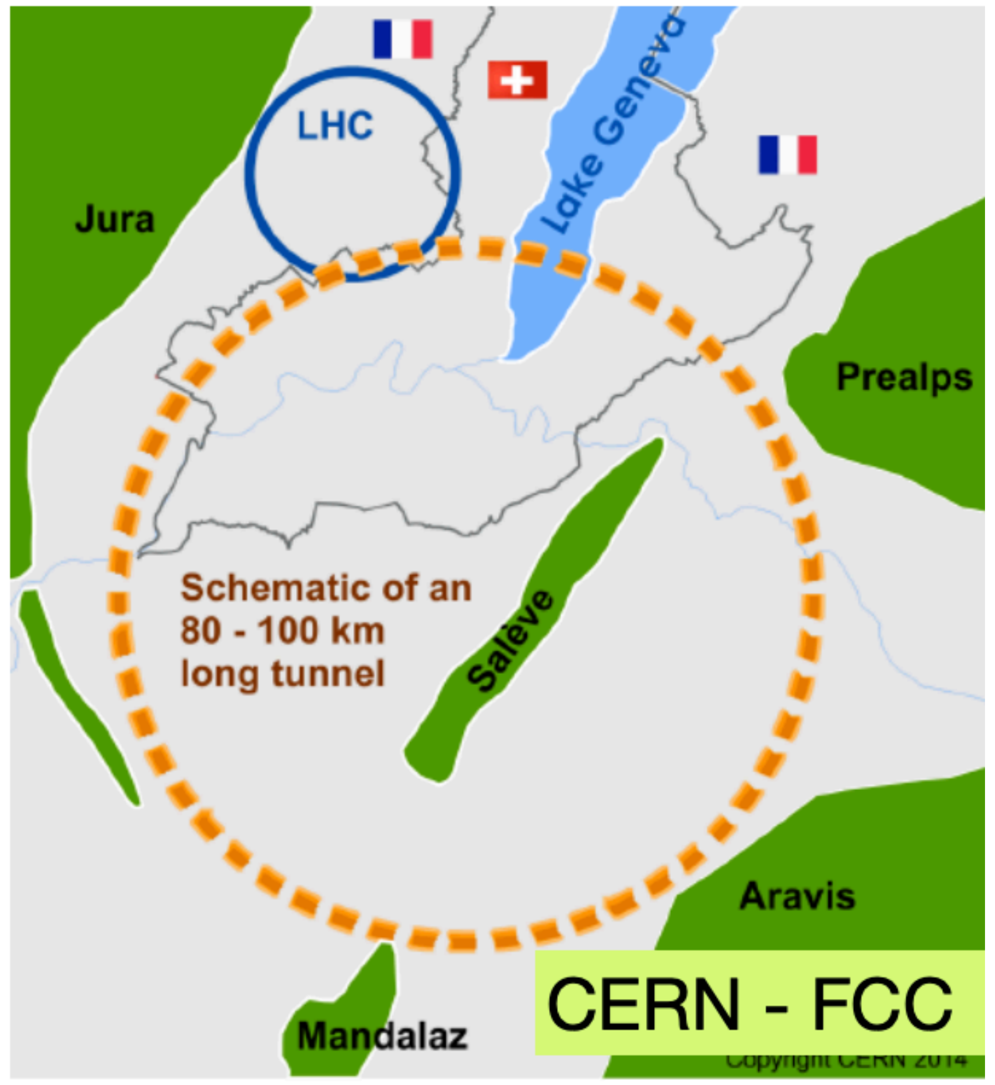
CEPC 240 GeV



250/550/… GeV

CLIC 380/1500/3000 GeV



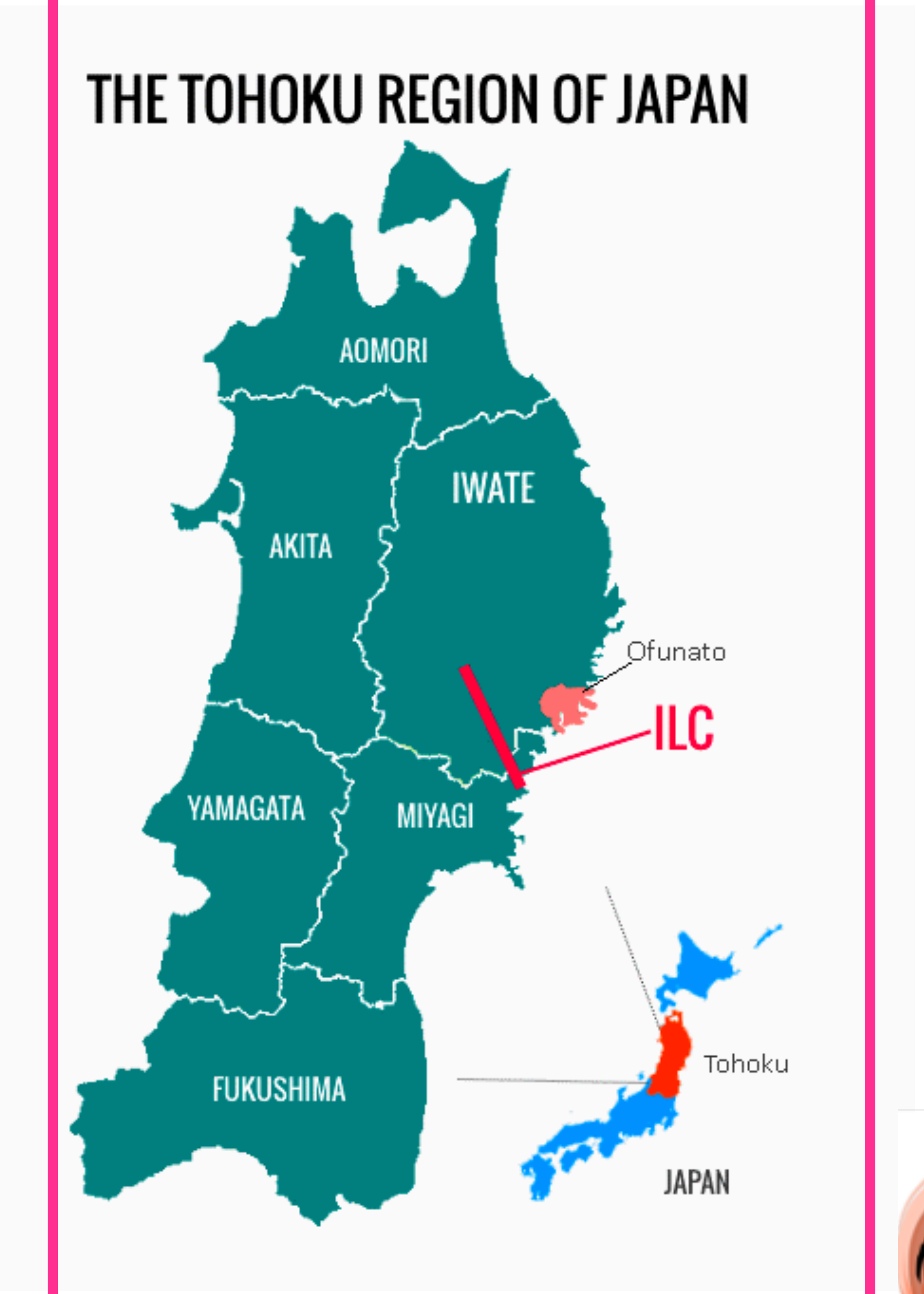


FCC-ee

90/240/365 GeV

Various proposals during Snowmass

P5 report



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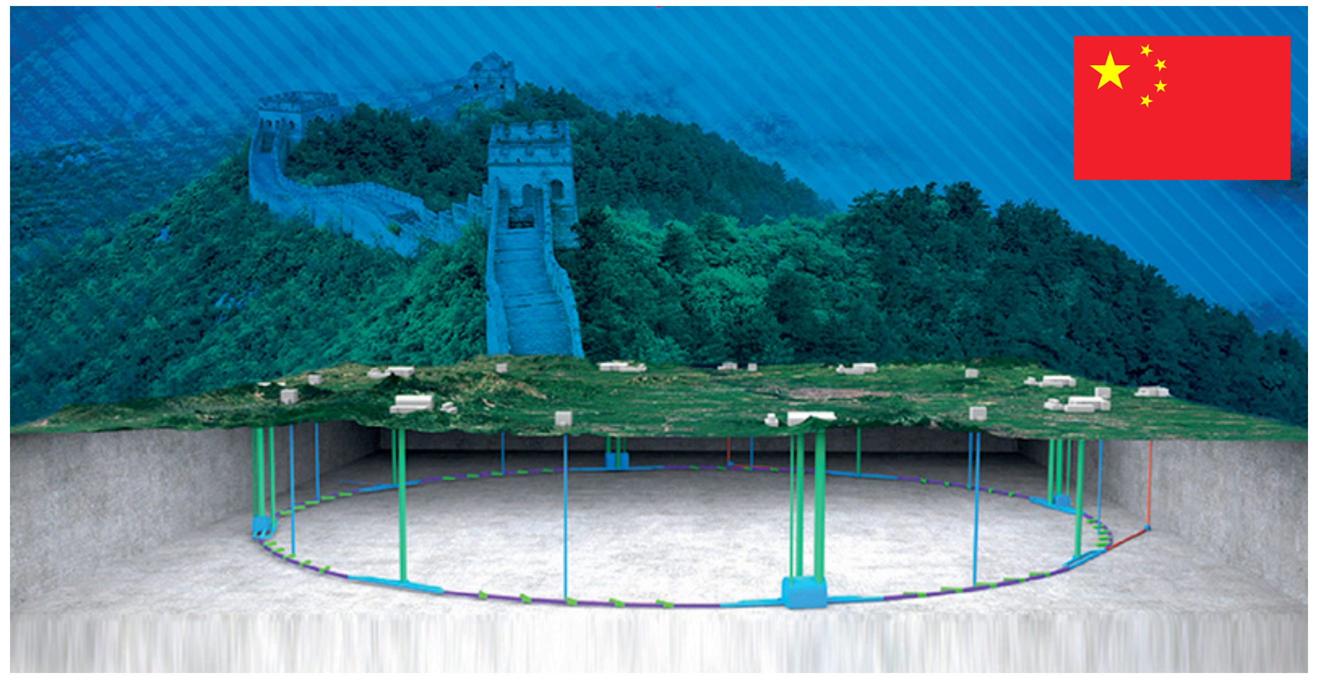

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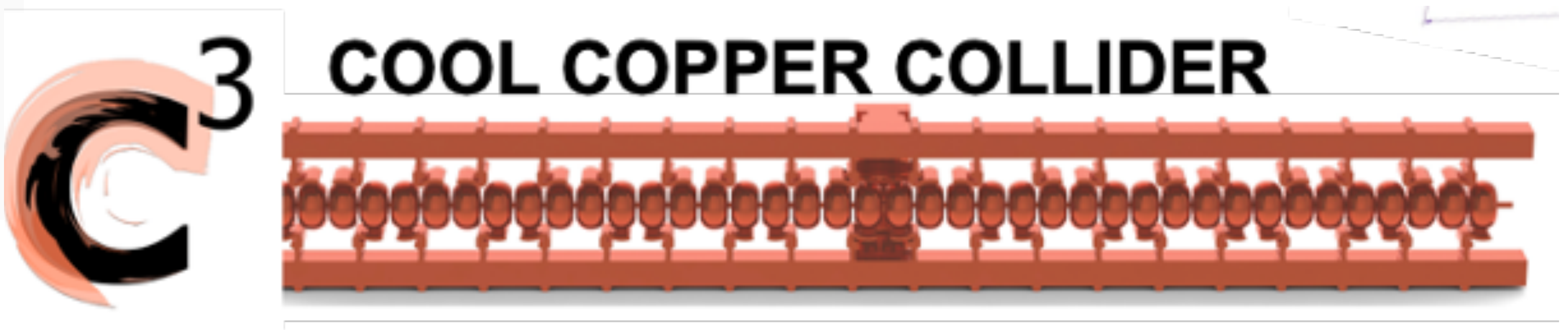

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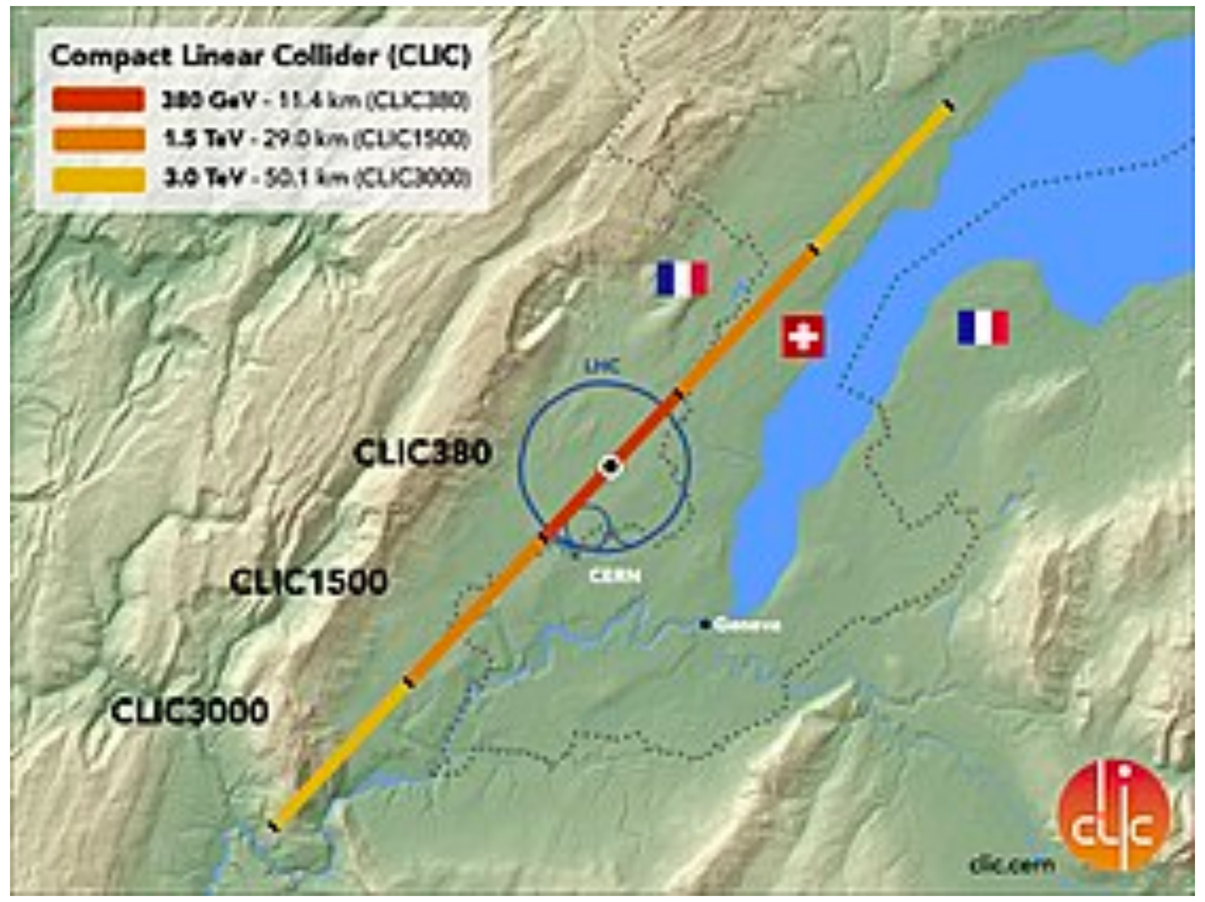
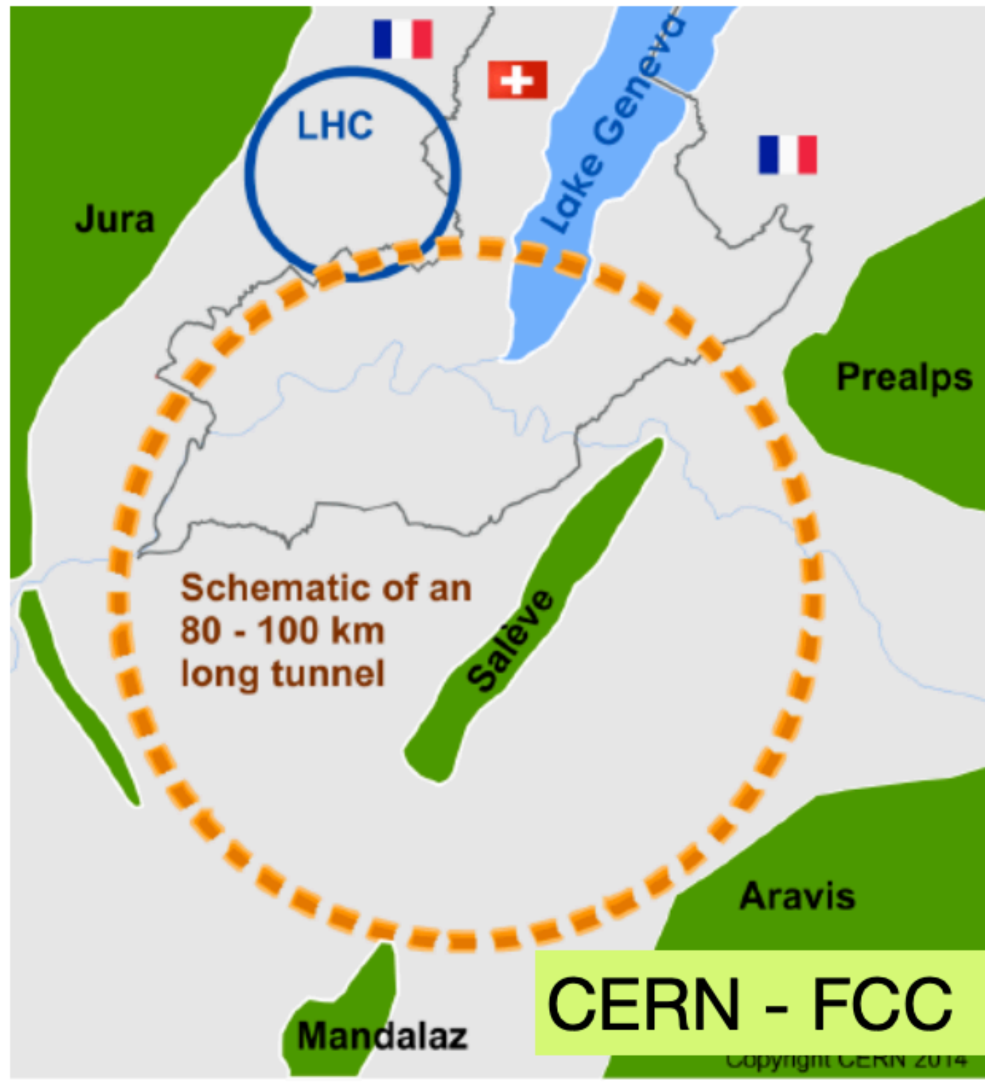




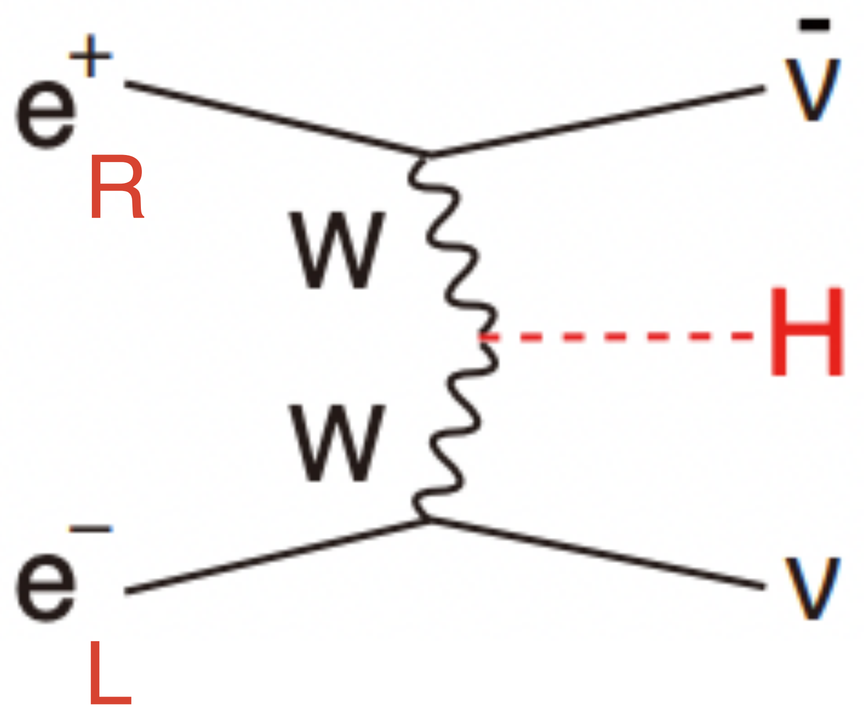
FCC-ee
90/240/365 GeV

arXiv:2209.07510

Projected sensitivity

One note: Polarization to compensate for luminosity

2 ab^{-1} of polarized running is essentially equivalent to 5 ab^{-1} of unpolarized running within SMEFT analysis



	ILC/C³		FCC	
coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+1.5/ab-350 unpol.
hZZ	0.50	0.35	0.41	0.34
hWW	0.50	0.35	0.42	0.35
$hb\bar{b}$	0.99	0.59	0.72	0.62
$h\tau\tau$	1.1	0.75	0.81	0.71
hgg	1.6	0.96	1.1	0.96
$hc\bar{c}$	1.8	1.2	1.2	1.1
$h\gamma\gamma$	1.1	1.0	1.0	1.0
$h\gamma Z$	9.1	6.6	9.5	8.1
$h\mu\mu$	4.0	3.8	3.8	3.7
htt	-	6.3	-	-
hhh	-	20	-	33%*
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

* indirect constraints

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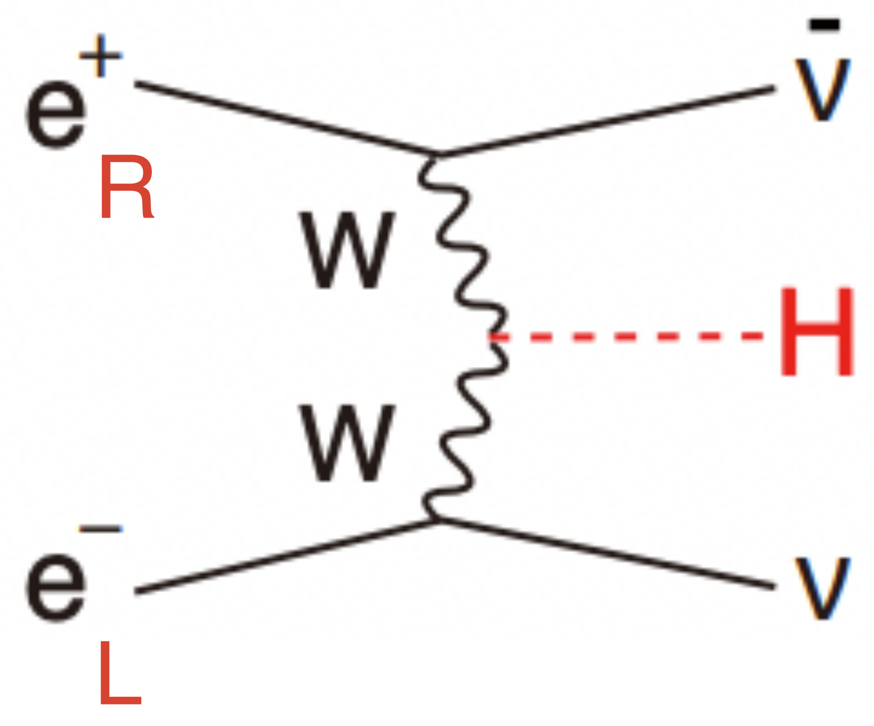

O(20%) precision on the Higgs self-coupling would allow to exclude/demonstrate at 5σ models of electroweak baryogenesis

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Ingredients for Detector requirements

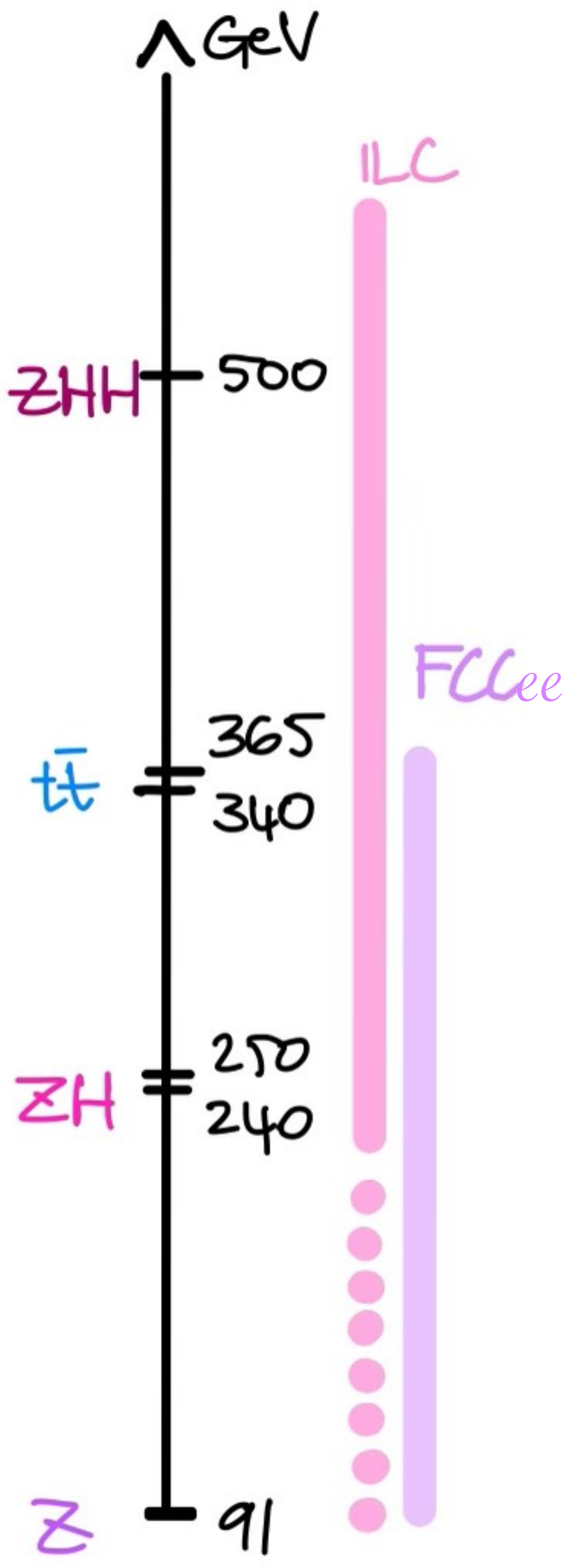
(Higgs) Physics drivers have informed preliminary detector designs

more to investigate

Beam structure and beam induced backgrounds add constraints

Physics benchmarks

ILC and FCC have different & complementary energy reach and goals



Higher Energies, O(500) GeV

- ZHH and ttH: multi-(b)jets final state

tt, top mass

Higgs boson physics at 240-250 GeV

- Measurement of the total ZH cross section with <1% uncertainty
- Measure Higgs boson mass to 0.01% accuracy and branching ratio to invisible particles using Z recoil, with 0.1% or better uncertainty.

Z pole run, TeraZ program, WW threshold

- Precision measurement of electroweak parameters:
  - $\sin^2\theta_W$, Z and W masses and widths, …
- Limits B field to 2 T

Current benchmarks and next steps

The goal of measuring Higgs properties with sub-% precision translates into ambitious requirements for detectors at e^+e^-

- Requirements mostly driven by (Higgs) specific benchmarks
- Technological advances can open new opportunities and additional physics benchmarks (i.e. H→ss) can add more stringent requirements

Physics goal	Detector	Requirement
hZZ sub-%	Tracker	σ_{p_T}/p_T=0.2% for $p_T < 100$ GeV
		$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/$ GeV for $p_T > 100$ GeV
	Calorimeter	4% particle flow jet resolution
		EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2
		EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
		shower timing resolution 10 ps
$hb\bar{b}/hc\bar{c}$	Tracker	$\sigma_{r\phi} = 5 \oplus 15(p\sin\theta^{\frac{3}{2}})^{-1}\mu$m
		5μm single hit resolution

Arxiv:2209.14111 Arxiv:2211.11084 DOE Basic Research Needs Study on Instrumentation

	Topic	Lead group	Relevant $\sqrt{s}$ [GeV] 91	161	240–250	350–380	≥ 500
1	HtoSS	HTE			✓	✓	✓
2	ZHang	HTE (GLOB)			✓	✓	✓
3	Hself	GLOB			✓	✓	✓

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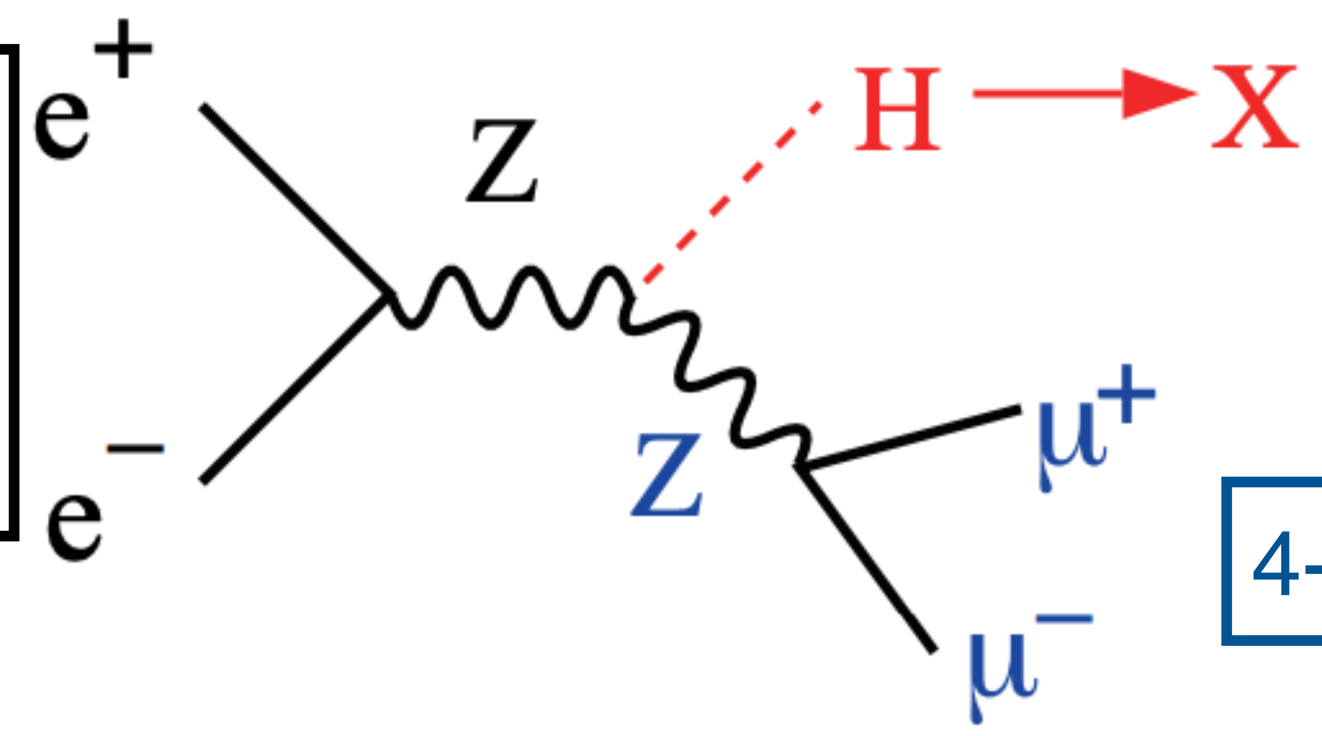
Focus topics for the ECFA study on Higgs / Top / EW factories *should* provide further detector design guidelines (2401.07564) by Spring 2025

arXiv:1604.07524
arXiv:2203.07622

How physics drives detector requirements

Unprecedented precision unlocked with a well defined initial state

initial 4-momentum
- nominal CM energy +
- beam energy spread [< 0.2%/beam] +
- beamstrahlung energy loss



$$m^2_{recoil} = s + m^2_Z - 2 \cdot E_Z \cdot \sqrt{s}$$

4- momentum measured by detector

smearing due to Z momentum ~ smearing due to beam energy spread
$dp_T / p_T \sim$ few x 10^{-5} p_T @ high momentum

(Higgs) physics requirements for detectors

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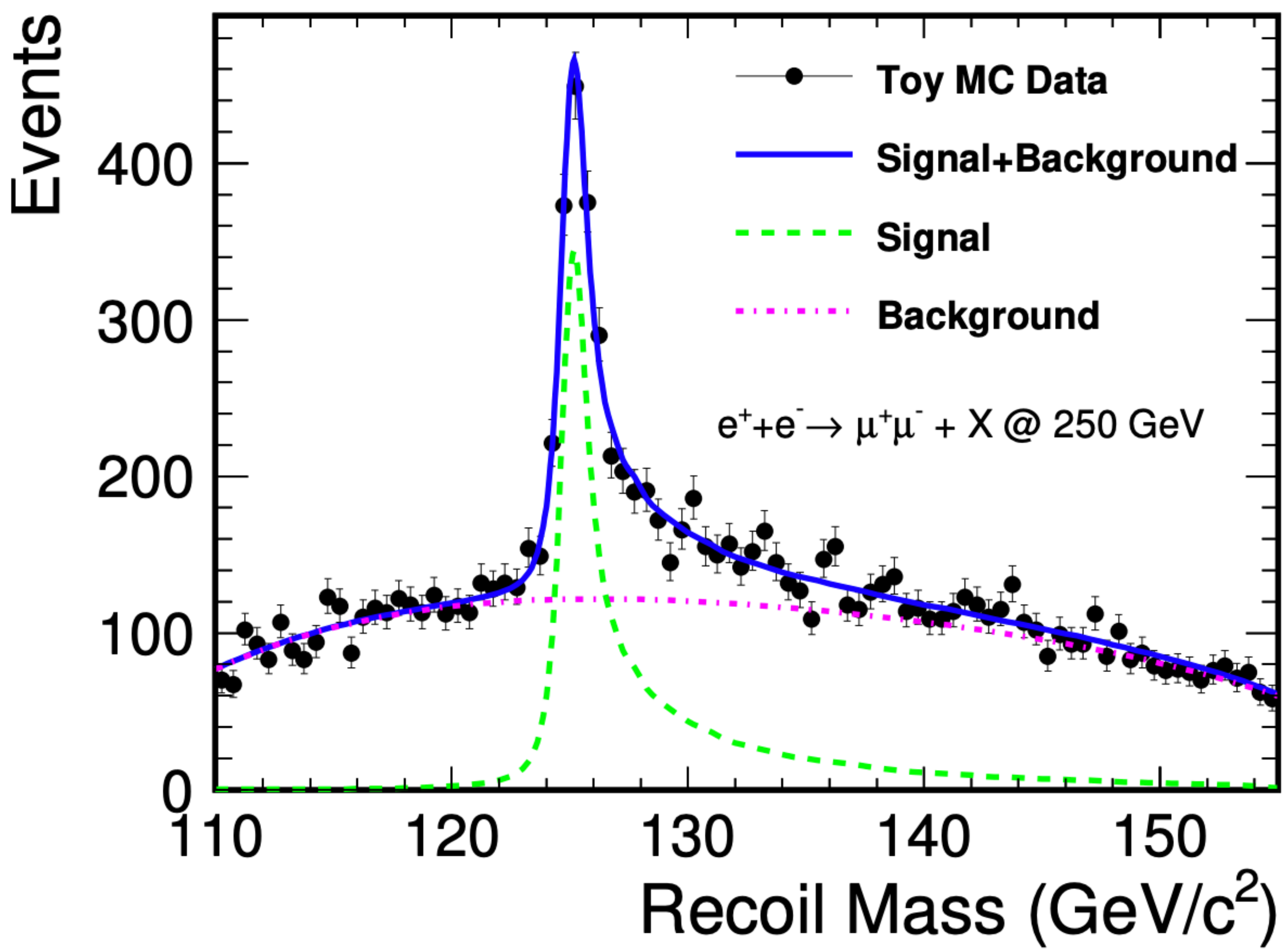
arXiv:2203.07622

Precision challenges detector design

ZH process: Higgs recoil reconstructed from Z decays

- ZH cross section can be measured with O(1%) precision and in a model independent way
- Drives need for high field magnets and high precision/ low mass trackers

peak ~ Higgs mass ~ 14 MeV



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Higgs → bb/cc decays: Flavor tagging tagging at unprecedented level

- Drives requirement on charged track impact parameter resolution → **low mass trackers near IP**

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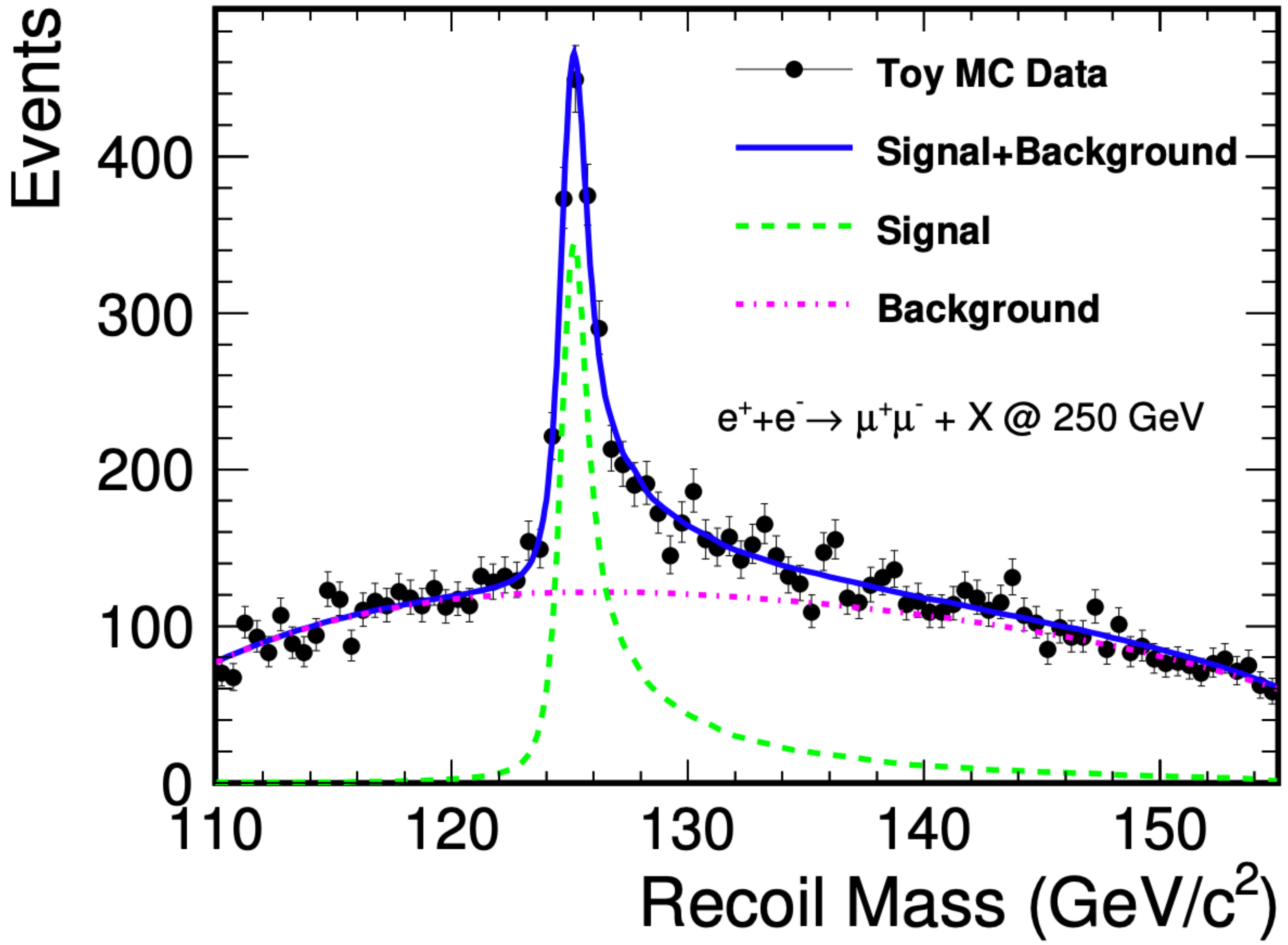

