Report from the 3rd FCC Physics and Detectors Workshop,

held at CERN, 13-17 Jan 2020

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- **251 registered participants**
- **Over 110 talks, plus a day-long software tutorial**
- **https://indico.cern.ch/event/838435/**

M.Koratzinos & J.Gao talks

A. Blondel talk

Timetable summary (see Indico for details)

Monday	Tuesday	Wednesday	Thursday	Friday
FCC & CEPC project reviews	Precision physics requirements (EW, QCD, H)	QCD and top physics at FCC	Higgs physics and EW interactions at high energy	Flavour physics
Theory progress for precision calculations	MC event generators for FCC	Higgs physics and EW interactions at high energy	BSM physics	ee@125 GeV
MDI issues and luminosity measurement	FCC software	Software tutorial (3/4 day)	Tracking and flavour tagging	Linear vs circular ee complementarity
ee detector overviews, E calibration and physics studies	Trigger, R/O, DAQ	Particle ID	Calorimetry	Next steps
	Tracking		Detector physics performance examples	

This review will focus on the physics sessions

Precision: theory progress

- Numerical and analytical approaches to multiloop calculations
- Recent results:
    - $H \to gg$, $gg \to HH$ at finite mtop
    - 5-point amps at 2 loops
    - jet observables at NNLO+N3LL
- MC event generators for precision physics

Precision: the needs and the potential

- Projected post-LHC status
- Luminosity, EW and QCD challenges
- Impact on EW+Higgs EFT fits & new physics sensitivity

QCD physics: observables and tools

- α_S measurements in ee, the role of E_{beam}
- QCD challenges at FCC-hh
- Role of FCC-eh and FCC-eA

Top-quark properties

- mtop
- precision coupling measurements and implications for BSM and Higgs
- Exotics (FCNC, …)

Higgs physics

- Higgs at large-Q^2
- Precision BSM Higgs properties
- Higgs selfcoupling in HH and HHH production
- The EW phase transition

BSM physics

- DM, Dark sectors and axions
- Leptoquarks
- EW SUSY in eh

Flavour physics

- Charm, Bottom
- Tau *(updated Tera-Z projections, Lusiani)*
- Sterile neutrinos
- Lepton flavour violation

Rather than superficially flying through all the various talks, I'll select a few issues and novel results that have a direct impact on the definition, scope and needs of the physics programme

TH progress towards Tera-Z MCs

Monte Carlos for TeraZ, S.Jadach
— *defines specs of MCs for different EW observables (sin θ_W, m_W, A_{FB}, N_ν, …)*

Whizhard (Reuter), Babayaga (Piccinini), MCSANCee (Yermolchyk), MG-BSM (Costantini)

Jadach:

Specification of TeraMC will be determined going observable-wise as much as subprocess-wise.

At least in the initial phase, one will probably start with the upgrade of KKMC, BHWIDE and BHLUMI but most likely later on a completely new code, or better two, will have to be developed.

- QED corrections are bigger, hence they have to be calculated at the 1-2 orders higher level than pure EW corrections. For instance at LEP era QED corrections were soft-resumed to infinite and non-soft QED typically up to $\mathcal{O}(\alpha^2)$, while EW corrections up to $\mathcal{O}(\alpha^1)$.
- In TeraZ era non-soft QED corrections will have to be calculated to $\mathcal{O}(\alpha^4)_{LO}$ and non-soft EW corrections up to $\mathcal{O}(\alpha^2)$.
- Is there any systematic and practical scheme of calculating the two classes of corrections separately and recombining them without violating gauge invariance, IR cancellations etc.?

QED precision evolution

Jadach, Skrzypek: arxiv:1903.09895

(a) 0.6%

PETRA, PEP, early LEP

1				
αL	α			
α^2L^2	α^2L	α^2		
α^3L^3	α^3L^2	α^3L	α^3	
α^4L^4	α^4L^3	α^4L^2	α^4L^1	α^4
$\vdots$	$\vdots$	$\vdots$		

(b) 0.03%

LEP updates

1				
αL	α			
α^2L^2	α^2L	α^2		
α^3L^3	α^3L^2	α^3L	α^3	
α^4L^4	α^4L^3	α^4L^2	α^4L^1	α^4
$\vdots$	$\vdots$	$\vdots$		

(c) 0.001%

FCC-ee

1				
αL	α			
α^2L^2	α^2L	α^2		
α^3L^3	α^3L^2	α^3L	α^3	
α^4L^4	α^4L^3	α^4L^2	α^4L^1	α^4
α^5L^5	$\vdots$	$\vdots$	$\vdots$	

Bluemlein et al, arxiv:1911.05029 (inclusive)

Jezabek, Z.Phys. C56 (1992) 285 (inclusive)

Frixione et al, arXiv:1909.03886, arXiv:1911.12040 (inclusive)

Different MCs implement various terms in different ways (inclusive vs exclusive, multi-photon at the amplitude or |amp|^2 level, fixed order vs resummed, etc.)

TH progress towards Tera-Z precision requirements

- The Path to 0.01% Theoretical Luminosity Precision for the FCC-ee, B.Ward (see also S. Jadach et al, arxiv:1812.01004)
- QED for Z pole and WW threshold at FCC-ee, M. Skrzypek
- NLO+NLL QED corrections to electron PDFs, S. Frixione

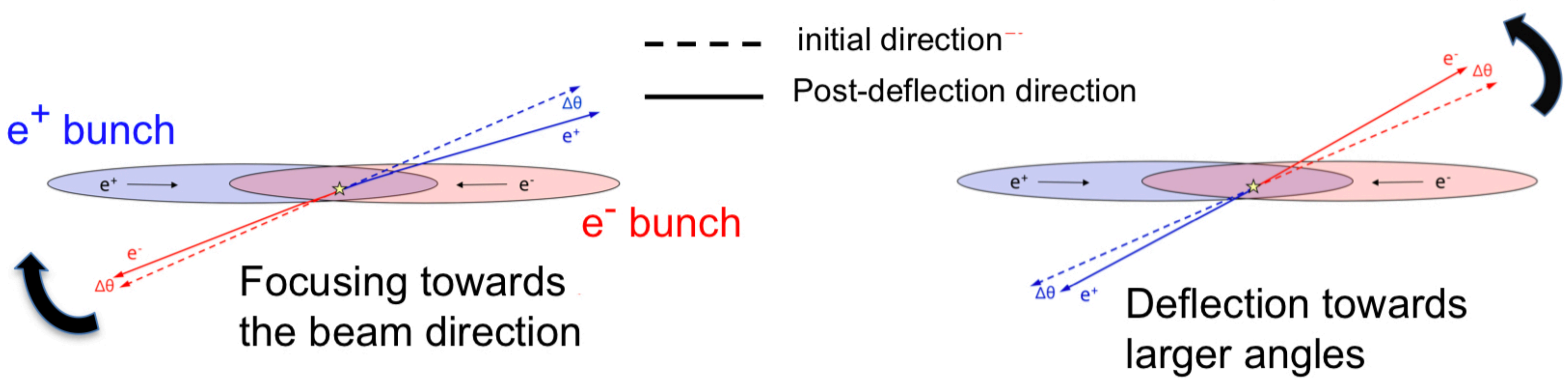
- Experimental conditions: beam related backgrounds, beam-beam effects on luminosity measurement and the number of neutrinos, E. Perez

See also G. Voutsinas, E. Perez, M. Dam and P. Janot, arxiv:1908.01704

Consequences of these strong fields at the IP [relevant or this talk]

- Beamstrahlung
  - Photons created in the interaction region
  - Low energy (<E> = 2 MeV at the Z peak), leave the IR in the beam-pipe (< θ > ≈ 80 μrad w.r.t. the beam direction)
  - Contribute (a bit) to the pair-production background, $\gamma^{(*)}\gamma^{(*)} \longrightarrow$ e+e-

- Particles in the final state feel the fields of the bunches – especially at small angles



- Because of the crossing angle : the particles in the bunches are accelerated along x, by the opposite charge bunch, until they reach the IP (see backup). Increase of the effective crossing angle, by about 0.5% at the Z peak.

