# Transverse polarization and the electron Yukawa at an FCC


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work with K. Simsek et al, in progress

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# Introduction

- Discussion of Higgs couplings status and FCC projections
- Previous work on the electron Yukawa coupling
- Introduction to transverse polarization observables at the FCC
- Opportunities in the bb and WW final states
- **This is work in progress.** Happy to get feedback and learn from experts!

# Higgs couplings at future e+e- colliders

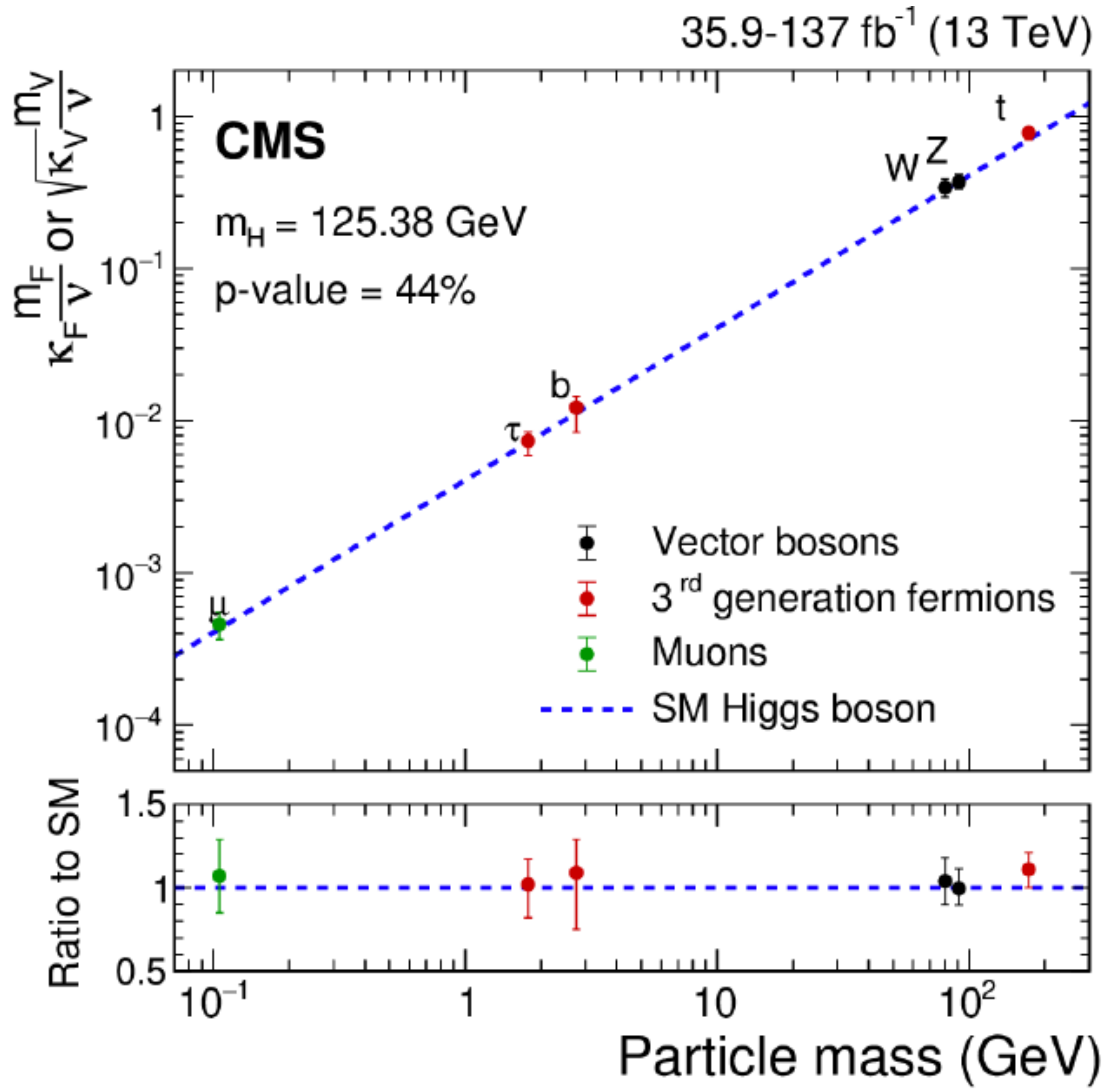
- The measurement of the Higgs couplings is a primary goal of future high-energy experiments. e+e- colliders will play a central role in this study.

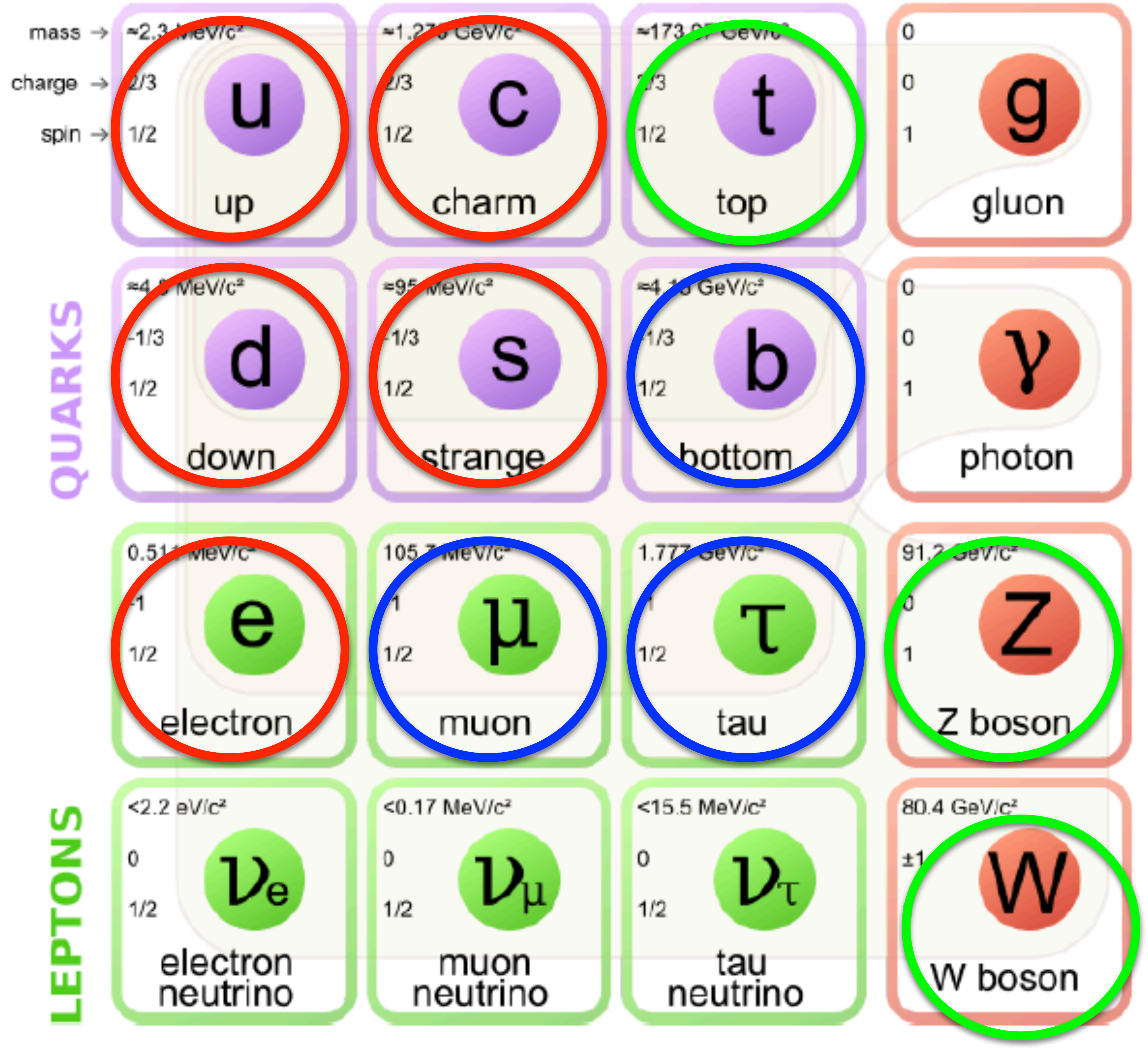
| | ILC | | FCC-ee | |
|---|---|---|---|---|
| coupling | 2/ab-250 pol. | +4/ab-500 pol. | 5/ab-250 unpol. | +1.5/ab-350 unpol. |
| hZZ | 0.50 | 0.35 | 0.41 | 0.34 |
| hWW | 0.50 | 0.35 | 0.42 | 0.35 |
| $hb\bar{b}$ | 0.99 | 0.59 | 0.72 | 0.62 |
| $h\tau\tau$ | 1.1 | 0.75 | 0.81 | 0.71 |
| $hgg$ | 1.6 | 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 | - | - |
| $\Gamma_{tot}$ | 2.3 | 1.6 | 1.6 | 1.4 |
| $\Gamma_{inv}$ | 0.36 | 0.32 | 0.34 | 0.30 |
| $\Gamma_{other}$ | 1.6 | 1.2 | 1.1 | 0.94 |

