The Strange Quark as a probe for new Physics in the Higgs Sector

FCC Higgs Kick-off meeting

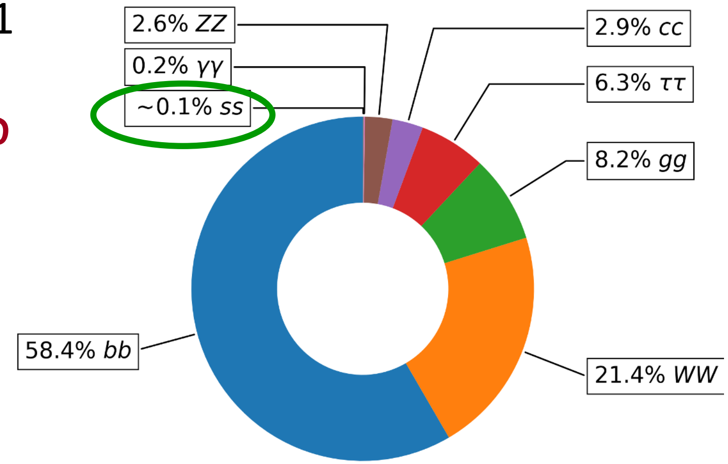
Monday 28 Mar 2022, 14:30 → 17:05 Europe/Zurich

See previous presentation at the FCC Physics Workshop in February 2022

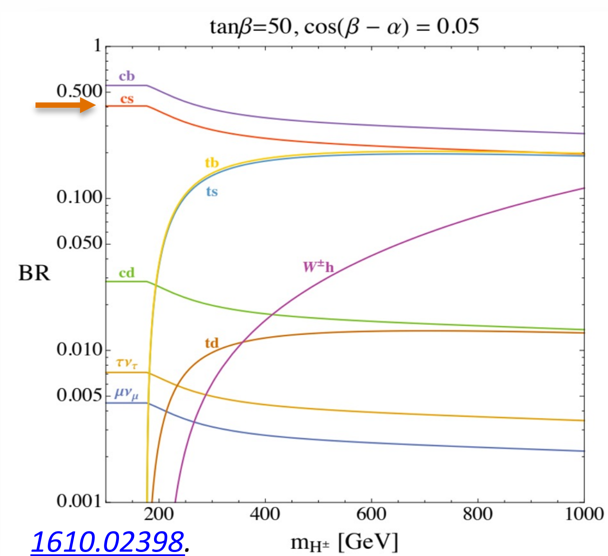
Matt Basso (U. of Toronto)
Valentina Maria Martina Cairo (CERN)

Goals of the *StrangeTeam*

- Started in August 2020 with an LoI for Snowmass 2021
- Derive sensitivity to **Higgs strange Yukawa coupling @ Future Higgs Factories**
- Develop a **strange tagger** and apply the tagger to a direct $SM\ h \rightarrow s\bar{s}$ or $BSM\ H \rightarrow cs$ analysis
    - $h \rightarrow ss$: likely out of experimental reach unless enhanced by BSM
    - $H \rightarrow cs$: BSM models allow for the 1st & 2nd generation fermion masses to be an additional source of EW symmetry breaking
        - Charged heavy Higgs can undergo "flavour violating" decays (e.g., cs)
            - both **s/c-tagging** can help here
- Provide **inputs to detector instrumentation**



$\sqrt{s}$ = 13 TeV, m_h = 125 GeV



1610.02398.

Results of the *StrangeTeam*

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/abs/2203.07535

Strange quark as a probe for new physics in the Higgs sector

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March 16, 2022

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Jerry Va'vra (jjv@slac.stanford.edu)

This is a preliminary study performed in the framework of the ILD concept group.

This paper describes a novel algorithm for tagging jets originating from the hadronisation of strange quarks (strange-tagging) with the future **International Large Detector (ILD) at the International Linear Collider (ILC)**.

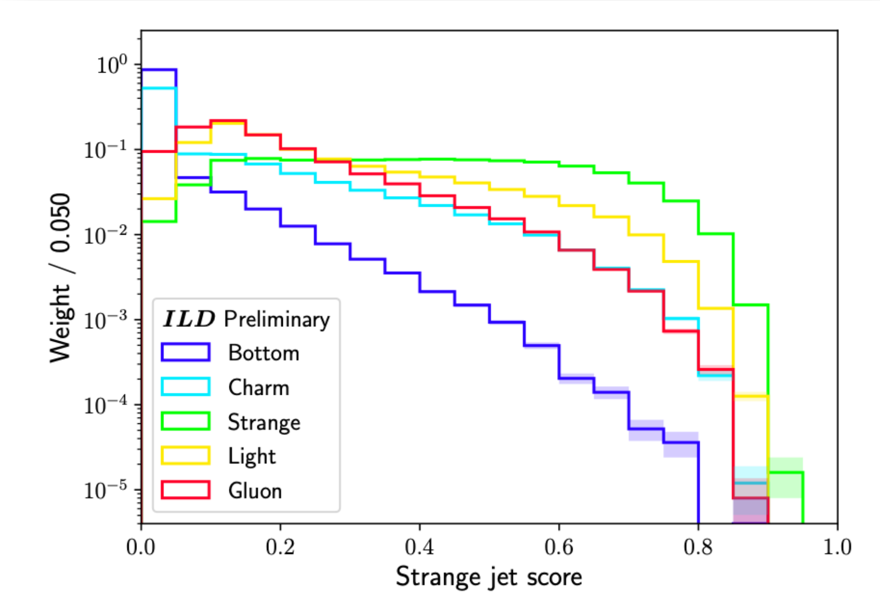
It also presents the first application of such a strange-tagger to a Higgs to strange (h->ss) analysis with the $P(e_-, e_+) = (-80\%, +30\%)$ polarisation scenario, corresponding to **900 fb^{-1} of the initial proposed 2000 fb^{-1} of data** which will be collected by ILD during its first 10 years of data taking at **$\sqrt{s}$ = 250 GeV**.

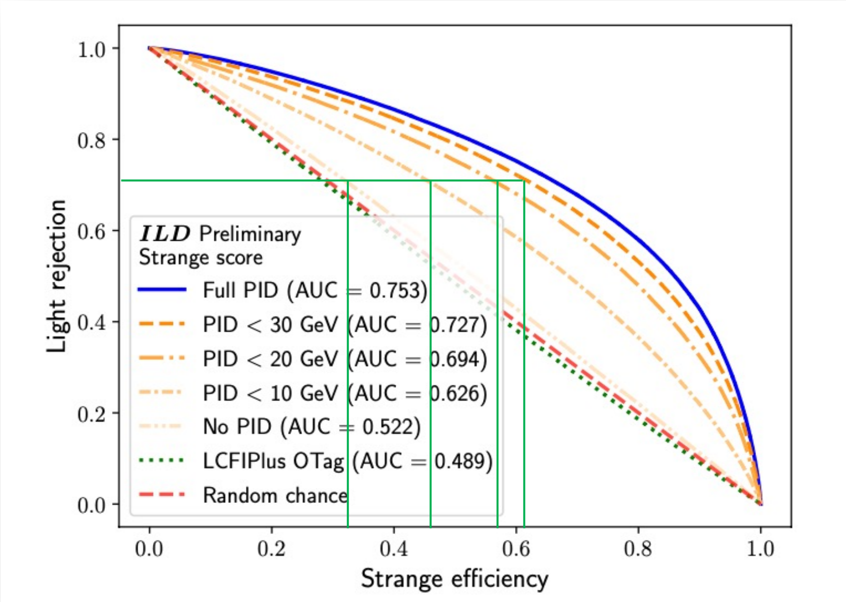
Upper limits on the Standard Model Higgs-strange coupling strength modifier, **k_s**, are derived at the 95% confidence level to be **6.74**.

The paper includes as well a preliminary study of a **Ring Imaging Cherenkov (RICH) system** capable of discriminating between **kaons and pions at high momenta (up to 25 GeV),** and thus enhancing strange-tagging performance at future Higgs factory detectors.

Strange Tagging

- π/k **discrimination at high momentum** is crucial for tagging strange jets from Higgs decays
  - Dedicated appendix in the paper, more plots in the extra slides
- Use a NN-based tagger for classifying jet-flavour, train on $(Z \rightarrow inv)(H \rightarrow qq/gg)$ samples and include **per-jet level inputs** & variables on the **10 leading particles** in each jet (**including PDG-based PID!**)





- Separation of *s* and *u*/*d* is **possible** with using truth likelihoods
- Also **good discrimination of *s* jets from *g* jets** – here, $N_{particles}$ is powerful
- At **50% strange tagging efficiency**, we have **90% background rejection** over **70%** for LCFIPlus Otag
- **From PID < 10 GeV to PID < 30 GeV** → at fixed mistag rejection (70%), **eff increases by almost 20%**

Analysis overview & results

Define Signal/Bkg

- Signal: Z(inv)H(ss)+: Z(ll)H(ss)
- Bkg: Z(inv/ll)H(bb,cc,gg), Z(qq & semil), ZZ(qqqq &semil), ZZ/WW(had), WW(had)