The Guinea-Pig program (D. Schulte) allows all these effects to be simulated.

Preliminary: re-assessment of LEP's luminosity

Janot and Jadach arxiv:1912.02067

- Inclusion of up-to-date TH inputs (shifts plus reduction in uncertainty) for
  - impact of light-fermion pairs (w. muons and u/d)
  - improved vacuum polarization in t channel
  - Z s-channel contribution
- Inclusion of beam-induced effects (previous slide)
- Update of extracted σ^0_{had} and of the neutrino counting

Relative shifts in the integrated LEP luminosity at m_Z, wrt the pre-update results (10^{-4})

Source / Experiment	ALEPH	DELPHI	L3	OPAL
Z exchange	0.52	0.35	0.06	0.00
Light fermion-pairs	3.35	4.07	3.76	0.40
Vacuum polarization	3.36	5.62	3.83	3.83
Beam-induced [4]	10.29	5.67	9.60	10.55
Total	17.52	15.71	17.24	14.78

NB results vary with expt, depending on the TH tools used in the original analyses

$\Delta\sigma^{\mathrm{Bhabha}}_{(\mathrm{old})} = \pm 0.061\%$

$\sigma^{\mathrm{Bhabha}}_{(\mathrm{new})} / \sigma^{\mathrm{Bhabha}}_{(\mathrm{old})} = (1 - 0.064\%) \pm 0.037\%$

$N_{\nu\,(\mathrm{old})} = 2.9840 \pm 0.0082$ ($\sim 2\sigma$) $\Longrightarrow$ $N_{\nu\,(\mathrm{new})} = 2.9975 \pm 0.0074$ ($\sim 0.3\sigma$)

TH progress towards 10^{-4} luminosity measurements @ Tera-Z

B.Ward talk,
S. Jadach et al, arxiv:1812.01004

LEP error budget (luminometer acceptance 28-58 mrad)

NB: $L_e = \log(s/m_e^2)$

Type of correction / Error	1999	Update 2018
(a) Photonic $O(L_e\alpha^2)$	0.027% [5]	0.027%
(b) Photonic $O(L_e^3\alpha^3)$	0.015% [6]	0.015%
(c) Vacuum polariz.	0.040% [7,8]	0.013% [26]
(d) Light pairs	0.030% [10]	0.010% [18,19]
(e) Z and s-channel γ exchange	0.015% [11,12]	0.015%
(f) Up-down interference	0.0014% [28]	0.0014%
(f) Technical Precision	–	(0.027)%
Total	0.061% [13]	0.038%

FCC-ee (luminometer acceptance 64-86 mrad => Z contribution not negligible, but easy to include)

Type of correction / Error	Update 2018	FCC-ee forecast
(a) Photonic $[O(L_e\alpha^2)]$ $O(L_e^2\alpha^3)$	0.027%	0.1×10^{-4}
(b) Photonic $[O(L_e^3\alpha^3)]$ $O(L_e^4\alpha^4)$	0.015%	0.6×10^{-5}
(c) Vacuum polariz.	0.014% [26]	0.6×10^{-4}
(d) Light pairs	0.010% [18,19]	0.5×10^{-4}
(e) Z and s-channel γ exchange	0.090% [11]	0.1×10^{-4}
(f) Up-down interference	0.009% [28]	0.1×10^{-4}
(f) Technical Precision	(0.027)%	0.1×10^{-4}
Total	0.097%	1.0×10^{-4}

✓ **2019**: Frixione talk, and arXiv:1909.03886, arXiv:1911.12040

NLO+NLL QED corrections to electron PDFs (S. Frixione)

arXiv:1909.03886, arXiv:1911.12040

Factorization theorem

Log(E/m_e) terms arise from collinear emissions => universal structure, absorb in PDFs, like for the factorization of mass singularities in QCD

logs of E/m_e resummed here

$$d\bar{\sigma}_{kl}(p_k,p_l) = \sum_{ij=e^+,e^-,\gamma} \int dz_+ dz_- \Gamma_{i/k}(z_+,\mu^2,m^2)\,\Gamma_{j/l}(z_-,\mu^2,m^2) \times d\hat{\sigma}_{ij}(z_+p_k,z_-p_l,\mu^2) + \Delta$$

massless matrix elements

process-dependent, $(m^2/s)^n$ power corrections

with:

$$d\bar{\sigma}_{kl} = d\sigma_{kl} + \mathcal{O}\left(\left(\frac{m^2}{s}\right)^p\right), \qquad s=(p_k+p_l)^2, \qquad p \geq 1$$

Γ_i ($i=e^-$, γ, e^+) calculable with DGLAP-like evolution, from perturbatively calculable initial conditions

$$\Gamma_i = \Gamma_i^{[0]} + \frac{\alpha}{2\pi}\Gamma_i^{[1]} + \mathcal{O}(\alpha^2)$$

$$\begin{aligned}
\Gamma_i^{[0]}(z,\mu_0^2) &= \delta_{ie^-}\delta(1-z)\\
\Gamma_{e^-}^{[1]}(z,\mu_0^2) &= \left[\frac{1+z^2}{1-z}\left(\log\frac{\mu_0^2}{m^2} - 2\log(1-z) - 1\right)\right]_+ + K_{ee}(z)\\
\Gamma_{\gamma}^{[1]}(z,\mu_0^2) &= \frac{1+(1-z)^2}{z}\left(\log\frac{\mu_0^2}{m^2} - 2\log z - 1\right) + K_{\gamma e}(z)\\
\Gamma_{e^+}^{[1]}(z,\mu_0^2) &= 0
\end{aligned}$$

factorization scheme def, K=0 in MSbar

NLO+NLL QED corrections to electron PDFs (S. Frixione)

arXiv:1909.03886,
arXiv:1911.12040

Previously available precision: LO initial condition plus LL resummation

$$\left[\alpha \log(E/m_e)\right]^k$$

- $0 \le k \le \infty$ for $z \simeq 1$ (Gribov, Lipatov)
- $0 \le k \le 3$ for $z < 1$ (Skrzypek, Jadach; Cacciari, Deandrea, Montagna, Nicrosini; Skrzypek)
- matching between these two regimes

New results: NLO initial condition plus NLL resummation

$$\left[\alpha \log(E/m_e)\right]^k + \alpha \times \left[\alpha \log(E/m_e)\right]^{k-1}$$

- $0 \le k \le \infty$ for $z \simeq 1$
- $0 \le k \le \{3, 2\}$ for $z < 1 \iff \mathcal{O}(\alpha^3)$
- matching between these two regimes
- for e^+, e^-, and γ
- both numerical and analytical

=> captures the $\alpha^3 L^2$ terms required by FCC-ee precsion

=> to be implemented in MG5_aMC@NLO

QED systematics projections *(beyond luminosity)*

Detailed discussion, observable by observable, of the TH challenge: see Skrzypek talk, and Jadach, Skrzypek: arxiv:1903.09895

