Higgs Physics and (some) Experimental challenges

HFCC meeting - June 3rd, 2026

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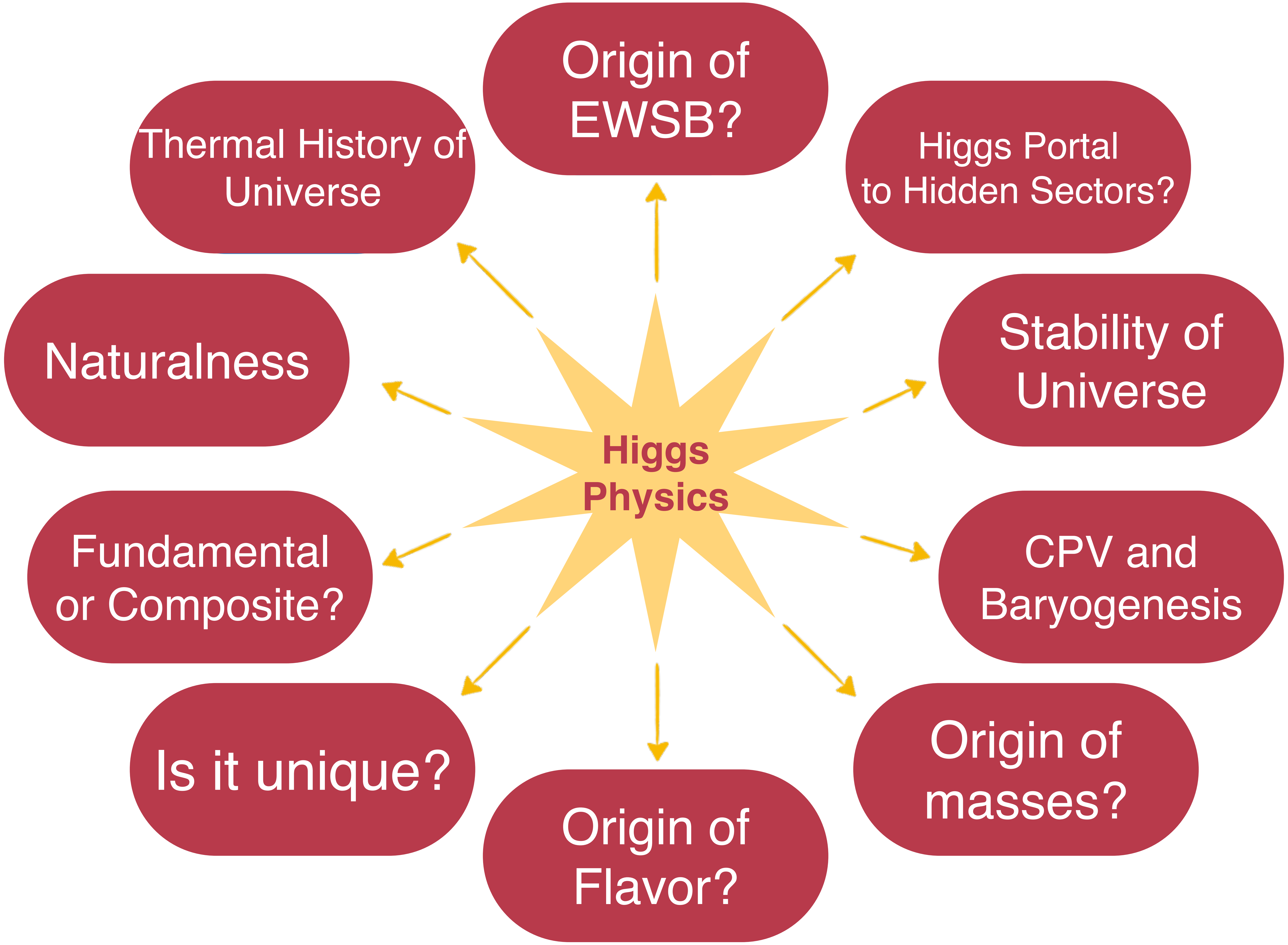
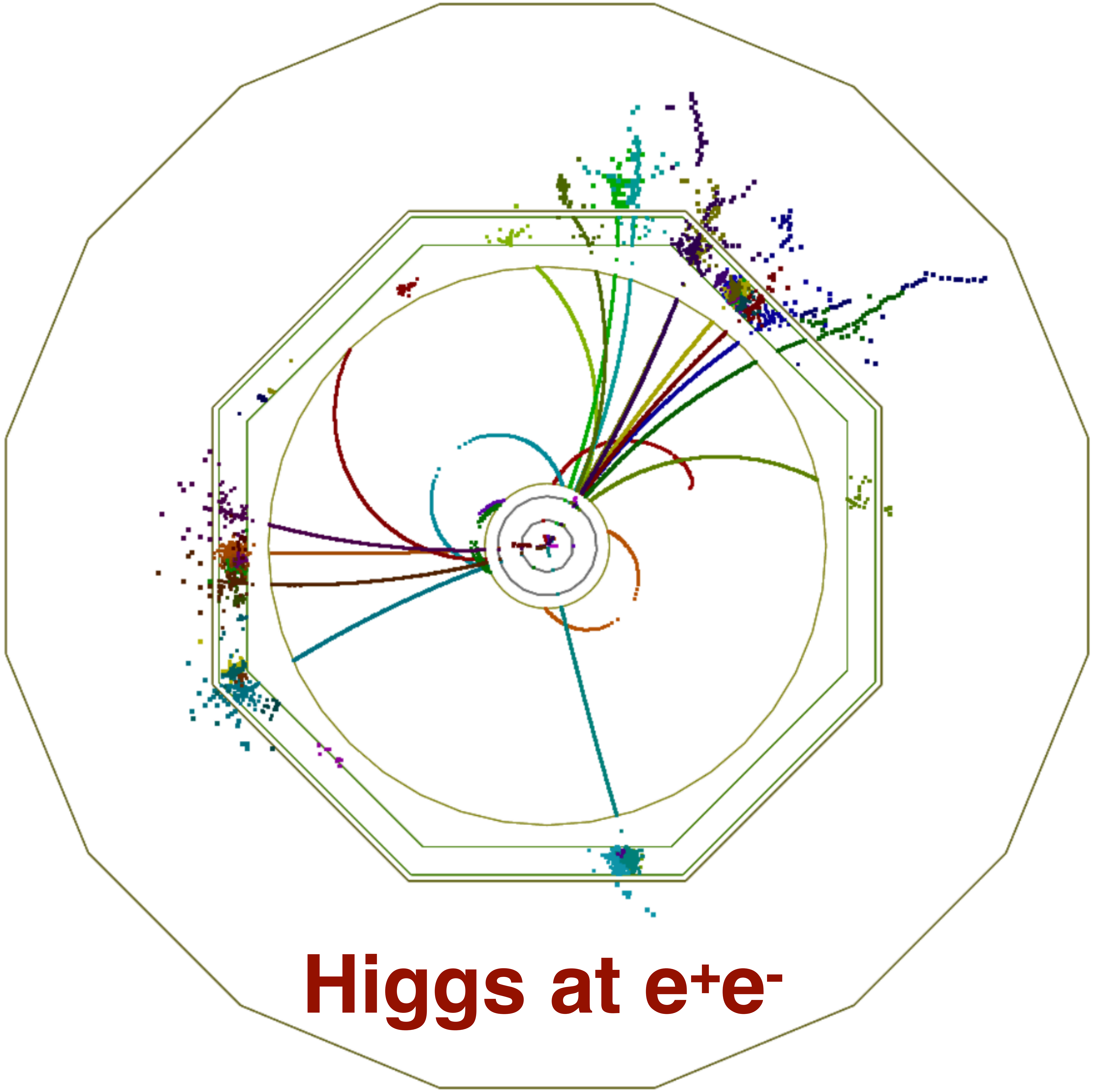
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY



[The Energy Frontier 2021 Snowmass Report]



Higgs at e^+e^-

Initial state well defined

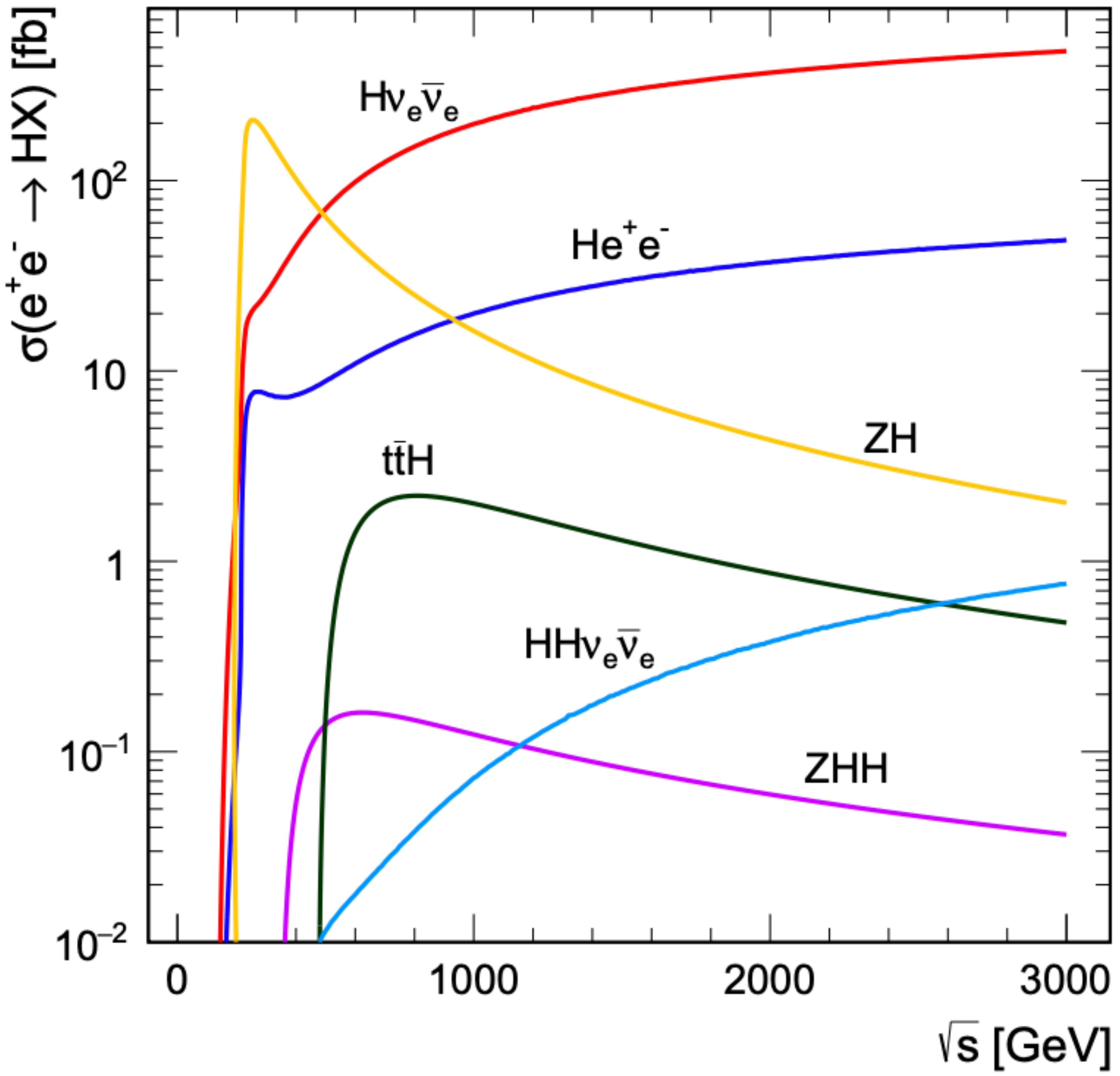
⟹ High-precision measurements

Higgs bosons appear in 1 in 100 events

⟹ Clean experimental environment and trigger-less* readout

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**

Higgs at e^+e^-

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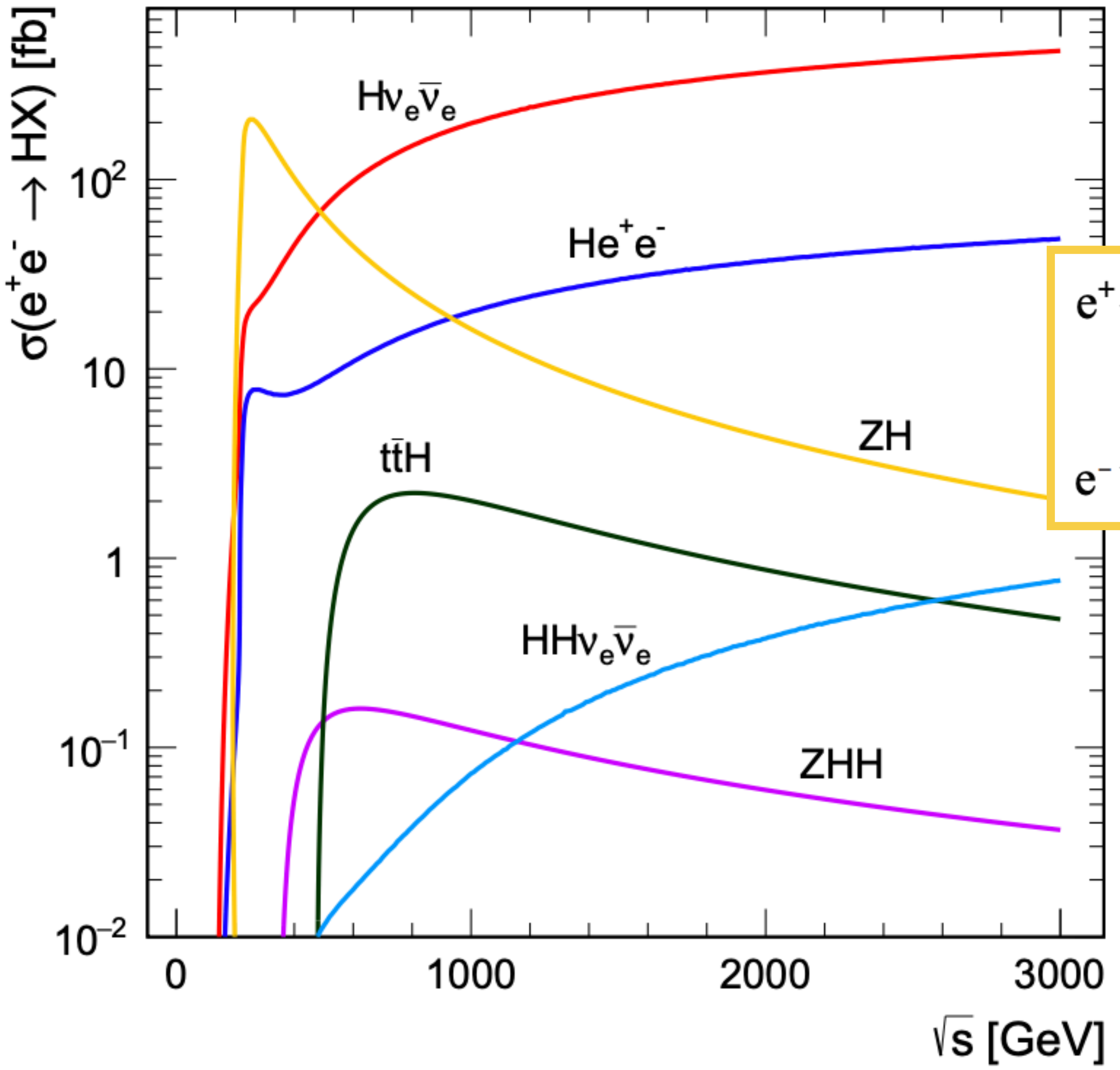

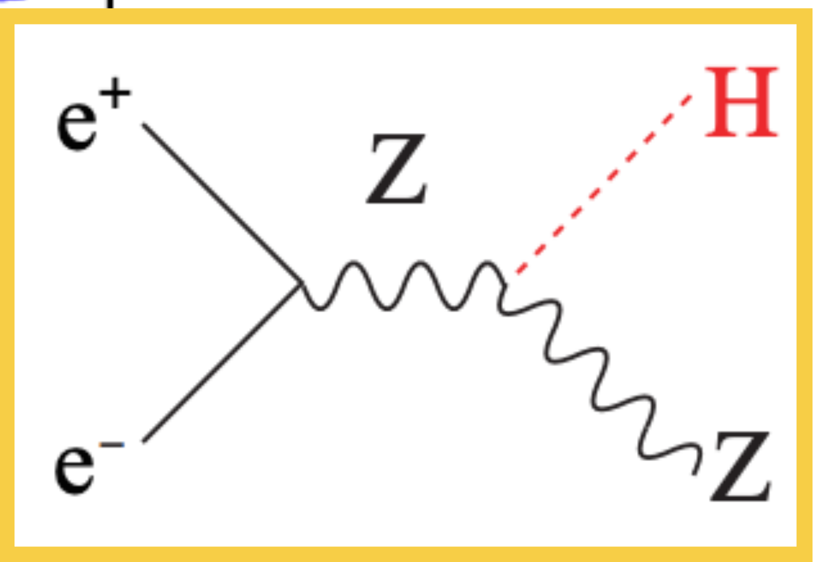

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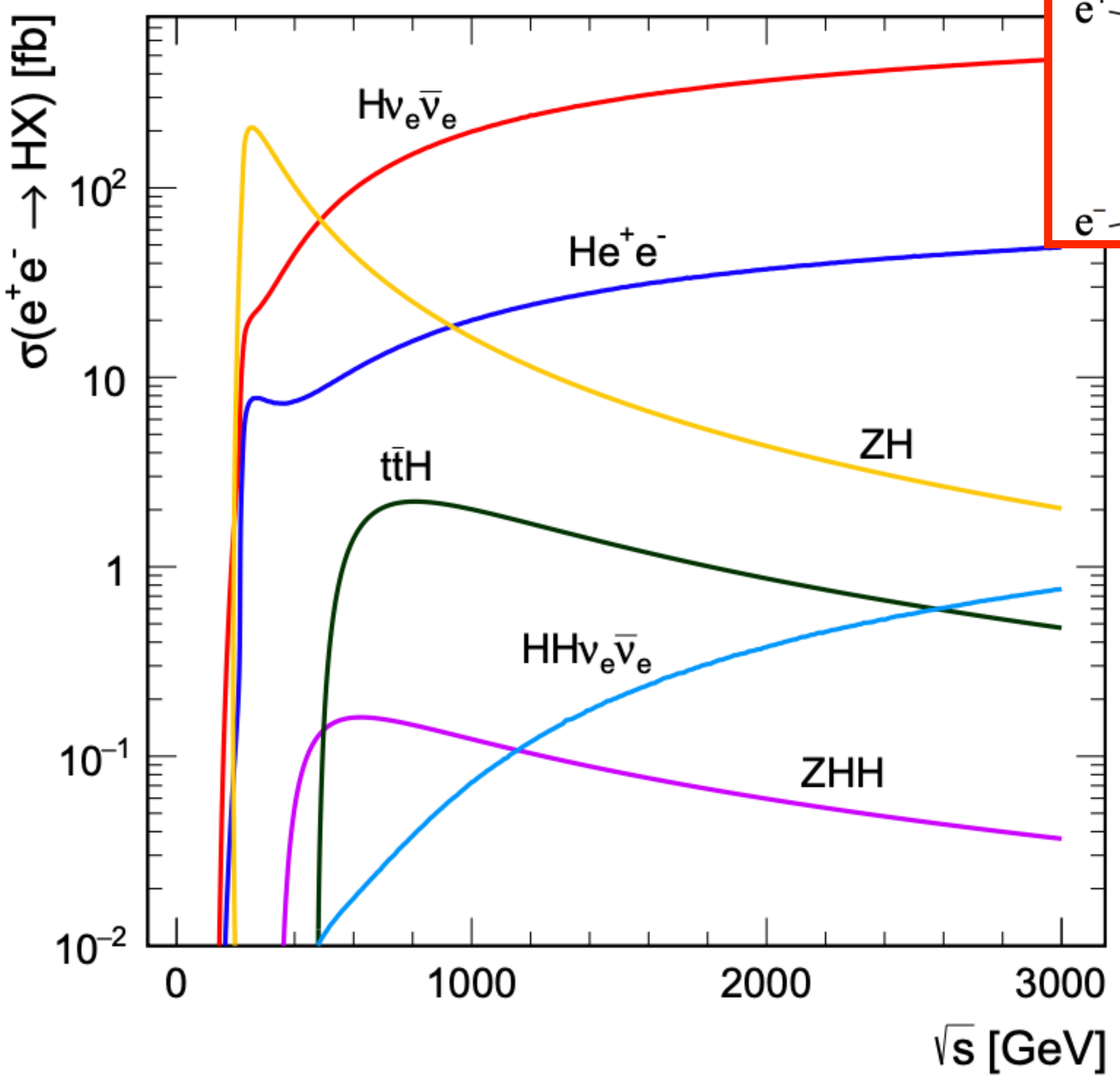

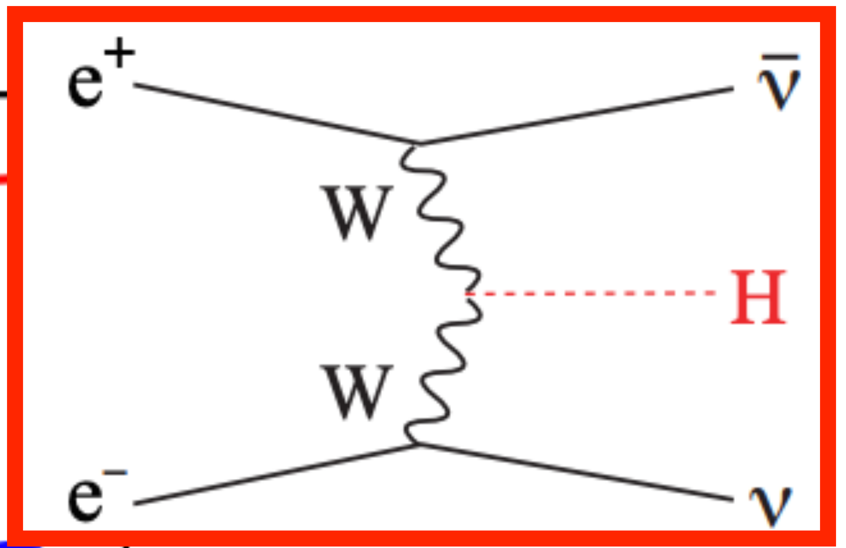

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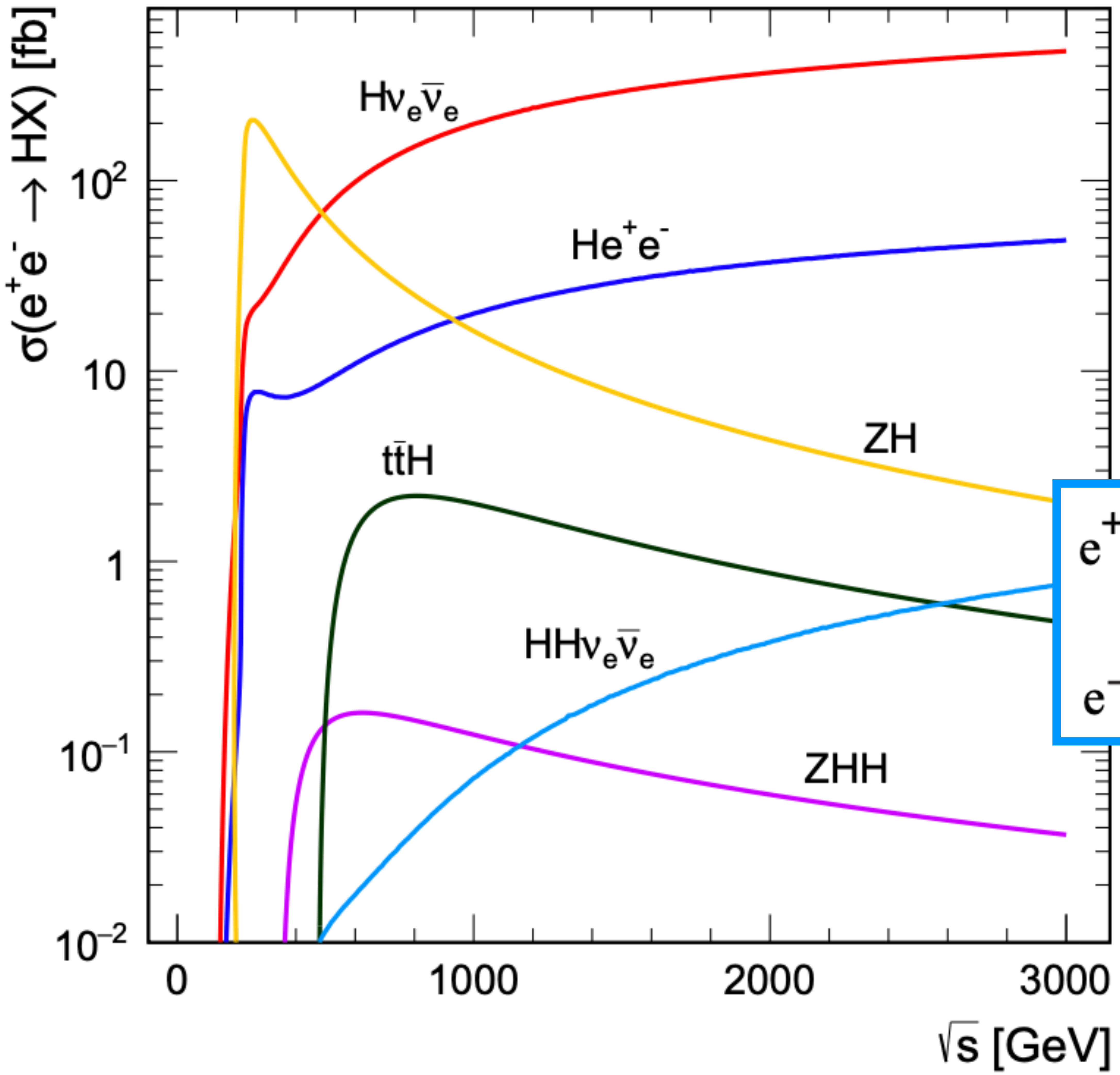

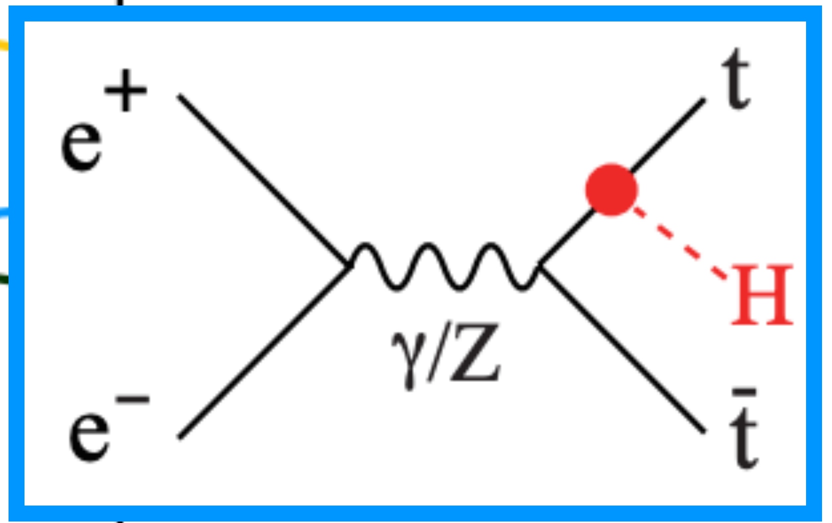

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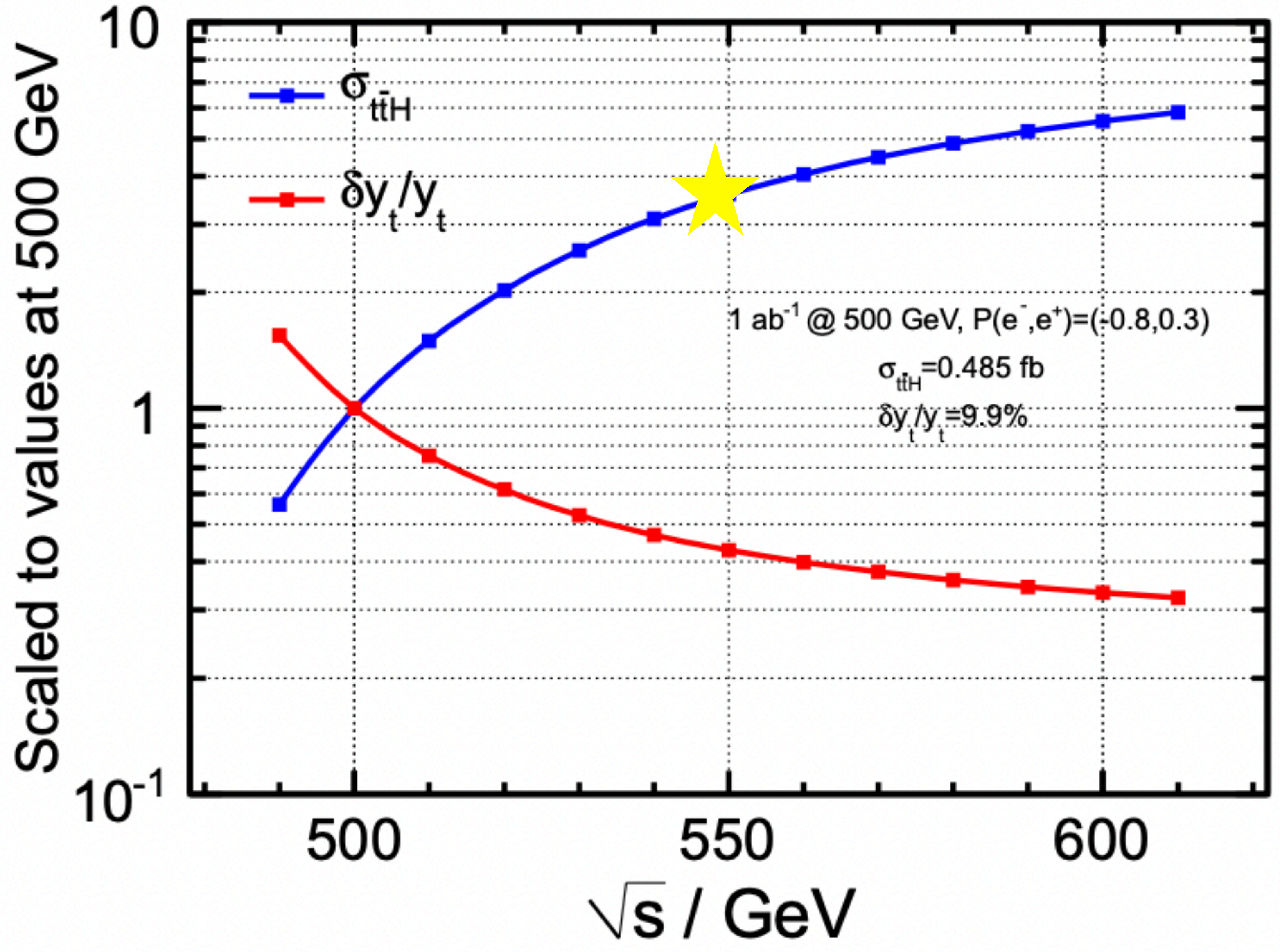

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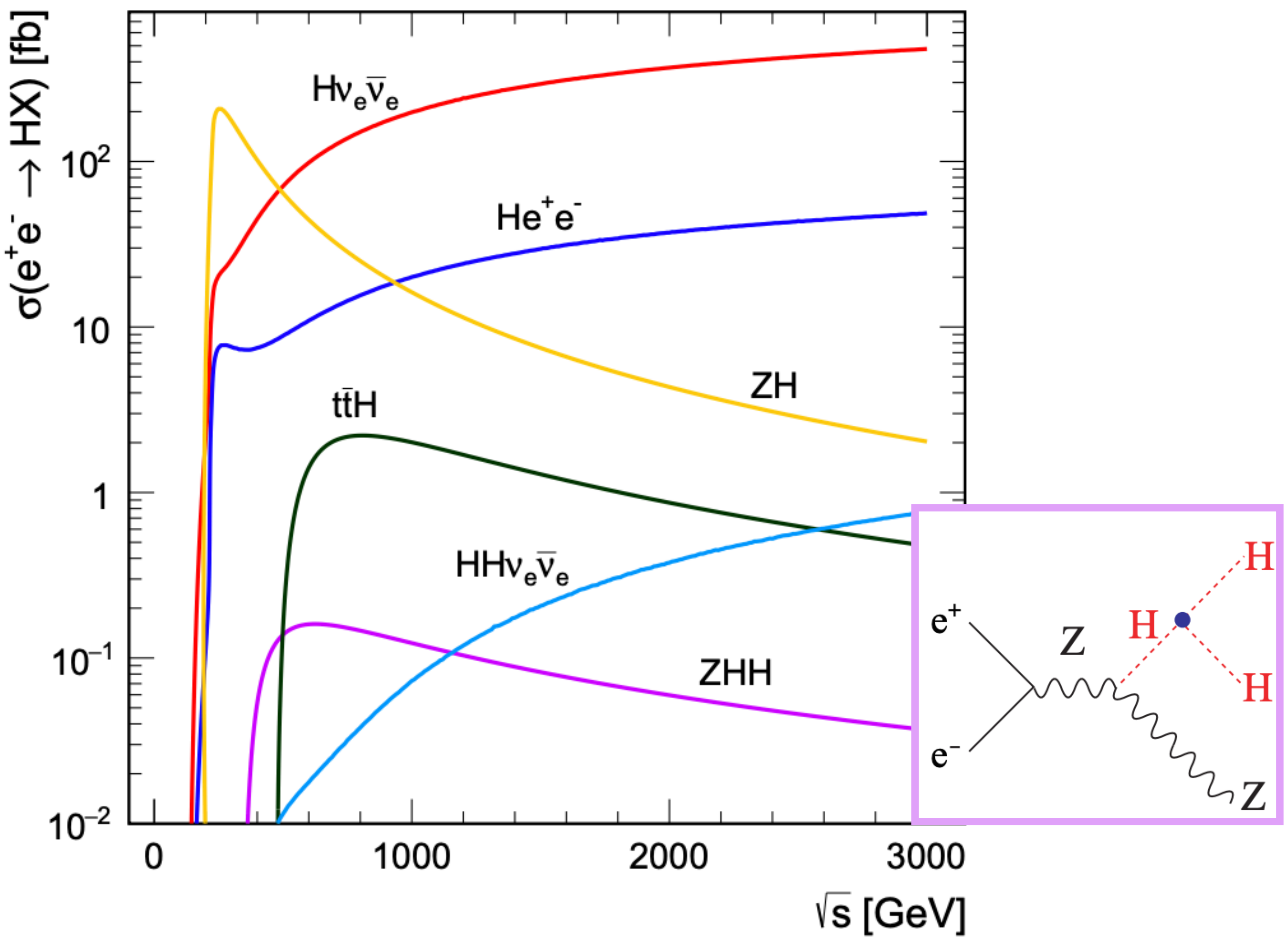

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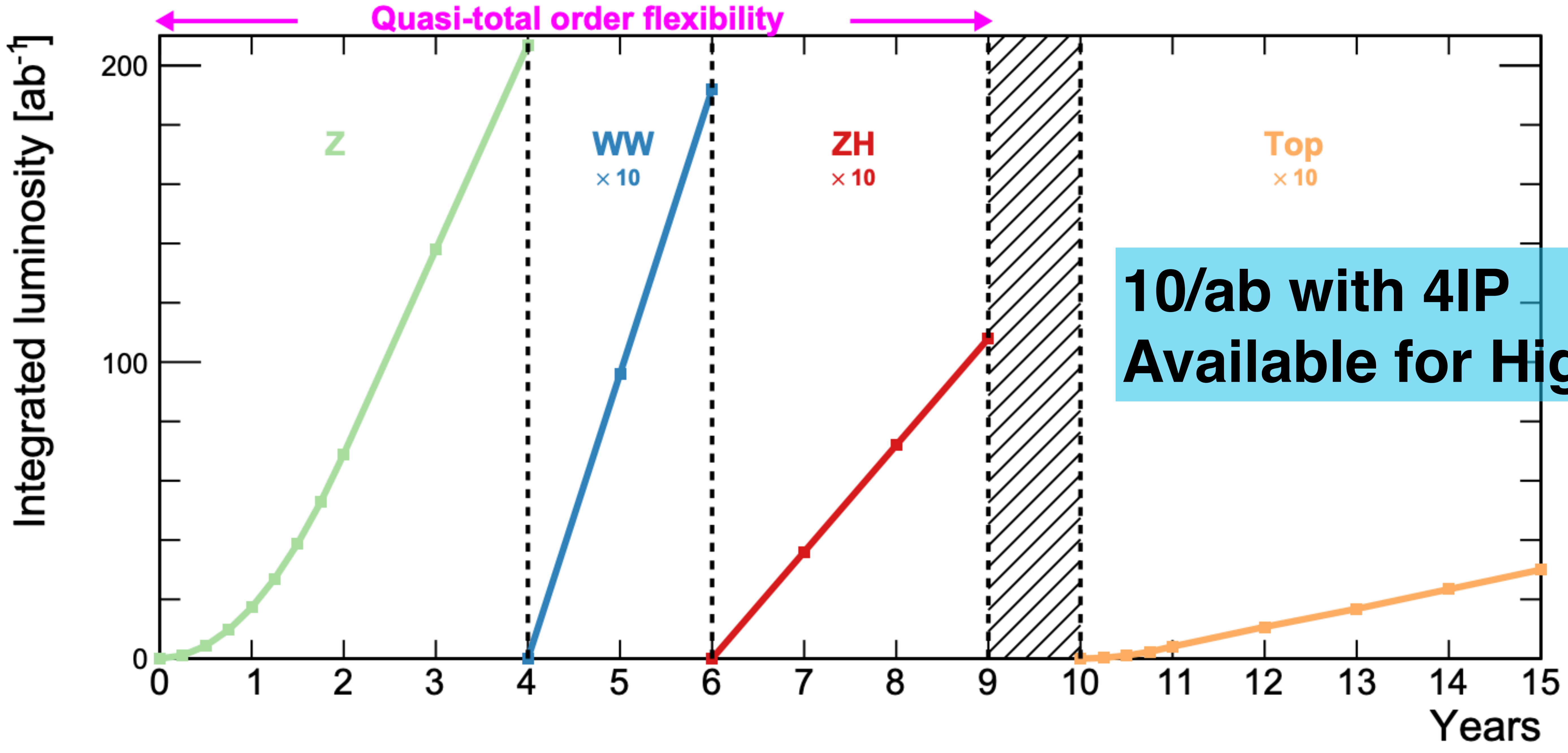
FCC Run plans

