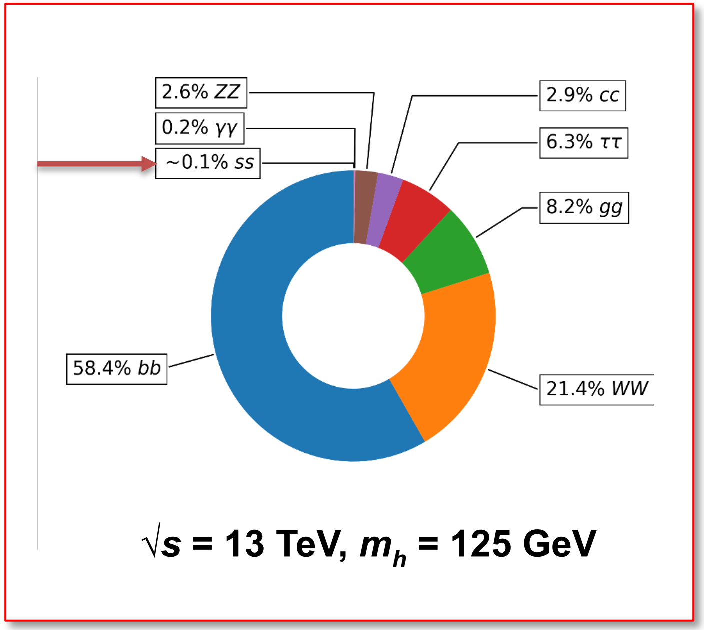
Higgs to strange

Taikan Suehara (Kyushu University)
on behalf of ECFA focused topic H→ss expert team

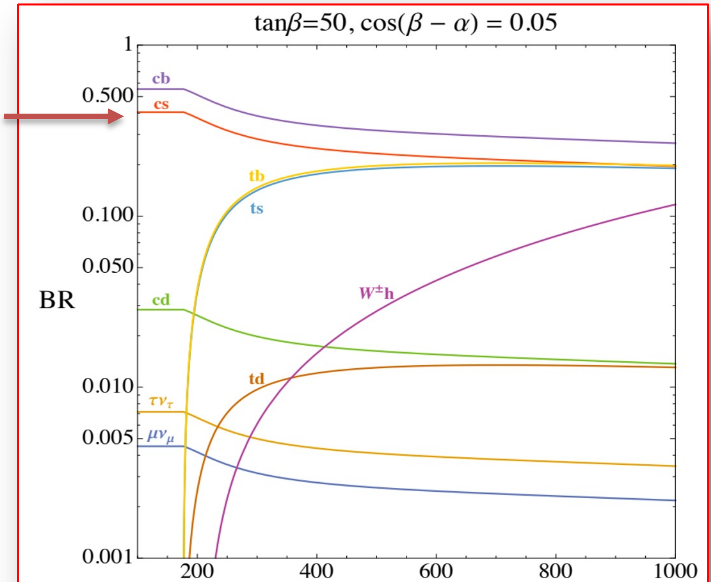
Contents are mostly taken from Valentina's slides at ECFA HF coordination meeting on June 28

The Strange quark as a probe for New Physics

SM Higgs



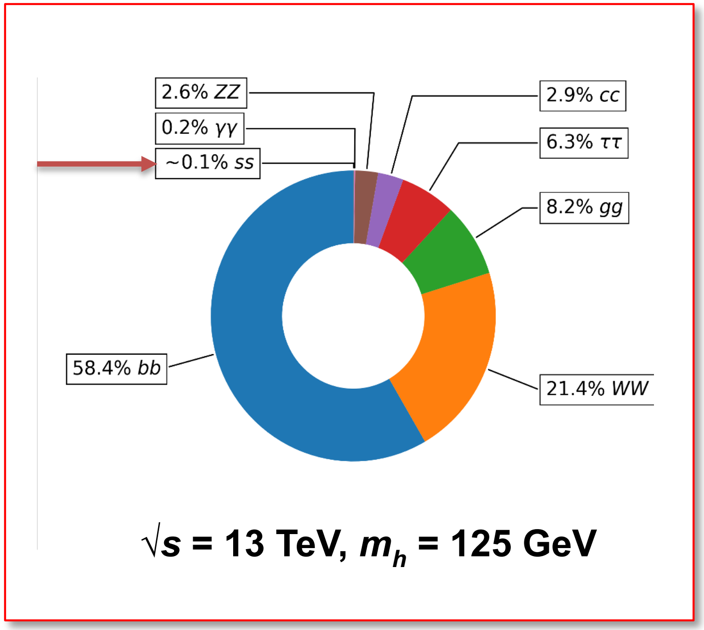
BSM Charged Higgs



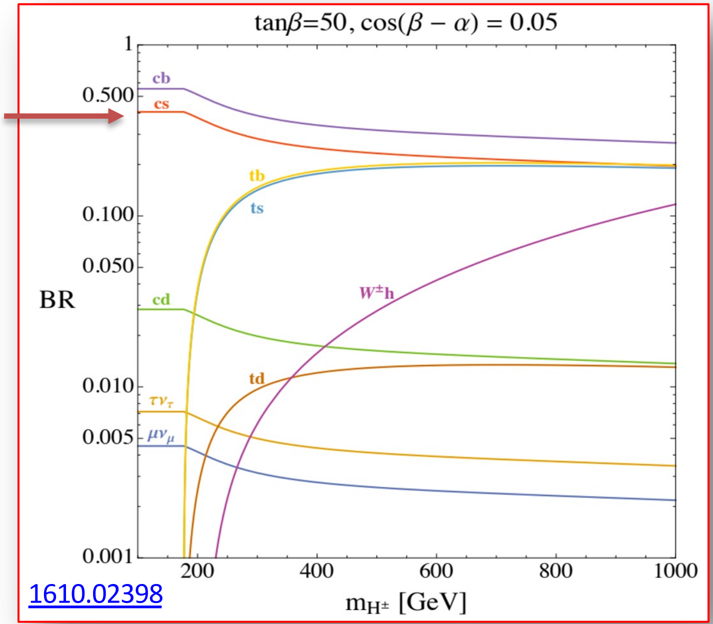
[1610.02398](https://arxiv.org/abs/1610.02398)

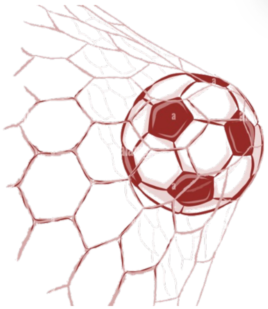
The Strange quark as a probe for New Physics

SM Higgs



BSM Charged Higgs





Assess the sensitivity of Higgs to strange couplings(*) at future Higgs Factories and study detector design enabling strange jet tagging

(*)many more SM analyses would benefit from strange tagging, e.g. $ee \rightarrow ss$, $Z \rightarrow ss$, $W \rightarrow cs$, etc!