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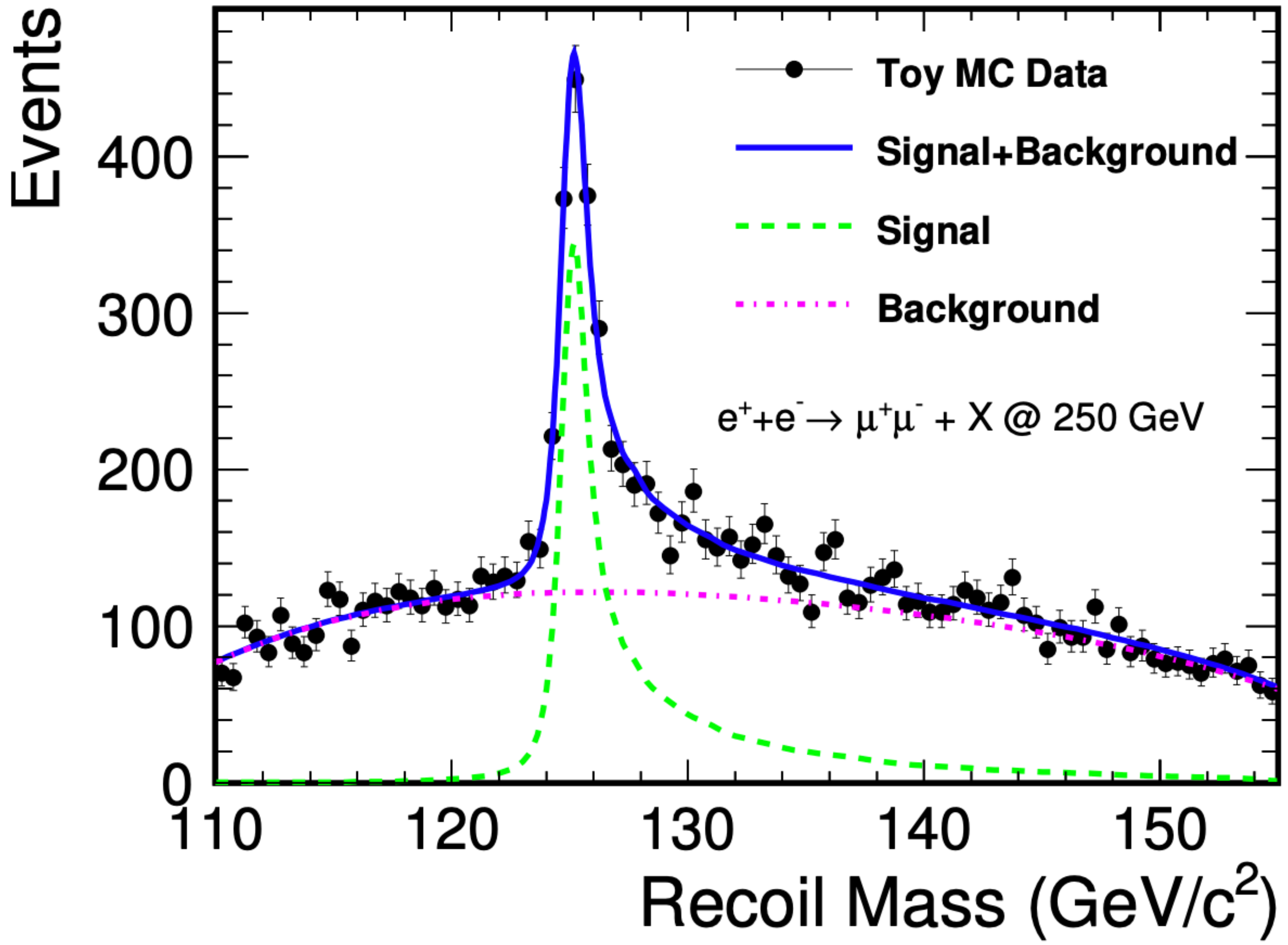
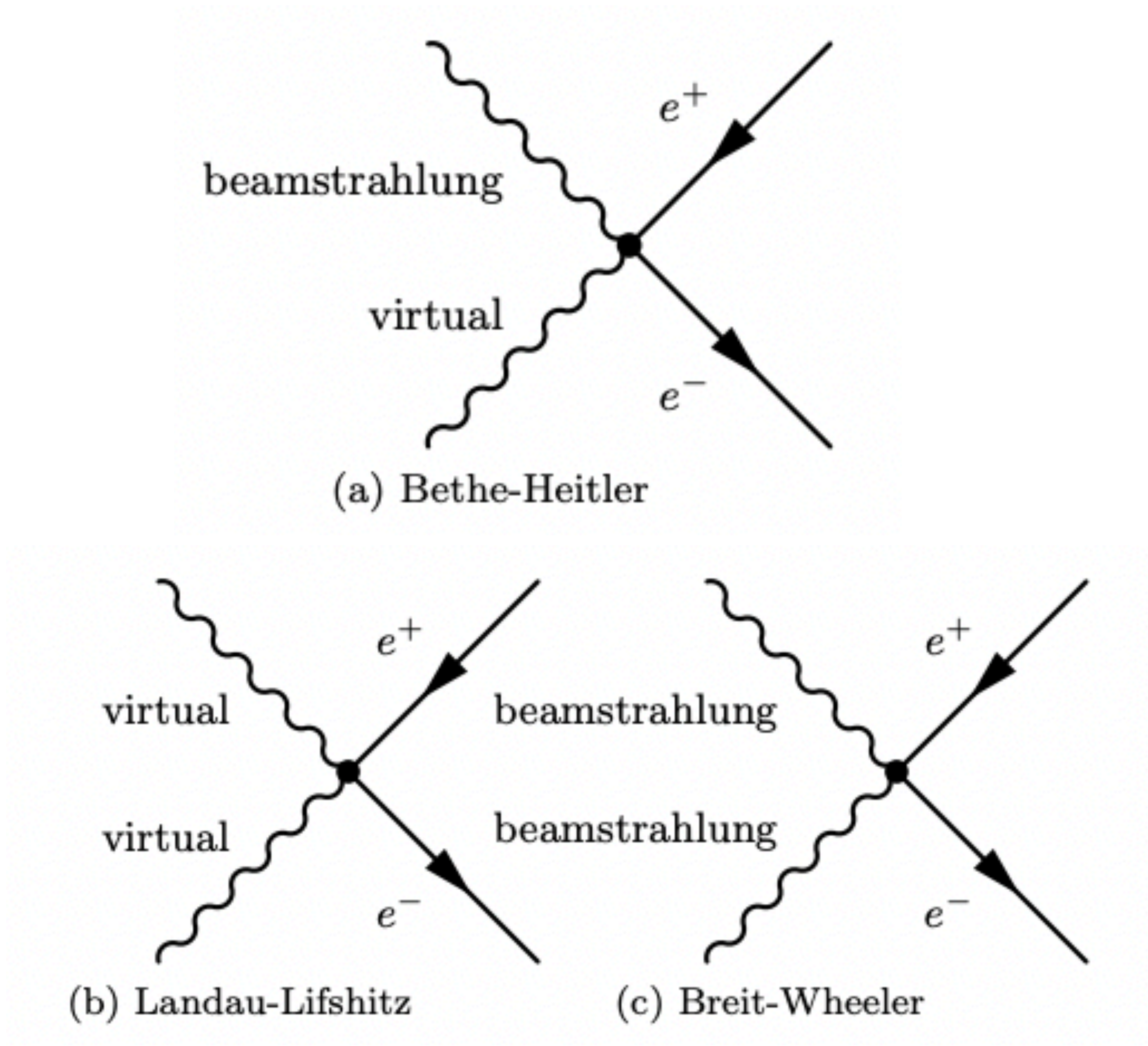
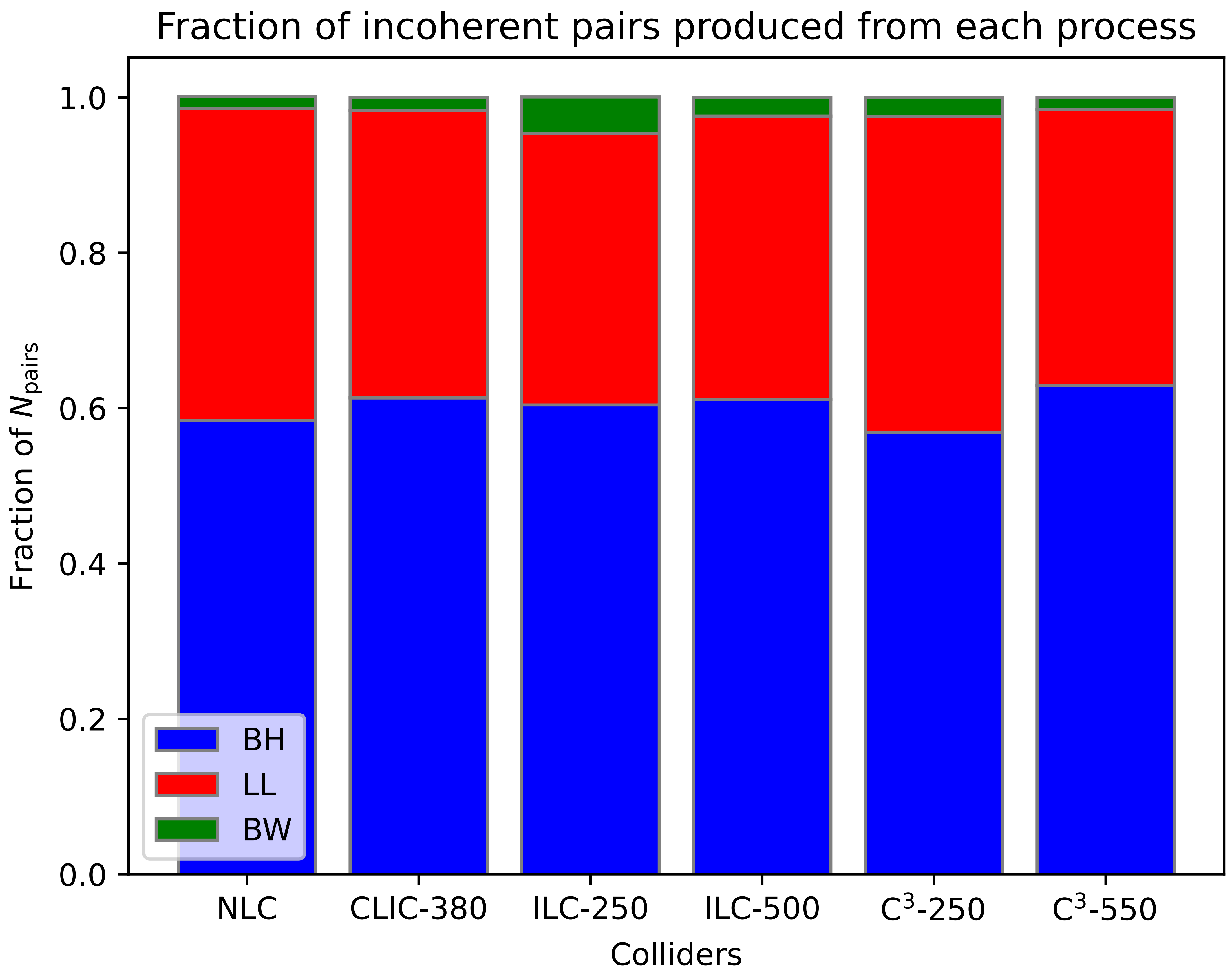
peak ~ Higgs mass ~ 14 MeV



Need new generation of ultra low mass vertex detectors with dedicated sensor designs

Beam-beam background



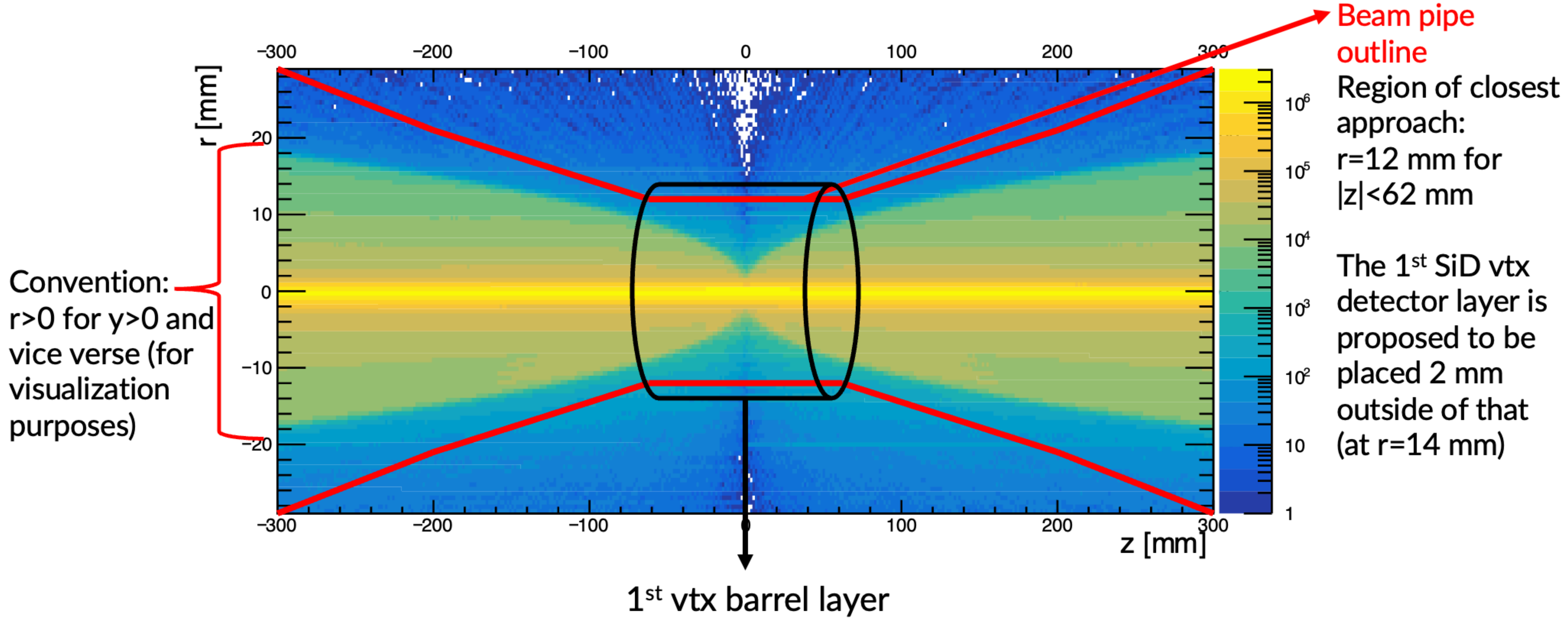


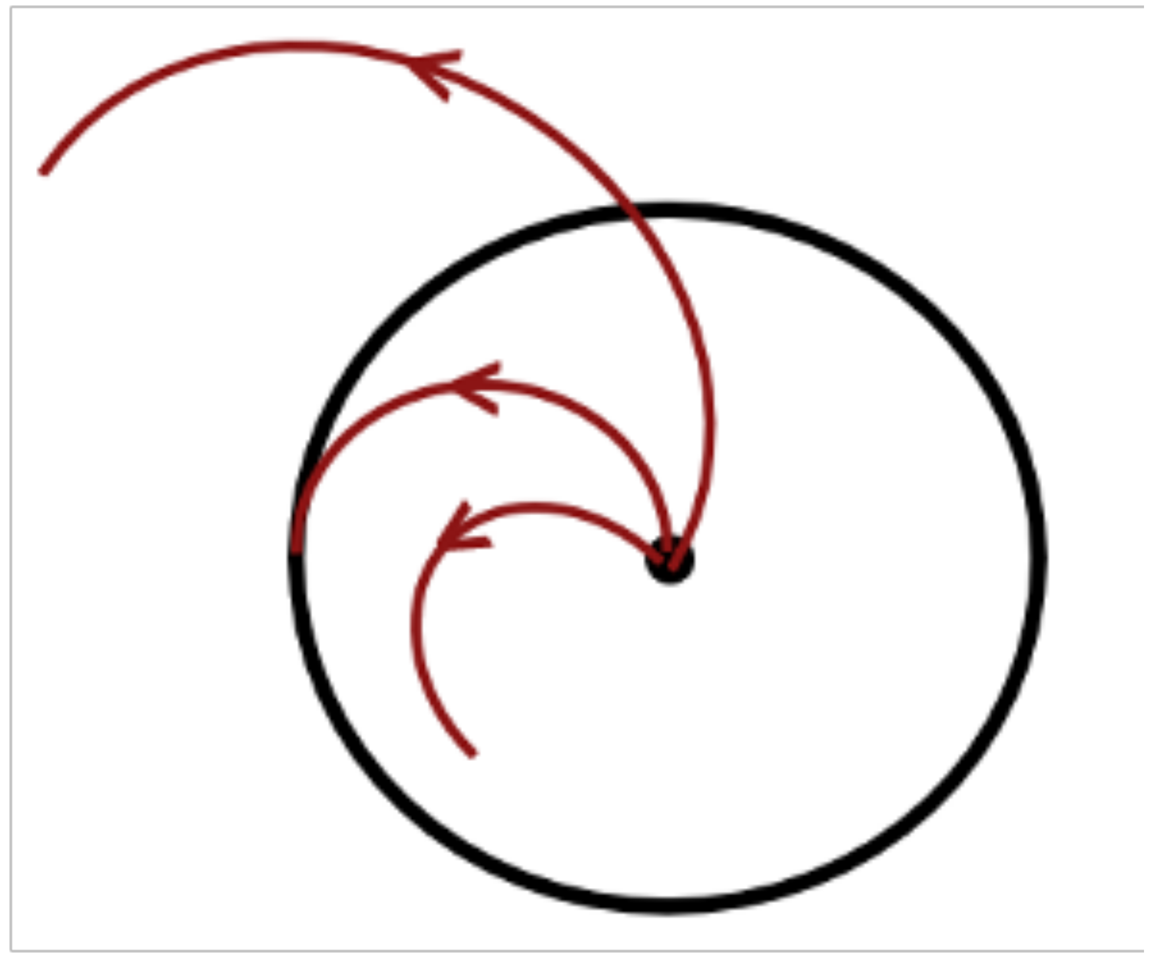
Importance of beam-beam background

The effects of beam-beam interactions have to be careful simulated for physics and detector performance

- High flux in vertex barrel and forward sub detectors
  - Increase in detector occupancy → Impacts detector design
  - At low momentum incoherent pairs deflected by B field

$$p_T^{(\min)}[\text{MeV}] = 0.3 \cdot B[\text{T}] \cdot \frac{\rho}{2}[\text{mm}] \simeq 10 \text{ MeV}$$



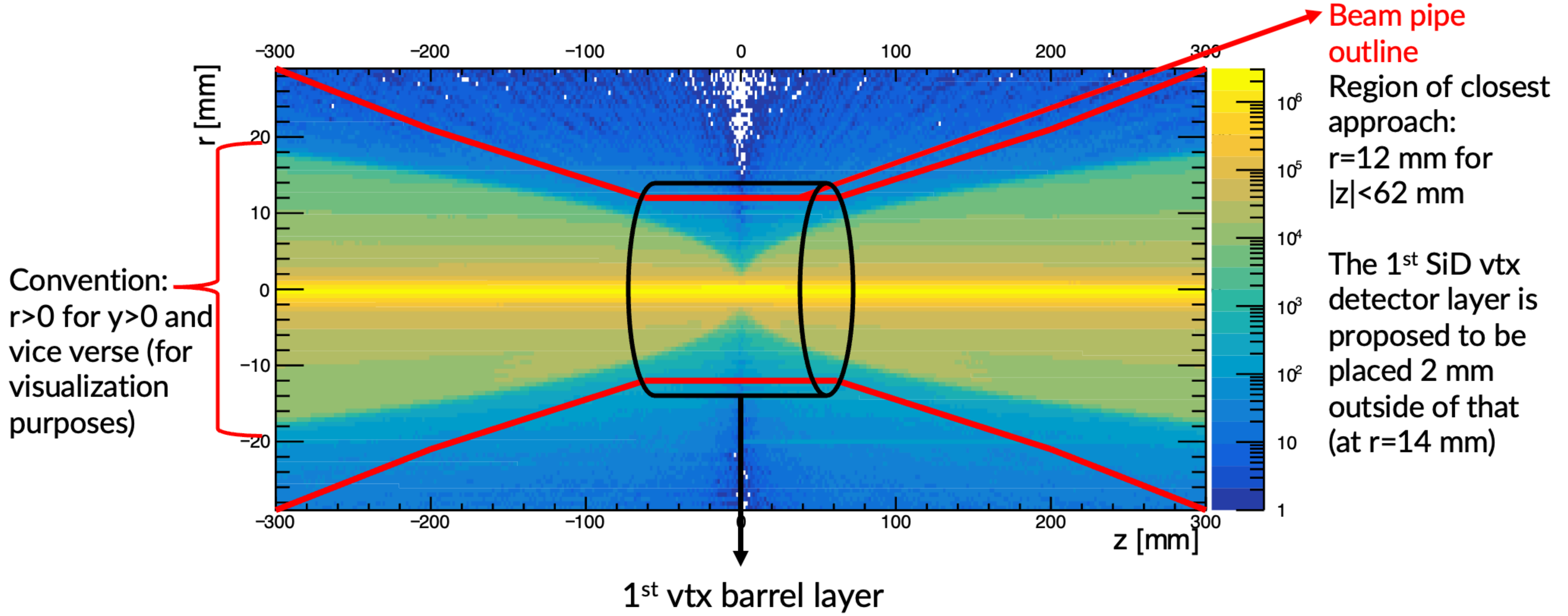


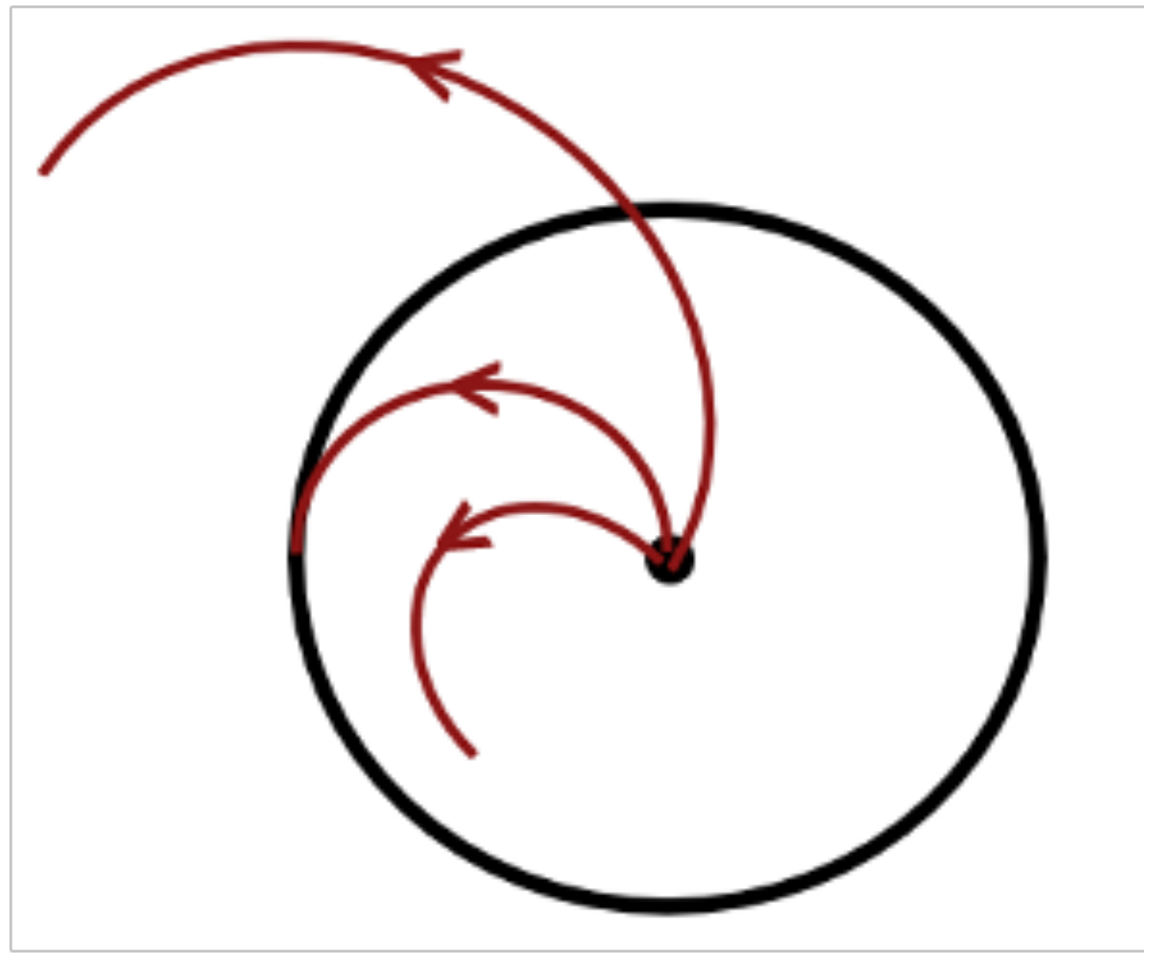
Importance of beam-beam background

The effects of beam-beam interactions have to be careful simulated for physics and detector performance

- High flux in vertex barrel and forward sub detectors
  - Increase in detector occupancy → Impacts detector design
  - At low momentum incoherent pairs deflected by B field

$$p_T^{(\min)}[\text{MeV}] = 0.3 \cdot B[\text{T}] \cdot \frac{\rho}{2}[\text{mm}] \simeq 10 \text{ MeV}$$

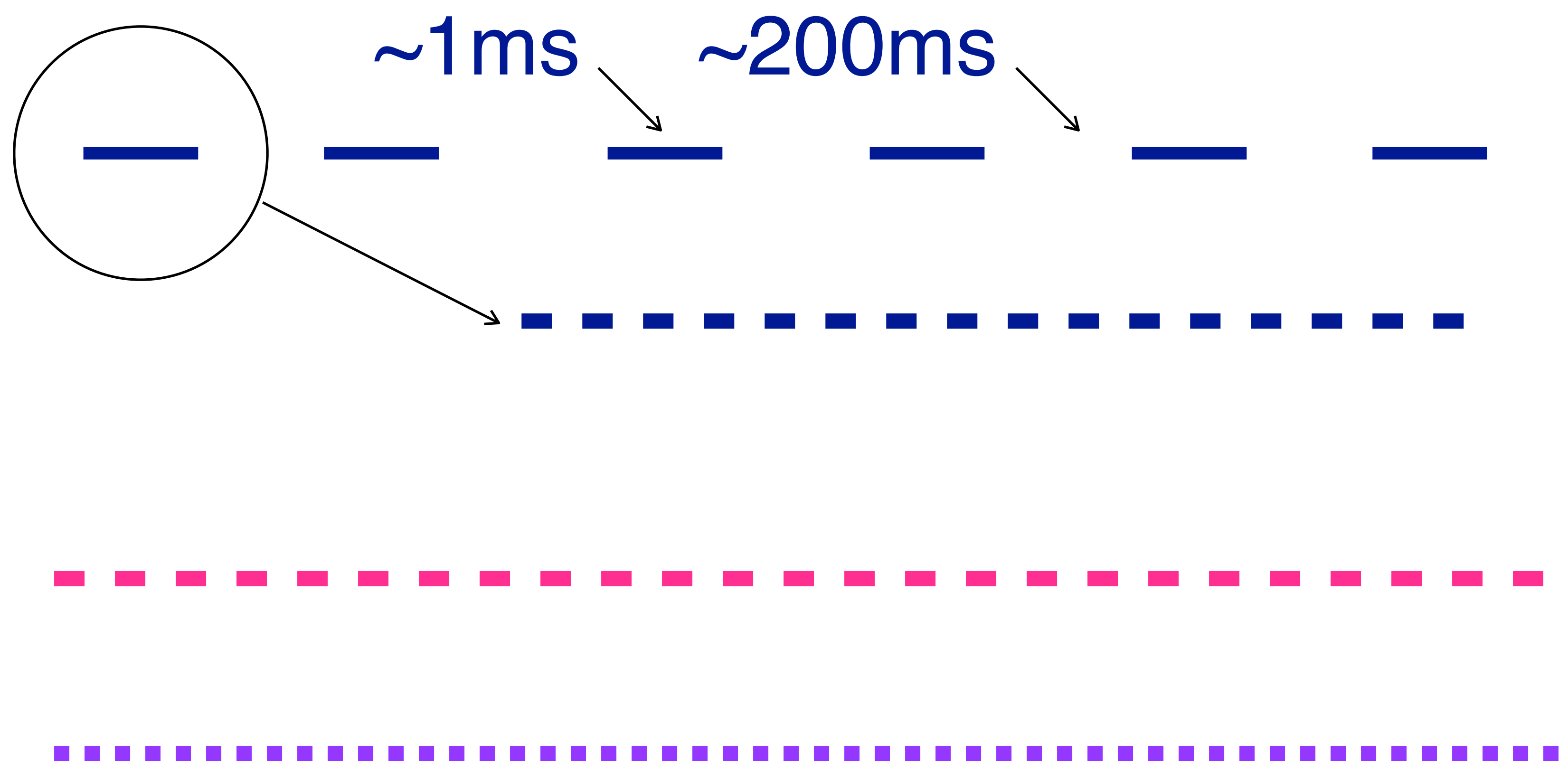




Synergistic studies among all collider options to inform detector design and ongoing optimizations

Beam Format and Detector Design Requirements

arXiv:2003.01116
FCC Mid Term Report



ILC Trains at 5Hz, 1 train 1312 bunches
Bunches are 369 ns apart

FCC@ZH Bunches 1 μs apart

FCC@Z Bunches 20 ns apart

- Very low duty cycle at LC (0.5% ILC, 0.03% C^3) allows for trigger-less readout and power pulsing
  - Factor of 100 power saving for front-end analog power
  - **O(1-100) ns bunch identification capabilities**
- For CW machines, the impact of beam-induced background can be mitigated through MDI and detector design
  - Timing resolution of O(ns) can further suppress beam-backgrounds and keep occupancy low
  - **O(1-10) ns for beam background rejection and/or trigger decision before reading out the detector**
  - Tracking detectors need to achieve good resolution while mitigating power consumption

Accelerator R&D

Post P5, motivating accelerator R&D

P5 report

Enabling the machines of the future

“Incorporate innovative concepts like cryogenic **cool copper** in the normal conducting RF program”

Area Recommendation 8: Future test facilities could include the **second stage cool copper** test for high gradient RF technology

Accelerator technologies play a key role in **sustainability**

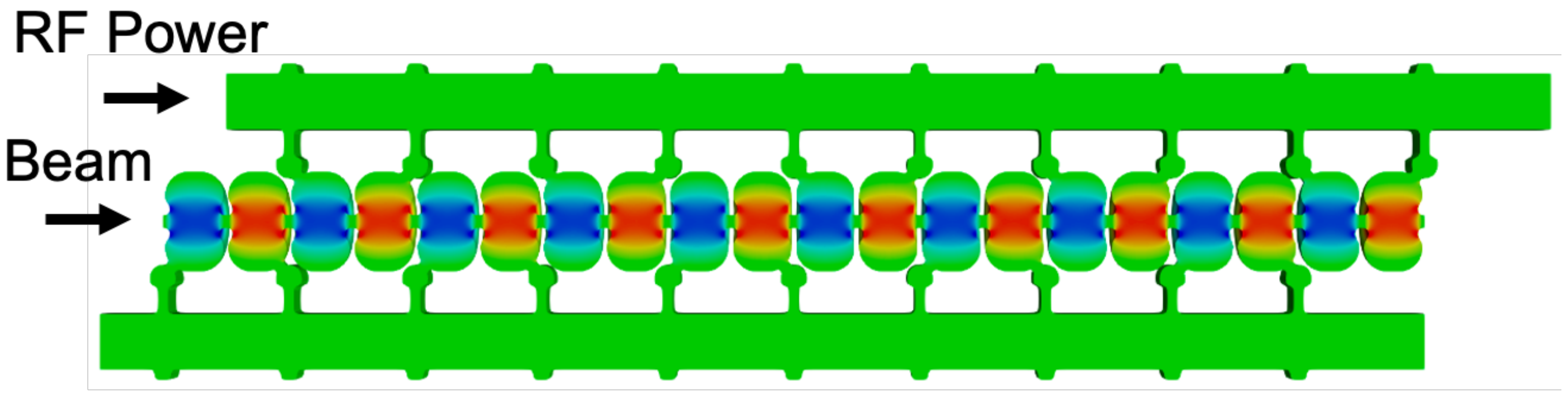
“Accelerator structure improvements can also play an important role, including higher quality factor, and concepts like **cool copper**.”

Area Recommendation 20: HEPAP, potentially in collaboration with international partners, should conduct a dedicated study aiming at developing a sustainability strategy for particle physics.

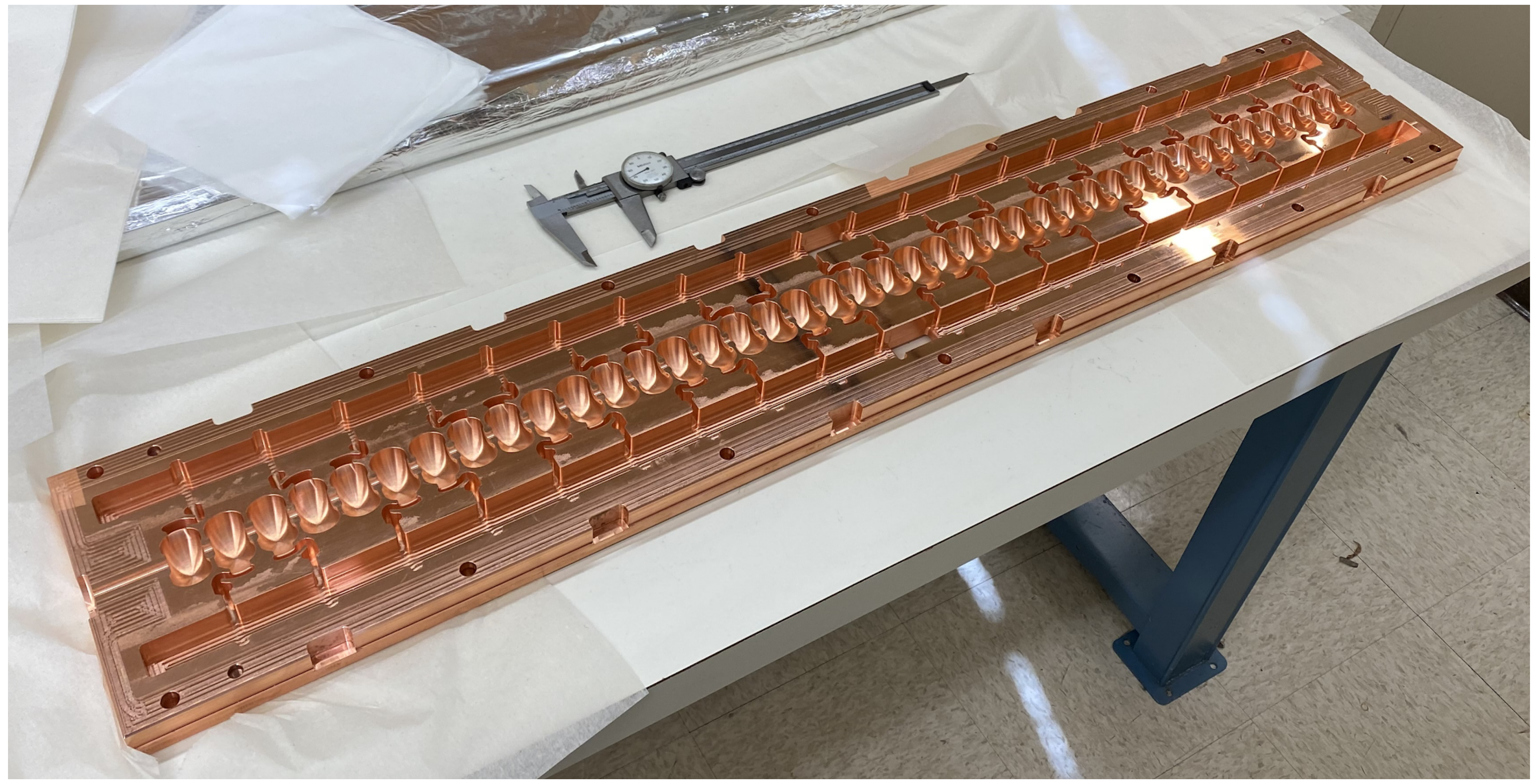
The Cool Copper technology

C^3 is a new linac **normal conducting technology**

- An ab-initio study of on axis accelerating fields and **cavity breakdown rates** – successful, but with relatively small iris.
  - RF fundamental does not propagate through irises.
- Distributed power to each cavity from a common RF manifold
  - modern super-computing for solution
  - Seemingly complex structure can easily and inexpensively be built with **modern CNC Machines**

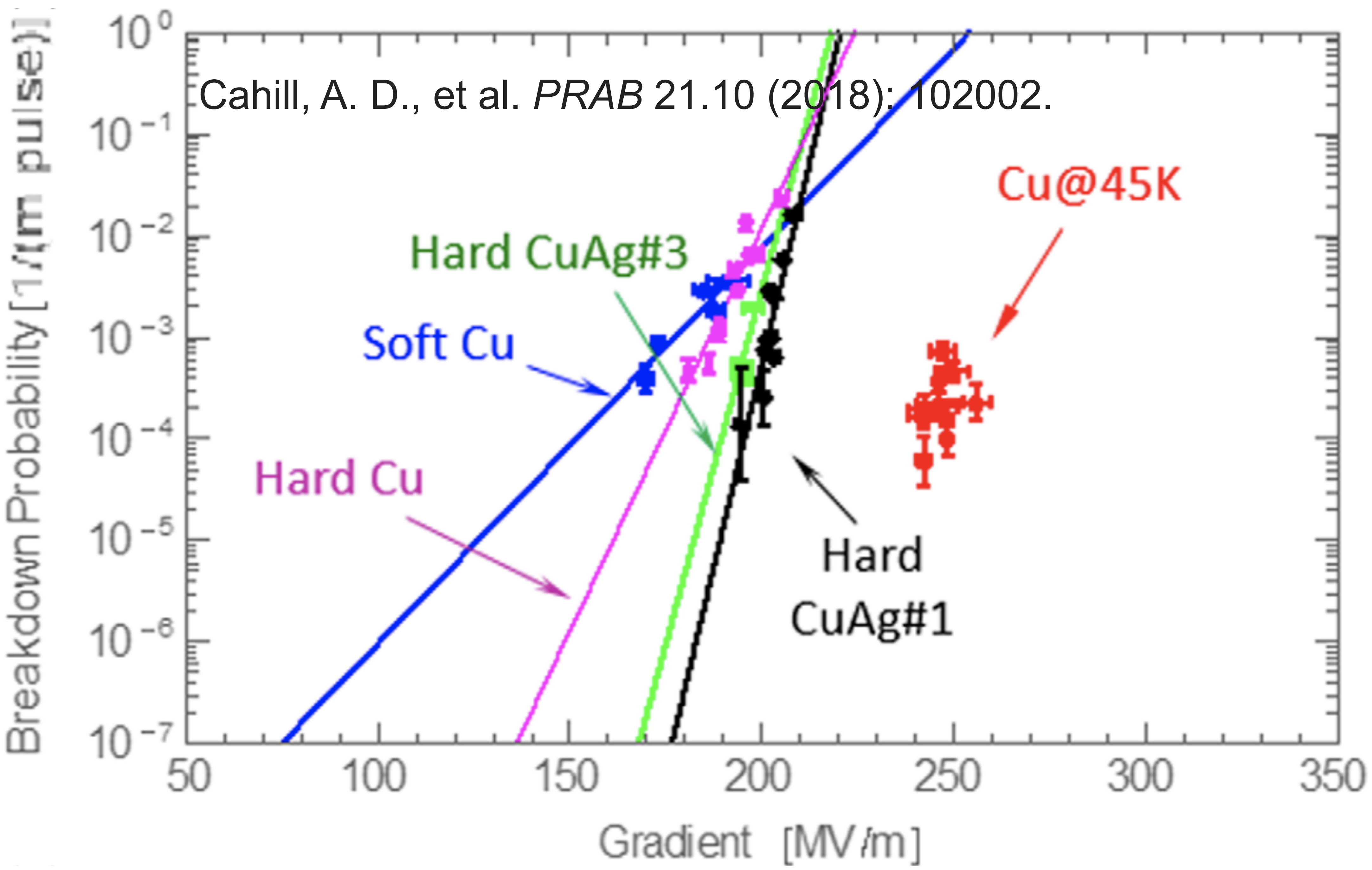


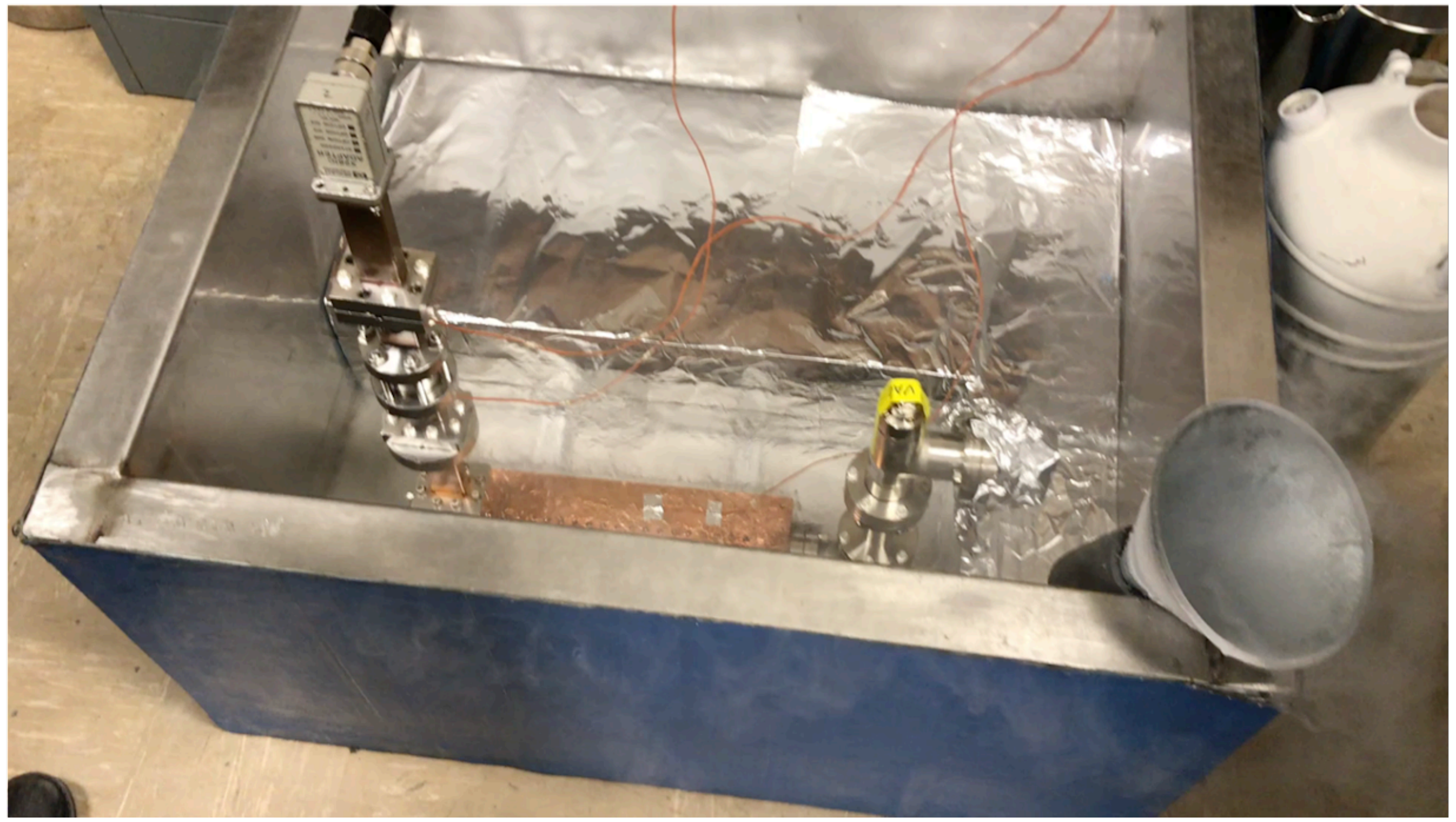
Electric field magnitude for equal power from RF manifold



First C^3 structure at SLAC

Why cool?



