Strange-quark Tagging for Higgs and EW Physics

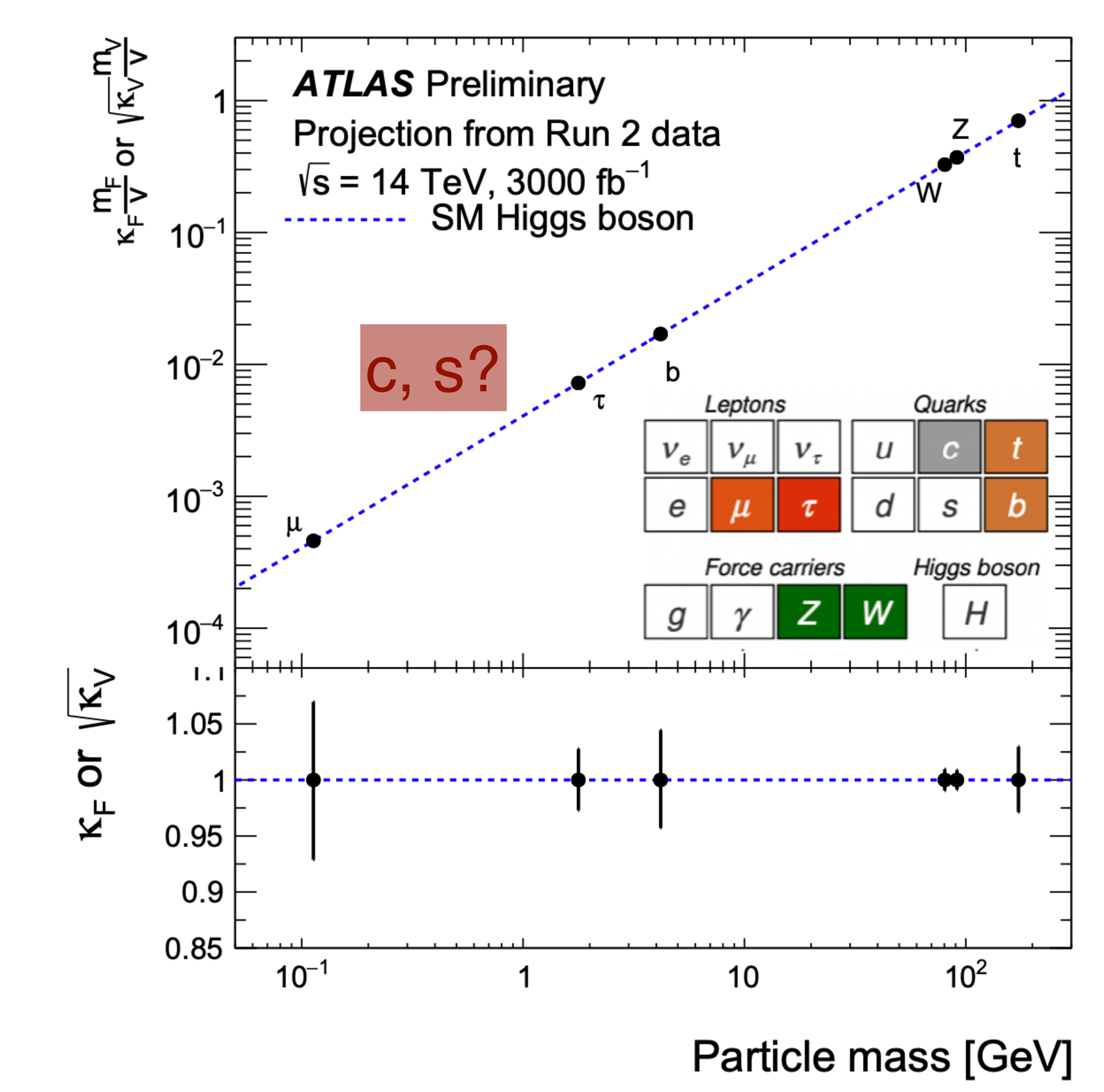
Caterina Vernieri on behalf of the **HtoSS group (twiki)**

Valentina Cairo, Taikan Suehara, Loukas Gouskos, Matt Basso, John Alison, Yotam Soreq, Valerio Dao, Karsten Koeneke (ex officio)

October 11, 2023

Paestum, ECFA Workshop on e+e-

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 Zγ and charm and ~50% on the self-coupling**

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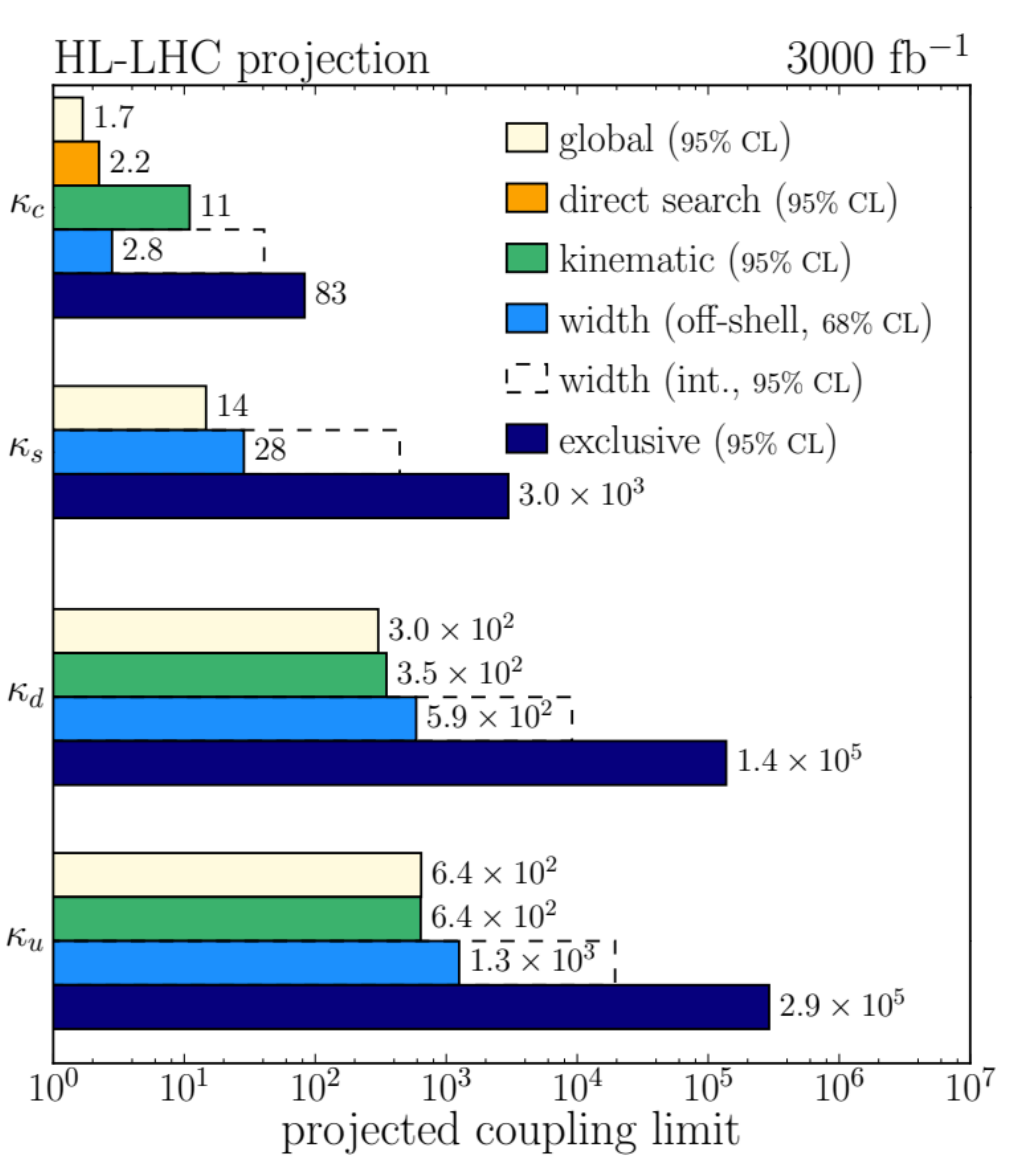
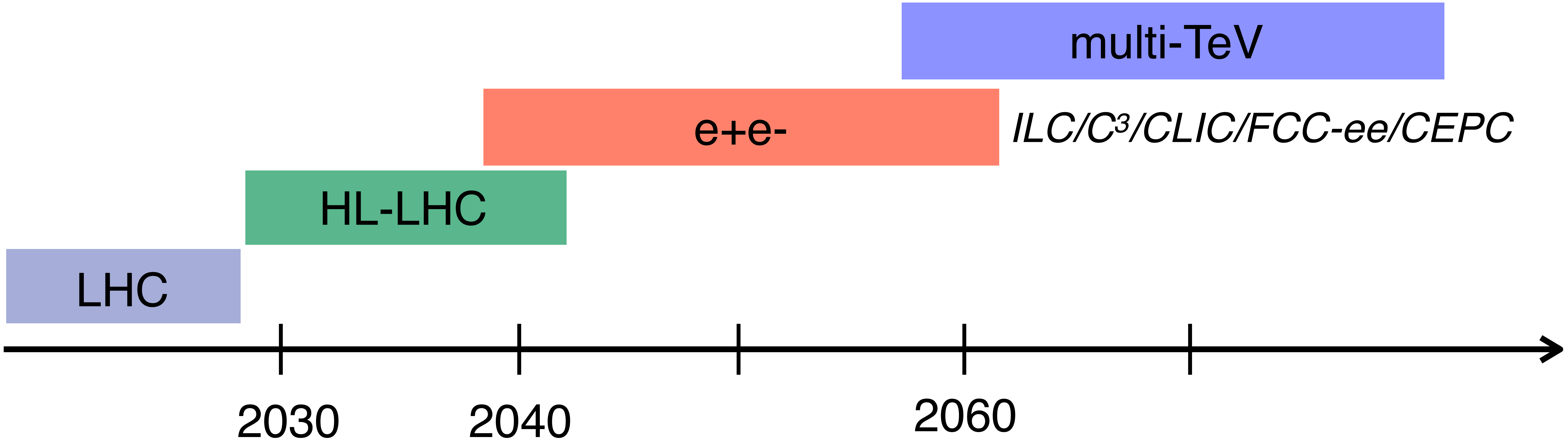
CERN-LPCC-2018-04

Higgs at HL-LHC



Light Yukawa out of reach in the LHC environment

Beyond - A dreamy roadmap

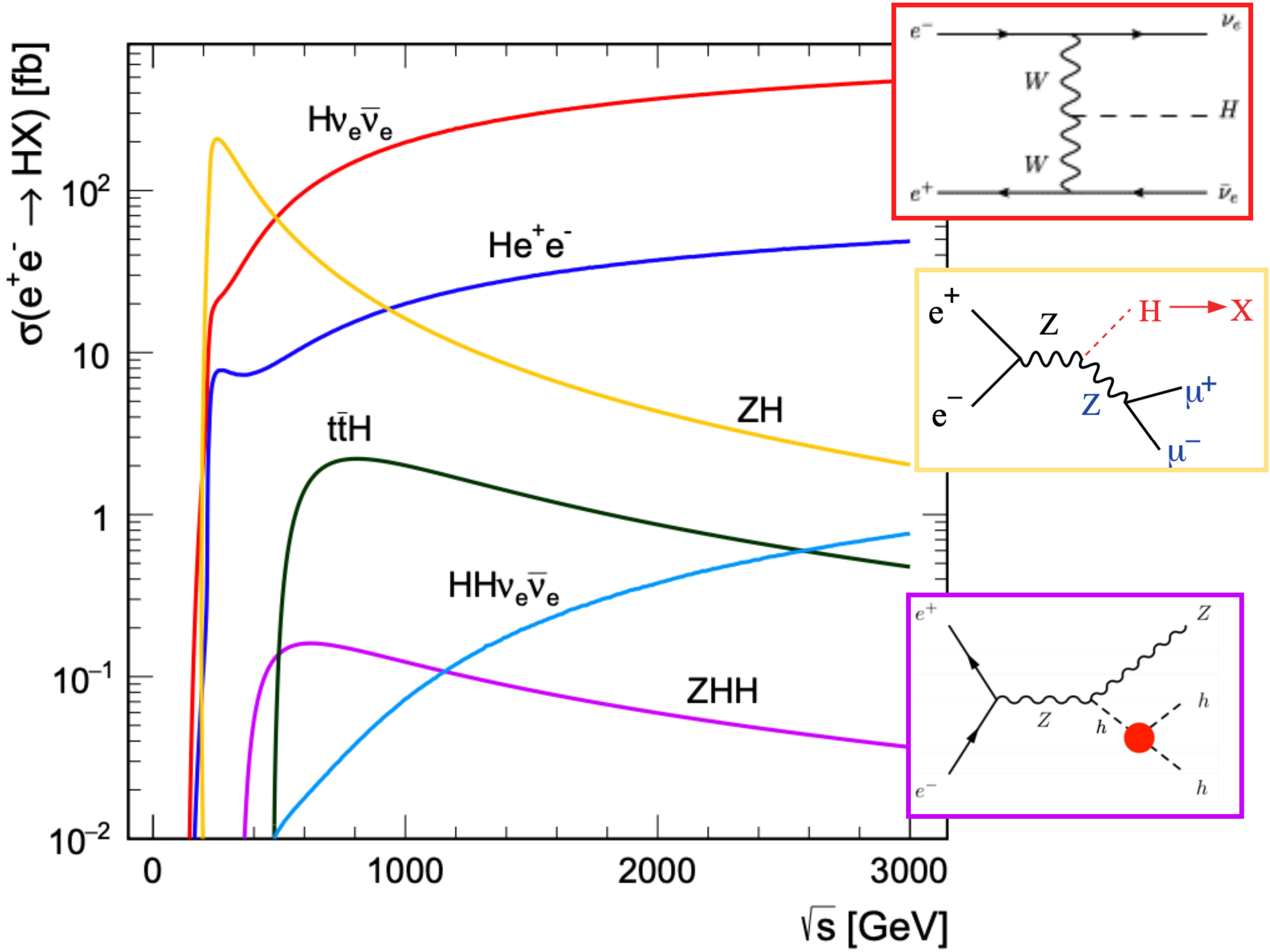


H couplings to: **O(5-10)%** **O(0.1-1)%** **O(1)‰**

Physics goals beyond HL-LHC:

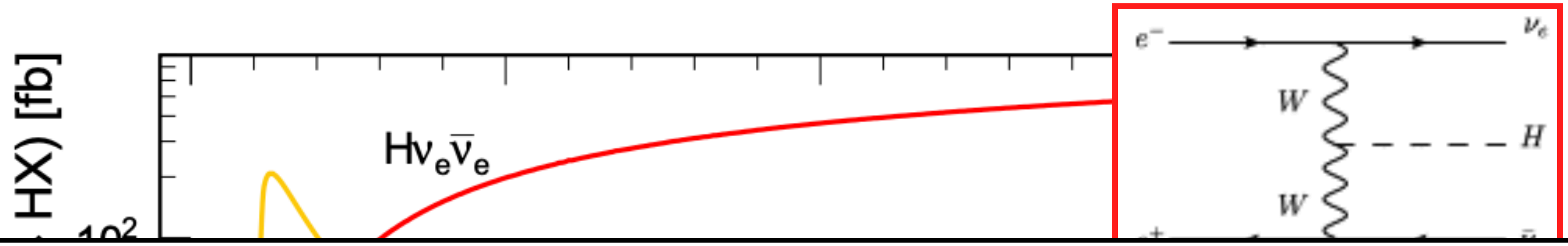
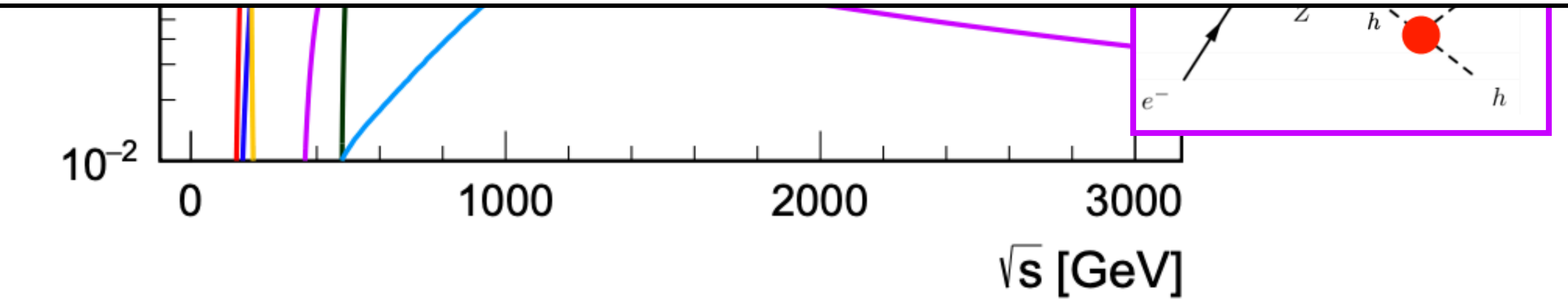
1. Establish Yukawa couplings to light flavor ⟹ precision & lumi
2. Search for invisible/exotic decays and new Higgs ⟹ precision & lumi
3. Establish self-coupling ⟹ > 500 GeV e+e- operations

Higgs at e+e-



- 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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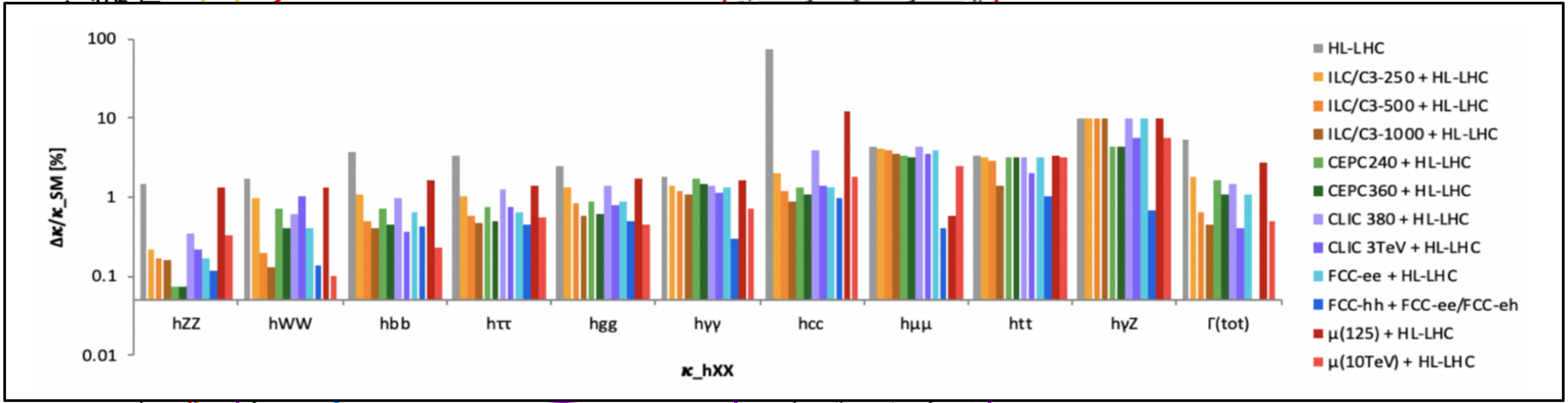


Beyond EFT, is there more?

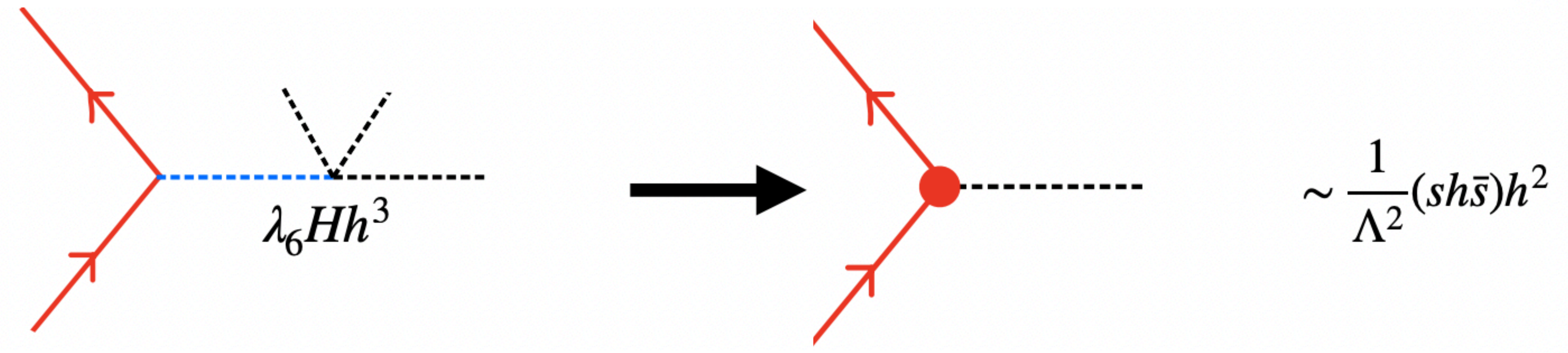
Higgs to strange coupling is an appealing signature to probe new physics

Is the Higgs the source for all flavor?