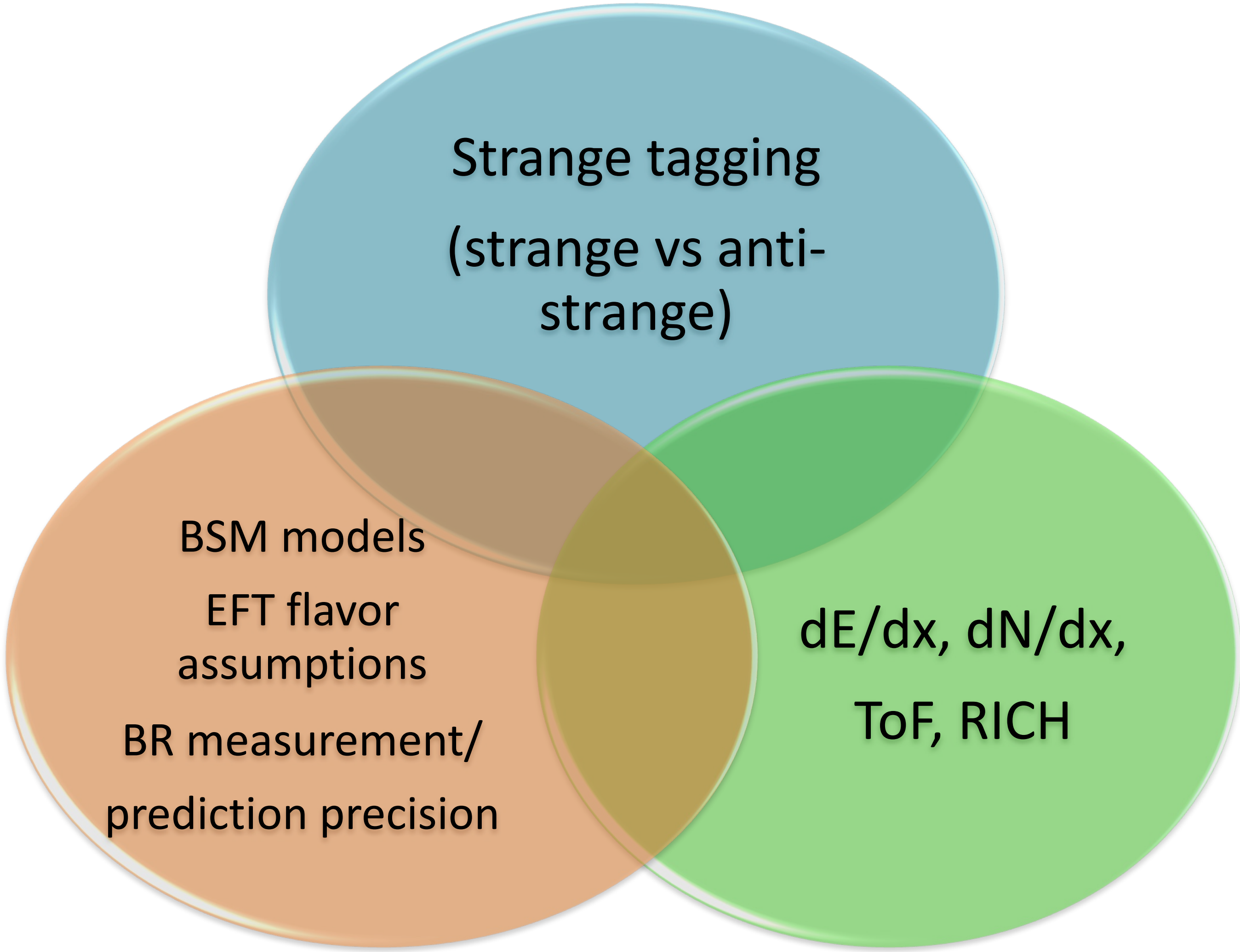
$H \to s\bar{s}$ and strange-Yukawa Expert Team

Newly established team (*), areas of work indicative only:

- Valentina Cairo (coordination)
- Taikan Suehara (ILD)
- Loukas Gouskos (FCC-ee, IDEA)
- Matt Basso (FCC-ee)
- Caterina Vernieri (SiD)
- Valerio Dao (ATLAS)
- John Alison (CMS)
- Yotam Soreq (Theory / Interpretation)

(*) We haven’t met yet (team formed this Monday)

$H \to s\bar{s}$ and strange-Yukawa Activities to Cover



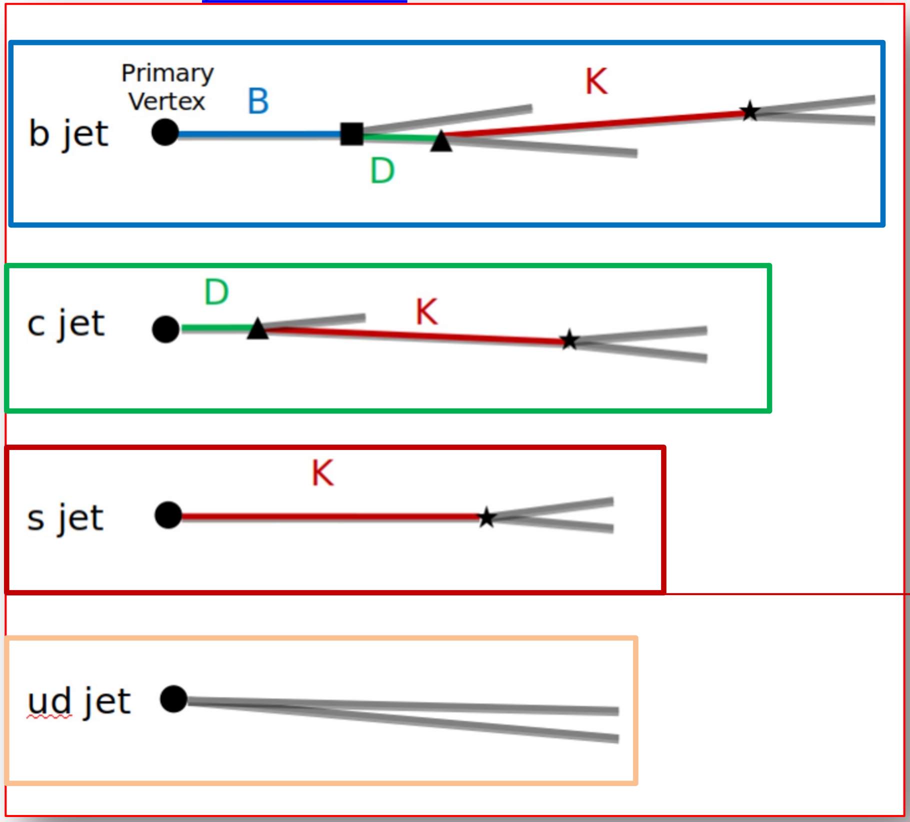
Where do we stand?

