Linear colliders

The Future of High Energy Physics: A New Generation, A New Vision

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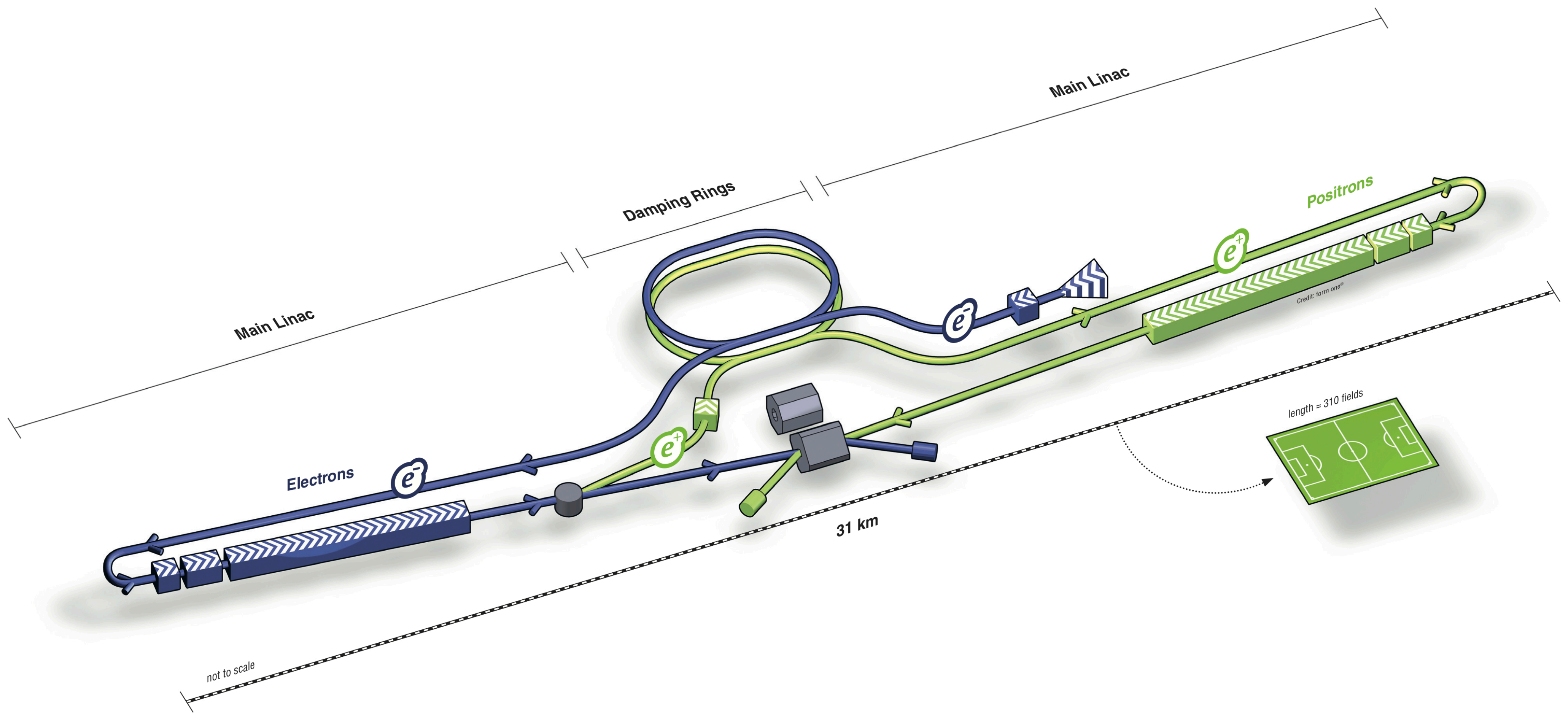
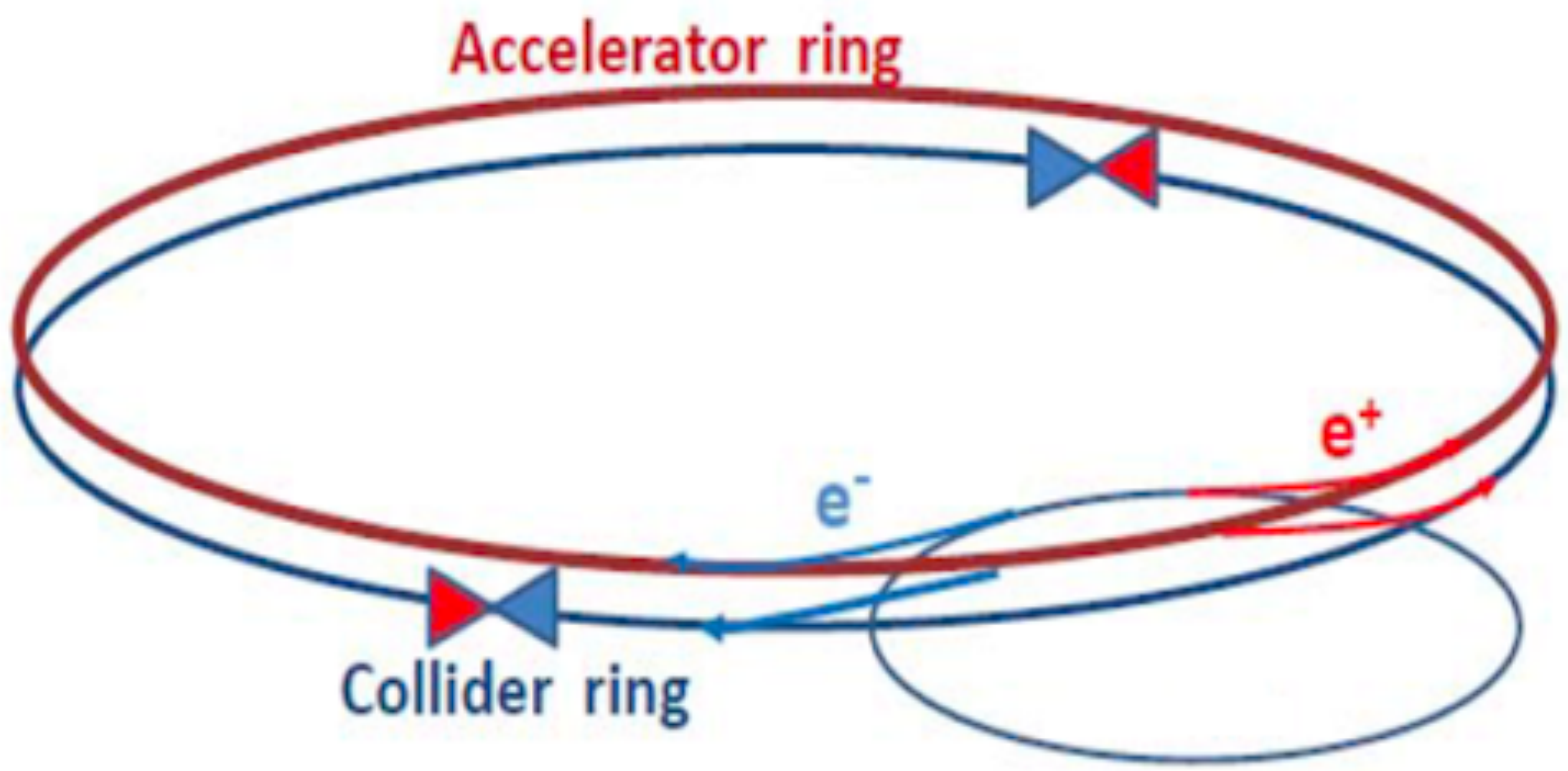
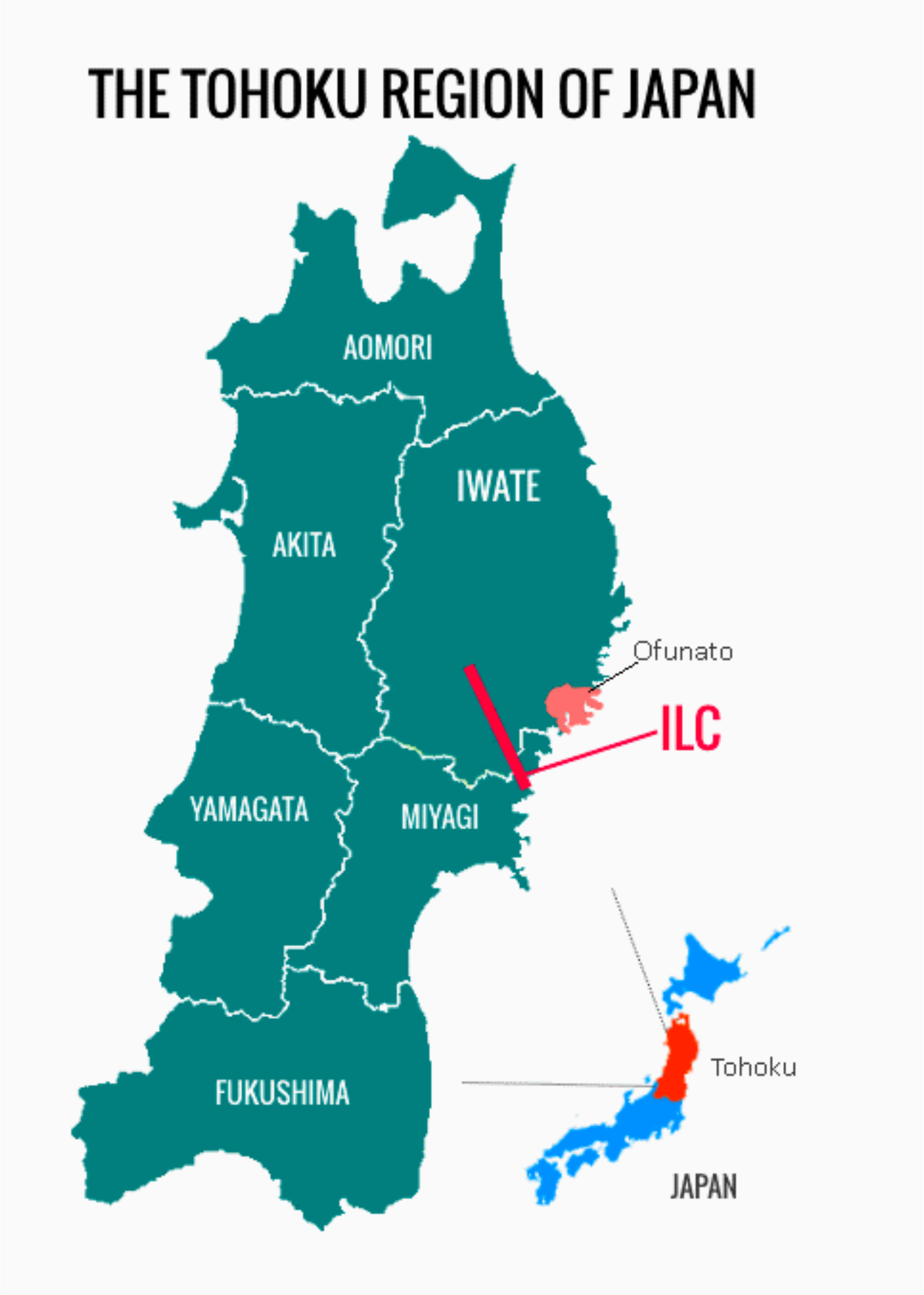
e^+e^-: Linear vs. Circular

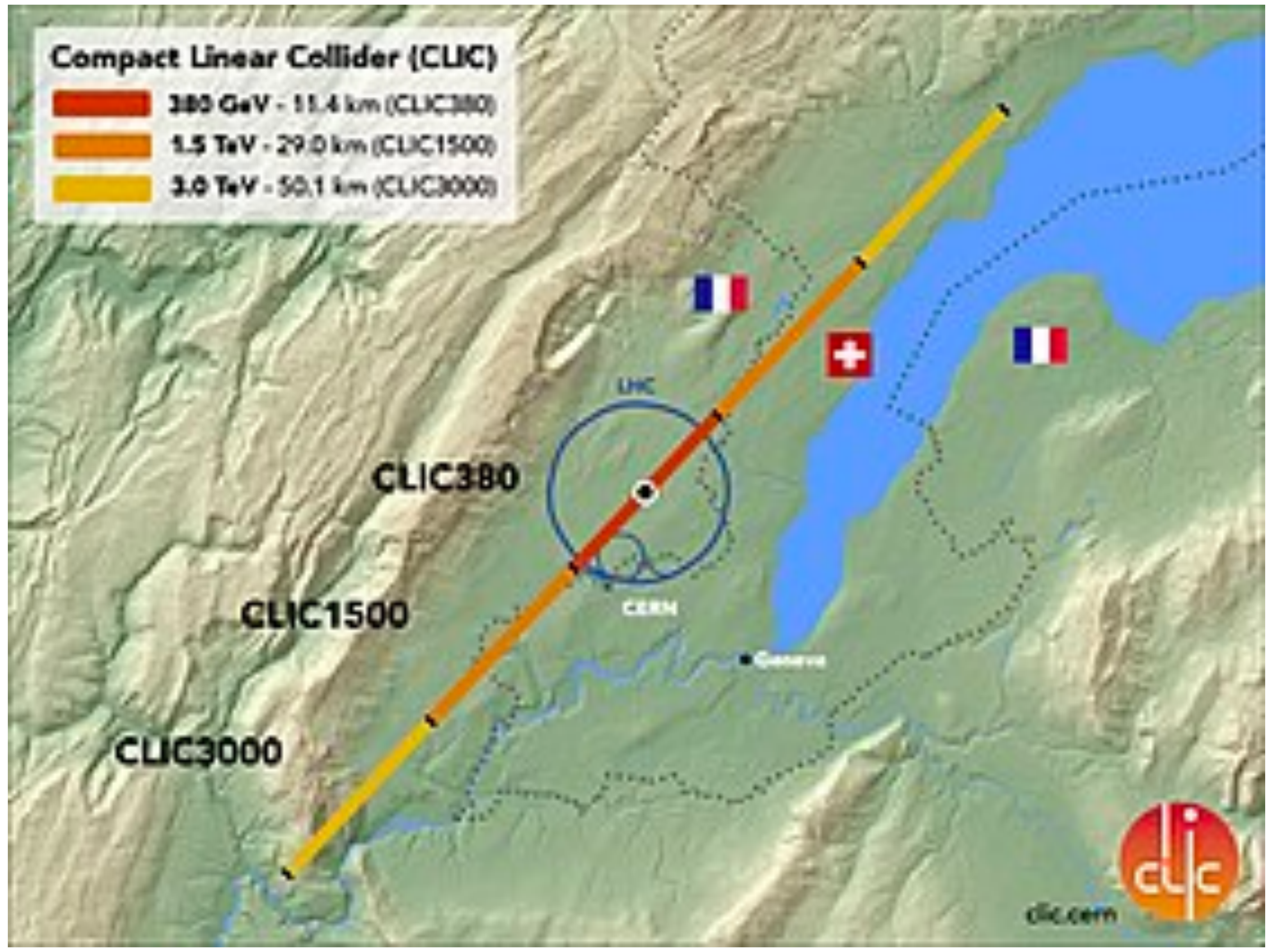
- **Linear** e^+e^- colliders: **higher energies** (~ TeV)
  - Can use **polarized** beams
  - Collisions in bunch trains (~0.5% duty cycle)
    - Trigger-less readout
    - Power pulsing → Significant power (& material) saving for detectors
  - **One interaction point** with two detectors alternating with push-pull
- **Circular** e^+e^- colliders: **highest luminosity** at Z/WW/Zh
  - Limited by synchrotron radiation above 350/400 GeV
  - Beam continues to circulate after collision
    - Detectors need active cooling (more material)
  - **Multiple interaction points**

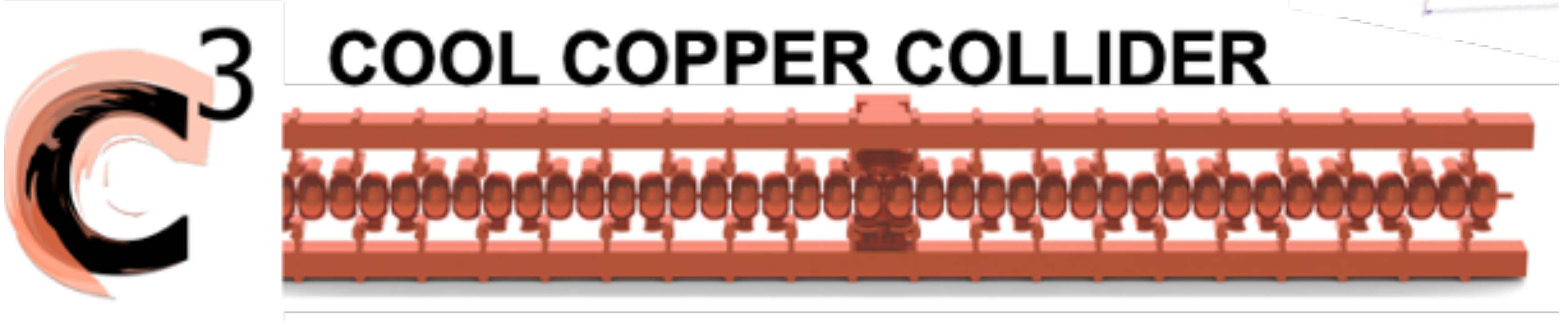




Various proposals …





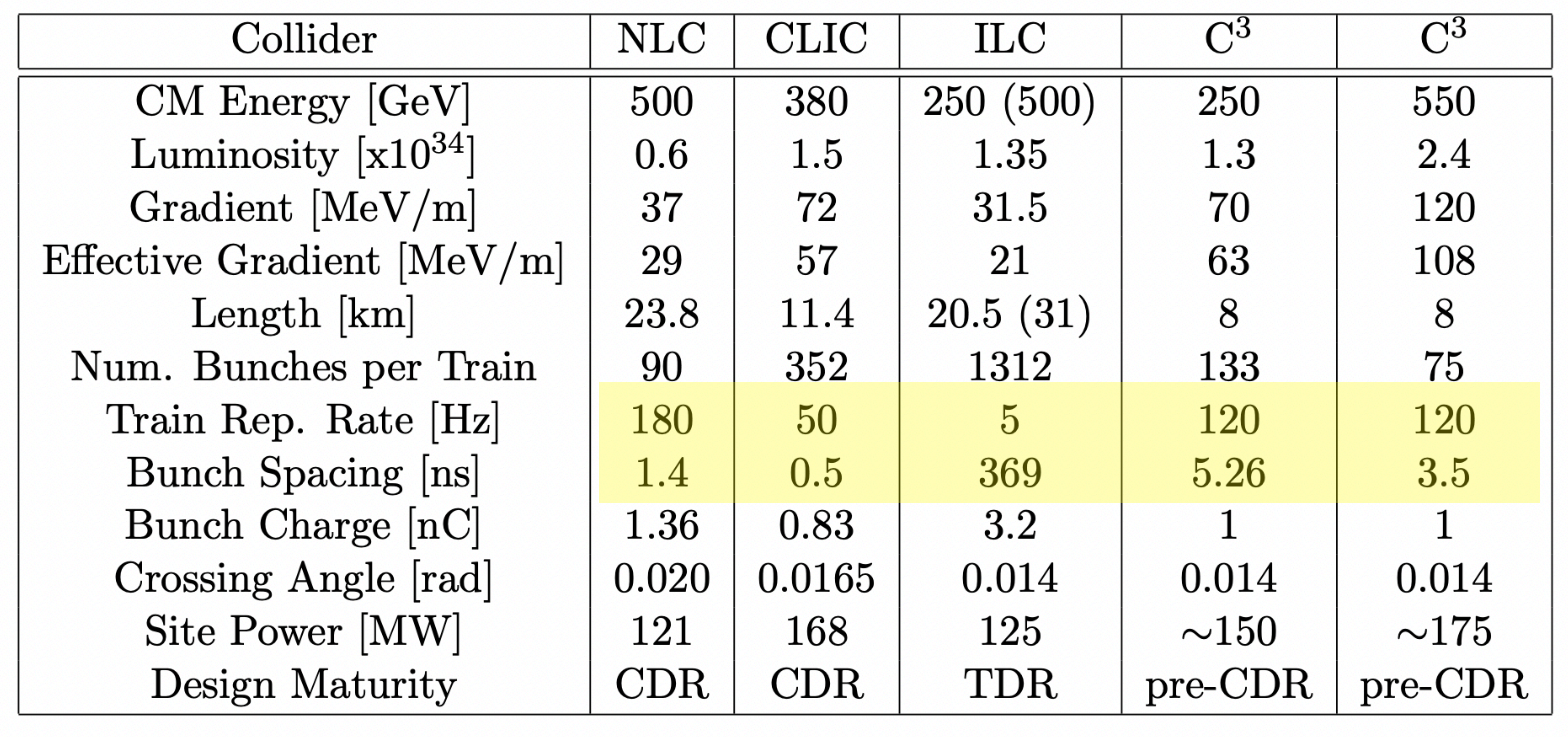


250/500 GeV

380/1500/3000 GeV

250/550 GeV
… > TeV

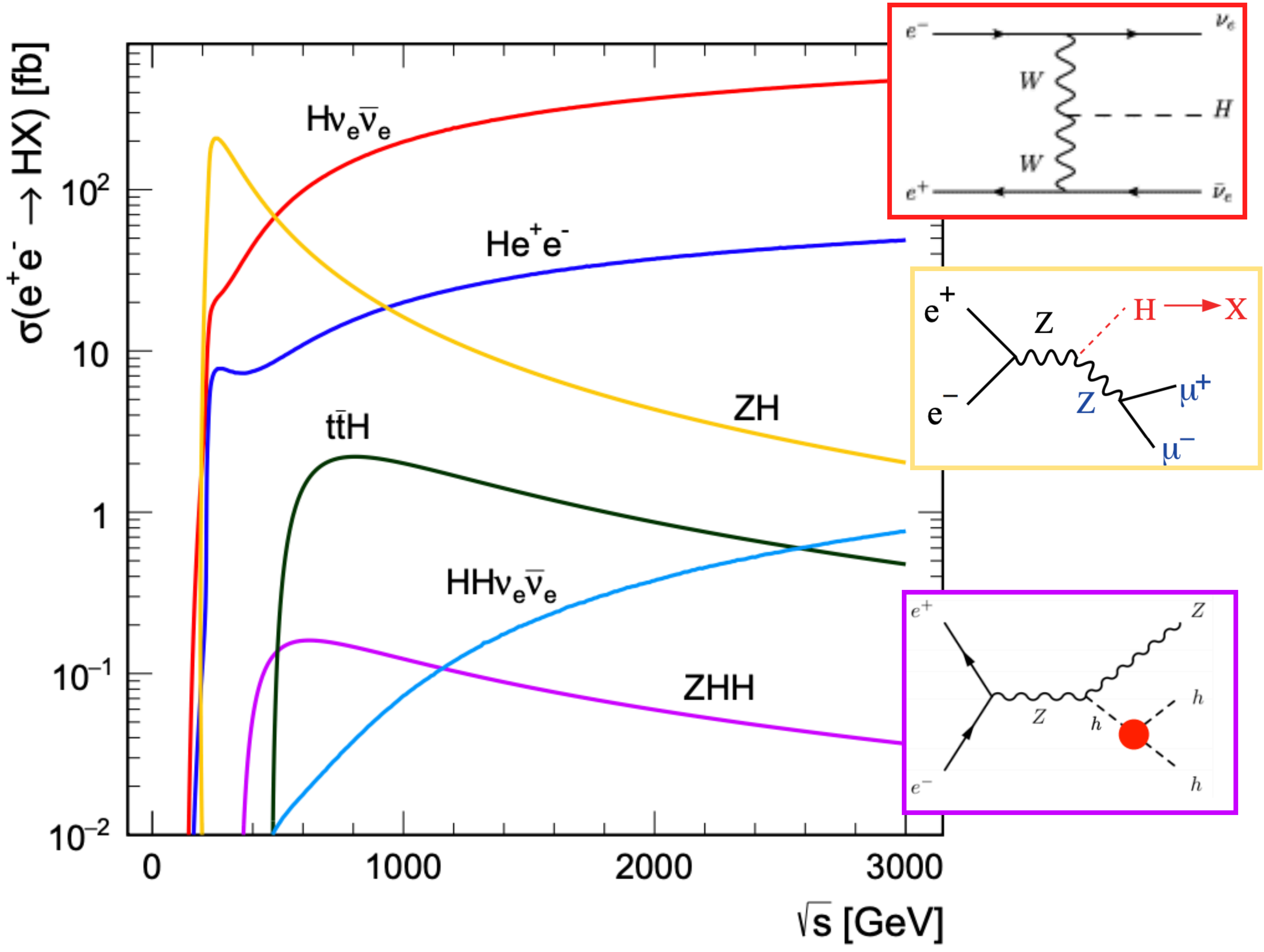
A quick comparison of parameters



Collider	NLC	CLIC	ILC	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
Luminosity [x10^{34}]	0.6	1.5	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Length [km]	23.8	11.4	20.5 (31)	8	8
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	120	120
Bunch Spacing [ns]	1.4	0.5	369	5.26	3.5
Bunch Charge [nC]	1.36	0.83	3.2	1	1
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014
Site Power [MW]	121	168	125	~150	~175
Design Maturity	CDR	CDR	TDR	pre-CDR	pre-CDR

(Quick recap) Higgs at e^+e^-

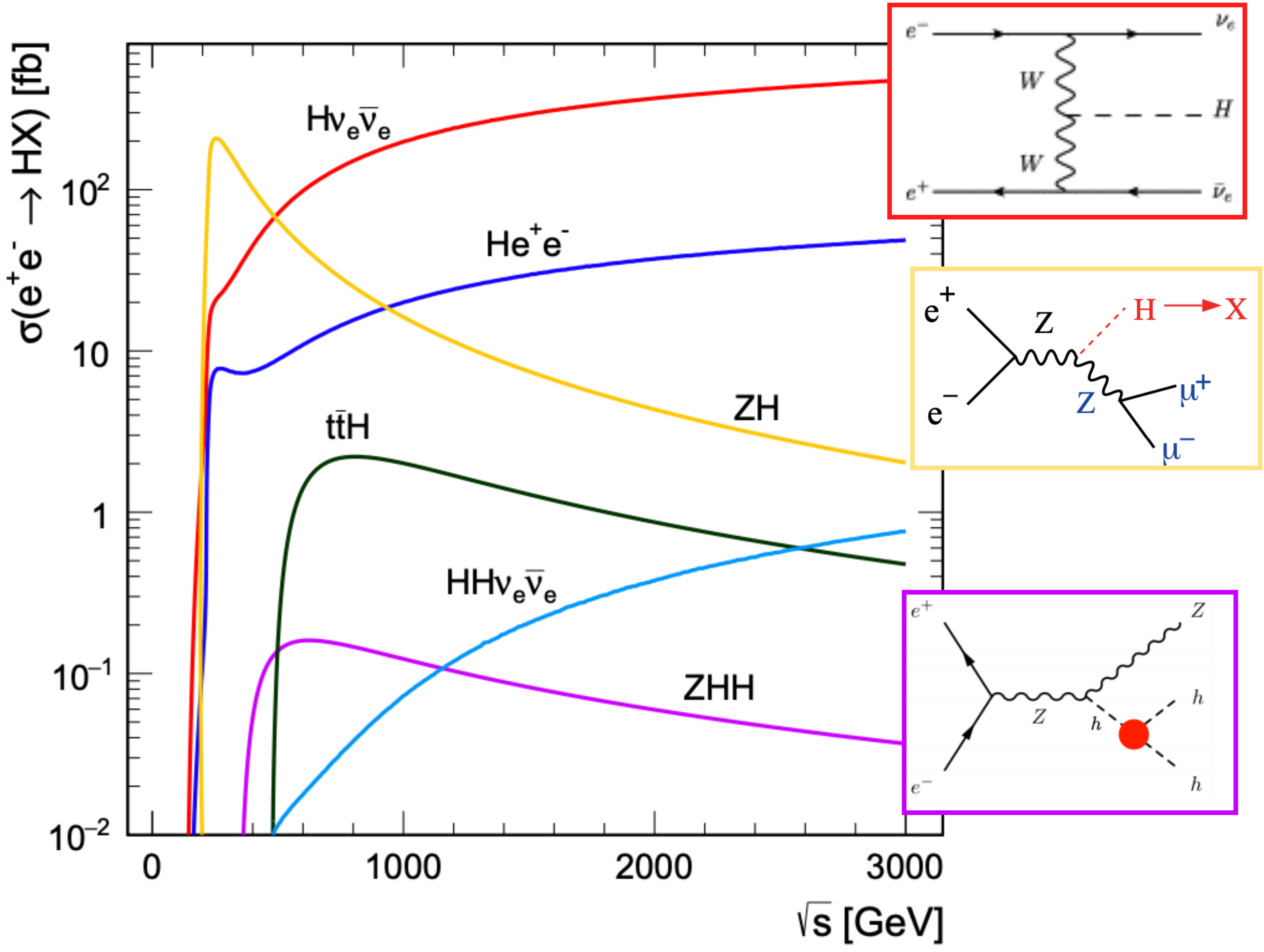
[The Energy Frontier 2021 Snowmass Report]



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

(Quick recap) Higgs at e+e-

The Energy Frontier 2021 Snowmass Report



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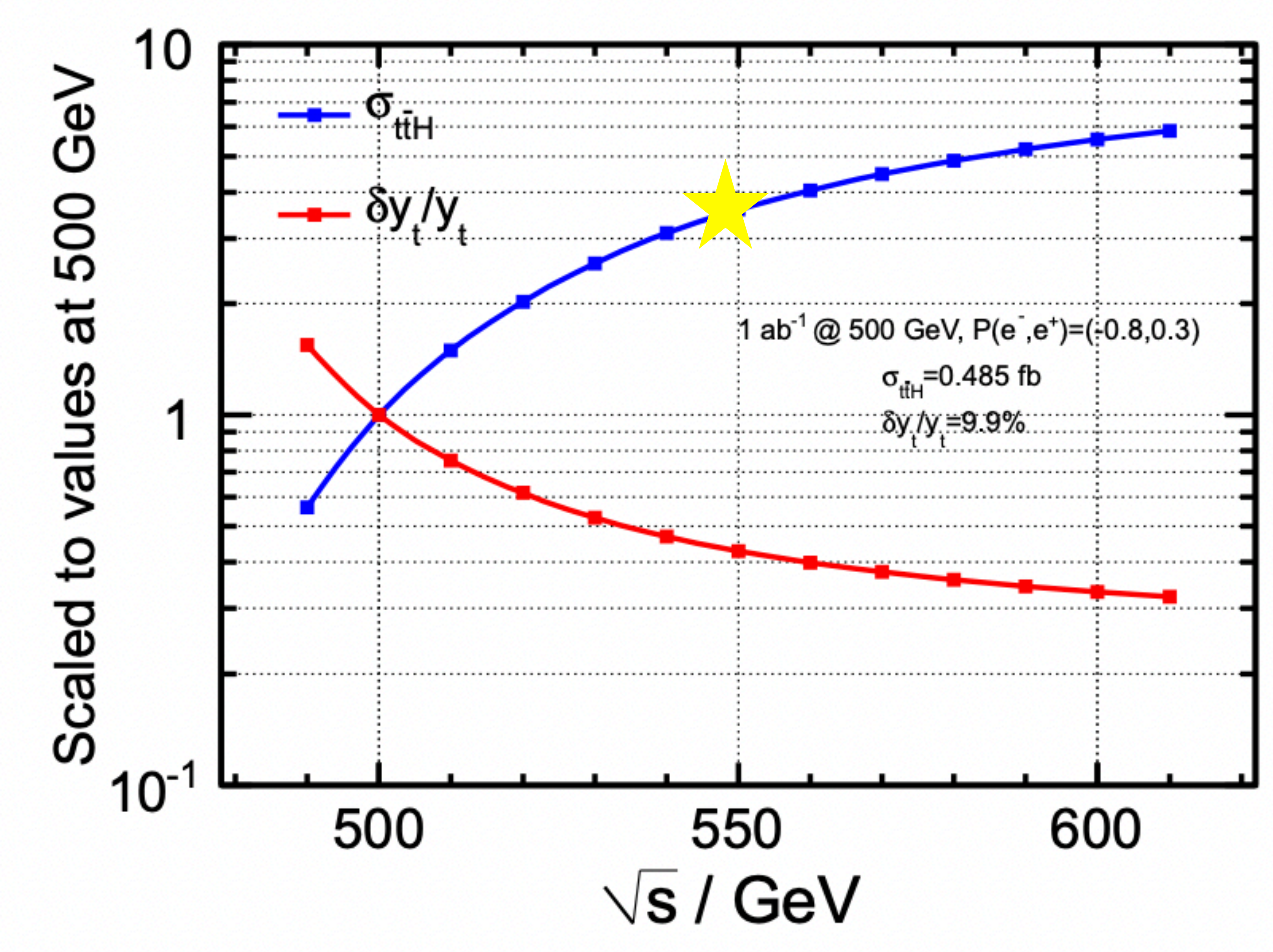

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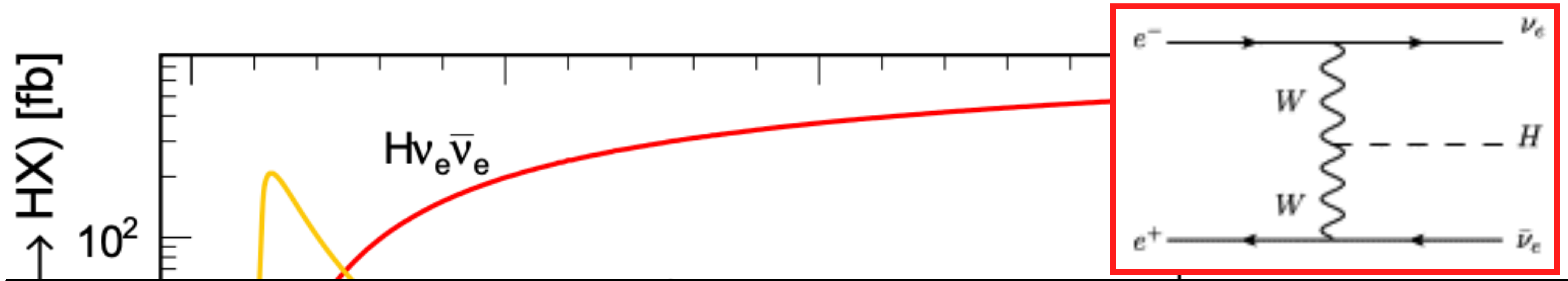
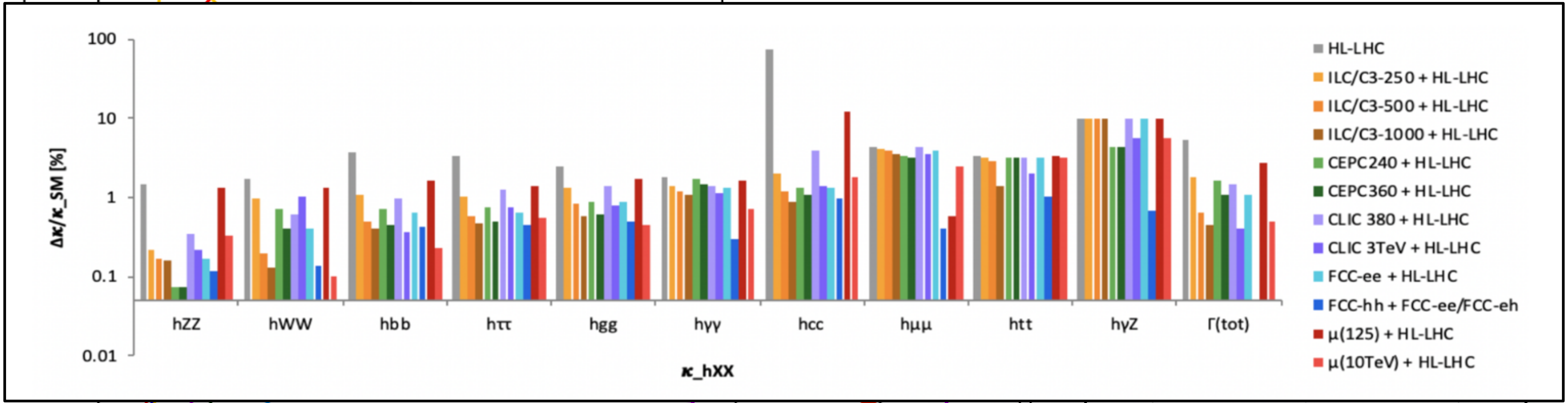
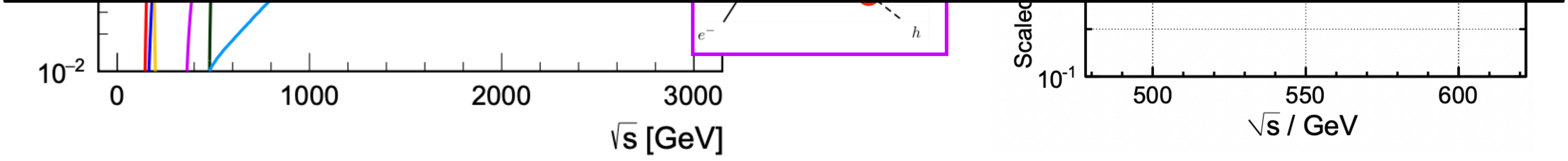




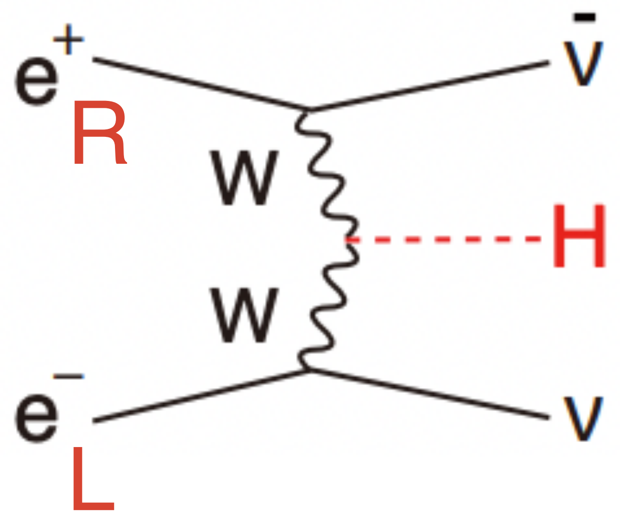


One note on polarization

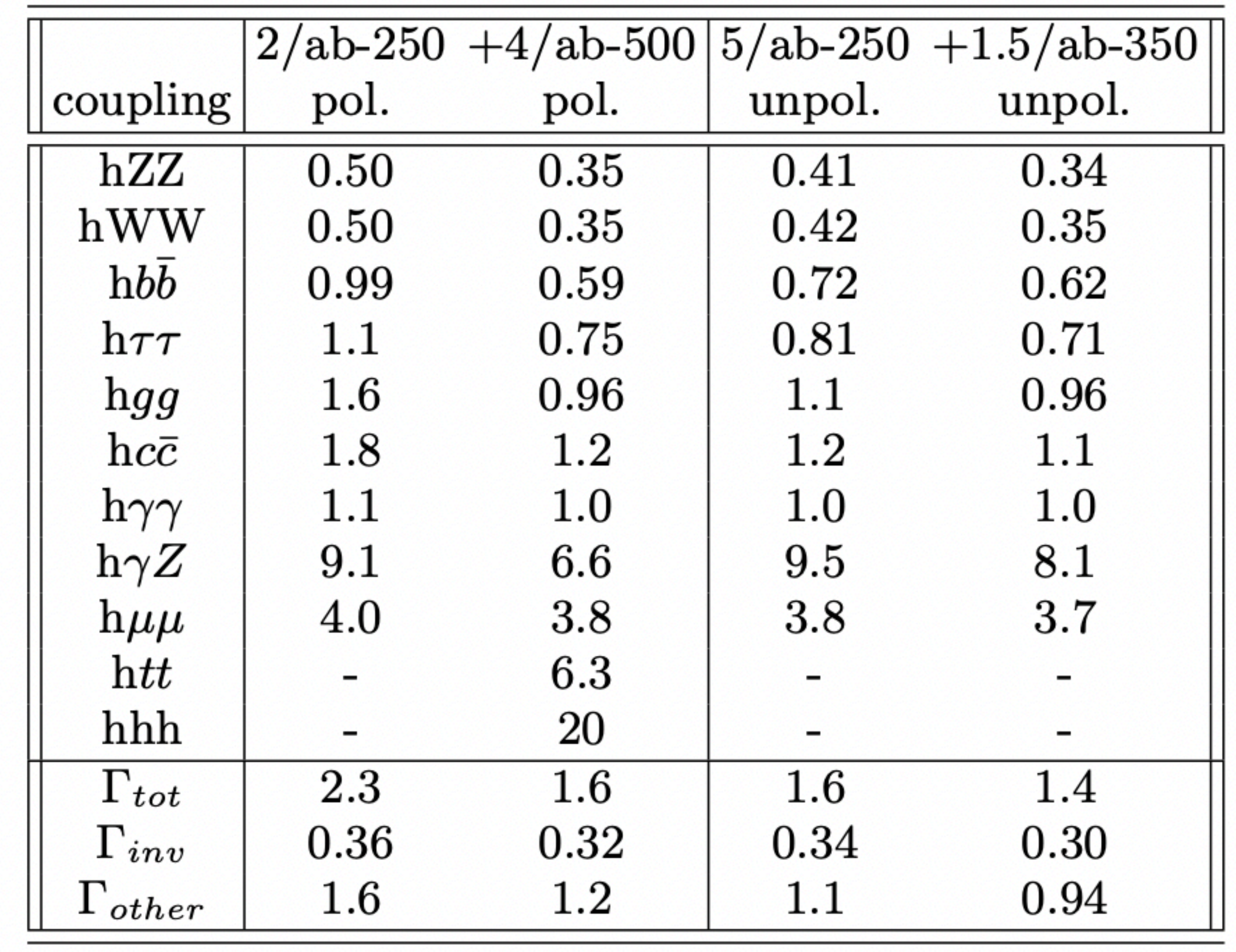
arXiv:2209.07510

Polarization to compensate for luminosity

- 2 ab^{-1} of polarized running is essentially equivalent to 5 ab^{-1} of unpolarized running within SMEFT analysis
  - Electron polarization is essential for this
  - Positron polarization enhance signal cross section at very high energy
    - it also allows more cross-checks of systematic errors.



