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

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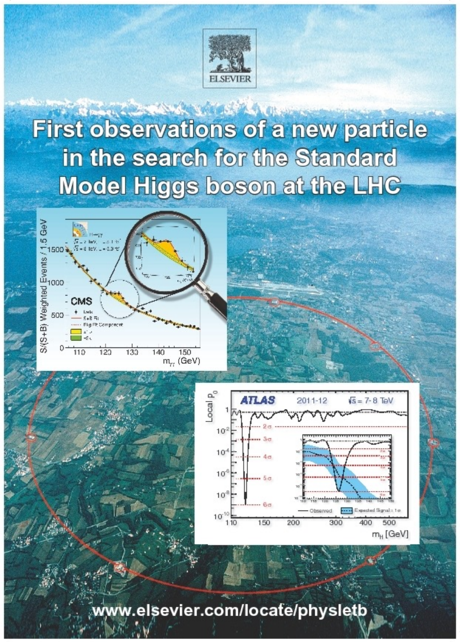
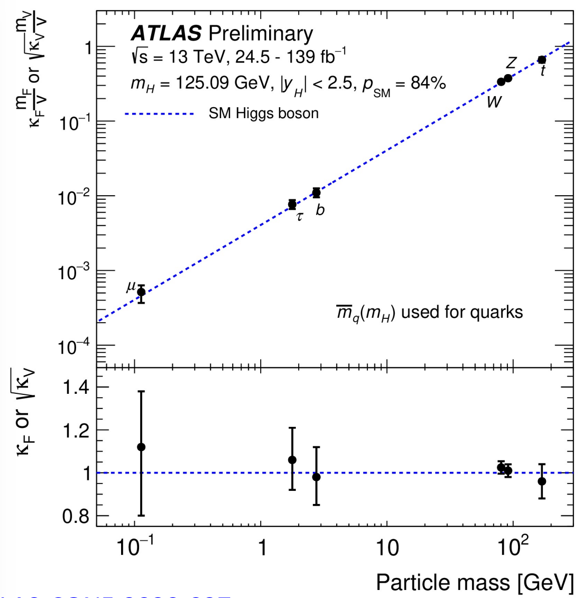
The Higgs Puzzle

Past

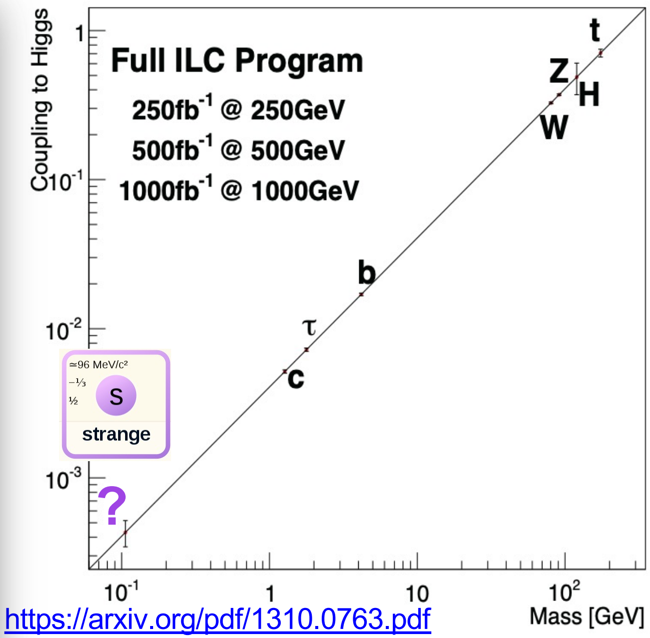


Present



ATLAS-CONF-2020-027

Future

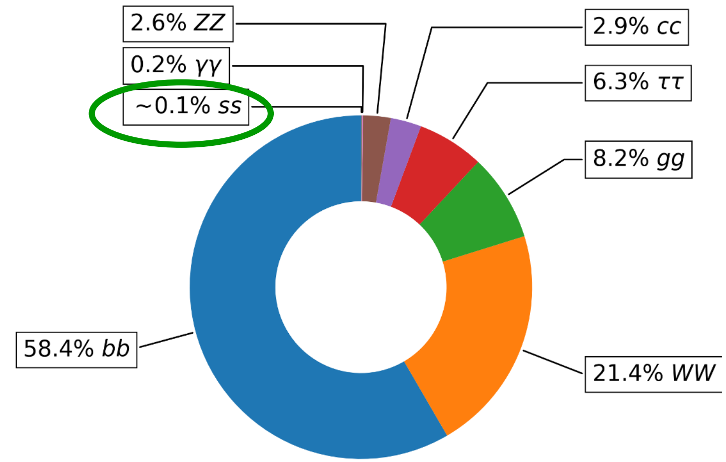


https://arxiv.org/pdf/1310.0763.pdf

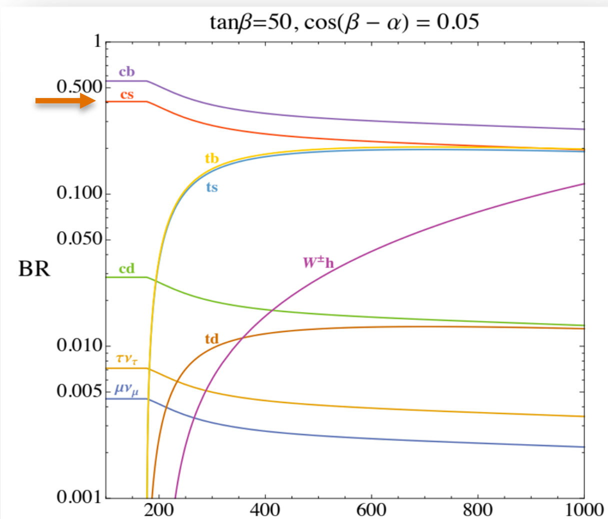
So far, only 3rd generation demonstrated…
Is Yukawa coupling really universal between families?
Could current flavour anomalies have origin in the Higgs sector?