Past activities have been presented in several occasions, see two presentations given in the context of ECFA meetings:

1. https://indico.cern.ch/event/1138771/
2. https://indico.cern.ch/event/1271419/

Experimental Handles for Flavor Tagging

T. Tanabe's presentation



	# of secondary vertices (excluding V^0)	# of strange hadrons ($K^{\pm}$, K_L^0, K_S^0, Λ^0)
b	2	≥1
c	1	≥1
s	0	≥1
ud	0	0

Strange Hadron reconstruction

- $K^{\pm}$ [PID]
- $K_S^0 \rightarrow \pi^+\pi^-$ [Vertex] (BF ~69.2%)
- $\Lambda^0 \rightarrow p\pi^-$ [Vertex] (BF ~64%)
- K_L^0 [Particle Flow]

…and SLD actually measured strange hadrons from $Z \rightarrow s\bar{s}$!

See SLD A_s PRL 85 (2000), 5059

Detector Requirements

Key ingredients for b/c-tagging:

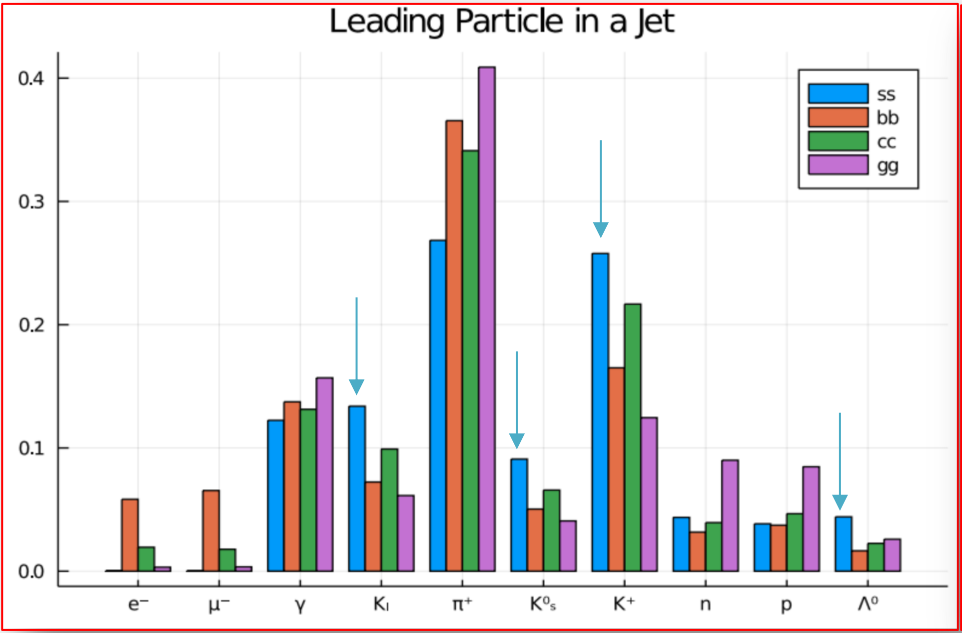
- Track Impact Parameters
- Secondary Vertices
- Multi-Vertex Decay chain

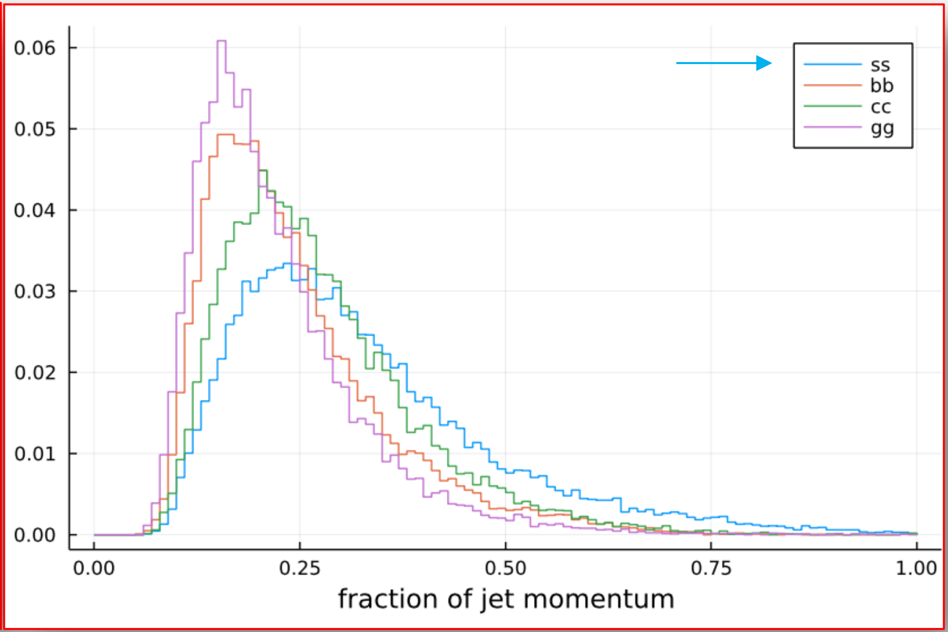
Need tracking & vertexing detectors with:

- excellent spatial resolution
- layers close to IP
- light weight

How about strange-tagging then?

The *strange* features



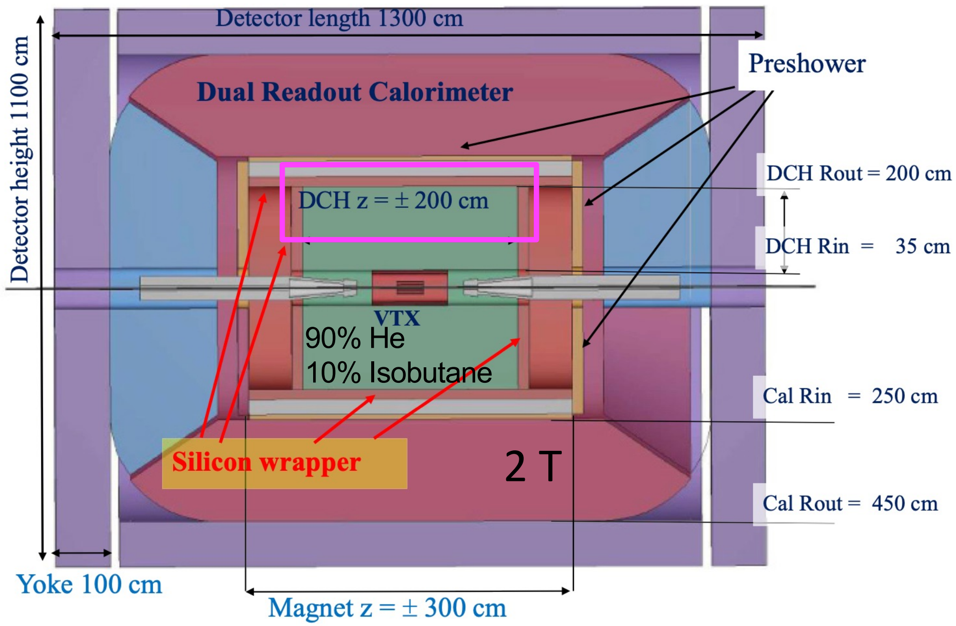


Particle Identification is crucial!