FCC Feasibility Report
ESG Physics Briefing book 2025

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^{8} WW	2.2×10^{6} ZH + 65k WW $\to$ H	2×10^{6} $t\bar{t}$ + 370k ZH + 92k WW $\to$ H	

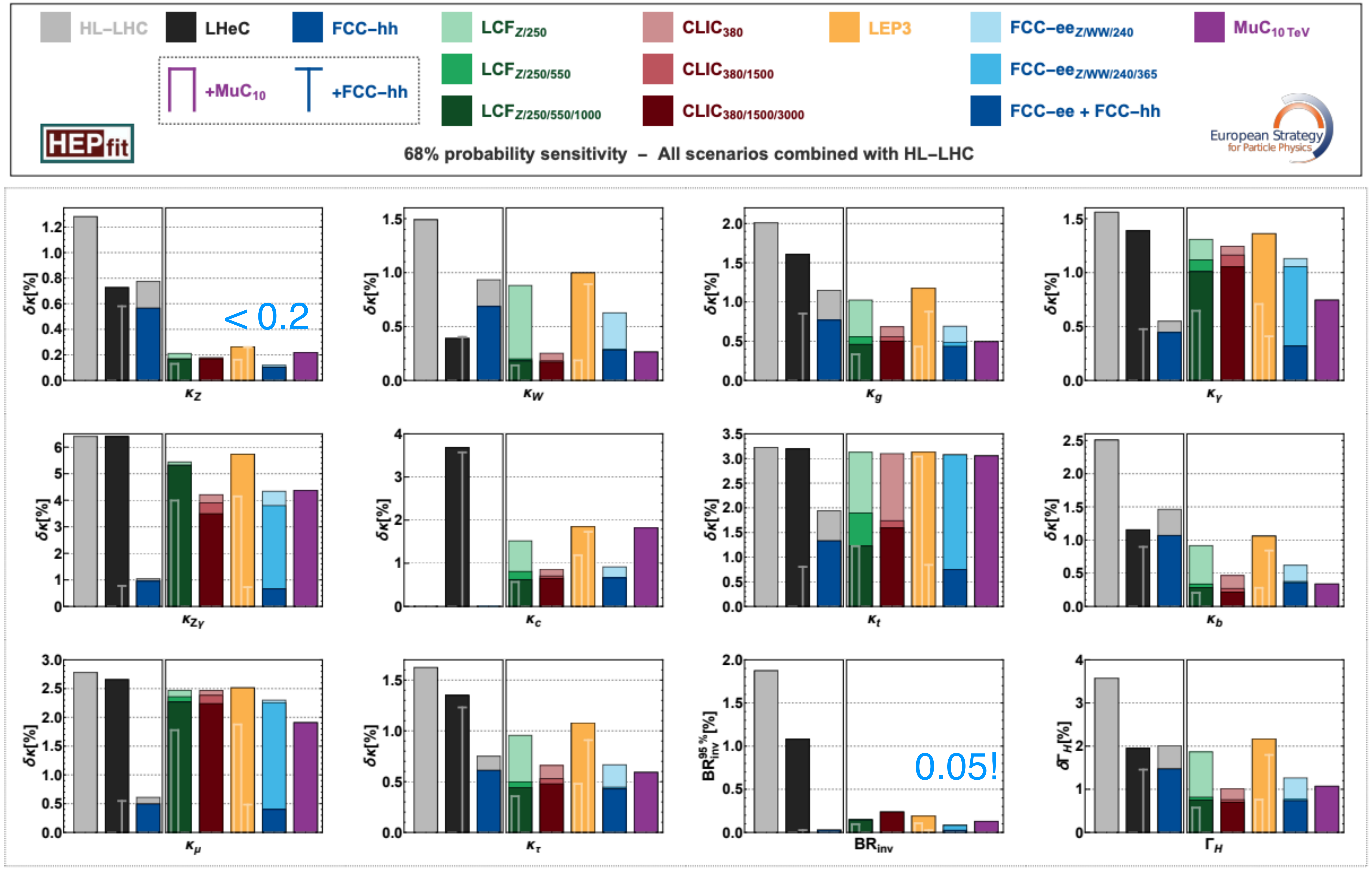


10/ab with 4IP
Available for Higgs physics

Higgs couplings at future machines

[ESG Physics Briefing book 2025]

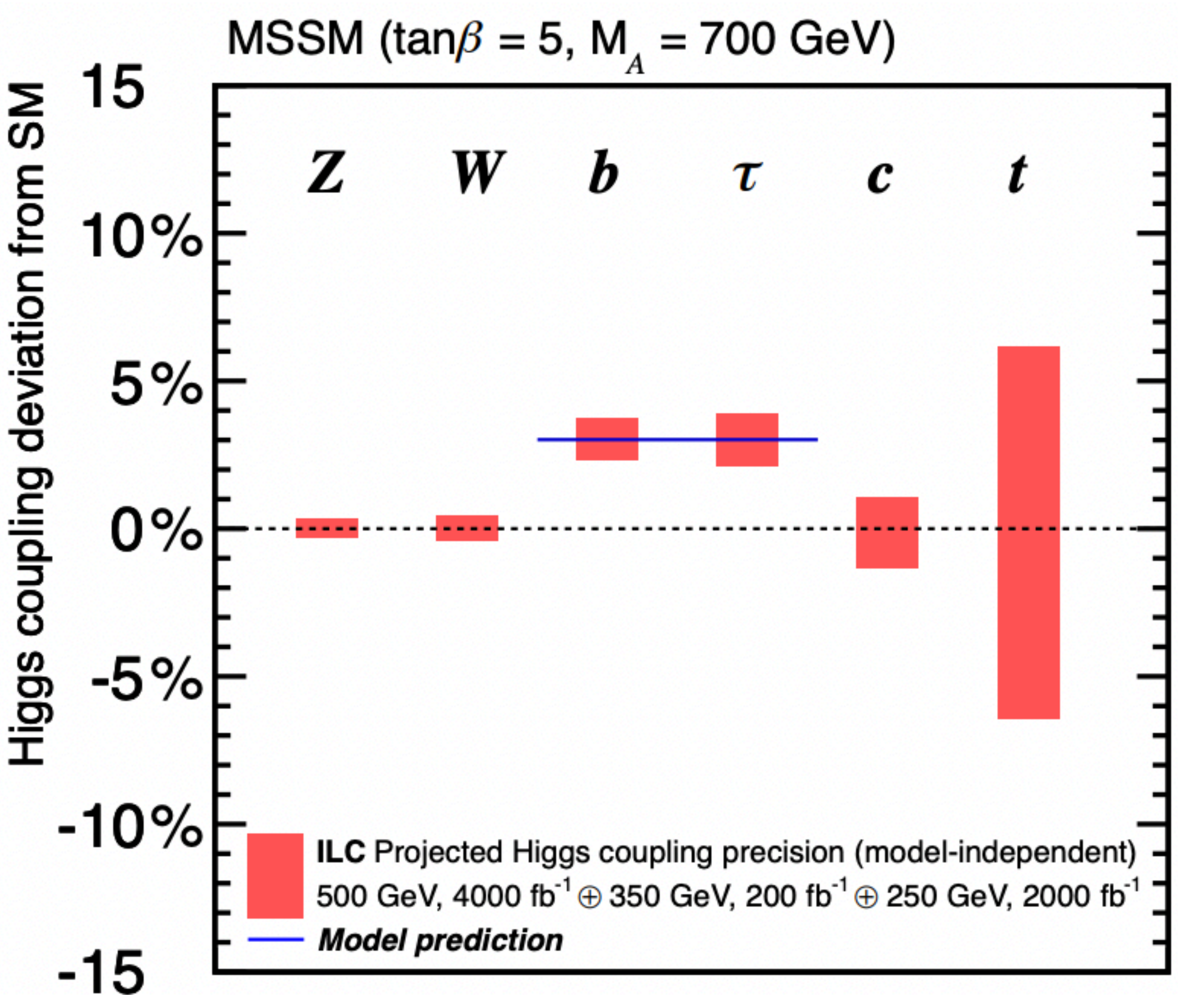
- The rare $Z\gamma/\mu$ couplings challenging to measure at all future machines
  - HL-LHC 3/ab data remains essential
- FCC-ee achieves the best precision across the accessible couplings
- HL-LHC + FCC-ee (running below HH threshold) achieves ~17-20% precision on λ_3 through EW corrections in single-H processes

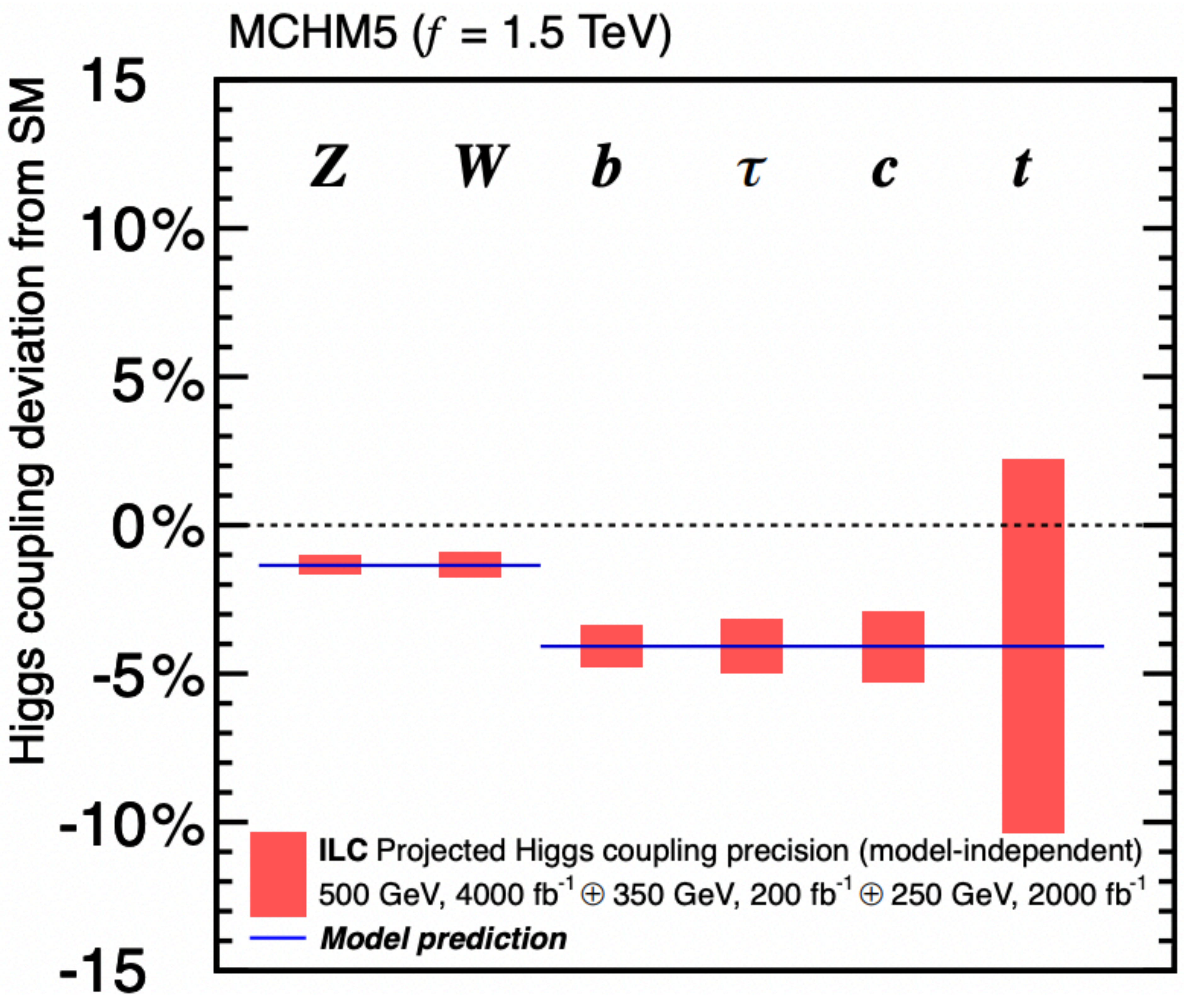


arXiv:2209.07510
arXiv:1506.05992

Precision and discovery potential

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





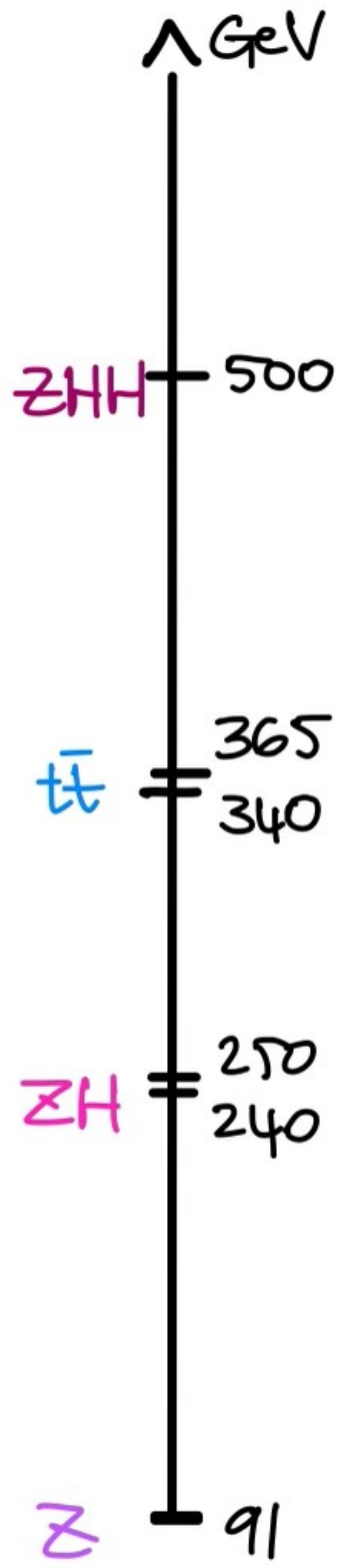
Precision is complementary to direct searches at LHC

Precision physics and its experimental challenges

(Higgs) Physics benchmarks
Z physics imposes additional constraints - *next talk*
(Beam structure and beam-induced backgrounds further limit design choices) - not today

Physics benchmarks for e+e-

Different energies → different physics goals → different detector requirements?



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 and stability to 10^{-6}
  - Absolute normalization of luminosity to 10^{-4}
  - Track angular resolution < 0.1 mrad

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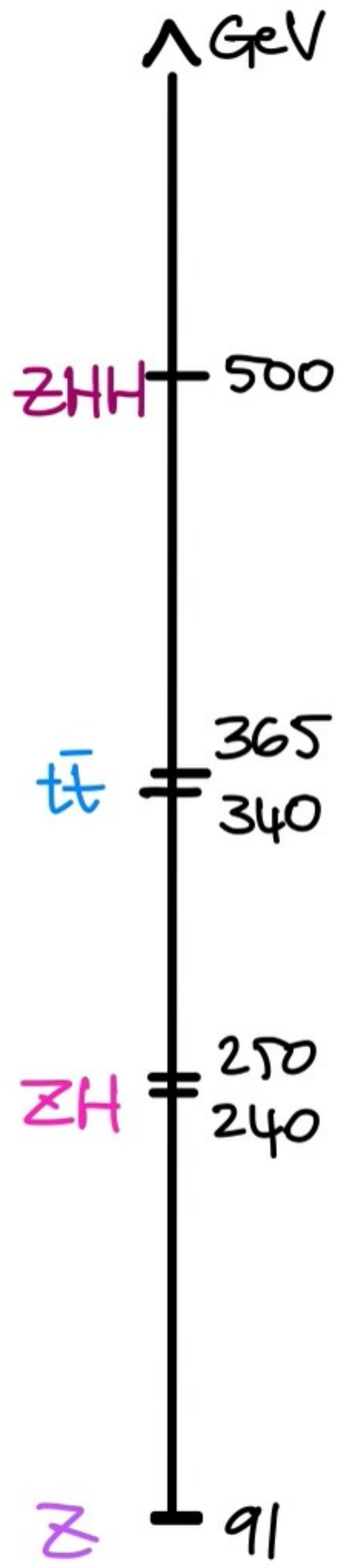

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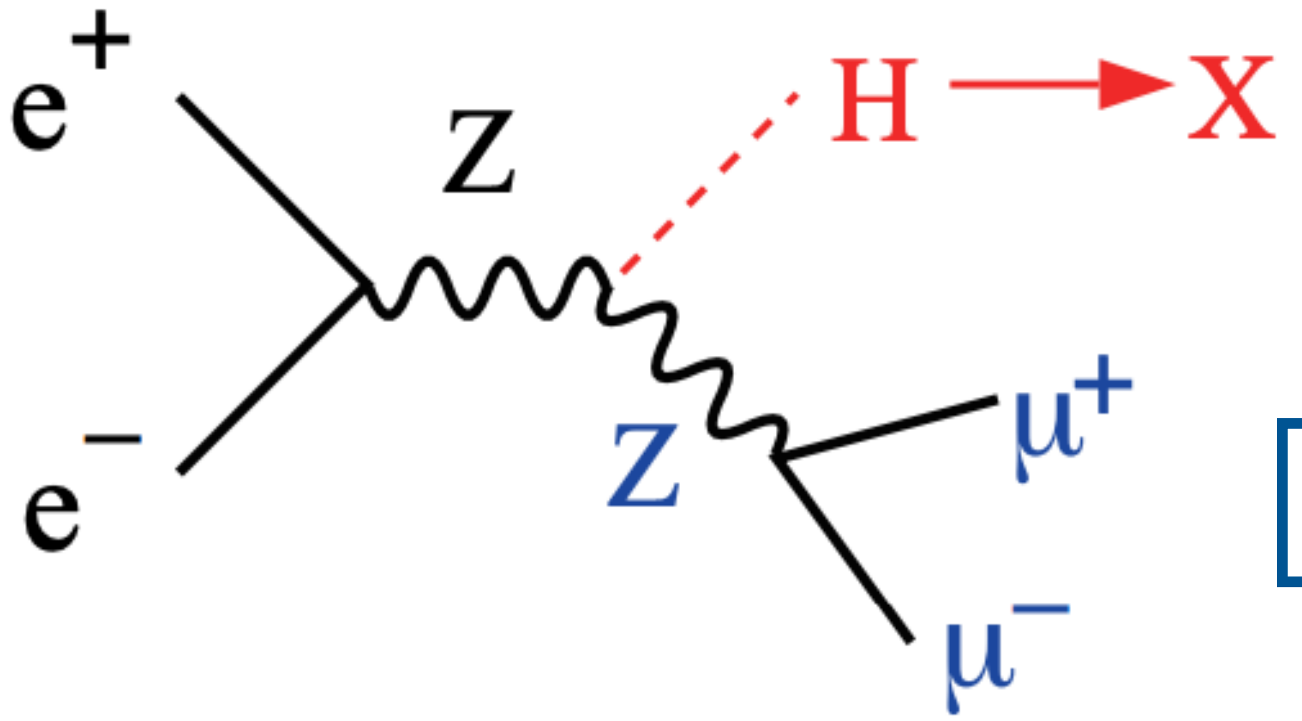
[arXiv:1604.07524](https://arxiv.org/abs/1604.07524)
[arXiv:2203.07622](https://arxiv.org/abs/2203.07622)

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

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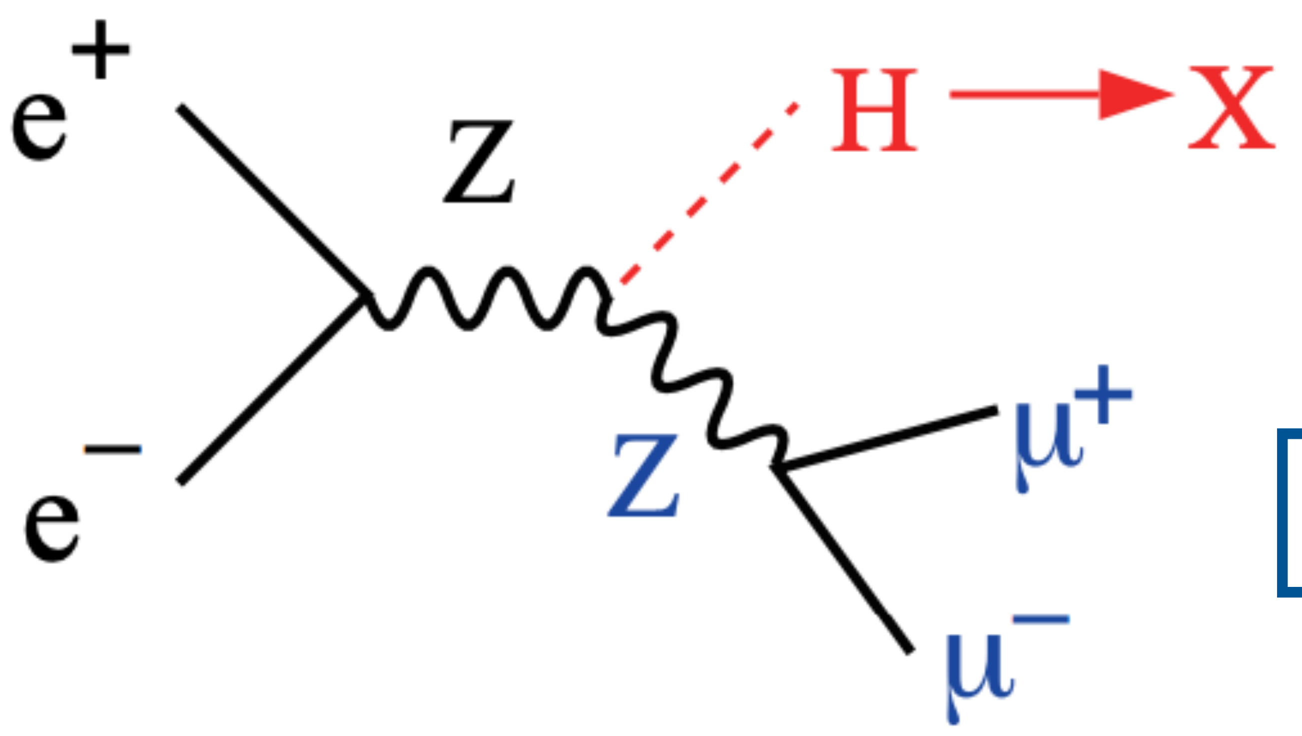

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with typical momentum of O(50) GeV, momentum resolution dominated by MS term
R&D Light weight ultra granular tracking

How (Higgs) physics drives detector requirements

arXiv:2503.19983
FCC Feasibility Report

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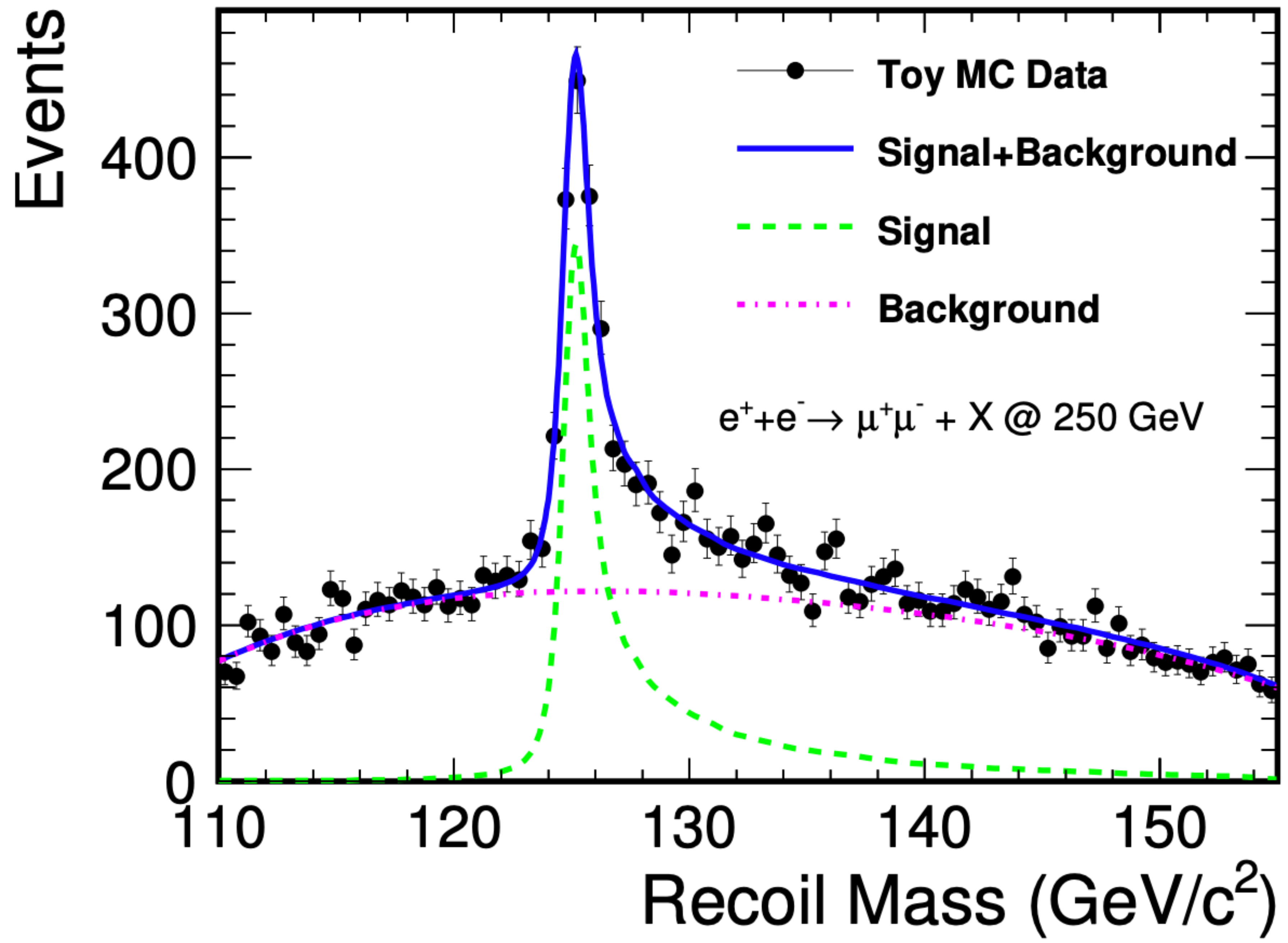
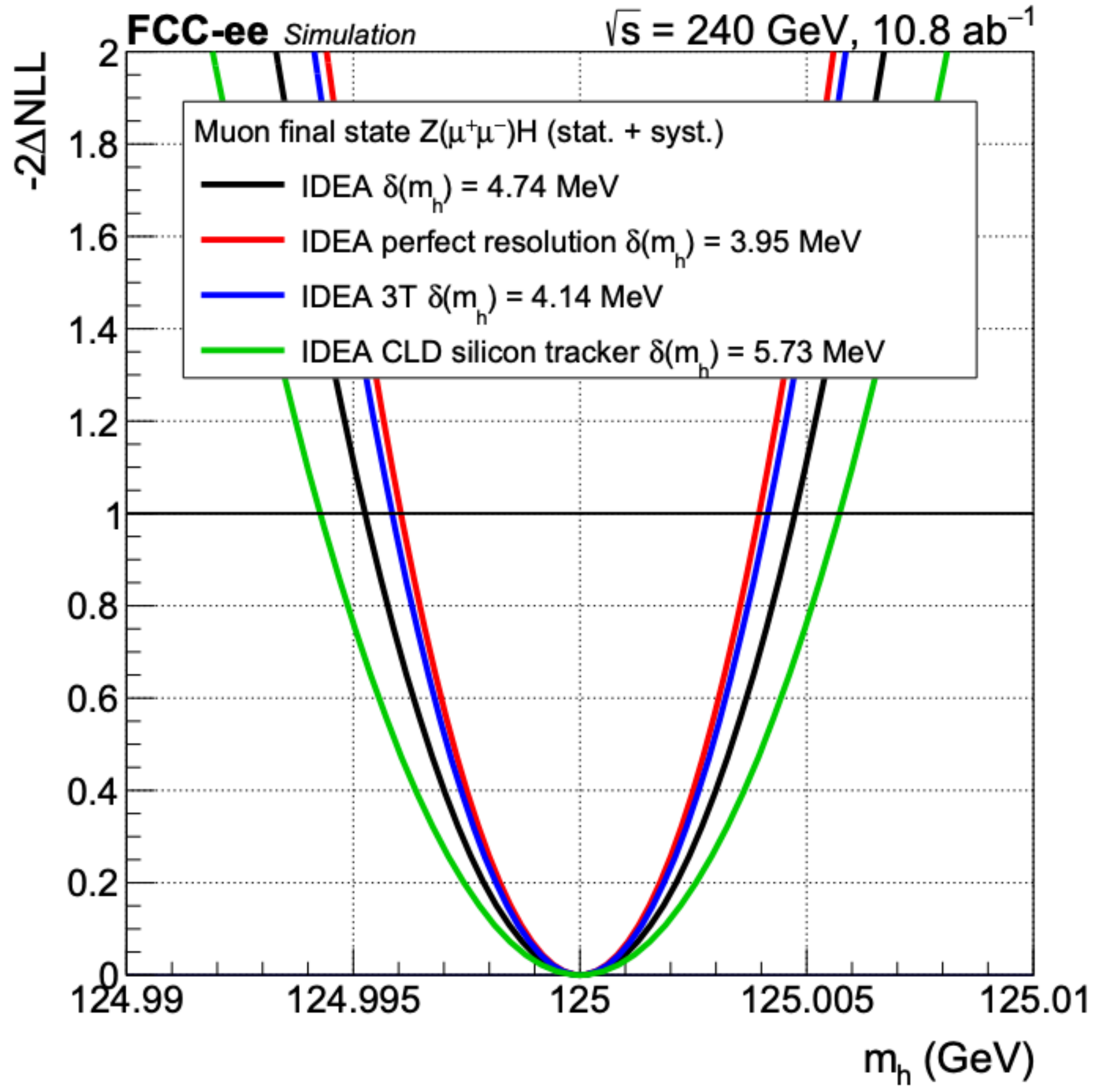


ZH process: Higgs recoil reconstructed from Z decays

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

peak ~ Higgs mass ~ 4-12 MeV



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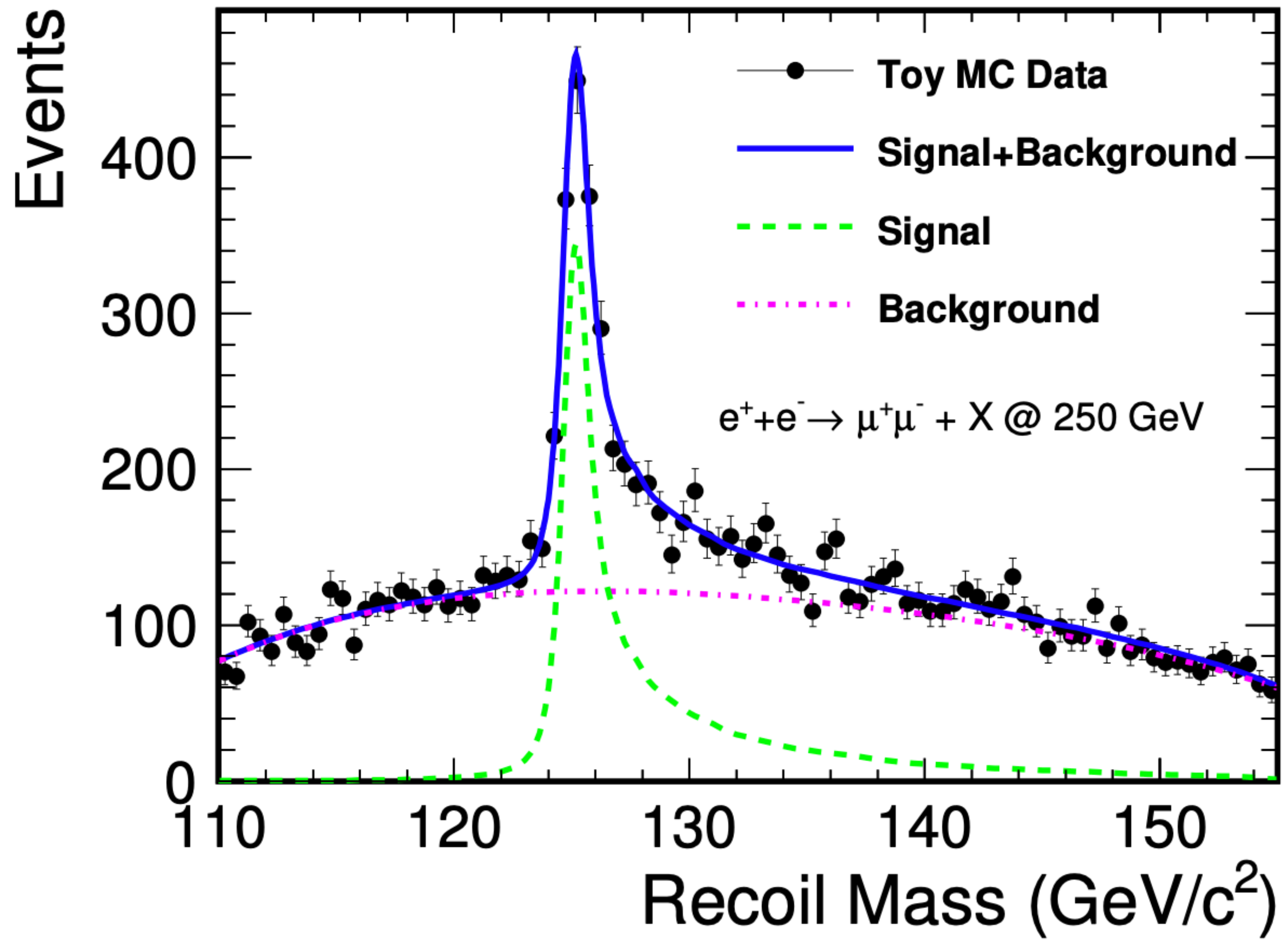

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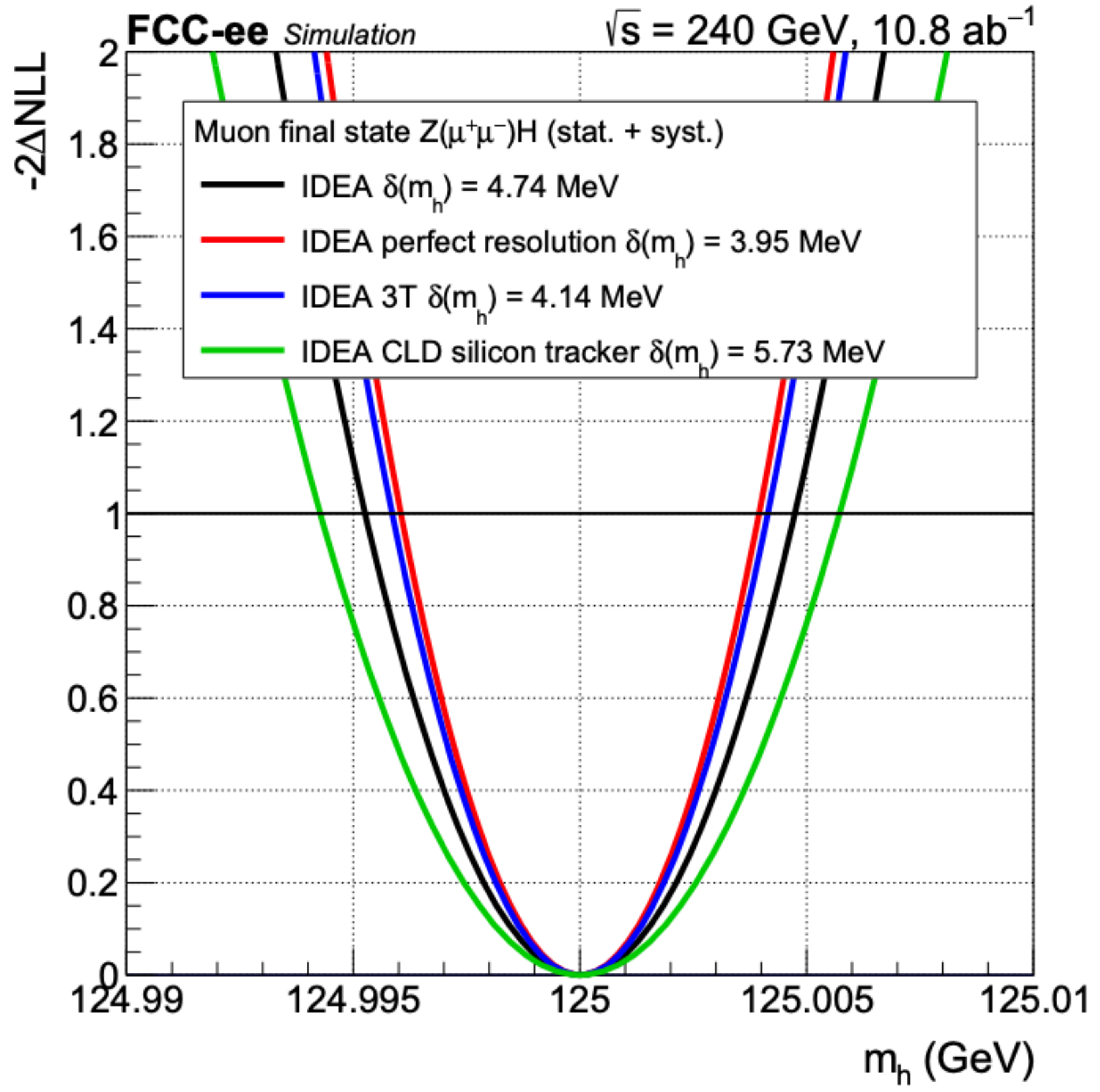
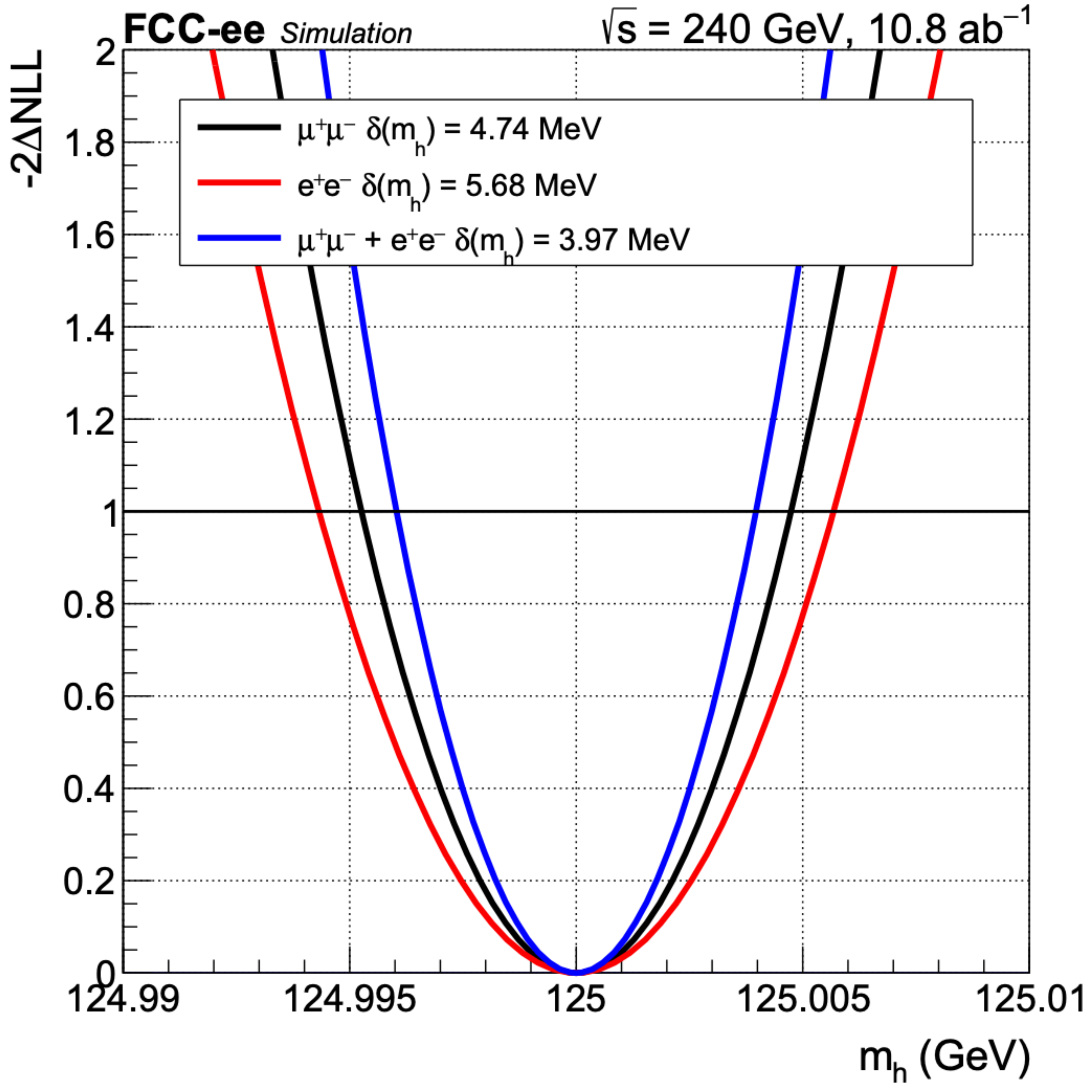