Dawson et al, 2209.07510

# Measuring fermion Yukawa couplings

- An important aspect of this program is determining whether the single Higgs boson found so far gives mass to all elementary fermions.




Some Yukawa interactions known well; some known with large errors; many are completely unmeasured

# Measuring fermion Yukawa couplings

- Ideas exist to measure light-quark couplings using ee→ZH production and multivariate techniques to separate cc, ss, gg, bb final states.

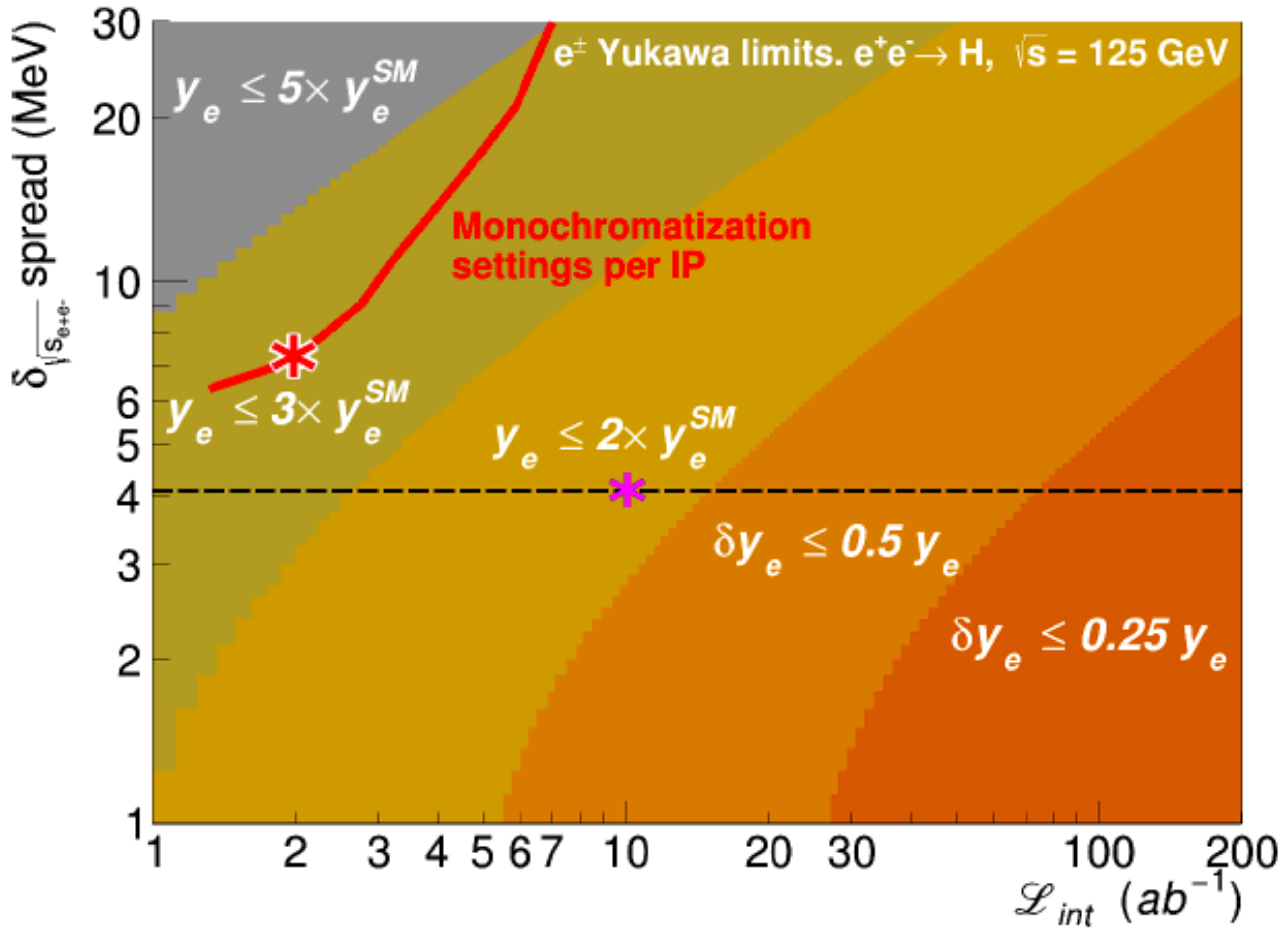
| Final state | Z(ll)H(jj) [%] | Z(vv)H(jj) [%] | Z(jj)H(jj) [%] | Comb. [%] |
|---|---|---|---|---|
| H → bb | 0.81 | 0.36 | 0.3 | 0.22 |
| H → cc | 4.93 | 2.6 | 3.5 | 1.92 |
| H → gg | 2.73 | 1.1 | 2.4 | 0.94 |
| H → ss | 410 | 137 | 436 | 124 |