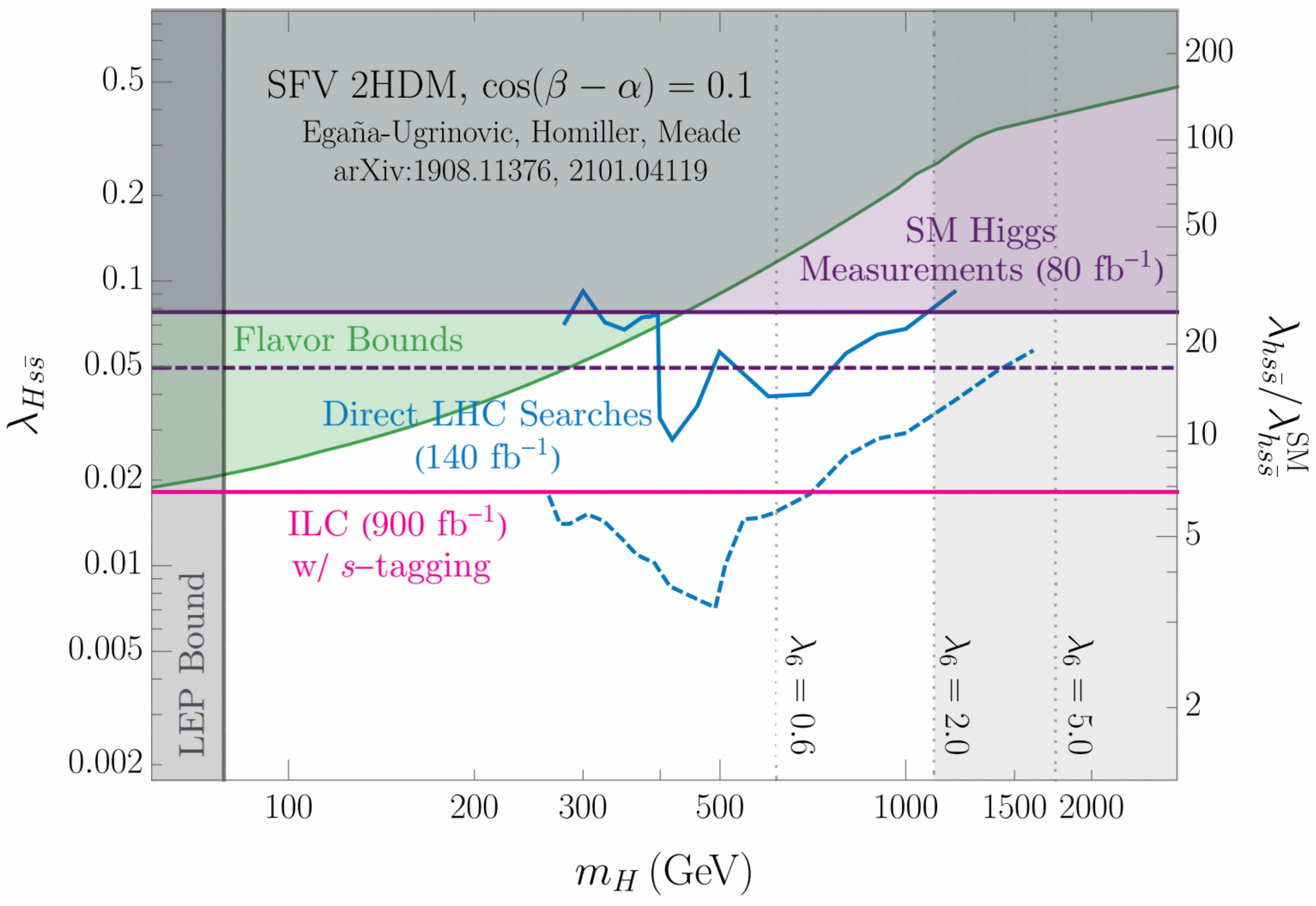
An option, **Spontaneous Flavor Violation**

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

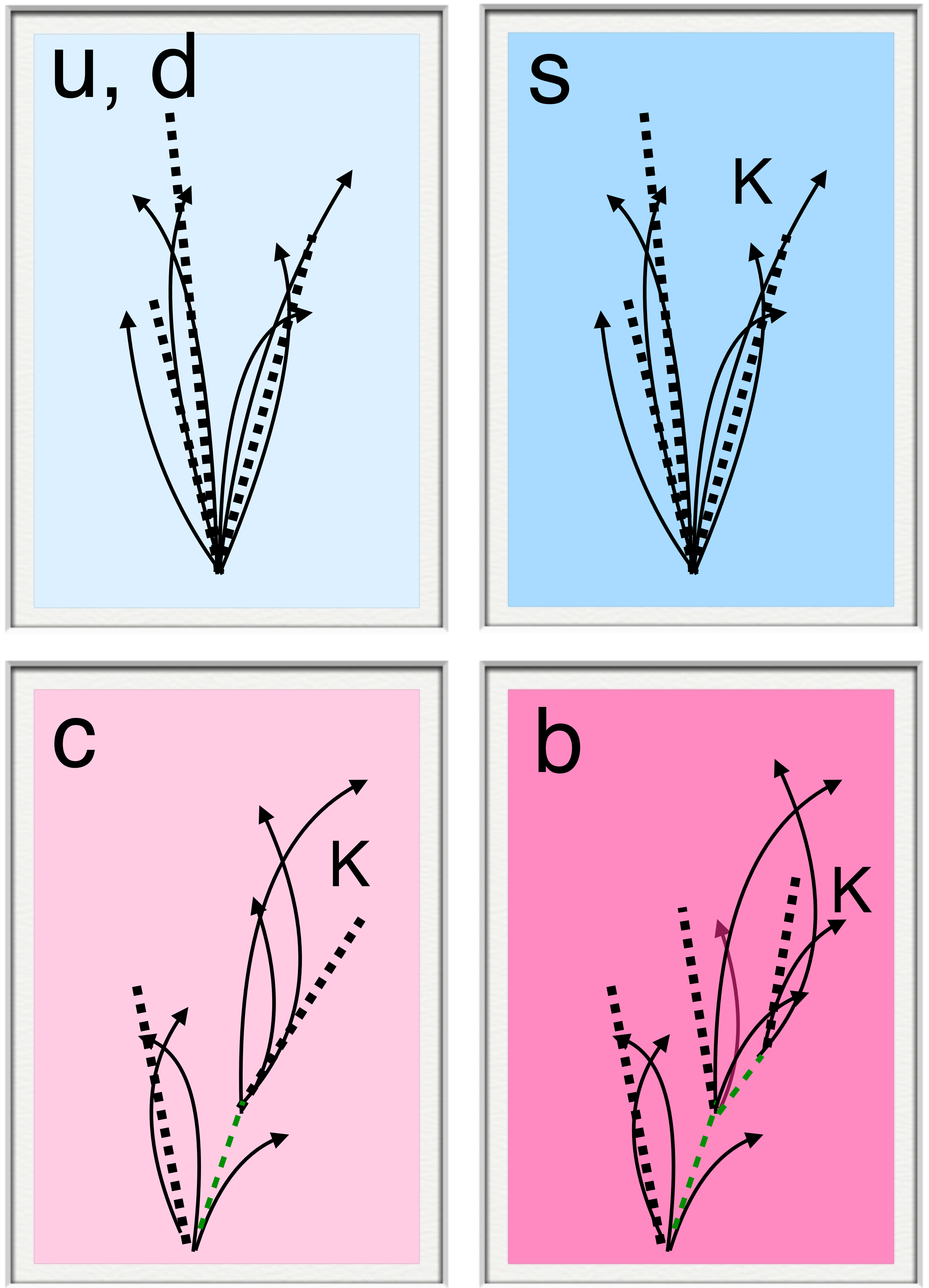


P. Meade



s-tagging

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



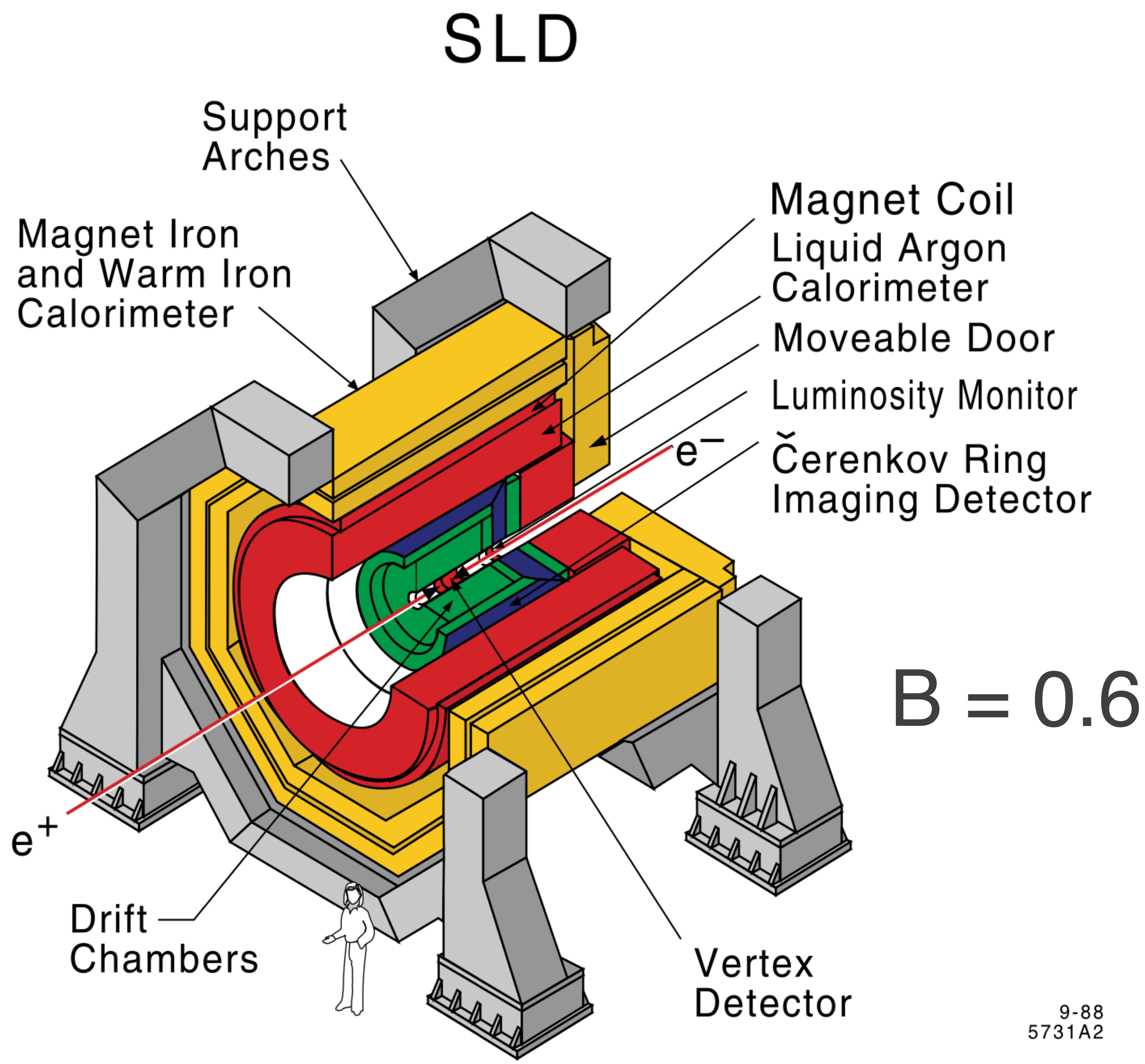
- As b,c, and s jets contain at least one strange hadron
- Strange quarks mostly hadronize to prompt kaons which carry a large fraction of the jet momentum
- Strange hadron reconstruction:
  - $K^{\pm}$ PID
  - K^0_L PF (neutral)
  - $K^0_S \rightarrow \pi^+\pi^-$ (~70%) / $\pi^0\pi^0$ (~30%)
  - $\Lambda^0 \rightarrow p\pi^-$ (~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

s-tagging in the past

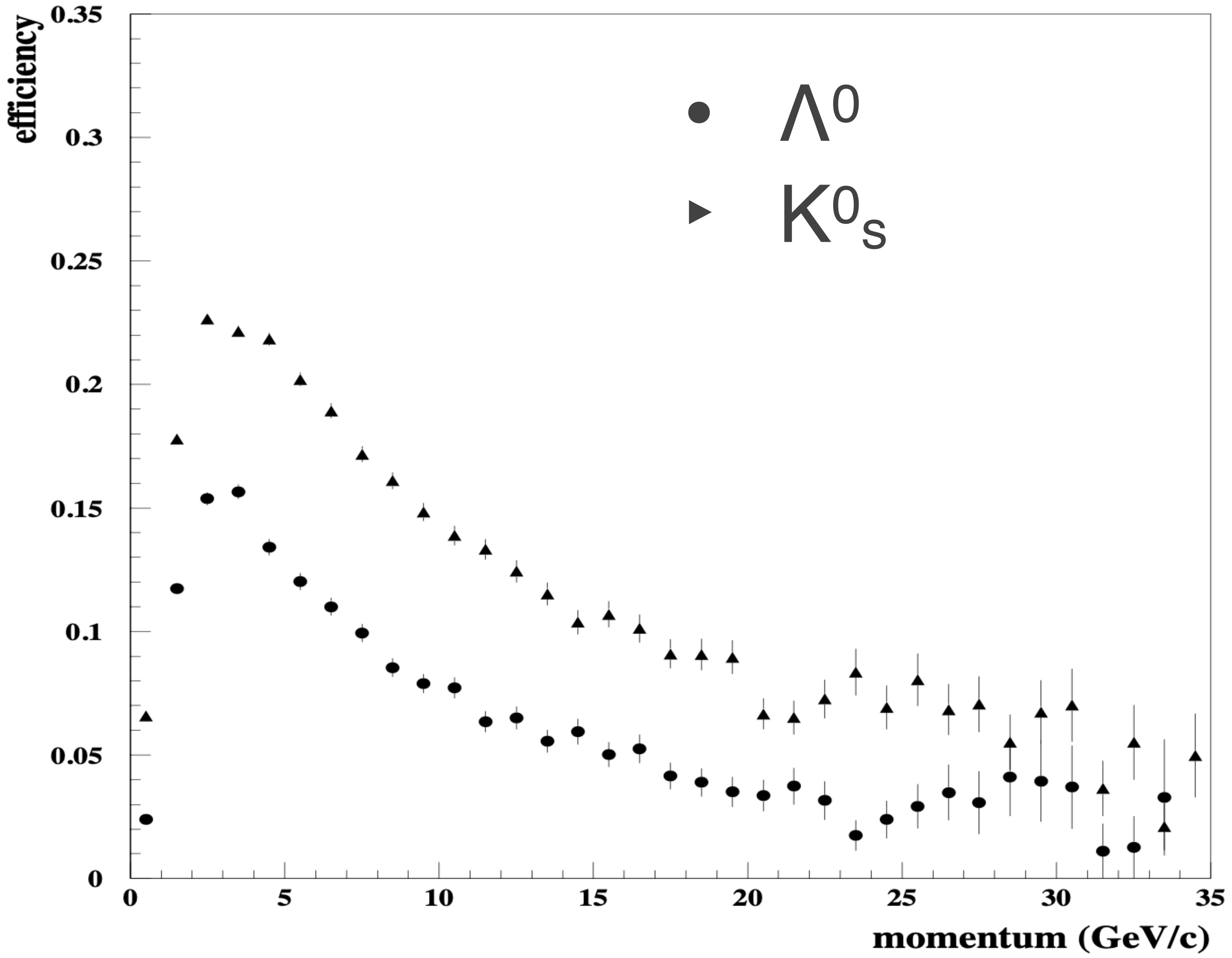
SLD at SLC (e+e- at the Z) measured asymmetry in $Z \to s\bar{s}$



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 %)

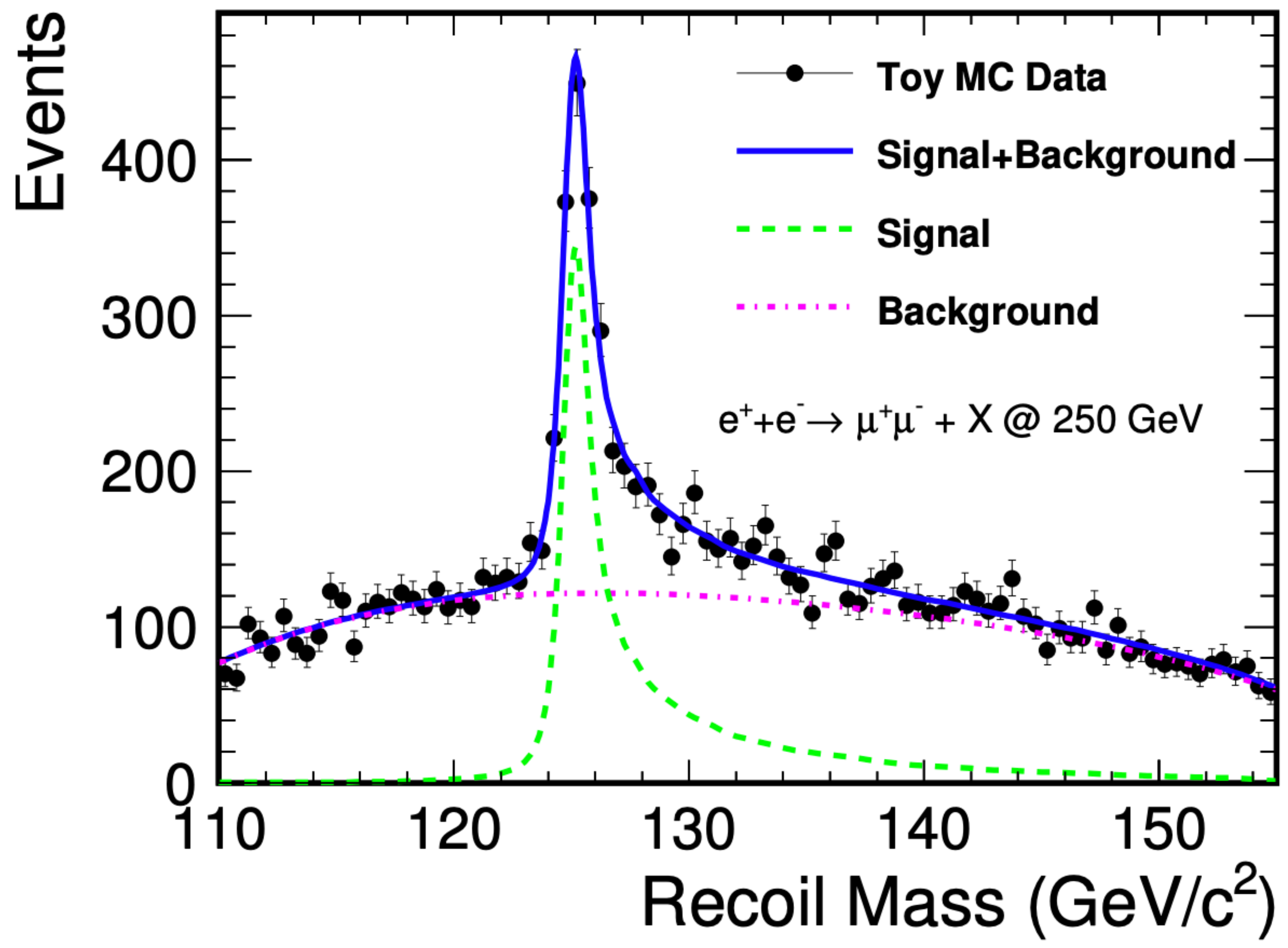


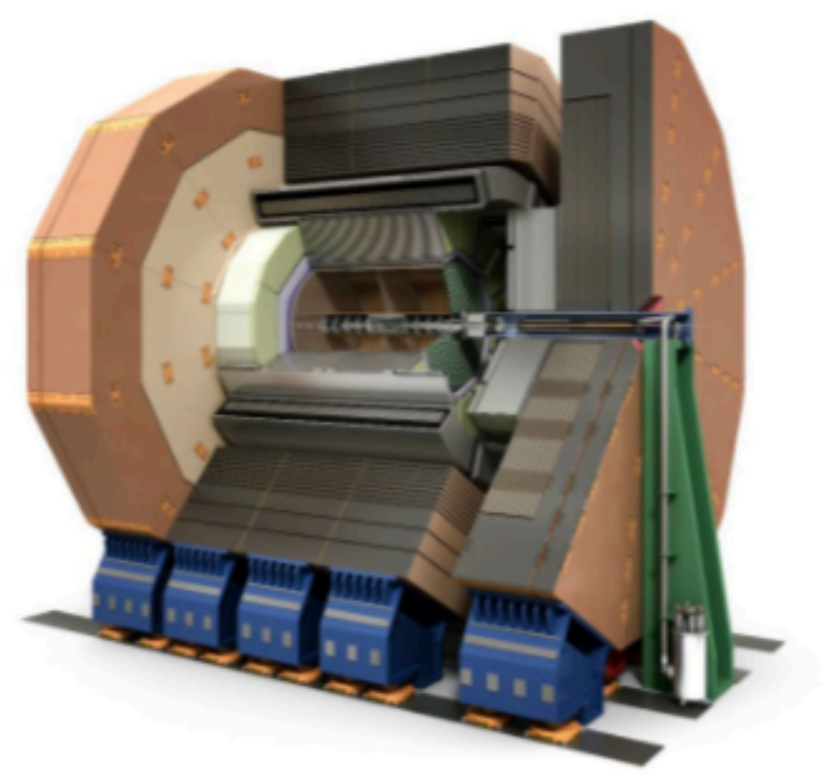
Detectors at future e^+e^-

Stringent detector requirements from ZH reconstruction

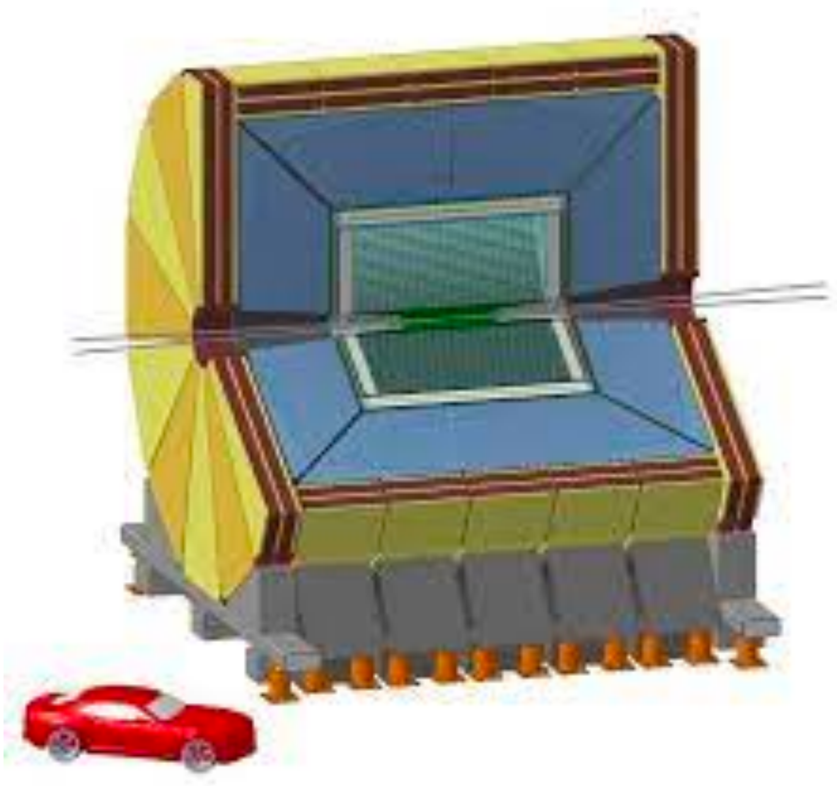
Detector designs at e^+e^- colliders are converging to very similar strategies