ZH cross section can be measured with O(1%) precision and in a model independent way

Impact on calorimeter performance

FCC Feasibility Report



O(50) GeV electrons (2T field) arrive **2–3 cm** from the electron at the calorimeter entrance
→ transverse granularity ≤ 1×1 cm² and longitudinal segmentation to resolve overlapping showers

Efficient photon bremstralung recovery for Z(ee)H
→ assuming ECAL high granularity and **3%/√E EM resolution**
→ **improves m_H by 22% compared to *μ*-channel alone**

Also: Distinguish W, Z, H → hadronic jet energy resolution
σ_E/E ~ 3 → 5 % over wide energy range

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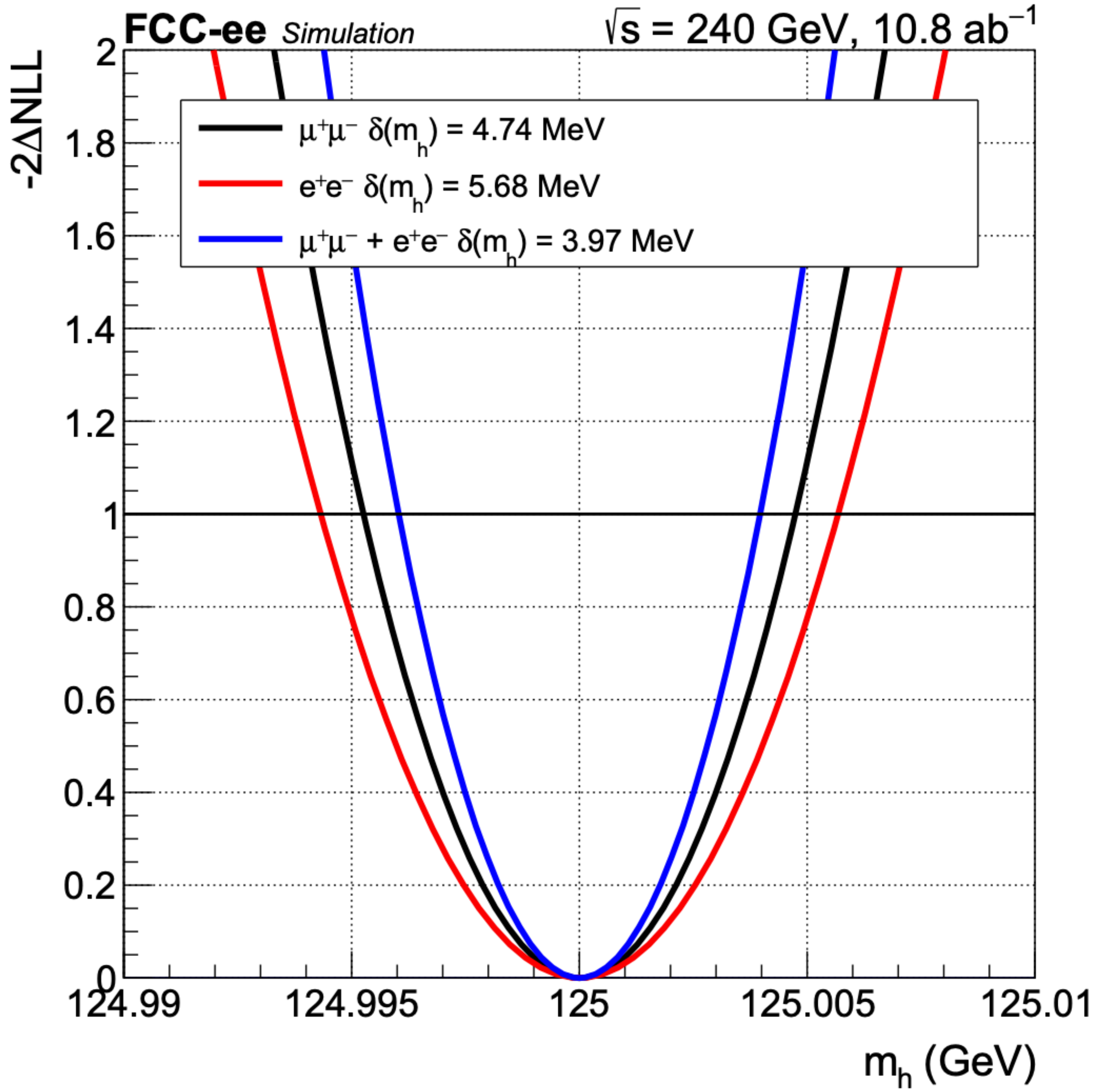

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More studies needed to assess needs on granularity / segmentation

Flavor tagging and vertex detector

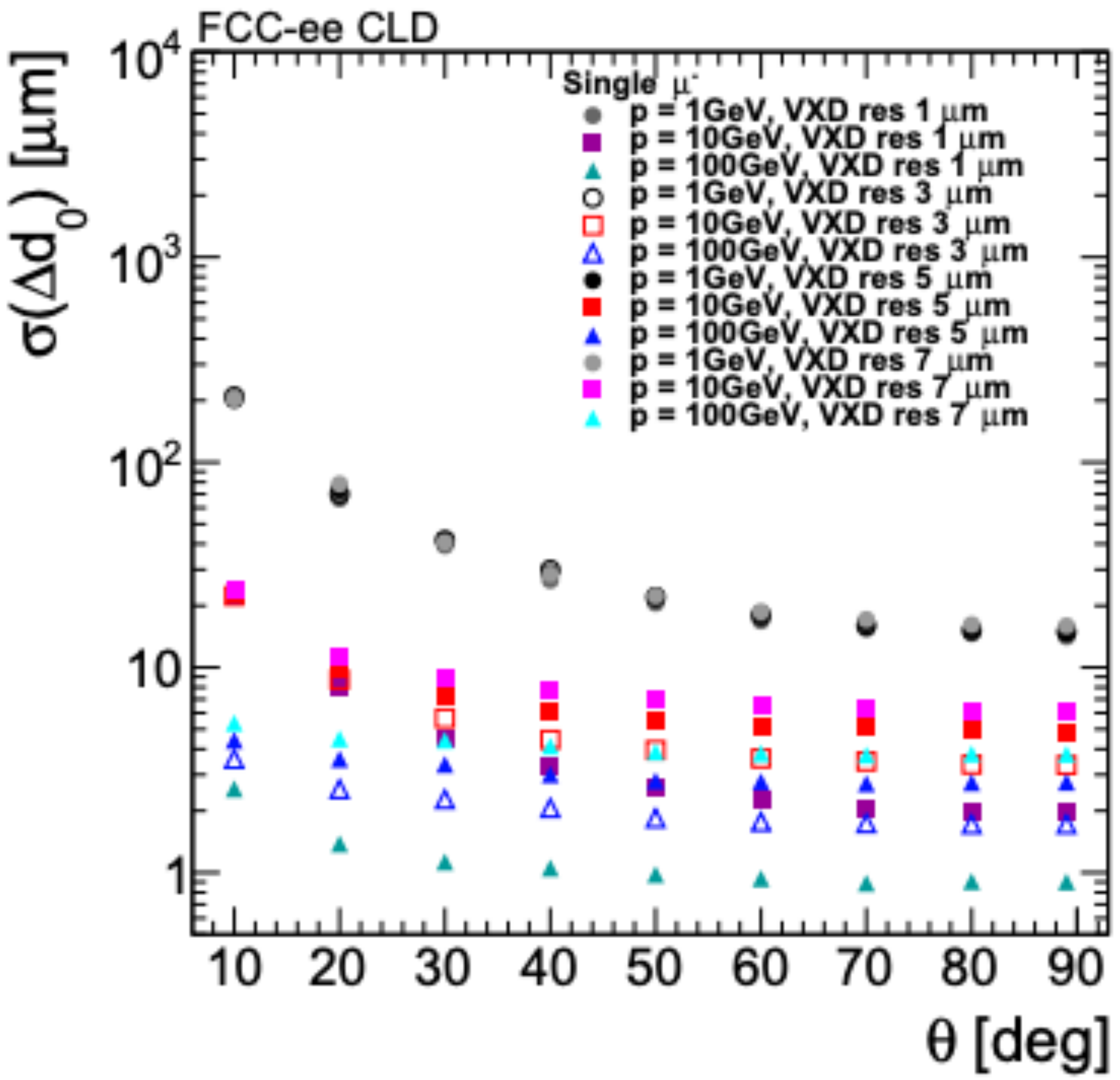
Higgs → bb/cc decays challenges vertex detector

Flavor tagging at unprecedented level

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

<0.3% X0 per layer (ideally 0.1% X_0)

$$\sigma_{d_0} = a \oplus \frac{b}{p_T sin^{1/2}\theta}$$



Constant term describing **resolution** ~ 3-5μm
Multiple scattering term decreasing with p_T ~ 15μm* GeV

Flavor tagging and vertex detector

G. Sadowski LCWS 2024
arXiv:2003.01116

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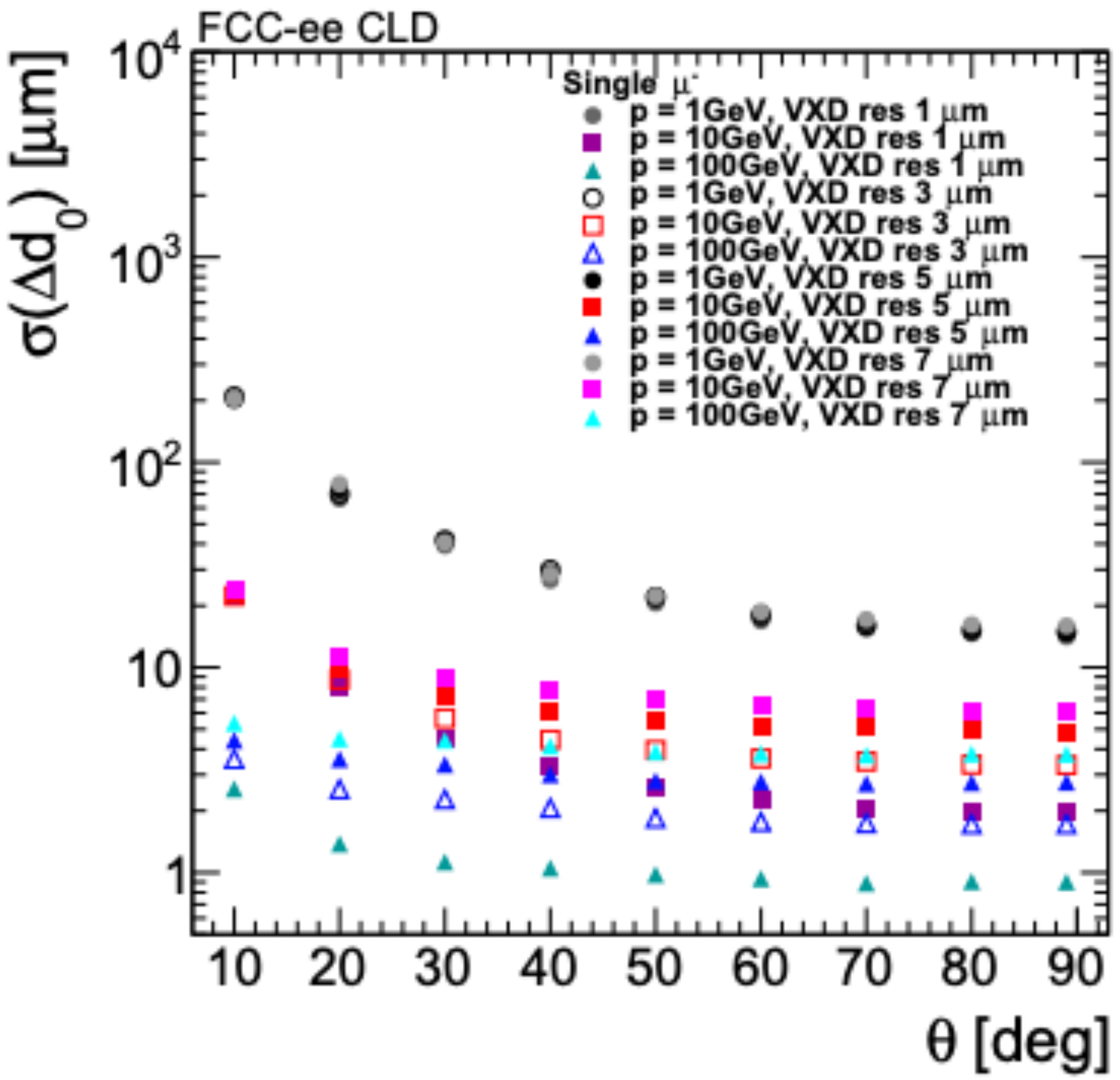

Need new generation of ultra low mass vertex detectors with dedicated sensor designs

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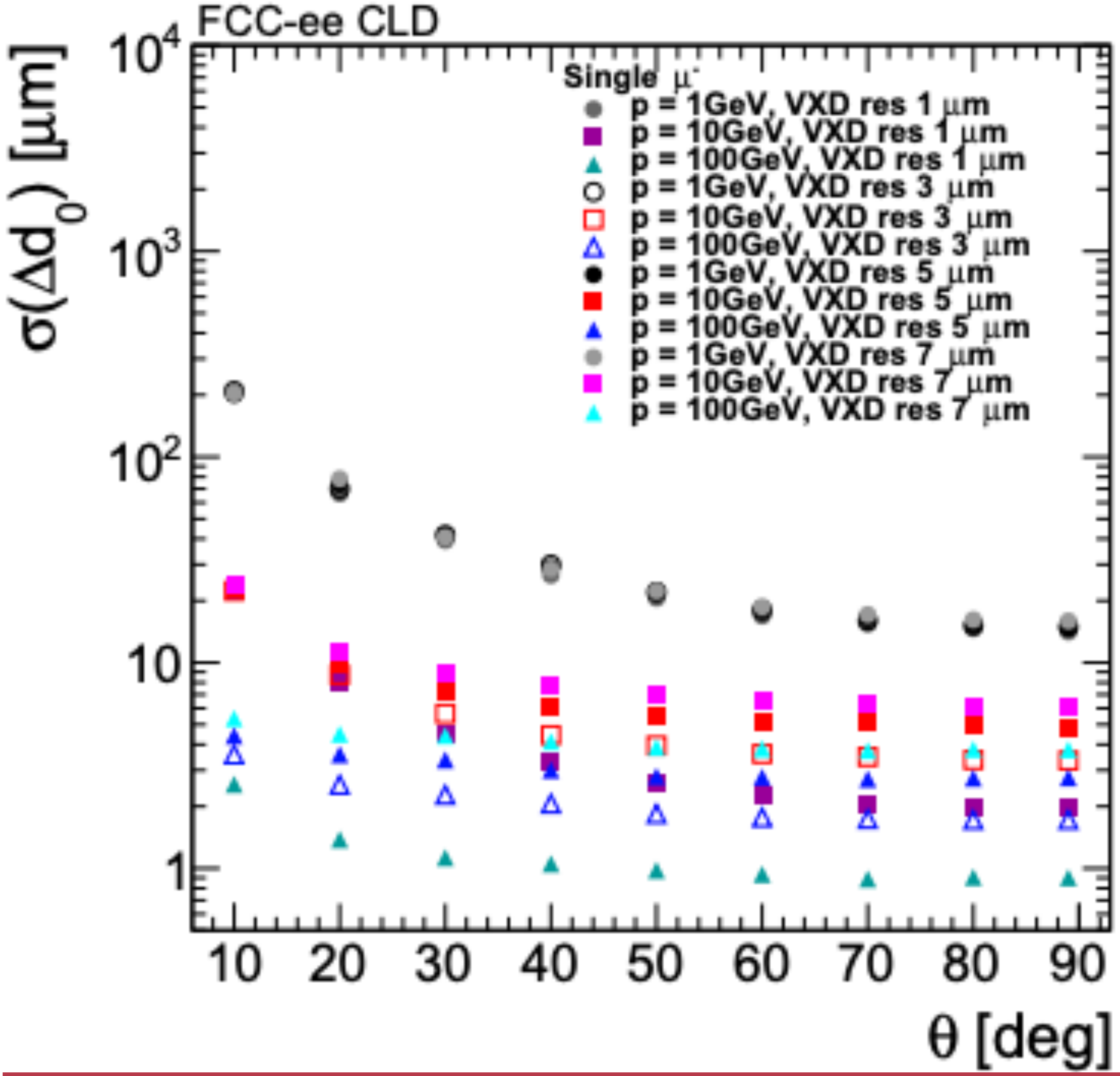

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ALICE ITS3 is the state-of-the art, achieving all the requirements at once remains a challenging - opportunities for MAPS involvments & services optimization

Higgs to invisible & jj

[FCC Feasibility Report](#)

Strong constraints on hadronic calorimeter performance

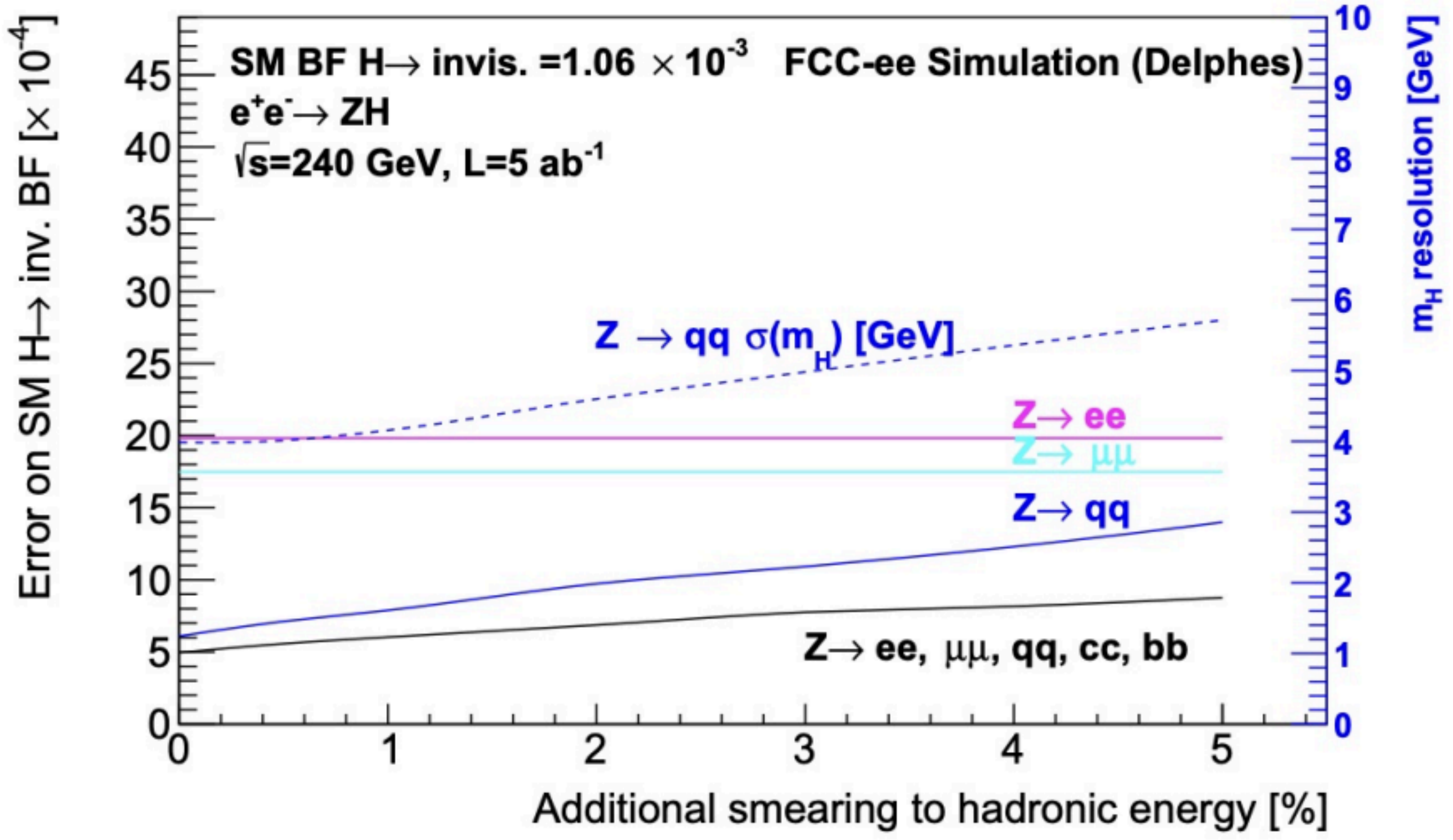
SM: BR(H→νννν) = 1.06×10^{-3} - beyond HL-LHC reach

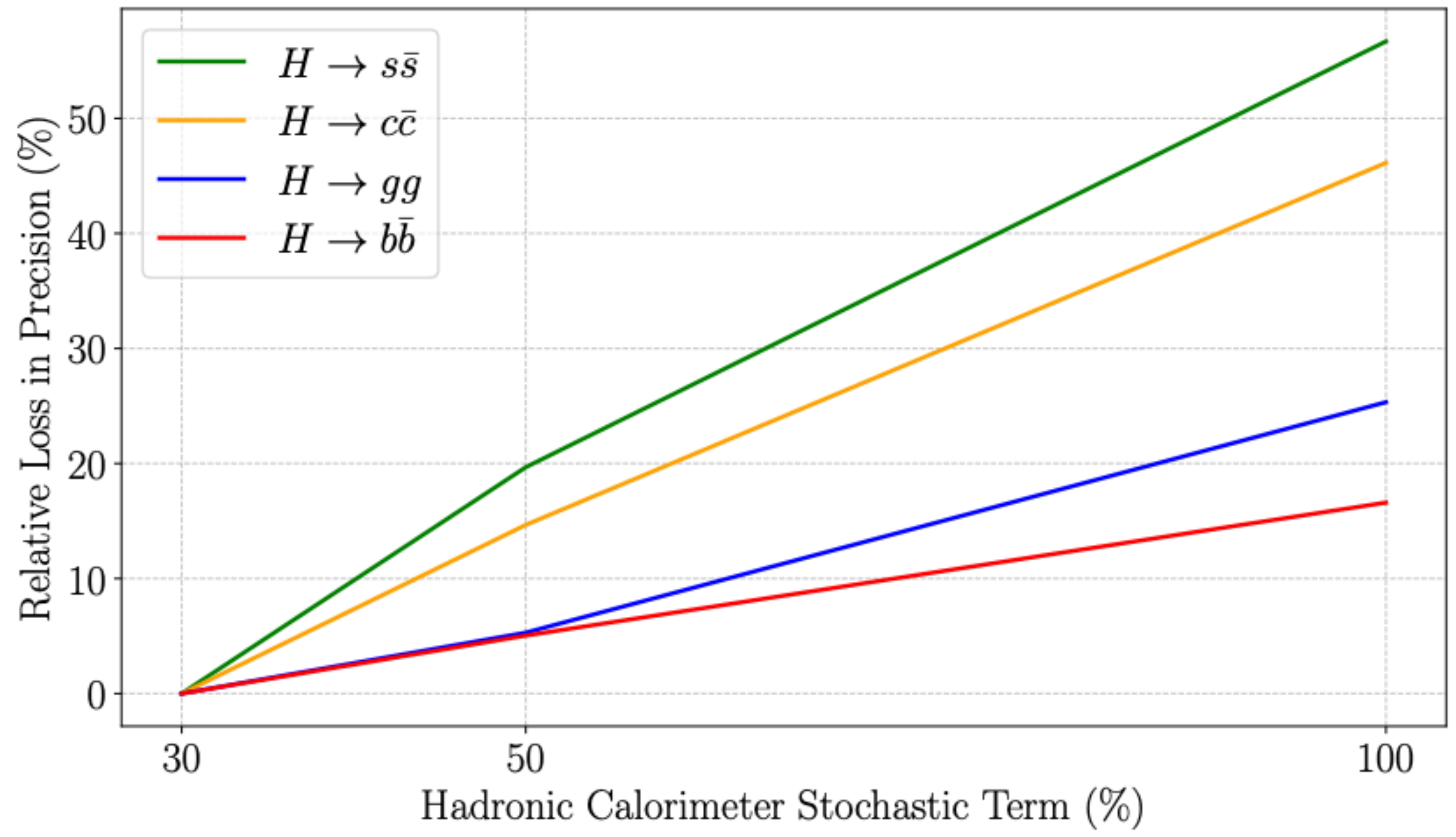
Z(ee, μμ, bb, cc, qq); M_{vis} as discriminant

- **Results (10.8 ab^{-1} @240 + 3 ab^{-1} @365 GeV) → SM BR measured to 25% precision**
- 95% CL BR > 0.05% or 5 σ if BR> 0.13%
- Z → qq best sensitivity; 240 GeV run dominate
- 5% extra hadronic smearing → +130% uncertainty (Z→qq)

H→cc/gg/ss

- Baseline performance 30% (IDEA dual-readout) vs 50% (ATLAS-type) vs 100% (CMS-type)
- Assuming an ideal PFA reconstruction setup with highly-efficient tracking and neutral hadron identification capabilities, t**he neutral hadron resolution drives the sensitivity to the strange Yukawa coupling**
  - Degrading by 50% (100%) HCAL stochastic term, **H→ss gets 20% (55%) worse**





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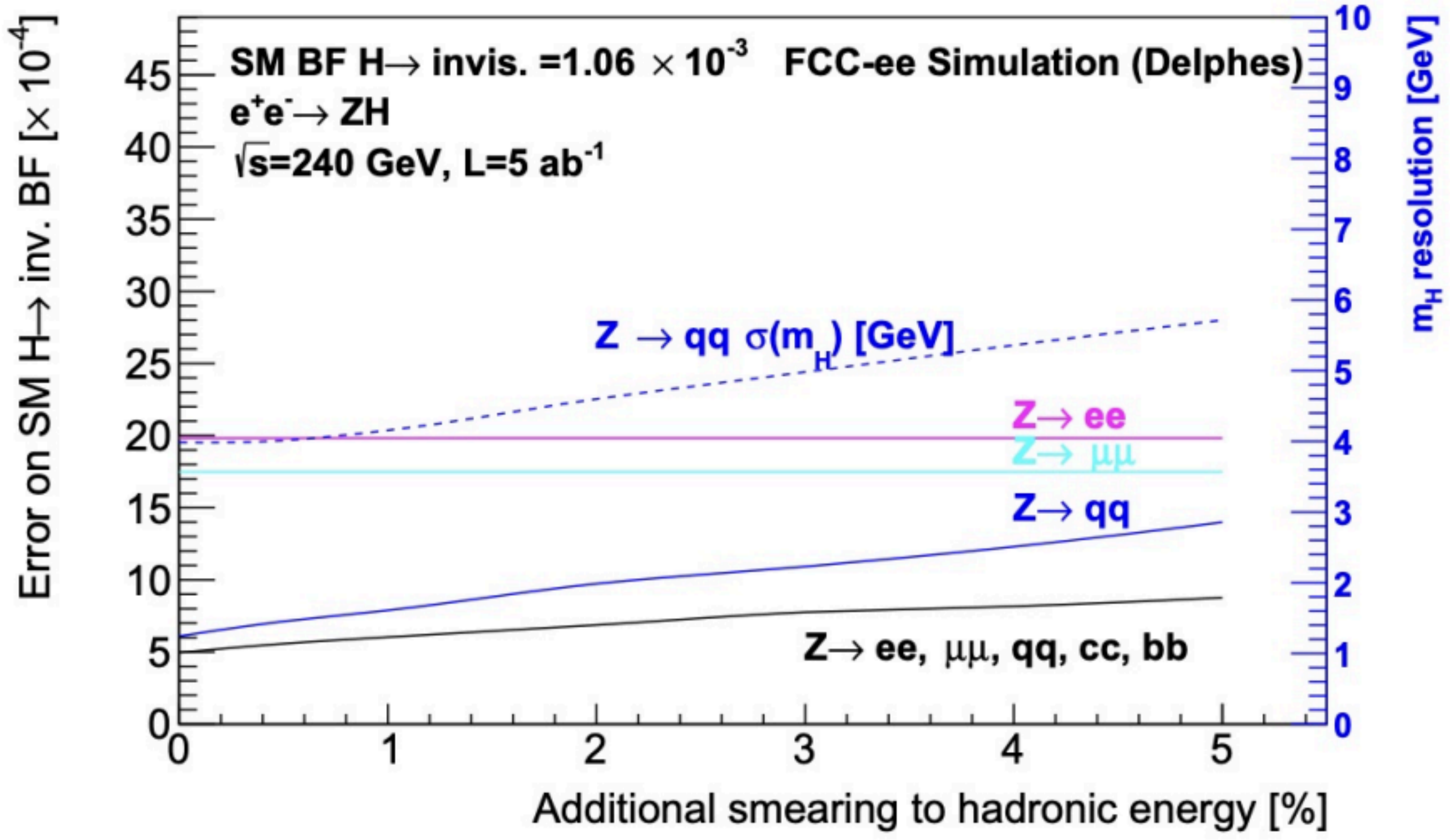
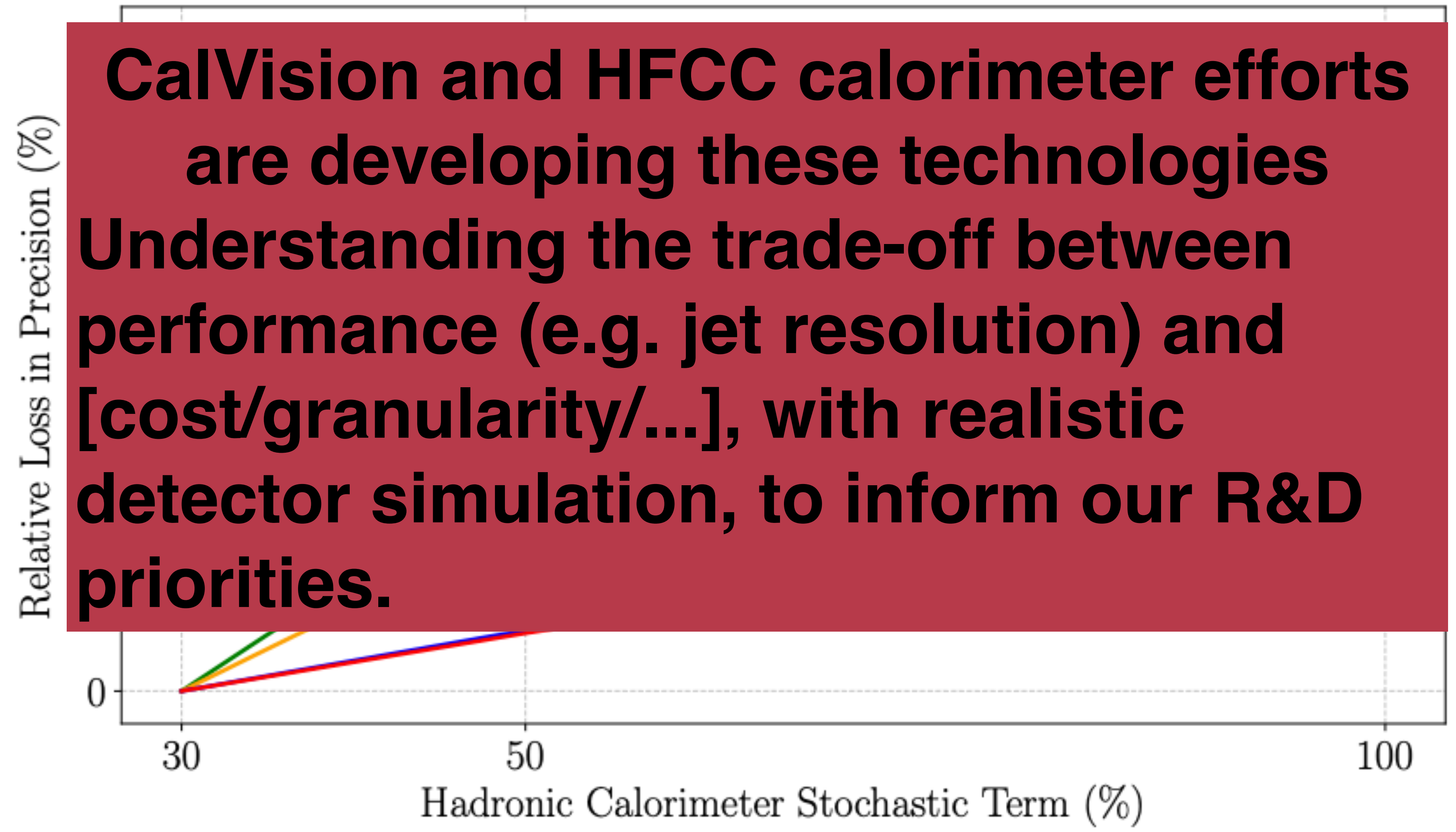


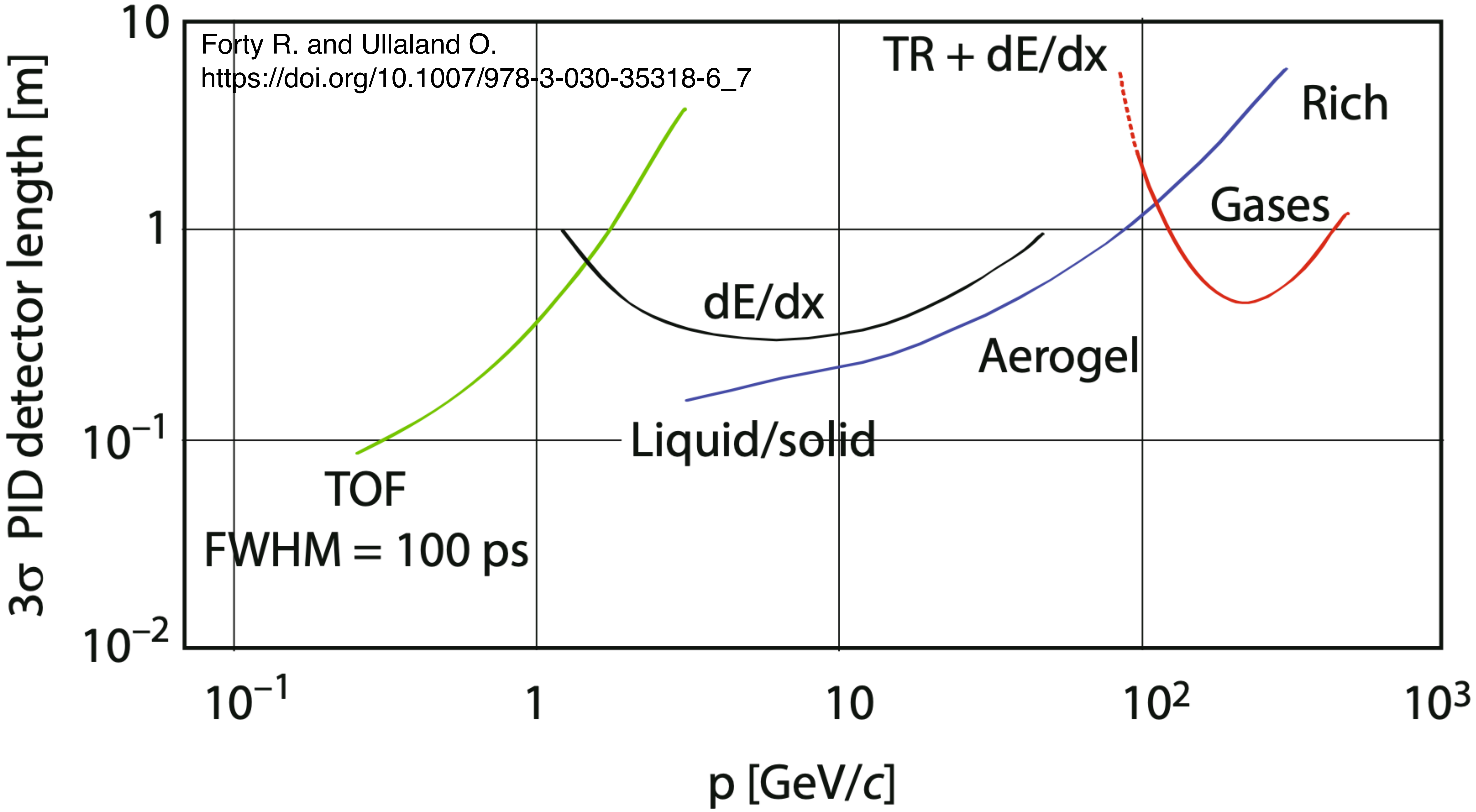


CalVision and HFCC calorimeter efforts are developing these technologies
Understanding the trade-off between performance (e.g. jet resolution) and [cost/granularity/...], with realistic detector simulation, to inform our R&D priorities.