Select Events

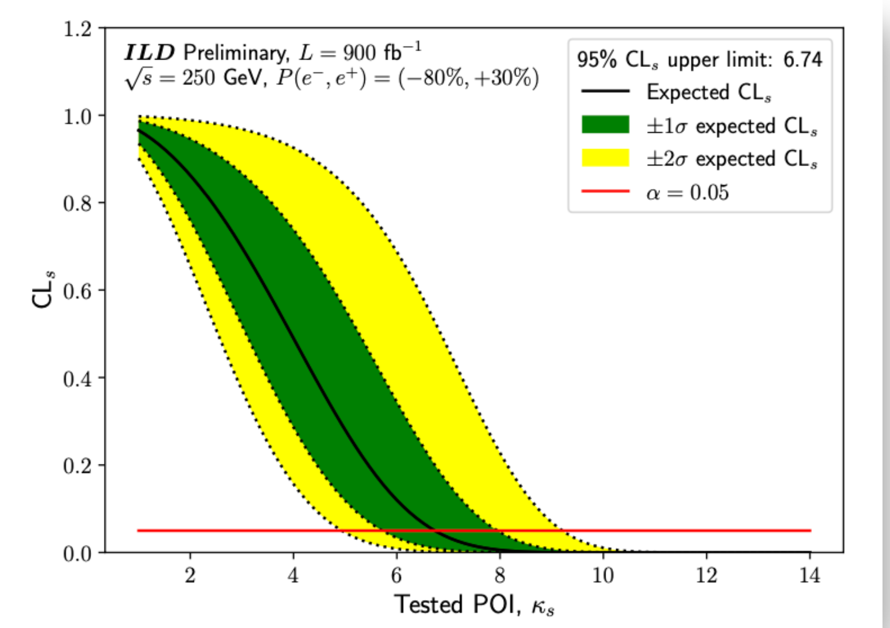
Most powerful cut on M_{jj} (see extra-slides for more details)

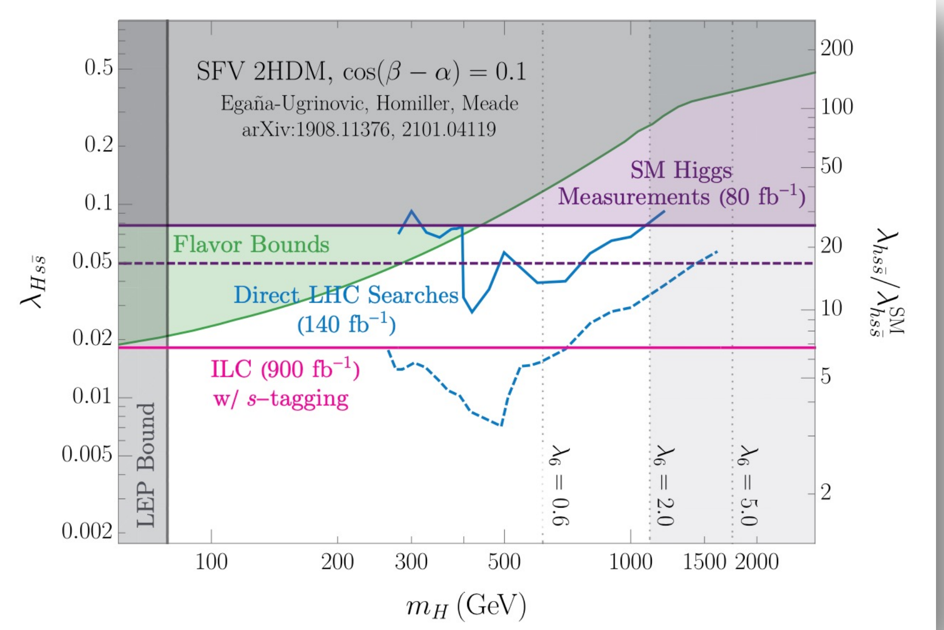
Build Signal discriminant

Sum of leading and sub-leading strange-jet score

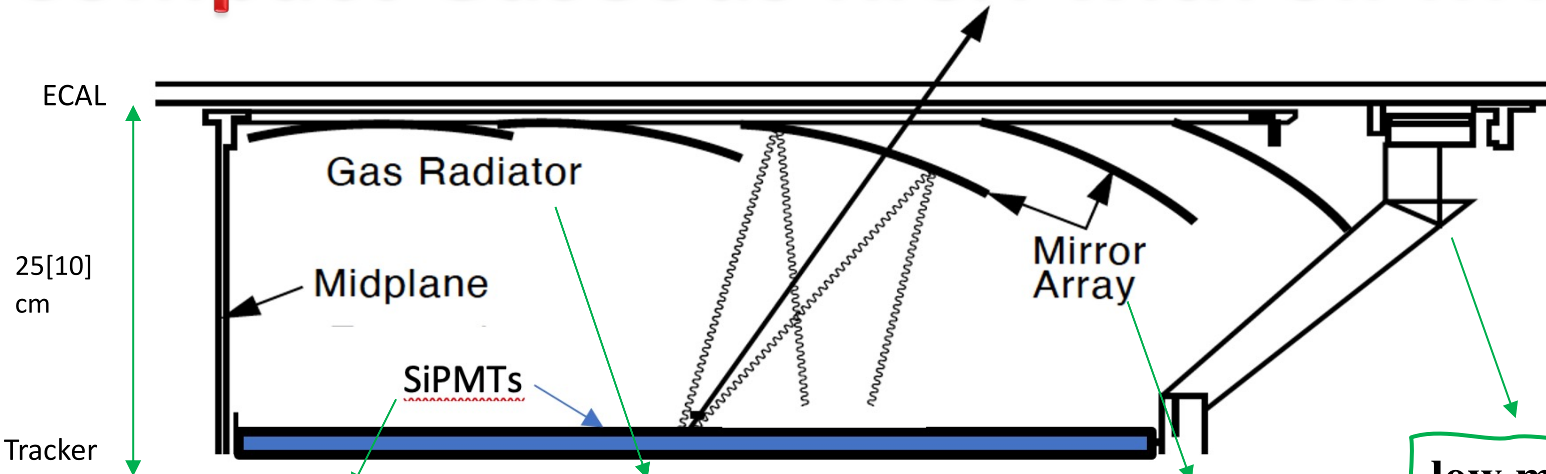
s-Yukawa coupling

Probe various BSM regimes





Compact Gaseous RICH with SiPMTs

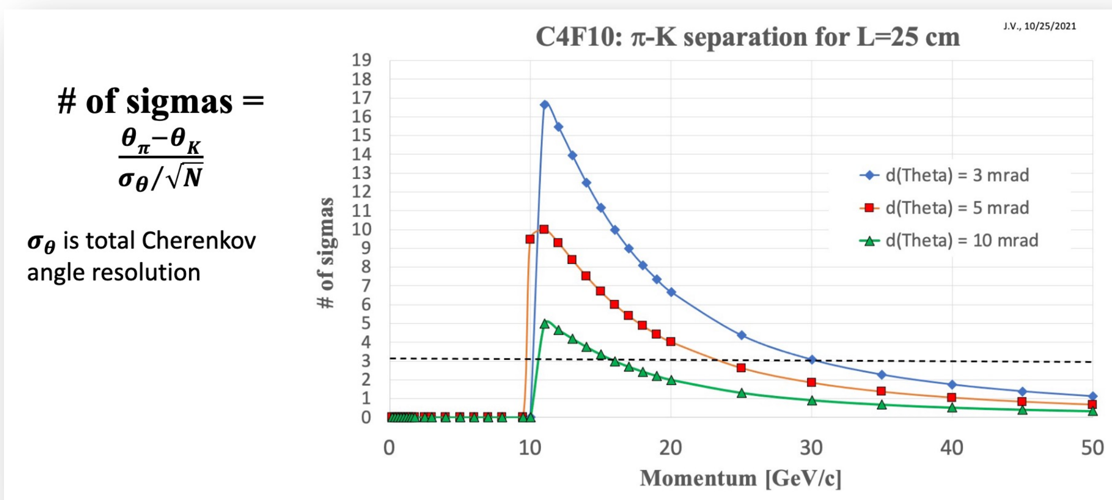


Fast timing device (<100 ps) to provide ToF covering the lower p range and complementing the RICH

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



Plans for the Future

- Current work done with the ILD @ the ILC (based on ILCSoft)
- A few outstanding points to add to finalise the results:
  1. **Additional polarization scenarios to perform the analysis on the full 2000 fb-1 dataset**
  2. **Fixed dE/dx info from TPC**

  On the wish list we also have:

  3. Alternative network for Flavour Tagging (studies are ongoing)
  4. H->cs analysis (studies have started on generating the events)
  5. Switch from cut-based to MVA-based analysis

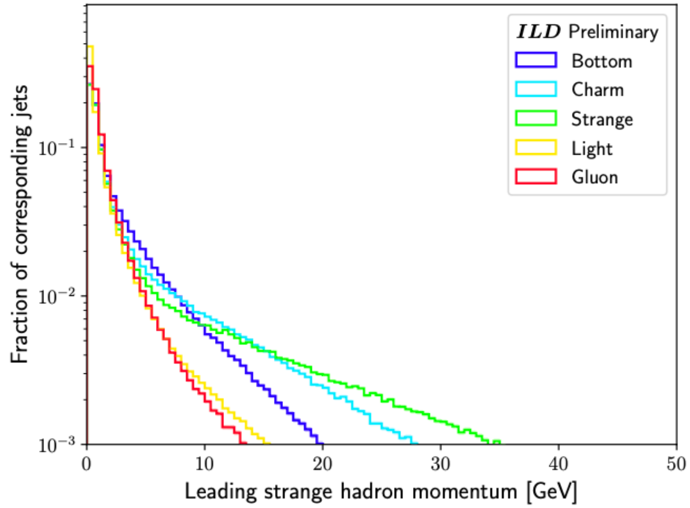
  Long term project: RICH in full simulation