- Strong magnetic field 2-5 T
- (Ultra) low material budget tracker (<0.3% X0)
  - Close to the interaction region (10-25 mm)
- High granularity calorimetry
  - Particle Flow reconstruction → plays a big part in many designs

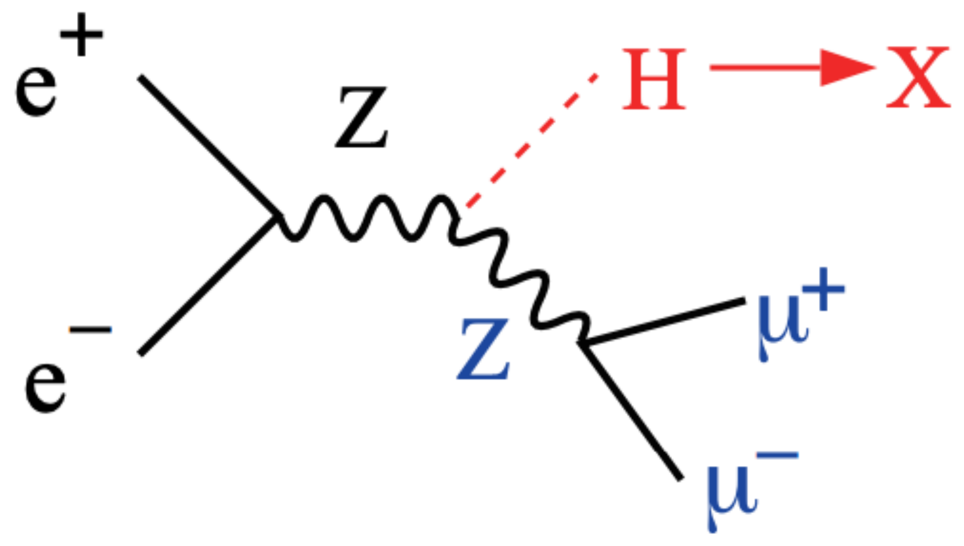




ILD

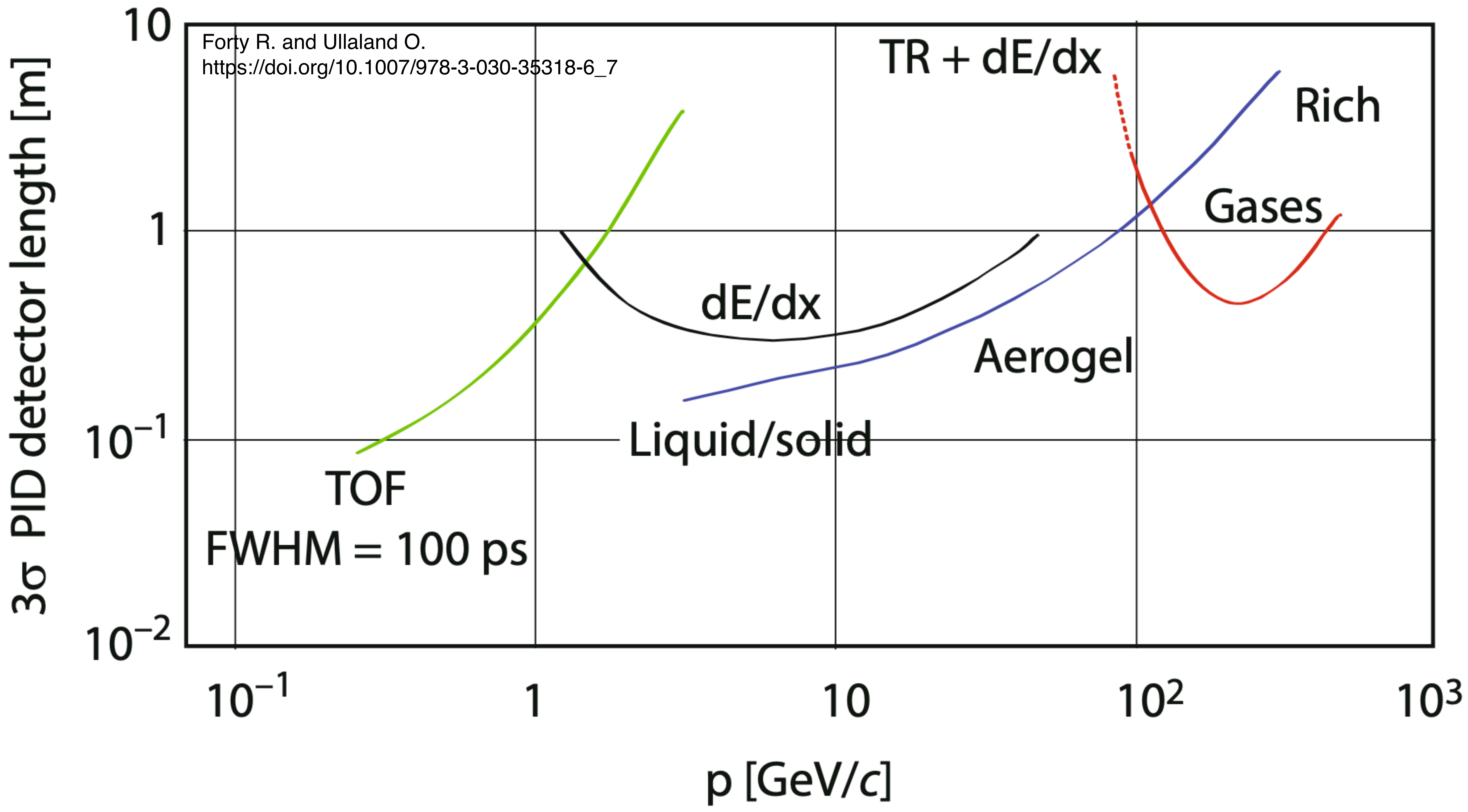


IDEA



Particle ID for s-tagging

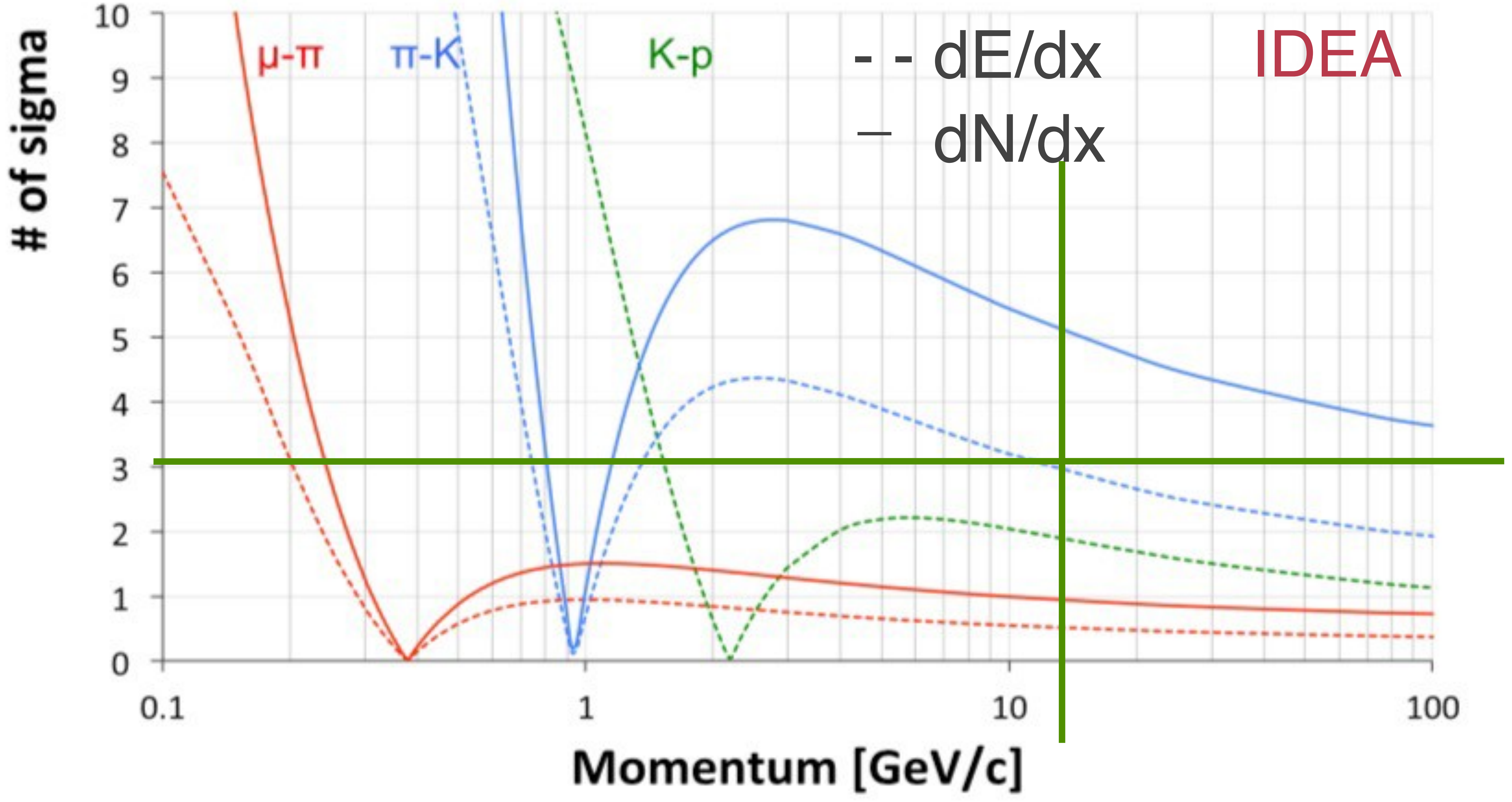
Combining different strategies for optimal PID performance across a wide p_T range

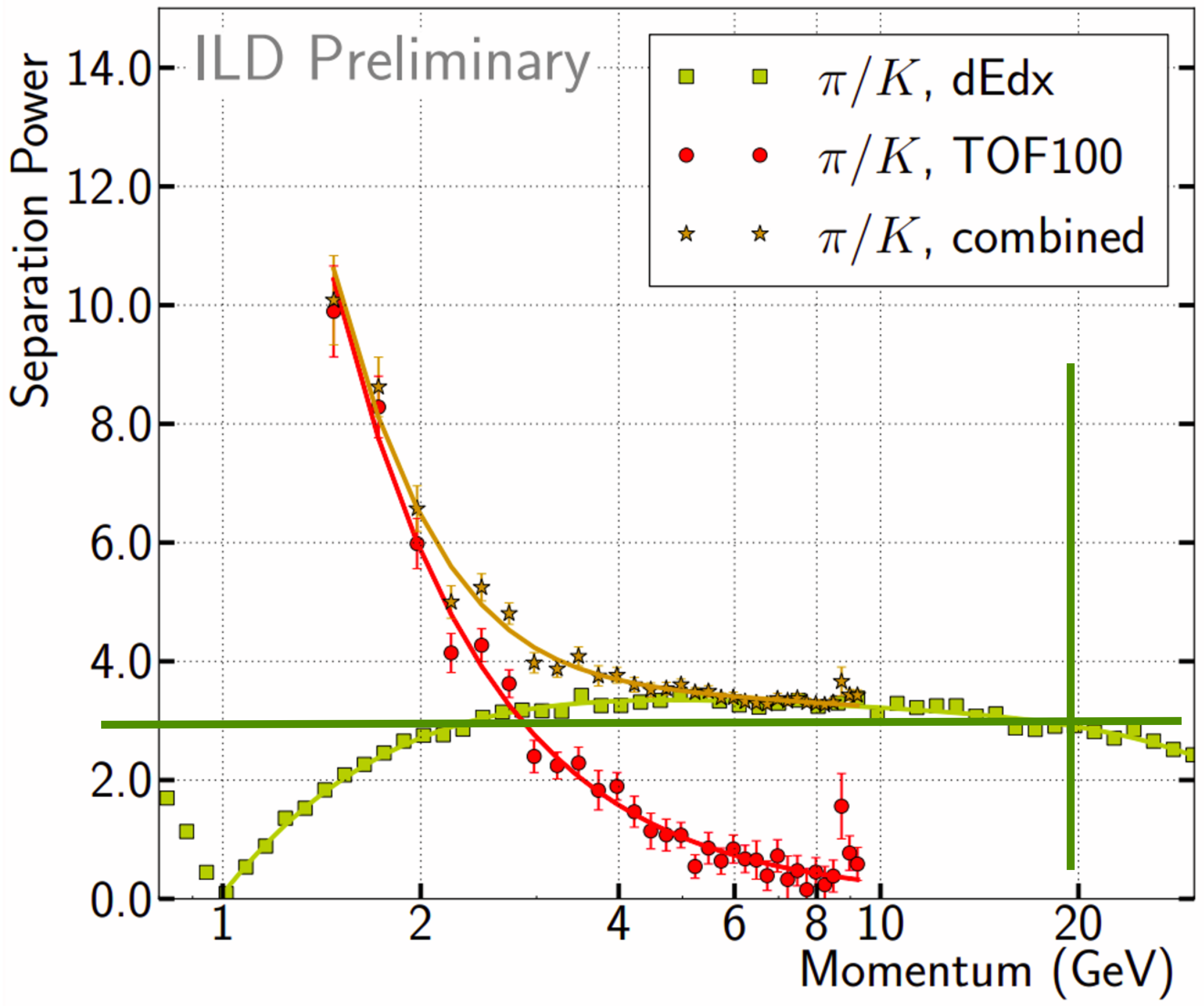


Particle ID for s-tagging

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

- dE/dx from silicon (< 5 GeV) and large gaseous tracking detectors (< 30 GeV)
- < 5 GeV, time-of-flight (i.e. 100 ps from ECAL)



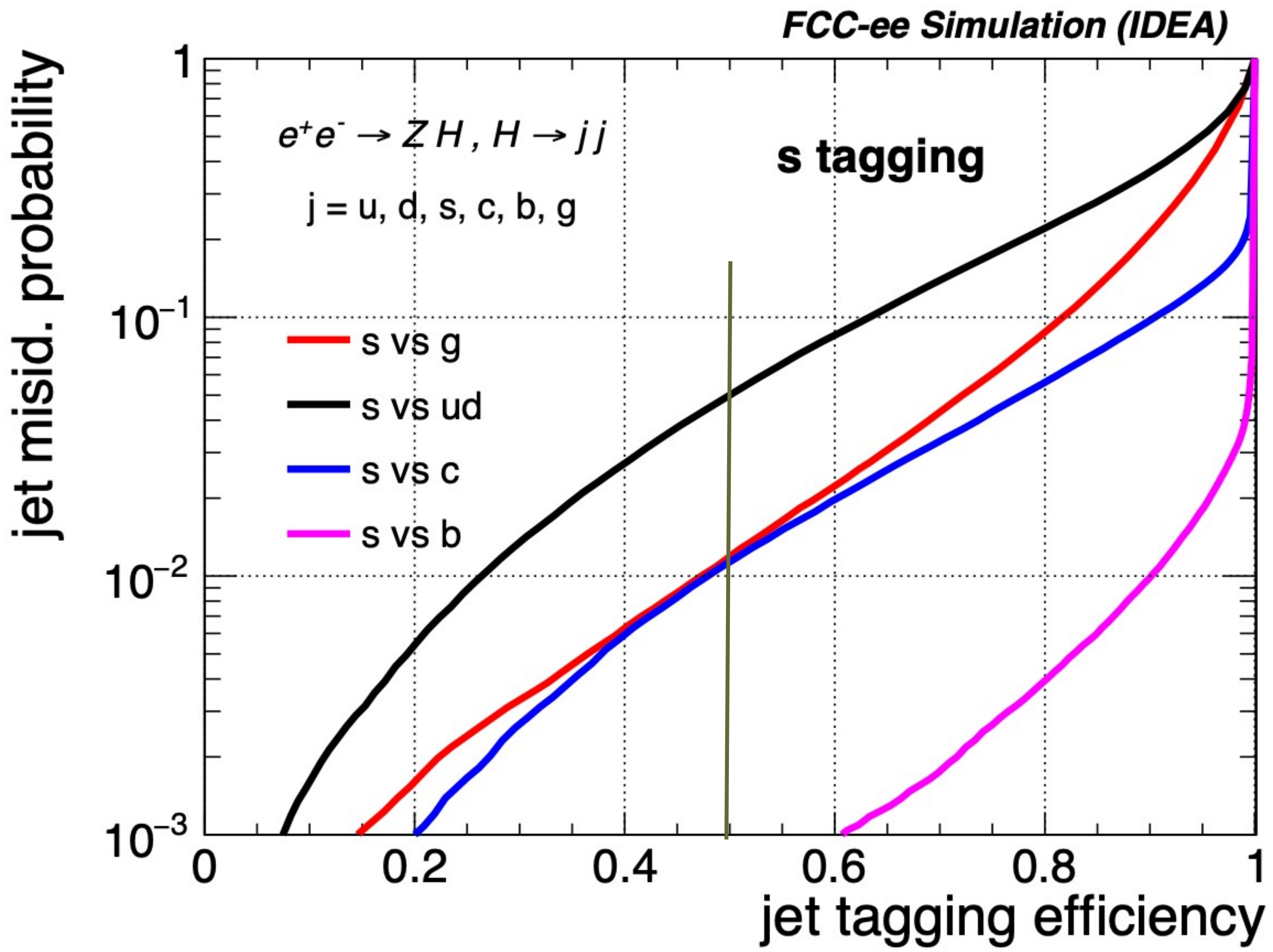


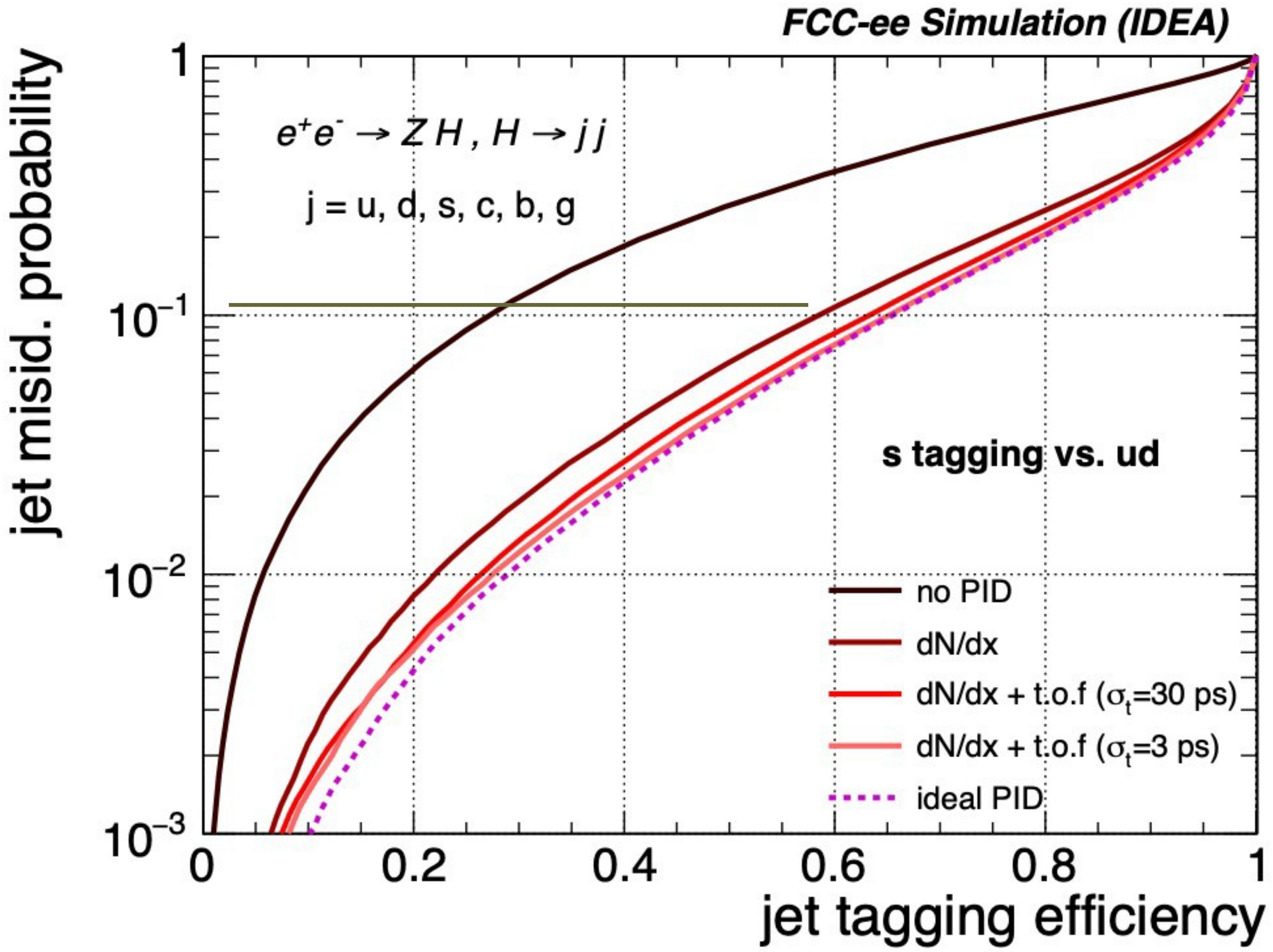
PRD 101 056019 (2020)
EPJ C 82 646 (2022)
L. Gouskos @FCC week