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

Particle ID

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



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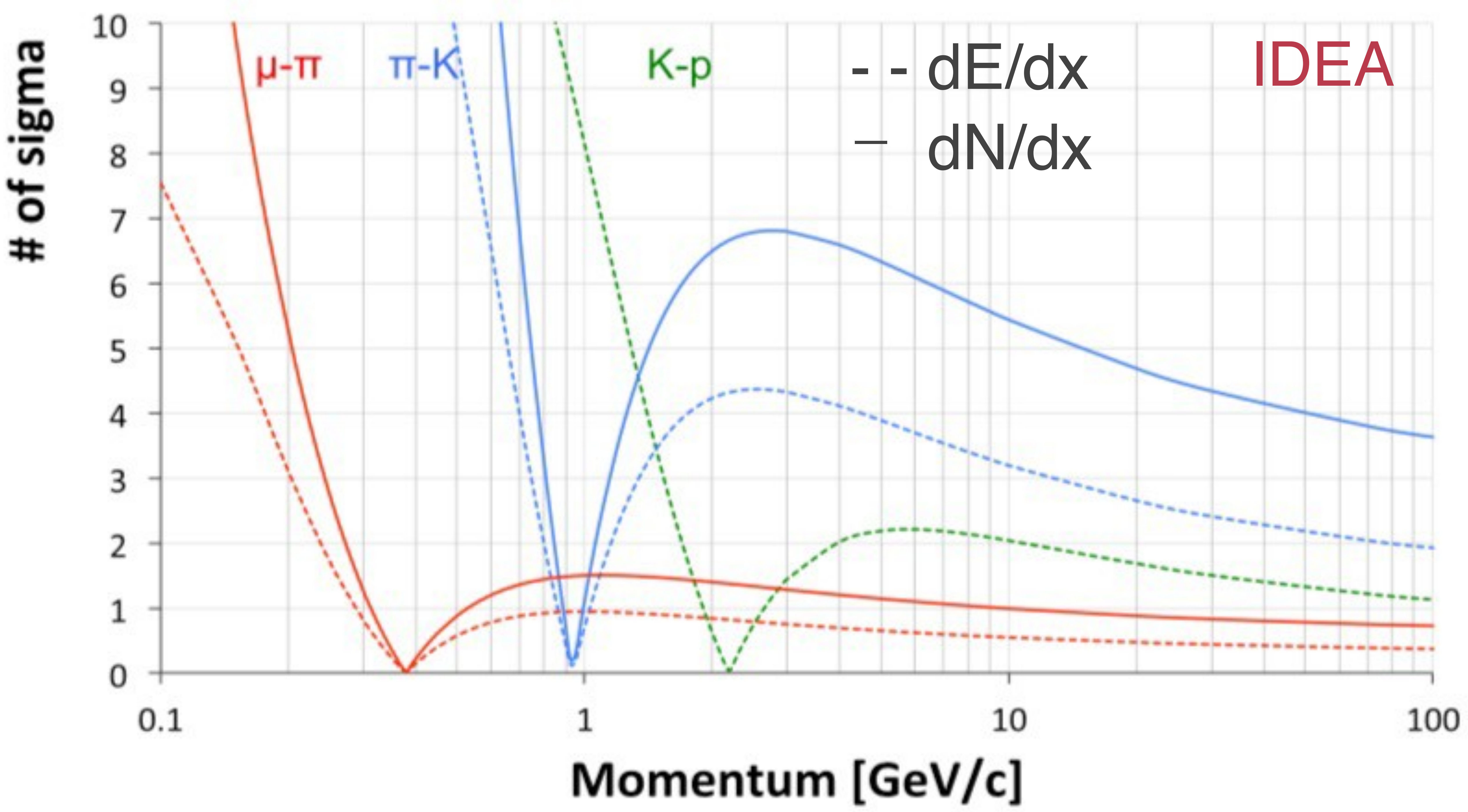
- Timing (e.g. ECAL, HCAL or timing layer) for time-of-flight for momentum < 5 GeV
- dE/dx from silicon (< 5 GeV) and large gaseous tracking detectors (< 30 GeV)
  - PID for momentum larger than few GeVs via ionisation loss measurement (dE/dx or dN/dx)
- Use H → ss to inform detector design, while monitoring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



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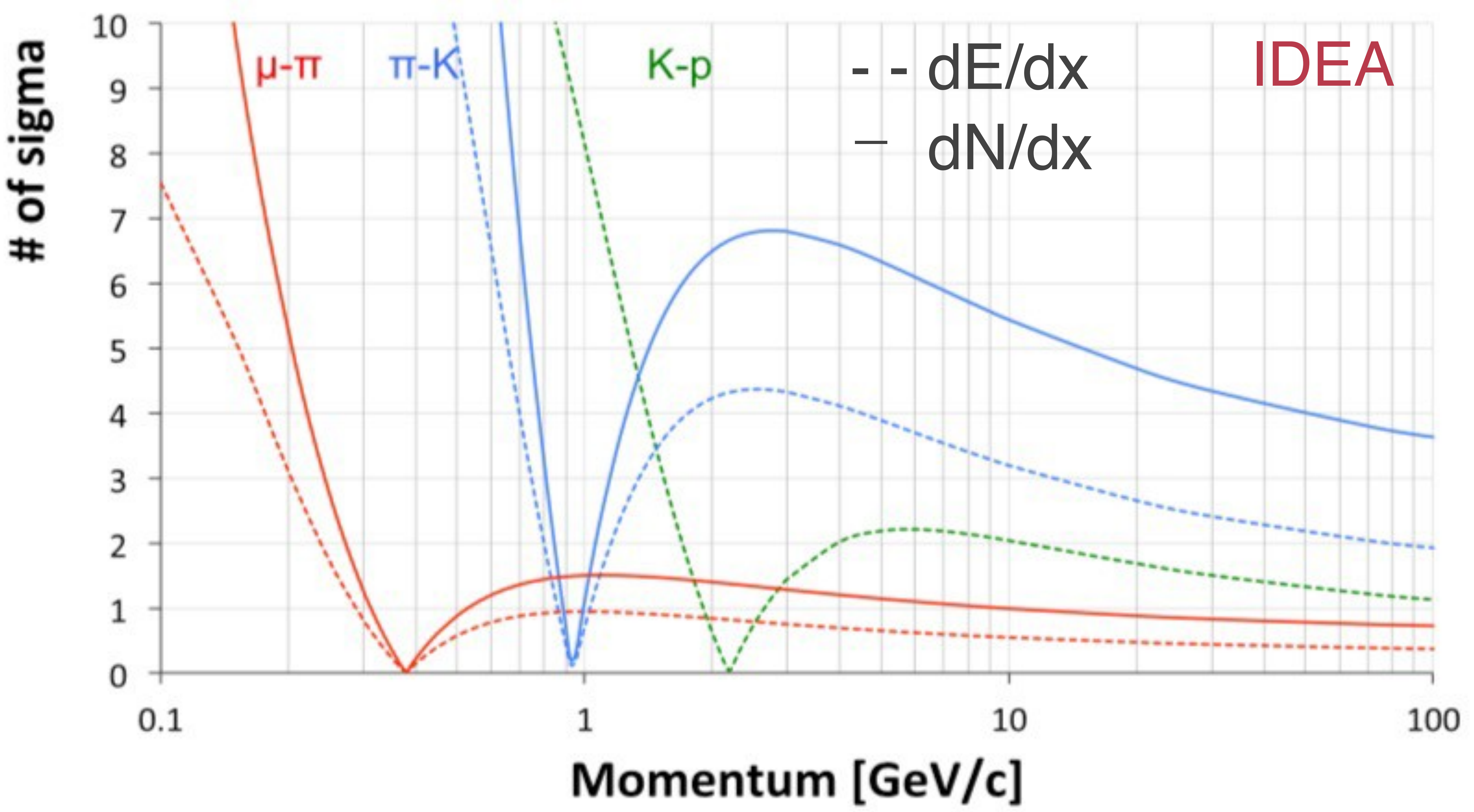


Priority: understand how timing / RICH performance trades off against overall detector performance

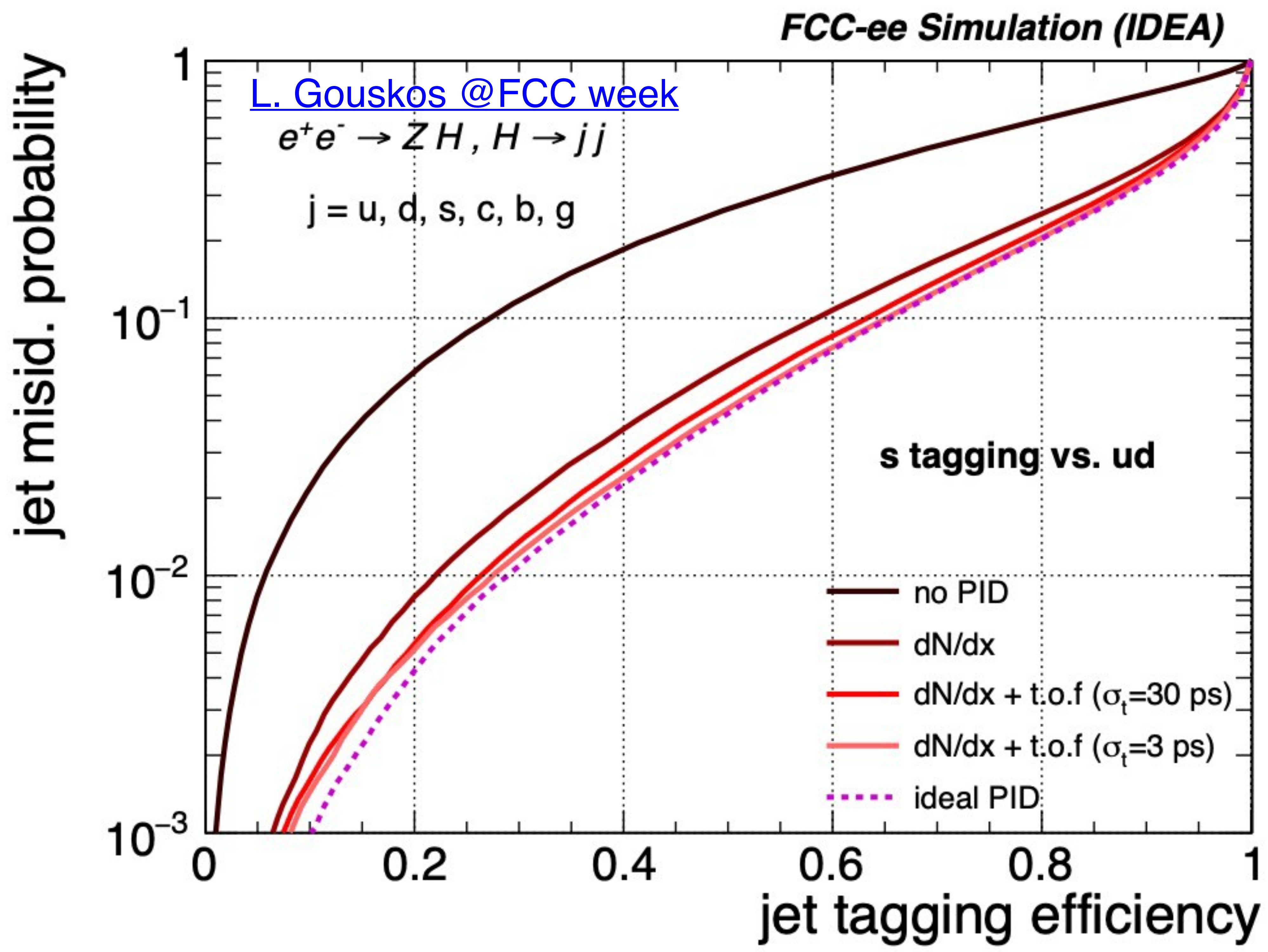
Strange tagging

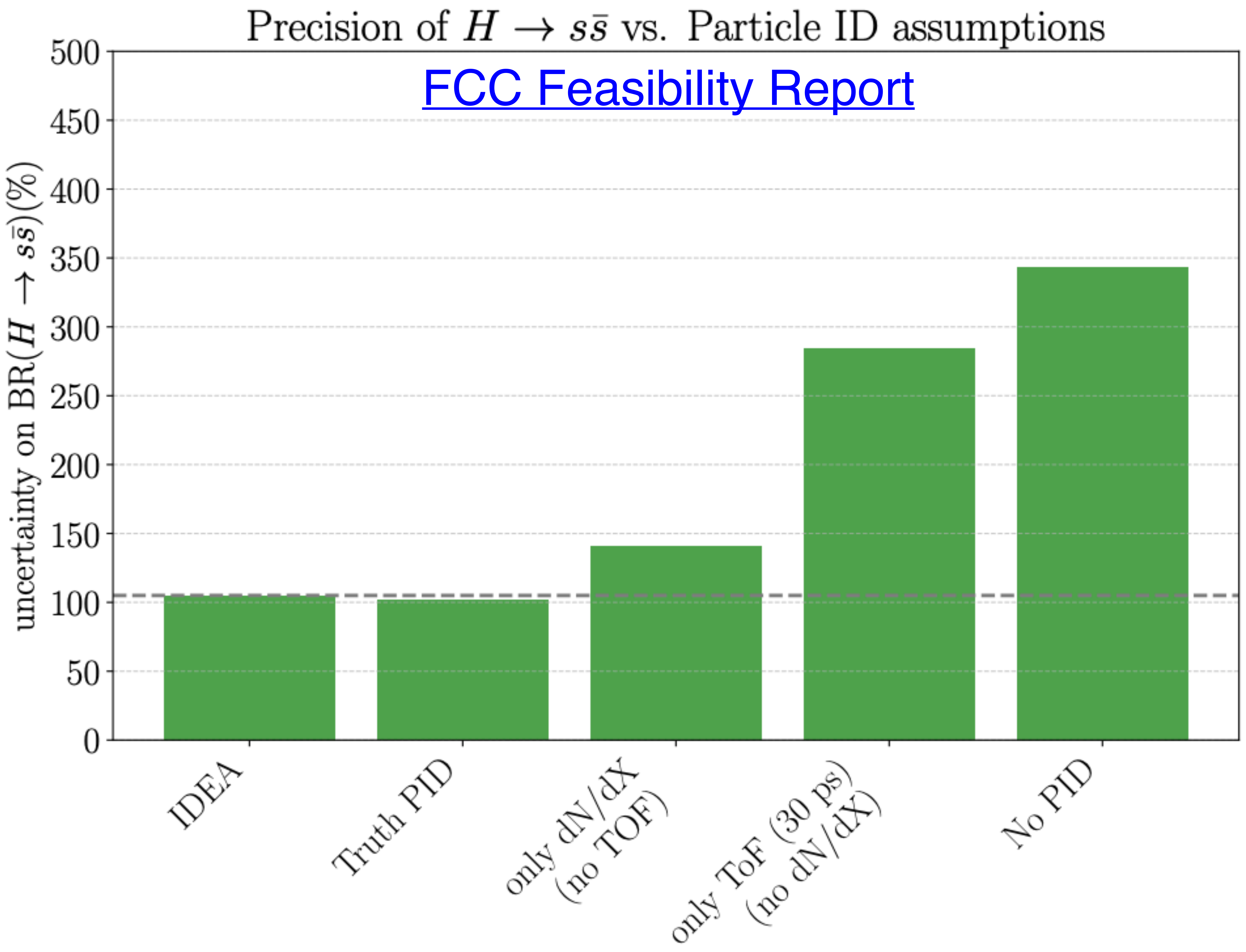
A key lesson from the LHC is that ML combination of detector inputs maximizes performance

State of the art tagger : ParticleNet Tagger, O(1000) inputs/jet = [O(50) properties/particle] x [~50-100 particles/jet] and ~2M jets per flavor.

Evaluating impact of different PID detector configurations: PID: cluster-counting (dN/dx) + 30ps ToF system

Findings: limited impact of TOF mass measurement on strange tagging





Current benchmarks and next steps

	Aggressive	Conservative	Comments
Vertex	$X/X_0 < 1\%$	–	R_c, flavor tagging
Tracking	$\sigma_p/p < 0.1\%$ for $\mathcal{O}(50\,\mathrm{GeV})$ tracks	$\sigma_p/p < 0.2\%$	$\delta M_H = 4$ MeV, $\delta\Gamma_Z < 10$ keV
ECAL	$\sigma_E/E = 3\%/\sqrt{E}$	$10\%/\sqrt{E}$	$Z \to \nu_e\bar{\nu}_e$, $H \to \gamma\gamma$
HCAL	$\sigma_E/E = 30\%/\sqrt{E}$	$50\%/\sqrt{E}$	$H \to s\bar{s}$, $c\bar{c}$, gg, inv.
Particle ID	3σ K/π, $p < 40$ GeV	3σ K/π, $p < 30$ GeV	$H \to s\bar{s}$, $b \to s\nu\bar{\nu}$

FCC Feasibility Report

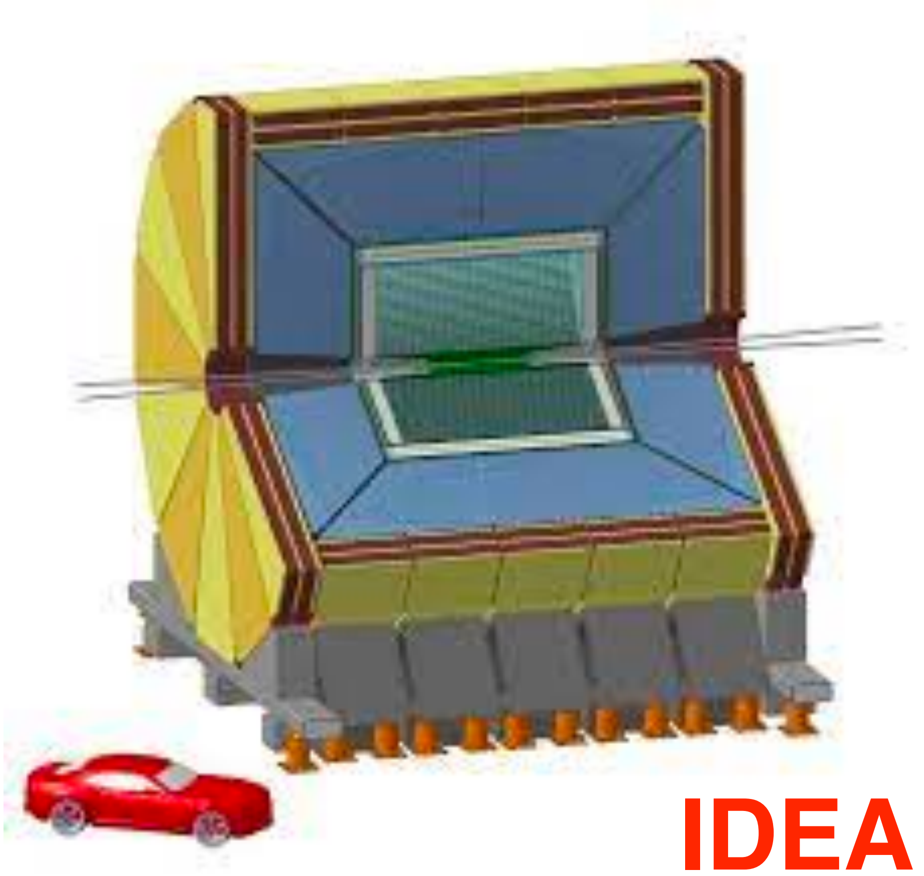
Current benchmarks and next steps

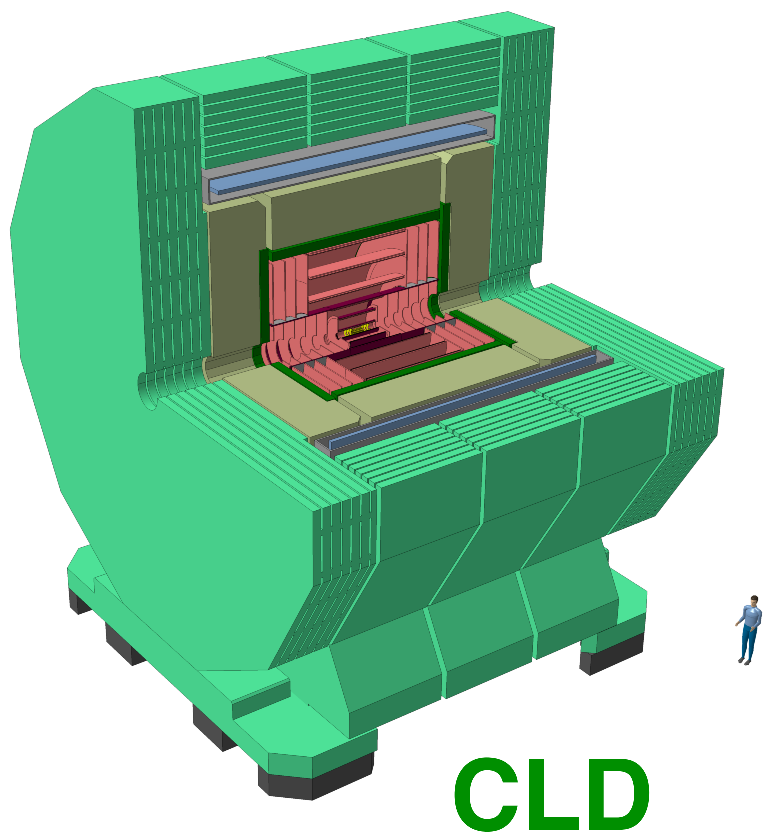
	Aggressive	Conservative	Comments
Vertex	$X/X_0 < 1\%$	–	R_c, flavor tagging
Tracking			keV
ECAL			
HCAL			
Particle I			

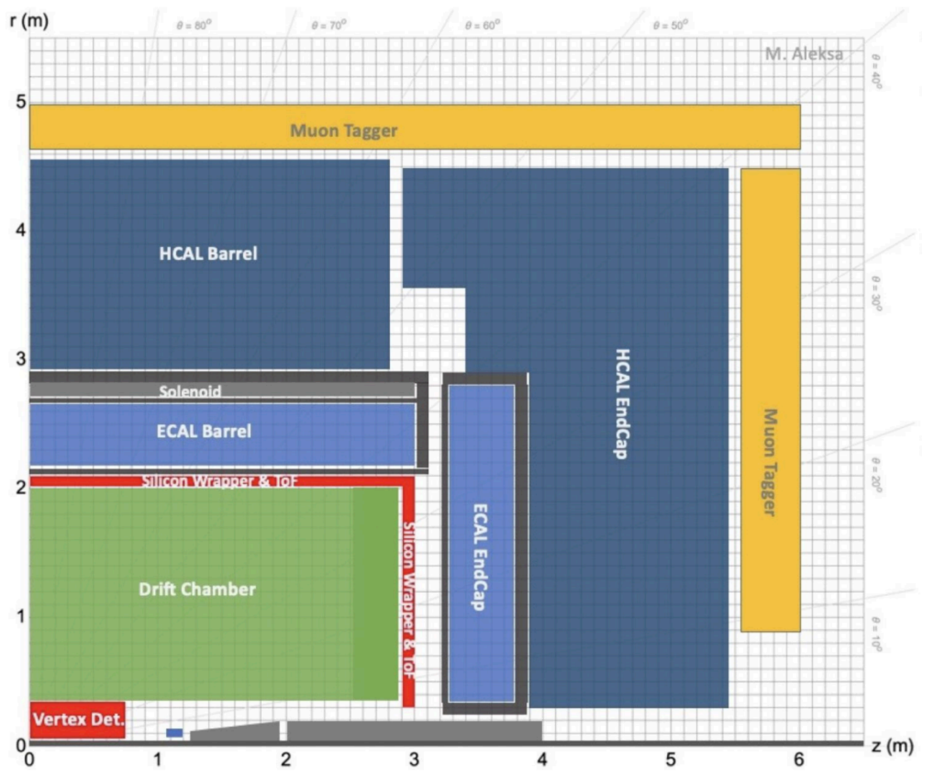
Technology	EM energy resolution stochastic term	EM energy resolution constant term
Highly granular Si/W based	15–17%	1%
Dual readout fibre (ECAL+HCAL)	11%	$< 1\%$
Hybrid crystal (dual readout)	3%	$< 1\%$
Highly granular noble liquid based ECAL	8–10%	$< 1\%$

[FCC Feasibility Report]

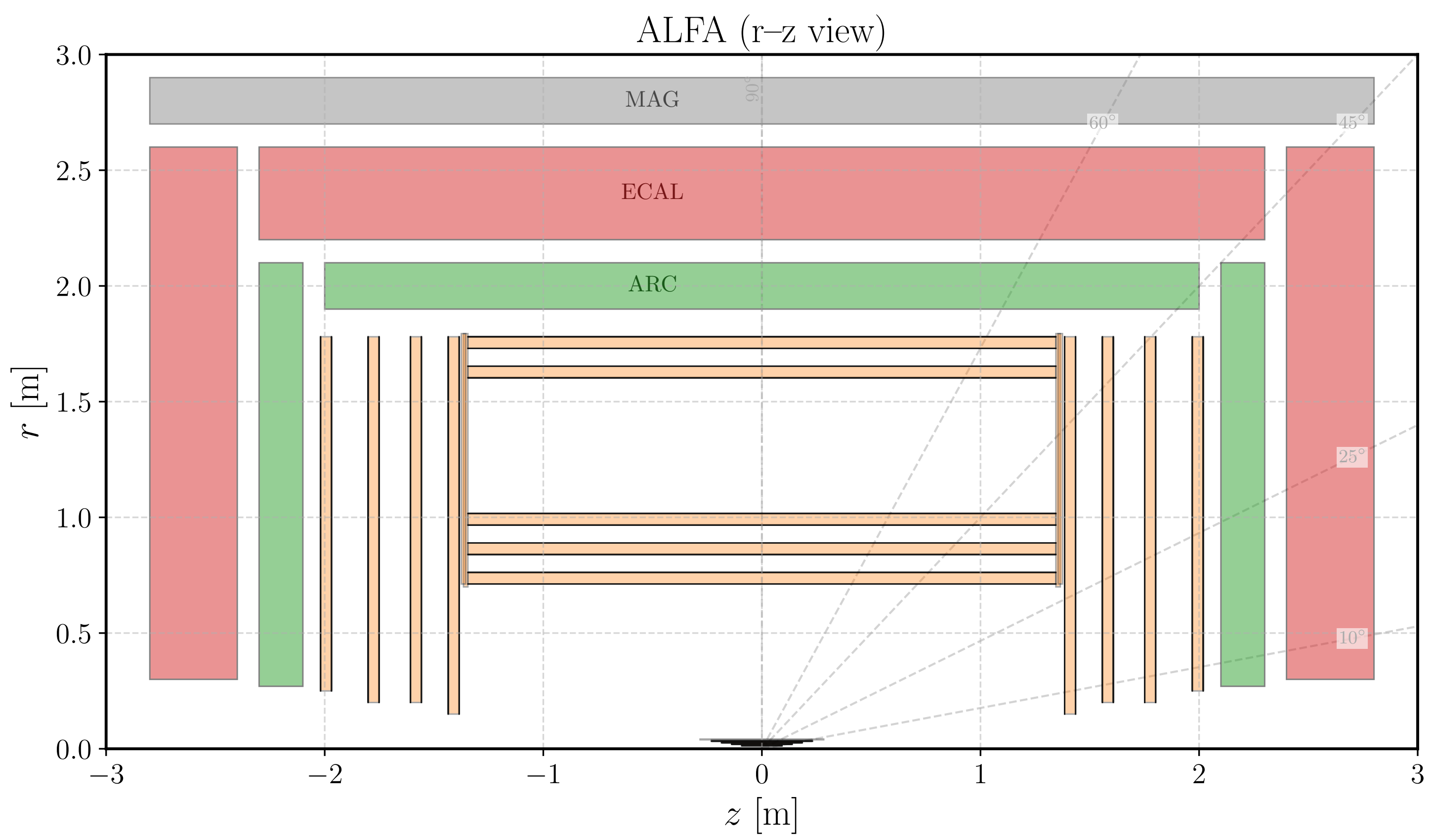
Detector Designs, a quick overview


IDEA


CLD



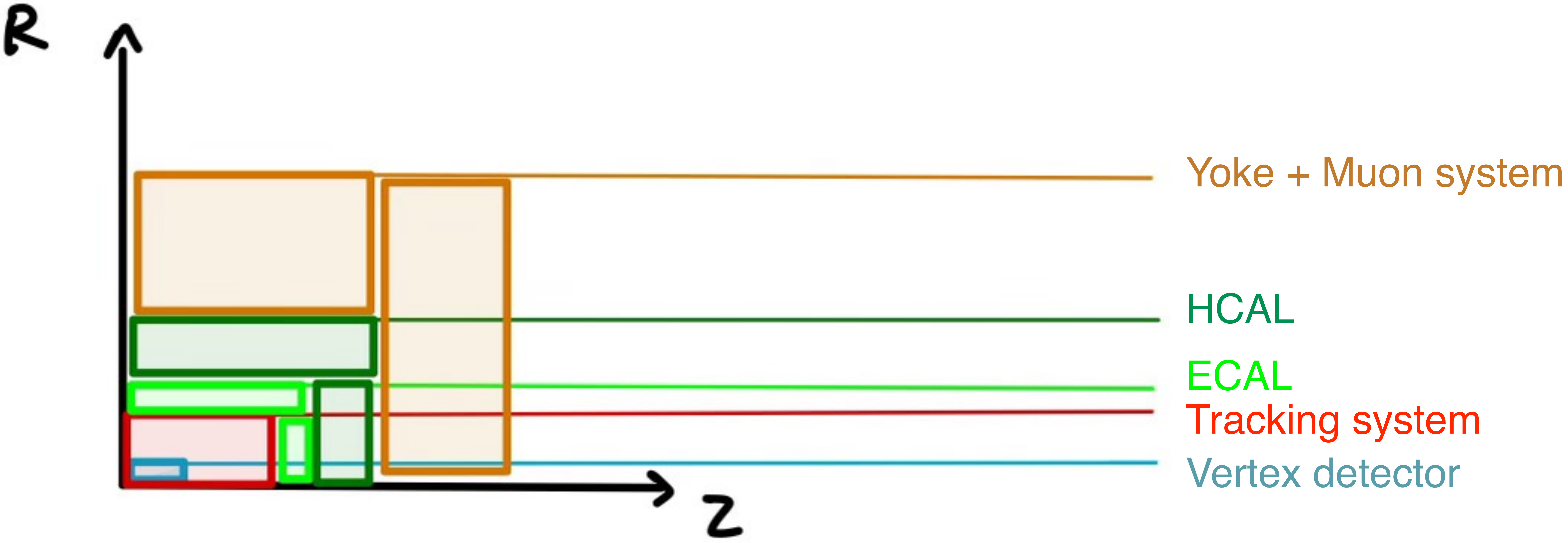
ALLEGRO



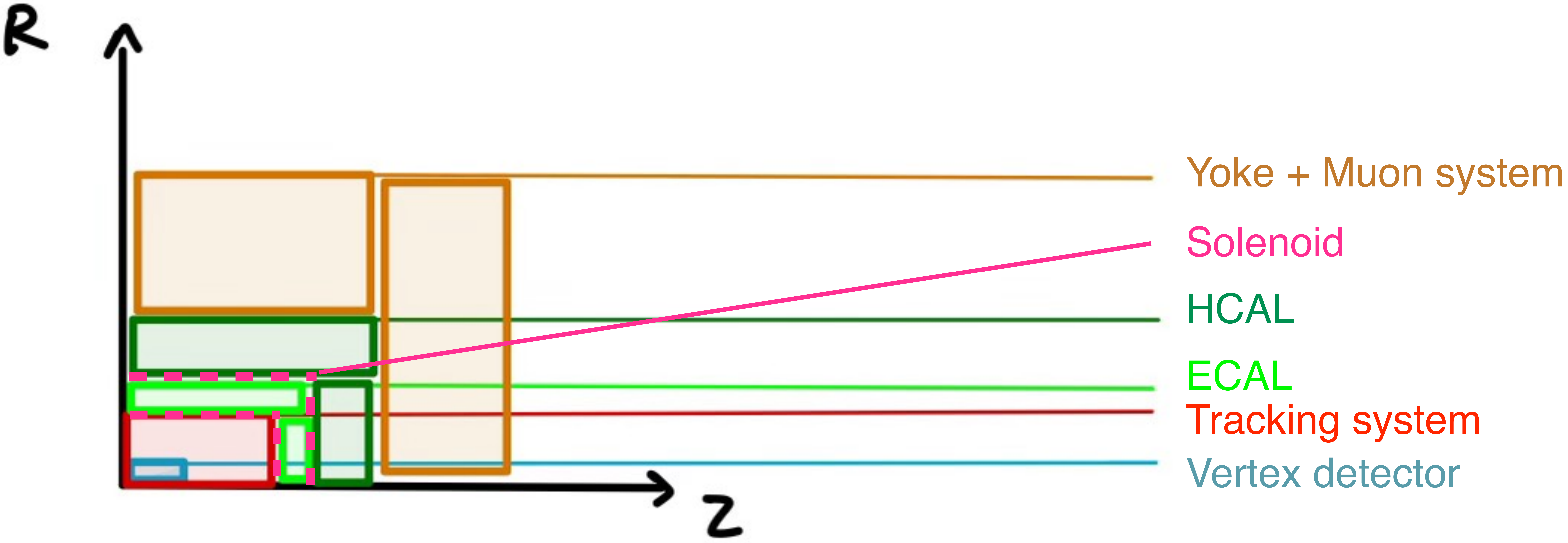
- Detector designs at all colliders features very similar strategies, main difference is in the B field
  - FCC@Z limits B field to 2 T to avoid a blow up of the vertical beam emittance
- CLD/ALFA - Compact all silicon tracking systems with highly segmented calorimeters optimized for PFA
  - compensates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

Lots of work in the past decades into ILC/CLIC detectors designs and more recently into first CEPC/FCC detector concepts

Detector concepts



Detector concepts



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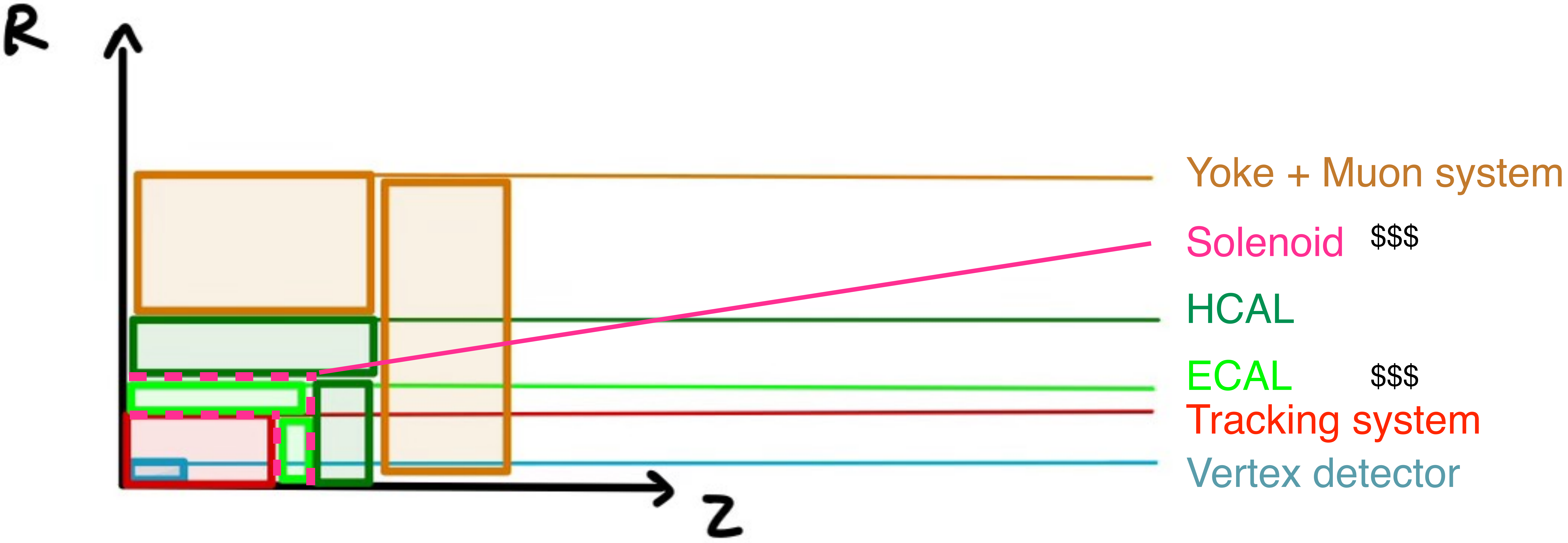

