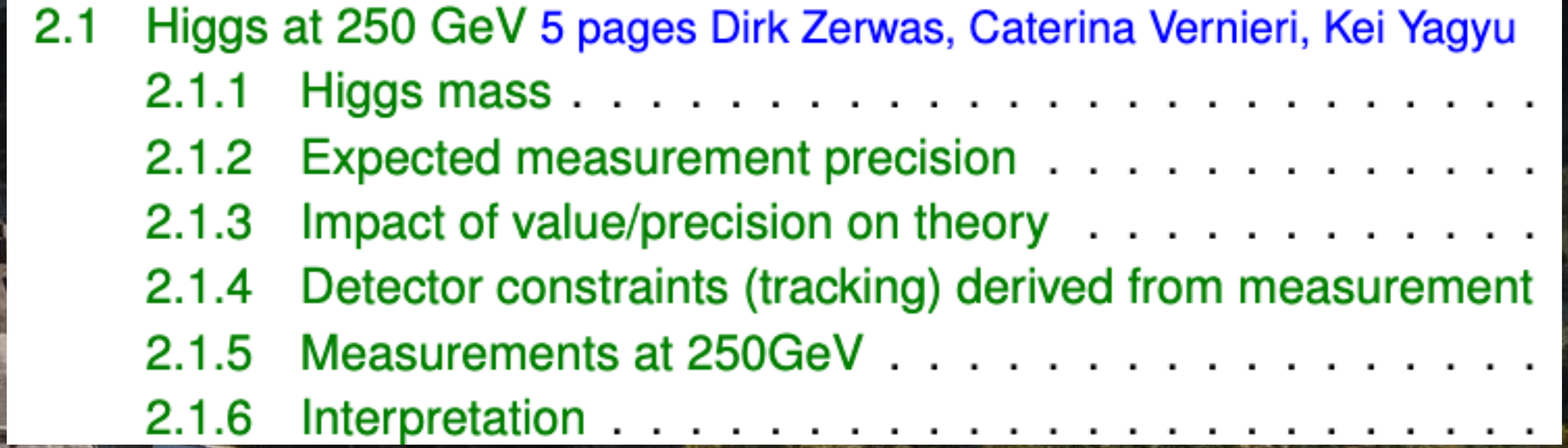
Higgs at 250 GeV



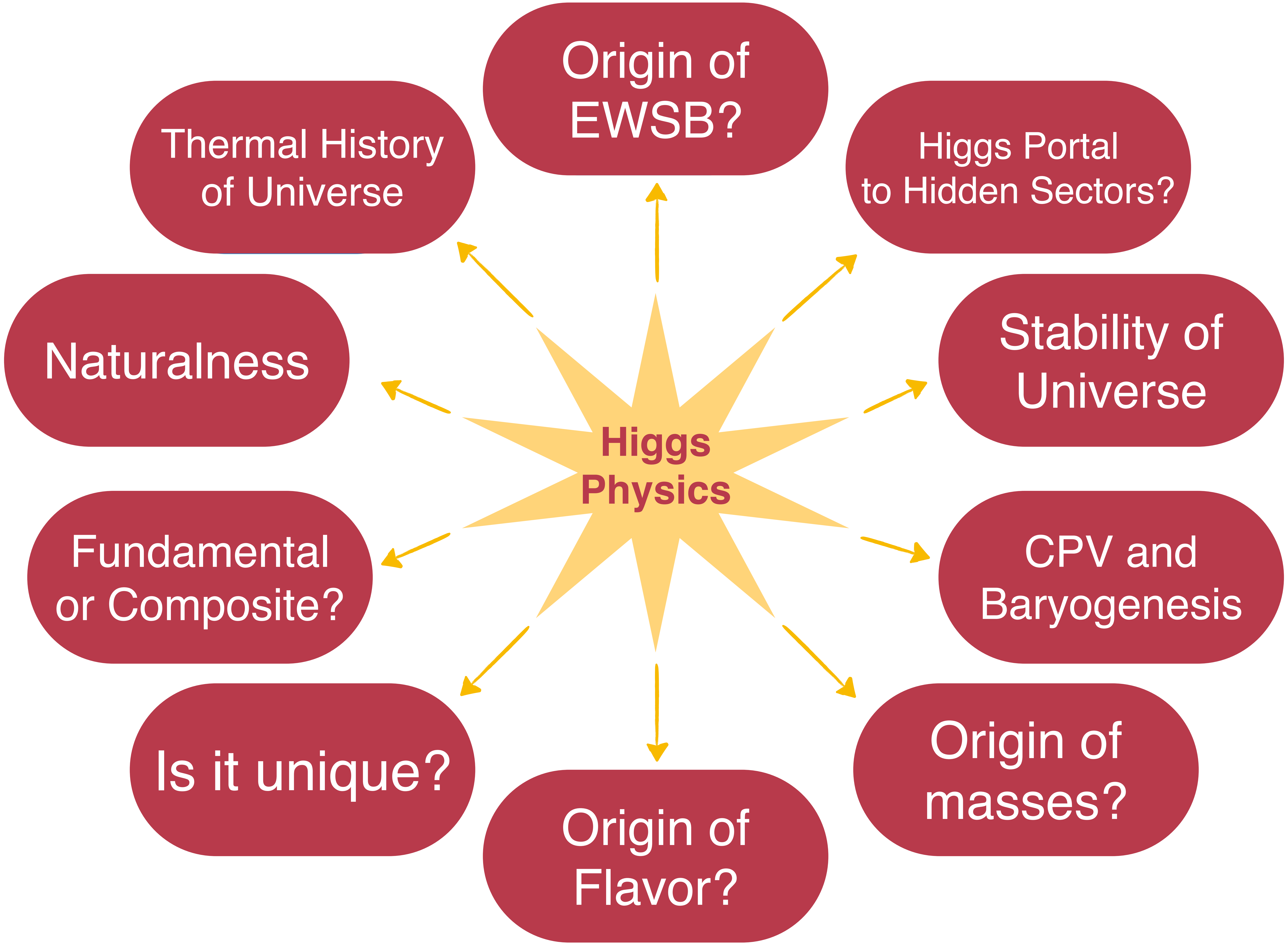
2.1 Higgs at 250 GeV 5 pages Dirk Zerwas, Caterina Vernieri, Kei Yagyu
  2.1.1 Higgs mass
  2.1.2 Expected measurement precision
  2.1.3 Impact of value/precision on theory
  2.1.4 Detector constraints (tracking) derived from measurement
  2.1.5 Measurements at 250GeV
  2.1.6 Interpretation

LC Vision meeting
CERN

Caterina Vernieri, Dirk Zerwas, Key Yagyu

January 8, 2025

SLAC NATIONAL ACCELERATOR LABORATORY
Stanford University | U.S. DEPARTMENT OF ENERGY



Higgs Physics

Origin of EWSB?

Higgs Portal to Hidden Sectors?

Stability of Universe

CPV and Baryogenesis

Origin of masses?

Origin of Flavor?

Is it unique?

Fundamental or Composite?

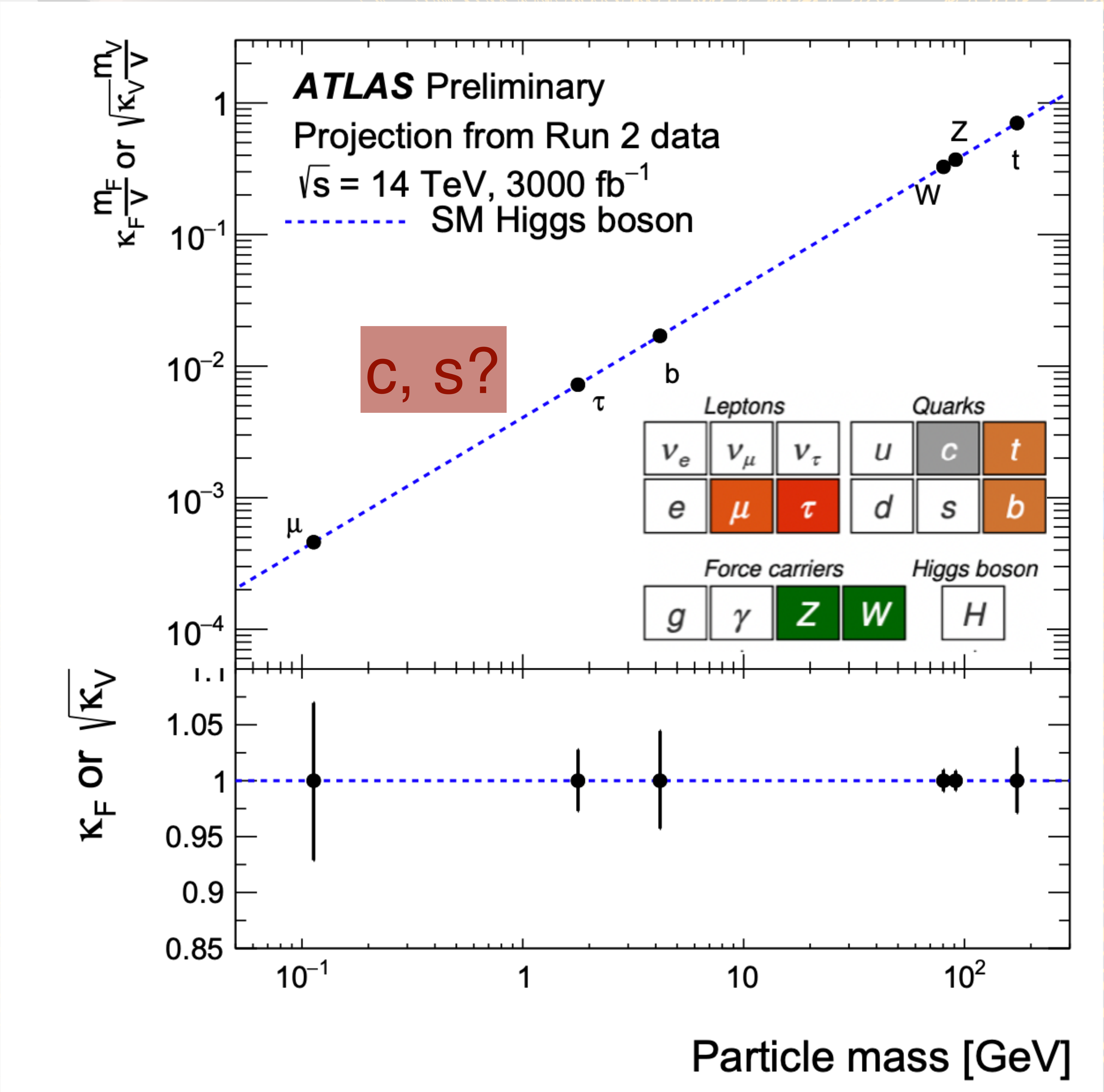
Naturalness

Thermal History of Universe

[The Energy Frontier 2021 Snowmass Report]

1902.10229
CERN-LPCC-2018-04

Higgs at HL-LHC



c, s?

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

- **2-5% precision for many of the Higgs couplings**
- **BUT much larger uncertainties on $Z\gamma$ and charm and ~30% (?) on the self-coupling**

Higgs at HL-LHC

1902.10229
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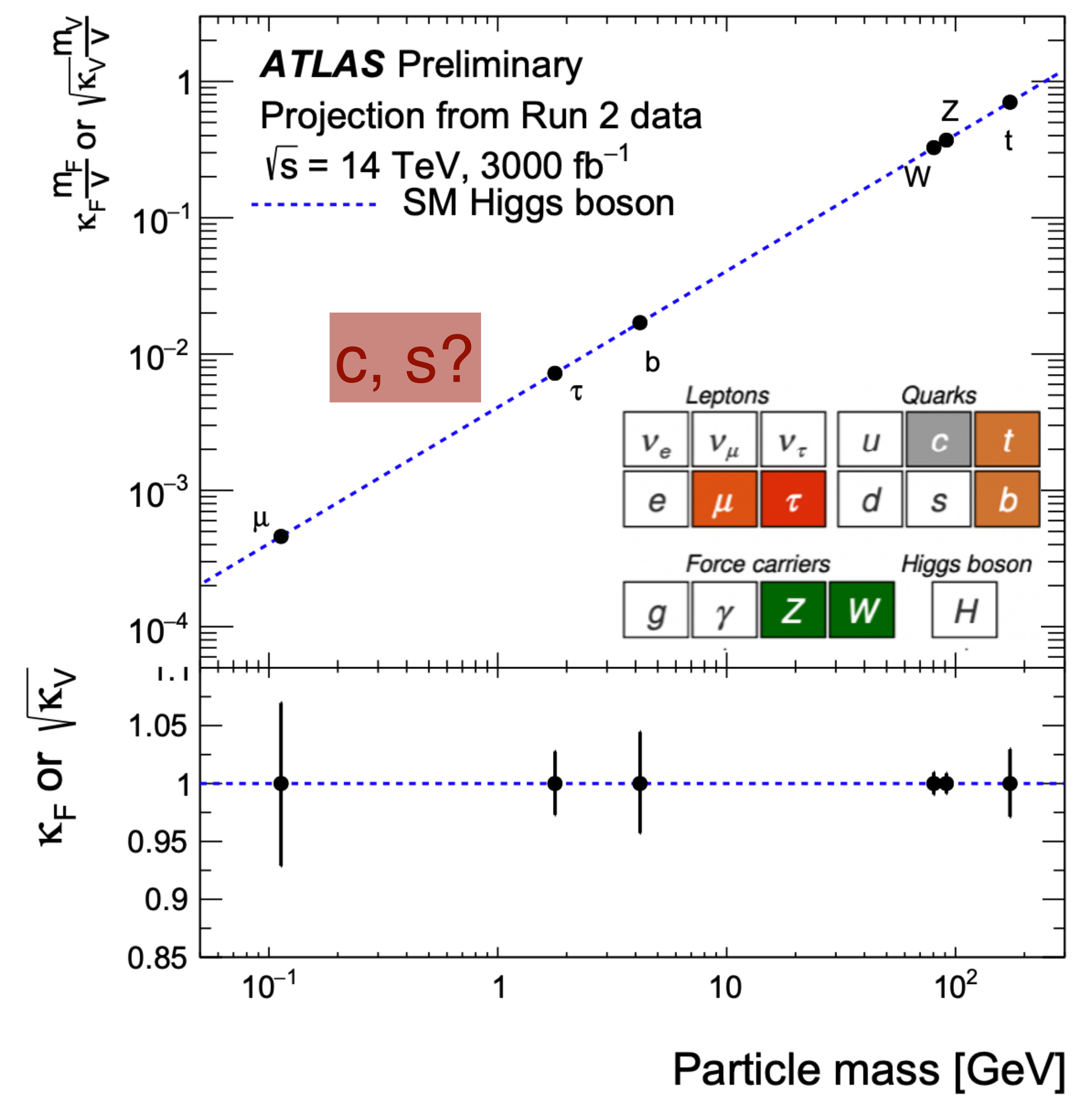