- **Important question for today: how can we transfer this knowledge to the FCC-ee case?**
  - Comparison of underlying perfomance (Vertexing, Ftag, etc) due to different machine & detector features
    - Will be partially done for the ECFA Seminar on April 8th
  - Any physics samples we could use (ZH, ZZ, etc)?
  - How feasible would it be to simulate a RICH system in FCC-ee?
    - Could start from one of the existing detector design and create a third version with a compact RICH

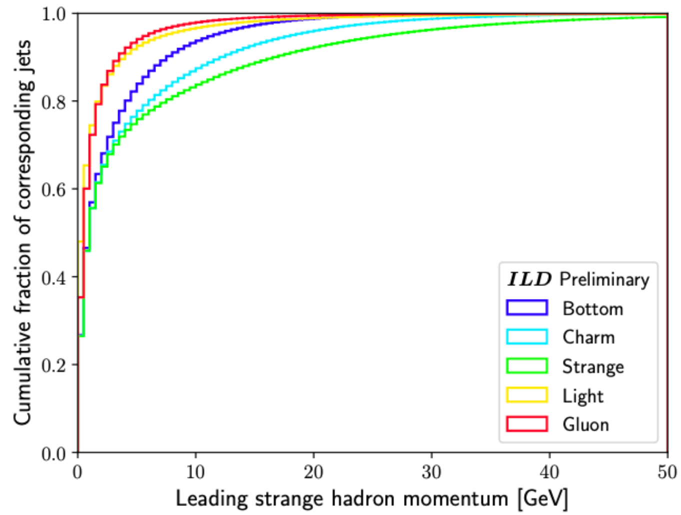
Thanks for your attention!

Valentina Cairo

Extra Slides

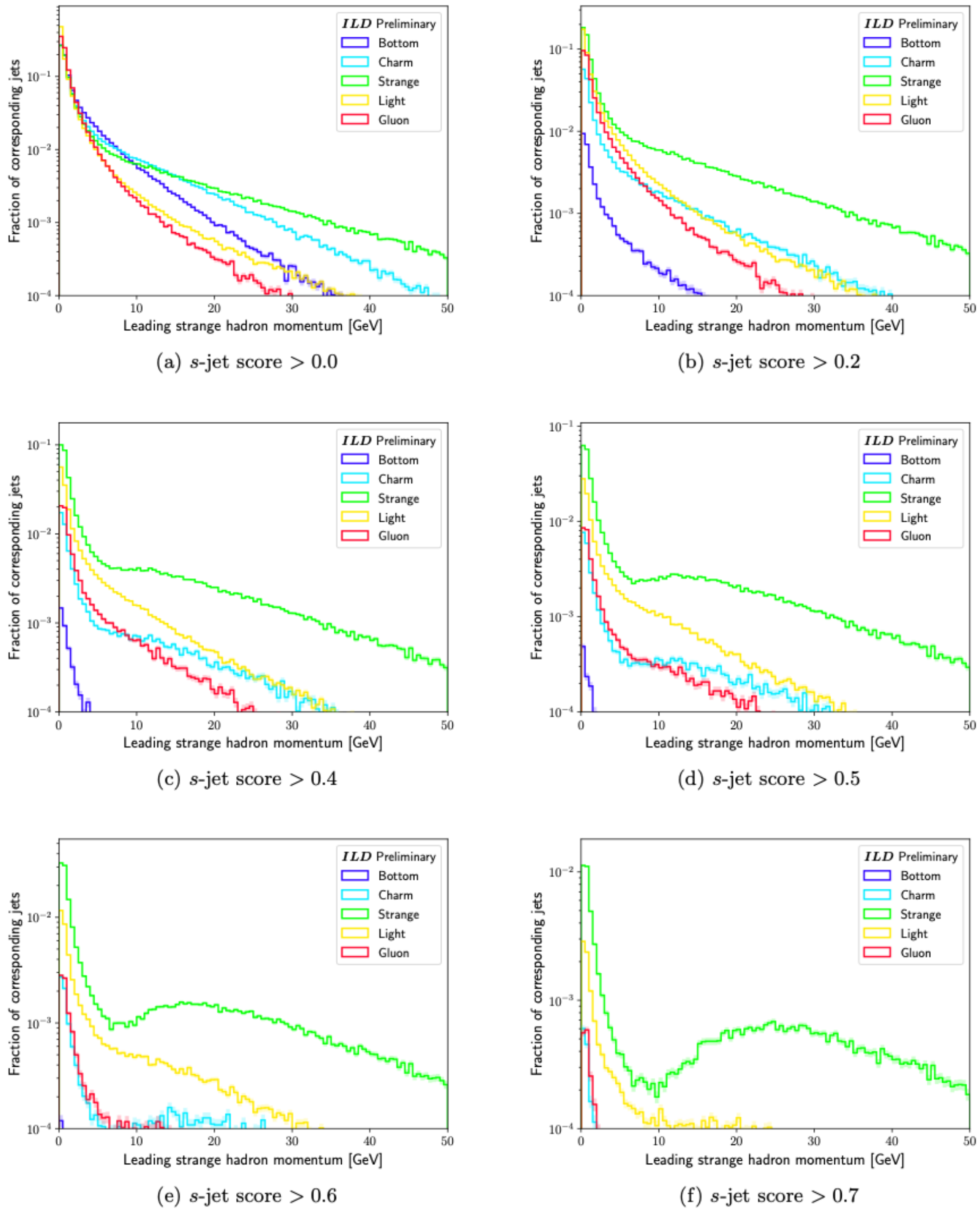


(a) Differential



(b) Cumulative

Figure 2: Differential and cumulative distributions of the momentum of the leading strange particle in the leading or subleading momentum jet of the $h(\rightarrow q\bar{q}/gg)Z(\rightarrow \nu\bar{\nu})$ events described in Table 2. The choice of leading or subleading jet is random. The leading strange particle is identified by iterating over the momentum-ordered PFOs in the jet and selecting the first PFO which is truth-matched to a strange hadron. If no strange particle is found, a momentum of 0 GeV is assigned. The sum-of-weights for each class is normalised to 1.



(a) s-jet score > 0.0

(b) s-jet score > 0.2

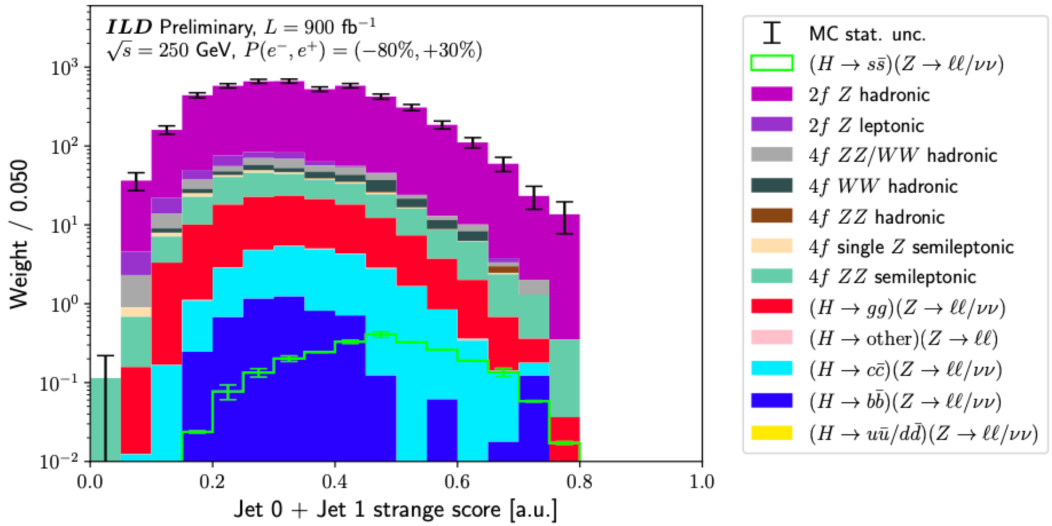
(c) s-jet score > 0.4

(d) s-jet score > 0.5

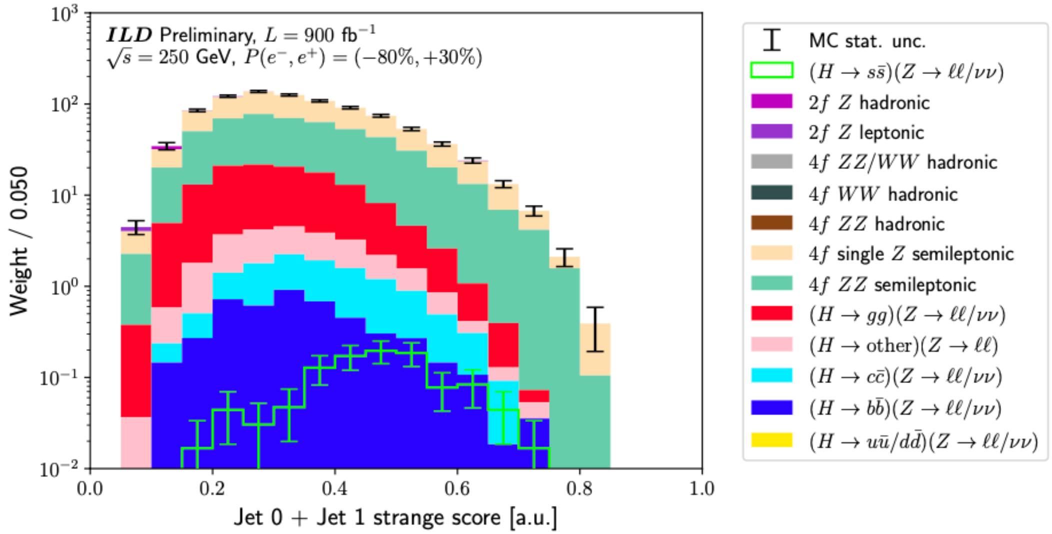
(e) s-jet score > 0.6

(f) s-jet score > 0.7

Figure 7: Distributions of the momentum of the leading strange particle in jets from $h(\to q\bar{q}/gg)Z(\to \nu\bar{\nu})$ events. The distributions are shown for different choices of cut on s-jet score of the described jet flavour tagger, Eq. 5. The momentum of the leading strange particle is determined by following the same procedure as for Fig. 2. The sum-of-weights for each class is normalised to 1 in (a) but is *not* renormalised following the application of cuts in (b) through (e).