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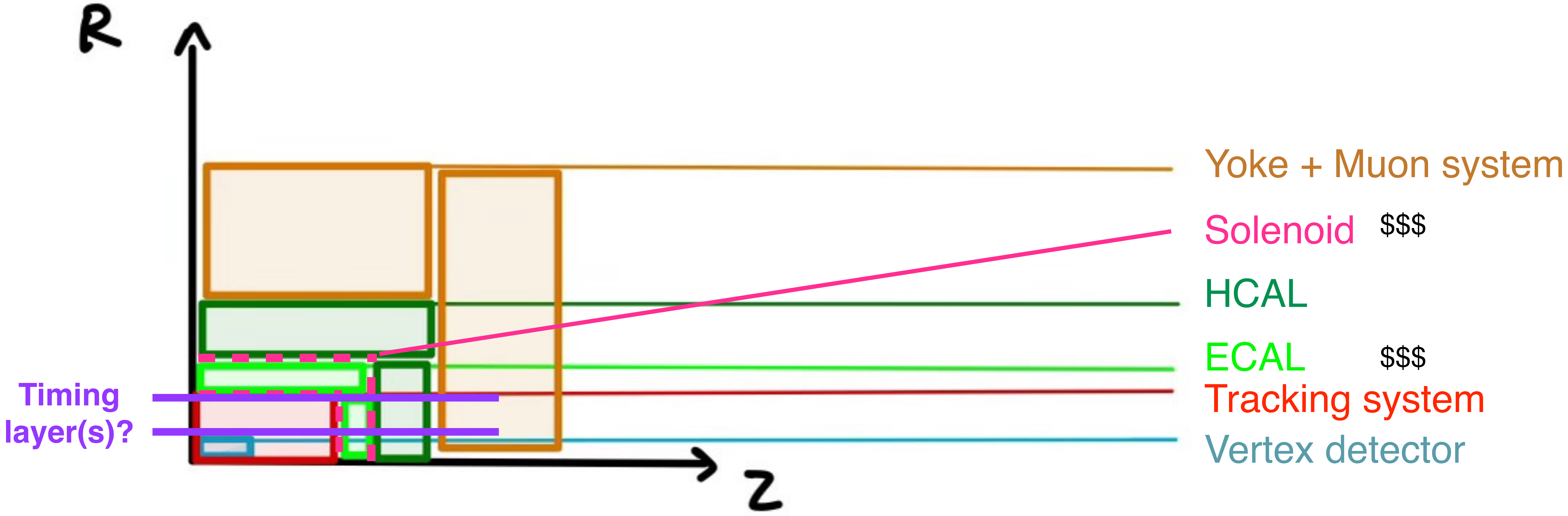
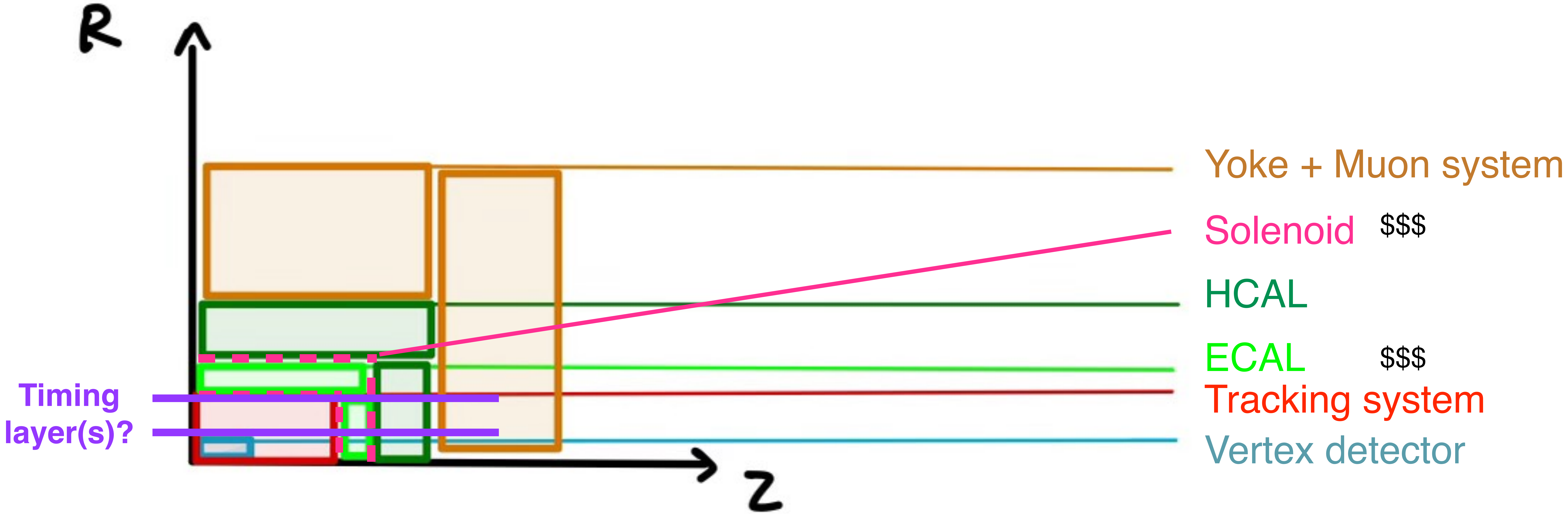


Detector concepts

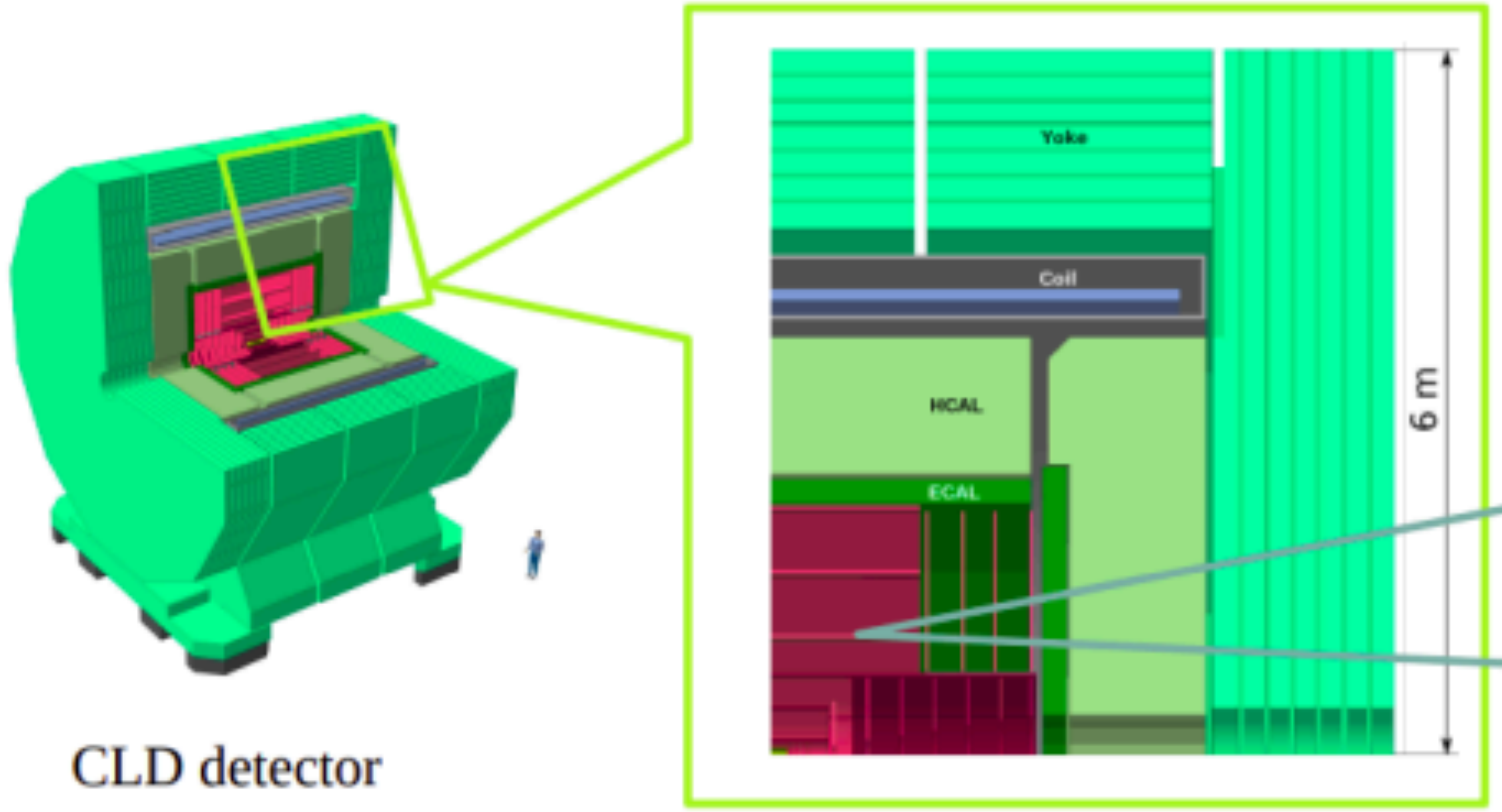


Magnet and Calorimeters are generally driving detector cost (>30% each)
Optimizations and cost reduction are possible with targeted R&D
Physics benchmarks will have to guide overall detector optimization

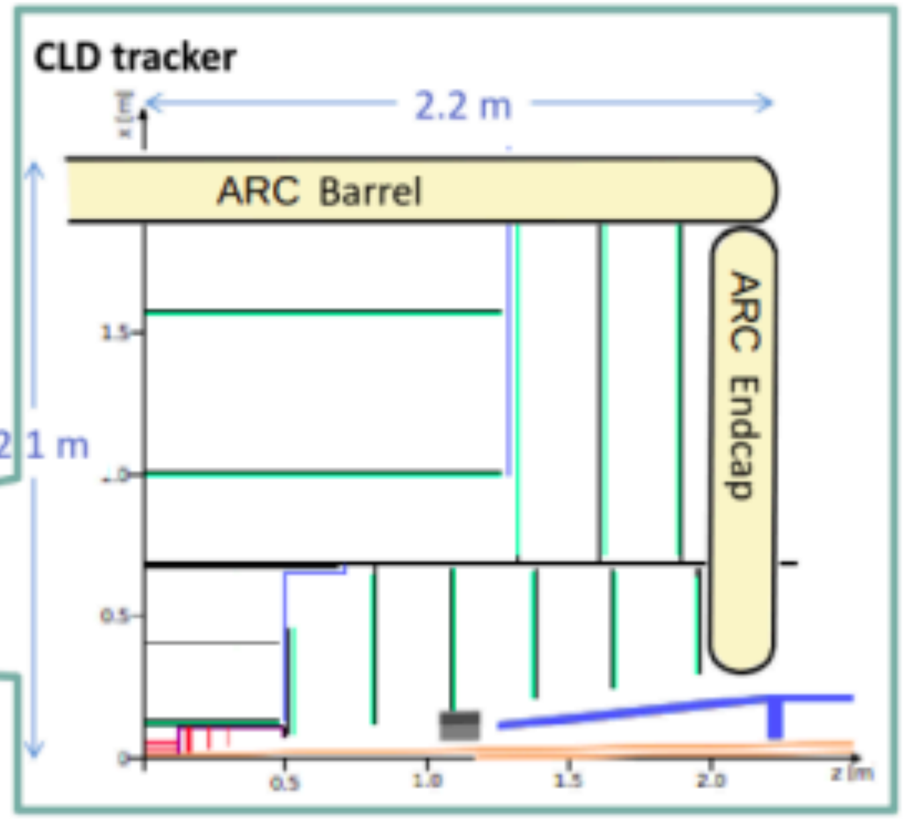
Adding RICH?

G. Sadowski LCWS 2024

A dedicated PID detector will need to take space from something else…



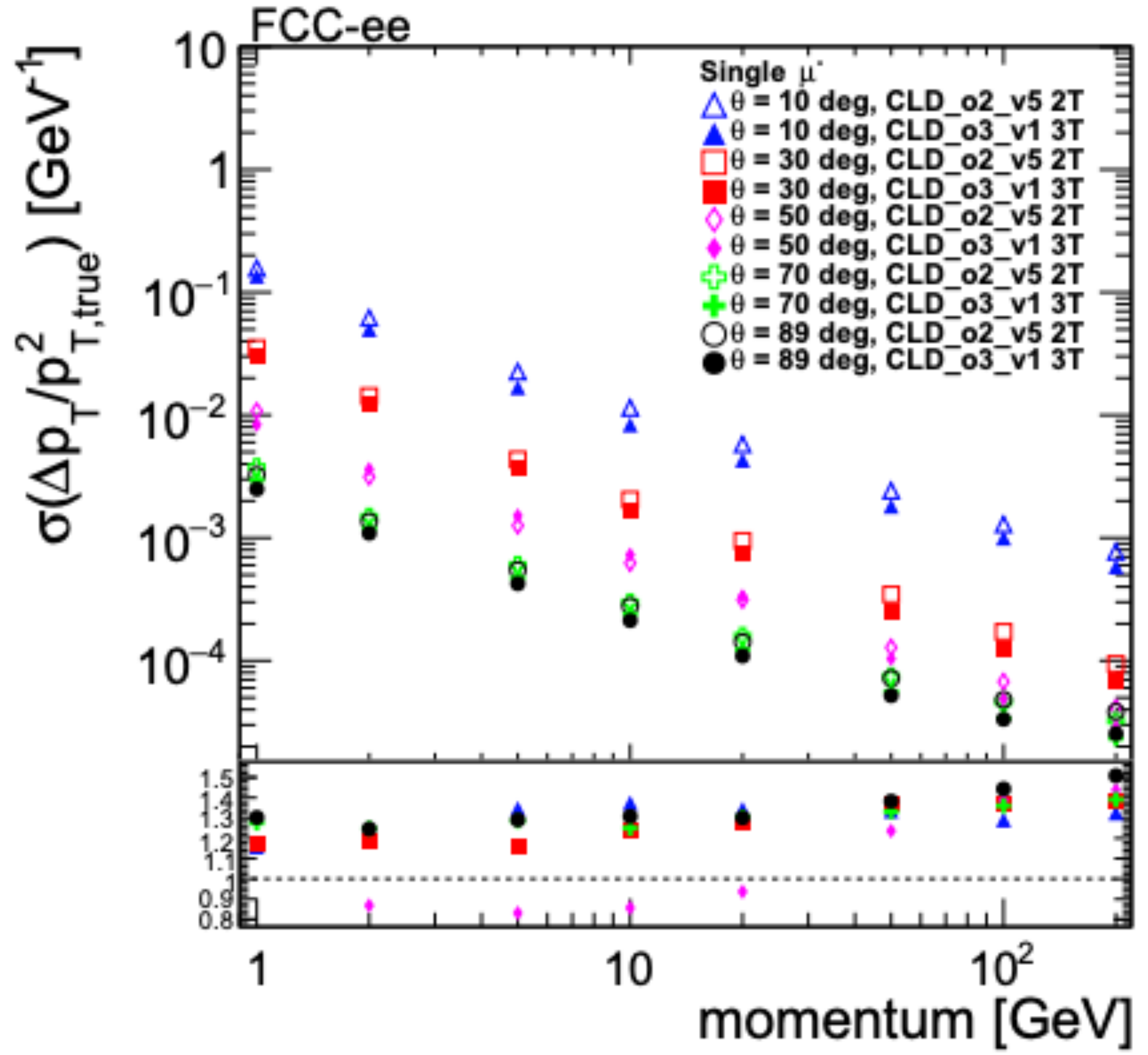
CLD detector



Outer Tracker Barrel [mm]	R_1	R_2	R_3	
o2_v05	1000	1568	2136	
o3_v01	**1000**	**1446.8**	**1849.2**	
Outer Tracker Endcap [mm]	Z_0	Z_1	Z_2	Z_3
o2_v05	1310	1617	1883	2190
o3_v01	**1310**	**1547**	**1752**	**1990**

- Lever arm reduced by 10%
  ⇒ p_T resolution should degrade by ≈ 20%
- 2 T to 3 T increases p_T resolution and compensate the loss of p_T resolution caused by the reduced tracker length

What about the calorimeter energy resolution ?



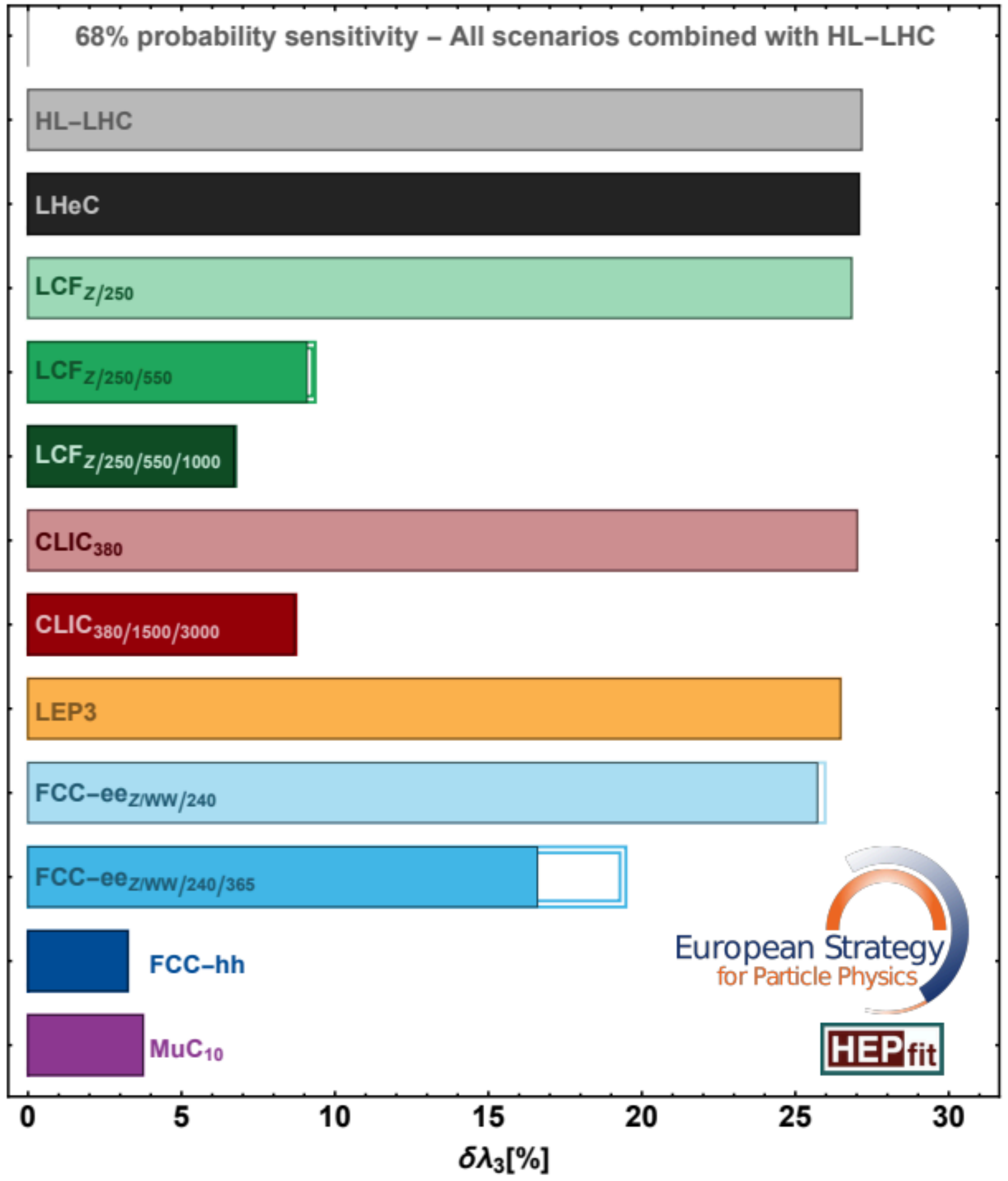
Outlook

- FCC-ee will measure Higgs couplings to sub-percent precision across the widest set of accessible channels - a qualitative advance beyond the HL-LHC program
  - H→invisible: FCC-ee can exclude BSM branching fractions below 0.05% at 95% CL - uniquely sensitive to Higgs portal dark matter, well beyond HL-LHC reach
- Achieving this physics program places stringent, (to be?) quantified requirements on detector performance
  - especially vertexing and calorimetry (HCAL stochastic term);
- Legacy linear collider detector work provides a foundation, but new technologies and full simulations are needed to meet FCC-ee's more demanding and broader physics goals
- **Revisit physics goals to refine detector requirements in light of new technologies**
- **Full simulations remain crucial** to derive quantitative, optimized design choices
  - **AI tools can help reducing the parameter phase space**

Thank you!

Higgs self-coupling

ESG Physics Briefing book 2025



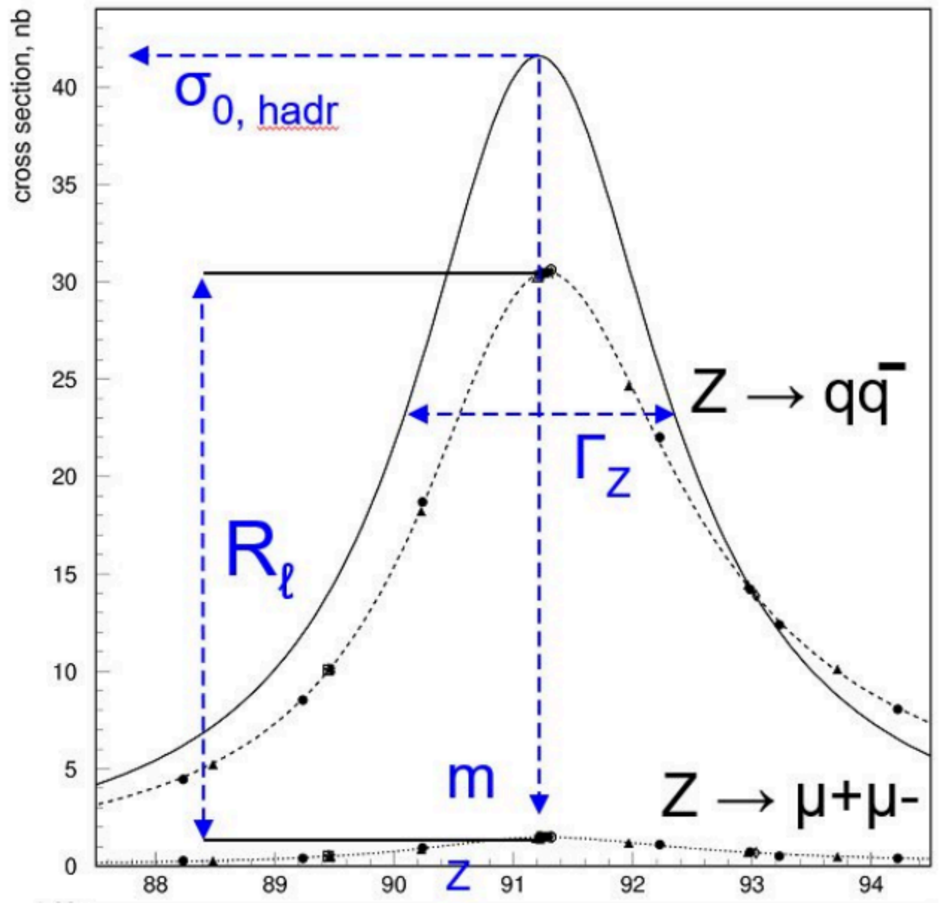
- HL-LHC + FCC-ee (running below HH threshold) achieves ~17-20% precision on λ_3
- Running above the HH threshold improves this; linear colliders at 550 GeV and 3 TeV can reach 7-11%
- Few-percent precision requires high-energy machines: a hadron collider or muon collider can reach 3-4%

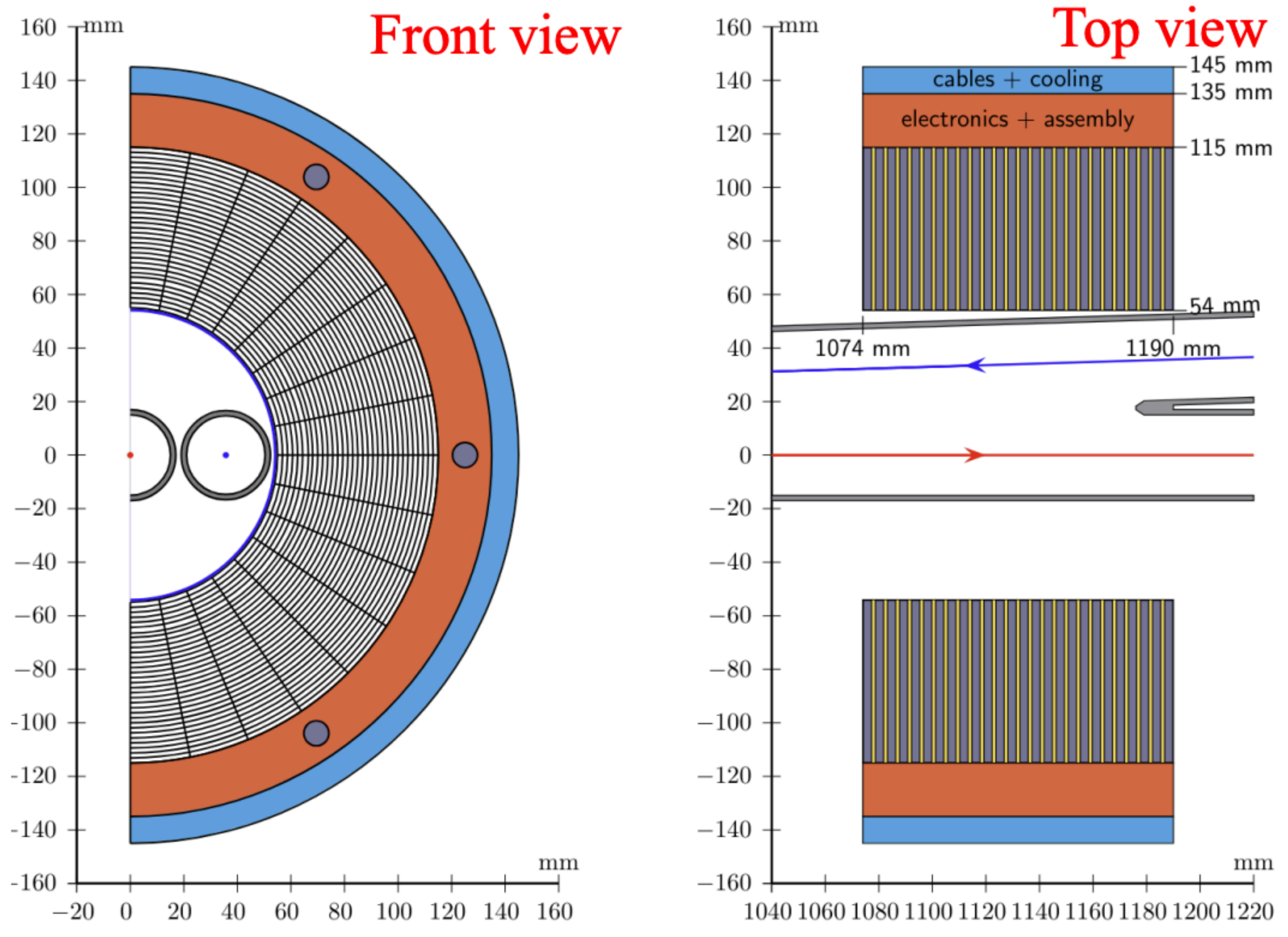
(Z pole) physics requirements for detectors

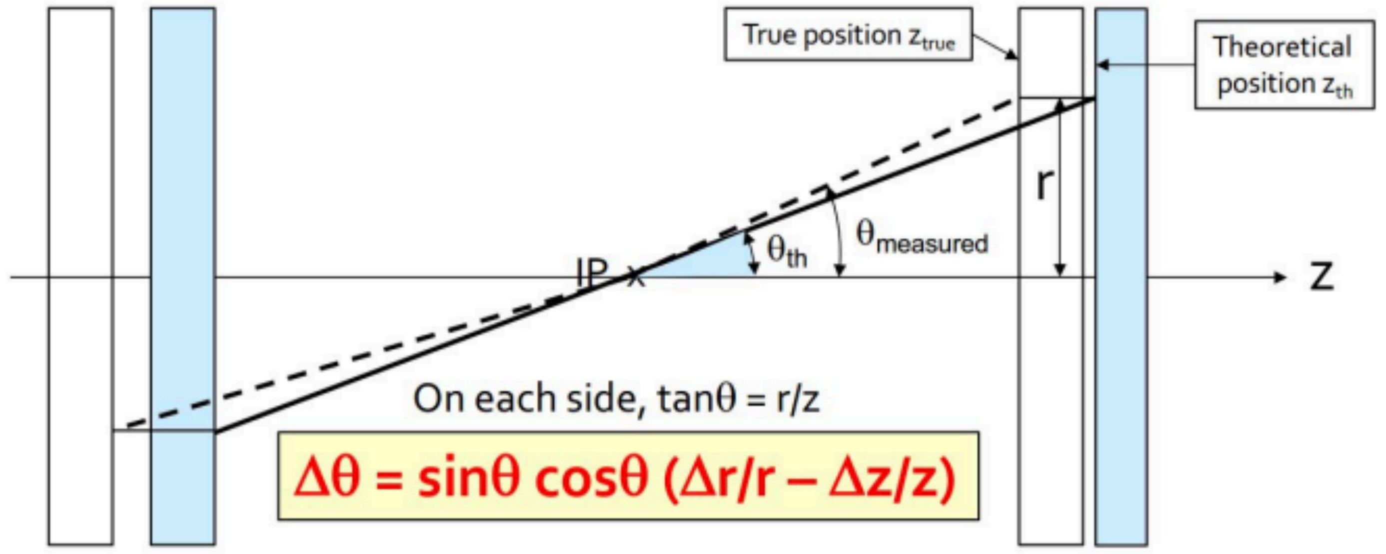
[A. Blondel FCC 2024](#)
[J. Eysermans (2024)](#)

Z pole precision challenges even more detector design

- Γ_Z is extracted from the Z lineshape
  - systematic uncertainty should be ~ 5 keV to match statistical precision
    - Requires exquisite **control and stability of the beam momentum scale**
    - $\delta\Gamma_Z \sim 20$ (40) keV → sub-ppm ($\approx 10^{-6}$) precision on beam-energy calibration
- R_l demands precise knowledge of the **geometrical acceptance**
- Absolute luminosity measurement at Z pole, required by peak Z cross section
  - $\Delta\theta_{min} \sim 10$ µrad to match statistical precision (2×10^{-5})
    - equivalent to $\Delta r \sim 30$ µm, $\Delta z \sim 80$ µm at $\theta = 20°$ and $z = 2.6$m
- Luminosity Monitors centered around outgoing beam lines
  - $\delta R_{min} \sim O(1\ \mu m)$, $\delta z \sim O(100\ \mu m)$
  - **Ambitious goal: absolute normalization to 10^{-4}** *note $O(10^{-2})$ for LHC* and **relative (energy scan points) to 10^{-5}**
  - Current theoretical uncertainty: 3.8×10^{-4} , **major theory efforts also needed**







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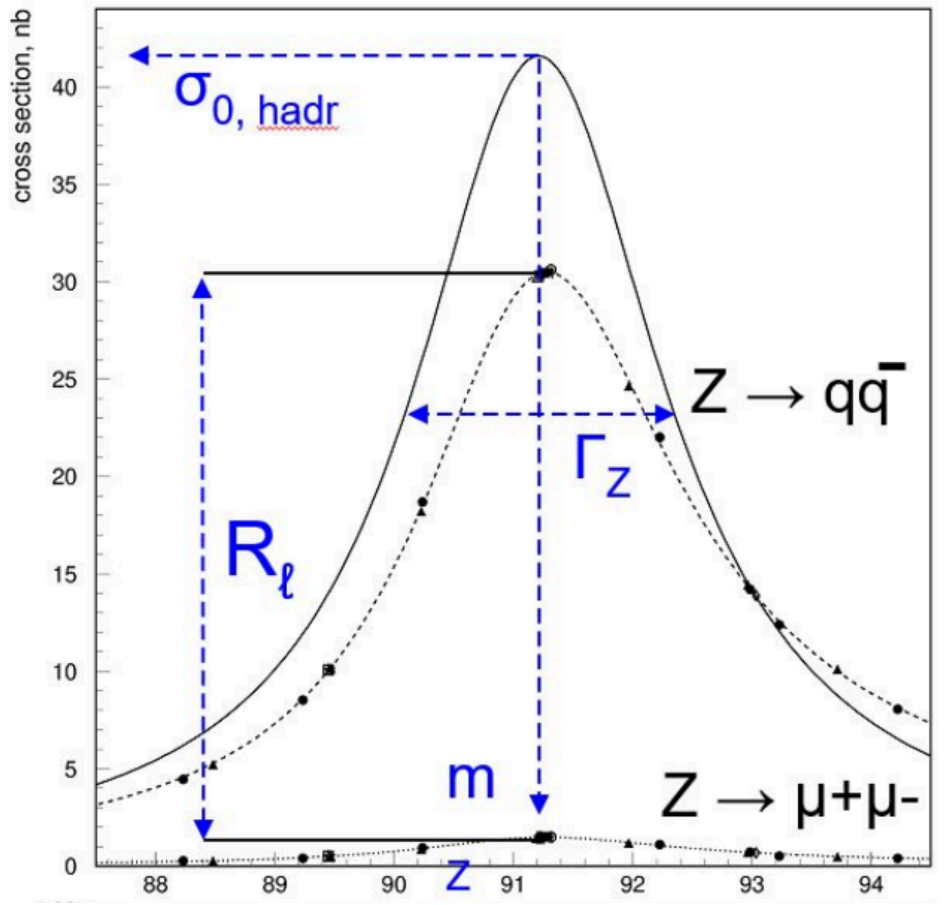
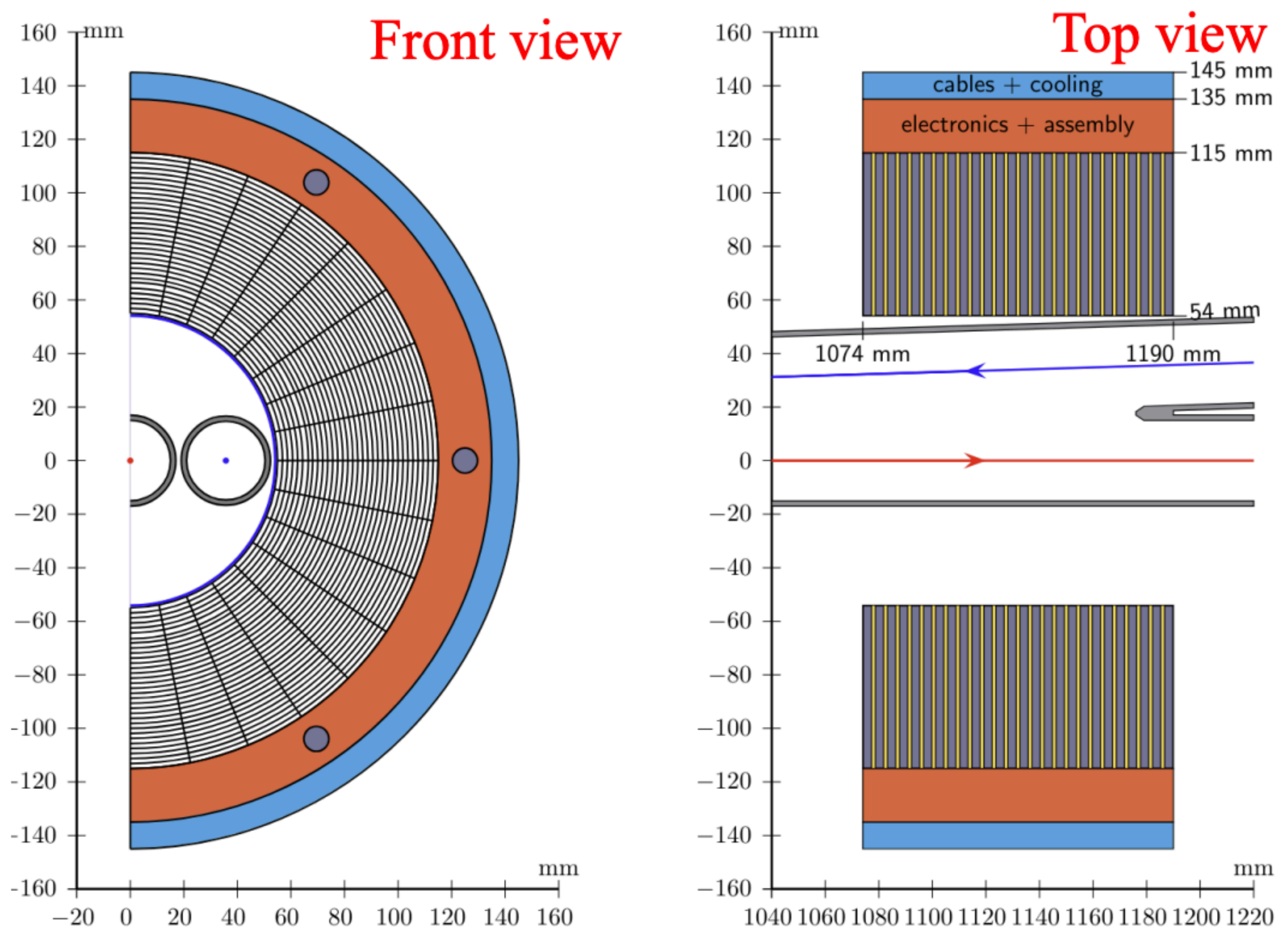
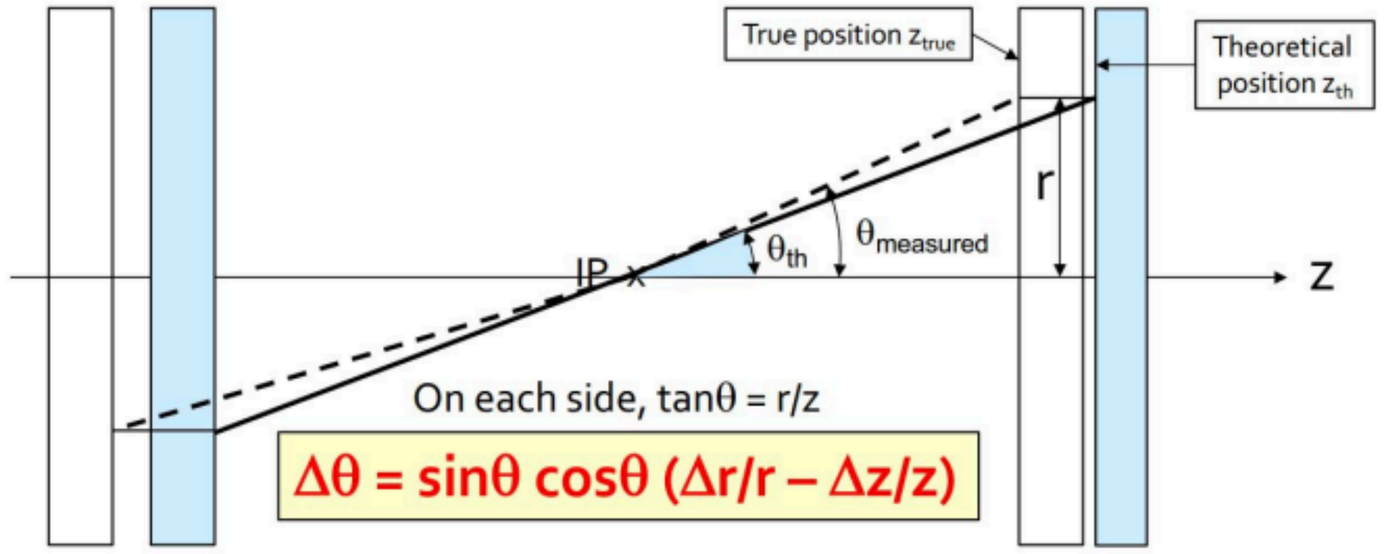




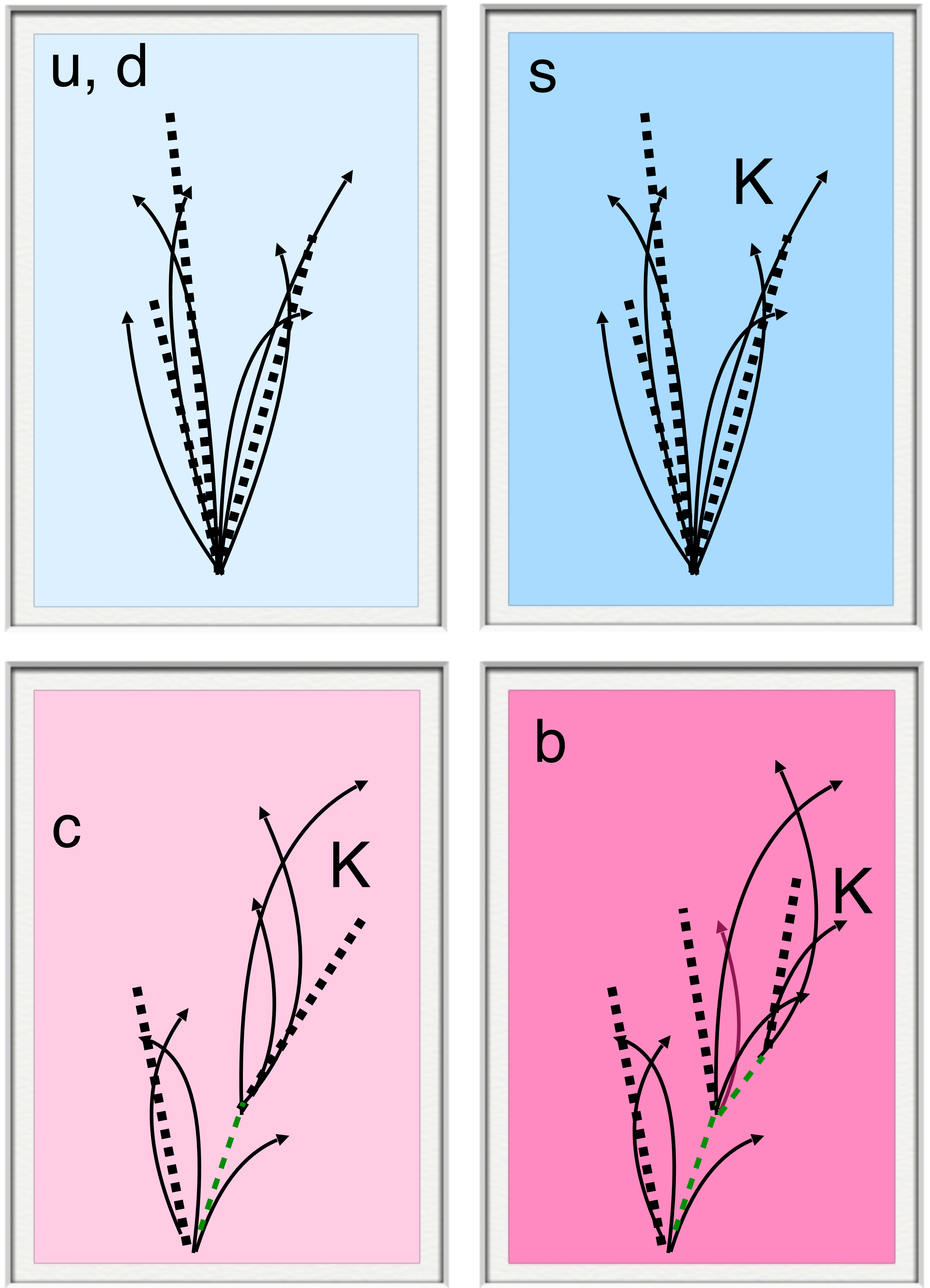


This in-situ calibration technique could be used to determine lumiCal acceptance

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

H($s\bar{s}$), a new opportunity?