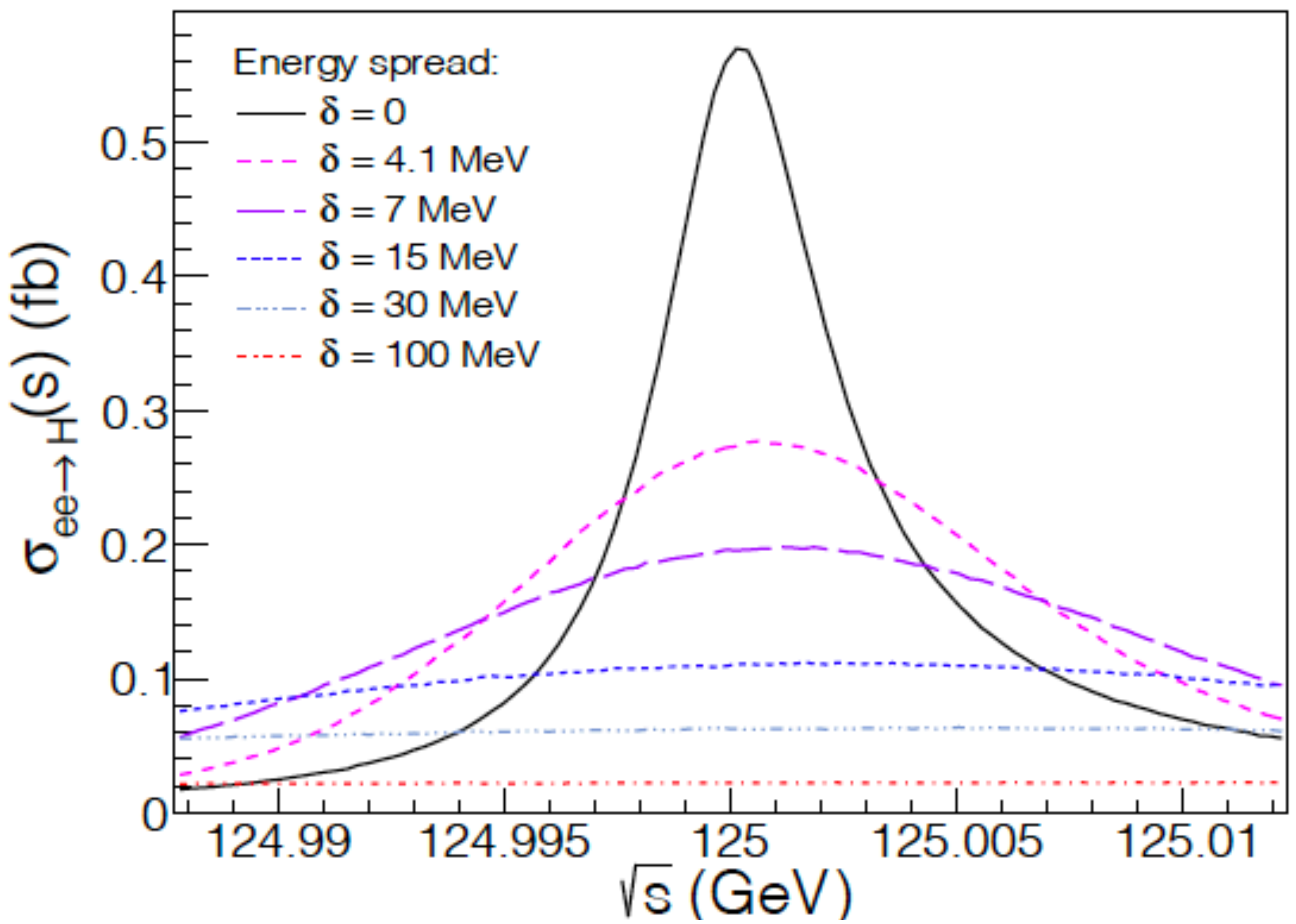
**Z(ll)H(XX):** neural to categorize in H flavour decay modes; fit on recoil distribution
**Z(vv)H(XX):** neural to categorize in H flavour decay modes; 2D fit on visible and missing mass
**Z(qq)H(qq):** multi-jet environment – categorization in flavours, 2D fit on recoil and dijet system

from J. Eysermans, talk at 7th FCC workshop (2024)

# The electron Yukawa at the FCC

- The most inaccessible of the Yukawa couplings studied so far is the electron coupling. Requires exquisite control over beam spread and combination of many channels.




| $H \to gg$ | $H \to WW^* \to \ell\nu\, 2j;\ 2\ell\, 2\nu;\ 4j$ | $H \to ZZ^* \to 2j\, 2\nu;\ 2\ell\, 2j;\ 2\ell\, 2\nu$ | $H \to b\bar{b}$ | $H \to \tau_{had}\tau_{had};\ c\bar{c};\ \gamma\gamma$ | Combined |
|---|---|---|---|---|---|
| $1.1\sigma$ | $(0.53 \otimes 0.34 \otimes 0.13)\sigma$ | $(0.32 \otimes 0.18 \otimes 0.05)\sigma$ | $0.13\sigma$ | $< 0.02\sigma$ | $1.3\sigma$ |