Goals of the *StrangeTeam*

- LoI for Snowmass 2021
- Derive sensitivity to **Higgs strange Yukawa coupling**
- 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
- Most of the above was already discussed in an FCC physics meeting
- Provide **inputs to detector instrumentation**



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



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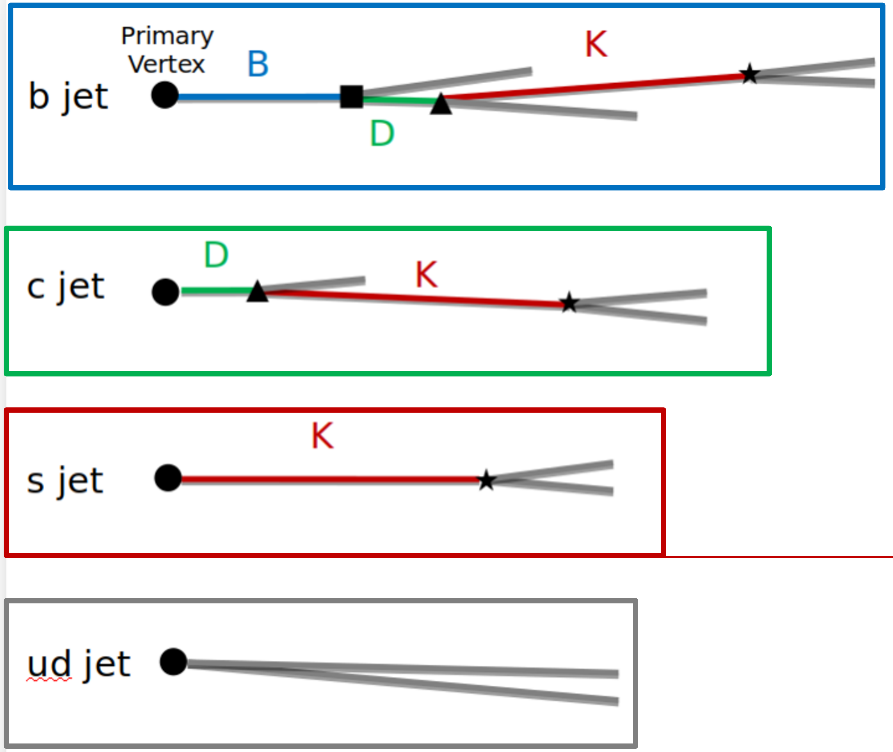
Experimental Handles for Flavour Tagging

T. Tanabe's presentation



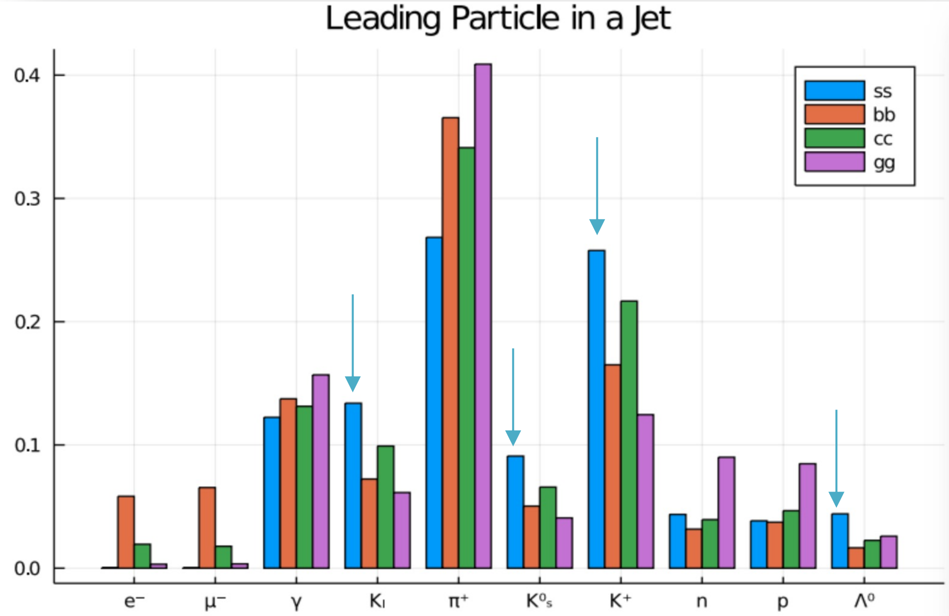
	# of secondary vertices (excluding V^0)	# of strange hadrons ($K^{\pm}$, K_L^0, K_S^0, Λ^0)
b	2	≥1
c	1	≥1
s	0	≥1
ud	0	0