Strange tagging performance 1/2

IDEA-like detector and Particle cloud graph neural network (fast sim)

- Both TOF and dN/dx ($3\sigma < 30$ GeV) included as inputs
- No PID to PID with dN/dx → at fixed mistag, efficiency doubles



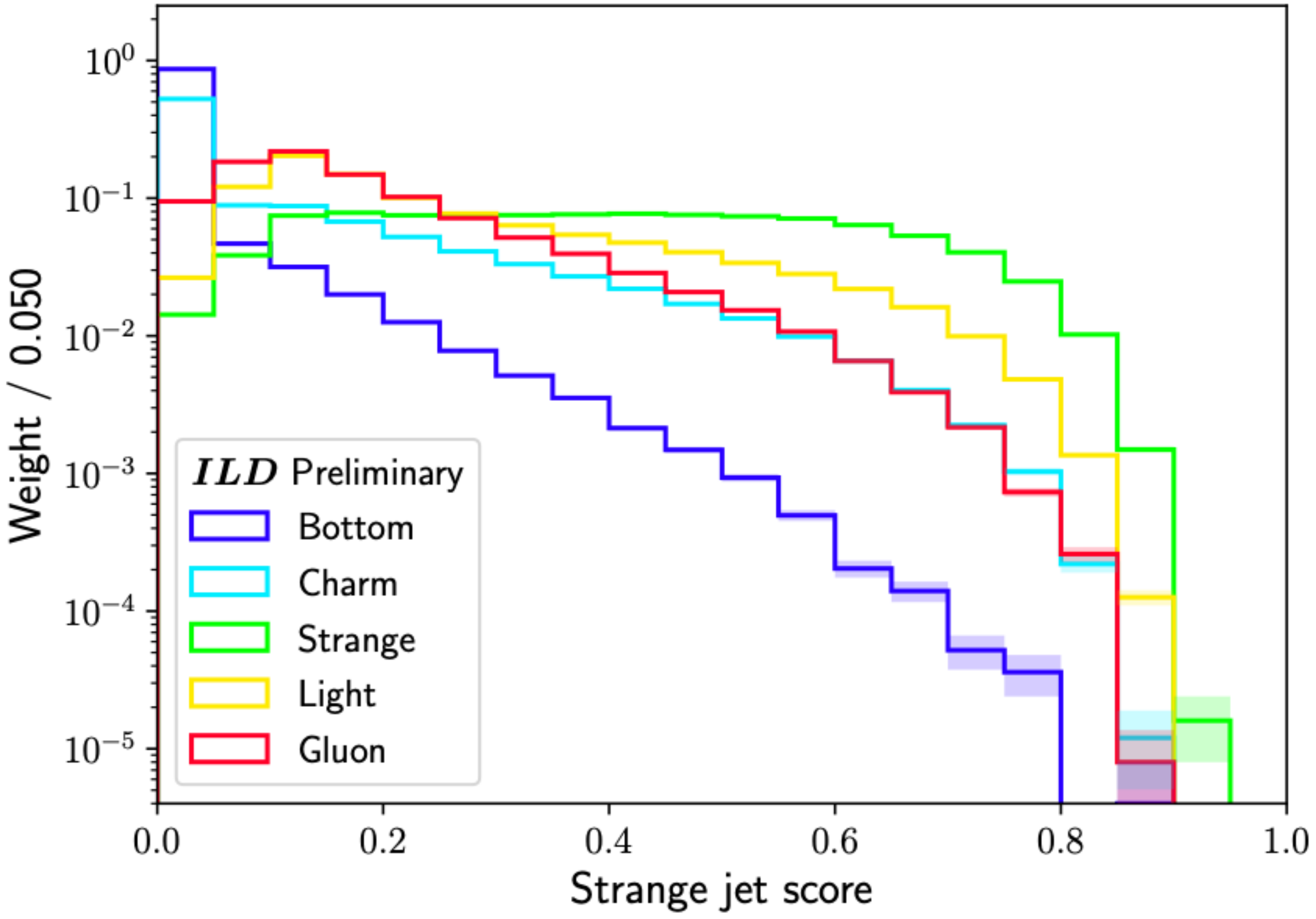


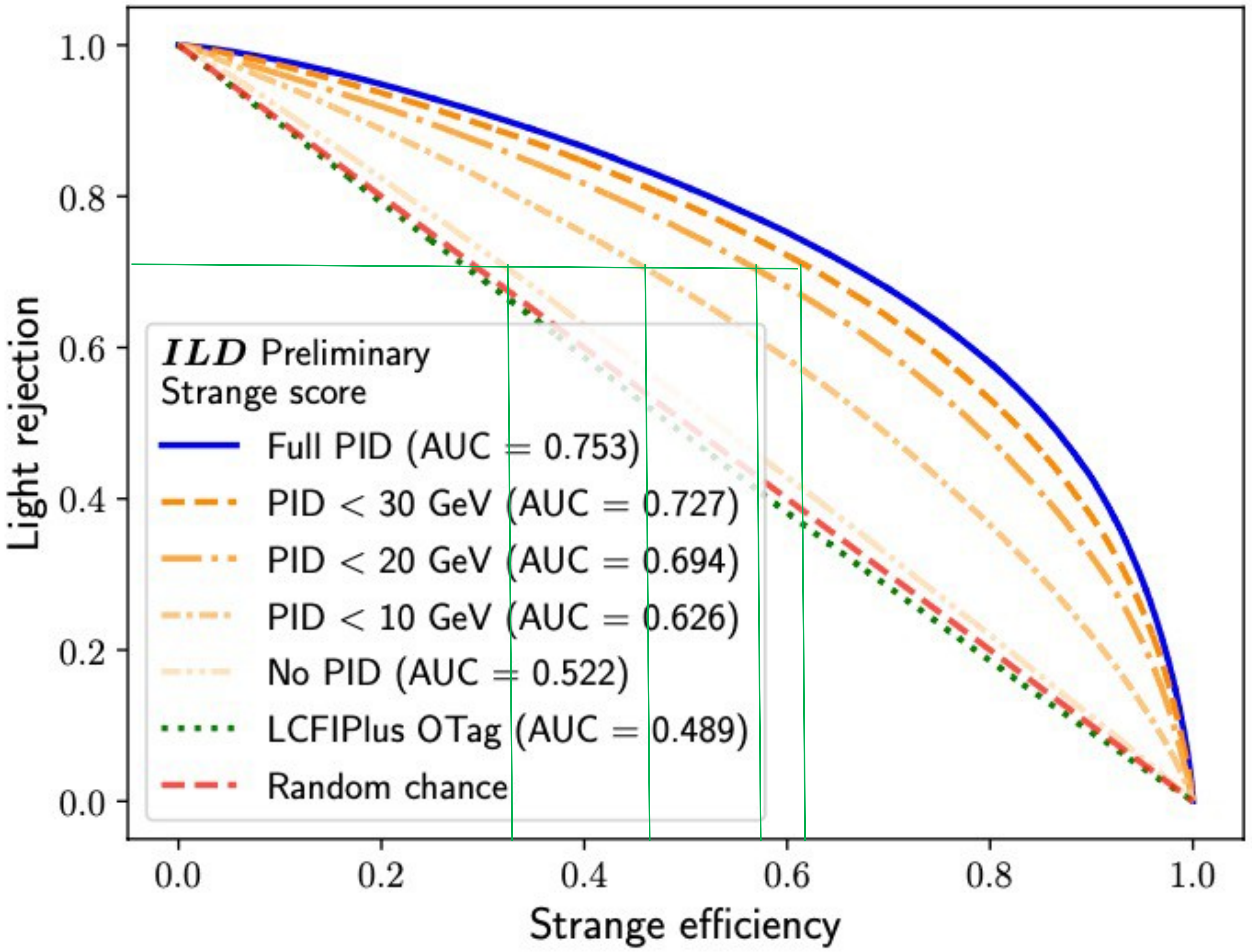
WP	Eff (s)	Mistag (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	20%	40%	10%	1%
Medium	80%	9%	20%	6%	0.4%

Strange tagging performance 2/2

ILD-like detector with full simulation and Recurrent NN

- Includes PDG-based PID → assuming perfect detector capability
- At 50% s-tag efficiency, 90% background rejection
- No PID to PID < 10 (30) GeV → at fixed mistag, 1.5x (2x) efficiency

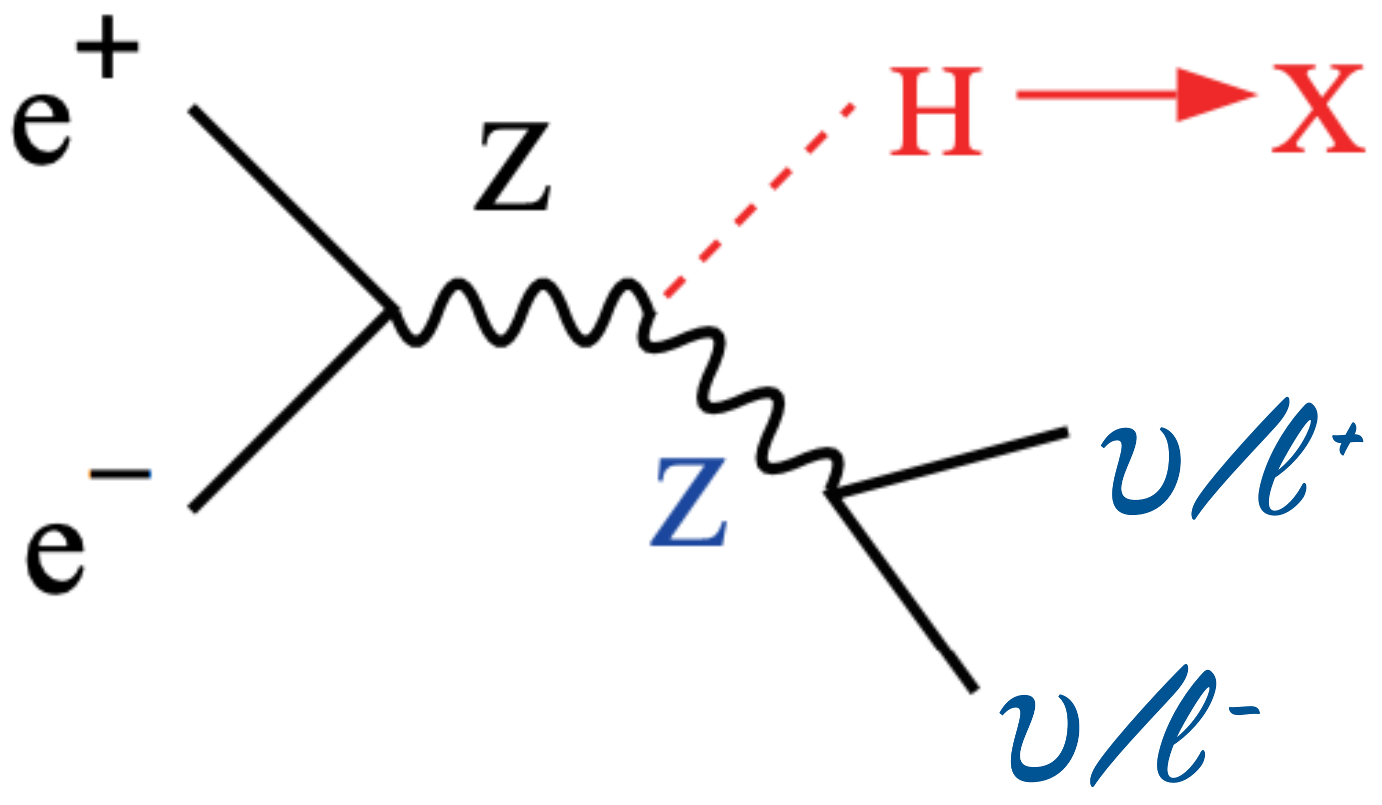


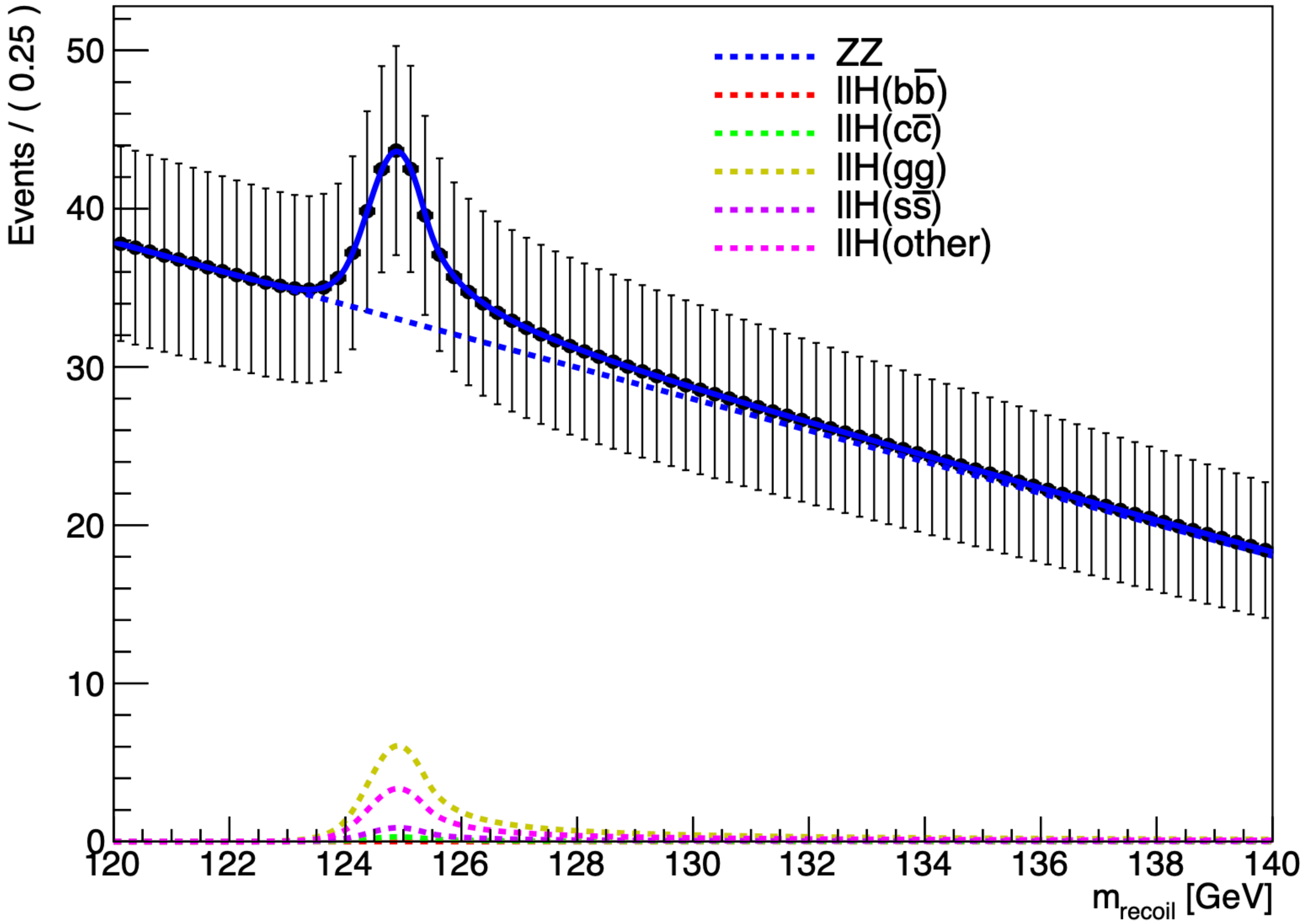


Analysis strategy to target H → ss

Exploit Z boson reconstruction in the ZH associated mode

- At 250 GeV the total Zh cross section can be extracted independently of the Higgs boson's detailed properties by counting events with an identified Z boson
- Looking at 0 or 2 leptons Z decay modes





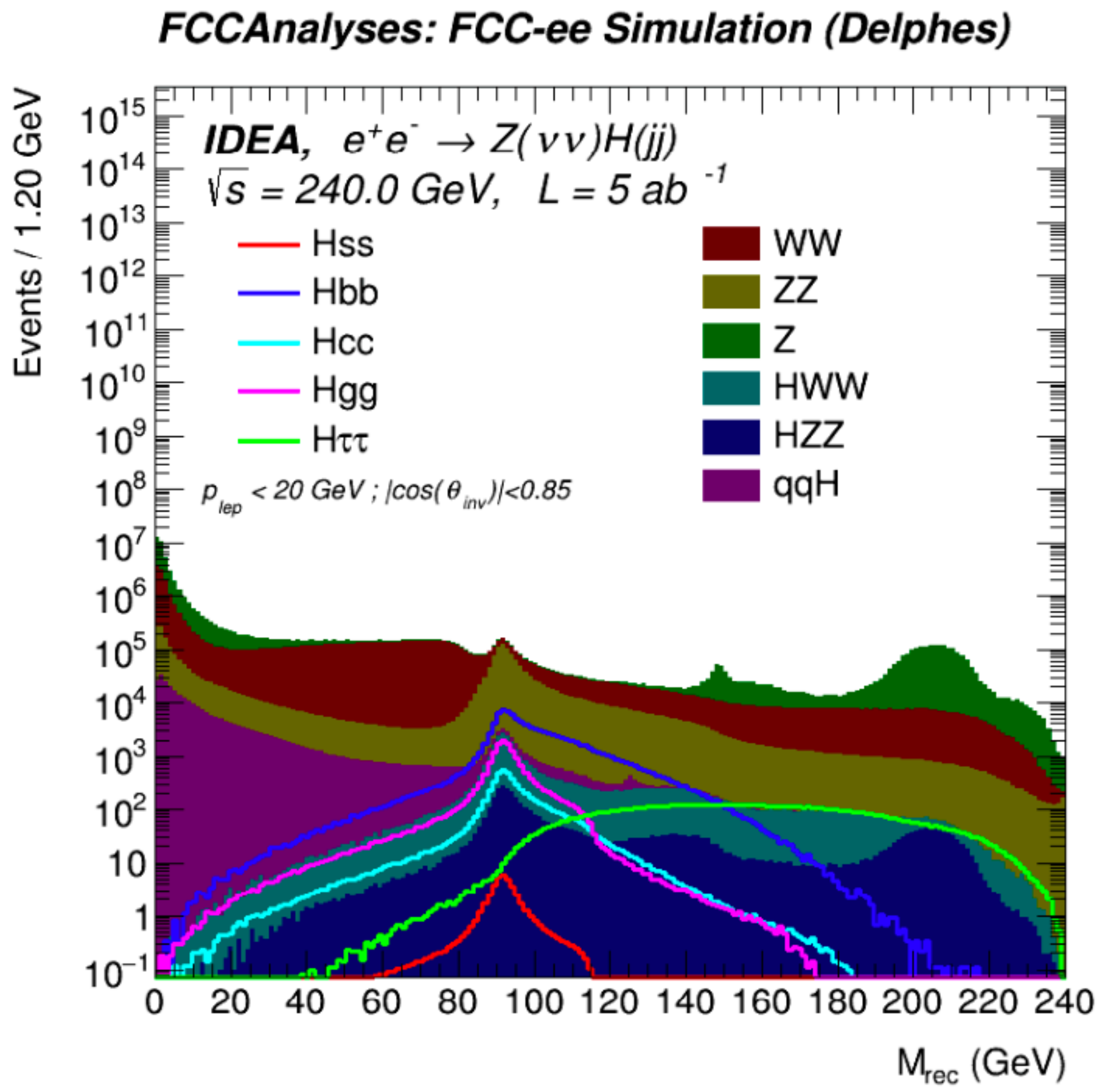
$$M_{\rm rec} = \sqrt{(\sqrt{s} - E_Z)^2 - \vec{p}_Z^{\,2}}$$