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- **2-5% precision for many of the Higgs couplings**
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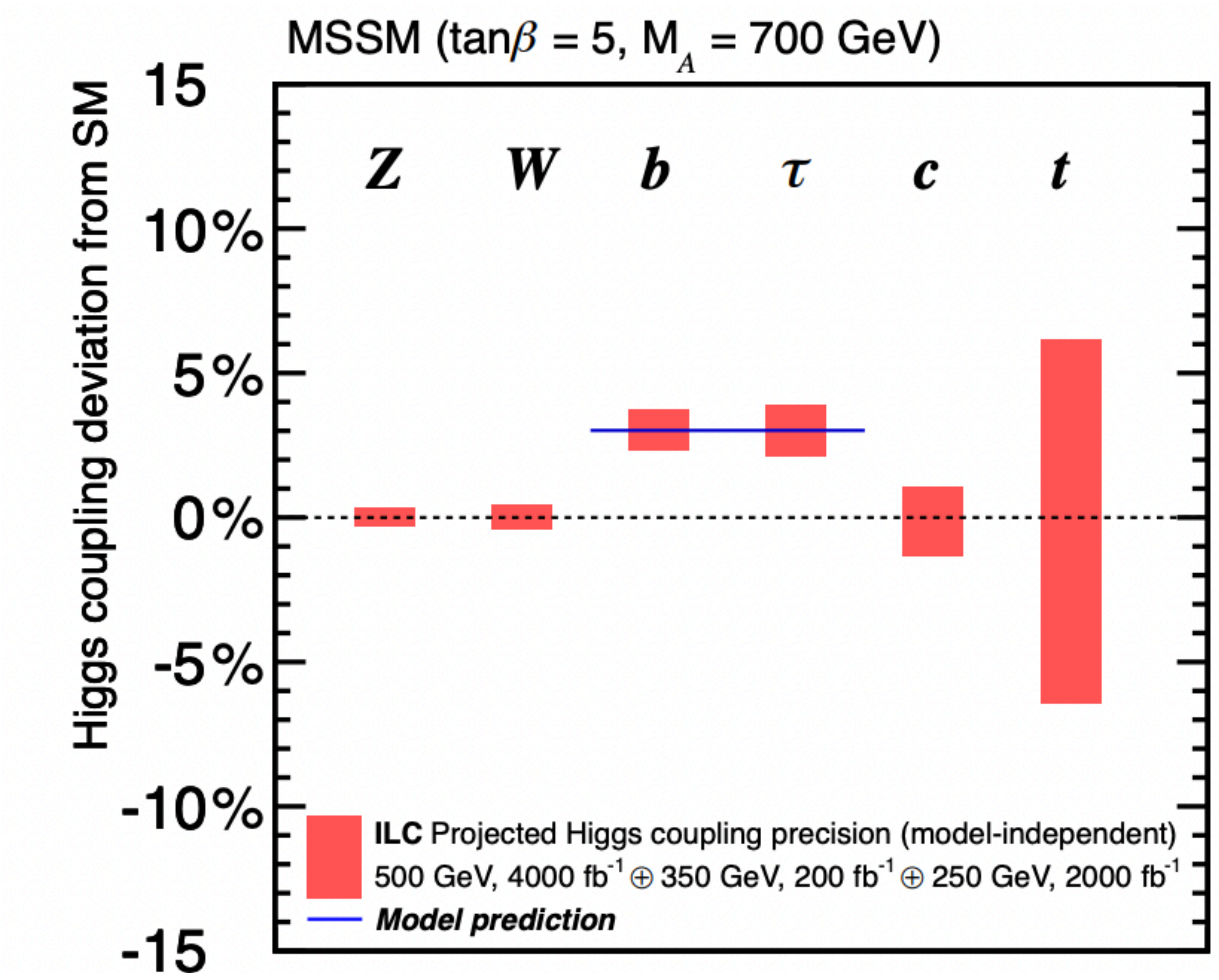
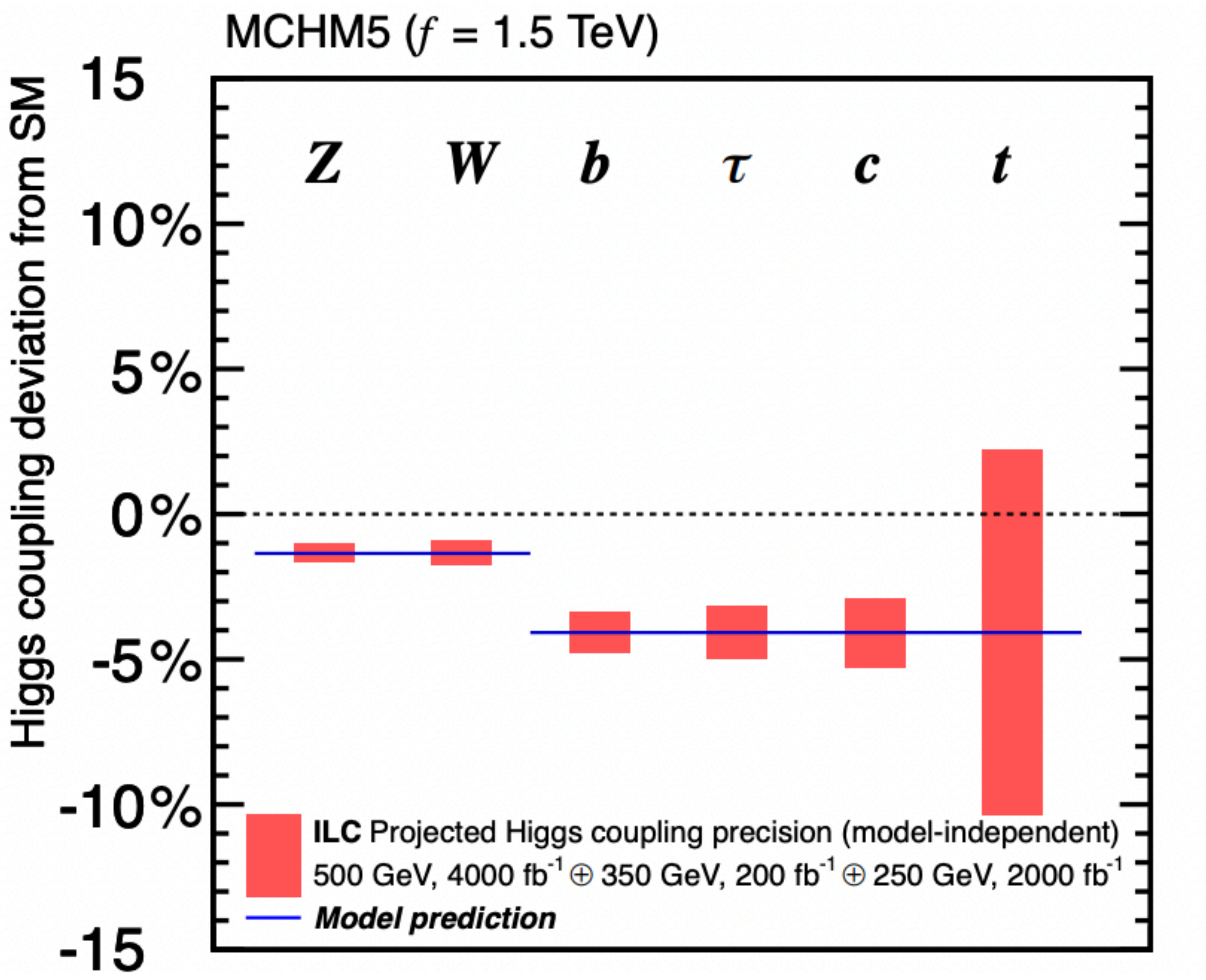
Light Yukawa out of reach in the LHC environment

ArXiv:2209.07510
ArXiv:2203.07622

No new particles discovered at the LHC so far…

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





ArXiv:2209.07510
ArXiv:2203.07622

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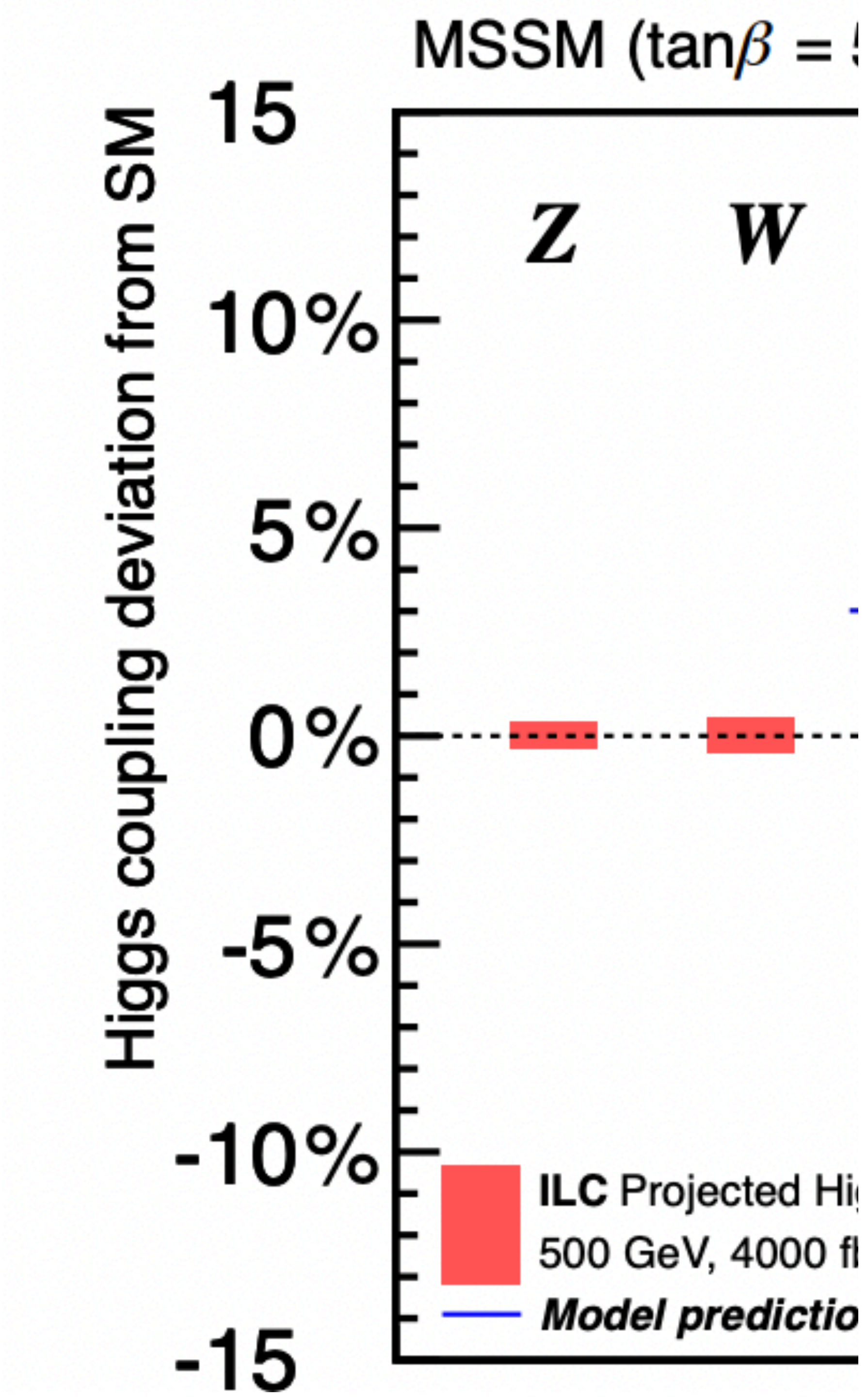
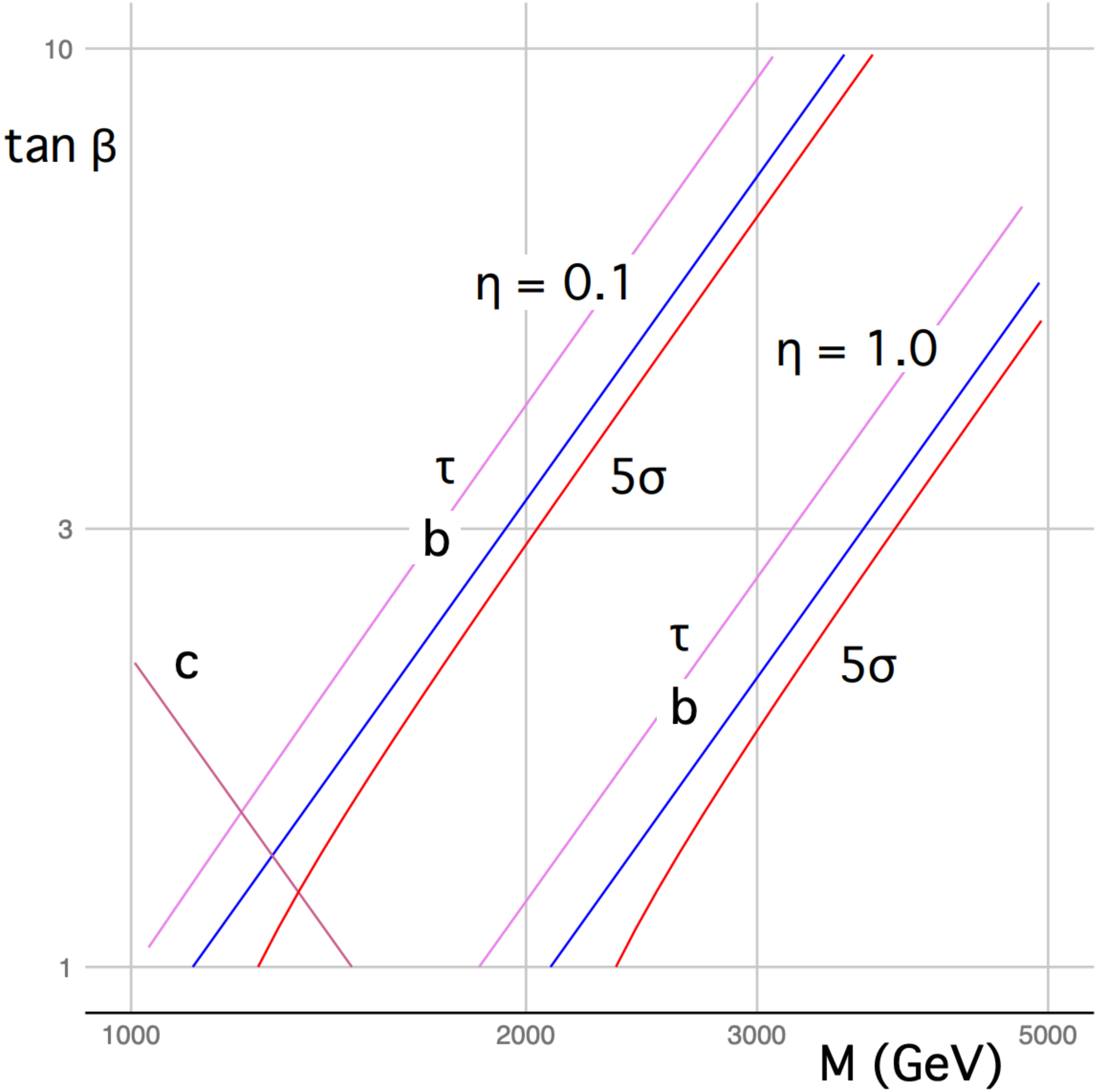
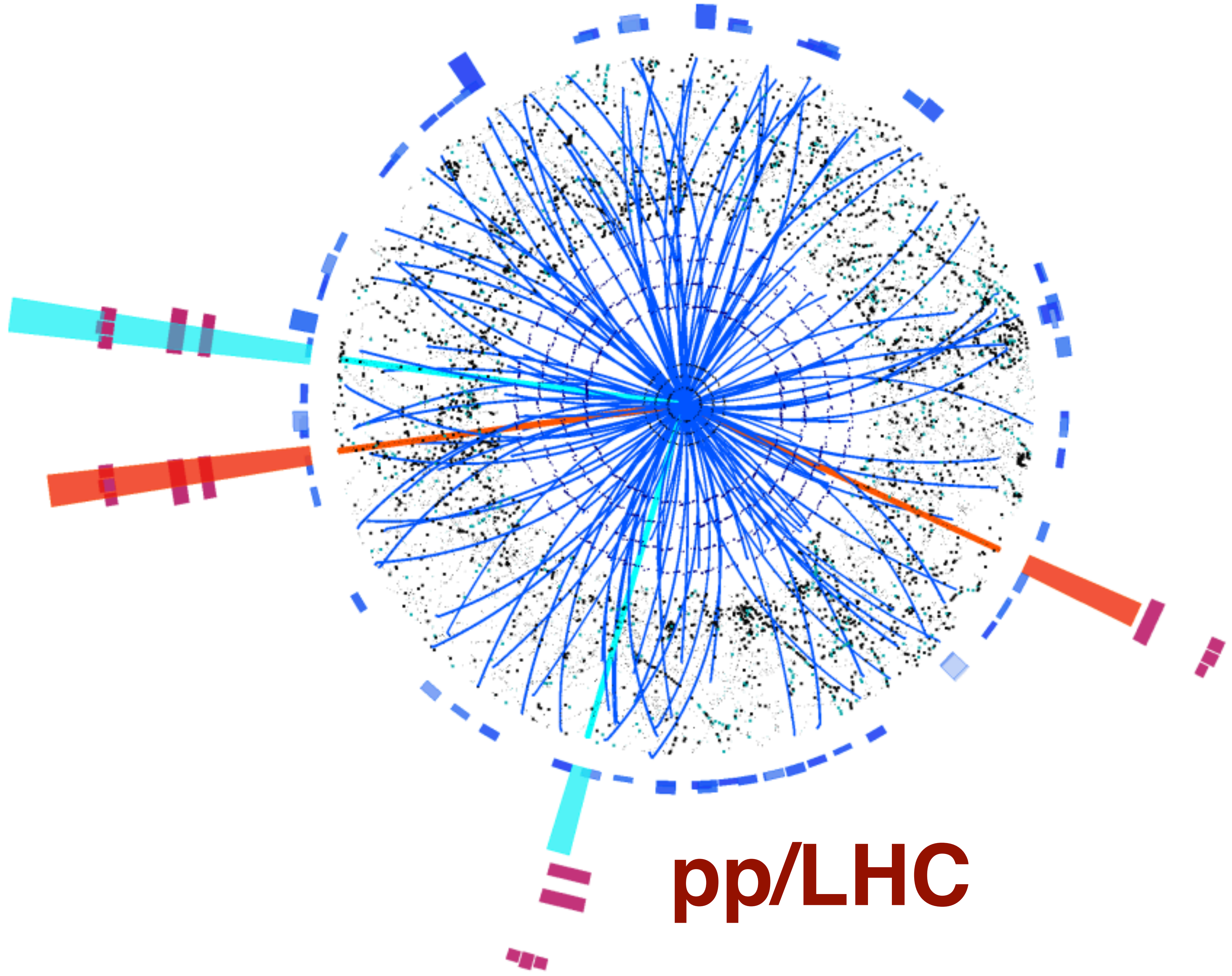