Need **π/K discrimination** over a momentum range of approximately (0.2-0.7) x 0.5 x 125 ≅ **12 to 50 GeV**

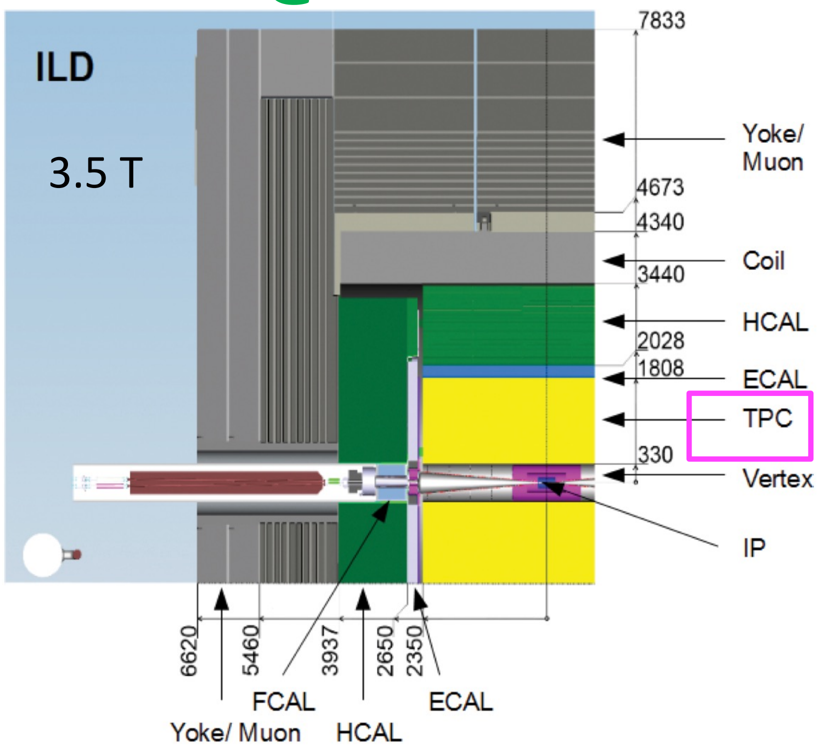
Two examples:
IDEA @ FCC-ee & ILD @ ILC

IDEA @ FCC-ee



e2019-900045-4

ILD @ ILC



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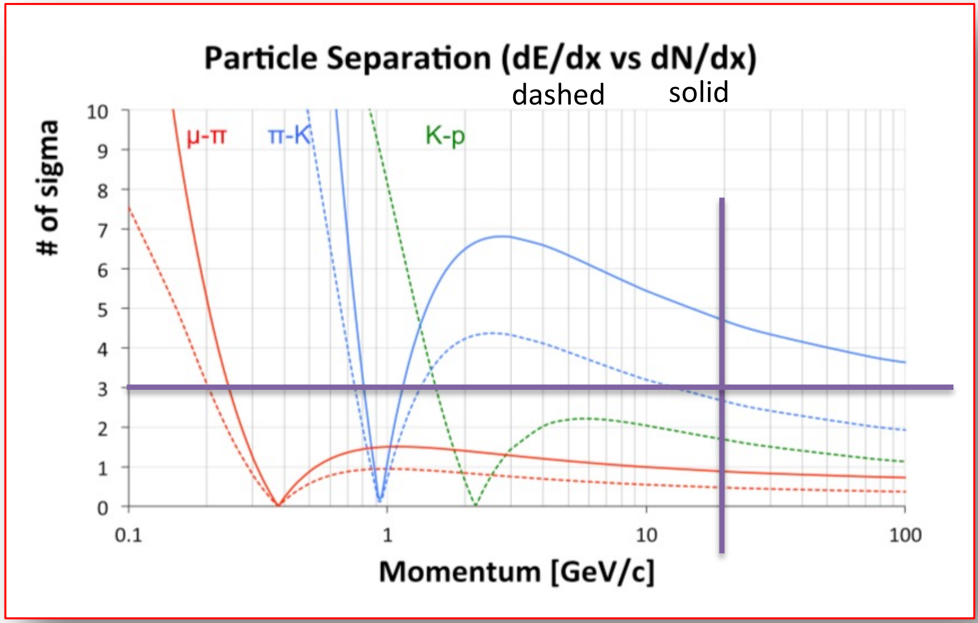
Two examples:
IDEA @ FCC-ee & ILD @ ILC

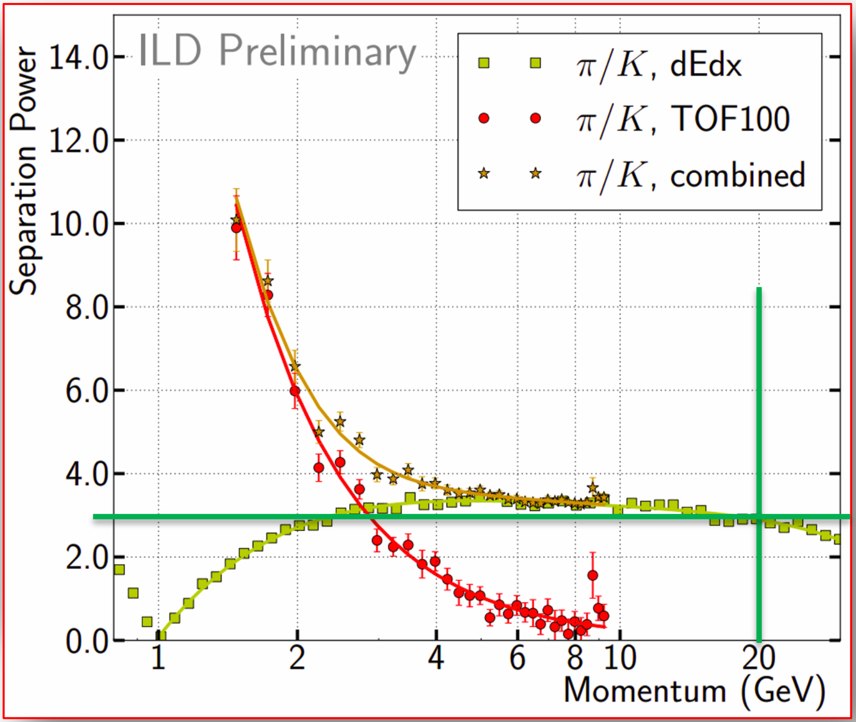
IDEA @ FCC-ee



Analitical calculations

[e2019-900045-4](e2019-900045-4)