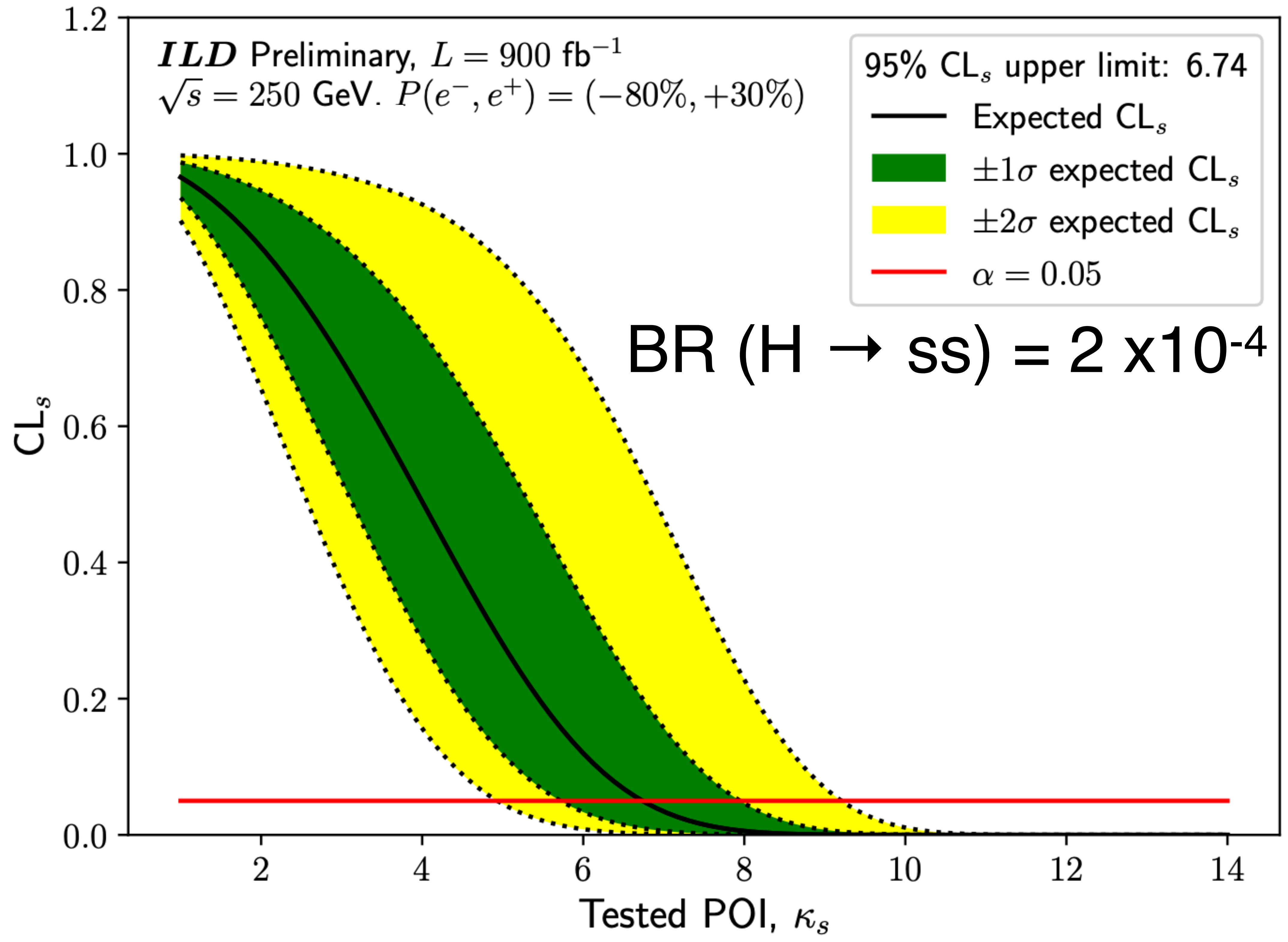
arXiv:2203.07535
L. Gouskos @FCC week

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





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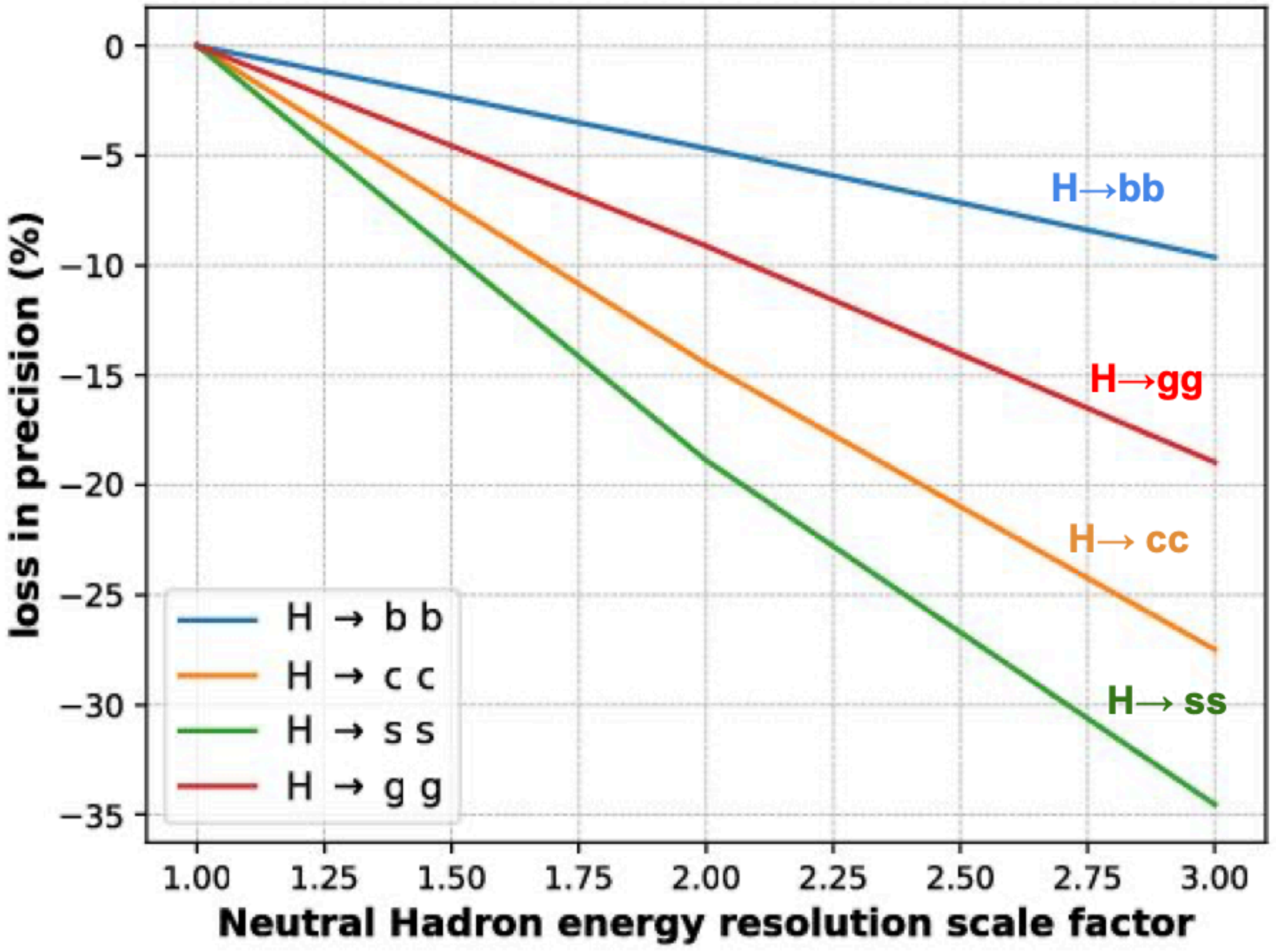
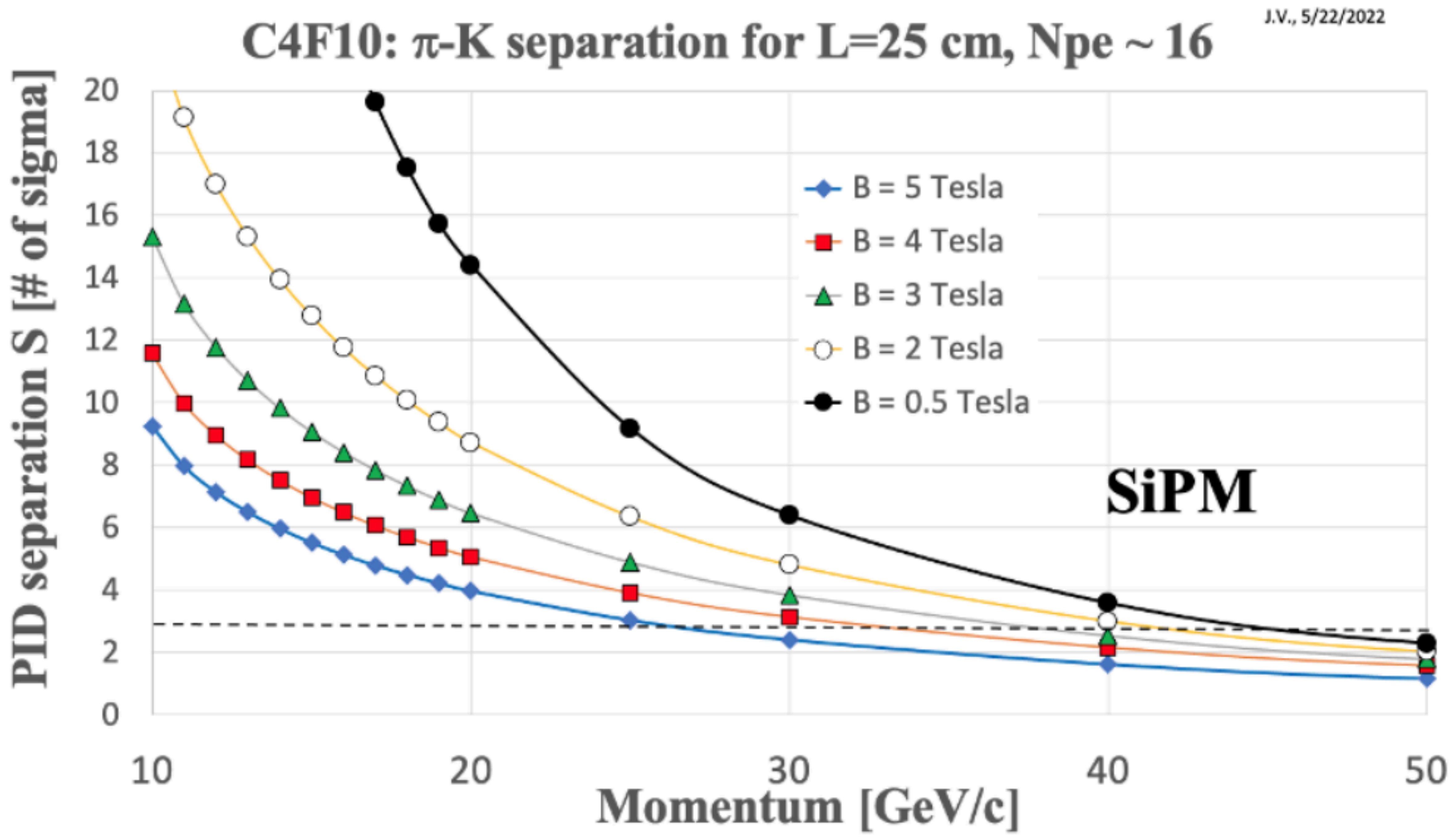
Lesson learned and moving forward

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

- Neutral Hadron energy resolution
- dE/dx and dN/dx: powerful PID essential 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



Conclusions and next steps

s-tagging & PID would allow for a complete exploration of the 2nd generation Yukawa couplings

- First simulations with some assumptions on detector performance show promise to test κ_s
- Moving forward we want to:
  - map this into phenomenological targets
    - i.e. BSM models predicting deviations in $h \to ss$, or $h \to cs$
  - refine the analysis for $e^+e^- \to Zh$ with $h \to ss$ ($Z \to X$) at 240/250 GeV
    - higher center of mass energies still unexplored
  - study detector benchmarks:
    - the complementarity in momentum reach of charged hadron ID from dN/dx, dE/dx, ToF, RICH
    - reconstruction of in-flight decays, $K^0_S \to \pi^+\pi^-$
    - strangeness-tagging and s/sbar separation
    - ***Important to evaluate simultaneously other Higgs benchmarks***

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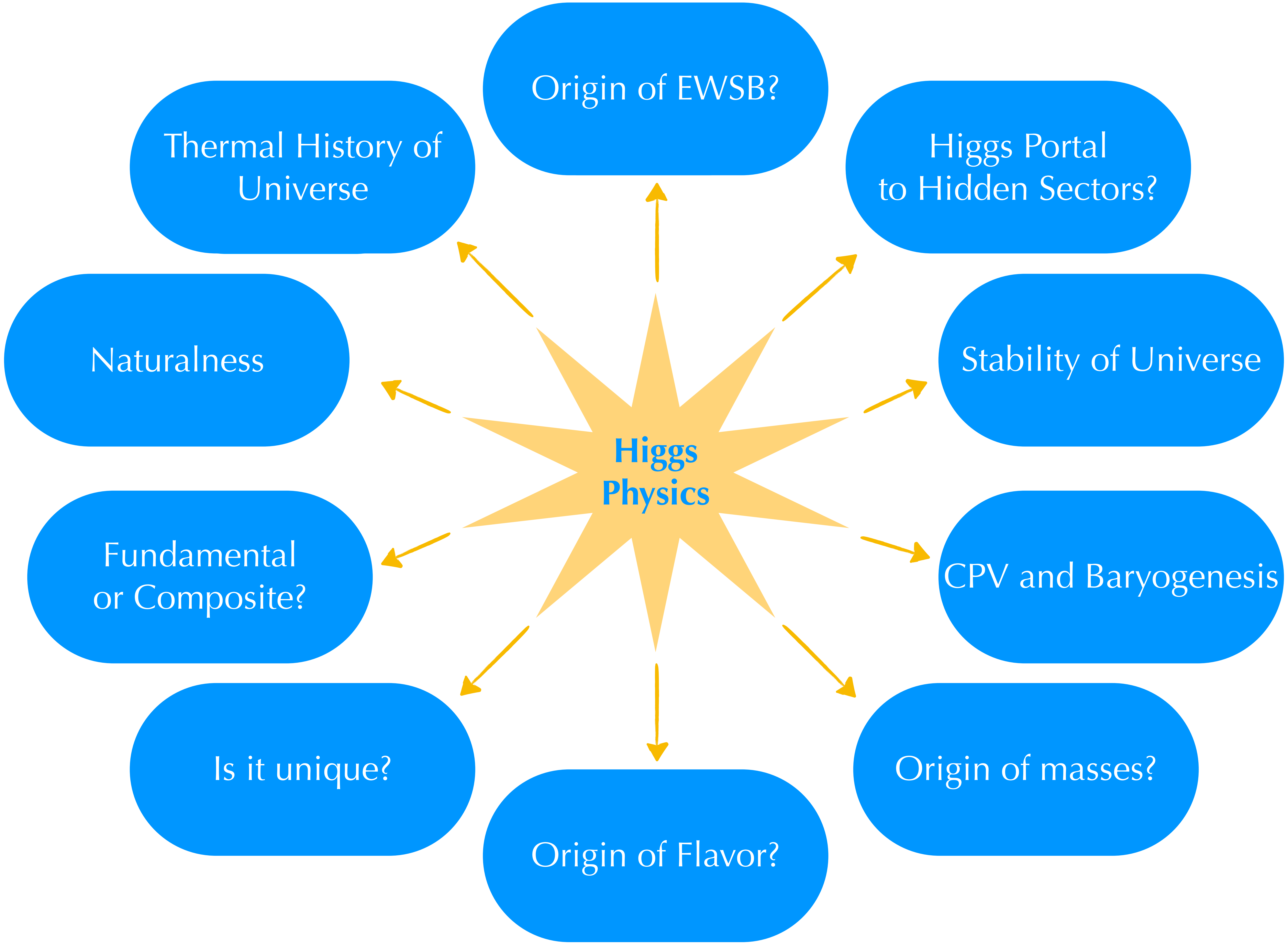
self-subscription CERN e-group

Join us! Discussion session T. Suehara
Oct 11, 2023, 11:30 AM

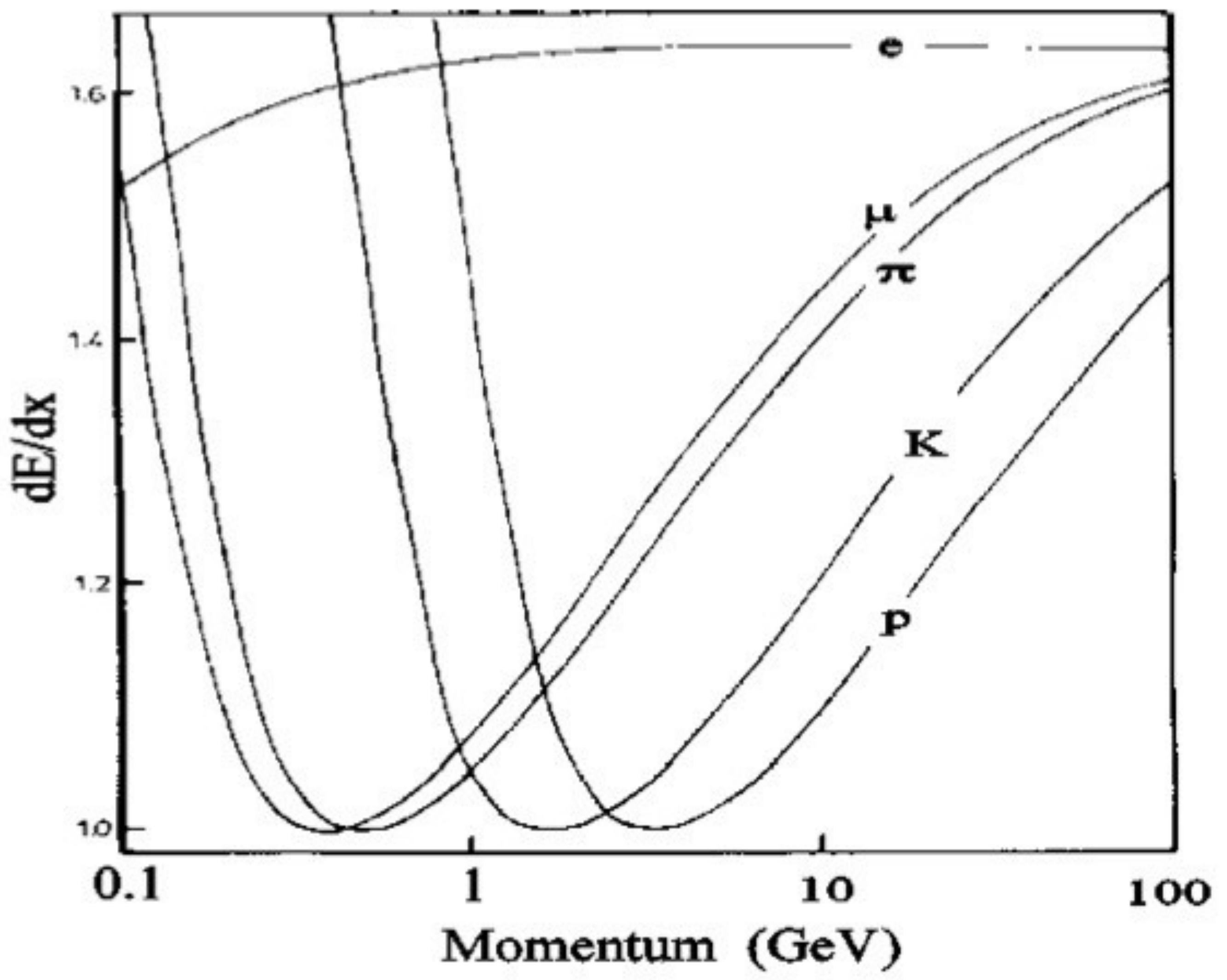

Thank you!

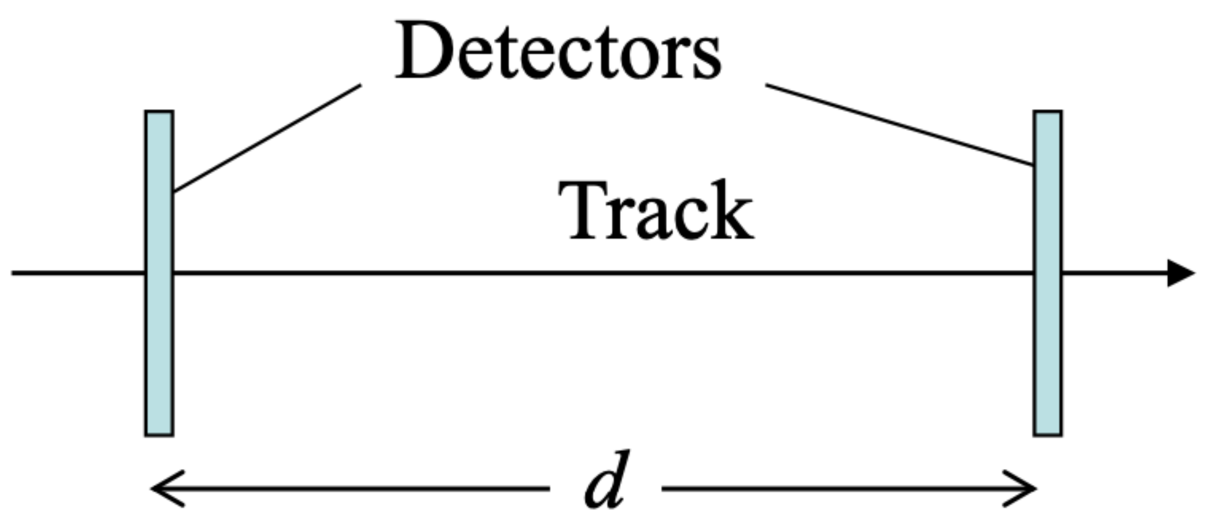

Origin of EWSB?
Thermal History of Universe
Higgs Portal to Hidden Sectors?
Naturalness
Stability of Universe
Higgs Physics
Fundamental or Composite?
CPV and Baryogenesis
Is it unique?
Origin of masses?
Origin of Flavor?