ILC/C3 FCC



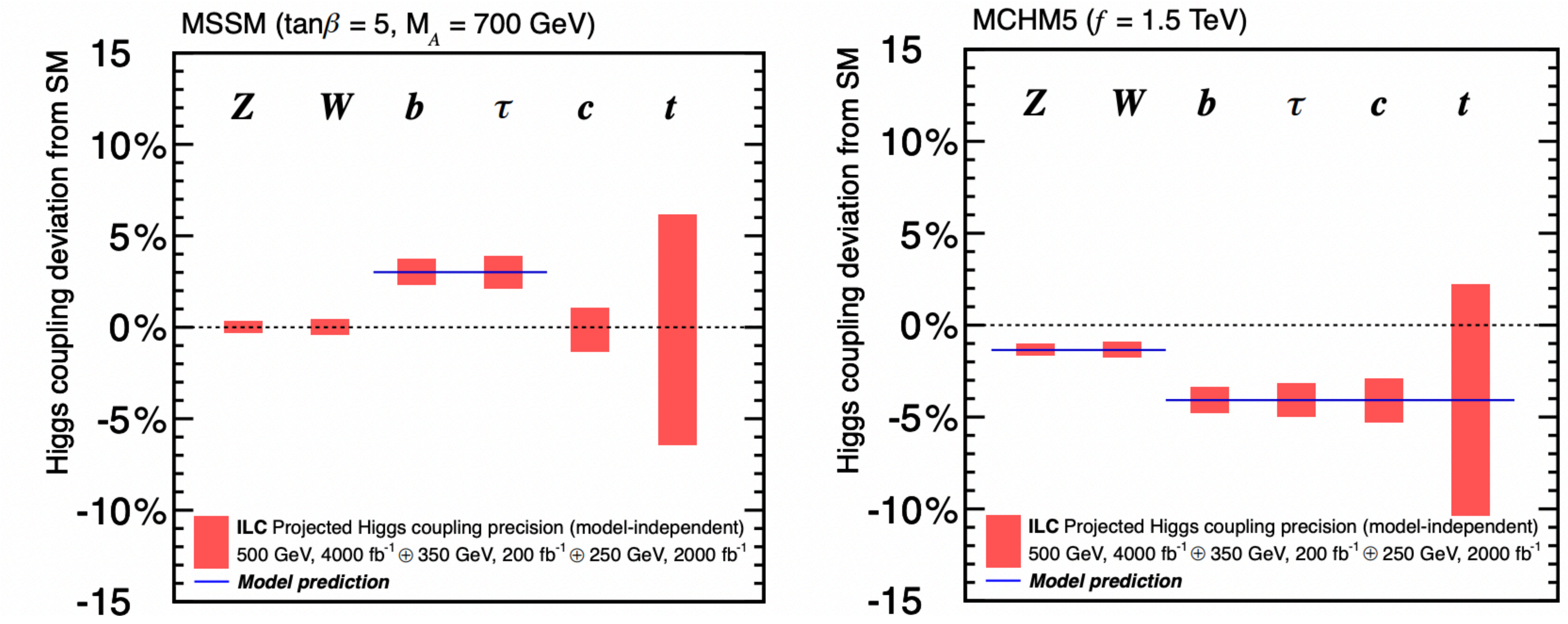
coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+1.5/ab-350 unpol.
hZZ	0.50	0.35	0.41	0.34
hWW	0.50	0.35	0.42	0.35
$hb\bar{b}$	0.99	0.59	0.72	0.62
$h\tau\tau$	1.1	0.75	0.81	0.71
hgg	1.6	0.96	1.1	0.96
$hc\bar{c}$	1.8	1.2	1.2	1.1
$h\gamma\gamma$	1.1	1.0	1.0	1.0
$h\gamma Z$	9.1	6.6	9.5	8.1
$h\mu\mu$	4.0	3.8	3.8	3.7
htt	-	6.3	-	-
hhh	-	20	-	-
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

arXiv:2209.07510

arXiv:1506.05992

Precision and discovery potential

New physics can show up with different patterns of deviations from the SM values

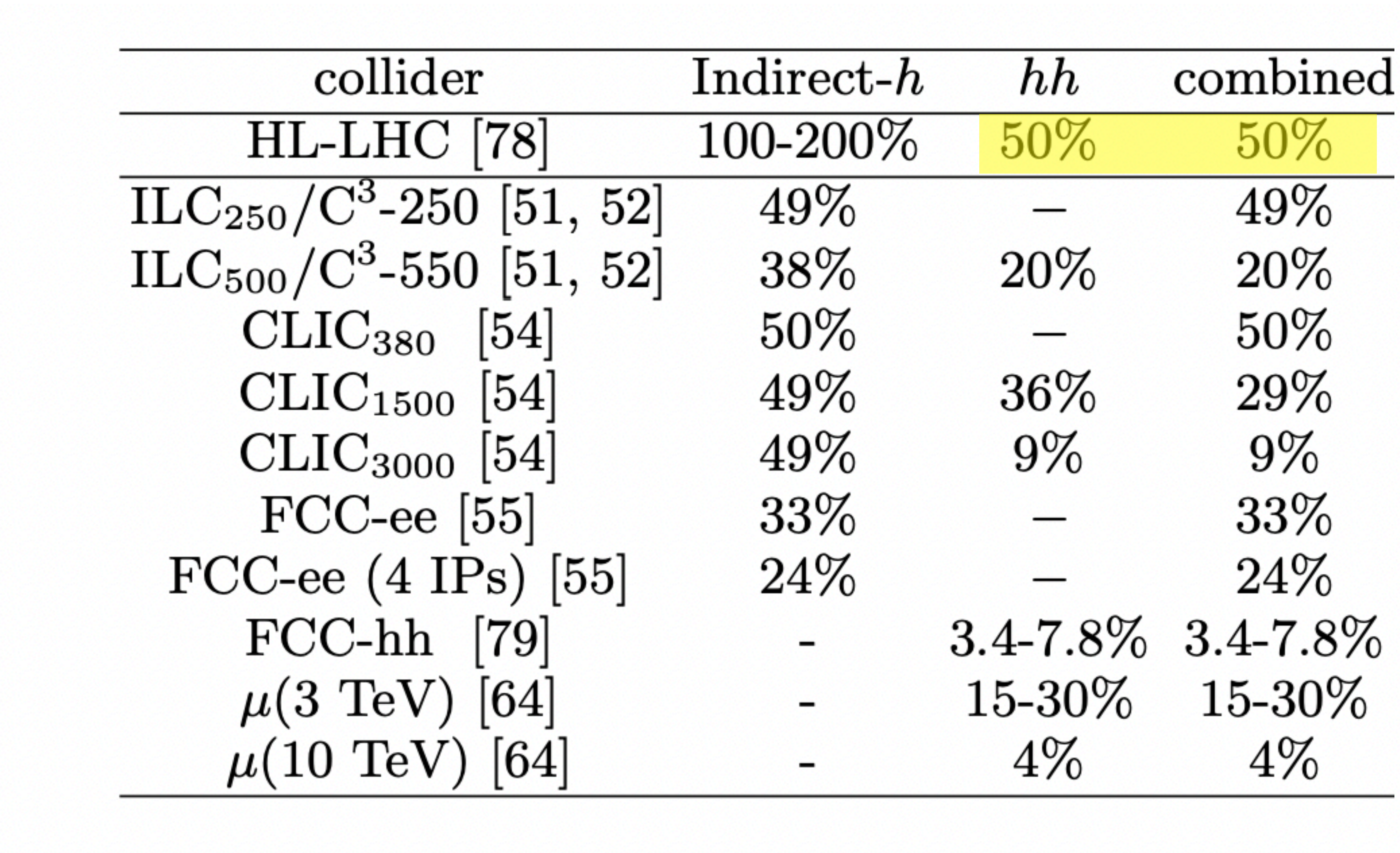


Precision is complementary to direct searches at LHC
Important to have access to higher energies in case we find a discrepancy at 250 GeV

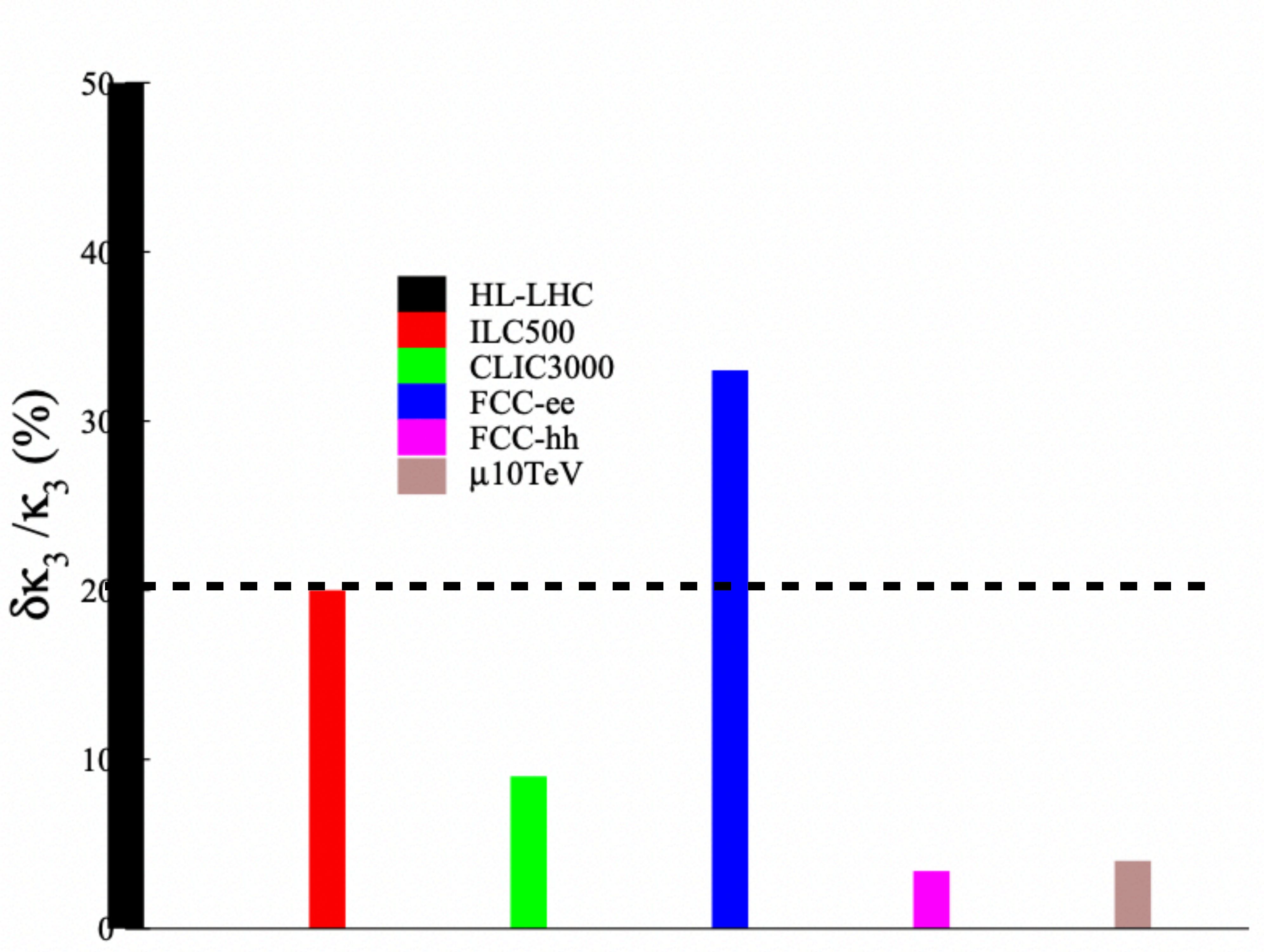
arXiv:2209.07510

The Higgs self-coupling

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%
$\mathrm{ILC}_{250}/\mathrm{C}^3$-250 [51, 52]	49%	–	49%
$\mathrm{ILC}_{500}/\mathrm{C}^3$-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%



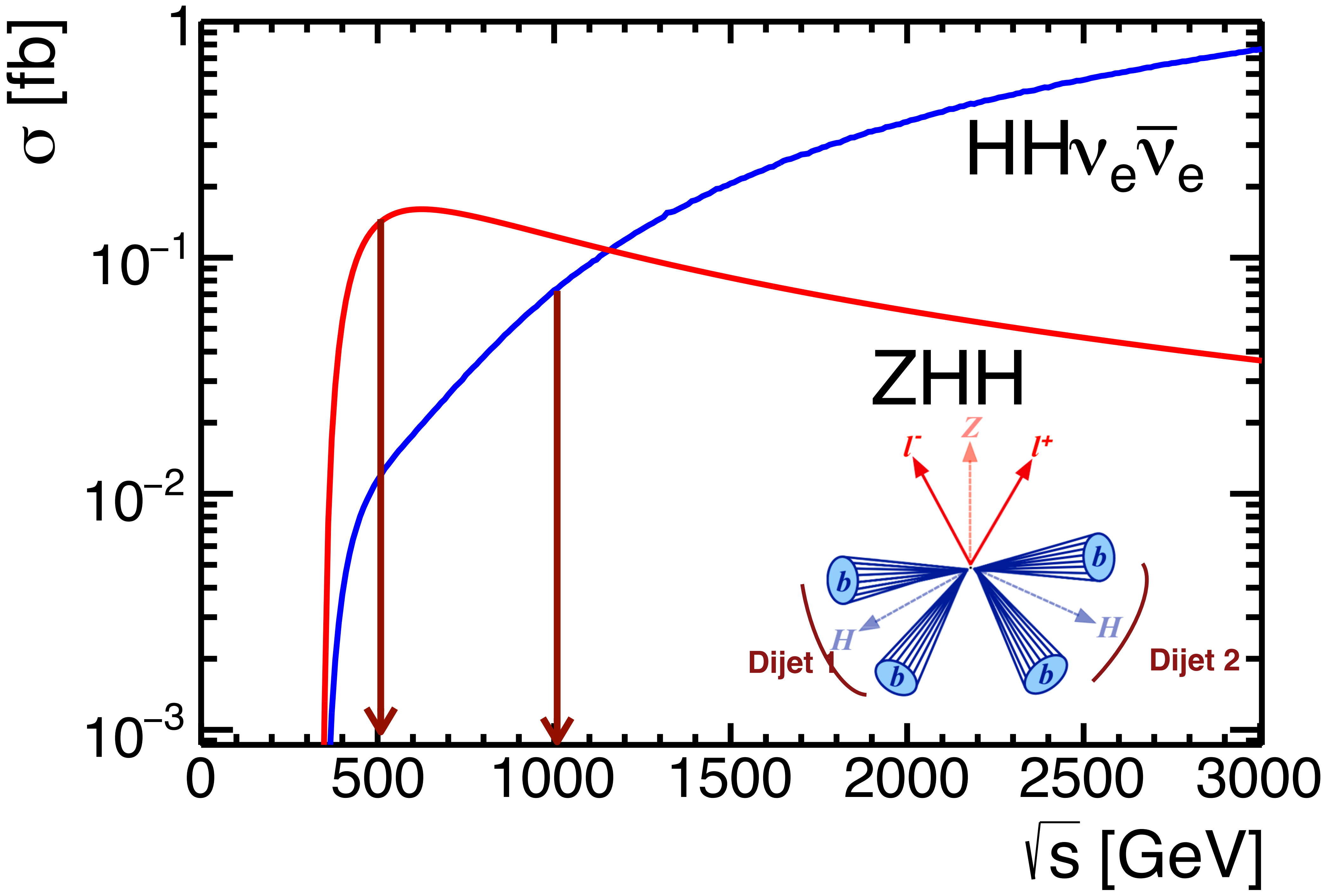
O(20%) precision on the Higgs self-coupling would allow to exclude/ demonstrate at 5σ models of electroweak baryogenesis

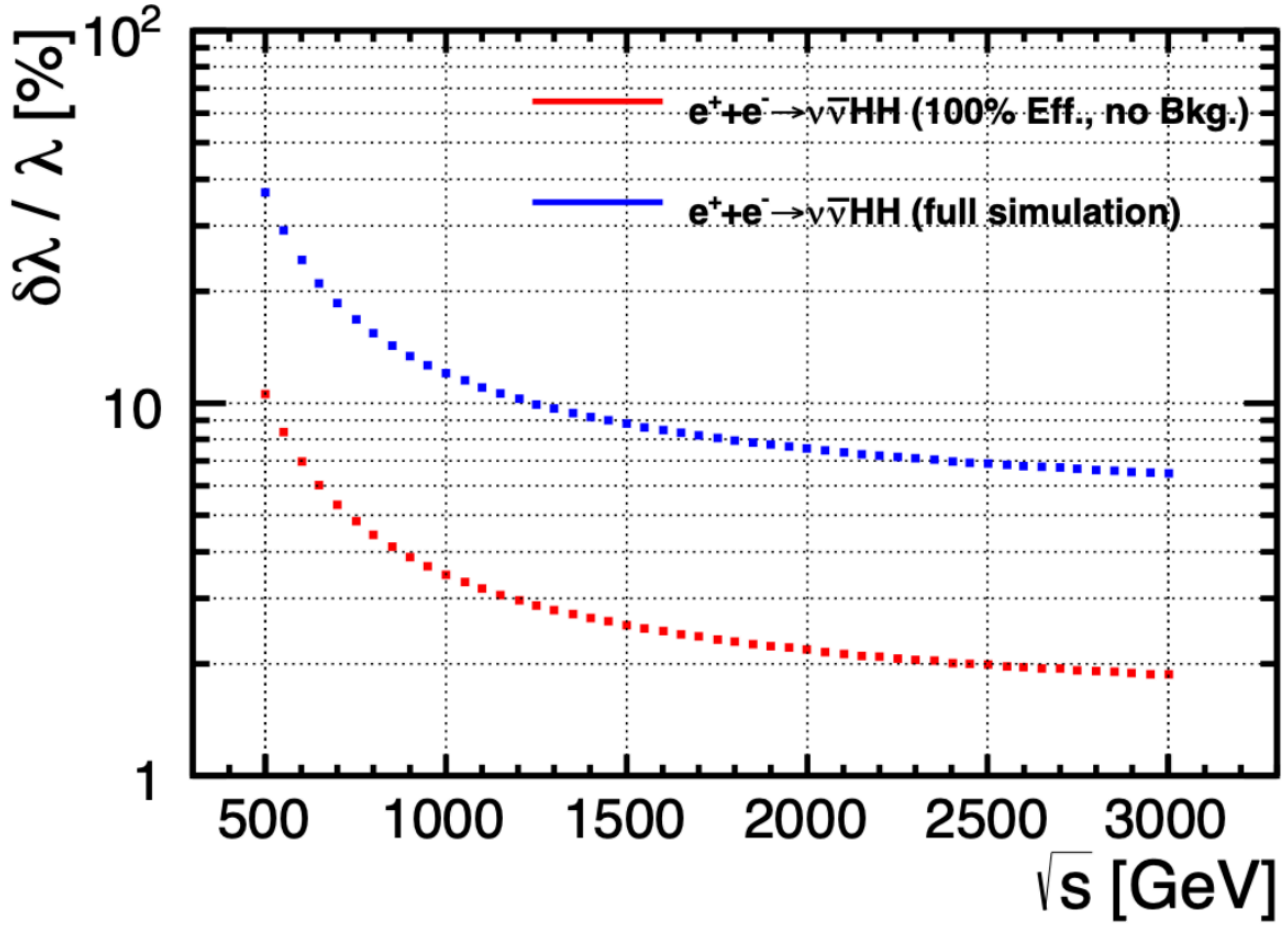
arXiv:2209.07510

What is next for HH?

Evaluate dependency as a function of CM and further analysis improvements

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





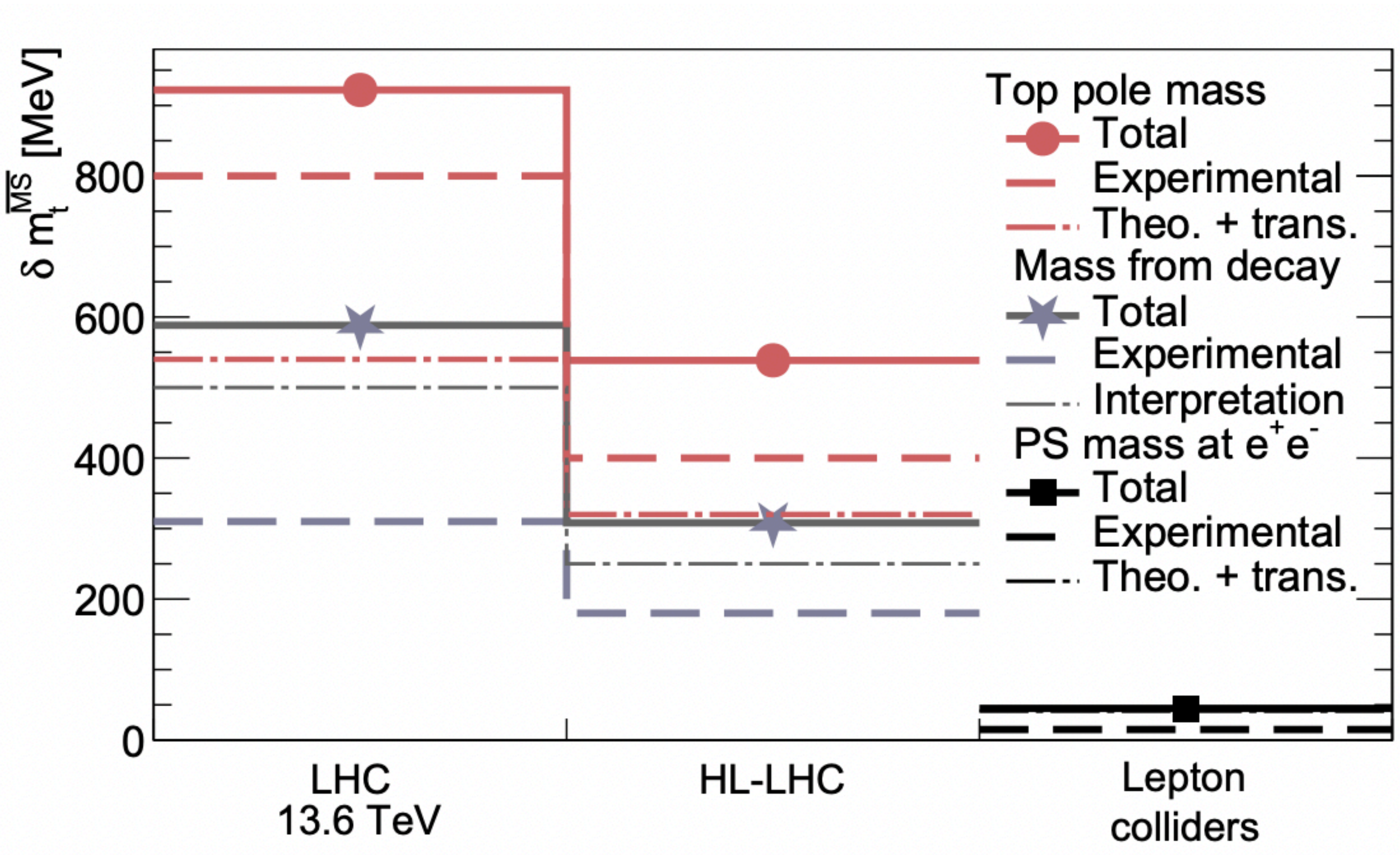
Review of ongoing studies for ZHH (talk, arXiv)

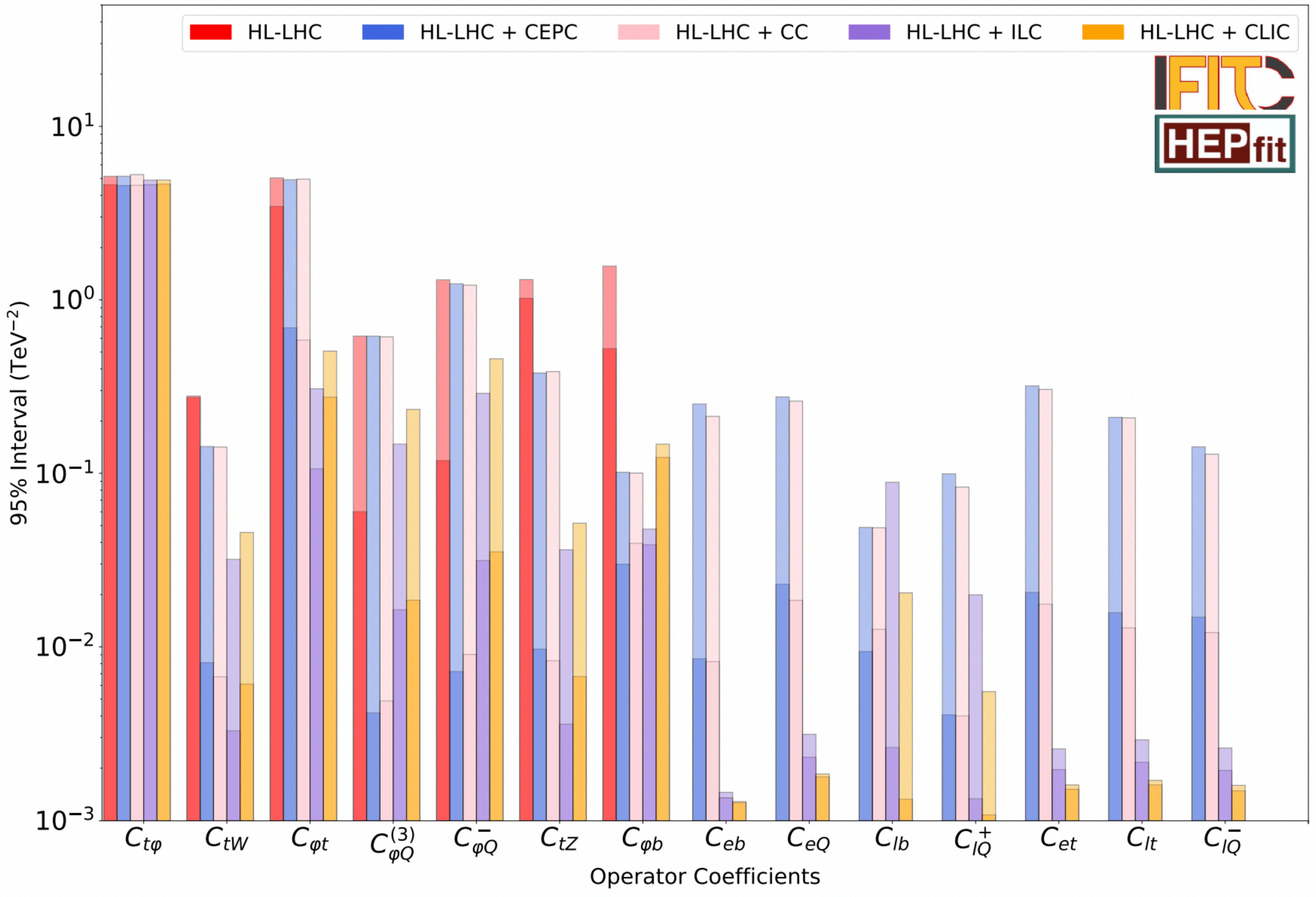
arXiv:2205.02140
arXiv:2209.07510

Top physics at e^+e^-

Unique opportunities for theoretically clean precision observables

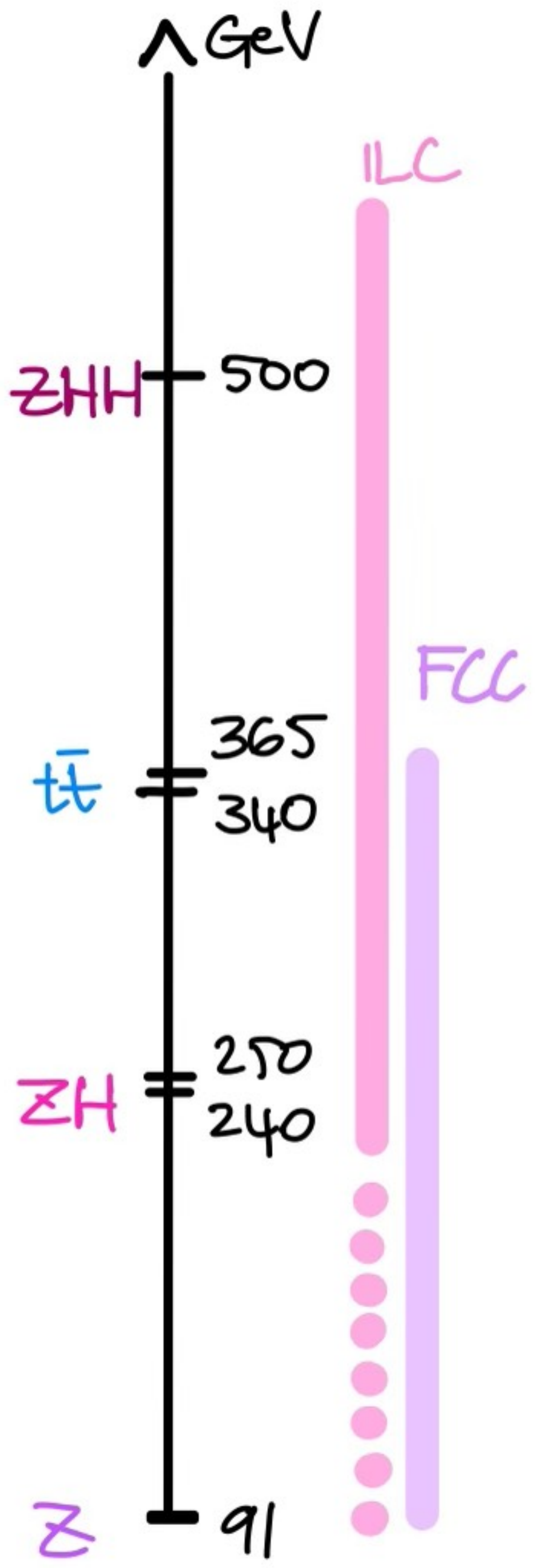
- The measurement of the tt cross-section with a threshold scan can determine the top mass with 50 MeV uncertainty
- Global fits demonstrate e^+e^- sensitivity of10-100 times above HL-LHC for some operators top electroweak couplings at energies > 500 GeV





(Recap) Physics benchmarks

LC and CC have different & complementary energy reach and goals



Higher Energies, O(500) GeV

- ZHH and ttH: multi-(b)jets final state
  - Set needs to resolve large secondary vertex decay lengths and collimated decays

tt, top mass, O(350) GeV

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.
  - Requirements on: charged track momentum and impact parameters, jet resolutions.

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
- *Z width extraction* - Requires excellent control of acceptance
  - Constraints on Tracking, LumiCal and forward Calorimeters
  - Requirements for muon tracks from Z decays: angular resolution of 100 mrad to control the beam energy spread; Stability of the track momentum scale (40 KeV/91 GeV ≈) 10^{-7} to control measurement of COM energy.

(Higgs) physics requirements for detectors

arXiv:2003.01116

Precision challenges detector design

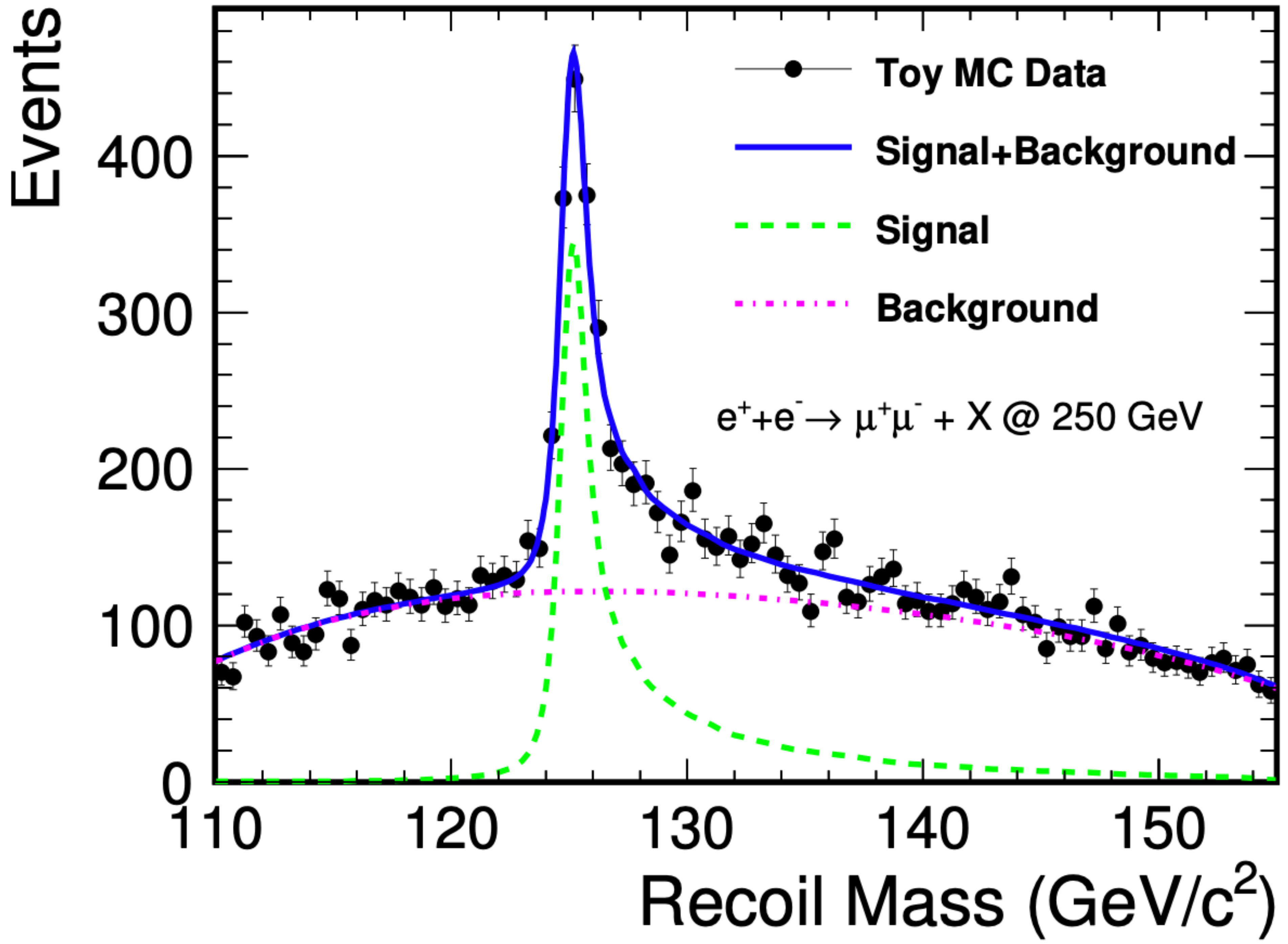
ZH process: Higgs recoil reconstructed from Z decays

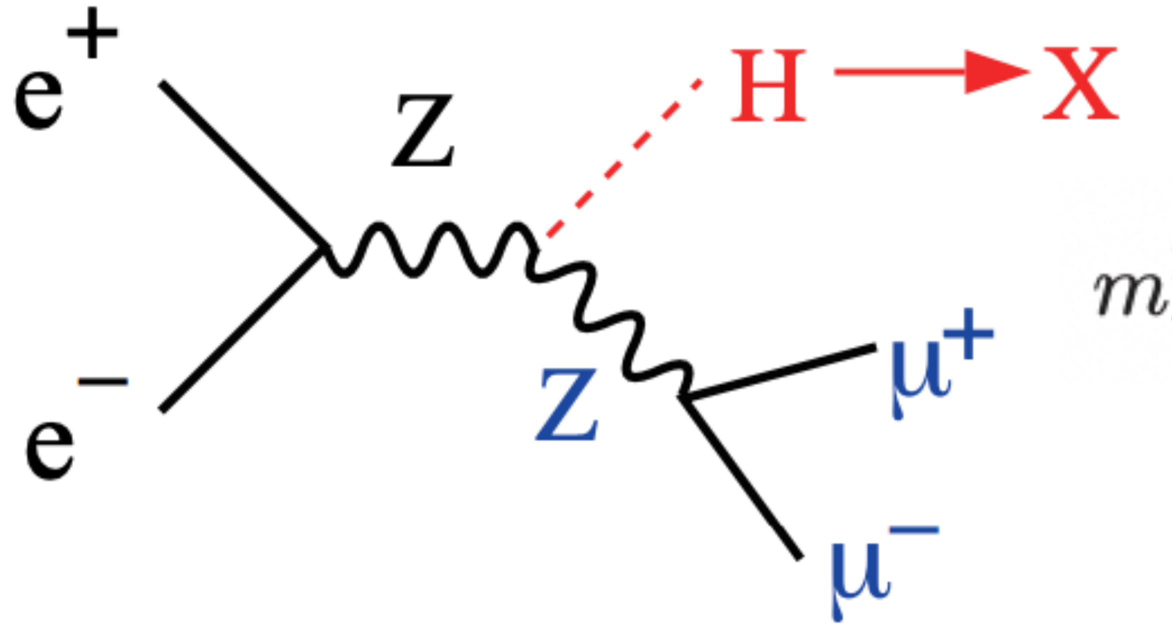
- Drives requirement on charged track momentum and jet resolutions
- Drives need for high field magnets and high precision / low mass trackers

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

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

  <0.3% X_0 per layer (ideally 0.1% X_0)



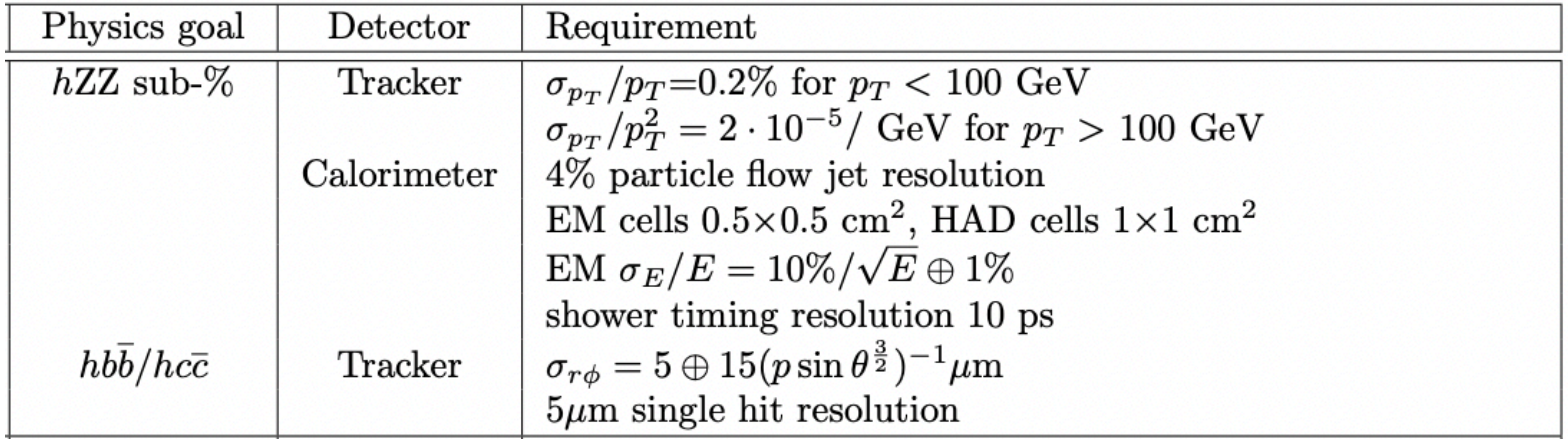


$$m^2_{recoil} = s + m_Z^2 - 2 \cdot E_Z \cdot \sqrt{s}$$

Current benchmarks and next steps

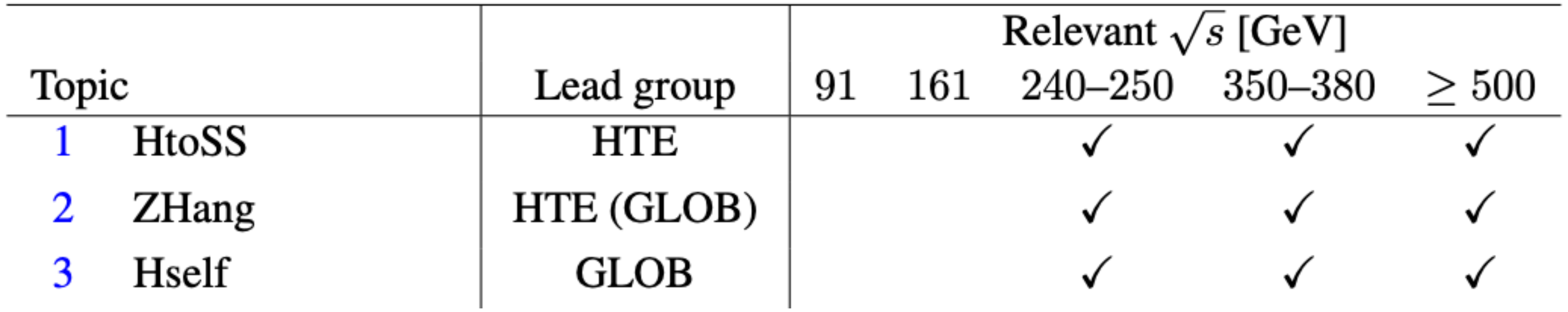
The goal of measuring Higgs properties with sub-% precision translates into ambitious requirements for detectors at e^+e^-