Tagging strange is a challenging but not impossible task for future detectors at e^+e^-



- As b,c, and s jets contain at least one strange hadron
- Strange quarks mostly hadronize to prompt Ks
- s-tagging demonstrated by SLD at SLC (e^+e^- at the Z)
  - measured asymmetry in Z($s\bar{s}$)

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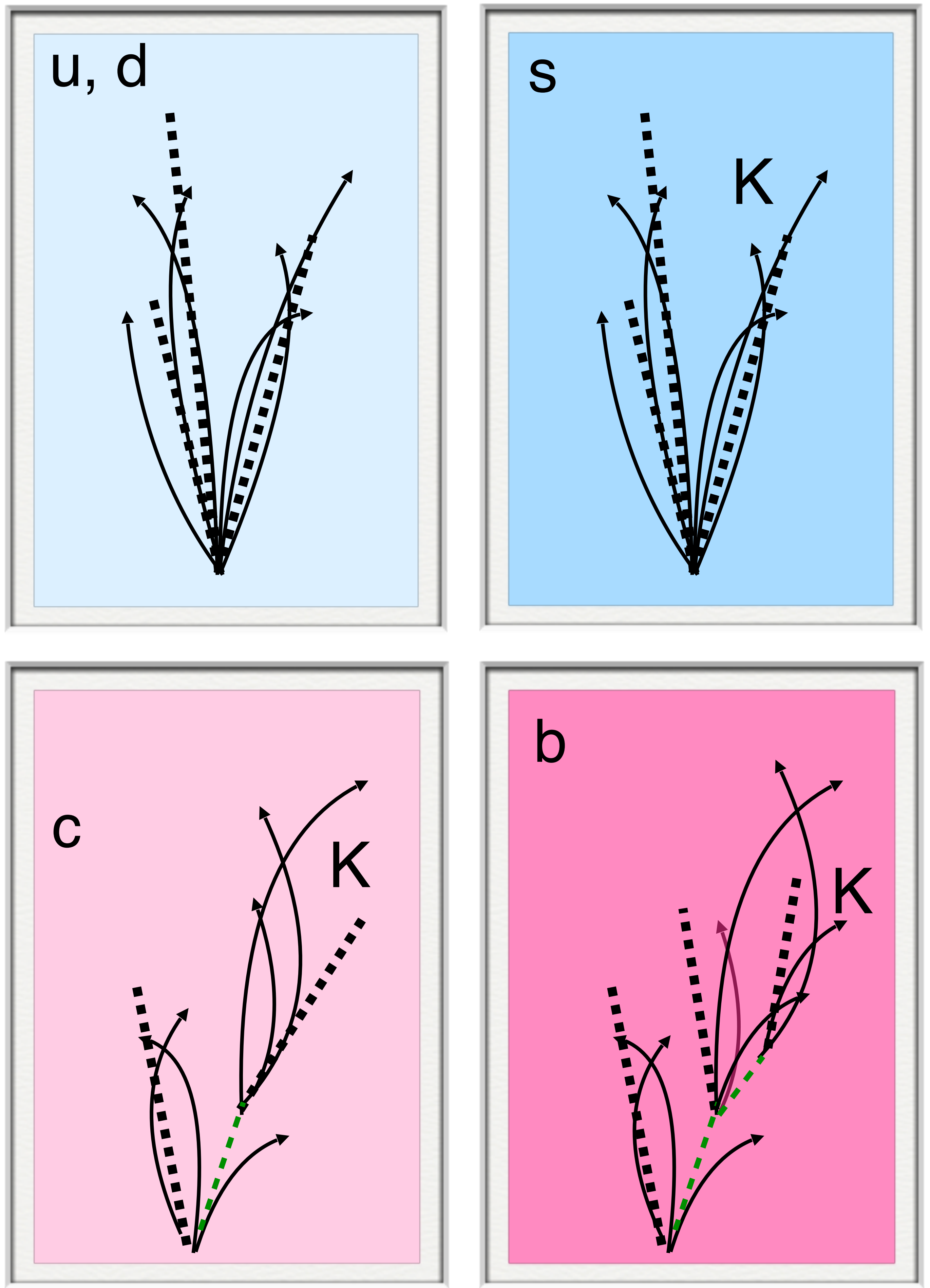

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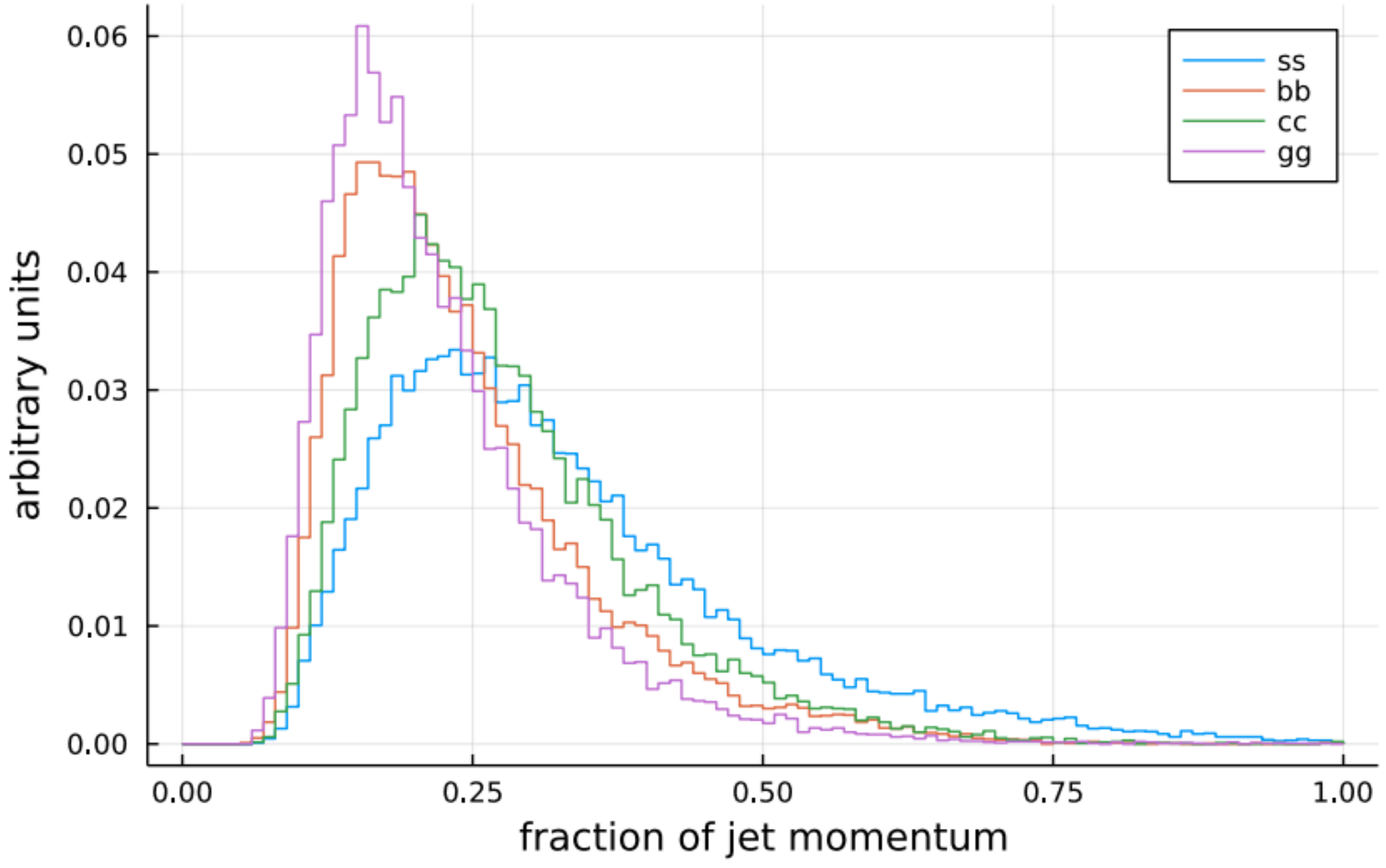
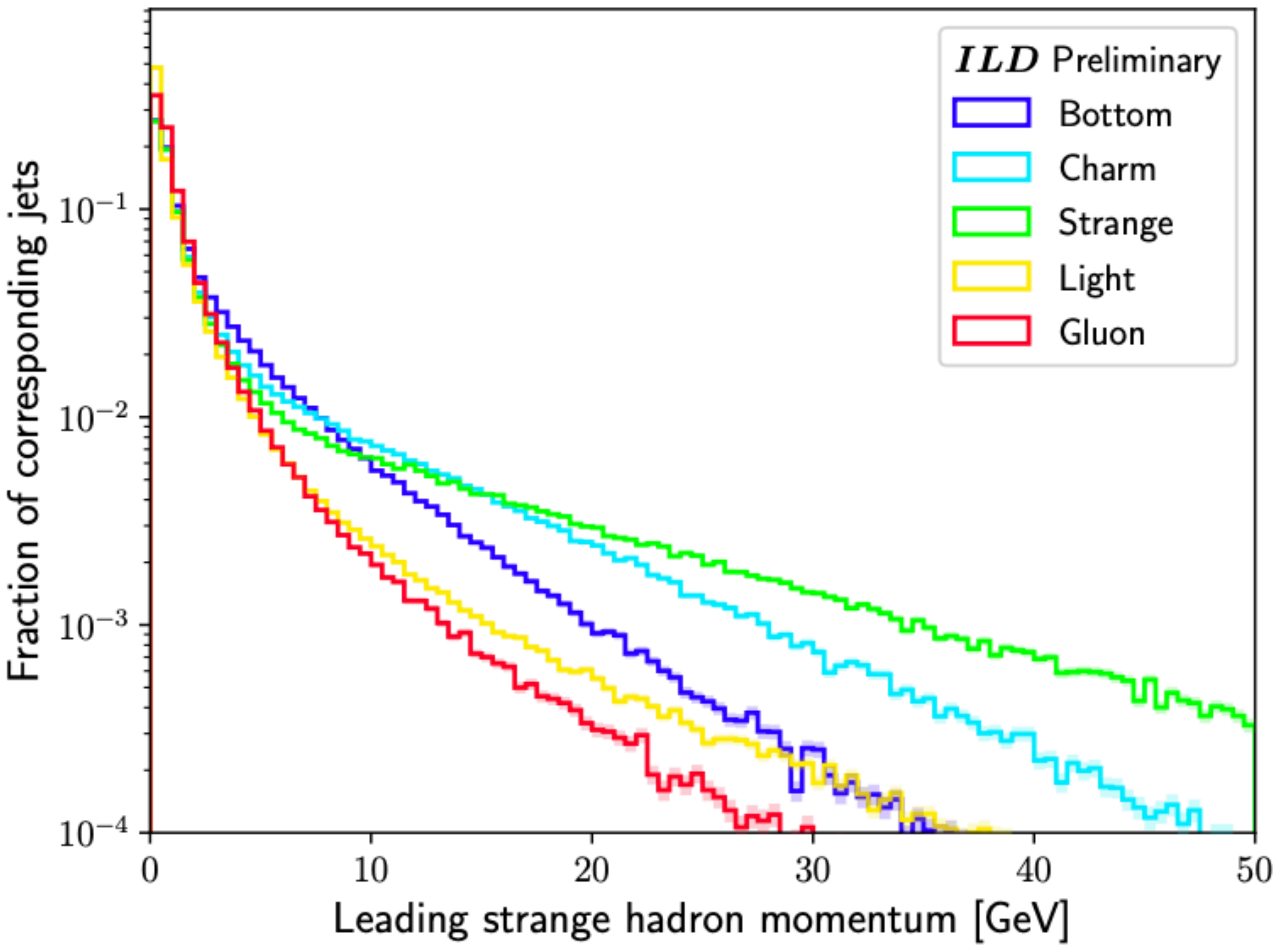
A limit on the BR H($s\bar{s}$) at <u>~5x above the SM value</u> would already be a significant probe to new physics.
This would be achievable at future e^+e^-

Strange tagging

[2203.07535](2203.07535)

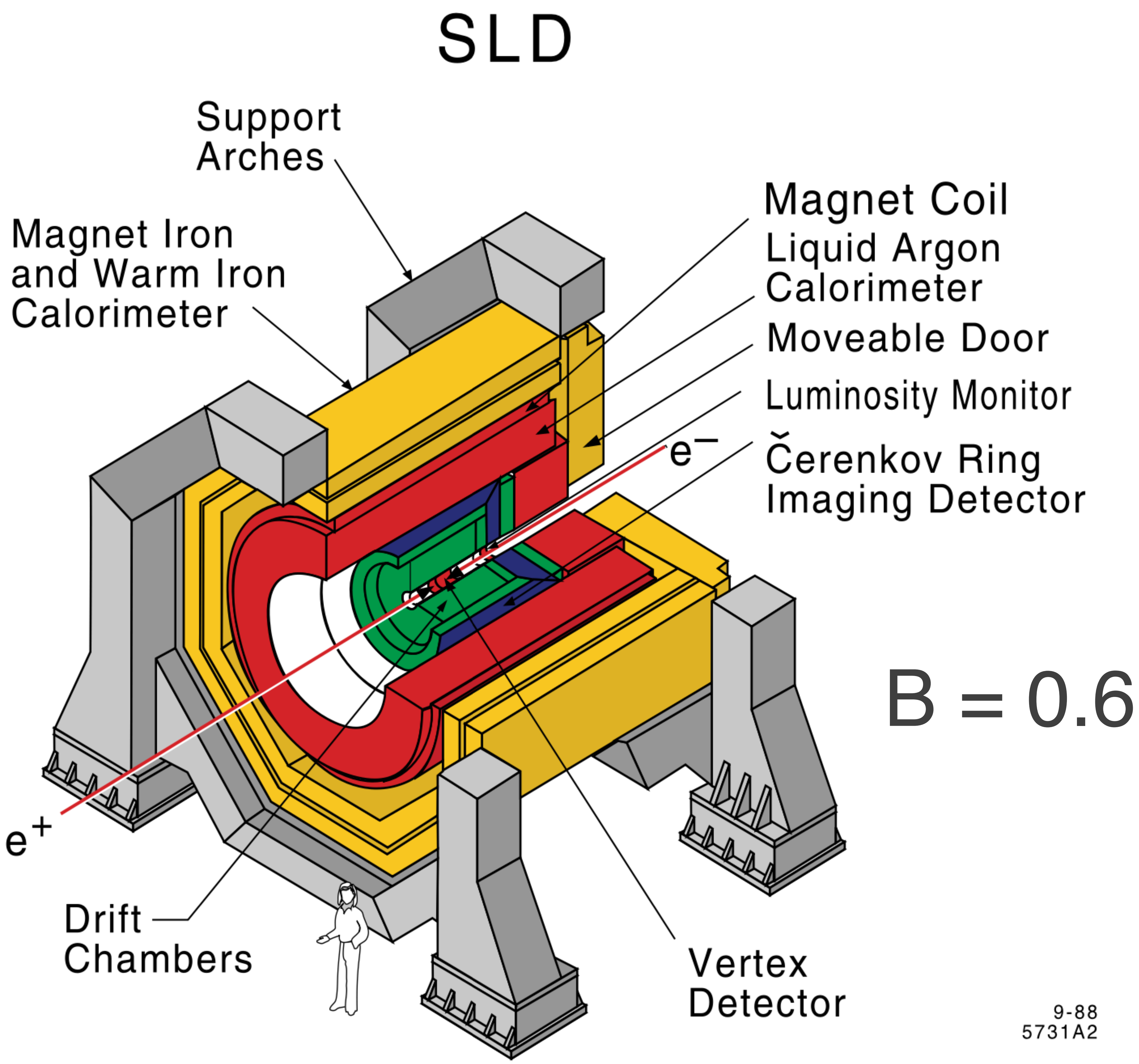
Momentum spectrum





s-tagging in the past

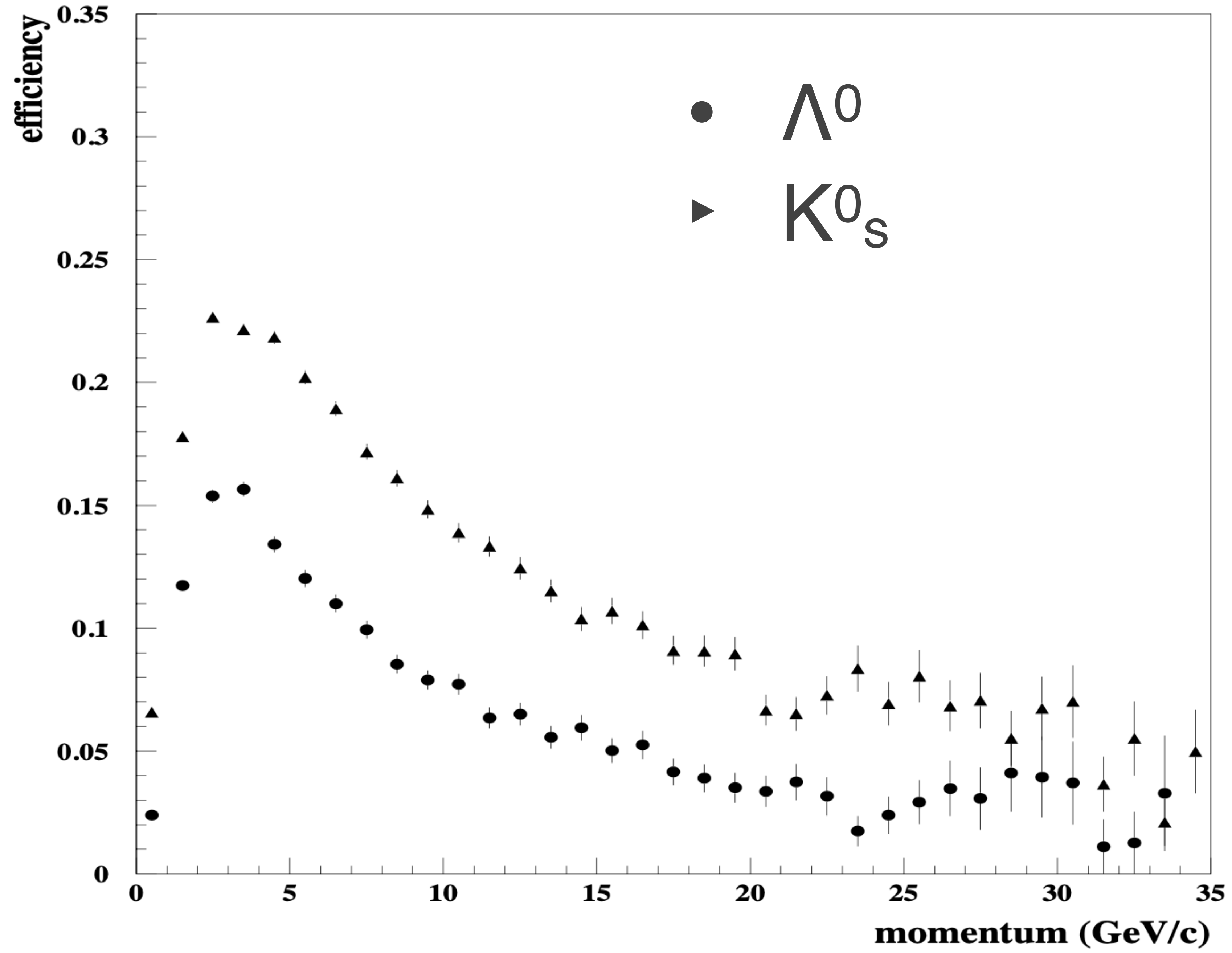
SLD at SLC (e+e- at the Z) measured asymmetry in $Z \rightarrow s\bar{s}$



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 %)



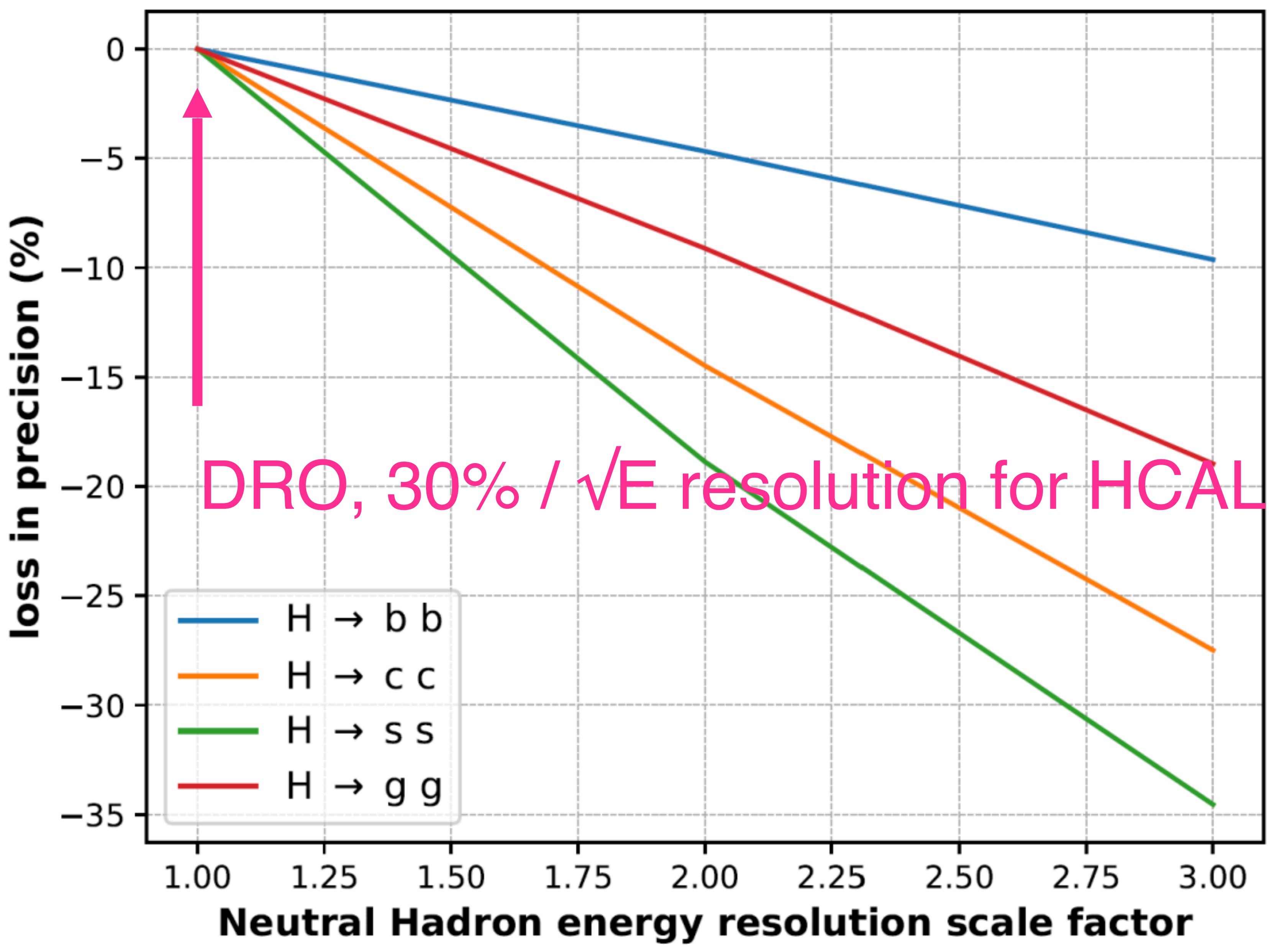
P. Azzi FCC week 2024

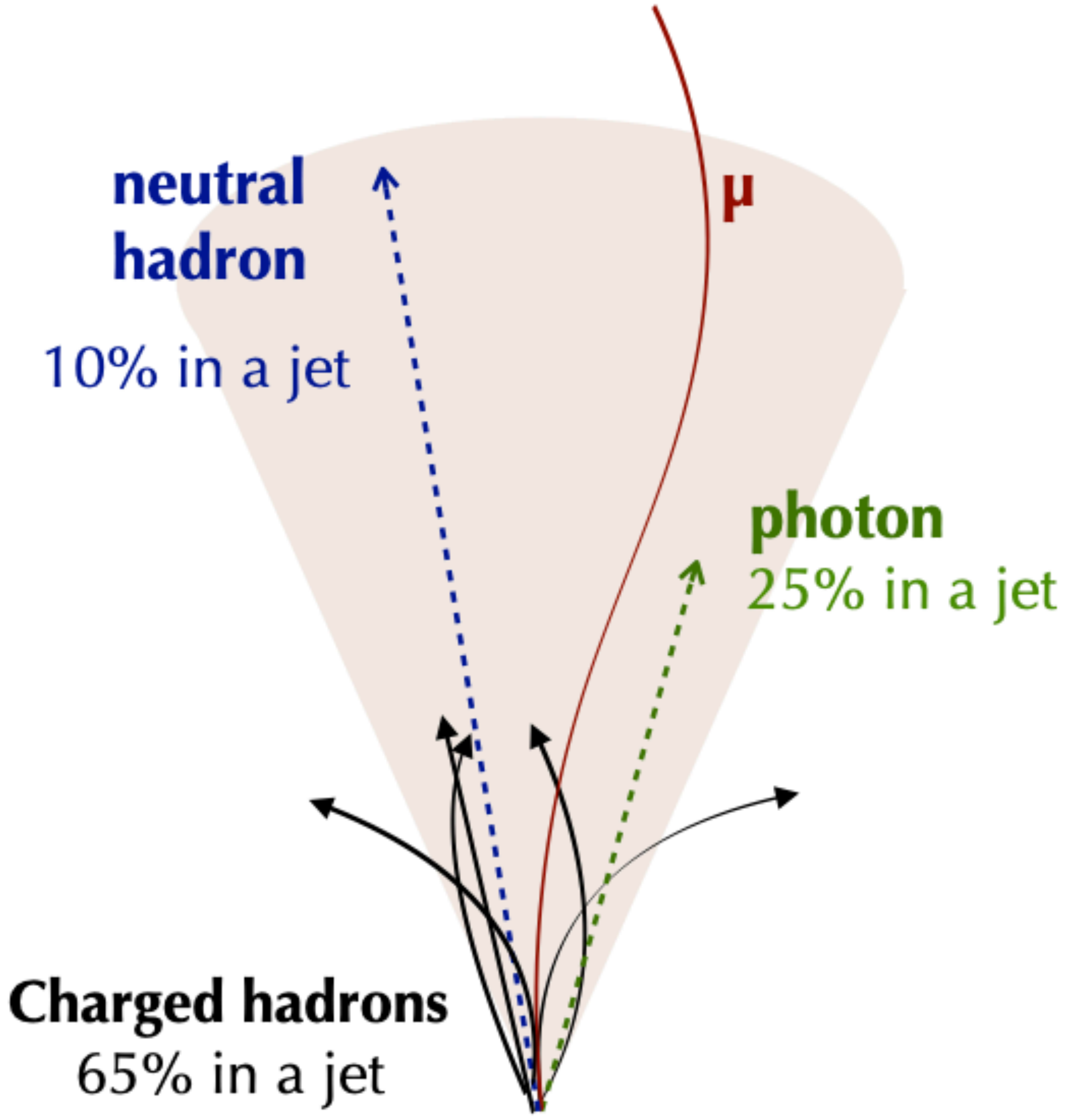
What does that mean for the calorimeter?

Two approaches - DualReadOut (DRO) and Particle-flow algorithm (PFA)

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

- with a ***perfect*** Particle-flow algorithm jet energy energy resolution is dominated by neutral hadron (HCAL) resolution
- with a ***realistic*** Particle-flow algorithm granularity and thresholds matter

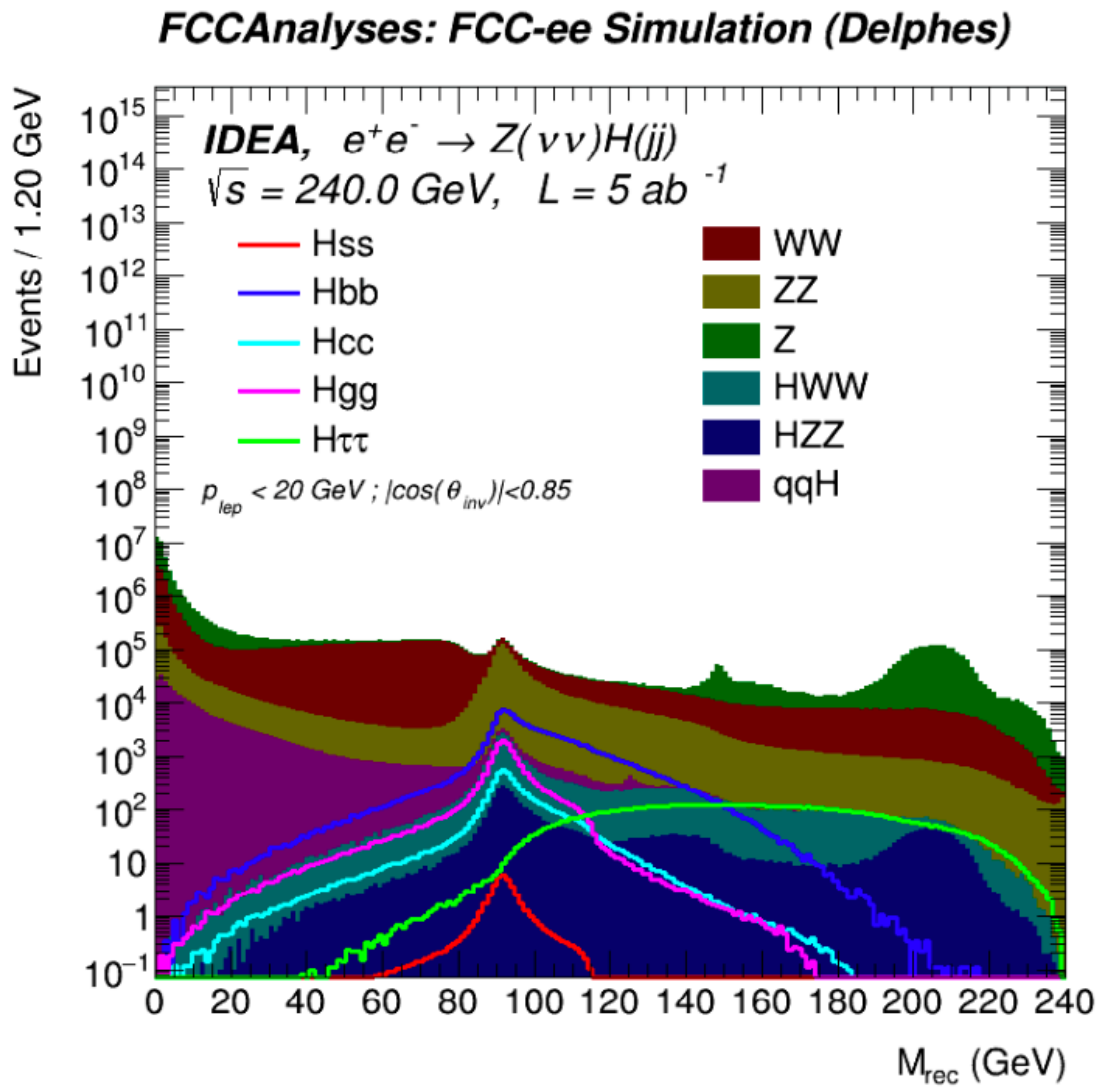


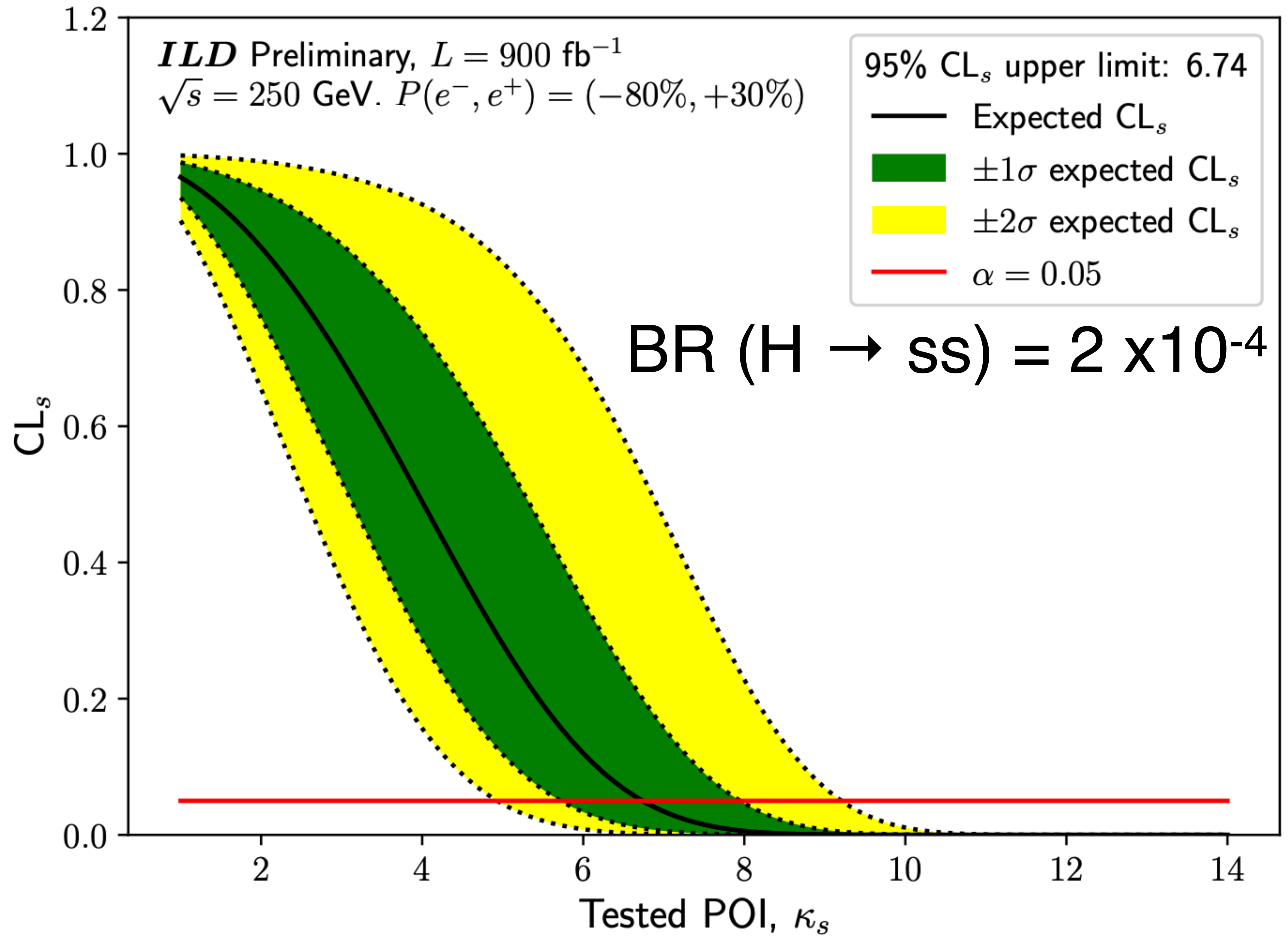


Constraints on s-coupling

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





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	*Dig 10μm or Analog 15-20μm*
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 $12\text{-}14\ mm$	Beam-background	Fast Readout	*~1-10 μs*
r of the Inner most layer	Radiation damage	Radiation Tolerance	*10 MRad, $10^{14}\ n_{eq}$ / /cm²*