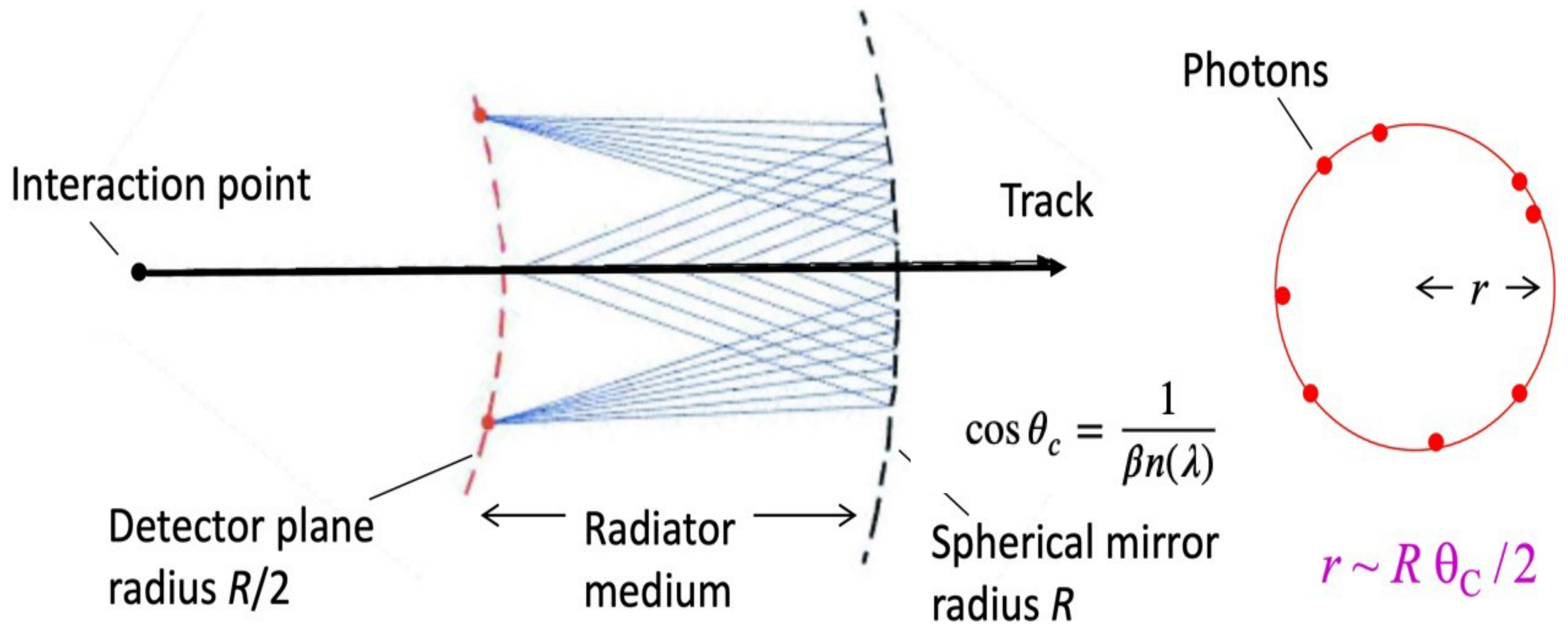
How to enhance s-tagging capabilities

Depending on the hadron energy, different technologies are available for $3\sigma\ \pi/K$ separation

dE/dx in silicon	**Time-of-flight** via Fast Timing in silicon envelopes or calorimetry	**dE/dx** in Time Projection or Drift Chambers	**Ring Imaging Cherenkov Detectors**
< 5 GeV	< 5 GeV	< 30 GeV (volume dependent)	O(10)GeV





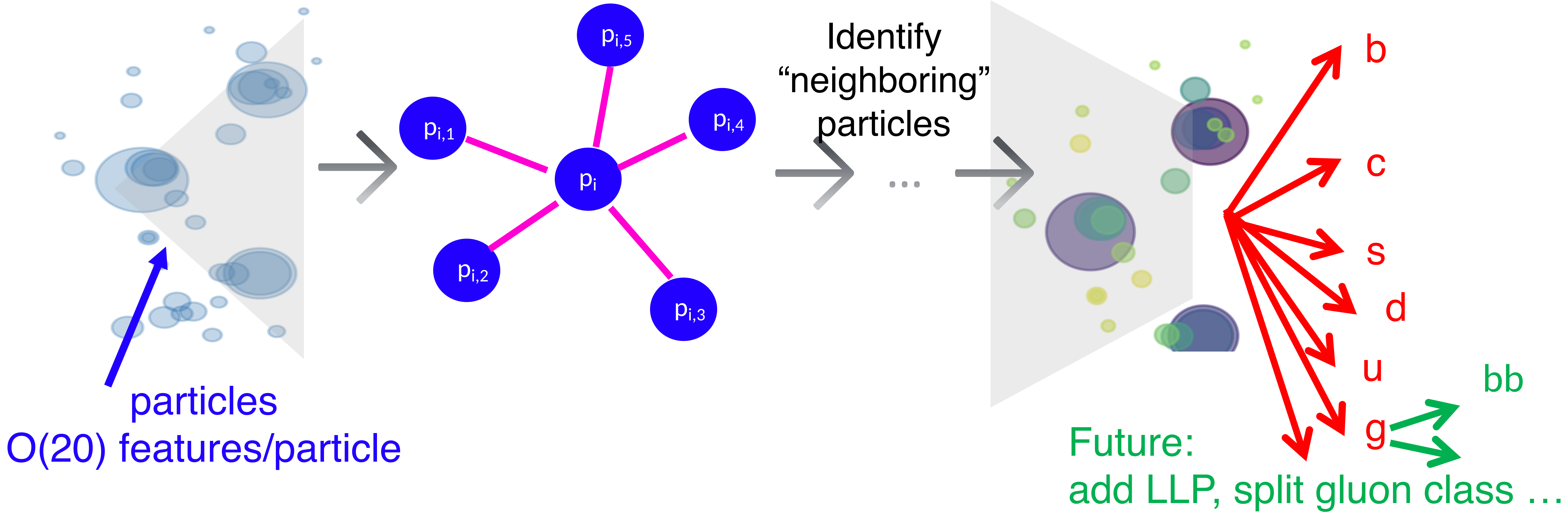


V. Cairo

PRD 101 056019 (2020)
EPJ C 82 646 (2022)

Particle cloud represented as a graph

Jet representation: Particle cloud i.e. unordered set of particles
Network architecture: Graph Neural Networks
Particles: vertices of graph; interactions b/w particles: edges of graph
Hierarchical learning approach: local → global structures



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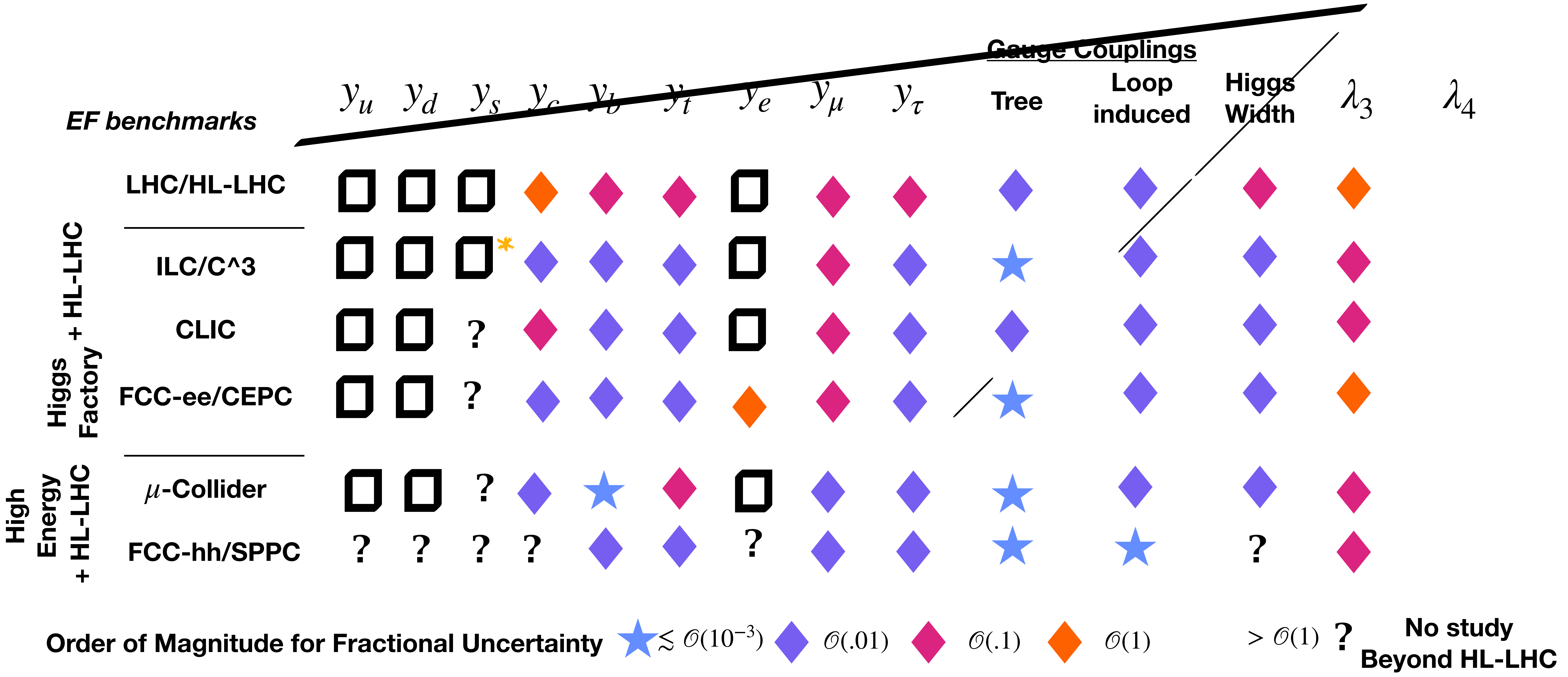
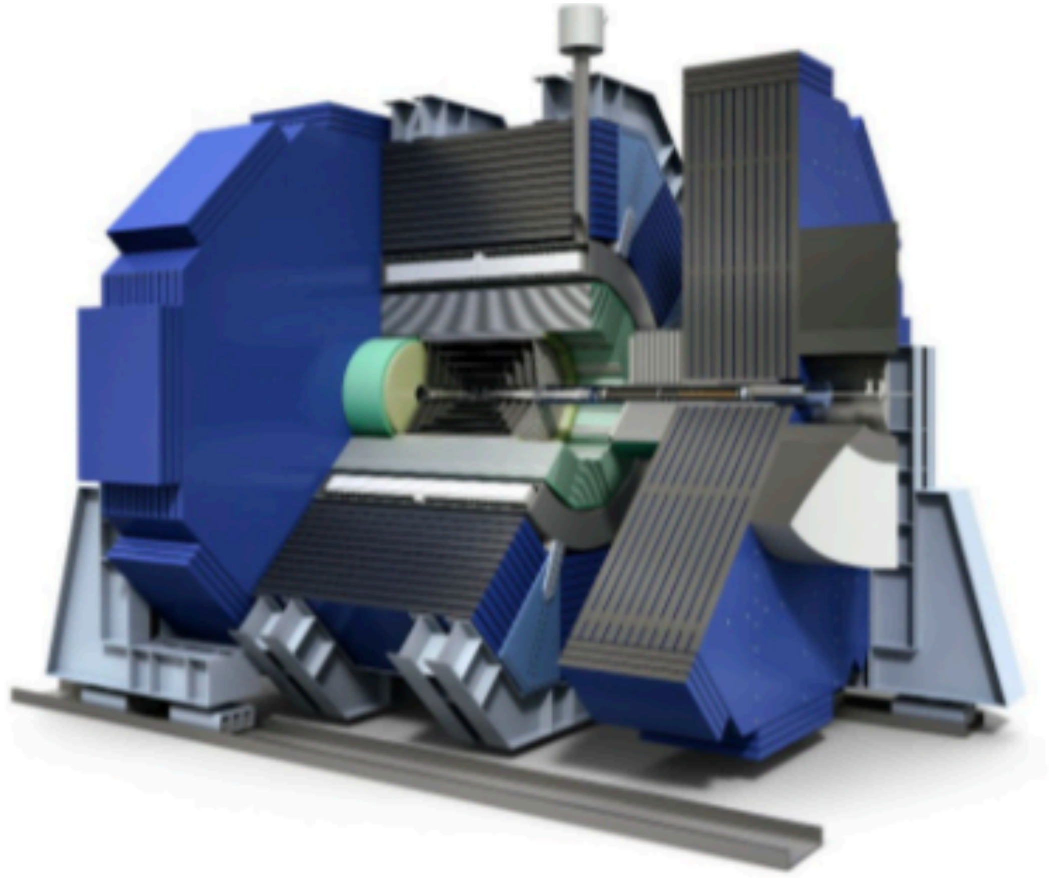
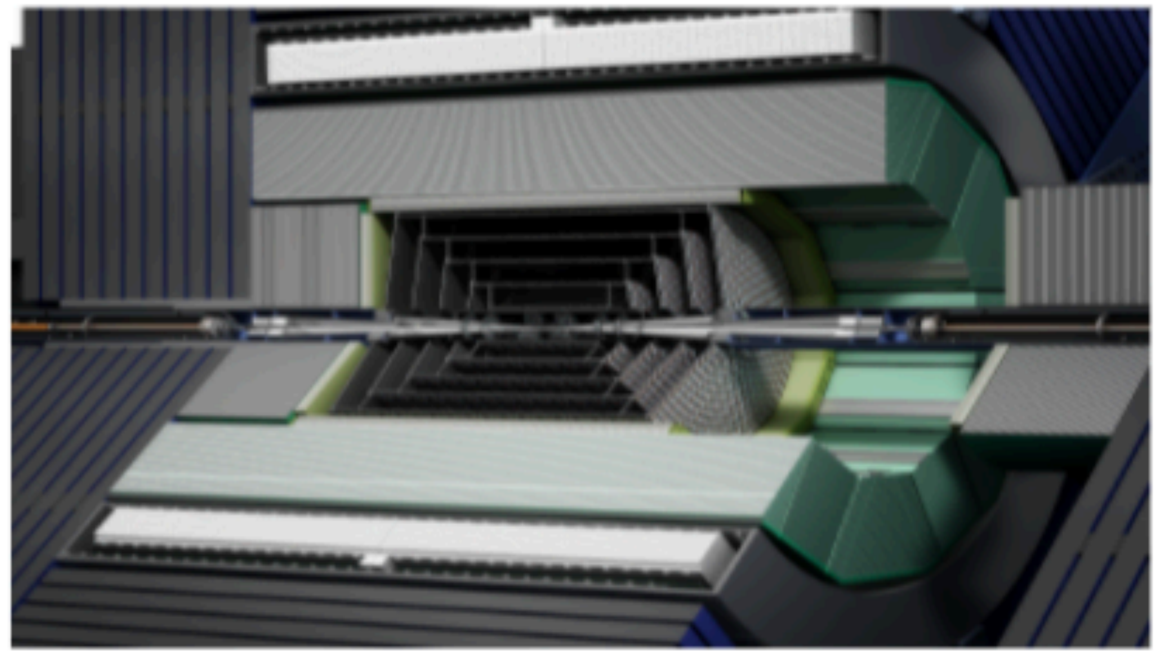
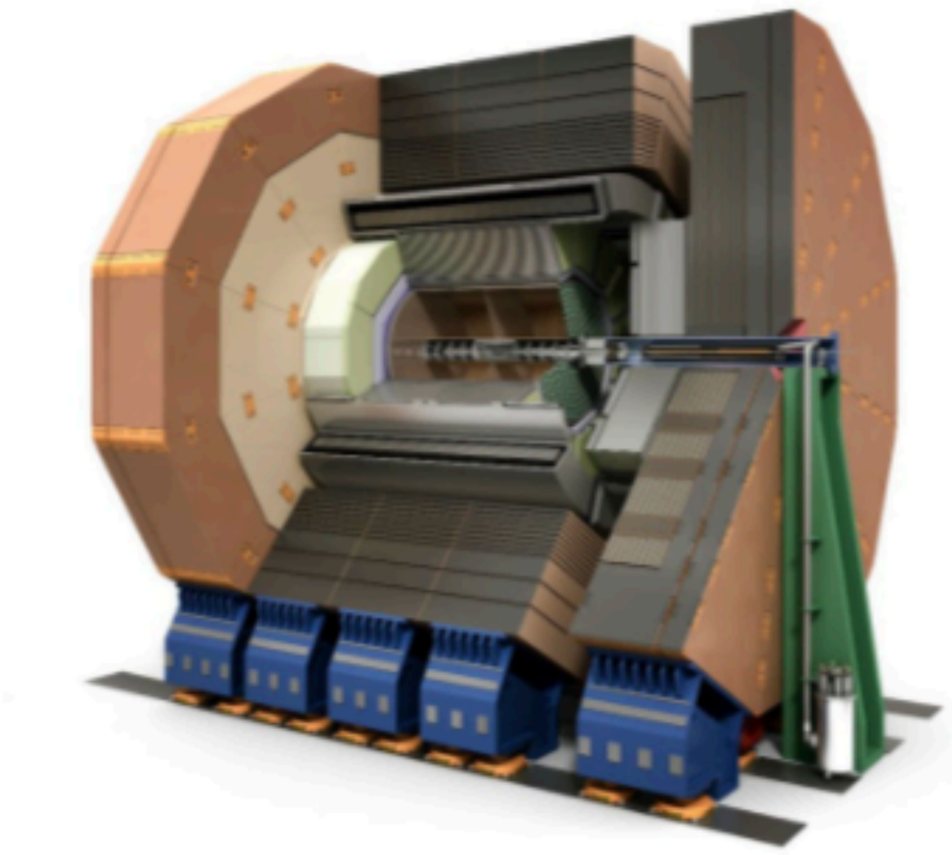
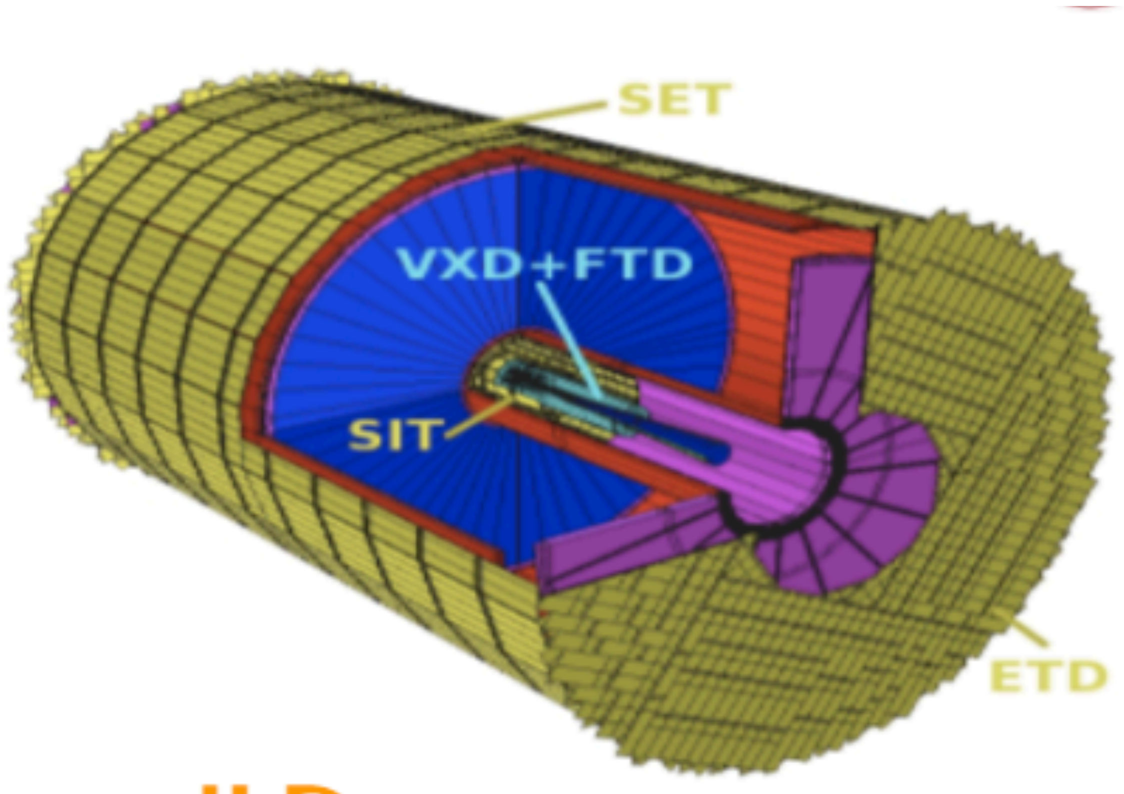
Moving forward



Detectors design at lepton colliders

SiD

ILD

- Detector designs at e+e- colliders are converging to very similar strategies
    - Particle Flow reconstruction → plays a big part in many designs
- SiD like detector - Compact all silicon detector
- ILD like detector - Larger detector with Silicon+TPC tracker
    - Larger detector. Simulation and design work active in Europe / Japan
- IDEA detector - Using dual readout calorimeter, under study at CEPC/FCC-ee