- 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



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

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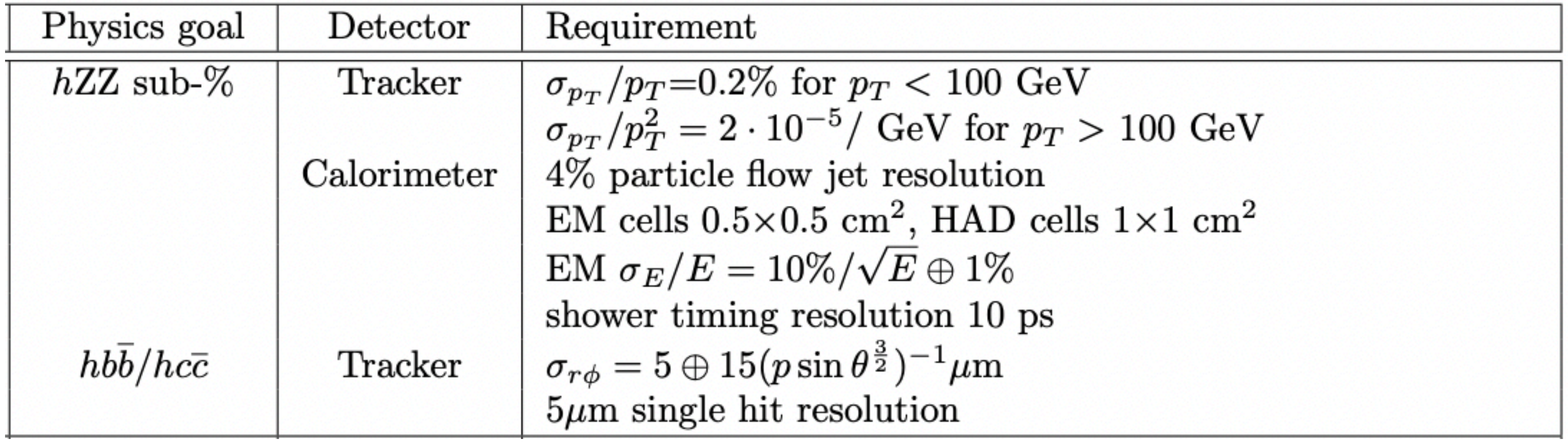

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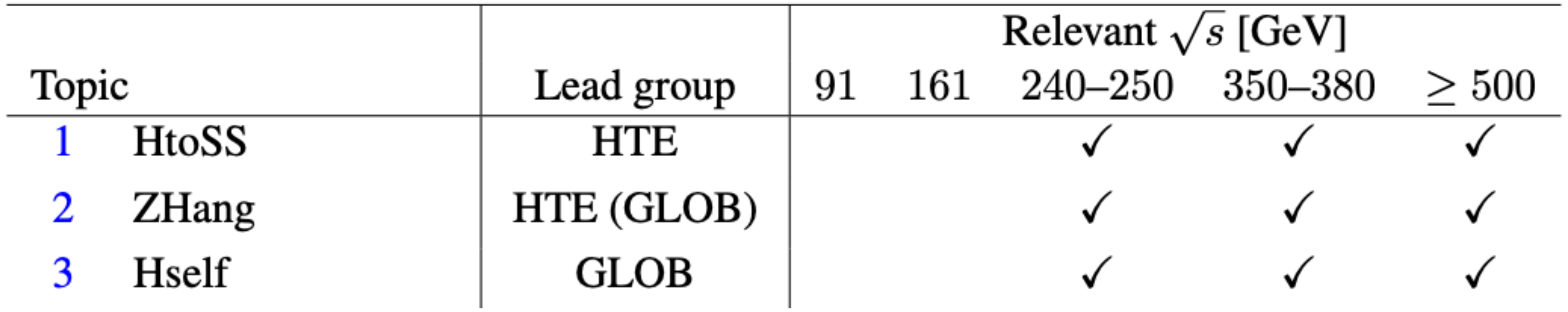

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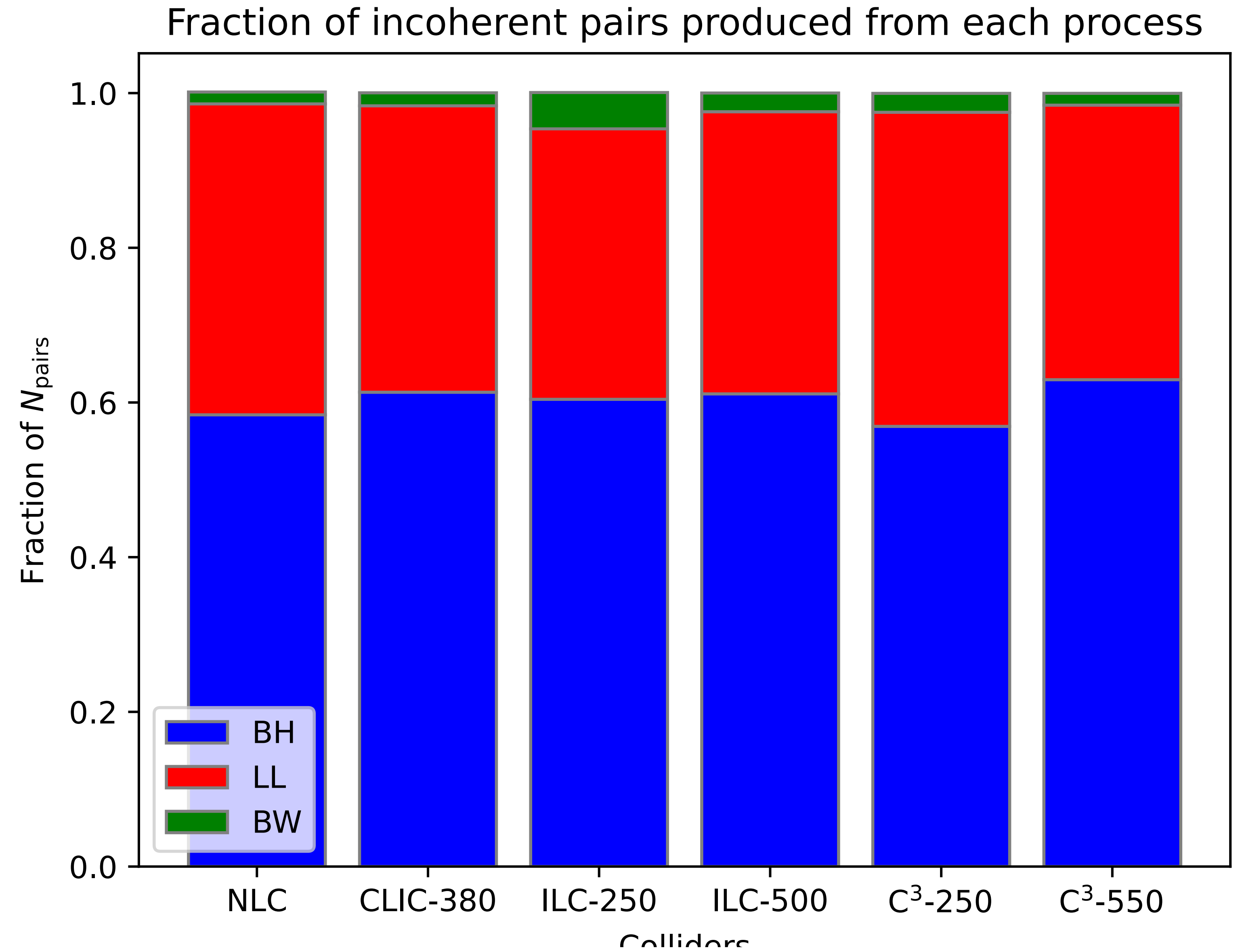
Focus topics for the ECFA study on Higgs / Top / EW factories *should* provide further detector design guidelines (2401.07564) by Spring 2025

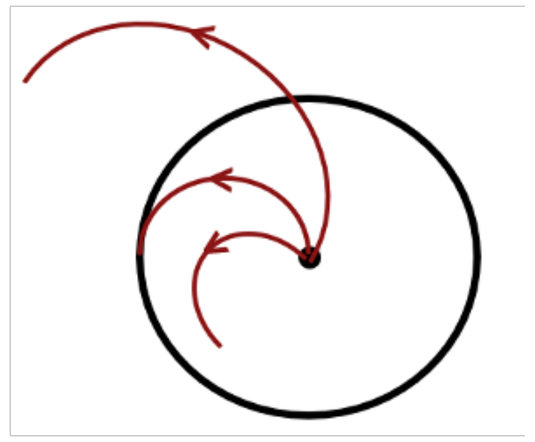
Joint simulation/detector optimization effort
ILC WG3 March 21
arXiv:2403.07093

Importance of beam-beam background

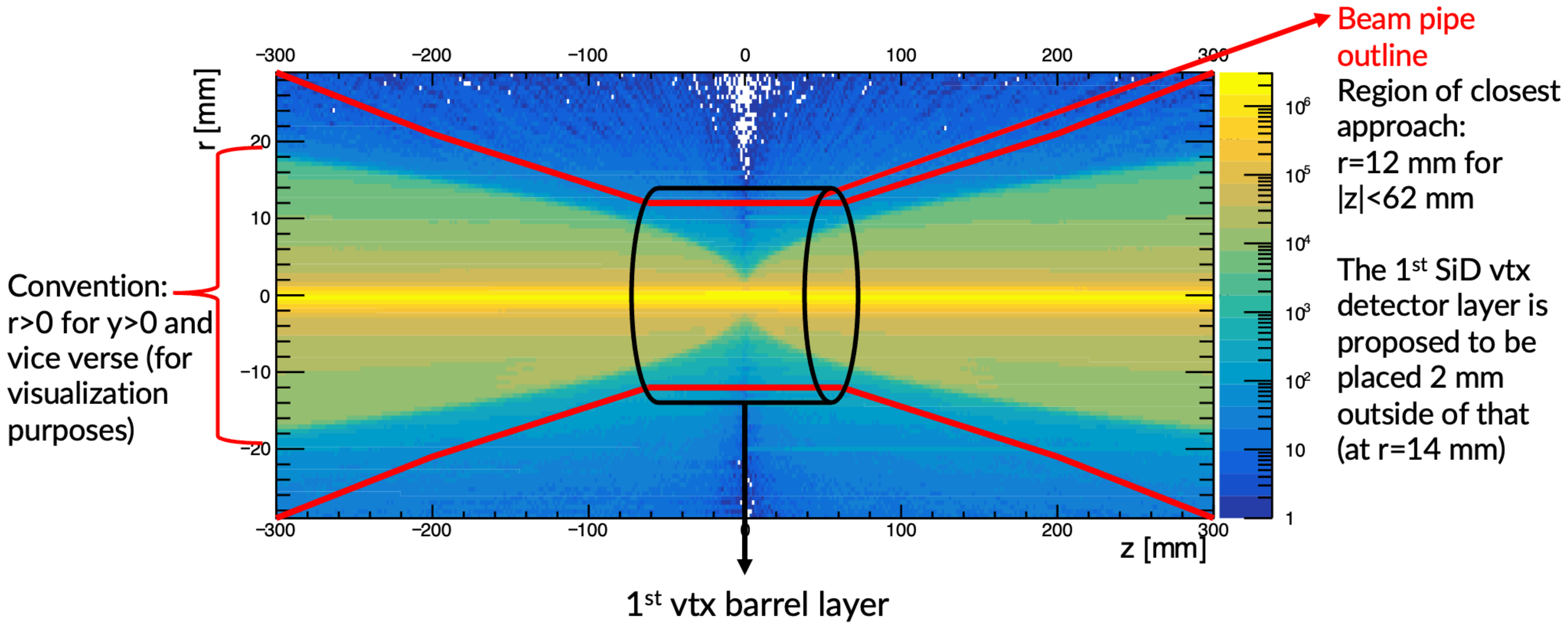
The effects of beam-beam interactions have to be careful simulated for physics and detector performance

- Beamstrahlung photons are radiated at the IP:
  - Incoherent pair production
  - Muon and Hadron photo-production
- Beamstrahlung widens the luminosity spectrum
  - Enables collisions at lower $\sqrt{s}$ and softens initial state constraints → important for physics observables (ZH)
  - Photoproduced jets affect clustering performance, JER, JES
  - 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





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



Beam pipe outline

Region of closest approach: r=12 mm for |z|<62 mm

The 1st SiD vtx detector layer is proposed to be placed 2 mm outside of that (at r=14 mm)

Convention: r>0 for y>0 and vice verse (for visualization purposes)

1st vtx barrel layer

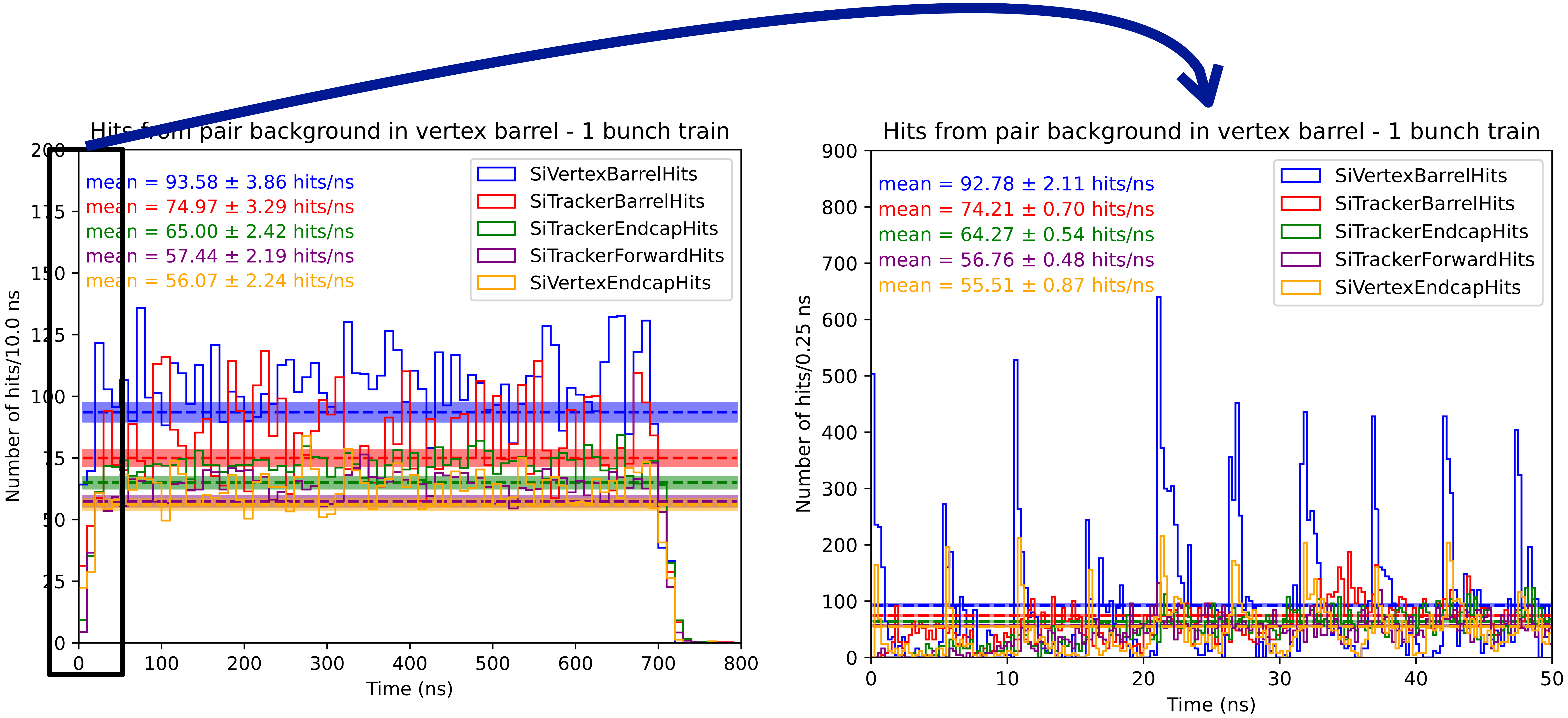
D. Ntounis (2023)
G. Marchiori (2023)

Current status of beam-background studies

O(ns) timing capabilities as an additional handle to suppress beam induced backgrounds

Time distribution of hits per unit time and area: $\sim 4.4 \cdot 10^{-3}$ hits/(ns·mm^2) $\simeq$ 0.03 hits/mm^2 /BX
in the 1st layer of the vertex barrel SiD-like detector for ILC/C^3

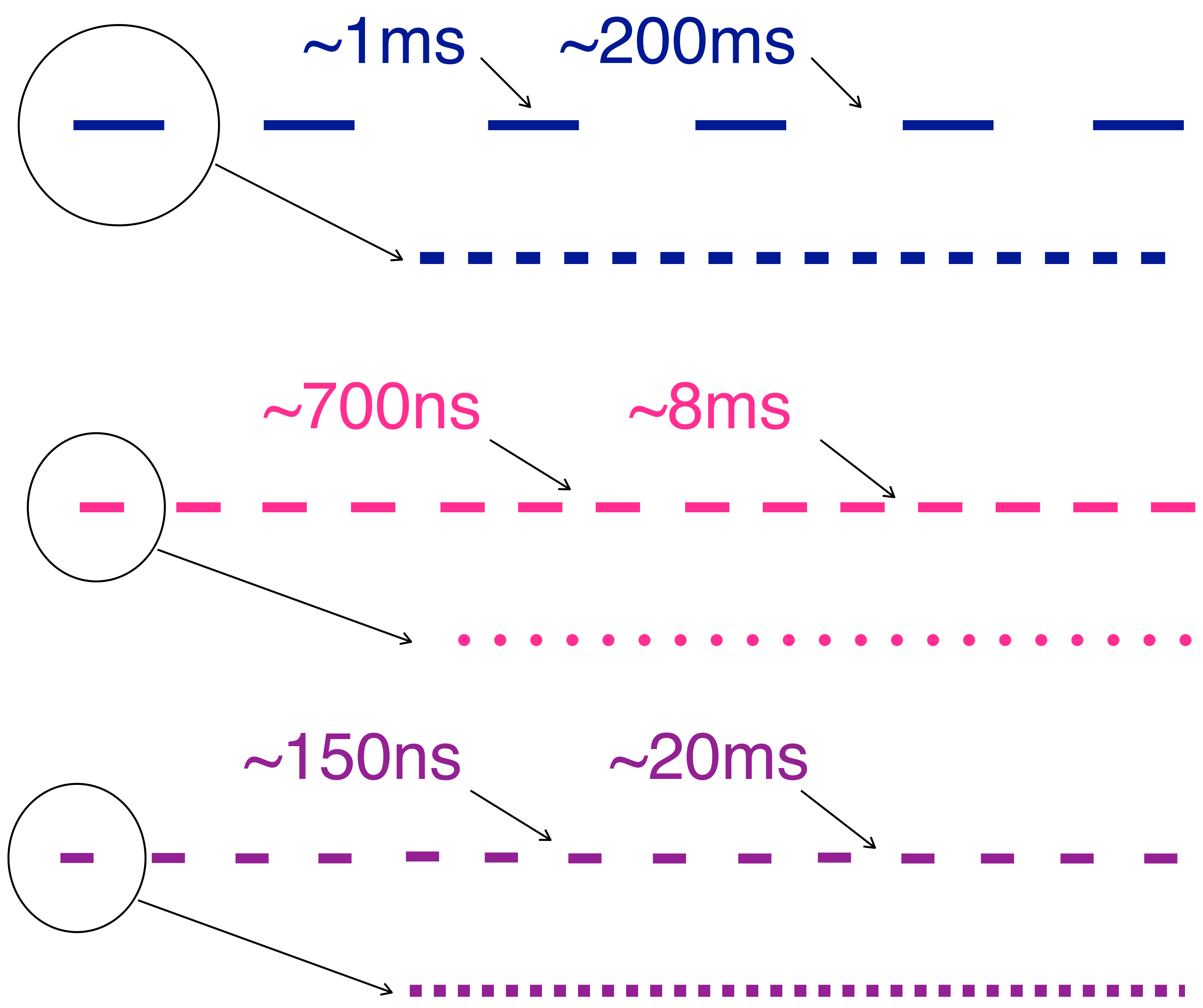
C^3 time structure is compatible with ILC-like detector overall design and ongoing optimizations.



Parameter	**Value**
Time resolution	1 ns-rms
Spatial Resolution	7 μm
Expected charge from a MIP	500 – 800 e/h
Minimum Threshold	200 e-
Noise	< 30 e-rms
Power density	< 20 mW/cm^2
Maximum particle rate	1000 hits/cm^2

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

C^3 Trains at 120Hz, 1 train 133 bunches
Bunches are 5 ns apart

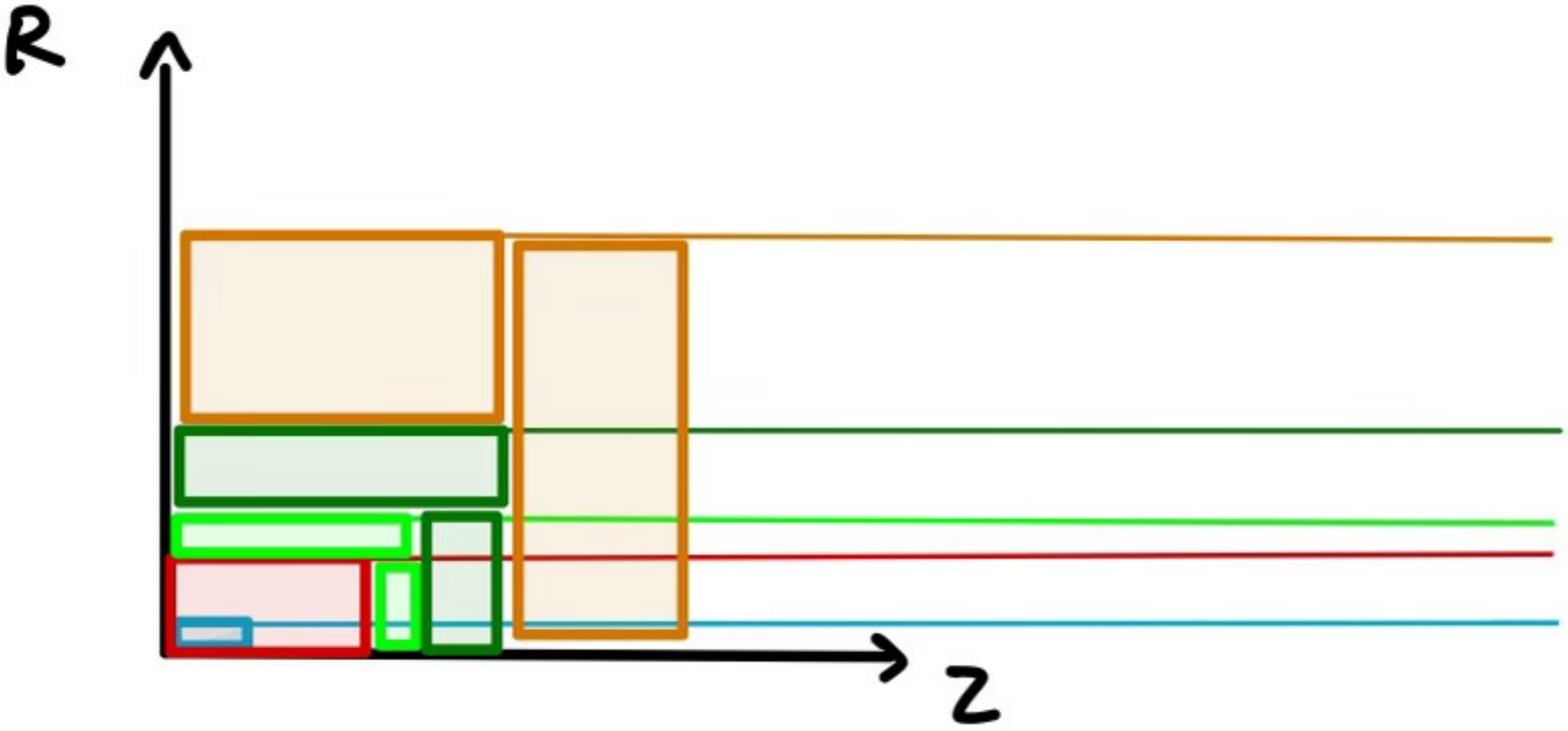
CLIC Trains at 50Hz, 1 train 312 bunches
Bunches are 0.5 ns apart

- **Very low duty cycle at LC** (0.5% ILC, 0.08% C^3) allows for trigger-less readout and power pulsing
  - Factor of 100 power saving for front-end analog power
- Impact of beam-induced background to be mitigated through MDI and detector design
- **O(1-100) ns bunch identification capabilities** (hit-time-stamping) can further suppress beam-backgrounds and keep occupancy low - same as for FCC-ee

Detector concepts

Different approaches to achieve *same* physics goals
Many synergistic R&D directions, **a couple of highlights**

Detector concepts



Yoke + Muon system

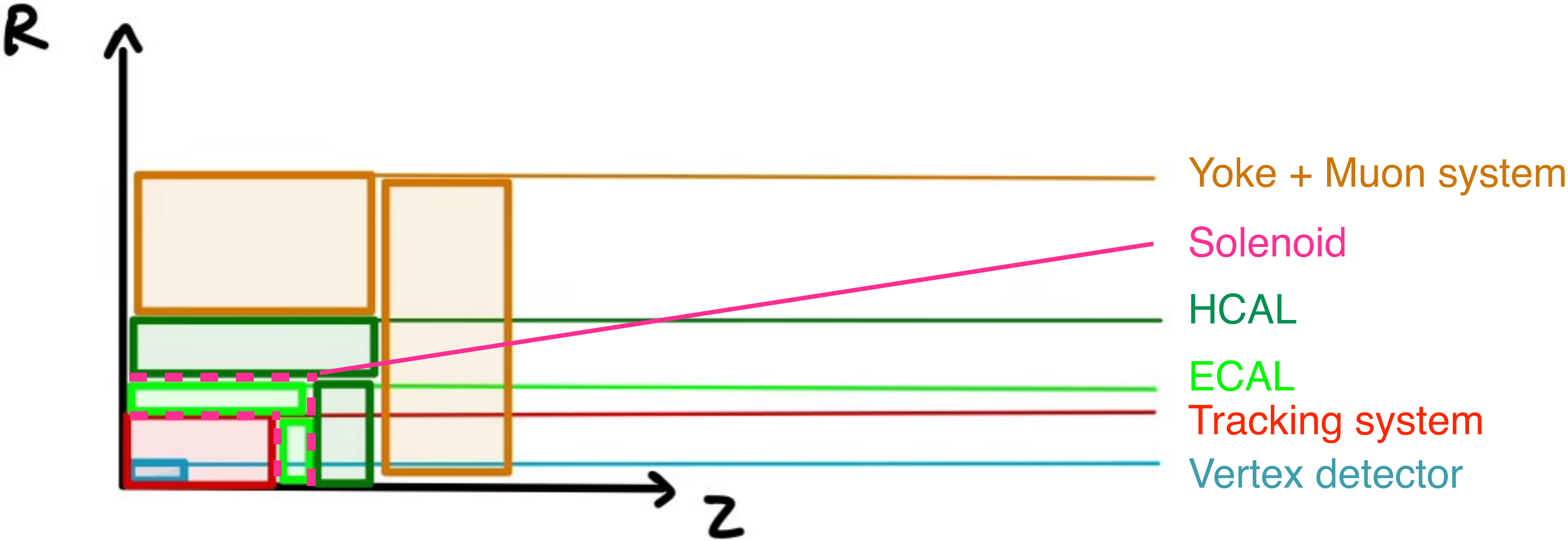
HCAL

ECAL

Tracking system

Vertex detector

Detector concepts



Yoke + Muon system

Solenoid

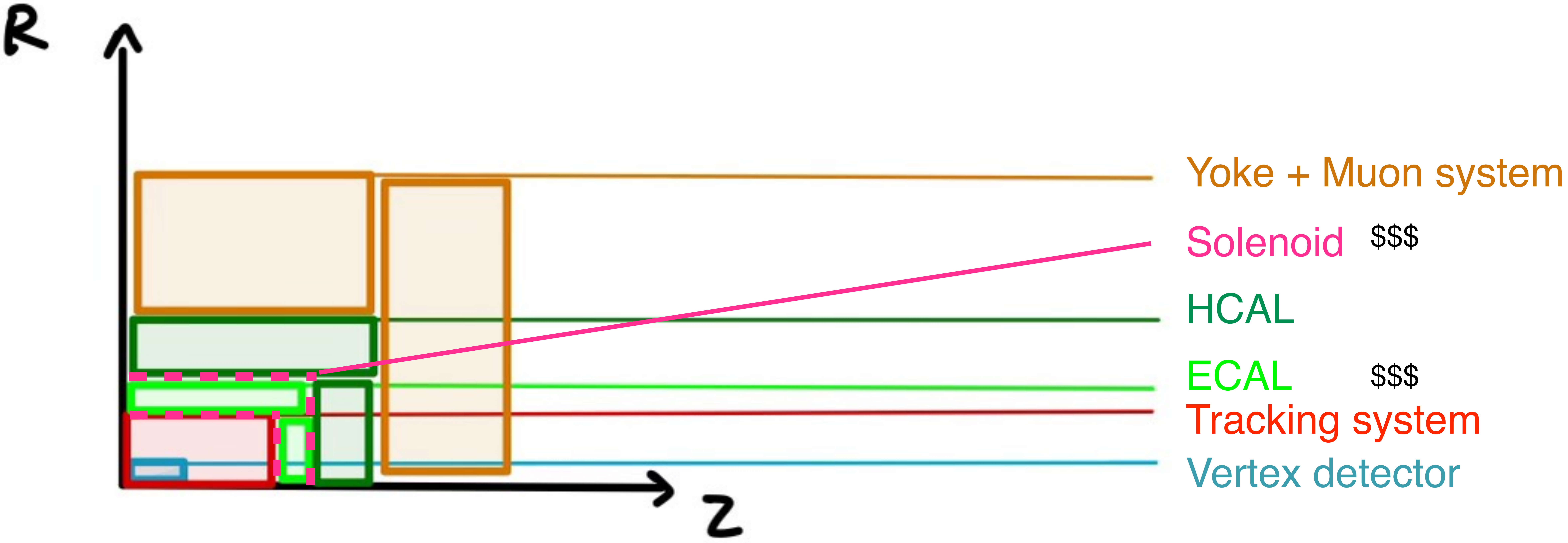
HCAL

ECAL

Tracking system

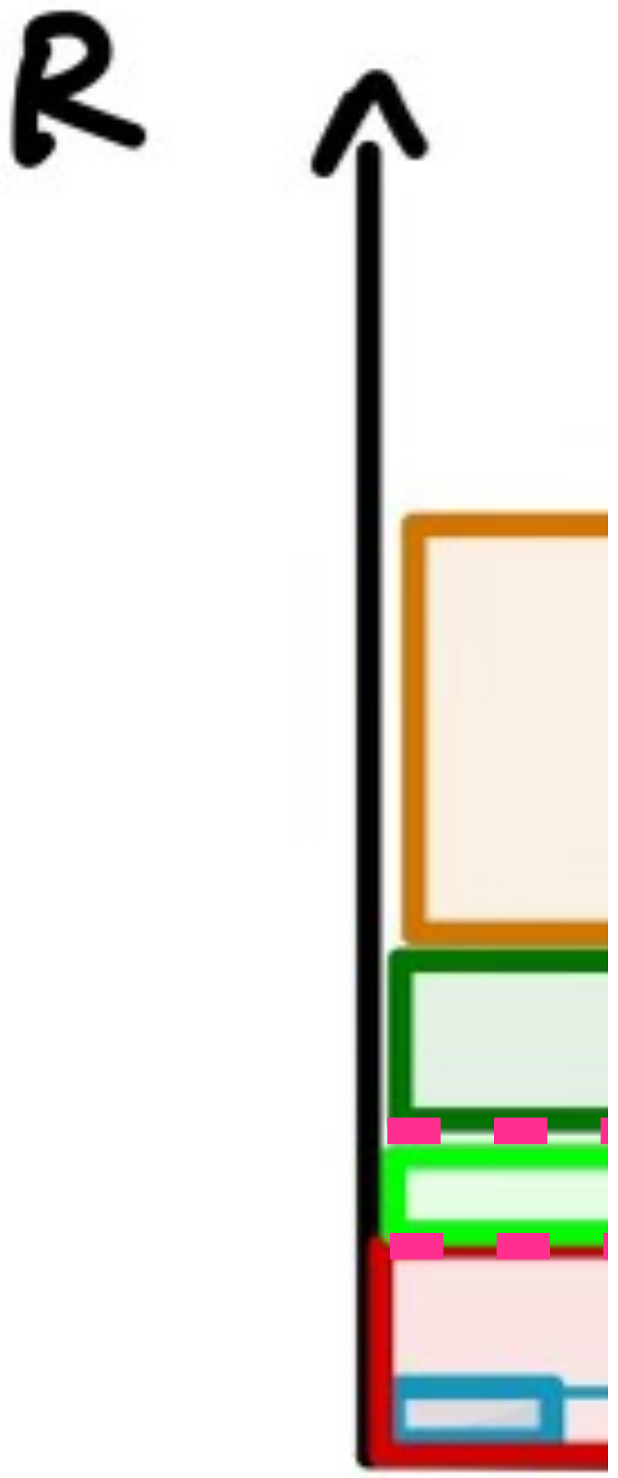
Vertex detector

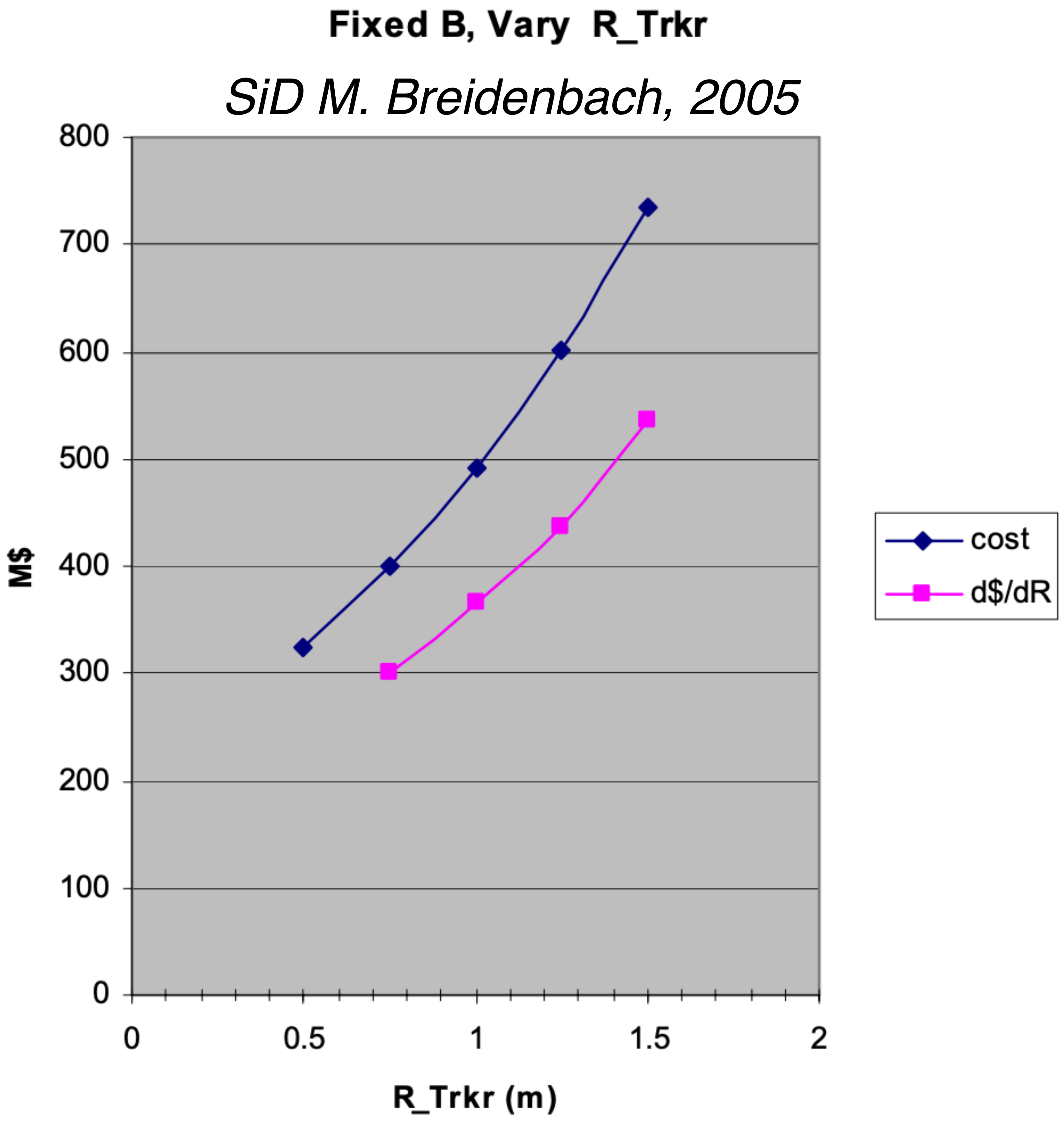
Detector concepts



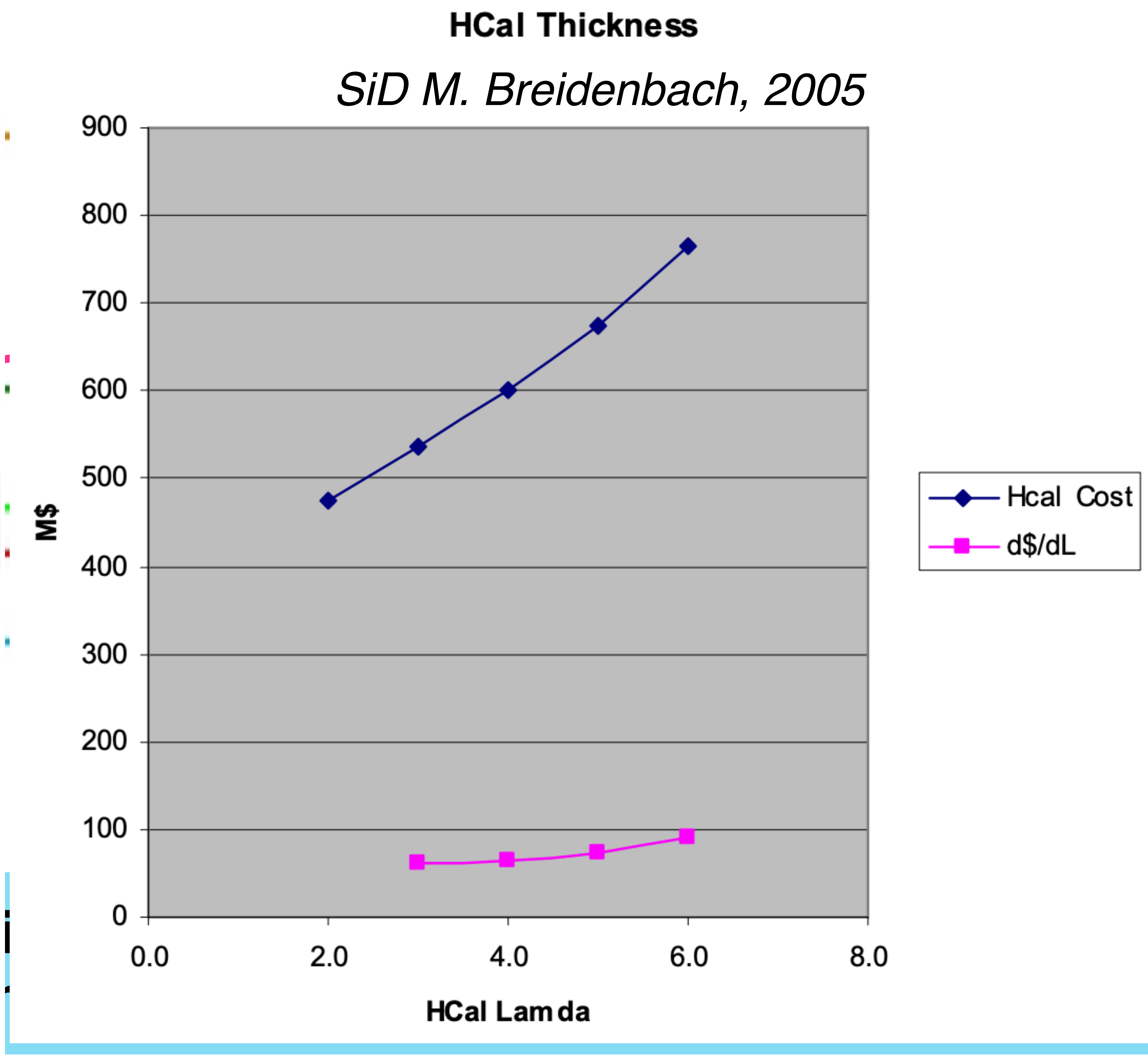
Magnet and Calorimeters are generally driving the cost (>30% each) of the detector
Optimizations and cost reduction are possible with targeted R&D