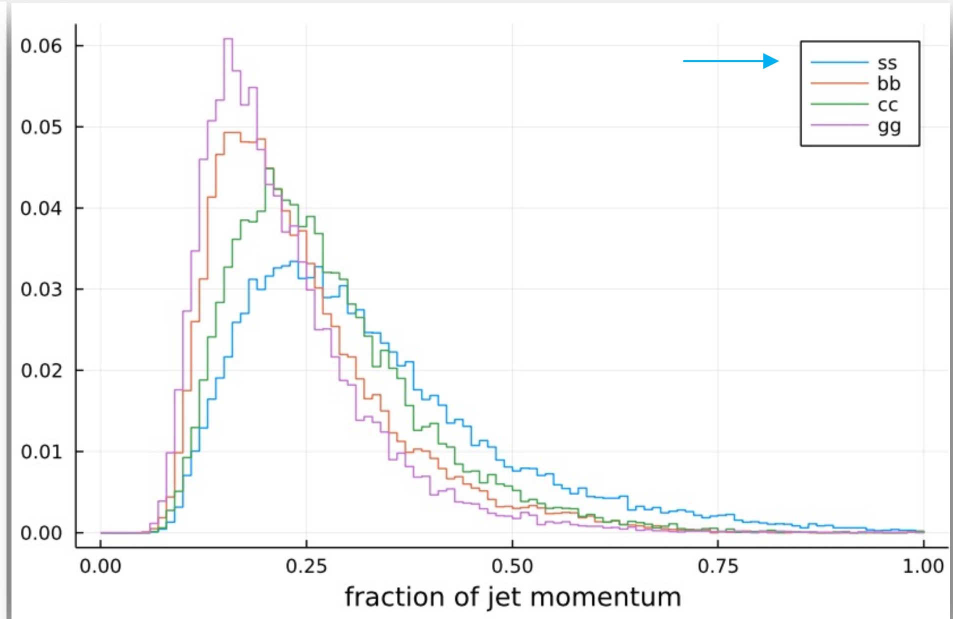
Strange Hadron reconstruction
- $K^{\pm}$ [PID]
- $K_S^0 \rightarrow \pi^+\pi^-$ [Vertex] (BF ~69.2%)
- $\Lambda^0 \rightarrow p\pi^-$ [Vertex] (BF ~64%)
- K_L^0 [Particle Flow]

…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

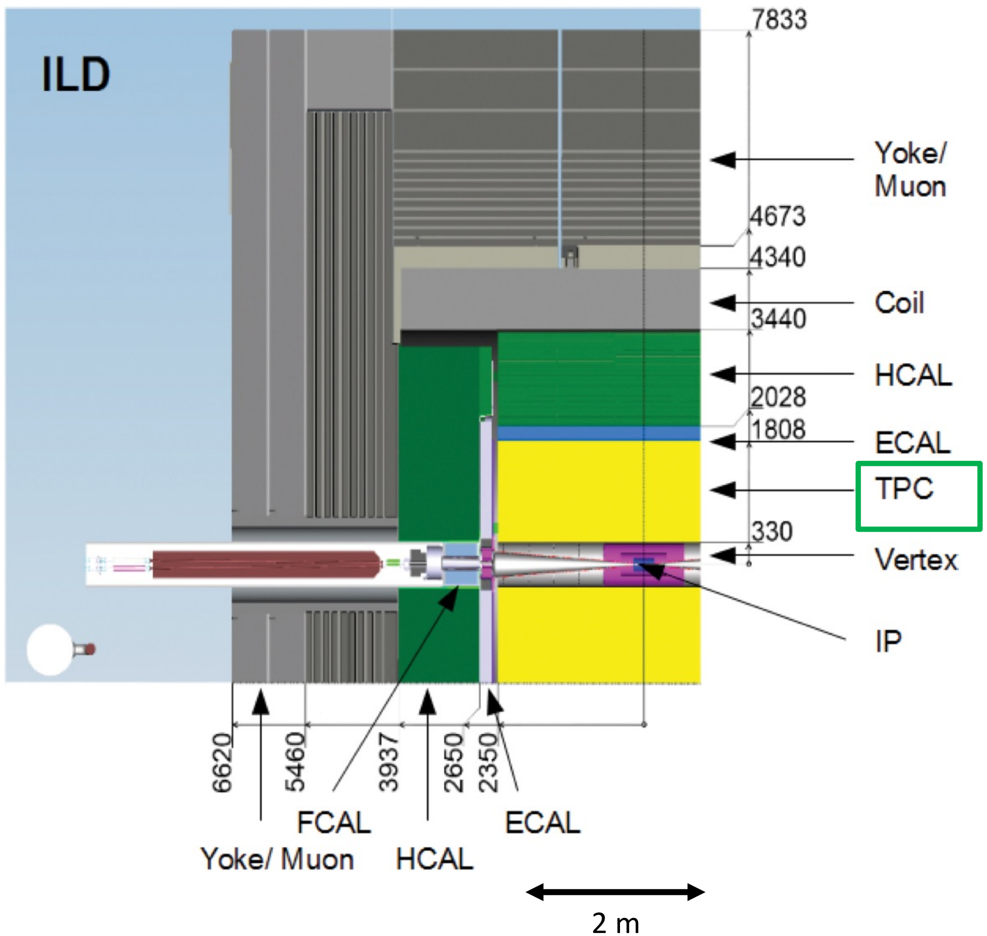
J. Strube's studies





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: $h \rightarrow s\bar{s}$ analysis with ILD @ the ILC



3.5 T

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

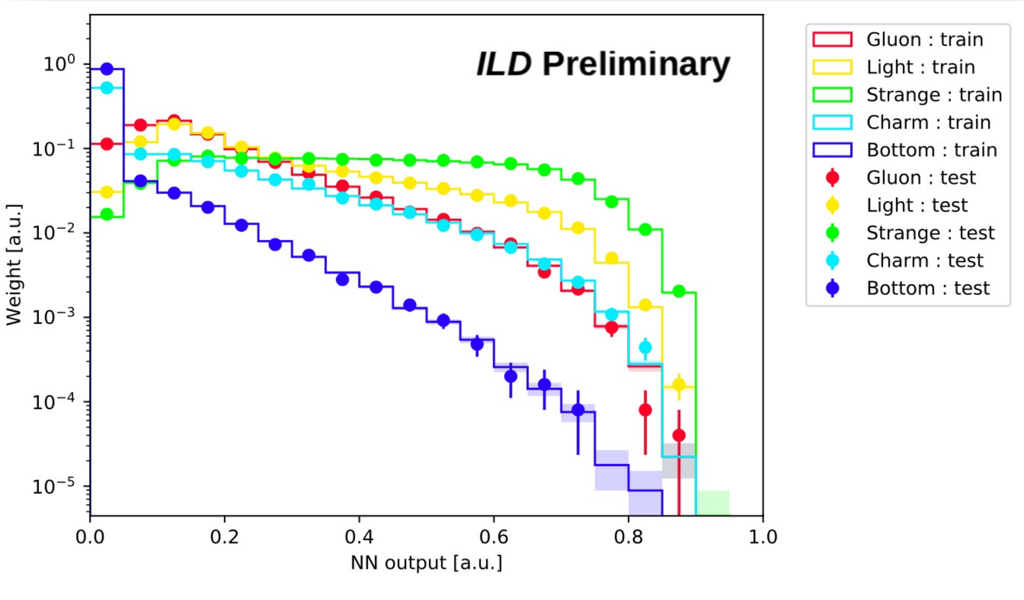
σ_H @ $\sqrt{250}\text{GeV} \sim 200$ fb