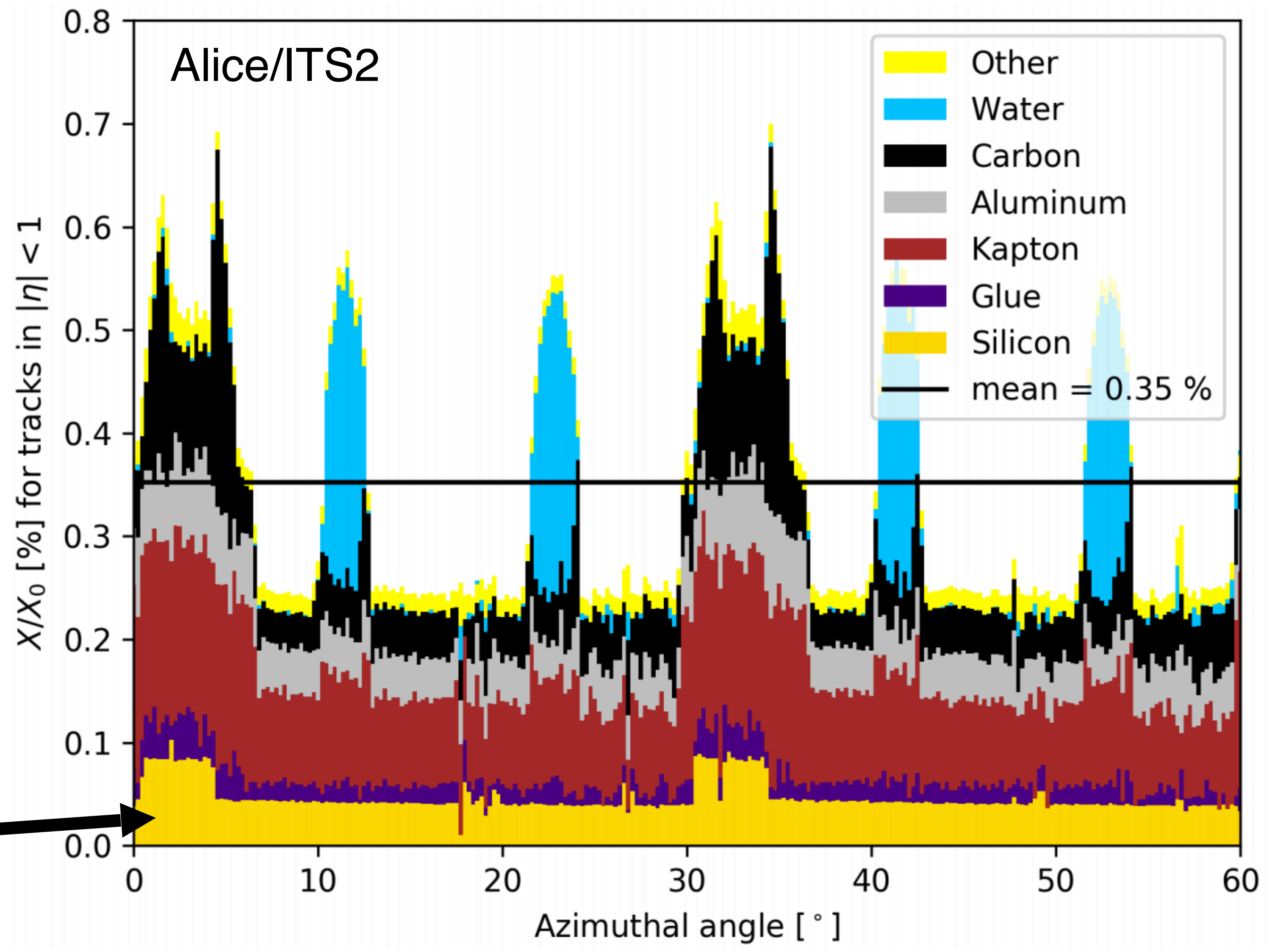
Sensors technology requirements for Vertex Detector

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

Serial Powering and Optical powering could further reduce the impact of the services

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

CERN-LHCC-2019-018



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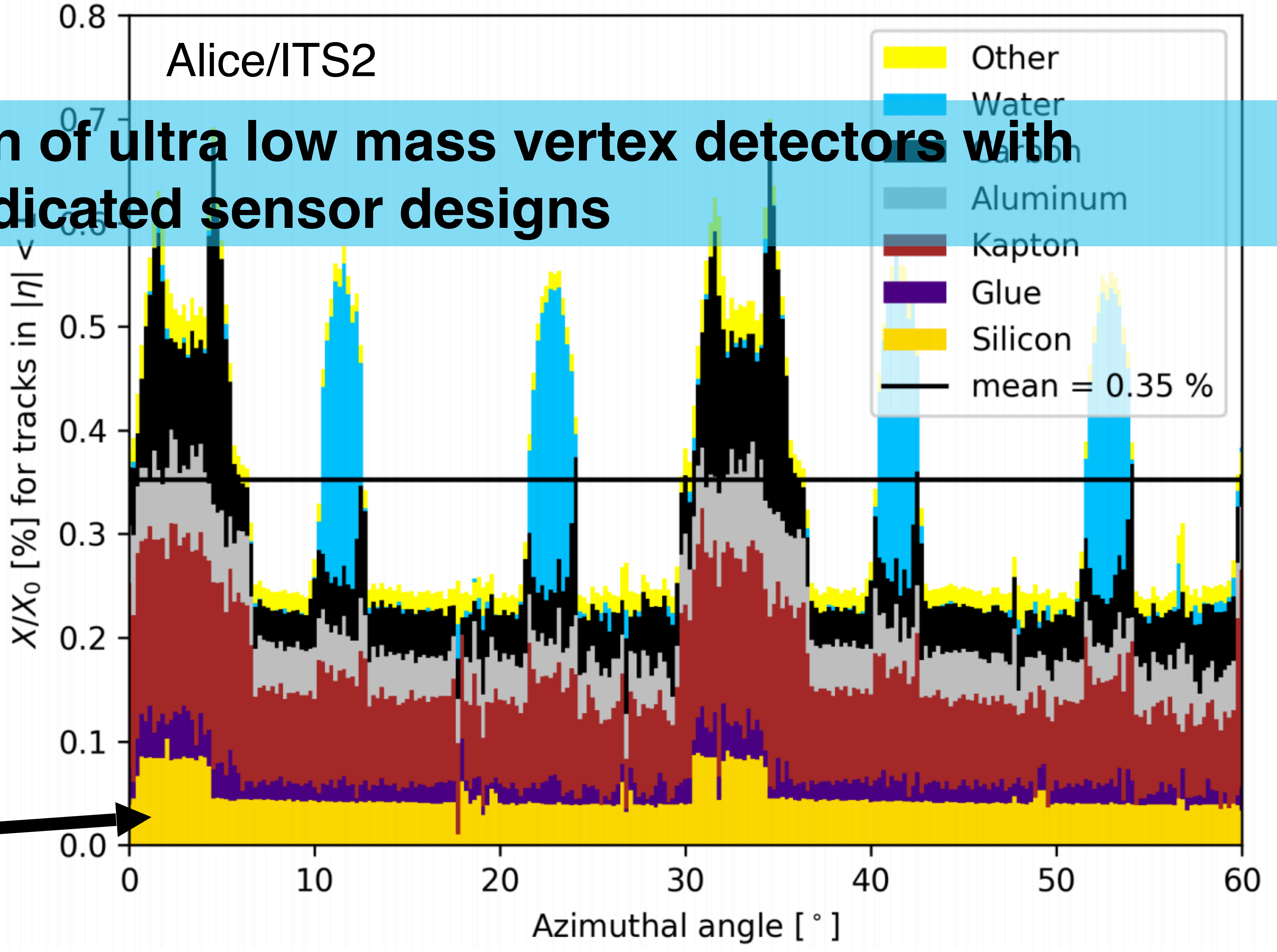


Need new generation of ultra low mass vertex detectors with dedicated sensor designs

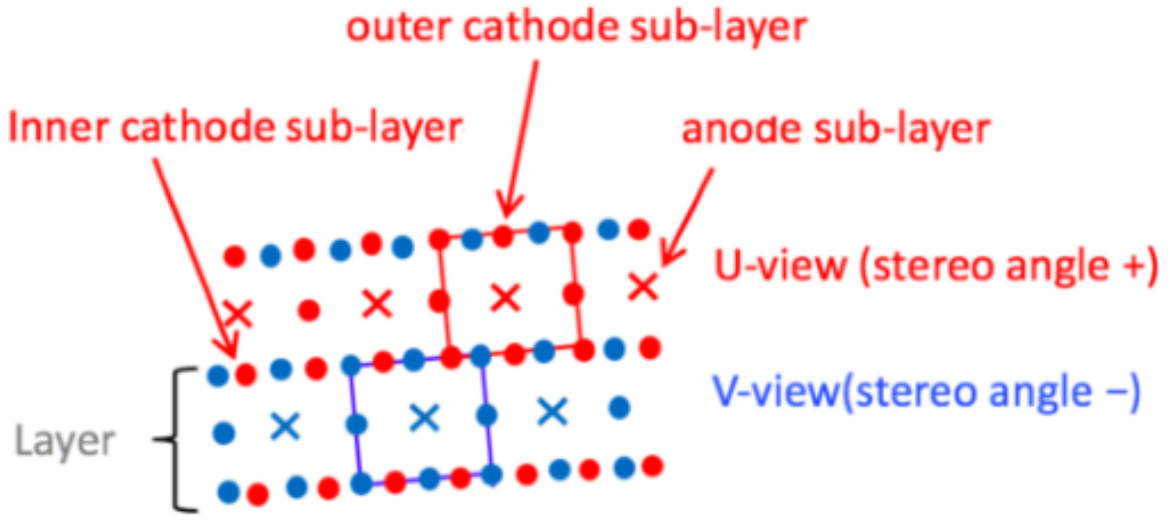
Serial Powering and Optical powering could further reduce the impact of the services

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

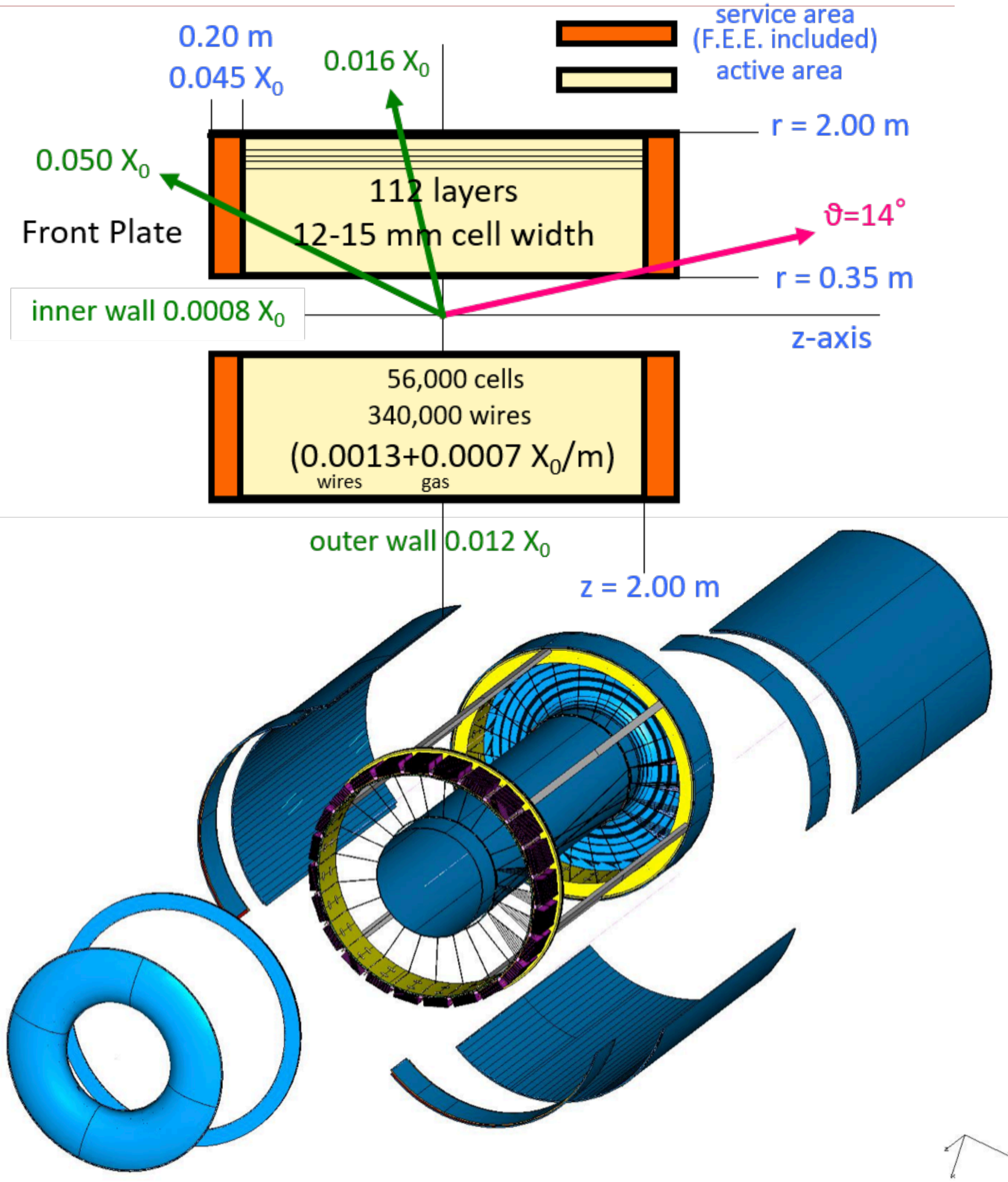
Drift chambers

tracking efficiency ε ≈ 1
for ϑ > 14° (260 mrad)
97% solid angle

$0.016\ X_0$ to barrel calorimeter
$0.050\ X_0$ to end-cap calorimeter



- Unique volume
  - 4 -5 meters (active) long
    - Challenging mechanics
  - 35<R[cm]<200
- Low mass (He 90%: - C4H10 10%)
  - ~1.6% X0 in the barrel
  - ~5% X0 in the endcap
- High & stereo spatial resolution
  - $\sigma_r \approx 150\mu m; \sigma_z \approx 1mm$
- Decouple wire supports from the gas vessel
  - Feedthrough-less design
  - Experienced in MEG-II (but over 2 m and fewer layers)
- Full length 10 layers prototype to be build in 2025 in INFN-Lecce



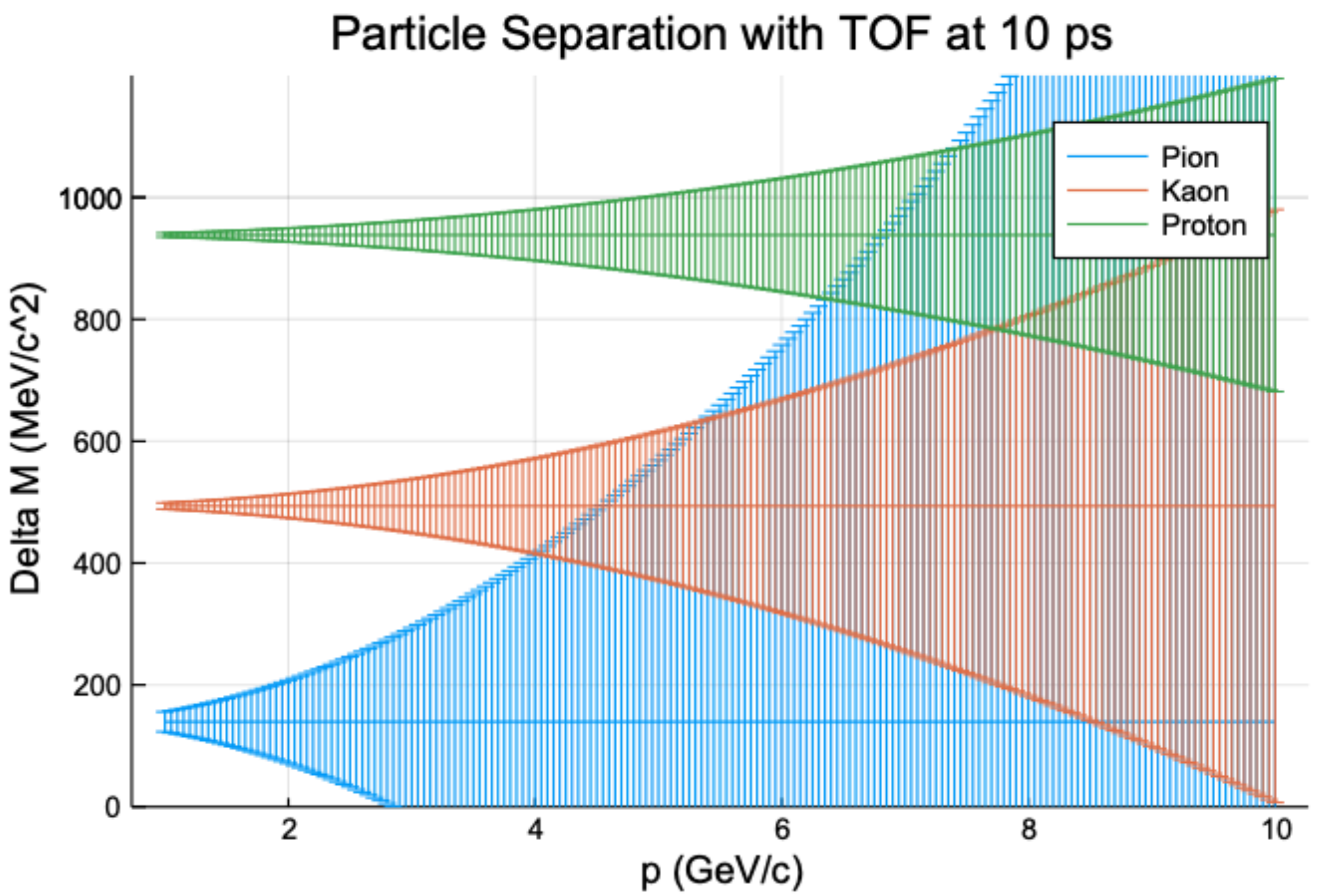
Timing layer(s)

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 ECAL could serve as a powerful Time-of-Flight (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

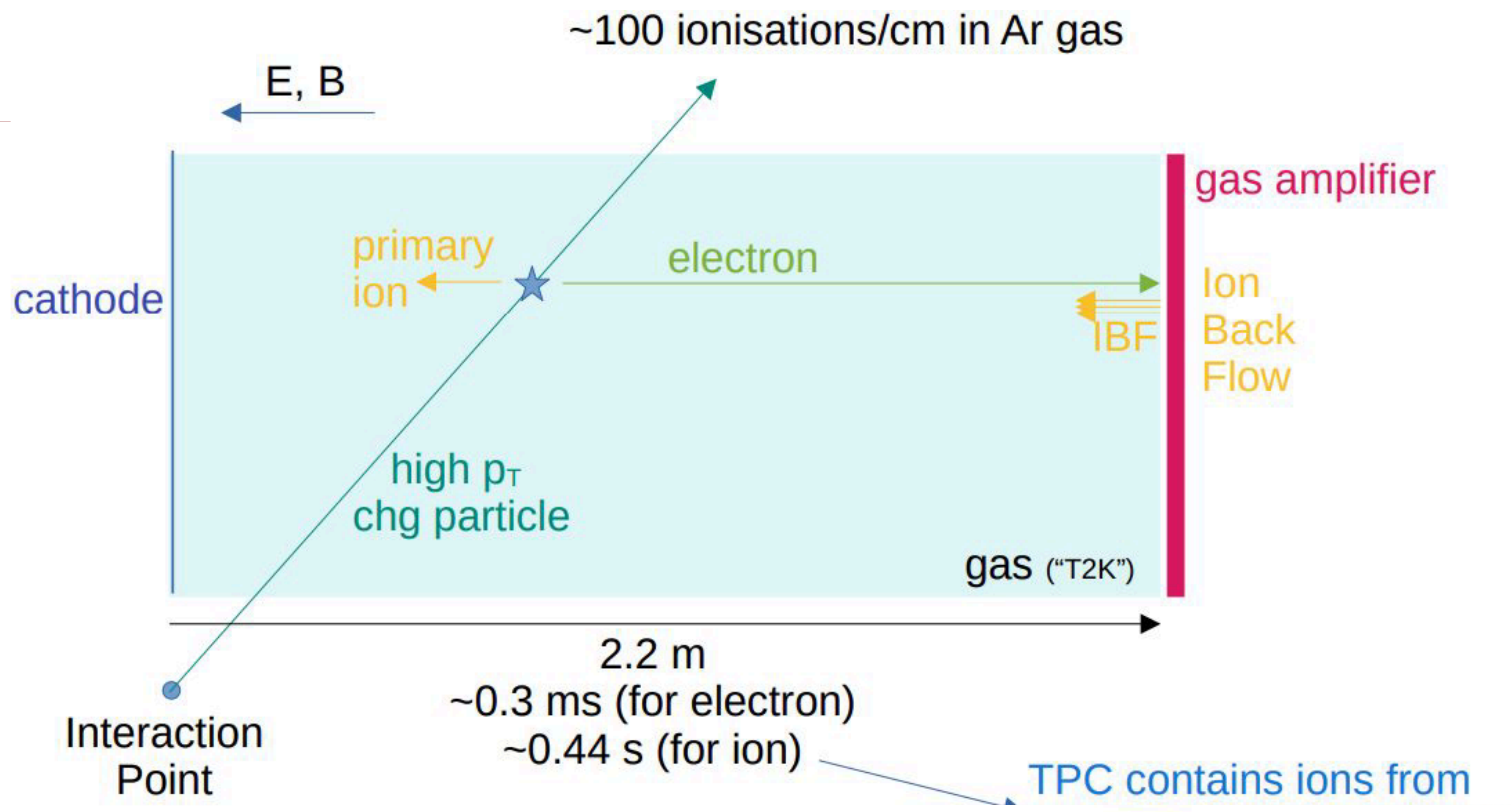
More physics/detector simulation studies needed to refine the case for timing layers

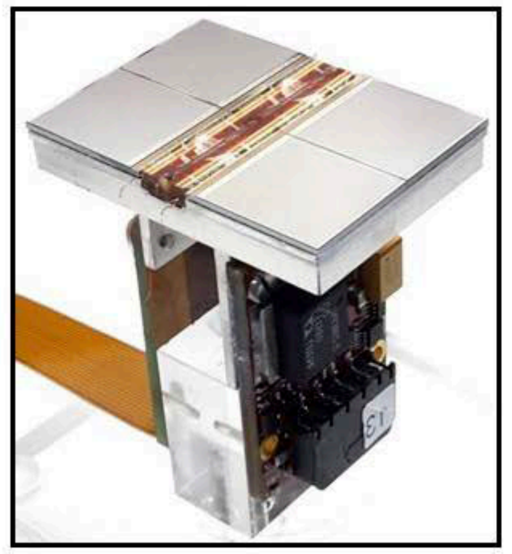


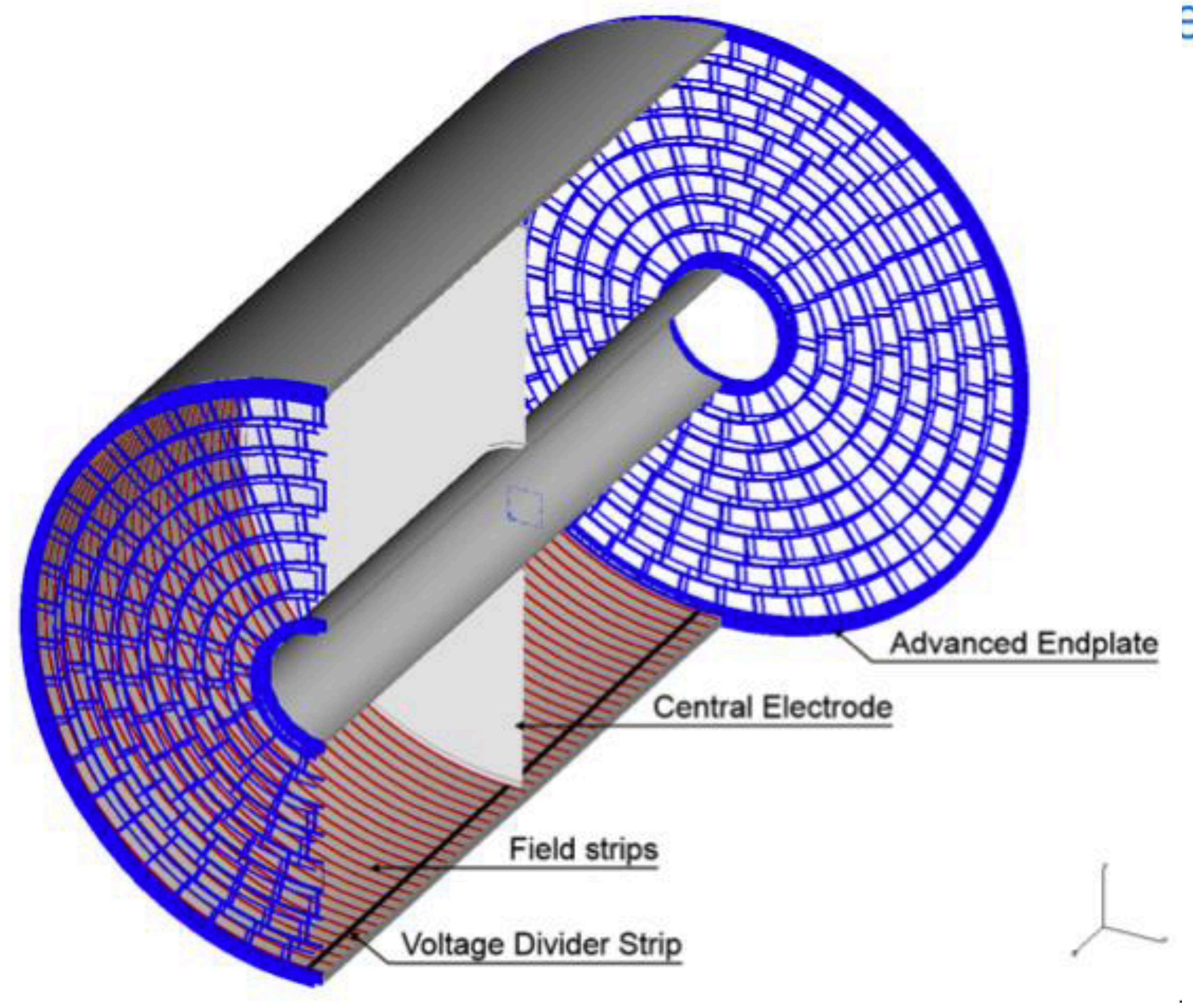
Mass resolution for a TOF system with a performance of 10 ps in SiD

TPC

- Large volume
  - 5-6 meters long, 30 < R[cm] < 200
- Low material budget
  - 5% X0 in the barrel and 25% X0 in endcap
- Use MPGD readout
  - Pad readout
    - Double/Triple GEM
    - Resistive Micromegas
  - Pixel readout
    - GridPix, InGrid (MM+pixel)
      - Superior 2-hit resolution and low gain x IBF
- Good spatial resolution
  - $\sigma_{r-\phi} = 60(\text{near}) - 100(\text{far})\mu m$
  - $\sigma_{r-z} = 0.4(\text{near}) - 1.4(\text{far})mm$
  - Different B-fields might impact resolution
    - 3 T for ILC ; 2 T for FCC-ee



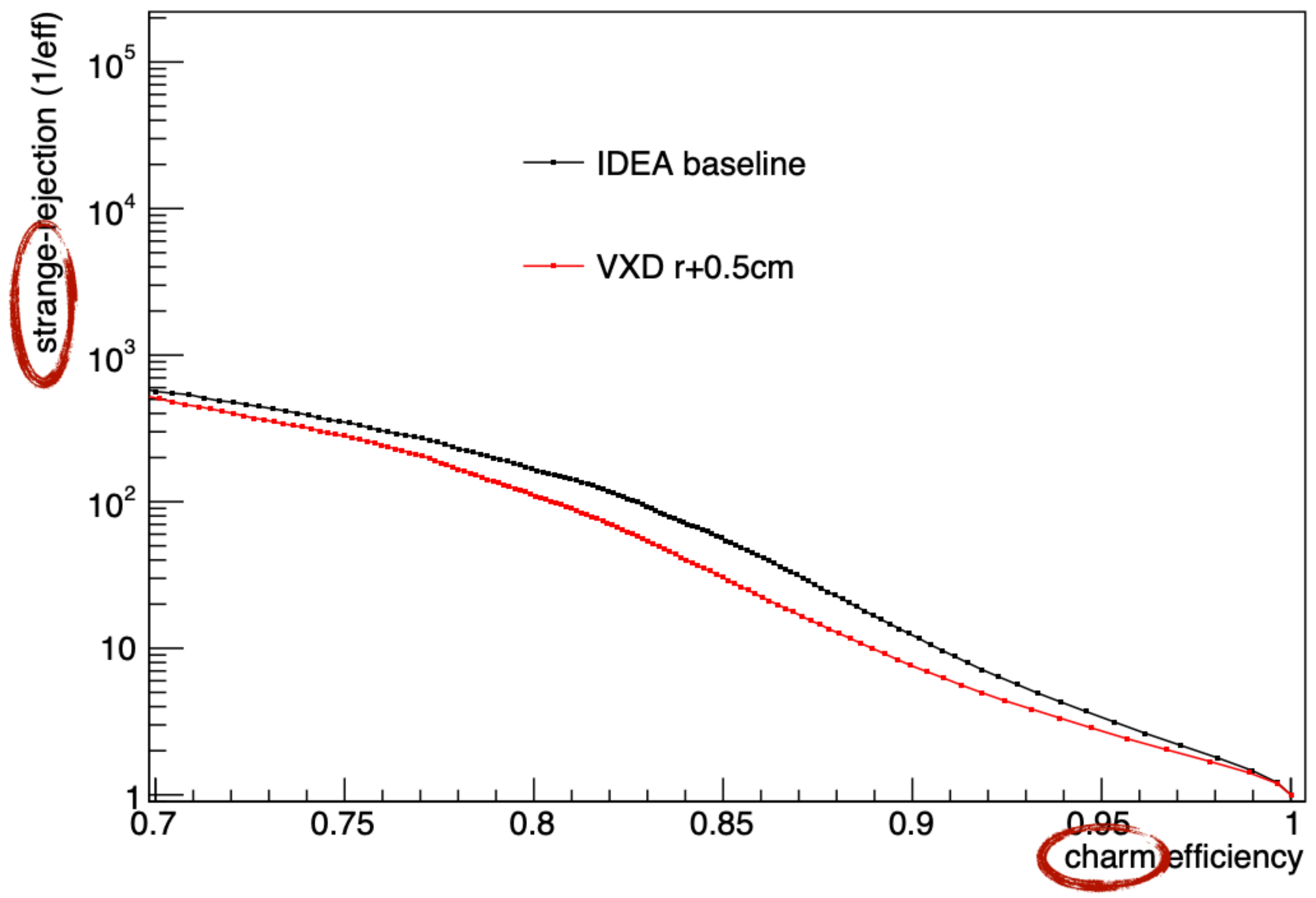


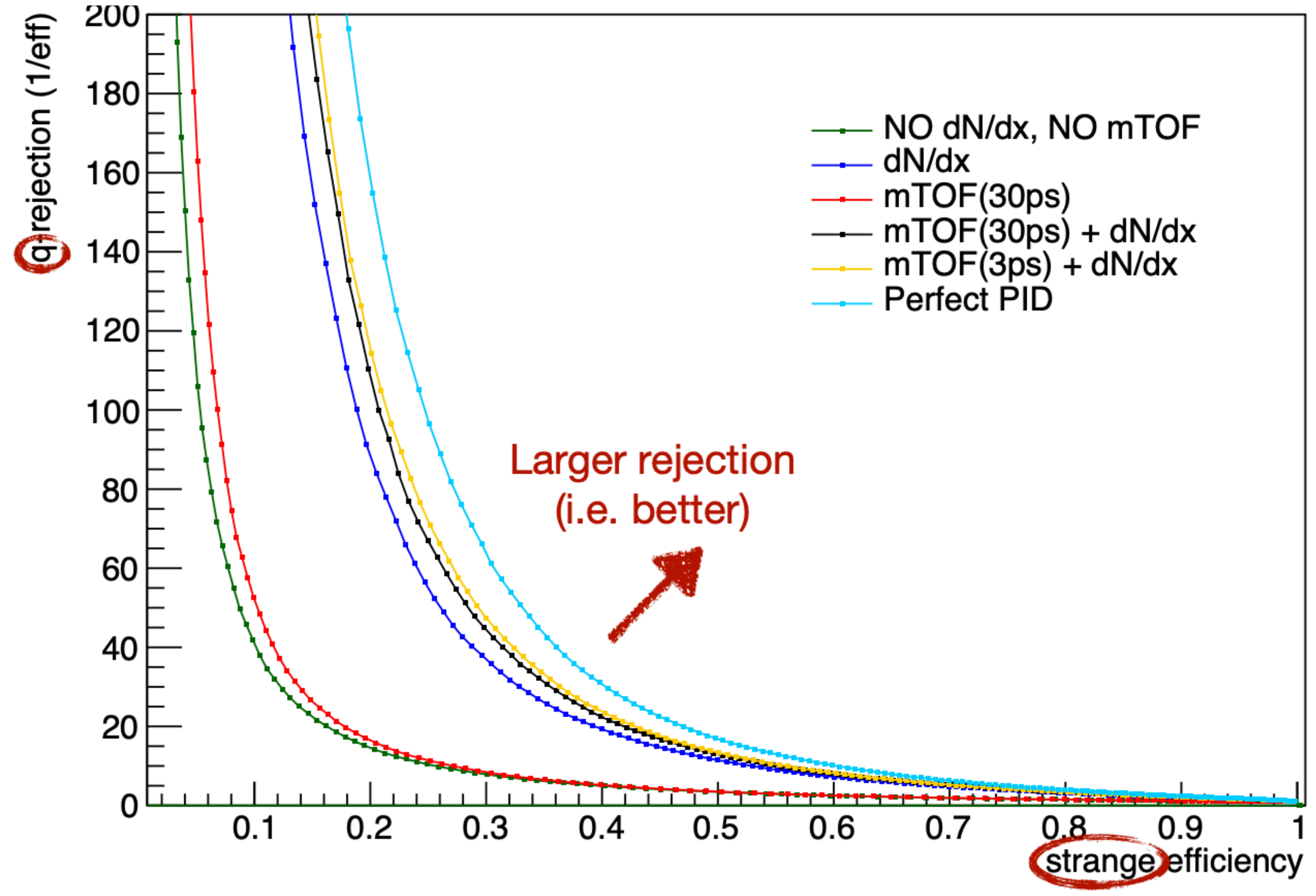


IDEA: tagging performance vs detector configurations

Evaluating impact of different silicon and particle-identification detector configurations

- Current IDEA pixel/tracking system:
  - beam pipe at 1cm and 3 innermost silicon barrel layers: 1.2cm, 2cm, 3.15cm
  - PID: cluster-counting (dN/dx) + 30ps ToF system
- Number of pixel layers and various configurations have been tested
  - Hit resolution & position first layer
  - PID capabilities: timing, energy loss (gas/silicon)
- ***Findings***:
  - Very limited impact of TOF mass measurement on strange tagging
  - Ideal PID shows visible enhancement, especially at low efficiency