Summary

Observable	Source LEP	Err.{QED} LEP	Stat[Syst] FCC-ee	LEP / FCC-ee	main development to be done
M_Z [MeV]	Z linesh.	2.1{0.3}	0.005[0.1]	$3\times3^{\star}$	light fermion pairs
Γ_Z [MeV]	Z linesh.	2.1{0.2}	0.008[0.1]	$2\times3^{\star}$	fermion pairs
$\sigma^0_{\rm had}$ [pb]	$\sigma^0_{\rm had}$	37{25}	0.1[4.0]	$6\times3^{\star}$	better lumi MC
$R_l^Z \times 10^3$	$\sigma(M_Z)$	25{12}	0.06[1.0]	$12\times3^{\star\star}$	better FSR
$N_\nu \times 10^3$	$\sigma(M_Z)$	8{6}	0.005[1.0]	$6\times3^{\star\star}$	CEEX in lumi MC
$N_\nu \times 10^3$	$Z\gamma$	150{60}	0.8[<1]	$60\times3^{\star\star}$	$\mathcal{O}(\alpha^2)$ for $Z\gamma$
$\sin^2\theta_W^{eff} \times 10^5$	$A_{FB}^{lept.}$	53{28}	0.3[0.5]	$55\times3^{\star\star}$	h.o. and EWPOs
$\sin^2\theta_W^{eff} \times 10^5$	$\langle\mathcal{P}_\tau\rangle, A_{\rm FB}^{pol,\tau}$	41{12}	0.6[<0.6]	$20\times3^{\star\star}$	better τ decay MC
M_W [MeV]	mass rec.	33{6}	0.3[?.?]	$20\times3^{\star\star}$	$\mathcal{O}(\alpha)$, FSR$_{exp}$
M_W [MeV]	threshold	200{30}	0.5[0.3]	$100\times3^{\star\star\star}$	$\mathcal{O}(\alpha^2)$ at thresh.
$A_{FB,\mu}^{M_Z\pm3.5{\rm GeV}} \times 10^5$	$\frac{d\sigma}{d\cos\theta}$	2000{100}	1.0[0.3]	$100\times3^{\star\star\star}$	improved IFI

Table: Comparing experimental and theoretical errors at LEP and FCC-ee. 3rd column shows LEP experimental error together with uncertainty induced by QED and 4th column shows anticipated FCC-ee experimental statistical [systematic] errors. Factor $\times3$ in the 5-th column reflects what is needed for QED effects to be *subdominant*. Rating from * to *** marks whether the improvement is relatively straightforward, difficult or very difficult to achieve.

M. Skrzypek (IFJ PAN, Kraków, Poland) QED for Z pole and WW threshold ... CERN, 13-17.01.2020 26 / 30

NB *Several talks on progress with multiloop calculations (mostly for QCD), but no report of new purely EW results of relevance to Tera-Z and to the* ***Higgs programme*** *(=> Heinemeyer talk)*

Precision Higgs physics

Precision predictions for Higgs observables

S.Heinemeyer

In the SM

Intrinsic uncertainties

	today TH			future TH	future data
Partial width	QCD	electroweak	total	future	ILC/CEPC/FCC-ee
$H \to WW \to 4f$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.4\%$	0.6/1.9/0.8%
$H \to ZZ \to 4f$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.3\%$	0.4/0.4/0.3%
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$	$\sim 1\%$	1.7/2.2/1.8%
$H \to \gamma\gamma$	$< 0.1\%$	$< 1\%$	$<1\%$	$< 1\%$	2.4/2.4/2.4%
$H \to Z\gamma$	$\lesssim 0.1\%$	$\sim 5\%$	$\sim 5\%$	$\sim 1\%$	22/13/20%
$H \to b\bar{b}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	1.2/1.8/1.3%
$H \to c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	2.4/4.0/2.6%
$H \to \tau^+\tau^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	1.3/1.9/1.3%
$H \to \mu^+\mu^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	7.8/7.8/7.8%
Γ_{tot}				$\sim 0.3\%$	1.1/1.8/1.2%

Parametric uncertainties will be typically under control, provided:

1. M_H: better than 20 MeV $\Rightarrow$ negligible
2. M_Z: ~ 0.1 MeV with negligible theory uncertainties $\Rightarrow$ negligible
3. $\alpha_s(M_Z)$: from (mainly) R_ℓ
   $\delta\alpha_s^{\text{exp}} \sim 10^{-4}$, $\delta\alpha_s^{\text{theo}} \sim 1.5 \times 10^{-4}$
4. m_t: from threshold scan
   $\delta m_t^{\text{exp/theo}} \lesssim 50$ MeV
5. m_b: from lattice calculations
   $\delta m_b \sim 10$ MeV
6. $\Delta\alpha_{\text{had}}$: BES III and Belle II: $\delta(\Delta\alpha_{\text{had}}) \sim 5 \times 10^{-5}$
   better from measurements "around the Z pole? $\sim 3 \times 10^{-5}$?

$\Delta\sigma_{SM}$[ee→ZH] < 0.3% $\Delta\sigma_{SM}$[ee→Hνν] ~ 1% (will require EW $O(\alpha^2)$ for 2→3, challenging!)

(on α_S and m_{top} precision at FCC)

Precise determination of the strong coupling from jet rates, *G. Somogyi*
QCD TH needs for FCC-ee, *P.Monni*
PDFs and α_S at FCC-eh, *M.Klein*
QCD aspects of top physics at FCC-ee, *A.Hoang*

Perspectives of α_S from e+e->hadrons at FCC-ee, *A. Verbytskyi:*

Optimal α_S extraction at FCC-ee: multiple low-energy runs

FCC–e^+e^- data in range $\sqrt{s} = 20 - 91$ GeV[3] can help to solve exp./pheno problems simultaneously and will have side benefits.

- Fast to collect – $10^7 - 10^9$ events/day – supersedes **all** collected data in one day.
- Background free – perfect for most α_s analyses.

A perfect scenario would be ≈ 10 equidistant energy points in range $20 - 90$ GeV with $10^7 - 10^8$ events each.

- Perfect data for hadronisation studies.
- Additional data for electroweak fits, quark masses extraction and other analyses.
- Perfect data for detector calibration, e.g. $e^+e^- \to 2jets$, $e^+e^- \to \mu^+\mu^-$, etc.

Pseudo-data analysis

Two basic scenarios were compared:

- FCC: 3×10^{12} ev @91 GeV, 3.6×10^9 ev @161 GeV, 8×10^8 ev @240 GeV
- FCC+: FCC + 10^7 ev 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85 GeV
- The central values were generated as (massless NNLO pQCD+small ad-hoc α_S^4 term)×(MC hadronisation) for given energy.
- Systematic uncertainty is the best LEP systematic uncertainty at given energy, or, for $\sqrt{s} < M_Z$ at Z pole.
- It was assumed that 50% of systematic uncertainty is correlated.

Results

The analysis fas performed as a global fit with

- massless NNLO predictions from Ref. [26]
- MC hadronisation modelling similar to one from Ref. [22]

with multiple observables.

Observable	Data	Result	$\chi^2/ndof$
$\langle C \rangle + \langle T \rangle$ simultaneously	FCC	$0.11680 \pm 0.00032(exp.)$	3.43/5
	FCC+	$0.11649 \pm 0.00009(exp.)$	57.61/27

The FCC+ scenario provides visibly smaller uncertainty even taking into account quality of fit.

(on α_S and m_{top} precision at FCC)

QCD aspects of top physics at FCC-ee, *A.Hoang*

Strong Coupling

$$\frac{d\alpha_s(R)}{d\log R} = \beta(\alpha_s(R)) = -2\,\alpha_s(R)\sum_{n=0}^{\infty}\beta_n\left(\frac{\alpha_s(R)}{4\pi}\right)^{n+1}$$

Baikov, Chetyrkin, Kühn '17

- Running known to 5 loops (β_4) : fully sufficient
- Uncertainty in $\alpha_S(M_Z)$: debated, under constant scrutiny, but always a limiting factor

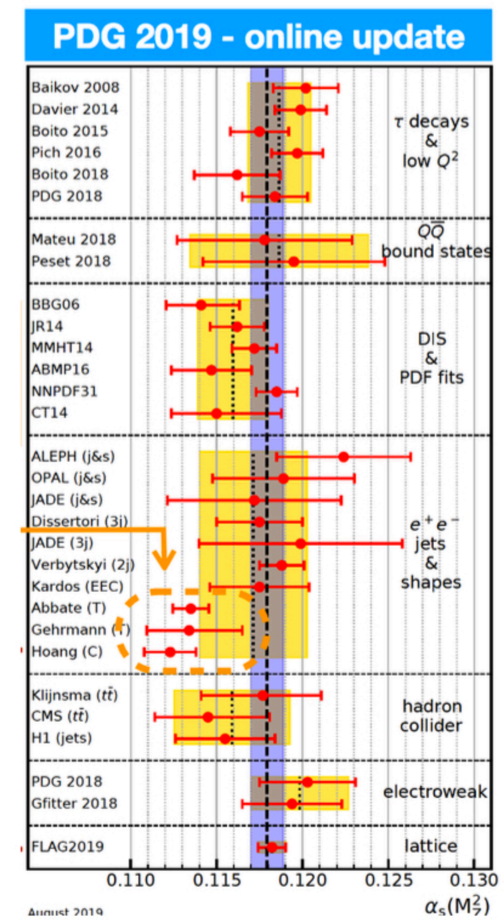
example: MSbar-pole mass relation
$\delta\alpha_S$ = 0.001 gives 70 MeV uncertainty

$$m_t^{\rm pole} - \overline{m}_t(\mu) = \frac{4}{3}\left(\frac{\alpha_s(\mu)}{\pi}\right)\overline{m}_t(\mu) + \dots$$

Improvement expected, but lots of hard work.