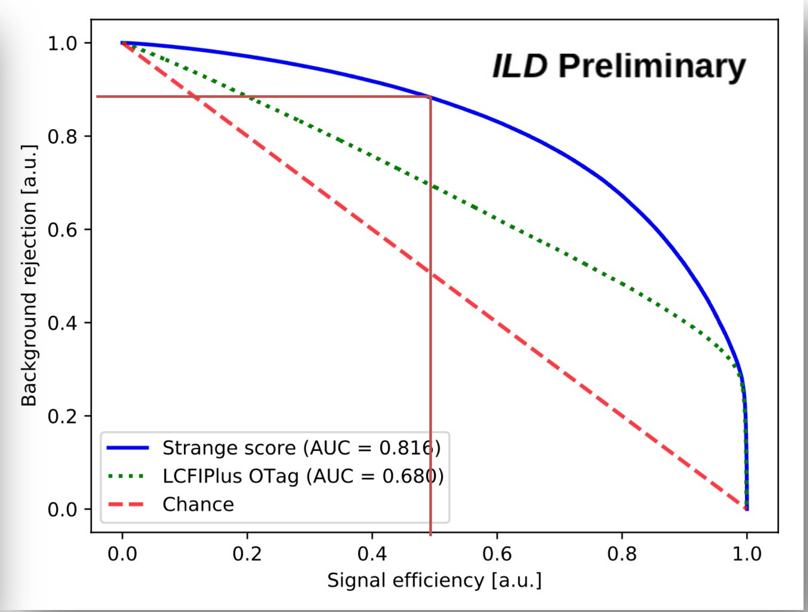
- 2000 fb^{-1} collected by the ILC after 10 years
- → 400k Higgs out of which only about 80 will decay to strange quarks

But of course, new physics boosts these numbers!

Performance: s and u/d jets

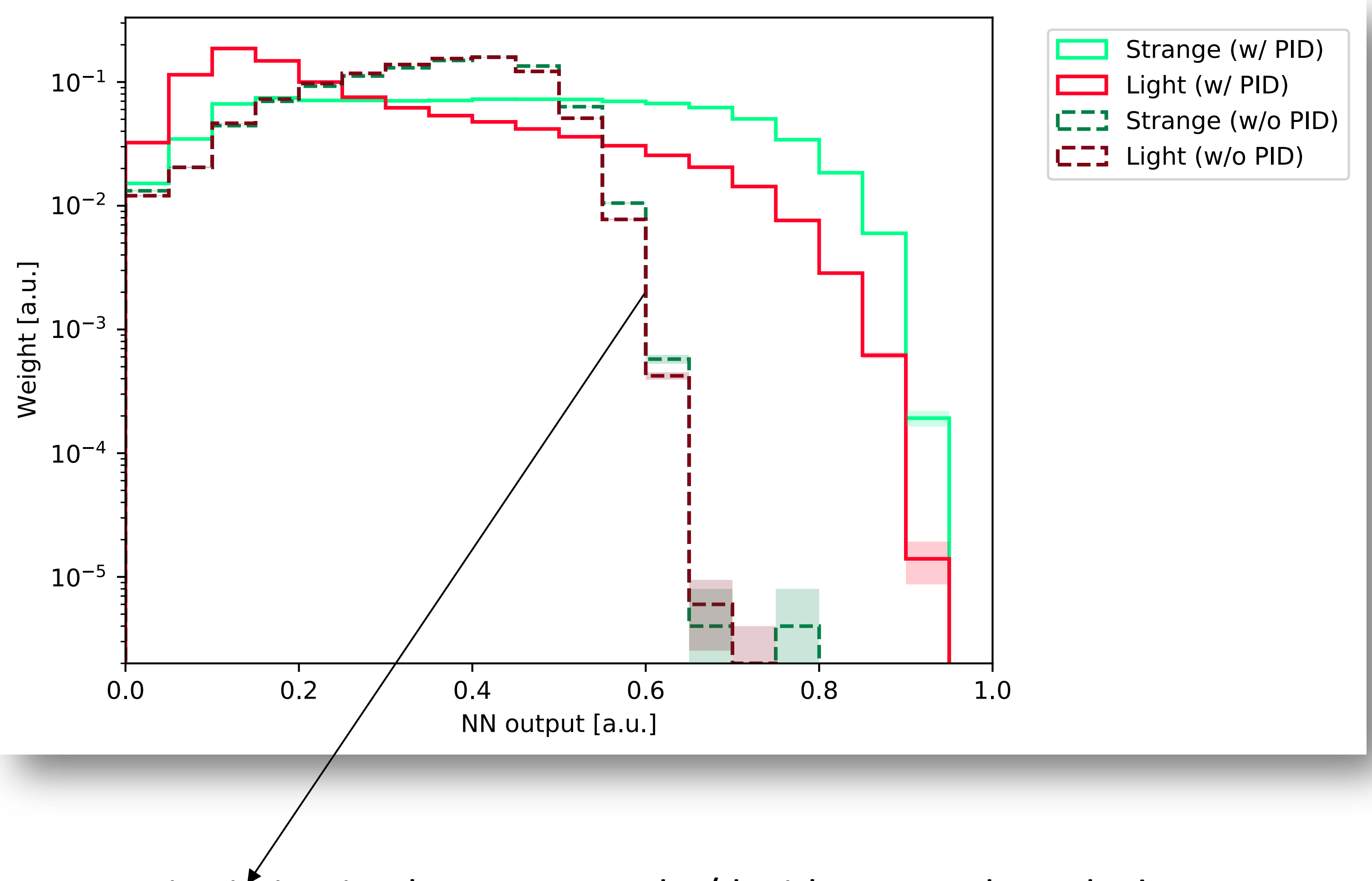
- Use a NN-based tagger for classifying jet-flavour, train on $(Z \rightarrow inv)(H \rightarrow qq/gg)$ samples and include **per-jet level inputs** & variables on the **10 leading particles** in each jet (**including PDG-based PID!**)