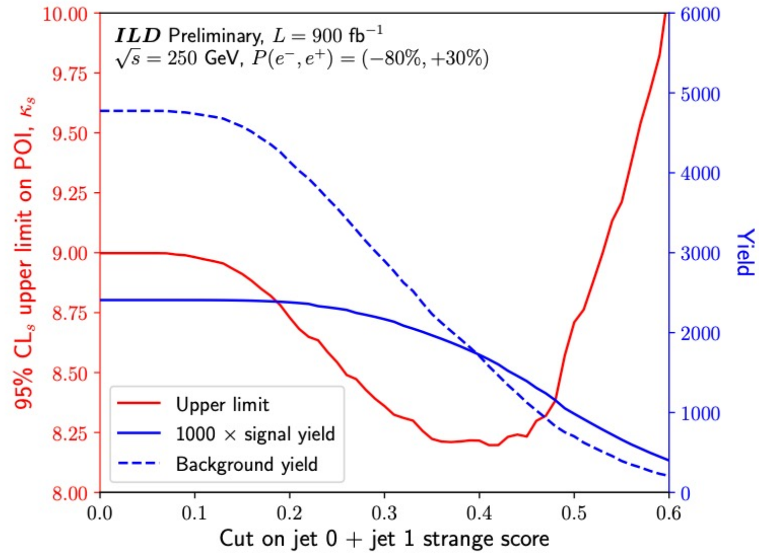


(a) $Z \to \nu\bar{\nu}$ channel

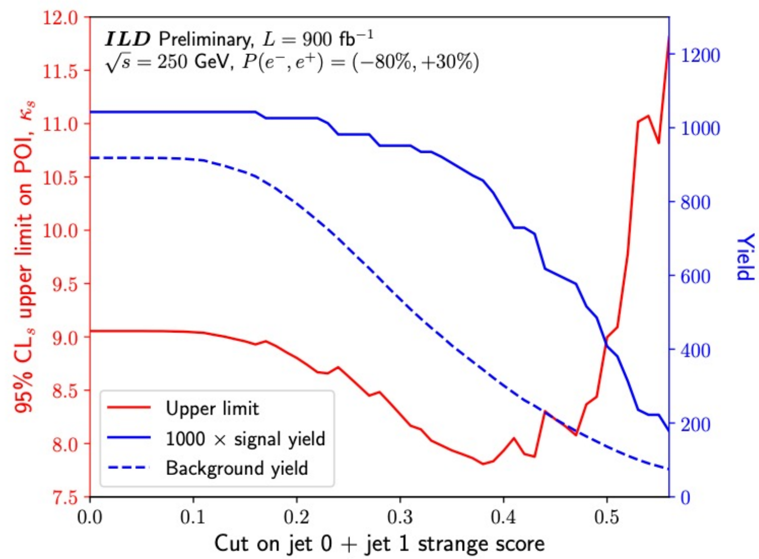


(b) $Z \to \ell\bar{\ell}$ channel

Figure 17: Fit discriminants for each channel of the SM $h \to s\bar{s}$ analysis: $(0.5\times)$ the sum of the strange scores for leading and subleading jets, using the jet flavour tagger described in section 4. Each histogram is produced at the level of the last selection of their respective channel in Table 3. The error bars represent the MC statistical uncertainties. The sum-of-weights per process is normalised to the SM cross section. N.B. the $h(\to s\bar{s})Z(\to \ell\bar{\ell}/\nu\bar{\nu})$ signal is unstacked.

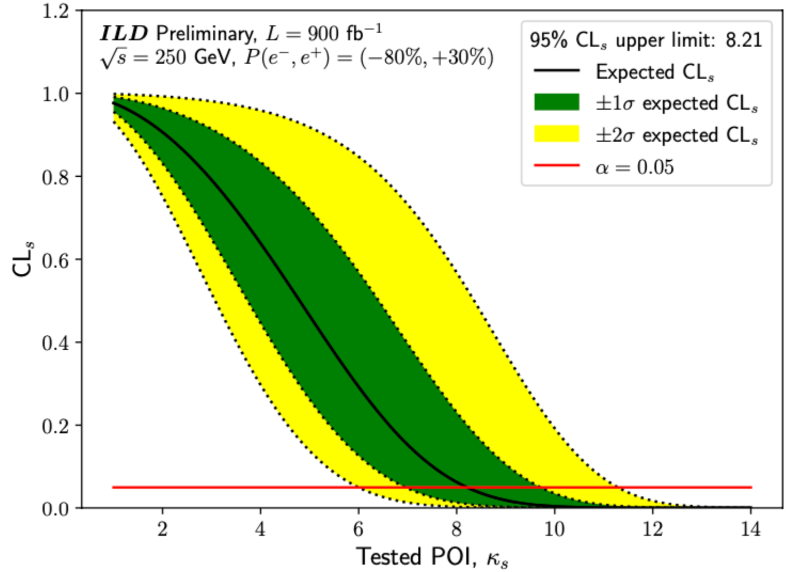


(a) $Z \to \nu\bar{\nu}$ channel

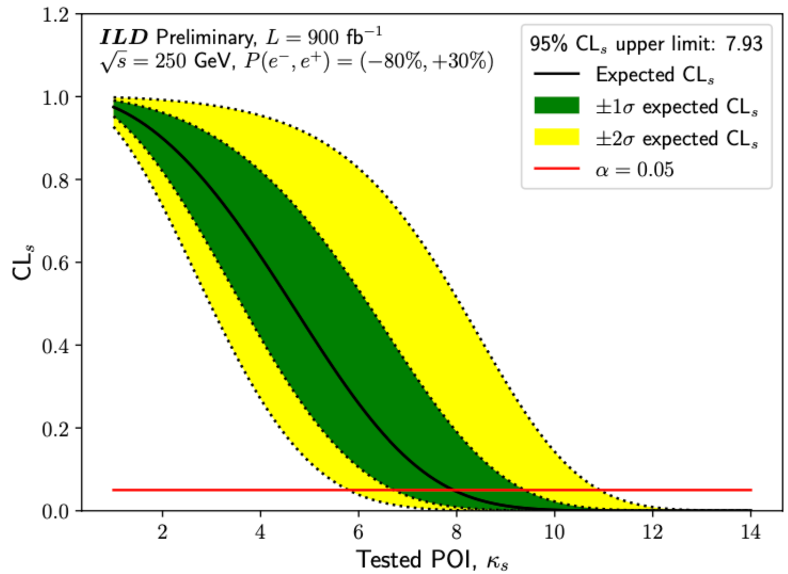


(b) $Z \to \ell\bar{\ell}$ channel

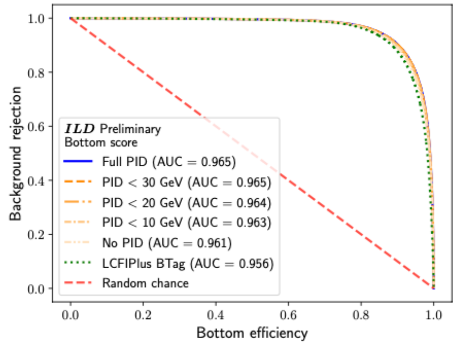
Figure 18: Scans of the 95% CL$_s$ upper limit for the Higgs-strange coupling strength modifier κ_s, obtained by varying the choice of the lower thresholds on the discriminants shown in Fig. 17. Also shown are the signal (i.e., $h(\to s\bar{s})Z(\to \ell\bar{\ell}/\nu\bar{\nu})$) and background (i.e., non-$h(\to s\bar{s})Z(\to \ell\bar{\ell}/\nu\bar{\nu})$) yields in the resulting regions.



