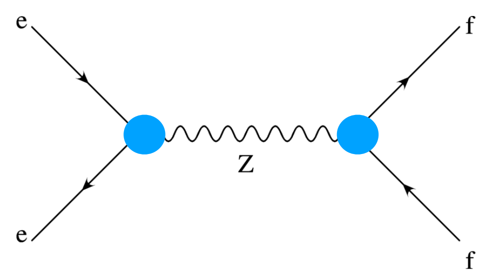
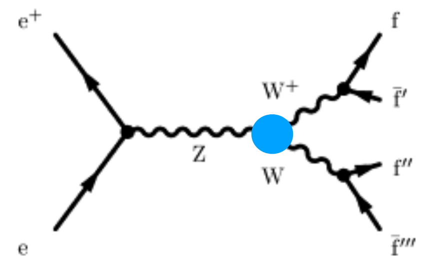
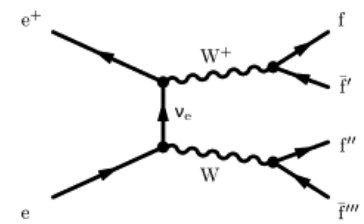
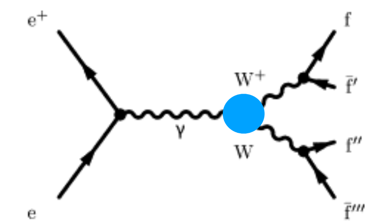
Electroweak and QCD measurements at e^+e^- colliders

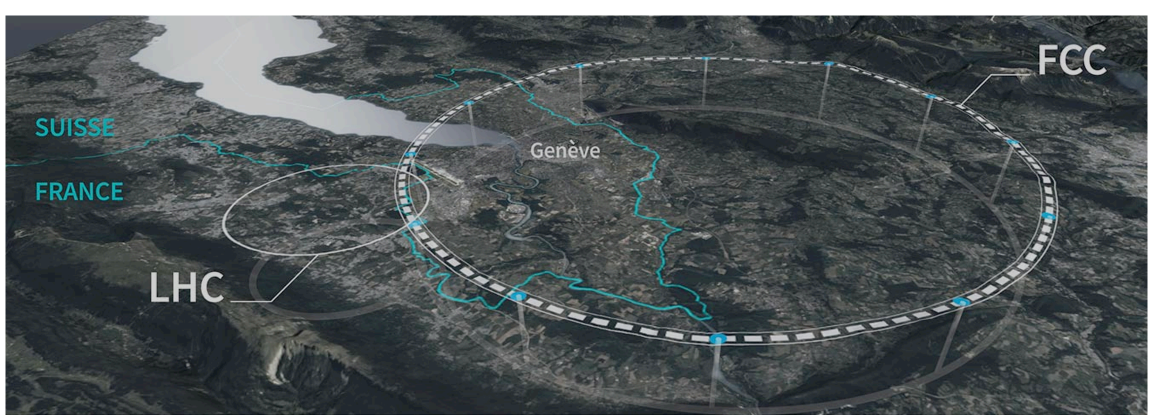








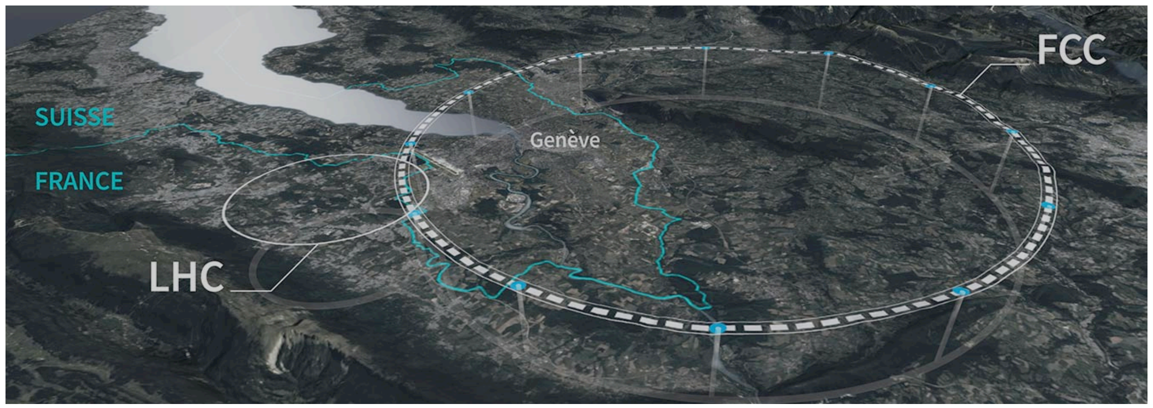
Chris Hays, Oxford University



European Strategy Update

ECFA UK meeting
23 September 2024

Proposals for a future e^+e^- collider



4 years @ $\sqrt{s} = 90$ GeV: **6 trillion** Z bosons
2 years @ $\sqrt{s} = 160$ GeV: **240 million** W bosons
3 years @ $\sqrt{s} = 240$ GeV: **1.5 million** Higgs bosons
5 years @ $\sqrt{s} = 365$ GeV: **2 million** top quarks

2 years @ $\sqrt{s} = 90$ GeV: 1.4 trillion Z bosons
1 year @ $\sqrt{s} = 160$ GeV: 80 million W bosons
7 years @ $\sqrt{s} = 240$ GeV: 2 million Higgs bosons

11 years @ $\sqrt{s} = 250$ GeV: 0.4 million Higgs bosons
2 years @ $\sqrt{s} = 350$ GeV: 1.3 million top quarks
9 years @ $\sqrt{s} = 500$ GeV: 0.2 million Higgs bosons
with longitudinal polarization

also CLIC, HALHF, C^3

ECFA physics studies for a future e^+e^- collider

WG1 physics performance

Identified ‘focus topics’ for study (arXiv:2401.07564)

Organization

- *Coordinators*: Jorge de Blas (Univ. Granada), Patrick Koppenburg (Nikhef), Jenny List (DESY), Fabio Maltoni (UC Louvain / Bologna)

Focus Groups

WG1 is organised in five focus groups.

Global interpretations (WG1-GLOB):

- *Conveners*: Jorge de Blas (Granada), Sven Heinemeyer (IFCA/IFT), Alexander Grohsjean (DESY), Junping Tian (Tokyo), Marcel Vos (Valencia)
- Dedicated wiki page

Precision (WG1-PREC):

- *Conveners*: Ayres Freitas (Pittsburgh), Paolo Azzurri (Pisa), Adrian Irles (Valencia), Andreas Meyer (DESY)
- Dedicated wiki page

Higgs/Top/EW (WG1-HTE):

- *Conveners*: Chris Hays (Oxford), Karsten Köneke (Freiburg), Fabio Maltoni (Louvain)
- Dedicated wiki page

HTE subgroup held series of meetings focussing on each $\sqrt{s}$

Flavour (WG1-FLAV):

- *Conveners*: David Marzocca (Trieste), Stephane Monteil (Clermont Ferrand), Pablo Goldenzweig (KIT)
- Dedicated wiki page

Searches (WG1-SRCH):

- *Conveners*: Roberto Franceschini (Rome III), Rebeca Gonzalez Suarez (Uppsala), Filip Zarnecki (Warsaw)
- Dedicated wiki page

Electroweak and QCD measurements

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and dominant exp. error
m_Z (keV/c^2)	91,186,700 ± 2200	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2,495,200 ± 2300	8	100	From Z line shape scan beam energy calibration
R_ℓ^Z ($\times 10^3$)	20,767 ± 25	0.06	0.2–1	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above
R_b ($\times 10^6$)	216,290 ± 660	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	41,541 ± 37	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231,480 ± 160	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	128,952 ± 14	4	Small	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV/c^2)	80,350 ± 15	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan beam energy calibration
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R_ℓ^W
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172,740 ± 500	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5–1.5%	Small	From E_{CM} = 365 GeV run

FCC

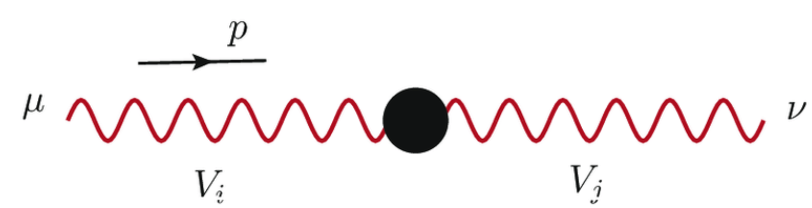
Electroweak measurements

Precision EW measurements probe multi-TeV physics

Effective field theory used to check consistency and sensitivity across measurements

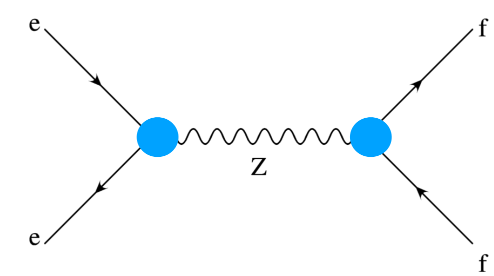
W boson mass measurement

(*Wmass* focus topic)



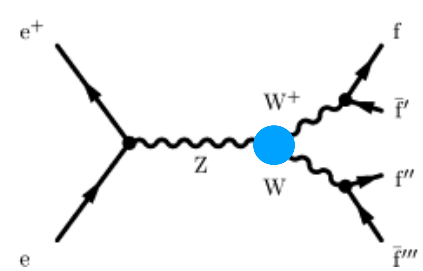
Two-fermion asymmetries and cross-sections

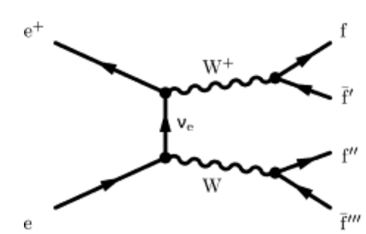
(*TwoF* focus topic)

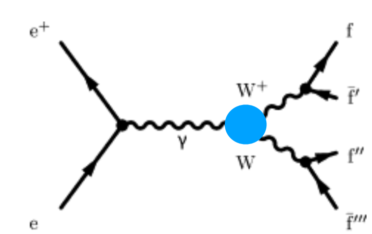


Differential WW measurements

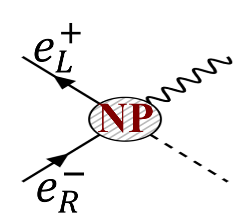
(*WWdiff* focus topic)