Consistency has actually higher priority at this time!!

Recall: Measurements of QCD parameters more subtle than of physical observables.



See: Pier, Andrii, Gabor, Zoltan

universität wien

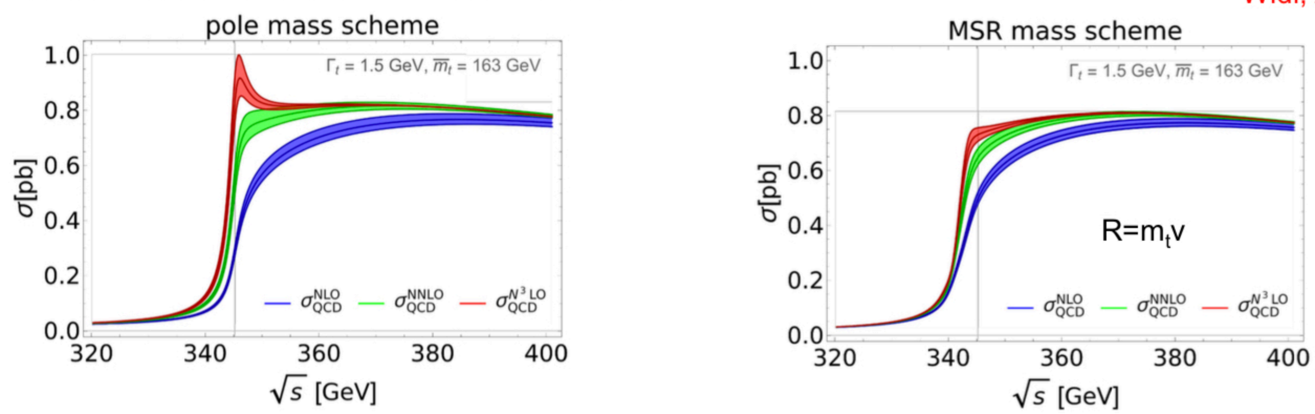
(on α_S and m_{top} precision at FCC)

QCD aspects of top physics at FCC-ee, *A.Hoang*

Improved perturbative behavior by choosing appropriate scale R

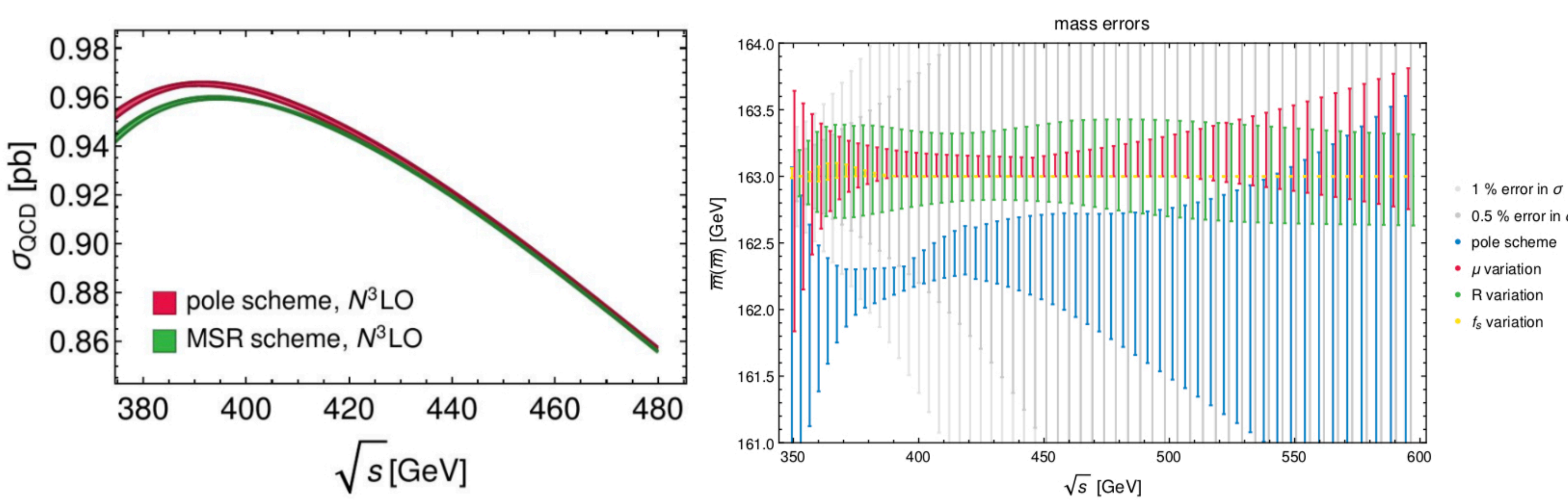
e.g. total inclusive ttbar FO cross section

Widl, AHH to appear



Interesting observation: There is a mass sensitive region above the threshold region where the renormalization scale uncertainty is much smaller than the mass scheme change uncertainty.

Widl, AHH to appear



Could be related to the pole mass renormalon, but hard to tell, but MSR certainly favoured.

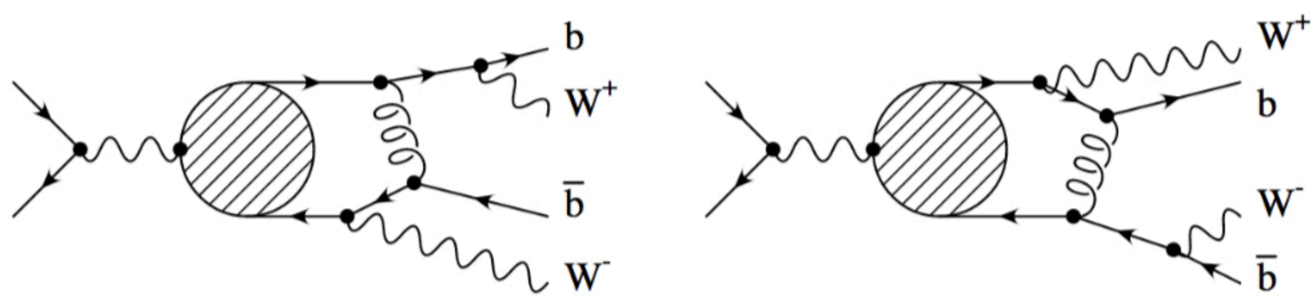
NNNNLO $O(\alpha_S^4)$ computation may resolve the issue.

In principle mass measurement with uncertainty ± 200 MeV possible at E_{cm}=360-370 GeV

(on α_S and m_{top} precision at FCC)

QCD aspects of top physics at FCC-ee*, A.Hoang*

- There are still many interesting unresolved problems to work on to sharpen the theoretical tools for FCC and other future lepton colliders.
- MCs do not include same level of sophistication as inclusive threshold cross-section calculations, missing ingredients crucial for a precise description of kinematics (relevant eg for acceptance studies). Eg:



- Development of a new generation of more precise Monte-Carlo generators must receive high priority and more appreciation in the community as being theory work that is valuable by itself (such as loop calculations).
    - We can use direct top mass measurements (in comparison with top threshold measurements) as a benchmark test for the precision of MC event generators.