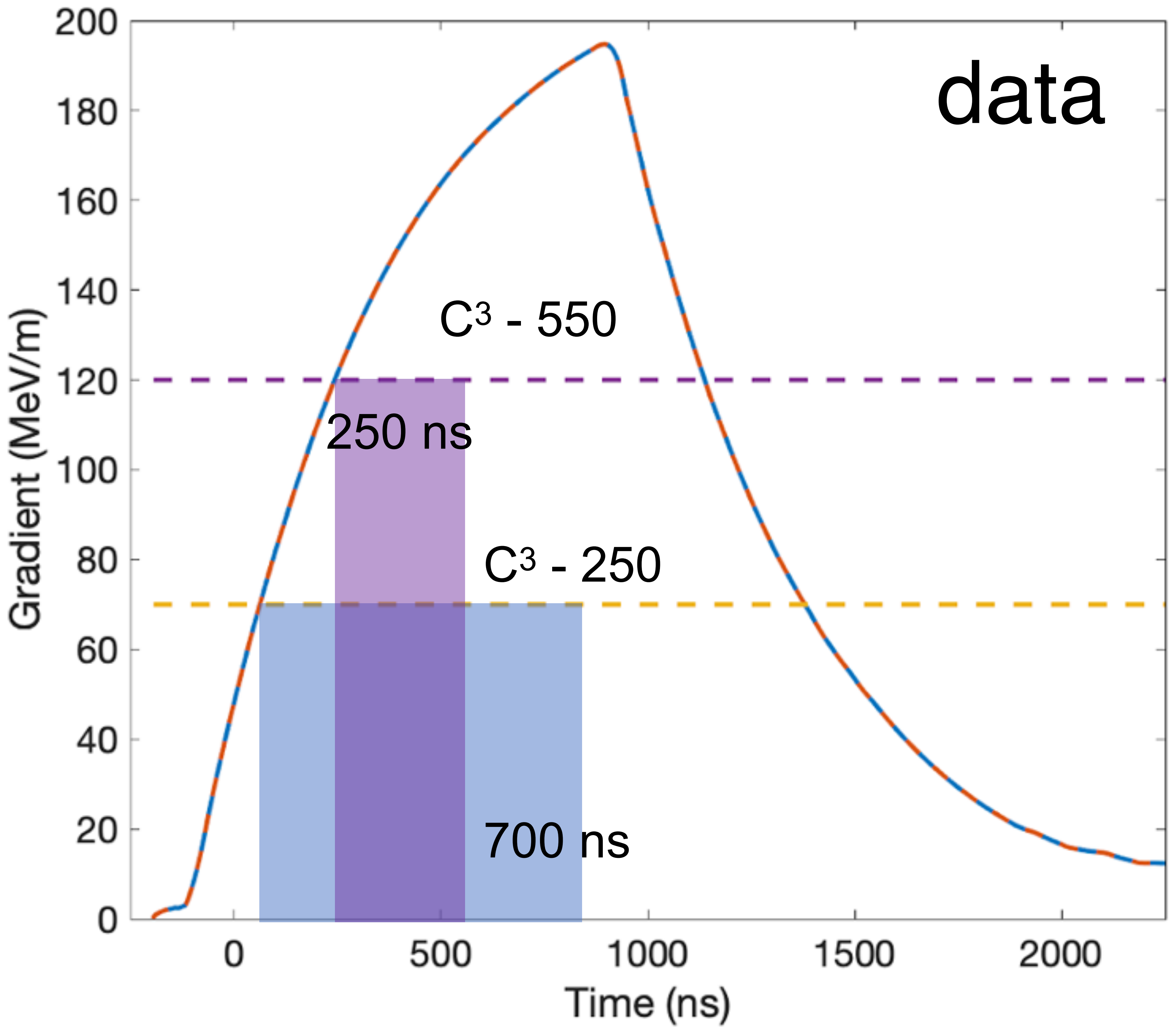


Nasr, et al. *PRAB* 24.9 (2021): 093201.

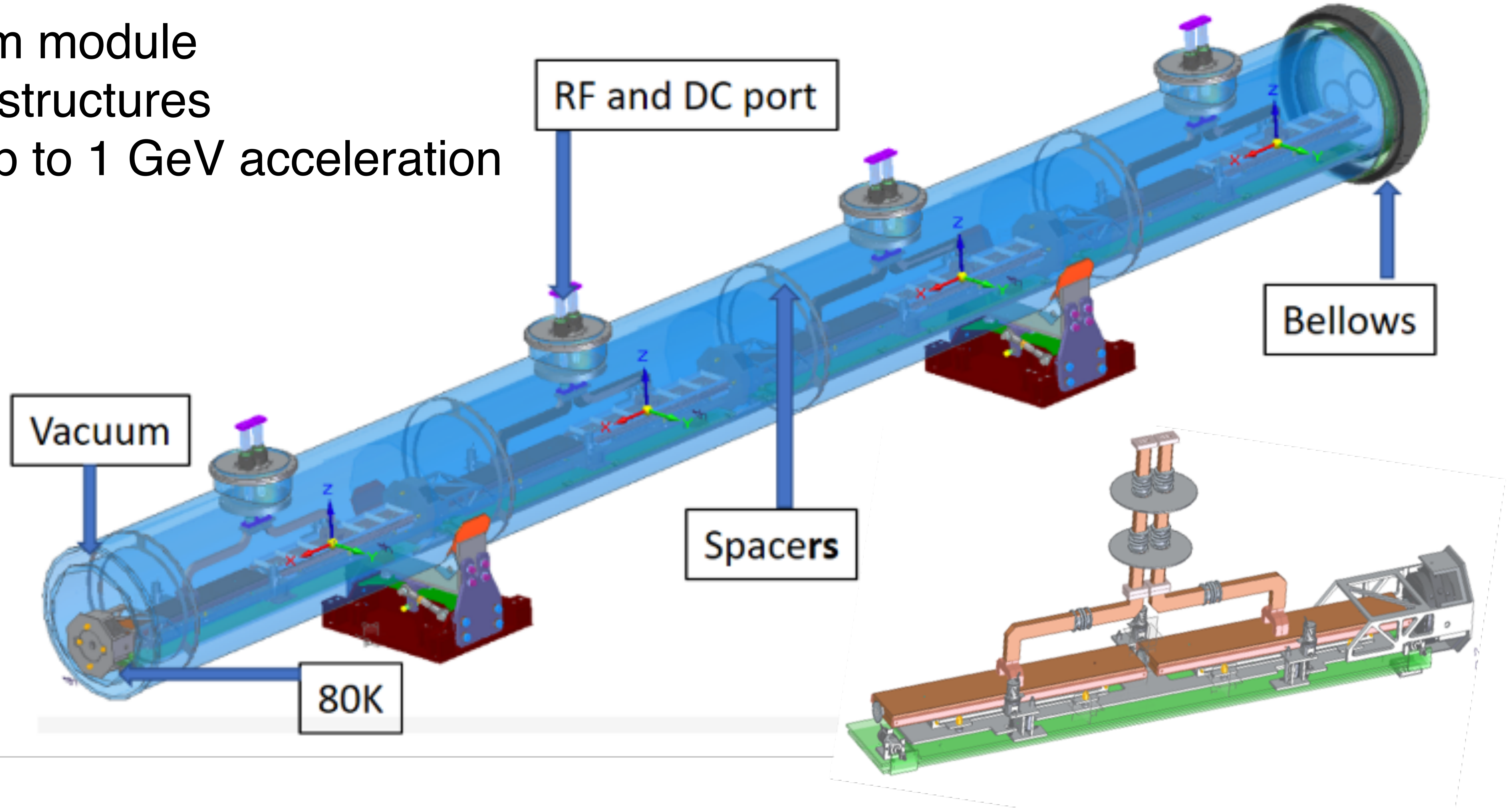
- Cryogenic temperature elevates performance in gradient
  - Increased material strength for gradient
  - Increase electrical conductivity reduces pulsed heating in the material
- Operation at 77 K with liquid nitrogen is simple and practical

Cool Copper Collider

- Planning for operations at high gradient **at 550 GeV, 120 MeV/m**
  - **Start at 70 MeV/m for C^3-250**

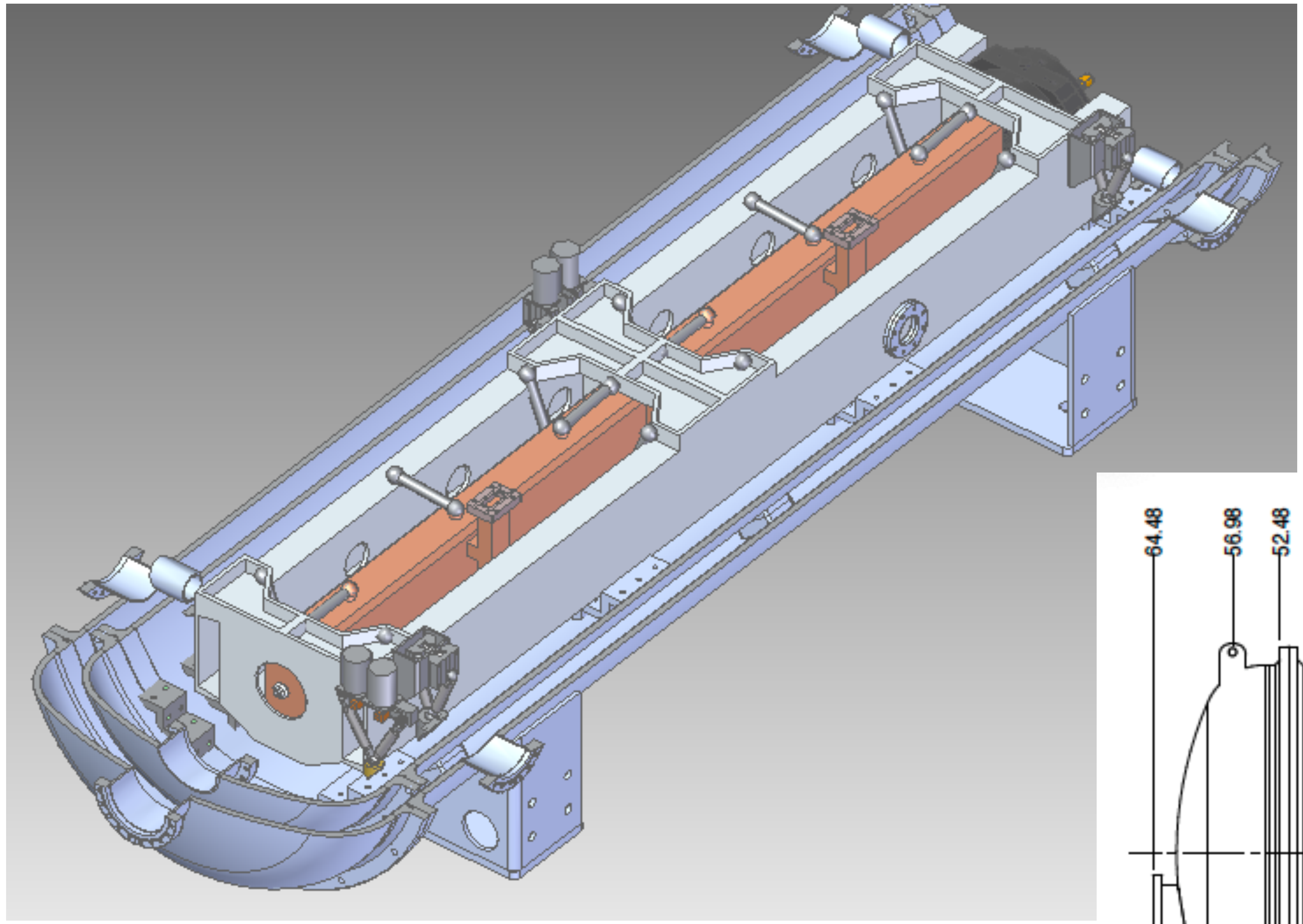


9m module
8 structures
Up to 1 GeV acceleration



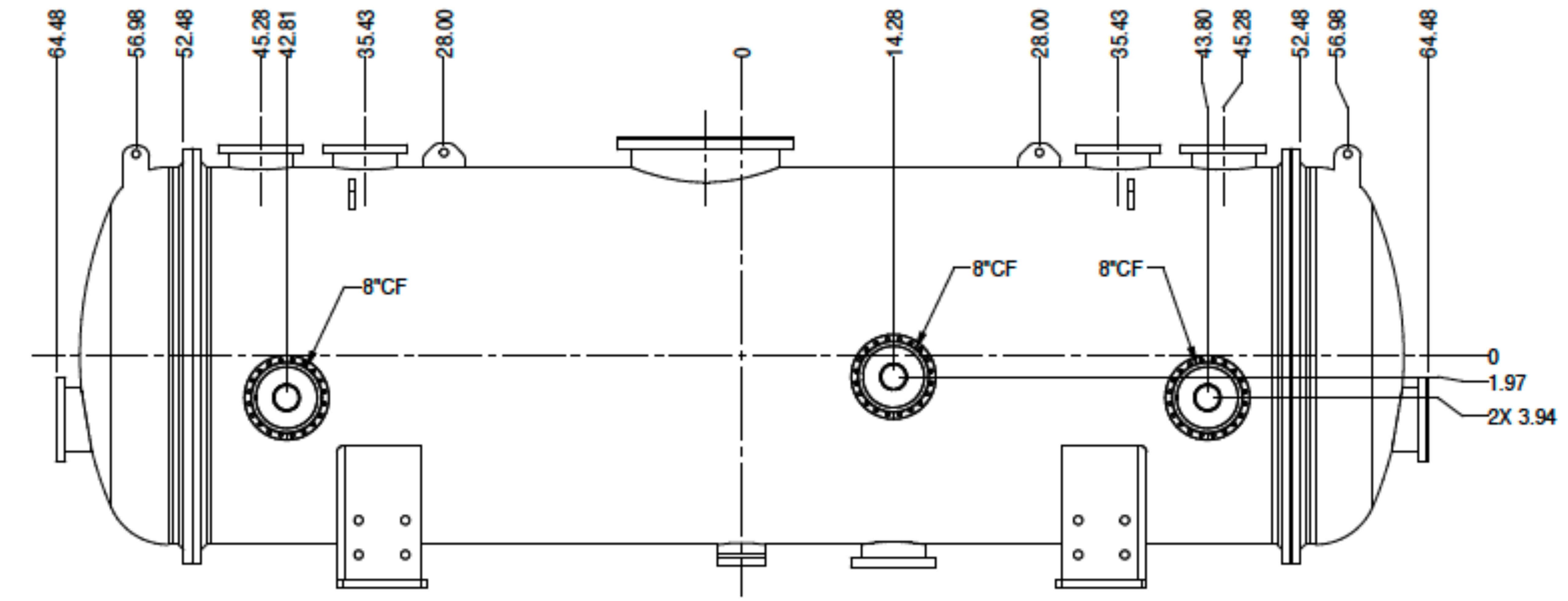
Quarter cryomodule

An important first step towards multi-structure operations



Order placed and expected delivery by Fall **2024**

- Outfit for alignment and vibration testing
- Follow-on experiments with structures at high gradient and beam acceleration

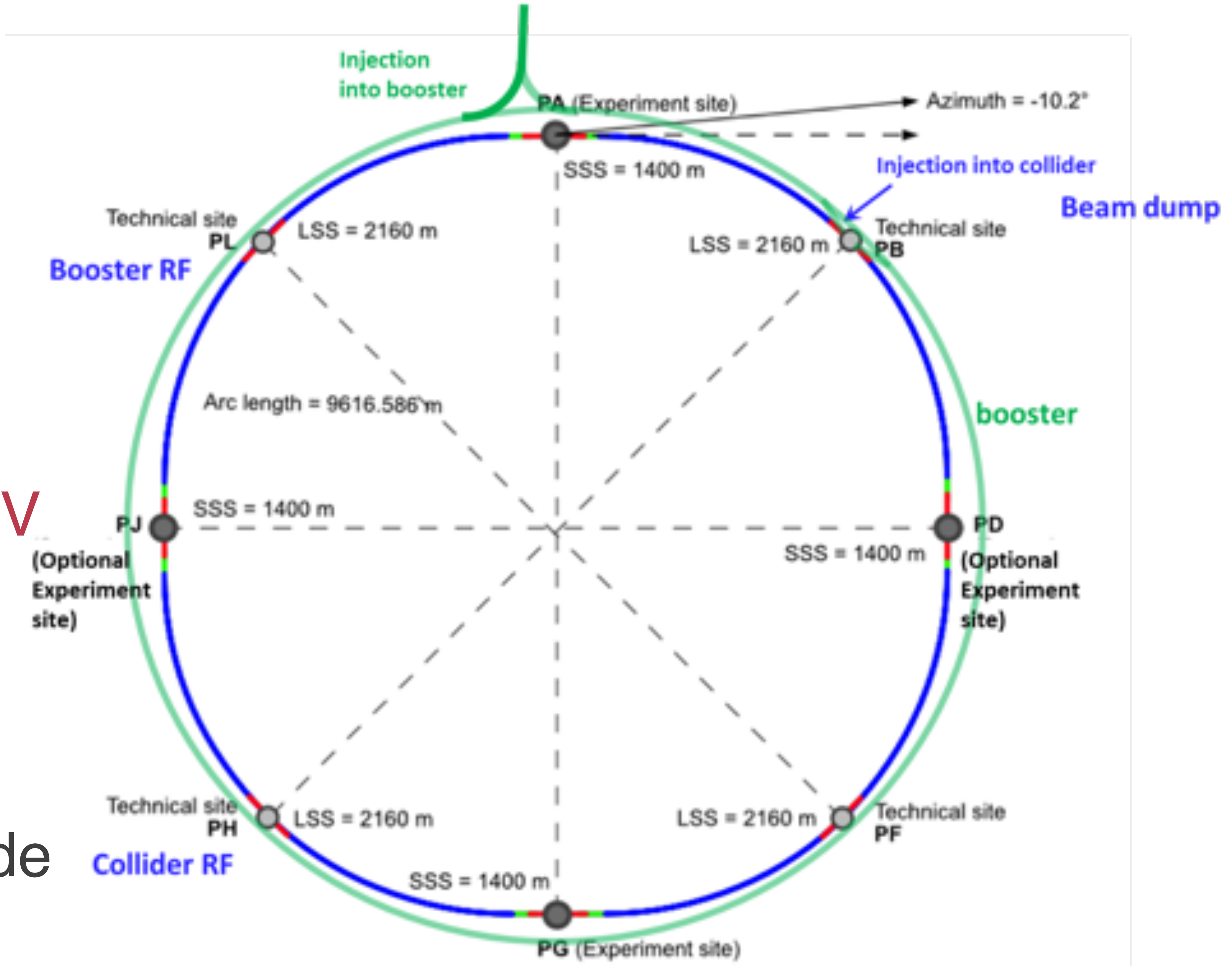


Synergies with Future Colliders

RF Accelerator Technology Essential for All Near-Term Collider Concepts

C3 Demo is positioned to contribute synergistically or directly to all near-term collider concepts

- ILC - options for electron driven positron source based C3 technology and high energy upgrades
- FCC-ee - common electron and positron injector linac from 6 to 20 GeV
  - **reduce length 3.5X OR reduce rf power 3.5X**
- Muon Collider - high gradient cryogenic copper cavities in cooling channel, alternative linac for acceleration after cooling
- AAC - C3 Demo utilized for staging, C3 facility multi-TeV energy upgrade reutilizing tunnel, $\gamma\gamma$ colliders



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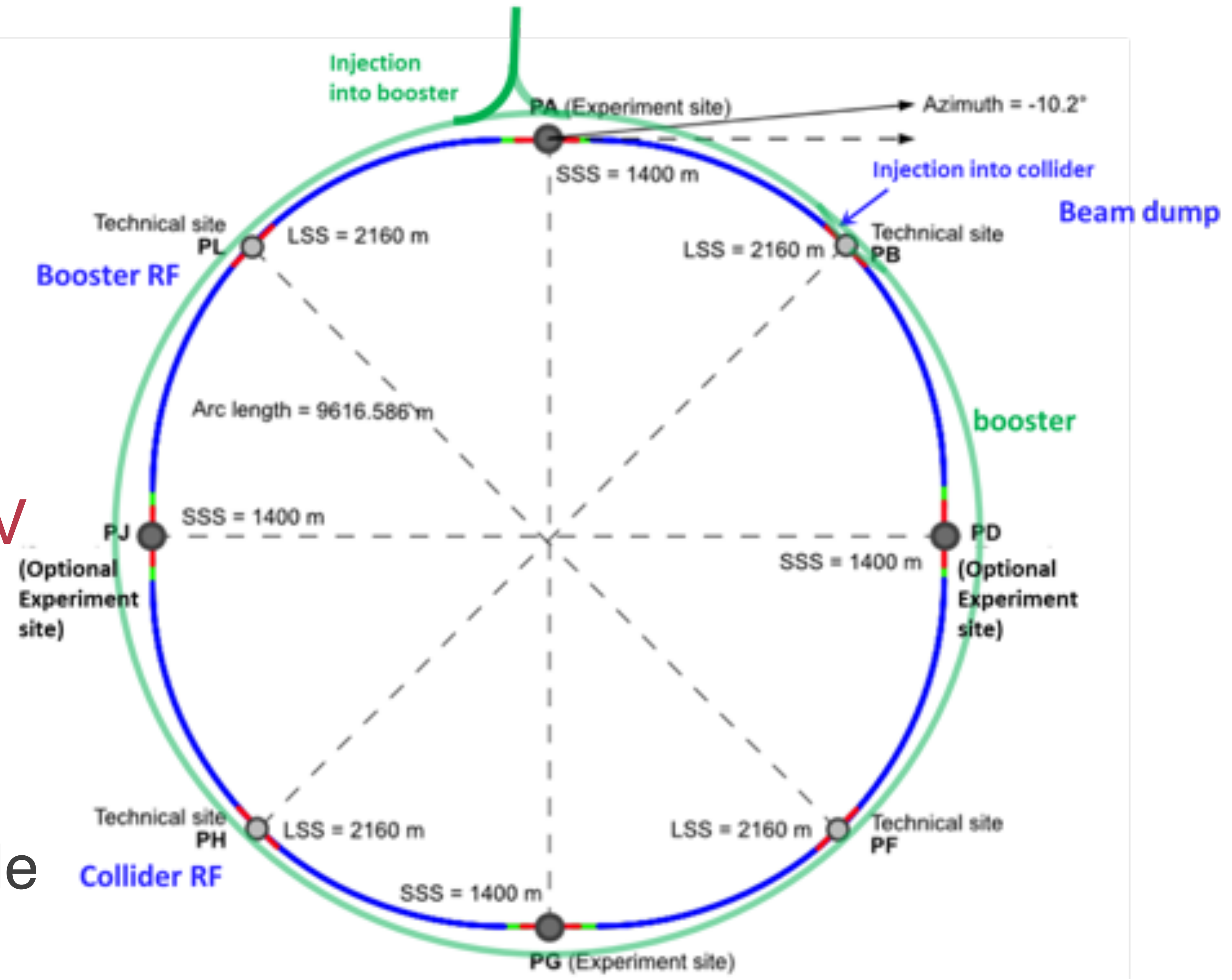

C^3 cryomodule could yield to significant improvements to size and sustainability of FCC-ee high energy linac

One word on Sustainability

PRX Energy 2 047001

Construction + operations CO_2 emissions per % sensitivity on couplings

- Polarization and high energy to account for physics reach
- Construction CO_2 emissions → minimize excavation and concrete with cut and cover approach
- Main Linac Operations → limit power, decarbonization of the grid and dedicated renewable sources

Scenario	RF System (MW)	Cryogenics (MW)	Total (MW)	Reduction (MW)
Baseline 250 GeV	40	60	100	-
RF Source Efficiency Increased 15%	31	60	91	9
RF Pulse Compression	28	42	70	30
Double Flat Top	30	45	75	25
Halve Bunch Spacing	34	45	79	21
All Scenarios Combined	13	24	37	63

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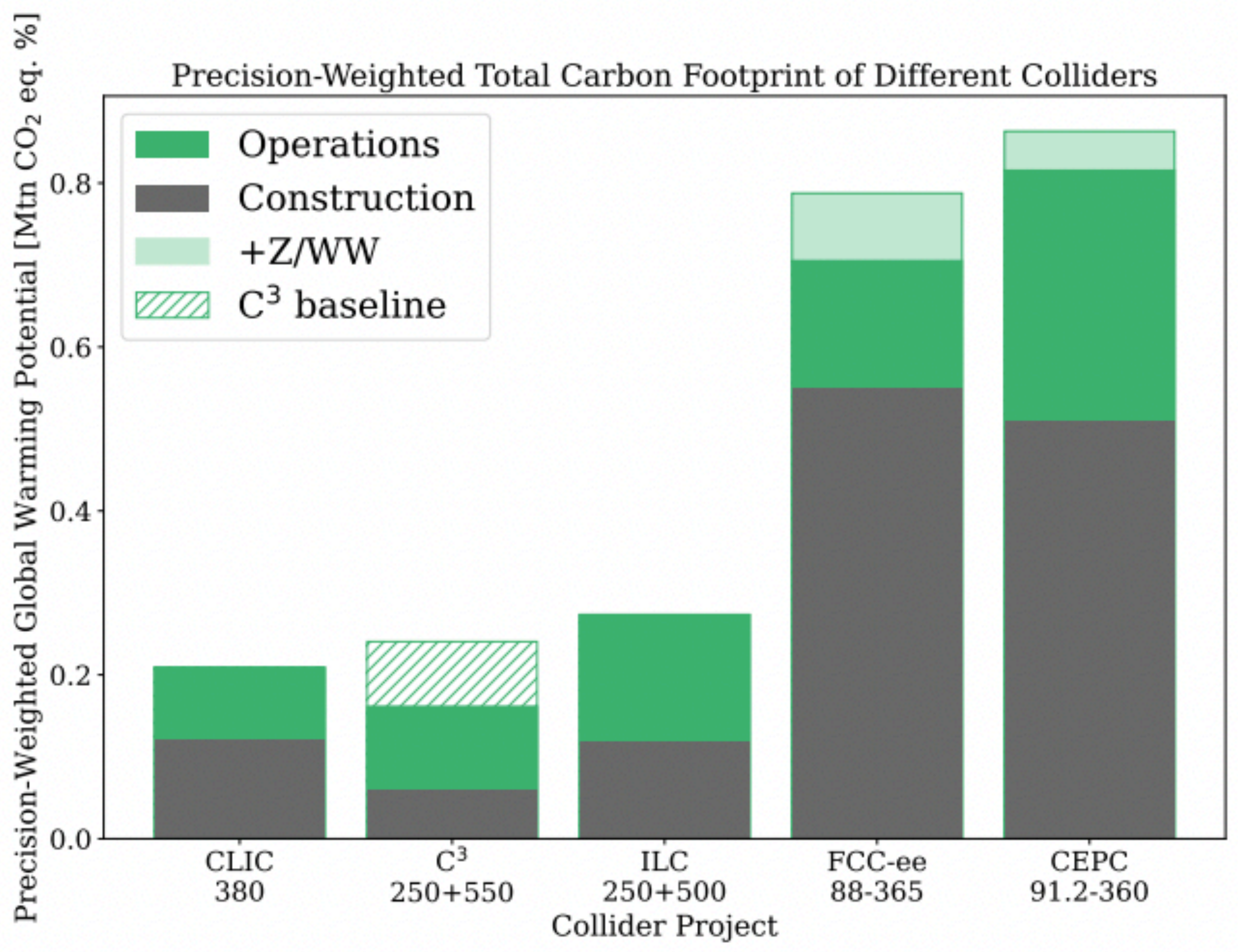


Outlook

- Higgs plays a central element for the **future colliders**
- Two Higgs Factory proposals on the table after P5, ILC and FCC-ee, to push our understanding of **Higgs properties** far **beyond HL-LHC sensitivity reach**
  - Above 500 GeV e^+e^- collisions can provide unique sensitivity to deviations in **Higgs self-coupling** predicted by models with first-order electroweak phase transitions and **new physics**
- Many opportunities for creativity in the **design of Higgs factory detectors**
- **Accelerator R&D** could enable new capabilities to boost "sustainably" collider performance

thank you!

Current status of beam-background studies TDAQ@Annecy2024

Same tools and methodology between ILC & FCC within Key4HEP

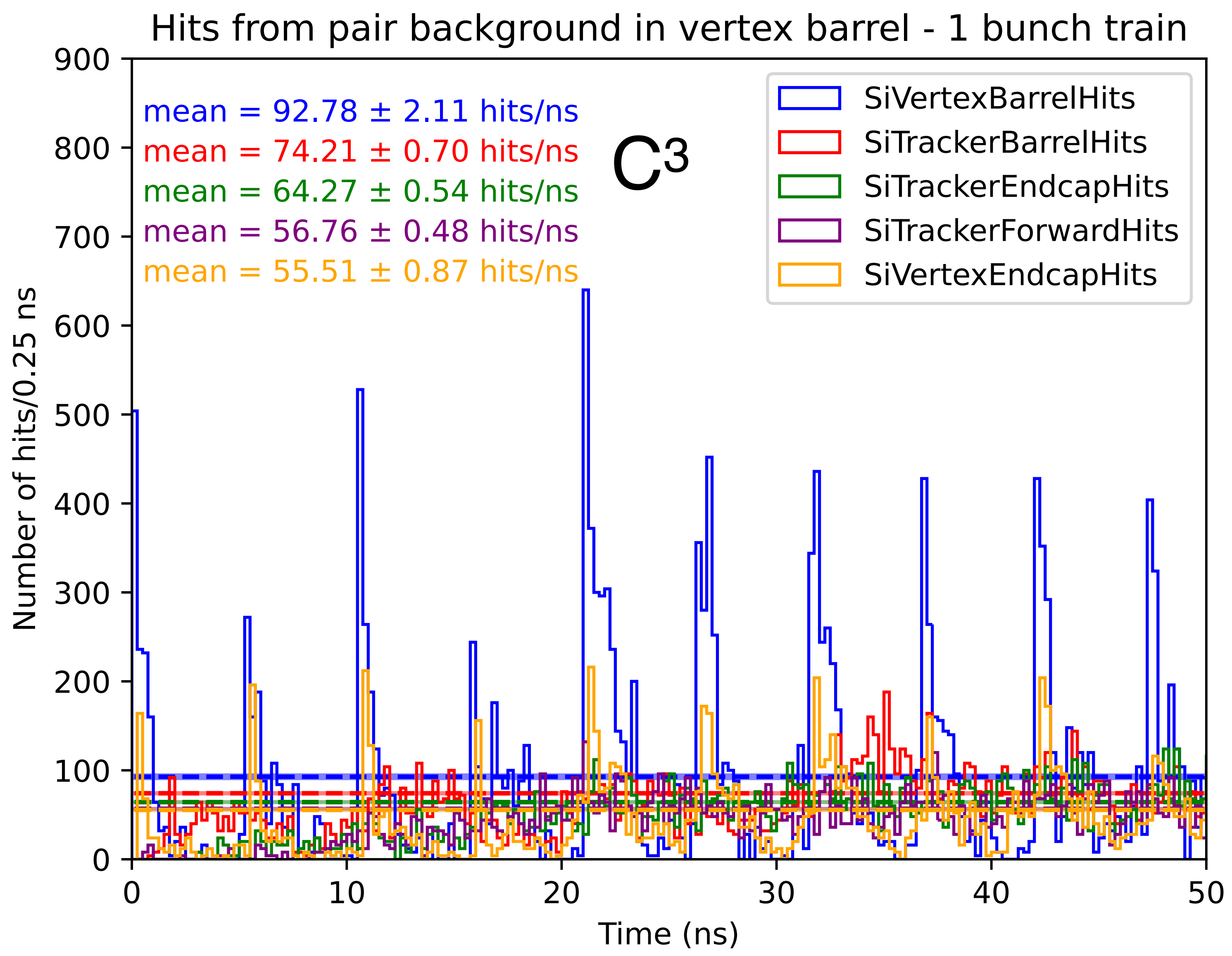
- ILC physics studies are based on full simulation data and some have been recently repeated for C^3
  - Time distribution of hits per unit time and area on 1st layer ~ $4.4 \cdot 10^{-3}$ hits/(ns·mm^2) ≃ 0.03 hits/mm^2 /BX
- CLD detailed studies @FCC show an overall occupancy of 2-3% in the vertex detector at the Z pole
  - assuming 10μs integration time

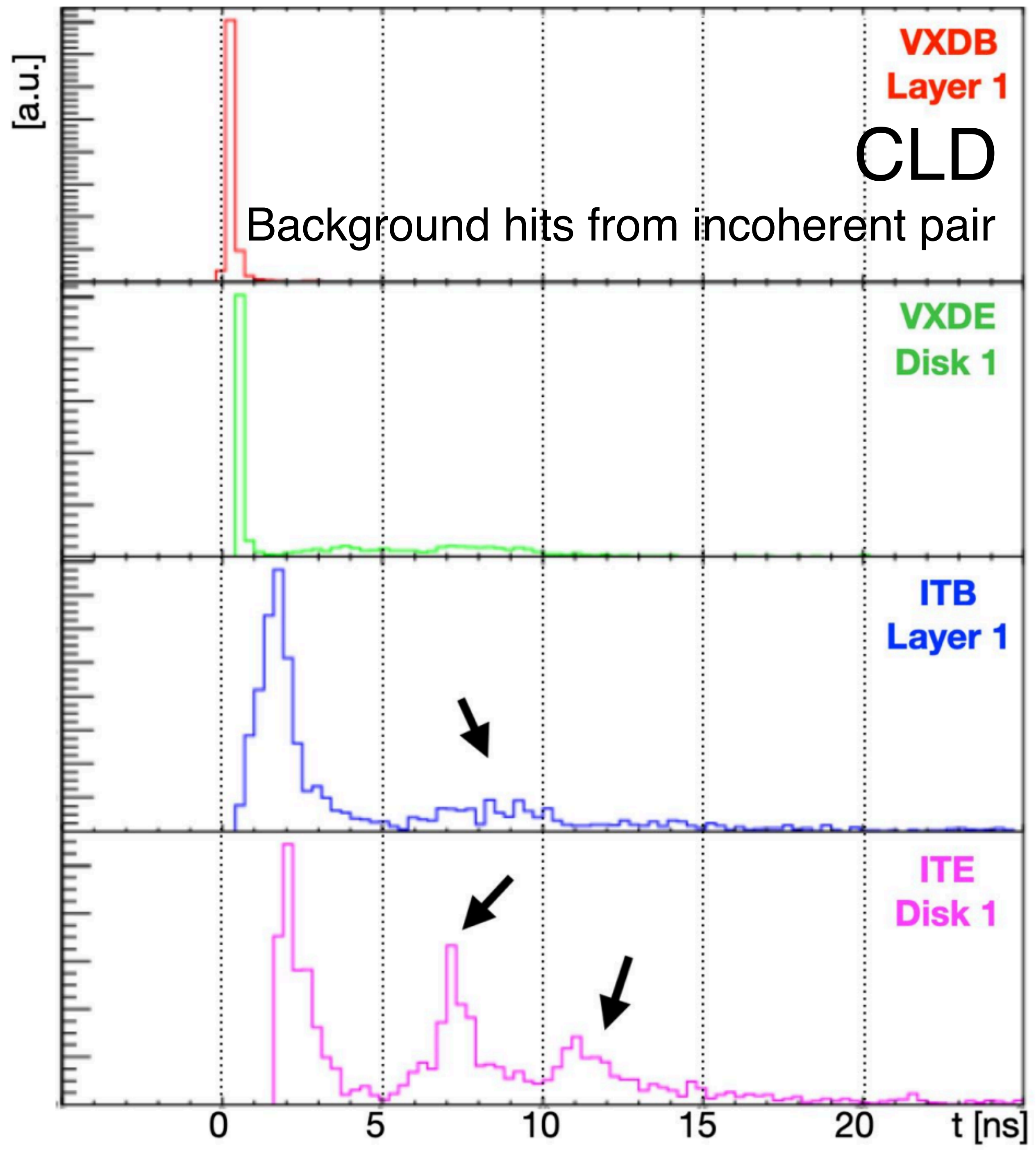
$$occupancy = hits/mm^2/BX \cdot size_{sensor} \cdot size_{cluster} \cdot safety$$

$$size_{sensor} = \begin{matrix} 25\mu m \times 25\mu m \ (pixel) \\ 1mm \times 0.05mm \ (strip) \end{matrix} \qquad size_{cluster} = \begin{matrix} 5 \ (pixel) \\ 2.5 \ (strip) \end{matrix} \qquad safety = 3$$

	Z	WW	ZH	Top
Bunch spacing [ns]	30	345	1225	7598
Max VXD occ. 1us	2.33e-3	0.81e-3	0.047e-3	0.18e-3
Max VXD occ.10us	23.3e-3	8.12e-3	3.34e-3	1.51e-3
Max TRK occ. 1us	3.66e-3	0.43e-3	0.12e-3	0.13e-3
Max TRK occ.10us	36.6e-3	4.35e-3	1.88e-3	0.38e-6

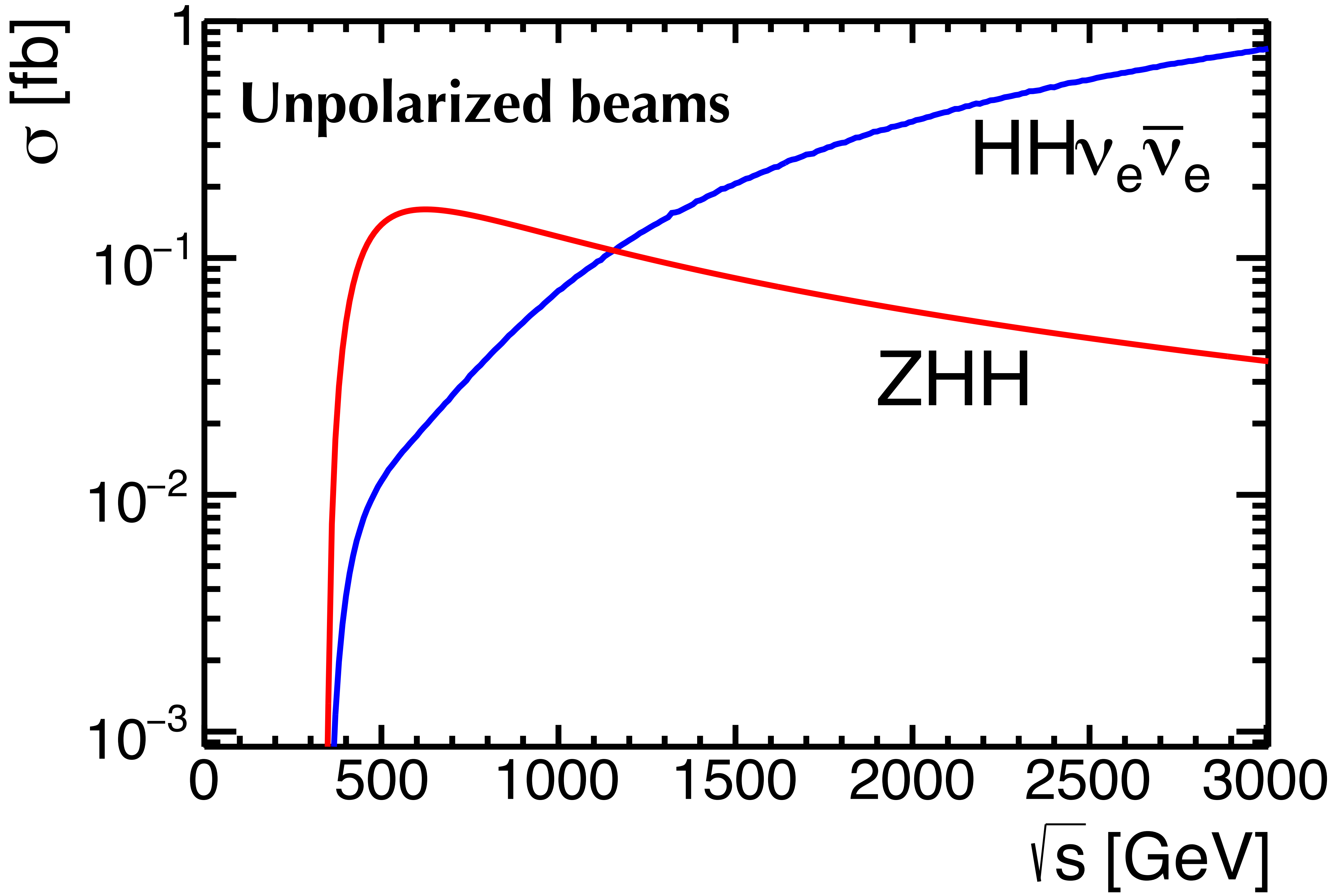
Occupancy in readout window (10μs)

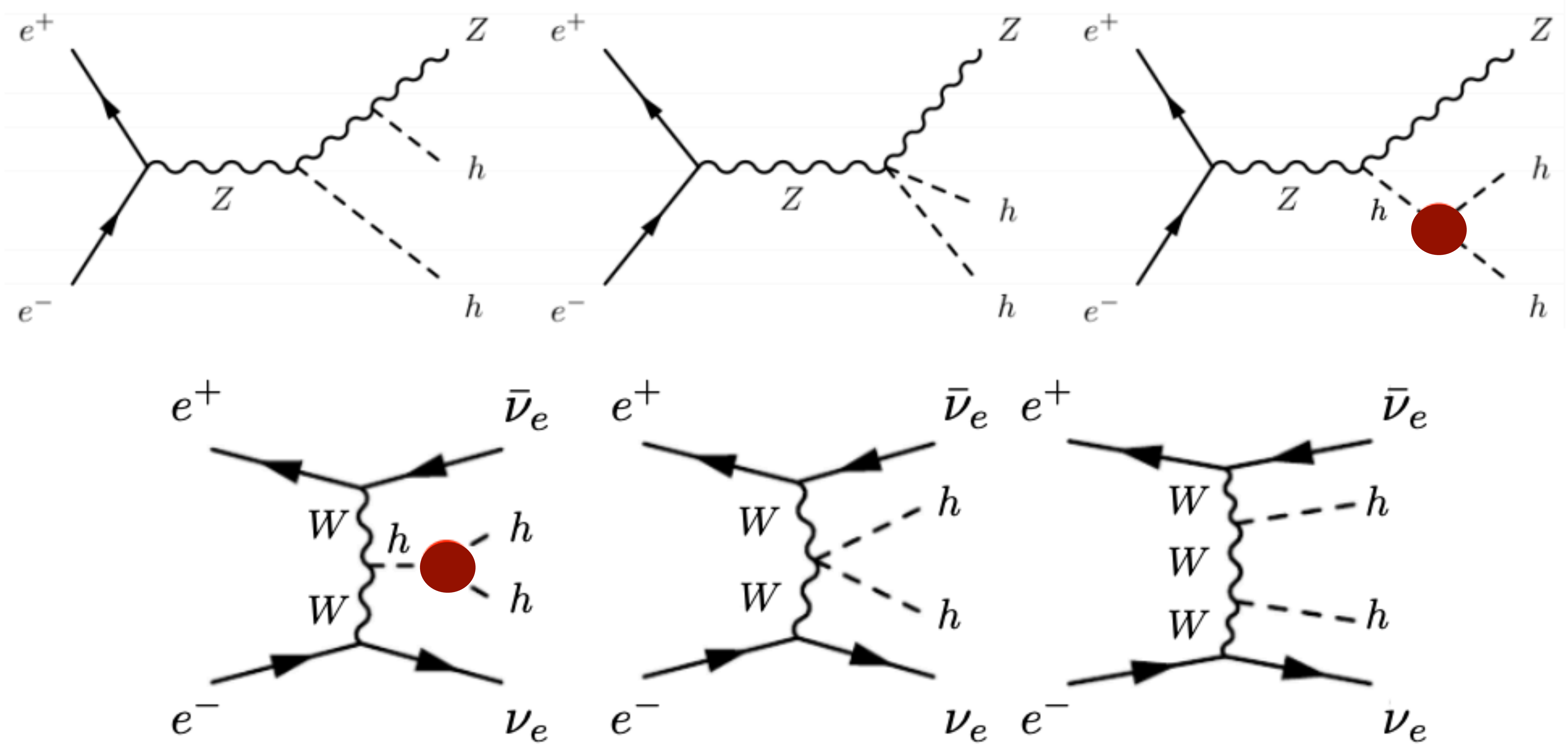




HH at e+e- colliders

Review in Physics (2020) 100045





The self-coupling can be probed at e+e− through HH with ZHH ~500GeV and vvHH ≥1TeV