d'Enterria, Poldaru, Wojcik 2107.02686

# The electron Yukawa at the FCC

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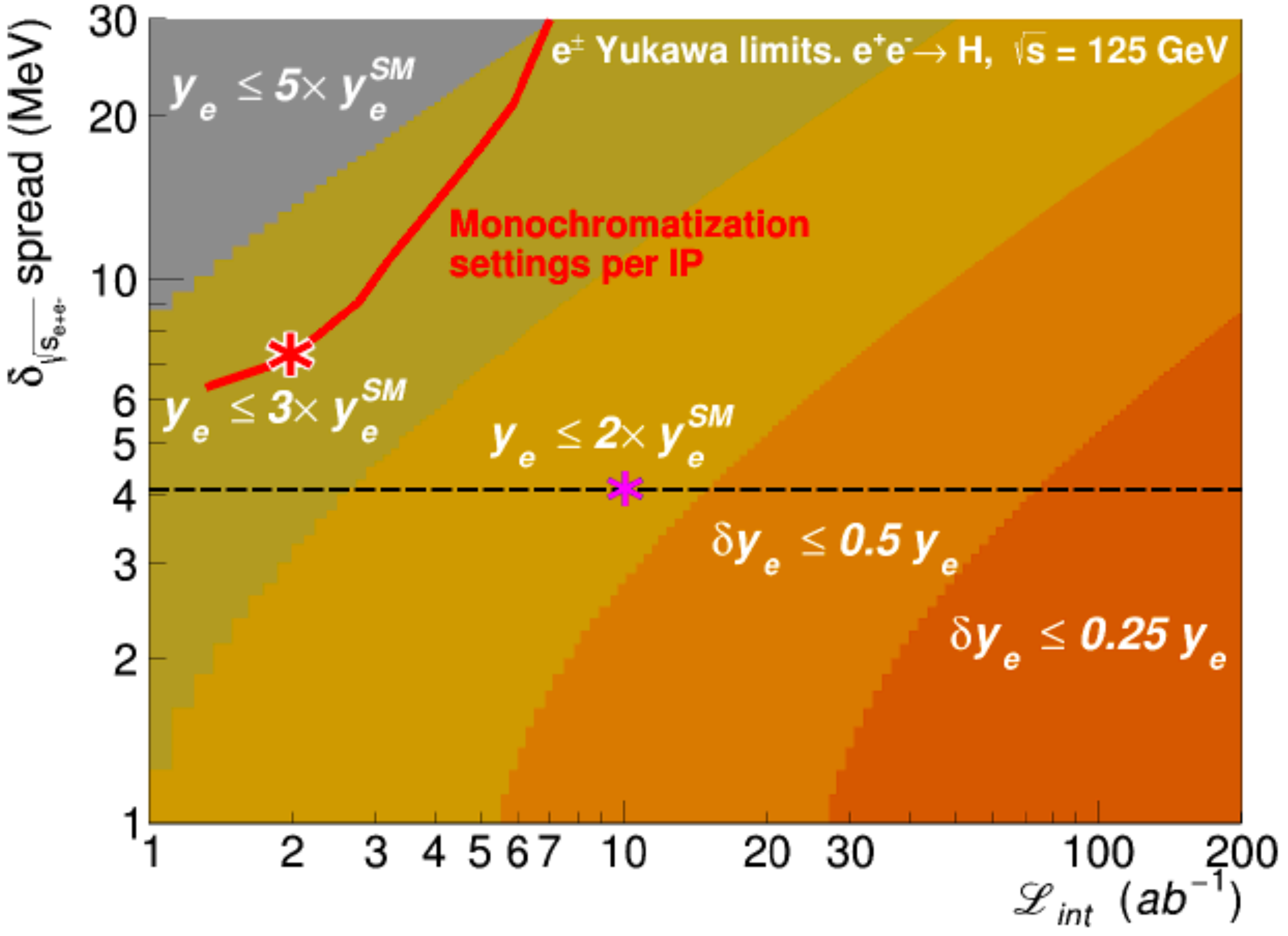
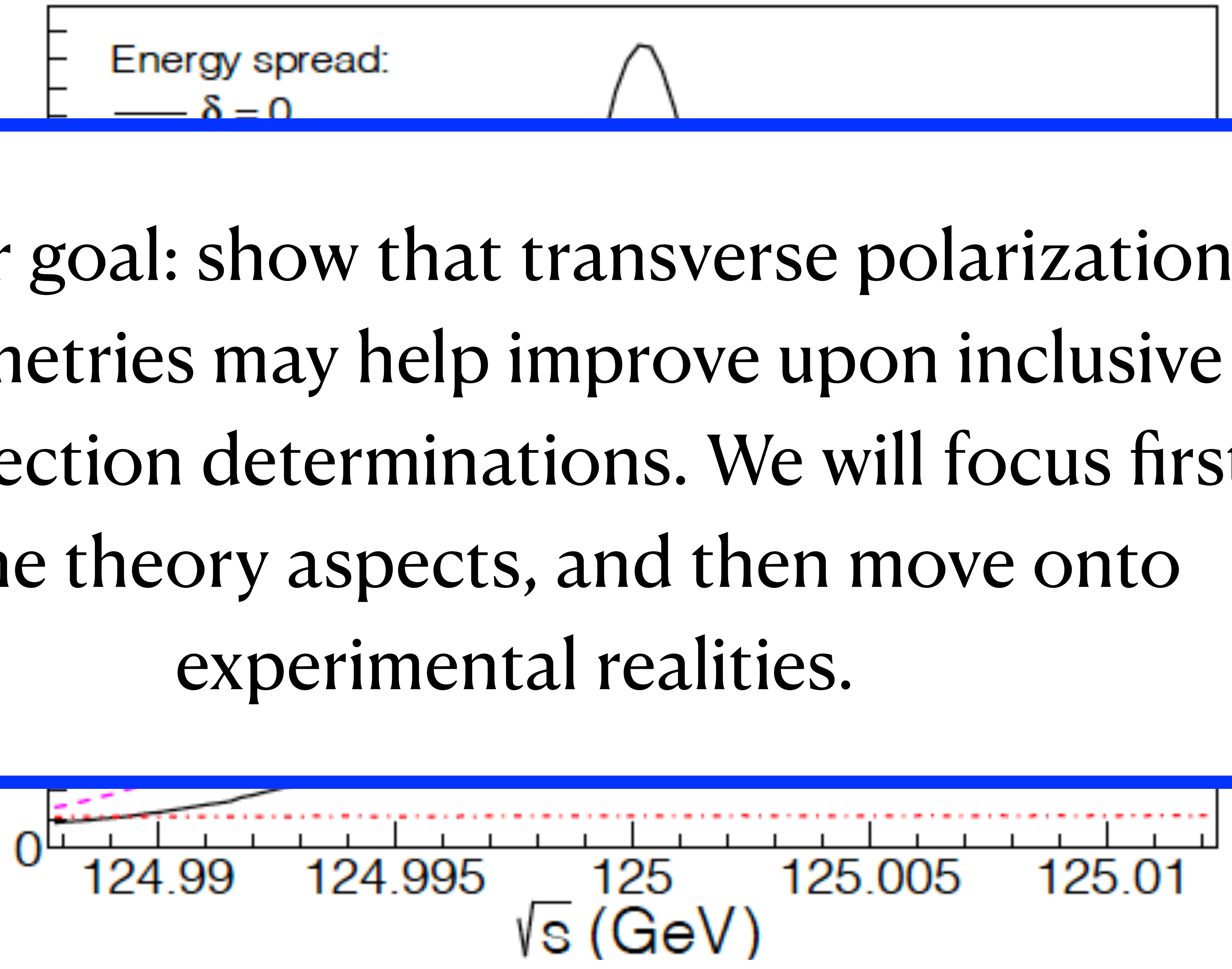


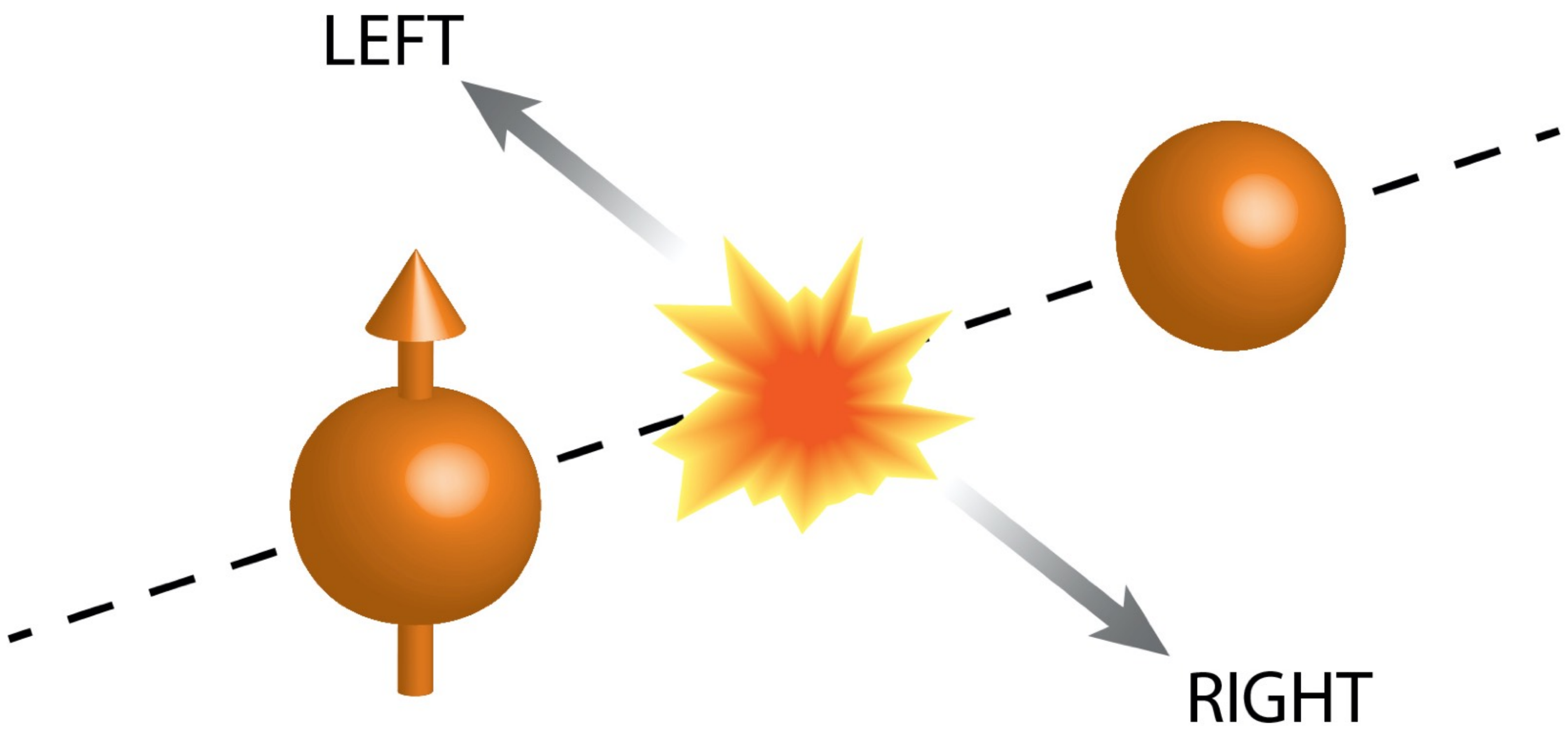

Our goal: show that transverse polarization asymmetries may help improve upon inclusive cross section determinations. We will focus first on the theory aspects, and then move onto experimental realities.

