

# 2-fermion processes at Higgs Factories

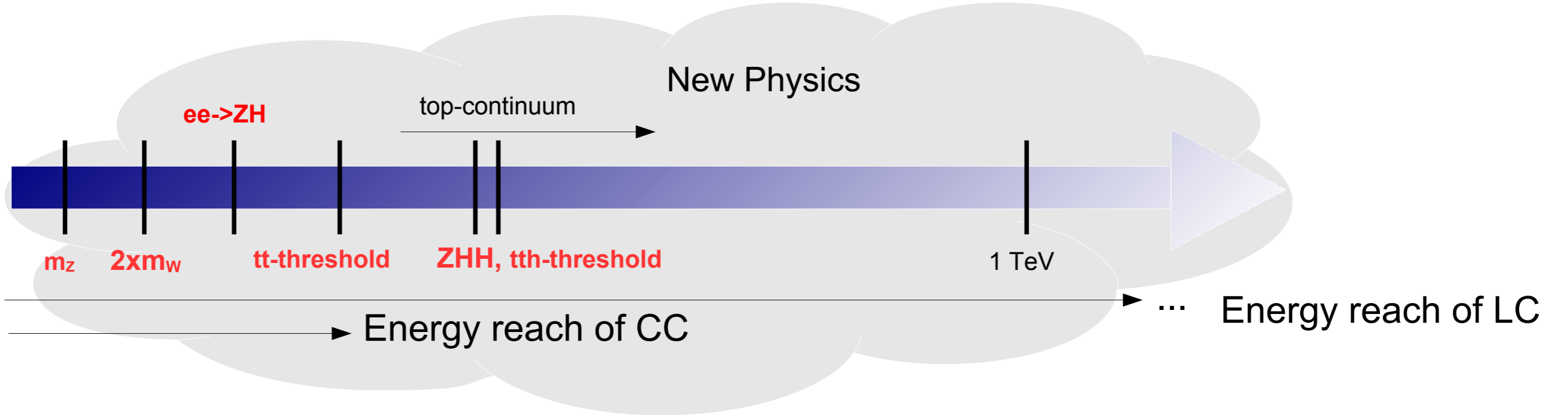
Roman Pöschl, Daniel Jeans, Taikan Suehara



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TYL-FJPPN/FKPPN Meeting May 2026 Hamamatsu



All Standard Model particles within reach of planned  $e^+e^-$  colliders

High precision tests of Standard Model over wide range to detect onset of New Physics

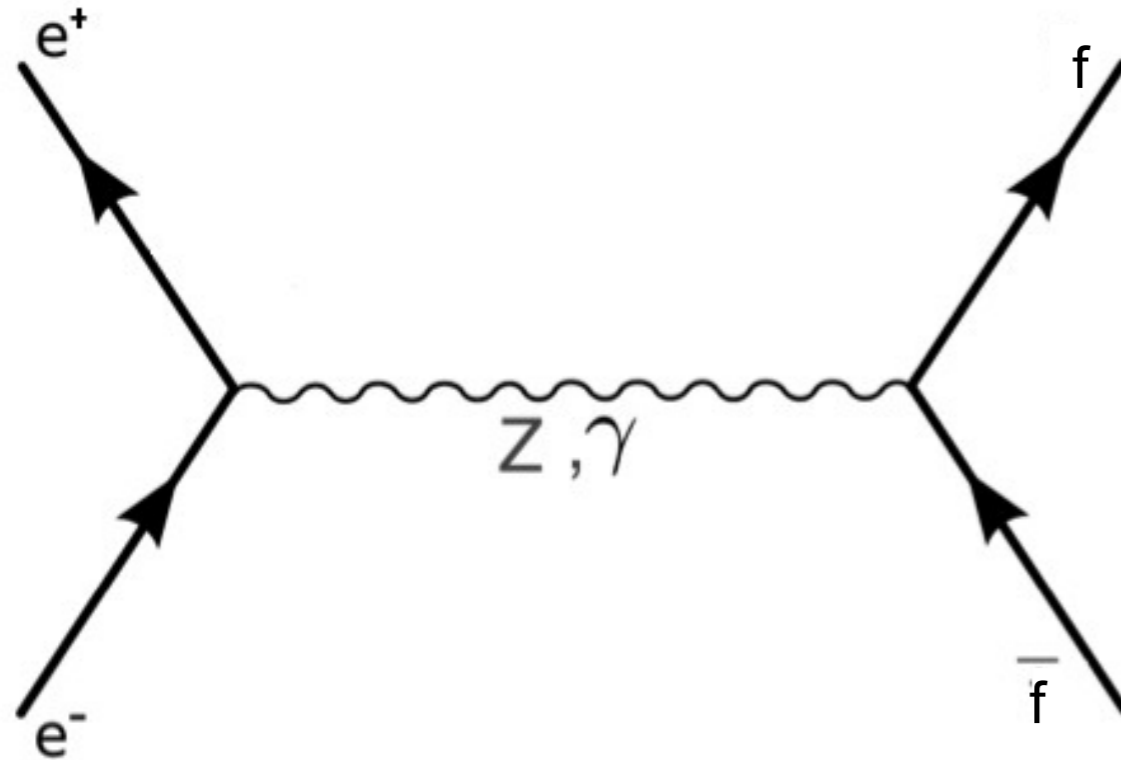
Machine settings can be “tailored” for specific processes

- Centre-of-Mass energy
- Beam polarisation (straightforward at linear colliders)

$$\sigma_{P,P'} = \frac{1}{4} [(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})]$$

**Background free** searches for BSM through beam polarisation

# Two fermion processes



$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \rightarrow f \bar{f}) = \Sigma_{LL}(1 + \cos\theta)^2 + \Sigma_{LR}(1 - \cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \rightarrow f \bar{f}) = \Sigma_{RL}(1 - \cos\theta)^2 + \Sigma_{RR}(1 + \cos\theta)^2$$

\*add term  $\sim \sin^2\theta$  in case of non-relativistic fermions e.g. top close to threshold

$\Sigma_{IJ}$  are helicity amplitudes that contain couplings  $g_L, g_R$  (or  $F_V, F_A$ )

$\Sigma_{IJ} \neq \Sigma_{I'J'} \Rightarrow$  (characteristic) asymmetries for each fermion

Forward-backward in angle, general left-right in cross section

**All four helicity amplitudes for all fermions only available with polarised beams**

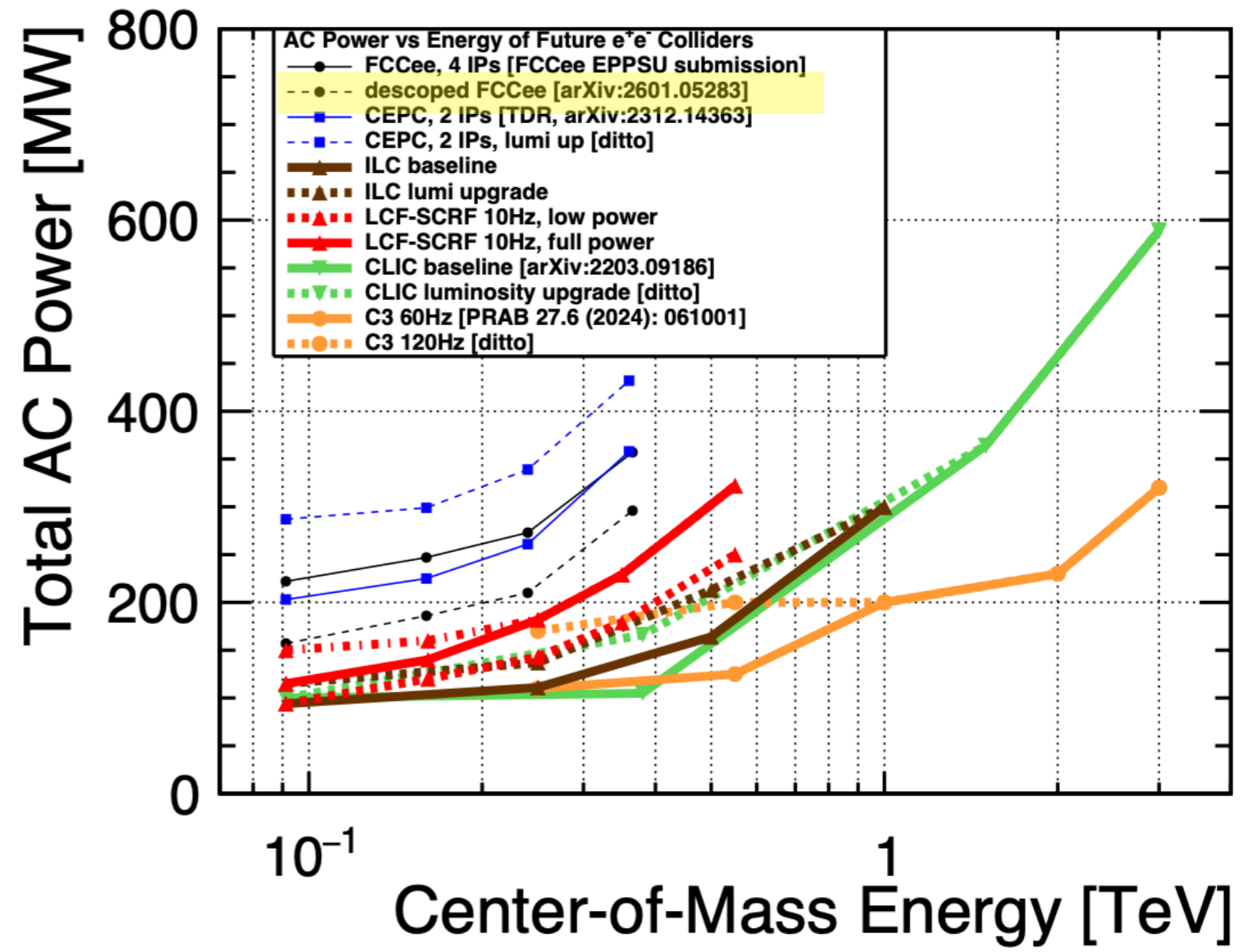
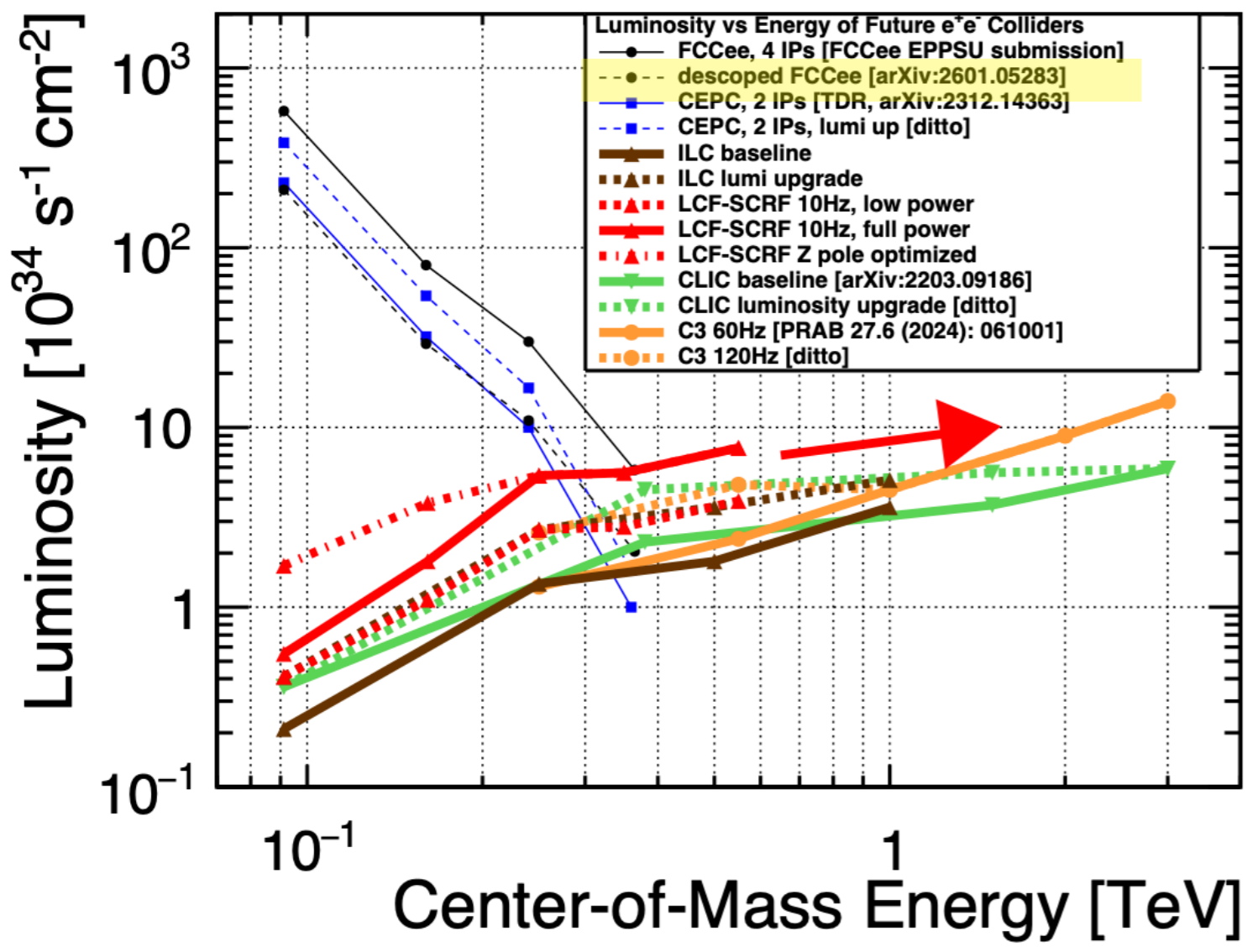