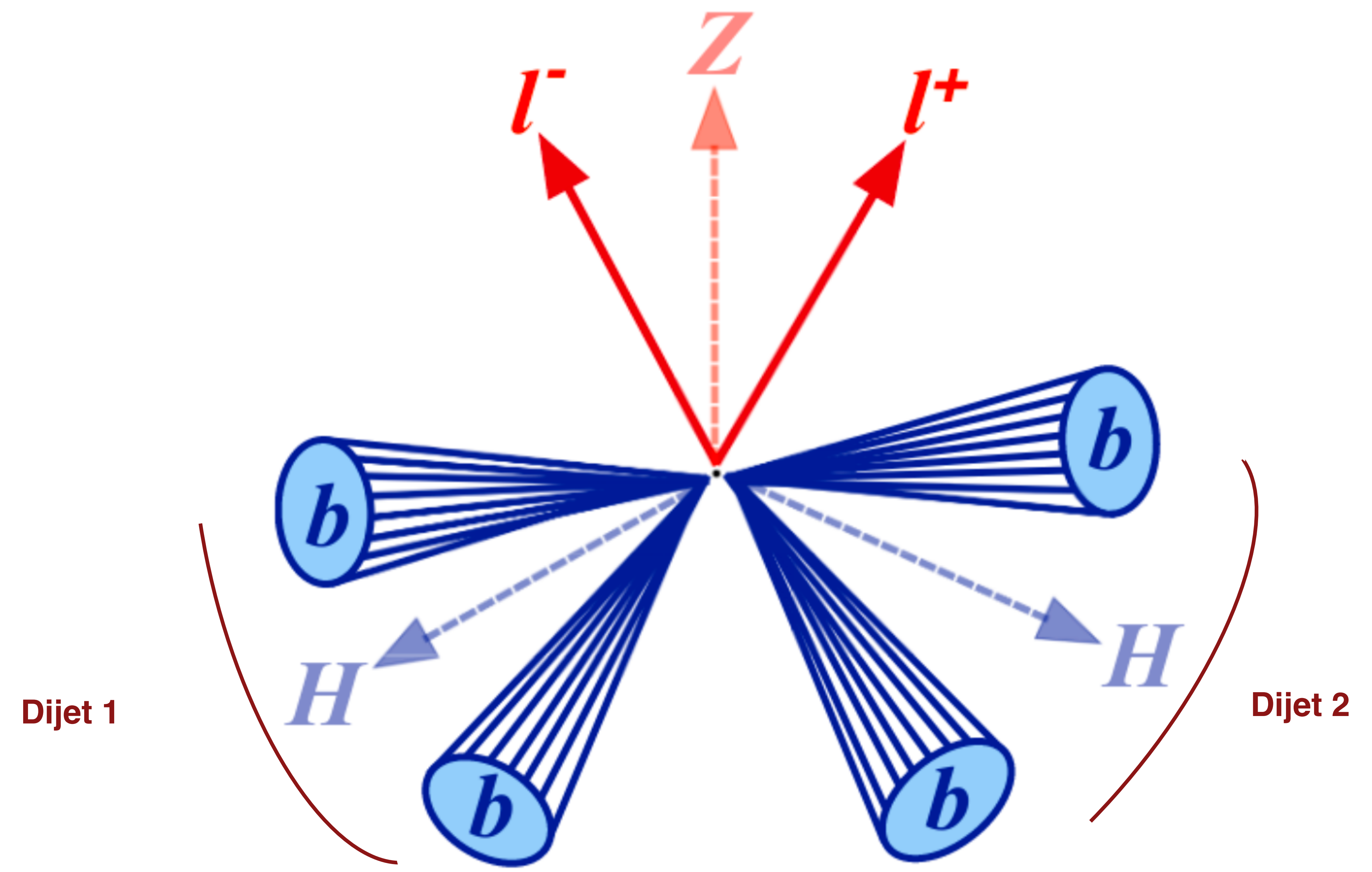
- **HHvv** requires $e_L^- e_R^+$, the use of polarized beams could increase the cross-section by a factor ~2

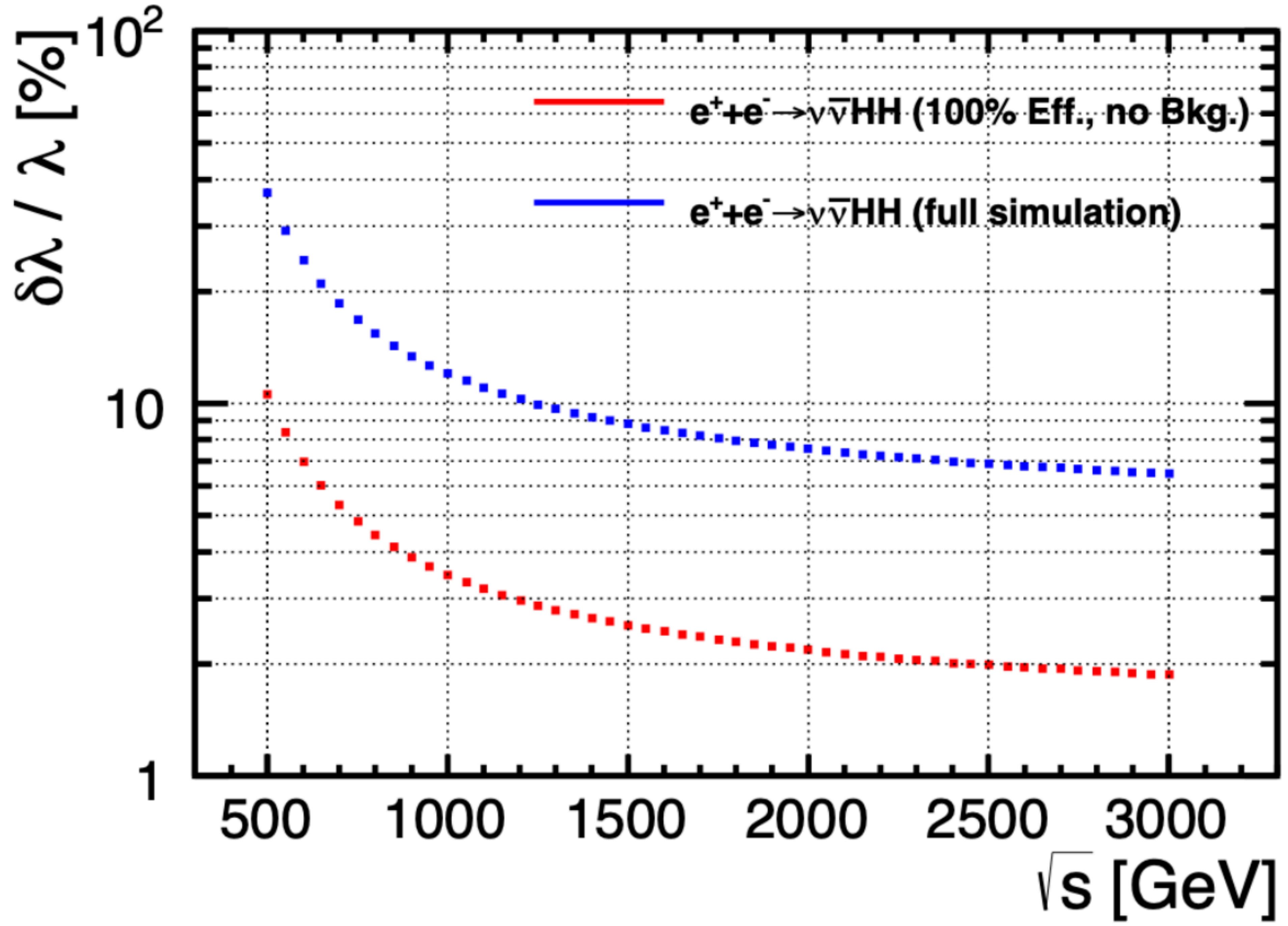
What is next for HH?

arXiv:2209.07510

Evaluate dependency as a function of √s and further analysis improvements

A lot of room for improvement by advanced analysis techniques:
flavor tagging, jet-clustering, kinematic fitting, matrix element method…



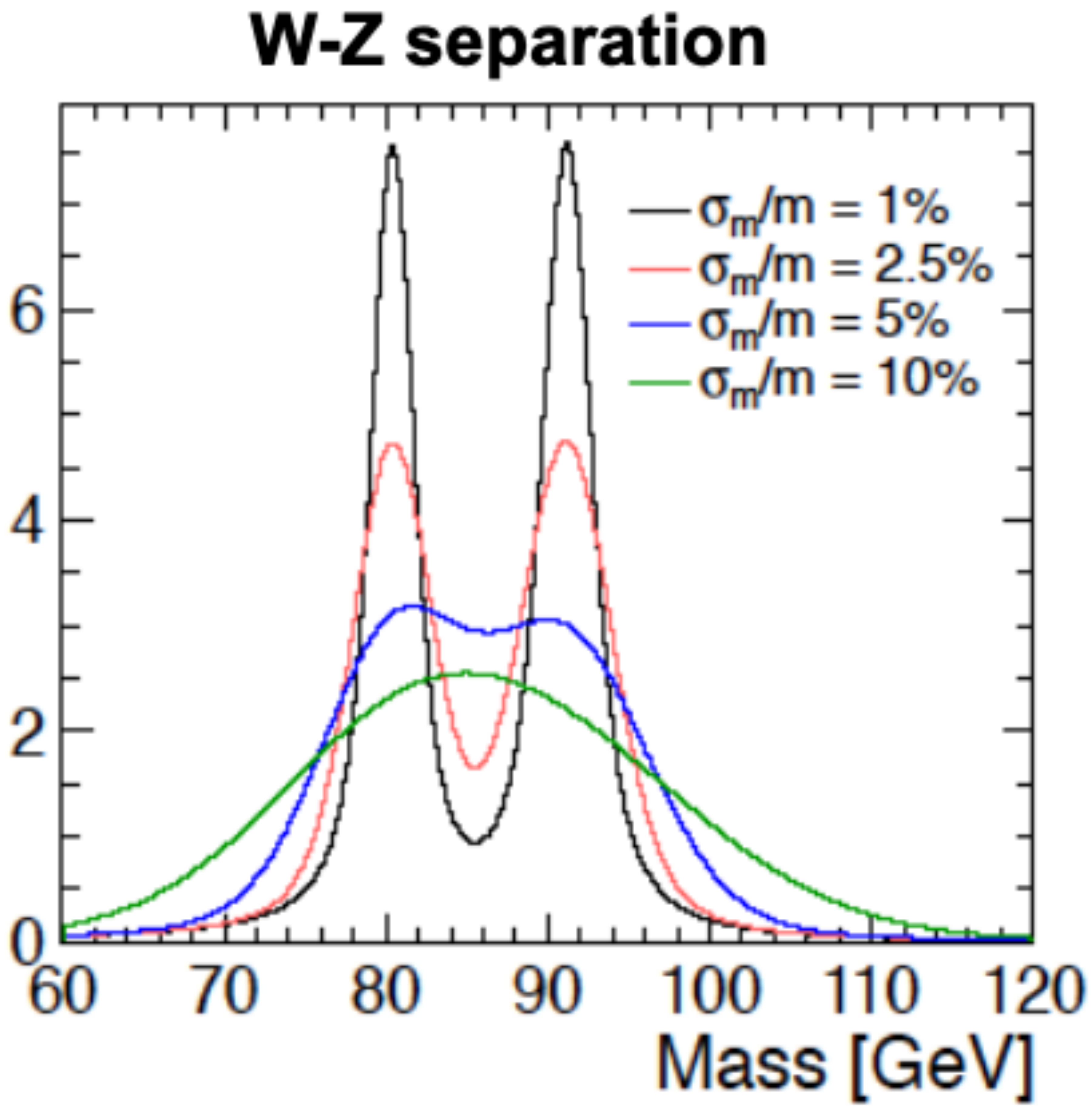


Review of ongoing studies for ZHH (talk, arXiv)

One more: W/Z separation

arXiv:2203.07622

Precision challenges detector design



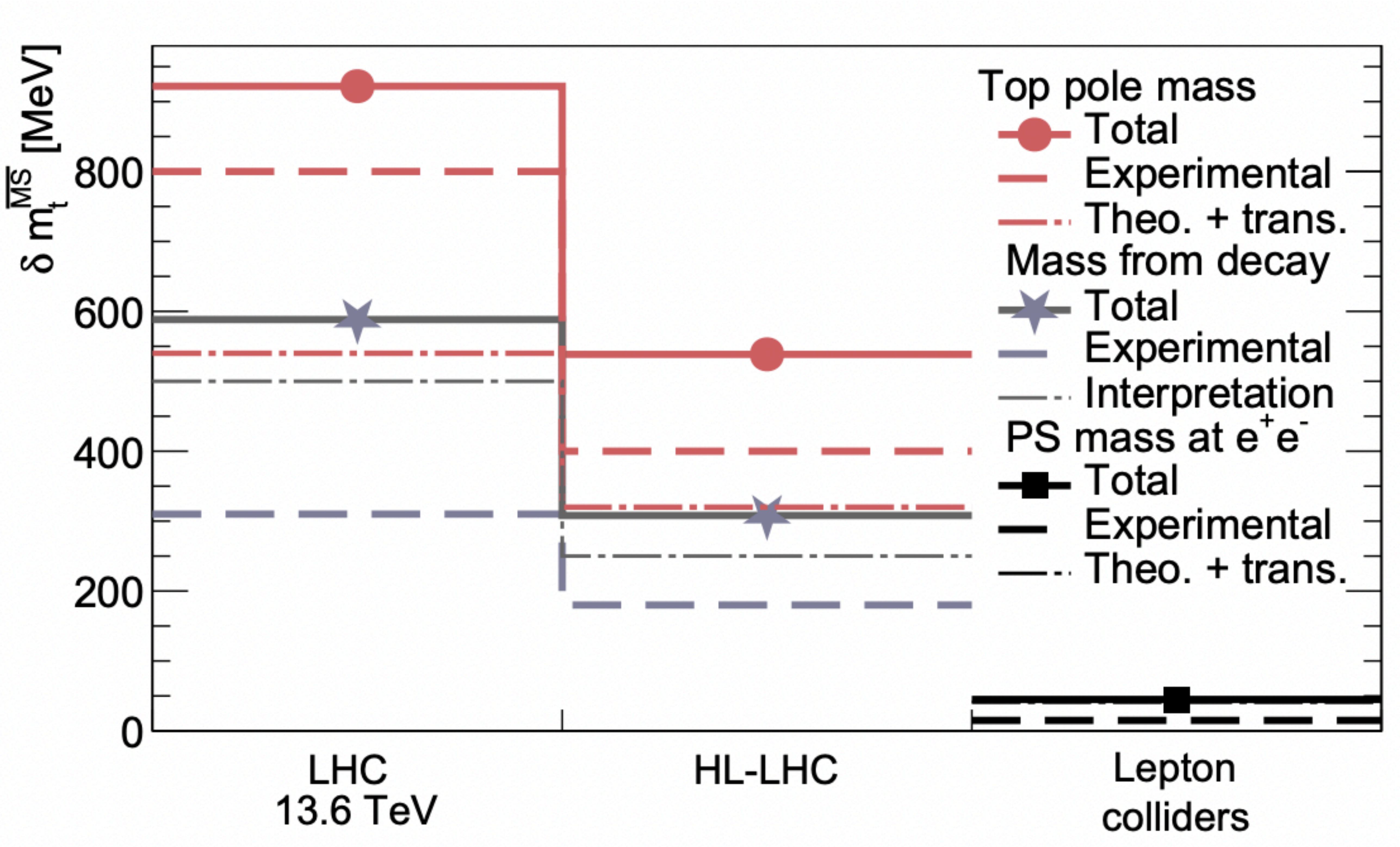
Drives the requirement on PFA jet resolution

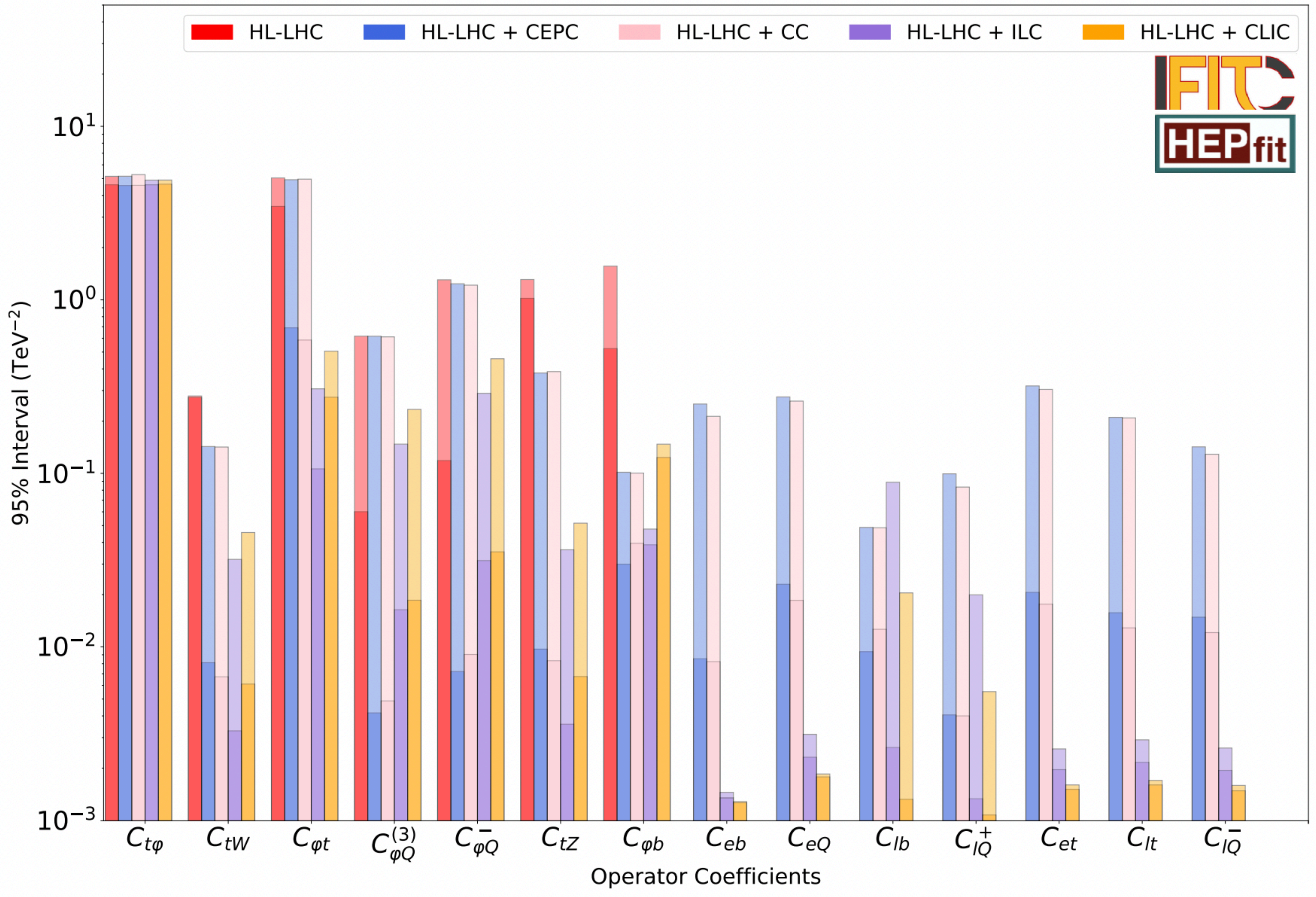
hadronic jet energy resolution $\sigma_E/E \sim 3 \rightarrow 5$ % over wide energy range
→ distinguish W, Z, H

Top physics at e+e-

Unique opportunities for theoretically clean precision observables

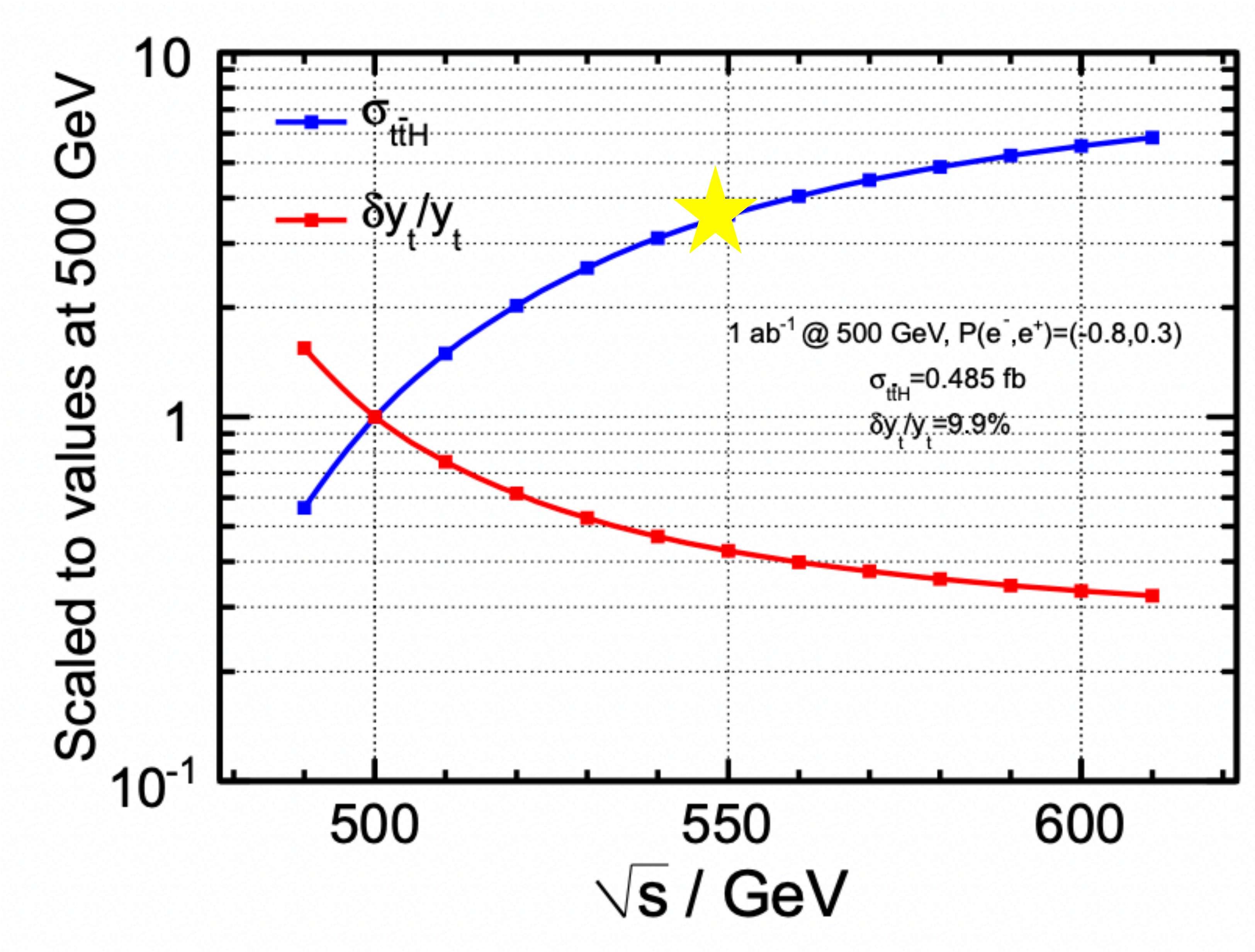
- The measurement of the tt cross-section with a threshold scan can determine the top mass with 50 MeV uncertainty
- Global fits demonstrate e+e- sensitivity of10-100 times above HL-LHC for some operators top electroweak couplings at energies > 500 GeV





Why 550 GeV?

A factor two in the top-yukawa couplin



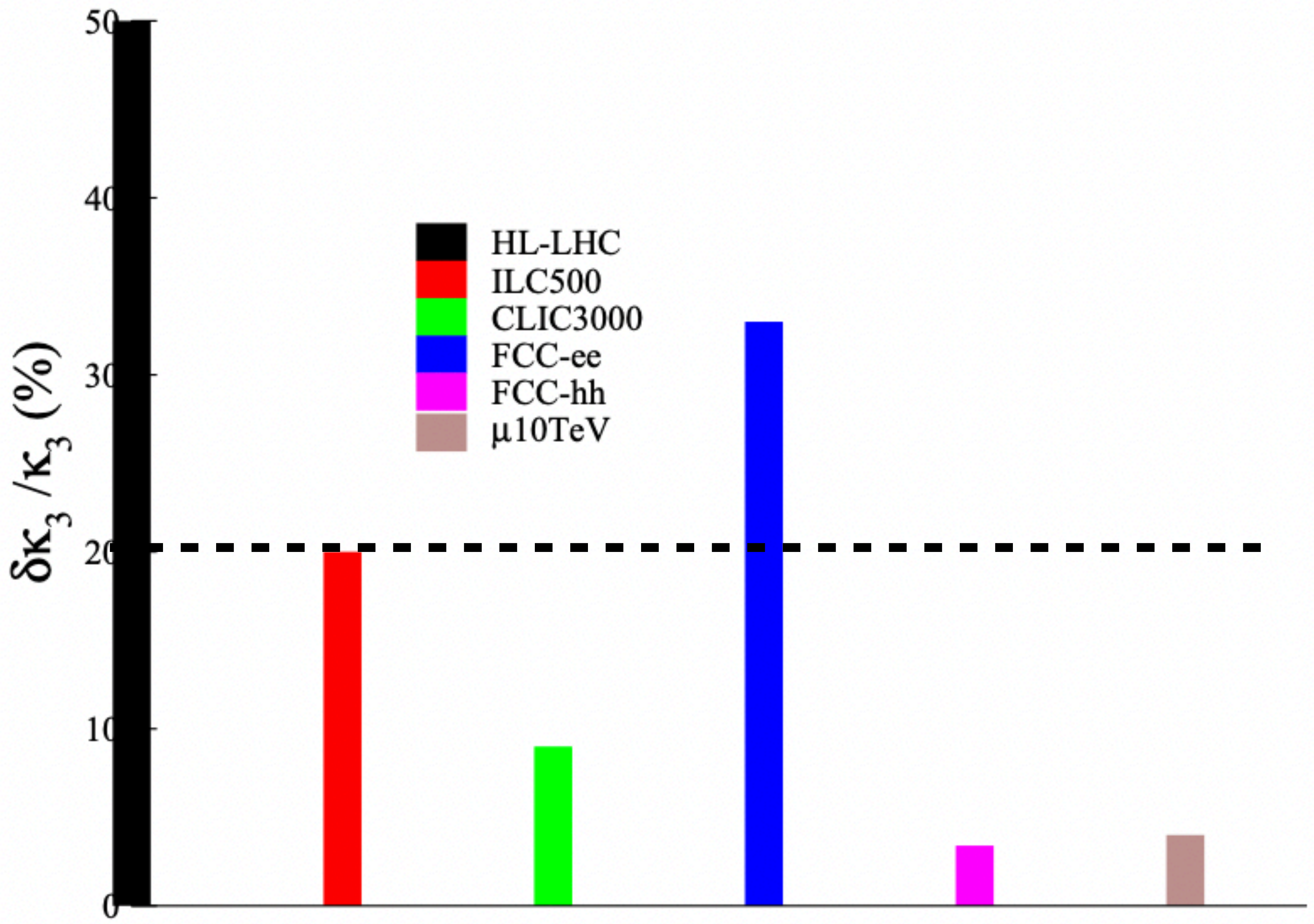
Collider Luminosity Polarization	HL-LHC 3 ab^{-1} in 10 yrs -	C^3 /ILC 250 GeV 2 ab^{-1} in 10 yrs $\mathcal{P}_{e^+}$ = 30% (0%)	C^3 /ILC 500 GeV + 4 ab^{-1} in 10 yrs $\mathcal{P}_{e^+}$ = 30% (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80 (0.85)	0.43 (0.44)
g_{Hcc} (%)	-	1.8 (1.8)	1.1 (1.1)
g_{Hgg} (%)	2.3	1.6 (1.7)	0.92 (0.93)
$g_{H\tau\tau}$ (%)	3.1	0.95 (1.0)	0.64 (0.65)
$g_{H\mu\mu}$ (%)	3.1	4.0 (4.0)	3.8 (3.8)
$g_{H\gamma\gamma}$ (%)	3.3	1.1 (1.1)	0.97 (0.97)
$g_{HZ\gamma}$ (%)	11.	8.9 (8.9)	6.5 (6.8)
g_{Htt} (%)	3.5	–	3.0 (3.0)*
g_{HHH} (%)	50	49 (49)	22 (22)
Γ_H (%)	5	1.3 (1.4)	0.70 (0.70)

The Higgs self-coupling

arXiv:2209.07510

HL-LHC projections are conservative, as they have still to be updated since 2018

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC_{250}/C^3-250 [51, 52]	49%	–	49%
ILC_{500}/C^3-550 [51, 52]	38%	20%	20%
$CLIC_{380}$ [54]	50%	–	50%
$CLIC_{1500}$ [54]	49%	36%	29%
$CLIC_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

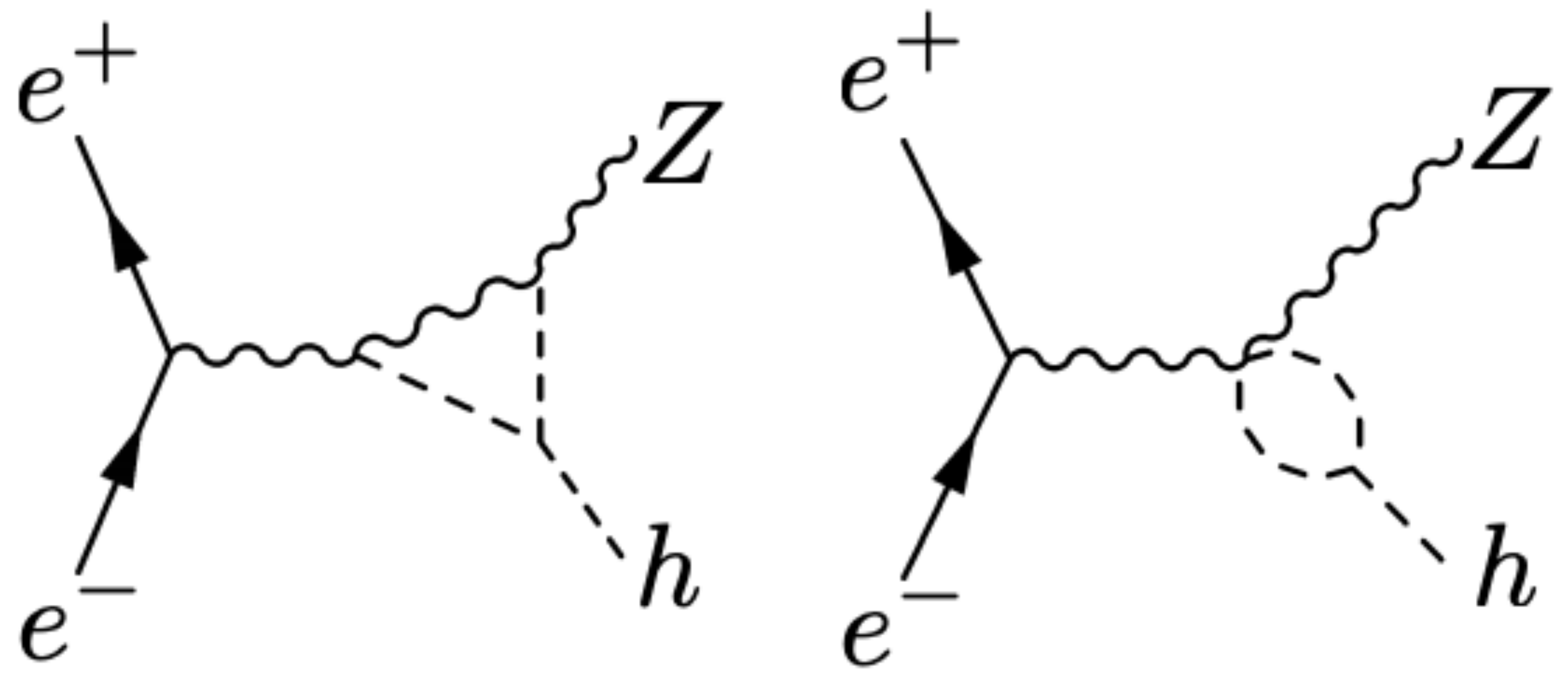


O(20%) precision on the Higgs self-coupling would allow to exclude/ demonstrate at 5σ models of electroweak baryogenesis

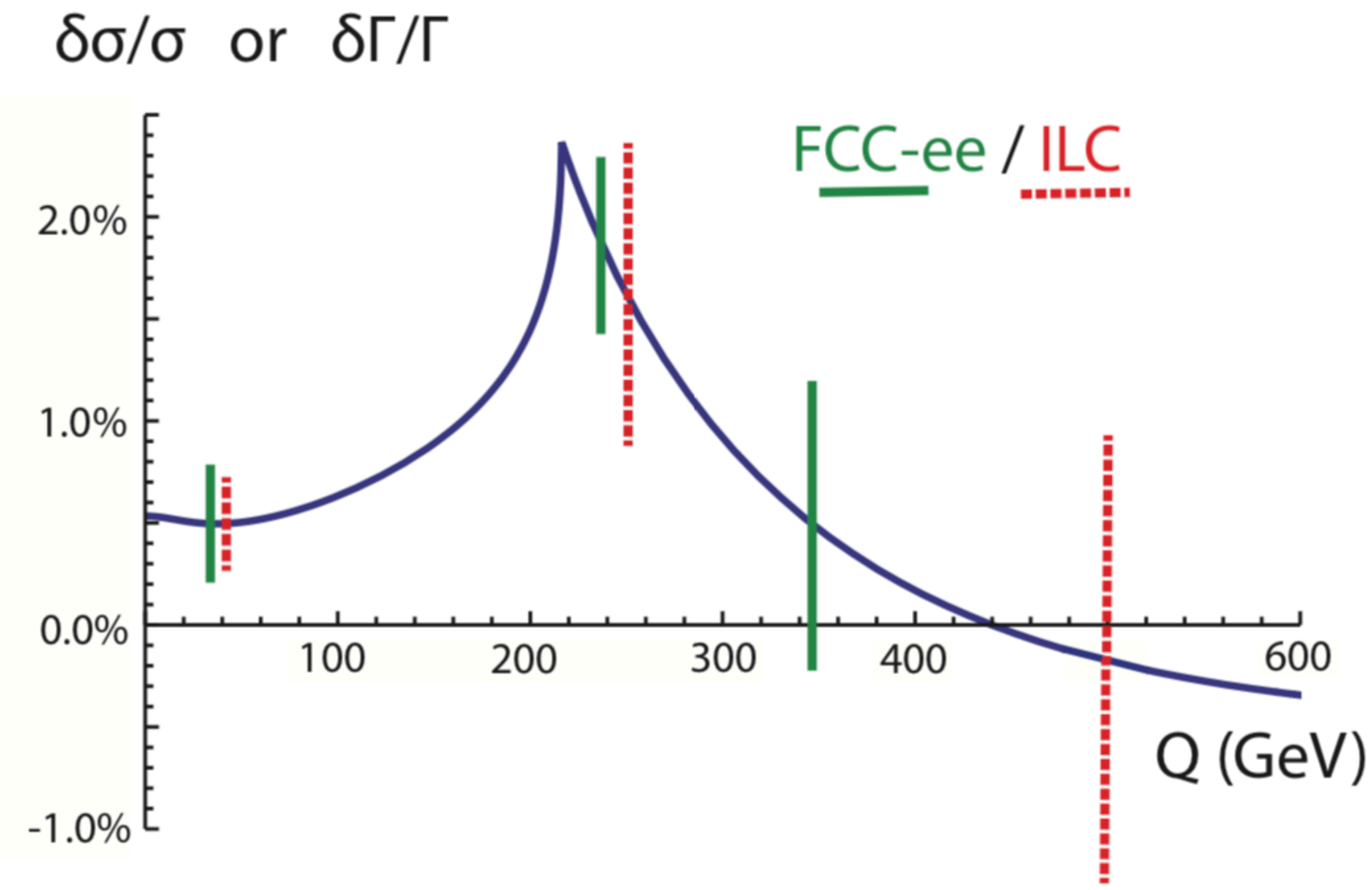
Self-coupling at e+e- with single Higgs

The self-coupling could be determined also through single Higgs processes

- Relative enhancement of the e+e– → ZH cross-section and the H→W+W– partial width
- Need multiple Q^2 to identify the effects due to the self-coupling



$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$



New observables? Top-quark uncertainties? Which is the optimal energy scan?

1811.00017
1908.11376
2101.04119

Beyond EFT, is there more?

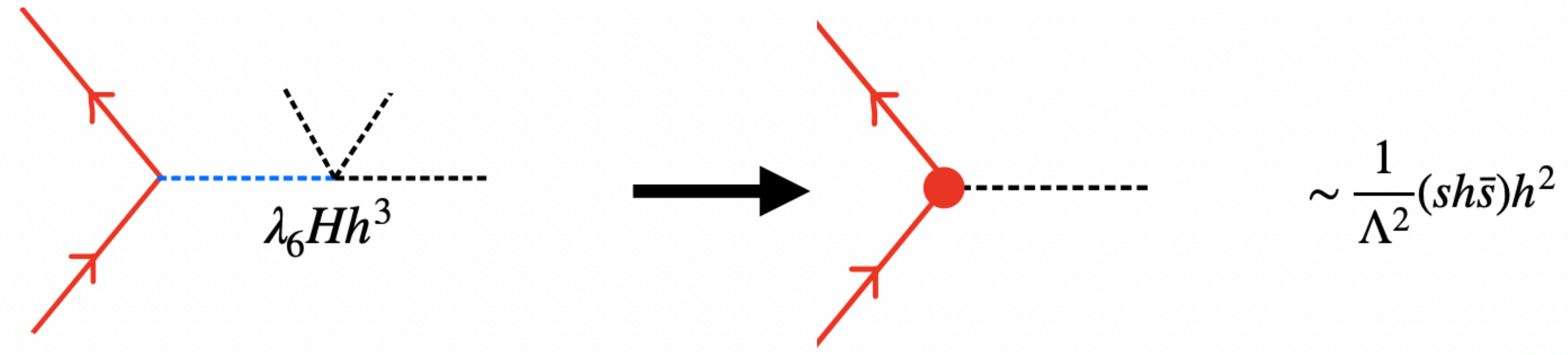
Higgs to strange coupling is an appealing signature to probe new physics

Is the Higgs the source for all flavor?