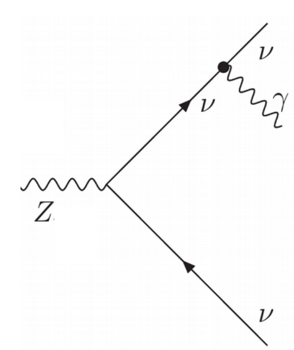


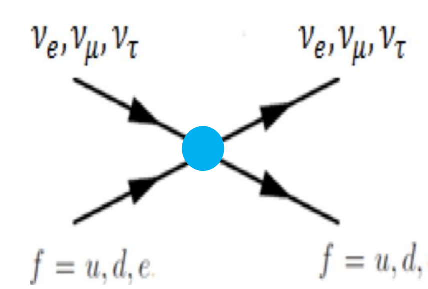




Other Z & neutrino interactions

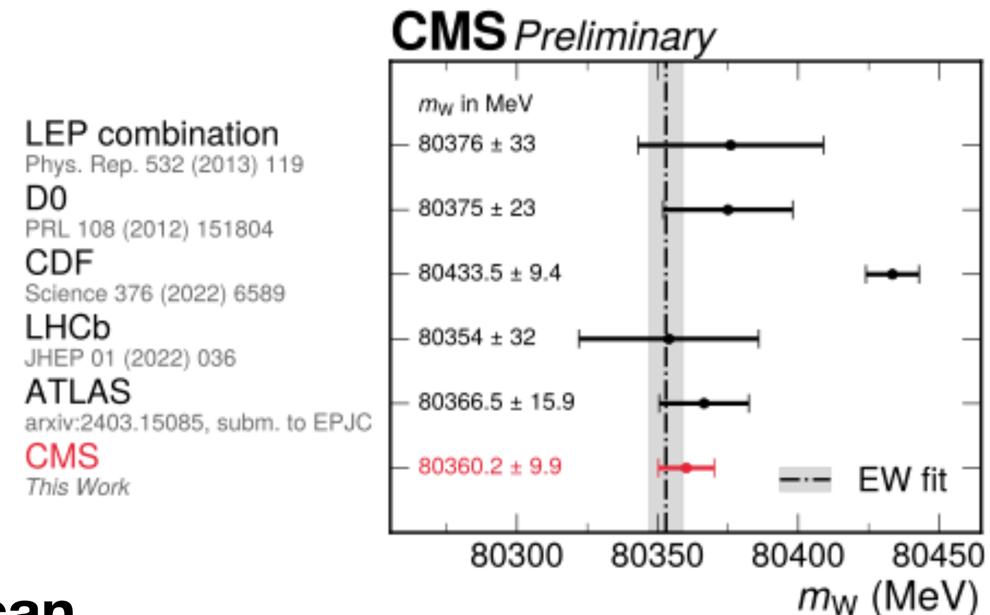




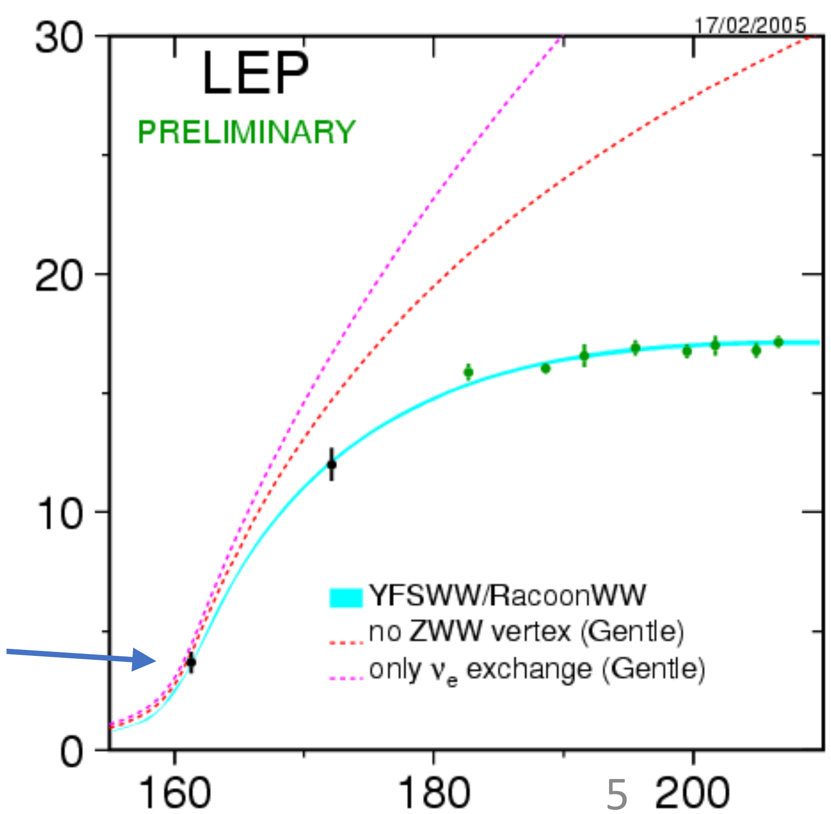


W boson mass measurement

Hadron-collider measurements reconstruct single W bosons



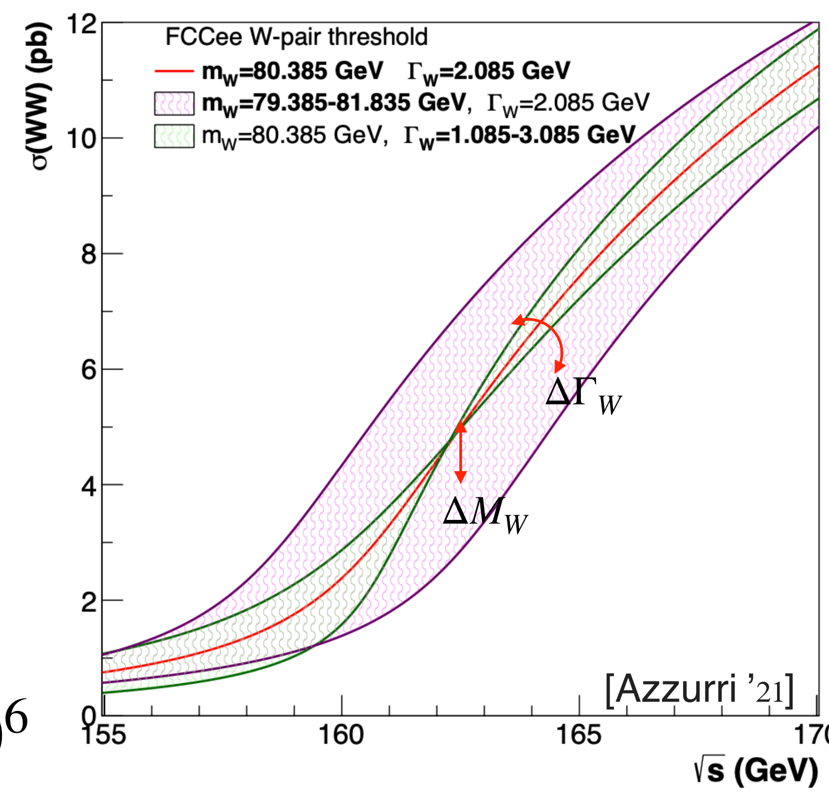
e⁺e⁻ colliders can perform a threshold scan



LEP: 340 MeV statistical uncertainty

$\mathscr{L} \times 10^6$

⟶



FCC: 0.3 MeV statistical uncertainty

Also:
1 MeV uncertainty
on the width

W boson mass measurement

achieving sub-MeV systematic precision is challenging

$$\Delta m_W(B) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \left(\frac{\Delta\sigma_B}{\varepsilon} \oplus \Delta\sigma_{TH}\right)$$

Background and Theory

$\Delta\sigma_{TH} < \mathbf{1fb}$ $(\Delta\sigma_{TH}/\,\sigma_{TH} < 2\cdot 10^{-4})$
$\Delta\sigma_B/\varepsilon < \mathbf{1fb}$ $(\Delta\sigma_B/\,\sigma_B < 4\cdot 10^{-3})$

$$\Delta m_W(\varepsilon) = \sigma\left(\frac{d\sigma}{dm_W}\right)^{-1} \left(\frac{\Delta\varepsilon}{\varepsilon} + \frac{\Delta L}{L}\right)$$

Acceptance and Luminosity

$\left(\frac{\Delta\varepsilon}{\varepsilon} \oplus \frac{\Delta L}{L}\right) < \mathbf{2\cdot 10^{-4}}$

$$\Delta m_W(E) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \left(\frac{d\sigma}{dE}\right)\Delta E \le \frac{1}{2}\Delta E$$

Collision energy

$\Delta E_b < 0.3\ MeV$ $(\Delta E_b/\,E_b < 4\cdot 10^{-6})$

FCC beam energy group led by Guy Wilkinson (Oxford)

ILC: 2.4 MeV statistical uncertainty

ILC polarised collisions : enhance (x4) t-channel WW production or suppress it to control background

A 4 MeV shift in M_W could be caused by new physics at 30 TeV

Uncertainty source	ΔM_W [MeV]	ΔM_W (syst.) [MeV]
Background	3.20	2.30
Polarization	3.73	1.27
Efficiency	3.86	1.18
Luminosity	3.76	0.78
A^B_{LR}	3.86	0.80
Statistical	2.43	
Systematic		3.10
Total Error	3.94	

+ theory

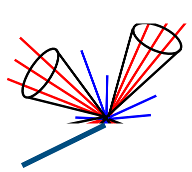
W boson mass measurement

e^+e^--collider measurements can also used reconstructed W-boson pairs ($\sqrt{s} = 160$ and 240 GeV)

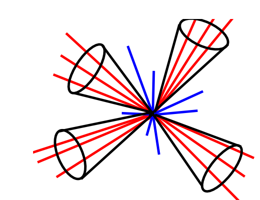
FCC

Stat uncertainty	Δm_W	$\Delta\Gamma_W$
eνqq	87 MeV → 0.9 MeV	200 MeV → 2 MeV
μνqq	82 MeV → 0.8 MeV	200 MeV → 2 MeV
τνqq	121 MeV → 1.2 MeV	320 MeV → 3.2 MeV
qqqq	70 MeV → 0.7 MeV	120 MeV → 1.2 MeV
combined	43 MeV → 0.4 MeV	90 MeV → 0.9 MeV

E_{CM} is again a main ingredient: sets jet energy scale
other main ingredients are the jets (and lepton) **angles**
secondary ingredients are the **jet velocities** (β=p/E)



Improvements in jet simulation will come from Z pole measurements



Source	Δm_W (MeV/c^2)				$\Delta\Gamma_W$ (MeV)			
	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$
e+μ momentum	3	8	-	4	5	4	-	4
e+μ momentum resoln	7	4	-	4	65	55	-	50
Jet energy scale/linearity	5	5	9	6	4	4	16	6
Jet energy resoln	4	2	8	4	20	18	36	22
Jet angle	5	5	4	5	2	2	3	2
Jet angle resoln	3	2	3	3	6	7	8	7
Jet boost	17	17	20	17	3	3	3	3
Fragmentation	10	10	15	11	22	23	37	25
Radiative corrections	3	2	3	3	3	2	2	2
LEP energy	9	9	10	9	7	7	10	8
Calibration ($e\nu q\bar{q}$ only)	10	-	-	4	20	-	-	9
Ref MC Statistics	3	3	5	2	7	7	10	5
Bkgnd contamination	3	1	6	2	5	4	19	7

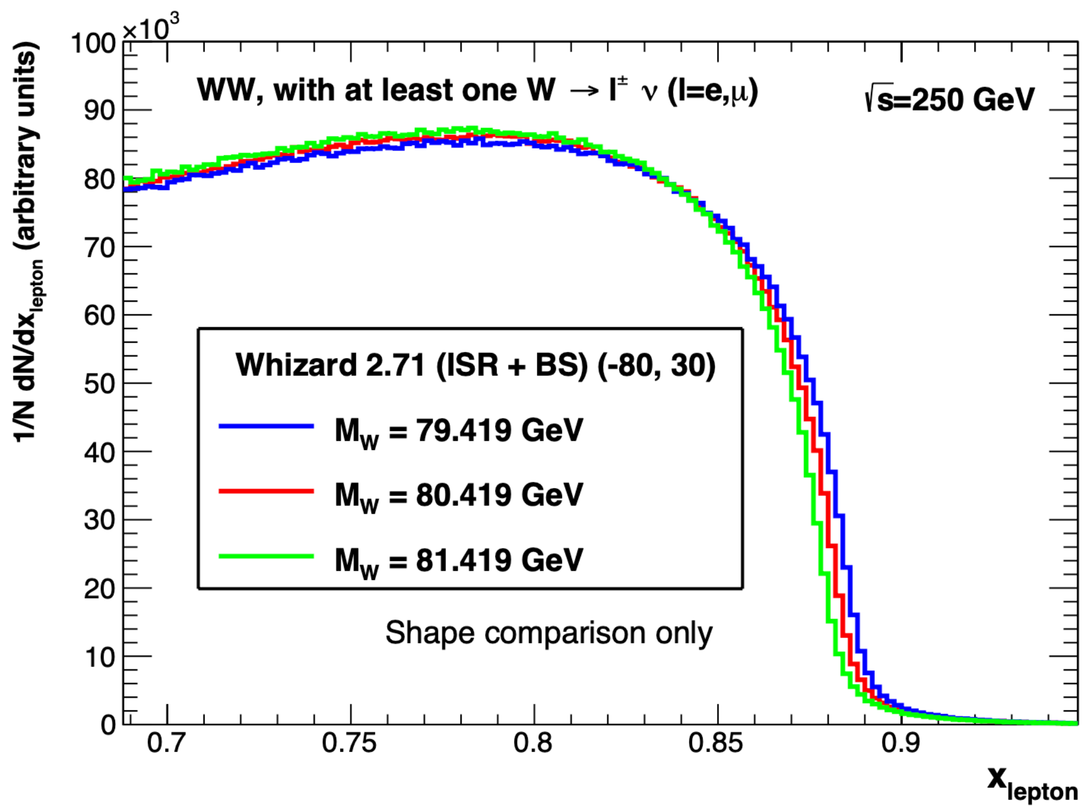
Source	Δm_W (MeV/c^2)			$\Delta\Gamma_W$ (MeV)		
	standard	PCUT	CONE	standard	PCUT	CONE
Jet energy scale/linearity	2	2	3	2	12	4
Jet energy resoln	0	1	0	7	9	10
Jet angle	6	6	6	1	3	3
Jet angle resoln	1	3	2	15	18	9
Jet boost	14	15	11	5	5	4
Fragmentation	10	20	20	20	40	40
Radiative Corrections	2	2	2	5	7	7
LEP energy	9	10	10	7	7	7
Ref MC Statistics	2	3	3	5	7	7
Bkgnd contamination	8	5	5	29	31	32
Colour reconnection	79	28	36	104	24	45
Bose-Einstein effects	6	2	3	20	10	10

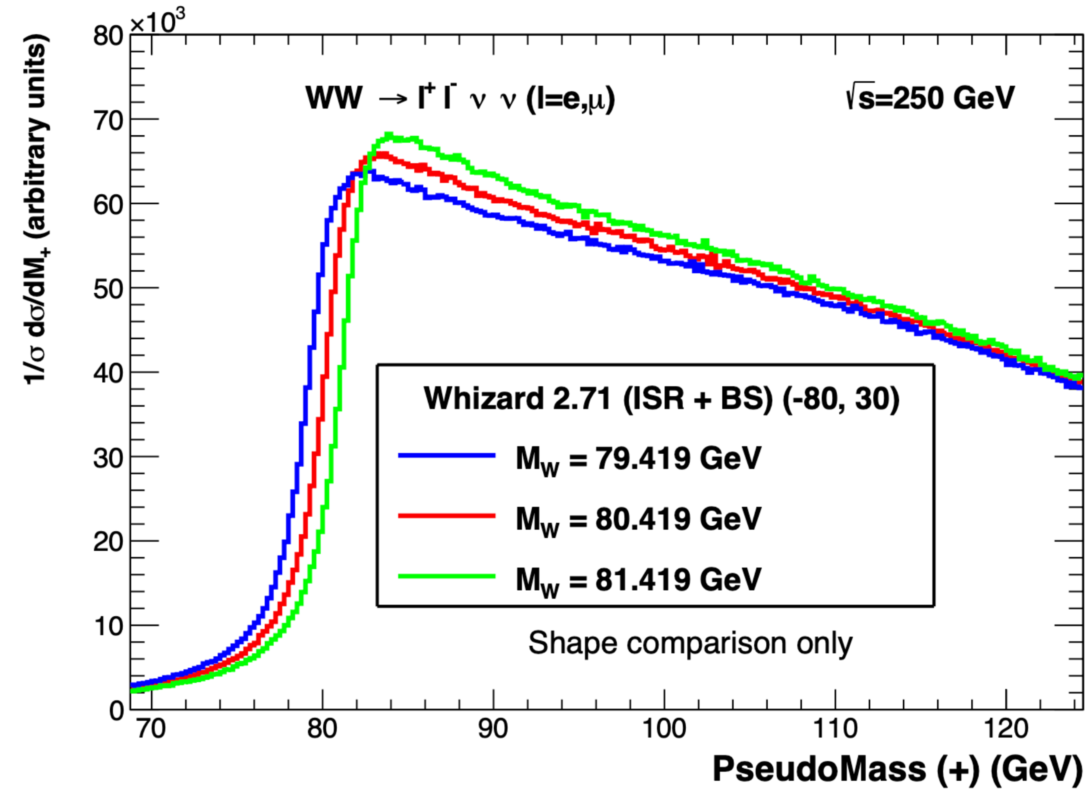
W boson mass measurement

Graham Wilson, arXiv:2203.07622

New ideas for observables could improve precision

Endpoints in the lepton (or jet) energy a $E\ell = E_{CM}(1 \pm \beta)$ where β is the W velocity





ILC

expected statistical Δm_W =4.4 MeV with 2/ab@250 GeV
experimental syst from lepton energy calibration

Focus topic team also considering single-W production at $\sqrt{s} = 91$ GeV

1 million W bosons expected

Graham Wilson, Josh Bendavid, Juergen Reuter, Keisho Hidaka, Martin Beneke, Raimund Strohmer, Simon Platzer, Stefan Dittmaier

Forward backward asymmetries

FCC

Z pole

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and dominant exp. error
$\sin^2\theta_W^{\text{eff}}$ $(\times 10^6)$	$231{,}480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$A_{FB}^{b,0}$ $(\times 10^4)$	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics

aggressive targets: systematic uncertainties are key

A_{FB}^{b} systematics studies ongoing

We know that statistical uncertainty will not be an issue

- LEP combination has ~equal stat and syst contributions
- We expect ~10^5 times more statistics at FCC-ee ⇒ ~300 times smaller stat. uncertainty