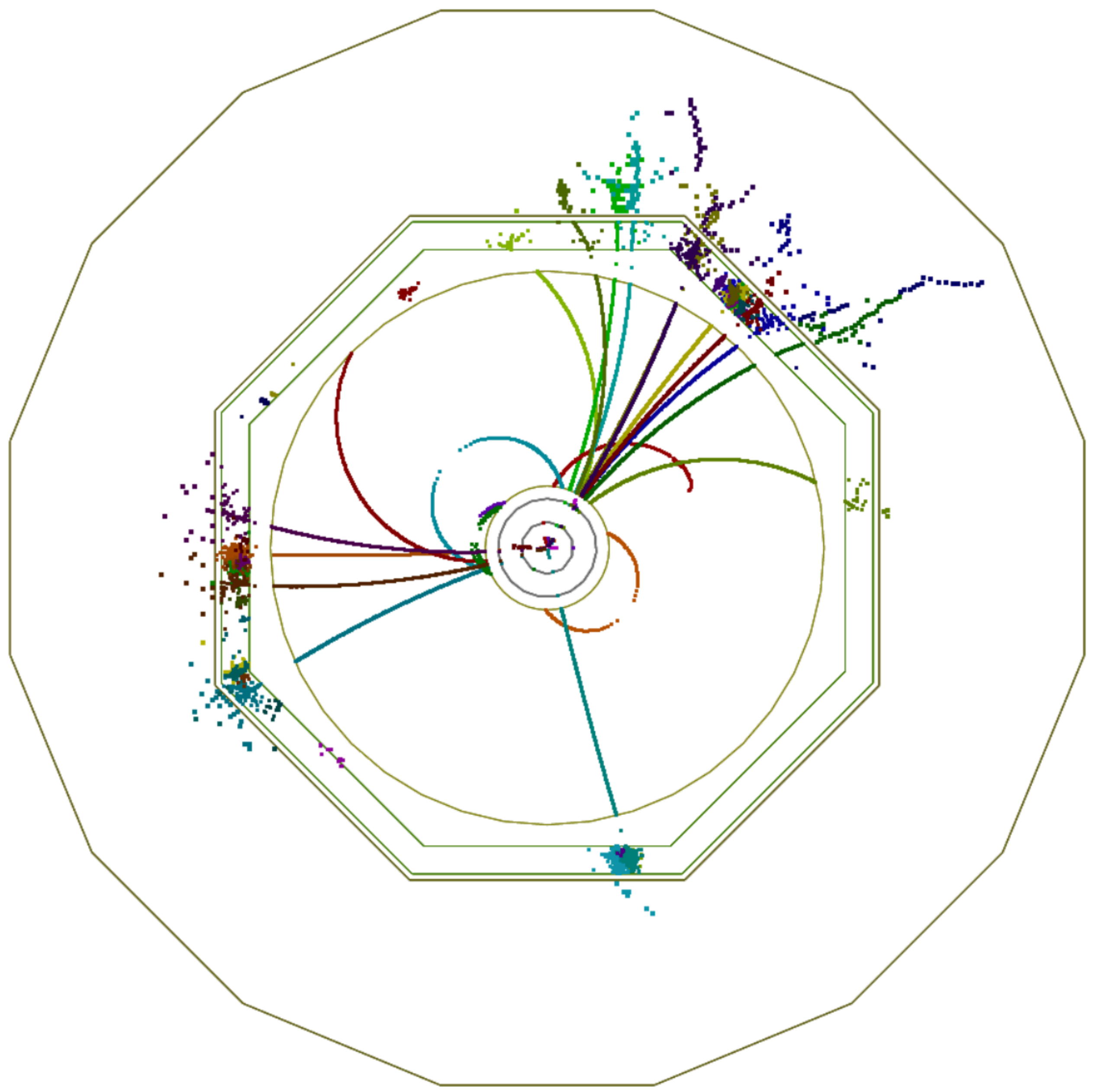
From pp to e^+e^-

Initial state well defined & polarization ⟹ High-precision measurements

Higgs bosons appear in 1 in 100 events ⟹ Clean experimental environment and trigger-less readout



pp/LHC

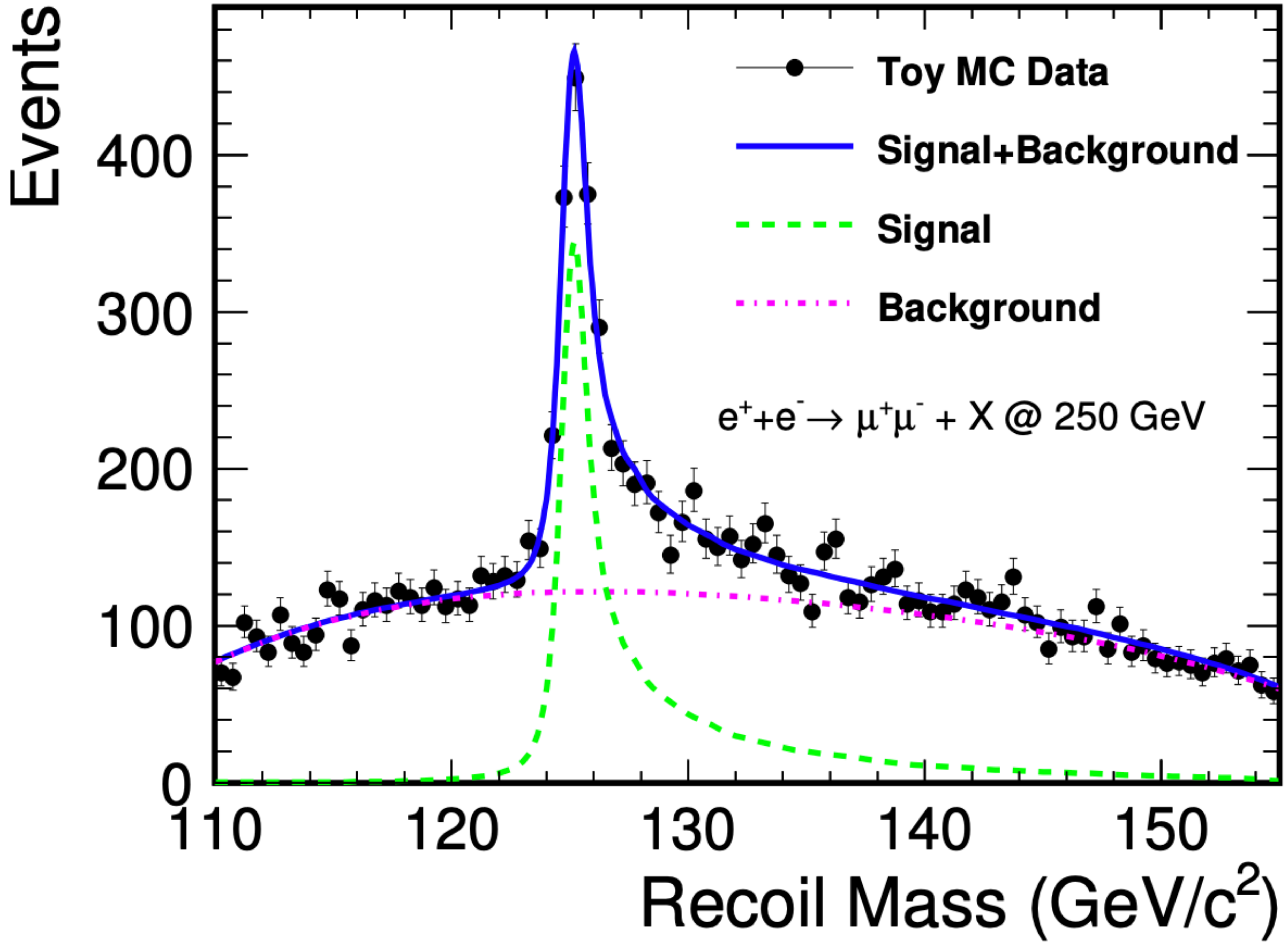


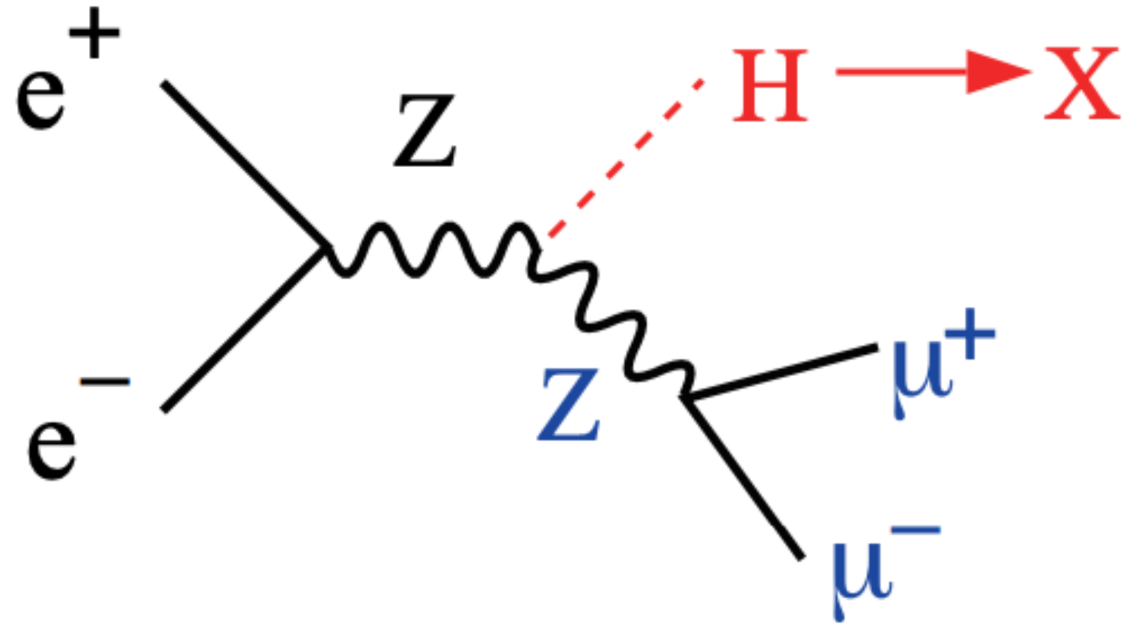
e^+e^-

Higgs at e+e-

arXiv:2203.07622

Unprecedented precision unlocked with a well defined initial state





peak ~ Higgs mass ~ 14 MeV

Higgs at e+e-

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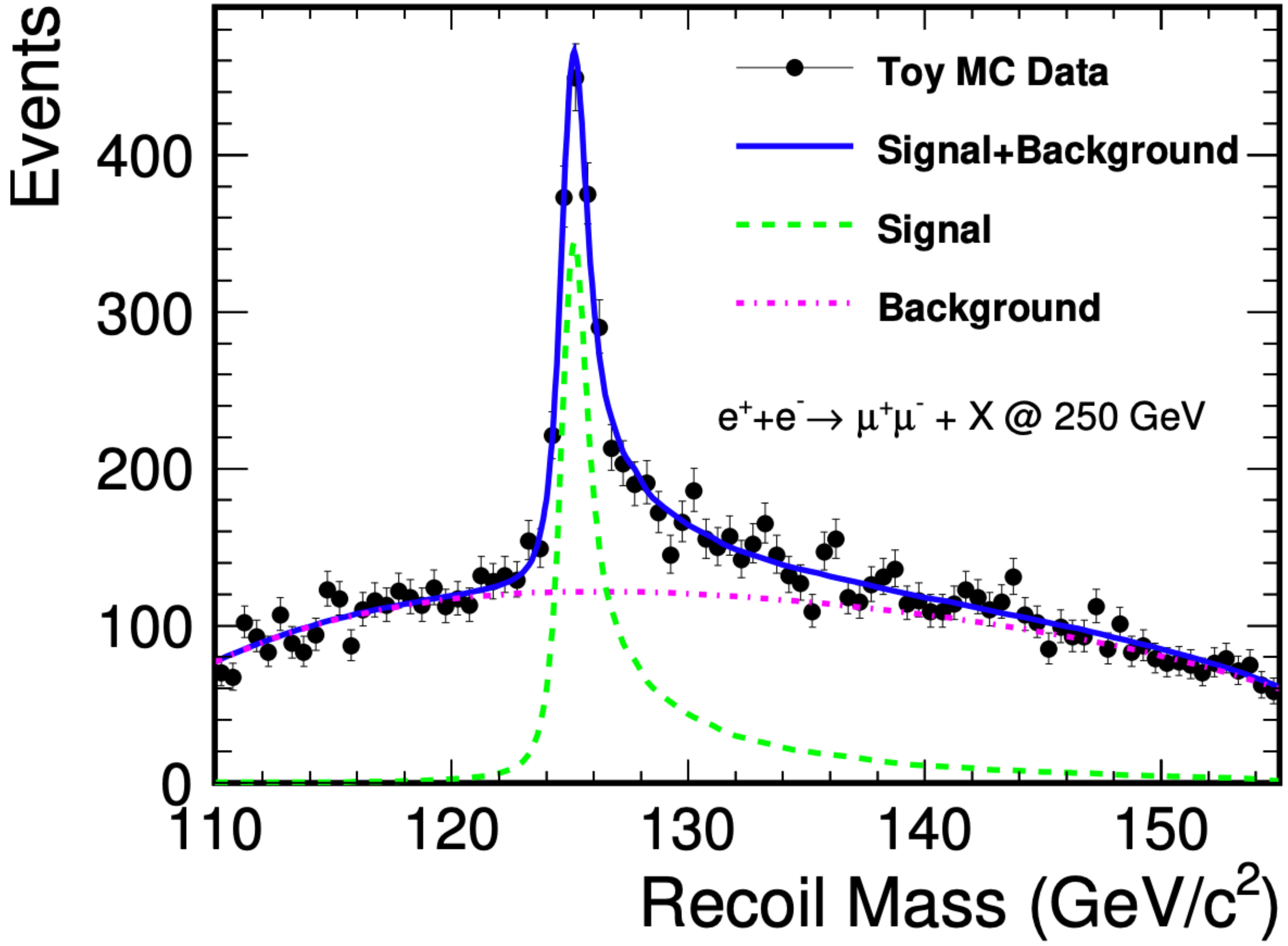
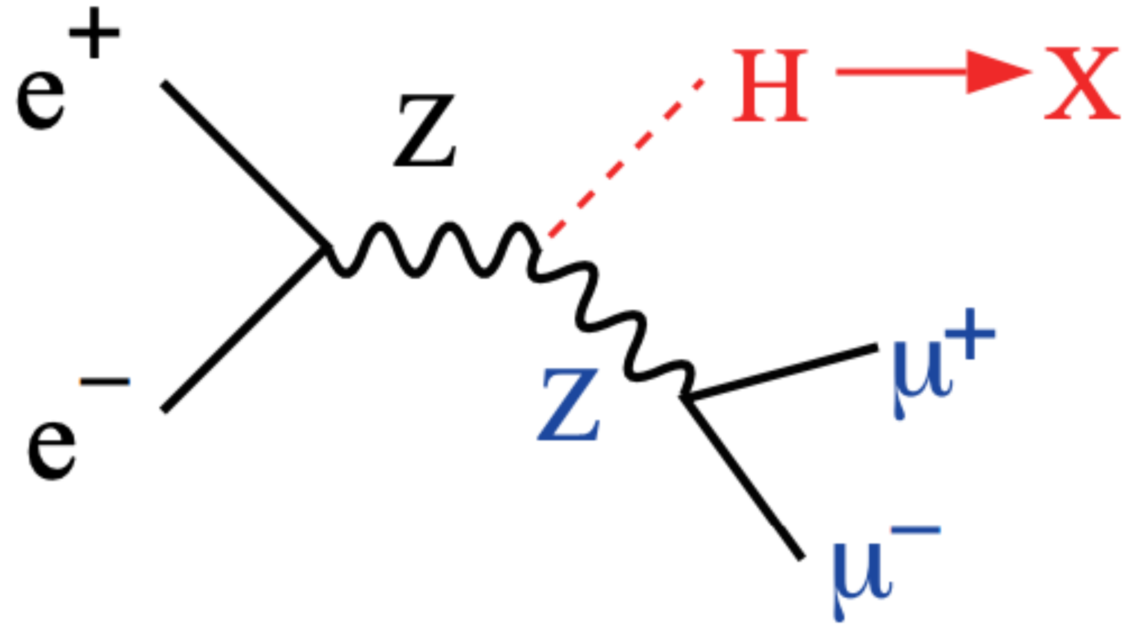




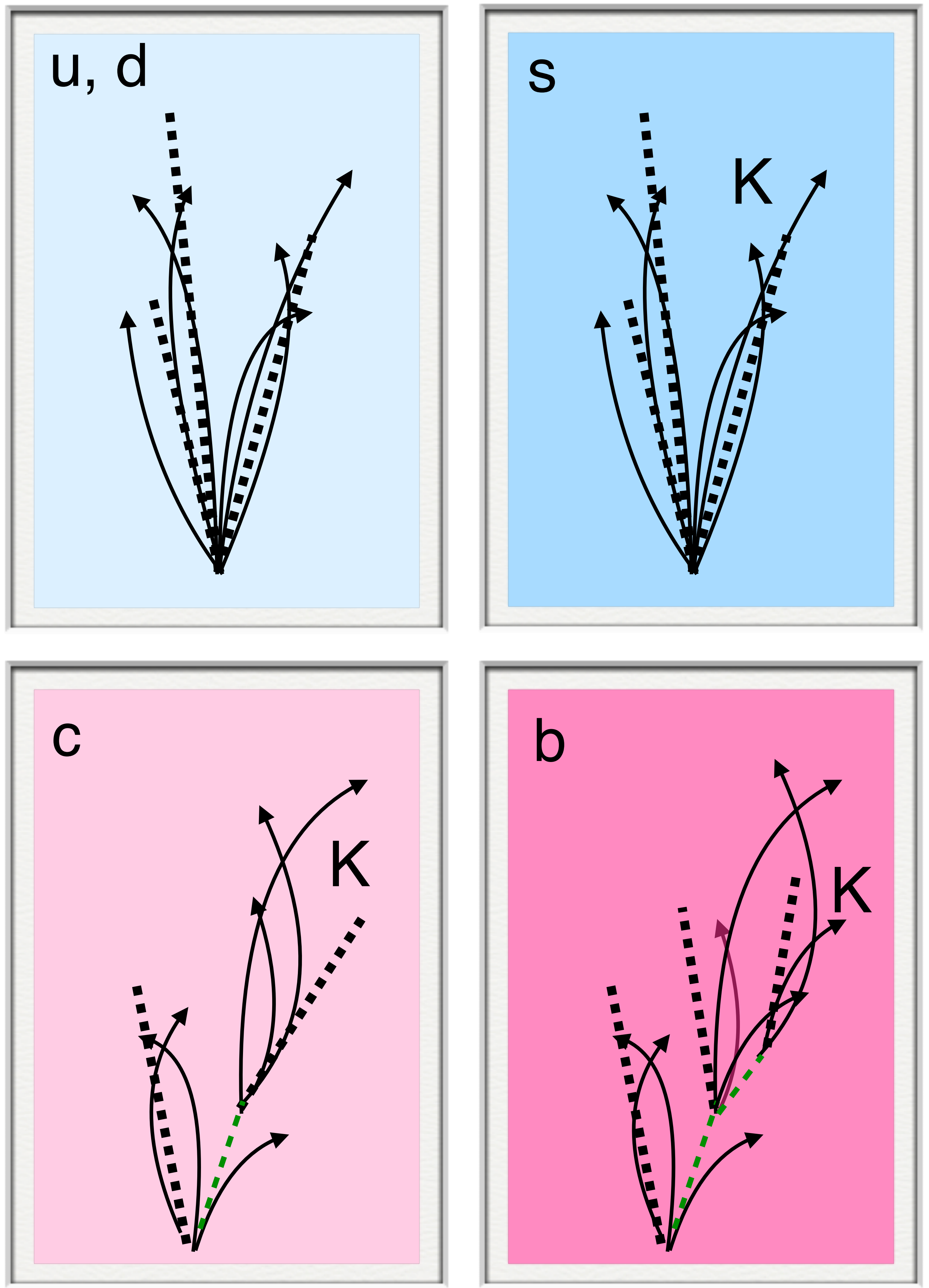
ZH cross section can be measured with O(1%) precision and in a model independent way