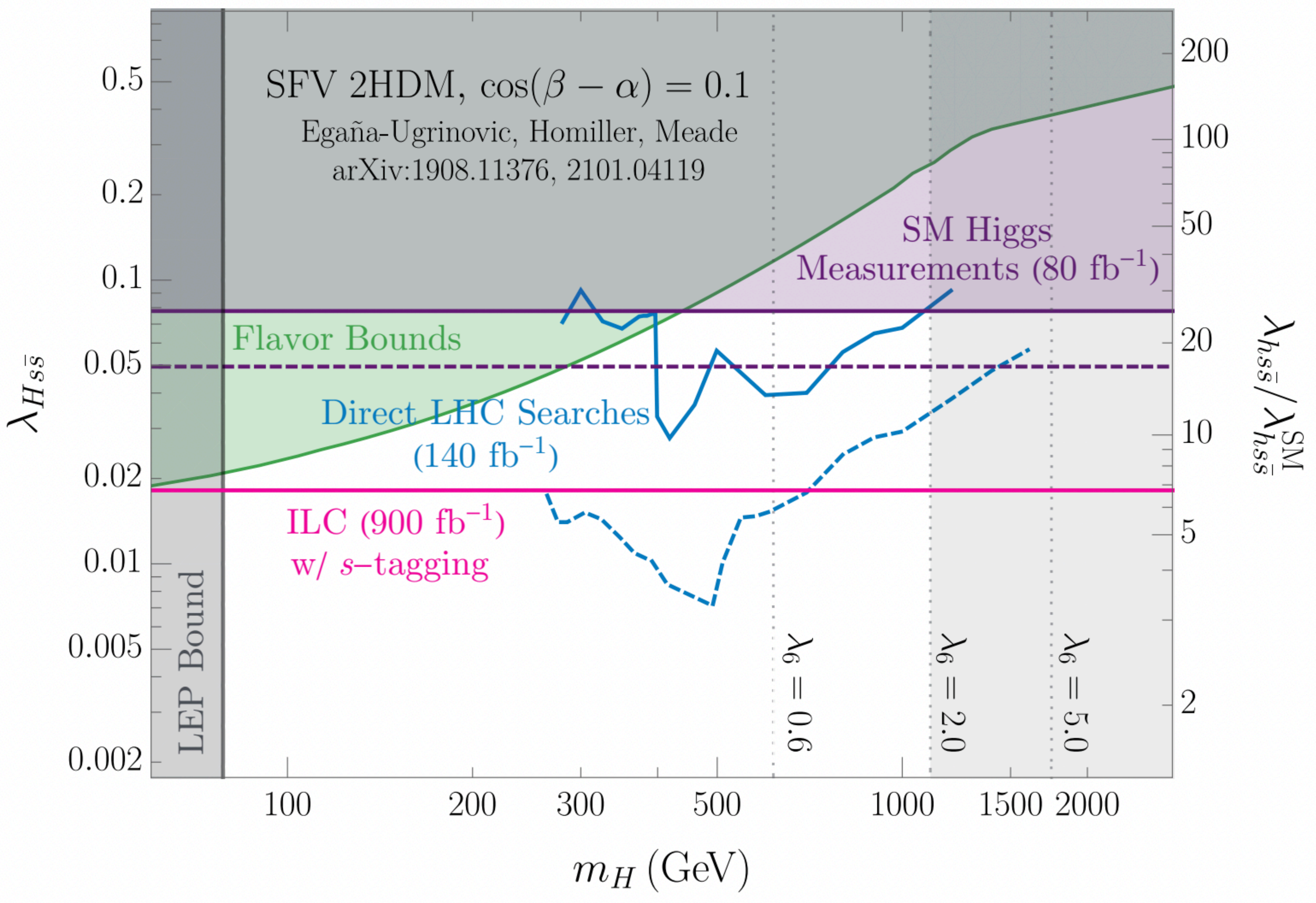
An option, **Spontaneous Flavor Violation**

New physics can couple in a strongly flavor dependent way if it is aligned in the down-type quark or up-type quark sectors

- It allows for large couplings of additional Higgs to strange/light quarks
- No flavor-changing neutral currents



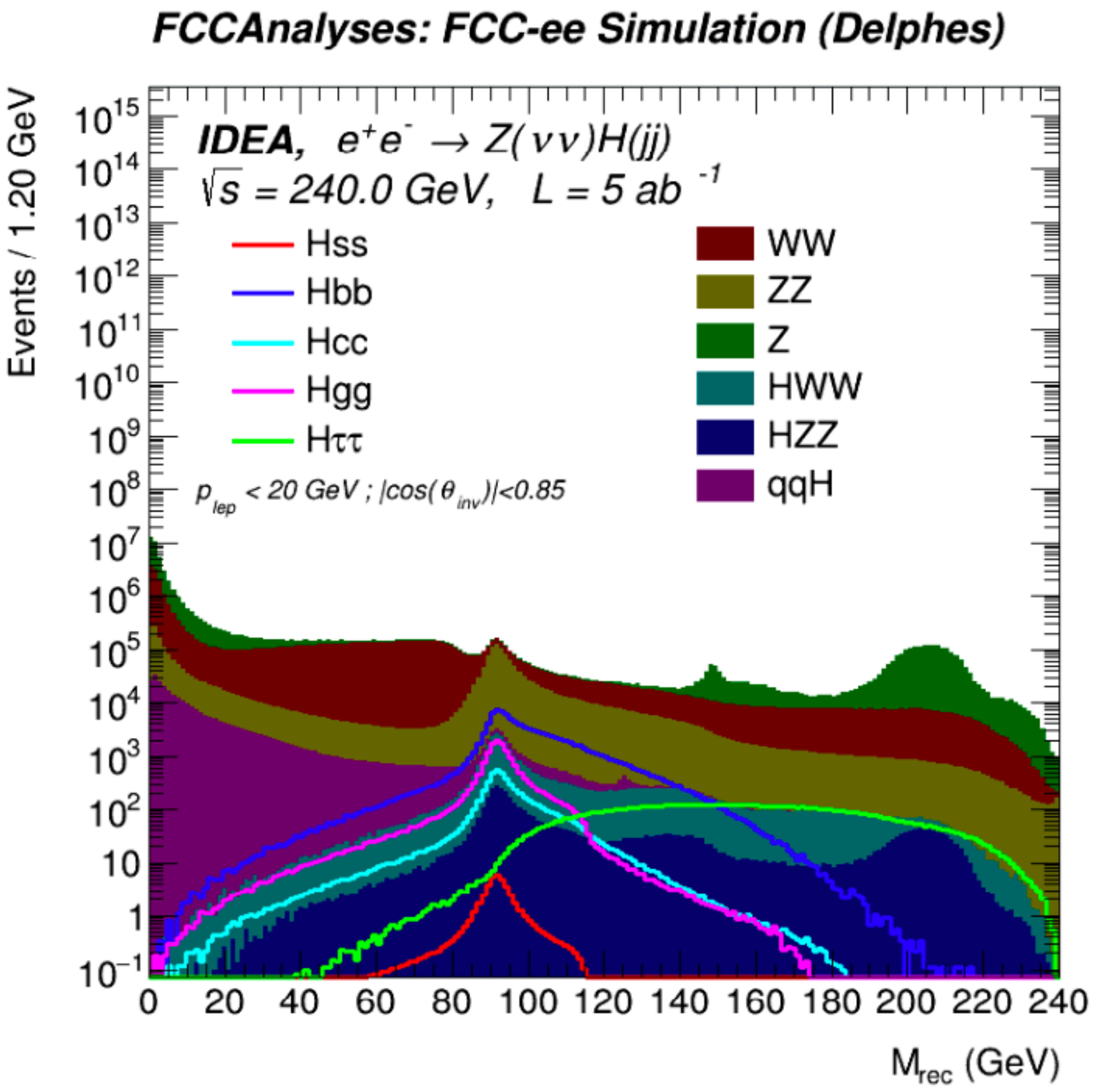
P. Meade

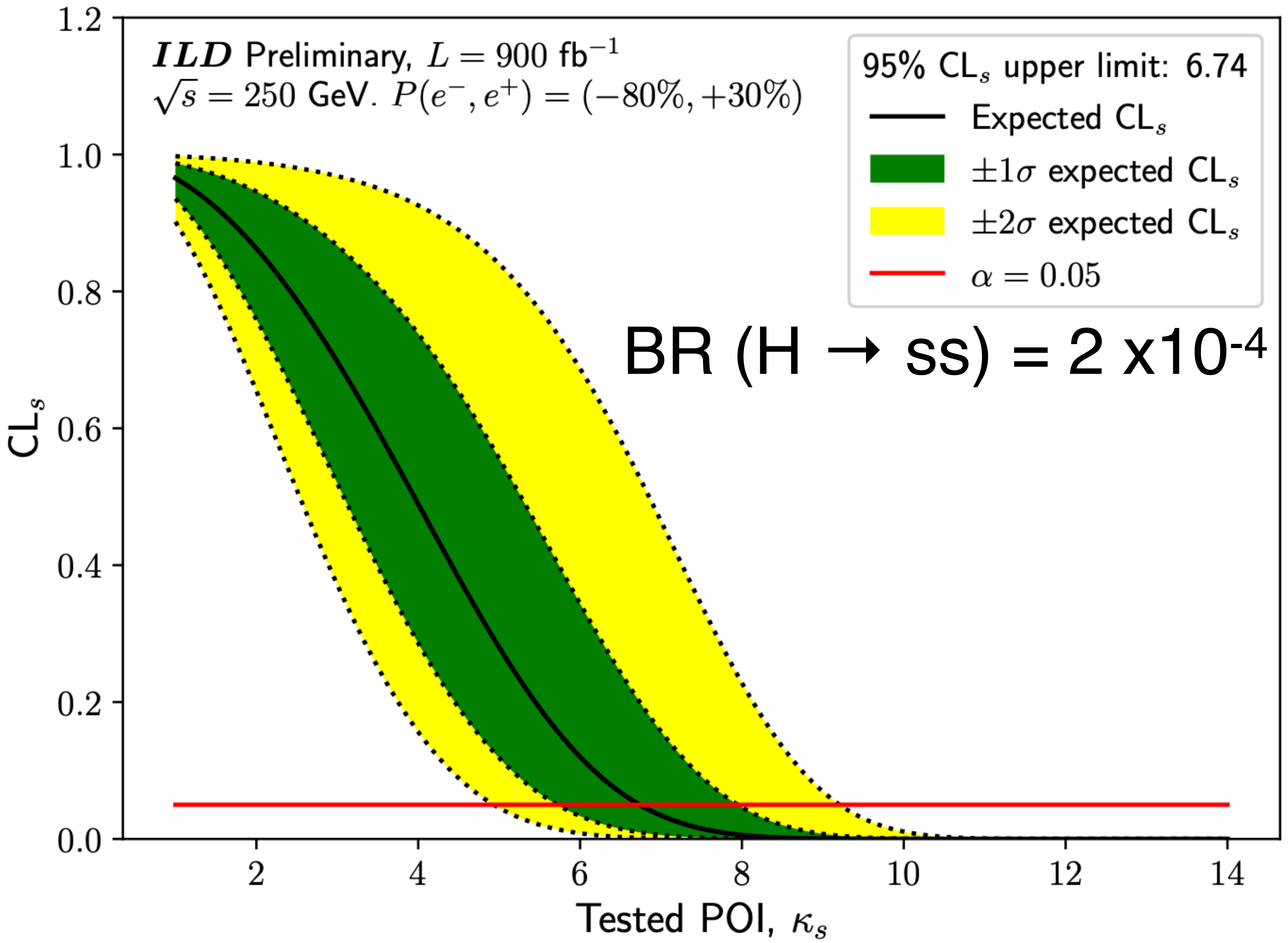


Constraints on s-coupling

Compatible results for both FCC and ILC like analyses

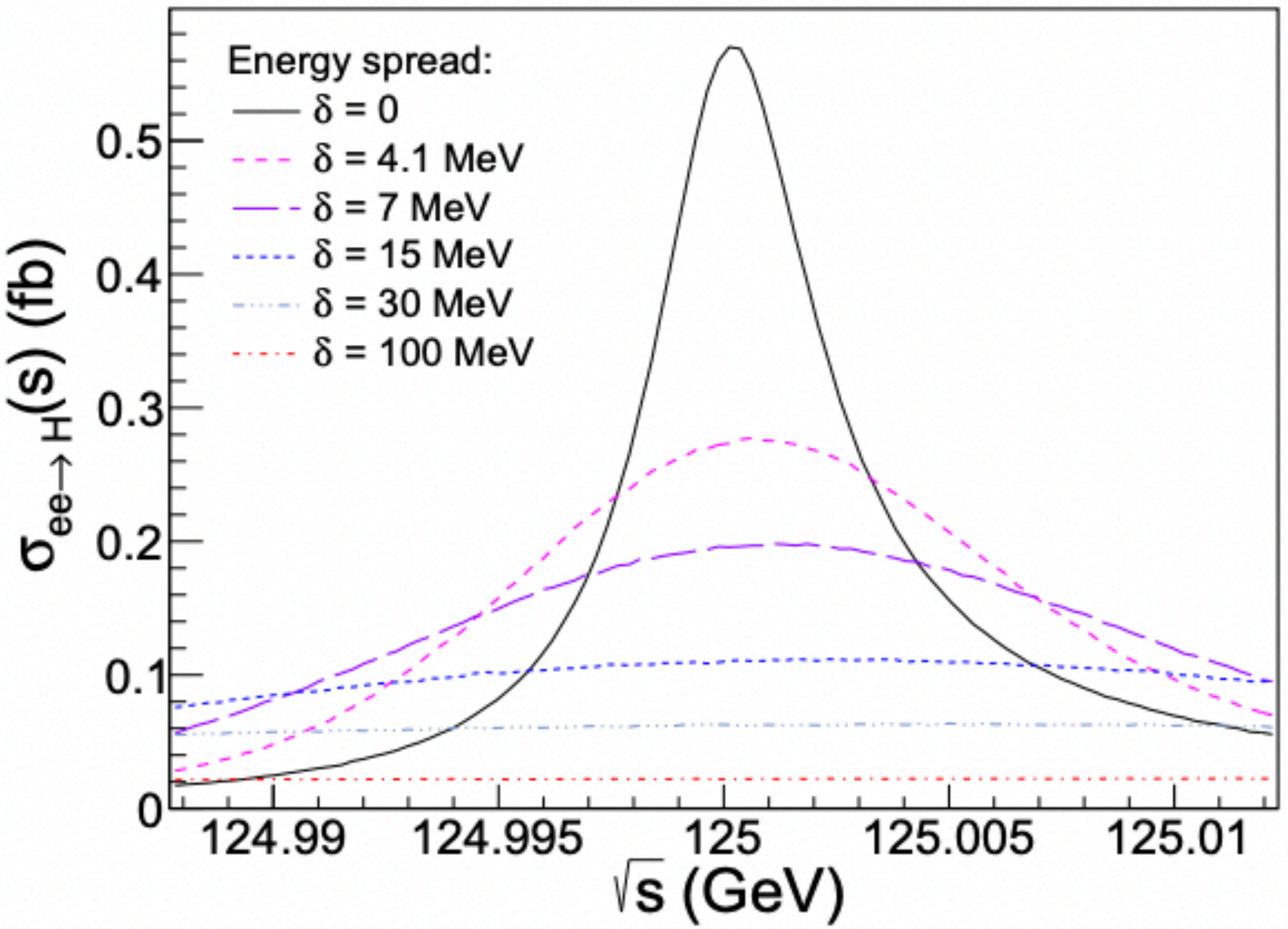
- ILD combined limit of $\kappa_s < 6.74$ at 95% CL with 900/fb at 250 GeV (i.e. half dataset)
  - No PID worsen the results by 8%
- FCC for Z(vv) only sets a limit of $\kappa_s < 1.3$ at 95% CL with 5/ab at 250 GeV and 2 IPs

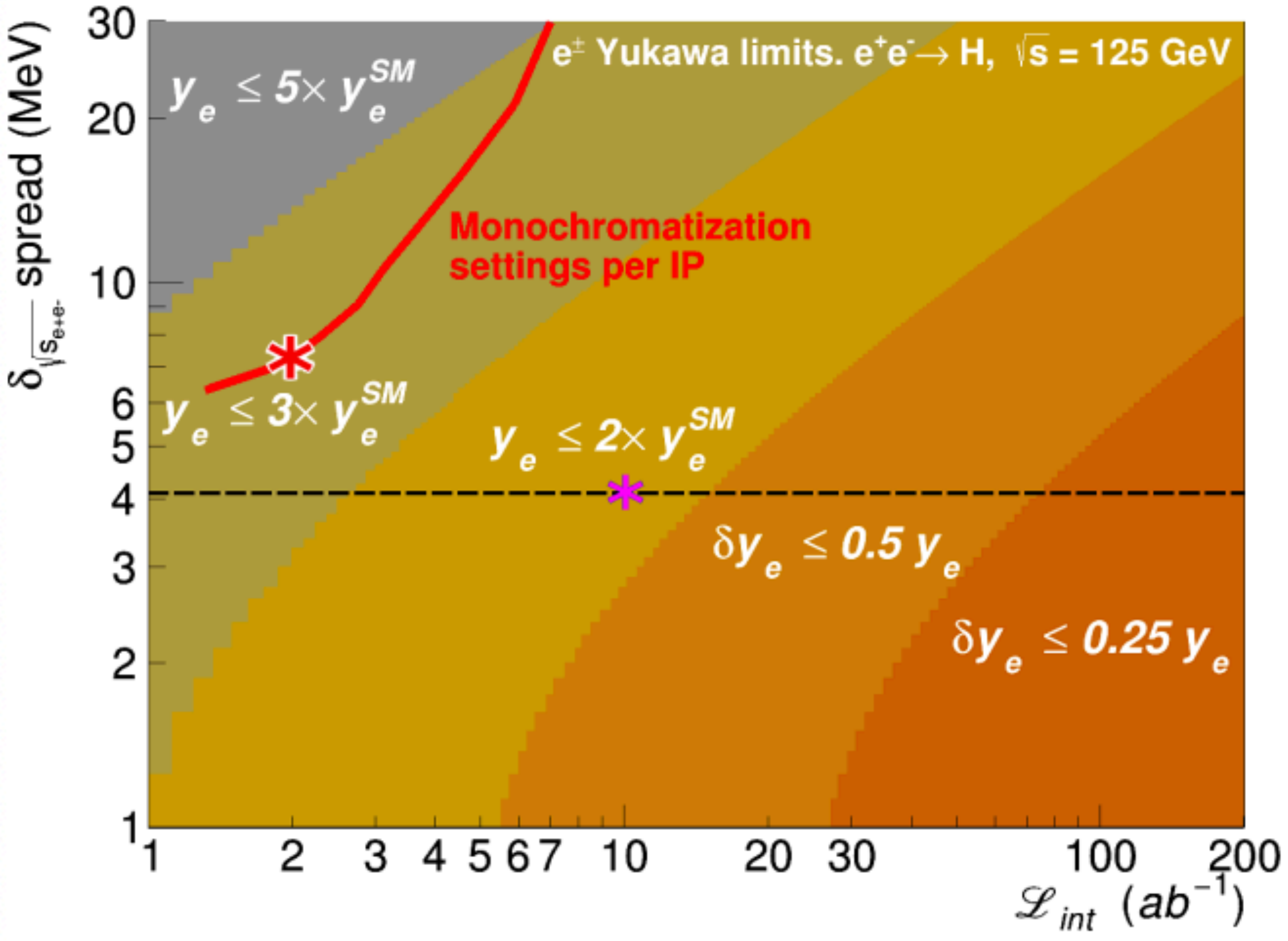




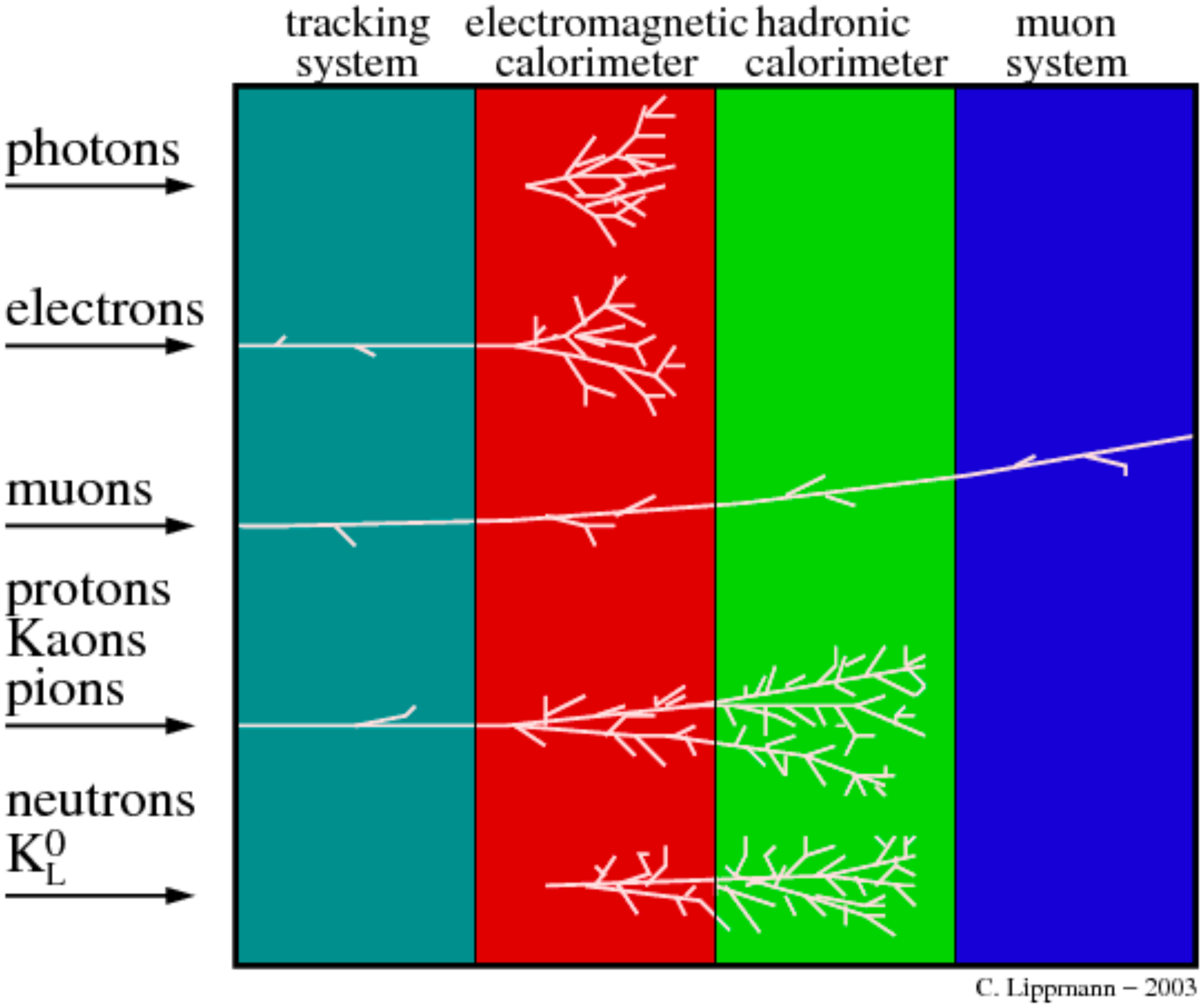
Higgs-electron Yukawa

- **Electron** Yukawa at FCC-ee with a dedicated 4 years run at the Higgs mass
  - $\kappa_e < 1.6$ at 95% CL





Detector concepts



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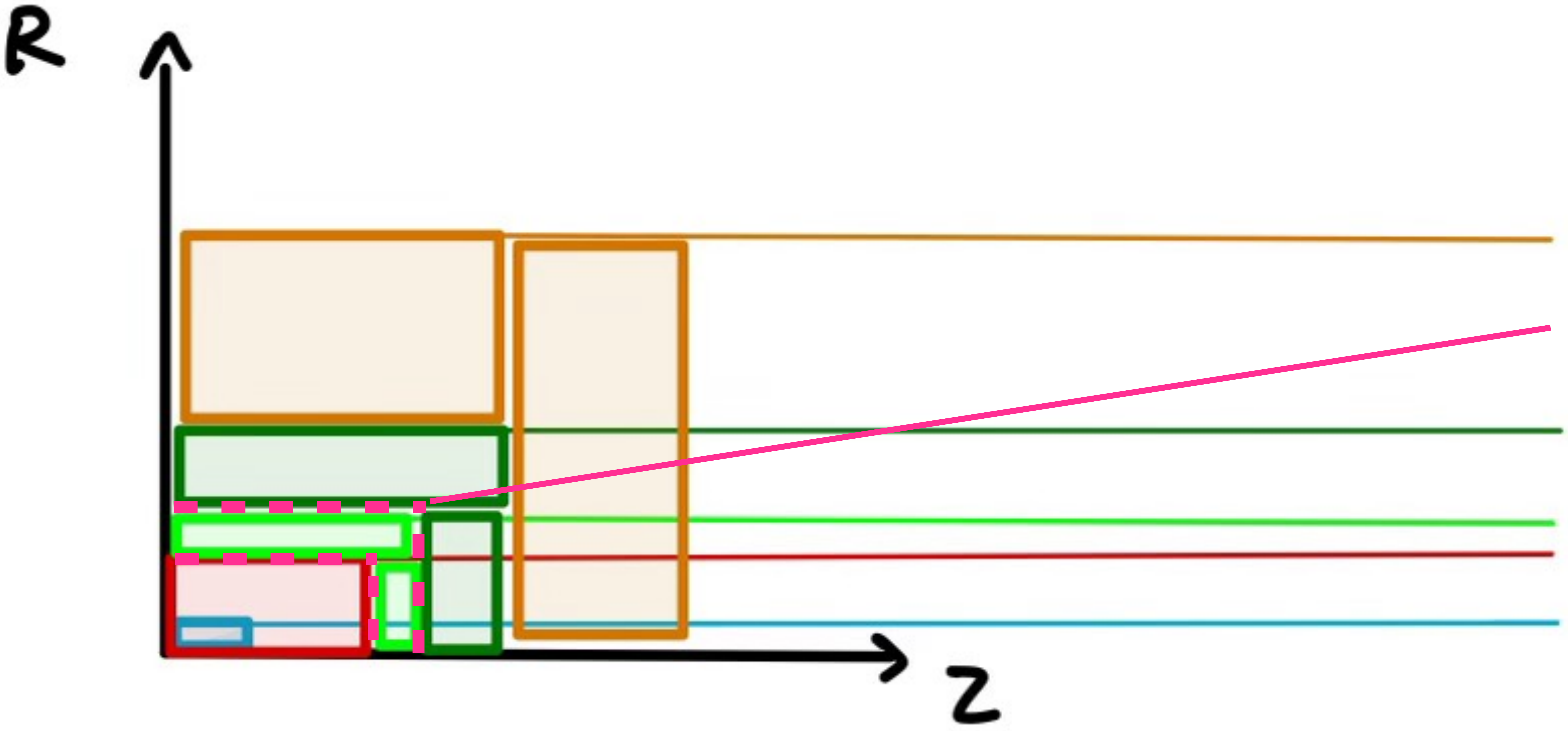


Yoke + Muon system

Solenoid $$$

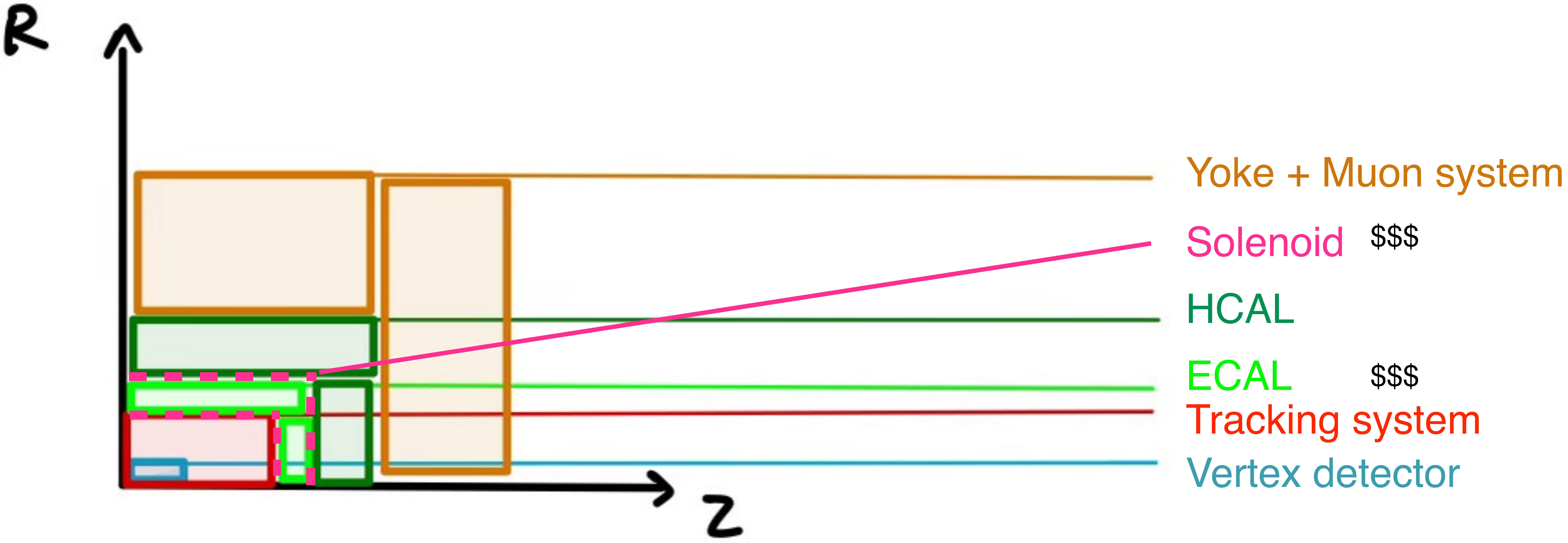
HCAL

ECAL $$$

Tracking system

Vertex detector

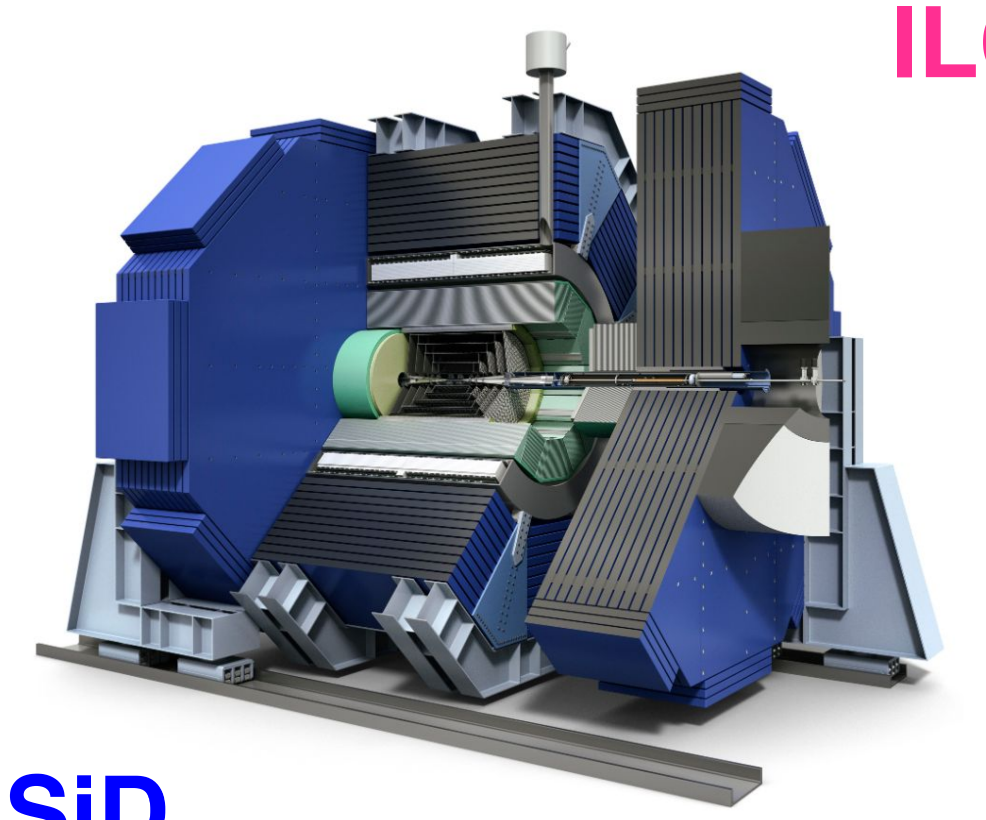
Detector concepts



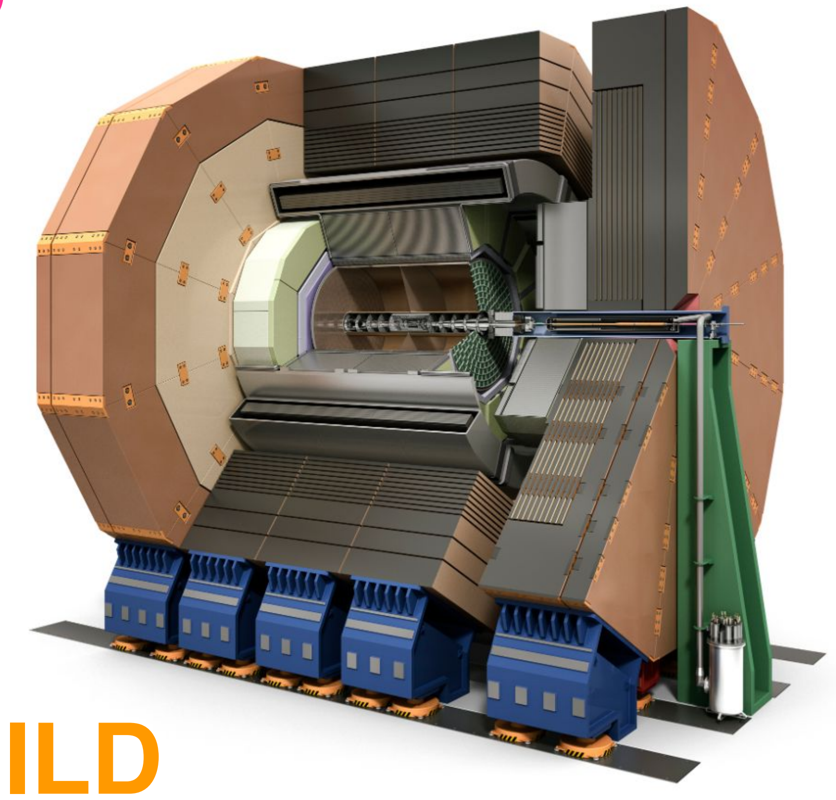
Magnet and Calorimeters are generally driving the cost (>30% each) of the detector
Optimizations and cost reduction are possible with targeted R&D

Detector Designs, a quick overview

ILC

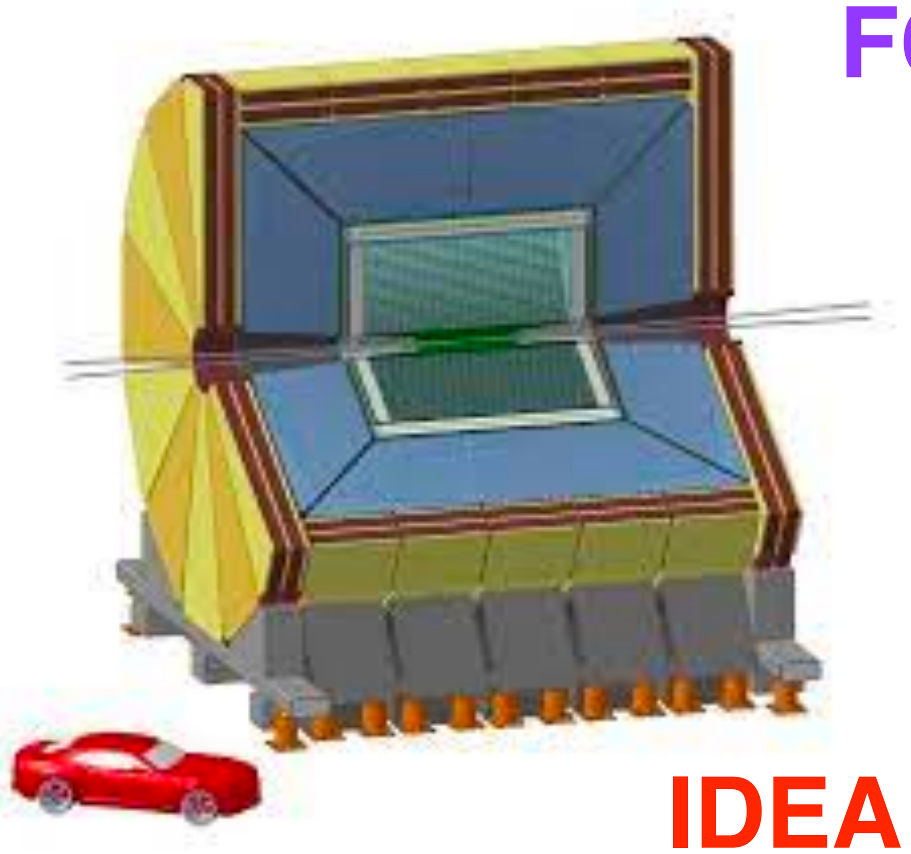


SiD

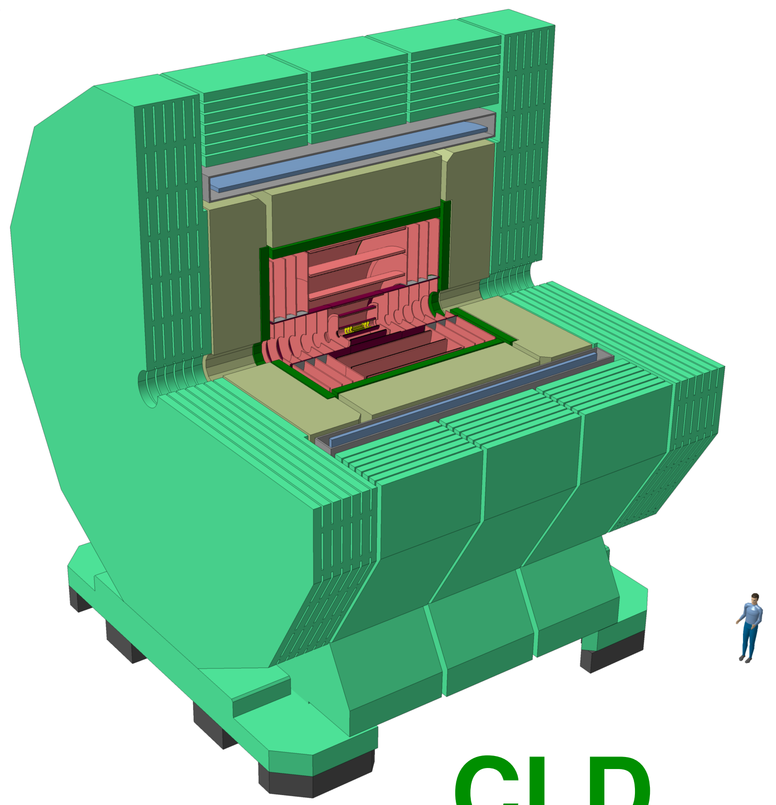


ILD

FCC



IDEA



CLD

ALLEGRO

- Detector designs at all colliders features very similar strategies, main difference is in the B field
  - FCC@Z limits B field to 2 T to avoid a blow up of the vertical beam emittance
- SiD/CLD - Compact all silicon tracking systems with highly segmented calorimeters optimized for PFA
  - CLD compensates the lower B field (2 T) with a larger tracking radius
- ILD - Larger detector with TPC tracker with PFA calorimeter
- IDEA - Drift chamber with PID and dual readout calorimeter
- Allegro - Drift chamber and silicon wrapper with timing information and noble gas calorimeter

Detector Designs, a quick overview

A tail of synergies and complementarity

	ILD	SID	IDEA	CLD	ALLEGRO
Vertex Inner Radius (cm)	1.6	1.4	1.2	1.2	1.2
Tracker technology	TPC+Silicon	Silicon	Si+Drift Chamber	Si	Si+Drift Chamber
Outer Tracker Radius (m)	1.77	1.22	2	3.3	2
ECal thickness	24 X_0	26 X_0	Dual RO	22 X_0	22 X_0
HCal thickness	5.9 λ_0	4.5 λ_0	7 λ_0	6.5 λ_0	9.5 λ_0
HCal Outer Radius (m)	3.3	2.5	4.5	3.5	4.5
Solenoid field (T)	3.5	5	2	2	2
Solenoid length (m)	7.9	6.1	6	7.4	6
Solenoid Radius (m)	3.4	2.6	2.1	4	2.7

Timing? Ongoing R&D to exploit O(10ps) capabilities

BUT nowadays there are several technologies to achieve O(10) ps resolution

Detector Designs, a quick overview

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BUT nowadays there are several technologies to achieve O(10) ps resolution

Sensors technology requirements for Vertex Detector

Services cables + cooling + support make up most of the detector mass

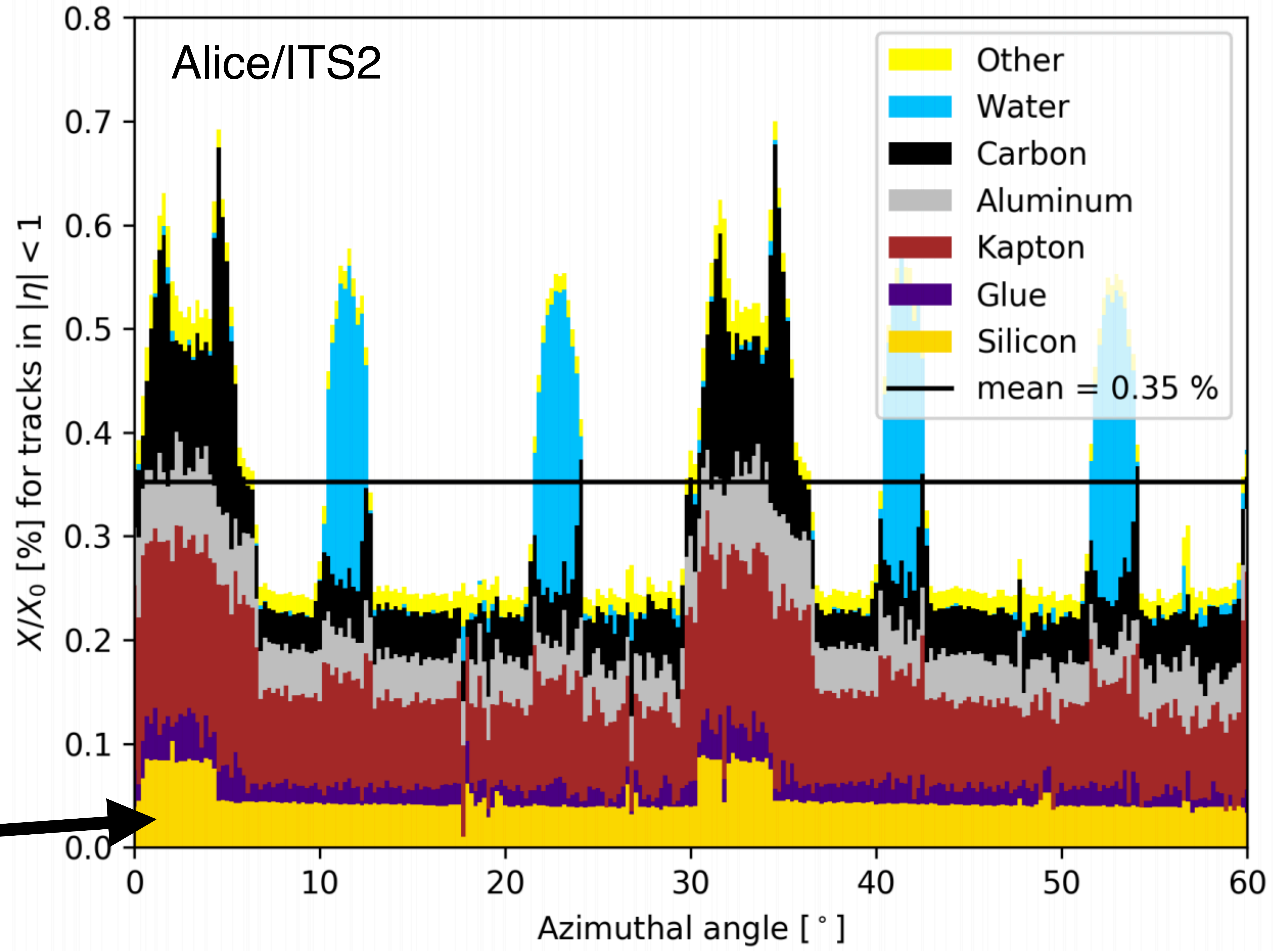
Physics driven requirements	Running constraints	Sensor specifications	
σ *$< 3\ \mu m$*		Small Pixel	*~15μm*
Material budget *$0.1\%X_0/layer$*		Thinning to	*50 μm*
Material budget	Cooling	Low Power	*20-50 mW/cm²*
r of the Inner most layer *12-14 mm*	Beam-background	Fast Readout	*~1-10 μs*
r of the Inner most layer	Radiation damage	Radiation Tolerance	*10 MRad, $10^{14}\ n_{eq}$ / /cm^2*