Figure J. List

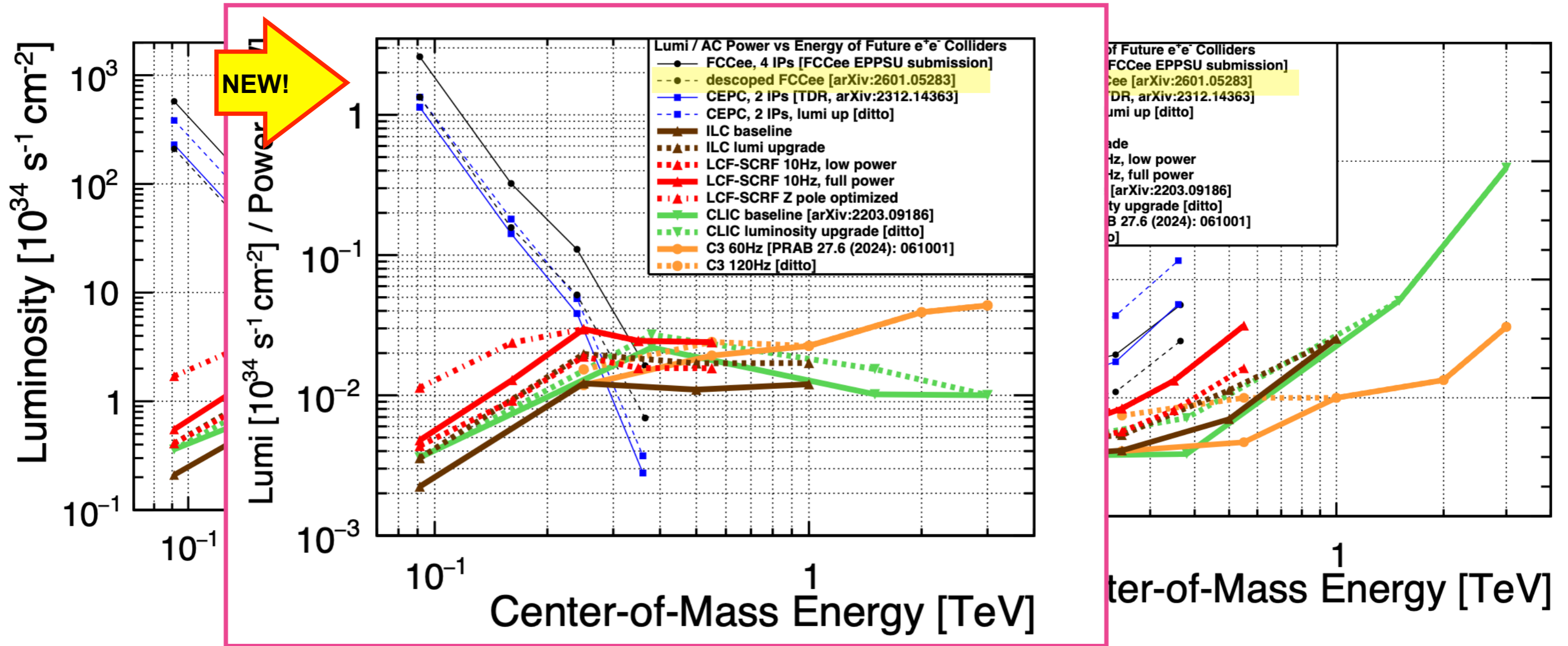
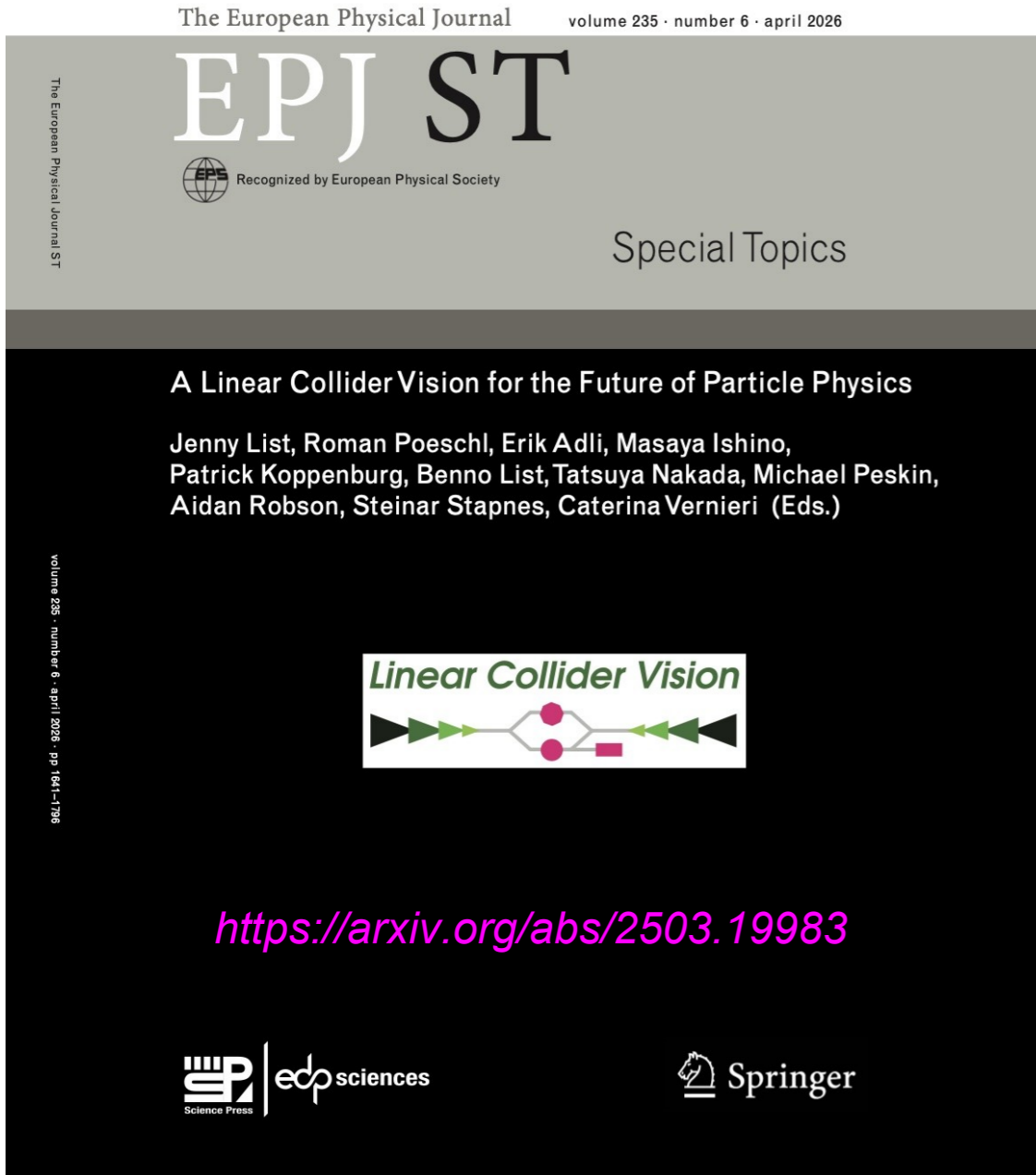


Figure J. List



Input to

Physics Briefing Book

<https://arxiv.org/abs/2511.03883>

CERN-ESU-2025-001  
4 November 2025

## Physics Briefing Book

*Input for the 2026 update of the European Strategy for Particle Physics*

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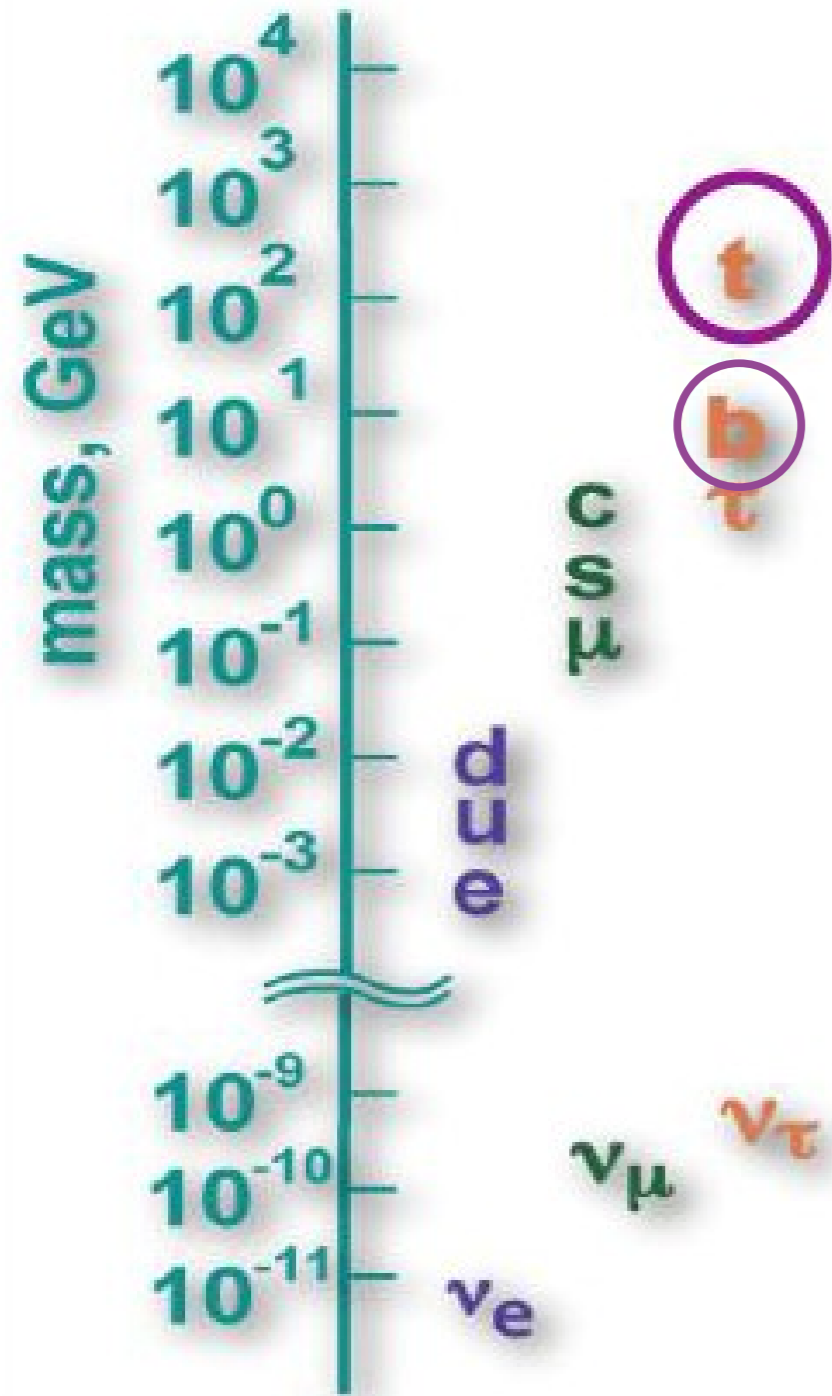
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Piloted by Jenny List  
Japanese and French editors  
Studies on 2f processes initiated by and/or  
carried out in TYL/FJPPN as input



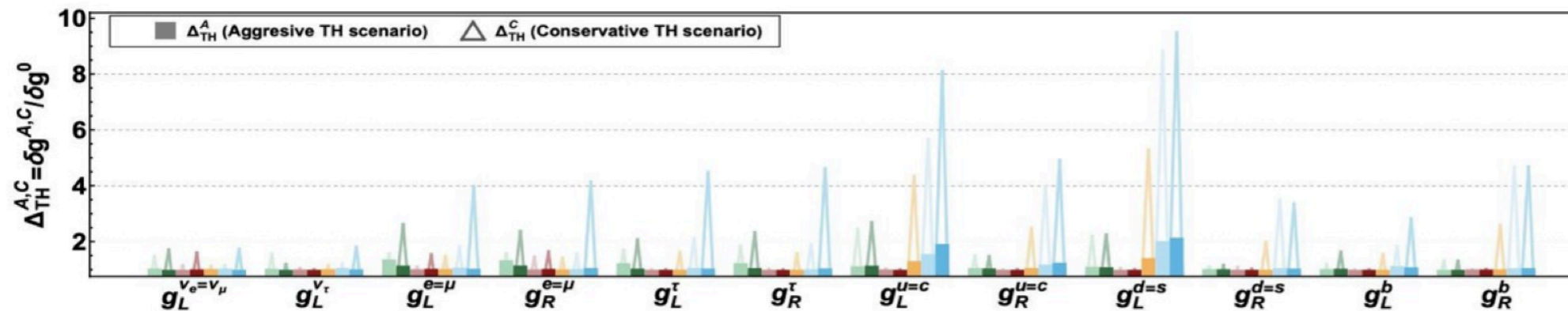
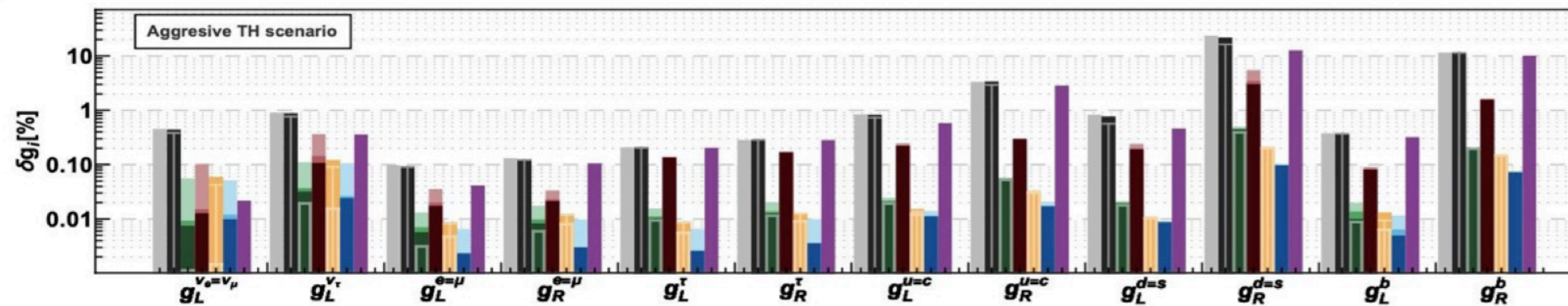
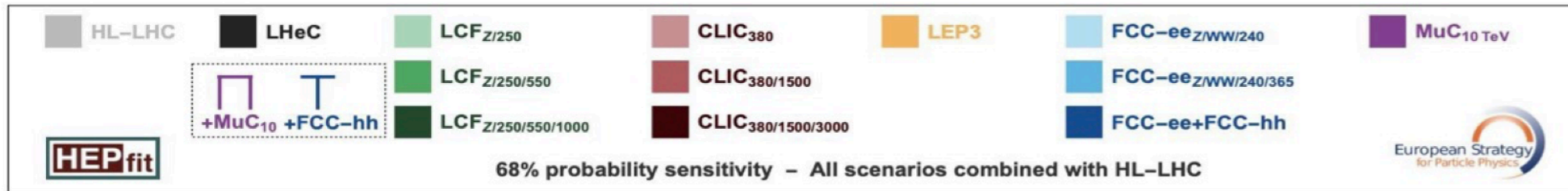
- SM does not provide an explanation for mass spectrum of fermions (and gauge bosons)
  - Fermion mass generation closely related to the origin electroweak symmetry breaking
  - Expect residual effects for particles with masses closest to symmetry breaking scale
- $$\begin{pmatrix} t \\ b \end{pmatrix}_L$$
- Heavy quark effect or effect on all fermions?