| $H \to gg$ | $H \to WW^* \to \ell\nu\, 2j;\ 2\ell\, 2\nu;\ 4j$ | $H \to ZZ^* \to 2j\, 2\nu;\ 2\ell\, 2j;\ 2\ell\, 2\nu$ | $H \to b\bar{b}$ | $H \to \tau_{had}\tau_{had};\ c\bar{c};\ \gamma\gamma$ | Combined |
|---|---|---|---|---|---|
| $1.1\sigma$ | $(0.53 \otimes 0.34 \otimes 0.13)\sigma$ | $(0.32 \otimes 0.18 \otimes 0.05)\sigma$ | $0.13\sigma$ | $< 0.02\sigma$ | $1.3\sigma$ |

d'Enterria, Poldaru, Wojcik 2107.02686

# Transverse spin asymmetries

- The idea is to use transverse spin asymmetries to increase the sensitivity to the electron Yukawa coupling. We consider the following observables in our study.




$$A = \frac{N}{D}$$

Electron polarized, positron unpolarized ($SP^0$):

$$N = \frac{1}{2}(\sigma^{+0} - \sigma^{-0})$$
$$D = \frac{1}{2}(\sigma^{+0} + \sigma^{-0})$$

Electron transversely polarized, positron longitudinally polarized (DP):

$$N = \frac{1}{4}(\sigma^{++} - \sigma^{+-} - \sigma^{-+} + \sigma^{--})$$
$$D = \frac{1}{4}(\sigma^{++} + \sigma^{+-} + \sigma^{-+} + \sigma^{--})$$

Electron transversely polarized, positron longitudinally polarized ($SP^+$):

$$N = \frac{1}{2}(\sigma^{++} - \sigma^{-+})$$
$$D = \frac{1}{2}(\sigma^{++} + \sigma^{-+})$$

Electron transversely polarized, positron longitudinally polarized ($SP^-$):

$$N = \frac{1}{2}(\sigma^{+-} - \sigma^{--})$$
$$D = \frac{1}{2}(\sigma^{+-} + \sigma^{--})$$

# Transverse spin asymmetries

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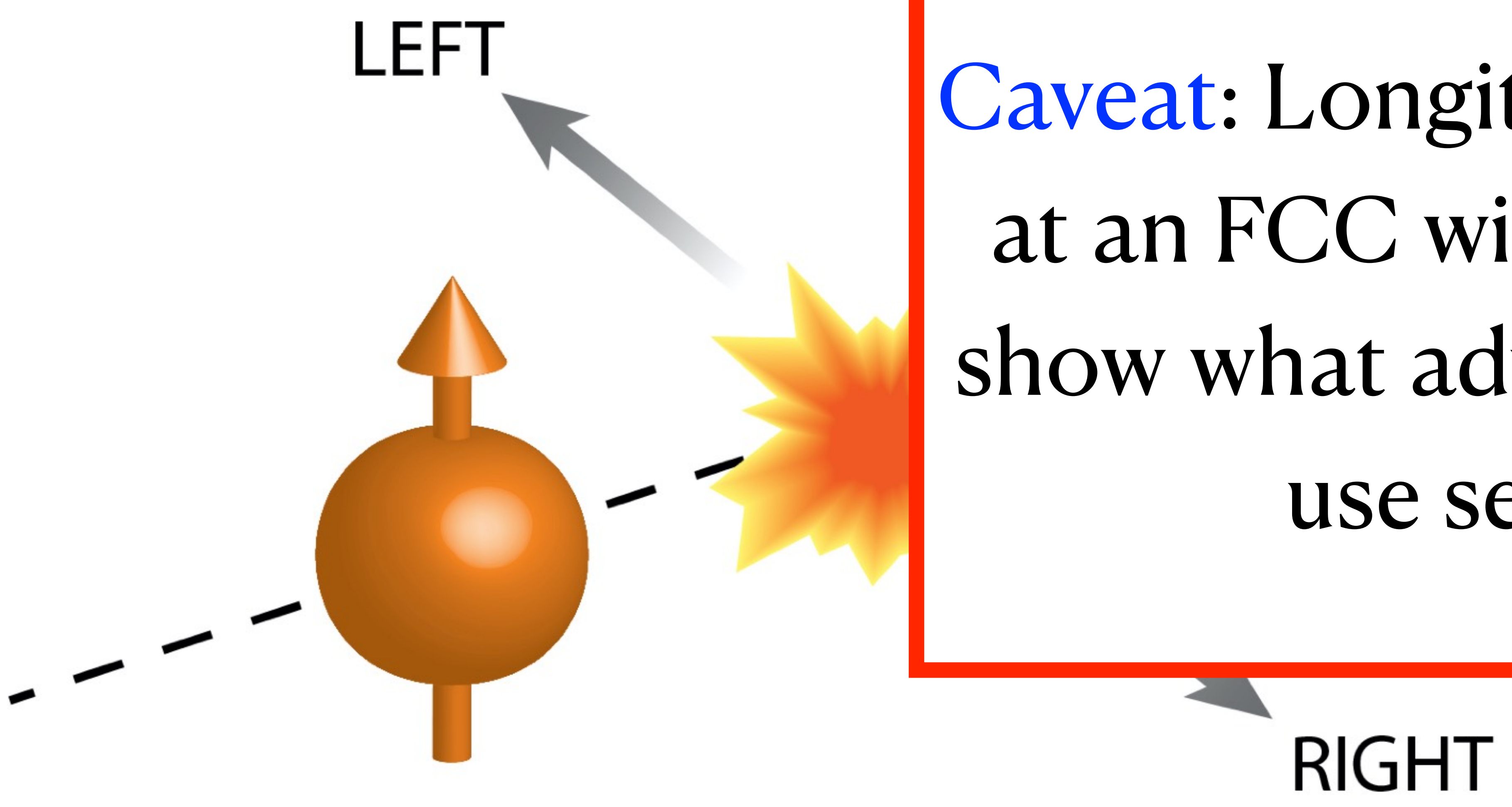



Caveat: Longitudinal polarization is difficult to obtain at an FCC without a decrease in luminosity. We will show what advantages it can provide, and attempt to use semi-realistic parameter choices.

$$N = \frac{1}{2}(\sigma^{+0} - \sigma^{-0})$$

$$\frac{1}{2}(\sigma^{+0} + \sigma^{-0})$$

$$- \sigma^{+-} - \sigma^{-+} + \sigma^{--})$$

$$+ \sigma^{+-} + \sigma^{-+} + \sigma^{--})$$

polarized, positron longitudinally polarized (SP+):

$$N = \frac{1}{2}(\sigma^{++} - \sigma^{-+})$$

$$D = \frac{1}{2}(\sigma^{++} + \sigma^{-+})$$

Electron transversely polarized, positron longitudinally polarized (SP-):

$$N = \frac{1}{2}(\sigma^{+-} - \sigma^{--})$$

$$D = \frac{1}{2}(\sigma^{+-} + \sigma^{--})$$

$$A = \frac{N}{D}$$

# Theoretical structure of transverse SSAs

- The structure of transverse SSAs is dictated by the discrete symmetries of the SM.