ILD @ ILC



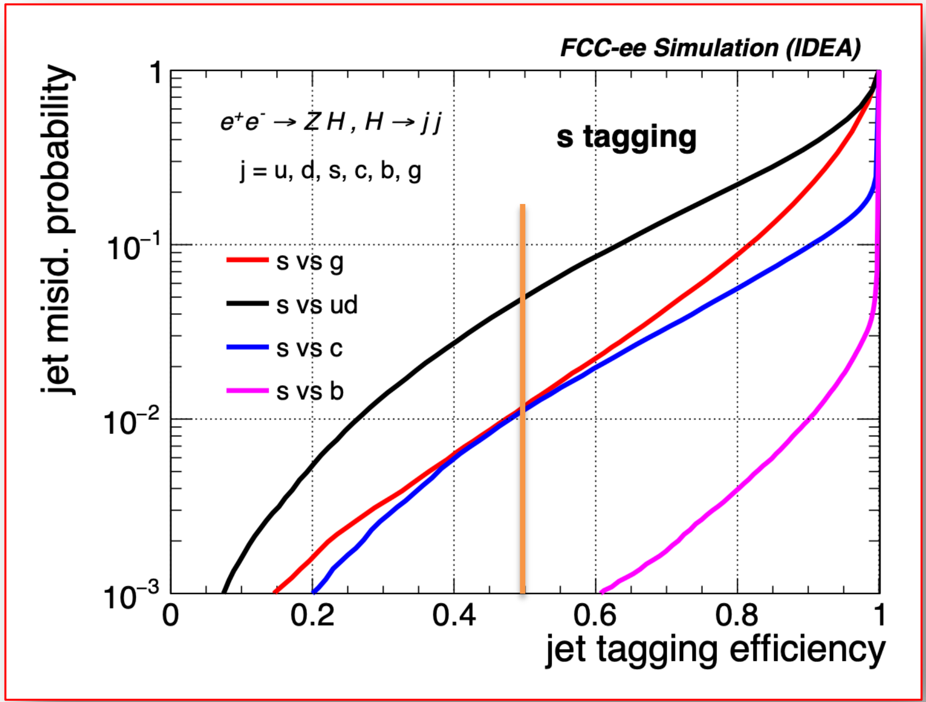
[1912.04601](1912.04601)

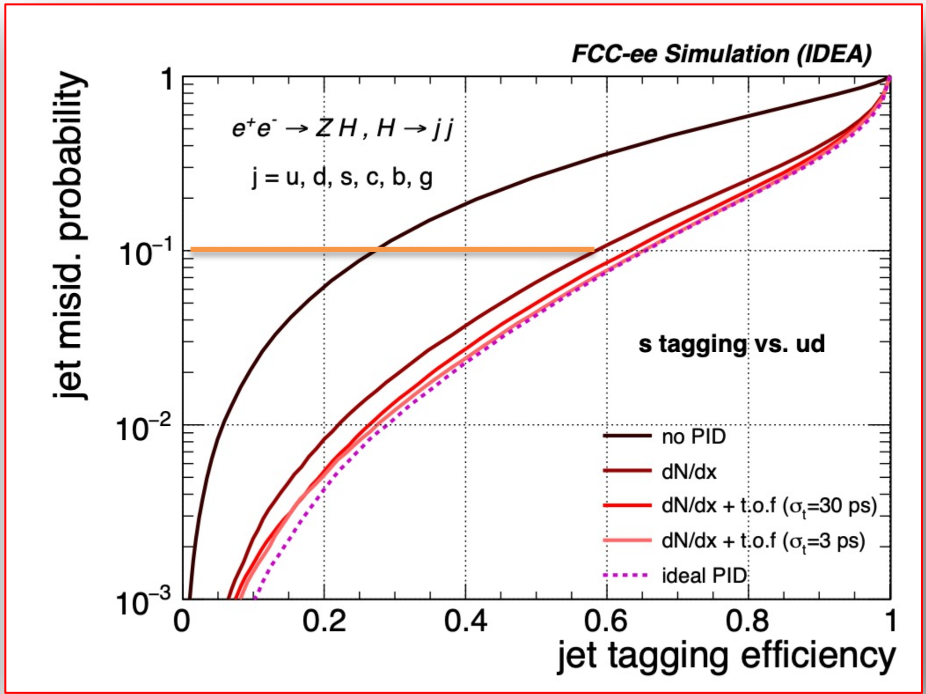
Comparable dE/dx performance at e.g. 20 GeV, boost from dN/dx

[2202.03285](https://arxiv.org/abs/2202.03285)

Strange Tagging with IDEA

- Use a Graph Neural Net *ParticleNetIdea*: jets represented as an un-ordered set of particles
- Train on $(Z \rightarrow inv)(H \rightarrow qq/gg)$ samples, **per-jet and per-particle level inputs** & **variables** (kinematics, displacement, identification)
- TOF and dN/dx (**3σ < 30 GeV**) considered
- **Fast Simulation and Fast Tracking**