peak ~ Higgs mass ~ 14 MeV

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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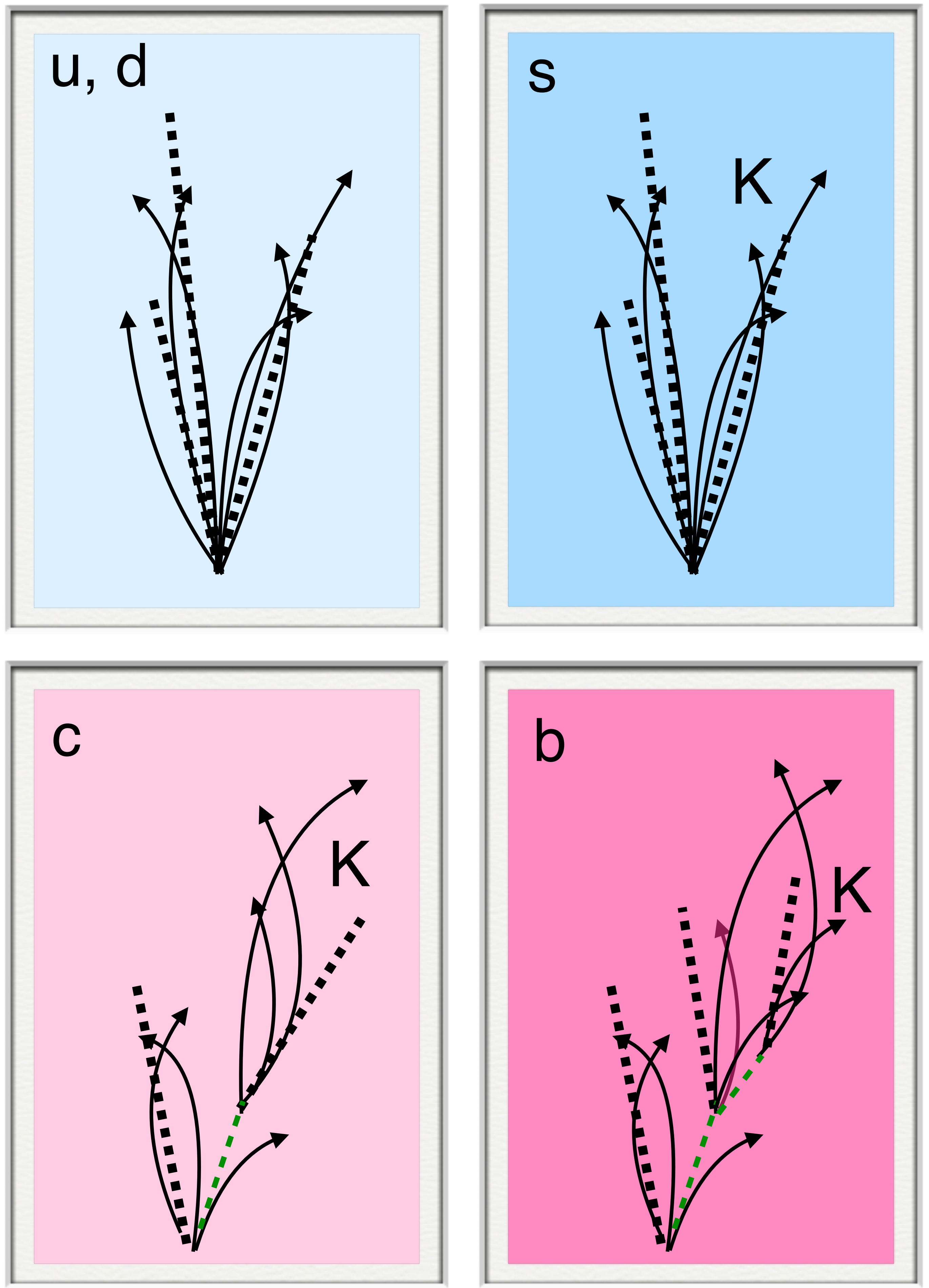

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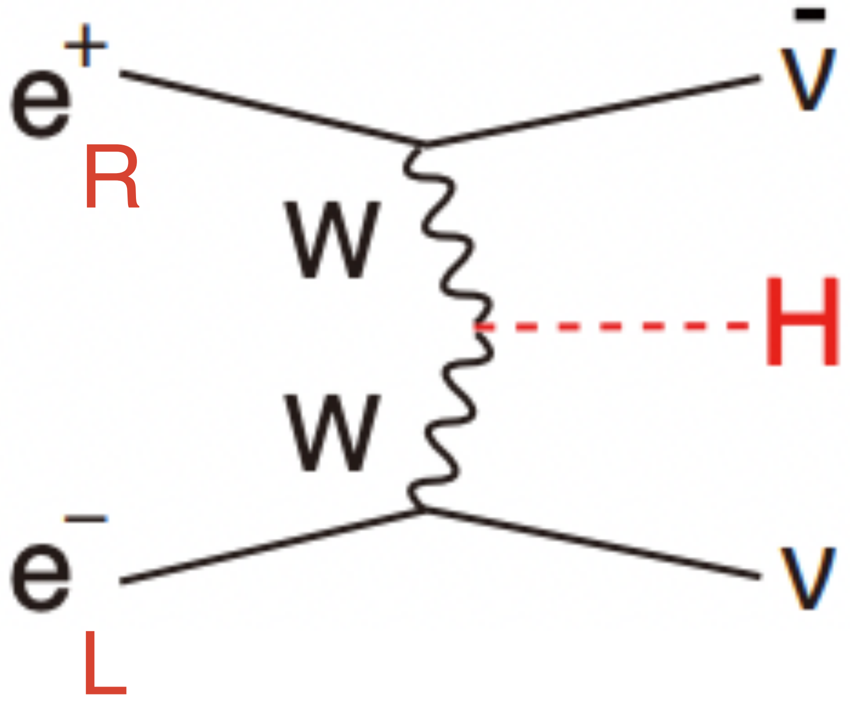
A limit on the BR H($s\bar{s}$) at ~5x above the SM value would already be a significant probe to new physics.
This would be achievable at future e^+e^-

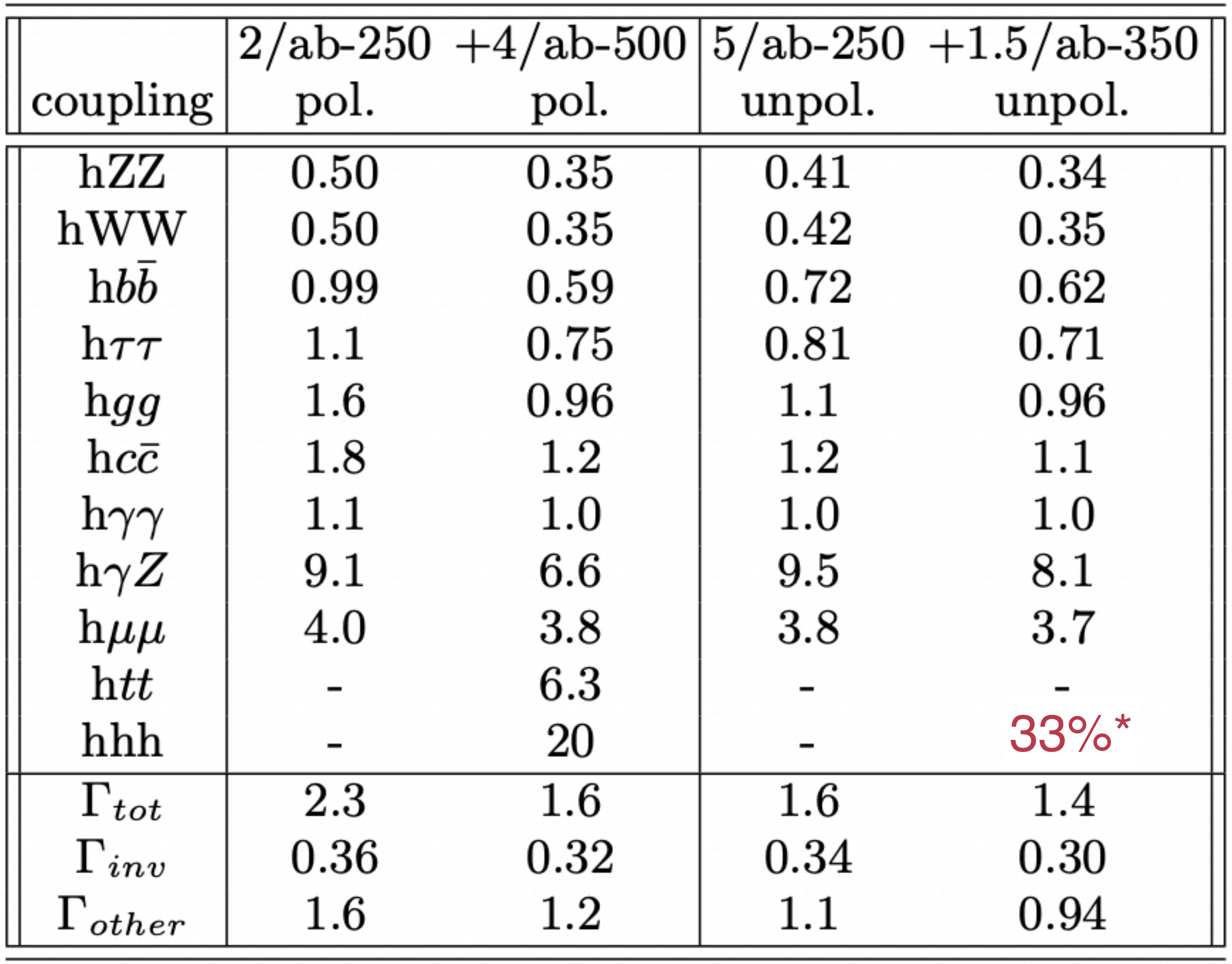
Projected sensitivity

arXiv:2209.07510

One note: Polarization to compensate for luminosity

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





	ILC/C^3		FCC	
coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+1.5/ab-350 unpol.
hZZ	0.50	0.35	0.41	0.34
hWW	0.50	0.35	0.42	0.35
$hb\bar{b}$	0.99	0.59	0.72	0.62
$h\tau\tau$	1.1	0.75	0.81	0.71
hgg	1.6	0.96	1.1	0.96
$hc\bar{c}$	1.8	1.2	1.2	1.1
$h\gamma\gamma$	1.1	1.0	1.0	1.0
$h\gamma Z$	9.1	6.6	9.5	8.1
$h\mu\mu$	4.0	3.8	3.8	3.7
htt	-	6.3	-	-
hhh	-	20	-	33%*
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

* indirect constraints

arXiv:2209.07510

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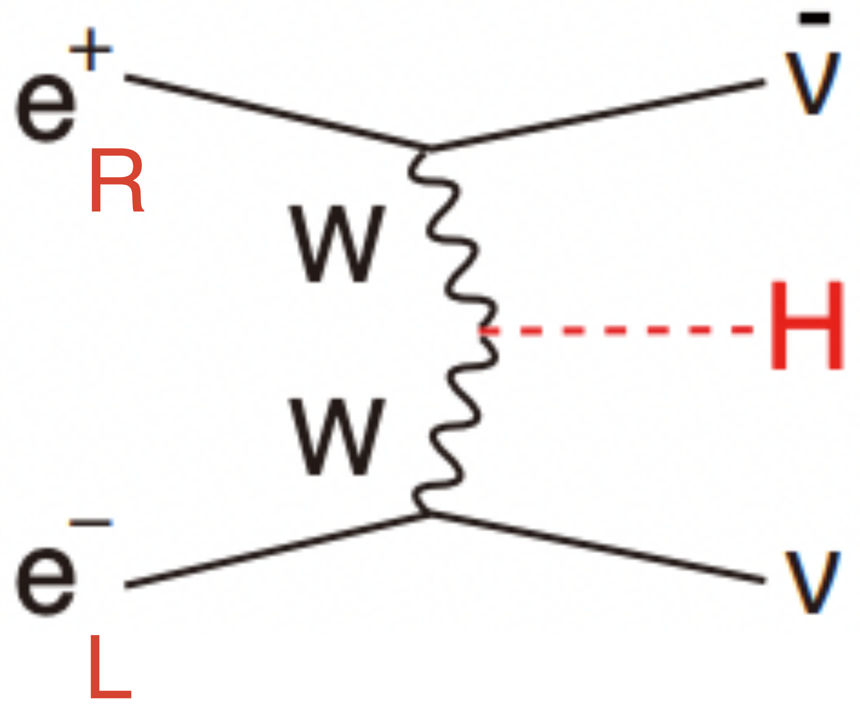
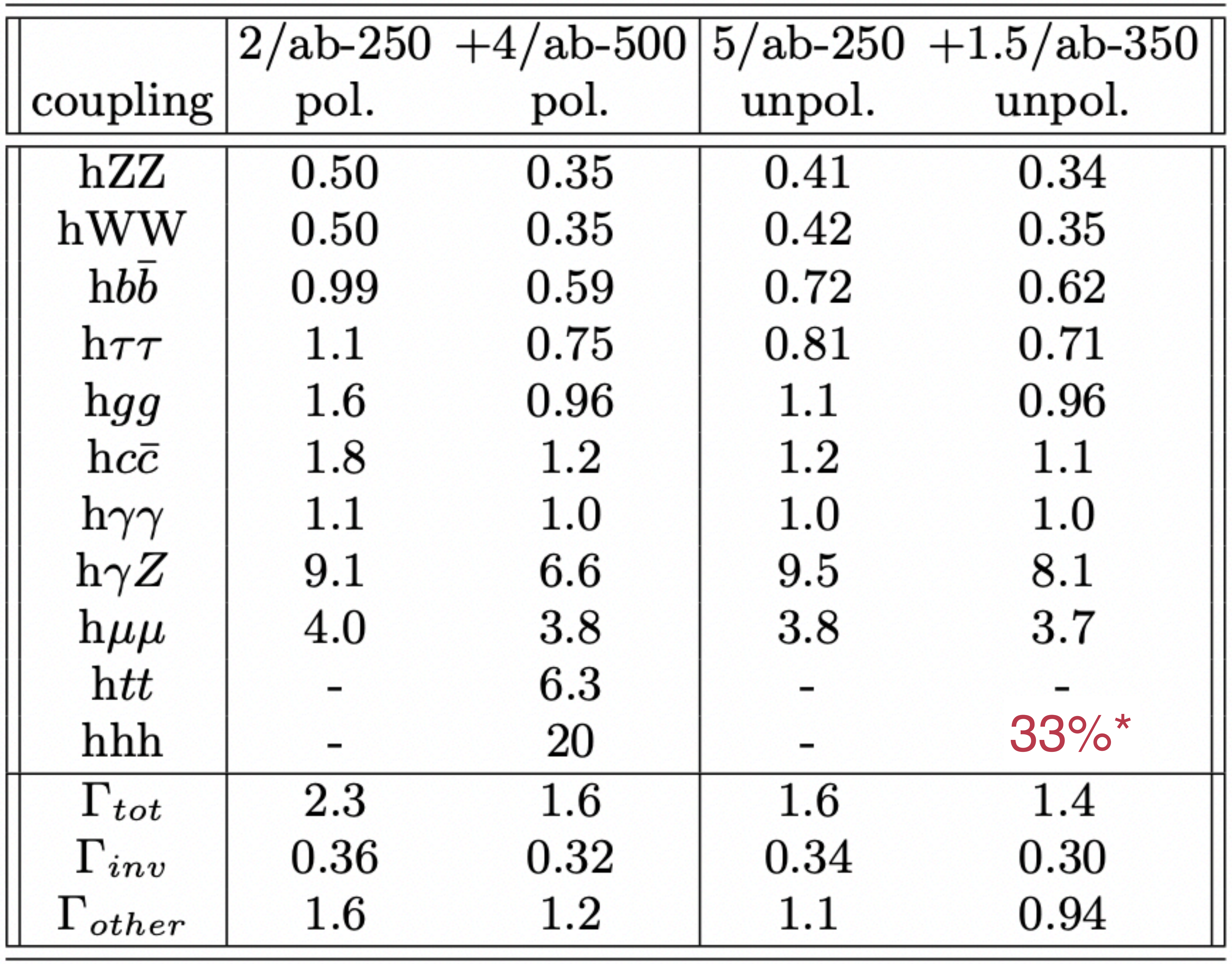


O(20%) precision on the Higgs self-coupling would allow to exclude/demonstrate at 5σ models of electroweak baryogenesis