A. Sciandra ECFA 2024

Detector Designs, a quick overview

A tail of synergies and complementarity

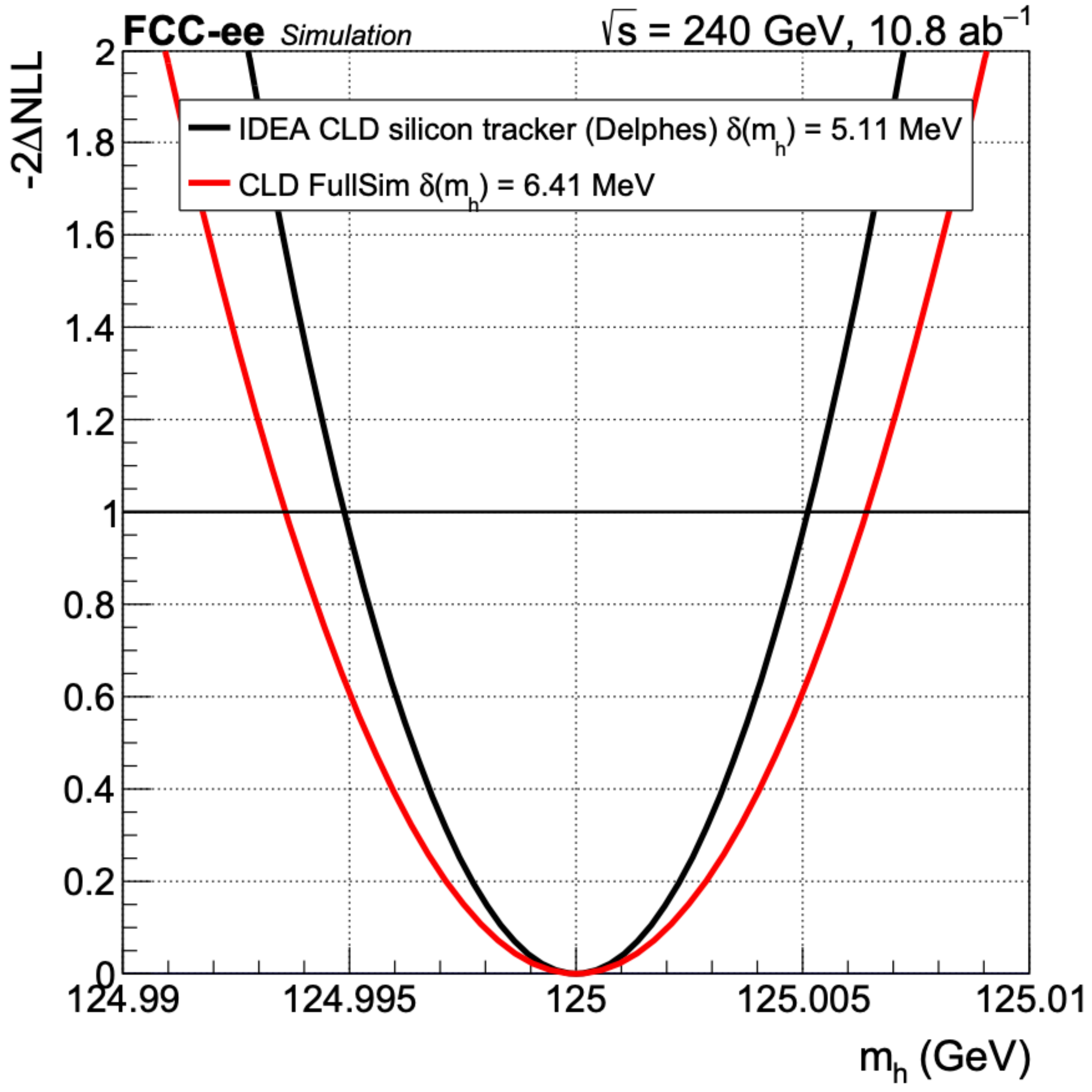
	IDEA	CLD	ALLEGRO
Vertex Inner Radius (cm)	1.2	1.2	1.2
Tracker technology	Si+Drift Chamber	Si	Si+Drift Chamber
Outer Tracker Radius (m)	2	3.3	2
ECal thickness	Dual RO	22 X_0	22 X_0
HCal thickness	7 λ_0	6.5 λ_0	9.5 λ_0
HCal Outer Radius (m)	4.5	3.5	4.5
Solenoid field (T)	2	2	2
Solenoid length (m)	6	7.4	6
Solenoid Radius (m)	2.1	4	2.7

RICH?
extra space at the expense of other sub-detectors

Timing? Different performance domains have different use cases:
O(nsec). Bunch identification.
< psec. pi/K separation for O(10 GeV) momentum

Fast vs Full Sim

arXiv:2503.19983
FCC Feasibility Report

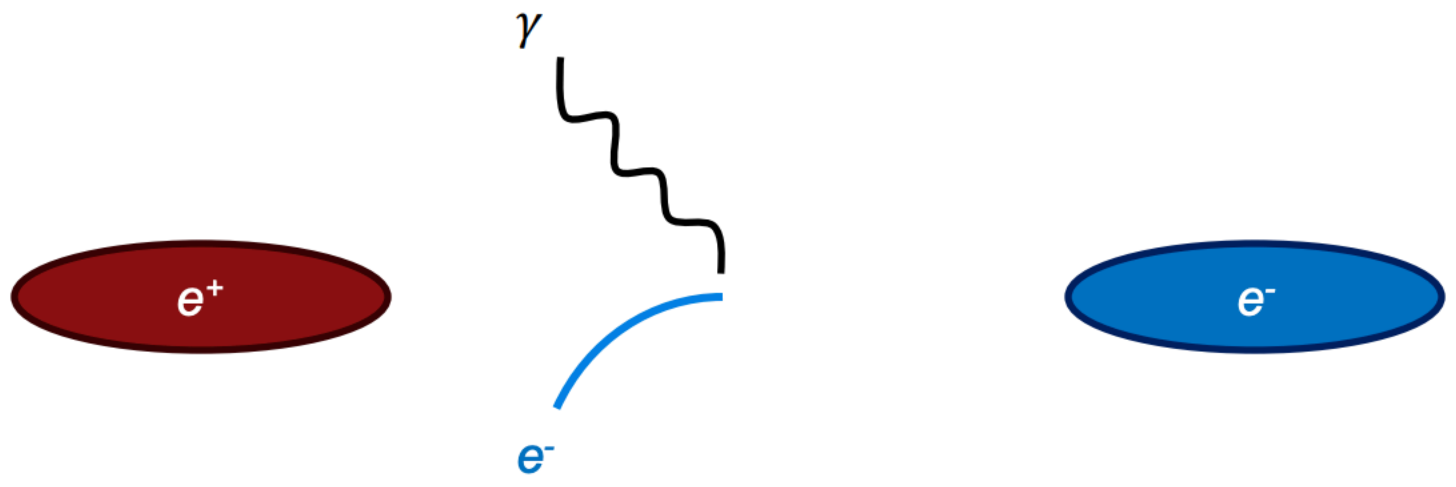


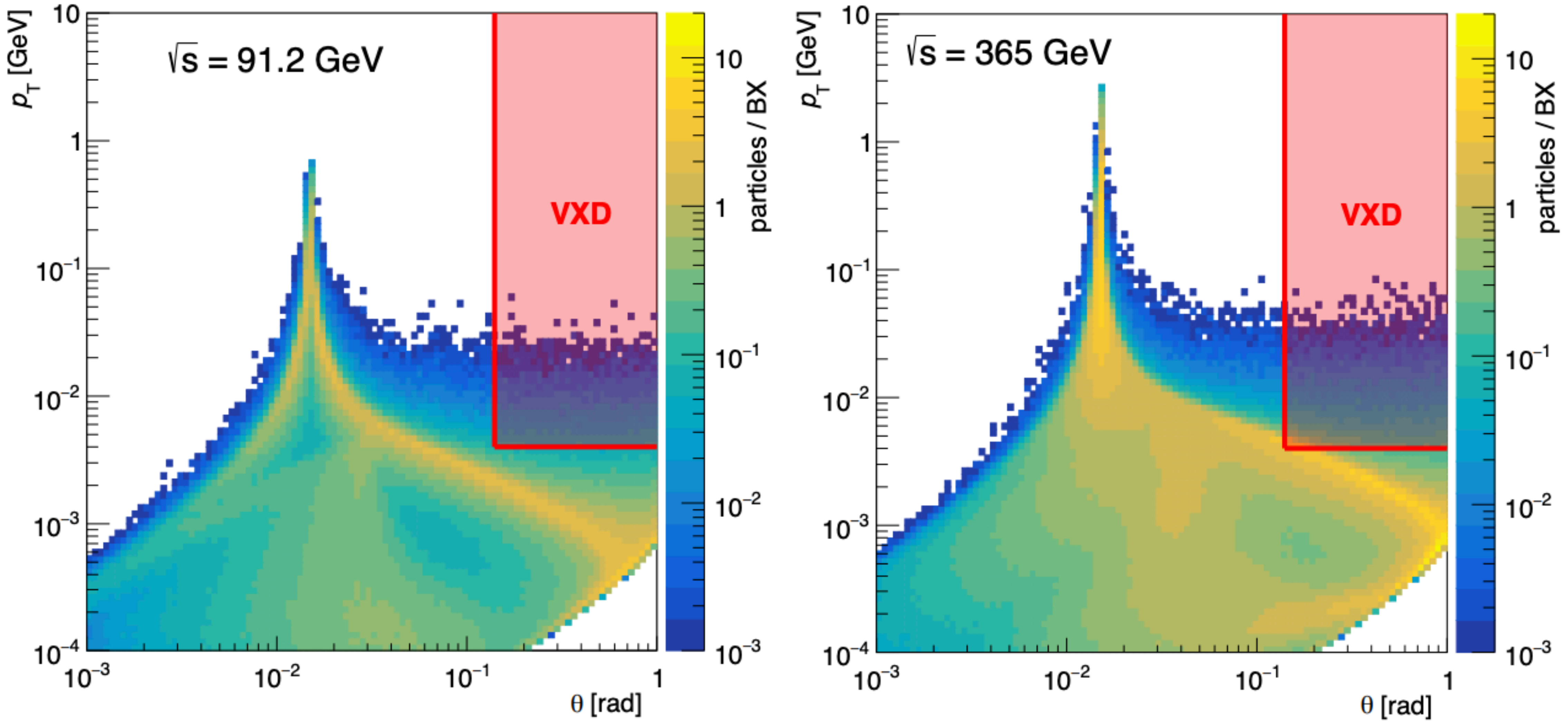
Importance of beam-beam background

D.Ntounis @LCWS 2025
FCC Feasibility Report
arXiv:2403.07093

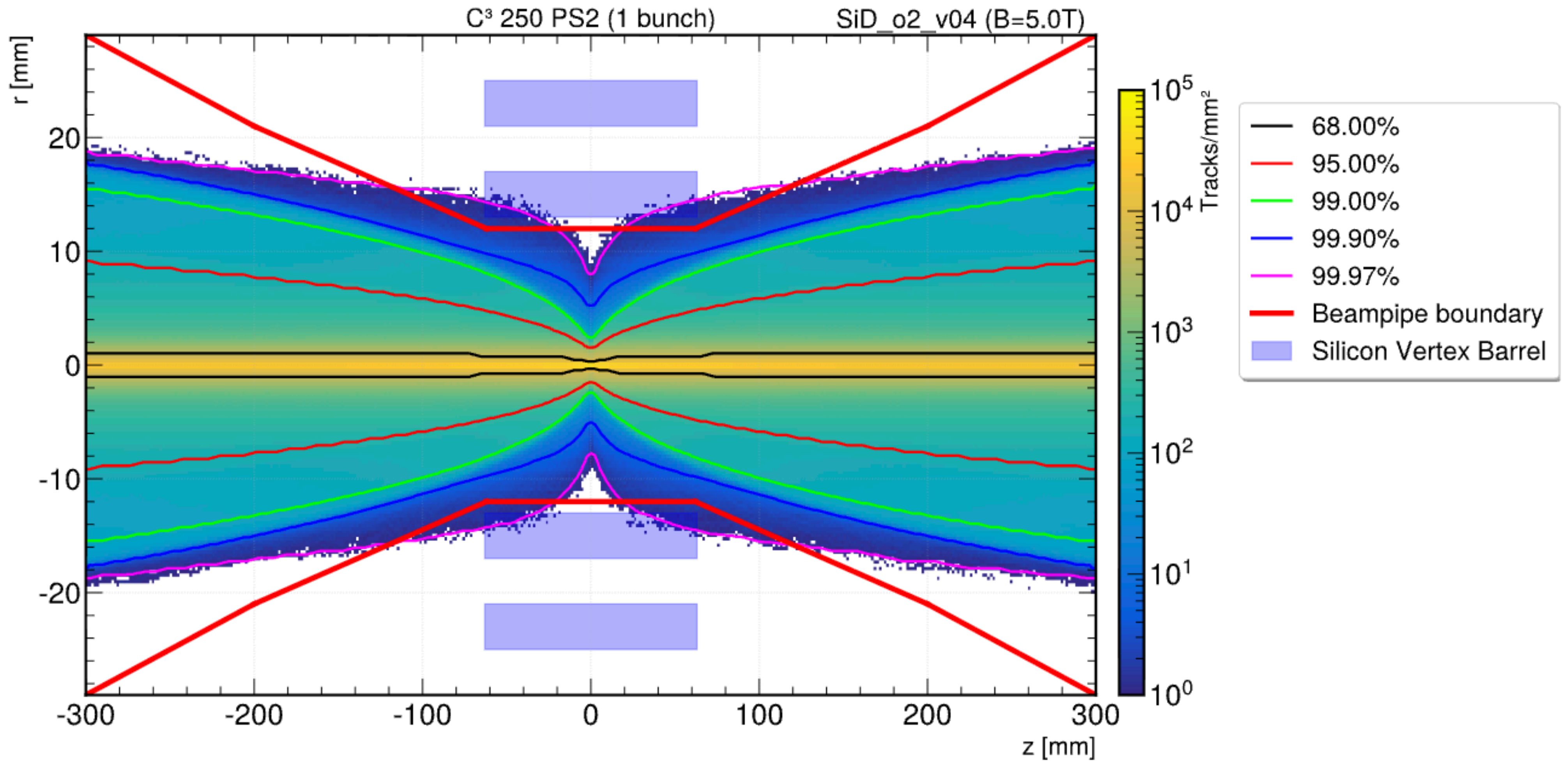
The effects of beam-beam interactions have to be careful simulated for physics and detector performance

Beamstrahlung photons are radiated at the IP and can produce:
- Incoherent pair production
- Muon and Hadron photo-production





Beamstrahlung widens the luminosity spectrum
- Enables collisions at lower $\sqrt{s}$
  → important for physics observables (ZH)
- High flux (occupancy) in vertex barrel and forward sub detectors
  → **Impacts (vertex) detector design**

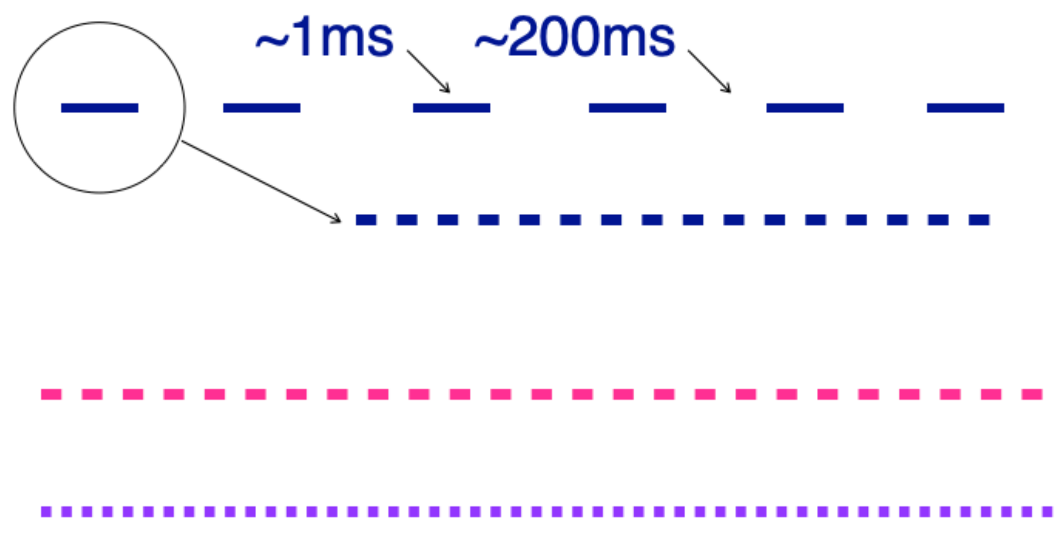


Beam-background studies

[G. Marchiori (2023)](#)
[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·mm²) ≃ 0.03 hits/mm² /BX
- CLD detailed studies @FCC show an overall occupancy of 2-3% in the vertex detector at the Z pole
  - assuming 10μs integration time



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

FCC@ZH Bunches 1 μs apart

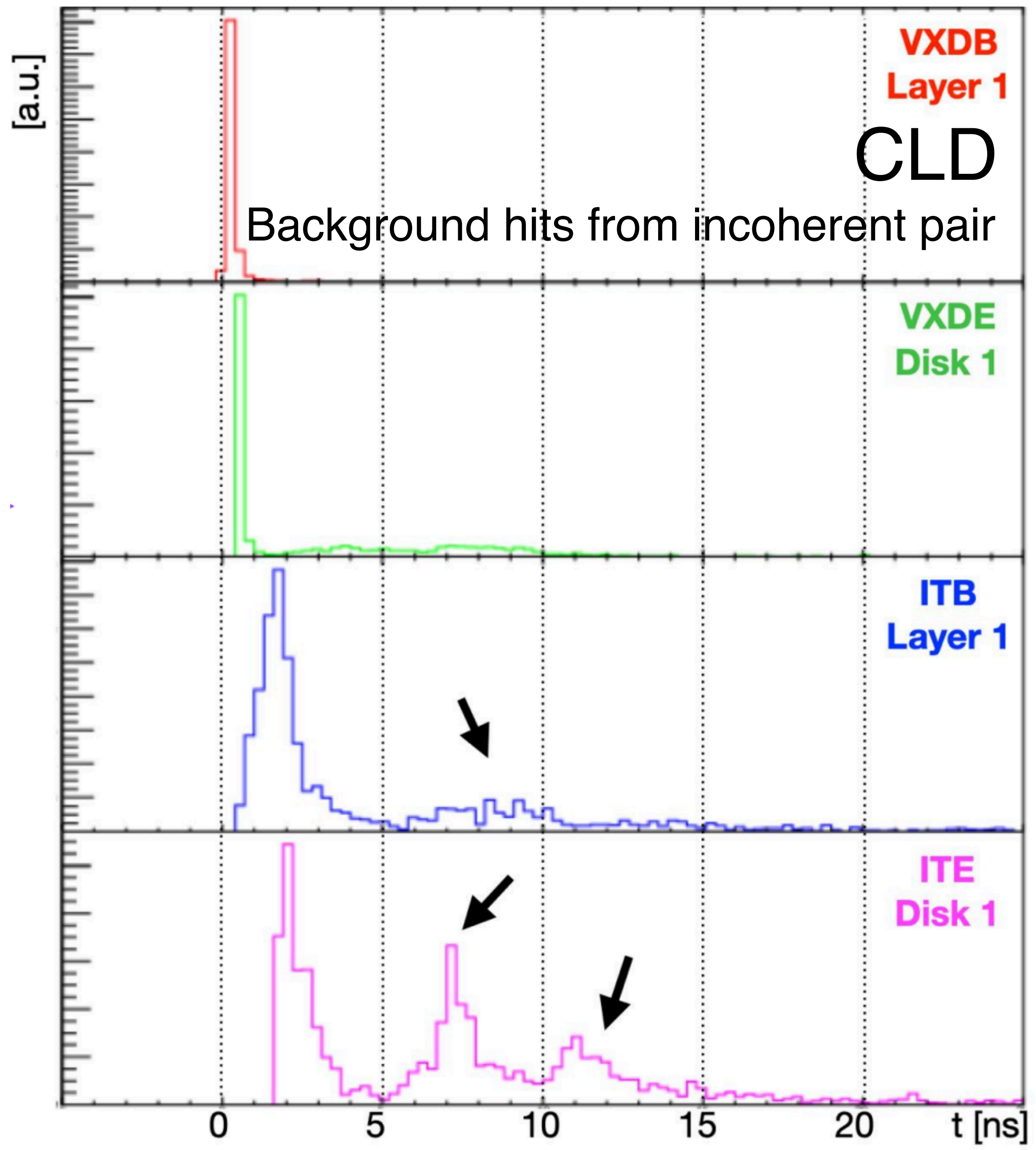
FCC@Z Bunches 20 ns apart

	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)

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

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



G. Marchiori (2023)
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Impact of beam-induced background to be mitigated through MDI and detector design

O(1-10) ns for beam background rejection and/or trigger decision before reading out the detector

	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
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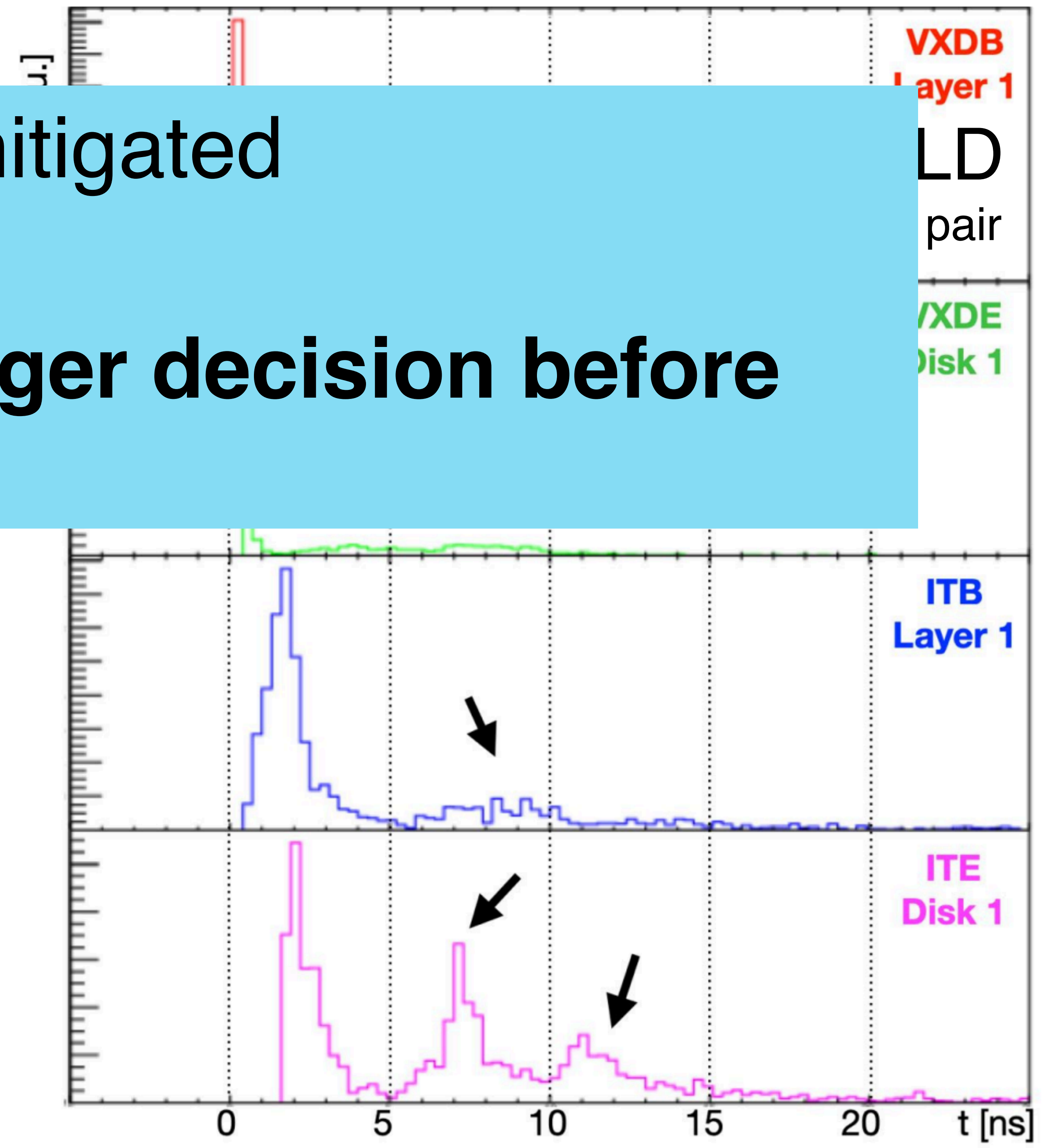
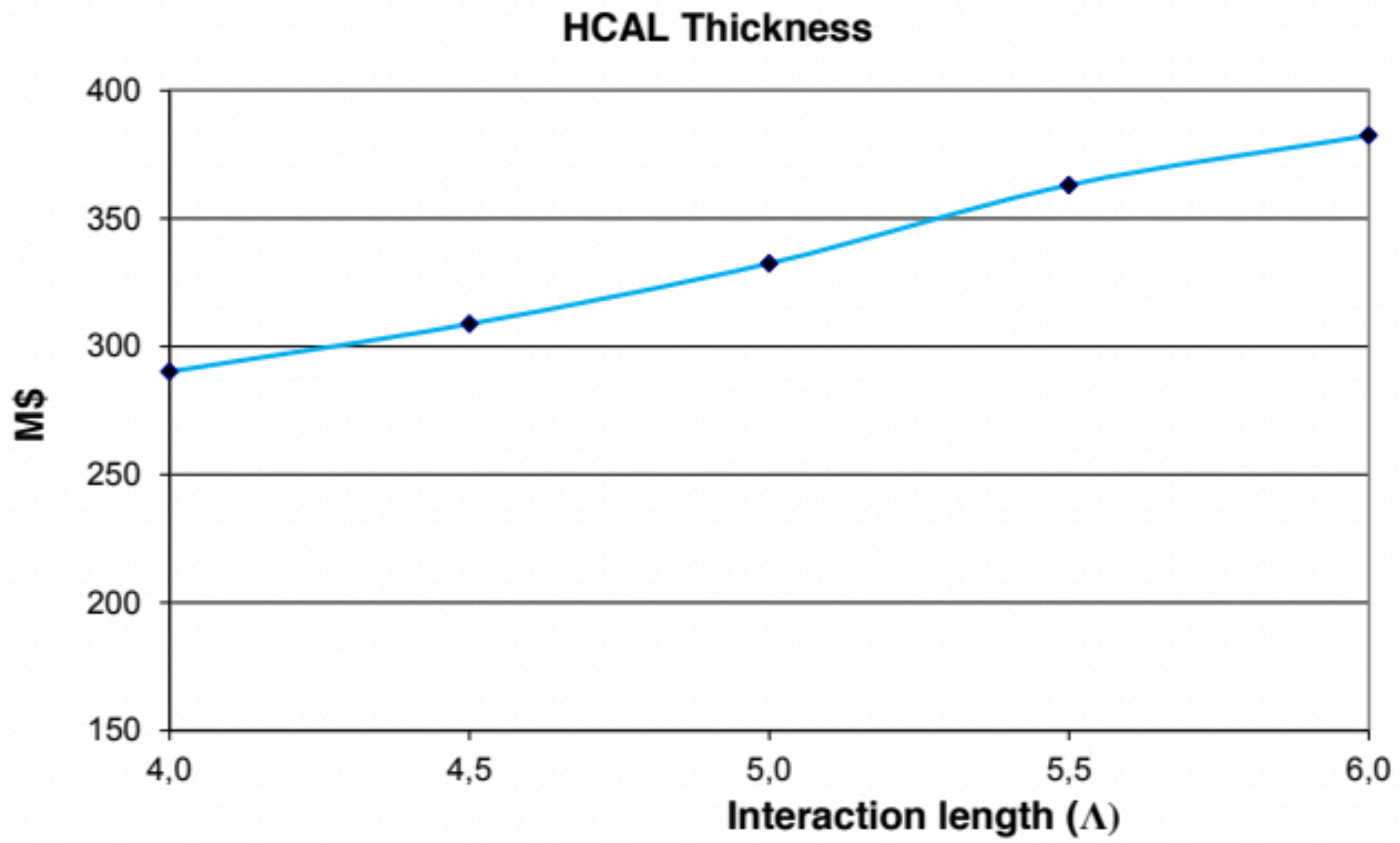
Occupancy in readout window (10μs)

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

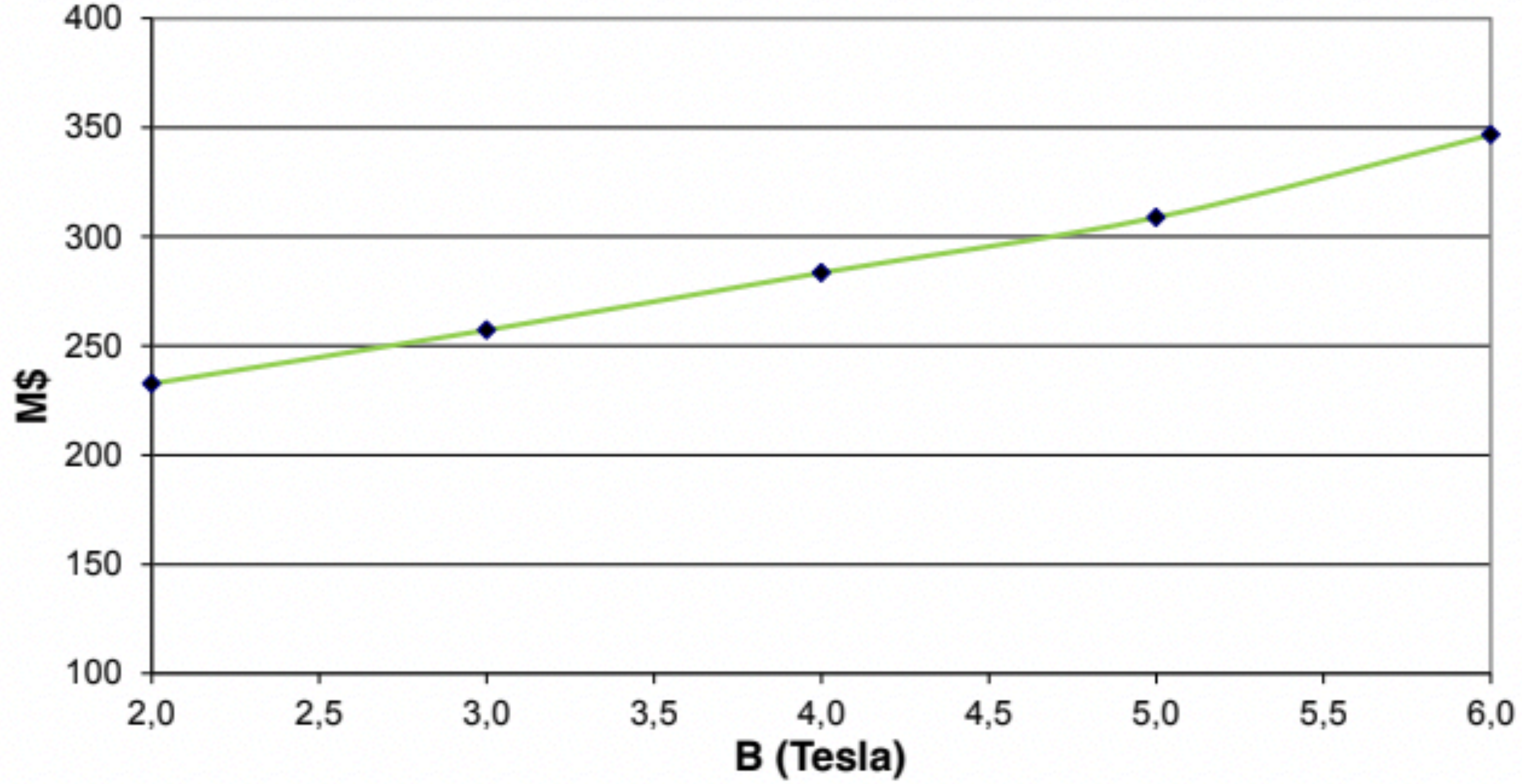
$$size_{sensor} = \begin{matrix} 25\mu m \times 25\mu m \ (pixel) \\ 1mm \times 0.05mm \ (strip) \end{matrix} \qquad size_{cluster} = \begin{matrix} 5 \ (pixel) \\ 2.5 \ (strip) \end{matrix} \qquad safety = 3$$



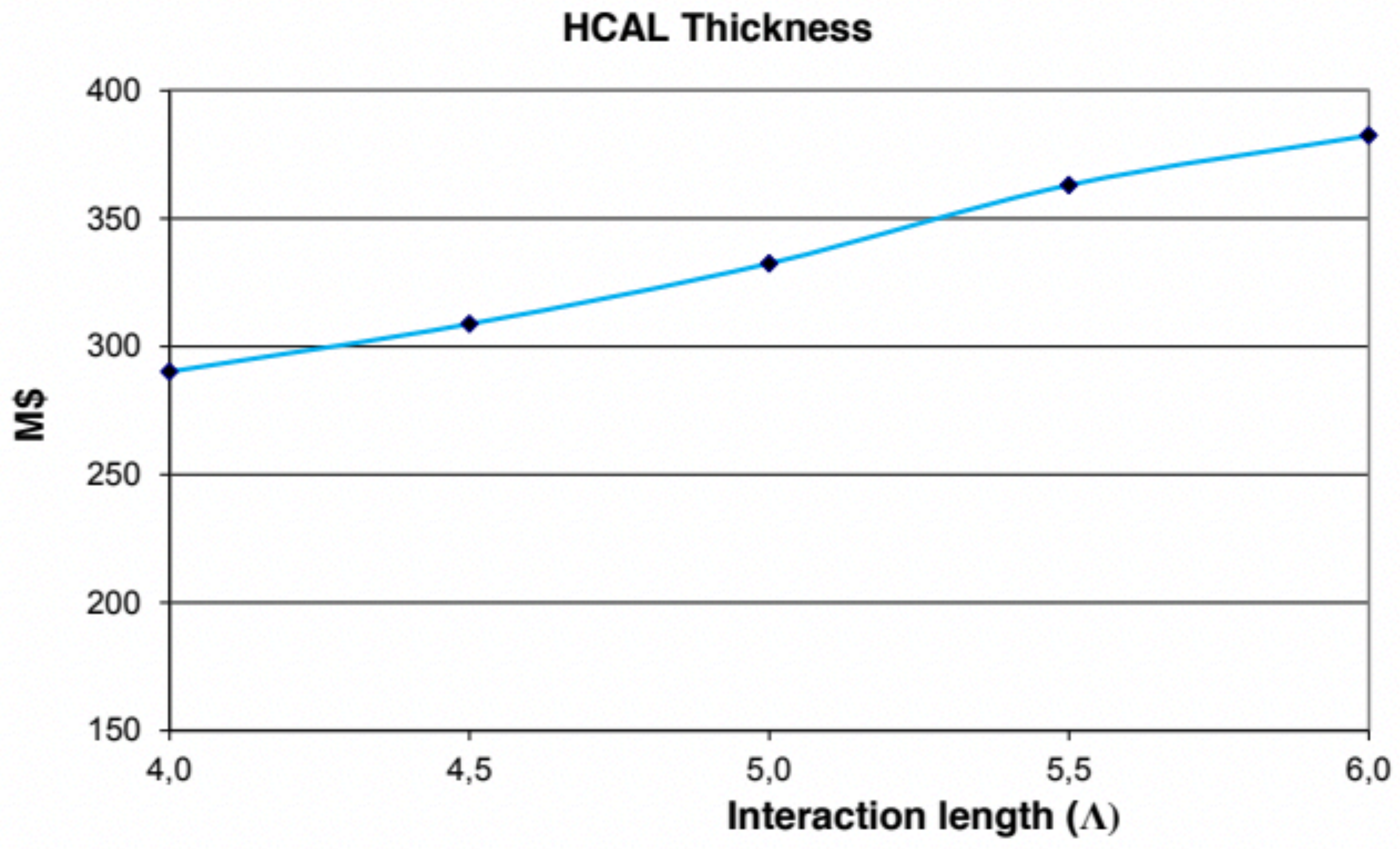
Cost profile



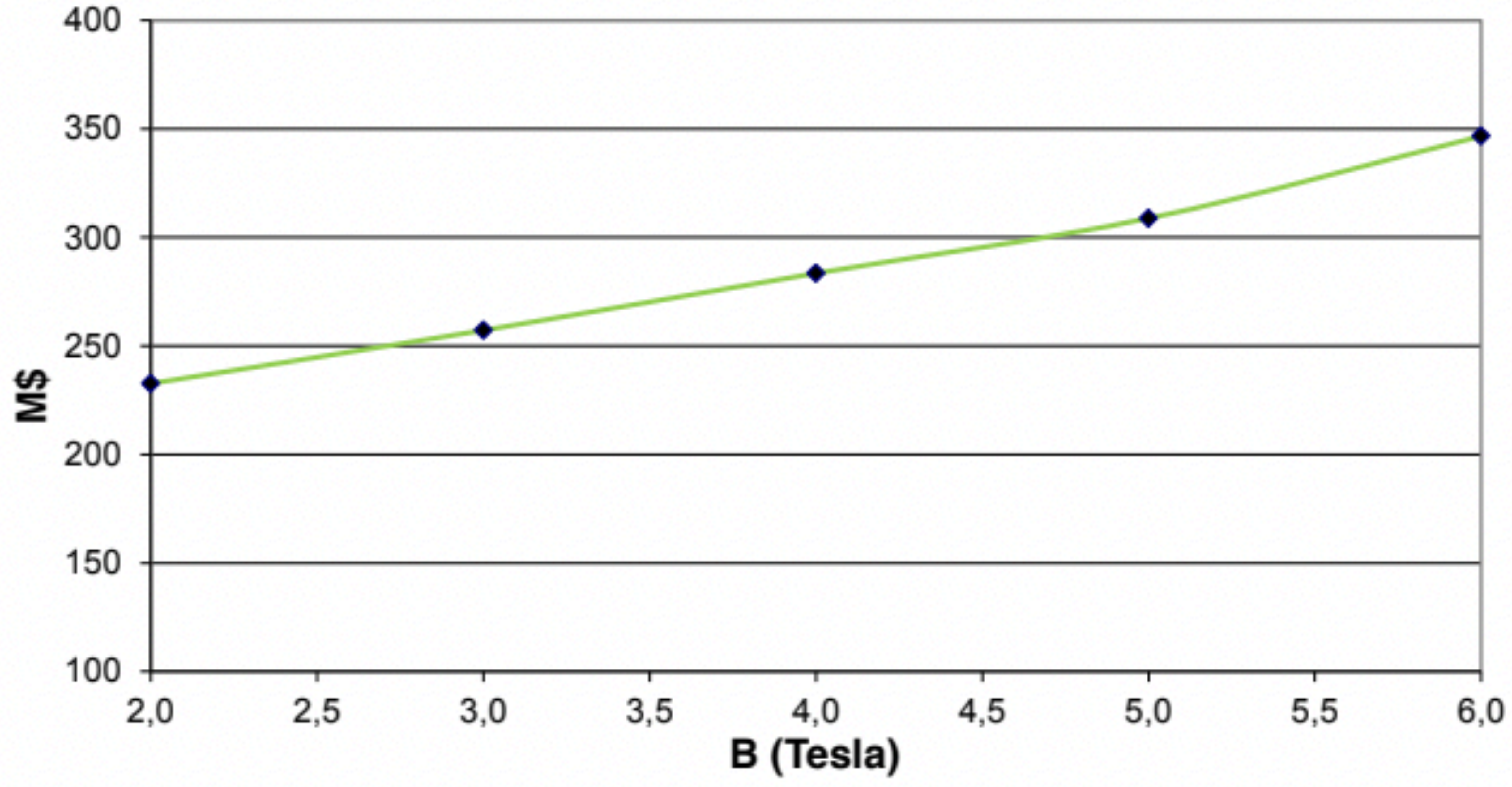
[ILC Technical Design Report 2013](#)



Cost profile



[ILC Technical Design Report 2013]



Magnet and Calorimeters are generally driving the cost (>30% each) of the detector
Optimizations and cost reduction are possible with targeted R&D
Physics benchmarks will have to guide overall detector optimization