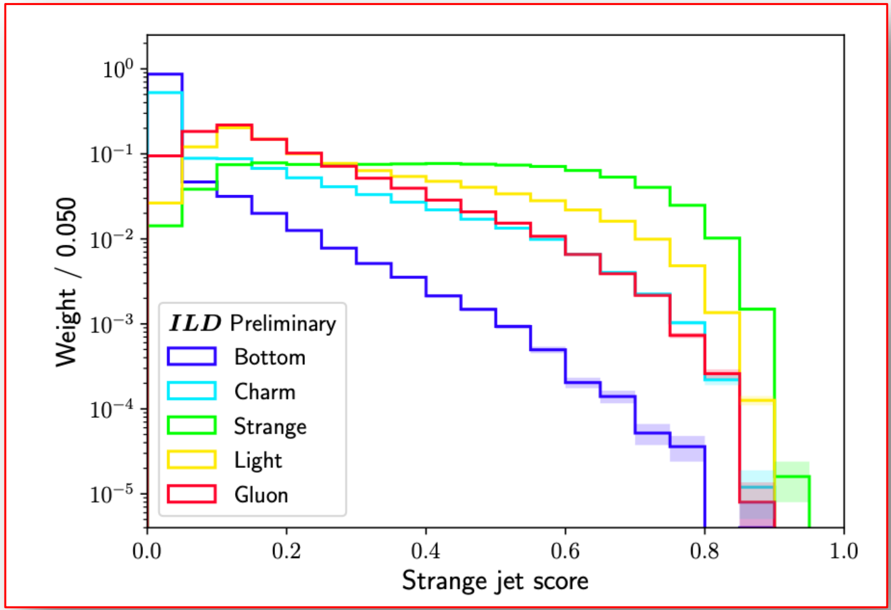


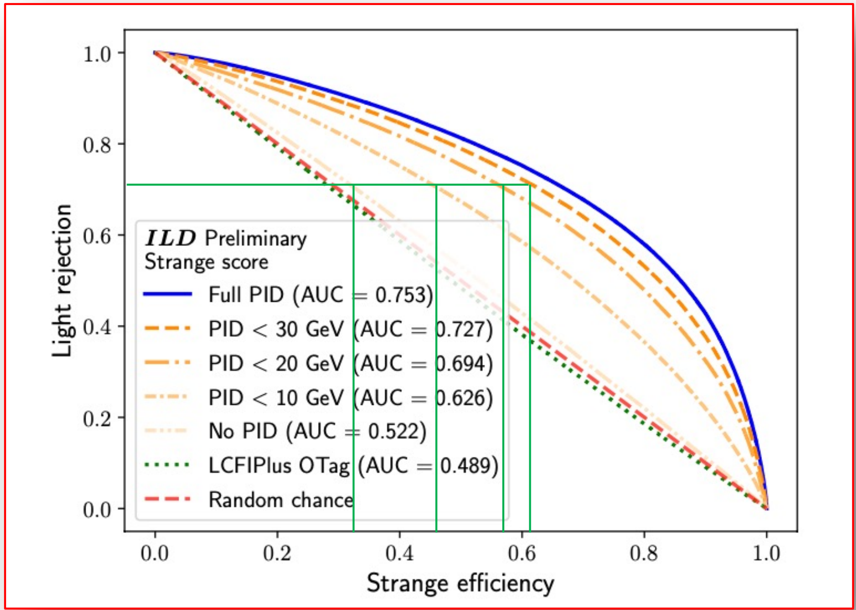
No PID to PID with dN/dx → at fixed mistag, **efficiency doubles**

2203.07535

Strange Tagging with ILD

- Use a Recurrent Neural Net tagger for classifying jet-flavour, train on **full simulation** $(Z \rightarrow inv)(H \rightarrow qq/gg)$ samples and include **per-jet level inputs** & **variables** on the **10 leading particles** in each jet (**including PDG-based PID**) → general validity!





- **Good discrimination of *s* jets from u/d and from *g* jets** – here, $N_{particles}$ is powerful
- At **50% s-tag efficiency**, **90% background rejection** over **70%** for LCFIPlus Otag
- **No PID to PID < 10 GeV** → at fixed mistag, **1.5x efficiency**
- **No PID to PID < 30 GeV** → at fixed mistag, **efficiency doubles**

A physics benchmark:

$h \to s\bar{s}$ analysis with ILD @ the ILC
and
$h \to s\bar{s}$ analysis with IDEA @ the FCC

σ_H @ $\sqrt{250}$GeV~200 fb

- 2000 fb^{-1} (5000) collected by the ILC (FCC) @ 250 (240) GeV
- → 400k (1M) Higgs out of which only about ~100 (200) will decay to strange quarks

But of course, new physics boosts these numbers!

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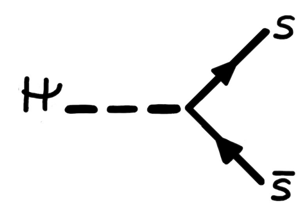
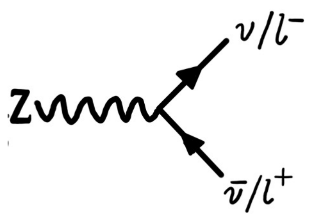
$h \to s\bar{s}$ analysis in a nutshell

ILD



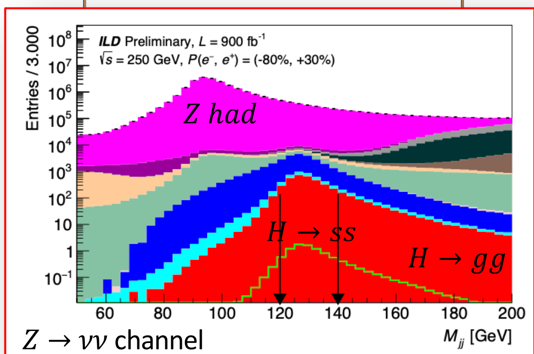
2 jets



0 or 2 SFOS leptons

Object definition

Event selection



$Z \to \nu\nu$ channel

Cut-based approach, reject $ZH(!ss), V, VV$

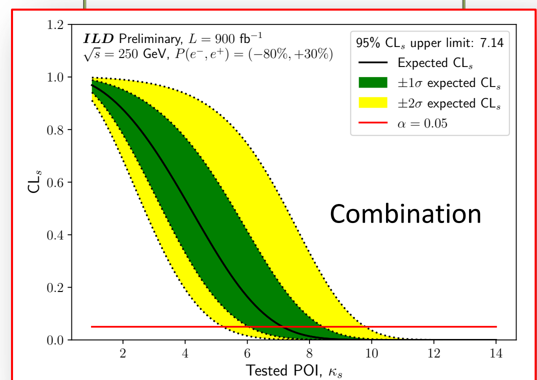
Sum of

$jet_0 + jet_1$

strange tagging scores

Signal discriminant

s-Yukawa constraints



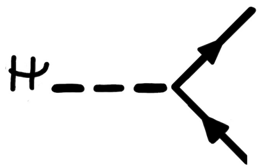
$k_s \lesssim$ **7 x SM**

Limits on u/d yukawas are also set

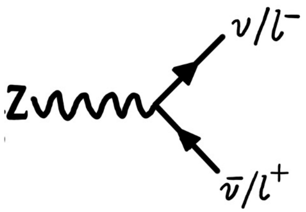
https://indico.cern.ch/event/1271419/

$h \to s\bar{s}$ analysis in a nutshell

FCC: simultaneous estraction of Higgs couplings (b, c, s, g, other)



2 jets



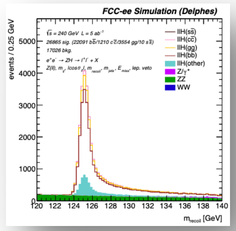
0 or 2 SFOS leptons

Object definition

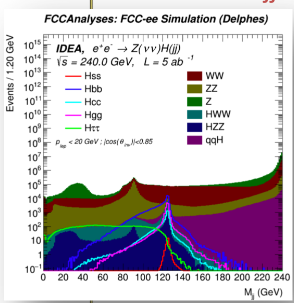
Event categorization

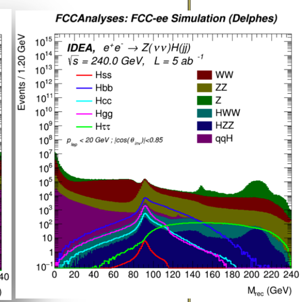
Sum of lead and sublead jet scores to build analysis categories

m_{rec} fit in Z(ll)



m_{rec} vs m_{jj} fit in Z(inv)





Signal discriminant

Results (5 ab^{-1})

Z(→νν)H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.4	2.9	140	1.2

*$|\kappa_s|<1.9$

- The two analyses demonstrate that if we can tag strange jets, we can probe the **Higgs strange Yukawa** coupling…
But **we need π/K discrimination at high momenta**!