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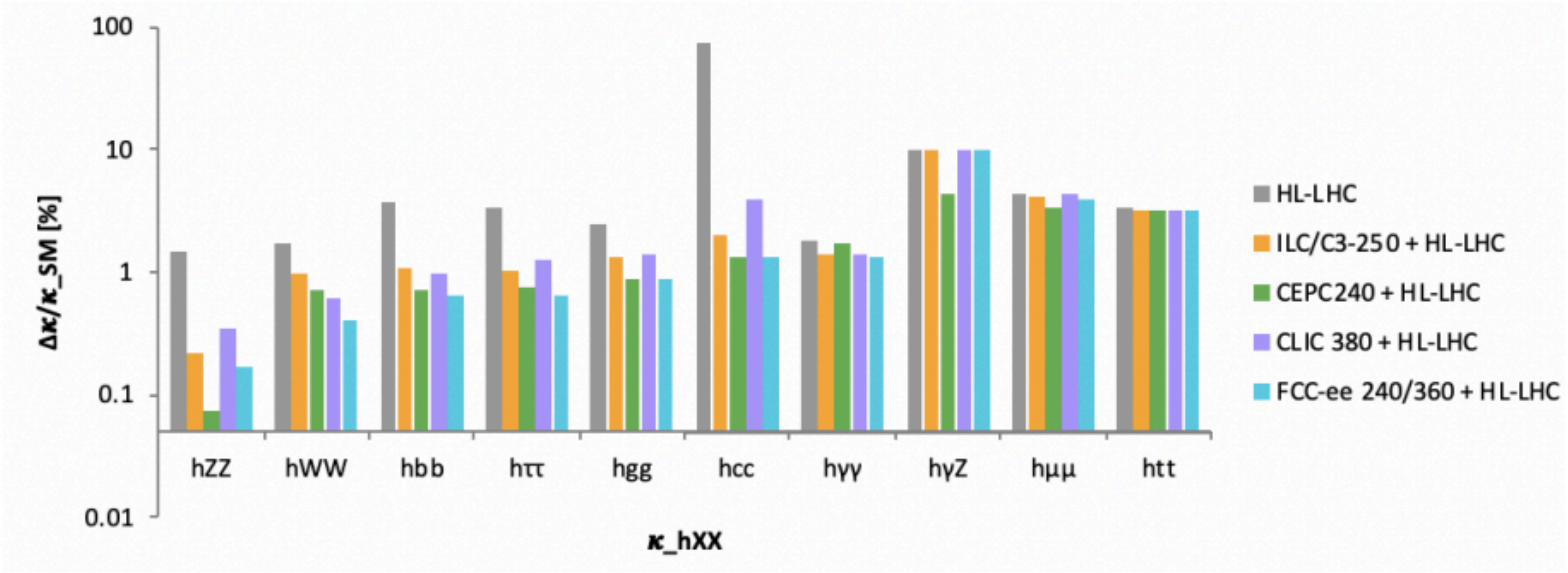
Higgs couplings at future machines

Higgs Report Snowmass 2022



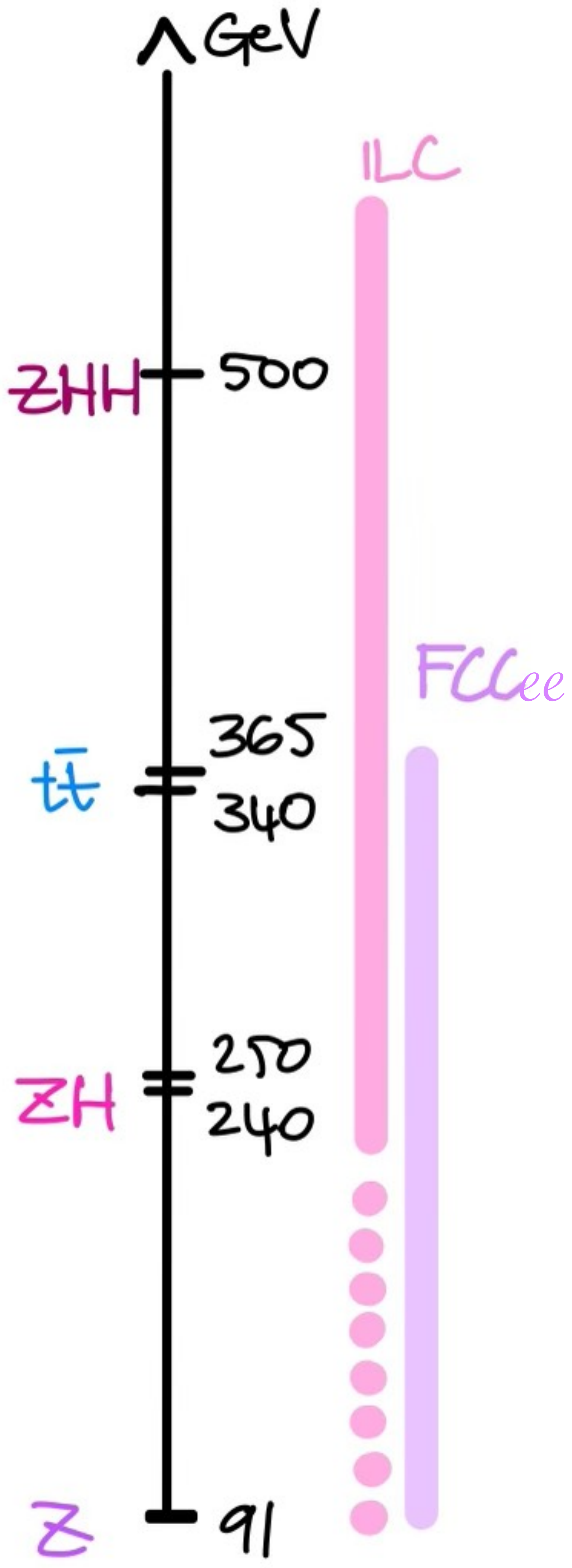
- Absolute measurements of couplings at future e+e-.
- The Zγ interaction remains difficult to measure at all future machines
- Higher energy collision is required (factor 2 from 500 to 550 GeV e+e-) to further constraints the Higgs-top and H-self couplings
- Note that these results depend ***on the assumptions on Run plans X-lumi/Y-energy***
  - Since Snowmass: FCC results are now taking into account 4IP, ie. ~ 5→10/ab.
    New comparisons are in preparation for the ESG, with also new HL-LHC & LC projections on self-coupling

Ingredients for Detector requirements

(Higgs) Physics drivers have informed preliminary detector designs
more to investigate
Beam structure and beam induced backgrounds add constraints

Physics benchmarks

ILC and FCC-ee have different & complementary energy reach and goals



Higher Energies, O(500) GeV

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

tt, top mass

Higgs boson physics at 240-250 GeV

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

Z pole run, TeraZ program, WW threshold

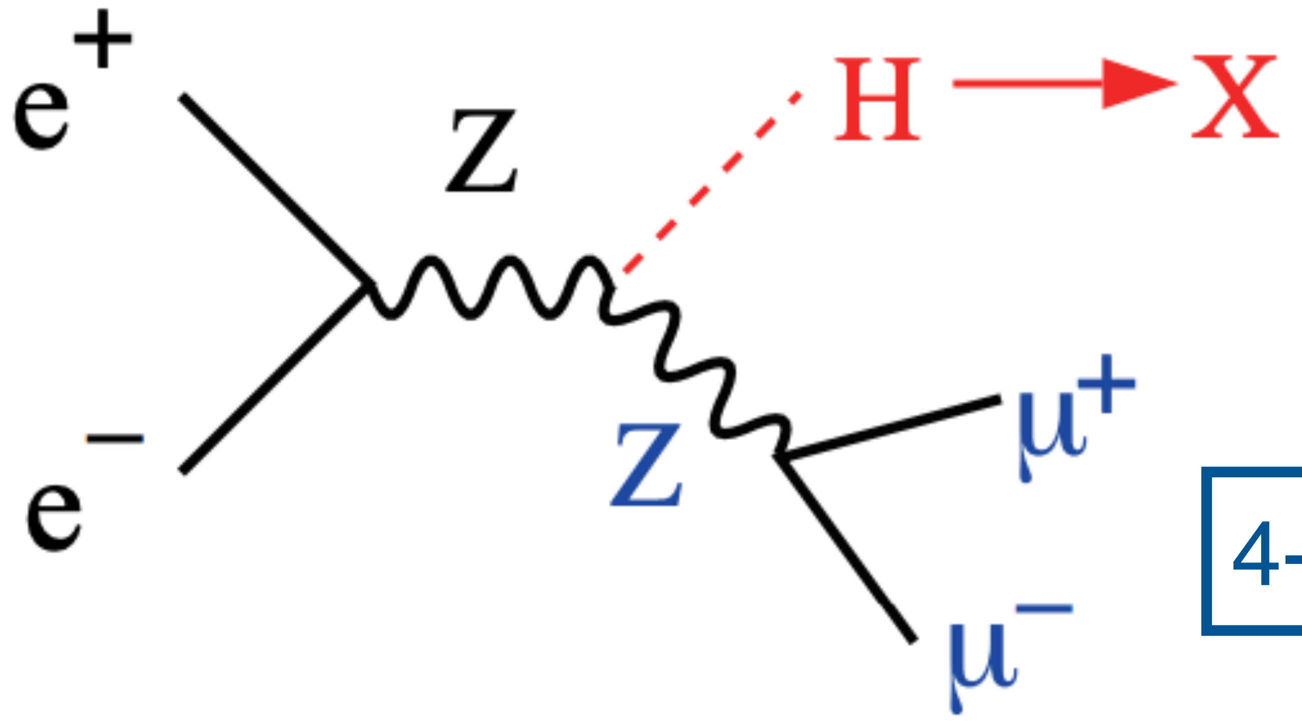
- Precision measurement of electroweak parameters: $\sin^2\theta_W$, Z and W masses and widths, …
  - Limits B field to 2 T and stability to 10^{-6}
  - Absolute normalization of luminosity to 10^{-4}
  - Track angular resolution < 0.1 mrad

How physics drives detector requirements

arXiv:1604.07524
arXiv:2203.07622

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

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

G. Sadowski LCWS 2024
arXiv:2003.01116

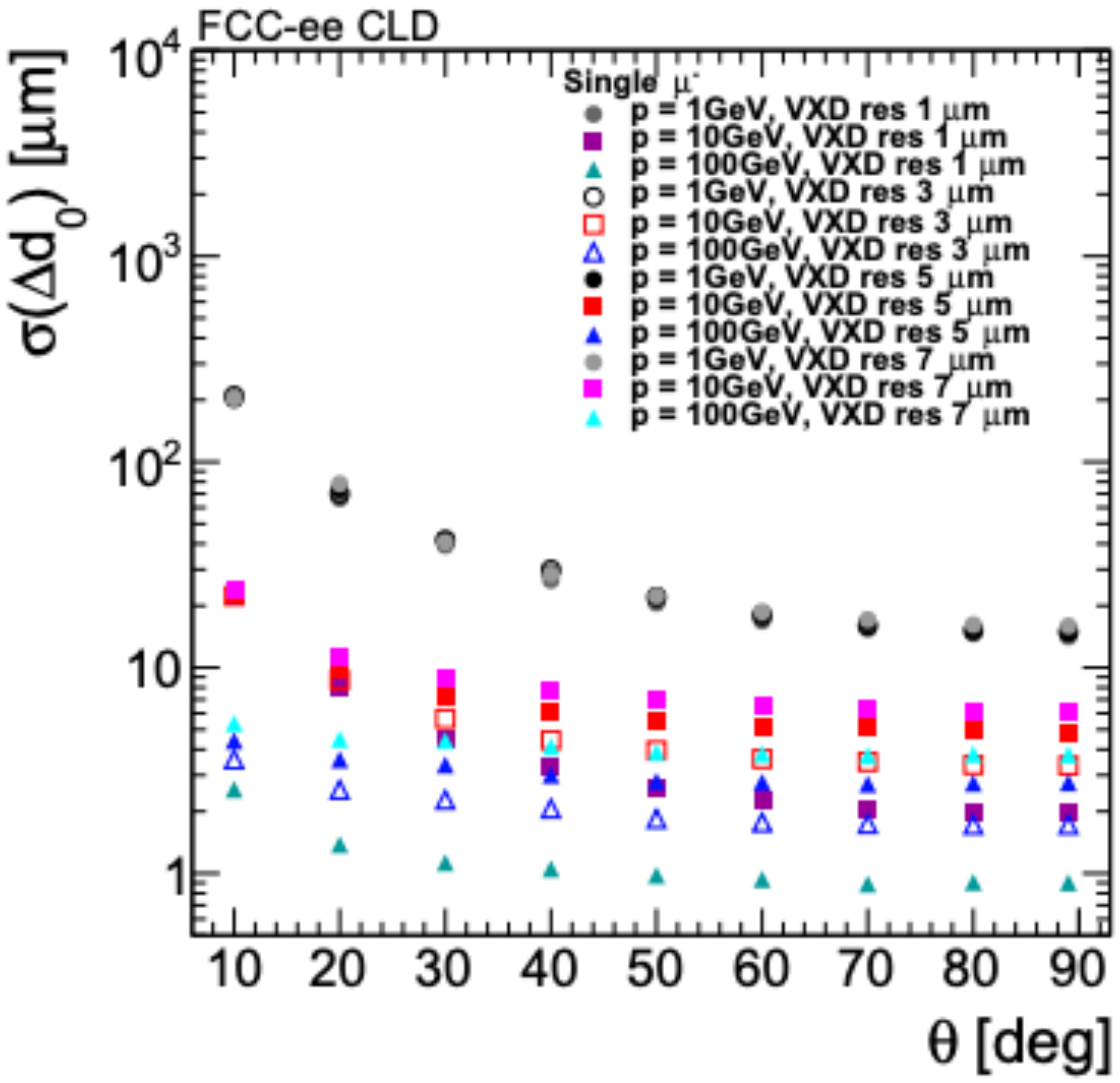
(Higgs) physics requirements for detectors

Precision challenges detector design

Higgs → bb/cc decays: Flavor tagging 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



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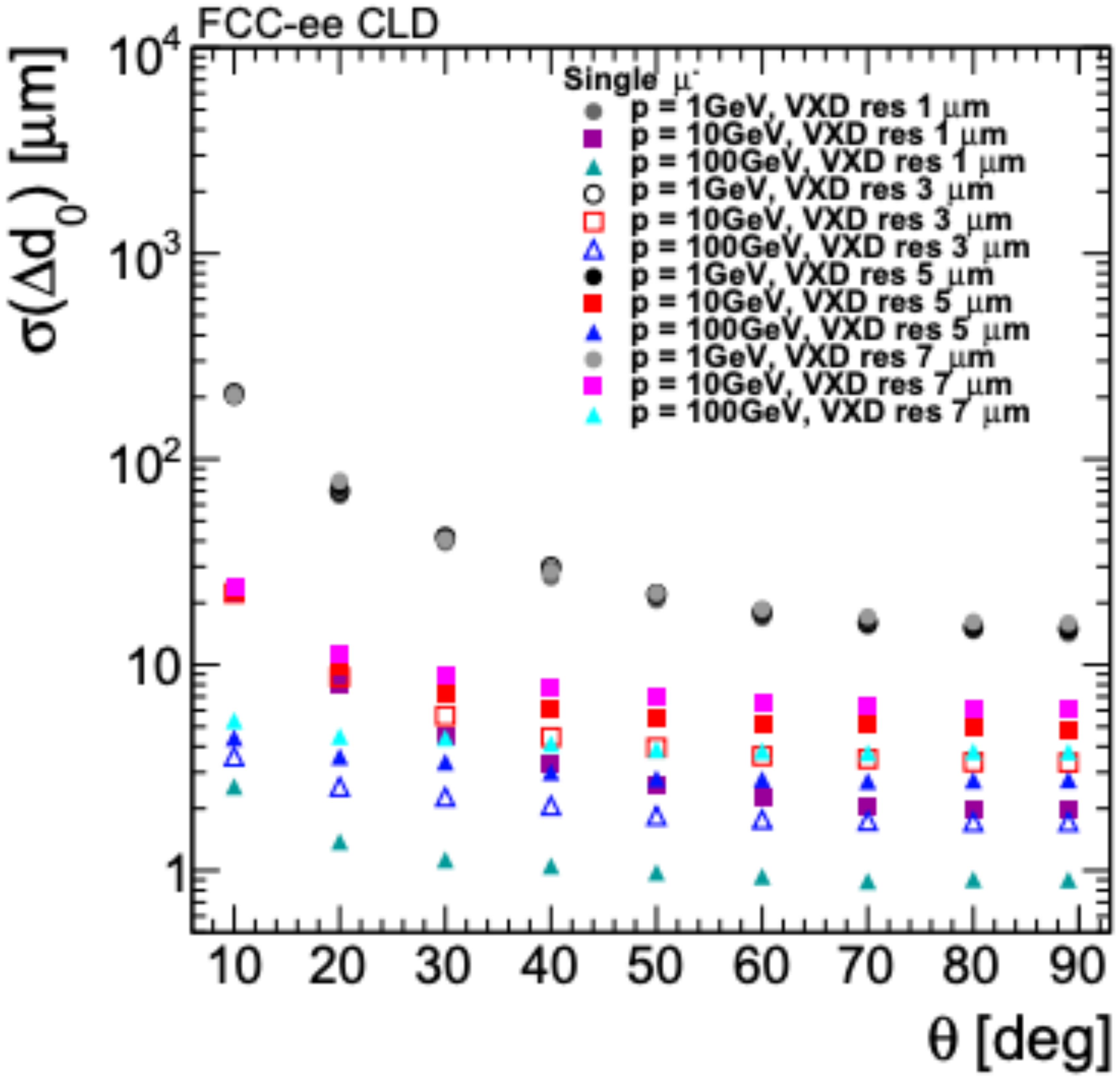
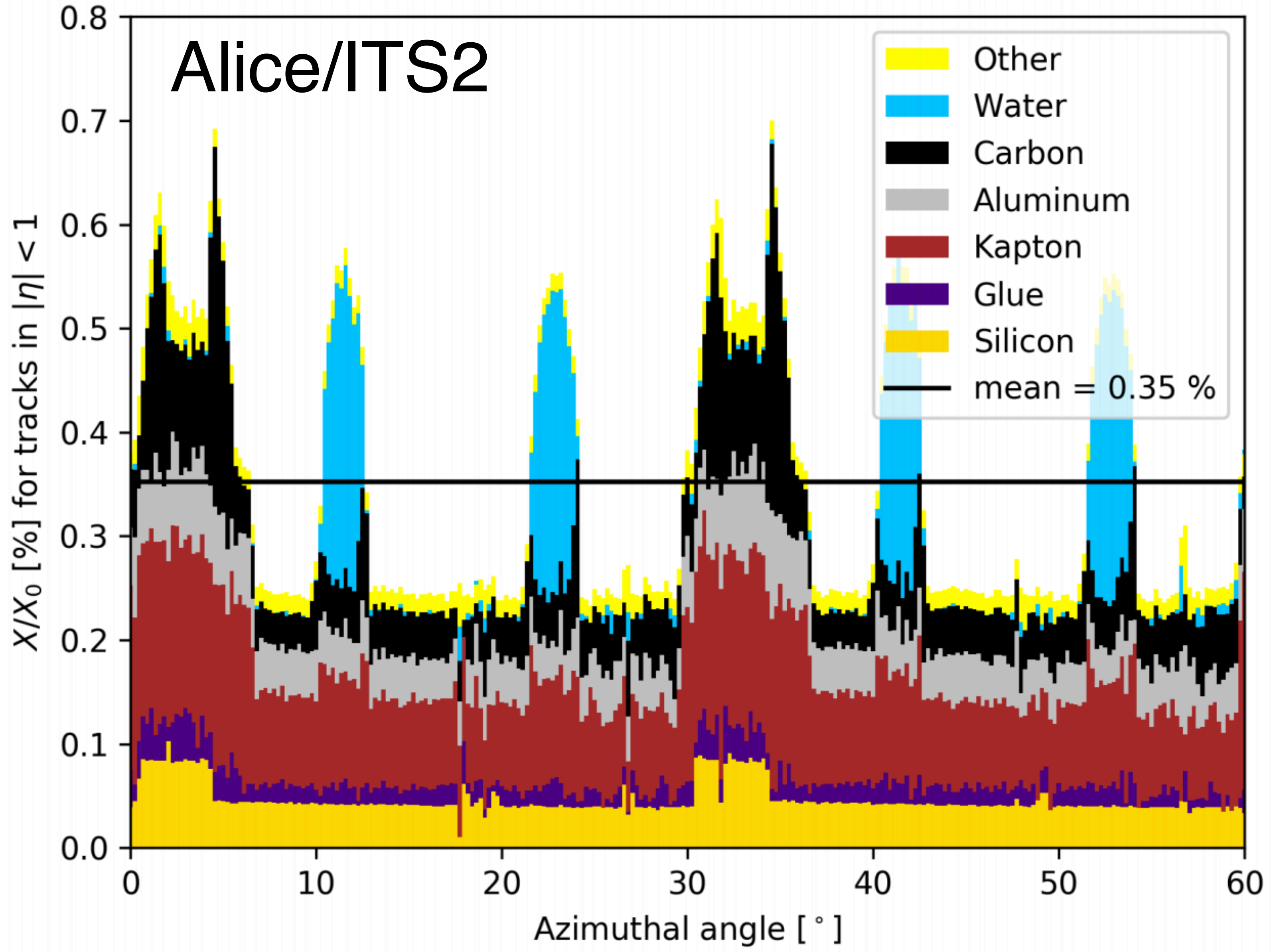