**Strong motivation to study chiral structure of (heavy) fermion vertices**

Today: Flash of ESPPU results

**See a detailed study by Jesus on Wednesday**

## EW Operators



Coupling precision at ‰ level

Considerable improvement by LC

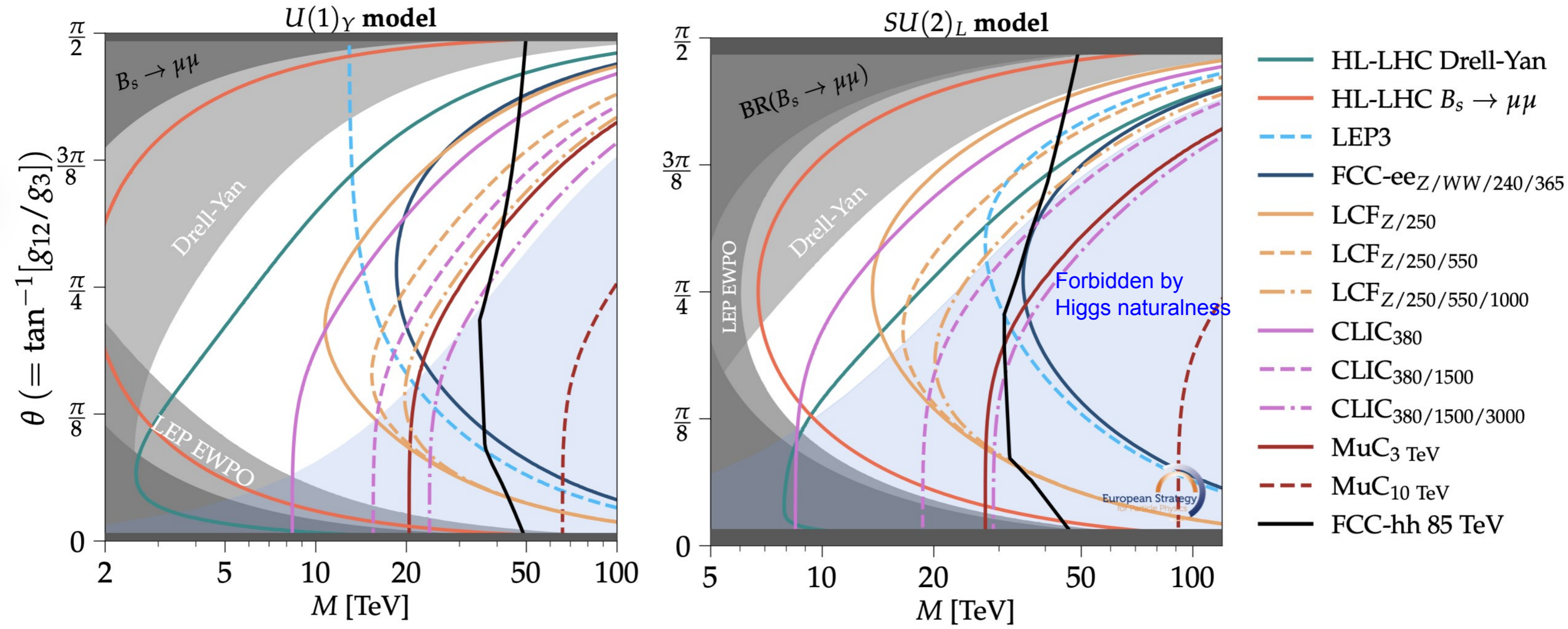
Competitive with FCCee

- Beam polarisation compensates for factor 40 in luminosity

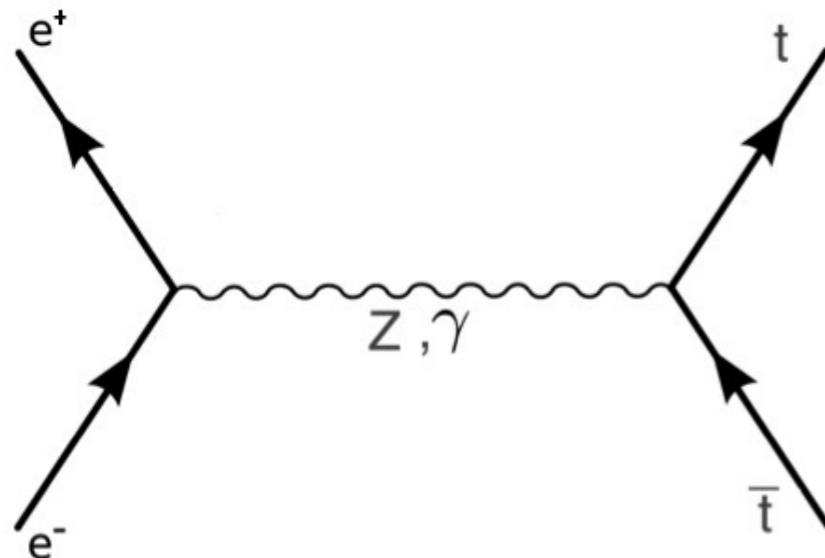
Differences dilute further when taking conservative (realistic?) theory errors into account

Experimental uncertainties not taken into account for FCC-ee projections

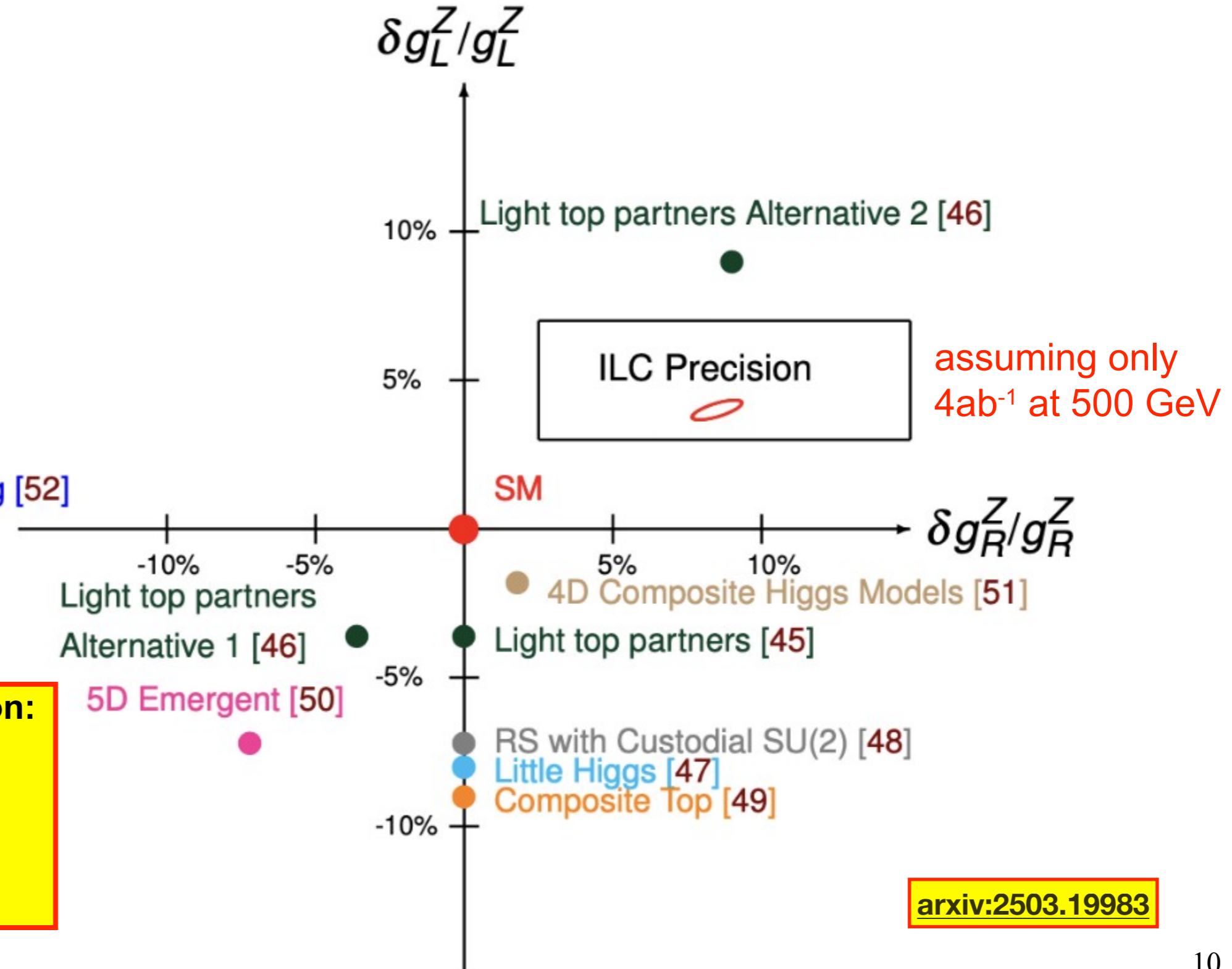
## Limits on Flavor Breaking Models as in ESPPU - Main input from two fermion processes



High energy lepton collisions may even outperform FCC-hh



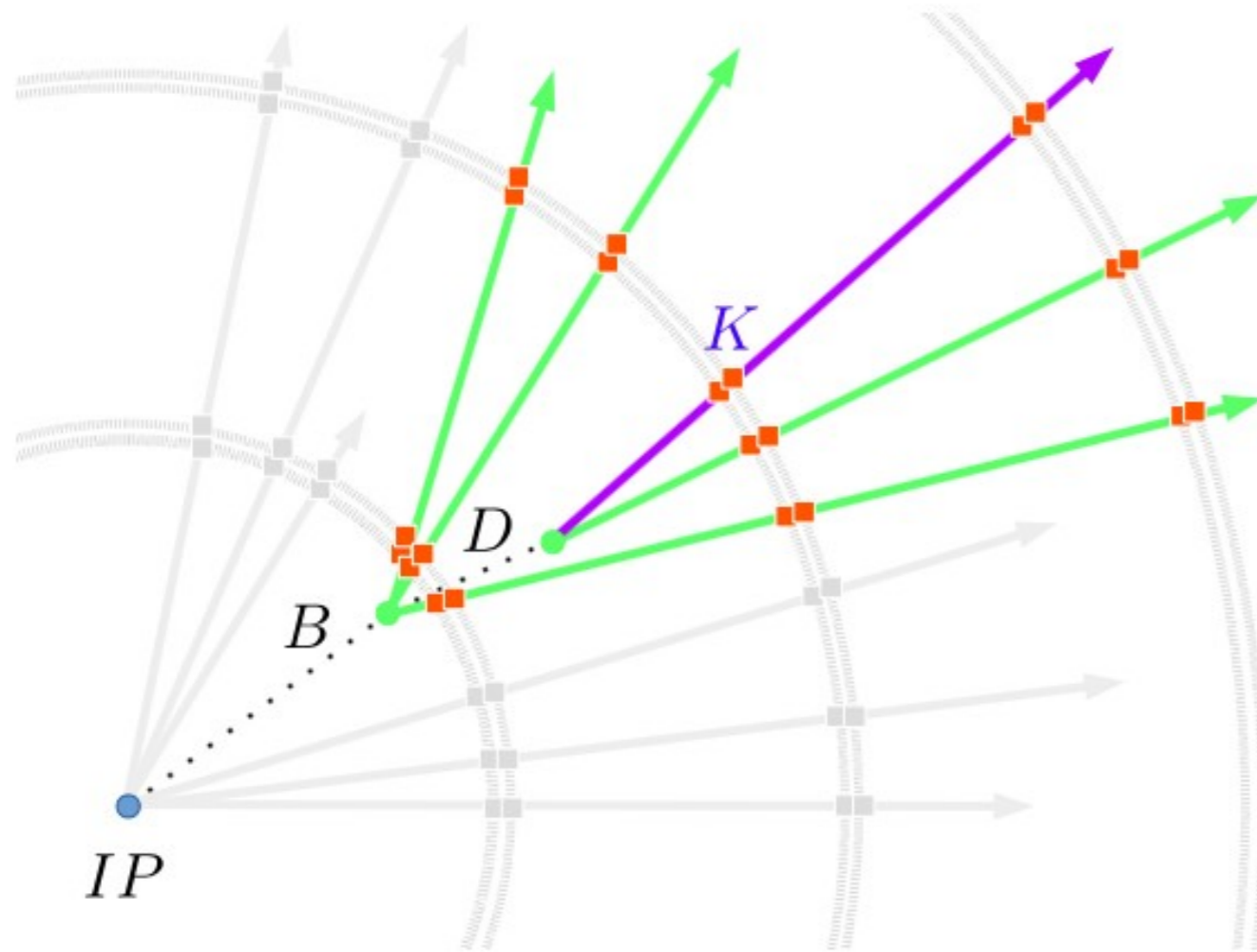
RS with Z-Z' Mixing [52]  
 -120%



**Couplings of the Top quark to the Z boson:**

- essential for NLO interpretation of Higgs measurements
- tremendous BSM sensitivity in its own right
- Displayed Models take LHC Constraints into account

[arxiv:2503.19983](https://arxiv.org/abs/2503.19983)

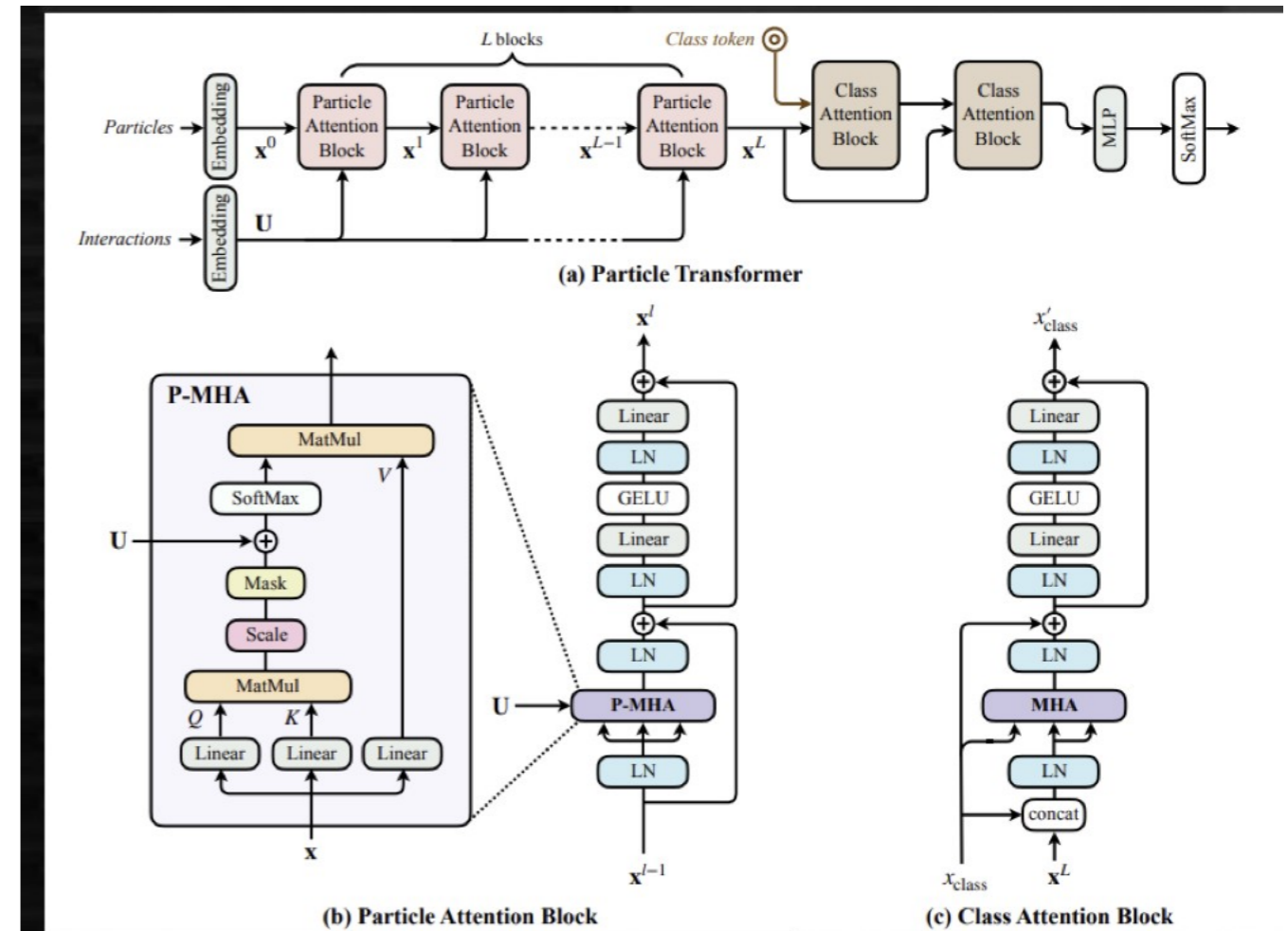


- **Flavor tagging**
  - Indispensable for analyses with final state quarks
- **Quark charge measurement**
  - Important for top quark studies,
  - indispensable for  $ee \rightarrow bb, cc, ss, \dots$
- **Control of migrations:**
  - Correct measurement of vertex charge
  - Kaon identification by  $dE/dx$  (and more)
- **Future detectors can base the entire measurements on double Tagging and vertex charge**
  - LEP/SLC had to include single tags and Semi-leptonic events