Detector concepts





SiD M. Breidenbach, 2005



SiD M. Breidenbach, 2005

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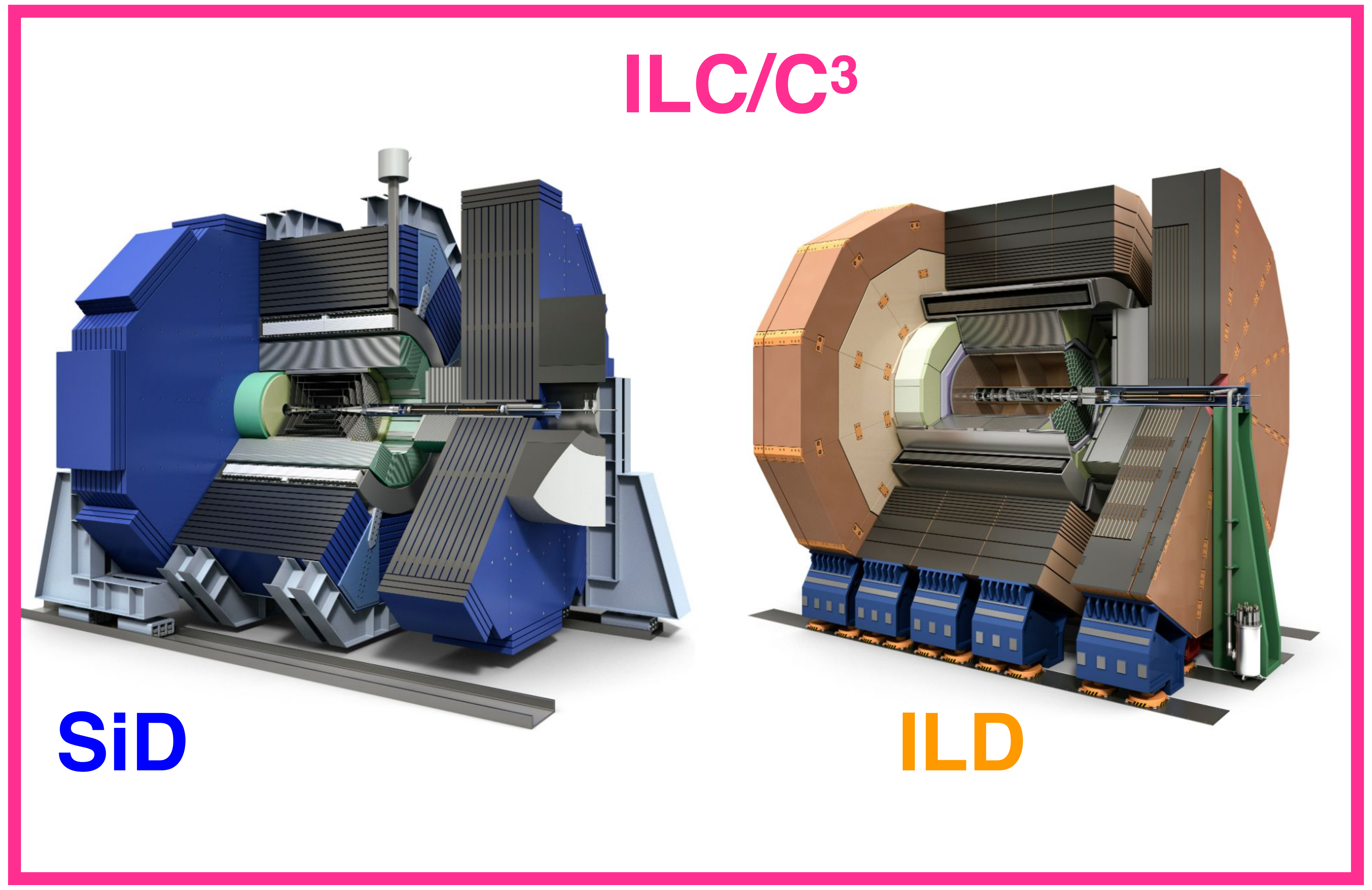
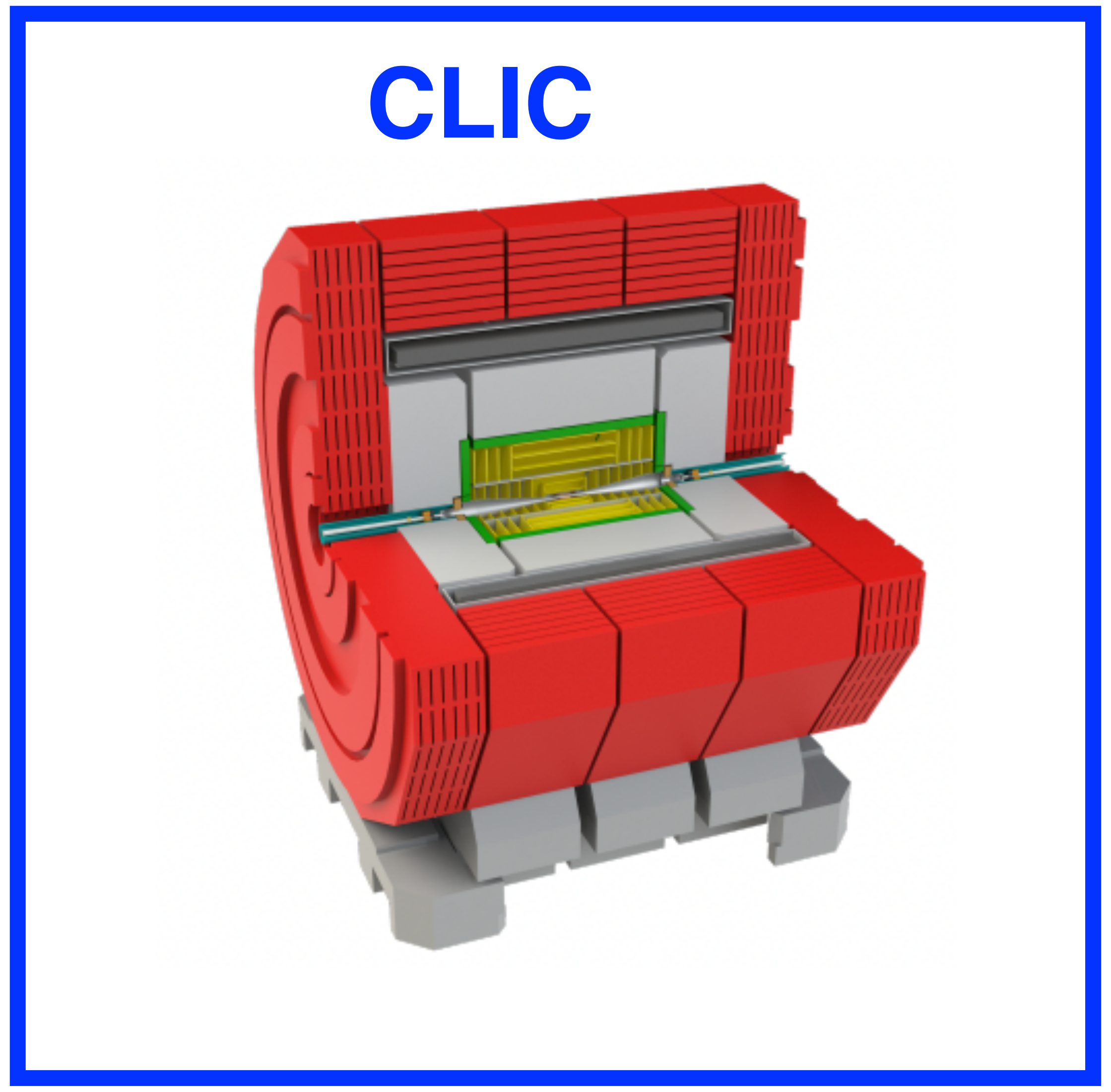
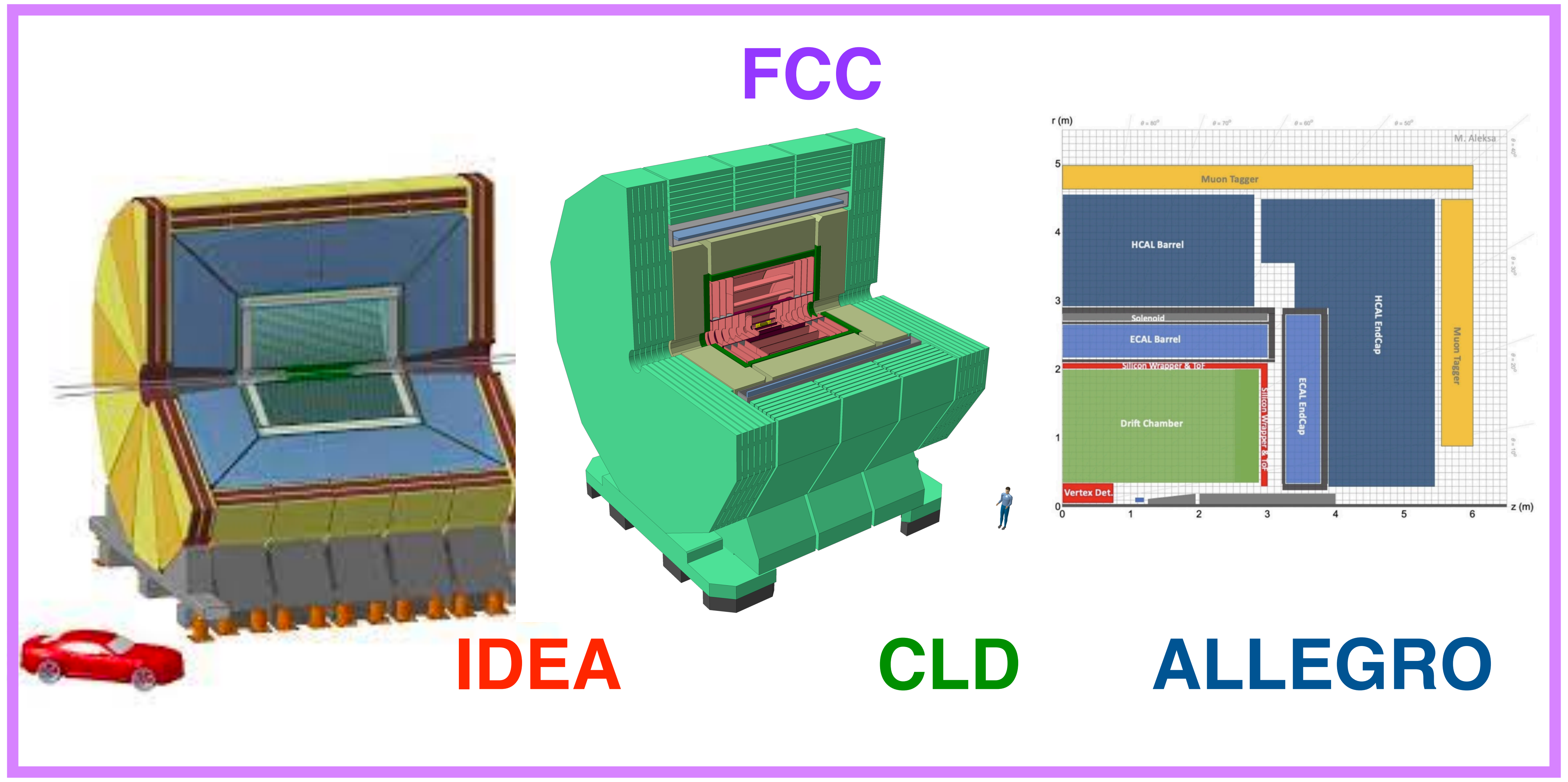
Detector Designs, a quick overview







- 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/CLICdet - 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

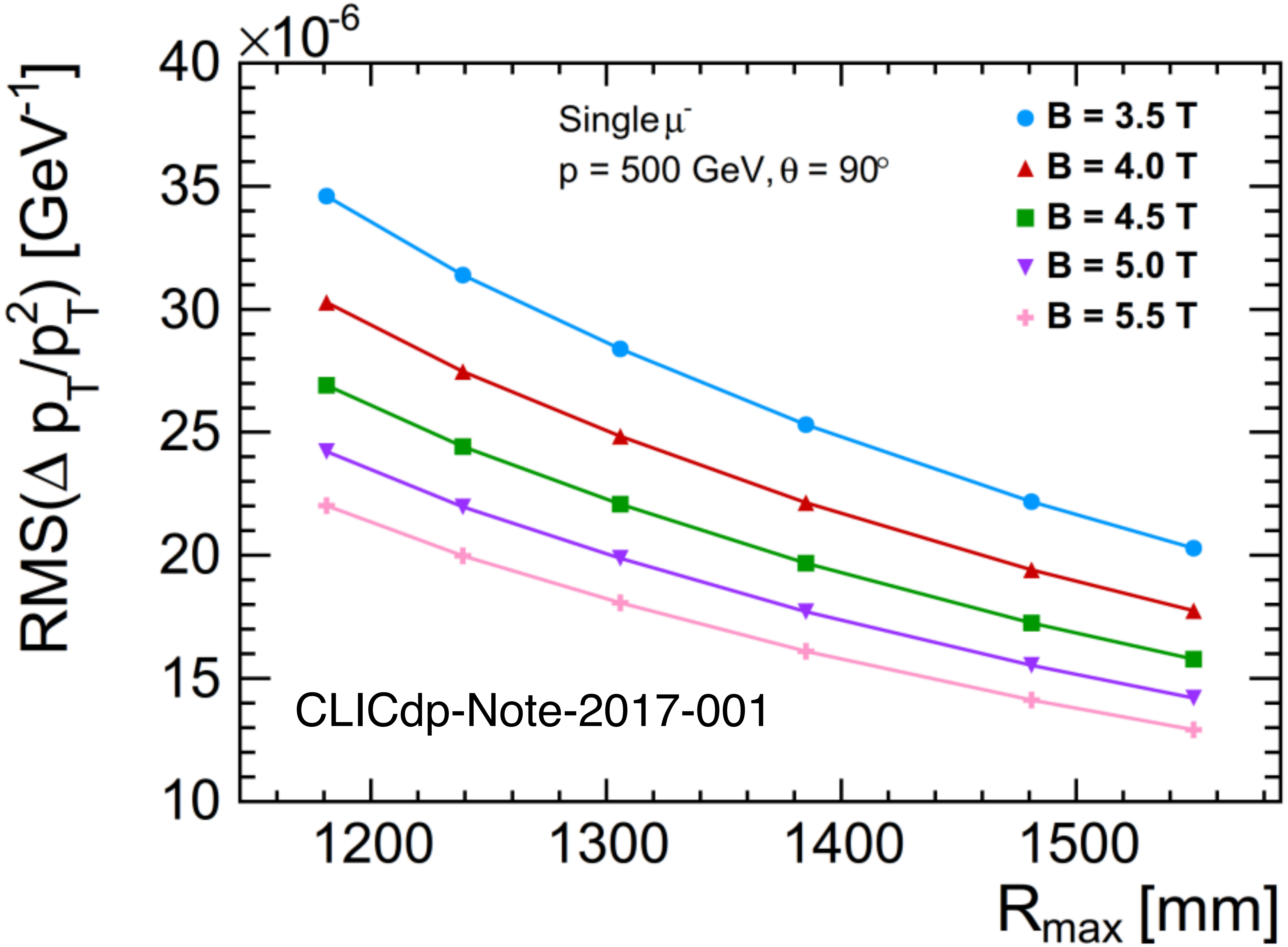
	ILD	SID	CLICdet	IDEA	CLD	ALLEGRO
Vertex Inner Radius (cm)	1.6	1.4	3.1	1.2	1.2	1.2
Tracker technology	TPC+Silicon	Silicon	Si	Si+Drift Chamber	Si	Si+Drift Chamber
Outer Tracker Radius (m)	1.77	1.22	1.5	2	3.3	2
ECal thickness	24 X_0	26 X_0	22 X_0	Dual RO	22 X_0	22 X_0
HCal thickness	5.9 λ_0	4.5 λ_0	7.5 λ_0	7 λ_0	6.5 λ_0	9.5 λ_0
HCal Outer Radius (m)	3.3	2.5	3.25	4.5	3.5	4.5
Solenoid field (T)	3.5	5	4	2	2	2
Solenoid length (m)	7.9	6.1	8.3	6	7.4	6
Solenoid Radius (m)	3.4	2.6	3.5	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

A tail of synergies and complementarity



CLICdp-Note-2017-001

	D	ALLEGRO
Vertex Inner Radi	2	1.2
Tracker techno	i	Si+Drift Chamber
Outer Tracker Ra	3	2
ECal thickne	X_0	22 X_0
HCal thickne	λ_0	9.5 λ_0
HCal Outer Radi	5	4.5
Solenoid field		2
Solenoid lengt	4	6
Solenoid Radiu		2.7

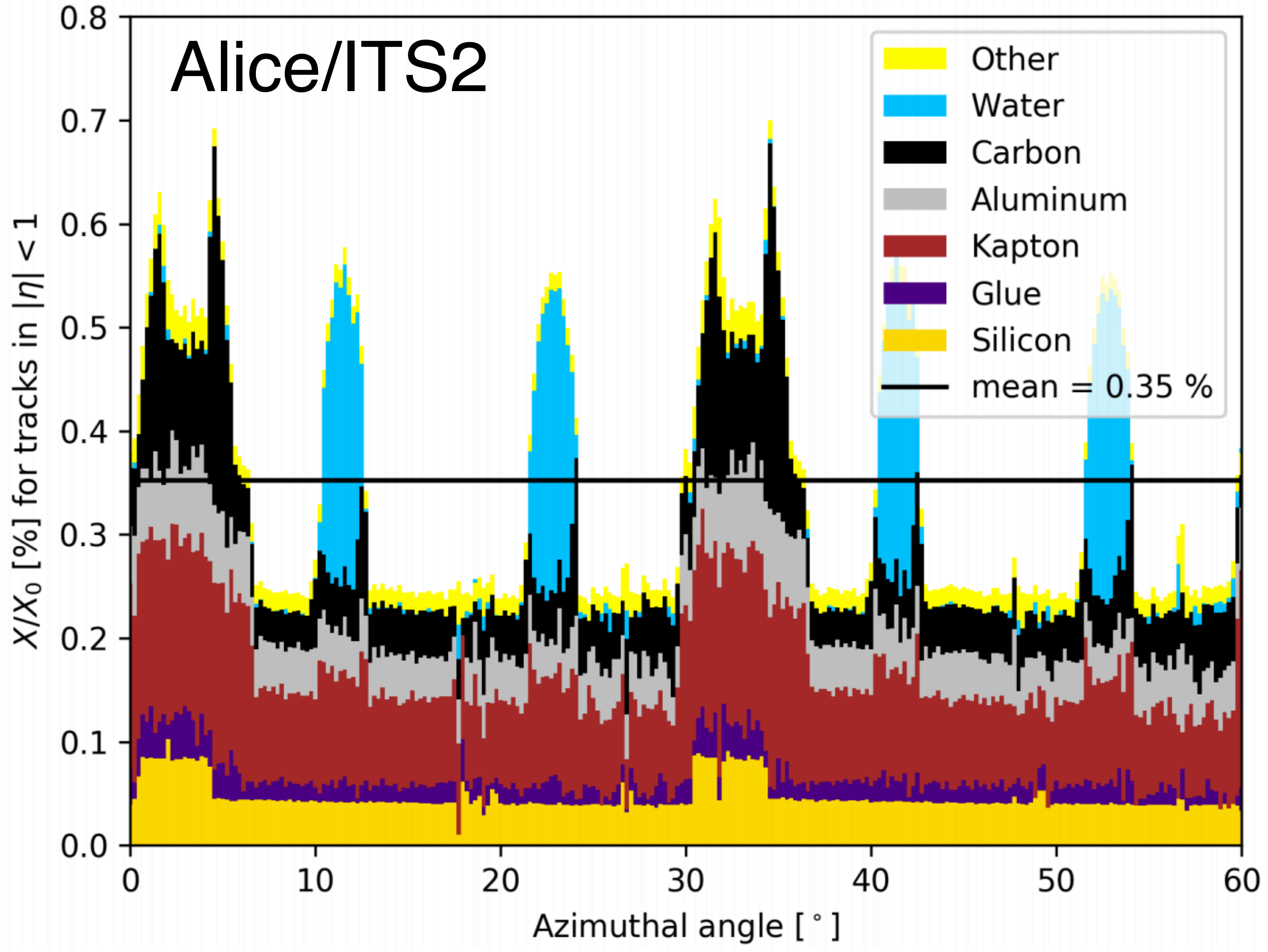
B-field and tracker radius optimization driven by:
PFA performance, vertex detector occupancy, technical considerations

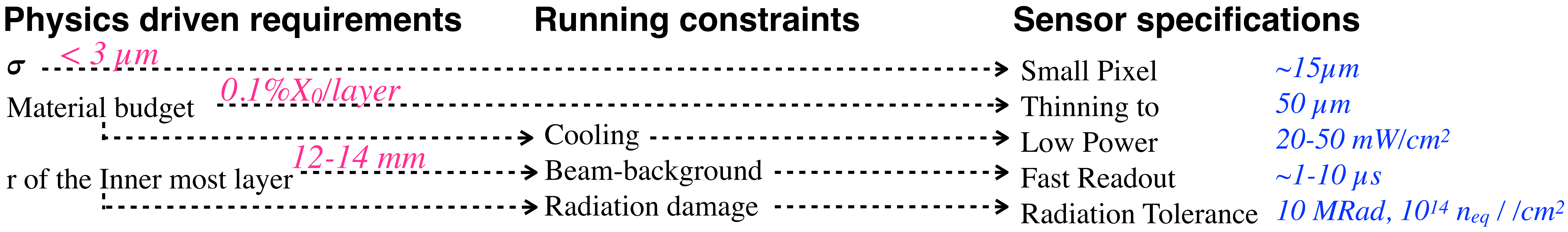
Sensors technology requirements for Vertex Detector

Several technologies are being studied to meet the physics performance

- Sensor's contribution to the total material budget is 15-30%
  - Services cables + cooling + support make up most of the detector mass
- Sensors will have to be less than 75 μm thick with at least 3-5 μm hit resolution (17-25 μm pitch) and low power consumption
- Beam-background suppression
  - ILC/C^3 - evolve time stamping towards O(1-100) ns (bunch-tagging)
  - FCC, continuous r/o integrated over ~10μs with O(1) ns timing resolution for beam background suppression

CERN-LHCC-2019-018

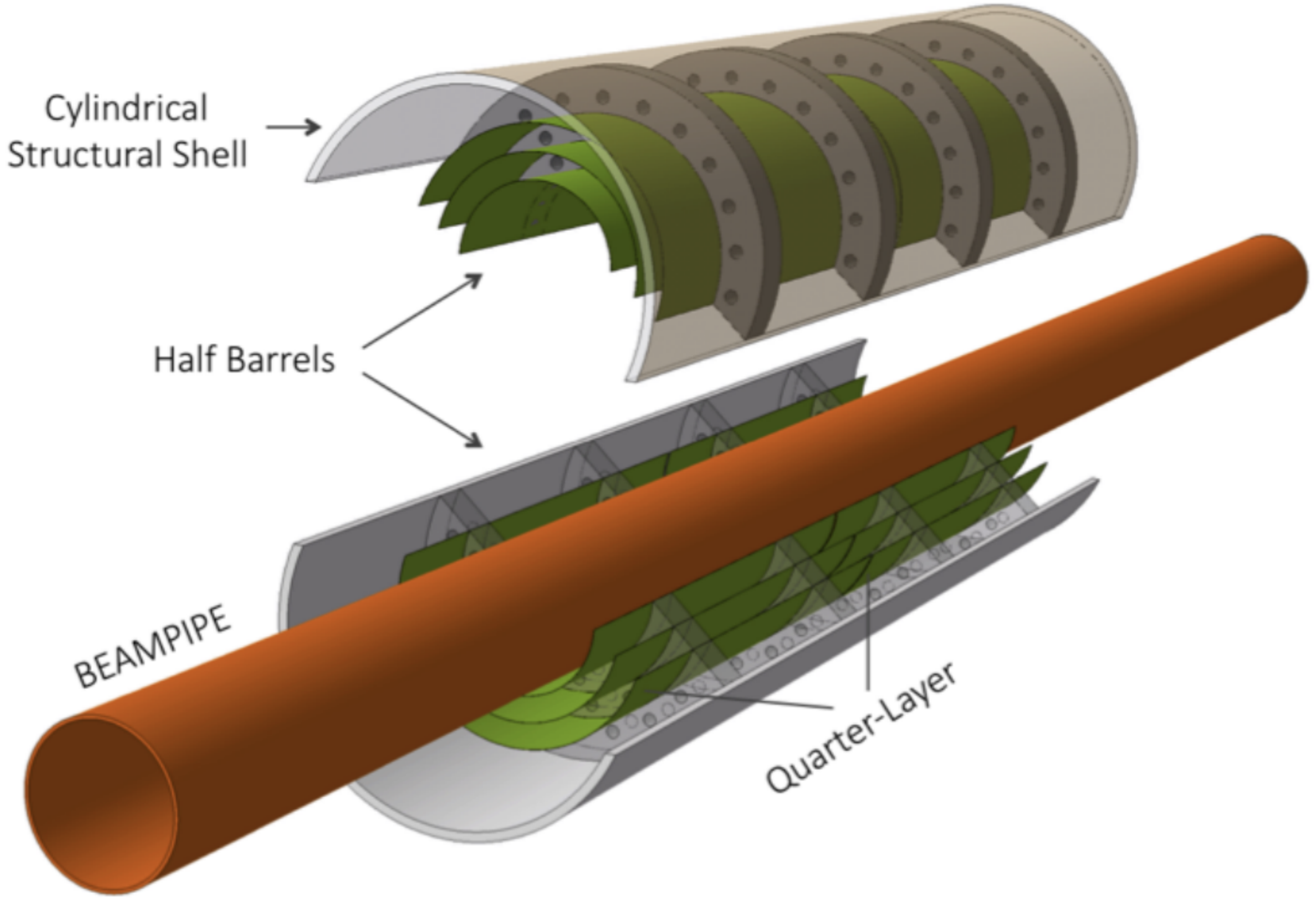




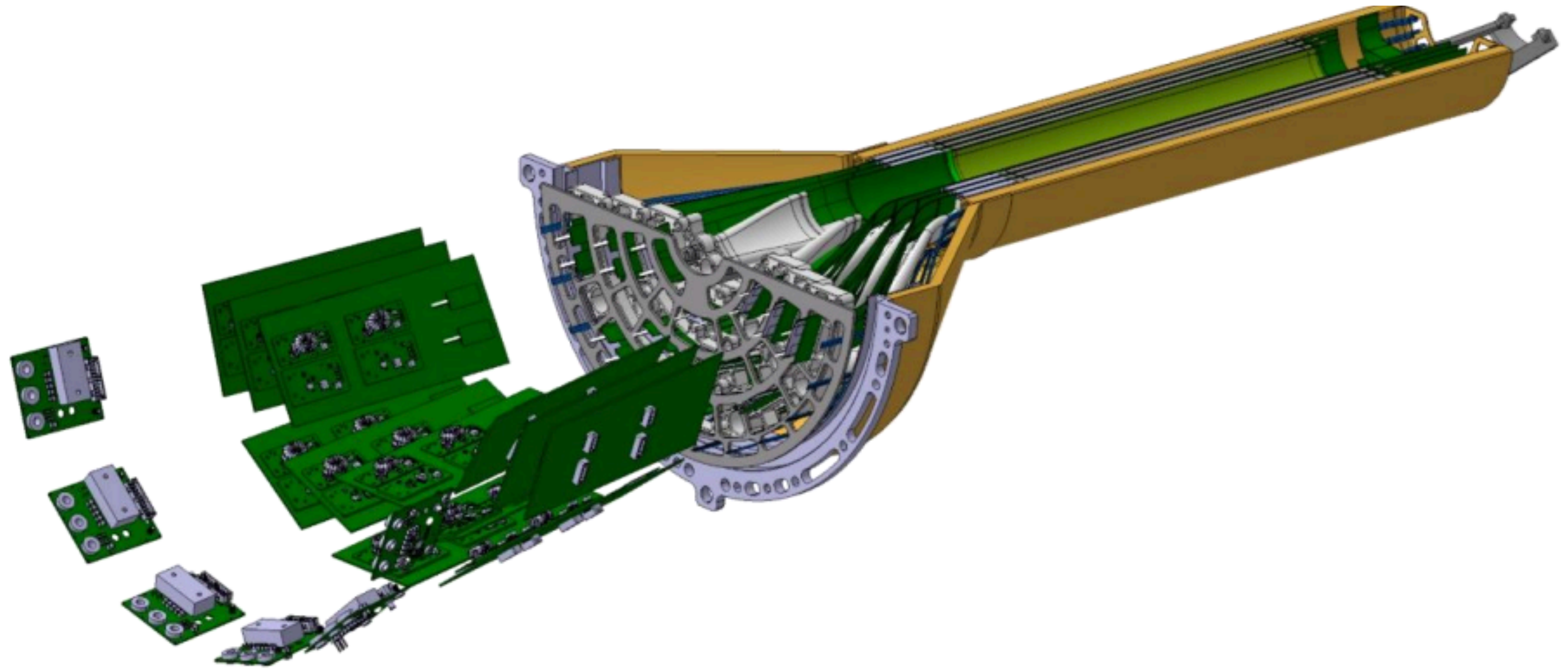
Physics driven requirements		Running constraints	Sensor specifications	
σ	$< 3\ \mu m$		Small Pixel	~15μm
Material budget	$0.1\% X_0$/layer		Thinning to	50 μm
		Cooling	Low Power	20-50 mW/cm^2
r of the Inner most layer	12-14 mm	Beam-background	Fast Readout	~1-10 μs
		Radiation damage	Radiation Tolerance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

ALICE: Bent MAPS for Run 4

CERN-LHCC-2019-018



Forced air flow at 8 m/s



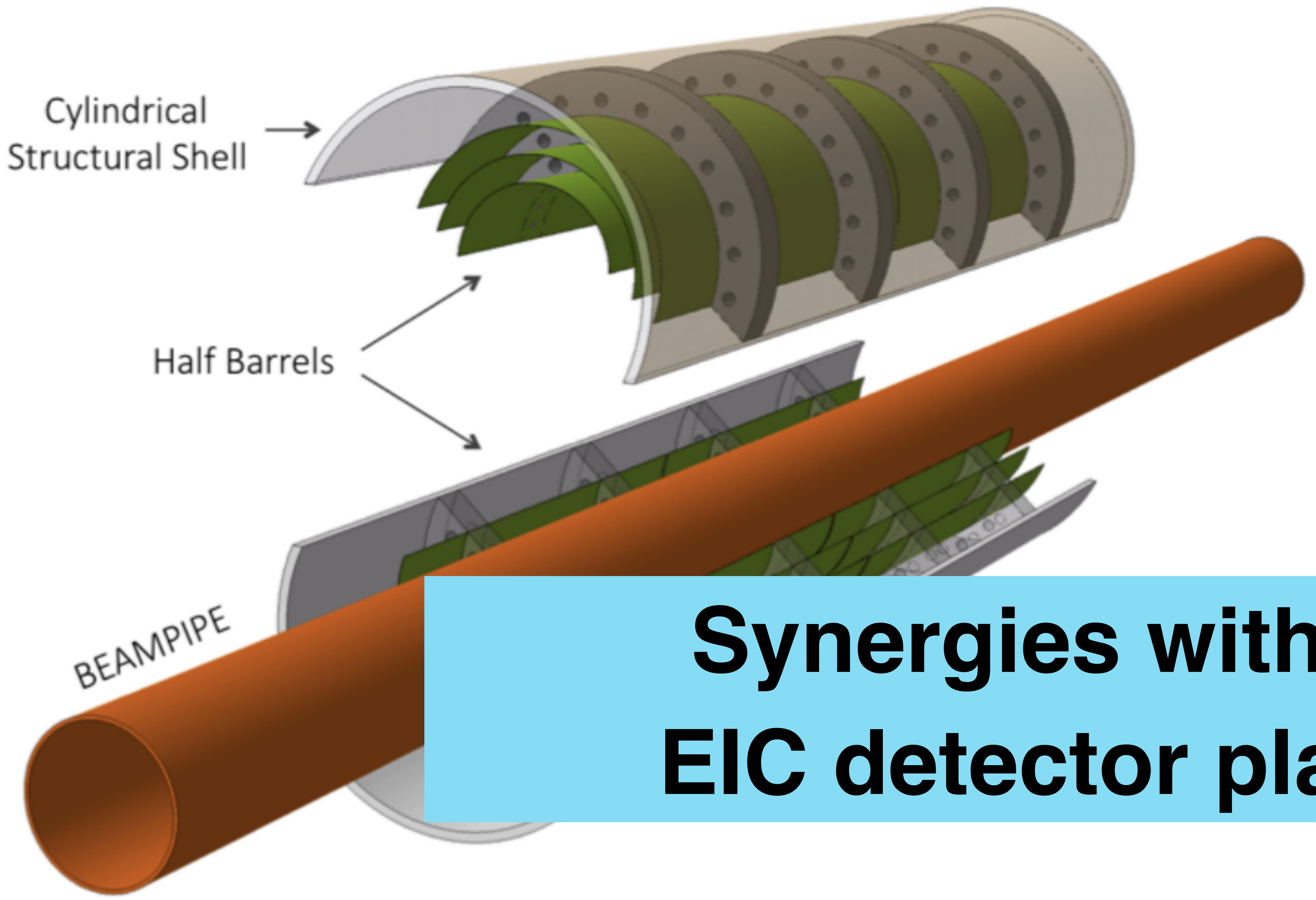
Bending Si wafers + circuits is possible

Recent ultra-thin wafer-scale silicon technologies allow:

- Sensor thickness of 20-40 µm - 0.02-0.04% X_0
- Sensors arranged with a perfectly cylindrical shape
  - a sensors thinned to ~30μm can be curved to a radius of 10-20mm (ALICE-PUBLIC-2018-013)
- Industrial stitching & curved CPS along goals of ALICE-ITS3, possibly with TJ 65 nm process

ALICE: Bent MAPS for Run 4

CERN-LHCC-2019-018



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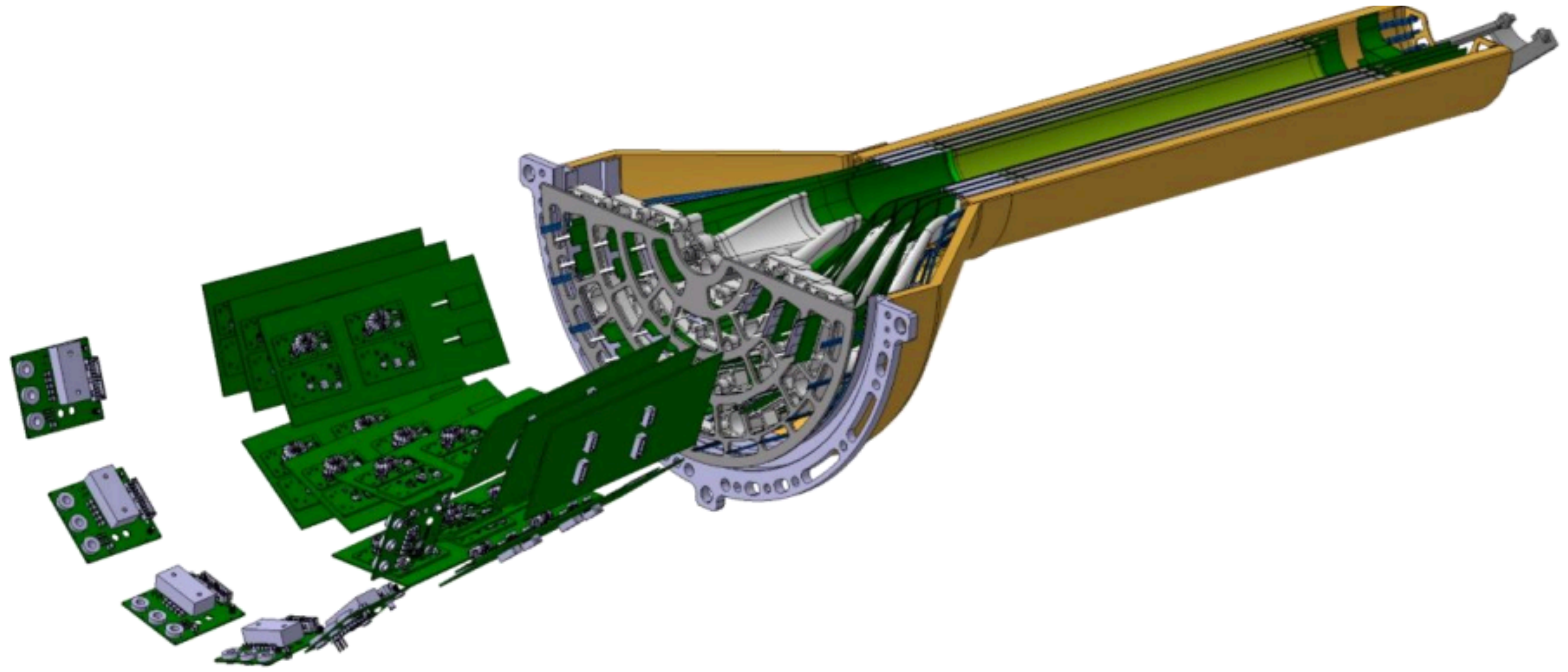


Synergies with every detector concepts at e^+e^-

EIC detector plans to use ITS3 detector concept

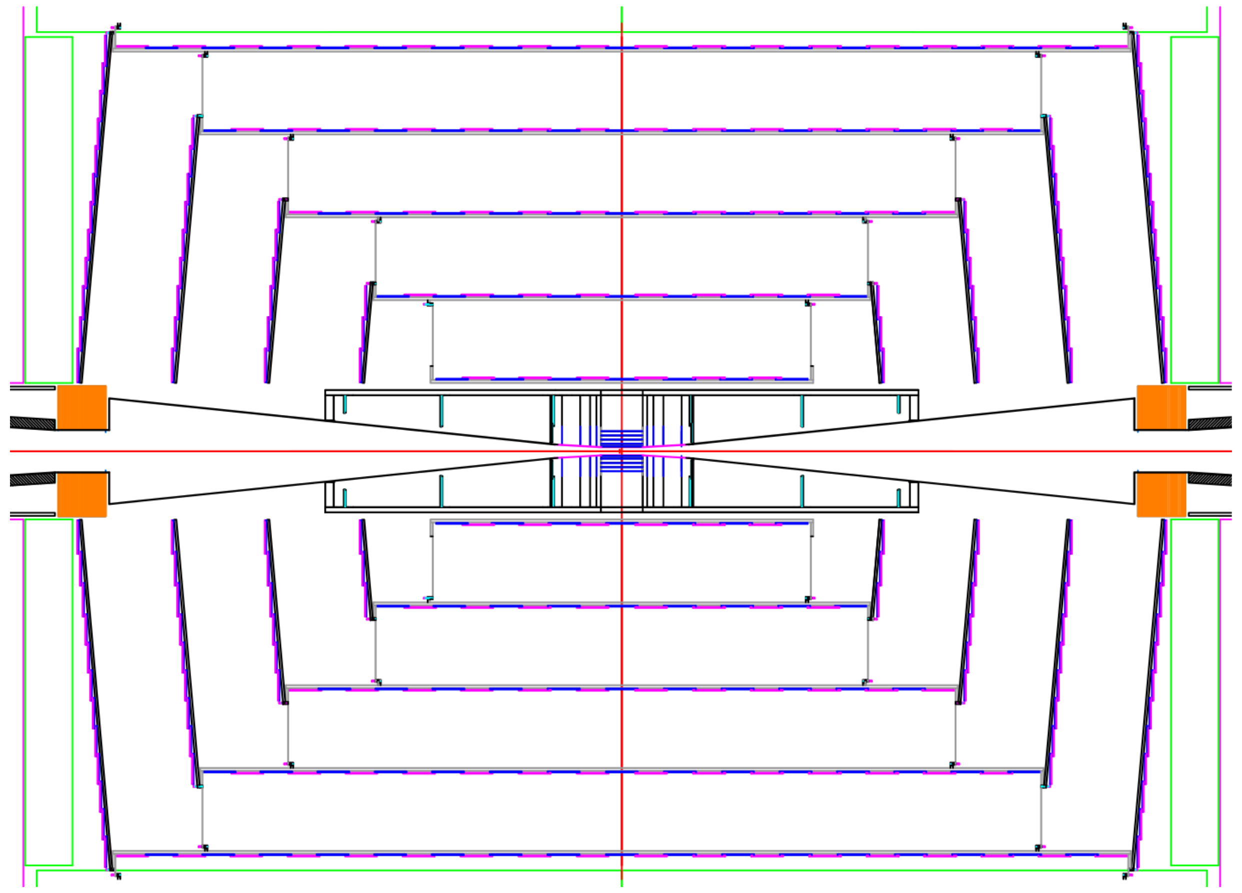
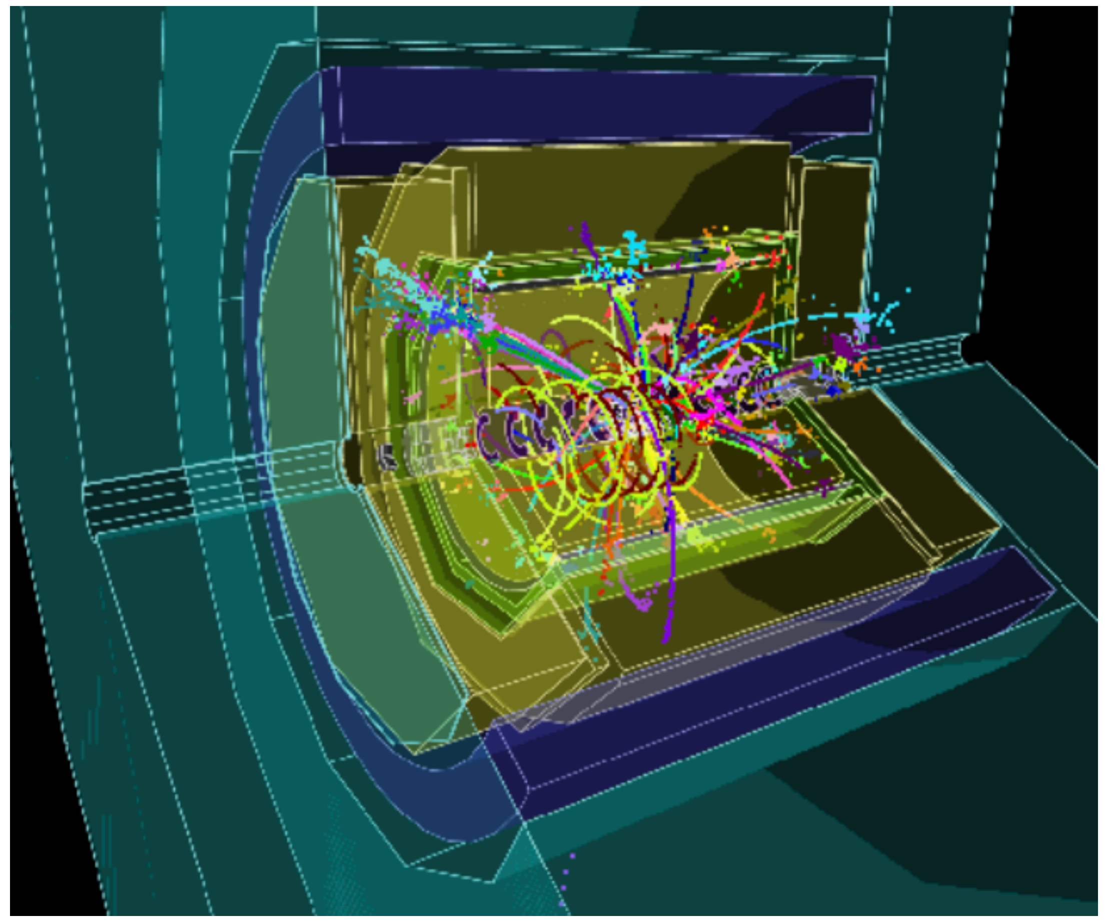
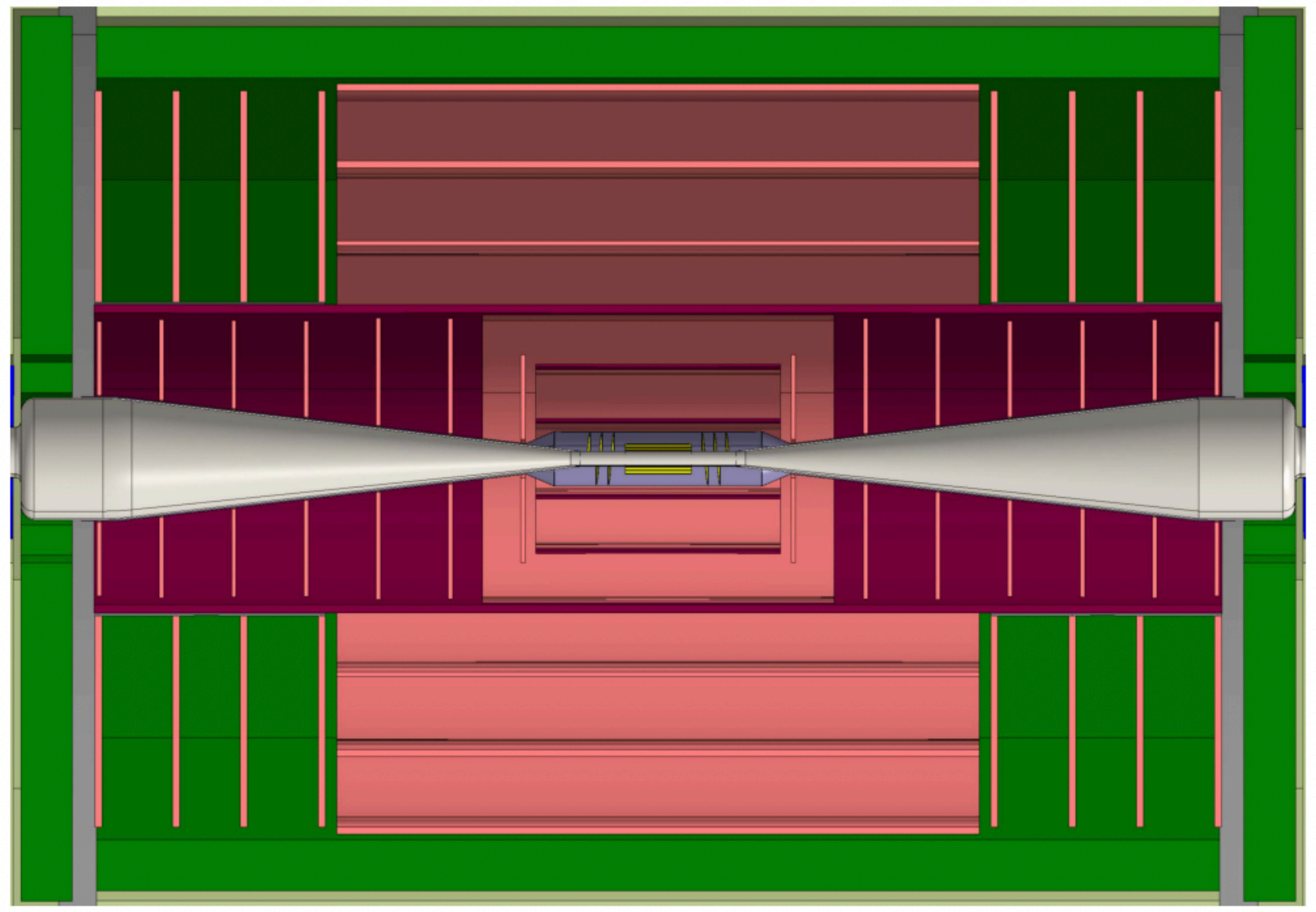
Recent ultra-thin wafer-scale silicon technologies allow:

- Sensor thickness of 20-40 µm - 0.02-0.04% X_0
- Sensors arranged with a perfectly cylindrical shape
  - a sensors thinned to ~30μm can be curved to a radius of 10-20mm (ALICE-PUBLIC-2018-013)
- Industrial stitching & curved CPS along goals of ALICE-ITS3, possibly with TJ 65 nm process

arXiv:1306.6329
arXiv:1912.04601
e2019-900045-4
CLICdet post CDR

Tracking detectors

A diverse set of options targeting unprecedented precision

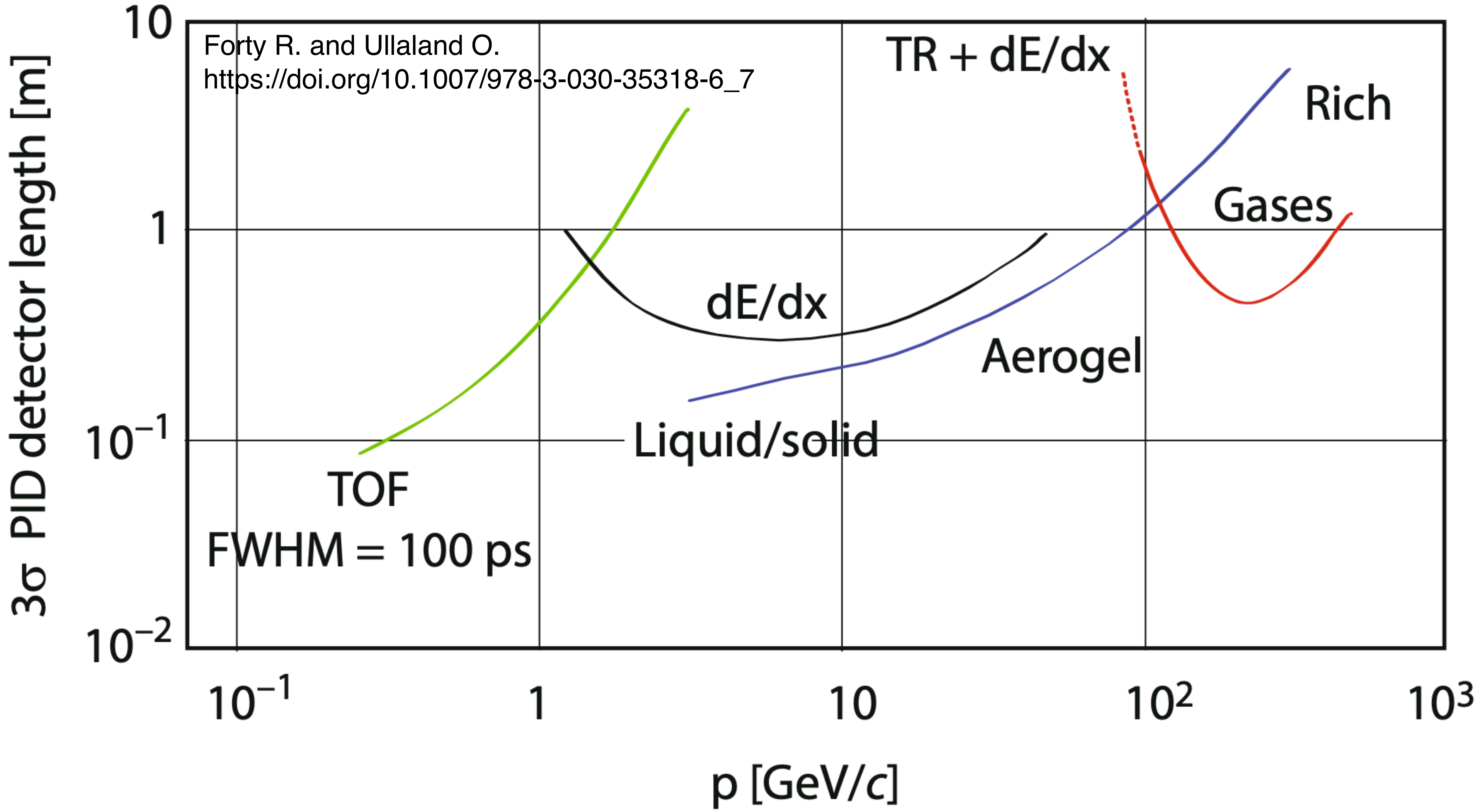




- Full **silicon detectors** (SiD, CLID, CLICdet) aiming at 0.1-0.15% X_0 in the central region
  - MAPS (TJ 65 nm) being investigated
- ILD features a **TPC**, which provides 3D track reconstruction exploiting timing of drift with low material budget
  - Pad (GEM or Micromegas) or pixelated (Gridpix) readout both achieve desired resolution

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

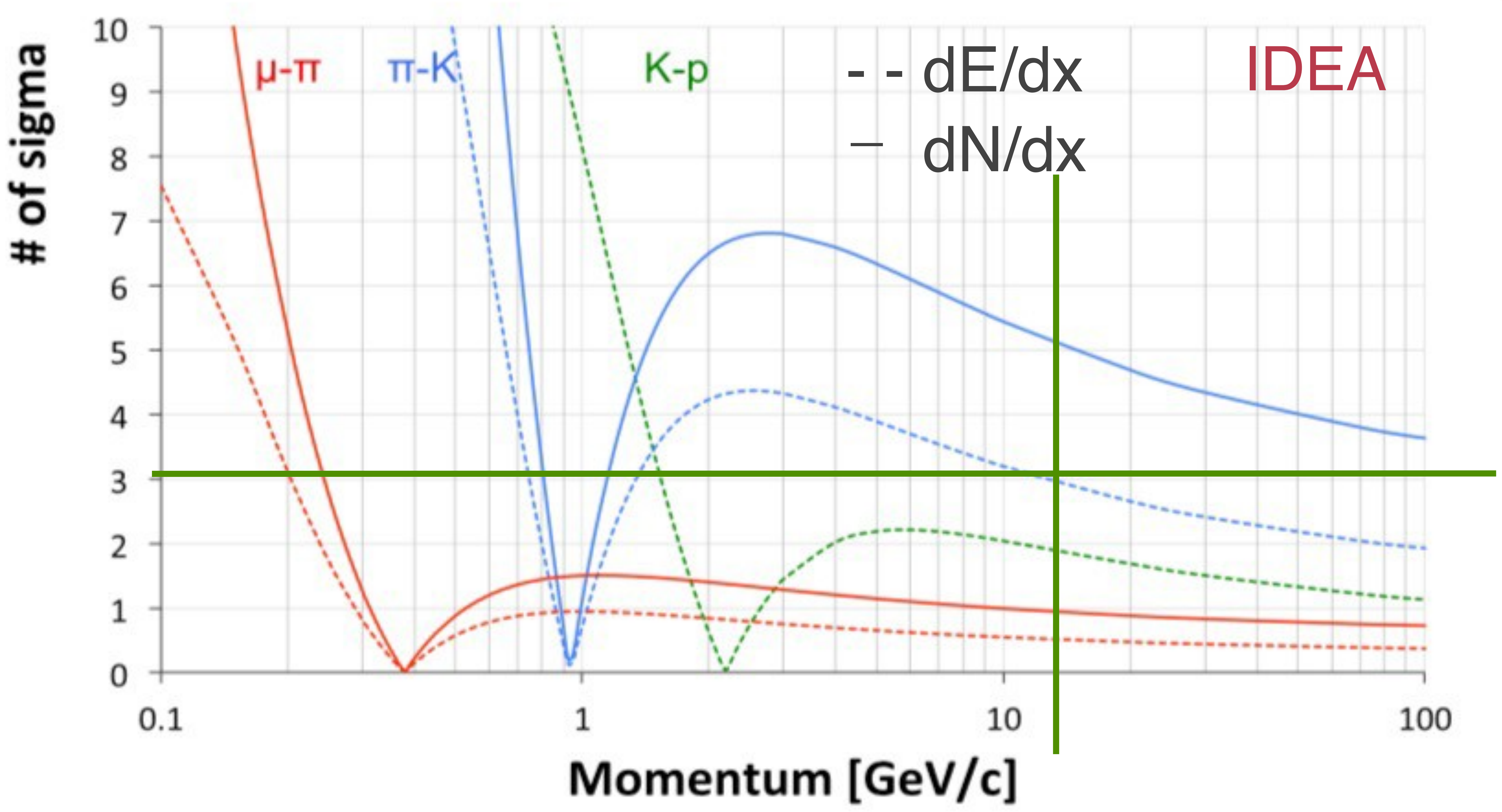


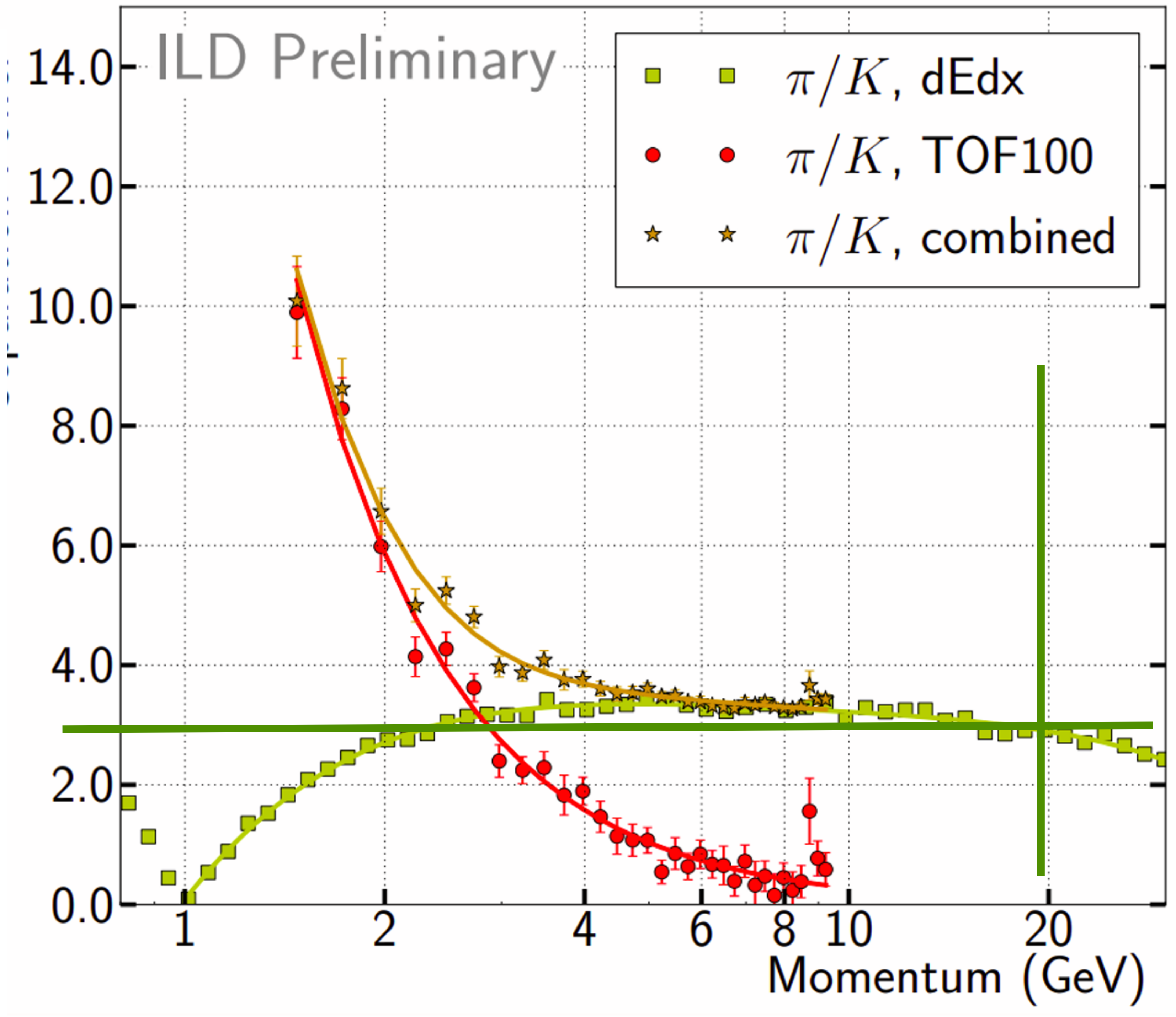
arXiv:2202.03285
arXiv:1912.04601
e2019-900045-4
NIMA 1059 (2024)

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)





Outlook

Linear e^+e^- collider offers many opportunities to search for new physics

- Above 500 GeV e^+e^- collisions can provide unique sensitivity to
  - **top mass** and couplings, deviations in **Higgs self-coupling** predicted by models with first-order electroweak phase transitions
  - **new physics** within kinematic reach of e^+e^- collisions at 500-1000 GeV and escape LHC detection
- ILC has developed two detector designs that have been studied in full simulation – ILD and SiD — but the bulk of this work is more than 10 years old
  - There are new emerging technologies that can inform designs for detectors at future e^+e^-
- Several big questions to be further evaluated, ***some examples***:
  - Silicon vs. gaseous (TPC) tracking
  - Does the Higgs factory detector need a dedicated device for strange quark identification?
- **Revisit physics goals:** different emphasis on various detector requirements together with new technology possibilities to sharpen up the requirements and optimize overall detector design.
- The linear collider community has built many tools that should be shared in this interest of building a common US Higgs factory community.
  - *Important to take advantage of what it has been built and what it has been learned already*

One word on Sustainability

PRX Energy 2 047001

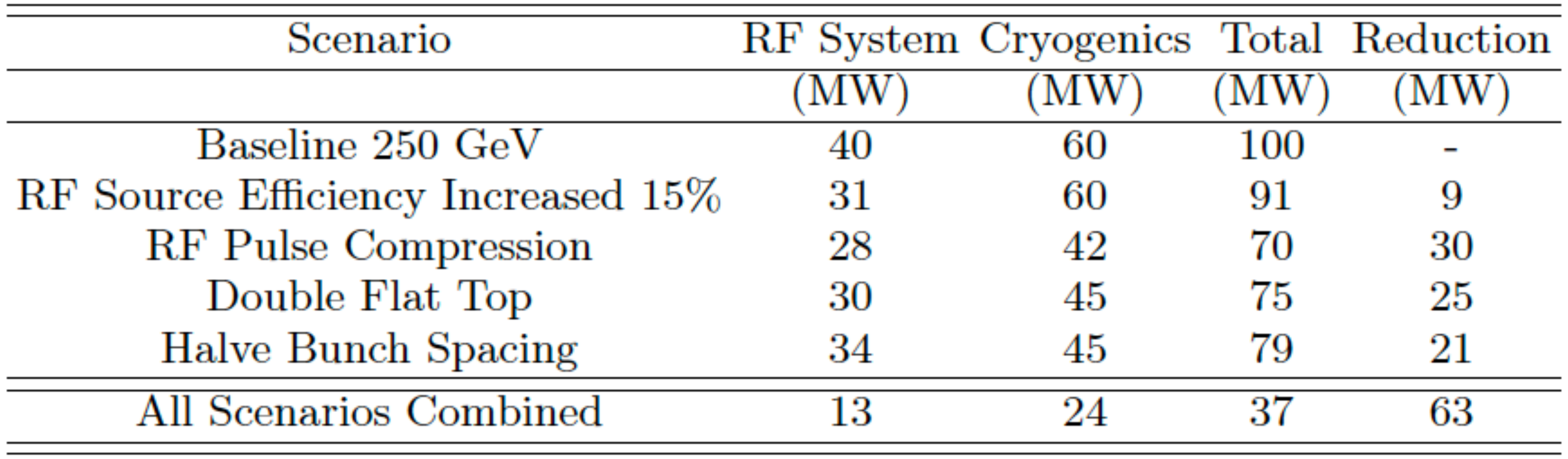
Construction + operations CO_2 emissions per % sensitivity on couplings

- 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

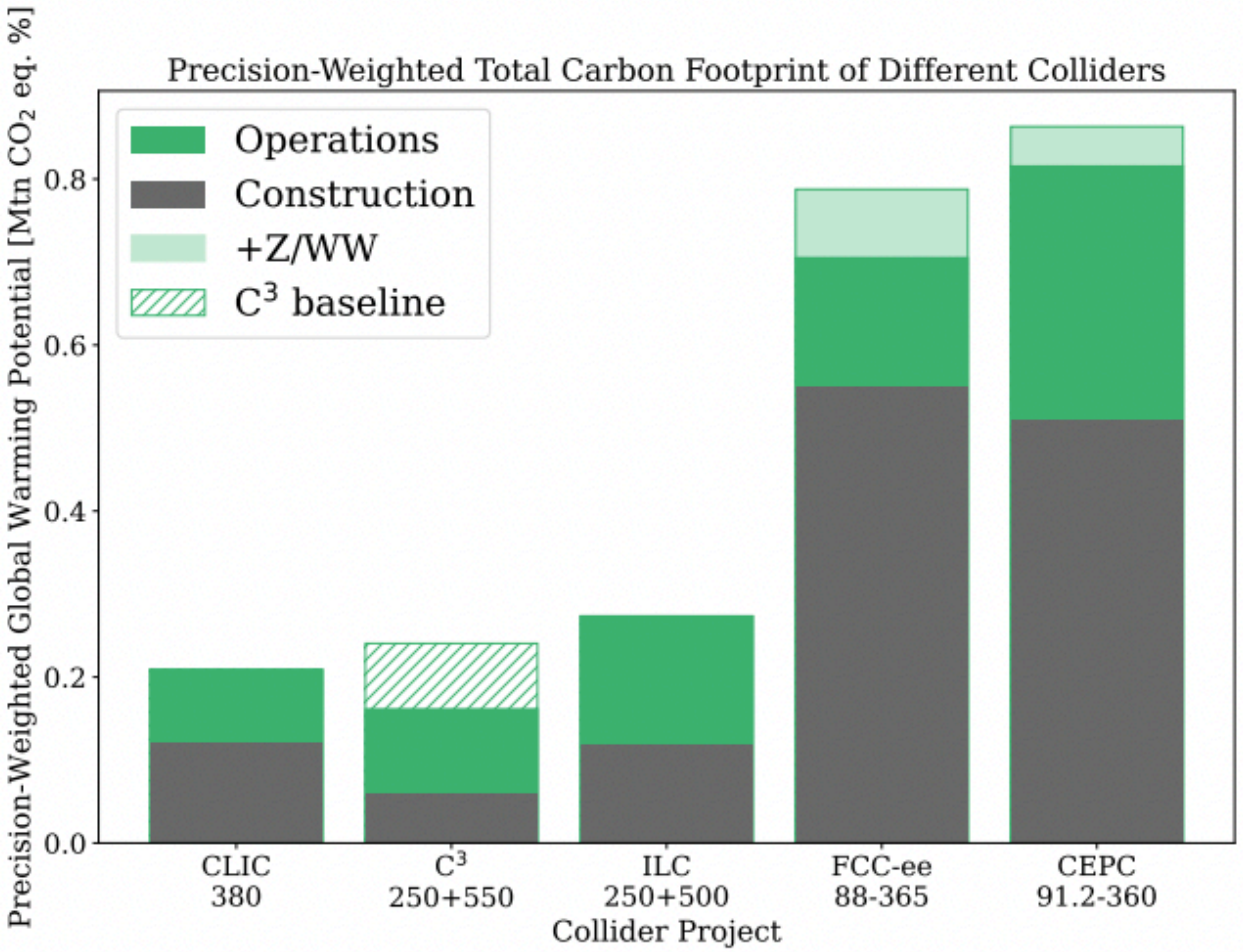
Energy consumption and carbon footprint are estimated ***per unit of physics output***

$$w = \frac{\left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC}} - \left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC+HF}}}{\left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC+HF}}}.$$

C^3



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



thank you!

D. Ntounis (2023)
G. Marchiori (2023)
TDAQ@Annecy2024

Current status of beam-background studies

Same tools and methodology between ILC & FCC within Key4HEP

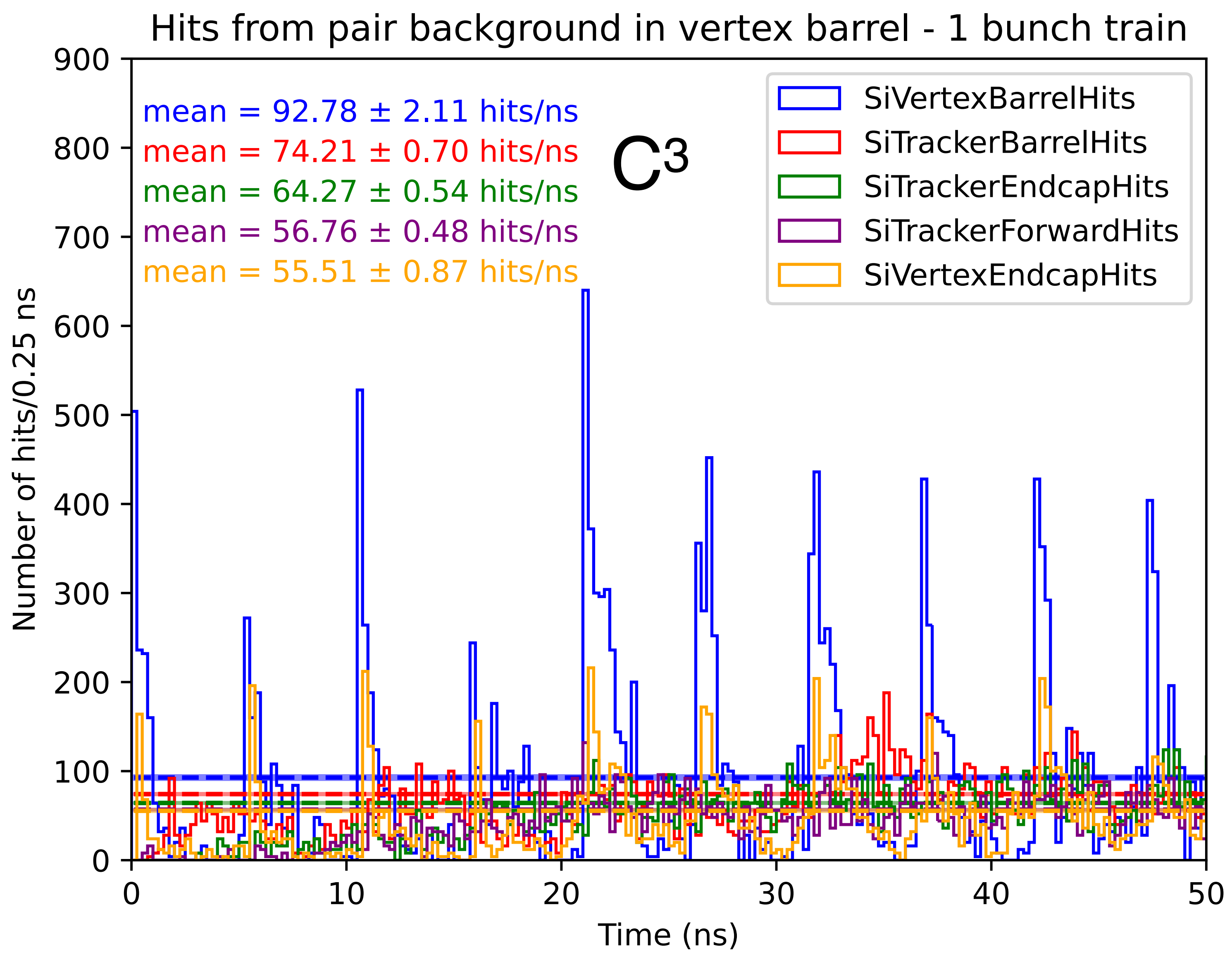
- ILC physics studies are based on full simulation data and some have been recently repeated for C^3
  - Time distribution of hits per unit time and area on 1st layer ~ $4.4 \cdot 10^{-3}$ hits/(ns·mm^2) ≃ 0.03 hits/mm^2 /BX
- CLD detailed studies @FCC show an overall occupancy of 2-3% in the vertex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

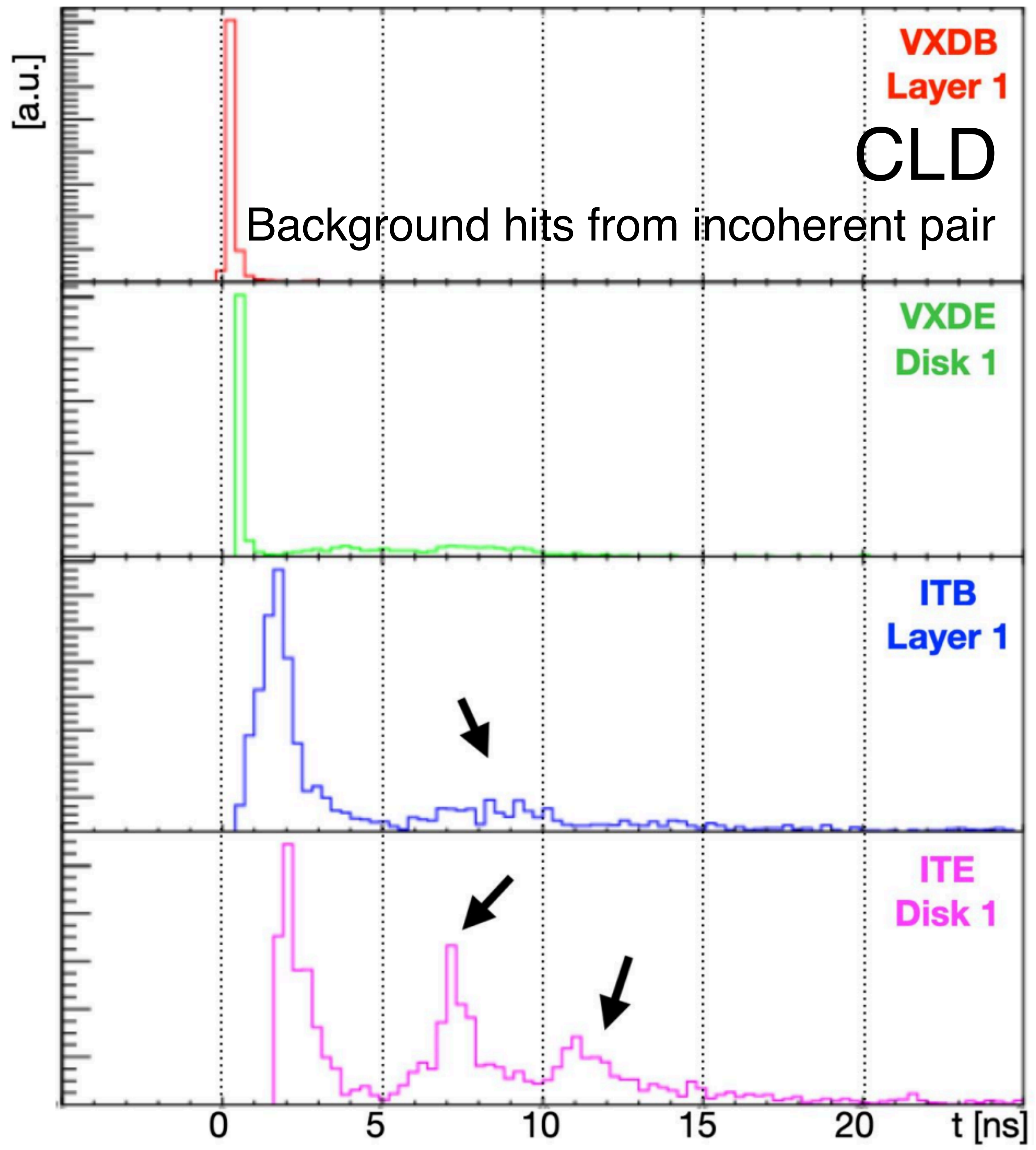
$$occupancy = hits/mm^2/BX \cdot size_{sensor} \cdot size_{cluster} \cdot safety$$

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

	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)

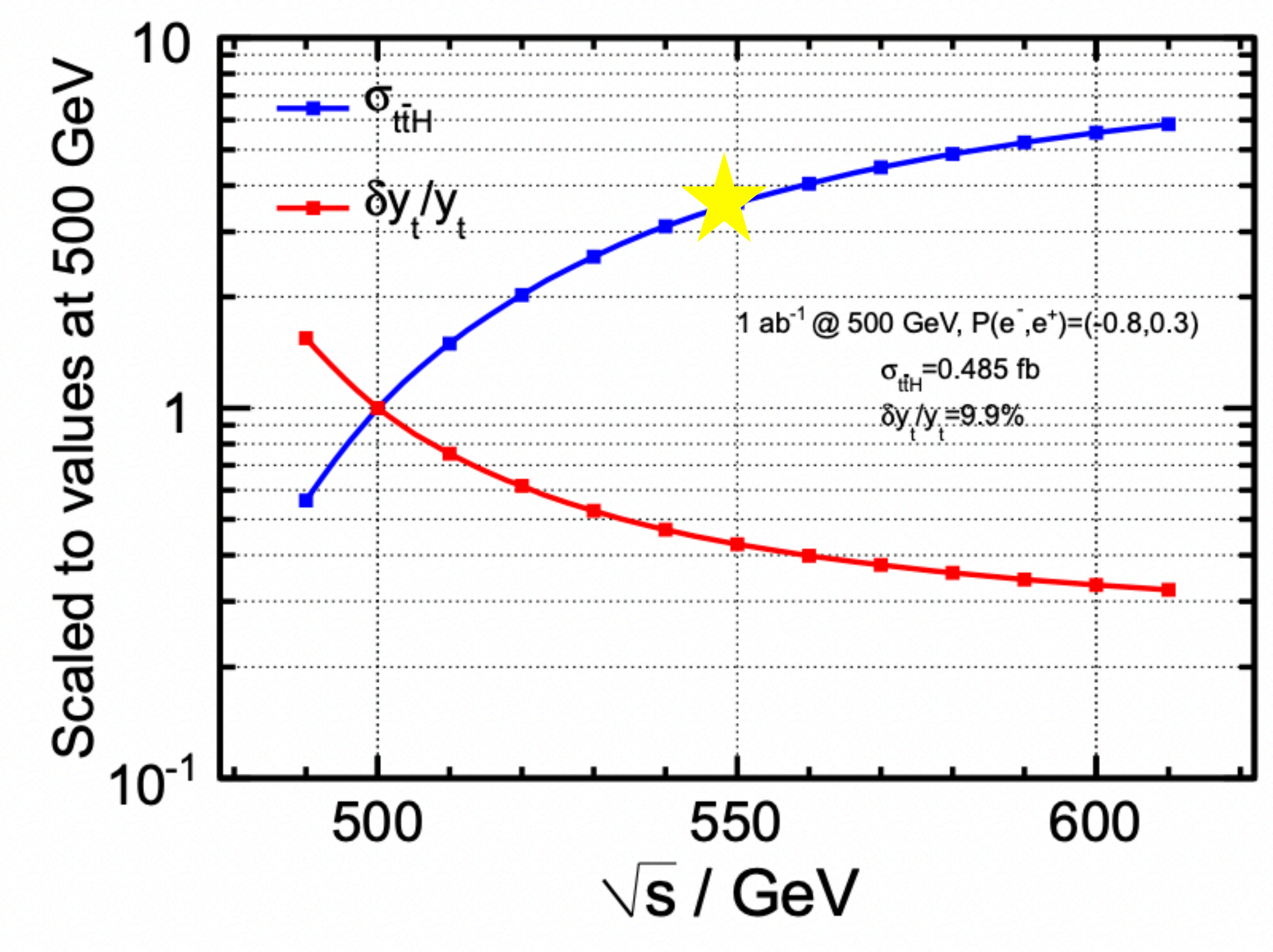




arXiv:1908.11299
arXiv:1506.07830

Why 550 GeV?

A factor two in the top-yukawa coupling

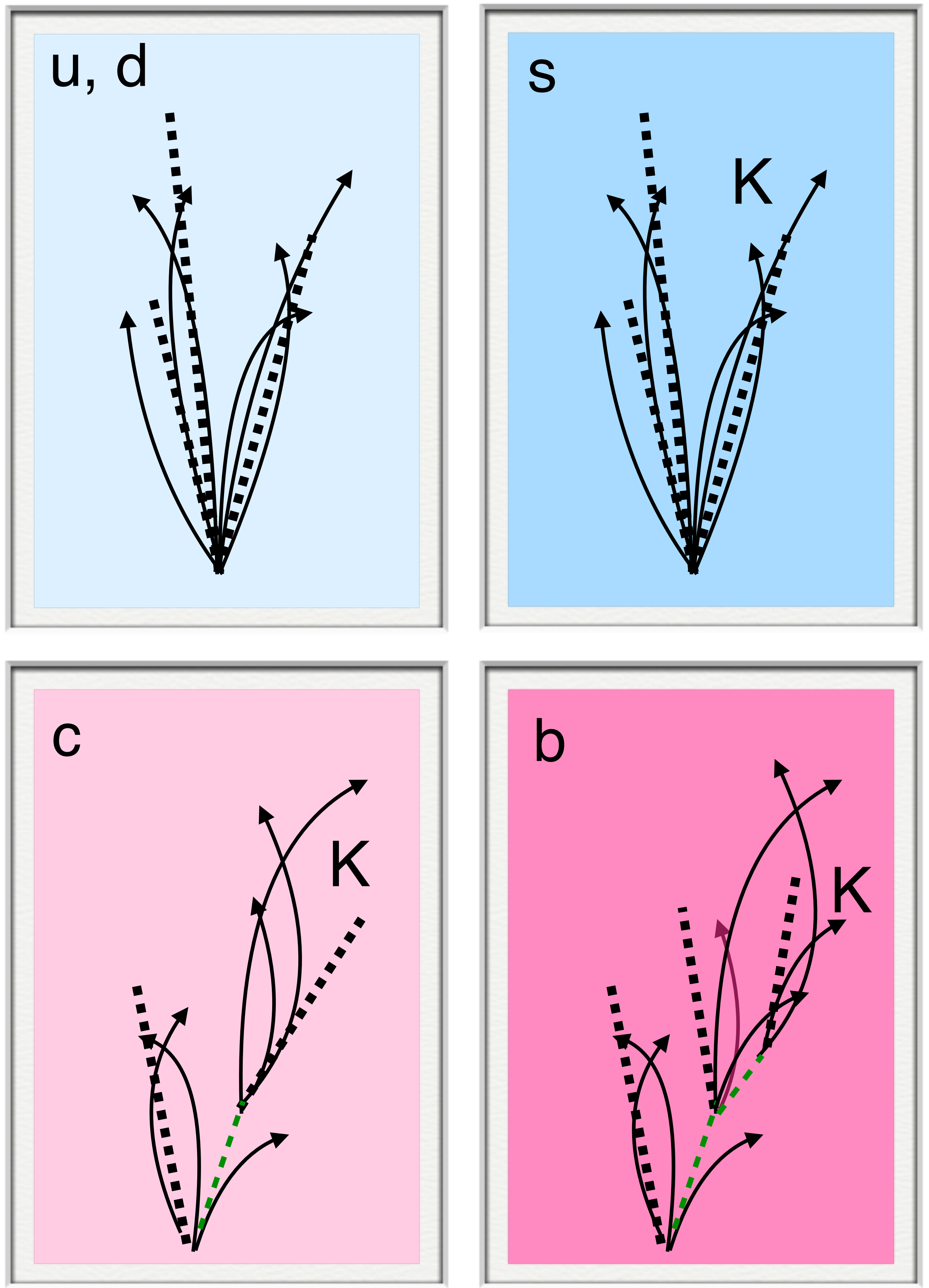


Collider Luminosity Polarization	HL-LHC 3 ab^{-1} in 10 yrs -	C^3 /ILC 250 GeV 2 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)	C^3 /ILC 500 GeV + 4 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80 (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)

PRL 85 (2000), 5059
SLAC-R-520
arXiv:2101.04119
arXiv:2203.07535

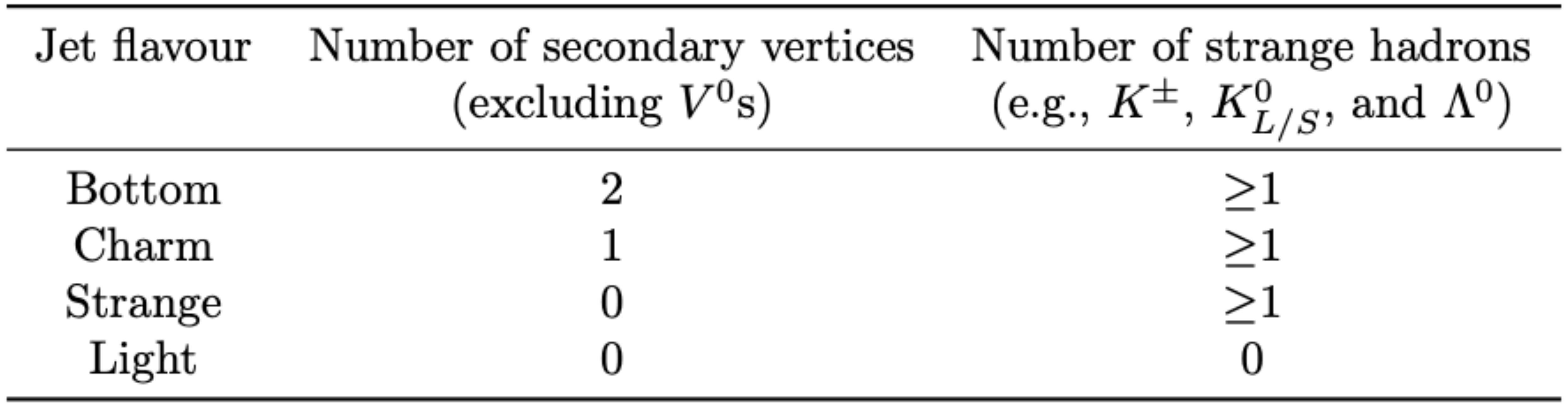
s-tagging, a new benchmark?