Sensors technology requirements for Vertex Detector

Services cables + cooling + support make up most of the detector mass

CERN-LHCC-2019-018

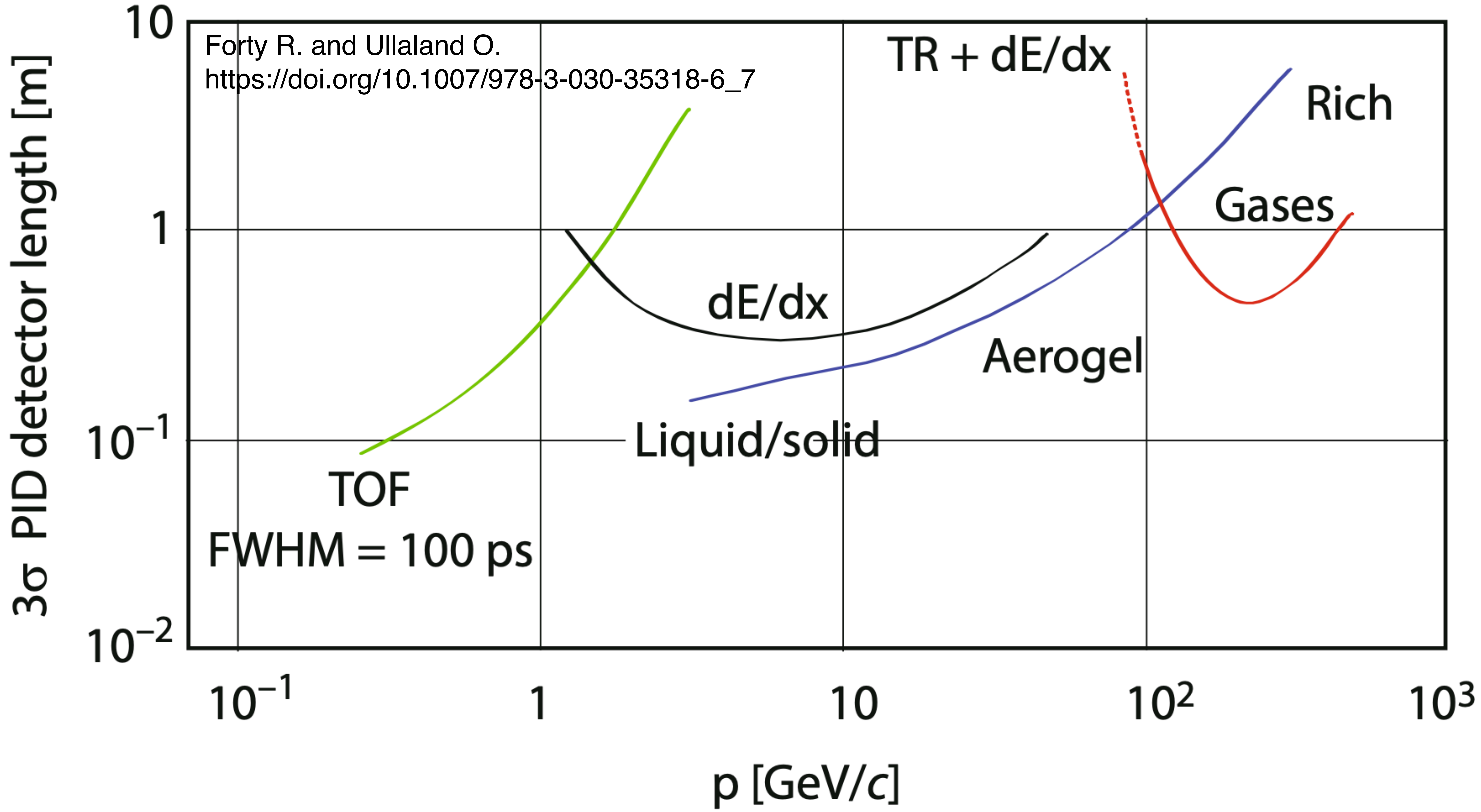
Sensor's contribution to the total material budget is 15-30%



arXiv:2202.03285
arXiv:1912.04601
e2019-900045-4
NIMA 1059 (2024)

Particle ID

Combining different strategies for optimal PID performance across a wide p_T range

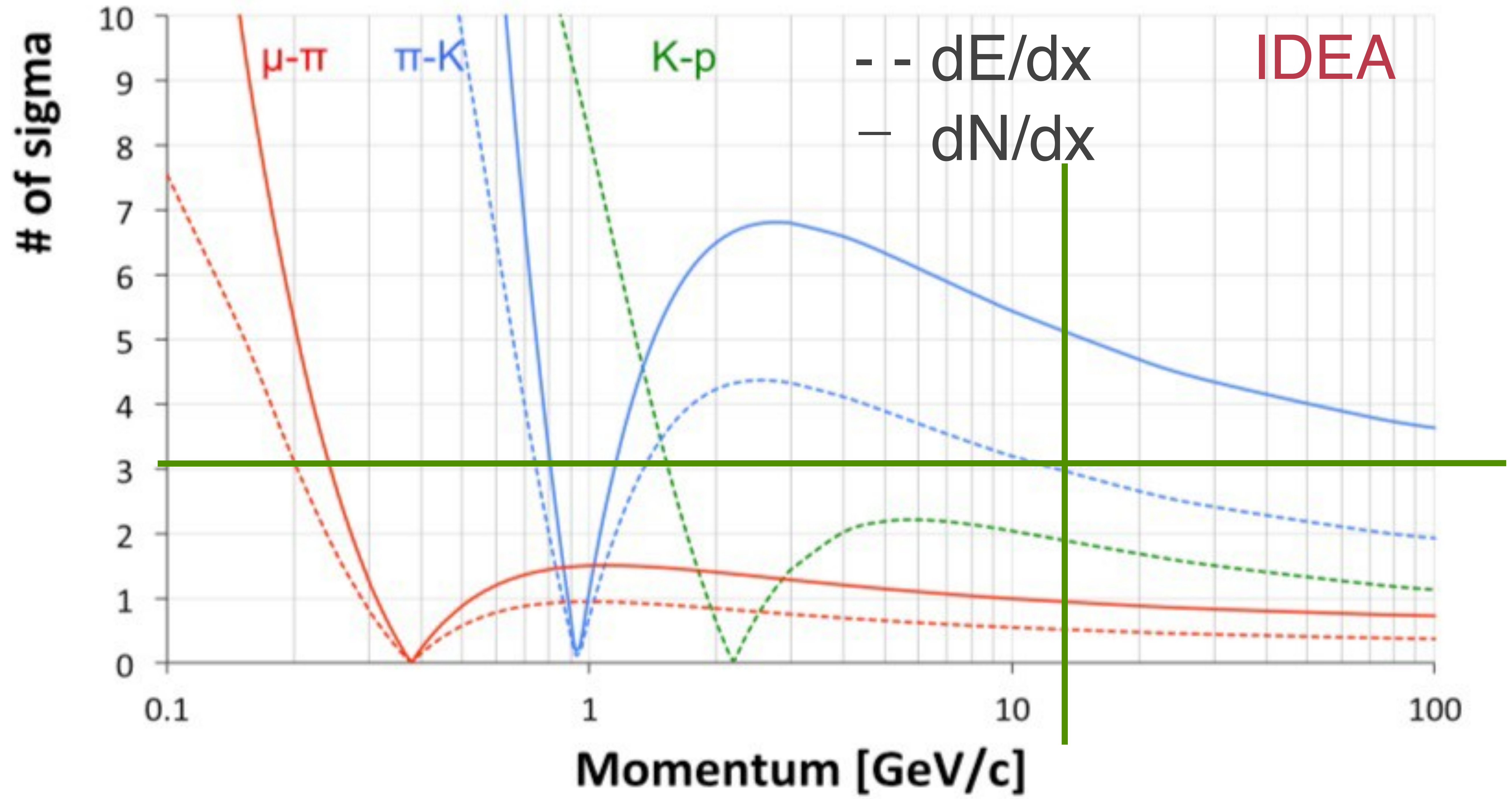


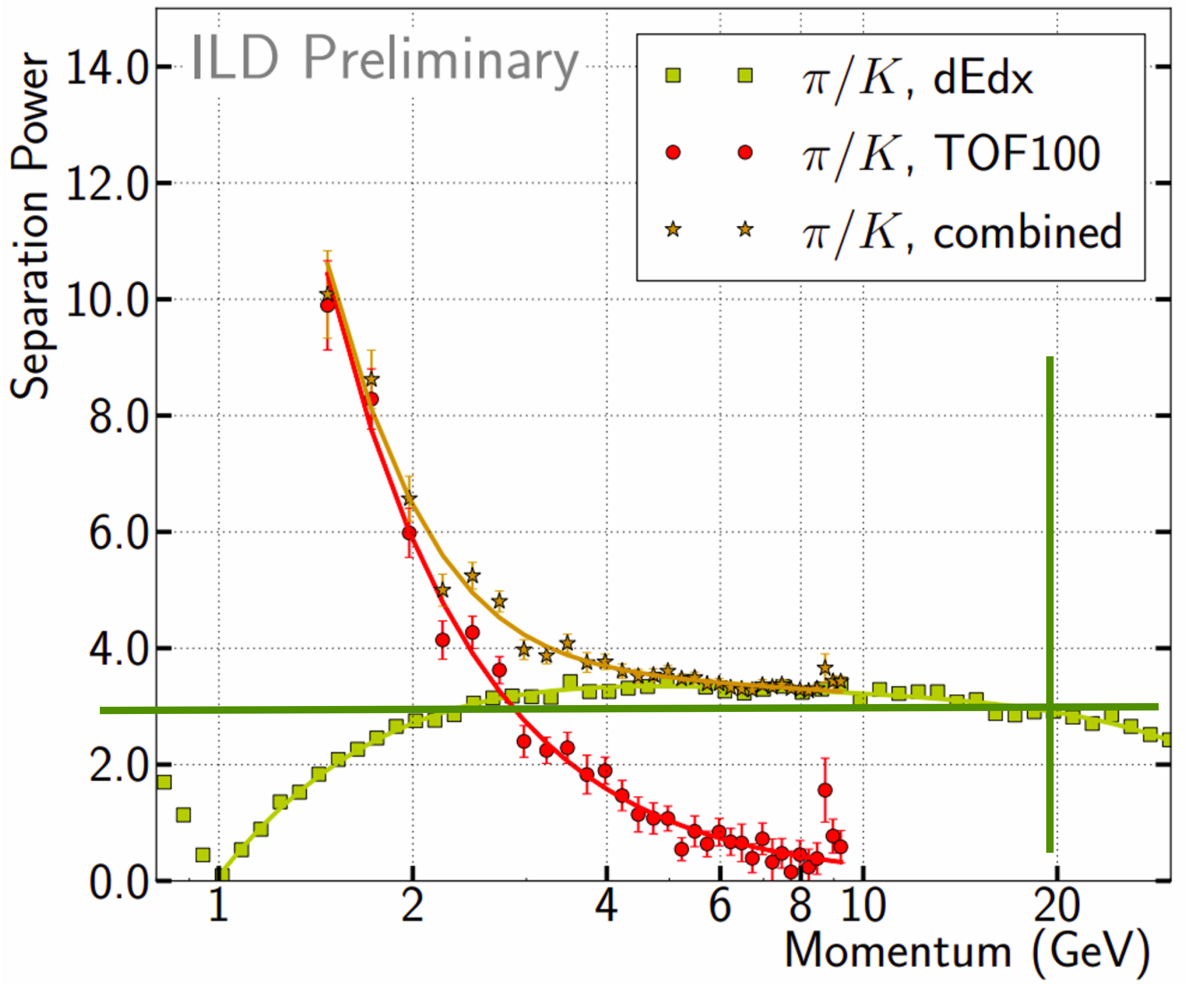
arXiv:2202.03285
arXiv:1912.04601
e2019-900045-4
NIMA 1059 (2024)

Particle ID

Combining different strategies for optimal PID performance across a wide p_T range

- Timing (e.g. ECAL, HCAL or timing layer) for time-of-flight for momentum < 5 GeV
- dE/dx from silicon (< 5 GeV) and large gaseous tracking detectors (< 30 GeV)
    - PID for momentum larger than few GeVs via ionisation loss measurement (dE/dx or dN/dx)
- Use H → ss to inform detector design, while monitoring other benchmarks' performance
    - RICH could improve reconstruction of $K^{+/-}$ at high momentum (10-30 GeV)

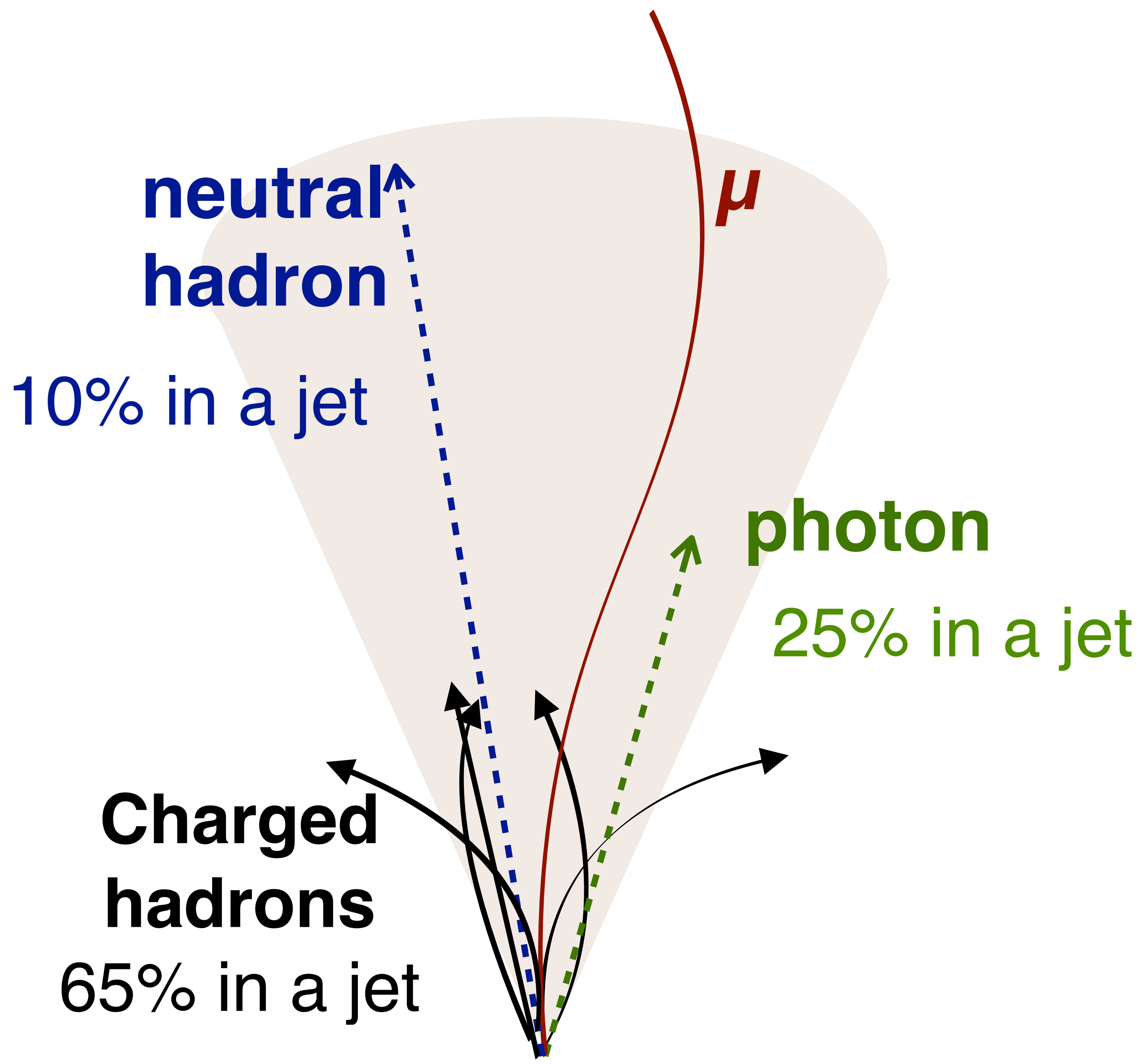


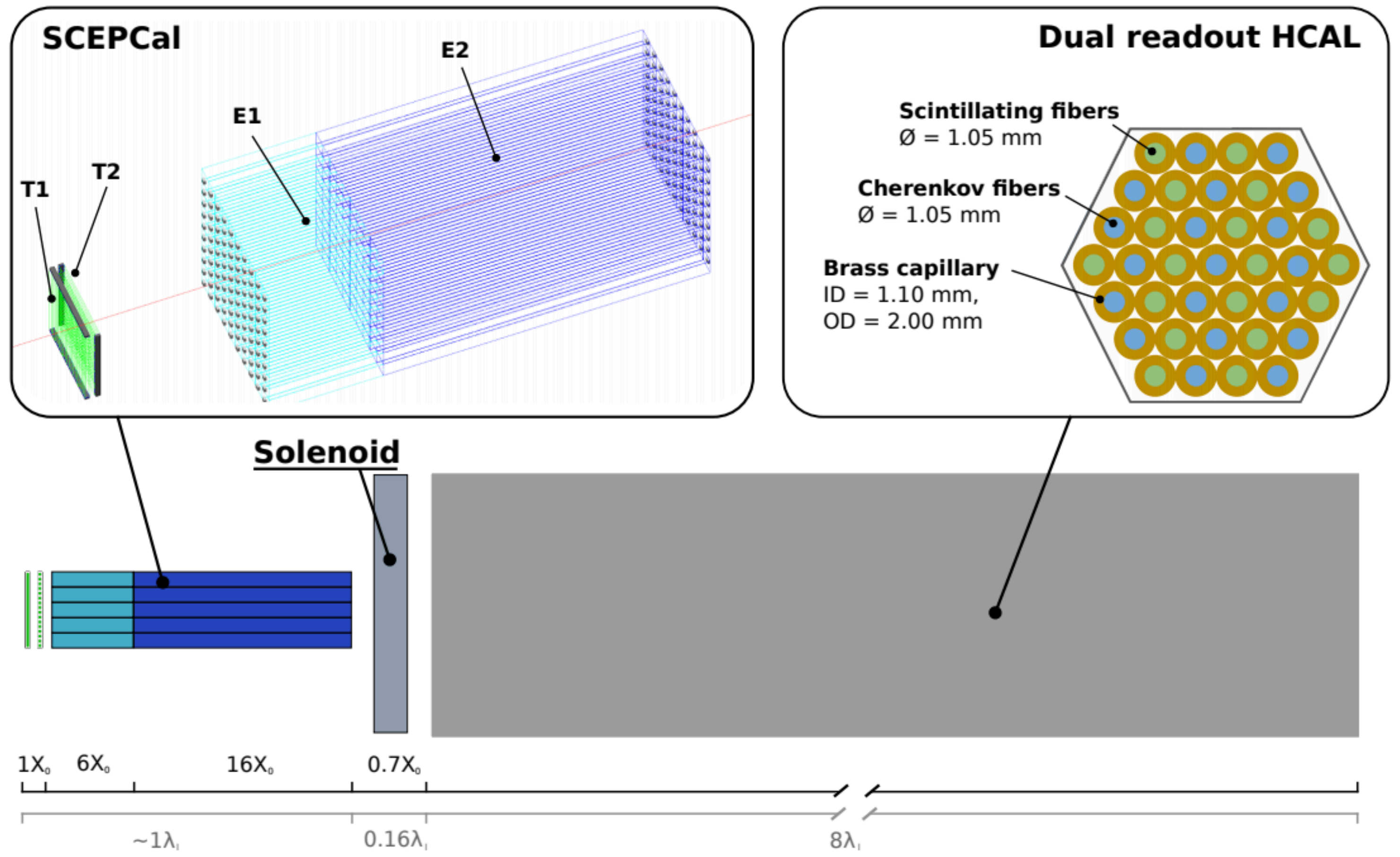


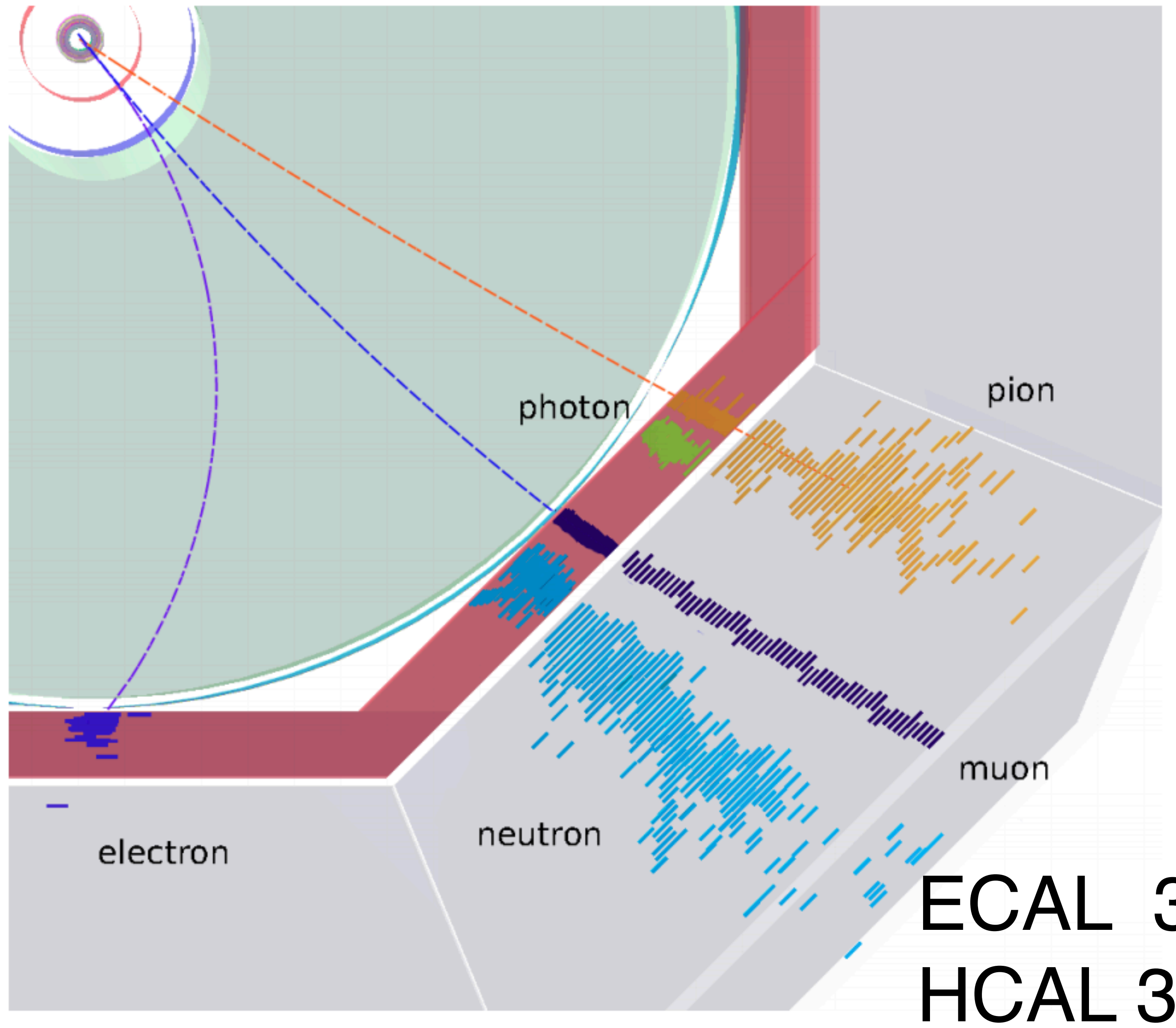
Particle Flow Calorimeters

CALICE

- Particle-flow algorithm (PFA) leverages excellent momentum resolution from tracker to measure charged hadron contribution to allow a precise reconstruction of each particle within the jet
  - This enables
- Fine granularity allows for identification of two showers down to the mm scale of separation
  - Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV







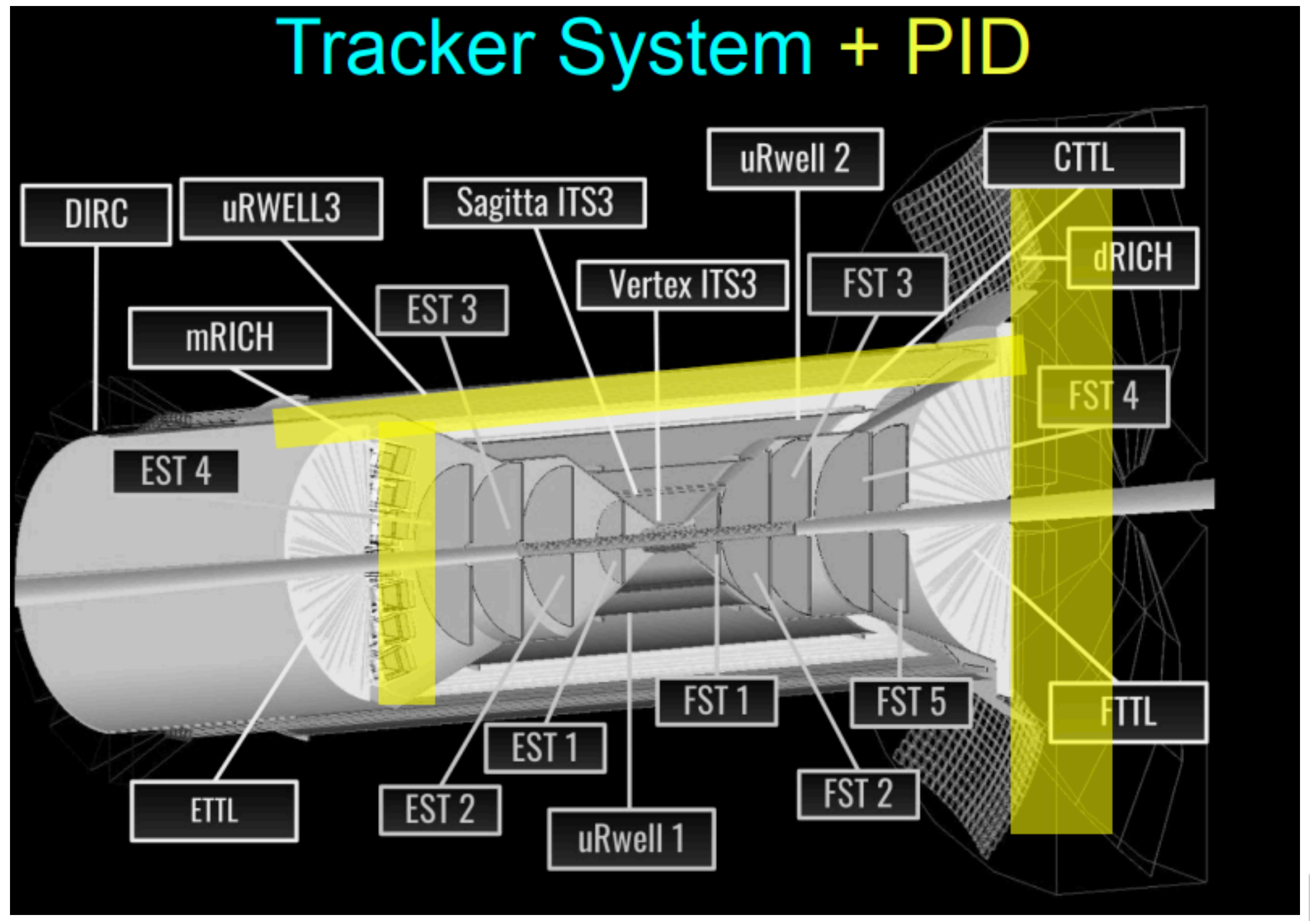
ECAL 3%/√E
HCAL 30%/√E

C. Fanelli EPIC (2023) arXiv:2205.09185
NeurIPS 33, 14650-14662 (2020)
arXiv:2308.16680

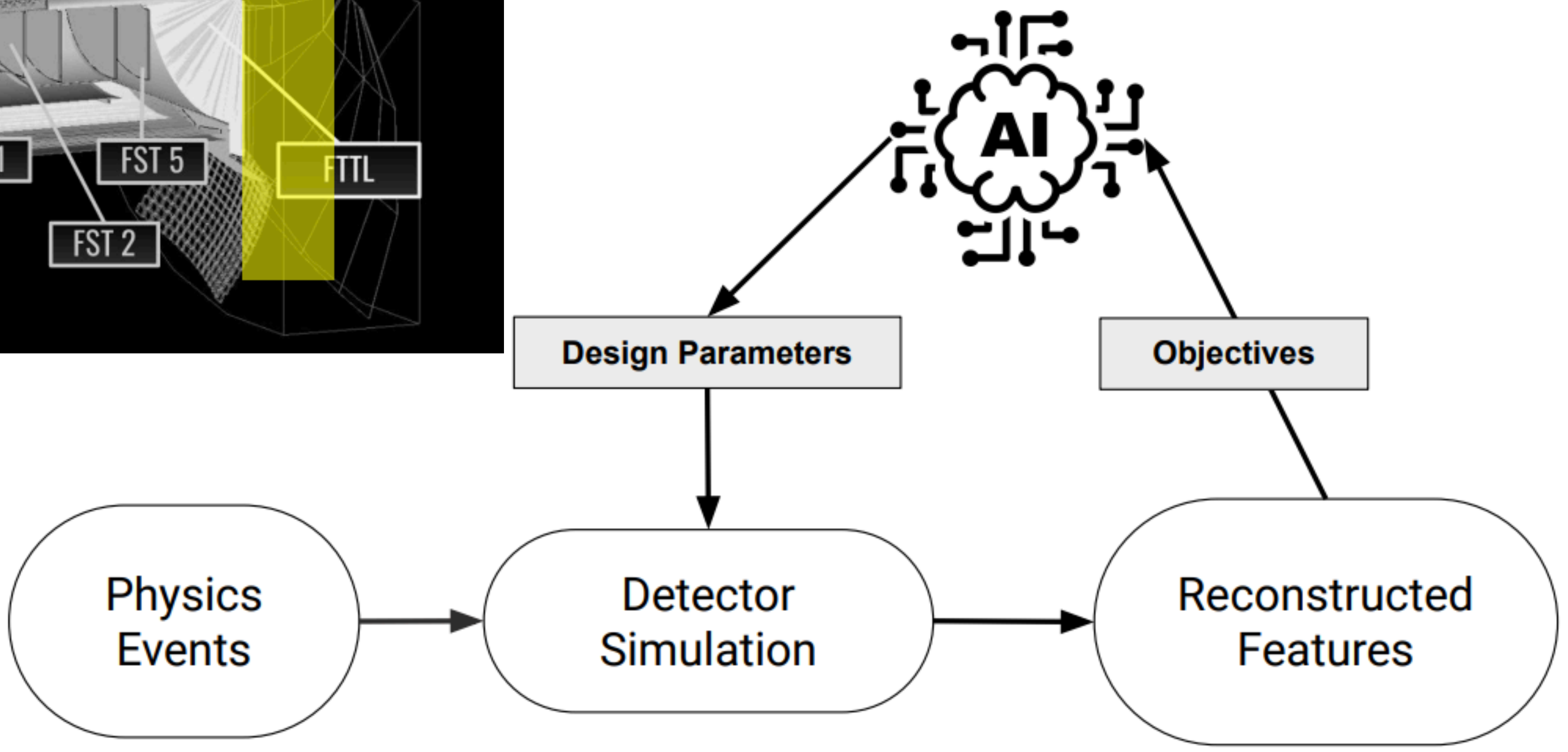
AI for detector optimization

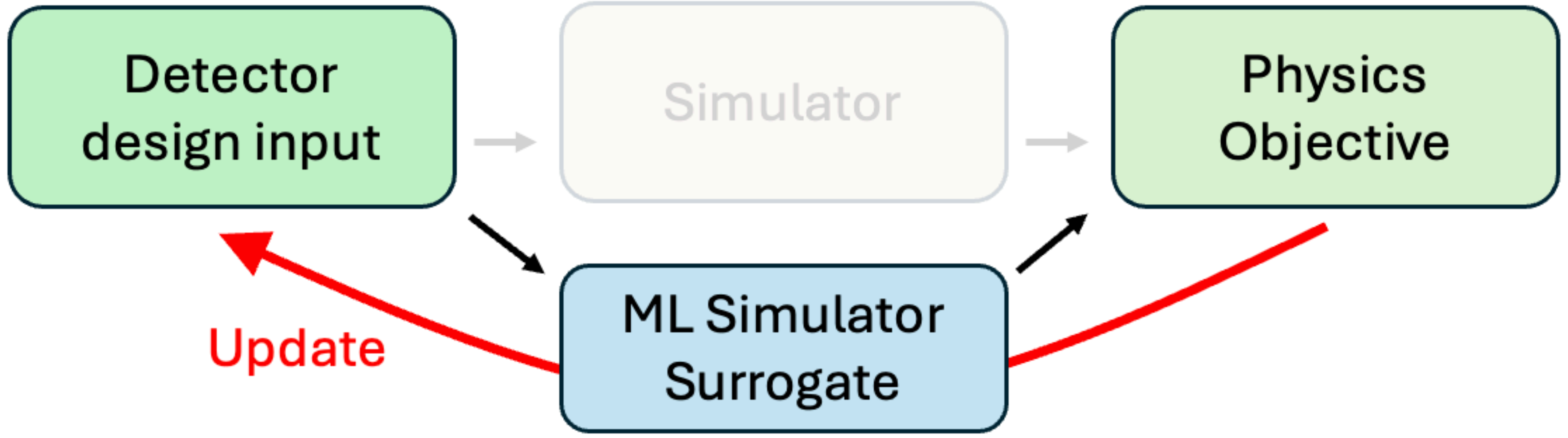
EIC is employing AI to assist detector design

- Detector optimization is a multi-dimensional design optimization problem
  - Multiple objectives that encode the detector performance and several mechanical constraints
  - The AI-assisted design is agnostic to the simulation framework and can be extended to any sub-detectors
- Train generative model as surrogate simulator to automatize detector design optimization
  - Recent work to integrate and optimize simulators directly into ML frameworks to optimize simulator directly