Systematic uncertainties expected to be dominant

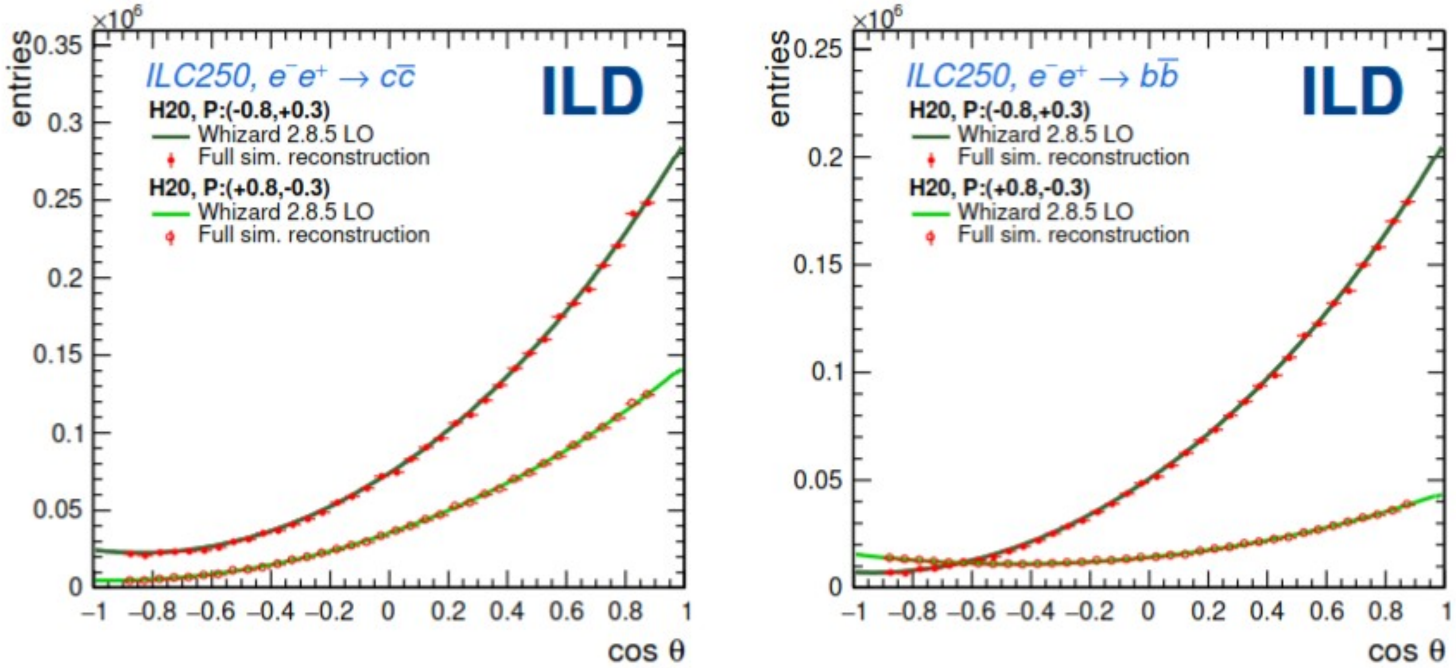
- Modelling b-fragmentation
  - Affecting B-hadron kinematics
- Final-state QCD radiation effects
  - Affecting jet shapes, distribution of charge, B-hadron kinematics…
- b-tagging efficiency:
  - Uncertainty on mis-tag rate affecting background prediction
  - p_T and η dependency of b-tagging eff. for signal

Forward backward asymmetries

ILC studying sensitivity to new physics off the Z-pole

▷ At least 4 observables for AFB at ILC250 per energy point

- 2 quarks and 2 polarisations (eLpR, eRpL)



▶ **Per mil level statistical uncertainties reachable for the nominal ILC250-500 program**

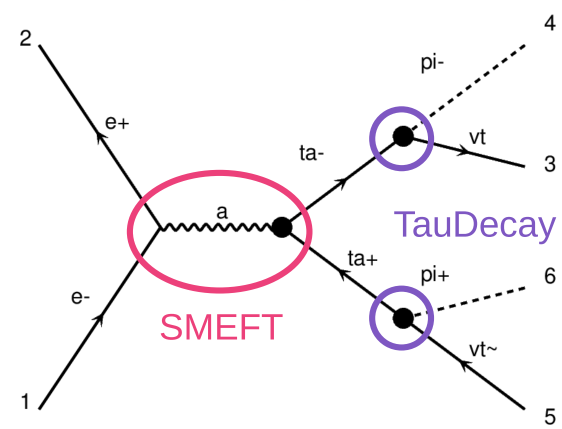
- **Smaller exp syst. Uncertainties**
- **Fragmentation, angular correlations → minimized** thanks to **double tagging** techniques and Data Driven measurement of efficiencies **à la LEP and SLC**

5-sigma sensitivity to Z' mass of 7 TeV

Increases to 10 TeV with running at 500 GeV

Adrian Irles et al, 2403.09144

Studies ongoing in tau-tau final states



Daniel Jeans, TwoF meeting

Forward backward asymmetries

Expansion to light flavours possible with particle id in the ParticleNet jet tagger

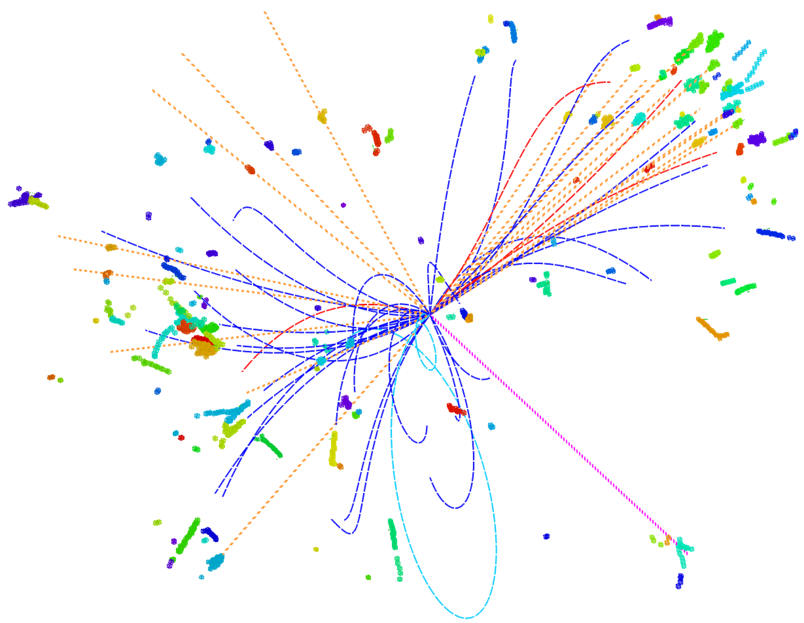


FIG. 1. Event display of an $e^+e^- \to \nu\bar{\nu}H \to \nu\bar{\nu}gg$ ($\sqrt{s}$ = 240 GeV) event simulated and reconstructed with the CEPC baseline detector [17]. Different particles are depicted with colored curves and straight lines: red for $e^{\pm}$, cyan for $\mu^{\pm}$, blue for $\pi^{\pm}$, orange for photons, and magenta for neutral hadrons.

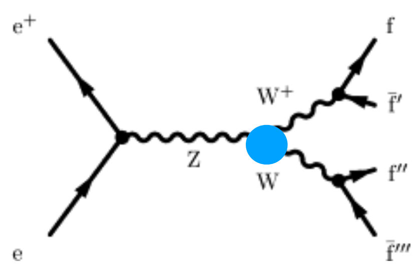
H Liang, M Ruan et al, 2310.03440

True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.745	0.163	0.033	0.025	0.004	0.003	0.002	0.003	0.002	0.002	0.017
$\bar{b}$	0.170	0.737	0.026	0.033	0.003	0.004	0.003	0.002	0.002	0.003	0.018
c	0.015	0.014	0.743	0.055	0.036	0.031	0.025	0.009	0.009	0.018	0.043
$\bar{c}$	0.016	0.015	0.056	0.739	0.032	0.037	0.009	0.026	0.017	0.010	0.043
s	0.003	0.002	0.020	0.018	0.543	0.102	0.030	0.080	0.063	0.045	0.092
$\bar{s}$	0.003	0.003	0.018	0.020	0.102	0.542	0.084	0.028	0.045	0.062	0.094
u	0.002	0.003	0.020	0.011	0.044	0.131	0.367	0.055	0.080	0.174	0.111
$\bar{u}$	0.003	0.003	0.011	0.019	0.132	0.043	0.062	0.356	0.178	0.081	0.111
d	0.003	0.003	0.012	0.019	0.112	0.092	0.082	0.207	0.277	0.079	0.112
$\bar{d}$	0.003	0.003	0.020	0.012	0.092	0.112	0.219	0.076	0.079	0.272	0.113
G	0.015	0.014	0.024	0.024	0.052	0.052	0.043	0.041	0.034	0.034	0.667

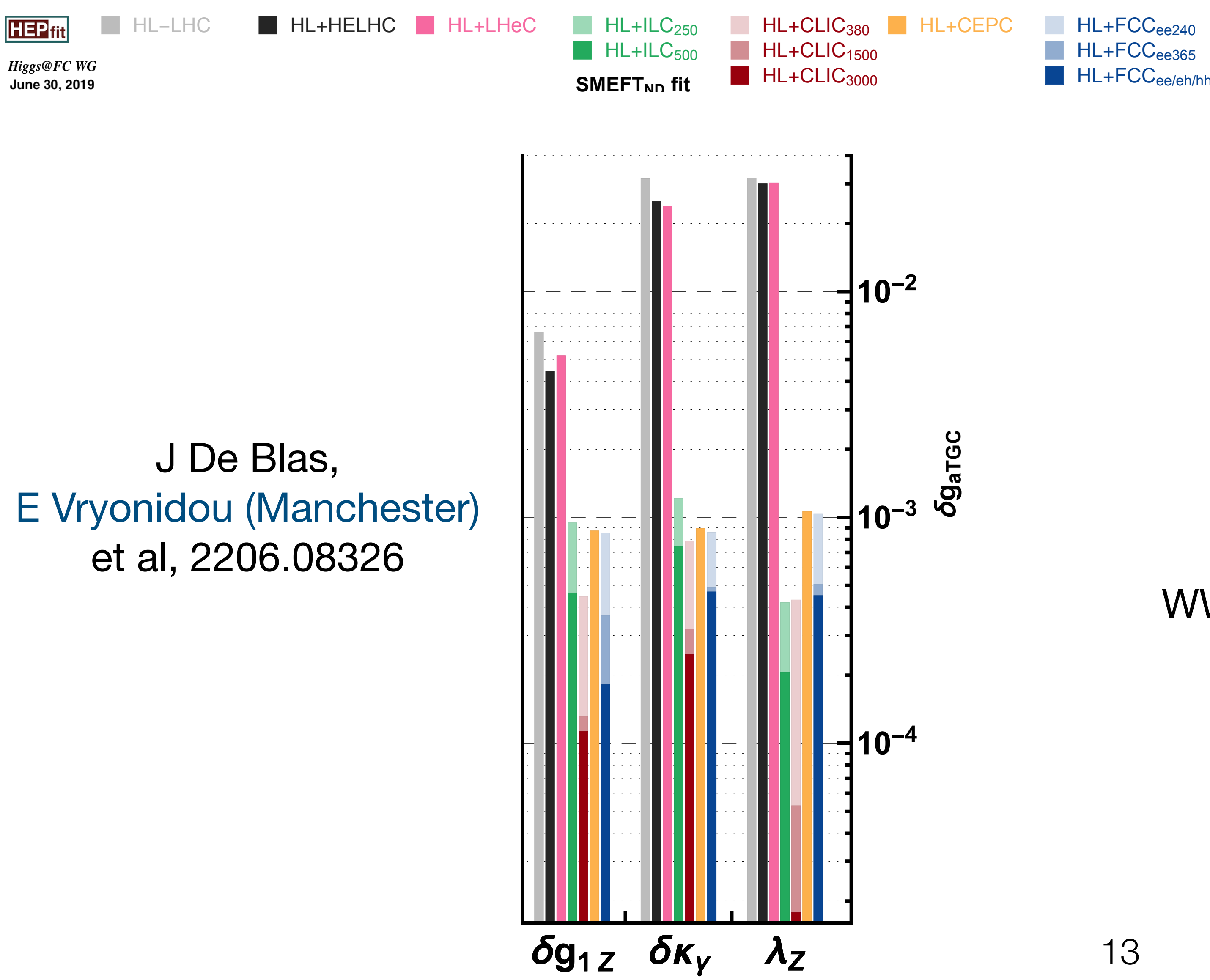
TwoF team to report at ECFA Paris workshop
E Bagnaschi, A Irles, D Jeans, A Vicini

Differential WW measurements

Snowmass study with HEPfit used optimal observables to estimate aTGC sensitivity

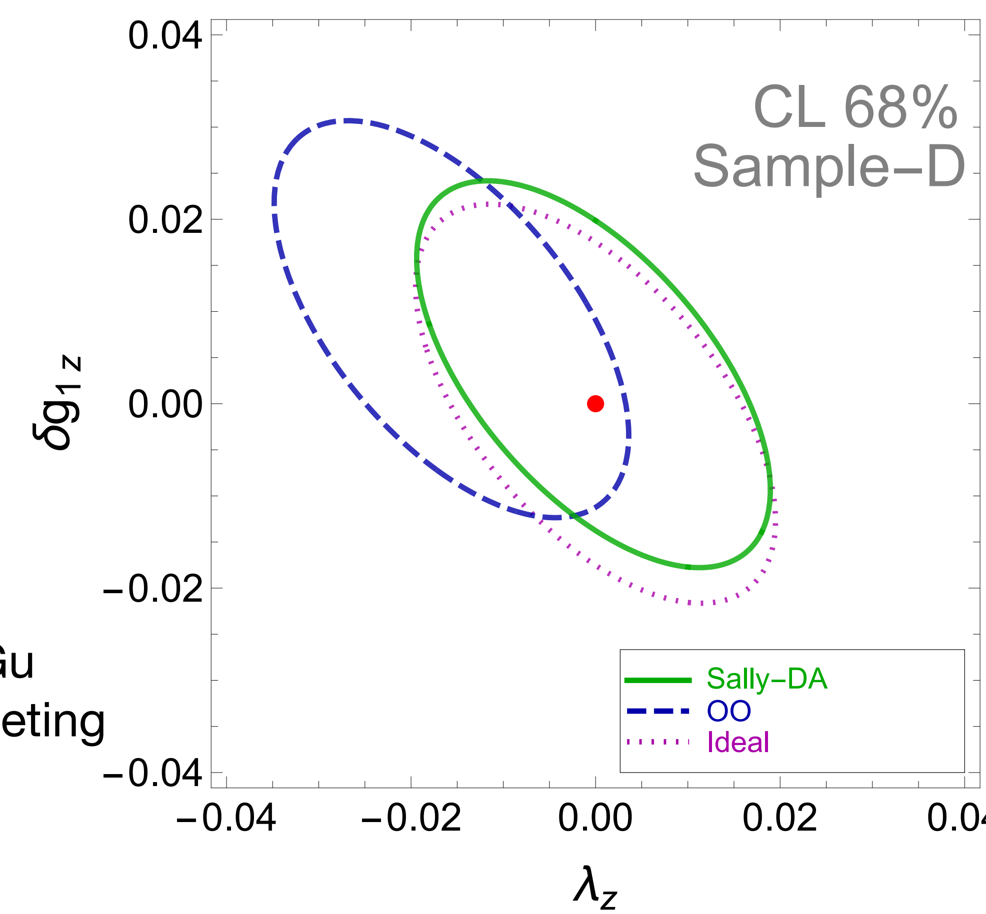


$$\Delta\mathcal{L}^{\rm aTGC} = ie\delta\kappa_\gamma\, A^{\mu\nu}W^+_\mu W^-_\nu + ig\cos\theta_w \left[\delta g_{1,Z}\,(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})Z^\nu + (\delta g_{1,Z} - \frac{g'^{\,2}}{g^2}\delta\kappa_\gamma)\, Z^{\mu\nu}W^+_\mu W^-_\nu\right] + \frac{ig\lambda_Z}{m_W^2}\left(\sin\theta_w W^{+\nu}_\mu W^{-\rho}_\nu A^\mu_\rho + \cos\theta_w W^{+\nu}_\mu W^{-\rho}_\nu Z^\mu_\rho\right), \quad (10)$$