- Separation of *s* and *u/d* is **possible** with using truth likelihoods
- Also **good discrimination of *s* jets from *g* jets** – here, $N_{\text{particles}}$ 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)

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!

Analysis overview & results

See also M. Basso's talk at Higgs2021

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

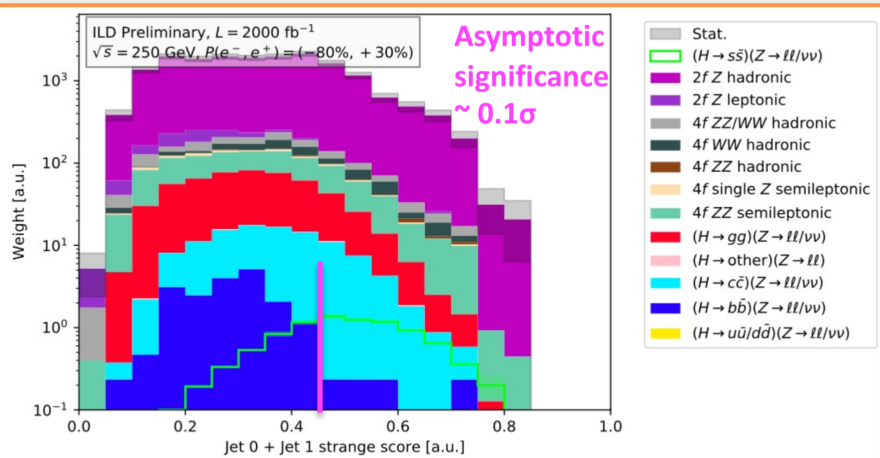
Most powerful cut on M_{jj} (see extra-slides for more details)

Build Signal discriminant

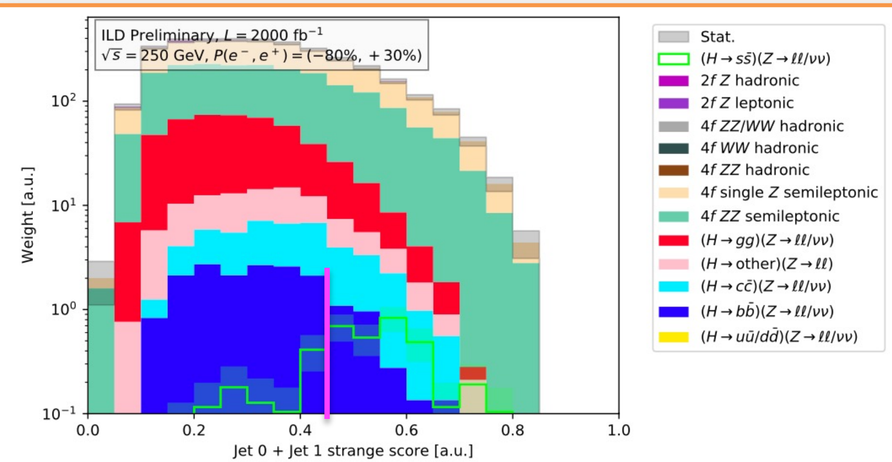
Sum of leading and sub-leading strange-jet score

s-Yukawa coupling

Probe various BSM regimes



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



(b) $Z \to \ell\ell$ channel

Analysis overview & results

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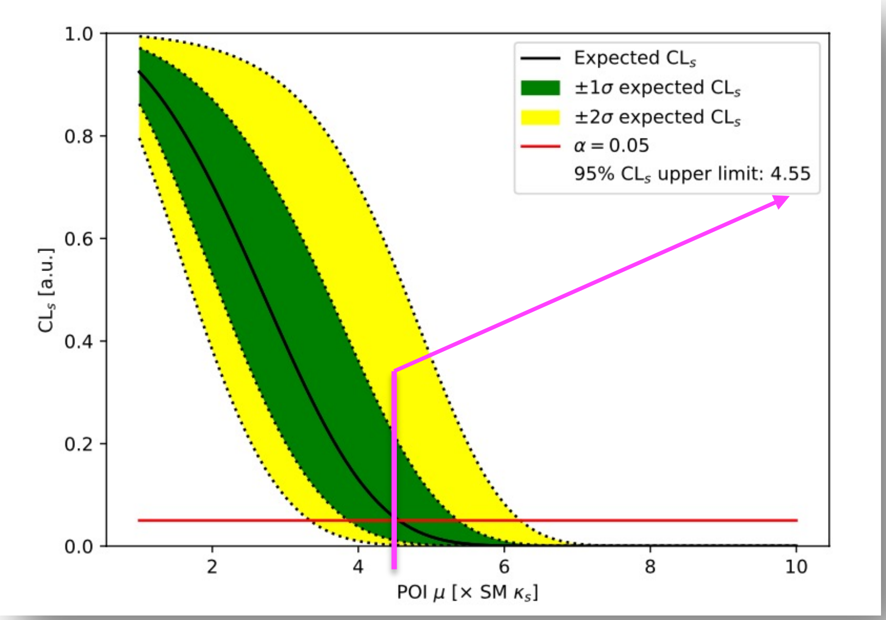