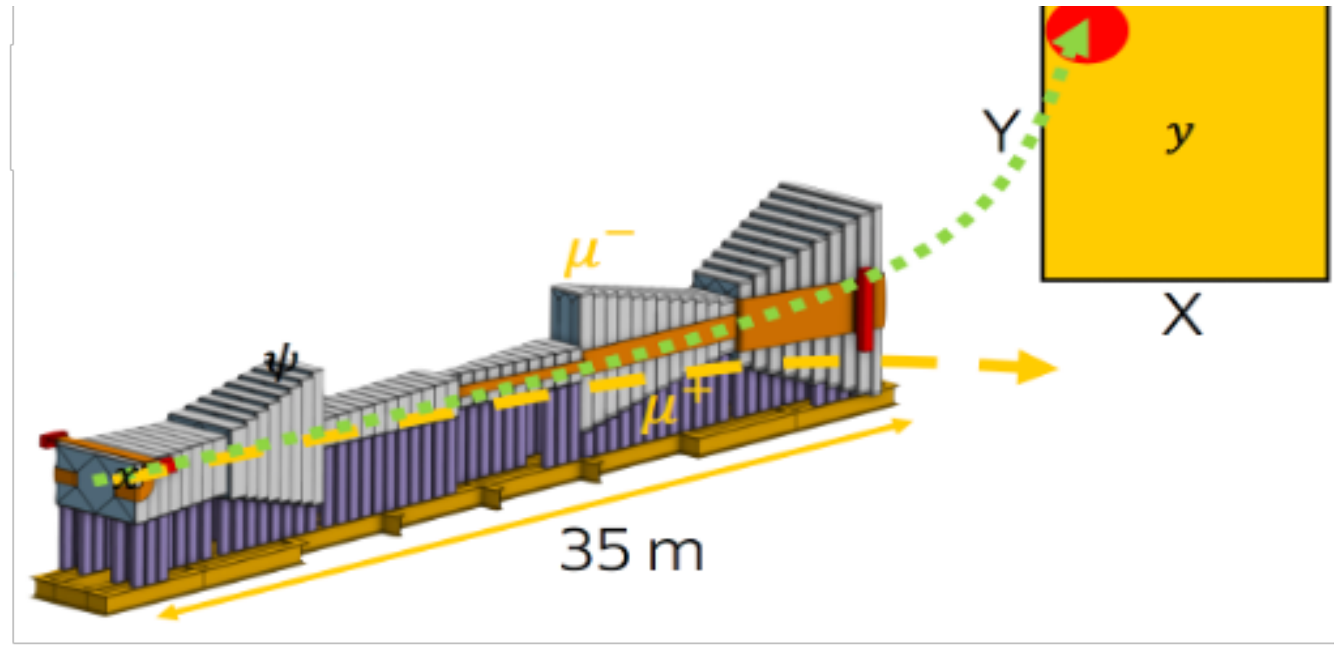


EIC

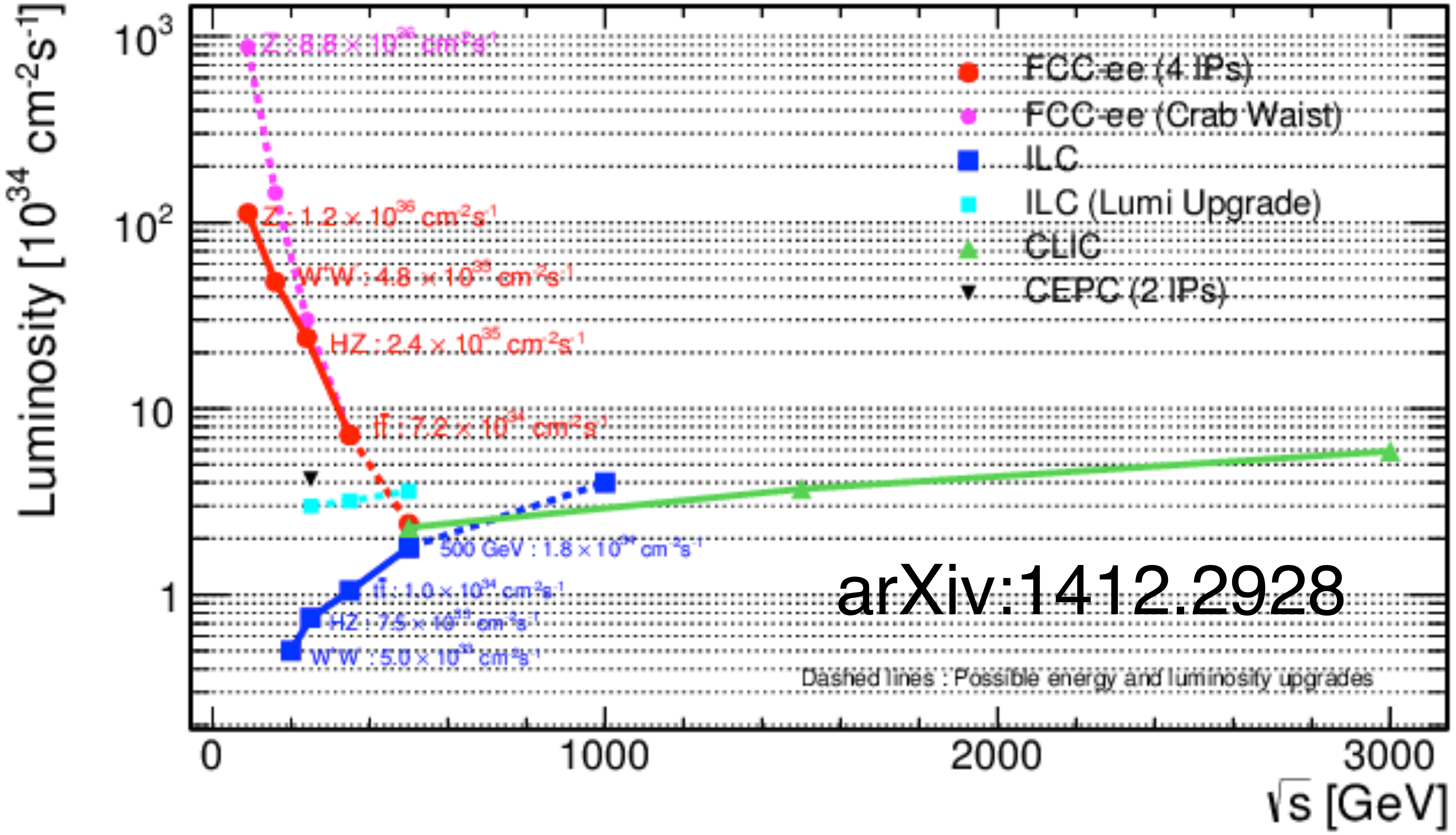


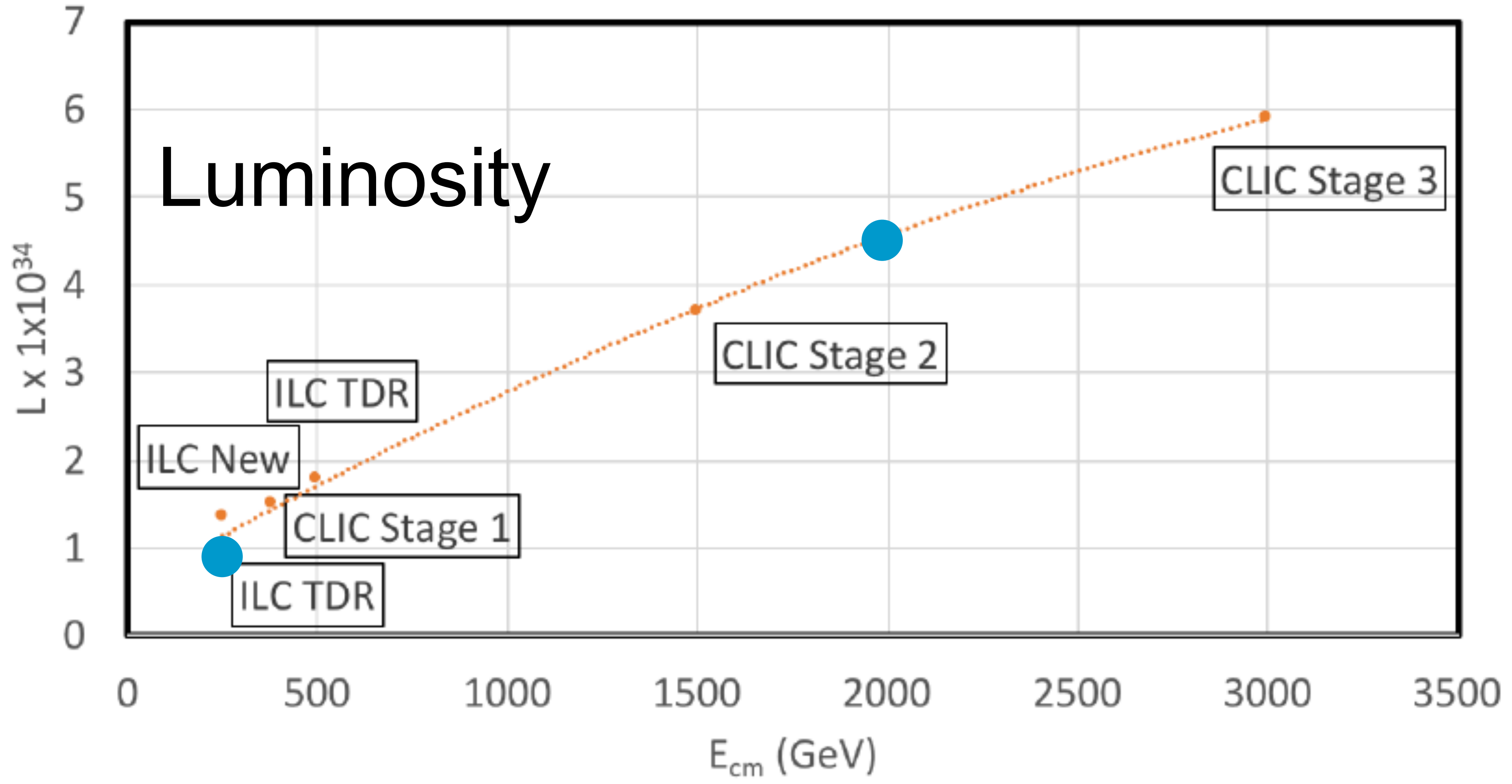


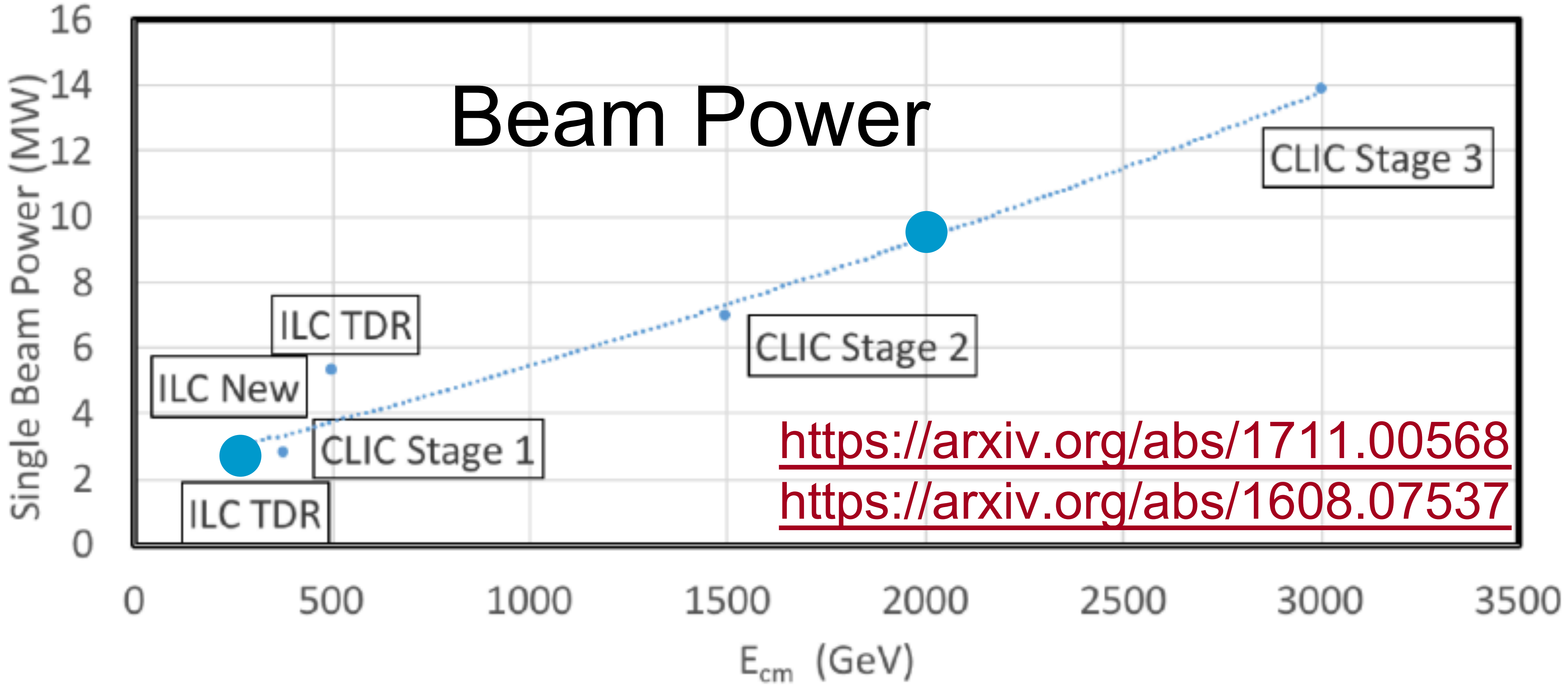
M. Kagan



Luminosity optimization



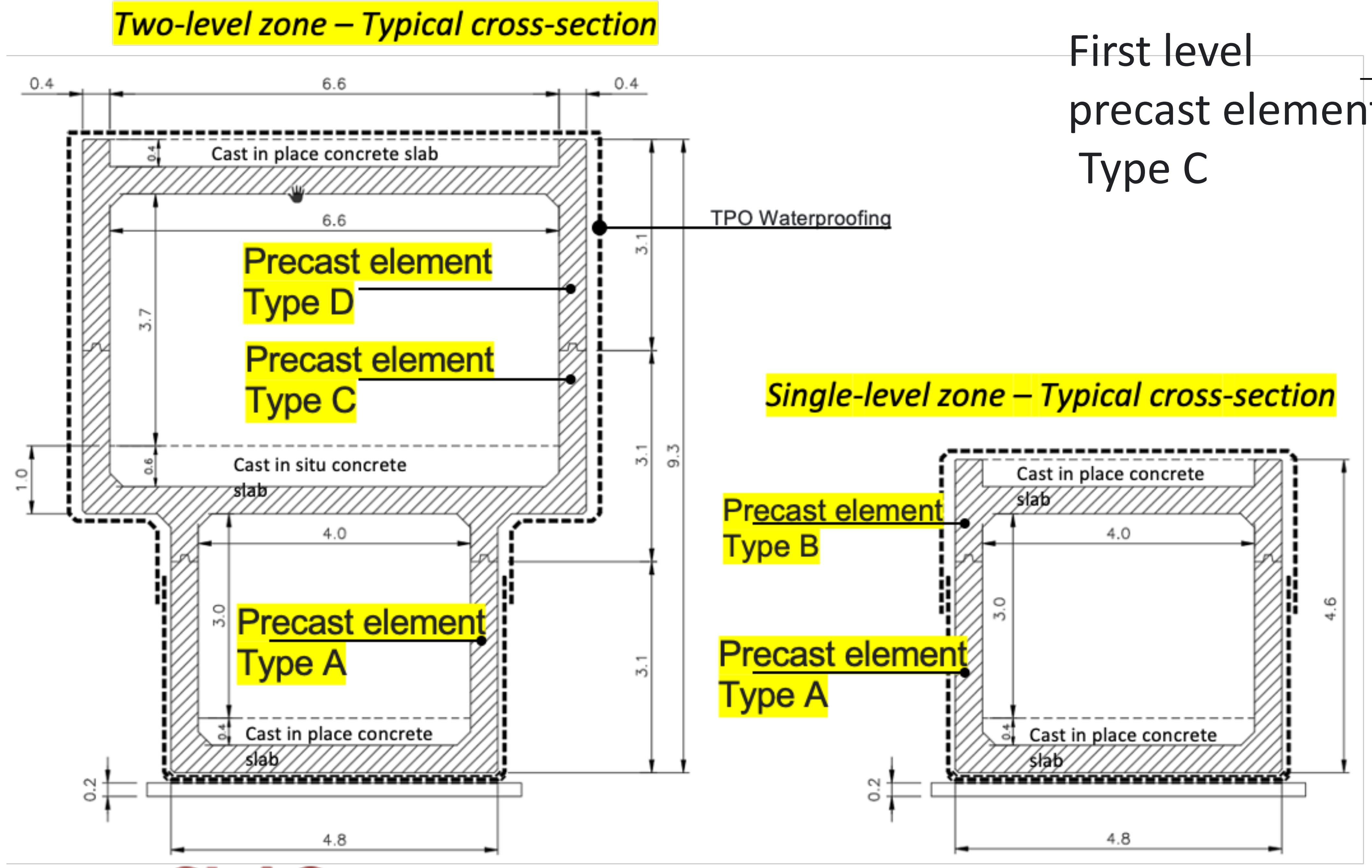




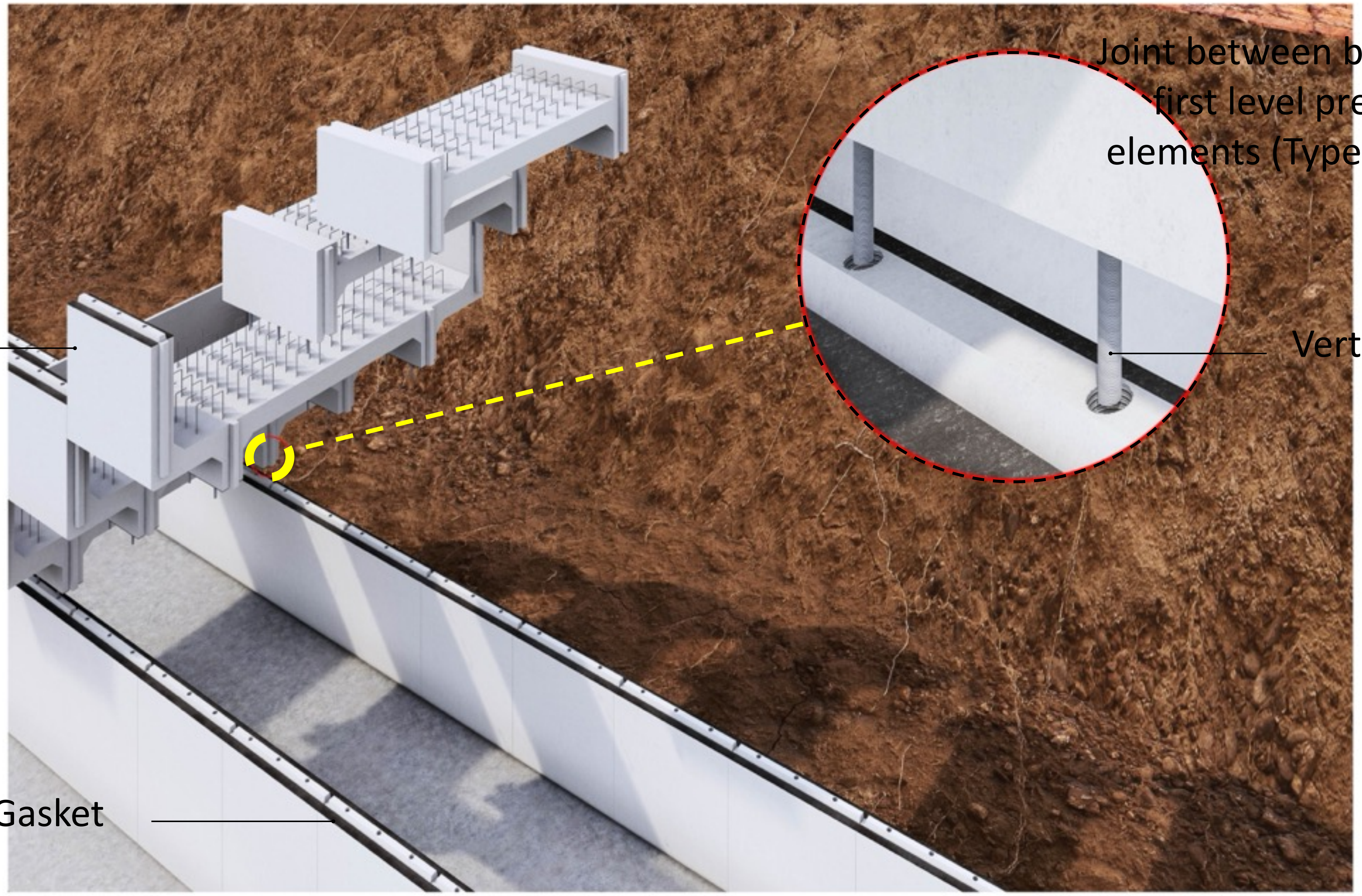
https://arxiv.org/abs/1711.00568
https://arxiv.org/abs/1608.07537

Rapid Construction with a Surface Site

- “Cut and cover” construction
- Precast concrete housing elements made on site
- Limited waster material – reuse material to cover tunnel
- Requires low density site e.g. Hanford



First level precast elements installation



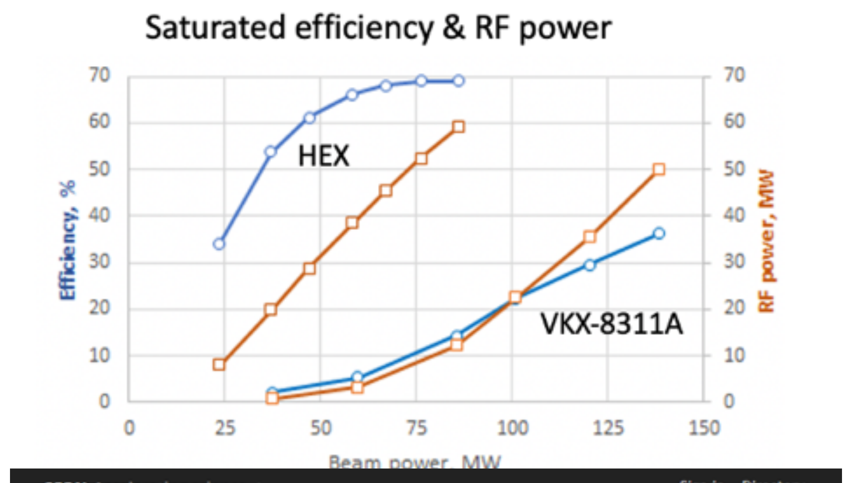
Global Contributions

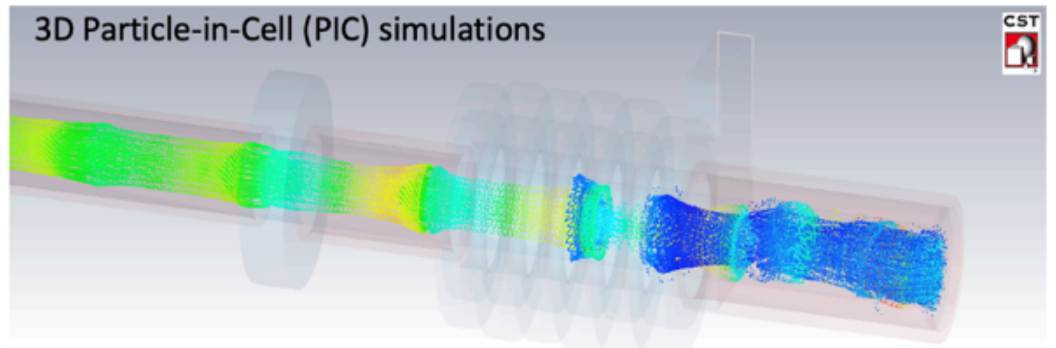
C³ Technical Timeline Only Possible with the Exceptional Progress of ILC and CLIC

- Benefit from injector complex and beam delivery concepts
- Continue to benefit from technological improvement by ILC and CLIC

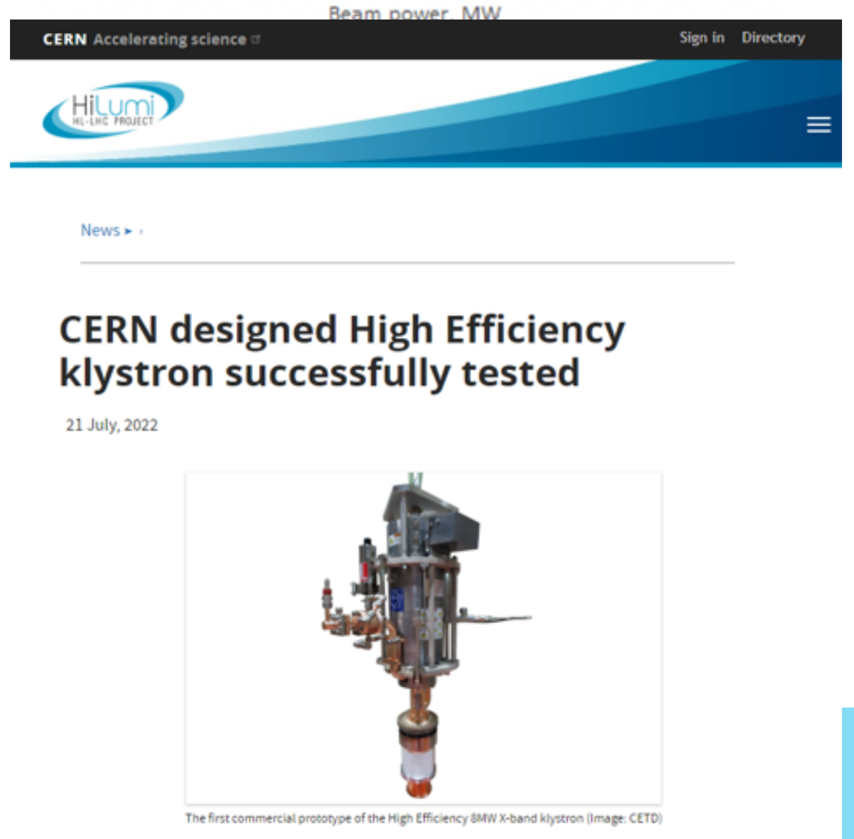
High Efficiency RF Sources (CLIC)

Retro-fit High Efficiency 50 MW, 12 GHz klystron (CERN/CPI).



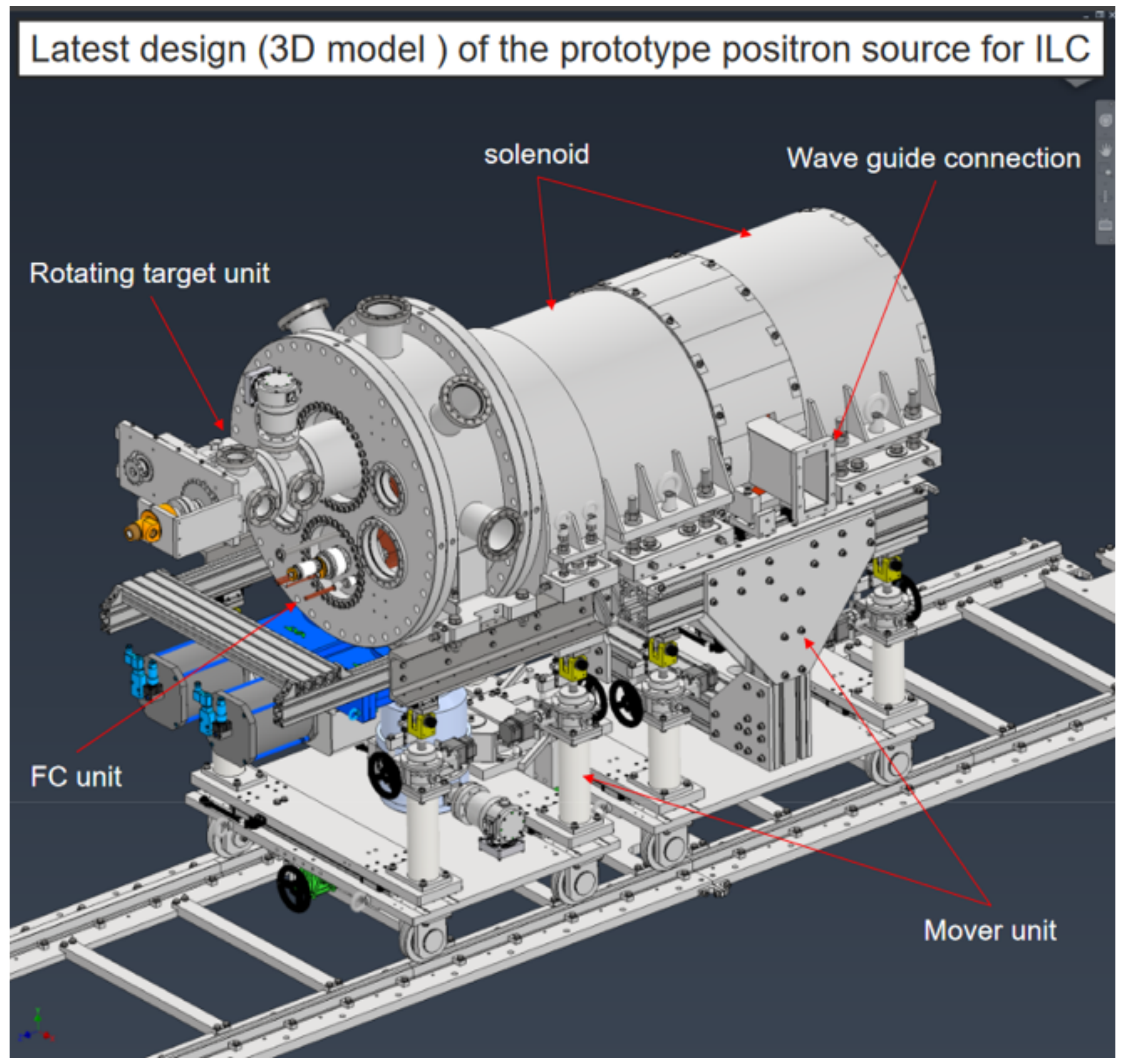


	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	59
Efficiency, %	36.2	69
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.37
RF circuit length, m	0.316	0.316



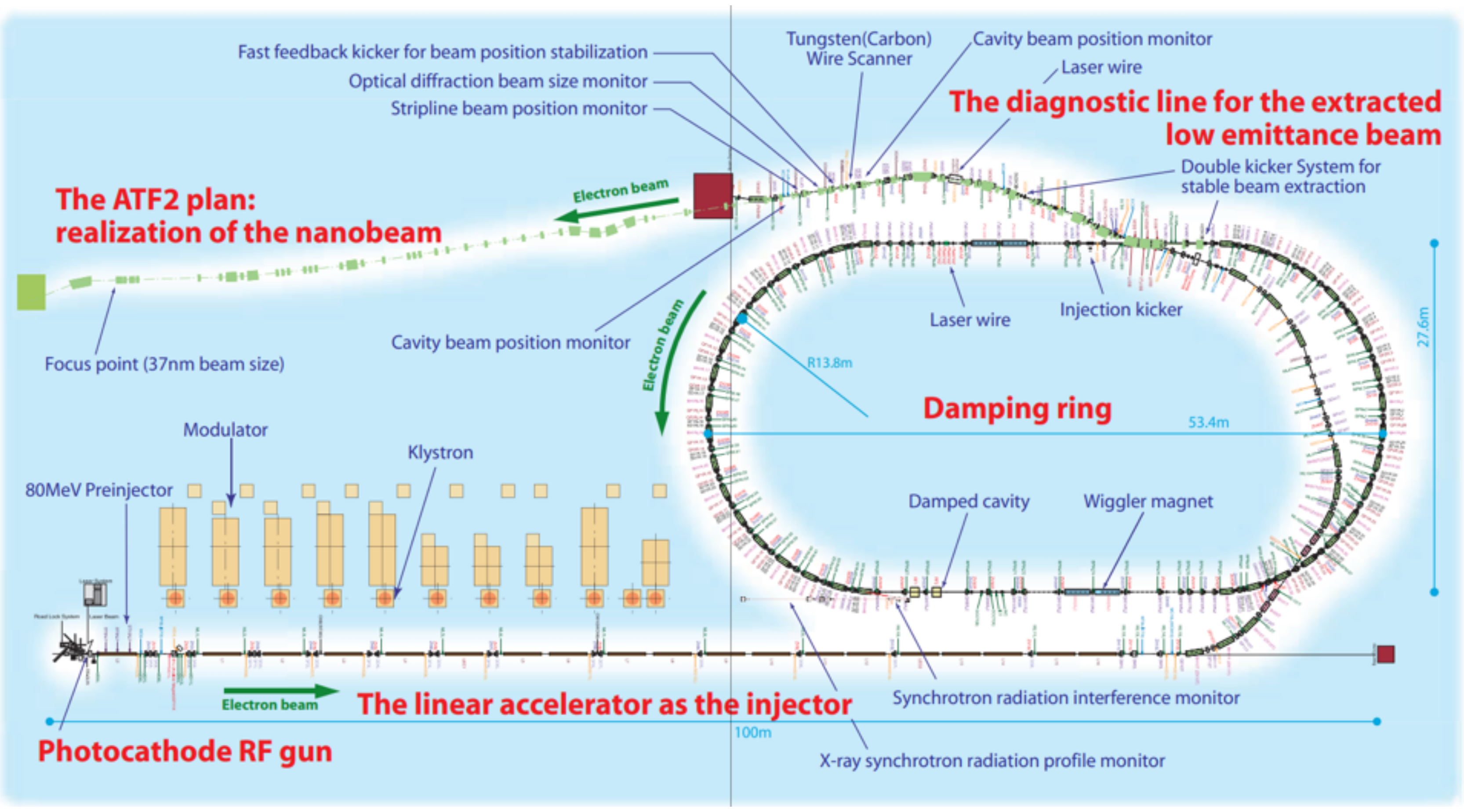
I. Sarchev, CERN

Electron Driven Positron Source



Courtesy of Y. Enomoto

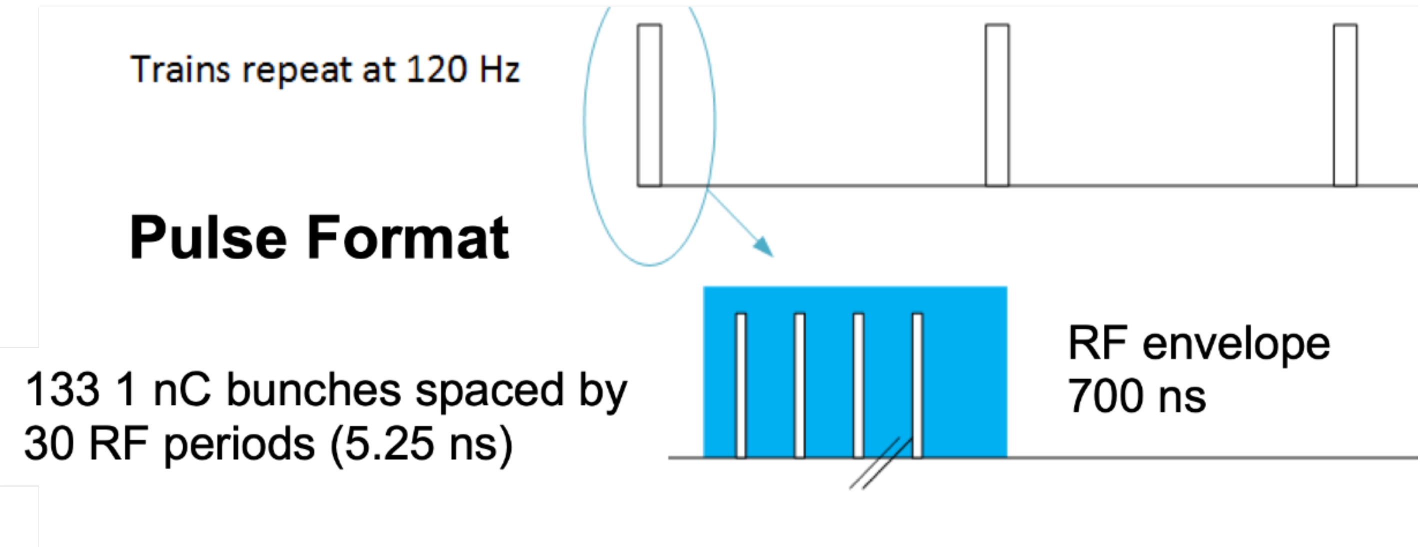
Nanobeams for IP (ATF)



https://www-atf.kek.jp/atf/

Vibrant International Community for Future Colliders is Essential
National Future Colliders R&D in the US to Optimize Efforts

Power Consumption and Sustainability



Temperature (K)	77
Beam Loading (%)	45
Gradient (MeV/m)	70
Flat Top Pulse Length (μs)	0.7
Cryogenic Load (MW)	9
Main Linac Electrical Load (MW)	100
Site Power (MW)	~150

Compatibility with Renewables
Cryogenic Fluid Energy Storage

Highview Power

Intermittent and variable power production from renewables mediated with commercial scale energy storage and power production

250 GeV CoM - Luminosity - 1.3×10^{34}

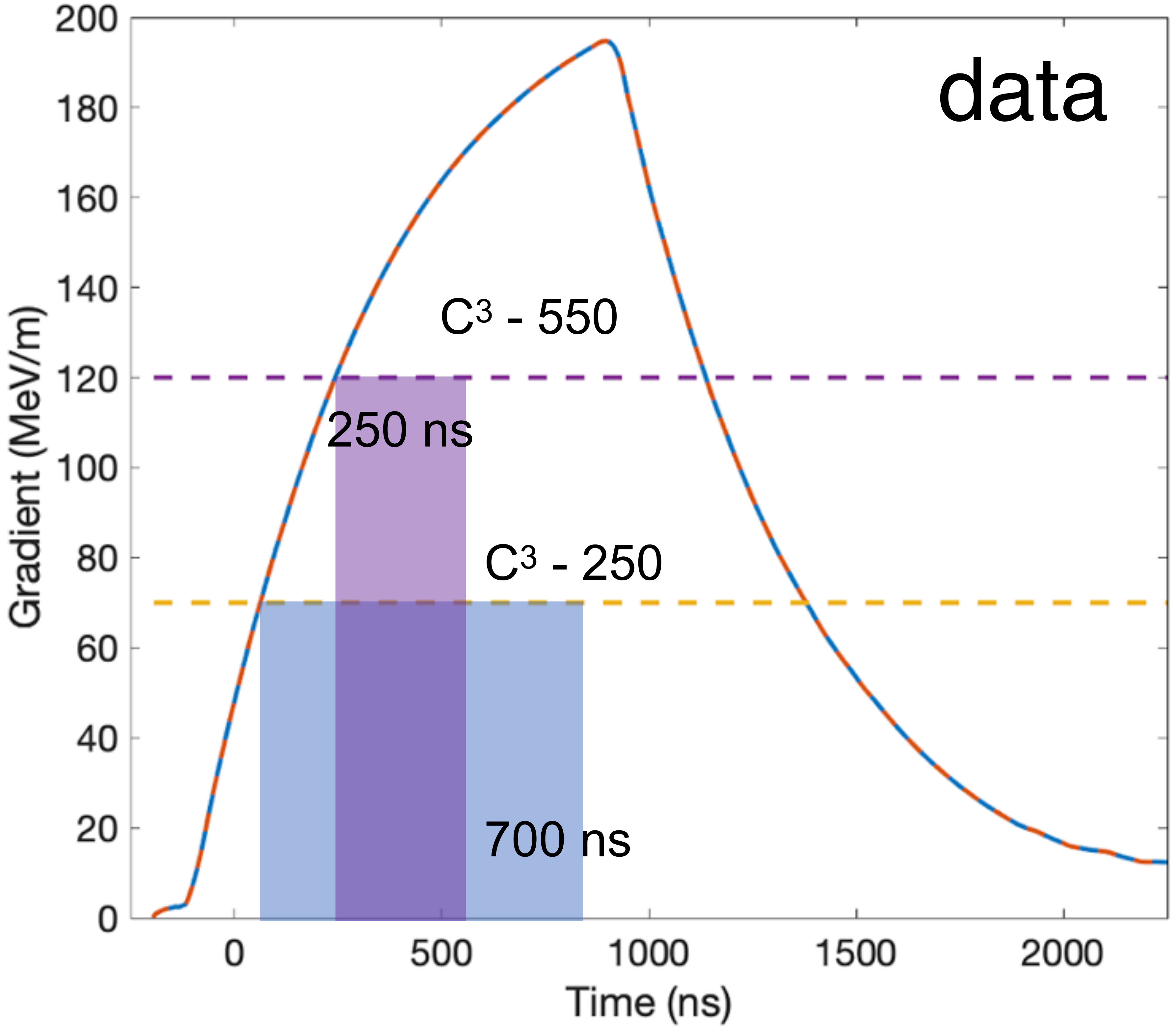
Parameter	Units	Value
Reliquification Plant Cost	M$/MW	18
Single Beam Power (125 GeV linac)	MW	2
Total Beam Power	MW	4
Total RF Power	MW	18
Heat Load at Cryogenic Temperature	MW	9
Electrical Power for RF	MW	40
Electrical Power For Cryo-Cooler	MW	60
Accelerator Complex Power	MW	~50
Site Power	MW	~150

New "sustainable" parameter set

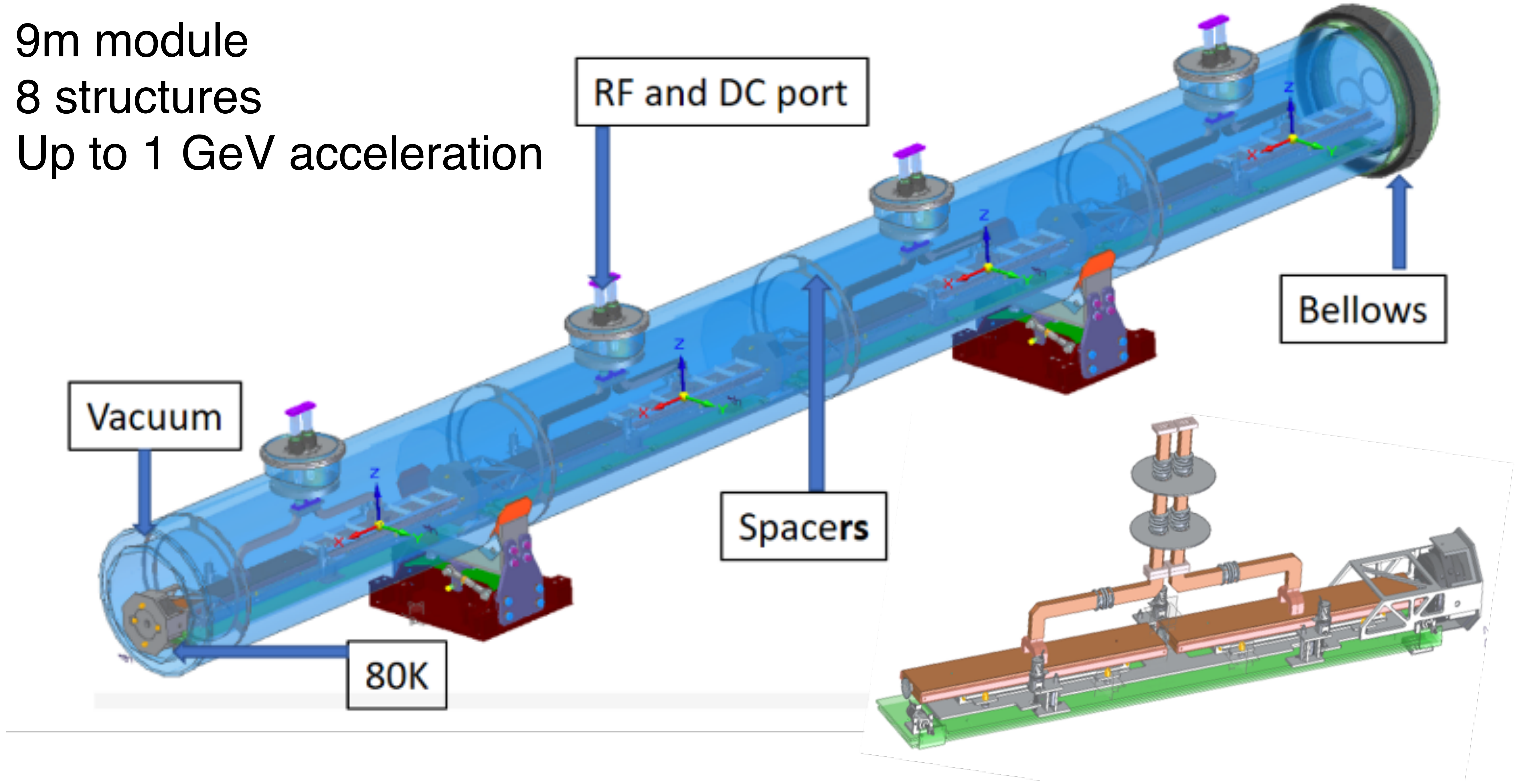
scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch Charge [nC]	1	1	1	1
Crossing Angle [rad]	0.014	0.014	0.014	0.014
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	~150	~175	~110	~125

Cool Copper Collider

- Planning for operations at high gradient **at 550 GeV, 120 MeV/m**
  - **Start at 70 MeV/m for C^3-250**
- Beam parameters optimized to record the same ILC luminosity within the same time frame and match physics goals



9m module
8 structures
Up to 1 GeV acceleration



Accelerator Complex

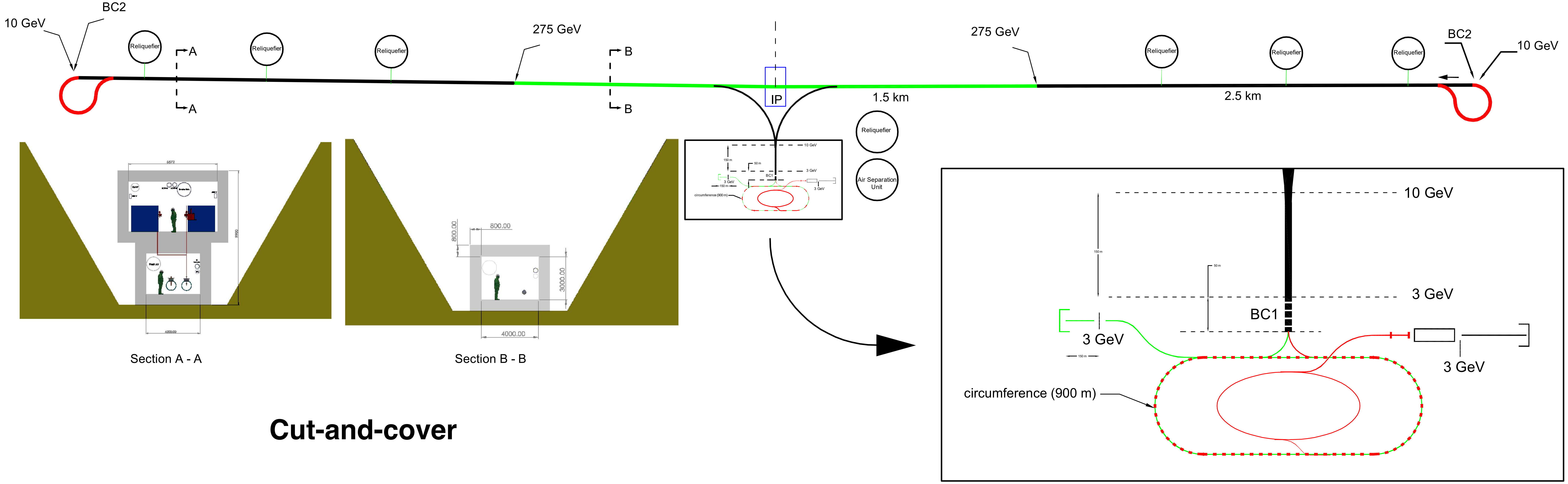
8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

- 7 km footprint at 155 MeV/m for 550 GeV CoM

Large portions of accelerator complex compatible between LC technologies

- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM)
- Damping rings and injectors to be optimized with CLIC as baseline

C^3 - 8 km Footprint for 250/550 GeV



Cut-and-cover

One word on Sustainability

PRX Energy 2 047001

Construction + operations CO_2 emissions per % sensitivity on couplings

- Polarization and high energy to account for physics reach
- Construction CO_2 emissions → minimize excavation and concrete with cut and cover approach
- Main Linac Operations → limit power, decarbonization of the grid and dedicated renewable sources

Scenario	RF System (MW)	Cryogenics (MW)	Total (MW)	Reduction (MW)
Baseline 250 GeV	40	60	100	-
RF Source Efficiency Increased 15%	31	60	91	9
RF Pulse Compression	28	42	70	30
Double Flat Top	30	45	75	25
Halve Bunch Spacing	34	45	79	21
All Scenarios Combined	13	24	37	63

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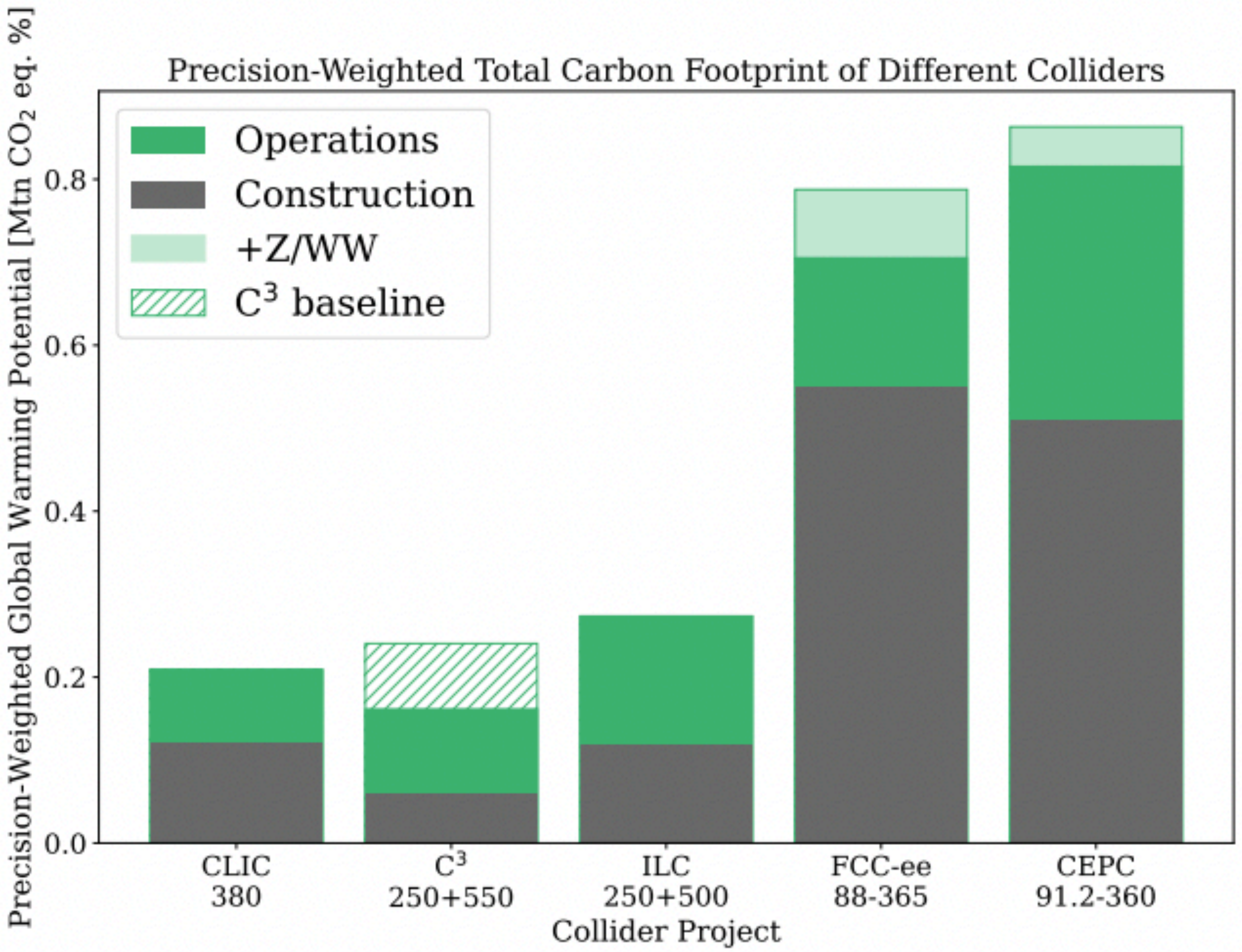
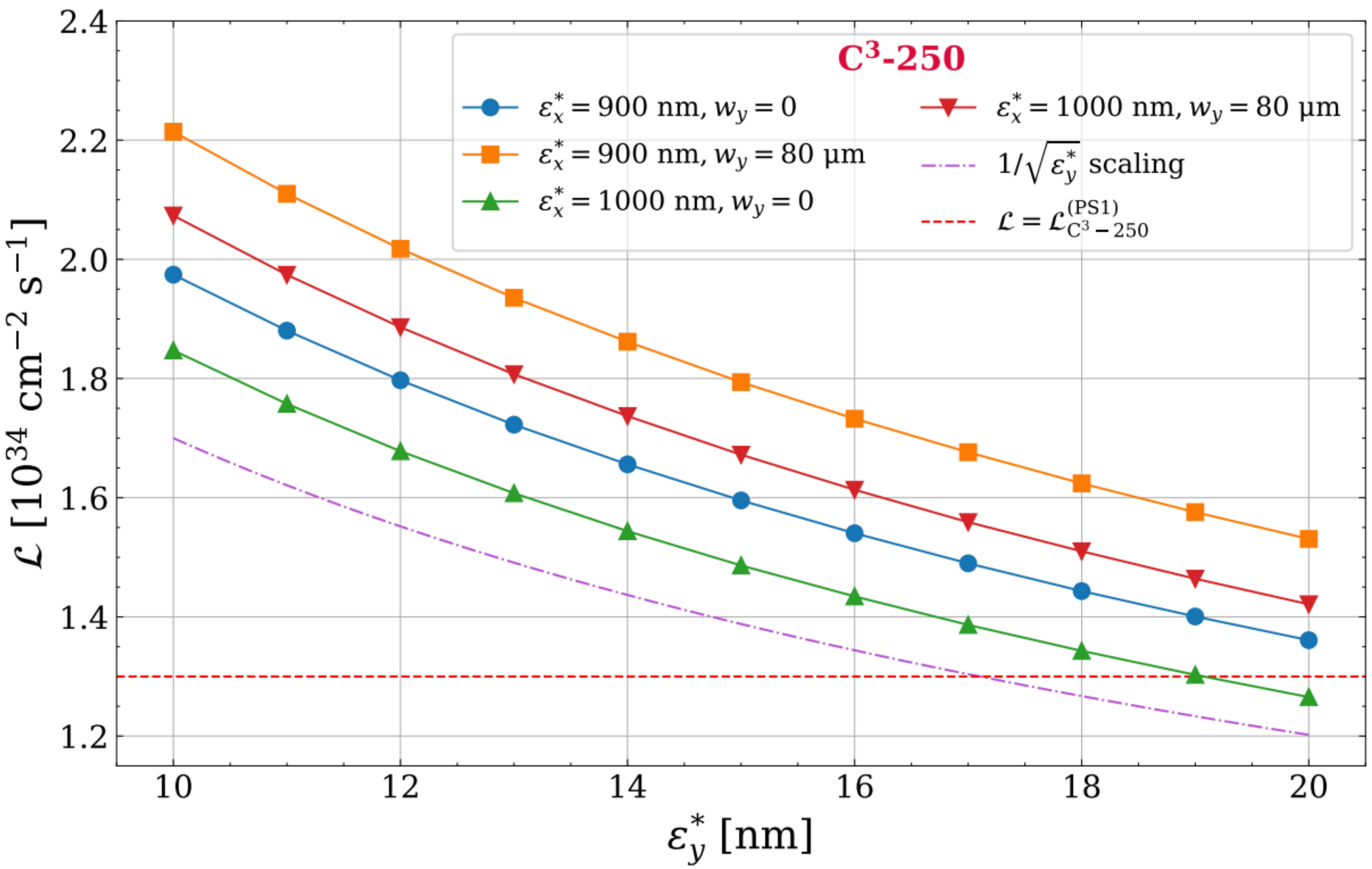


Optimized parameter sets

Phys. Rev. Accel. Beams 27, 061001, 2024

An improvement of around 40% while BIB is maintained at approximately the same levels.