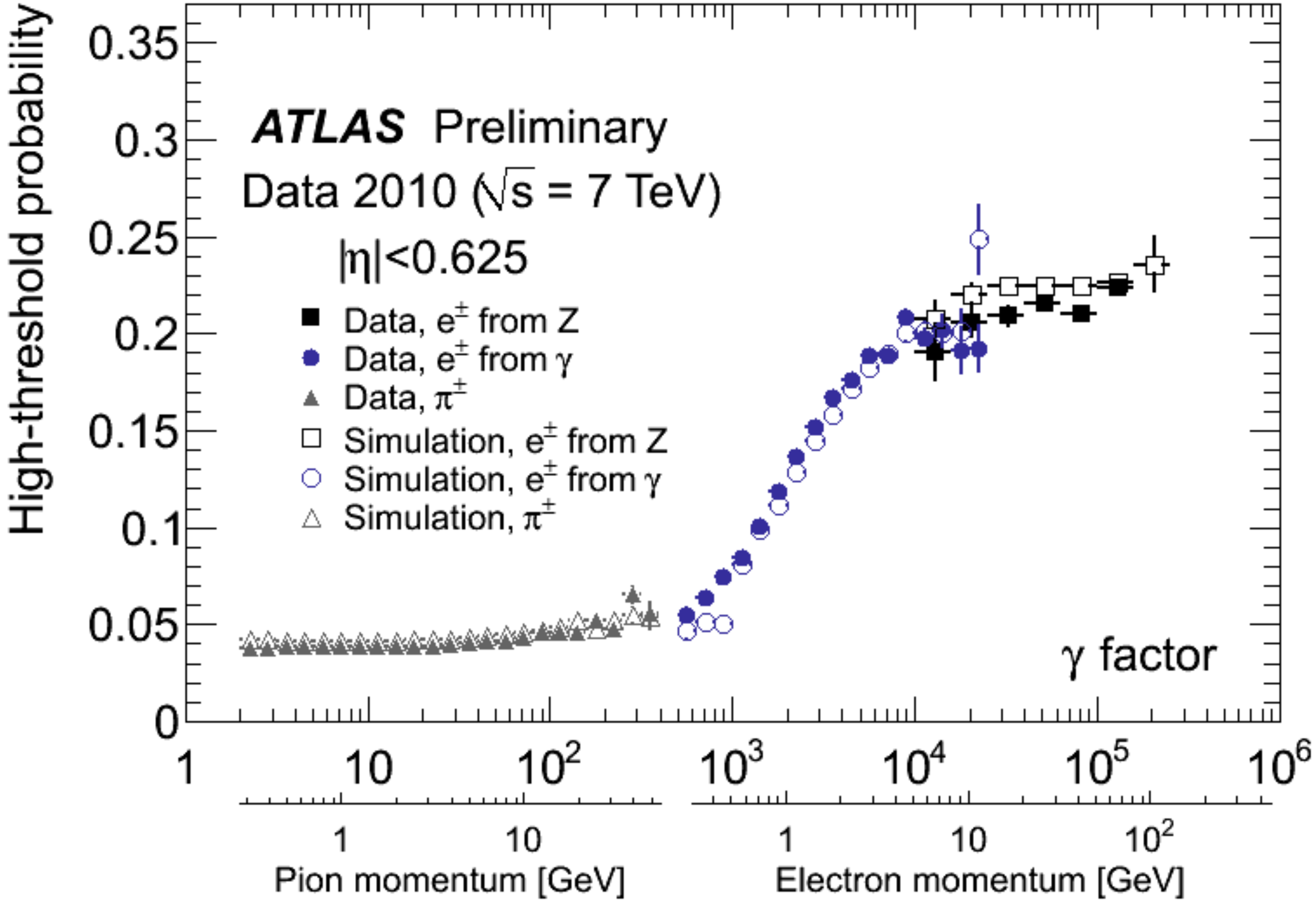
e/π separation with TR+dE/dx

e/π separation via detection of transition radiation photons

Transition radiation is emitted when a highly relativistic charged particle with a Lorentz factor $\gamma > 10^3$ traverses boundaries between materials of different dielectric constants.

To achieve the best e/π separation, TR and dE/dx-based measurements are combined in a single likelihood function for a particle type.

The HT fraction is defined as the fraction of hits on track that exceed the high threshold (6-7 KeV)



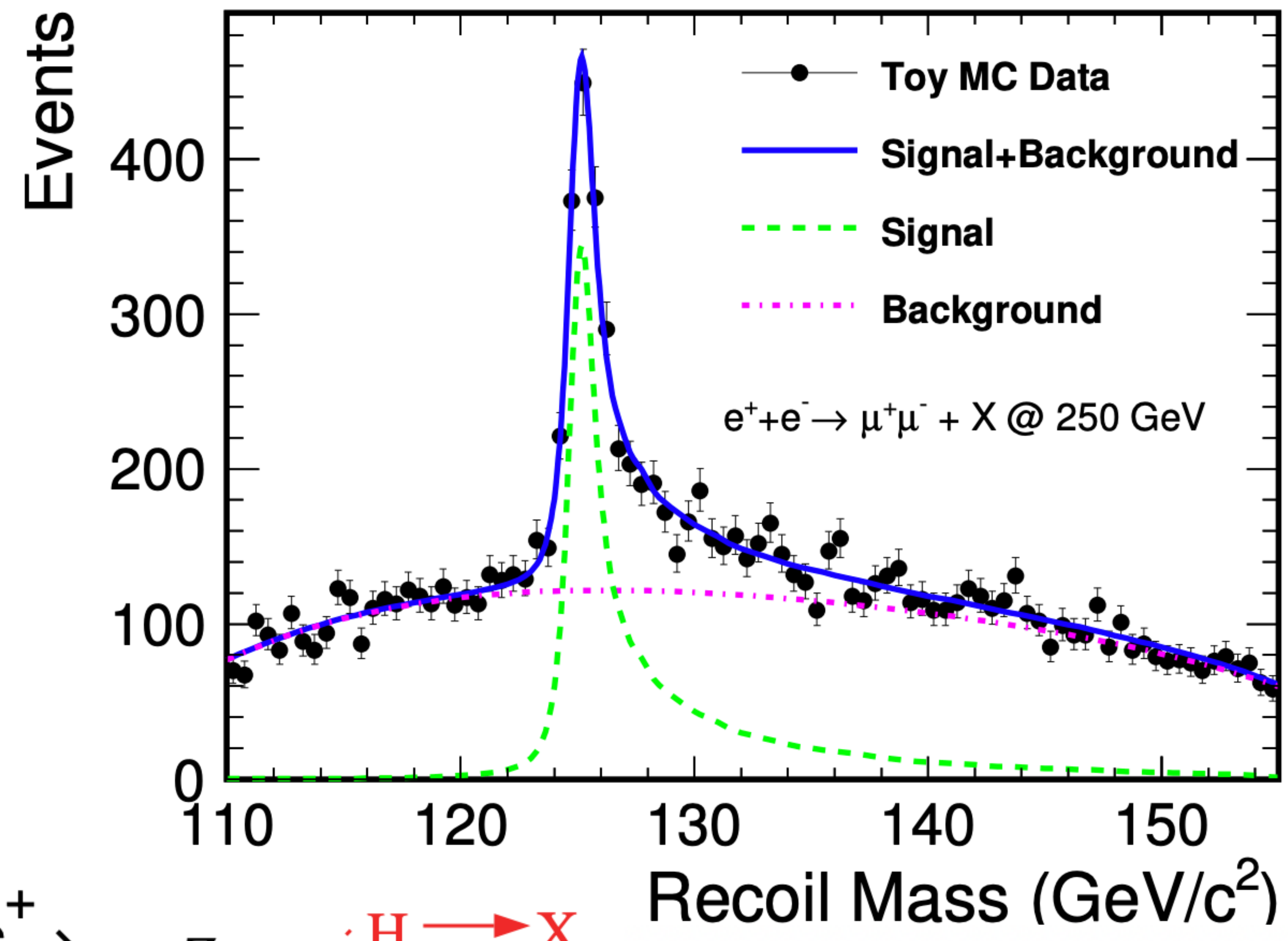
Physics requirements for detectors

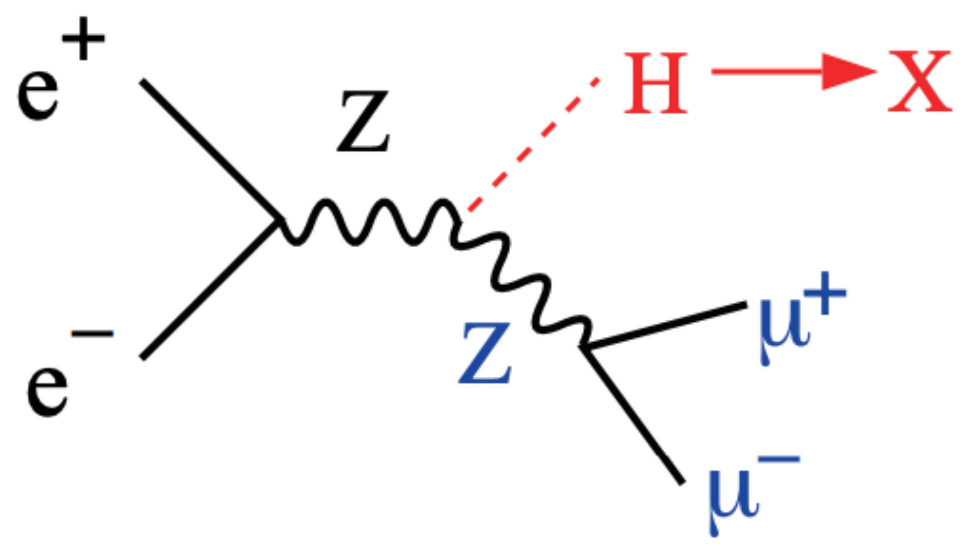
Precision challenges detectors

ZH process: Higgs recoil reconstructed from Z →$\mu\mu$
- Drives requirement on charged track momentum and jet resolutions
- Sets need for high field magnets and high precision / low mass trackers
- *Bunch time structure allows high precision trackers with very low X0 at linear lepton colliders*

Particle Flow reconstruction

Higgs → bb/cc decays: Flavor tagging & quark charge 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% X0) for vertex detector
- Sensors will have to be less than 75 μm thick with at least 5 μm hit resolution (17-25μm pitch)





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

Physics requirements for detectors

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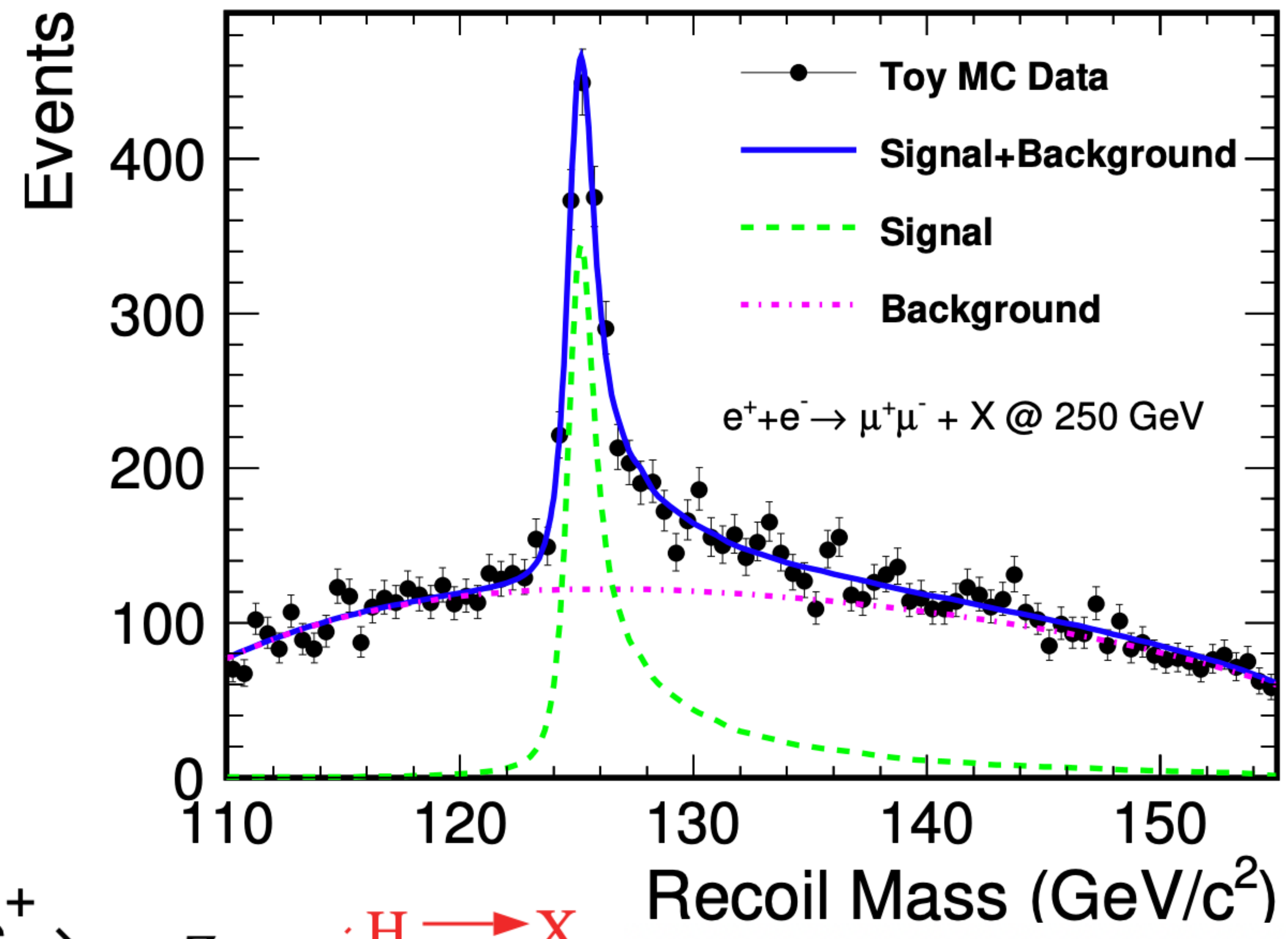
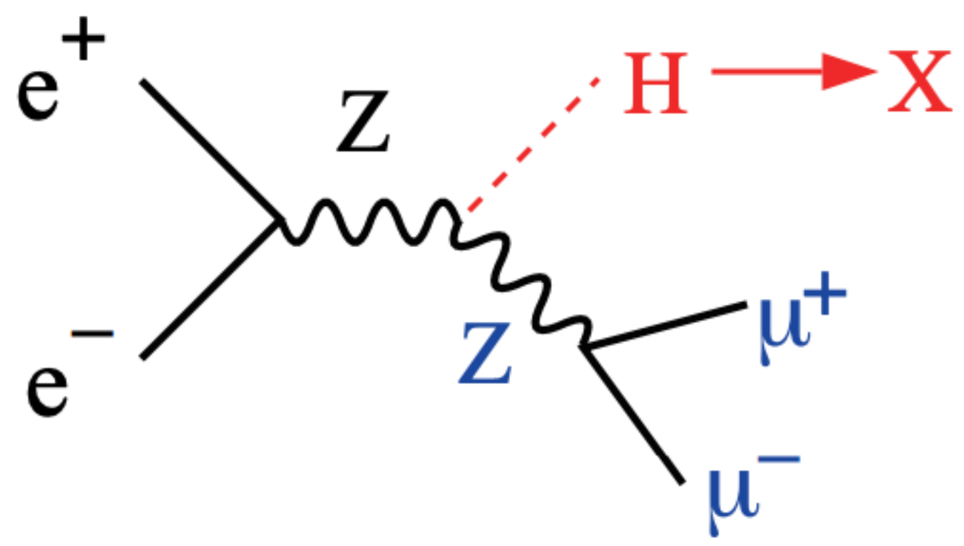
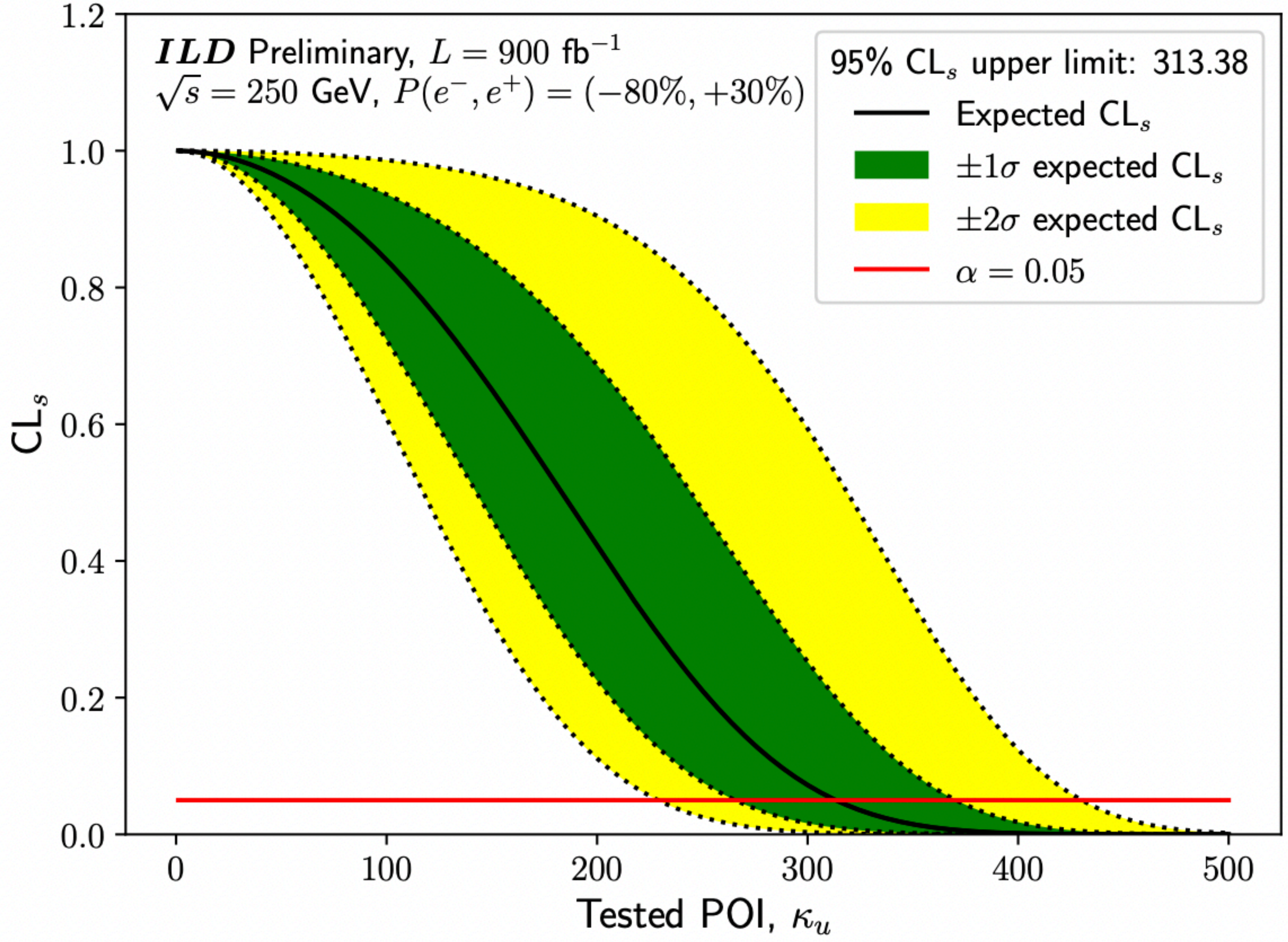