Recall the transformations of quantum operators under parity and time-reversal:

$$P\, c a^s_{\vec{p}}\, P^{-1} = c a^s_{-\vec{p}}$$
$$T\, c a^s_{\vec{p}}\, T^{-1} = c^* a^{-s}_{-\vec{p}}$$

c is a c-number; time reversal is an anti-linear operator

Consider the process $e^- e^+ \to bb$ as an example

It is useful to also consider a linear transformation related to time-reversal invariance, often called "naive" time-reversal (Sivers 1996):

$$A_t\, c a^s_{\vec{p}}\, A_t^{-1} = c a^{-s}_{-\vec{p}}$$

For transverse spin $S_T$, we can form the following structures in the asymmetry which can contribute to the asymmetry:

| | |
|---|---|
| $S_T \cdot p_q$ | ⇒P odd, $A_t$ even |
| $\epsilon(p_e, p_{\bar{e}}, p_q, S_T)$ | ⇒P even, $A_t$ odd |

# Theoretical structure of transverse SSAs

- The structure of transverse SSAs is dictated by the discrete symmetries of the SM.

Two key points:

$$S_T \cdot p_q \; = \; = \beta_q \frac{\sqrt{s}}{2} \sin(\theta) \cos(\phi),$$

$$\epsilon(p_e, p_{\bar{e}}, p_q, S_T) \; = \; -\beta_e \beta_f \frac{s^{3/2}}{4} \sin(\theta) \sin(\phi)$$

1. These two structures have different azimuthal dependence (orientation between final-state bottom quark and transverse spin direction); they can be separated by weighting the final-state phase-space integral

$S_T \cdot p_q$ ⇒P odd, $A_t$ even

$\epsilon(p_e, p_{\bar{e}}, p_q, S_T)$ ⇒P even, $A_t$ odd

2. To get a structure odd under $A_t$ we need an imaginary part in an amplitude. At tree-level this can only come when we are on a particle resonance

$$\frac{1}{s - M^2 + iM\Gamma}$$

# Application to the ee→bb process

- Study the structure of the asymmetry numerator (DP in this example). Three diagrams contribute at tree-level: s-channel photon, Z-boson, and Higgs exchange.

$$N = \frac{1}{2s}\int d\text{LIPS}\left\{\frac{R_{\gamma\gamma}}{s^2} + \frac{R_{ZZ}}{(s-M_Z^2)^2} + \frac{R_{\gamma Z}}{s(s-M_Z^2)} + \frac{R_{\gamma H}(s-M_H^2)}{s[(s-M_H^2)^2+M_H^2\Gamma_H^2]} + \frac{R_{ZH}(s-M_H^2)+I_{ZH}M_H\Gamma_H}{(s-M_Z^2)[(s-M_H^2)^2+M_H^2\Gamma_H^2]}\right\}$$

$$\begin{aligned}
R_{\gamma\gamma} &= 96e^4Q_e^2Q_q^2m_e(S_T\cdot p_q)(t-u)\\
R_{ZZ} &= 96m_e(S_p\cdot p_b)g_Z^4g_{ve}^2(g_{vq}^2+g_{aq}^2)(t-u)+192m_e(S_T\cdot p_q)g_Z^4g_{ve}g_{ae}g_{vq}g_{aq}s\\
R_{\gamma Z} &= 192e^2g_Z^2Q_eQ_qm_e(S_T\cdot p_b)g_{ve}g_{vq}(t-u)+96e^2g_Z^2Q_eQ_um_e(S_p\cdot p_q)g_{ae}g_{aq}s\\
R_{\gamma H} &= -96e^2Q_eQ_qy_ey_q(S_T\cdot p_q)m_q\\
R_{ZH} &= -96g_Z^2g_{ve}g_{vq}y_ey_q(S_T\cdot p_q)s\\
I_{ZH} &= -192g_Z^2g_{ae}g_{vq}y_ey_qm_q\epsilon(p_e,p_{\bar{e}},p_q,S_T).
\end{aligned}$$

- Comes from the imaginary part of the Higgs propagator and is enhanced by a factor of $\mathbf{M_H/\Gamma_H}$.
- All terms are suppressed **linearly** by the electron mass; this structure is directly proportional to the electron Yukawa couplings
- Can be isolated due to its different azimuthal structure, which follows from the discussion on the previous slide

# Application to the ee→bb process

- Study the structure of the asymmetry numerator (DP in this example). Three diagrams contribute at tree-level: s-channel photon, Z-boson, and Higgs exchange.

$$N = \frac{1}{2s}\int d\text{LIPS}\left\{\frac{R_{\gamma\gamma}}{s^2} + \ldots R_{ZZ} \ldots R_{\gamma Z} \ldots R_{\gamma H}(s-M_H^2) \ldots R_{ZH}(s-M_Z^2) + I_{ZH}M_H\Gamma_H \ldots M_H^2\Gamma_H^2]\right\}$$

The same idea can be applied to the ee→WW. It can't be applied to ee→gg, as this relies upon quantum interference between amplitudes and there is no continuum ee→Z,γ→gg.

$$R_{\gamma\gamma} = 96e^4Q_e^2Q_q^2m_e(S_T \cdot \ldots$$
$$R_{ZZ} = 96m_e(S_p \cdot p_b)g_Z^4g_{ve}^2 \ldots$$
$$R_{\gamma Z} = 192e^2g_Z^2Q_eQ_qm_e(S \ldots$$
$$R_{\gamma H} = -96e^2Q_eQ_qy_ey_q(S_T \ldots$$
$$R_{ZH} = -96g_Z^2g_{ve}g_{vq}y_ey_q(S_T \cdot p_q)s$$
$$I_{ZH} = -192g_Z^2g_{ae}g_{vq}y_ey_qm_q\epsilon(p_e, p_{\bar{e}}, p_q, S_T).$$

…aginary part of the Higgs …enhanced by a factor of $\mathbf{M_H}$/

…essed **linearly** by the …electron mass, this structure is directly proportional to the electron Yukawa couplings

- Can be isolated due to its different azimuthal structure, which follows from the discussion on the previous slide

# Application to the ee→bb process

- The idea: go close to Higgs resonance, weight events with the appropriate angular factor to select the term linear in the Hee coupling, impose cuts following 2107.02686 to reduce backgrounds. Check private code results vs. Madgraph.
  - Default polarization values: $P_T$=80%, $P_L$=30% (we will discuss these more later)
  - Full ISR, beam spread with 4.1 MeV width
  - Assume 10 $ab^{-1}$ integrated luminosity
  - Assume 80% pre-selection efficiency for reconstruction of bb system
  - Default cuts: $5^o<\theta<175^o$, $M_{inv}$>120 GeV
  - Consider only continuum bbar background (consistent with results of 2107.02686)

$$A^{\rm exp} = \frac{1}{P_{e^-}} \frac{N_N}{N_D} \qquad \delta A^{\rm exp} = \frac{\delta P_{e^-}}{P_{e^-}} A^{\rm exp} \oplus \frac{1}{P_{e^-}} \frac{1}{\sqrt{N_D}}$$

| Observable | $e^-e^+ \to b\bar{b}$ |
|---|---|
| DP | 0.27 |
| SP$^0$ | 0.19 |
| SP$^+$ | 0.11 |
| SP$^-$ | 0.38 |
| Reference | 0.11 |