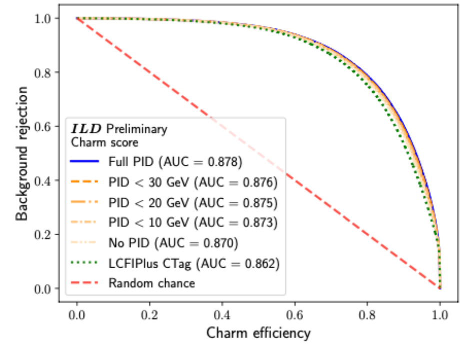
(a) $Z \to \nu\bar{\nu}$ channel



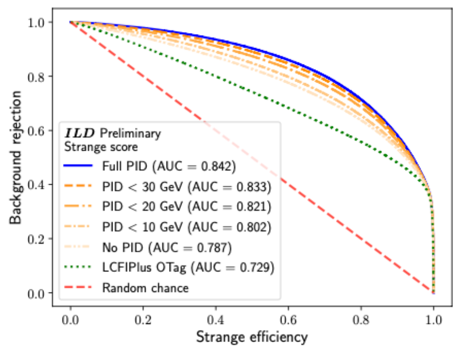
(b) $Z \to \ell\bar{\ell}$ channel



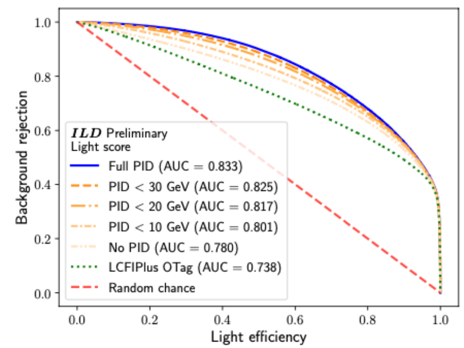
(a) *b*-jet score



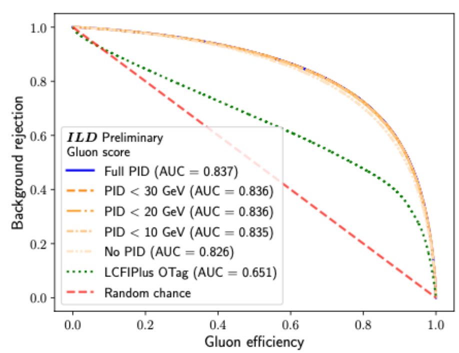
(b) *c*-jet score



(c) *s*-jet score



(d) Light-jet score

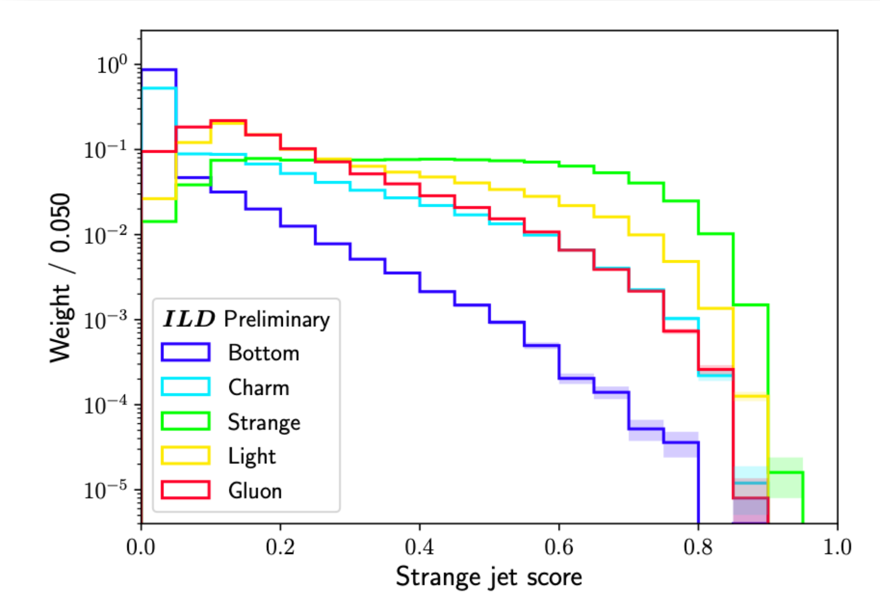


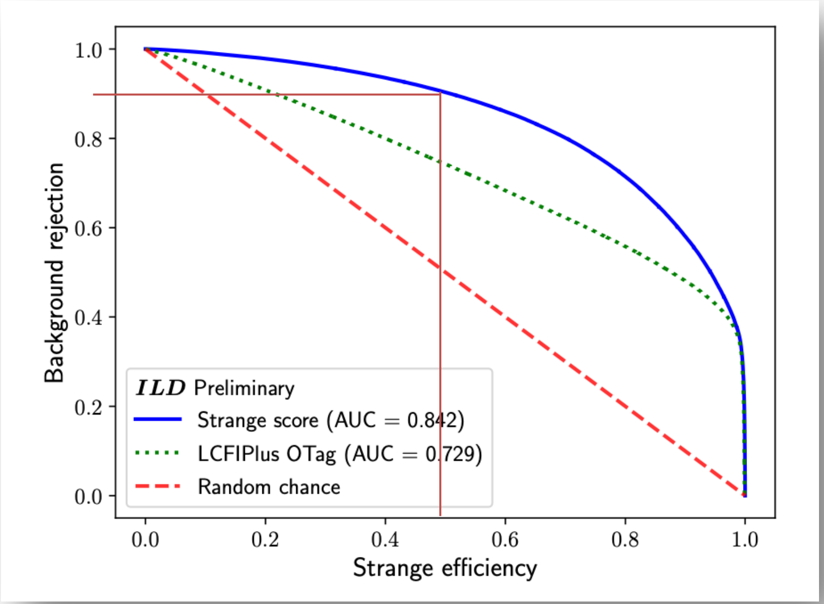
(e) *g*-jet score

Figure B3: ROC curves for each output node of the jet flavour tagger with full PID ("Full PID"), as described in Section 4, as well as for the jet flavour taggers without PID ("No PID") and with partial PID ("PID $< X$ GeV"), as described in Appendix B. The sum-of-weights for each class is normalised to 1. The "Background" in a given plot corresponds to all classes not targeted by that node of the tagger. N.B. the blue and orange curves lie nearly on top of one another in (a), (b), and (e).

Strange Tagging

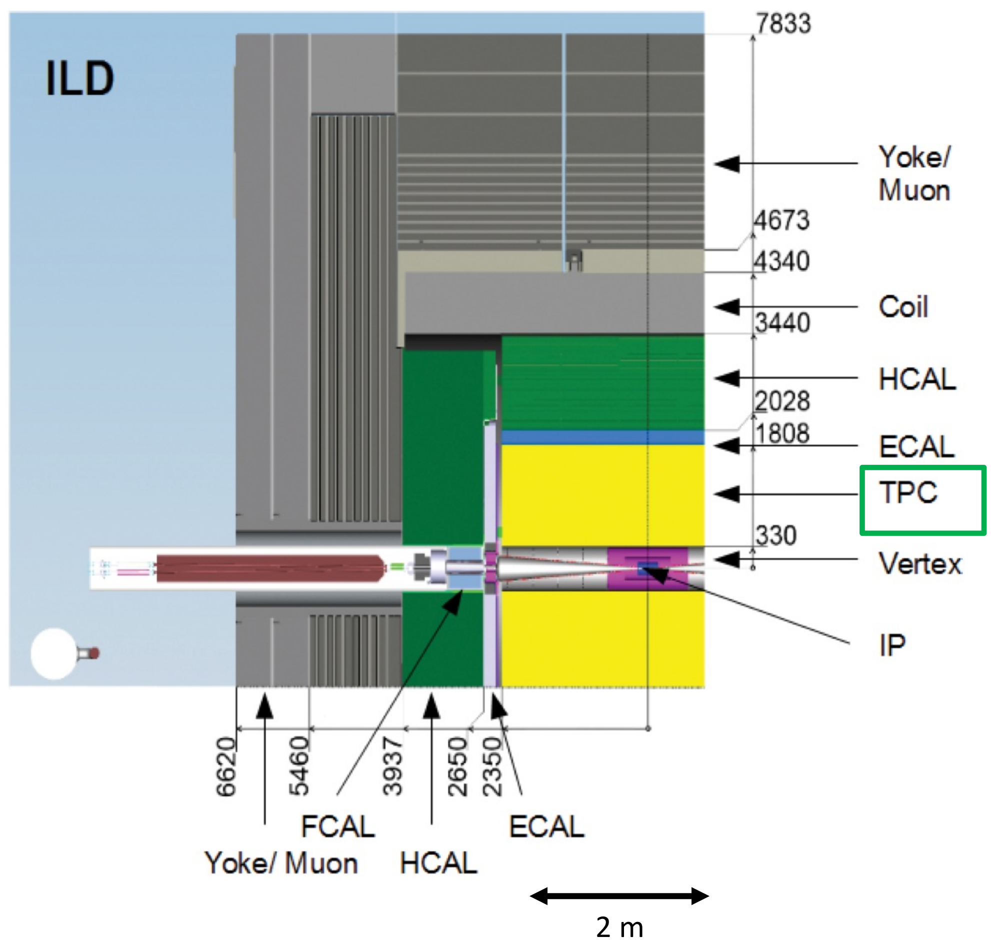
- **π/k discrimination at high momentum** is crucial for tagging strange jets from Higgs decays
  - Dedicated appendix in the paper, more plots in the extra slides
- Use a NN-based tagger for classifying jet-flavour, train on $(Z \rightarrow inv)(H \rightarrow qq/gg)$ samples and include **per-jet level inputs** & variables on the **10 leading particles** in each jet (**including PDG-based PID!**)





- Separation of *s* and *u*/*d* is **possible** with using truth likelihoods
- Also **good discrimination of *s* jets from *g* jets** – here, $N_{particles}$ is powerful
- At **50% strange tagging efficiency**, we have **90% background rejection** over **70%** for LCFIPlus Otag (more ROC curves in back-up and LCWS2021 talk)