J De Blas,
E Vryonidou (Manchester)
et al, 2206.08326

Recent studies consider effects of detector resolution and background

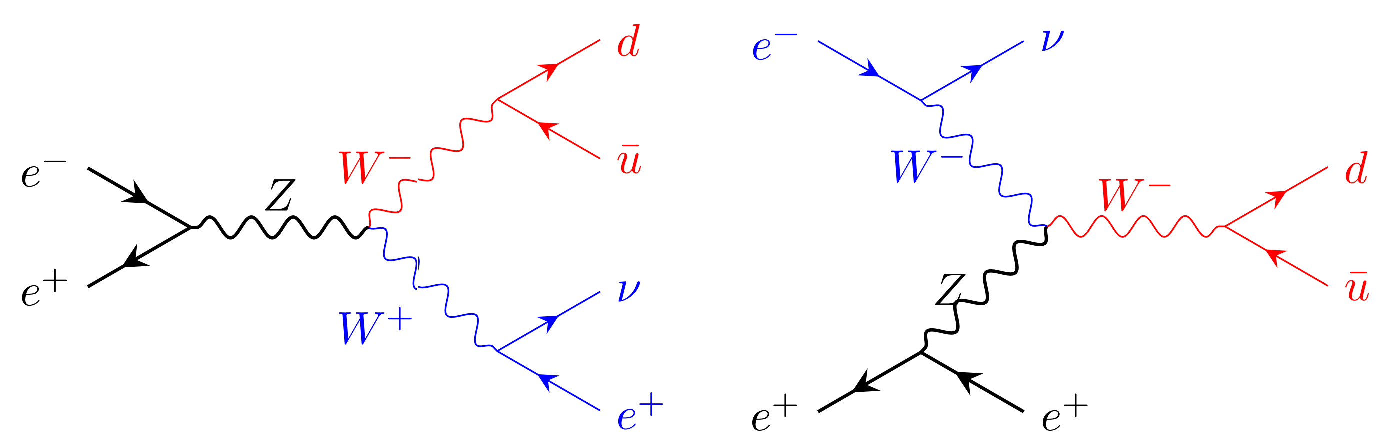


Jiayin Gu
WWdiff meeting

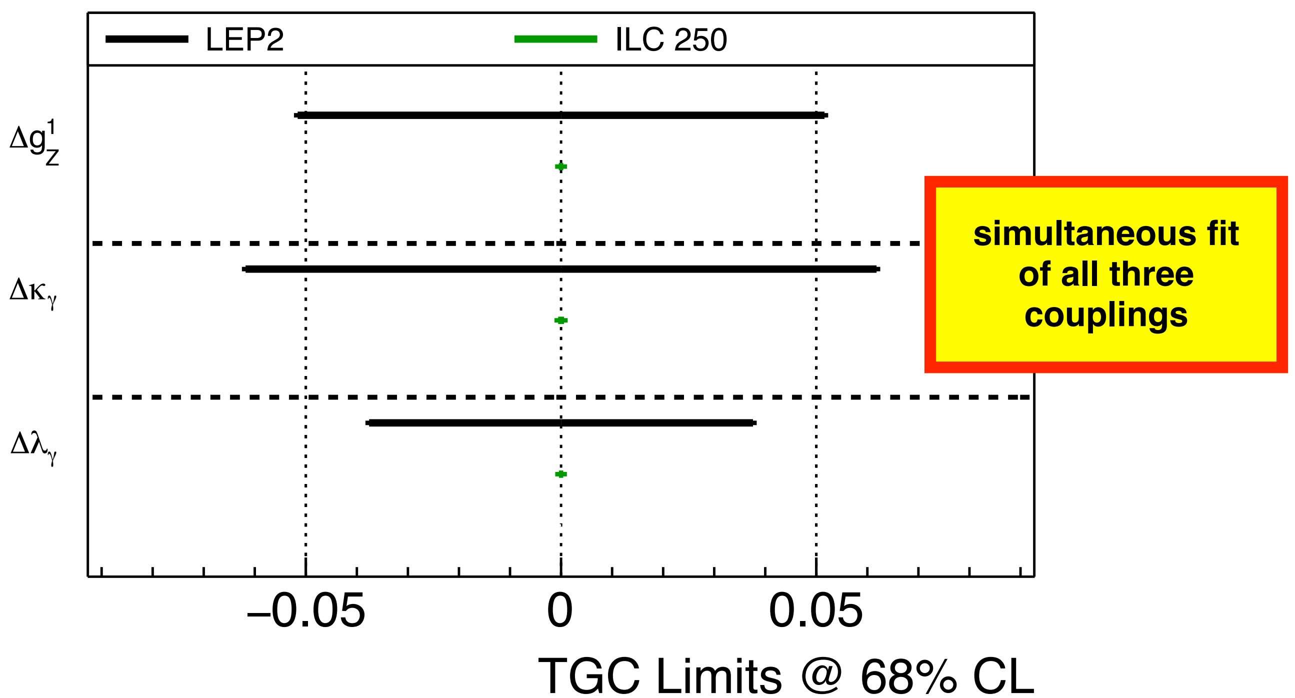
Neural network applied to detector-level sample gives similar performance to optimal observable

Differential WW measurements

ILC studies demonstrated the importance of single-W production



TGC	E_{CMS}[GeV]	$e^+e^- \to \mu\nu q\bar{q}$	$e^+e^- \to e\nu q\bar{q}$	**comb.**
$\Delta g\ [10^{-4}]$	250	45.8	15.8	13.9
	500	8.46	4.14	3.52
$\Delta\kappa\ [10^{-4}]$	250	54.9	19	16.5
	500	8.85	4.63	3.65
$\Delta\lambda\ [10^{-4}]$	250	68.6	22.5	21.6
	500	15.6	6.14	5.77



Recent studies consider detector acceptance and combined fits of 2f and 4f final states to reduce the associated systematic

Studies ongoing on impact of tracking efficiency

Focus topic team: P Azzi, T Barklow, J De Blas, A Denner, A Grohsjean, W Kilian, J List, F Siegert

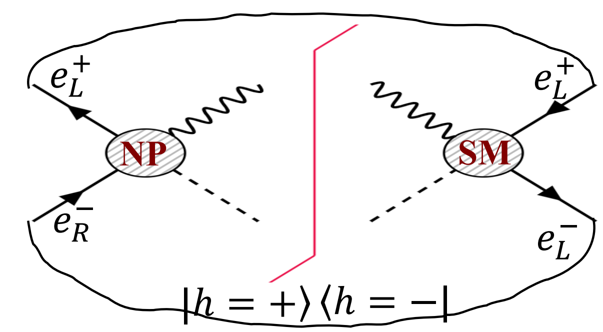
Electron couplings using transverse spin asymmetry

Recent study proposes transversely polarised beams to constrain dipole interactions

Unpolarized beams: dominant sensitivity to new physics decreases as $1/\Lambda^4$

Due to helicity flip in interference term

Transversely polarized beams: sensitive to interference with SM $(1/\Lambda^2)$



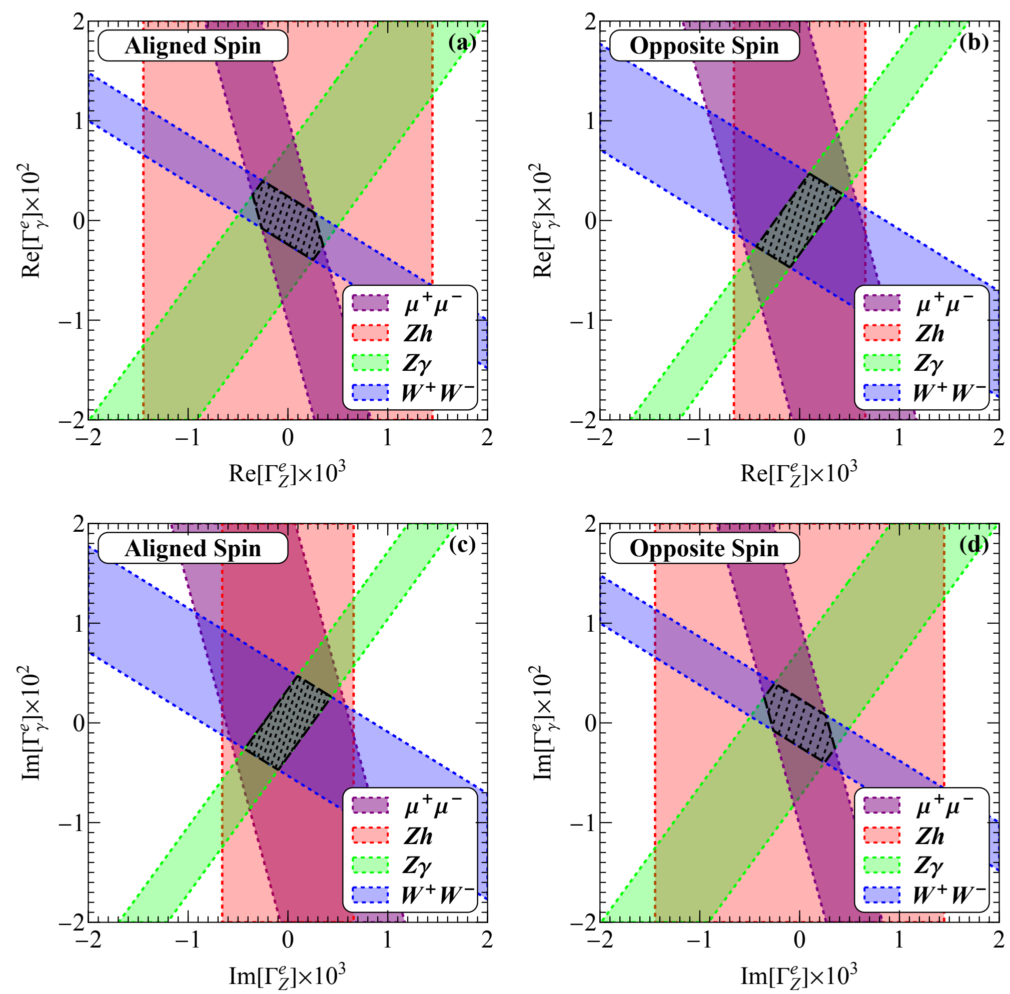
Spin dependent amplitude square:

$$|\mathcal{M}|^2 = \rho_{\alpha_1\alpha_1'}(\boldsymbol{s})\rho_{\alpha_2\alpha_2'}(\bar{\boldsymbol{s}})\mathcal{M}_{\alpha_1\alpha_2}(\phi)\mathcal{M}^*_{\alpha_1'\alpha_2'}(\phi)$$

$$\boldsymbol{s} = (b_1, b_2, \lambda) = (b_{\rm T}\cos\phi_0, b_{\rm T}\sin\phi_0, \lambda)$$

$$\rho = \frac{1}{2}(1+\boldsymbol{\sigma}\cdot\boldsymbol{s}) = \frac{1}{2}\begin{pmatrix} 1+\lambda & b_{\rm T}e^{-i\phi_0} \\ b_{\rm T}e^{i\phi_0} & 1-\lambda \end{pmatrix}$$

Term linear in b_T interferes with NP



	$\lvert\Gamma_Z^e\rvert$	$\lvert\Gamma_\gamma^e\rvert$
Our Study	**0.0002**	**0.005**
LHC Drell-Yan	0.0765	0.197
Z Partial Width	0.0582	0.093
$(g-2)_e$	10^{-2}	10^{-6}

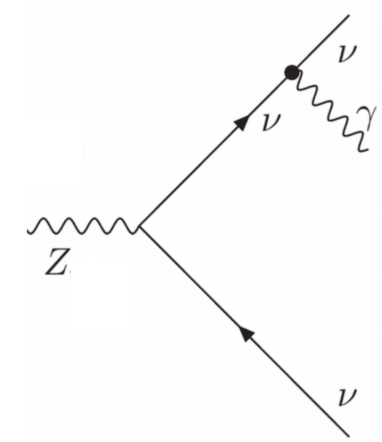
X-K Wen, B Yan, Z Yu, C-P Yuan, 2307.05236

Neutrino anomalous magnetic moment

Z-pole run could improve ν_τ magnetic moment constraints by two orders of magnitude

$$\mathscr{L}_\nu = \mu_B \sum_{i=e,\nu,\tau} k_i [\nu_i \sigma^{\mu\nu} \nu_i] F_{\mu\nu}$$

Bohr magneton



$$\Gamma(Z \to \nu \bar{\nu} \gamma) = \frac{\mu_B^2 \, \alpha \, m_Z^3 \left(\sum_i |k_i|^2\right)}{512 \pi^2 c_W^2 s_W^2}$$