Beyond the SM…

Neutral BSM Higgs decay: [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Overall (N)MSSM Higgs decay uncertainty estimates

- $h_i \to q\bar{q}$: SM-like: SM NNLO QCD, EW NNLO, SUSY 2L: $\sim 5\%$
  heavy: as SM-like, Sudakov logs: $\sim 5 - 10\%$
- $h_i \to \ell\bar{\ell}$: SM-like: $\lesssim 1\%$
  heavy: Sudakov logs for very heavy Higgses $\lesssim 10\%$
- $h_i \to WW^{(*)}, ZZ^{(*)}$: SM-like: $\lesssim 1\%$
  heavy: missing 2L (very small width): $\lesssim 50\%$
- $h_i \to \gamma\gamma, gg, \gamma Z$: $\gamma\gamma$: NNLO QCD, EW: $\lesssim 4\%$
  gg: NNLO QCD, EW: $\lesssim 4\%$
  γZ: NLO: $\sim 5\%$
- $h_i \to$ SUSY SUSY: [S.H., C. Schappacher '14-'16]
  1L effects $10 - 20\%$, 2L?
- all decays: $\mathbf{U}_{ij}$, $\mathbf{Z}_{ij}$: few %, effects close to threshold?

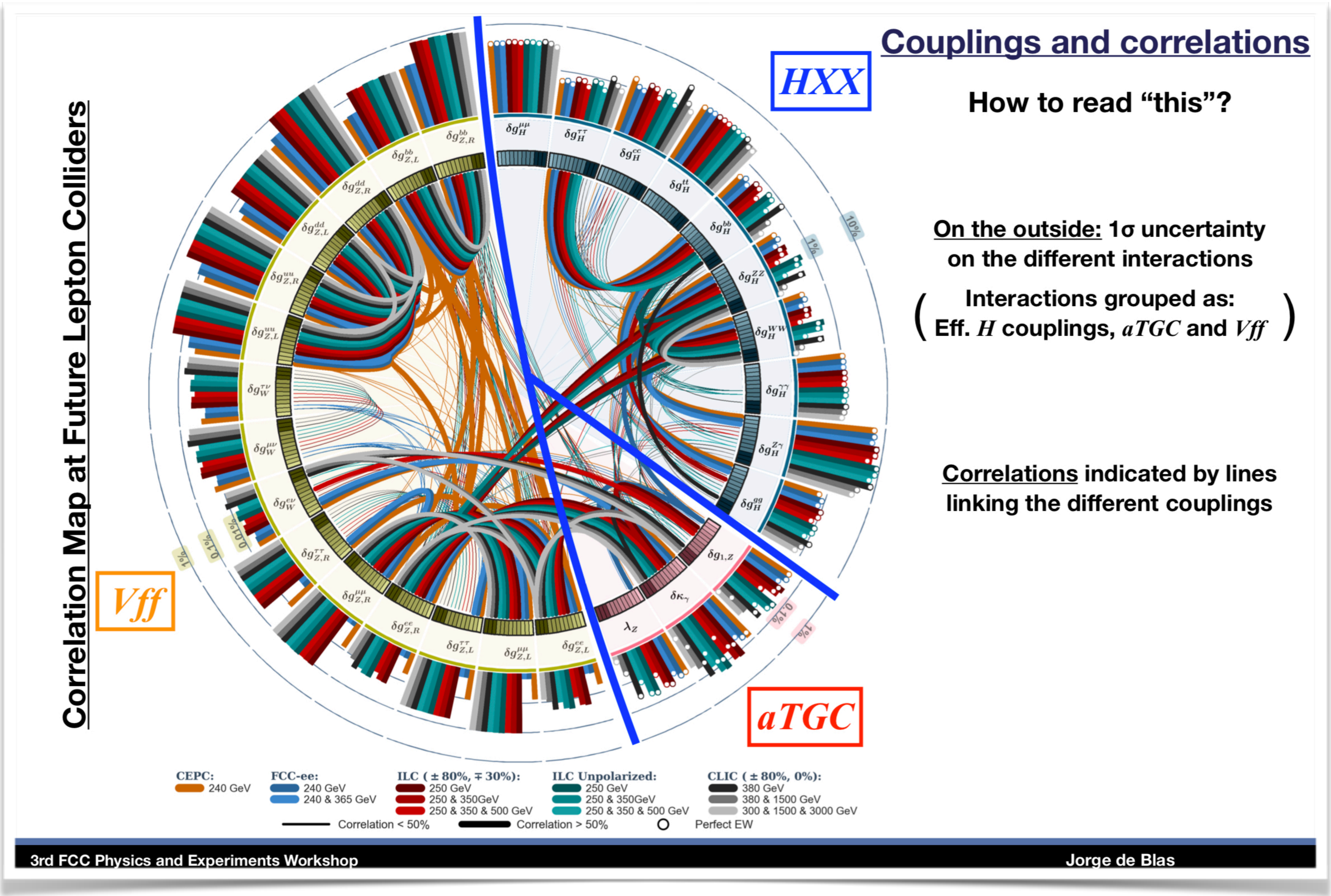
$\Rightarrow$ approaching e^+e^- prec. for SM-like Higgs (not for heavy Higgses yet)

$\Rightarrow$ please repeat in your favorite model!

Precision interpretation of Higgs observables

J. De Blas, "Interplay between Higgs, electroweak and diboson measurements at future colliders",
see also talk at this workshop and arxiv:1907.04311

EFT



NB Do not read this as ' *Higgs measurements will be a "piece of cake"* ' ...

Conclusions

- Motivated by the Higgs factory option, there seems to be a consensus that a future lepton collider must be the next step in particle collider experiments:
    - **“Model-independent”** determination of H couplings (unlike the HL-LHC)
    - Near **per-mille level** precision in some H couplings.
    - But **rare channels** limited by stats ⇒ **need Hadron collider** afterwards

- **But future lepton colliders are more than Higgs factories:** possibility of improving the knowledge of ALL EW interactions

- In fact, **a precise determination of Higgs properties requires to keep under control uncertainties associated to other EW parameters!**
    - We studied the impact of the EW uncertainties adding to the global Higgs + EW fit **a fully global EFT study of WW at future lepton colliders**

- Polarization and higher energies at LC can partially mitigate the impact of the absence of Z-pole run in some couplings (*HZZ*), but cannot the replace the net added value of the EW precision measurements.

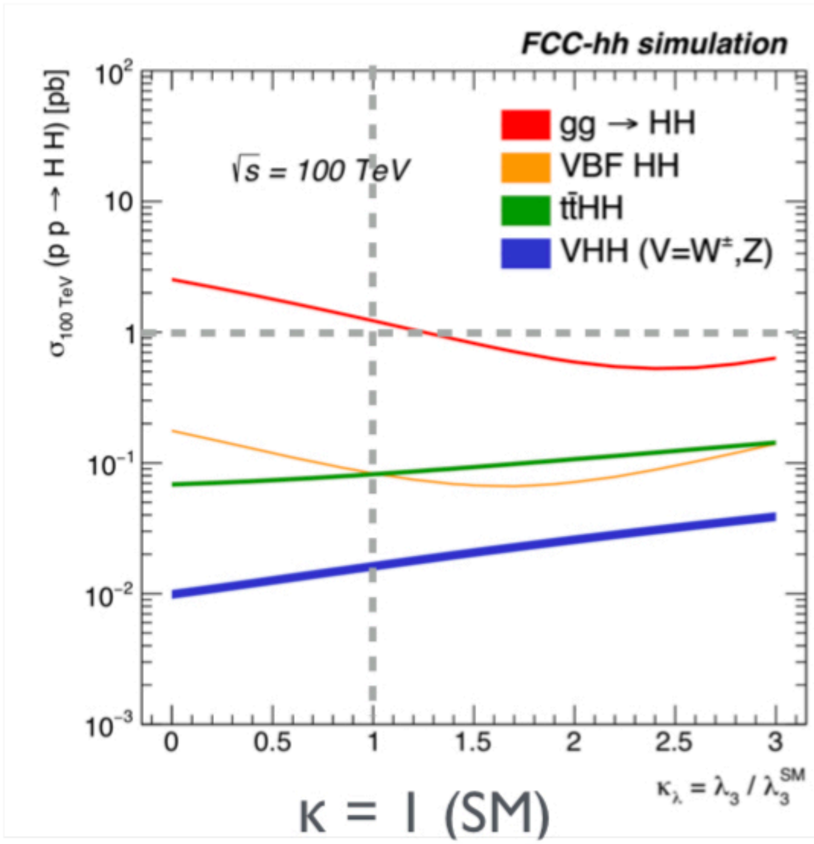
In addition, further FCC-hh inputs to Higgs/EW measurements, as complementary probes of EW/H dynamics in the Q~multi-TeV region, were discussed in several talks