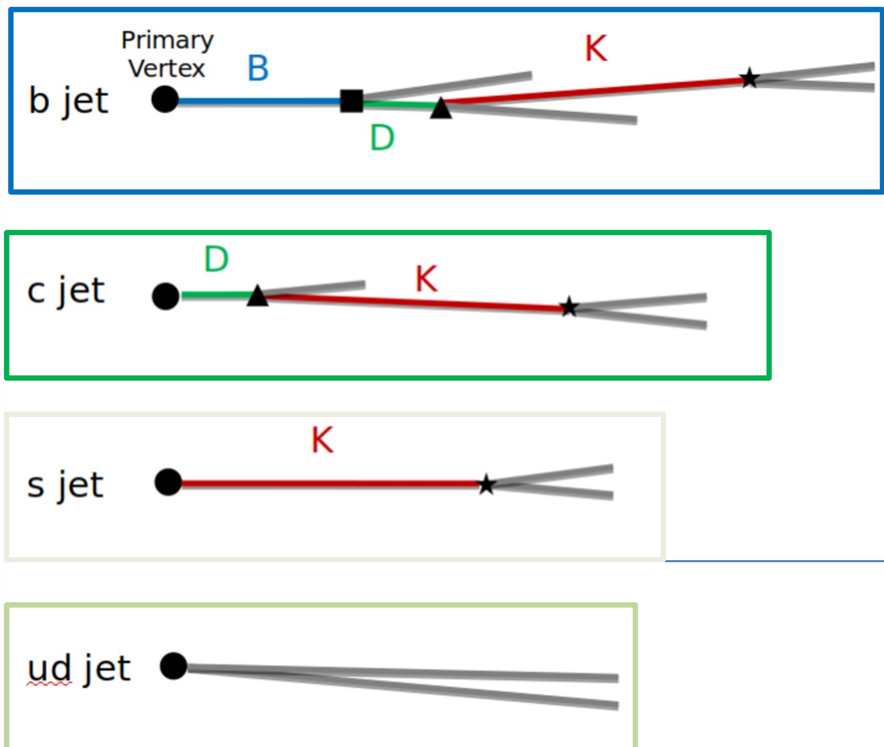
A physics benchmark: $h \to s\bar{s}$ analysis with ILD @ the ILC



3.5 T

Experimental Handles for Flavour 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

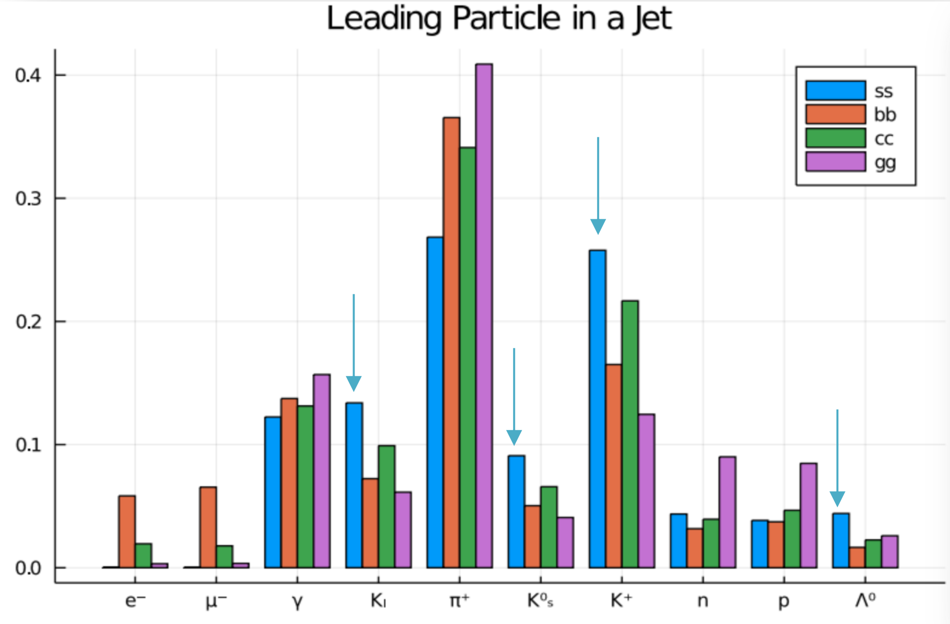
- $K^{\pm}$ [PID]
- $K_S^0 \rightarrow \pi^+\pi^-$ [Vertex] (BF ~69.2%)
- $\Lambda^0 \rightarrow p\pi^-$ [Vertex] (BF ~64%)
- K_L^0 [Particle Flow]

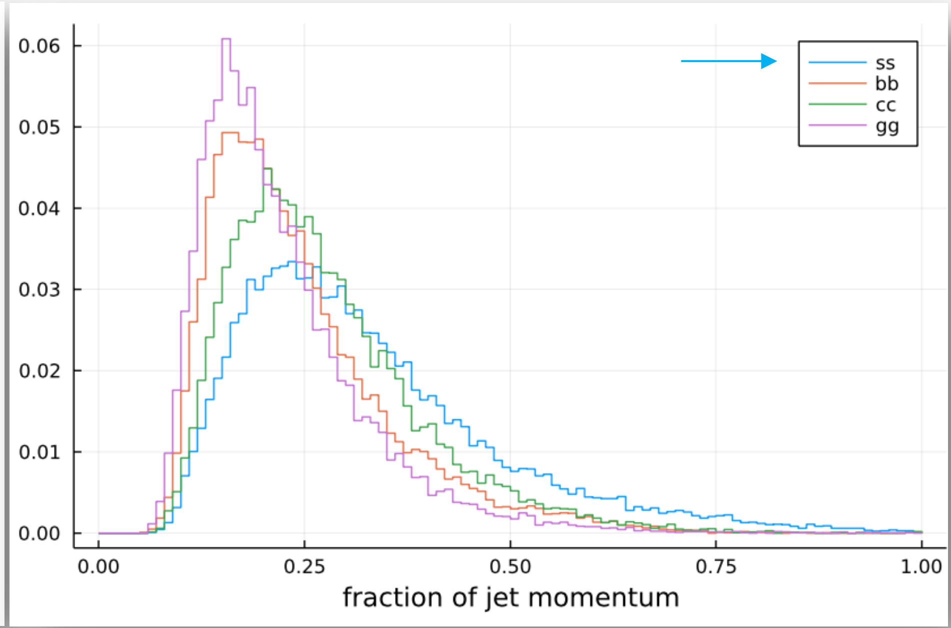
…and SLD actually measured strange hadrons from $Z \rightarrow ss$!

See Su Dong's talk & SLD A_s PRL 85 (2000), 5059

Experimental Handles for Flavour Tagging

J. Strube's studies





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

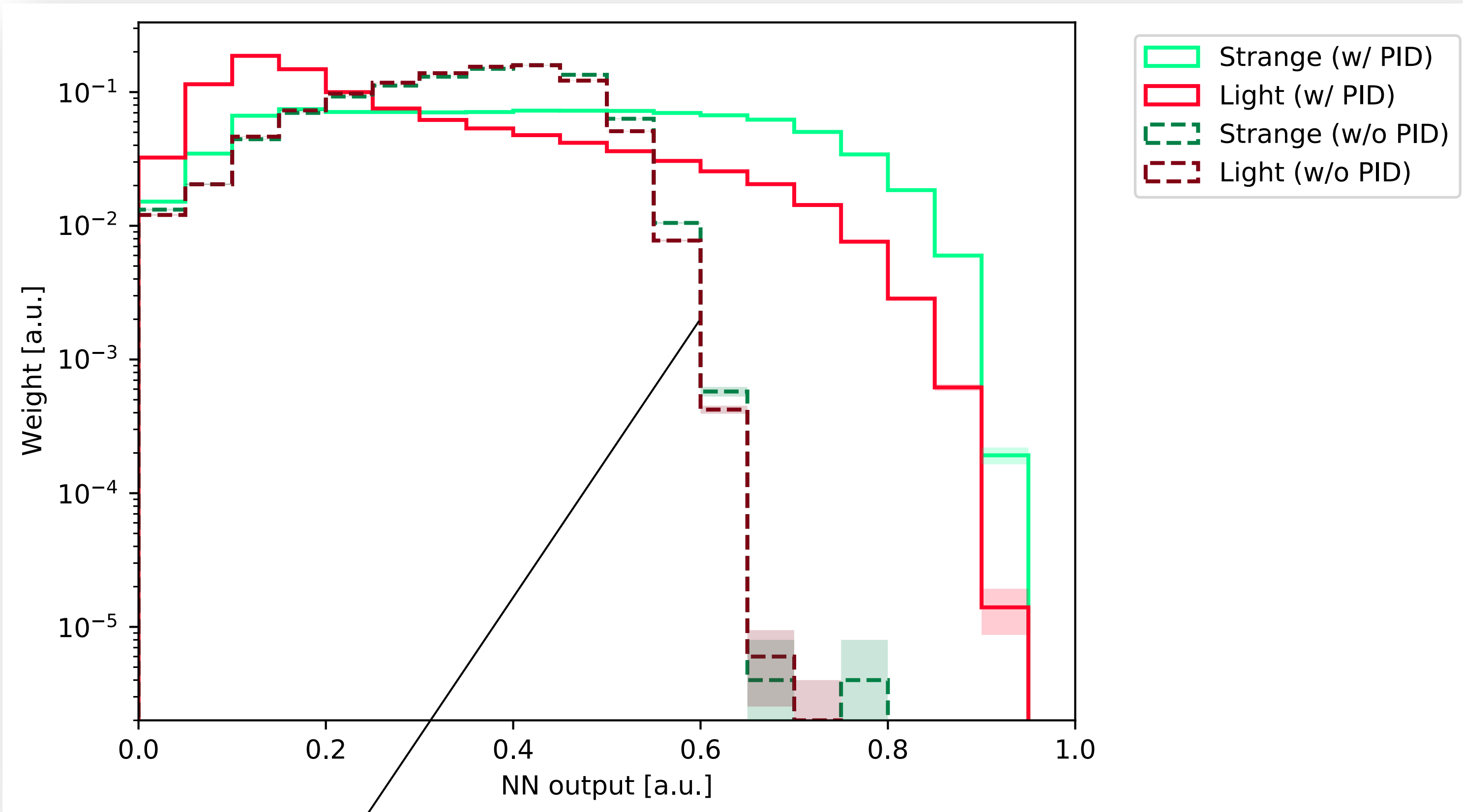
A physics benchmark: $h \to s\bar{s}$ analysis with ILD @ the ILC

σ_H @ $\sqrt{250}\text{GeV} \sim 200$ fb

- 2000 fb^{-1} collected by the ILC after 10 years
- → 400k Higgs out of which only about 80 will decay to strange quarks

But of course, new physics boosts these numbers!