PhD thesis: S. Bilokin  
A. Irles

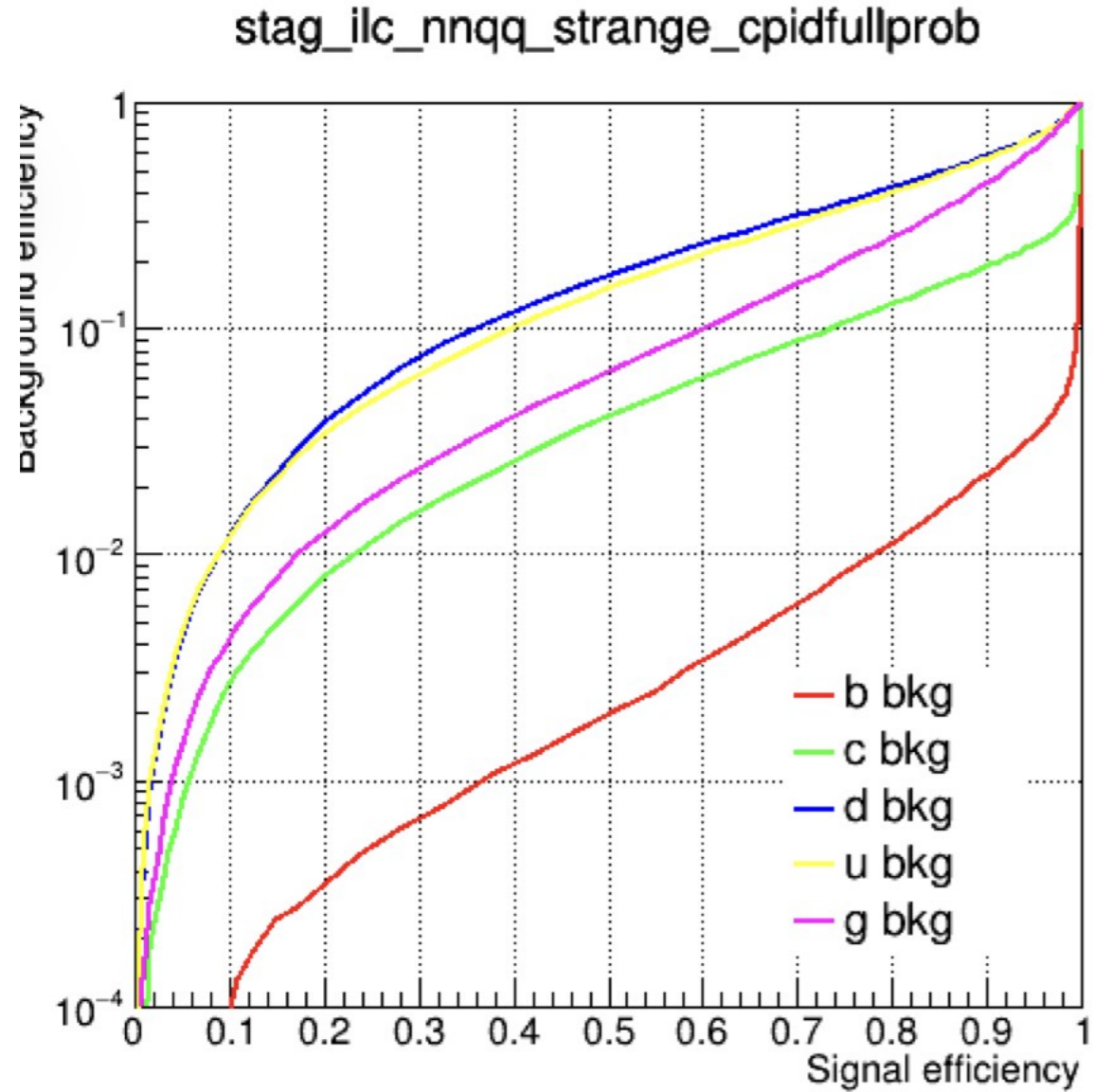
- **Transformer: self-attention-based algorithm**
  - intensively used for NLP (e.g. chatGPT)
  - Weak biasing: possible to train big samples efficiently (with more learnable weights) but demanding big training sample for high performance
- **ParT is a new Transformer-based architecture** for Jet tagging, published in 2022.
  - Pair-wise variable (angle, mass etc.) is added to plain Transformer encoder to boost attention

- For details ask Taikan
- For (an) application see Jesus' talk on Wednesday

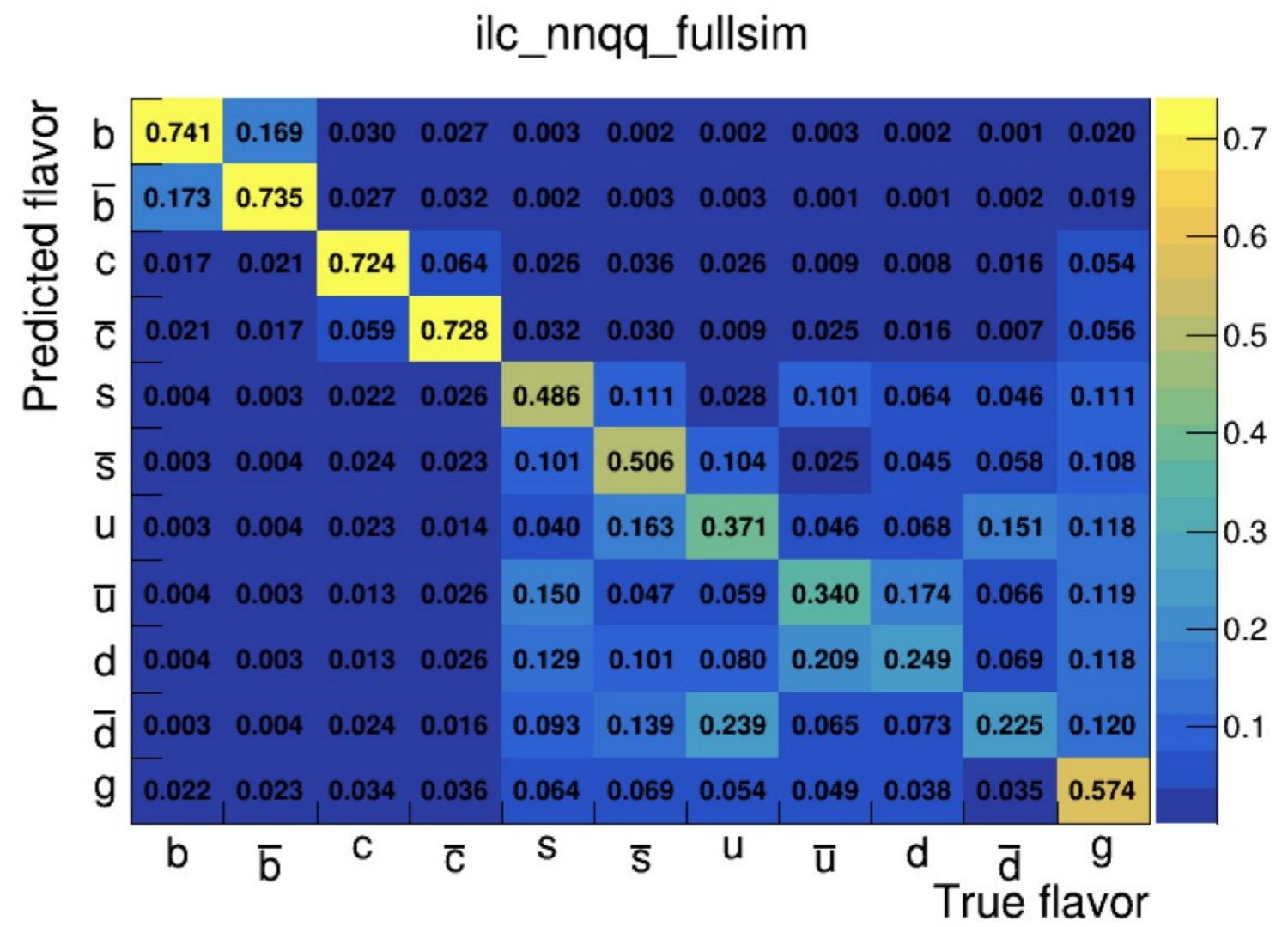


|             | All classes  |               |
|-------------|--------------|---------------|
|             | Accuracy     | AUC           |
| PFN         | 0.772        | 0.9714        |
| P-CNN       | 0.809        | 0.9789        |
| ParticleNet | 0.844        | 0.9849        |
| <b>ParT</b> | <b>0.861</b> | <b>0.9877</b> |

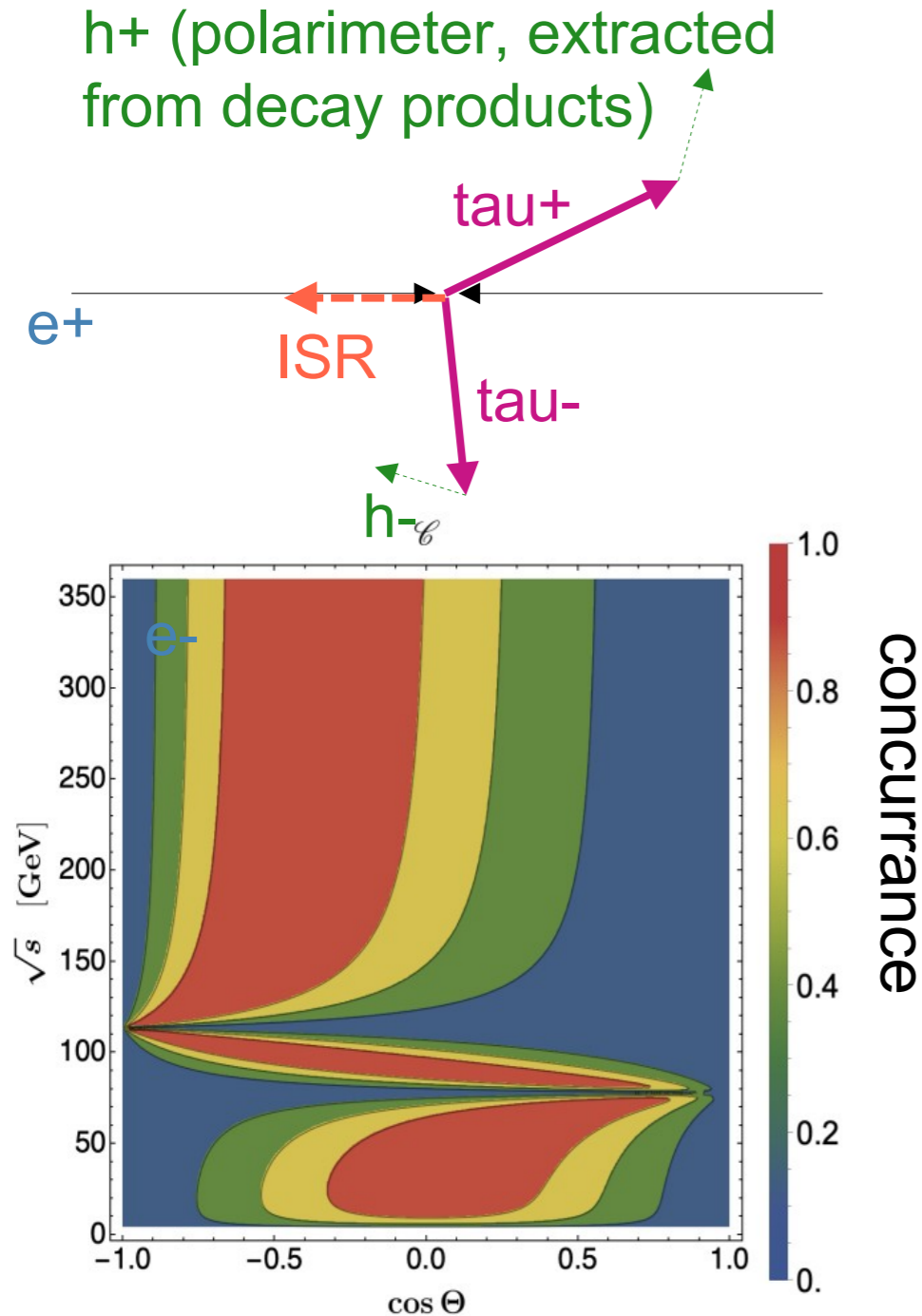
**Performance with JetClass event classification (100M sample)**



CPID ( $K/\pi/p$  probability) for strange tagging with 100 ps TOF ( $\times 10$  hits) +  $dE/dx$  (details on strange tagging see backup)



Vertical: truth jet PDG, horizontal: predicted jet PDG  
 PDG with highest score taken  
 Result for  $\nu\bar{\nu}q\bar{q}$  final state



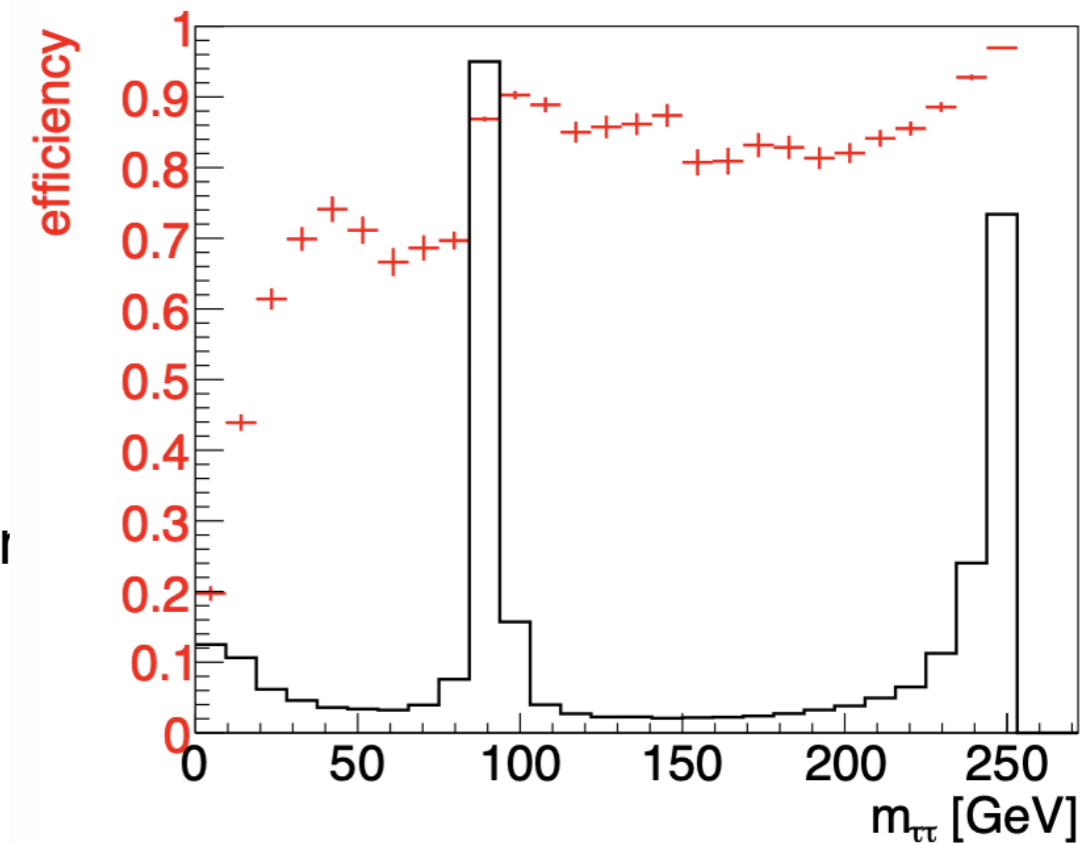
Measured parameters not enough to uniquely reconstruct kinematics