Higgs selfcoupling at FCC-hh

M. Selvaggi, "The Higgs self-coupling at the FCC-hh", see also report arxiv:1910.00012

==>> Major update of FCC CDR studies

Complete set of production processes



Update of decay processes

- bbγγ (golden channel) (UPDATED)
- bbbb (UPDATED)
- bbττ (UPDATED)
- bbZZ(4l)

Systematics assumptions (in red the HL-LHC reference benchmarks)

	Very aggressive (I)	Aggressive (II)	Conservative (III)	Process
τ -jet ID	1%	2.5%	5%	HH, tt, H
b-jet ID	0.5%	1%	2%	HH, tt, H
jet ID	1%	2%	3.5%	jjjγ, γγjj, Z+jets, QCD
e/μ ID	0.25%	0.5%	1%	HH, ZZ, Z+jets, ttV, ttVV, H
γ ID	0.5%	1%	2%	HH, H, jjjγ, γγjj
Luminosity	0.5%	1%	2%	All / jjjγ, γγjj, QCD
ttbar norm.	0.5%	1%	1.5%	tt
single H norm.	0.5%	1%	1.5%	H

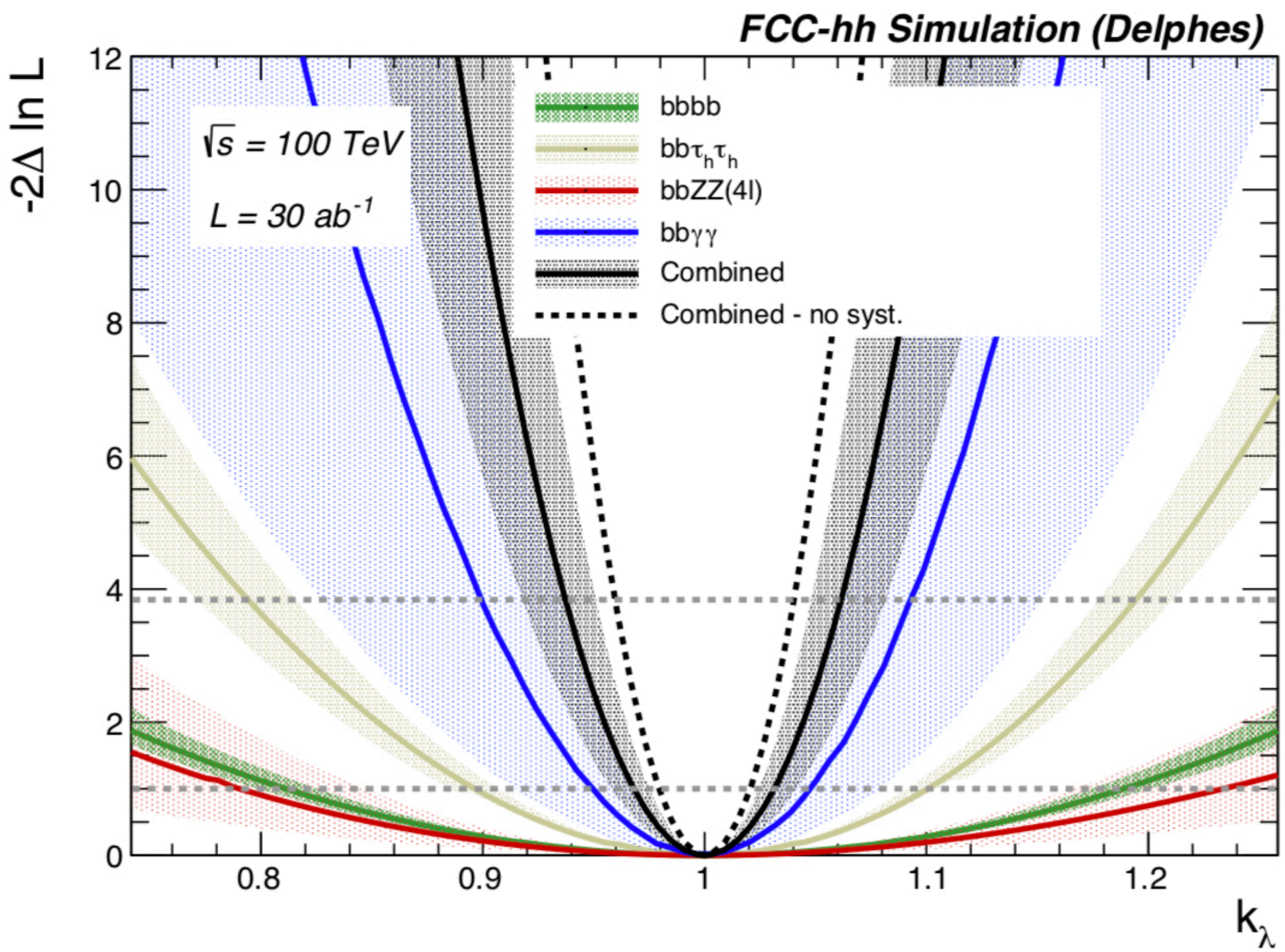
Examples of analysis improvements (bbγγ)

- Exploit full final state information and correlations $p_T(\gamma_i)$, $p_T(b_i)$, $\eta(\gamma_i)$, $\eta(b_i)$, etc… with a MVA
- Single H and QCD trained separately
- Fit 2D (BDT_H , BDT_{QCD}) spectrum

Higgs selfcoupling at FCC-hh

M. Selvaggi

Combination of all channels



PRELIMINARY !

Combined sensitivity:

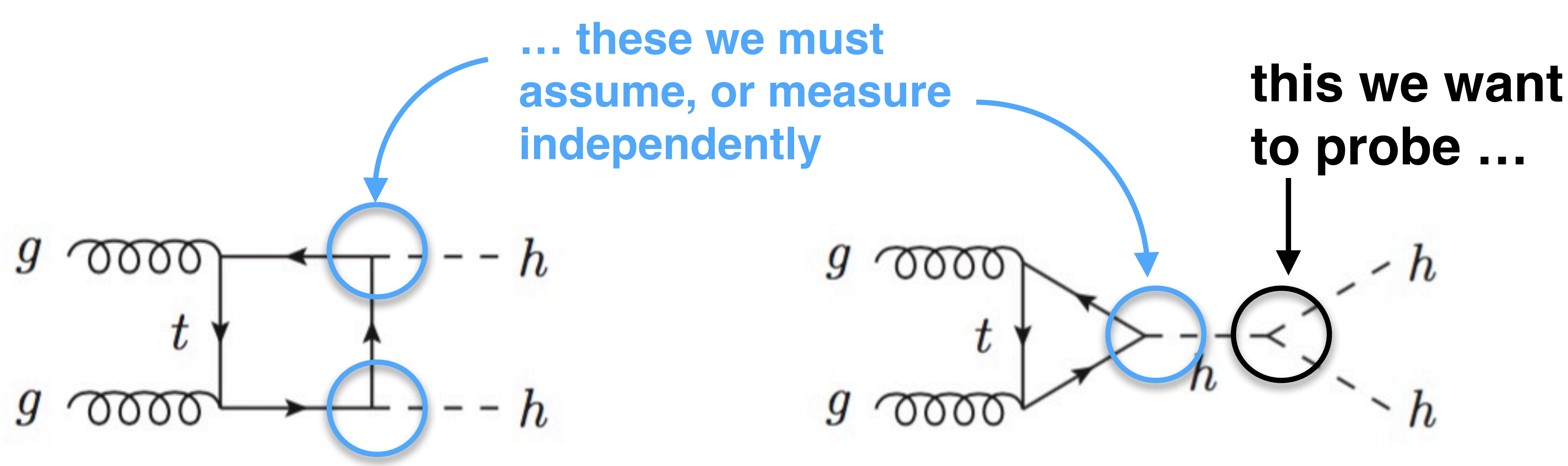
- $\delta\kappa_\lambda$(stat) = 2 % @68% CL
- $\delta\kappa_\lambda$(stat) = 5 % @95% CL