Performance: s and u/d jets



Discrimination between s and u/d without PID degrades!

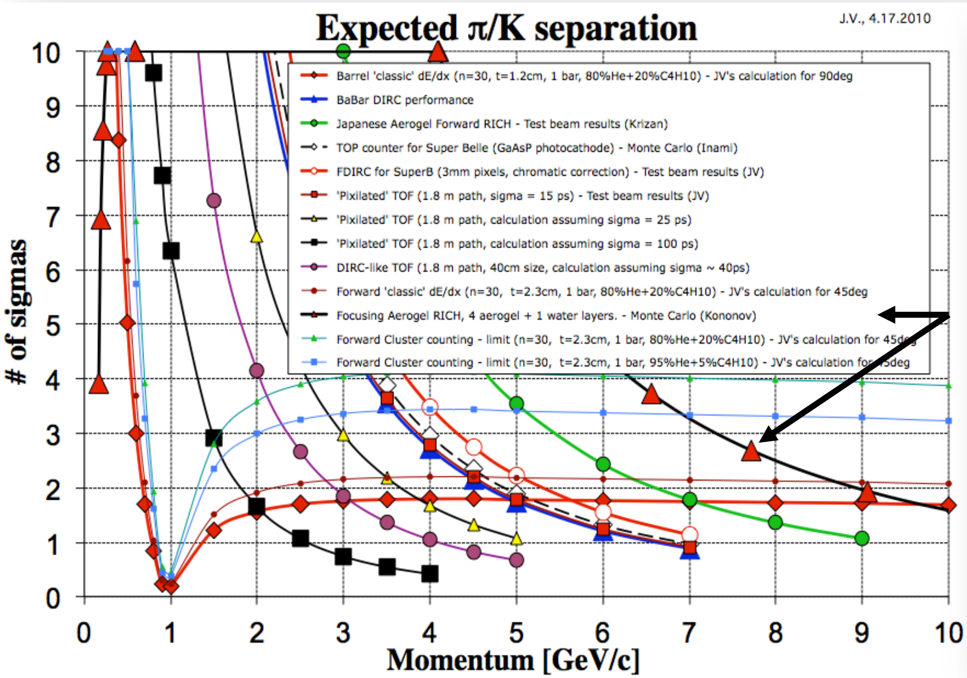
PID is a key ingredient for discriminating **strange** from **up/down** initiated jets!

- We can tag strange jets and we can probe the **strange Yukawa** coupling
  - But **we need K/π discrimination at high momenta**!

- This triggered our recent study of what may be possible with a **RICH system**…

Sketching the ideal detector…

TOF or dE/dX have great PID capabilities, but cover only the low momentum regime (unless very large tracker volumes are used)



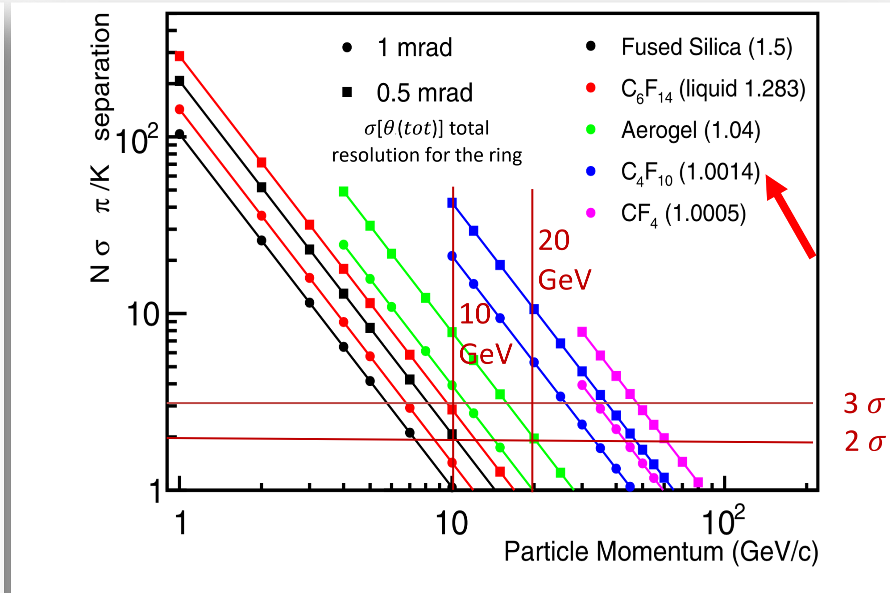


Fig. 2. The number standard deviations in $\pi - K$ separation versus momentum for different radiators and two different Cherenkov angle resolutions.

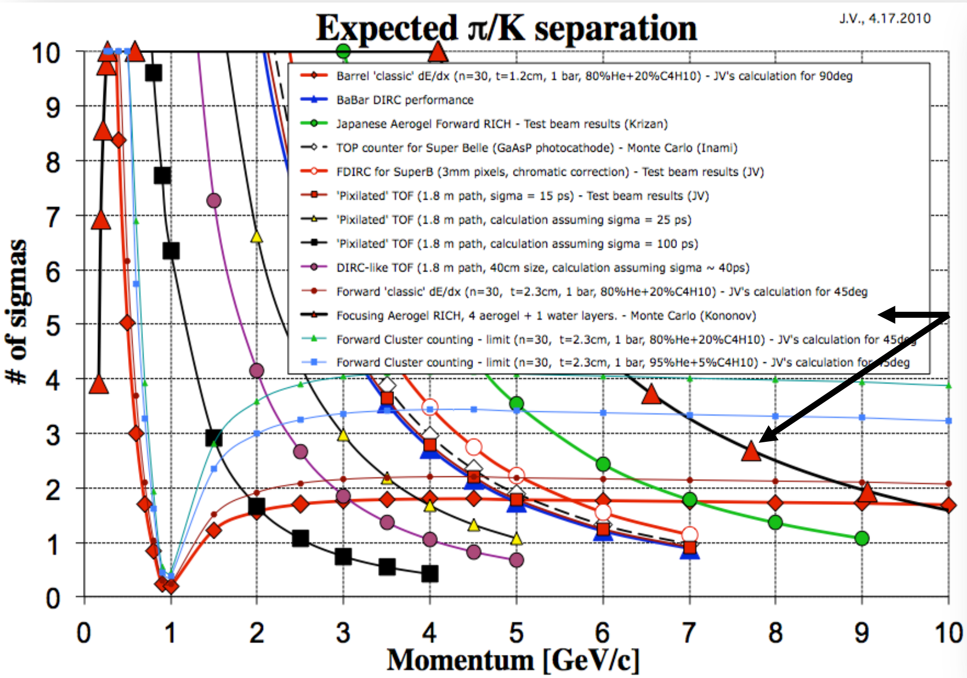
A. Papanestis, NIM,A 952 (2020) 162004

- **Ring Imaging Cherenkov Detectors (RICH)** is a favourable approach at high momentum

- **Gas** is the most promising radiator in a RICH
  - Requires excellent Cerenkov angle resolution

Sketching the ideal detector…

TOF or dE/dX have great PID capabilities, but cover only the low momentum regime (unless very large tracker volumes are used)



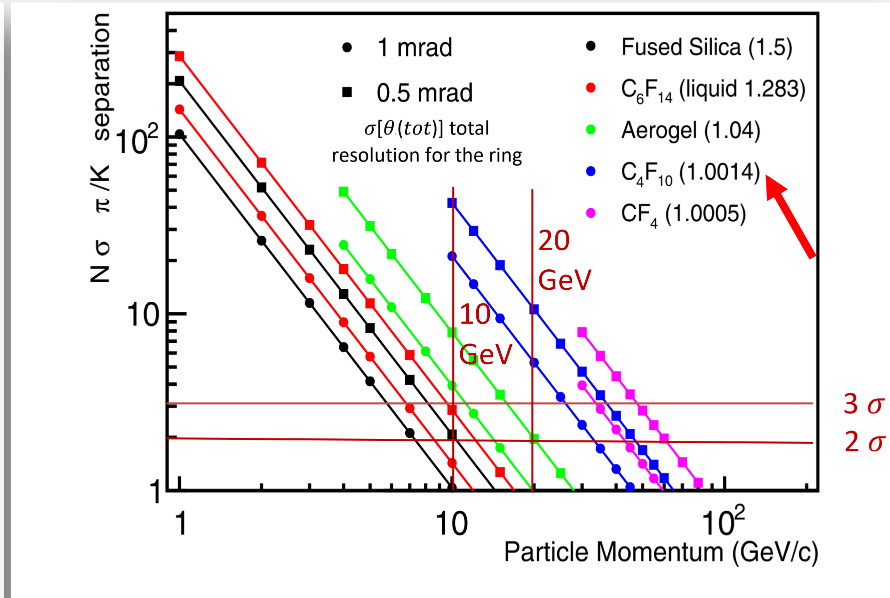


Fig. 2. The number standard deviations in $\pi - K$ separation versus momentum for different radiators and two different Cherenkov angle resolutions.