- This triggered recent studies of what may be possible with a system that pioneered particle ID: the **Ring Imaging Cherenkov detector**

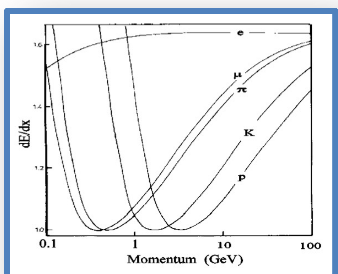
Particle Identification techniques

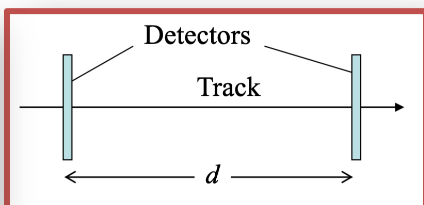
R. Forty's slides

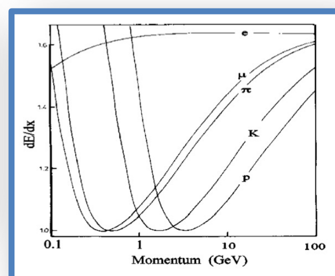
- Various technologies allow to identify hadrons in different momentum ranges

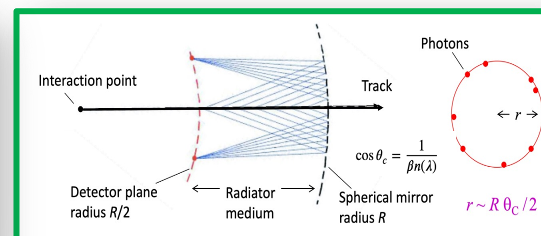
3σ *separation for* π/K			
dE/dx in silicon	Time-of-flight via Fast Timing in silicon envelopes or calorimetry	dE/dx in Time Projection or Drift Chambers	Ring Imaging Cherenkov Detectors
$\lesssim$ 5 GeV	$\lesssim$ 5 GeV	$\lesssim$ 30 GeV (scales with volume)	O(tens of GeV)

Momentum →









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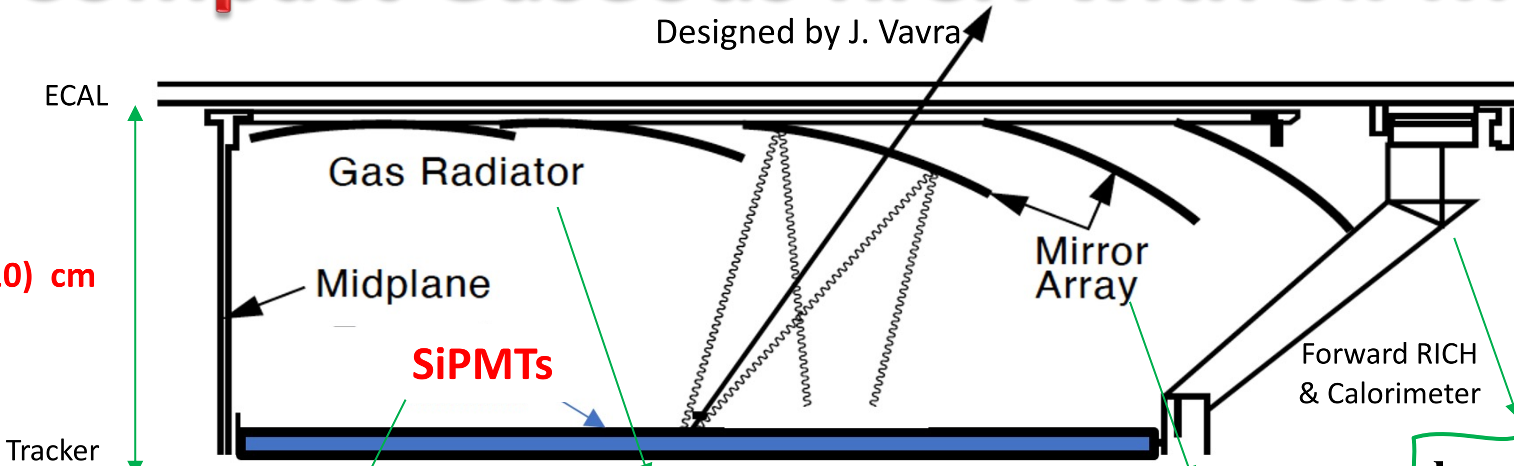
Compact Gaseous RICH with SiPMTs

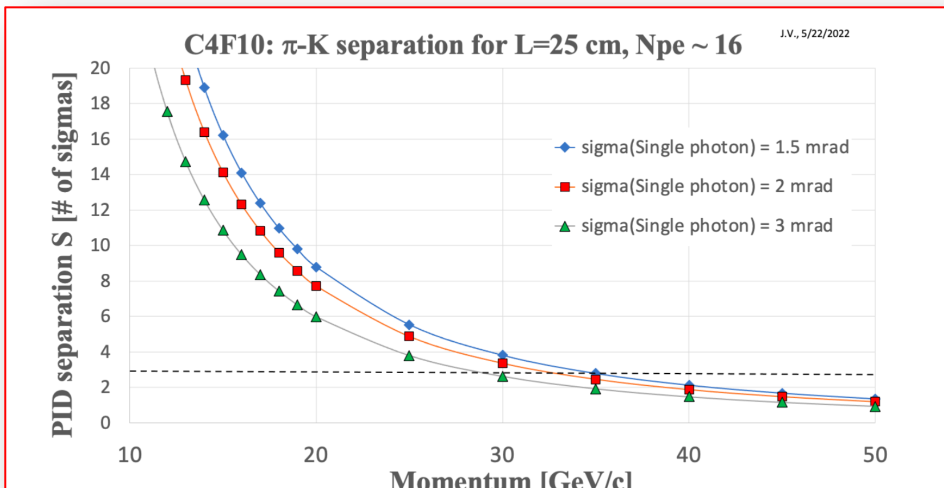


Fast timing device (<100 ps) to provide ToF covering the lower p range and complementing the RICH

Pure **C_4F_{10}** at 1 bar (boiling point -1.9 C at 1 bar, good refraction index)