Need new generation of ultra low mass vertex detectors with dedicated sensor designs

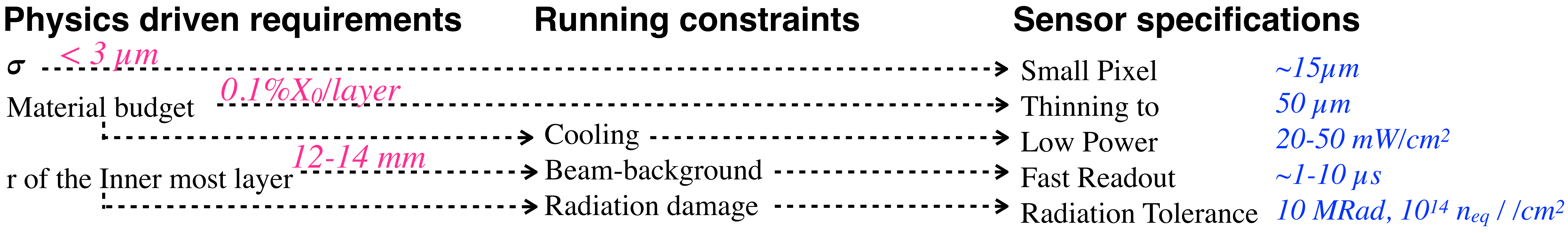
Sensors technology requirements for Vertex Detector

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)



CERN-LHCC-2019-018



Physics driven requirements **Running constraints** **Sensor specifications**

σ *< 3 μm* → Small Pixel *~15μm*

Material budget *0.1%X₀/layer* → Thinning to *50 μm*

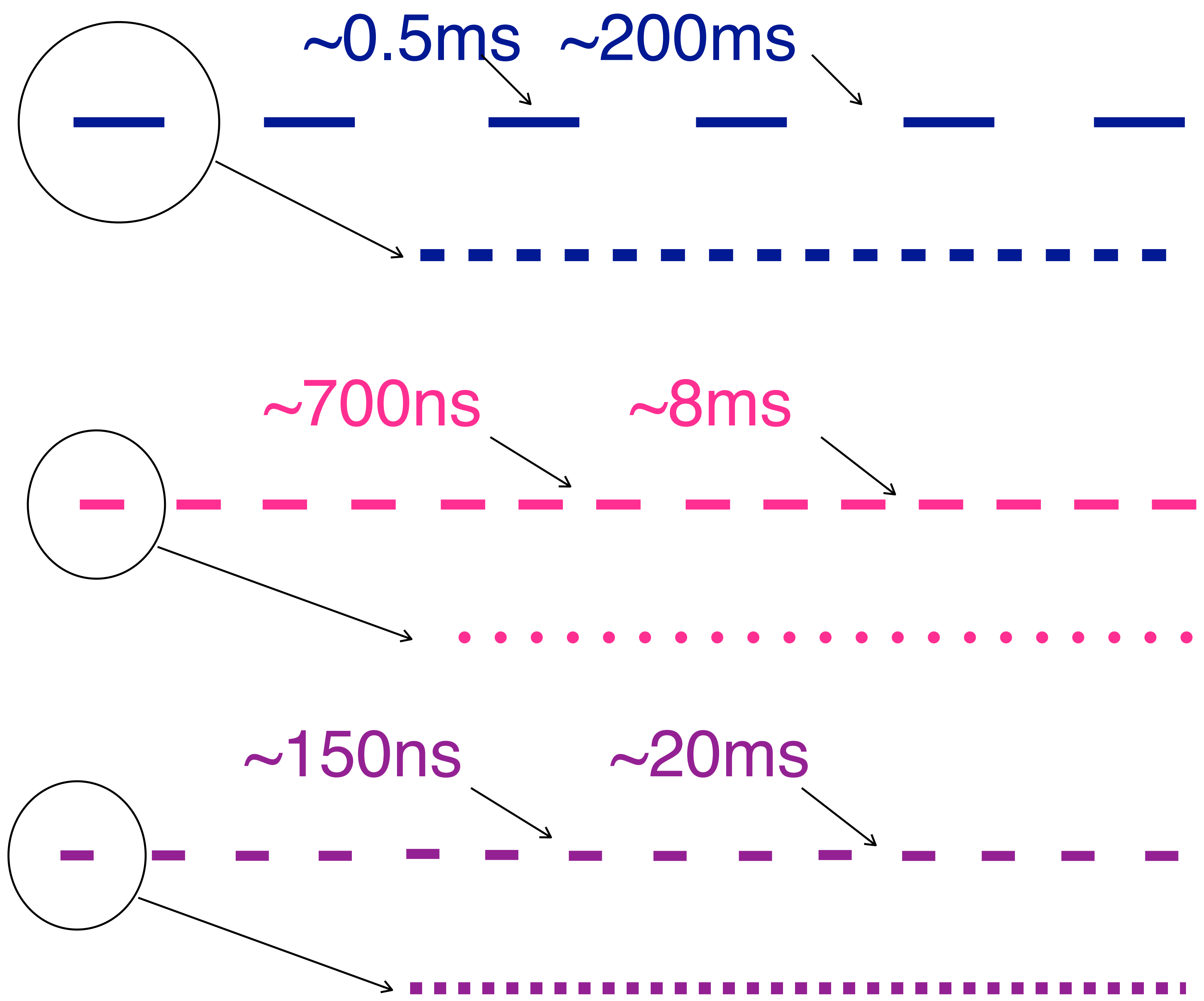
Material budget → Cooling → Low Power *20-50 mW/cm²*

r of the Inner most layer *12-14 mm* → Beam-background → Fast Readout *~1-10 μs*

r of the Inner most layer → Radiation damage → Radiation Tolerance *10 MRad, 10^{14} n_{eq} / /cm²*

Beam Format and Detector Design Requirements

arXiv:2003.01116



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

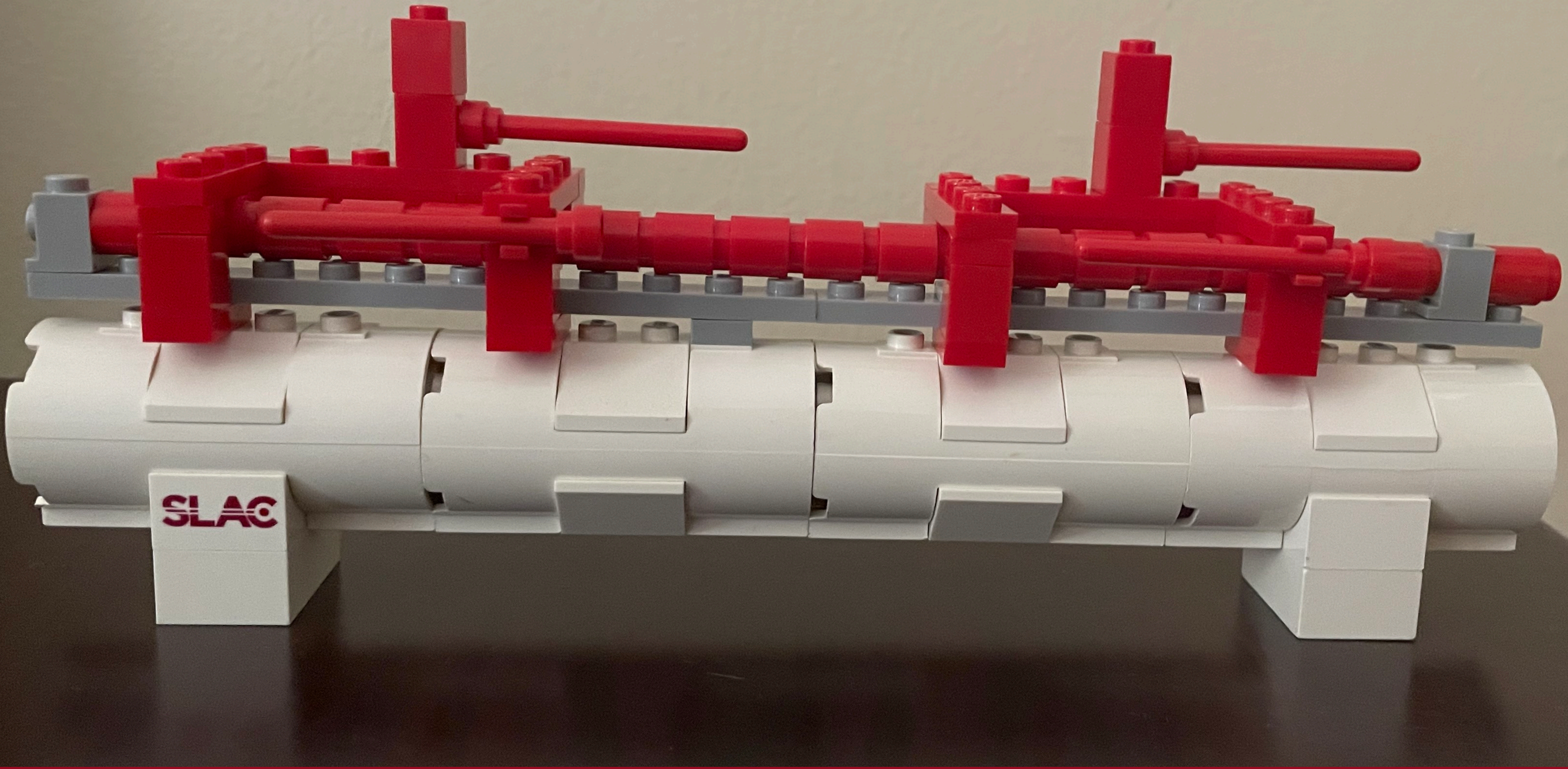
C³ Trains at 120Hz, 1 train 133 bunches
Bunches are 5 ns apart

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% C³) 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

Outlook

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



thank you!

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

Current status of beam-background studies

TDAQ@Annecy2024

Same tools and methodology between ILC & FCC within Key4HEP

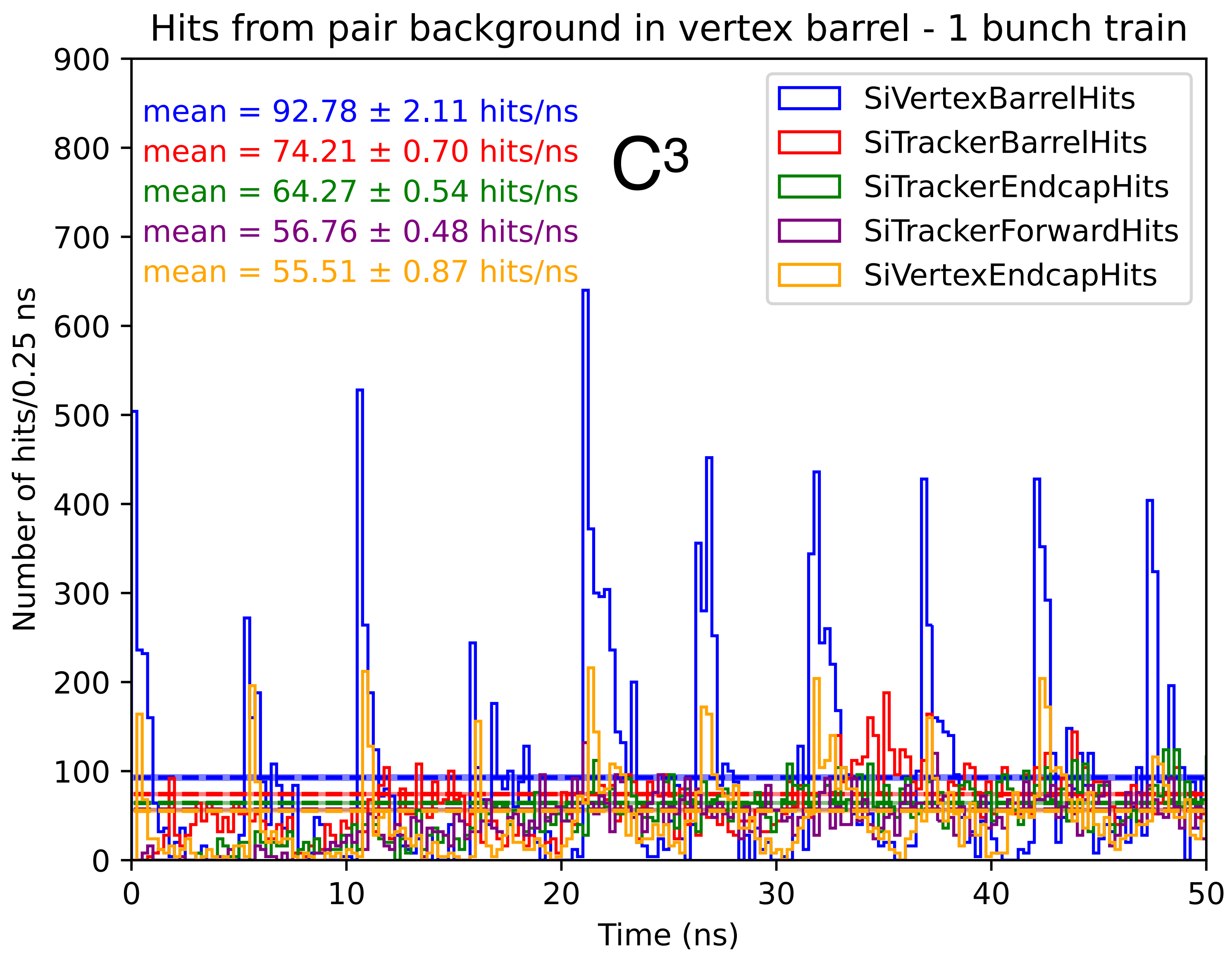
- ILC physics studies are based on full simulation data and some have been recently repeated for C^3
  - Time distribution of hits per unit time and area on 1st layer ~ $4.4 \cdot 10^{-3}$ hits/(ns·mm^2) ≃ 0.03 hits/mm^2 /BX
- CLD detailed studies @FCC show an overall occupancy of 2-3% in the vertex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