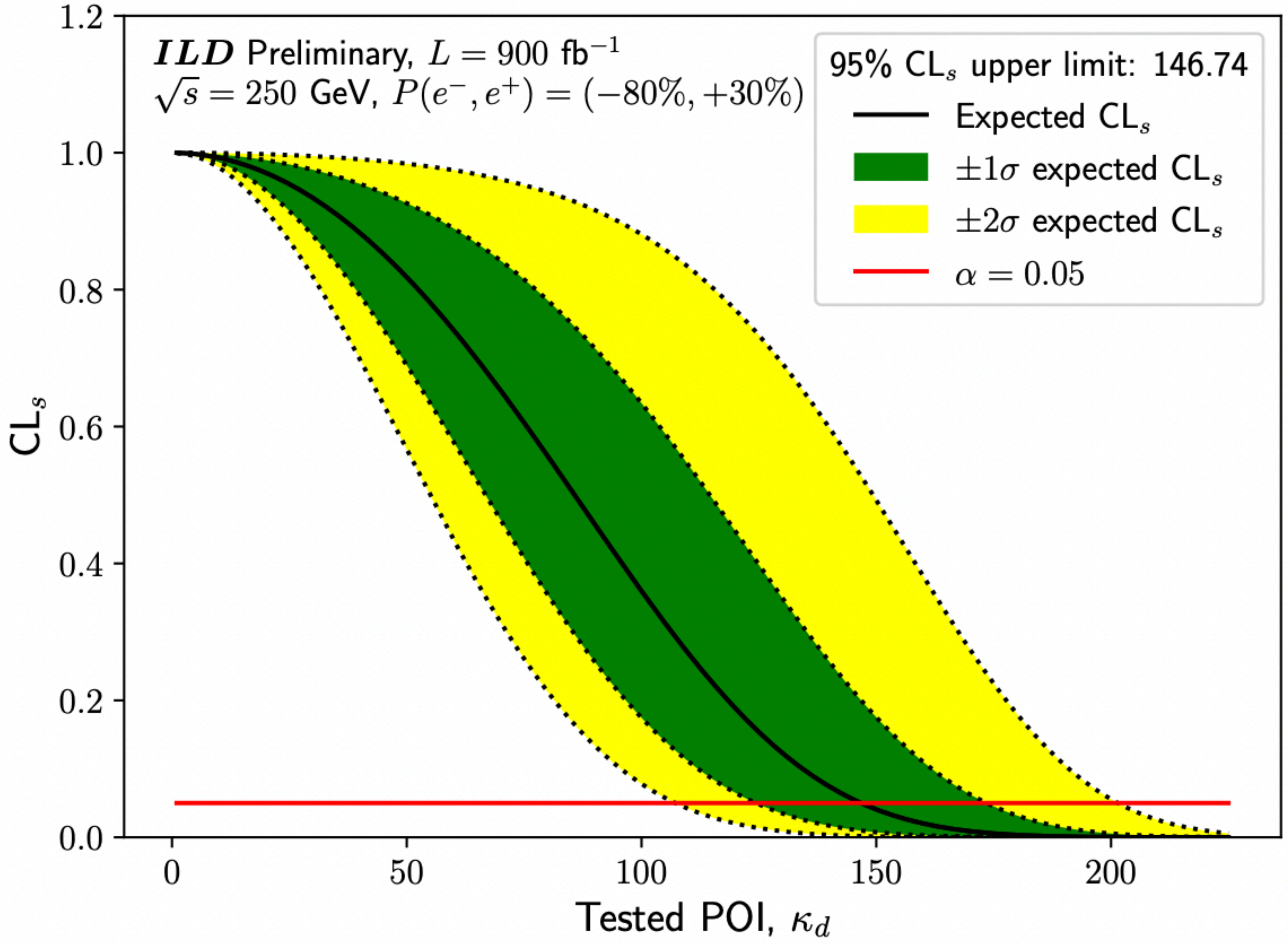


$$m^2_{recoil} = s + m^2_Z - 2 \cdot E_Z \cdot \sqrt{s}$$

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

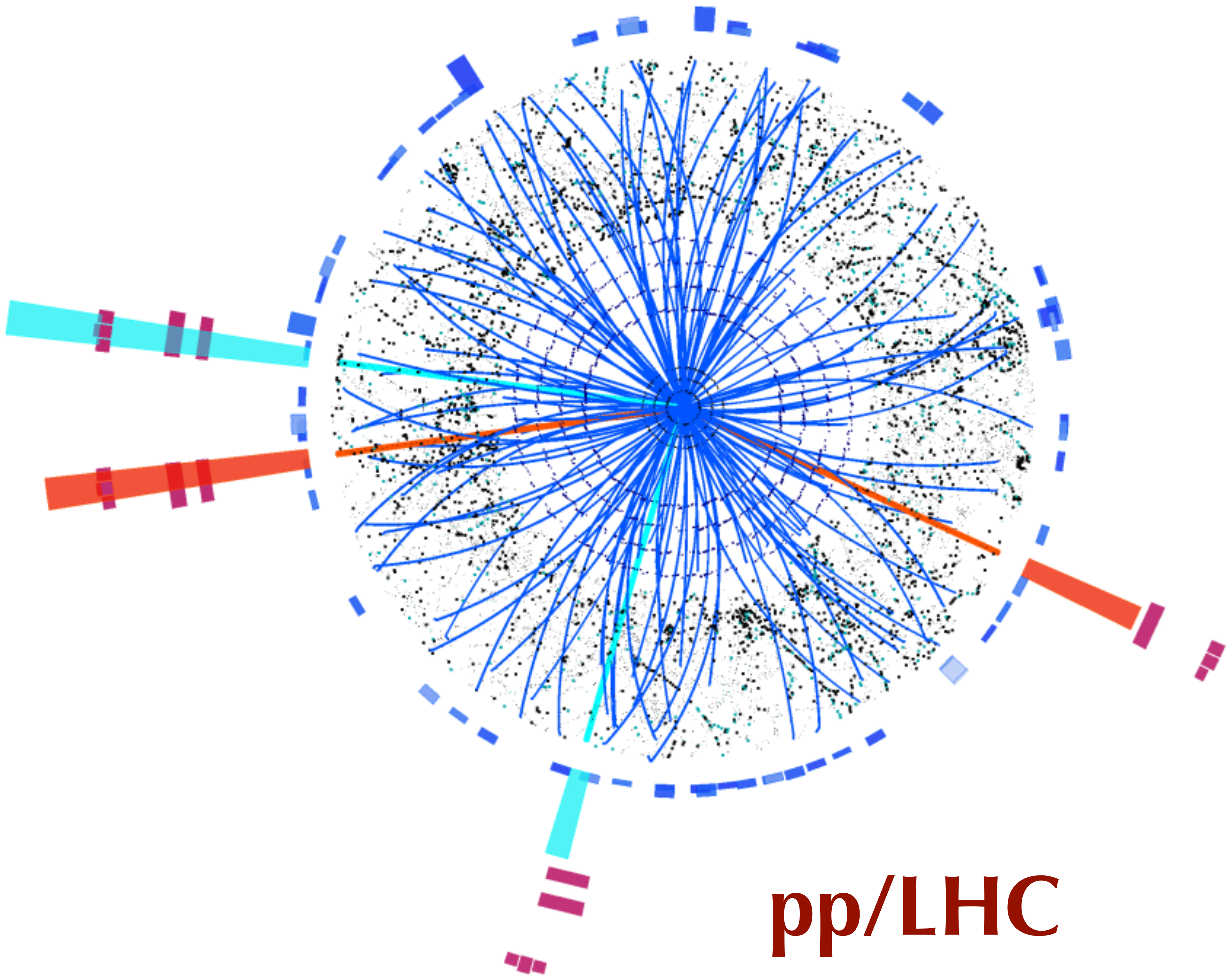
Light Yukawa ?



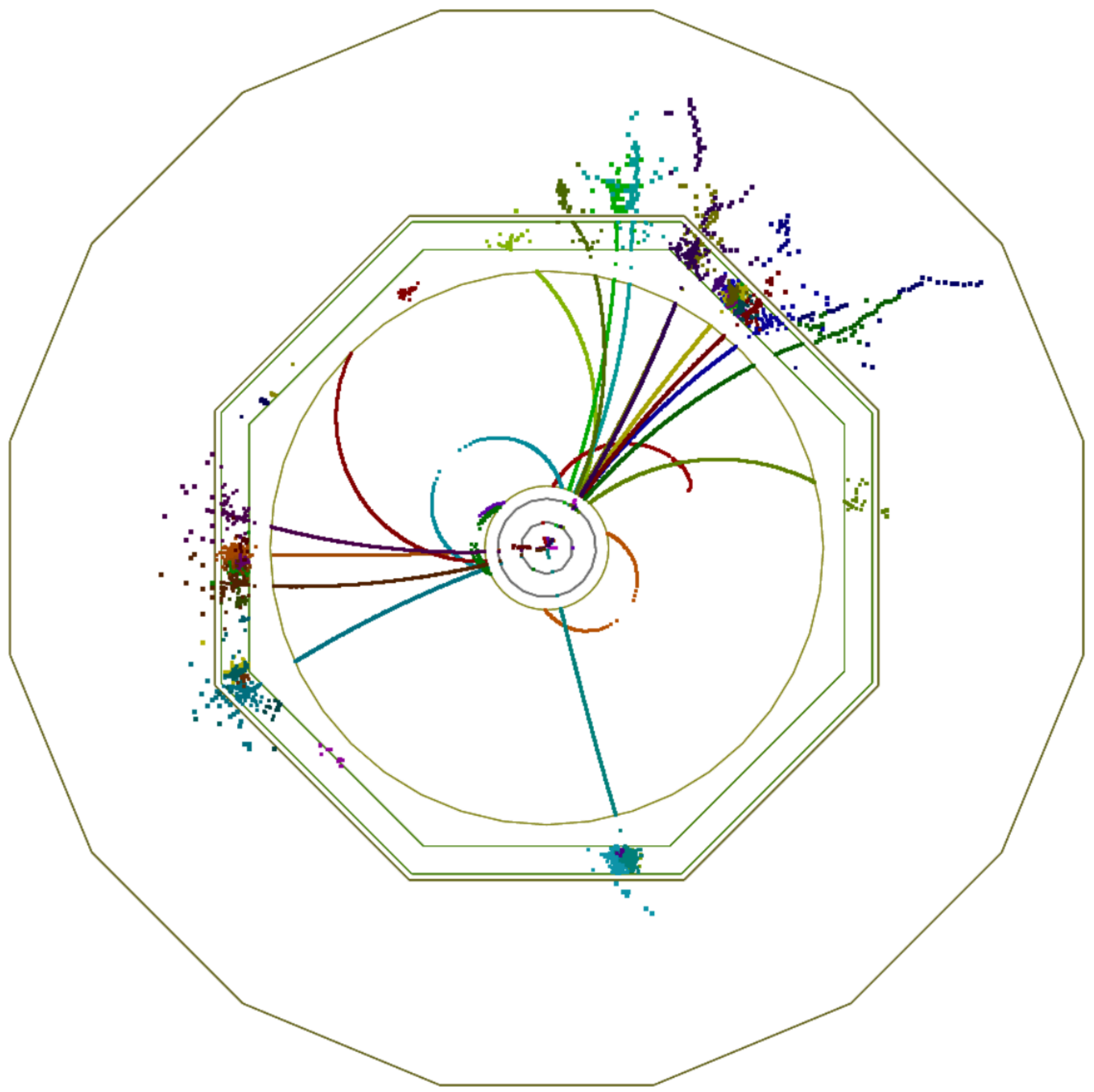


Why leptons?

- Initial state well defined (& polarization) ⟹ High-precision measurements
- Higgs bosons appear in 1 in 100 events ⟹ Clean experimental environment and less backgrounds, trigger-less readout



pp/LHC

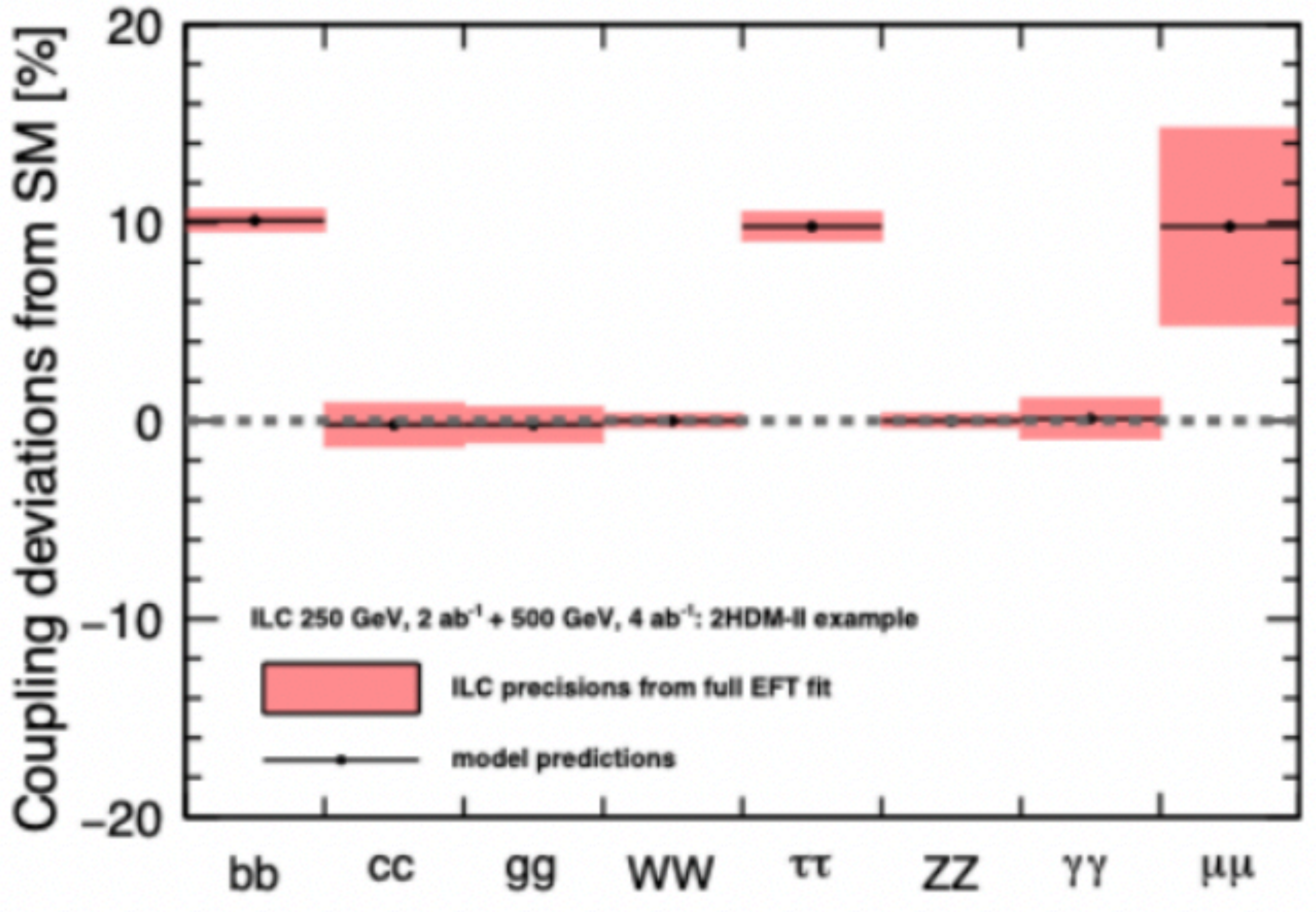


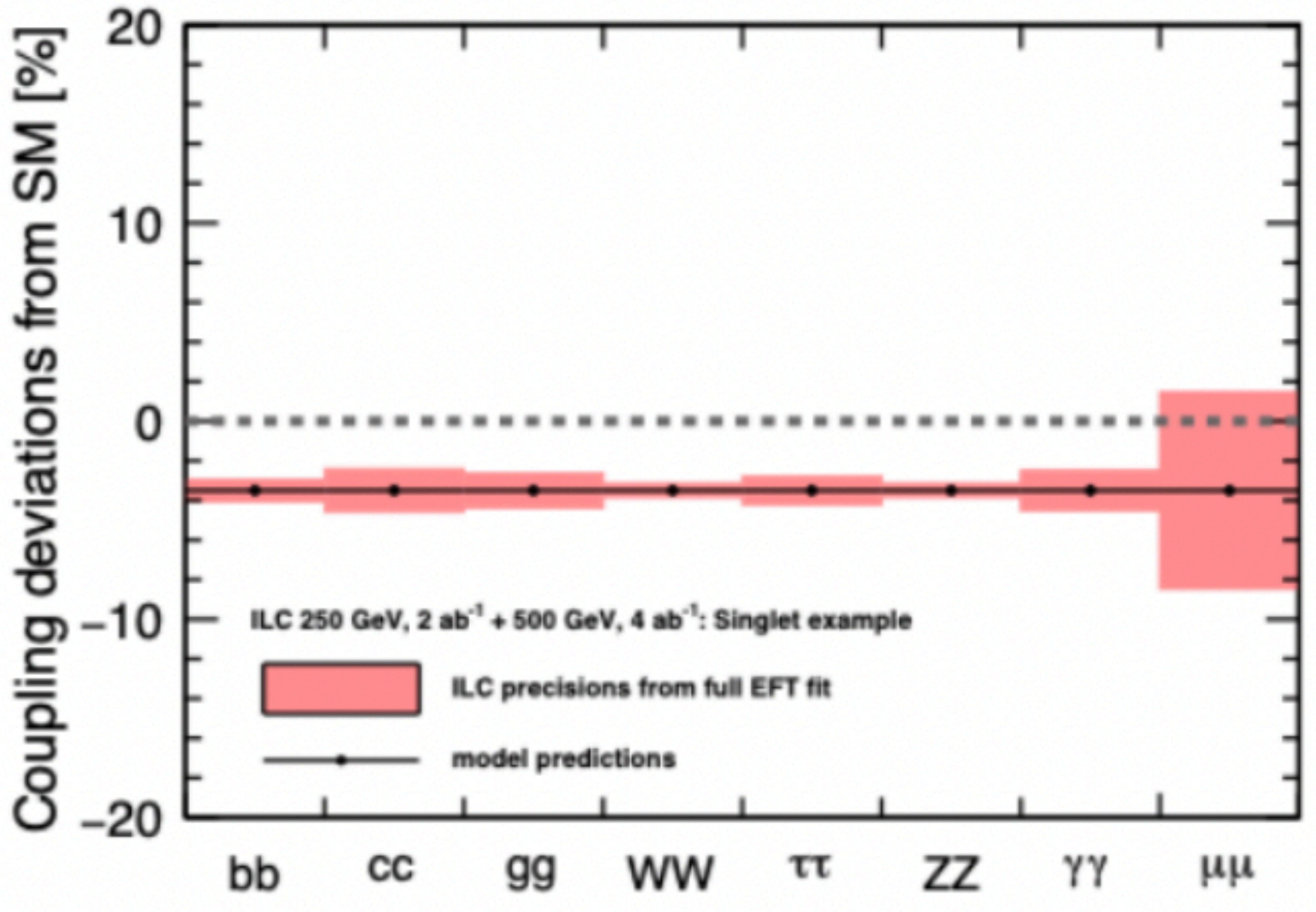
e^+e^-

An example of complementarity

arXiv:2203.07622

Pattern of deviations associated with a particular parameter point in a 2HDM model is quite different from a singlet model





- 2HDM with a 600 GeV mass scale and a singlet with a 2.8 TeV scalar. Both of these are clearly out of the direct search reach of circular e+e– Higgs factories despite having the precision to test them via Higgs couplings
- High energy collisions would be then required to study such new particles

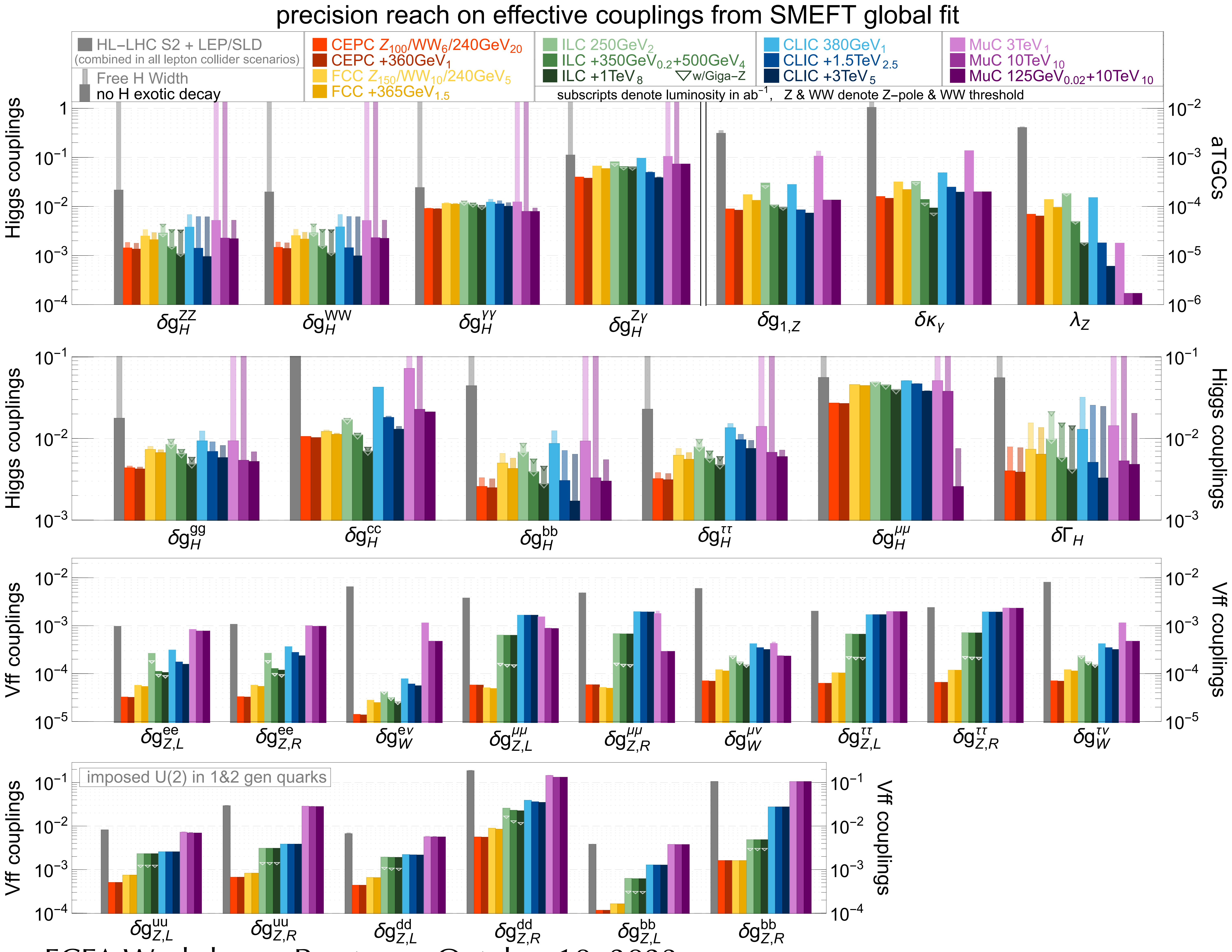
Various machines to consider

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3	ee	250 GeV	$\pm 80/\pm 30$	2
c.o.m almost		350 GeV	$\pm 80/\pm 30$	0.2
similar		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
CEPC	ee	M_Z		60
		$2M_W$		3.6
		240 GeV		20
		360 GeV		1
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HE-LHC	pp	27 TeV		15
FCC-hh	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh		3.5 TeV		2
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5
		3.0 TeV	$\pm 80/0$	5
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10

Global fit results - from EF04

- Solid has no exotic Higgs decays, the light fits the width



arxiv:2107.02686

Higgs-electron Yukawa

Electron Yukawa at FCC-ee with a dedicated 4 years run at the Higgs mass

κe < 1.6 at 95% CL