Tagging strange is a challenging but not impossible task for future detectors at e^+e^-, as demonstrated by SLD and DELPHI



- As b,c, and s jets contain at least one strange hadron
- Strange quarks mostly hadronize to prompt kaons which carry a large fraction of the jet momentum
  - H →ss requires strange tagging capability for $p_T > 10$ GeV
- Strange hadron reconstruction:
  - $K^\pm$ PID
  - K^0_L PF (neutral)
  - $K^0_S \rightarrow \pi^+\pi^-$ (~70%) / $\pi^0\pi^0$ (~30%)
  - $\Lambda^0 \rightarrow p\pi^-$ (~65%)

Distinctive two-prong vertices topology



Jet flavour	Number of secondary vertices (excluding V^0s)	Number of strange hadrons (e.g., $K^\pm$, $K^0_{L/S}$, and Λ^0)
Bottom	2	≥1
Charm	1	≥1
Strange	0	≥1
Light	0	0

PRL 85 (2000), 5059
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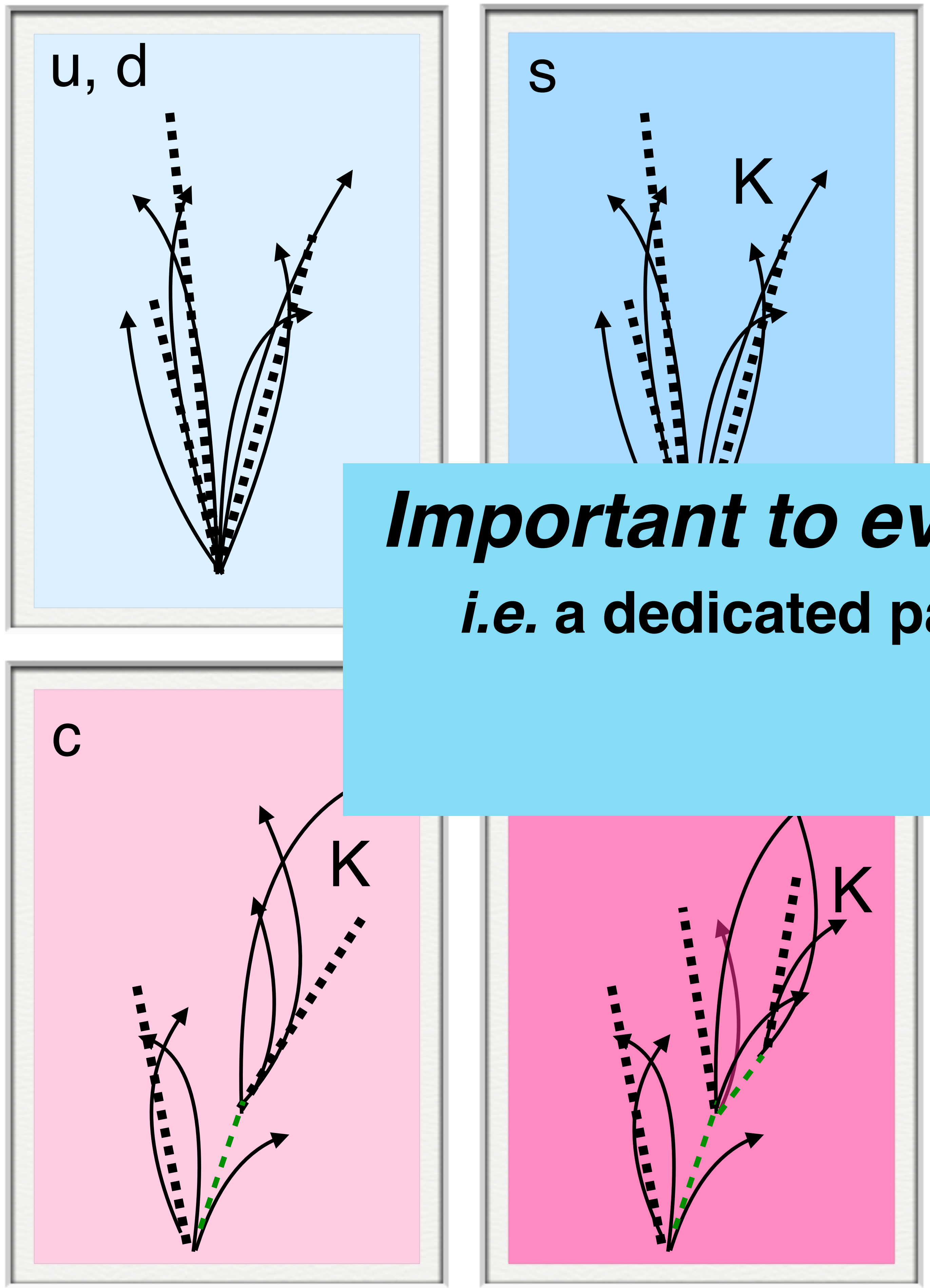

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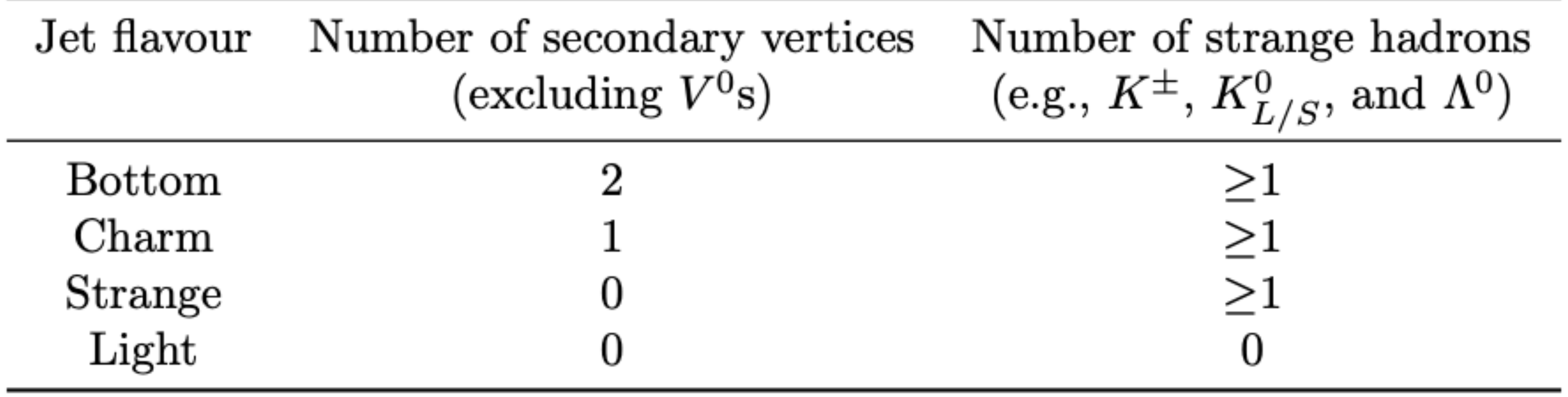
  - $K^\pm$ PID

o-prong
pology

Important to evaluate simultaneously other Higgs benchmarks

***i.e.* a dedicated particle ID device in front of the calorimeter could compromise other physics measurements**



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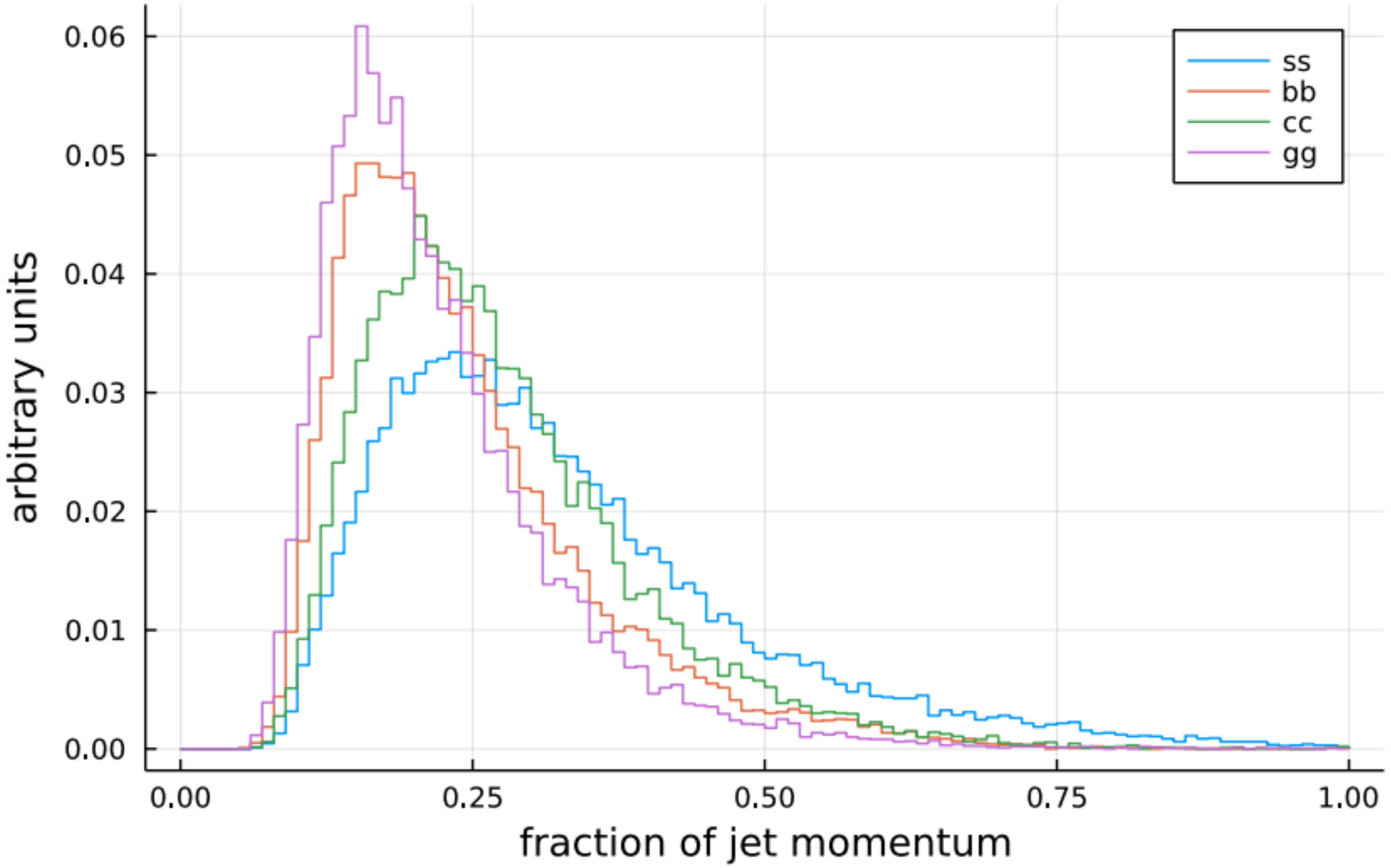
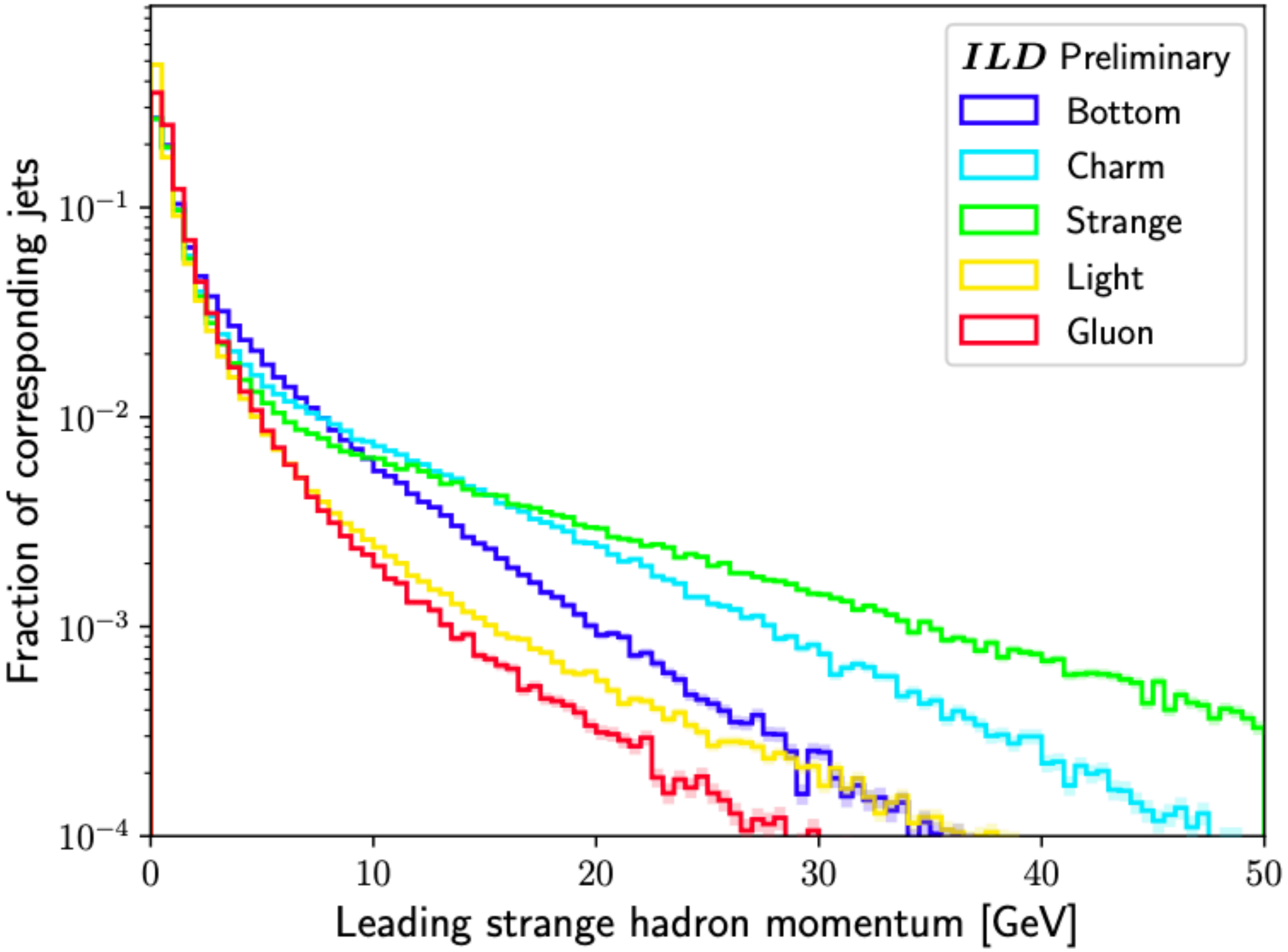
Strange tagging

2203.07535

Momentum spectrum



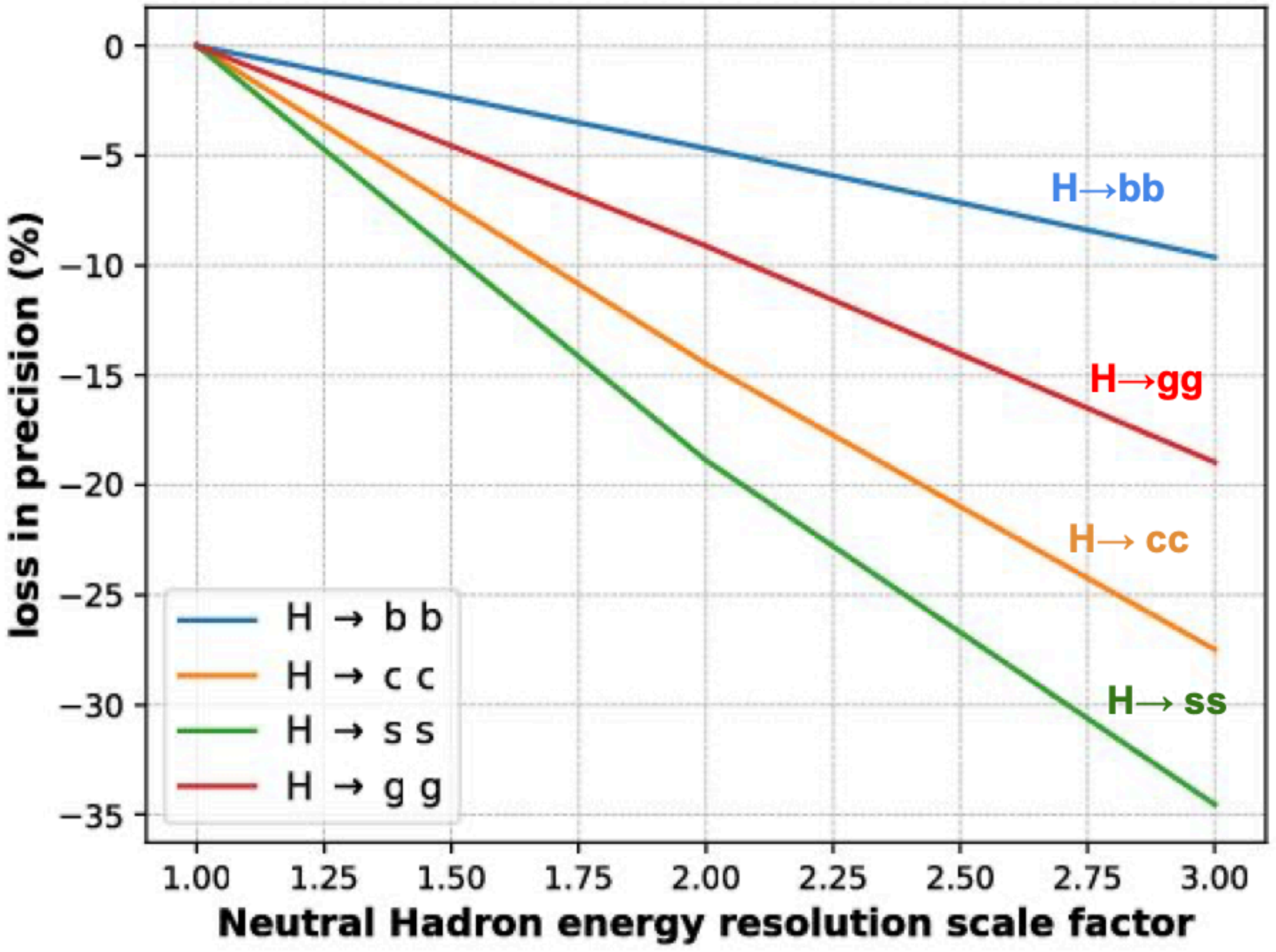


arXiv:2203.07535
L. Gouskos @FCC week

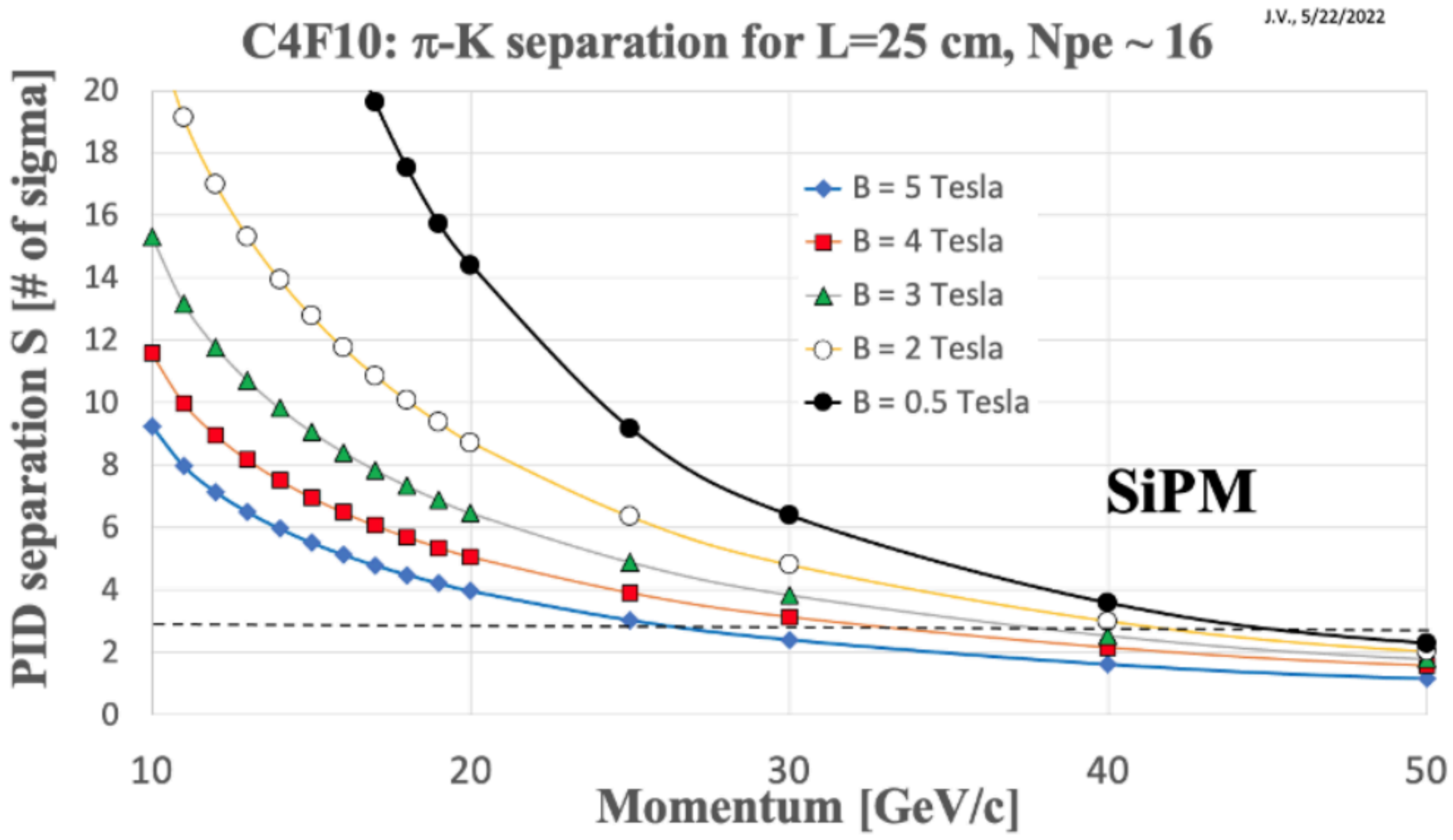
Application: s-tagging

Use H → ss to inform detector design, while monitoring other benchmarks’ performance

- Neutral Hadron energy resolution
- dE/dx and dN/dx: evaluate PID performance for H-strange coupling
- Timing resolution to be further investigated but less critical for s-tagging
- RHIC for improved reconstruction of $K^{+/-}$ at high momentum (< 30 GeV)



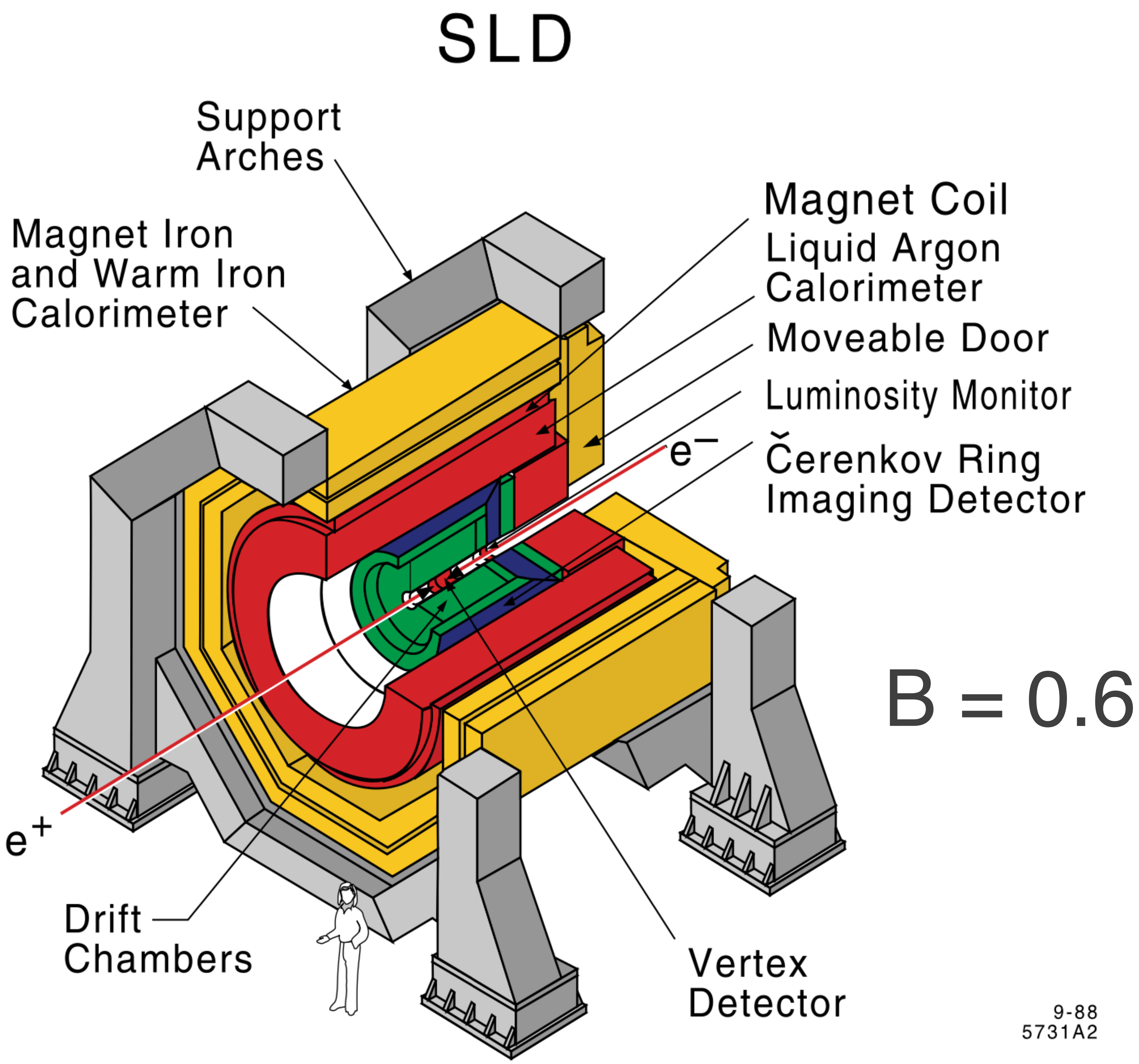
Compact RHIC



PRL 85 (2000), 5059
SLAC-R-520
PRD (1999) 59 52001

s-tagging in the past

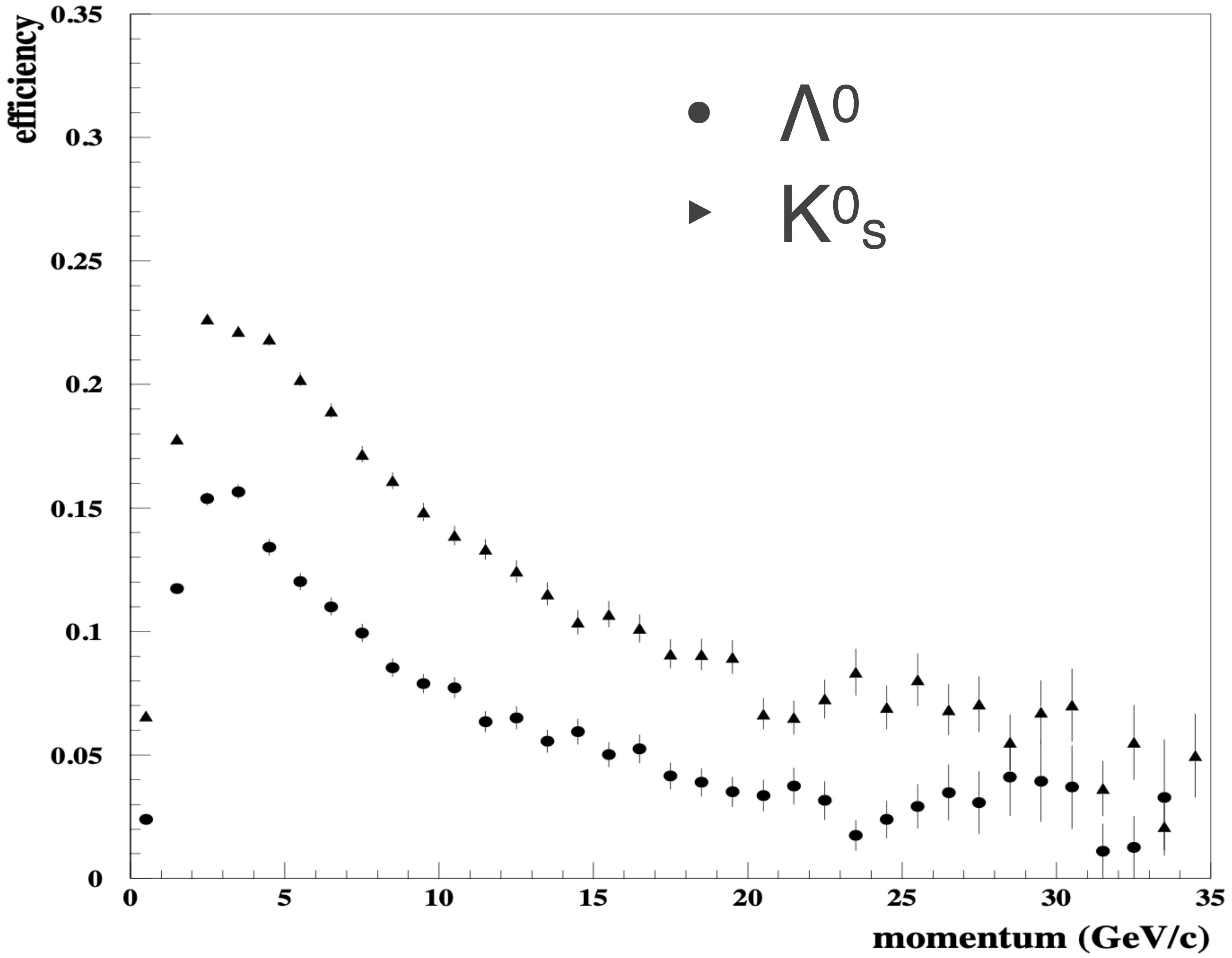
SLD at SLC (e+e- at the Z) measured asymmetry in $Z \to s\bar{s}$



B = 0.6 T

A Cherenkov Ring Imaging Detector combined with a drift chamber and vertex detector

- CRID only available for $K^{\pm}$ with $p_T > 9$ GeV with a selection efficiency (purity) of 48% (91.5%)
- K^0_S efficiency (purity) of 24% (90.7 %)

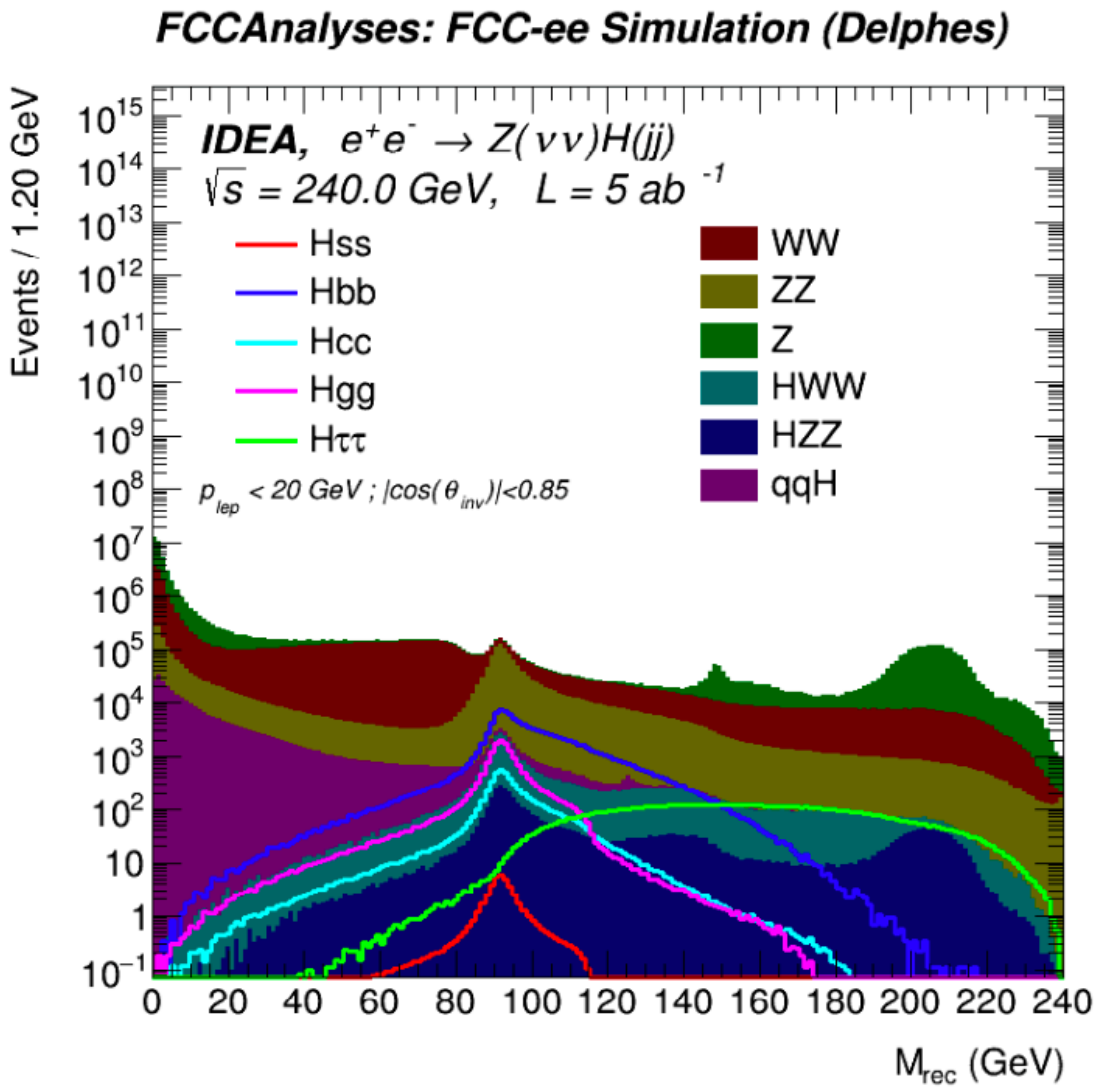


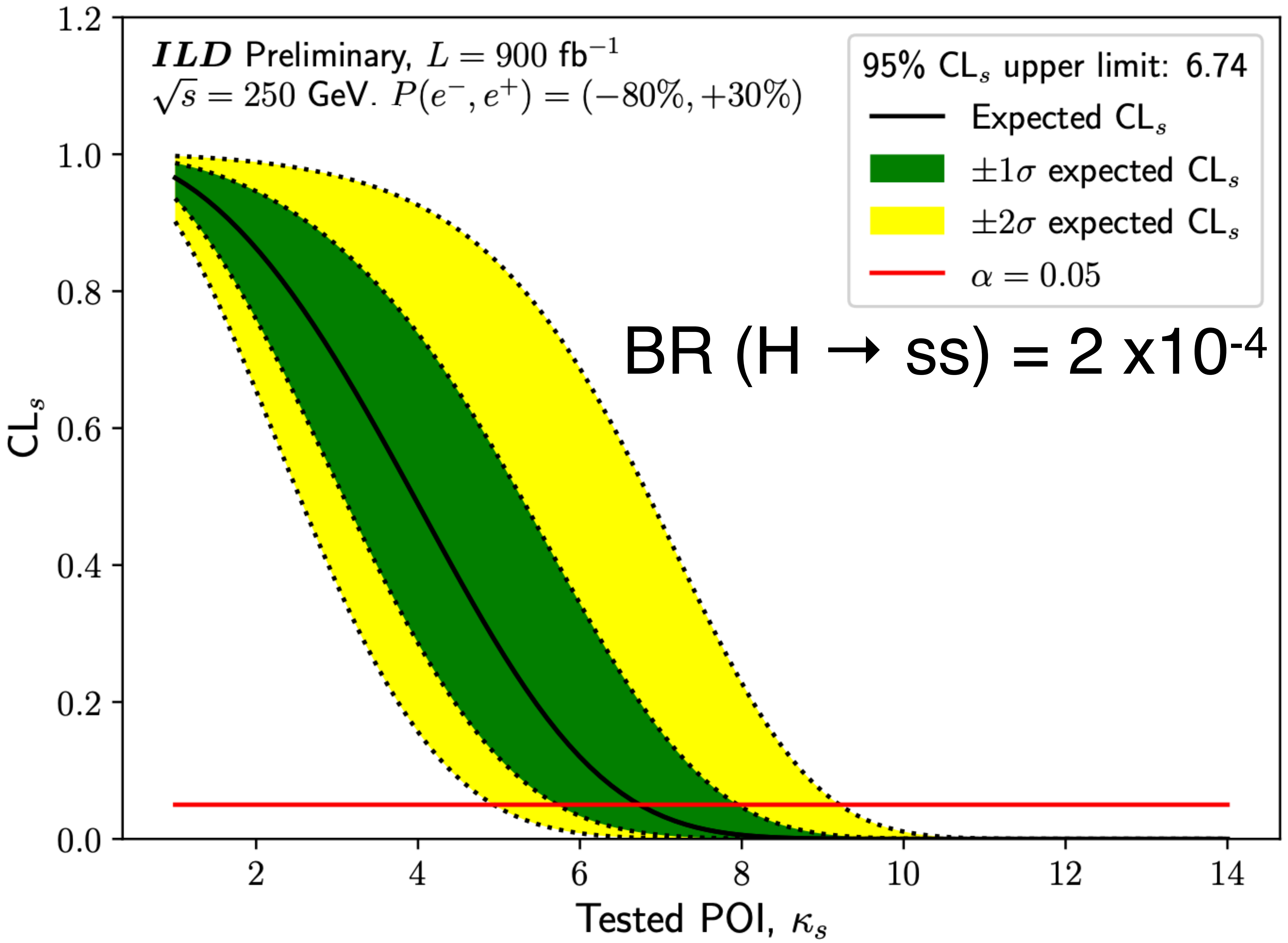
arXiv:2203.07535
L. Gouskos @FCC week

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
  - No PID to PID with dN/dx → at fixed mistag, efficiency doubles





BR (H → ss) = 2 x10^{-4}

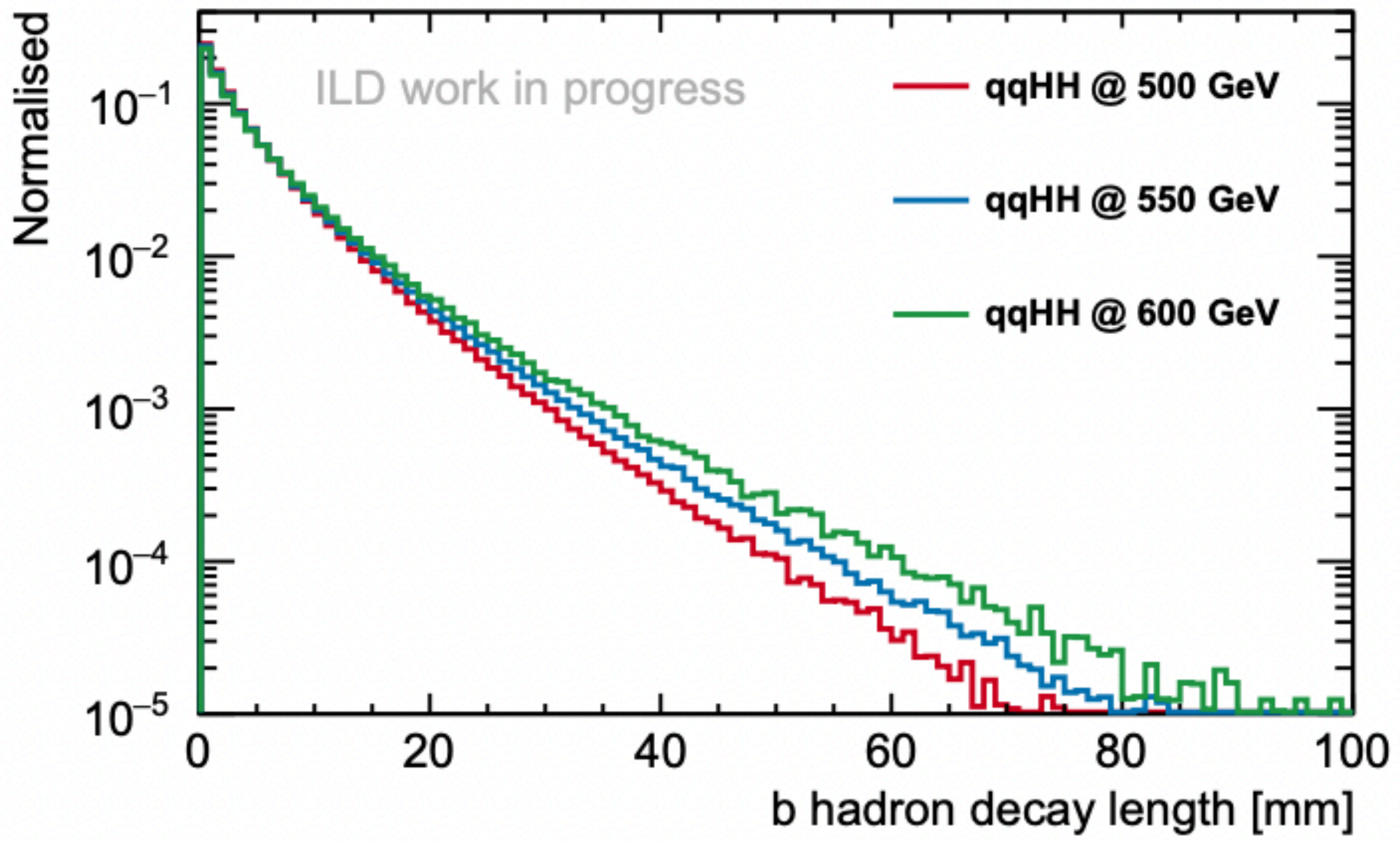
Goals of the HSelf focus studies

Talk at the ECFA workshop 2023
Ongoing work: 2311.16774

An example pertinent to detector optimization:

Double-Higgs observables at CM > 500 GeV:

- Evaluate how various algorithms can improve substantially di-Higgs cross section measurements
  - A 5% relative improvement in the b-tagging efficiency (at the same background rejection rate) could lead to an 11% relative improvement in the self-coupling precision
- Evaluate sensitivity as a function of center-of-mass energy
  - As a function of jet clustering, flavor tagging and kinematic reconstruction performance



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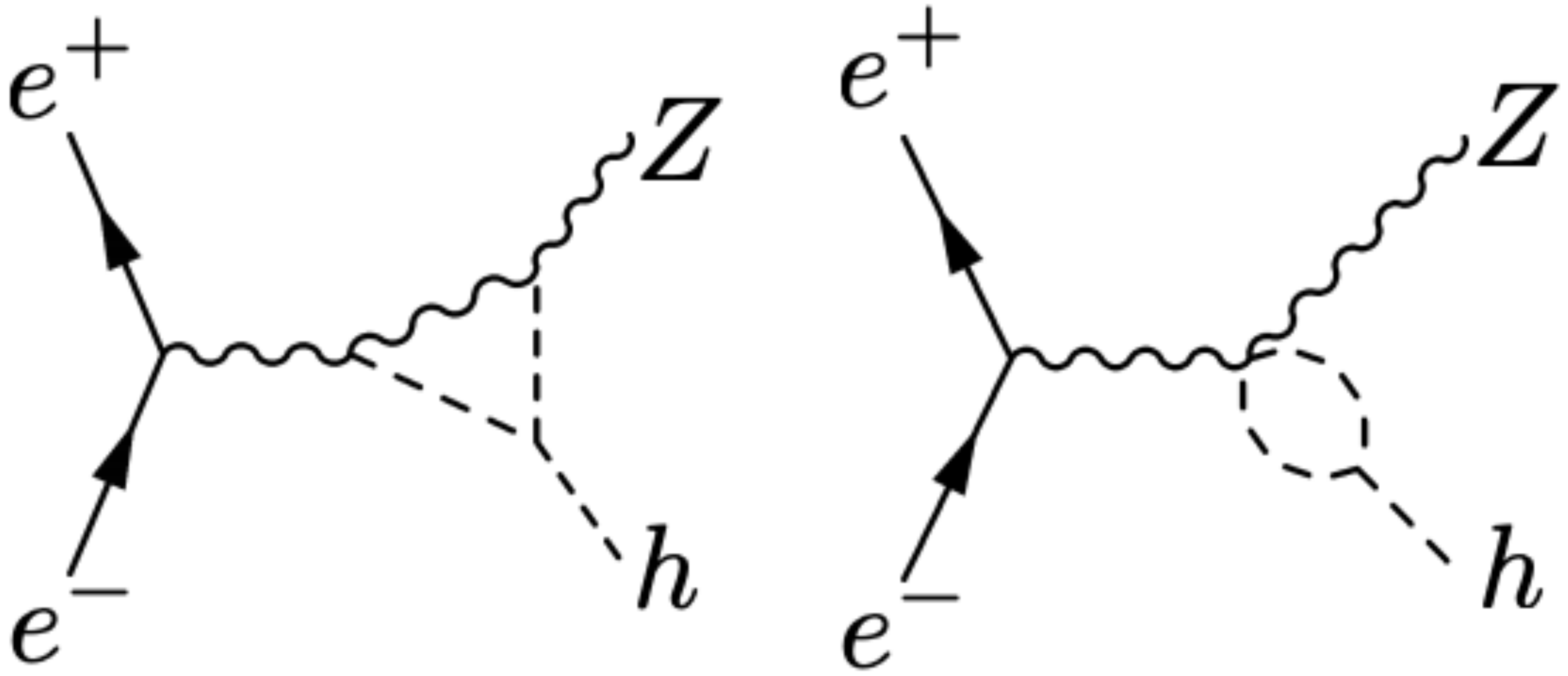
self-subscription CERN e-group

arXiv:1312.3322
arXiv:1910.00012

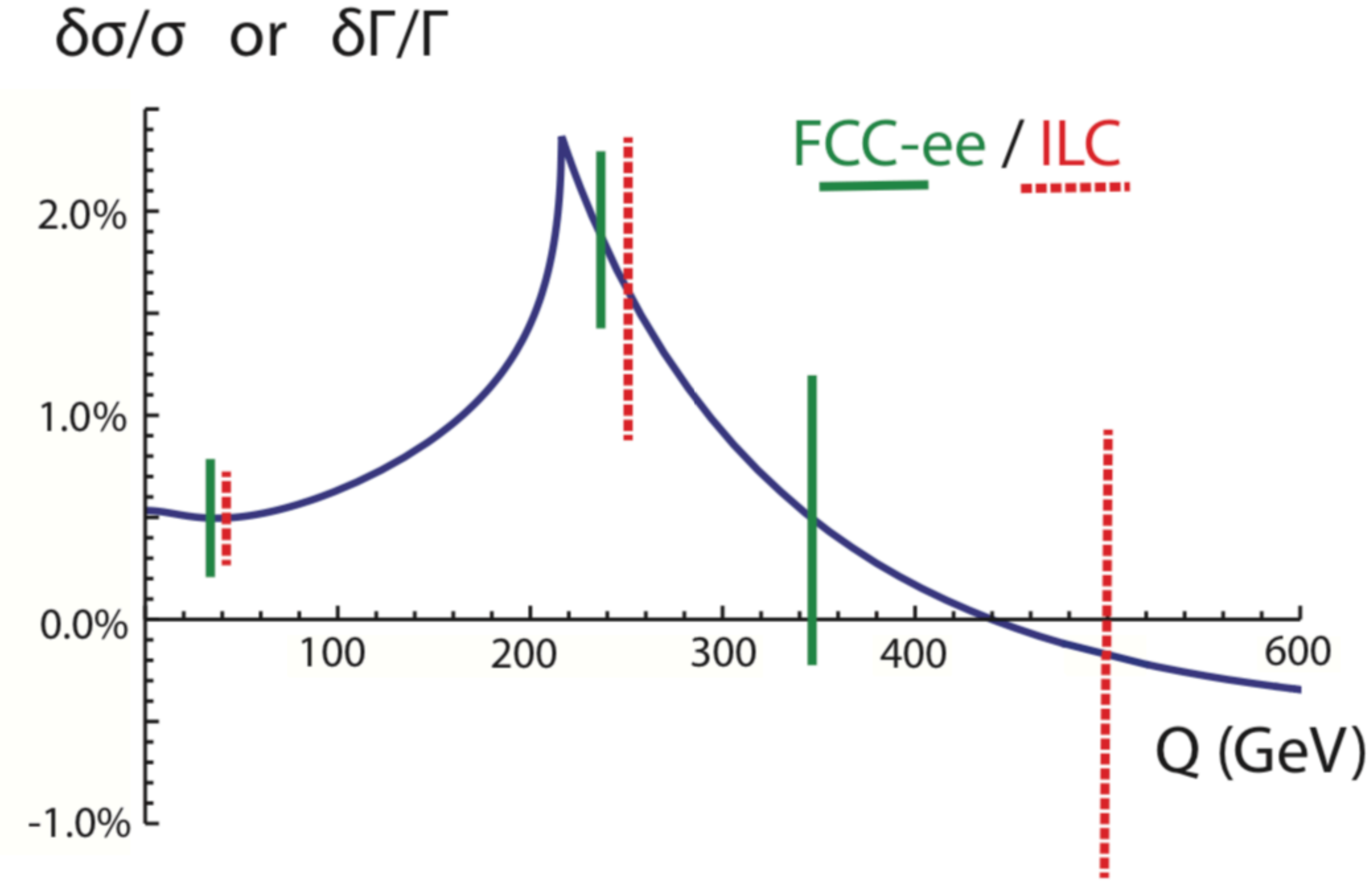
Self-coupling at e+e- with single Higgs

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



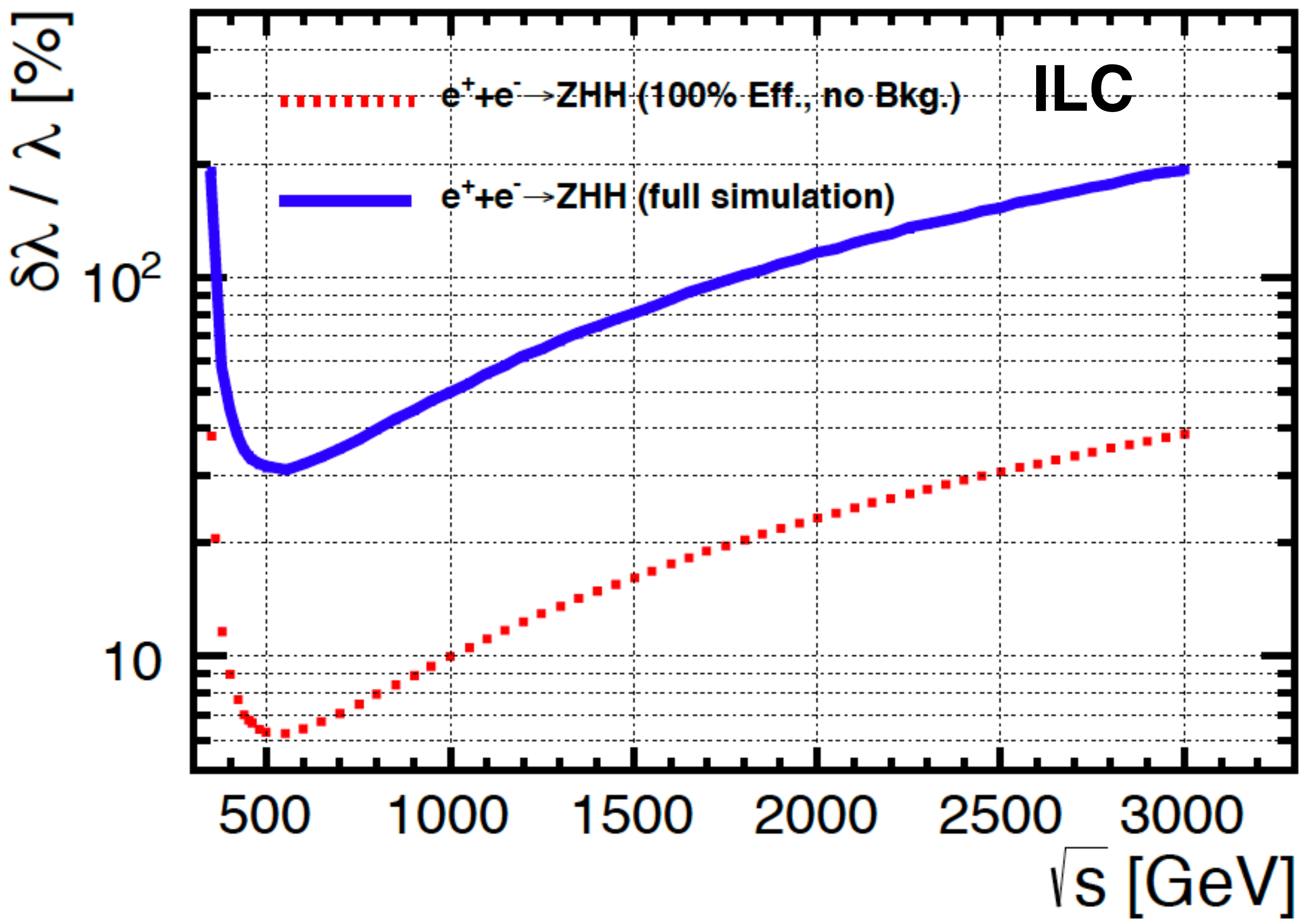
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

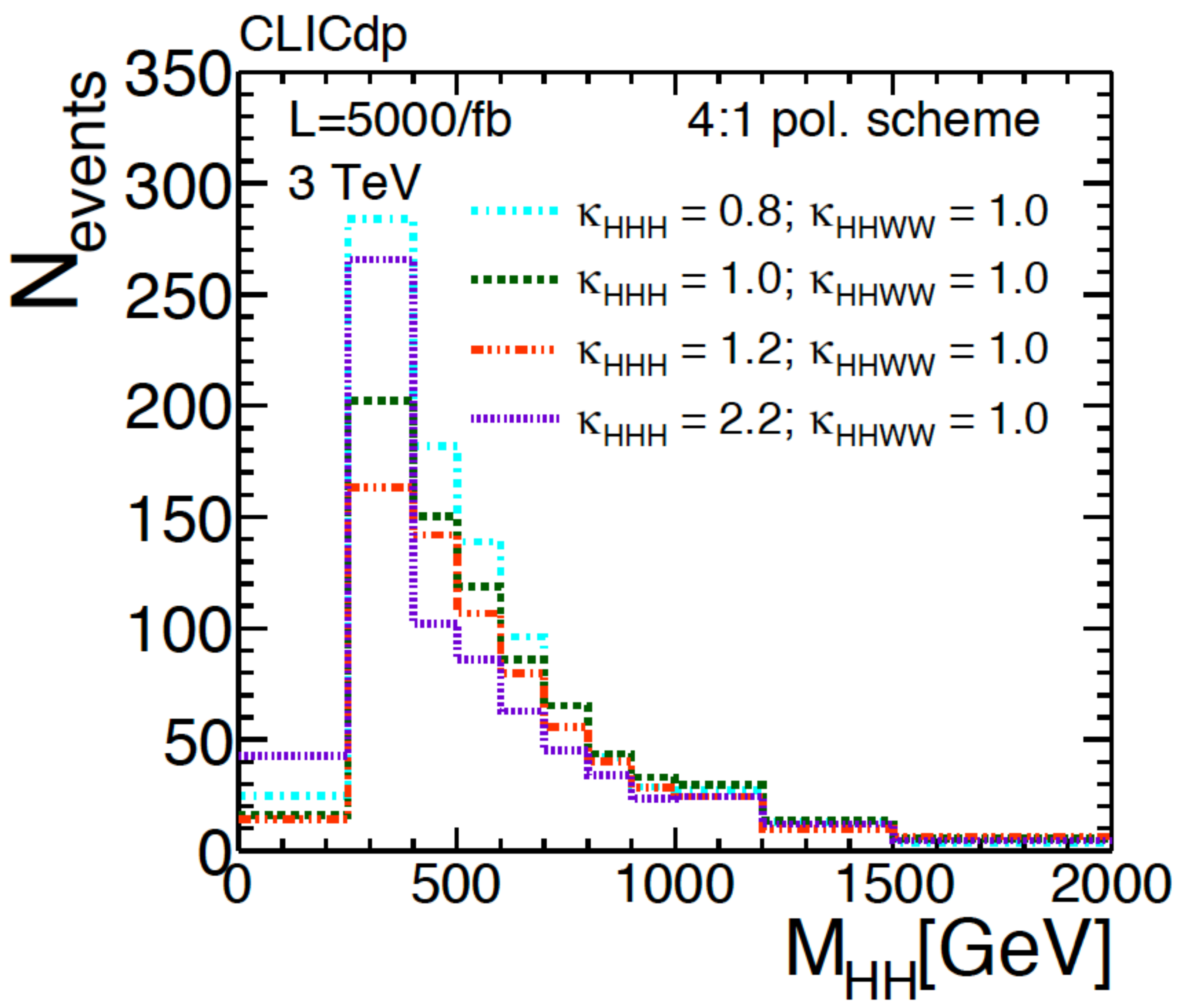


New observables? Top-quark uncertainties? Which is the optimal energy scan?

arXiv:1910.00012

Studying HH at e^+e^-



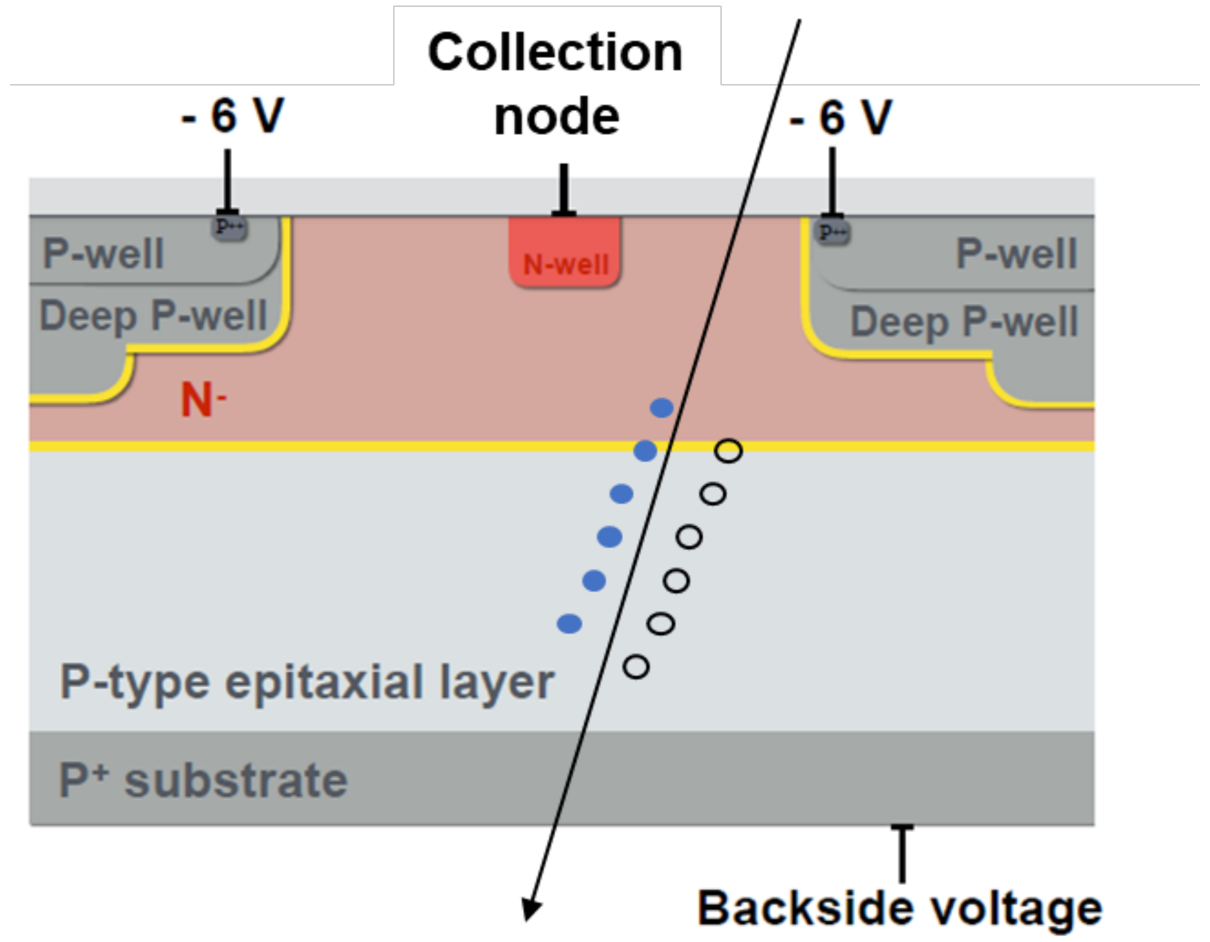


- Both the $b\bar{b}b\bar{b}$ and $b\bar{b}WW$ final states are considered with Z to leptons/neutrino/quarks
- For **ILC analyses** with an expected luminosity of 4/ab at 500 GeV, the combination of the various channels yield a precision of 16.8% on the HH total cross section which corresponds to an uncertainty of 27% on κ_λ coupling.
- For **CLIC studies** at 1.4 TeV, evidence for vvHH production is found with a significance of 3.6$\boldsymbol{\sigma}$, and the ZHH process can be observed at this stage with a significance of 5.9$\boldsymbol{\sigma}$
  - The ambiguity in the interpretation of the total cross-section results is resolved by measuring the HH invariant mass distribution in the vvHH process.

Monolithic Active Pixel Sensors - MAPS

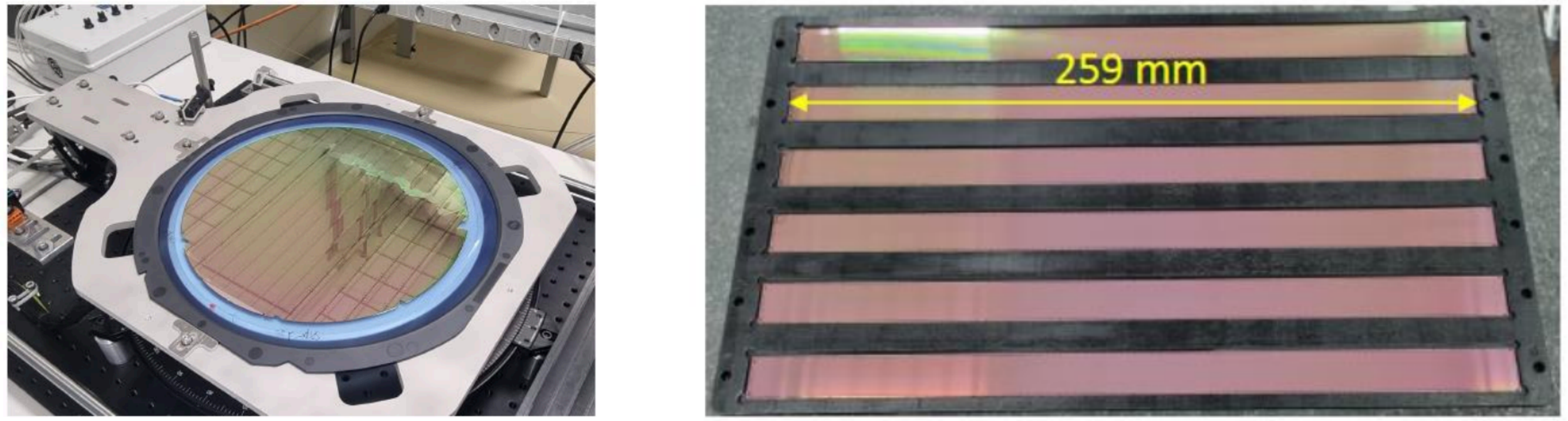
A suitable technology for high precision tracker and high granularity calorimetry

- Monolithic technologies can yield to higher granularity, thinner, intelligent detectors at lower overall cost
- Significantly lower material budget: sensors and readout electronics are integrated on the same chip
  - Eliminate the need for bump bonding : thinned to less to 50μm
  - Smaller pixel size, not limited by bump bonding (<25μm)
  - Lower costs : implemented in standard commercial CMOS processes technologies with small feature size (65-110 nm)
    - Either reduce power consumption or add more features
- Target big sensors (up to wafer size) through use of “stitching” (step-and-repeat of reticles) to reduce further the overall material budget



Current sensor optimization in TJ180/TJ65 nm process
Effort to identify US foundry on going

M. Winter, 2024



Snowmass White Paper [2203.07626](2203.07626)
Common US R&D initiative for future Higgs Factories [2306.13567](2306.13567)

Time resolution vs. power

O(ns) time resolution for beam-background suppression requires dedicated optimizations

Current designs that can achieve ns or sub-ns time resolutions compensate with higher power consumption

- Target power consumption is less than 20 mW/cm^2

Chip name	**Experiment**	**Subsystem**	**Technology**	**Pixel pitch [μm]**	**Time resolution [ns]**	**Power Density [mW/cm^2]**
ALPIDE	ALICE-ITS2	Vtx, Trk	Tower 180 nm	28	< 2000	5
Mosaic	ALICE-ITS3	Vtx	Tower 65 nm	25x100	100-2000	<40
FastPix	HL-LHC		Tower 180 nm	10 - 20	0.122 – 0.135	>1500
DPTS	ALICE-ITS3		Tower 65 nm	15	6.3	112
NAPA	SiD	Trk, Calo	Tower 65 nm	25x100	<1	< 20
Cactus	FCC/EIC	Timing	LF 150 nm	1000	0.1-0.5	145
MiniCactus	FCC/EIC	Timing	LF 150 nm	1000	0.088	300
Monolith	FCC/Idea	Trk	IHP SiGe 130 nm	100	0.077 – 0.02	40 - 2700
Malta	LHC, ..	Trk	Tower 180 nm	36	25	> 100
Arcadia	FCC/Idea	Trk	LF 110 nm	25	-	30

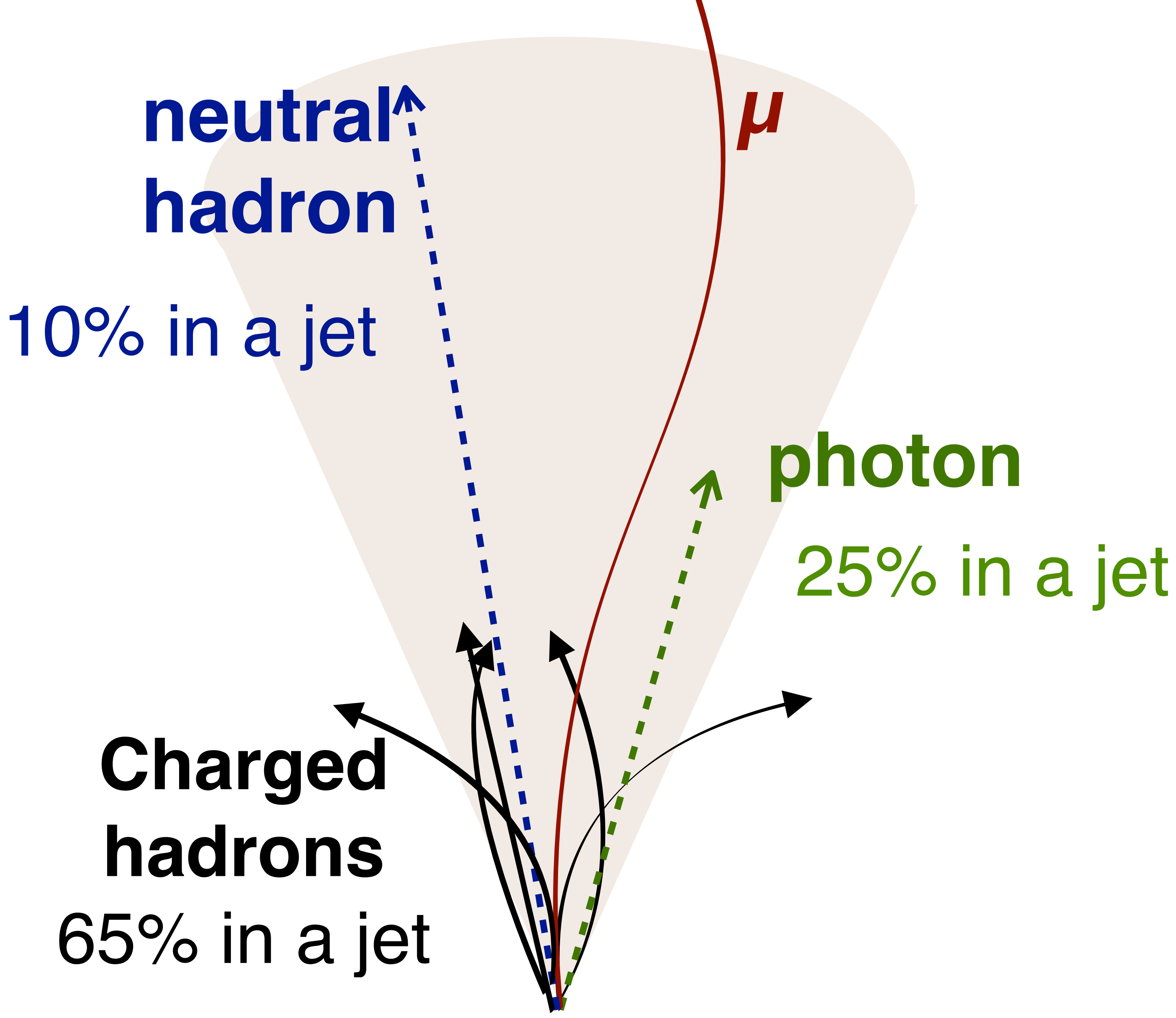
Dedicated ongoing effort to target O(ns) resolution with MAPS (slides)
First prototype (Napa-p1) produced in TJ 65 nm process 5x5 mm^2, 25 µm pitch

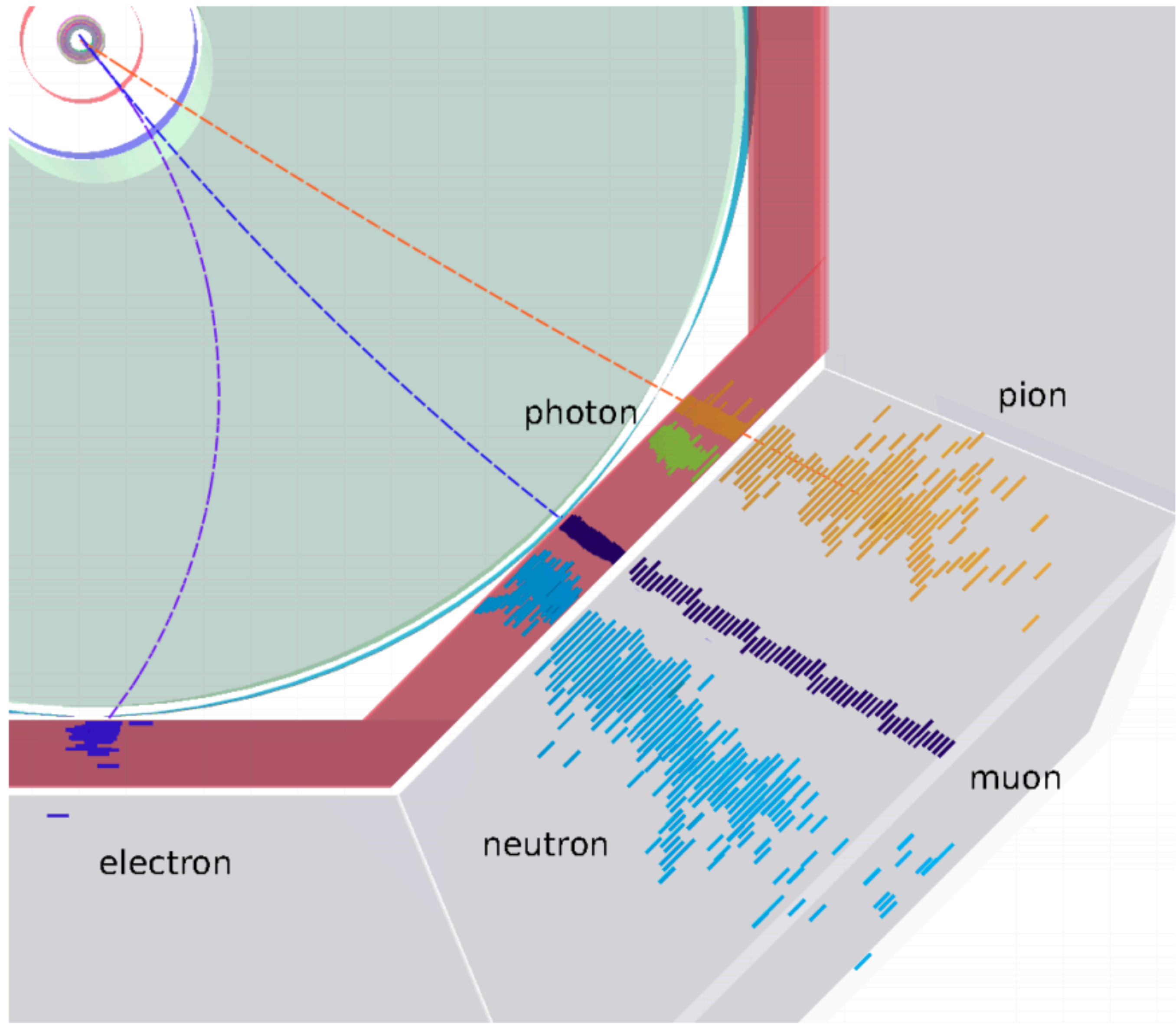
Particle Flow Calorimeters

CALICE

Build on studies by CALICE: development and study of finely segmented and imaging calorimeters

- 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
- **CALICE R&D** inspired CMS high granularity solution HGCAL - Common test beams with the AHCAL prototype
  - homogeneous crystal ECAL + scintillating glass HCAL
    - Integrated engineering prototypes already tested to address system level issue
- **R&D line**: MAPS (see Alice FoCAL) and (ns-ps) timing information (ex: LGADs)
- ALLEGRO concept for FCC-ee built around highly granular noble-liquid (Ar, Kr) ECAL with Pb or W absorbers





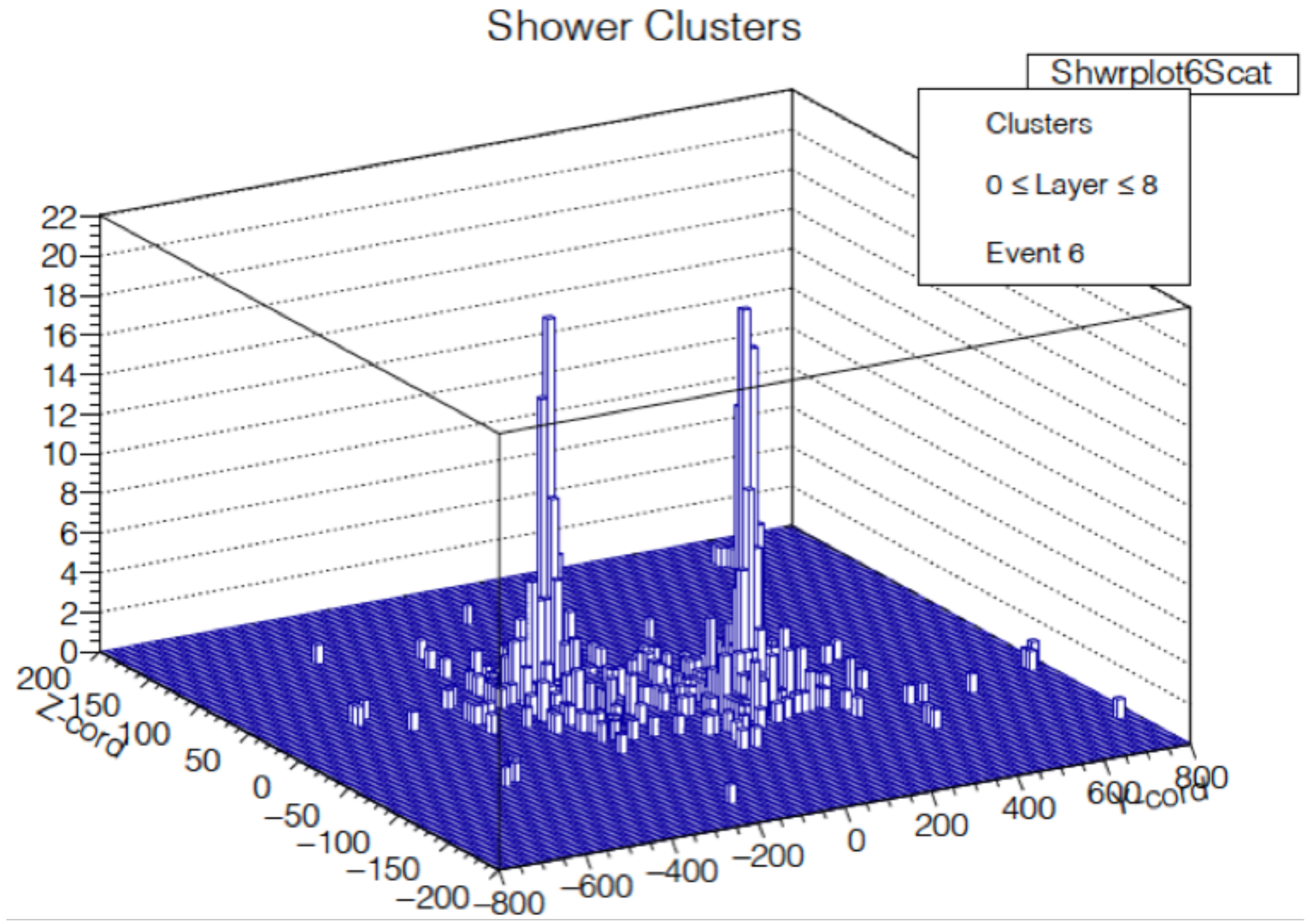
ECAL 3%/√E
HCAL 30%/√E

MAPS for ECal, SiD example

arXiv:2110.09965

Fine granularity allows for identification of two showers down to the mm scale of separation

- SiD detector configuration with 25x100 μm^2 pixel in the calorimeter at ILC
  - Changing analog to binary digital has no energy resolution degradation
- ***The design of the digital MAPS applied to the ECal exceeds the physics performance as specified in the ILC TDR***
- The 5T magnetic field degrades the resolution by a few per cent due to the impact on the lower energy electrons and positrons in a shower
- Future planned studies include the reconstruction of showers and π^0 within jets, and their impact on jet energy resolution



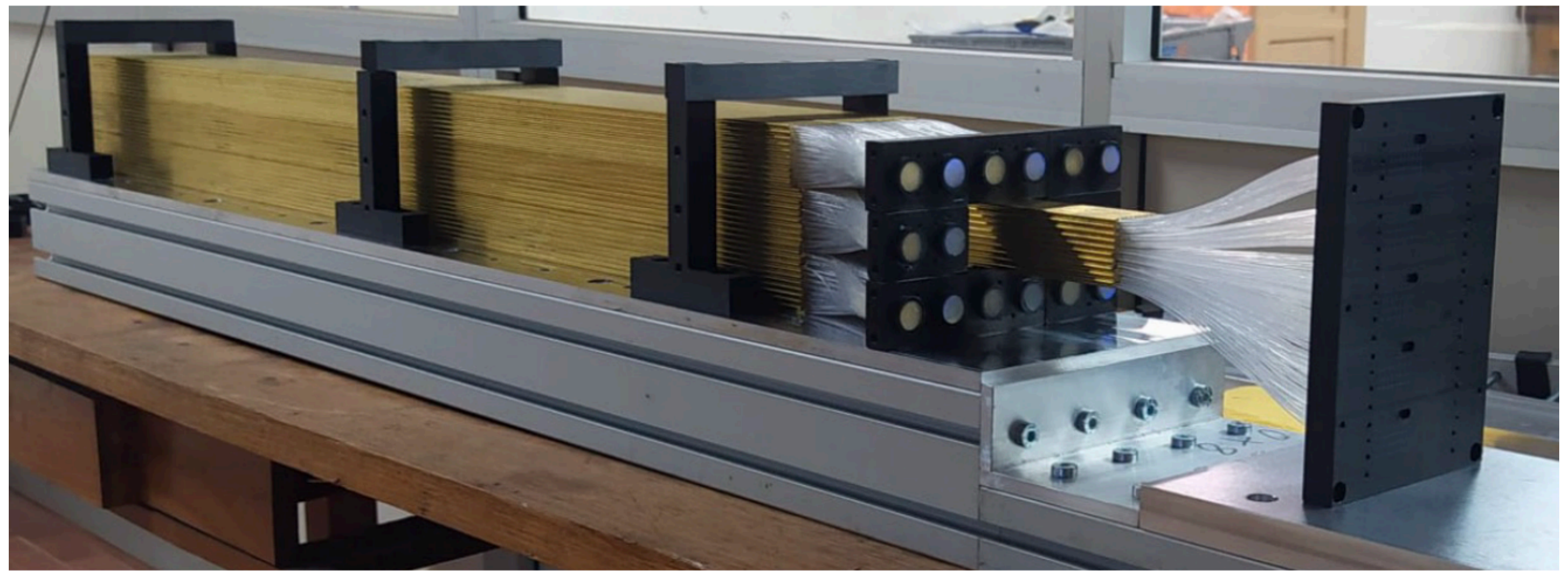
GEANT4 simulations of Transverse distribution of two 10 GeV showers separated by one cm

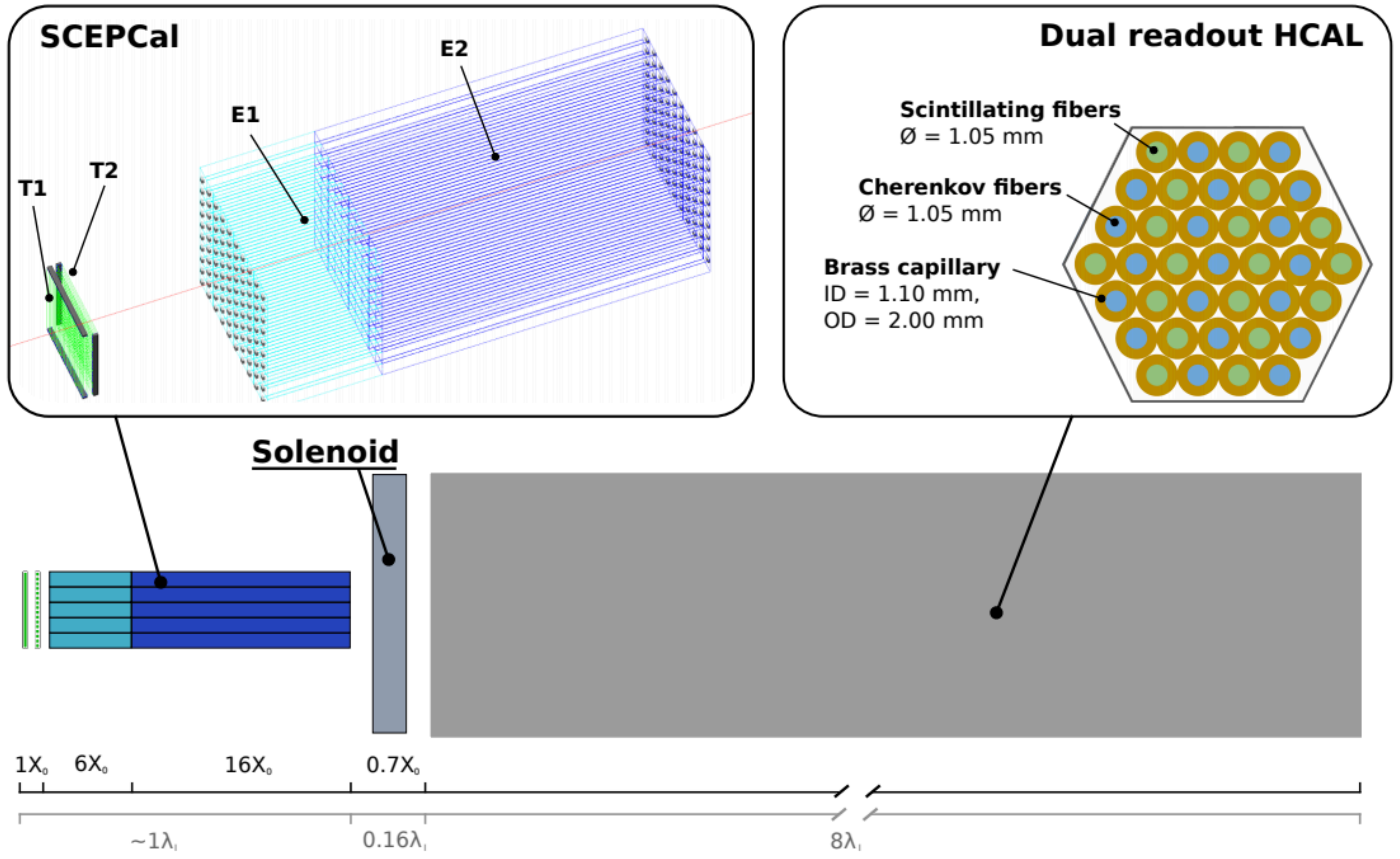
Dual Readout calorimetry

arXiv:2008.00338
JINST 15 (2020) P11005
G. Polesello (2023)