Can arrive at a **collection** of possible event solutions, by

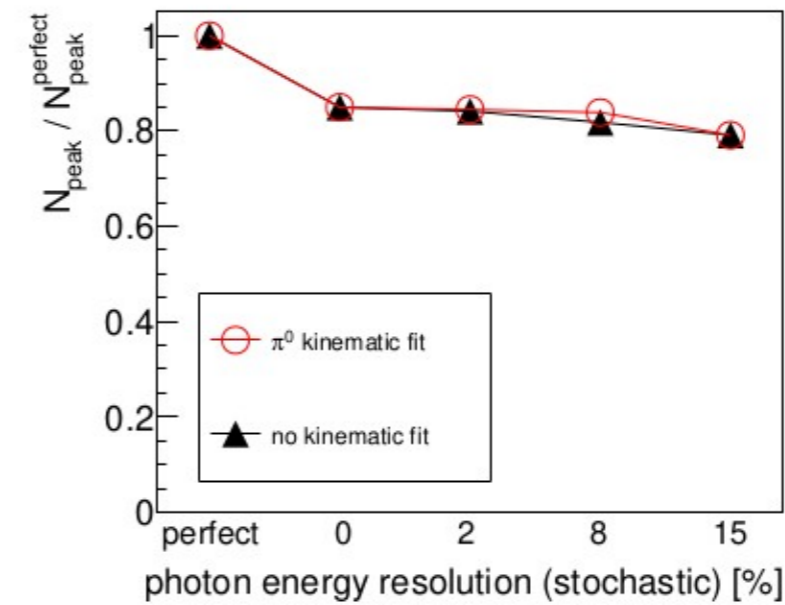
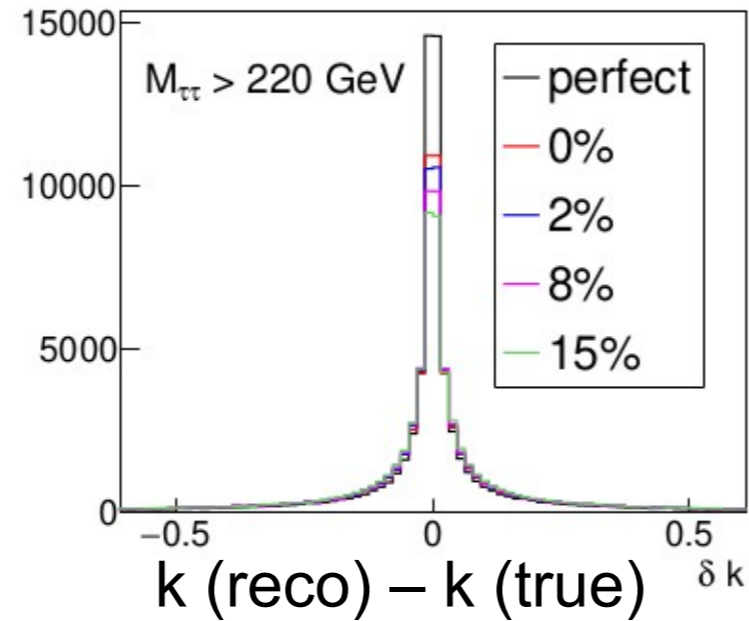
- semi-leptonic tau decays (1 neutrino per tau)
- tau mass
- 4-mom
- scan over unseen ISR

**weight** each solution:

- track impact parameter
- tau lifetime
- expected ISR distribution
- luminous region

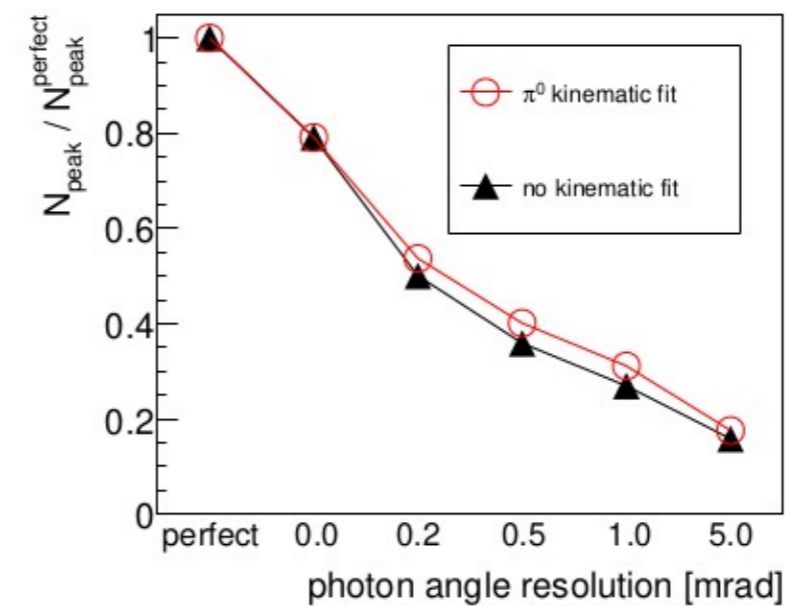
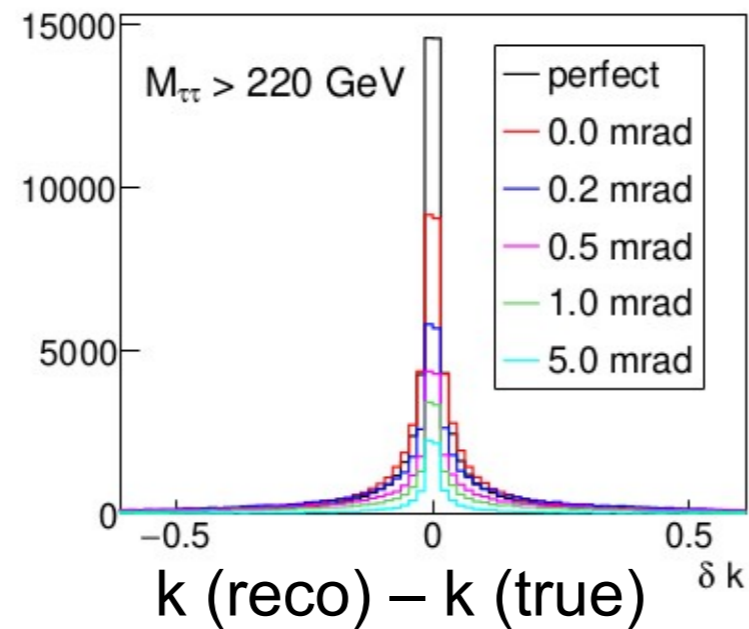


photon energy  
 stochastic term



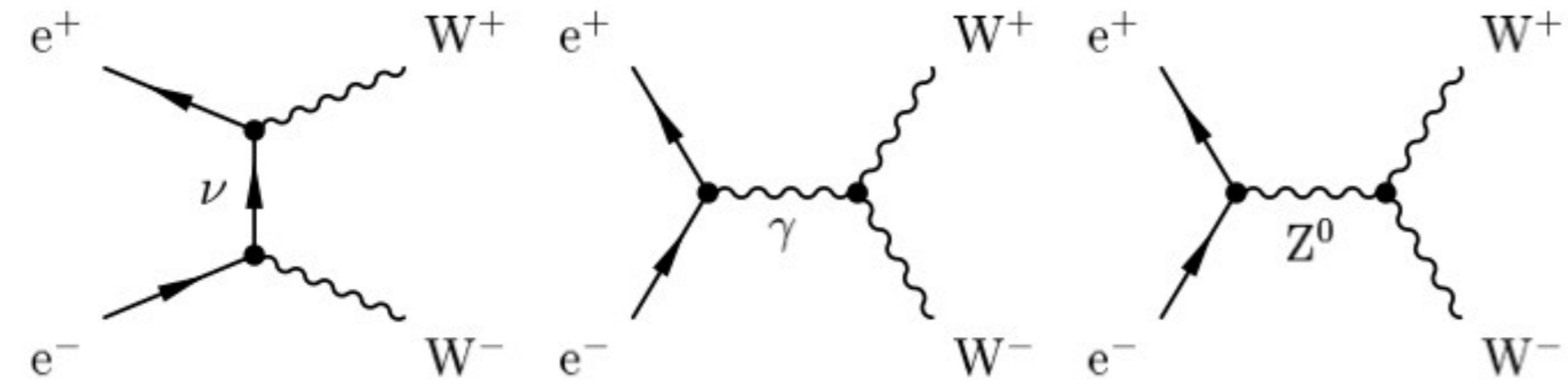
Energy:  
 Small effect

photon angle



Angle:  
 Large effect  
 even @ 0.2 mrad

# WW production at 250 GeV (and above)



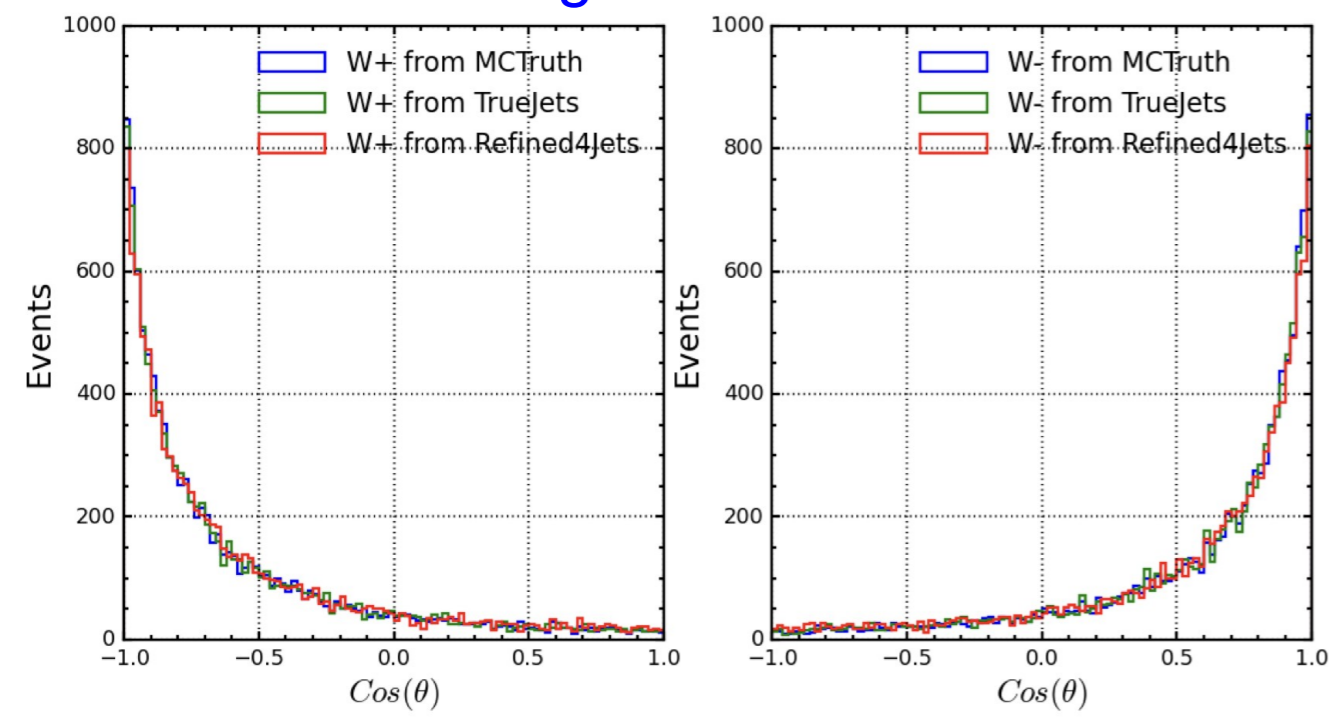
Sensitivity to triple and quartic gauge Boson couplings (TGC and QGC)

Observables depend strongly on beam polarisation

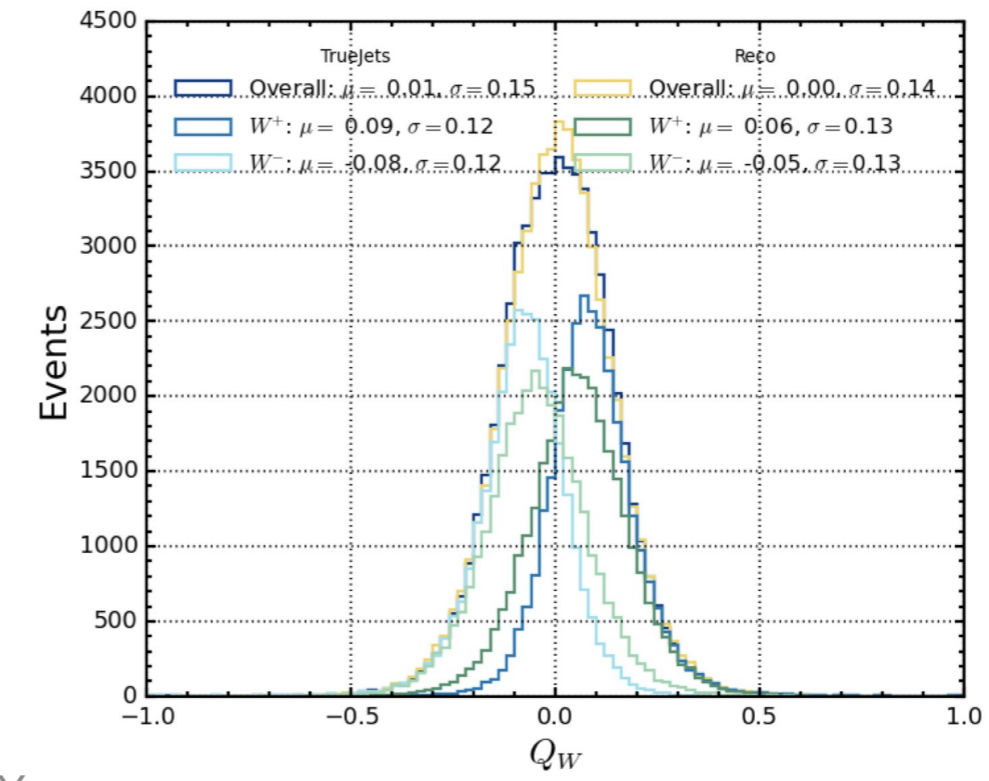
- => Enrich different helicity modes of W
- => Disentangling of couplings to Z and  $\gamma$
- => in situ measurement of beam polarisation (and luminosity)

Analysis of fully hadronic final state (first steps)

## The goal



## W charges (true jets and measured)



- Overlap leads to charge flips
- Correction compromised by correlation introduced by jet algorithm
- Improvement by Machine learning?