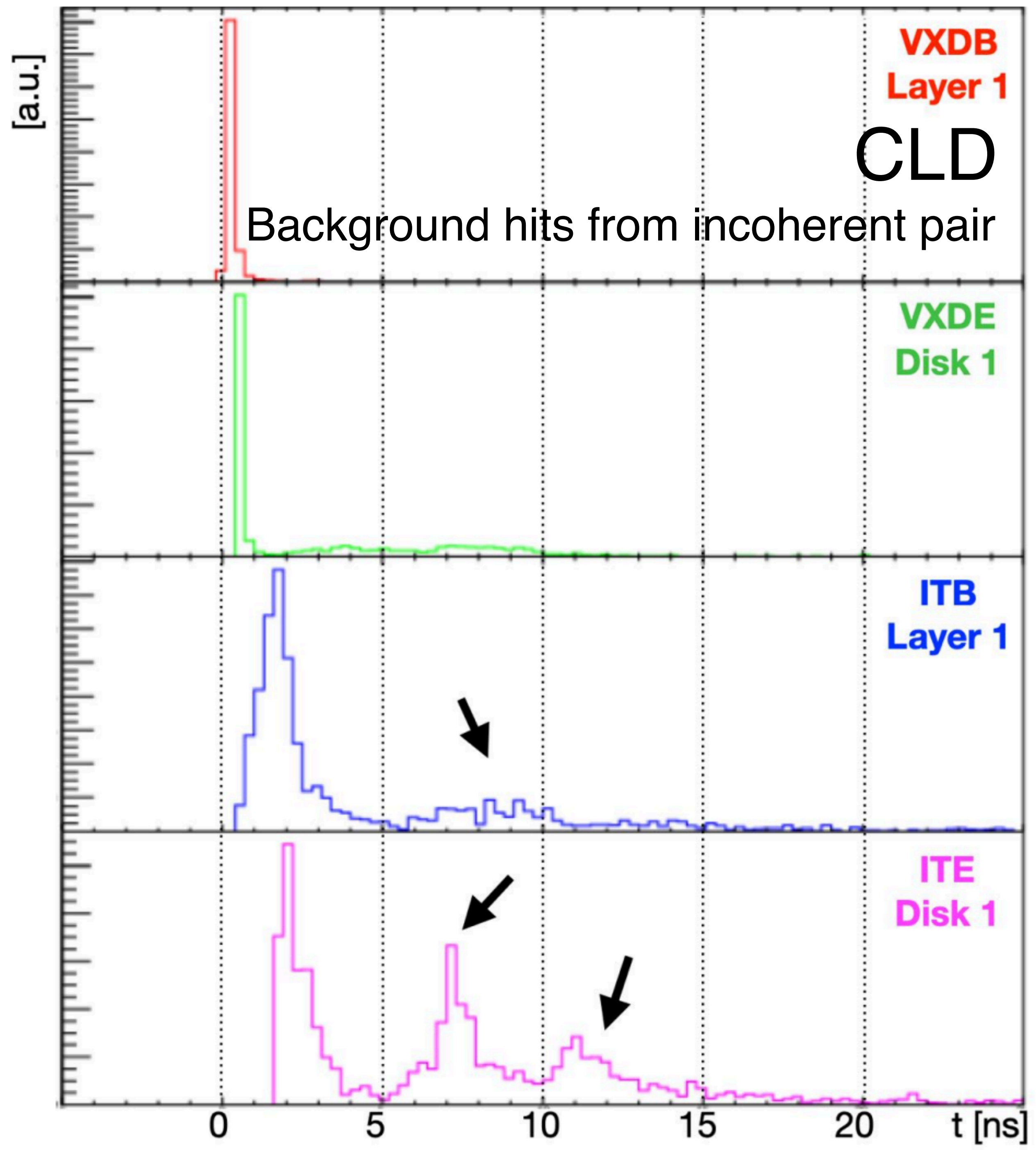
$$occupancy = hits/mm^2/BX \cdot size_{sensor} \cdot size_{cluster} \cdot safety$$

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

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

Occupancy in readout window (10μs)



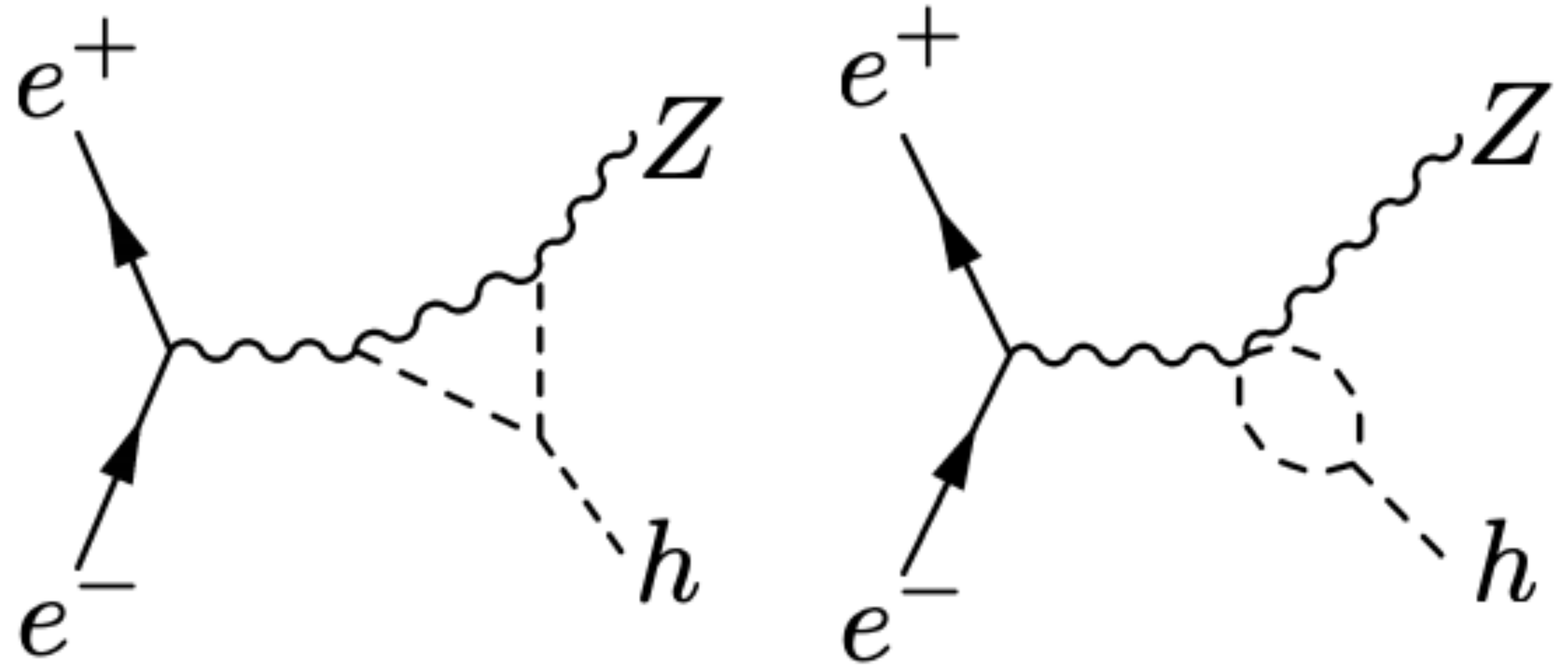


arXiv:1312.3322
arXiv:1910.00012

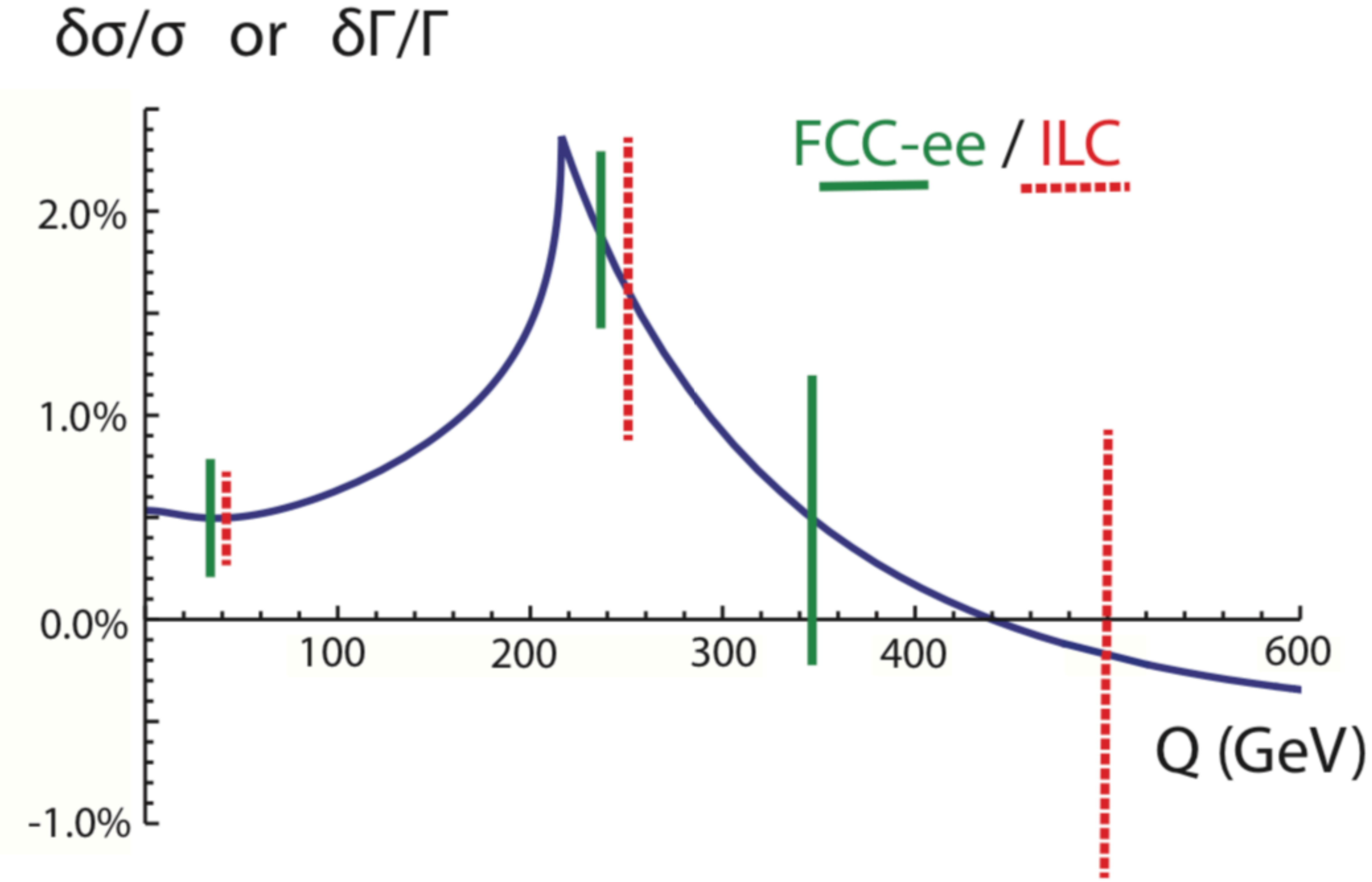
Self-coupling at e+e- with single Higgs

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?

1811.00017
1908.11376
2101.04119

Beyond EFT, is there more?

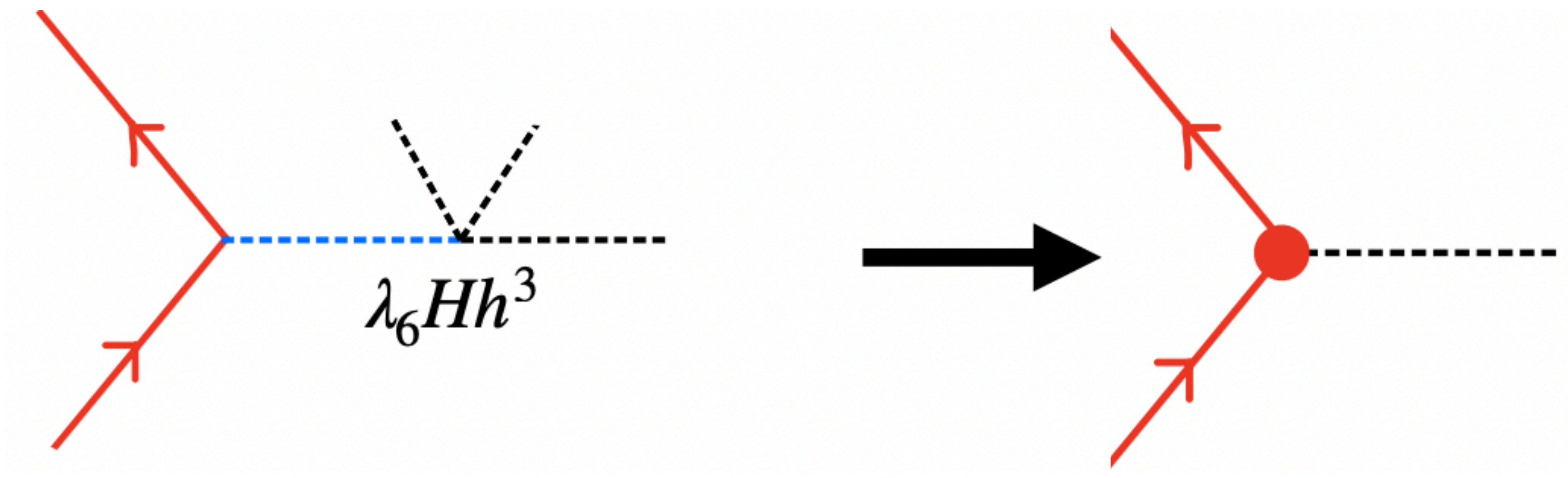
Higgs to strange coupling is an appealing signature to probe new physics

Is the Higgs the source for all flavor?

An option, **Spontaneous Flavor Violation**

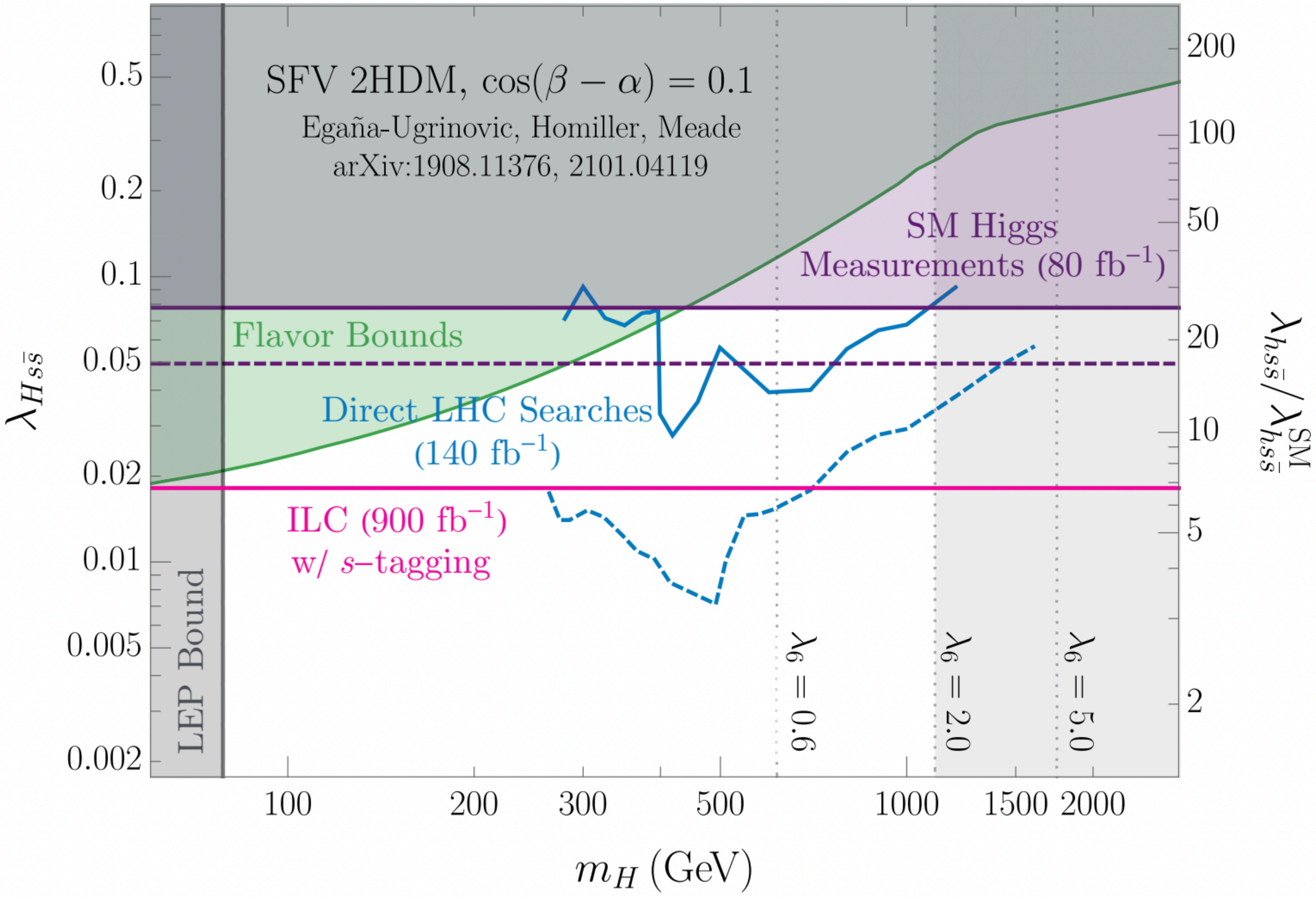
New physics can couple in a strongly flavor dependent way if it is aligned in the down-type quark or up-type quark sectors