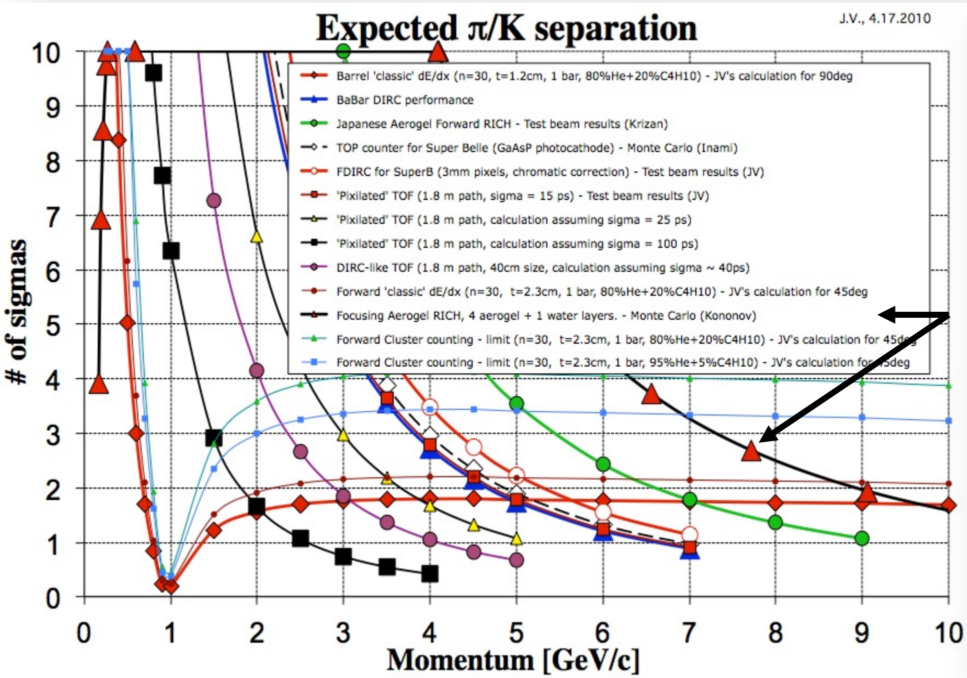
Most stringent constraints on k_s derived so far!

- 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)



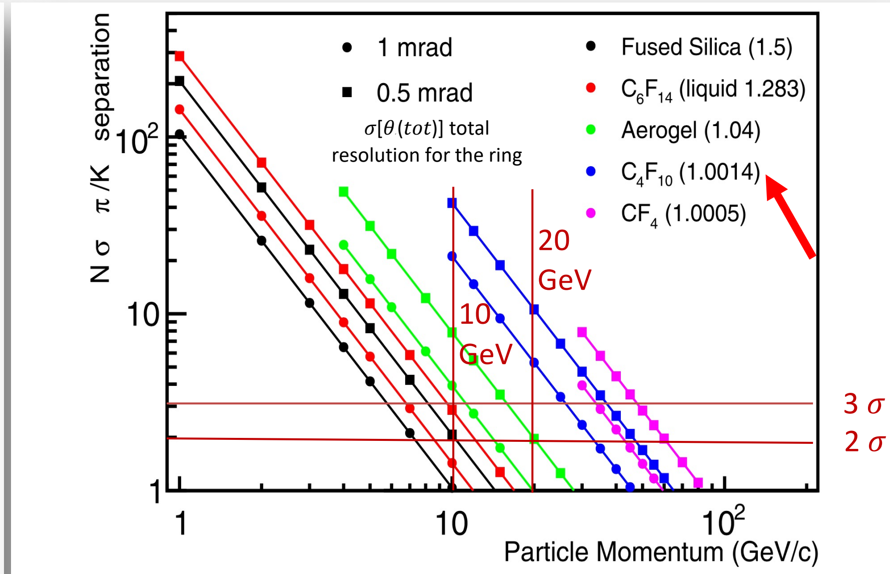


Fig. 2. The number standard deviations in $\pi - K$ separation versus momentum for different radiators and two different Cherenkov angle resolutions.

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…

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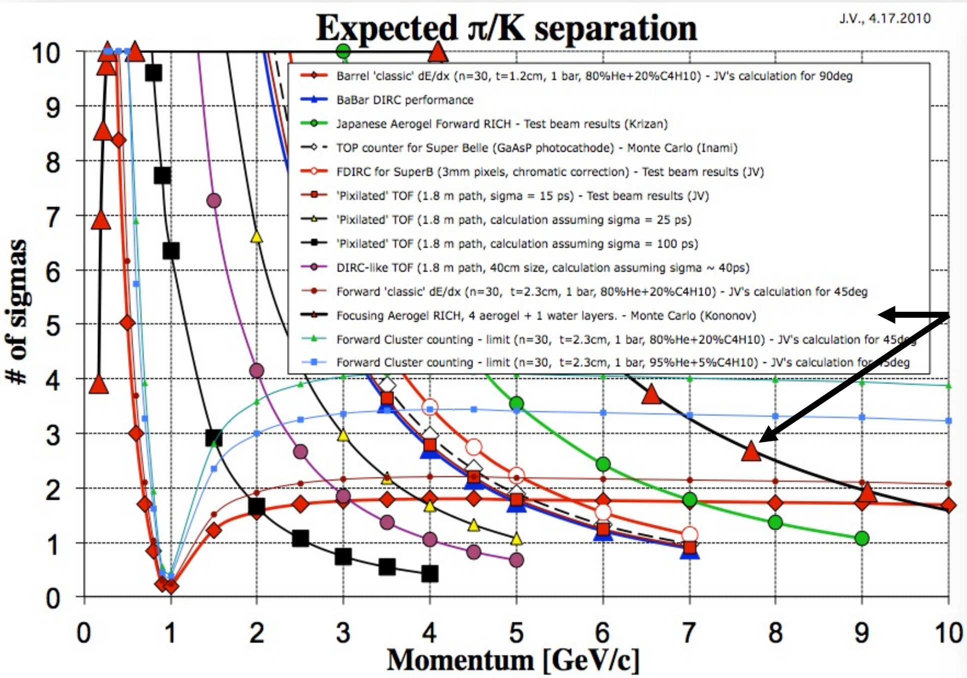