From PDG

$$k_e < 2.9 \times 10^{-11}$$
$$k_\mu < 6.8 \times 10^{-10}$$
$$k_\tau < 3.9 \times 10^{-7}$$

$$\mathrm{BR}(Z \to \nu \bar{\nu} \gamma) = 2.3 \times 10^5 \, k^2$$

Improving bounds on MDM of neutrino-tau

naive estimations

Giga Z → $k < 6.6 \times 10^{-8}$

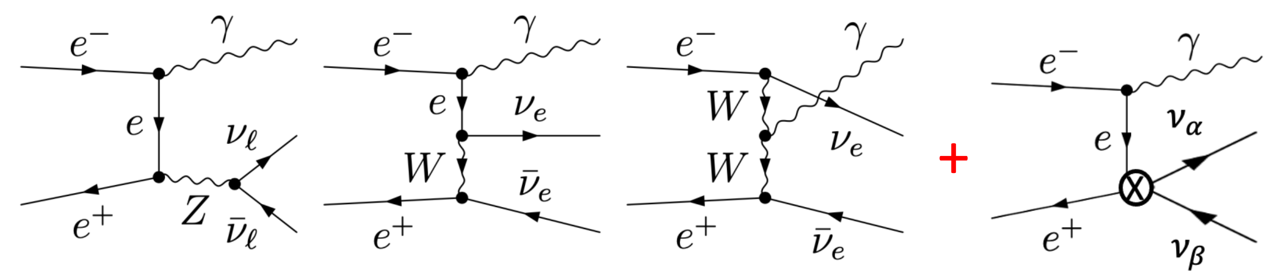
Tera Z → $k < 2.1 \times 10^{-9}$

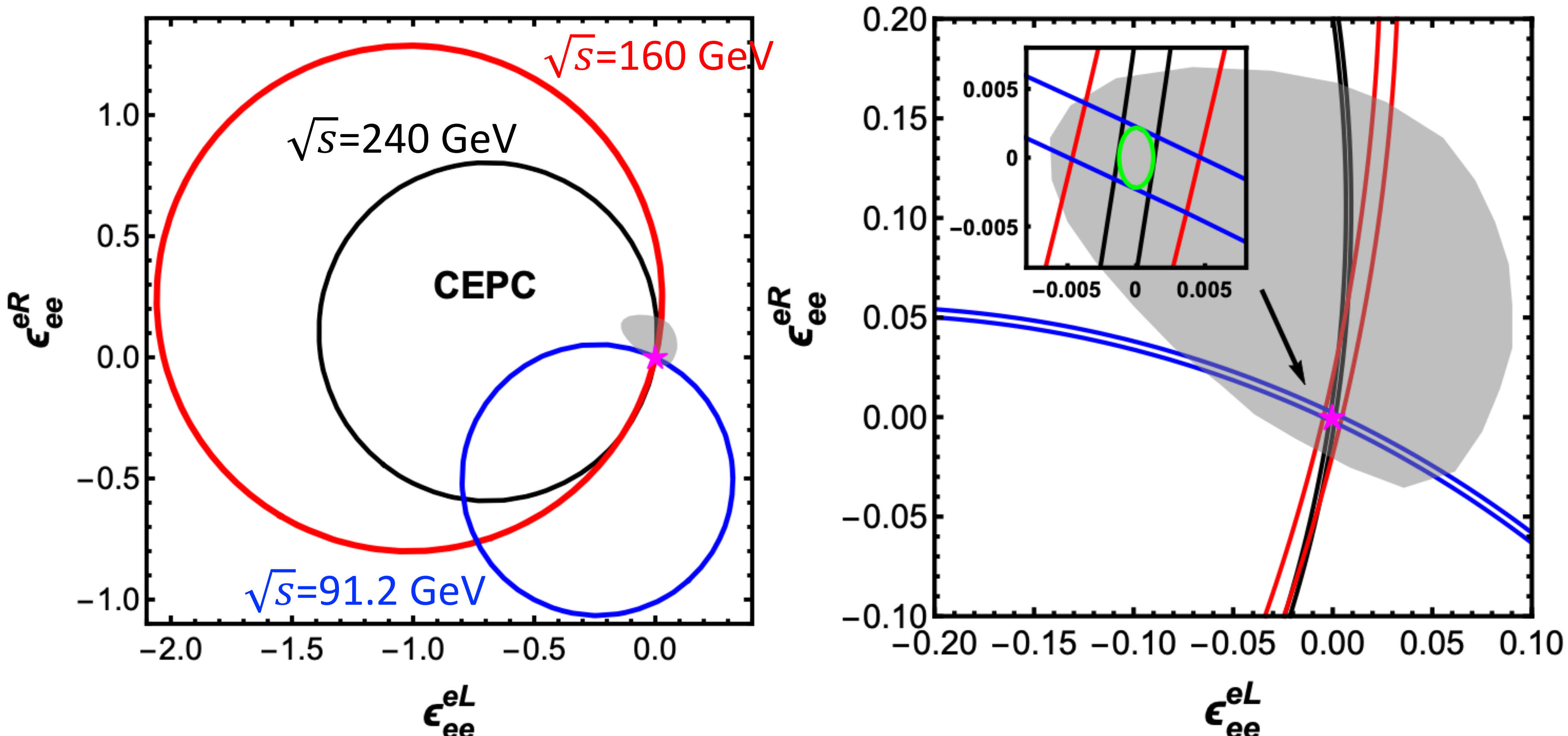
Neutrino four-fermion interactions

Single-photon final state also sensitive to four-fermion interactions involving neutrinos

Energy-dependent interaction

$$\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fC}[\overline{\nu_\alpha}\gamma^\rho P_L\nu_\beta]\,[\bar{f}\gamma_\rho P_C f]\ ,$$
$$\mathcal{L}_{\text{CC-NSI}} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{ff'C}[\overline{\nu_\beta}\gamma^\rho P_L\ell_\alpha]\,[\bar{f}'\gamma_\rho P_C f]$$





Y Zhang, J Liao, 2105.11215

QCD measurements

QCD measurements crucial to achieving precision physics goals
e.g. fragmentation & jet shapes

Heavy flavour production and fragmentation identified as a focus topic (*BCfrag and Gsplit*)

- anticipated (perturbative) theory precision: $\leq 1\%$ (personal take!)
  - at least $\mathcal{O}(\alpha_S^3)$ corrections for QCD event shapes
  - at least $\mathcal{O}(\alpha_S^2)$ corrections for QCD final states with up to four jets

    (I think we'll see the first of such calculations in the next 2-3 years)
  - systematic inclusion of $\mathcal{O}(\alpha_{EW})$ in a multiplicative scheme and a lot of mixed $\mathcal{O}(\alpha_S\alpha_{EW})$ corrections
  - NNLL parton shower matched to NNLO QCD

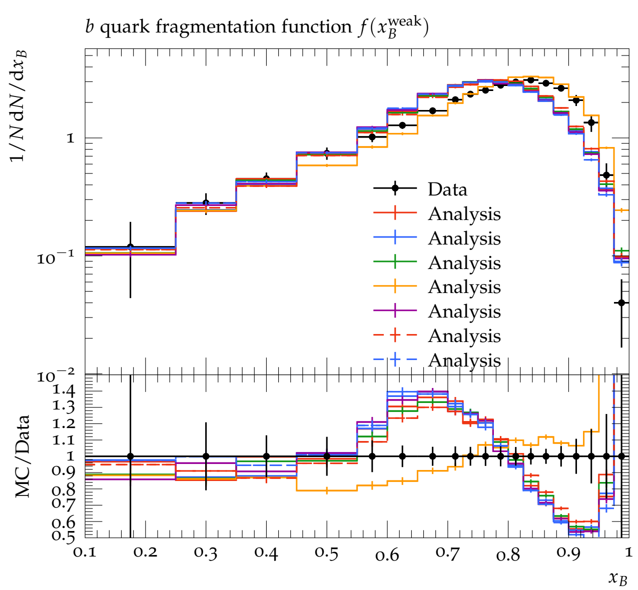
soft physics effects may dominate theory uncertainties:
no first-principles theory $\longrightarrow$ must measure!

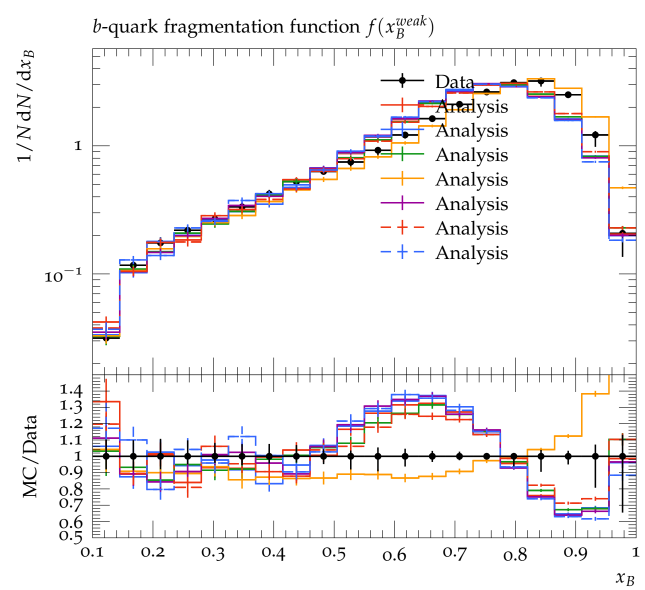
Frank Krauss (IPPP),
ECFA workshop
DESY

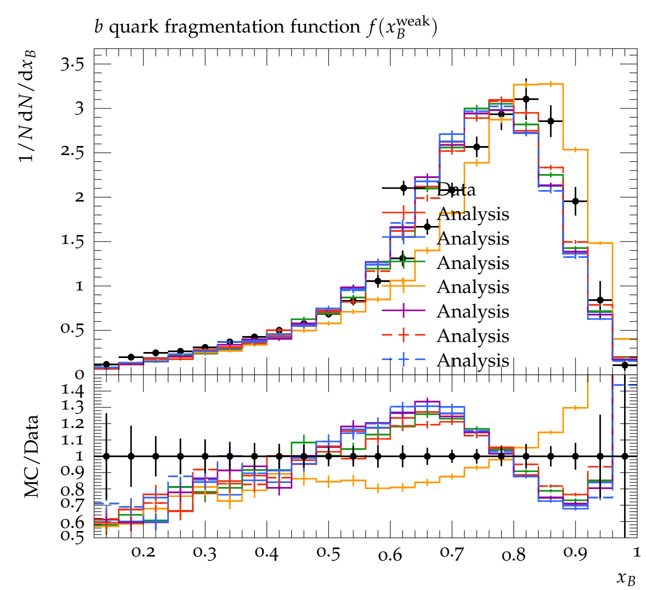
Heavy flavour production and fragmentation

- disagreement in b-quark fragmentation measurements

(look at results from ALEPH, OPAL, SLD $\longrightarrow$ need to chose one!)

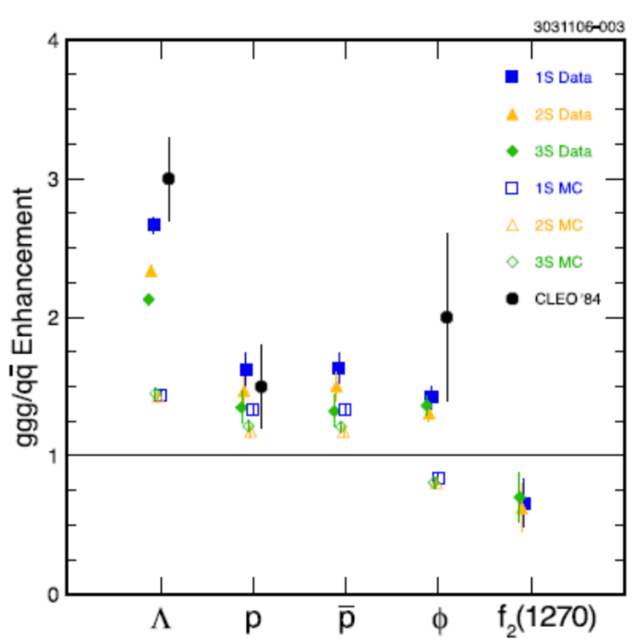






- $g \to Q\bar{Q}$ splitting tricky in parton showers

- measurement strategy:
  - "Mercedes star" with two id'd heavy quark jets $\longrightarrow$ third jet is gluon jet
  - jet-shape measurements: sub-jettiness & friends
  - hadron yields inside jet
  - leading hadron identity/x_p
  - di-baryon/di-strange correlations inside jet



Frank Krauss (IPPP),
ECFA workshop
DESY

Heavy flavour production and fragmentation

List of important observables produced by Torbjorn Sjostrand and the focus topic team

Observable	e^+e^-	pp
Event shapes and angular distributions		
Inclusive B/D production cross section	primary production is well known from theory, so any "excess" is from gluon splitting	combines primary production, gluon splitting, and MPI (multiparton interactions) contributions, each with significant theoretical uncertainties
Flavour composition as far back in decay chains as can be traced (even equal D^{*0} and D^{*+} rates gives unequal D^0 and D^+ ones)	we do not expect sizeable momentum dependence, but interesting to contrast mesons and baryons for smaller ones	significant p_T dependence observed and to be studied further, also high- vs. low-multiplicity events, rapidity, ..., which is important for development/tuning of colour reconnection models
Particle-antiparticle production asymmetries	none expected, except tiny from CP-violation in oscillations	asymmetries expected and observed from p flavour content, increasing at larger rapidities; relates to how string (and cluster?) fragmentation connects central rapidities to beam remnants
Momentum spectra	dn/dx_E with $x_E = 2E_\mathrm{had}/E_\mathrm{cm}$; basic distribution for tuning of "fragmentation function"	dn/dp_T and dn/dy give basic production kinematics, but the many production channels give less easy interpretation
Energy flow around B/D hadrons, excluding the hadron itself, as a test that dead cone effects are correctly described	$dE/d\theta$ where θ is the distance from B/D on the sphere	dp_T/dR where R is the distance in (η, ϕ) or (y, ϕ) space, only applied for B/D above some p_T threshold
B/D hadron momentum fraction of total E or p_T in a jet, with $x = p_\mathrm{T}^\mathrm{had}/p_\mathrm{T}^\mathrm{jet}$, as a test of the fragmentation function combined with almost collinear radiation, suitably for some slices of p_T (and in addition with a veto that no other B/D should be inside the jet cone, so as to suppress the gluon splitting contribution)	draw a jet cone in θ around B/D and measure x	draw a jet cone in R around B/D and measure x
B/D hadron multiplicity, as a measure of how often several pairs are produced		
Separation inside B/D pairs, where large separation suggests back-to-back primary production, while small separation suggests gluon splitting	separation in θ	separation both in ϕ and in R, since for primary production $\phi = \pi$ is hallmark with η/y separation less interesting, while gluon splitting means R is small while ϕ and y/η individually are less interesting
Hardness difference within (reasonably hard) pairs, $\Delta = (p_\mathrm{T}^\mathrm{max} - p_\mathrm{T}^\mathrm{min})/(p_\mathrm{T}^\mathrm{max} + p_\mathrm{T}^\mathrm{min})$, where for gluon splitting $x^2 + (1-x)^2$ translates to $1+\Delta^2$	separately for small or large θ	separately for large or small ϕ