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



$\sim \frac{1}{\Lambda^2}(sh\bar{s})h^2$

P. Meade

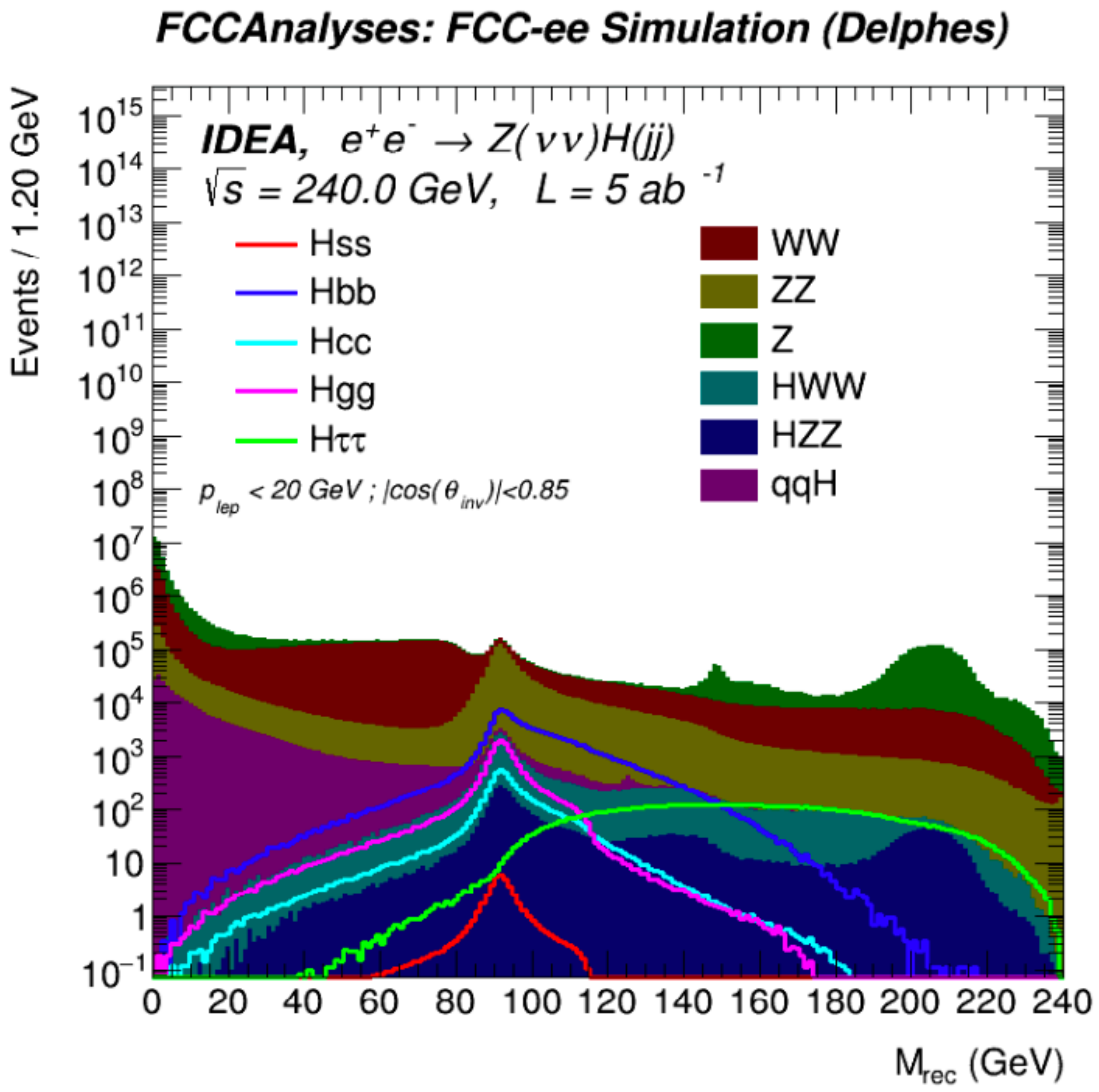


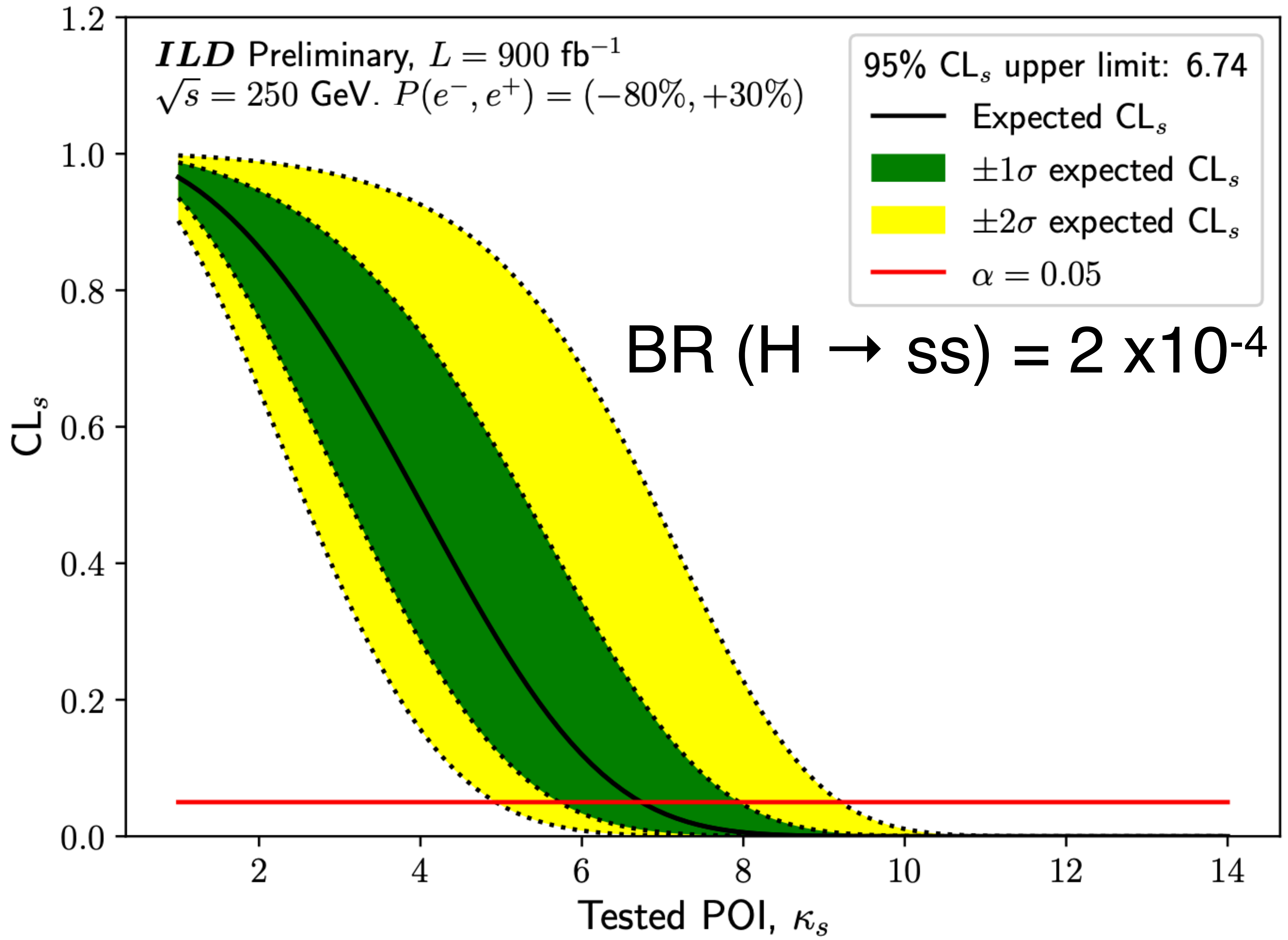
arXiv:2203.07535
L. Gouskos @FCC week

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



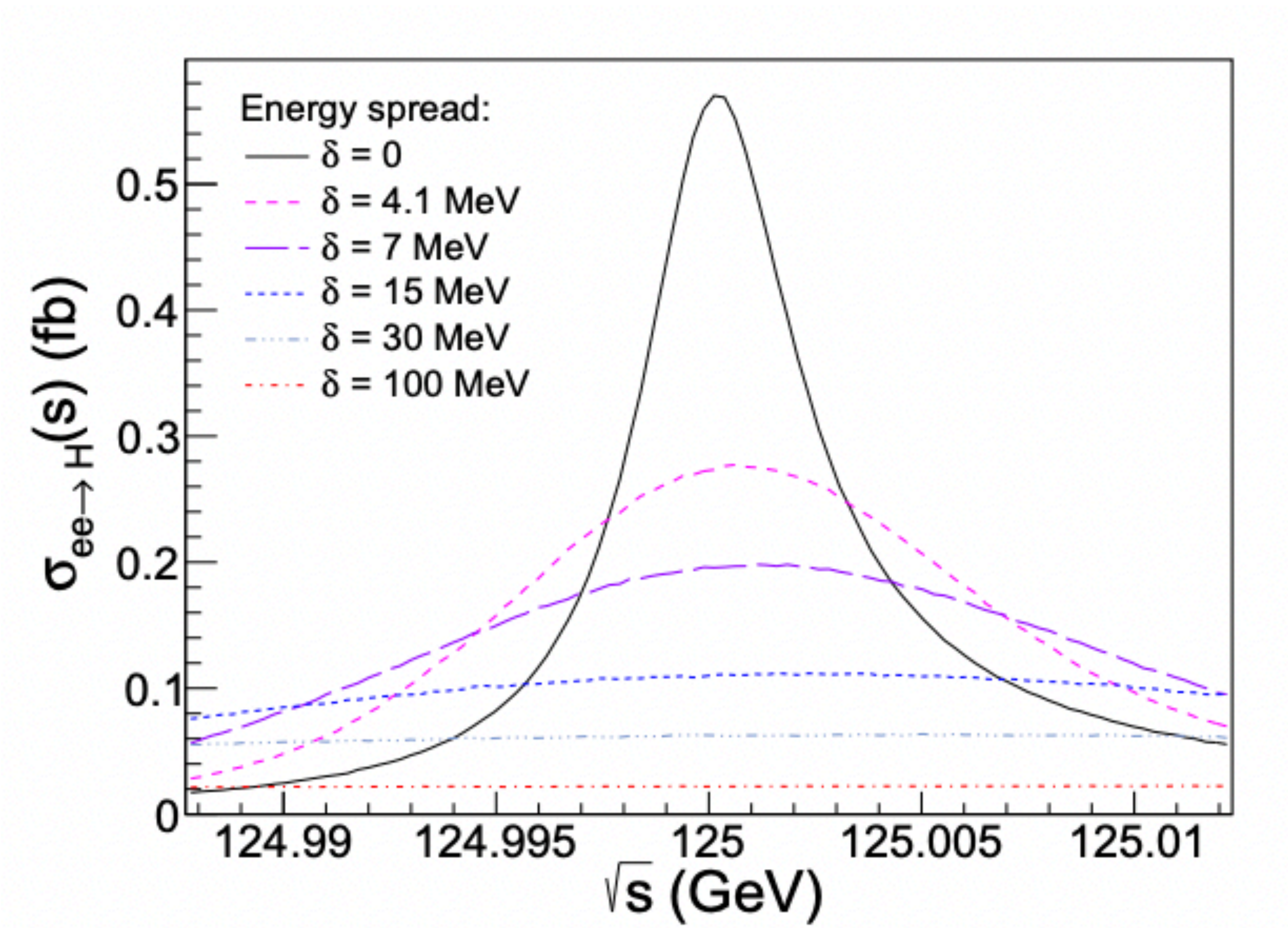


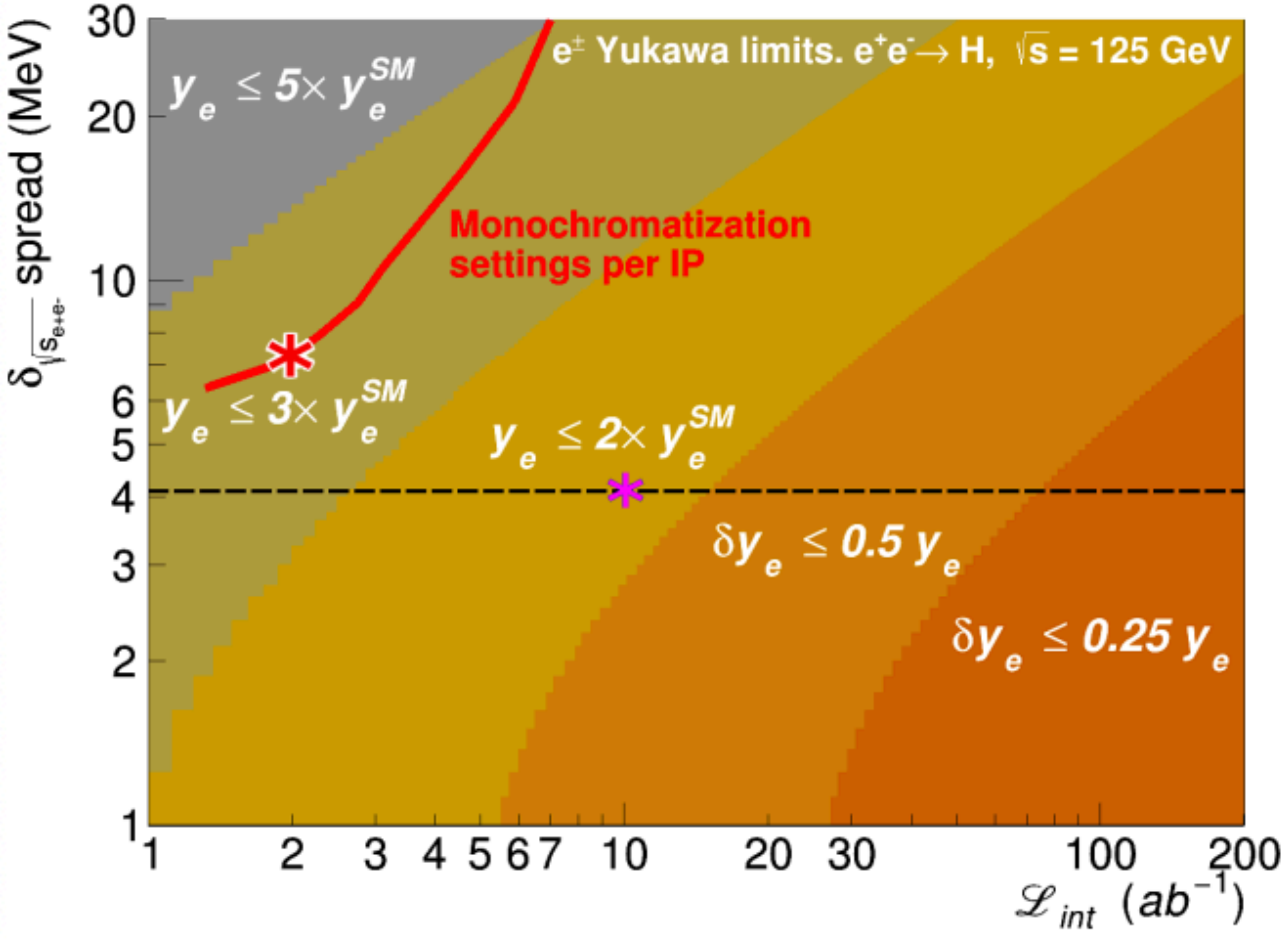
BR (H → ss) = 2 x10^{-4}

arxiv:2107.02686

Higgs-electron Yukawa

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

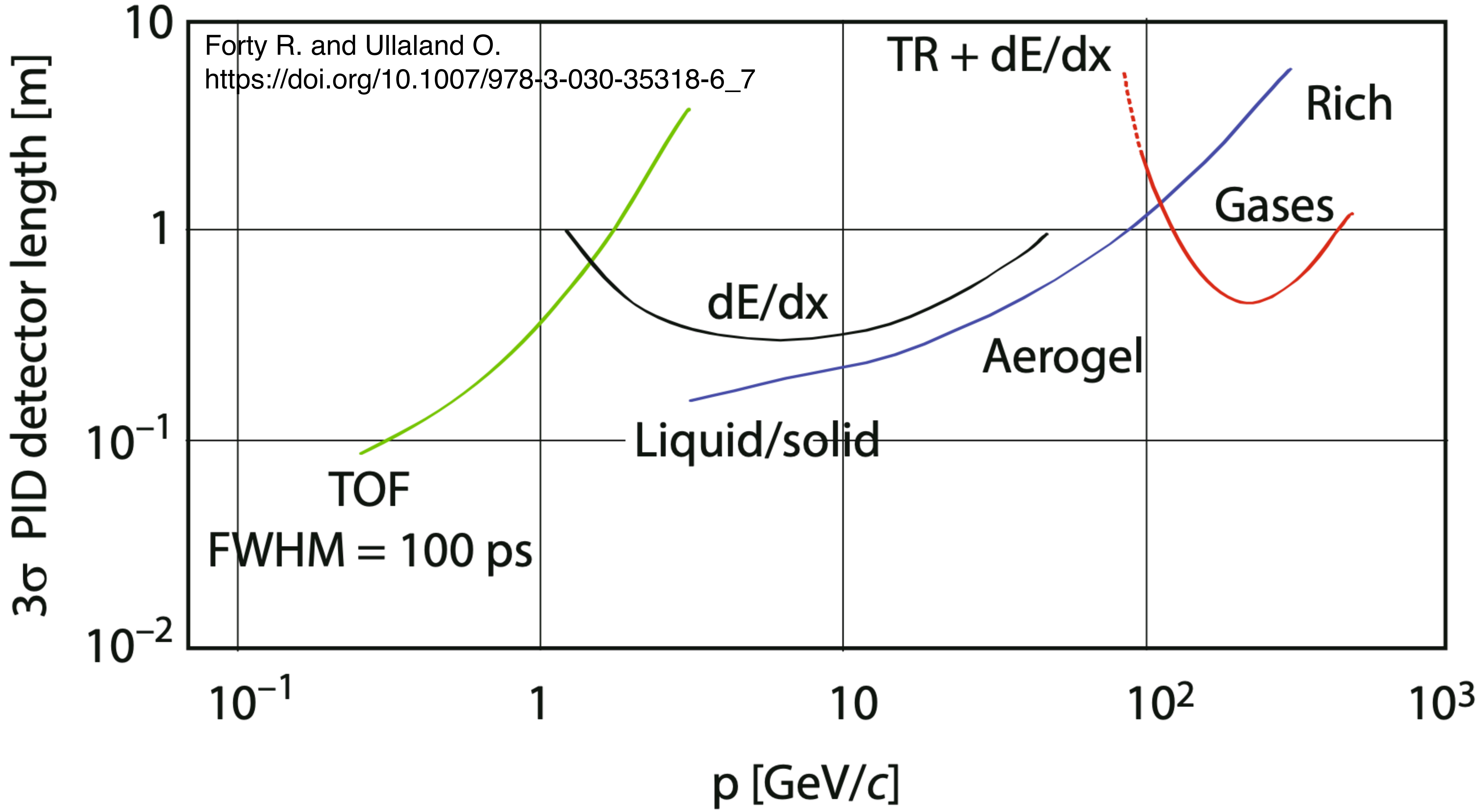




arXiv:2202.03285
arXiv:1912.04601
e2019-900045-4
NIMA 1059 (2024)

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)