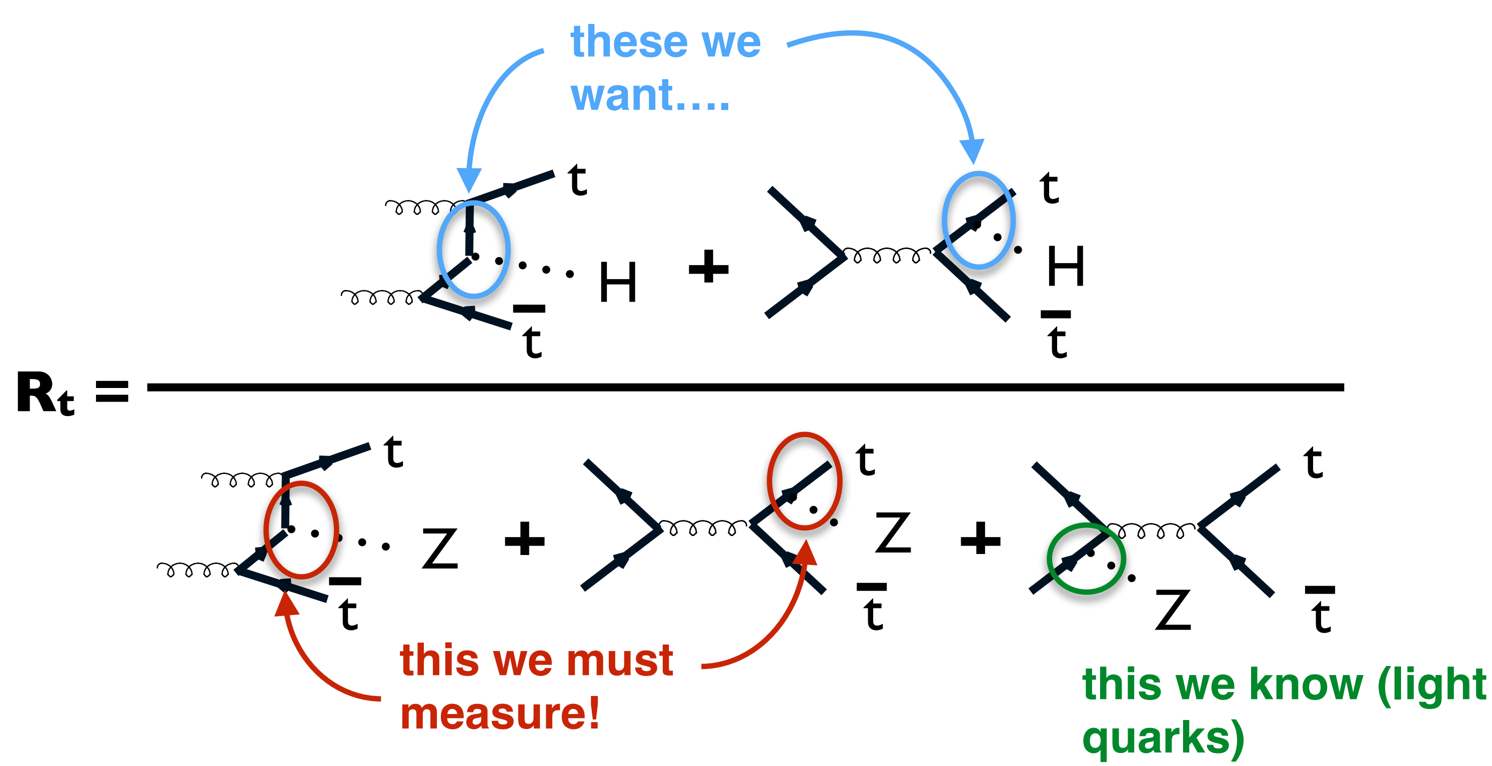
- **$\delta\kappa_\lambda$(syst) = 2.5 - 4.0 % @68% CL**
- $\delta\kappa_\lambda$(syst) = 4.0 - 8.2 % @95% CL

- bbγγ: $\delta\kappa_\lambda \approx$ 3-8% (large improvement due to MVA and use of secondary processes)
- bbττ: $\delta\kappa_\lambda \approx$ 9-12% (using $\tau_{had}\tau_{had}$)
- bb4l: $\delta\kappa_\lambda \approx$ 10-20%
- bbbb: $\delta\kappa_\lambda \approx$ 15-20%

For the first time ever a collider promises the measurement of the Higgs self-coupling to have statistical uncertainty at the % level. The challenge is now with systematics, including TH