### General Information Export

|                             |   |                             |                  |
|-----------------------------|---|-----------------------------|------------------|
| Title                       | 2-fermion production at Higgs Factories | Status                      | Submitted        |
| Follow-up ID                | HEP_16                                  |                             |                  |
| Created At                  | 2026/03/21 16:31                        |                             |                  |
| Principal Investigator (FR) | Mr. Roman PÖSCHL                        | Principal Investigator (JP) | Dr. Daniel JEANS |

Project Document (PDF)

[Download Project Document](#)

Application2026-HEP16-v3-submit.pdf

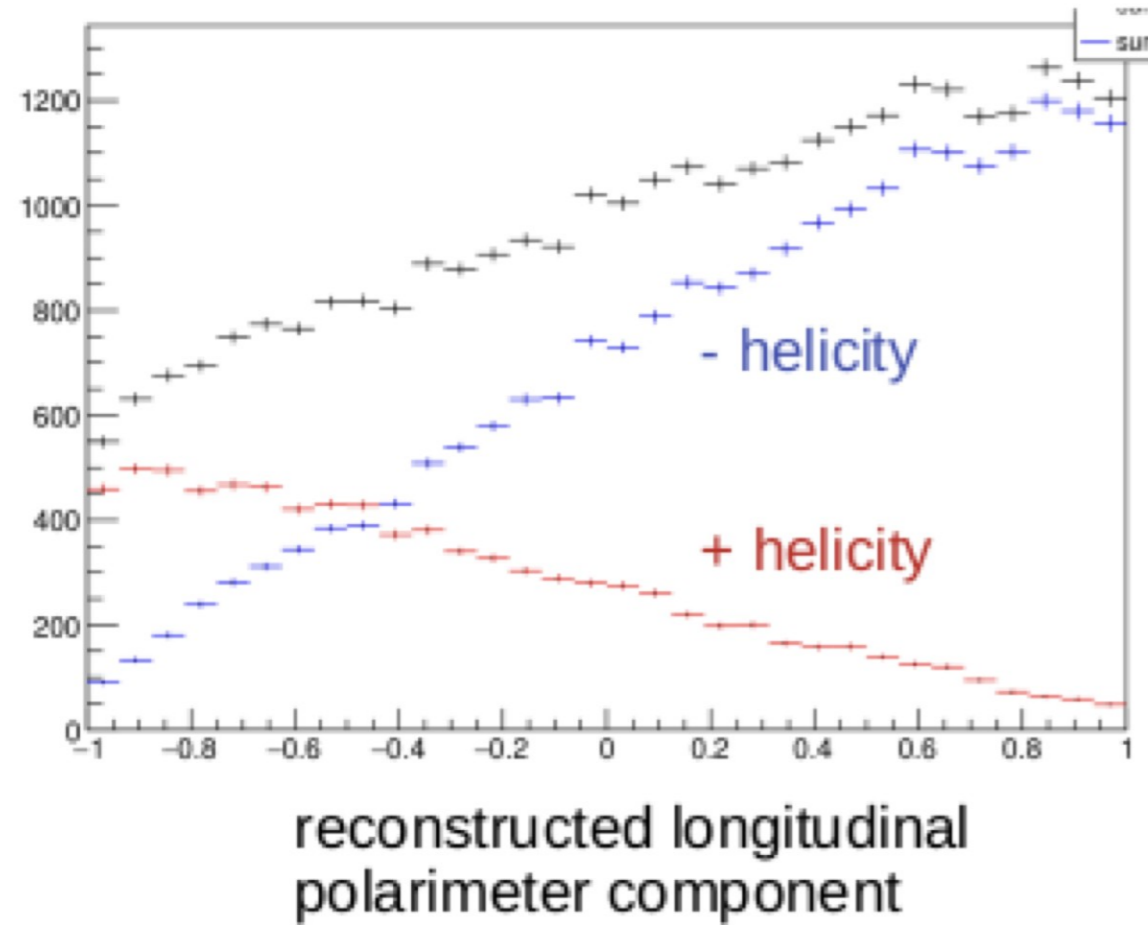
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- 2-fermion studies carried out in TYL/FJPPN project contributed to update of European Strategy
  - Major progress on flavor tagging by Particle Transformer
  - -> Input for revision of  $ee \rightarrow ss$  study (see Jesus talk on Wednesday)
  - Quantum Tomography with tau leptons
- Next fiscal year
  - Completion of revision of  $ee \rightarrow ss$  study based on modern flavor tagging
  - Phenomenology, e.g. global fits with 2-fermion quantities
  - Continuation of  $ee \rightarrow \tau\tau$
  - Study of  $ee \rightarrow WW$

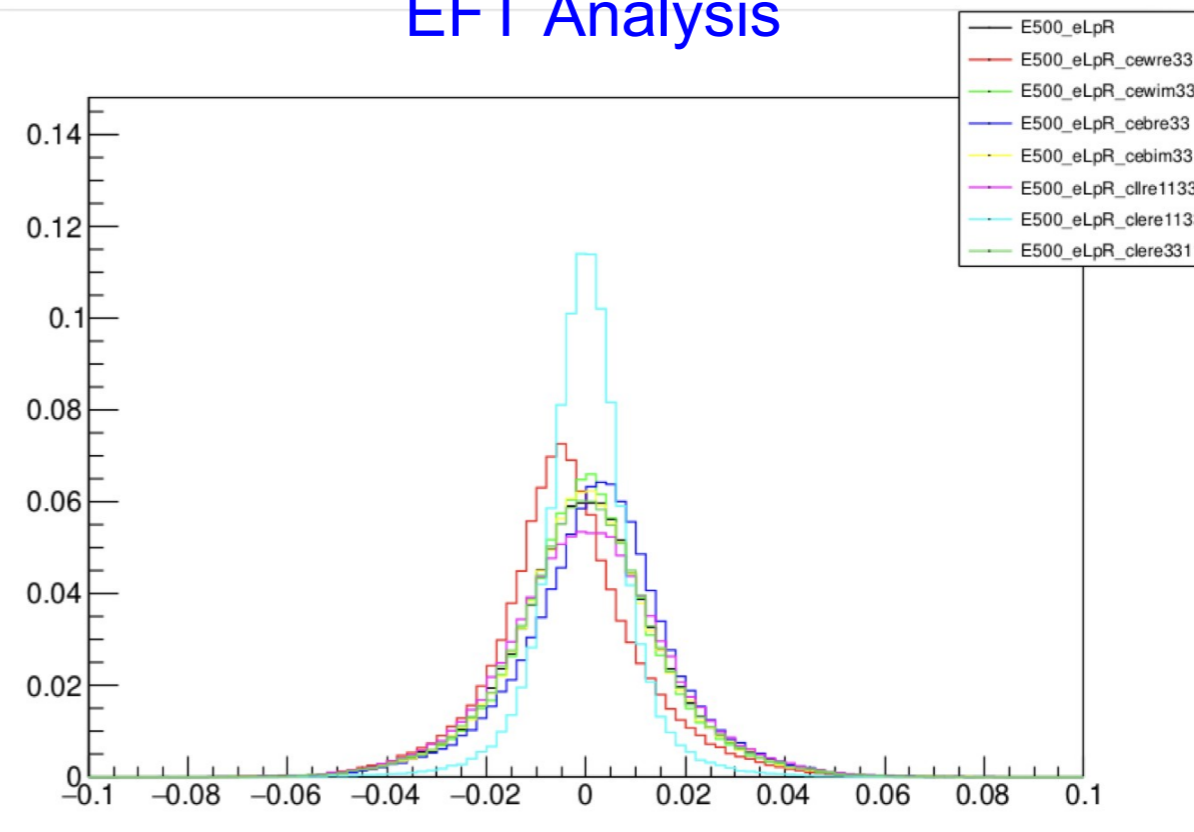
Backup

## $\tau$ -helicity

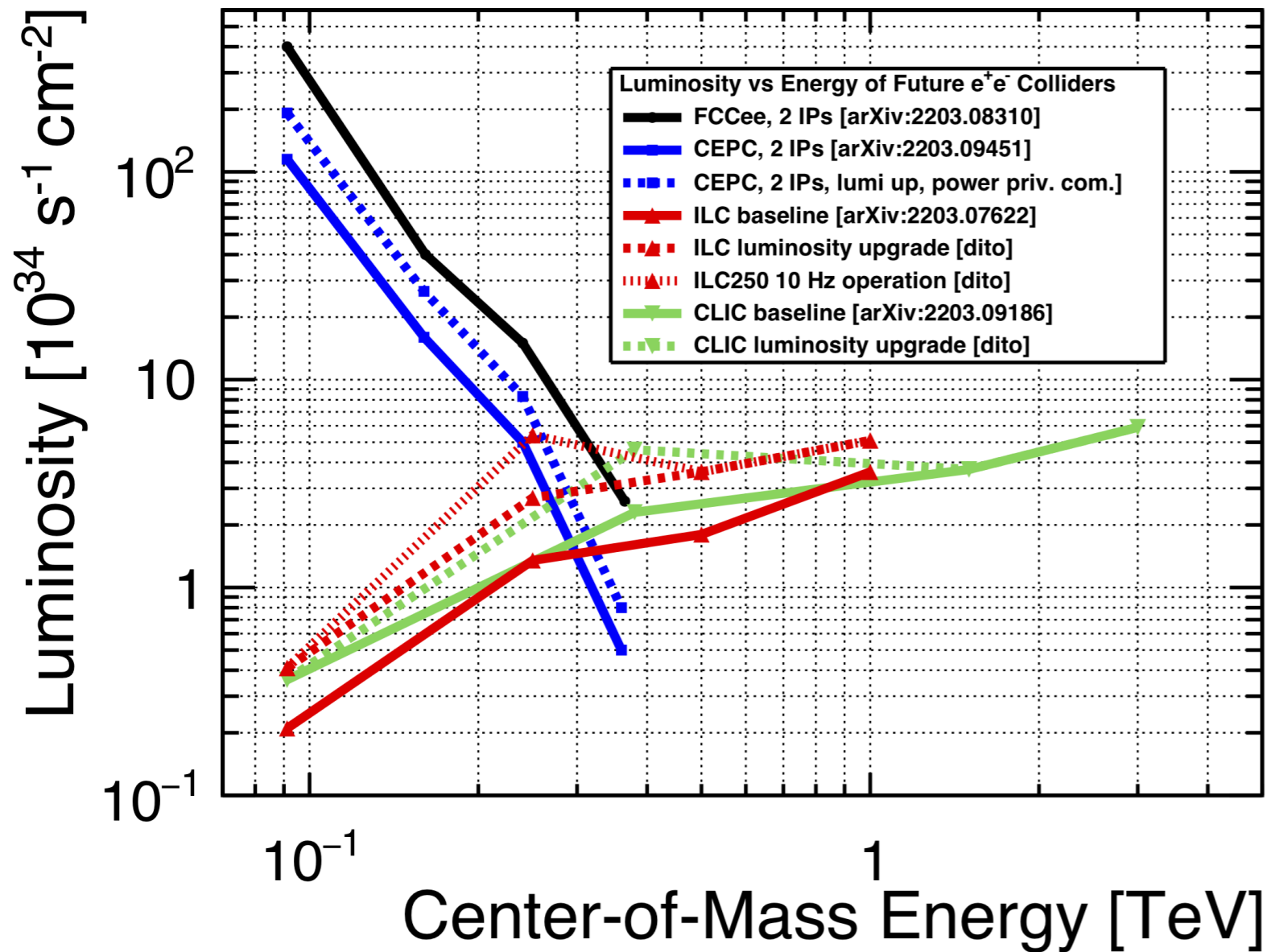


- At 500 GeV  $\tau$  production “plagued” by ISR
  - ... and ISR photon often unmeasurable
- Successful helicity analysis requires kinematic constraint
- Iterative procedure to determine  $\tau$  helicity

## EFT Analysis



- Interface MadGraph TauDecay
- Sensitivity of EFT operators to  $ttW/B$  operators and 4-fermion vertices



High energies ~above tt-threshold  
Domain of linear colliders

Low energies e.g. Z-pole  
Domain of circular machines  
However, ...

Transition region, i.e. HZ threshold  
Comparable Higgs Couplings uncertainties  
for all proposals (see later)

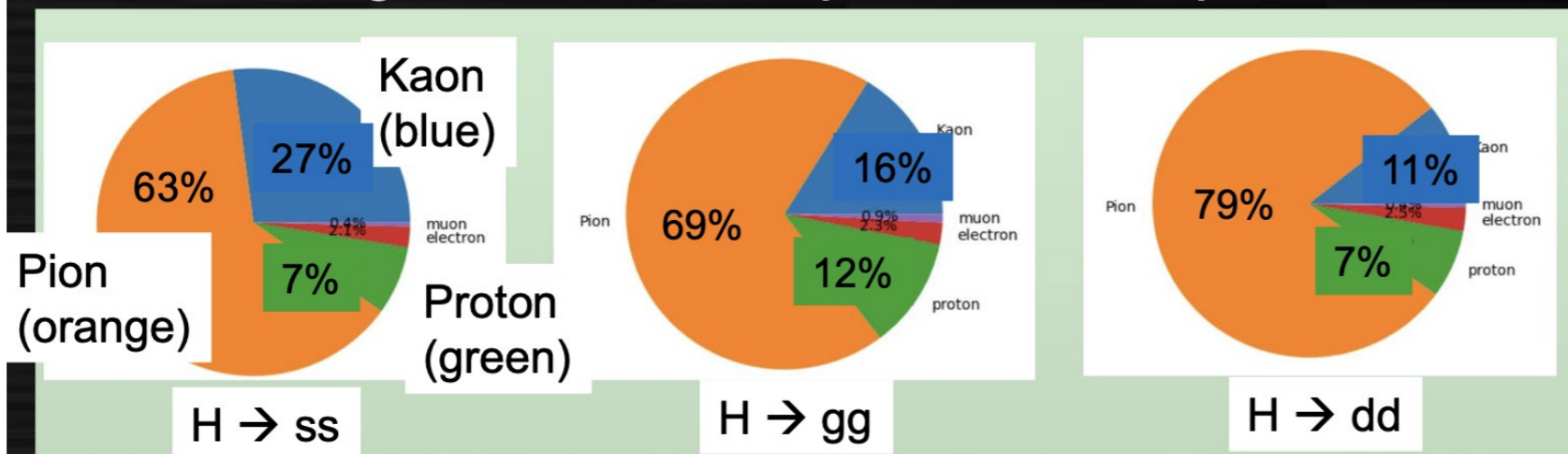
Linear colliders are more versatile  
to test chiral theory due to polarised  
beams

$$\sigma_{P,P'} = \frac{1}{4} [(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})]$$