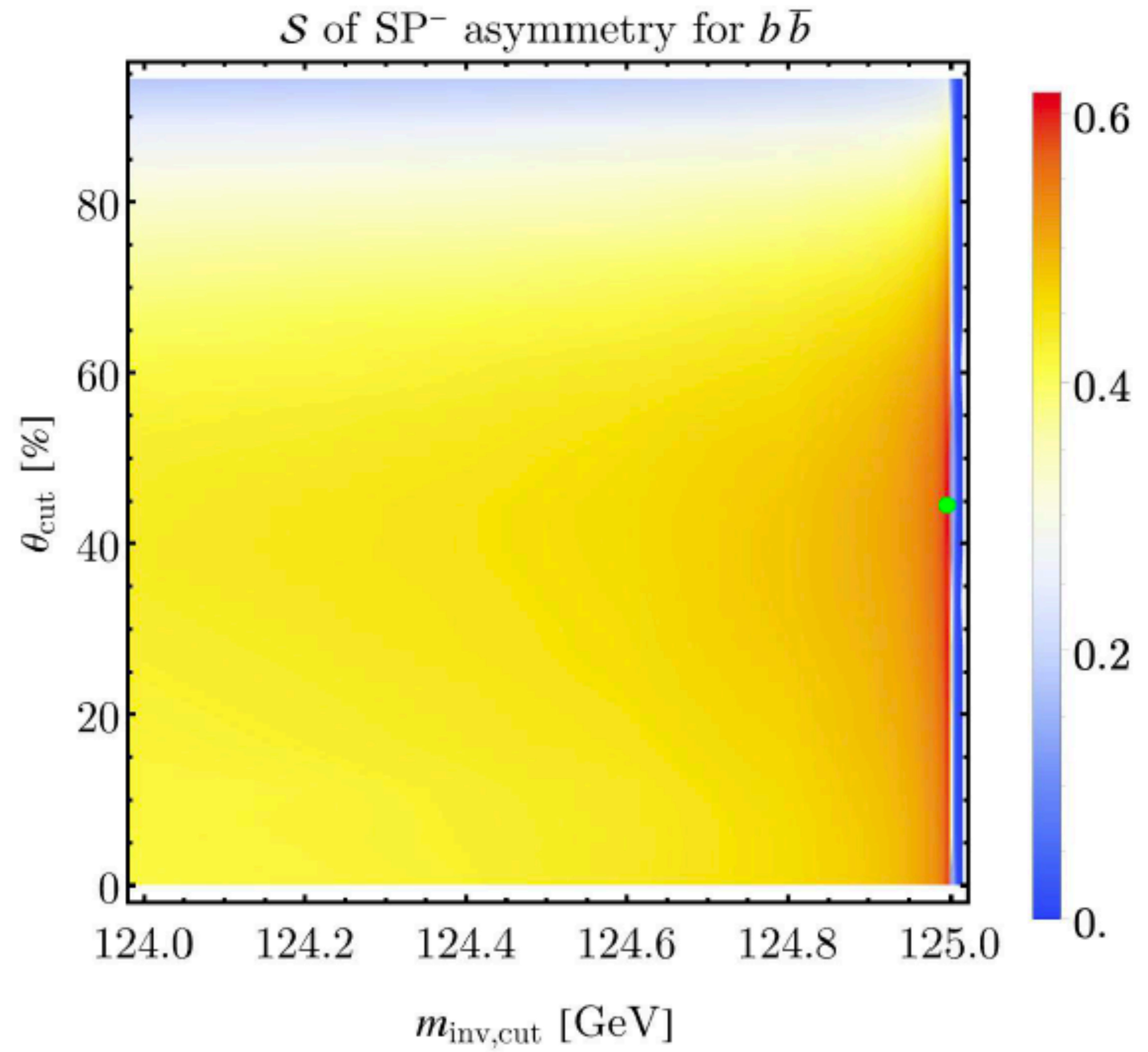
Preliminary

Definite improvement using transverse polarization; further improvement if the second beam can be longitudinally polarized

Obtained using unpolarized cross section; in good agreement with S/√B=0.13 in 2107.02686

# Improvements

- We can improve upon this using the properties of the Higgs signal versus the continuum background. Signal goes as $\sin^2\theta$ while background goes as $1+\cos^2\theta$, so a cut on polar angle helps. Increasing invariant mass cut also increases asymmetry.




10 MeV from resonance invariant mass cut

| Observable | $e^-e^+ \to b\bar{b}$ |
|---|---|
| DP | 0.41 (39%) |
| $SP^0$ | 0.30 (33%) |
| $SP^+$ | 0.17 (44%) |
| $SP^-$ | 0.58 (39%) |



Second column gives polar angle cut in terms of percentage of phase spaced removed

Best case: improve reference significance compared to unpolarized result by a factor of 5

# Applications to ee→WW process

- We will focus on the semi-leptonic final state as an example. The ideas are applicable to all three possibilities.
  - Same polarization, ISR, beam spread as before.
  - Default cuts: 5°<θ<175°, $M_{inv}$>120 GeV
  - Assume 100% preselection efficiency
  - Consider only continuum WW background
  - Use the azimuthal angle of the reconstructed WW system to project out the Yukawa contribution
  - Following cuts following 2107.02686 to remove backgrounds from other processes:

$E_{j1,j2}$<52, 45 GeV; $E_l$>10 GeV; $E_{miss}$>20 GeV; $m_{12}$>12 GeV
Note: these do not affect the orthogonality condition from above

| Observable | $e^-e^+\to WW\to ll\nu\nu$ |
|---|---|
| DP | 0.30 |
| $SP^0$ | 0.47 |
| $SP^+$ | 2.0 |
| $SP^-$ | 0.12 |
| Reference | 0.45 |