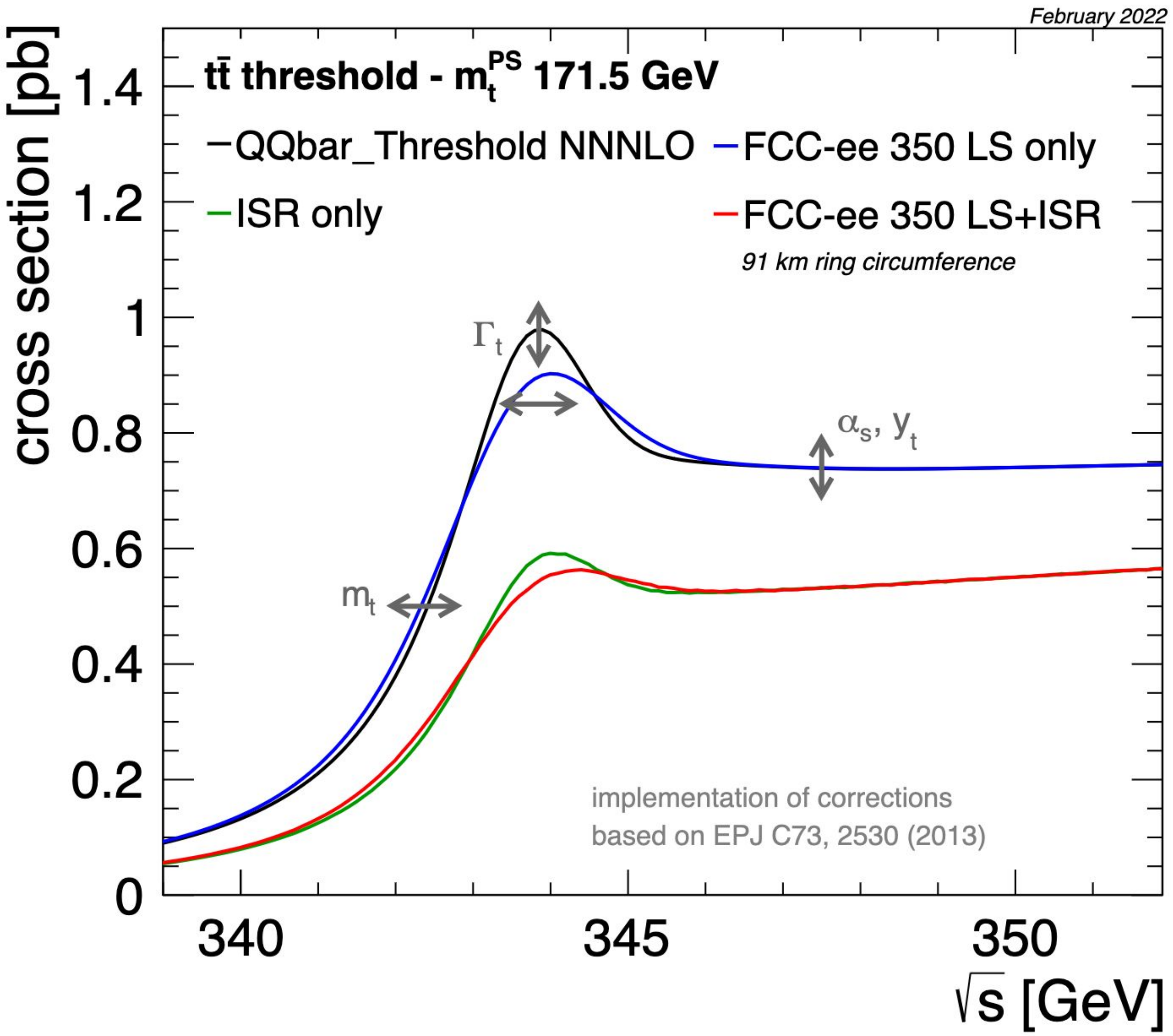
Table 3: Target physics observables at e^+e^- and pp.

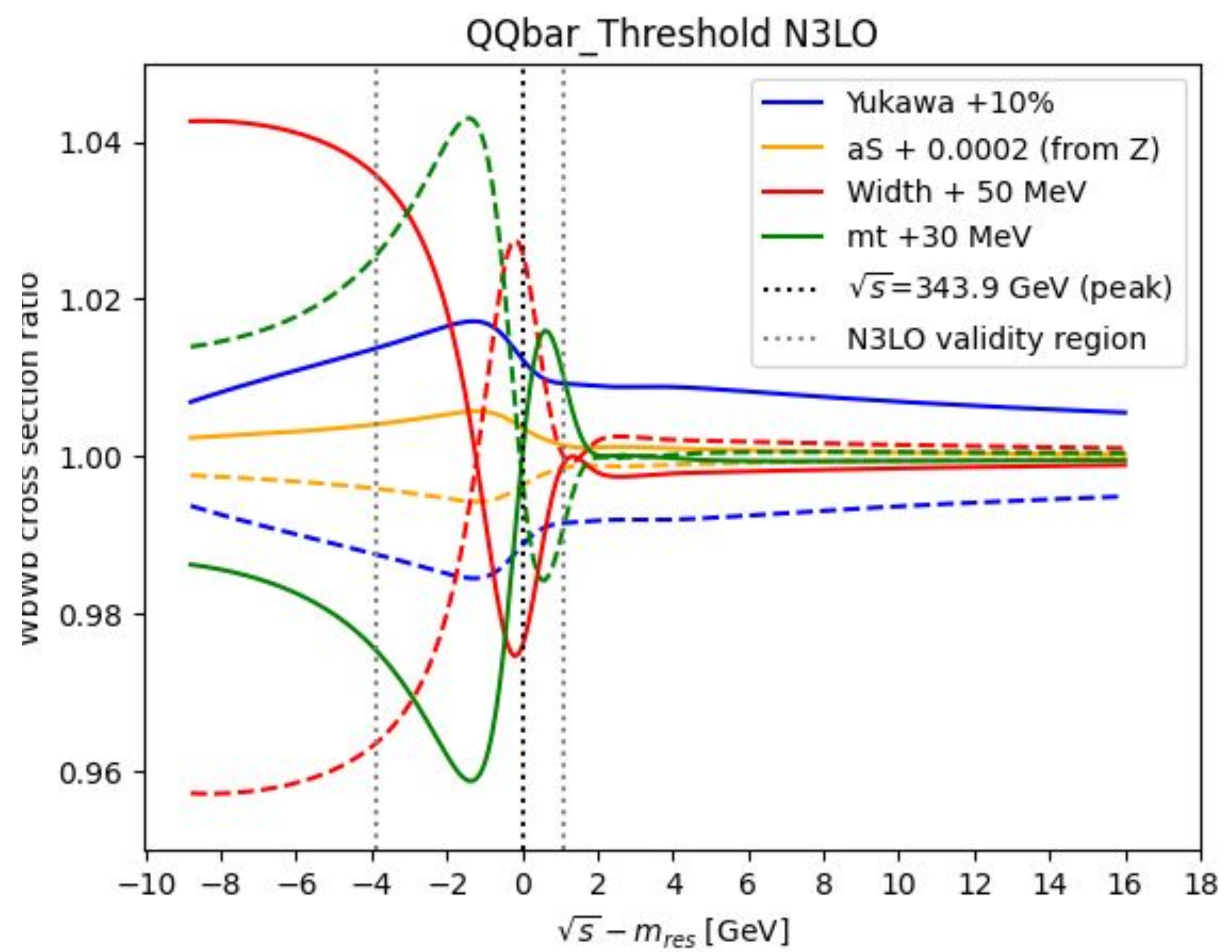
Eli Ben Haim, Loukas Gouskos, Simon Platzer, Andrzej Siodmok, Maria Ubiali (Cambridge)

Top-quark measurements

Top quark measurements can enter new realm of precision (*TTthresh* focus topic)

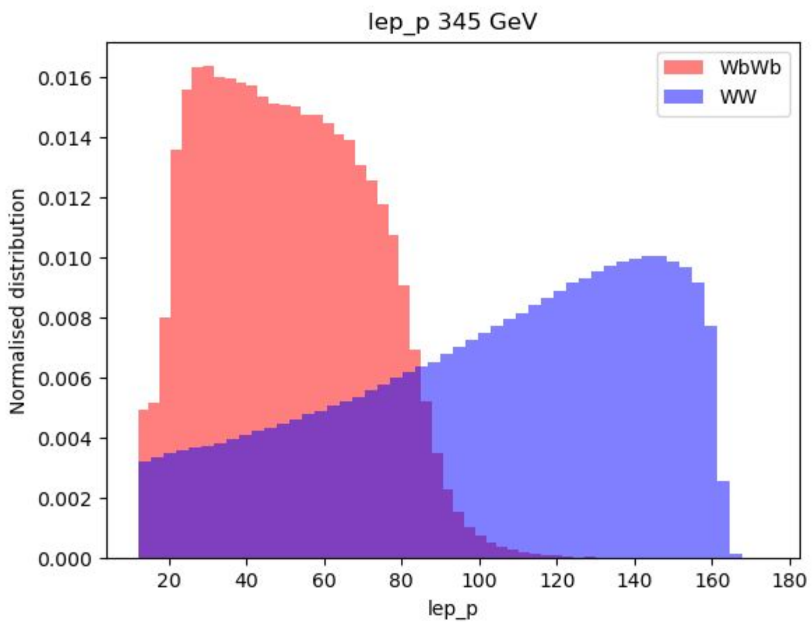
Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and dominant exp. error
m_{top} (MeV/c^2)	172,740 ± 500	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5–1.5%	Small	From E_{CM} = 365 GeV run

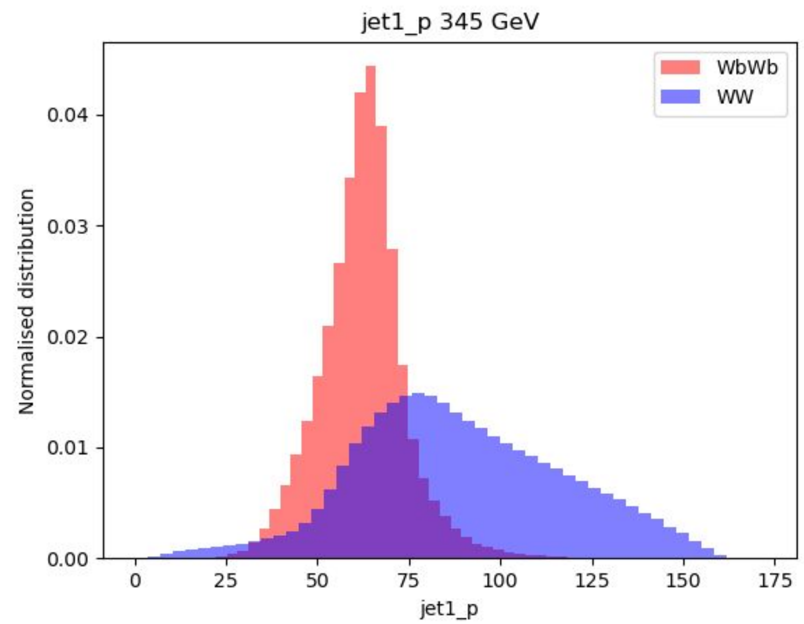


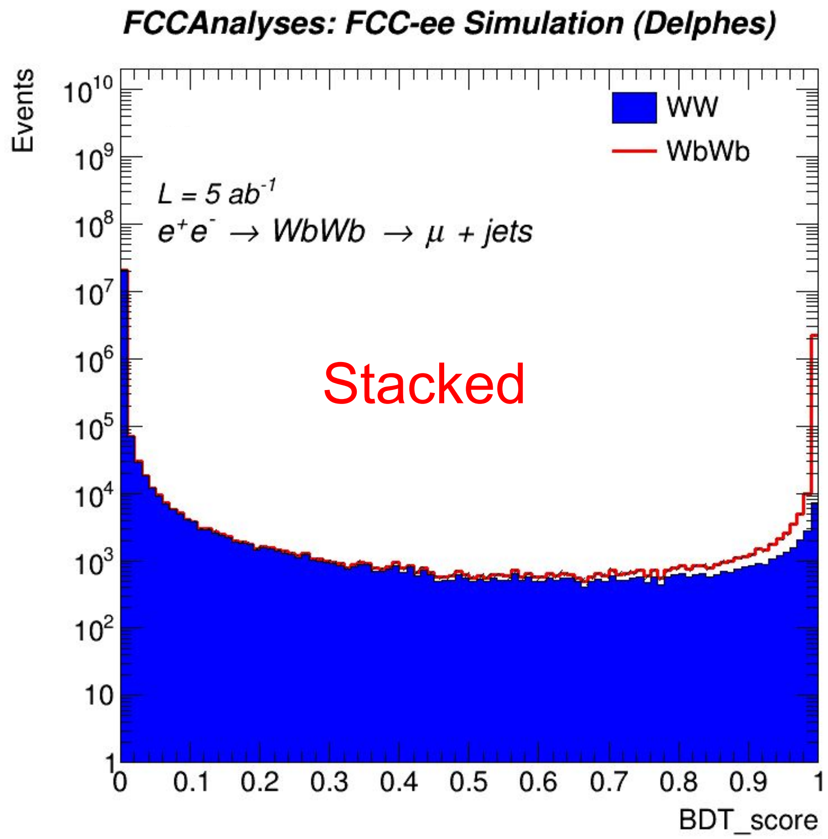


Top-quark measurements

Ongoing FCC effort to update experimental fit
Study detector-level distributions, use MVA to suppress backgrounds







- A **simultaneous fit of m_t, total width, and y_t** seems possible based on a threshold scan of [-4,+1] GeV around the threshold

- 30 (50) MeV shift in mass (width) induce a 4% shift in the xsec
- 10% shift in Yukawa produce a ~1% effect just above threshold
- Limited impact from aS assuming expected precision at Z pole