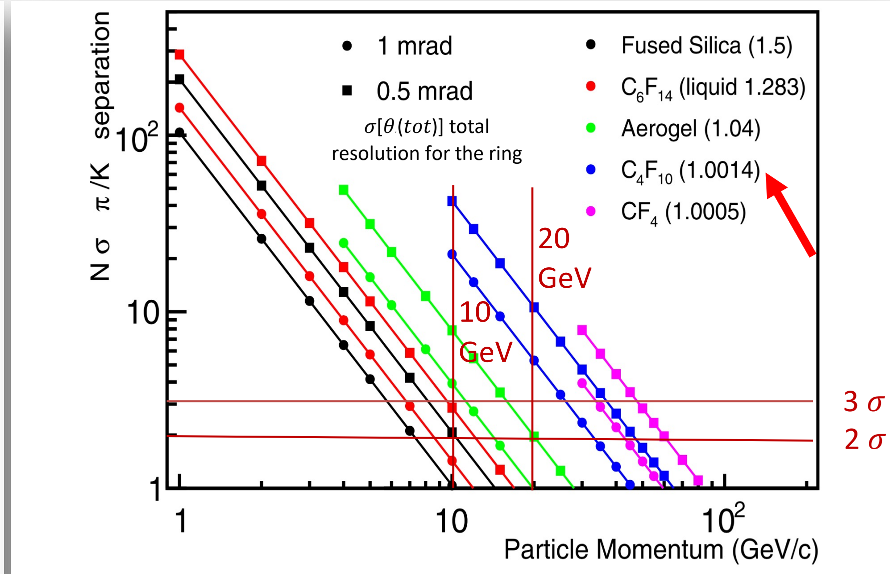

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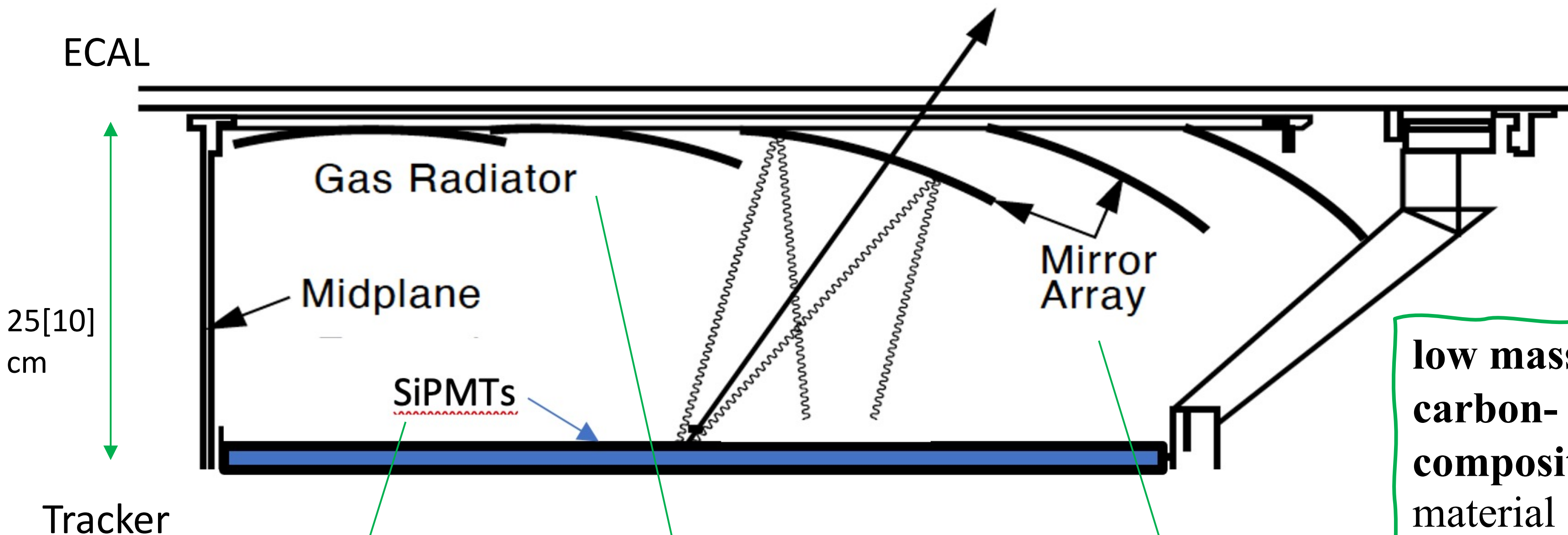
Historical Note:
CRID@SLD used a design with two radiators: a liquid layer of C_6F_{14} working in proximity focusing and a gas volume filled with C_4F_{10}

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 $\mathbf{C_4F_{10}}$ at 1 bar (boiling point -1.9 C at 1 bar, good refraction index)