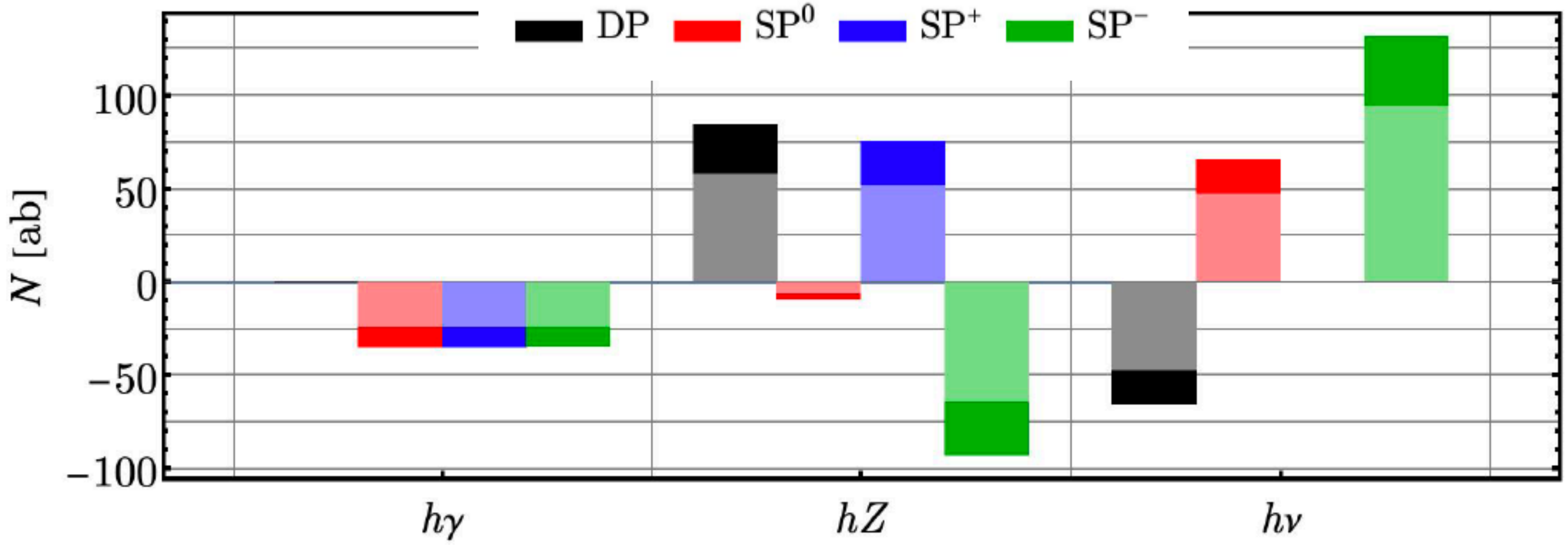
Preliminary

Over a factor of 4 improvement if $(P_T,P_L)$=(80,30)% can be obtained

Obtained using unpolarized cross section; S/√B=0.53 in 2107.02686, likely due to use of BDT rather than simple cuts

# Applications to ee→WW process

- Why does longitudinal polarization improve the result so significantly? Study the diagrammatic contributions to the asymmetry numerator.

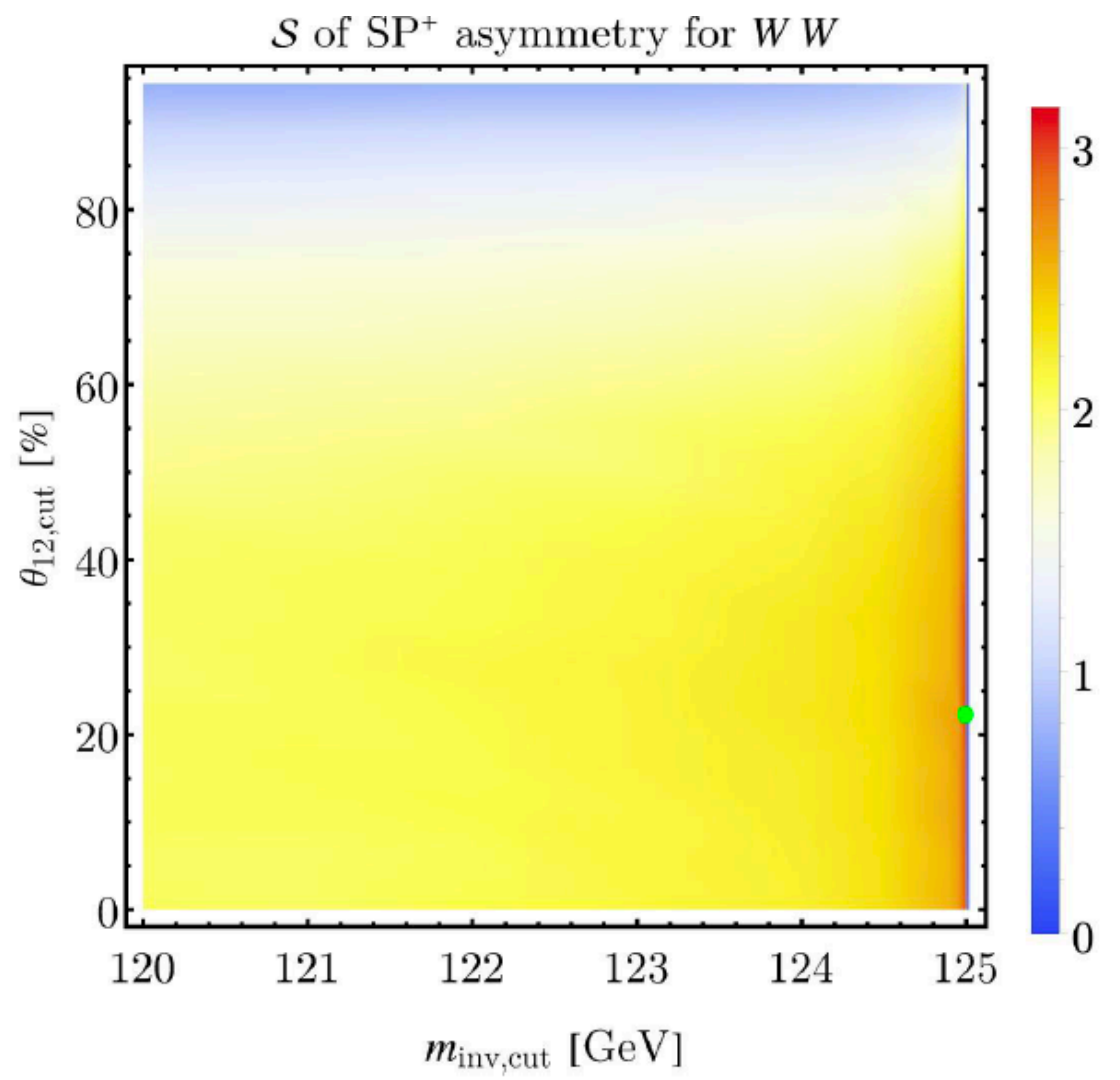



Large cancellation between hν interferences and other terms removed by the SP+ polarization choice

# Improvements



- Like in the bbar are we can further cut on the polar angle and invariant mass to improve the significance.




10 MeV from resonance invariant mass cut

| Observable | $e^-e^+ \to WW \to ll\nu\nu$ |
|---|---|
| DP | 0.45 |
| SP$^0$ | 0.80 |
| SP$^+$ | 2.9 |
| SP$^-$ | 0.33 |

Best case: improve reference significance compared to unpolarized result by a factor of 6

# Conclusions

- Recap: use the linear dependence of transverse polarization asymmetries on the electron Yukawa coupling to enhance FCC senstivity to this parameter.
- Caveats: well known that achieving polarization at an FCC, particularly longitudinal, leads to a decrease in luminosity. Note that a factor of 4 decrease in assumed luminosity would still leads to a WW significance over 1, a factor of 2 better than the inclusive cross section determination.
- Opportunities: initial results indicate that improvements of significance reaching 5-6 for the bb and WW channels.

| Lumi loss factor | L.10^34 | Figure of merit: sum(P²L) | Peff | Pmax |
|---|---|---|---|---|
| 1 | 220 | 0.195 | 0.03 | 0.03 |
| 2 | 110 | 0.367 | 0.059 | 0.06 |
| 4 | 55 | 0.627 | 0.1078 | 0.11 |
| 6 | 37 | 0.805 | 0.149 | 0.16 |
| 8 | 27 | 0.924 | 0.184 | 0.2 |
| 10 | 22 | 1.003 | 0.214 | 0.24 |
| 12 | 18 | 1.053 | 0.24 | 0.27 |
| 15 | 15 | 1.09 | 0.27 | 0.32 |
| **18** | 12 | **1.101** | 0.3 | 0.35 |
| 22 | 10 | 1.088 | 0.33 | 0.4 |
| 26 | 8 | 1.059 | 0.354 | 0.43 |
| 30 | 7 | 1.023 | 0.37 | 0.46 |
| 40 | 5 | 0.92 | 0.41 | 0.52 |

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