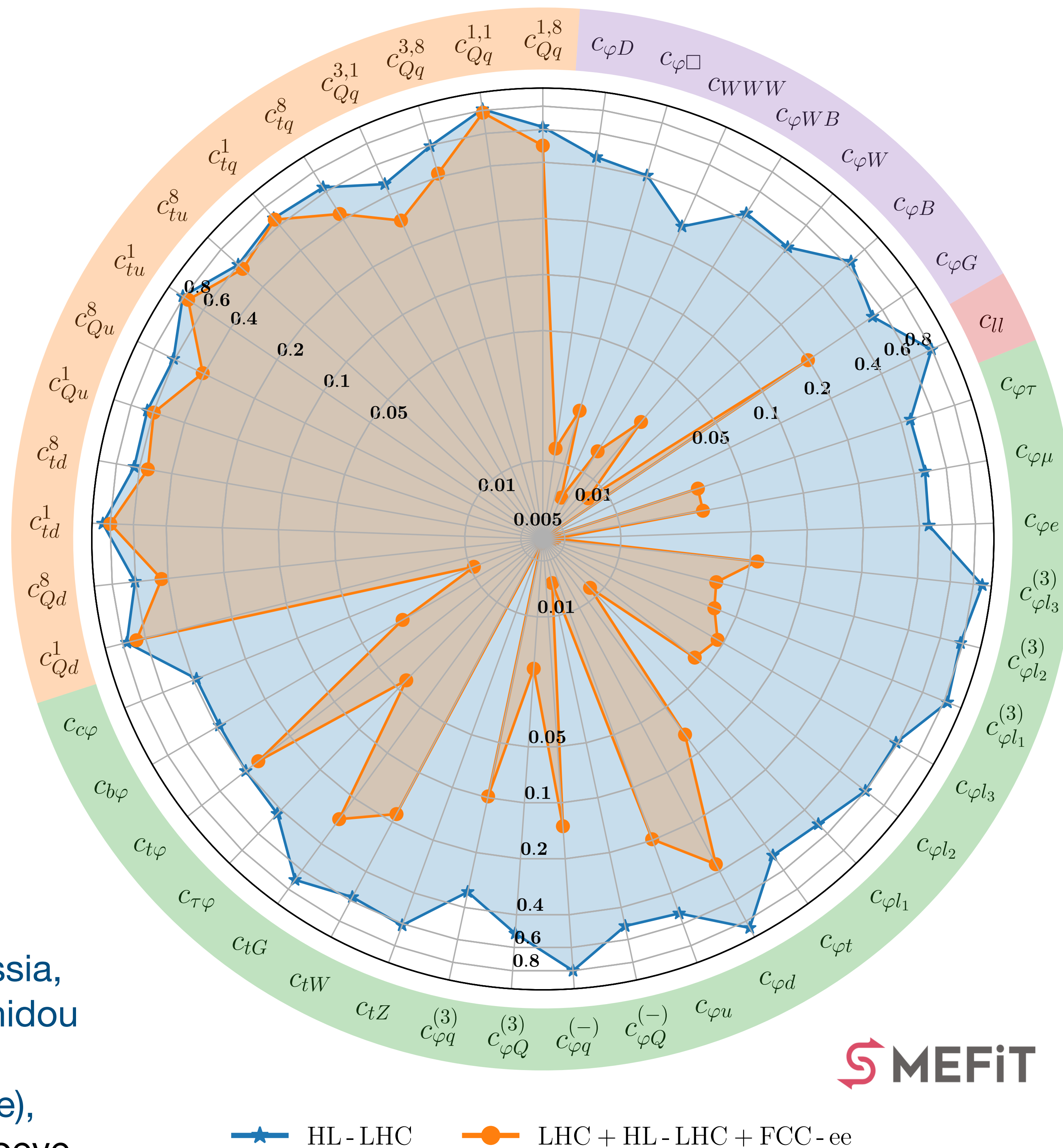
- Some residual sensitivity to y_t above threshold -> we will investigate the possibility of **one additional scan point well above threshold** (continuum)

- Presented studies do not include impact from ISR and beam energy resolution, which can be significant -> will be included at next update

Ankita Mehta & Matteo Defranchis, WG1 conveners meeting

Z Bahariyoon, M Beneke, F Cornet, G Durieux, A Hoang, A Jafari, J Kieseler, V Miralles (Manchester), M Moreno, L Pintucci, J Reuter, R Schweinworst, F Simon, F Zarnecki

Global EFT constraints



MEFiT

Eugenia Clelada, Alejo Rossia, Marion Thomas, Eleni Vryonidou (Manchester), Luca Mantani (Cambridge), Tommaso Giani, Jaco ter Hoeve, Juan Rojo

2404.12809

Summary

The proposed e^+e^- colliders can provide a step-change in precision

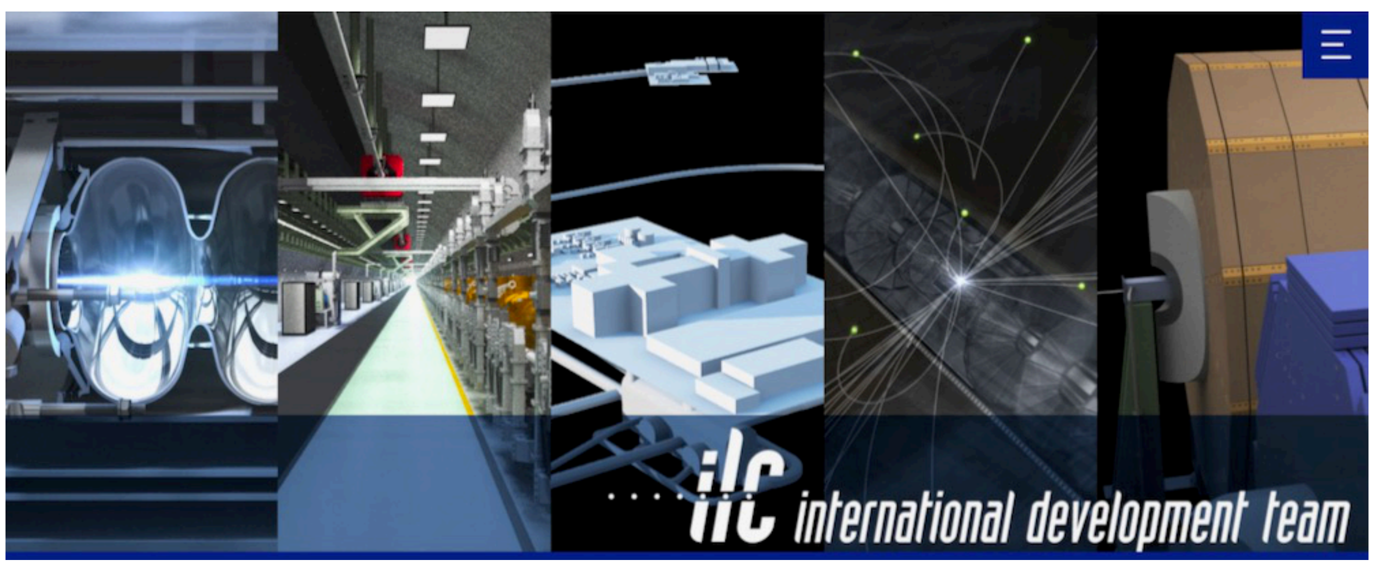
More than an order of magnitude in many cases

Broad range of physics topics within electroweak and QCD physics

LEP programme produced more than 1700 papers with no Higgs or top measurements

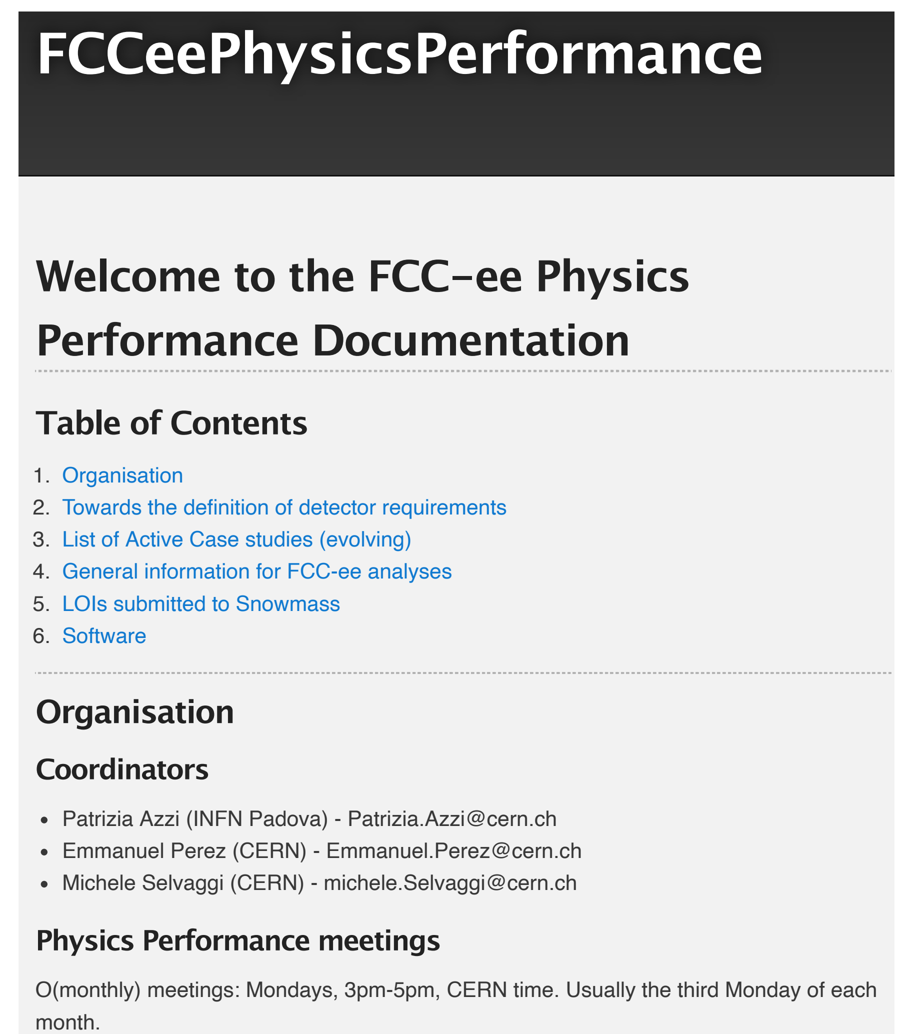
Truncated ECFA studies are only the tip of the iceberg

Active FCC and ILC physics working groups



Michael Peskin, Aidan Robson (Glasgow), Junping Tan,
ILC physics group conveners

https://agenda.linearcollider.org/event/9154/



Exotic Z decays

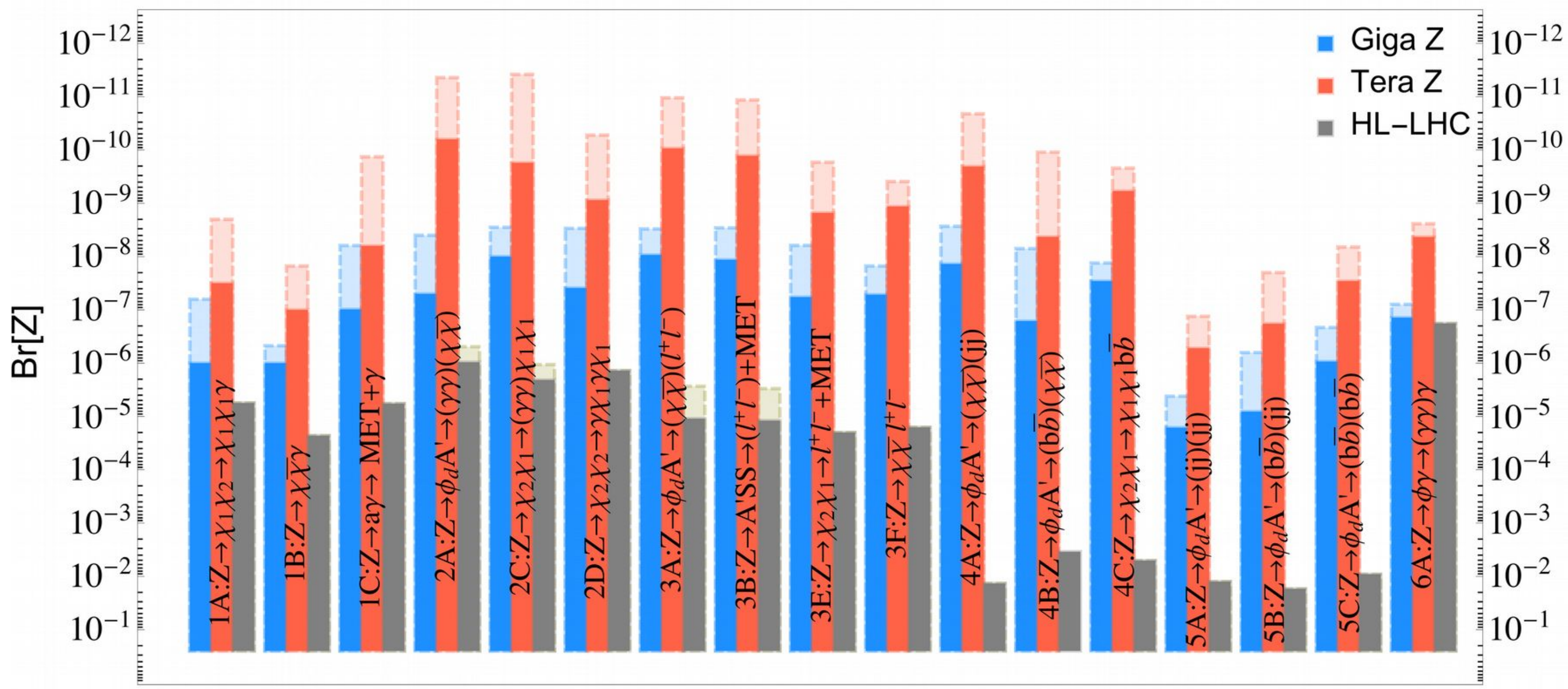
Emidio Gabrielli

University of Trieste, Italy

NICPB, Tallinn, Estonia

Sensitivity on BSM physics at the Z-pole: **Giga-Z** and **Tera-Z** factories

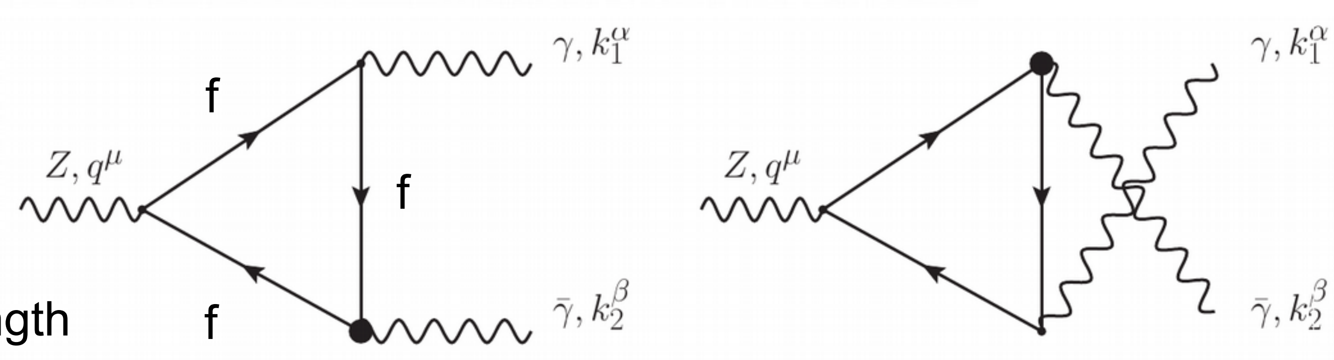
signatures: $Z \to \not{E} + \gamma$ $\quad Z \to \not{E} + \gamma\gamma$ $\quad Z \to \gamma\gamma\gamma$ $\quad Z \to \not{E} + \ell^+\ell^-$