Beryllium with reflective coating

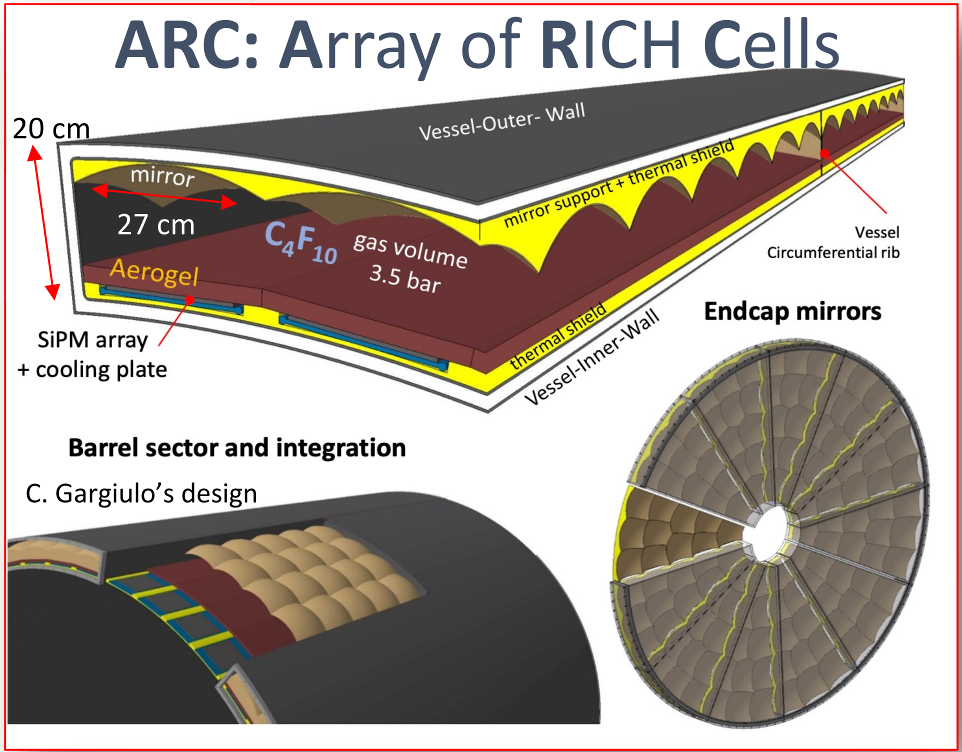
low mass carbon-composite material for the structure

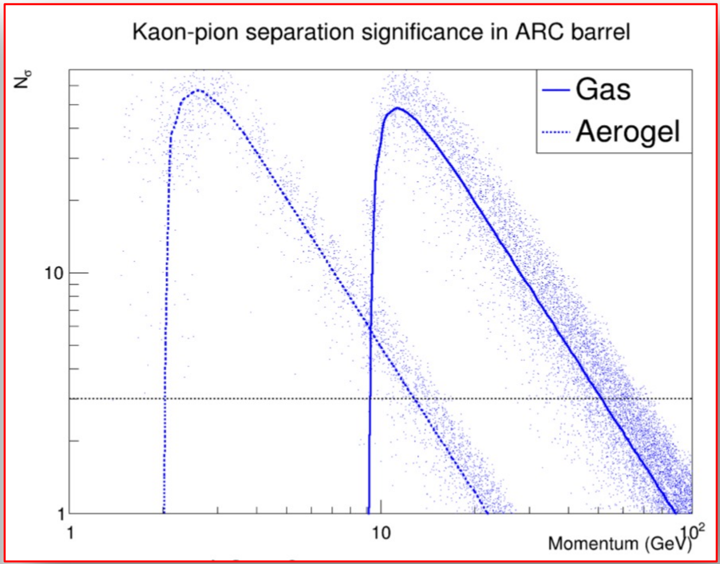


Can reach $3\sigma\ \pi/K$ separation up to 30 GeV with state-of-the-art technology! (updated results coming soon)

The ARC design

Designed by R. Forty





Can reach 3σ π/K separation up to tens of GeV!

Units of radiation length X/X_0		
Detector component	Pressurised	Non-pressurised
Vessel walls	5%	1%
Photosensor array/electronics	1%	1%
Cooling plate (3 mm CF)	1%	1%
Aerogel ($n = 1.03$)	1%	0.5%
C_4F_{10} gas	1%	0.5%
Focusing mirror	1%	1%
Total	10%	5%

- Ongoing work to include RICH in Geant 4 and run full simulation studies
- Work has also started for particle reconstruction in RICH

Next Steps

1 HtoSS – $e^+e^- \to Zh$: $h \to s\bar{s}$ ($\sqrt{s} = 240/250$ GeV) (JdB)

The core of the Higgs factory program, i.e. the determination of the absolute Higgs-strahlung cross-section with the least possible model-dependence, as well as precision measurements of the Higgs boson couplings to SM fermions, has been studied thoroughly in the past - most recently thanks to the efforts for the last European Strategy Update and in the context of the Snowmass community study. One prominent exception, being addressed only recently, is $h \to s\bar{s}$.

Theoretical, phenomenological and MC generator targets

- BSM models predicting deviations in $h \to s\bar{s}$, e.g. SUSY
- BSM models predicting for example charged Higgs boson with large branching ratios in final states including strange quarks, e.g. 2HDM $H^+ \to cs$ BR $\approx 50\%$
- $s\bar{s}$ vs. $b\bar{b}$ in BSM models: gain from $s\bar{s}$?
- flavor assumptions in EFTs: decouple 3rd from 1st/2nd family? Partially looked at in the context of the Spontaneous Flavour Violating framework.

Target physics observables

- $e^+e^- \to Zh$ with $h \to ss$ ($Z \to$ anything) at $\sqrt{s} = 240/250$ GeV (higher center of mass energies still unexplored)
- projected precision on branching fraction, and differential cross-section in $\cos\theta_s$
- Flavour changing decays are very rare in the SM , for example BR($h \to bs$) $\simeq 10^{-7}$. NP models, which can be encapsulated by an EFT, allow larger values.

Target methods to be developed

- charged hadron ID from dN/dx, dE/dx, ToF, RICH, study complementarity in momentum reach.
- reconstruction of in-flight decays, e.g. $K^0_S \to \pi^+\pi^-$
- strangeness-tagging
- s vs $\bar{s}$ separation
- control of strange-tagging related systematic uncertainties

Target analysis techniques

- diboson background suppression
- signal extraction (fit discriminant variables, counting experiement etc)

Target detector performance aspects

- dependence of the precision on physics observables on particle ID and reconstruction capabilities

MC samples needed

full SM and $e^+e^- \to f\bar{f}h$ at $\sqrt{s} = 240/250$ GeV and 350...380 GeV available in general samples listed in Section

Existing tools / examples

- similar ILD analysis for $h \to b\bar{b}/c\bar{c}/s\bar{s}$: https://github.com/ILDAnaSoft/ILDbench_Hbbccgg
- similar SiD analysis ...
- similar CLICdp analysis ...
- similar IDEA analysis ...
- similar CLD analysis ...

ECFA Detector R&D roadmap:

Sect. 4.3.1 “The limited space of the interaction region for hermetic-coverage collider experiments (mandatory at the EIC and FCC-ee) requires designing performant RICH detectors with a total length shorter than a metre”

Additional comments

- Accuracy of simulation
  - Bad tracks / scattering effect is especially important for flavor tagging / hadron ID (so simple smearing of 4-momentum should not work)
    - Currently FCCee flavor tagging is (~10x) better than ILD → Power of novel algorithm or just the simulation effect (probably both)
  - Need to confirm with full simulation
- For H → ss, separation of H → gg is critical
  - Can use jet shape or other gluon tagging algorithms which may be more important than s-tag

Summary

- H → ss is one of the 16 focused topics for the ECFA HF study
  (H → cs also possible with BSM)
- dE/dx at gas detector, Time-of-flight and RICH are the key detector elements for strange tagging
- Details of simulation, development of new algorithms, detailed design of PID-related detectors are all important aspects towards realistic strange tagging