Parameter	Symbol [unit]	C^3-250 (PS1)	C^3-250 (PS2)
Center-of-mass Energy	$\sqrt{s_0}$ [GeV]	250	
RMS bunch length	σ_z^* [µm]	100	
Horizontal beta function at IP	β_x^* [mm]	12	
Vertical beta function at IP	β_y^* [mm]	0.12	
Normalized horizontal emittance at IP	ϵ_x^* [nm]	900	1000
Normalized vertical emittance at IP	ϵ_y^* [nm]	20	12
RMS horizontal beam size at IP	σ_x^* [nm]	210	221
RMS vertical beam size at IP	σ_y^* [nm]	3.1	2.4
Vertical waist shift	w_y [µm]	0	80
Geometric Luminosity	$\mathscr{L}_{\text{geom}}$ [10^{34} cm^{-2} s^{-1}]	0.75	0.92
Horizontal Disruption	D_x	0.32	0.29
Vertical Disruption	D_y	21.5	26.5
Average Beamstrahlung Parameter	$\langle \Upsilon \rangle$	0.065	0.062
Total Luminosity	$\mathscr{L}$ [10^{34} cm^{-2} s^{-1}]	1.35	1.90
Peak luminosity fraction	$\mathscr{L}_{0.01}/\mathscr{L}$ [%]	73	74
Enhancement Factor	H_D	1.8	2.1
Average Energy loss	δ_E [%]	3.3	3.1
Photons per beam particle	n_γ	1.4	1.3
Average Photon Energy fraction	$\langle E_\gamma/E_0 \rangle$ [%]	2.5	2.4
Number of incoherent particles/BX	N_{incoh} [10^4]	4.7	5.9
Total energy of incoh. particles/BX	E_{incoh} [TeV]	58	71



More in Dimitri's talk

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Vertica[illegible]	[illegible]	[illegible]	[illegible]
Geome[illegible]	[illegible]	[illegible]	[illegible]
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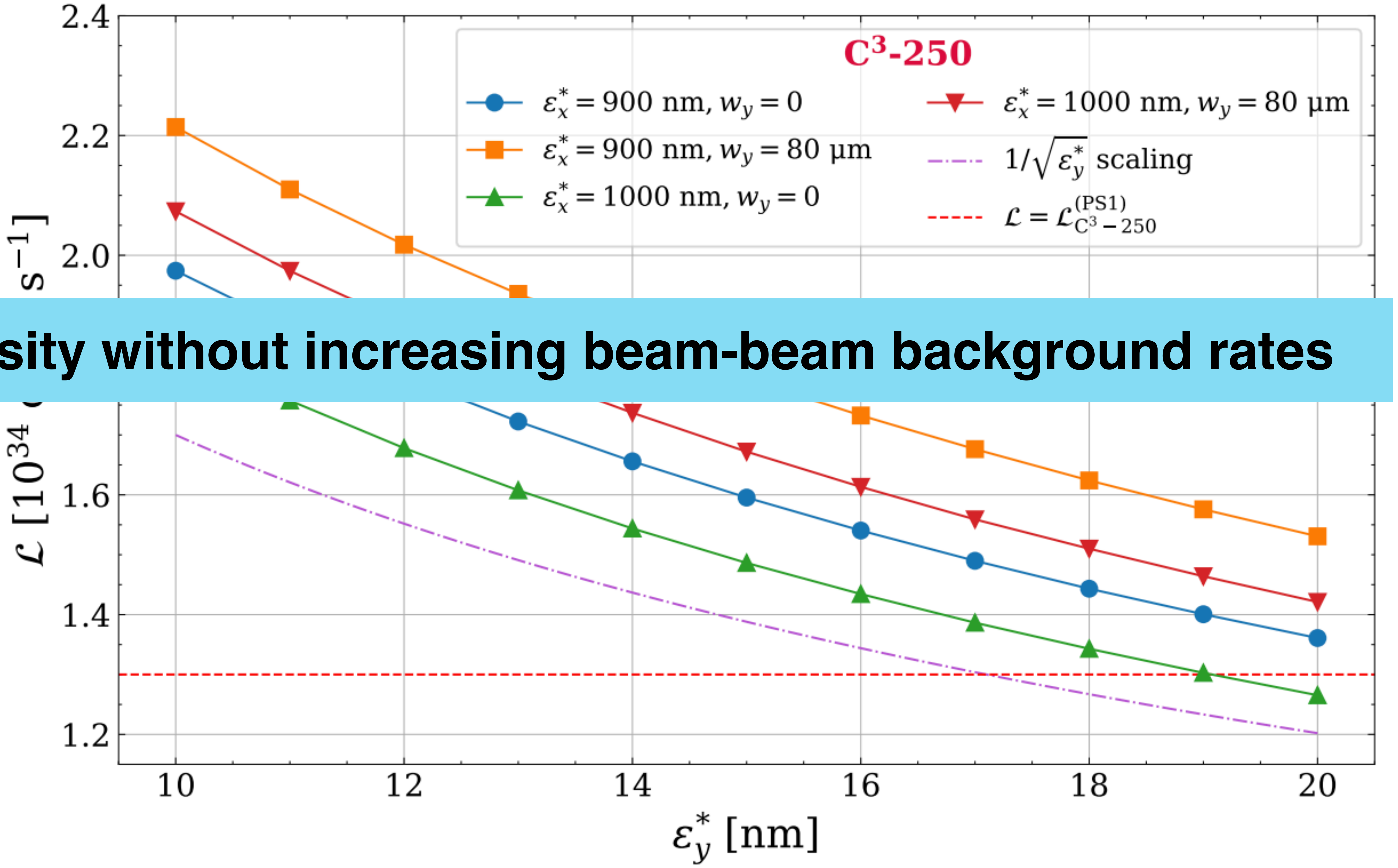
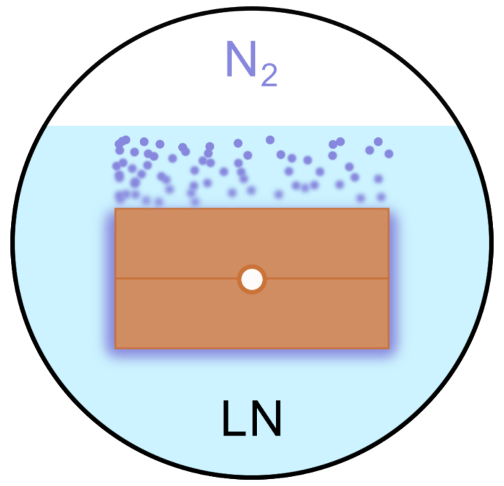


Beam parameters optimized for C^3 luminosity without increasing beam-beam background rates

More in Dimitri's talk

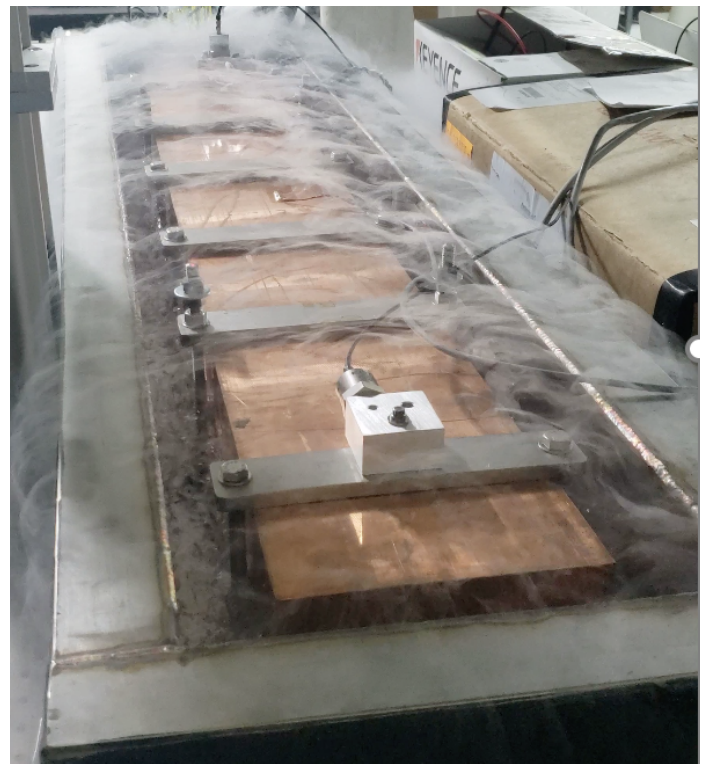
Technical progress and challenges



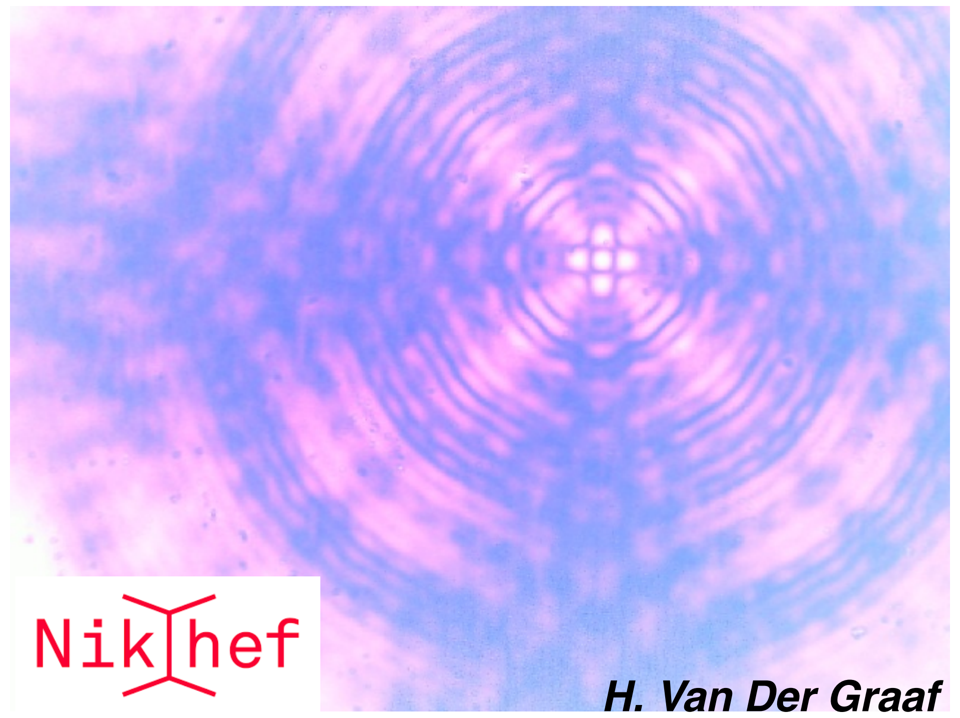
Over the last year, significant progress to tackle several challenges:

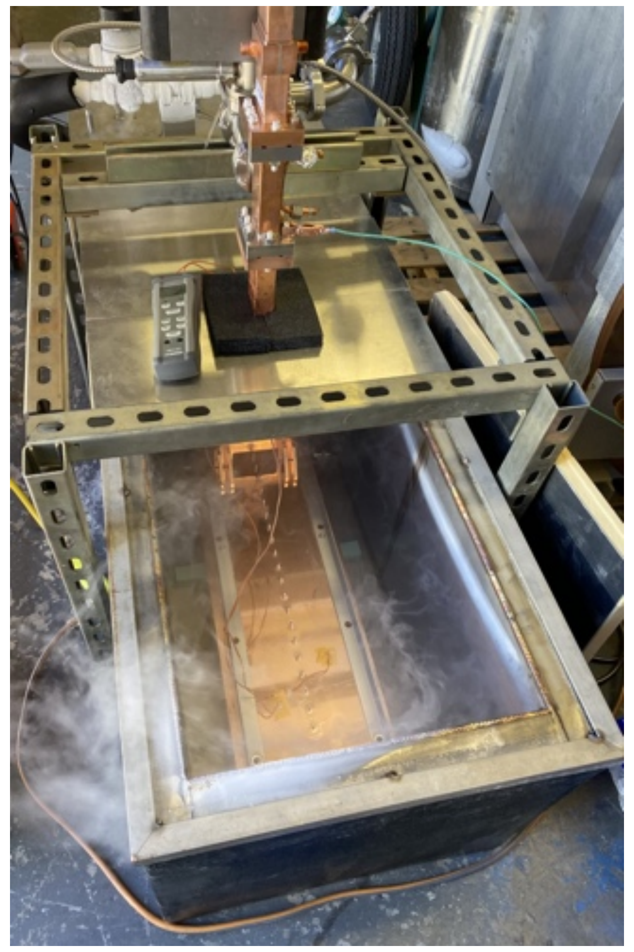
- **Gradient** – Scaling up to meter scale cryogenic tests (Emilio,Dennis)
- **Vibrations** – Measurements with full thermal load (Ankur)
- **Alignment** – Working towards raft prototype (Harry)
- **Cryogenics** – Two-phase flow simulations to full flow tests
- **Damping** – Materials, design and simulation (Wei-Hou, Shumail, Zhengai)
- **Beam Loading and Stability** - Beam test
- **Scalability** – Cryomodules and integration (Andy)
- **LLRF Control** with RF System on Chip (Ankur)

Laying the foundation for a demonstration program to address technical risks



Vibration Studies

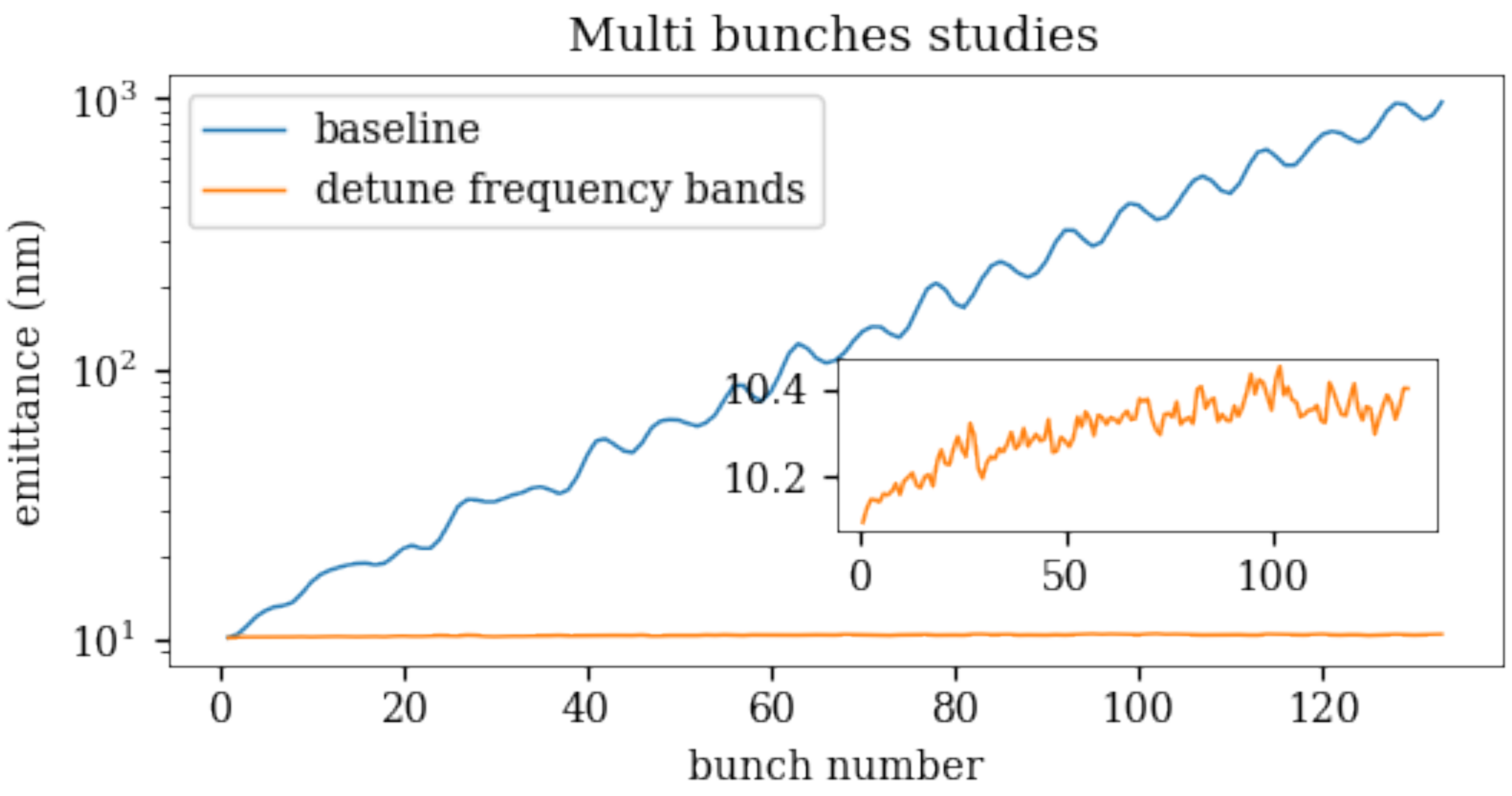


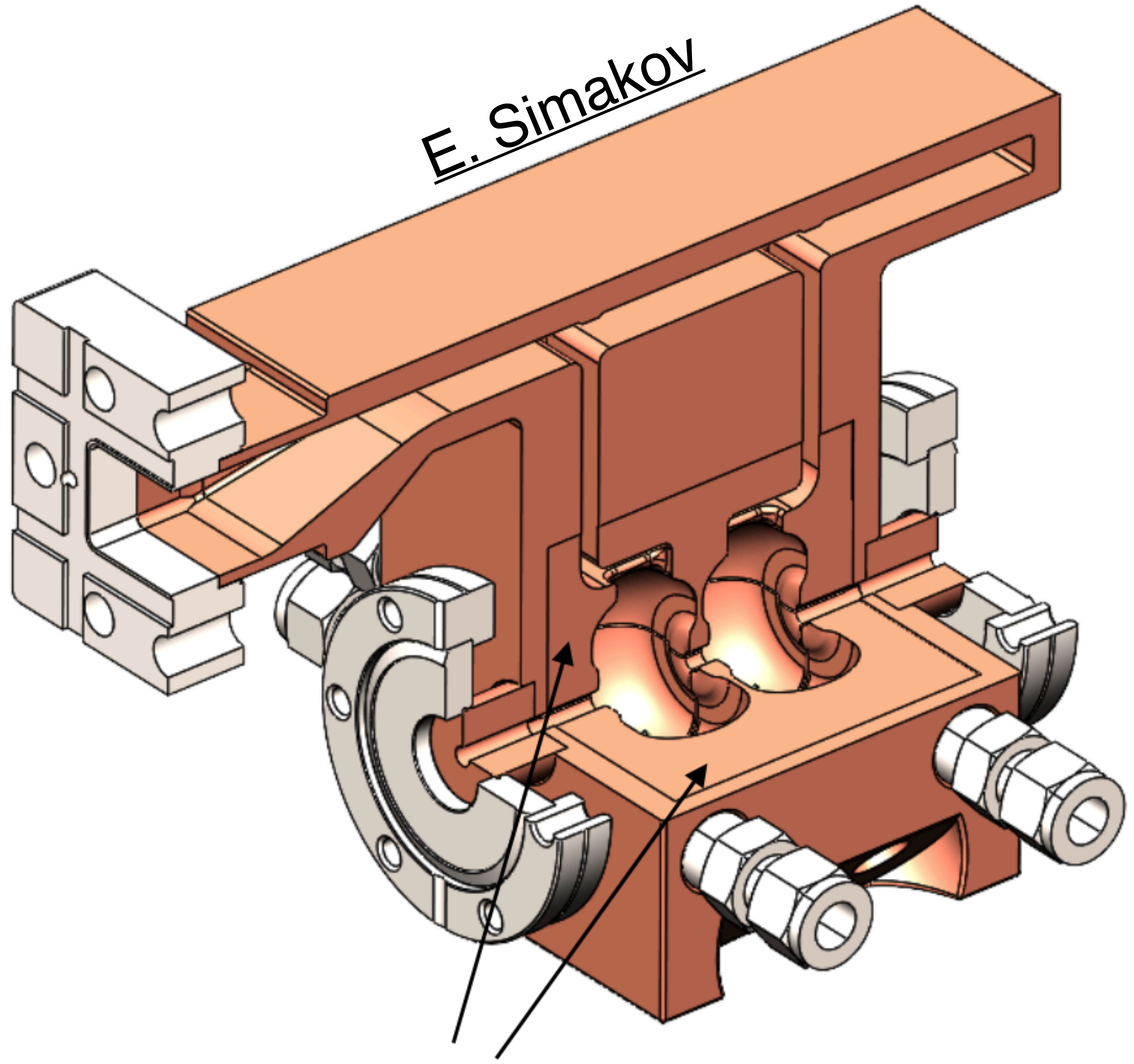


RadiaBeam

One highlight: damping & detuning

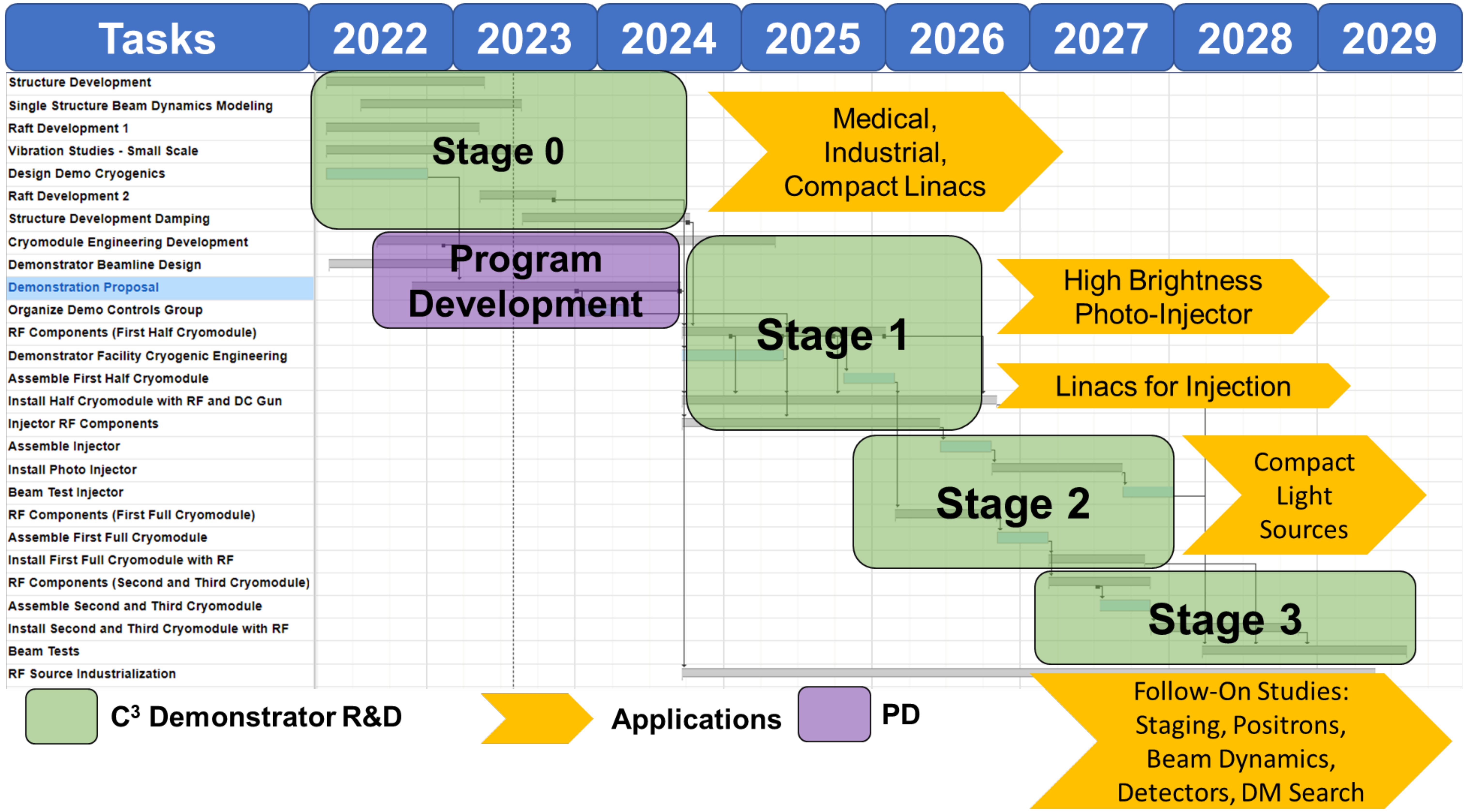
- Multi-bunch simulation studies have been conducted to identify required damping and detuning to mitigate long-range HOMs
- Single bunch studies also used for studying alignment tolerance
- Ni-Cr coatings for two-cells structures have been tested





C³ Demonstration R&D Plan Timeline *

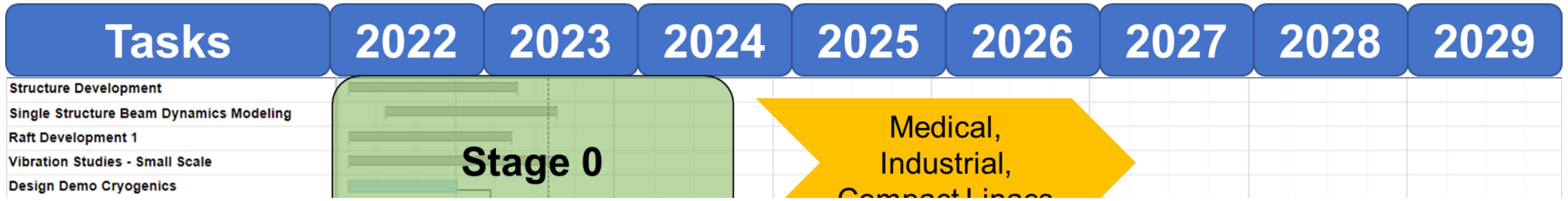
* Technically Limited

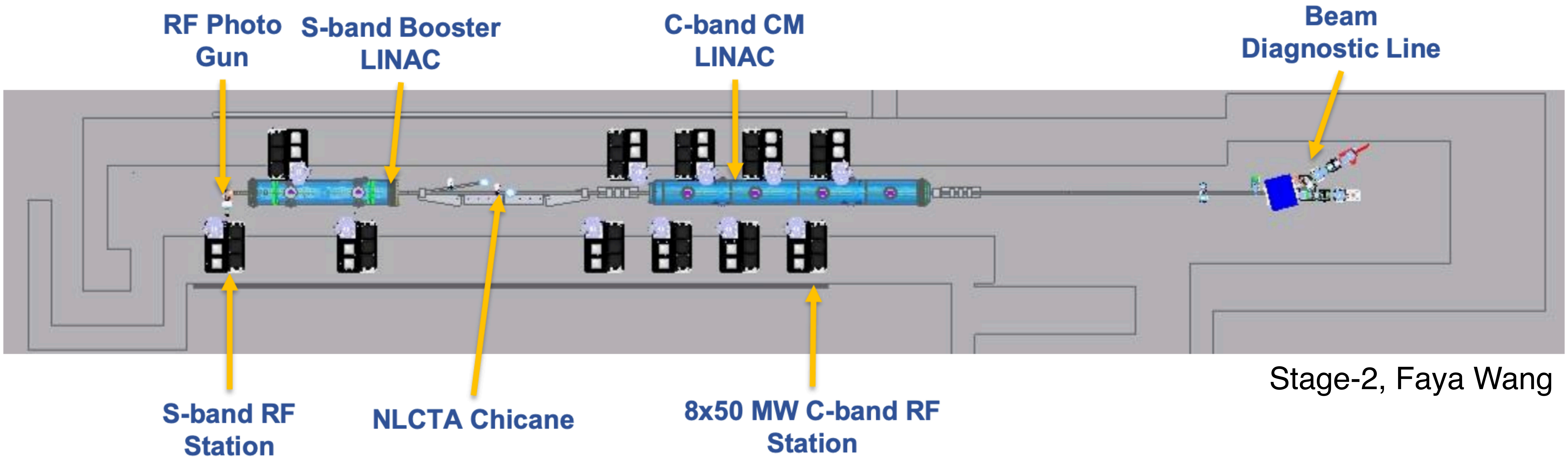


Area Recommendation 8 P5 report

Demonstration R&D Plan Timeline *

* Technically Limited

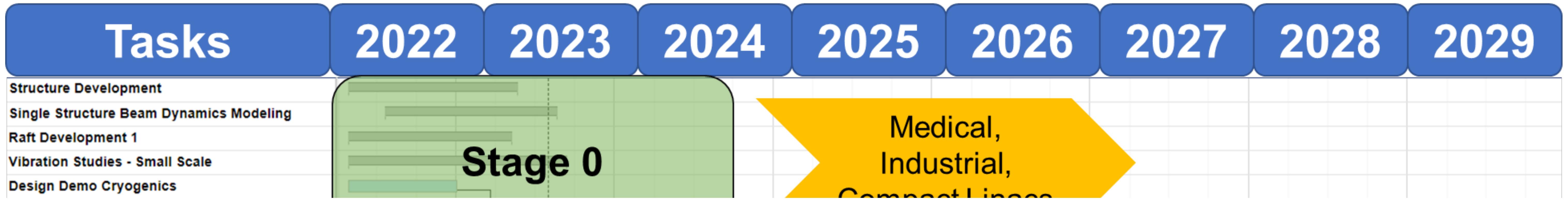


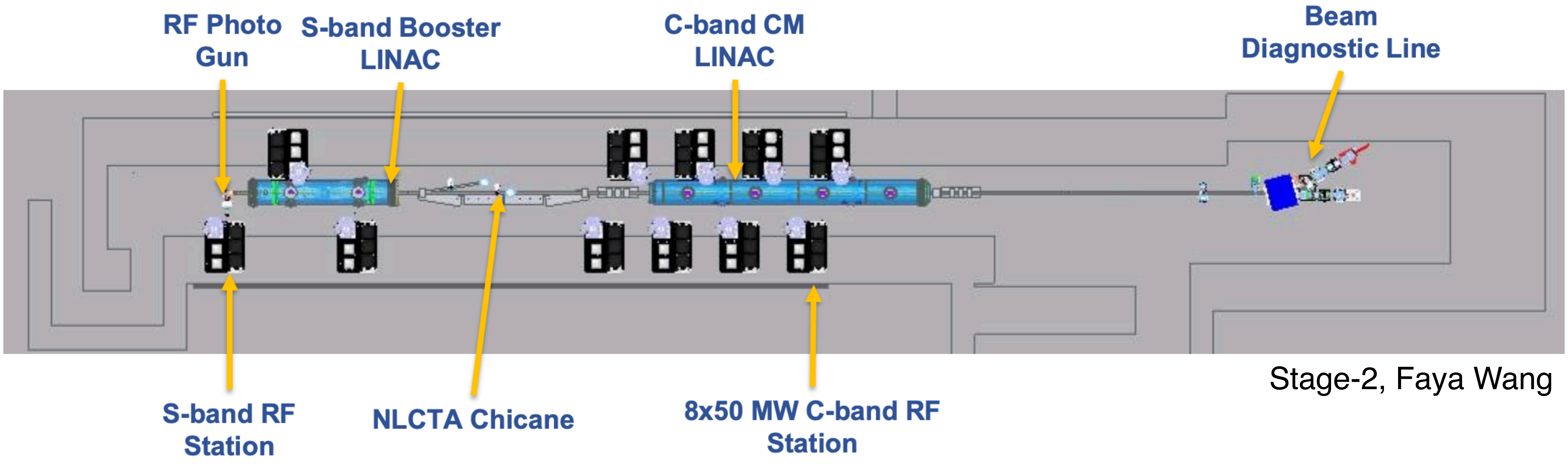


Stage-2, Faya Wang

Demonstration R&D Plan Timeline *

* Technically Limited



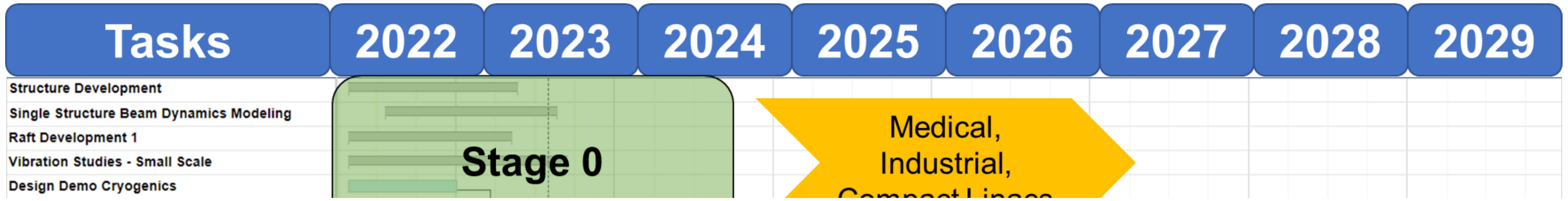


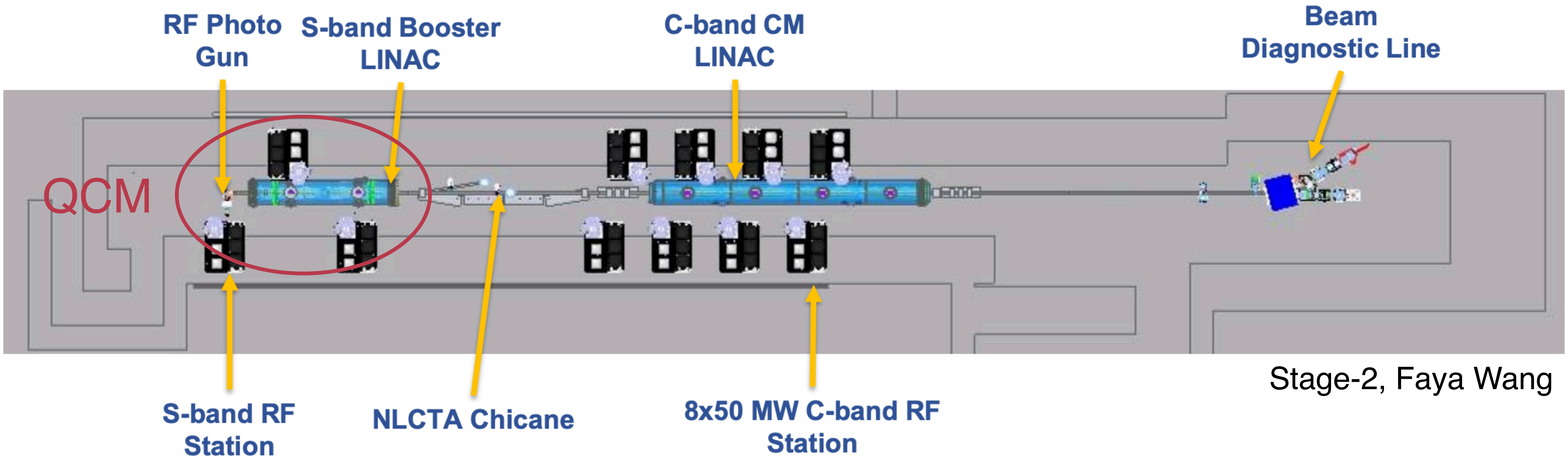
Stage-2, Faya Wang

Stage 1/2 will answer the most pressing technical questions - beam loading, damping, alignment, required to assess technical risks

Demonstration R&D Plan Timeline *

* Technically Limited



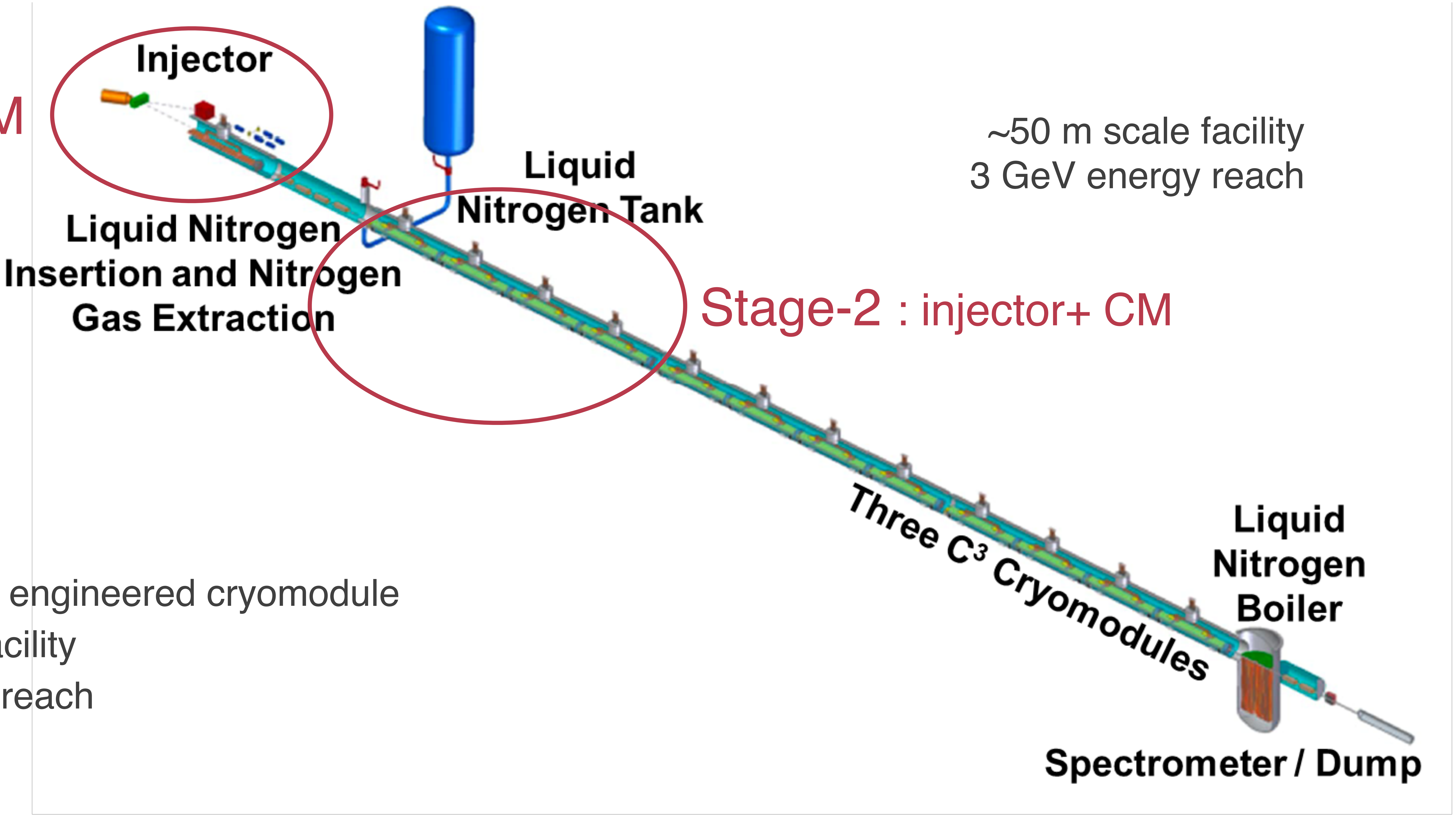


Stage-2, Faya Wang

Stage 1/2 will answer the most pressing technical questions - beam loading, damping, alignment, required to assess technical risks

The Complete C³ Demonstrator

QCM



Stage-2 : injector+ CM

~50 m scale facility
3 GeV energy reach

- Demonstrate fully engineered cryomodule
  - ~50 m scale facility
  - 3 GeV energy reach