$Z \to \gamma\bar{\gamma}$

$$\mathcal{L} = \sum_f \frac{e_D}{2\Lambda} \bar{\psi}_f \sigma_{\mu\nu} \left(d_M^f + i\gamma_5 d_E^f \right) \psi_f B^{\mu\nu}$$

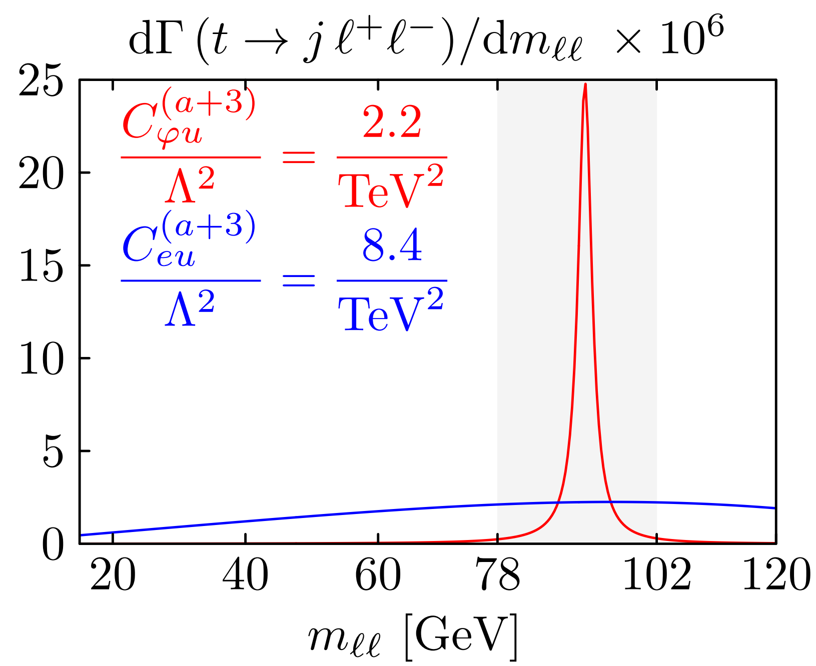
dark photon field strength

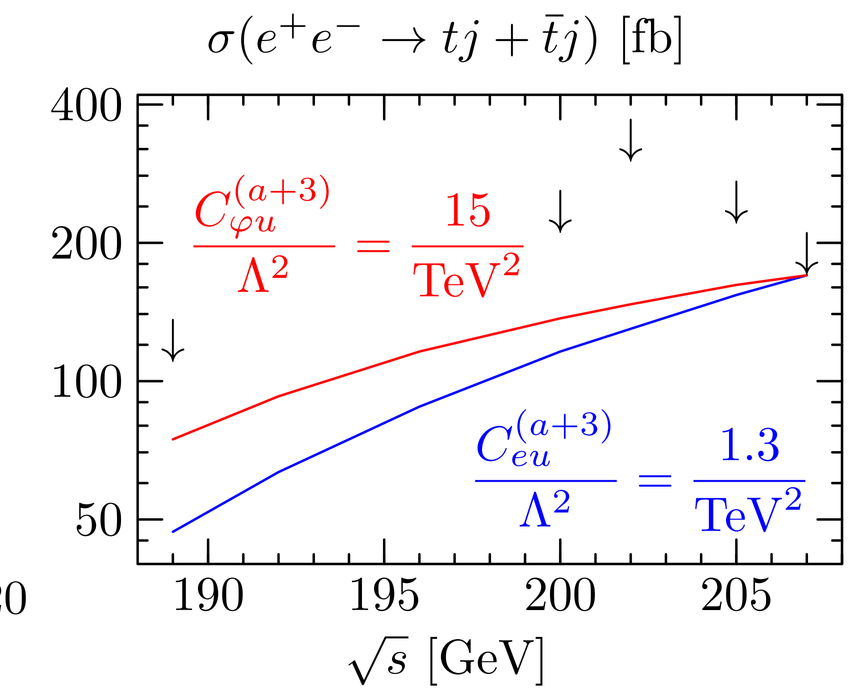


- Landau-Yang theorem forbids Z $\not\to$ 2 photons -> amplitude vanishes
- avoided due to distinguishability of photon and dark-photon interaction (blob)

Top quark FCNCs at the LHC and e^+e^- colliders

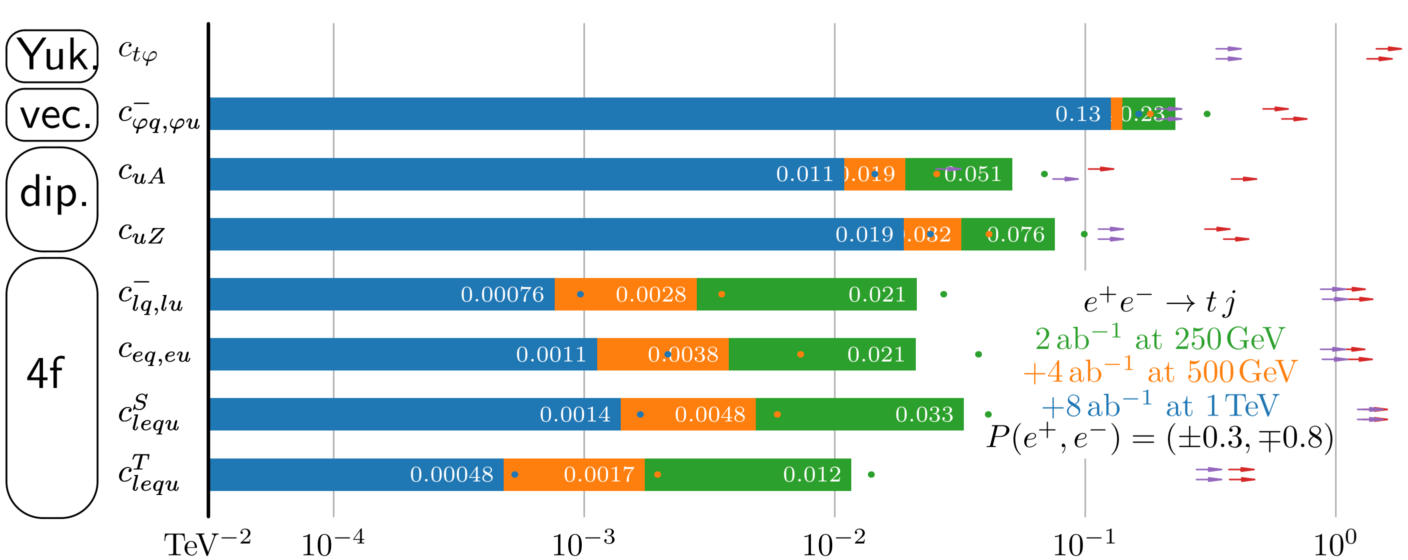
Gauthier Durieux
(CERN)

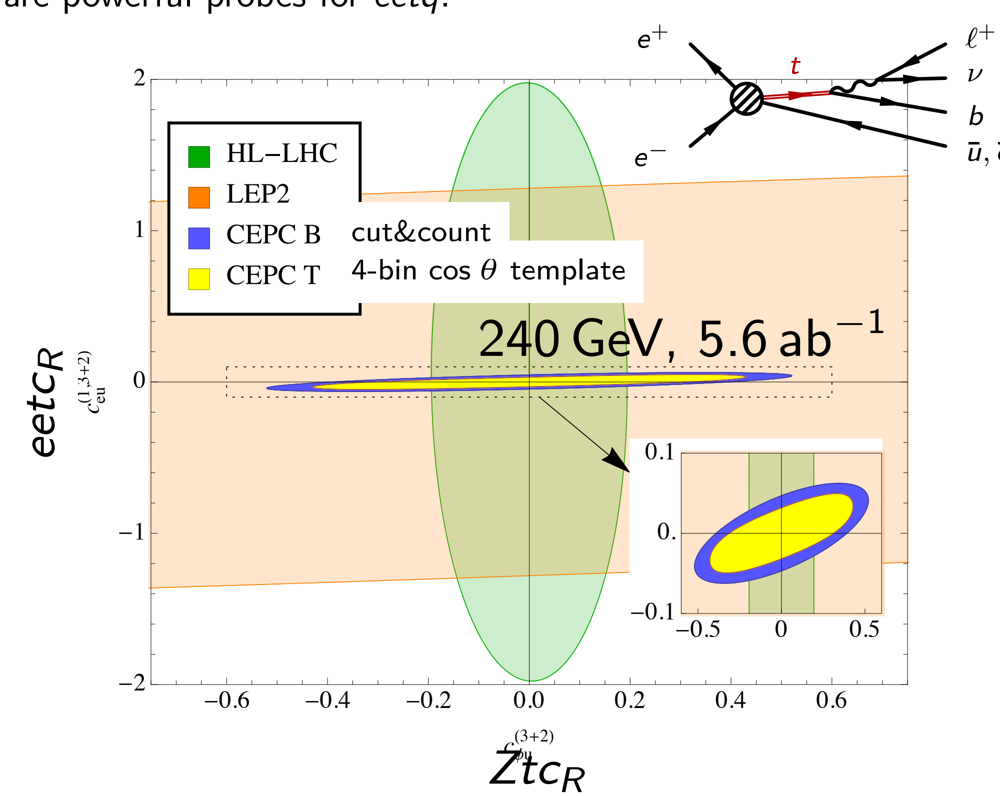




More sensitivity in off-Z-peak region of $t \to j\ell\ell$ (smaller Drell-Yan bkg).
High-energy lepton colliders are powerful probes for *eetq*.

global 95% CL limits, in TeV^{-2}, ILC scenario (2, 4, 8 ab^{-1})





top physics

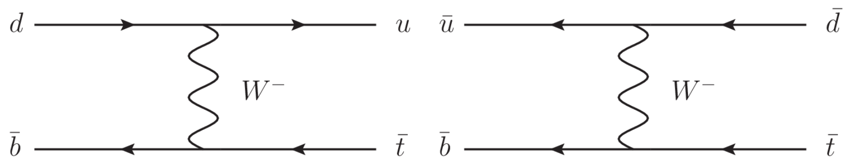
opportunities at a new e$^+$e$^-$ collider – CP violation in the top sector

Marcel Vos,

IFIC, CSIC/UV, Valencia, Spain

CP-odd (imaginary parts of) operators at the LHC

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2018-10/

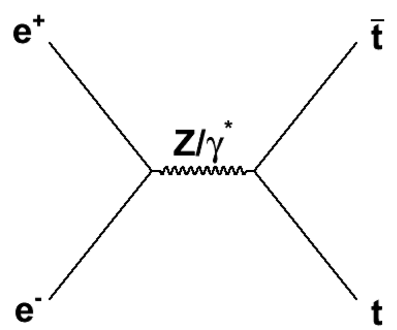


	C_{tW} 68% CL	C_{tW} 95% CL	C_{itW} 68% CL	C_{itW} 95% CL
All terms	[−0.3, 0.8]	[−0.9, 1.4]	[−0.5, −0.1]	[−0.8, 0.2]
Order $1/\Lambda^4$	[−0.3, 0.8]	[−0.9, 1.4]	[−0.5, −0.1]	[−0.8, 0.2]
Order $1/\Lambda^2$	[−0.3, 0.8]	[−0.8, 1.5]	[−0.6, −0.1]	[−0.8, 0.2]

CP violating analysis: construct dedicated CP-odd triple-product observables

$$\mathcal{O}^{Re}_{+} = (\hat{\mathbf{q}}_{\bar{X}} \times \hat{\mathbf{q}}^{*}_{+}) \cdot \hat{\mathbf{p}}_{+}\,,$$

$$\mathcal{O}^{Im}_{+} = -[1 + (\frac{\sqrt{s}}{2m_t} - 1)(\hat{\mathbf{q}}_{\bar{X}} \cdot \hat{\mathbf{p}}_{+})^2]\hat{\mathbf{q}}^{*}_{+} \cdot \hat{\mathbf{q}}_{\bar{X}} + \frac{\sqrt{s}}{2m_t}\hat{\mathbf{q}}_{\bar{X}} \cdot \hat{\mathbf{p}}_{+}\hat{\mathbf{q}}^{*}_{+} \cdot \hat{\mathbf{p}}_{+}\,.$$



Where p+ and p- are the momenta of the incoming leptons, q+ and q- those of the leptons from t → Wb → lvb decay, and qX that of the hadronic top quark

$$\Gamma^{t\bar{t}X}_{\mu}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(F^X_{1V}(k^2) + \gamma_5 F^X_{1A}(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF^X_{2V}(k^2) + \gamma_5 F^X_{2A}(k^2)\right)\right\}$$

collider	collision	$\sqrt{s}$ [TeV]	L_{int} [ab^{-1}]	Re F^{γ}_{2A}	Re F^{Z}_{2A}	Im F^{γ}_{2A}	Im F^{Z}_{2A}
Prospects derived in this study:							
CLIC initial	e^+e^-	0.38	0.5	0.015	0.019	0.013	0.026
ILC initial	e^+e^-	0.5	0.5	0.005	0.007	0.006	0.010
ILC nominal	e^+e^-	0.5	4	0.002	0.003	0.002	0.004
CLIC (parton-level)	e^+e^-	3	3	0.003	0.003	0.005	0.009
Previous studies for lepton colliders:							
TESLA (Aguilar et al. [80])	e^+e^-	0.5	0.3	0.007	0.008	0.008	0.010
Prospects for hadron colliders:							
HL-LHC (Baur et al. [81,82])	pp	14	3	0.12	0.25	0.12	0.25
HL-LHC (Röntsch & Schulze [5])	pp	14	3	-	0.16	-	-
FCChh (Mangano et al. [84])	pp	100	3	-	0.04	-	-
LHeC (Bouzas et al. [85])	ep	-	0.1	0.1	-	-	-

Bernreuther & Chen, in arXiv:1710.06737