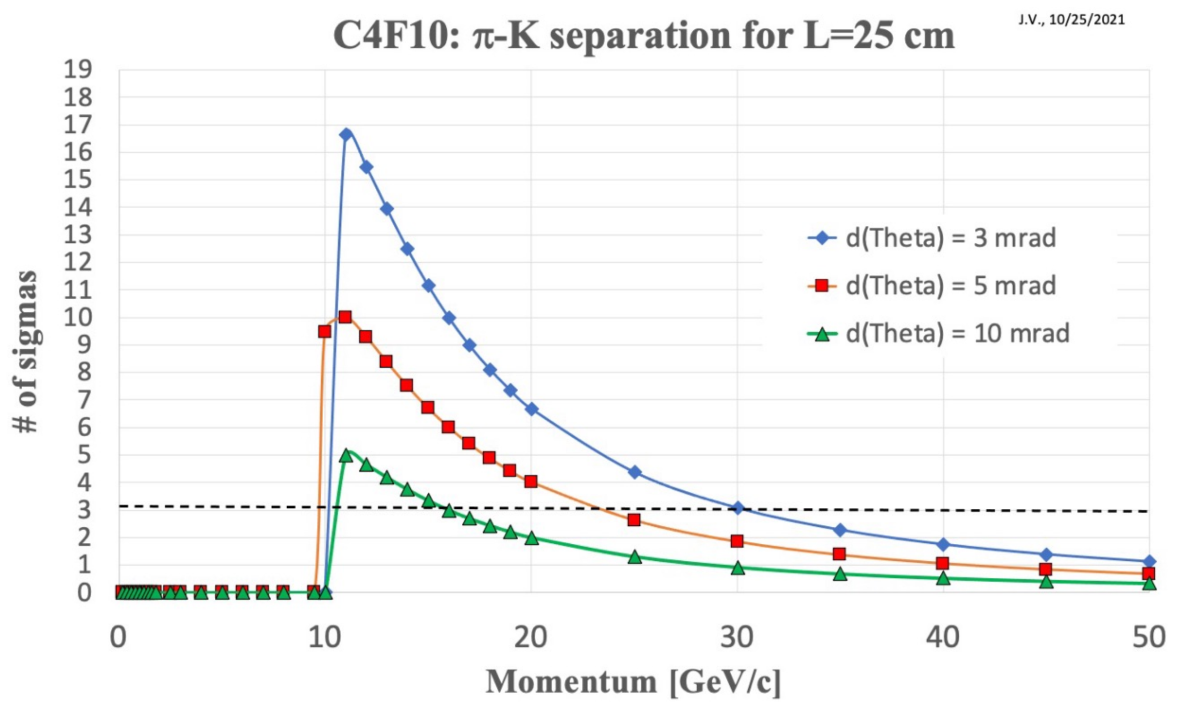
Beryllium with reflective coating

PID Performance of the Compact RICH with SiPMTs

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

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

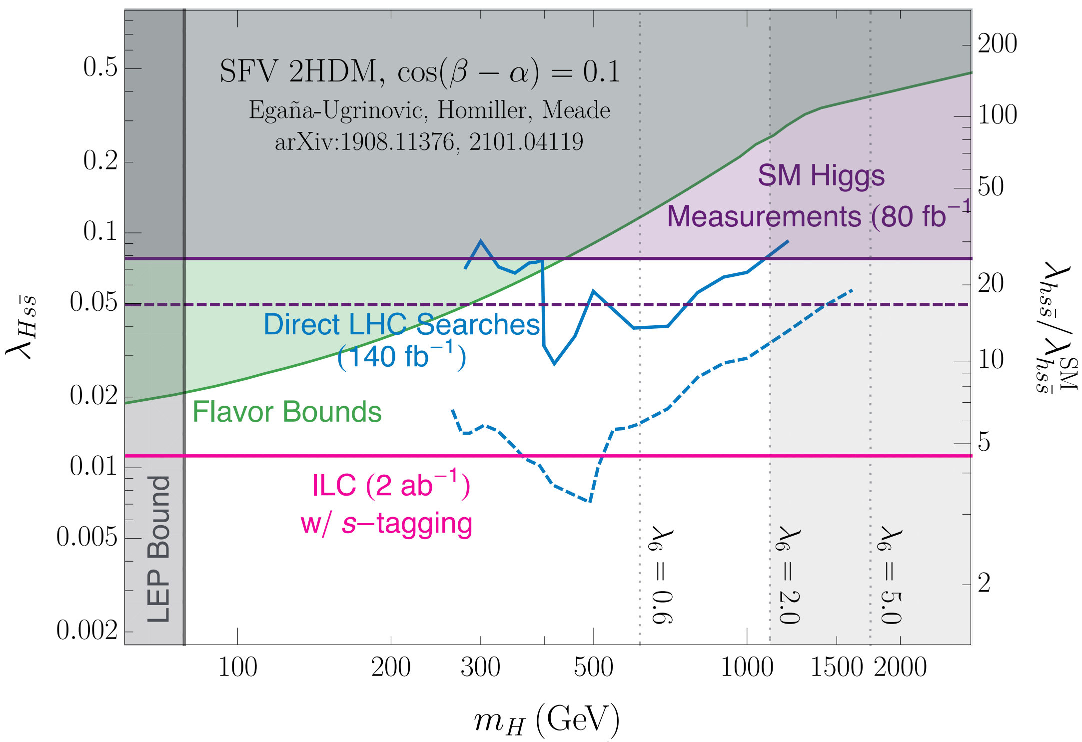
- Smearing effects increase with magnetic field and dip angles while decrease with momenta.
  - The contribution of various effects has been estimated, see much more in the back-up slides

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"

Thanks for your attention!

Valentina Cairo