Figure J. List

## Strange tagging

- High-momentum kaon in jet is a clue to strange jets
  - Contamination from  $g \rightarrow ss$  give relatively low momentum
- $dE/dx$  is essential for Particle ID in ILD
  - As well as ToF, but only effective in low energy tracks (which are less important in strange tagging)
- Using newly-developed **comprehensive PID**
  - Giving much better separation than previous PID



Fractions of tracks having > 5 GeV

CPID prediction

Fraction of true particles  
True particle

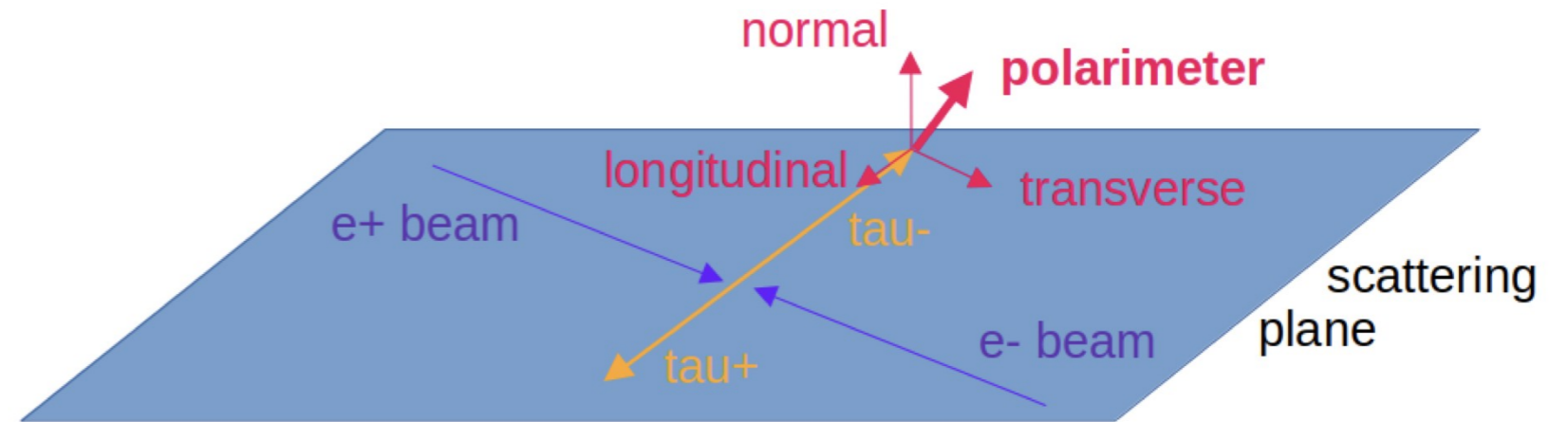
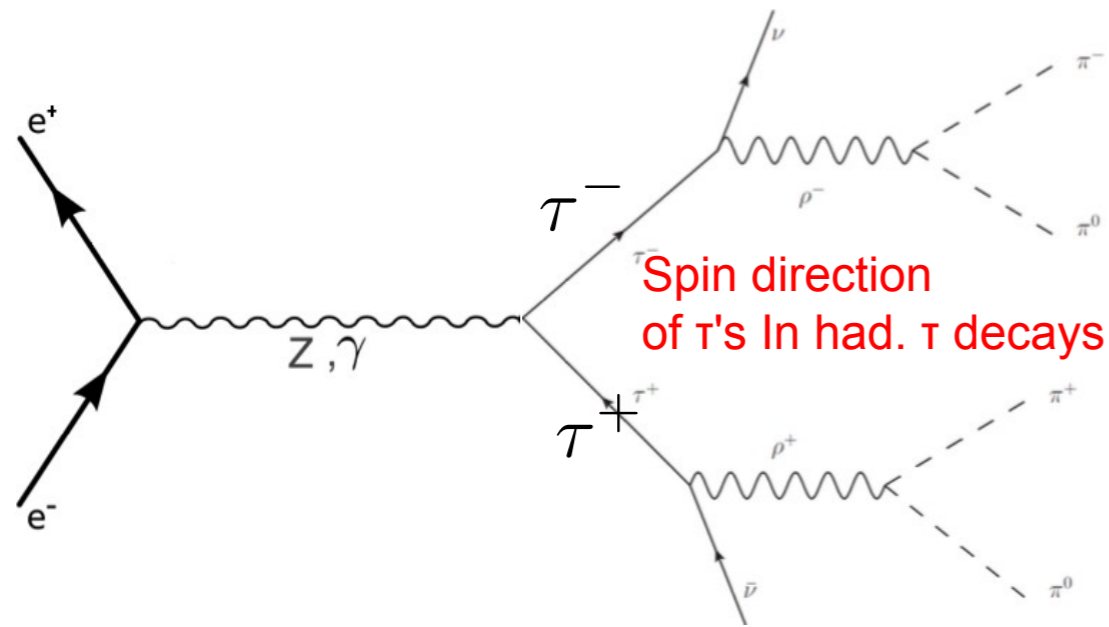
|       | K    | $\pi$ | p    | e    | $\mu$ |
|-------|------|-------|------|------|-------|
| K     | 0.65 | 0.04  | 0.20 | 0.04 | 0.10  |
| $\pi$ | 0.08 | 0.90  | 0.04 | 0.32 | 0.28  |
| p     | 0.26 | 0.04  | 0.76 | 0.09 | 0.08  |
| e     | 0.00 | 0.00  | 0.00 | 0.53 | 0.01  |
| $\mu$ | 0.01 | 0.02  | 0.00 | 0.01 | 0.53  |

$\uparrow 3 < p < 5 \text{ GeV}$

|       | K    | $\pi$ | p    | e    | $\mu$ |
|-------|------|-------|------|------|-------|
| K     | 0.74 | 0.07  | 0.20 | 0.13 | 0.16  |
| $\pi$ | 0.07 | 0.89  | 0.03 | 0.40 | 0.37  |
| p     | 0.18 | 0.03  | 0.76 | 0.09 | 0.06  |
| e     | 0.00 | 0.00  | 0.00 | 0.38 | 0.01  |
| $\mu$ | 0.01 | 0.01  | 0.00 | 0.01 | 0.40  |

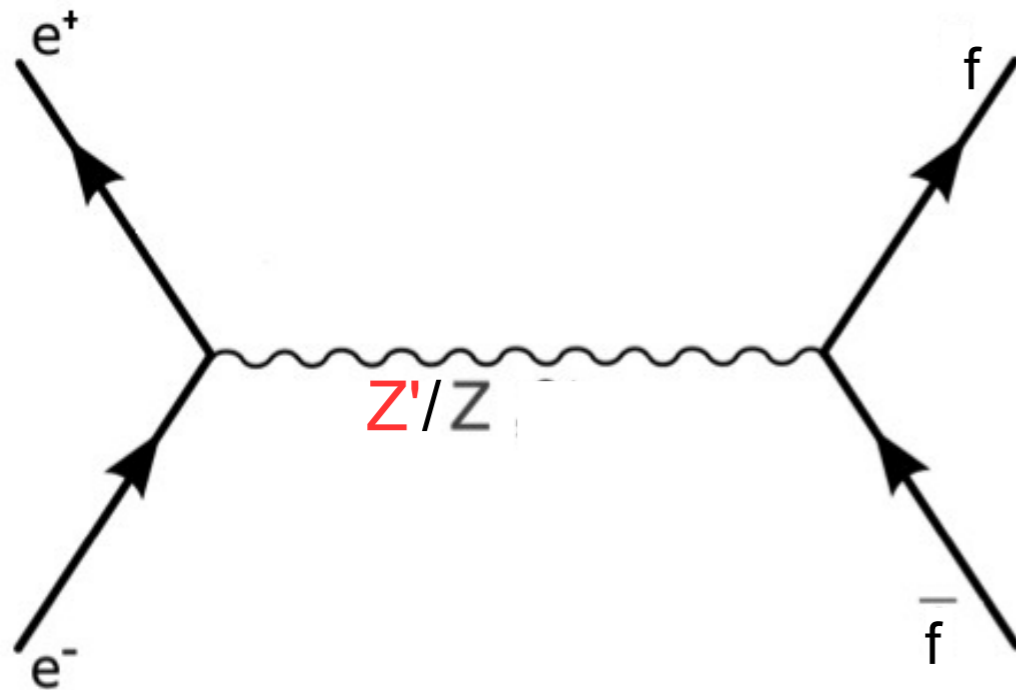
$\uparrow p > 5 \text{ GeV}$

More Kaons in ss  
More protons in gg



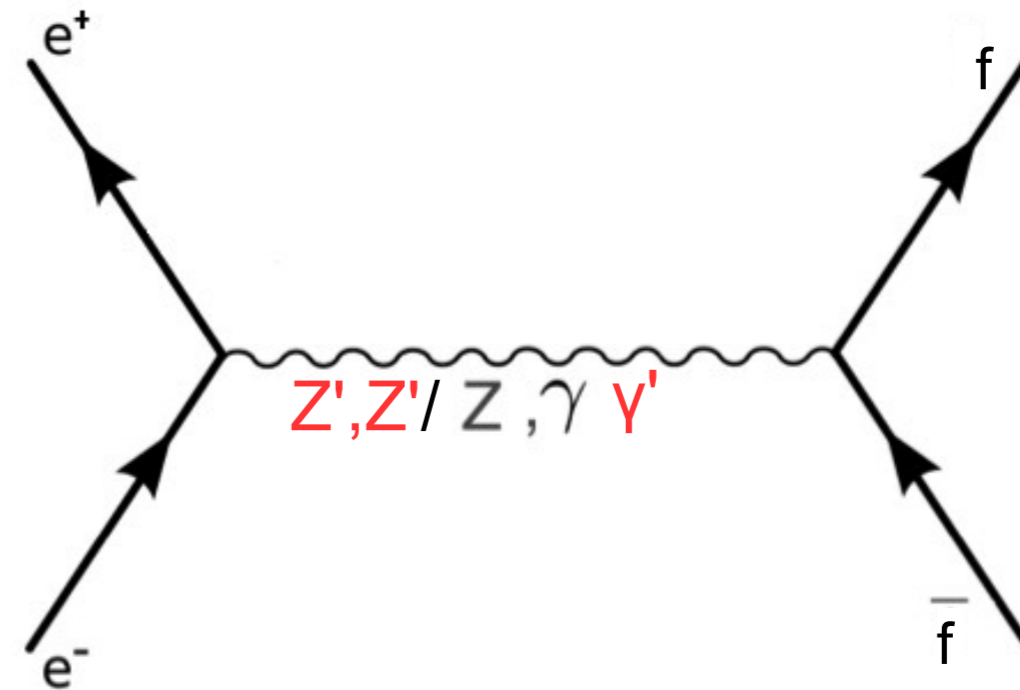
- The  $\tau$ -pair final state provides unique possibilities for testing the Standard Model and discovering the effects of new physics
  - access to the spin orientation of the final state fermions by consideration of the distribution of the  $\tau$  decay products
  - Probing of longitudinal polarisation (positive and negative helicity  $\tau$ )
  - transverse spin components
- Spin correlations between the two final state taus

## On the Z-pole



Sensitivity to  $Z/Z'$  mixing  
 Sensitivity to vector (and tensor) couplings of the  $Z$   
 •the photon does not “disturb”

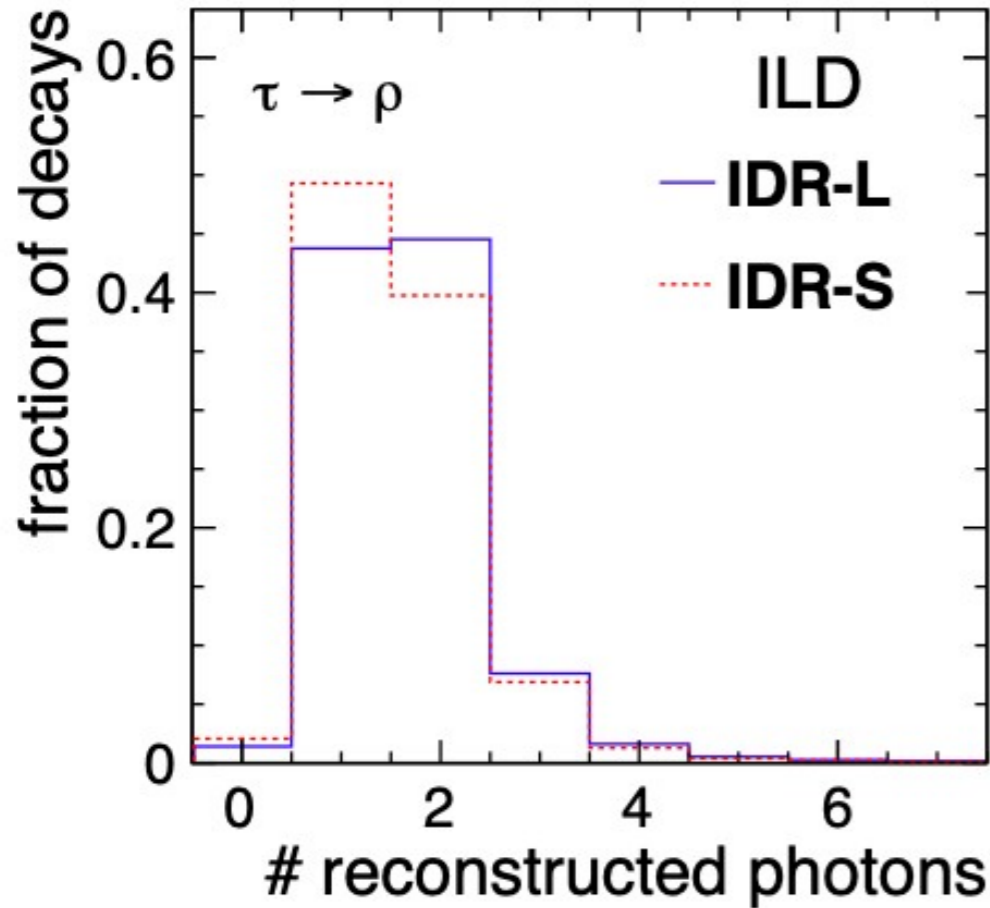
## Above the Z-pole



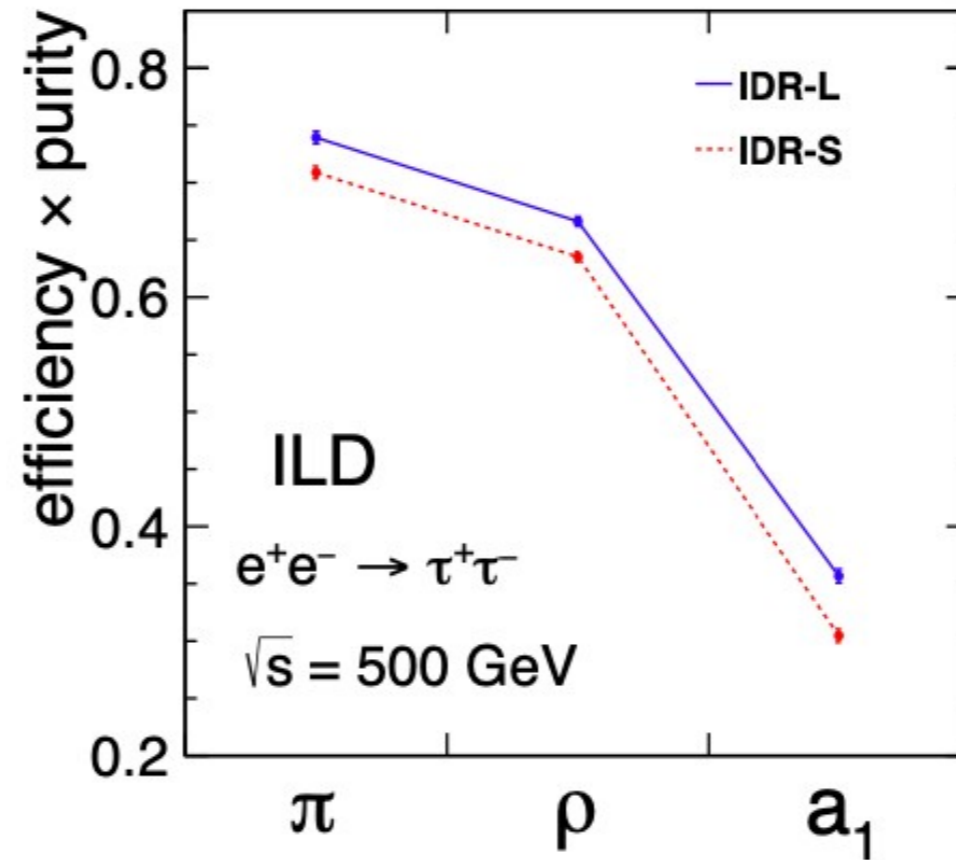
Sensitivity to interference effects of  $Z$  and photon!!  
 Measured couplings of photon and  $Z$  can be influenced by new physics effects  
 Interpretation of result is greatly supported by precise input from  $Z$  pole