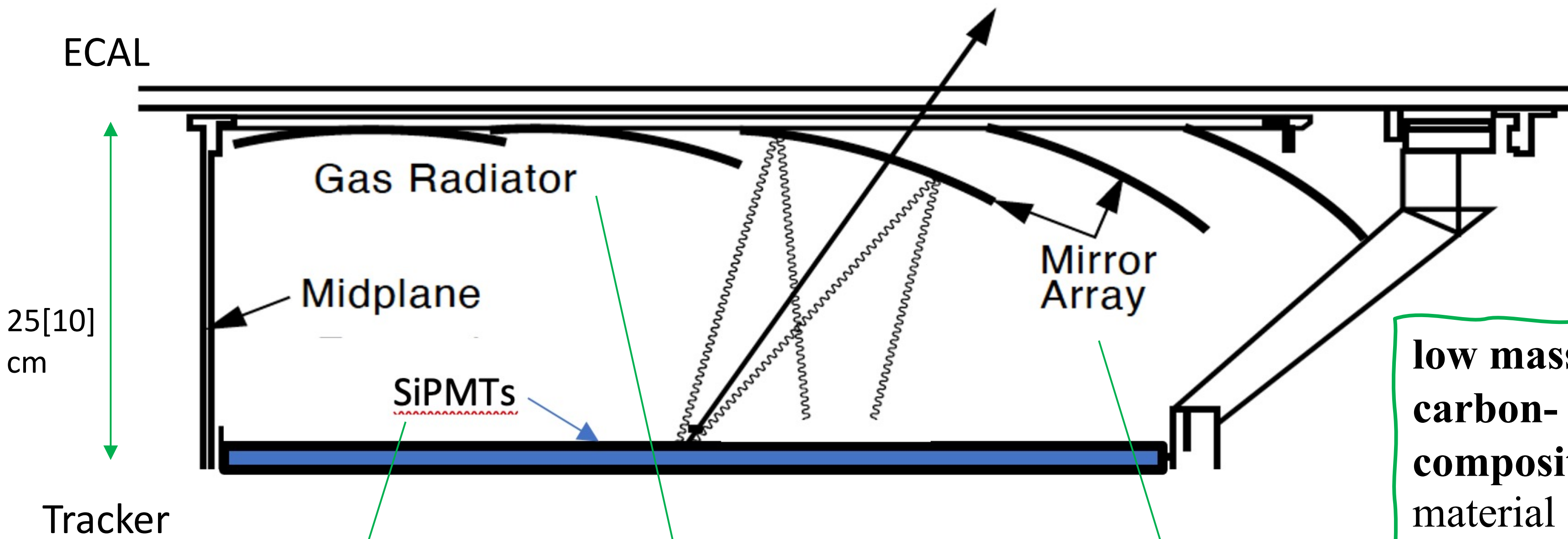
A. Papanestis, NIM,A 952 (2020) 162004

- **Ring Imaging Cherenkov Detectors (RICH)** is a favourable approach at high momentum

Historical Note:
CRID@SLD used a design with two radiators: a liquid layer of C_6F_{14} working in proximity focusing and a gas volume filled with C_4F_{10}

Compact Gaseous RICH with SiPMTs

- **Past** → **Future**:
  - Much **smaller RICH** radial length (CRID ~ 1m), **SiPMTs** rather than TPCs for photon detection
- **Many parameters to look into!**



low mass carbon-composite material for the structure

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)

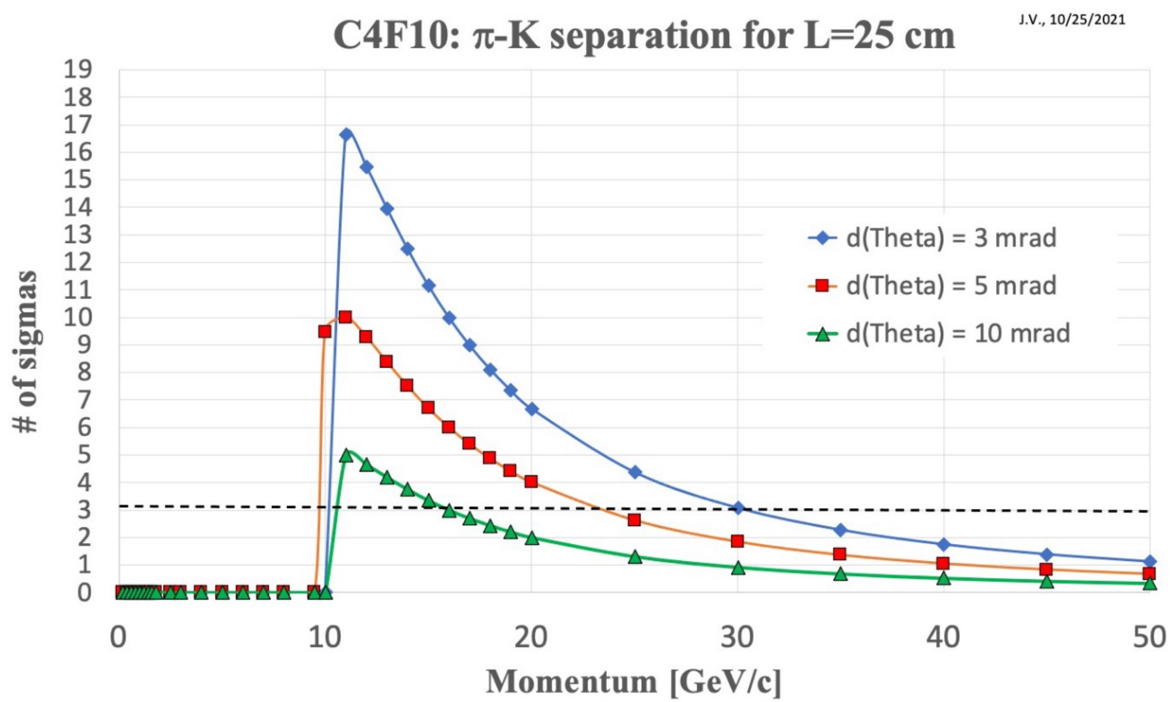
Beryllium with reflective coating

PID Performance of the Compact RICH with SiPMTs

# of sigmas = $$\frac{\theta_\pi - \theta_K}{\sigma_\theta/\sqrt{N}}$$

σ_θ is total Cherenkov angle resolution

N is number of photoelectrons per ring



If the Cherenkov error resolution is above the 5 mrad level, it will severely impact performance!

PID Performance of the Compact RICH with SiPMTs

- Smearing effects increase with magnetic field and dip angles while decrease with momenta.
  - The contribution of various effects has been estimated, see much more in the back-up slides

Single photon error source	SiD/ILD RICH detector [mrad]	SLD CRID detector [mrad]
Chromatic error	~0.9	~0.4
Pixel size error (1mm^2 - 3mm^2)	0.8 - 2.3	~0.5
Smearing effect due to magnetic field	1.5 - 2.5 B = 5 T	~0.5 B = 0.5 T
Mirror alignment	< 1	~1
Tracking angular error	< 1	~0.8 [9]
Other systematic errors	a few mrad	a few mrad
Total	**< 5**	**~ 4.3**

These results justify a full Geant 4 simulation!

Summary and Outlook (1)

- Testing **light Yukawa** coupling and, more generally, Yukawa universality is a **key physics benchmark** at future colliders
- The most stringent constraints on the **strange Yukawa** have been derived via a direct SM $\boldsymbol{h \rightarrow ss}$ search
  - The results allow to reduce the phase space for new physics down to $\boldsymbol{k_s \sim 5x\ SM}$
  - The analysis sensitivity is boosted by strange tagging in turn enabled by $\boldsymbol{\pi/K}$ **PID at high momenta**
- Next step: BSM interpretations, probe flavor violating decays or 2HDM such as H->cs ($BR \sim 0.5$, about 4 orders of magnitude larger than SM $\mathrm{h} \rightarrow ss$) or additional neutral $H \rightarrow ss$!

Summary and Outlook (2)

- **Complete re-look at Cherenkov gas detector technology**!
  - A **PID detector** added in between the tracker and the ECAL of a future detector at an e+e- machine can boost the potential of physics searches to study light Yukawas!
  - First studies show that **RICH technology with a compact design** can reach a **3sigma K/π** separation in the necessary **momentum range**
  - Evaluation of the **Cherenkov angle resolution**, and therefore reach of PID performance, has been performed (effects of chromaticity, bending of tracks, pixel size, tracking precision, noise, etc.).

- It **may be possible to accommodate a compact RICH system** while preserving the performance in tracking and calorimetry needed for physics
  - It's not just a question of space, but also of the **impact of the material** introduced between the tracker and ECAL
  - **This needs to be carefully studied**!
    - **Full simulation studies needed** to determine the precise performance, along with impact on the rest of the detector system

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"