Correct HCAL event-by-event through measurement of EM fraction with dual readout calorimeter

- **Dual readout Calorimetry**, e.g. DREAM (FCC-ee) improvement of the energy resolution of hadronic calorimeters for single hadrons:
  - Cherenkov light for relativistic (EM) component
  - Scintillation light for non-relativistic (hadronic)
  - EM prototype built and tested on beams (DESY/CERN) to understand construction issues + integration with SiPMs
  - Hadronic-size module funded and under construction
- **IDEA**: DR crystals inside solenoid + DR fibers outside
  - ECAL ~3%/√E, HCAL ~29%/√E
  - Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV



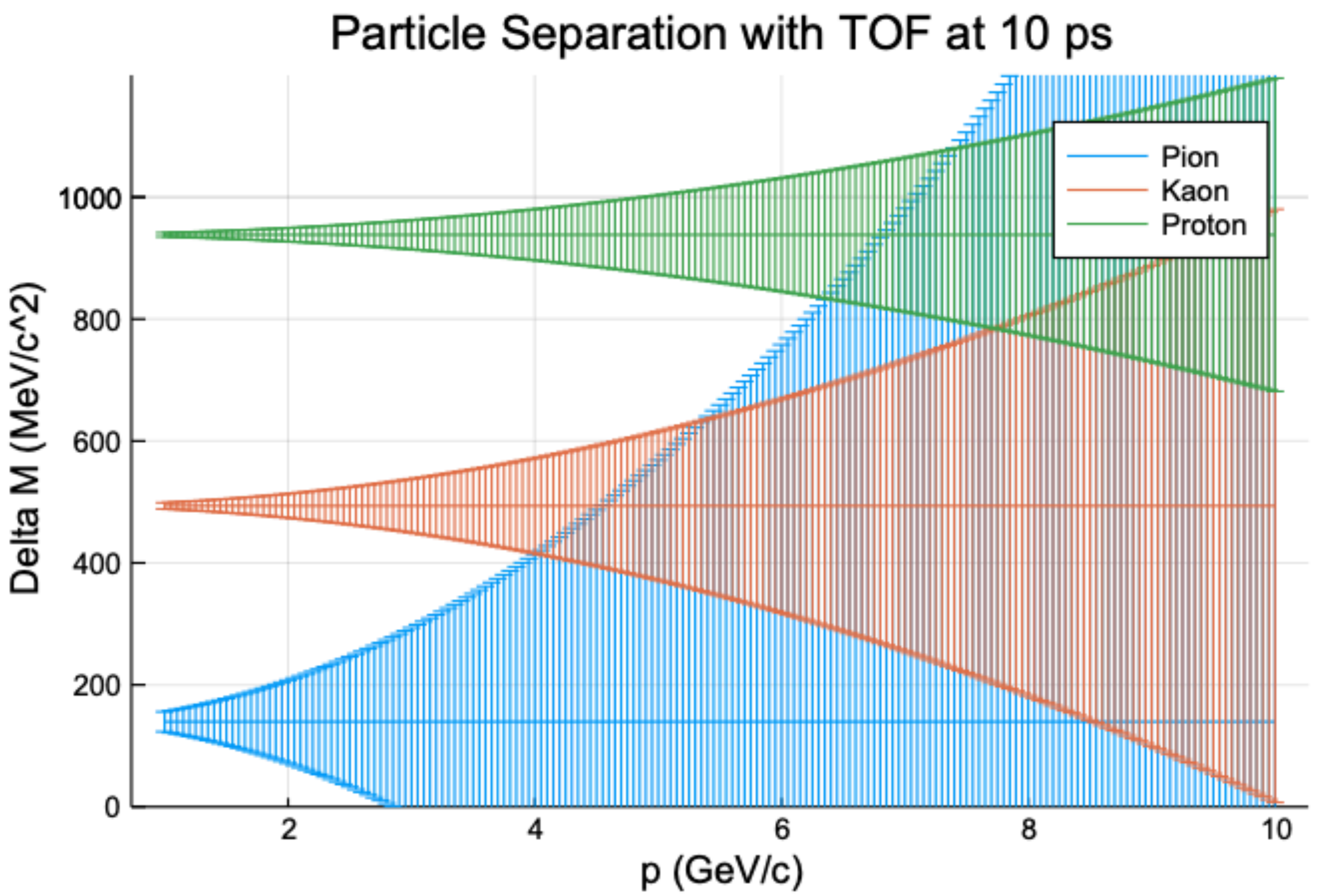


Timing layer(s)

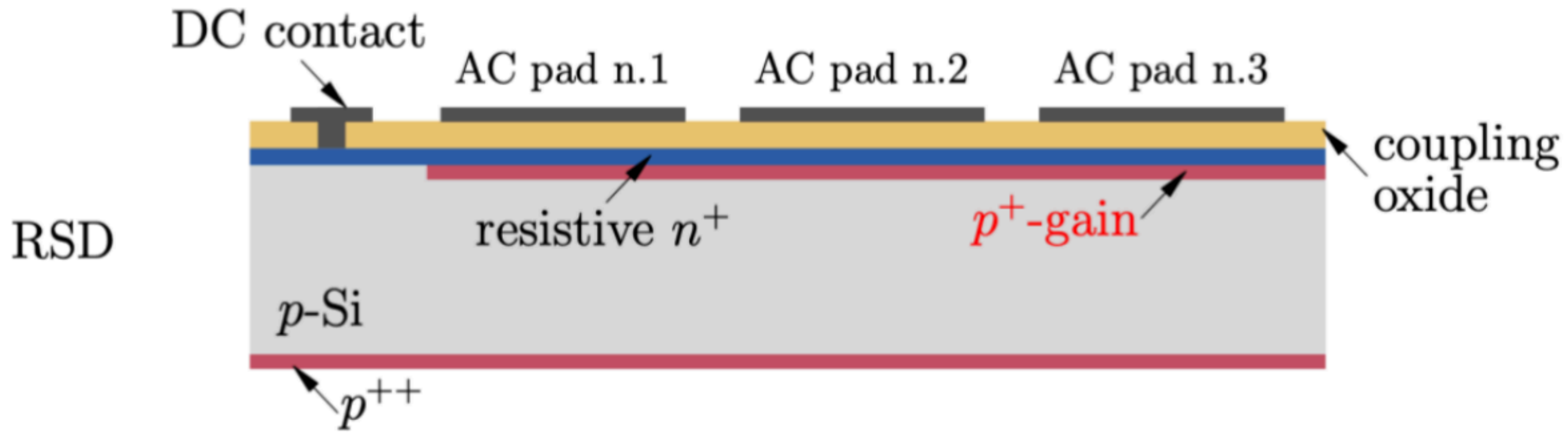
arXiv:2110.09965

Timing is being explored as additional information from the calorimeter and a dedicated layer

- A timing layer with O(ns) resolution into the HCAL could allow beneficial identification of slow shower components from prompt components
- A timing layer as part of the tracking system or between tracker and E (TOF) system
  - physics reach needs to be further studied
- Very attractive option for timing in Si wrapper region of IDEA/Allegro
  - O(10) ps needed for PID with TOF
  - Some “fast” devices prototyped by Arcadia & US groups based on
    - 35 ps time resolution so far


Particle Separation with TOF at 10 ps

Mass resolution for a TOF system with a performance of 10 ps in SiD



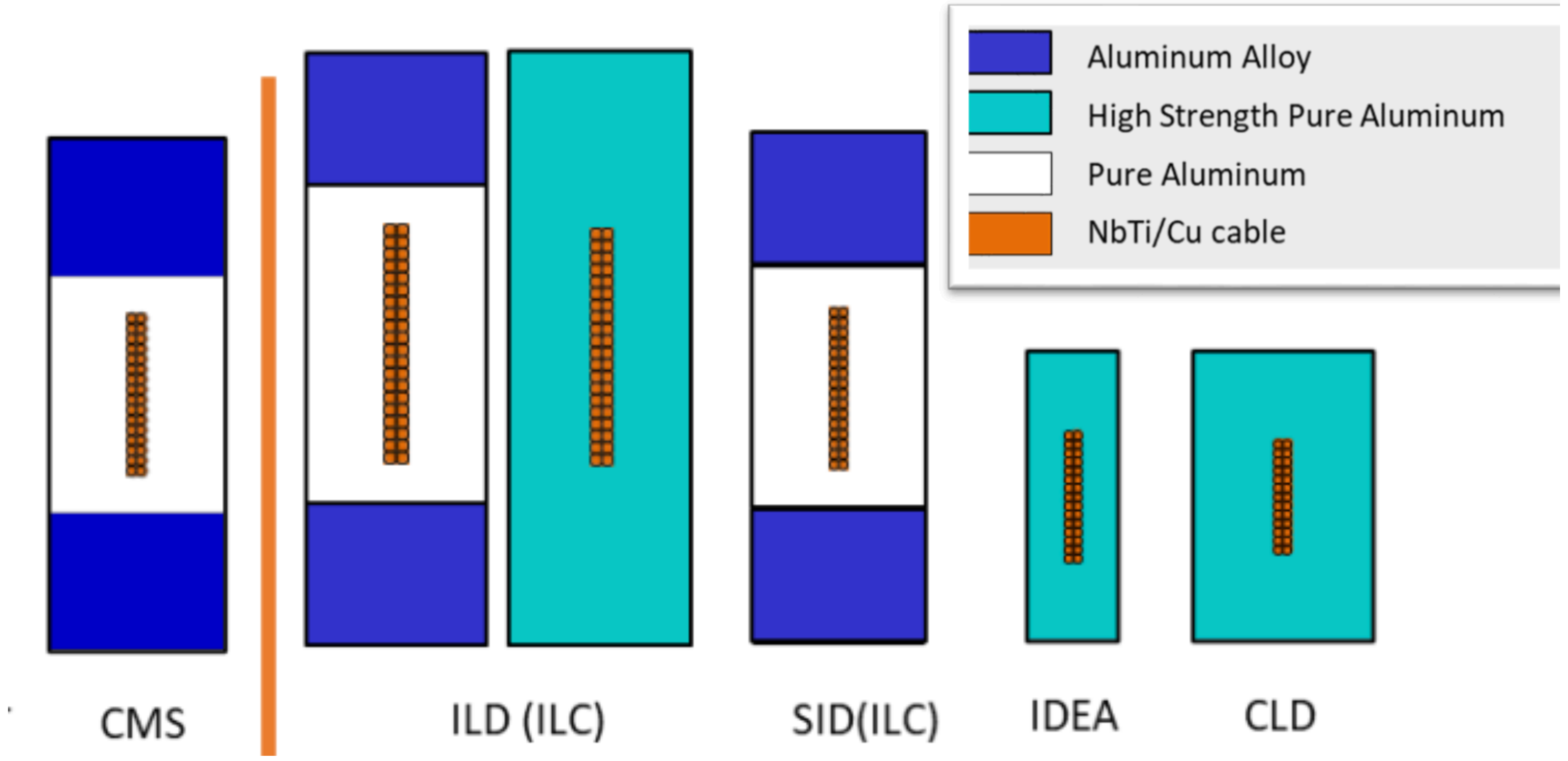
More physics/detector simulation studies needed to refine the case for timing layers

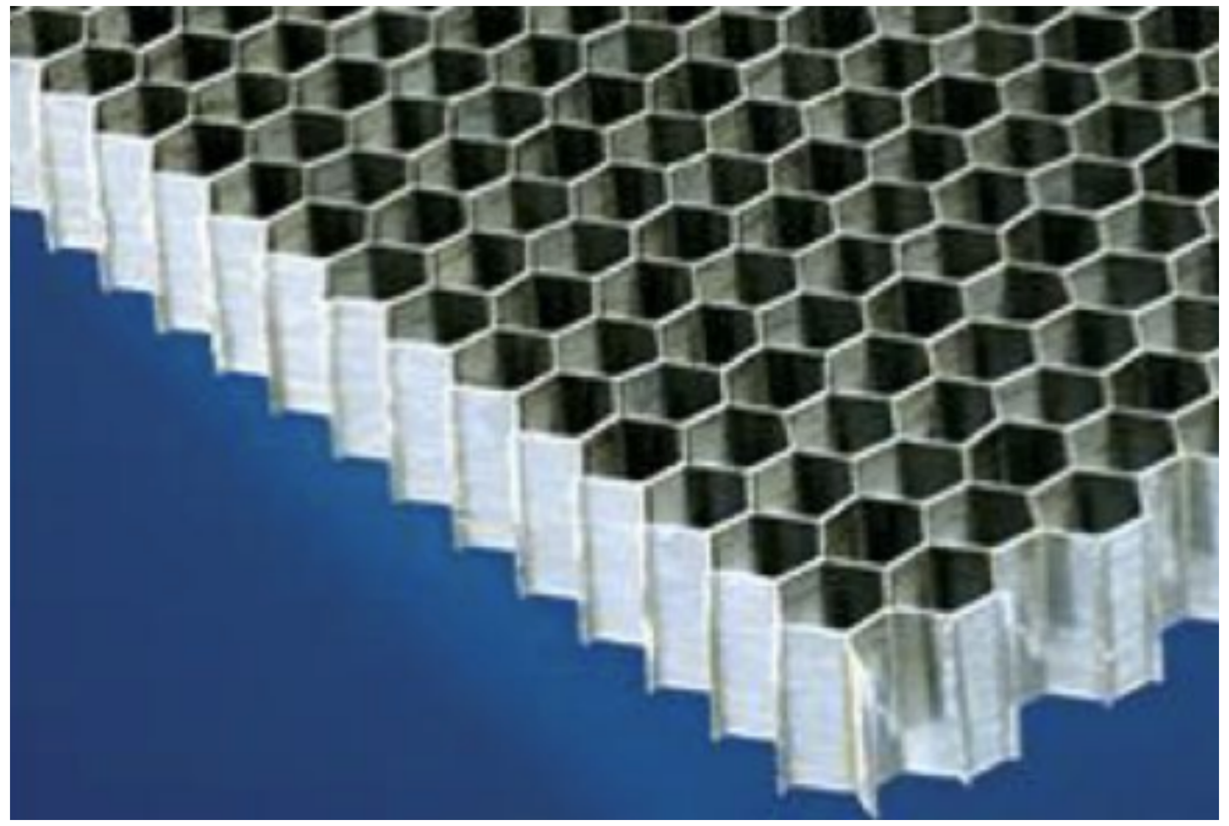
A. Yamamoto (2023)
JINST 18 T06013 (2023)
K. Buesser (2023)

Solenoid

A big, reliable, stable - and very thin - solenoid magnet to provide the field for charged track p_T measurement

- SiD/ILD - High field – 5/4 T for BR^2 - 5/4 layers of "CMS" conductor + more structural aluminum
  - Stored energy ~1.5 (2.3) GJ SiD (ILD)
- IDEA, ultra light 2 T solenoid with a vacuum vessel (25 mm Al) with honeycomb structure X0 = 0.04 to reduce material
- **Critical R&D area** – Al-stabilized technology needs to be resumed
  - No industrial production available, as of today
- Backup solutions:
  - CICC (Cable-in-conduit conductor) approach may also be a solution - requires different magnet system design
  - HTS: New types of conductor being investigated to allow higher temperature operations > 10K (lower cost)



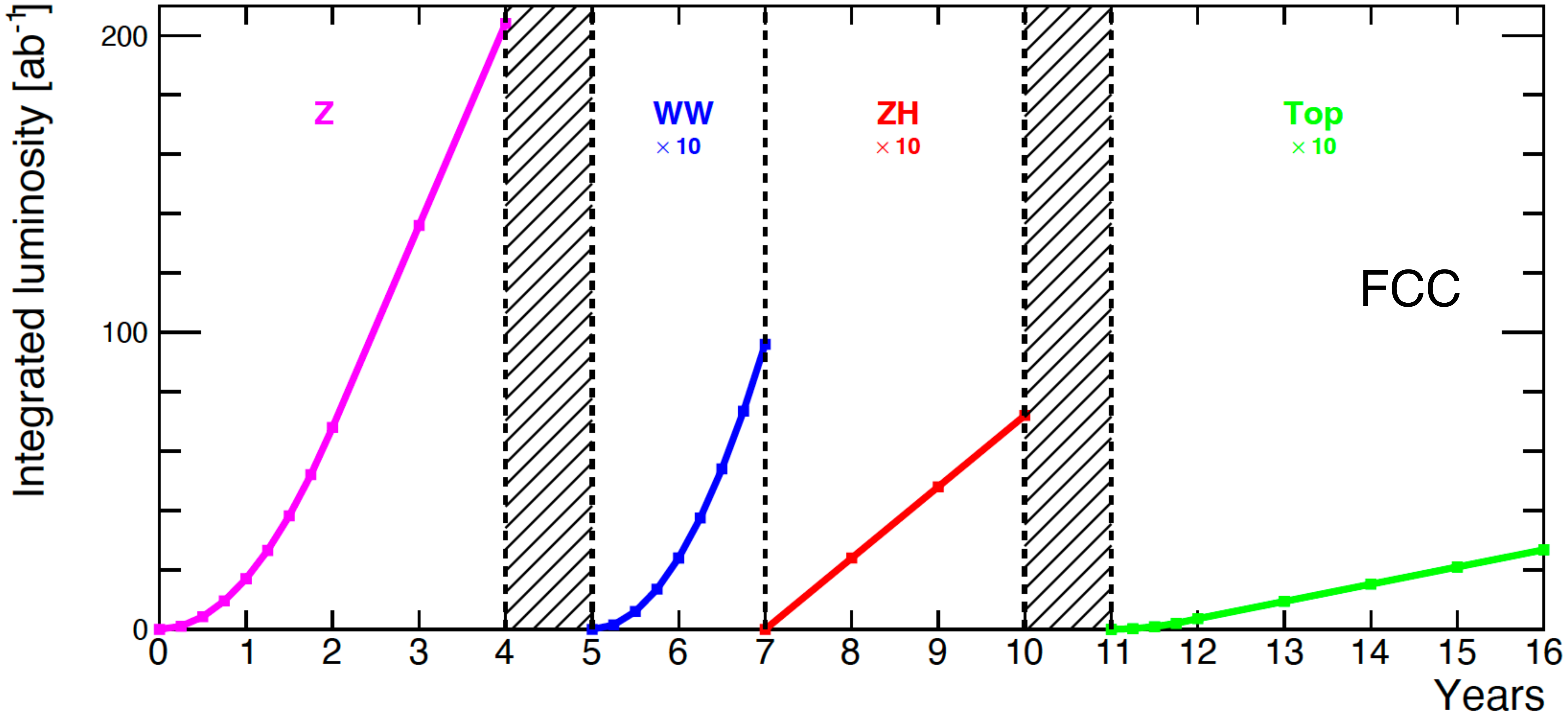


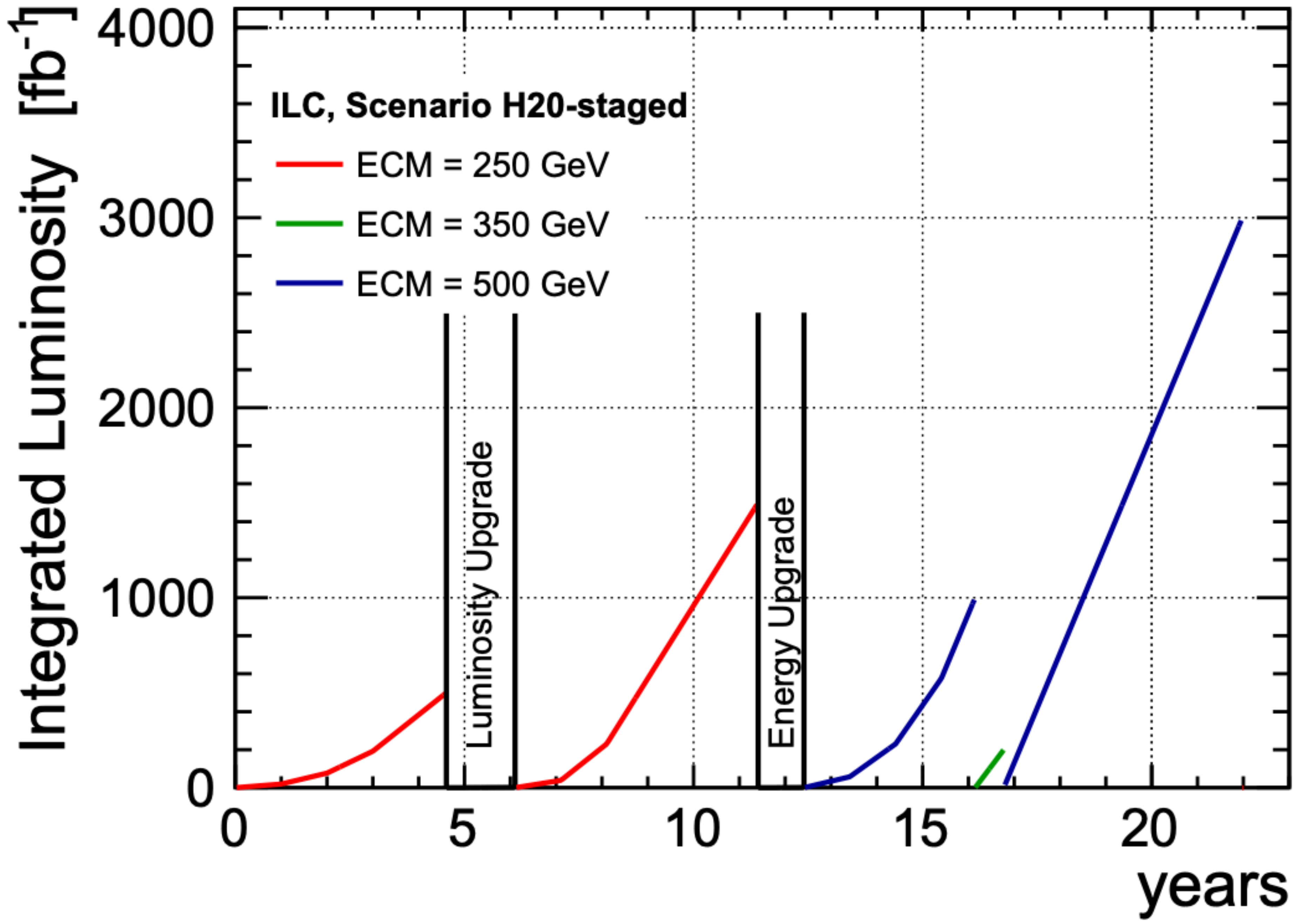
KEK-CERN leading R&D. But need to push for R&D in labs together with industry to keep the timelines of future projects!

Run Plans

1710.07621
FCC Mid Term Report

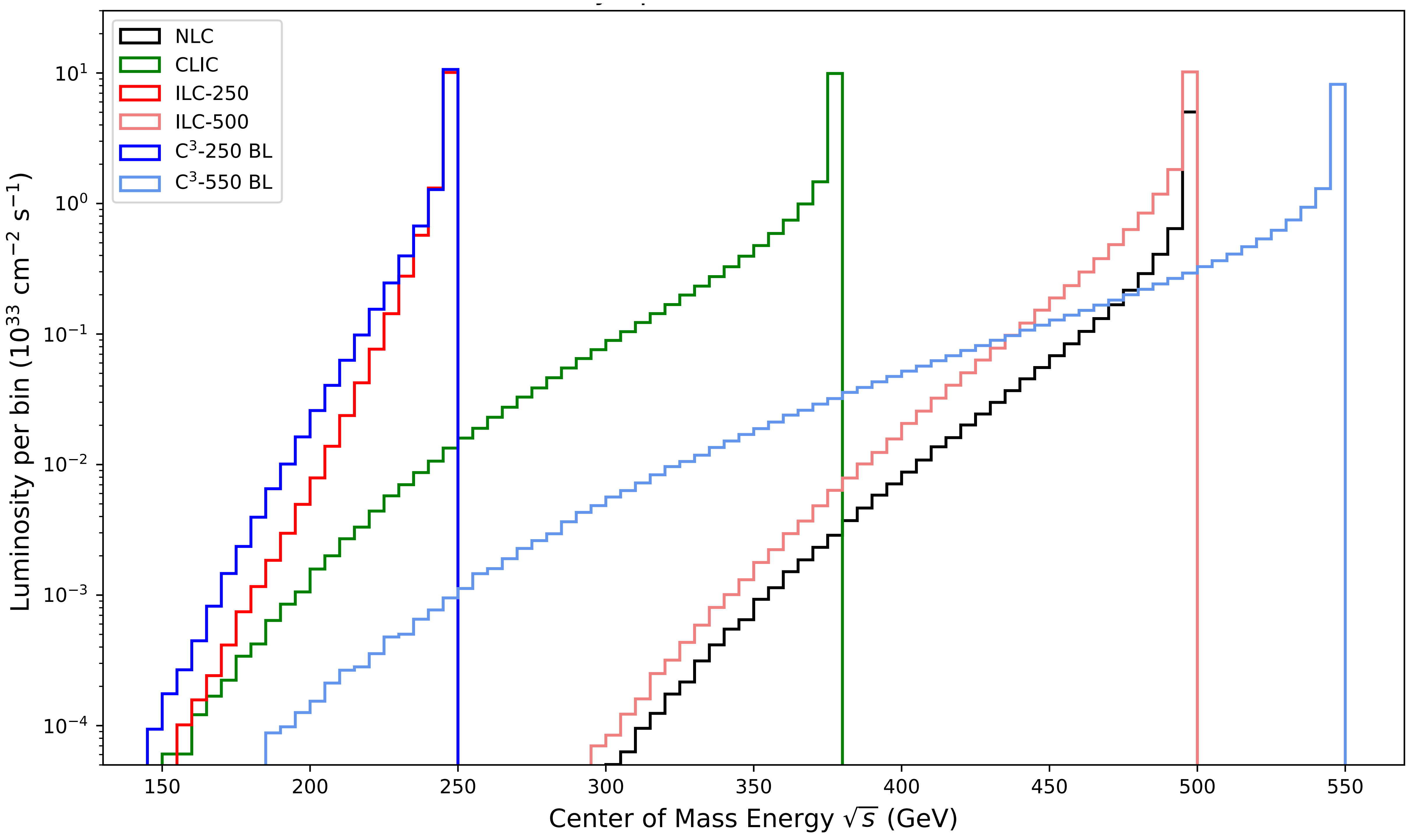
ILC and FCC

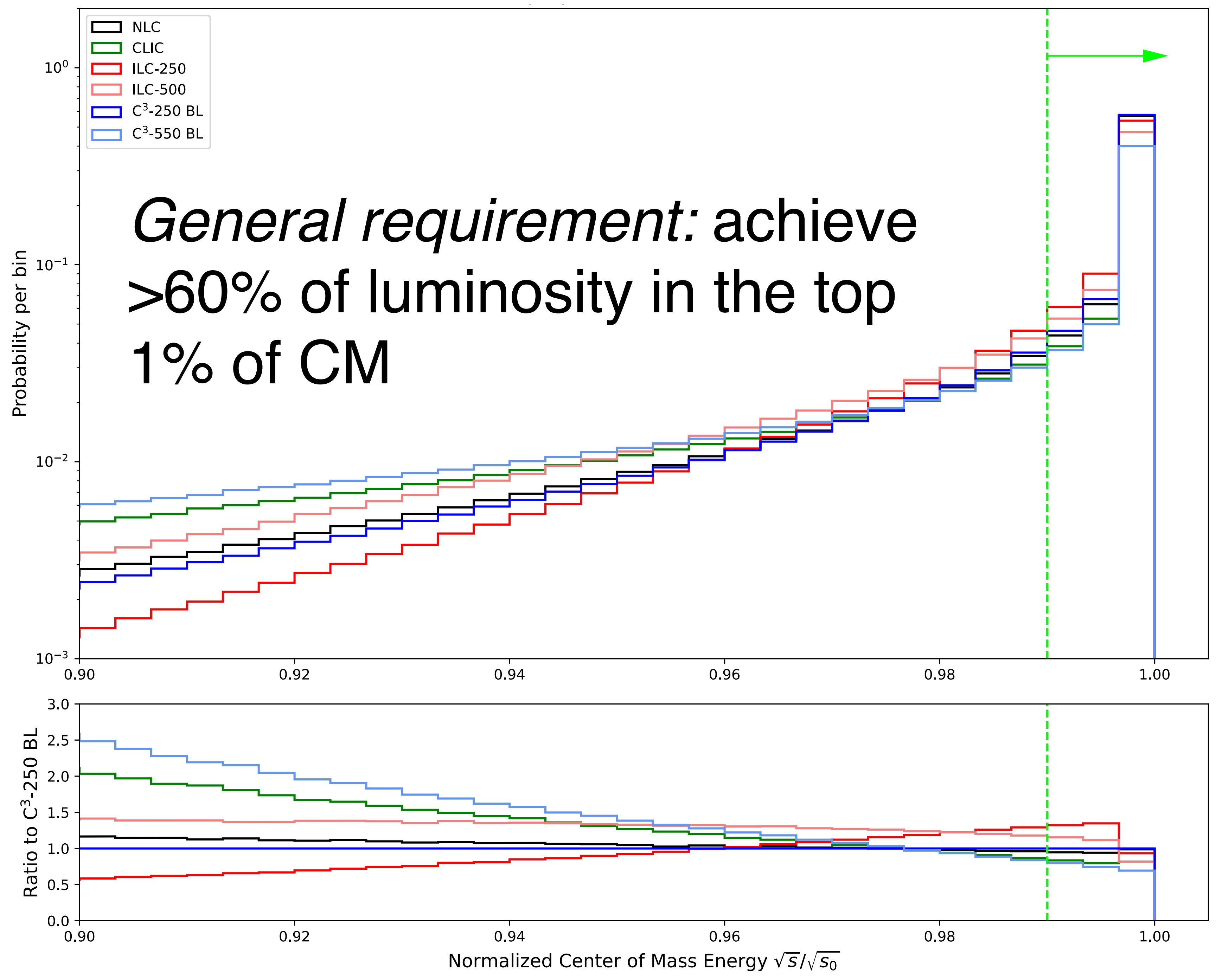




Luminosity Spectra

arXiv:2403.07093





General requirement: achieve >60% of luminosity in the top 1% of CM

arXiv:2403.07093

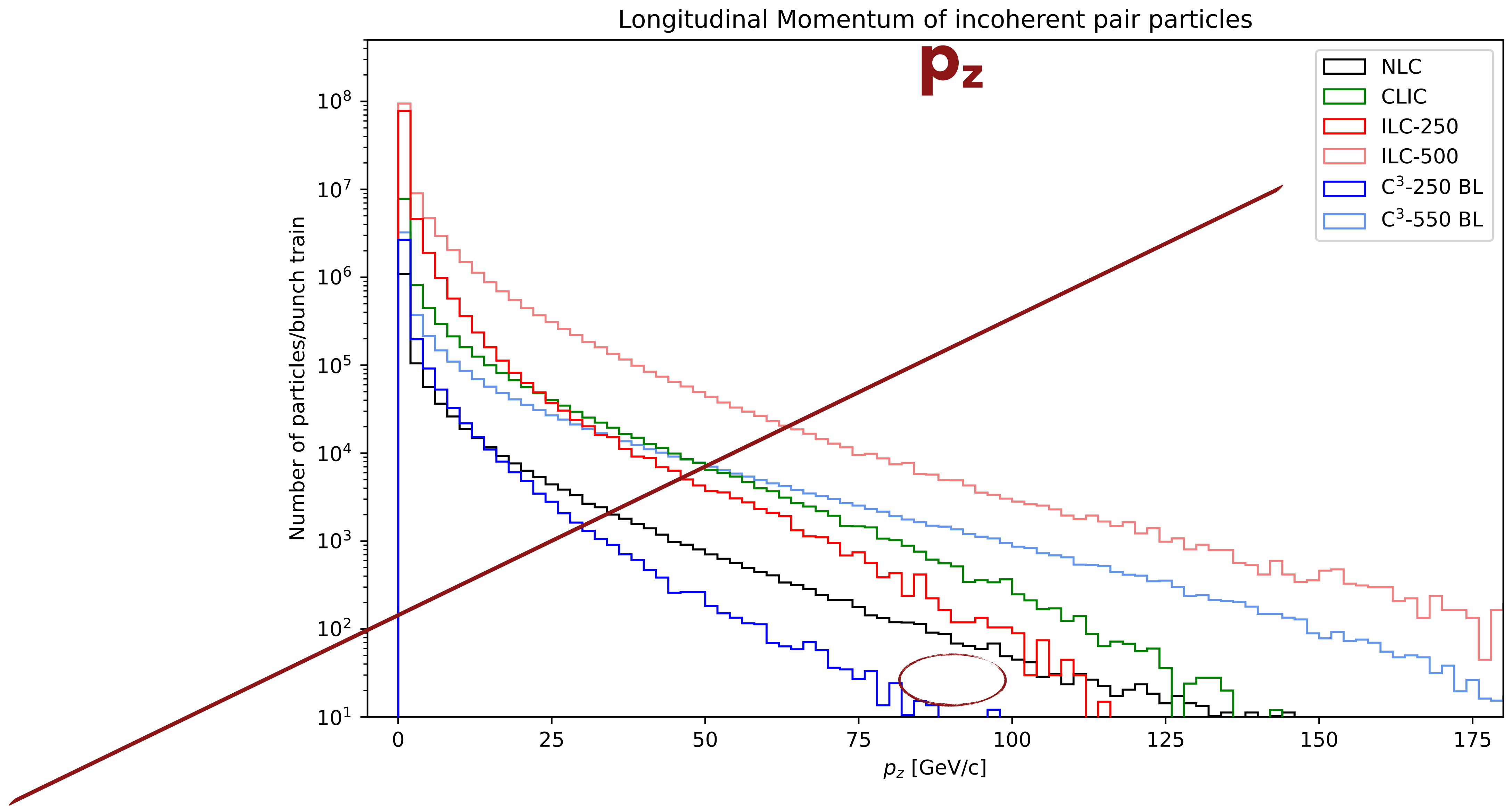
Incoherent Pair Production

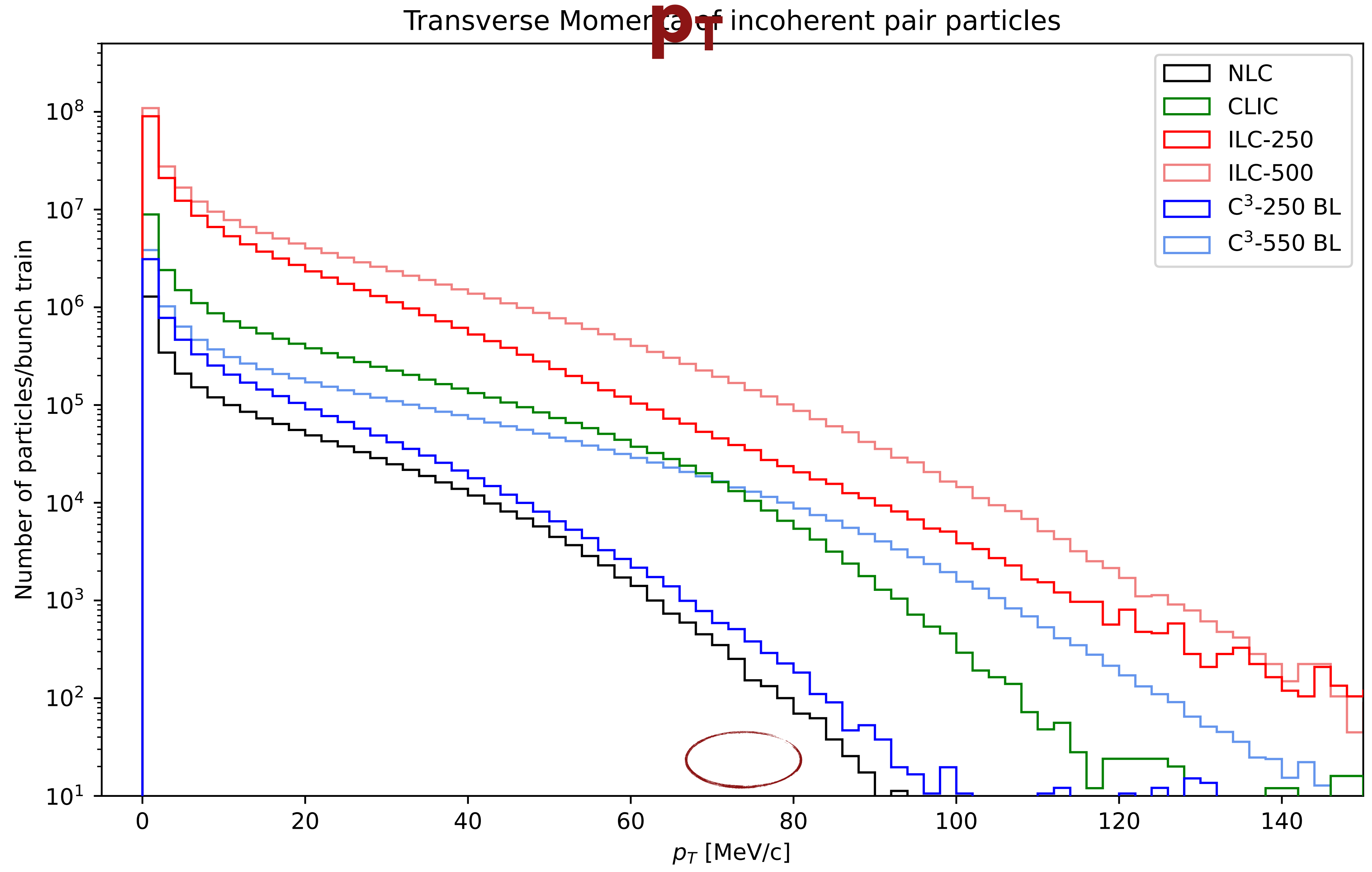
Incoherently produced pair particles are typically low-energetic and boosted in the forward direction.

Assuming a common per-bunch-train readout scheme, the expected number of such pair particles produced per bunch train is $\langle N_{\text{incoh}} \rangle \cdot n_b$.

The energy and momentum spectra are shown assuming this normalization.

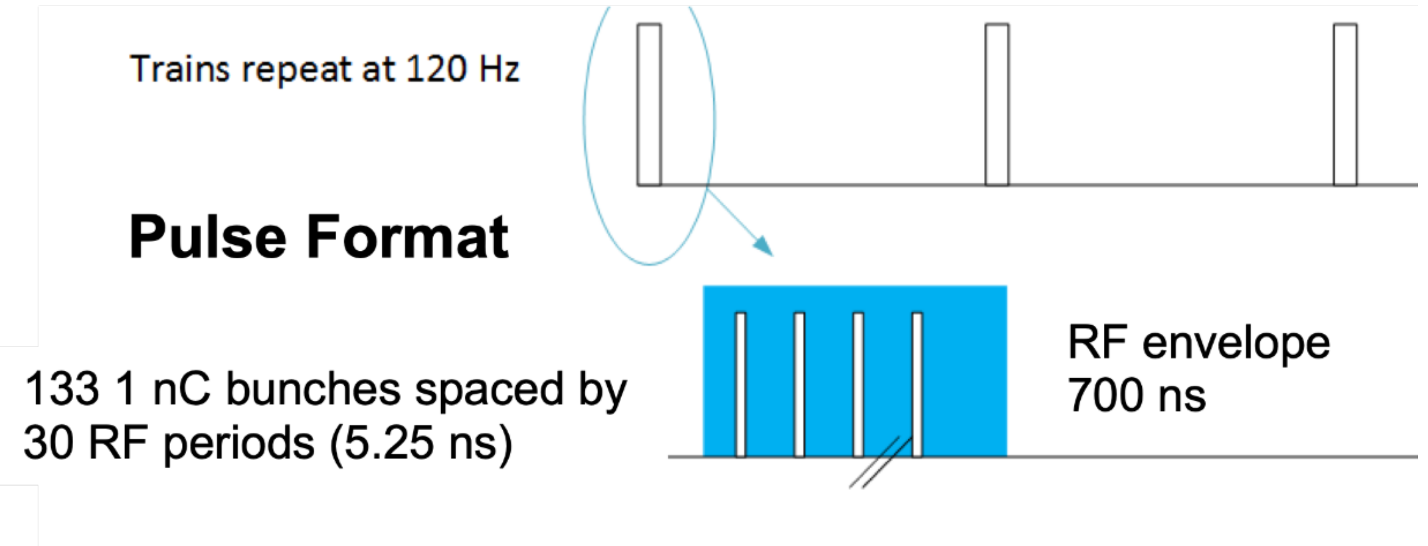
Coherent pairs/pairs from trident cascade are negligible for HFs at sub-TeV energies!





Power Consumption and Sustainability

Snowmass



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

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

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