# $\tau$ -lepton polarisation

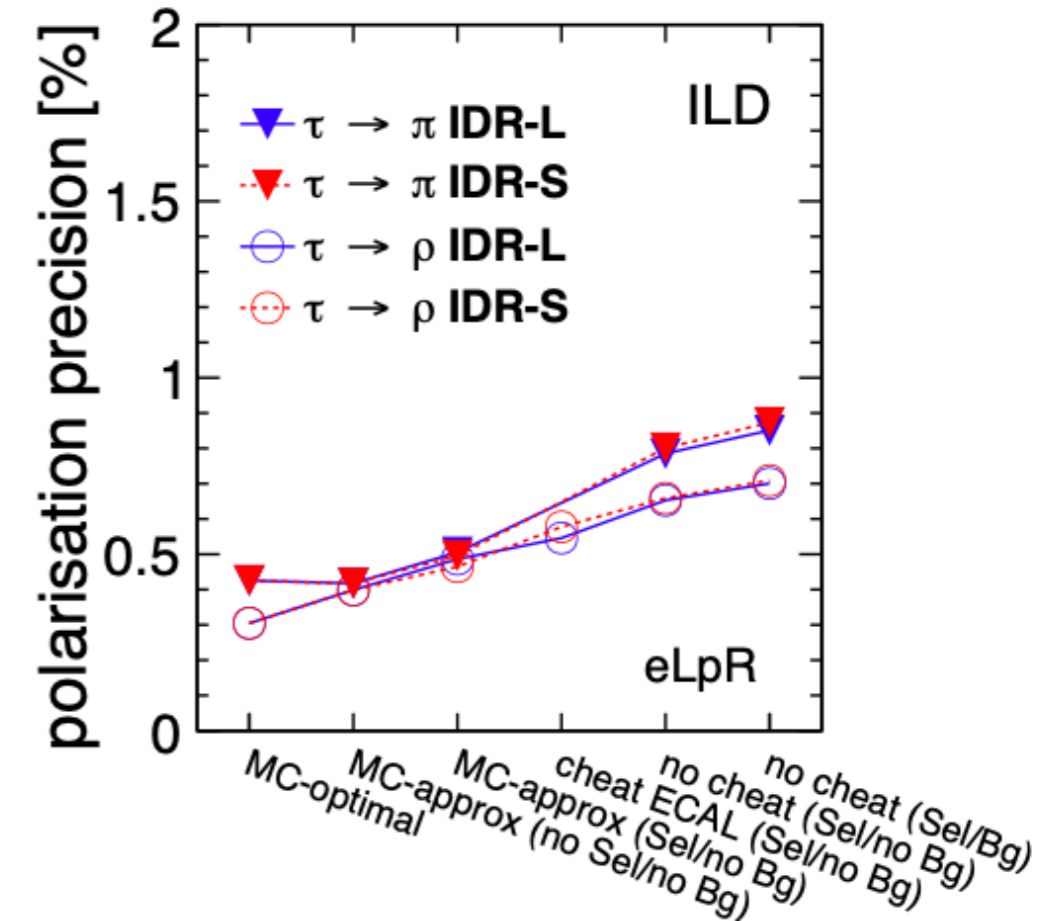
$e^+e^- \rightarrow \tau^+\tau^-$  Recent study at 500 GeV for ILD IDR



Photon separation gets involved at high energies  
Still often only one photon reconstructed

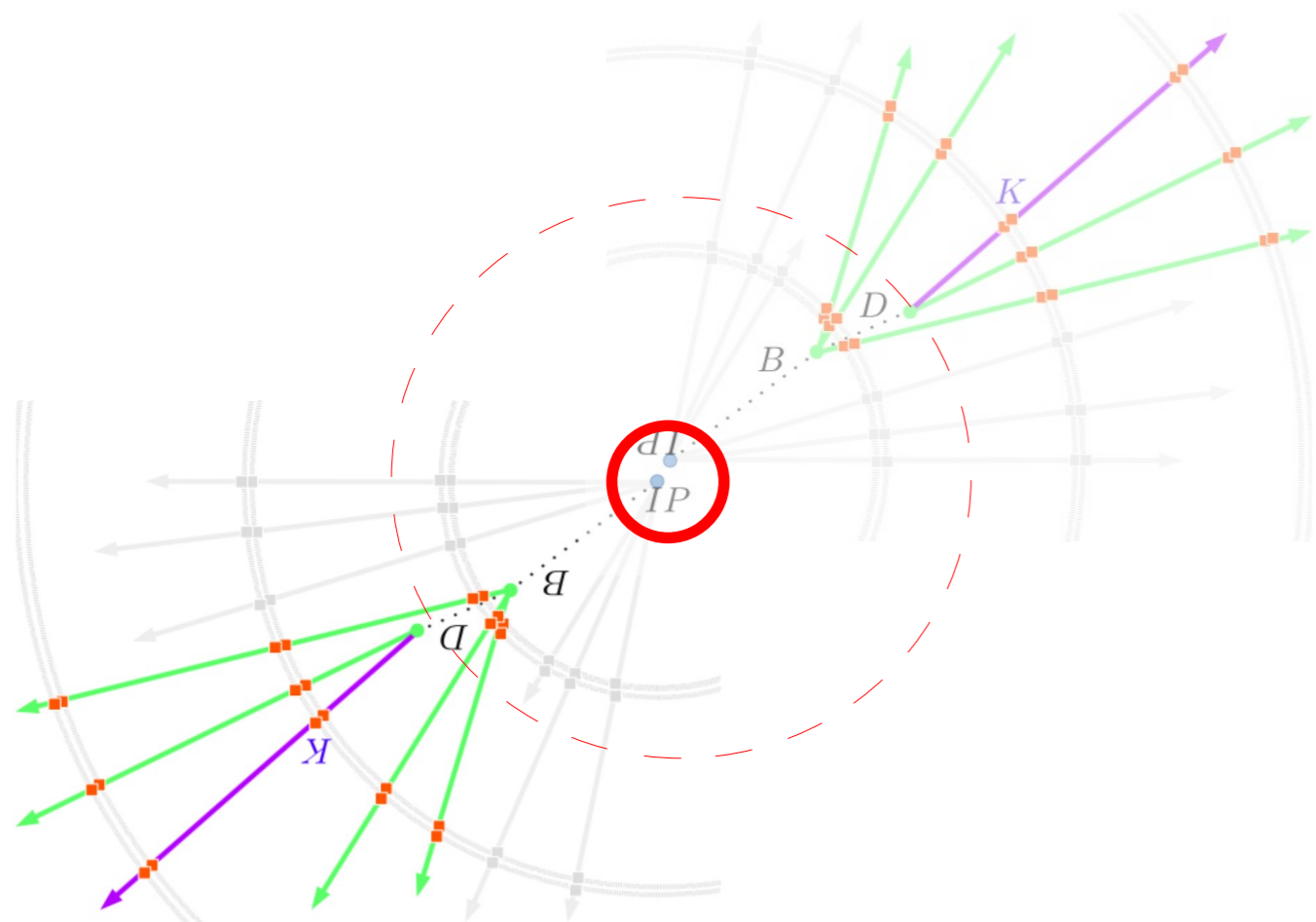


Efficiency x Purity drops with increasing photon multiplicity



Precision of tau polarisation of order 0.3%-1%

Close-by photons are challenge for highly granular calorimeters (in particular Ecal) at high-energies  
Ideal benchmark for detector optimisation  
Maybe still room for improvement, better algorithms?



Important systematic error is knowledge of tagging efficiency  $\epsilon_q$

Can be derived from data if tagging is independent in two hemispheres, i.e. if

$$C_q = \frac{\epsilon_{double}}{\epsilon_q^2} \approx 1$$

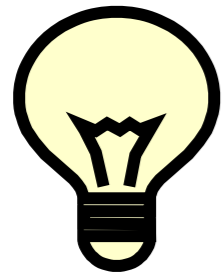
If  $C_q \neq 1 \Rightarrow$  Hemisphere correlations  $\Rightarrow$  systematic error

For example:

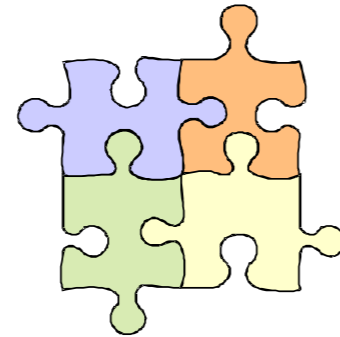
LEP (large beam spot):  $C_q - 1 \approx 3\% \Rightarrow \Delta R_b \approx 0.2\%$

SLC (smaller beam spot):  $C_q - 1 < 1\% \Rightarrow \Delta R_b \approx 0.07\%$

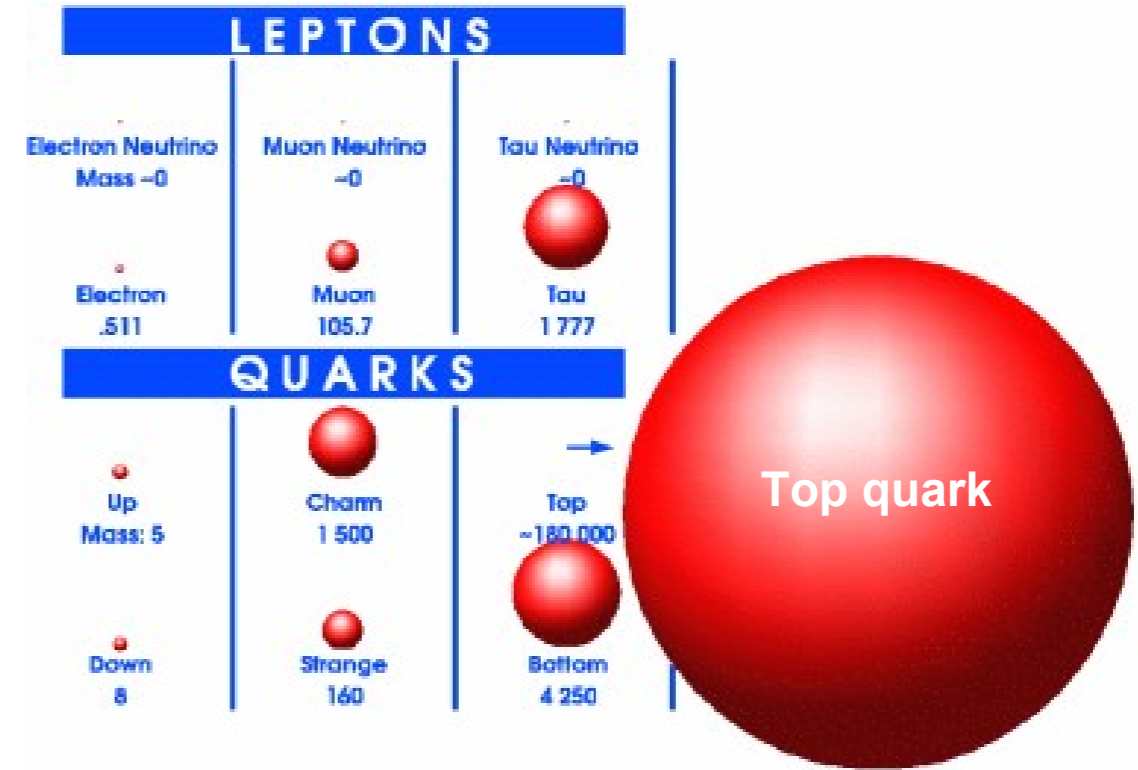
Future (small/tiny beam spot): Expect  $C_q - 1 = 0 \Rightarrow \Delta R_b \approx 0$   
to be verified however



Elementary Scalar?



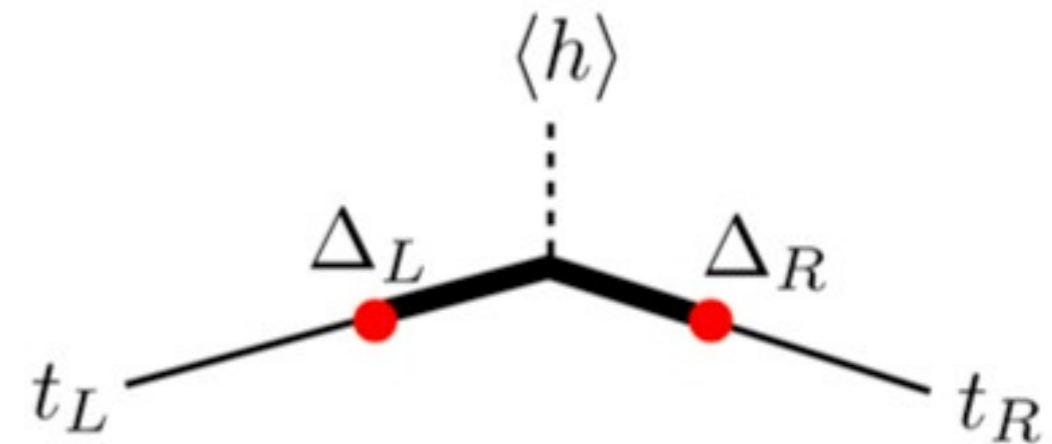
Composite object?



- Higgs and top quark are intimately coupled!  
Top Yukawa coupling  $O(1)$ !  
=> Top mass important SM Parameter

- New physics by compositeness?  
Higgs and top composite objects?

- **e+e- collider perfectly suited to decipher both particles**



Courtesy of S. Rychkov