Interpreting Higgs self-coupling from gg→HH at FCC-hh

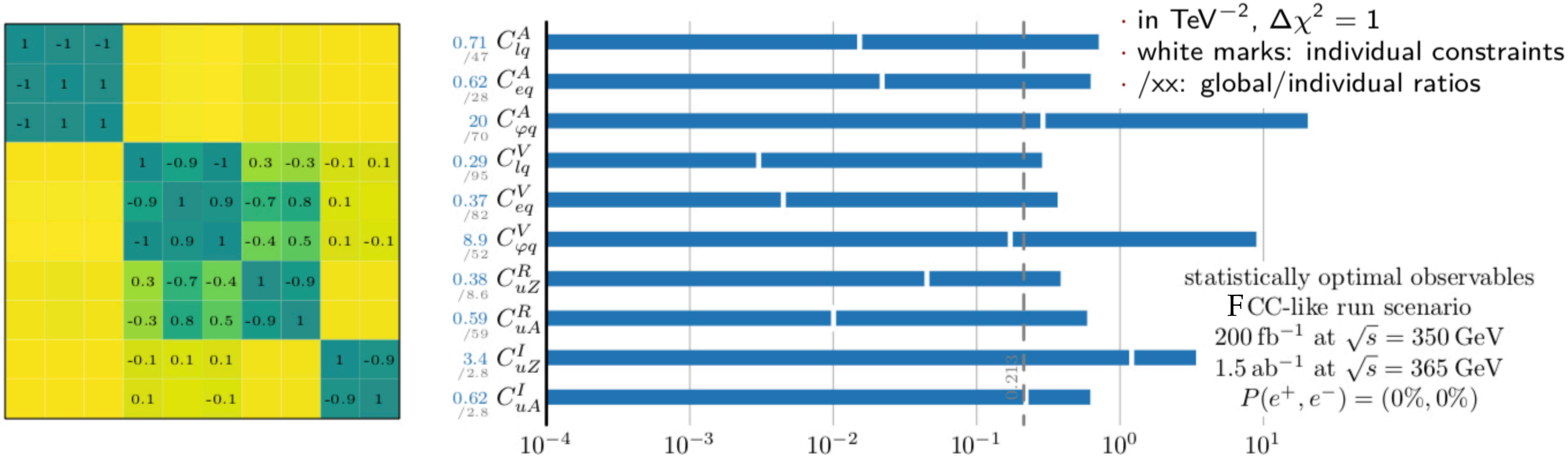




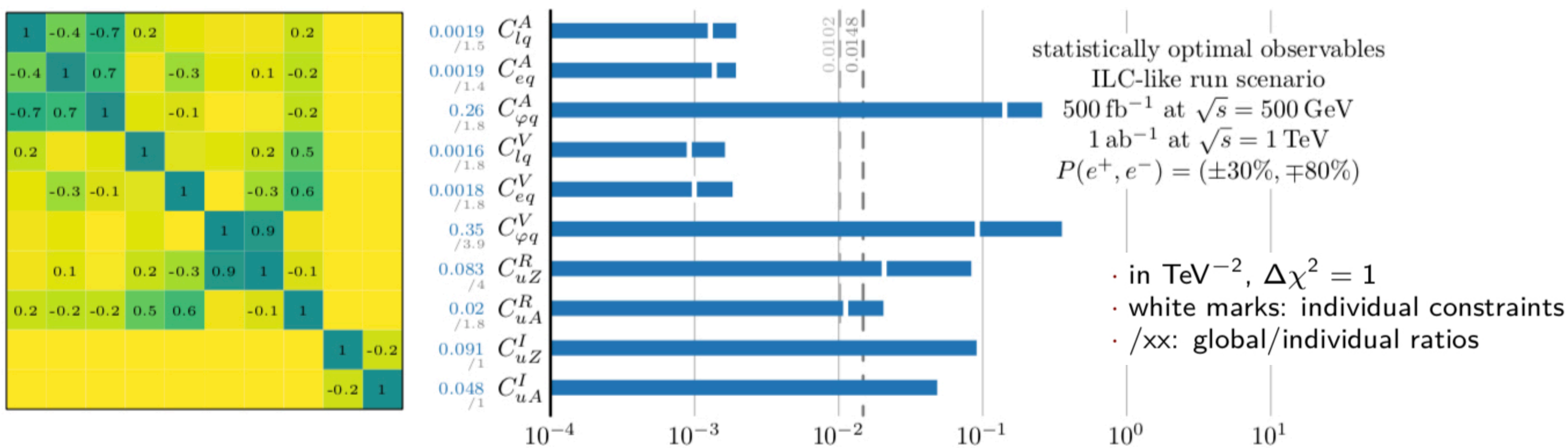
The importance of probing top EW couplings

G. Durieux, Impact of top-quark loops for Higgs precision measurements (see also arXiv:1809.03520, arXiv:1807.02121)

FCC-ee: 350+365



ILC: 0.5 + 1TeV



Questions

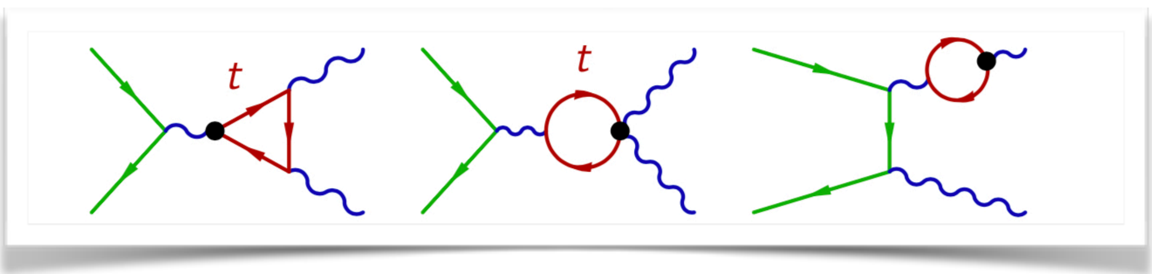
Q1: Can one get sensitivity to top interactions from top loops at $E<2m_{top}$?

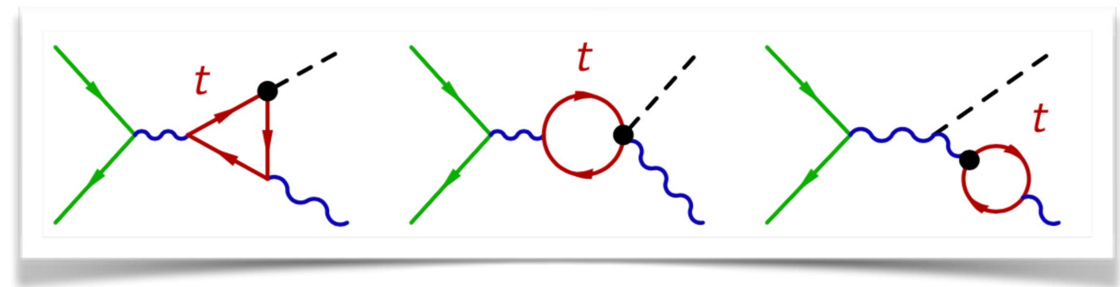
Q2: Do top uncertainties impede precise Higgs measurements?

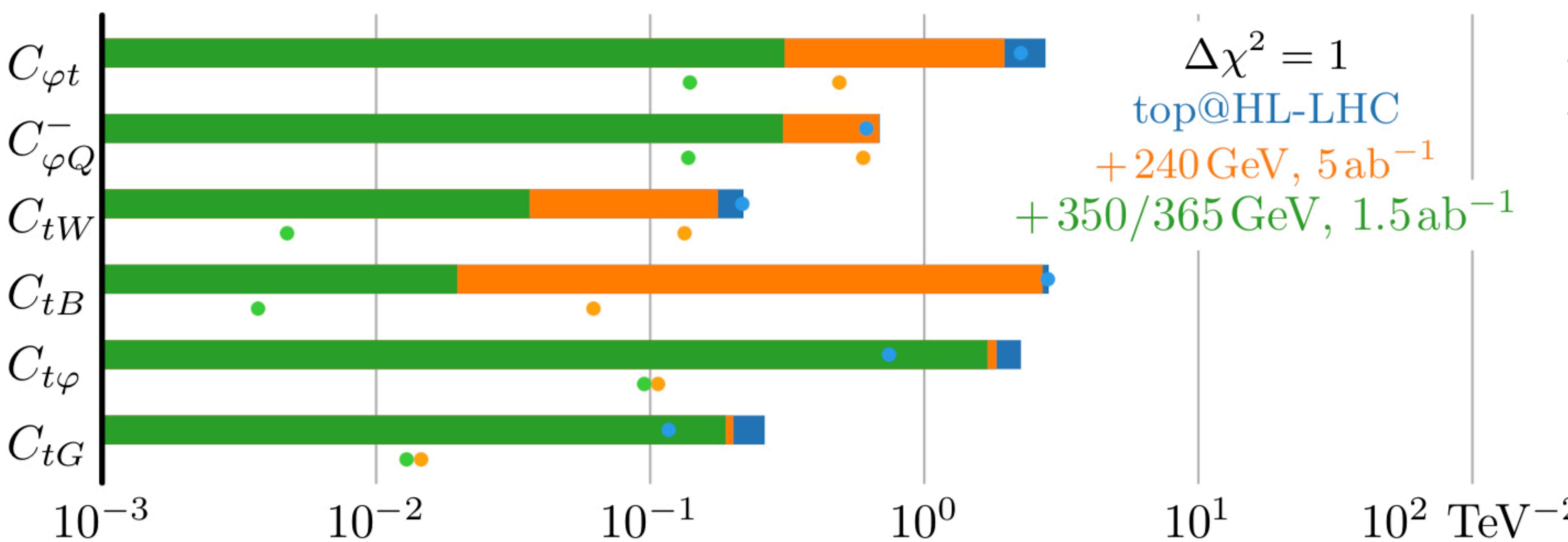
The importance of probing top EW couplings

G. Durieux, Impact of top-quark loops for Higgs precision measurements (see also arXiv:1809.03520)

Q1: Can one get sensitivity to top interactions from top loops? (Z pole, m_W and Γ_W , diboson production and kinematical distributions, Higgs production and decay BRs)





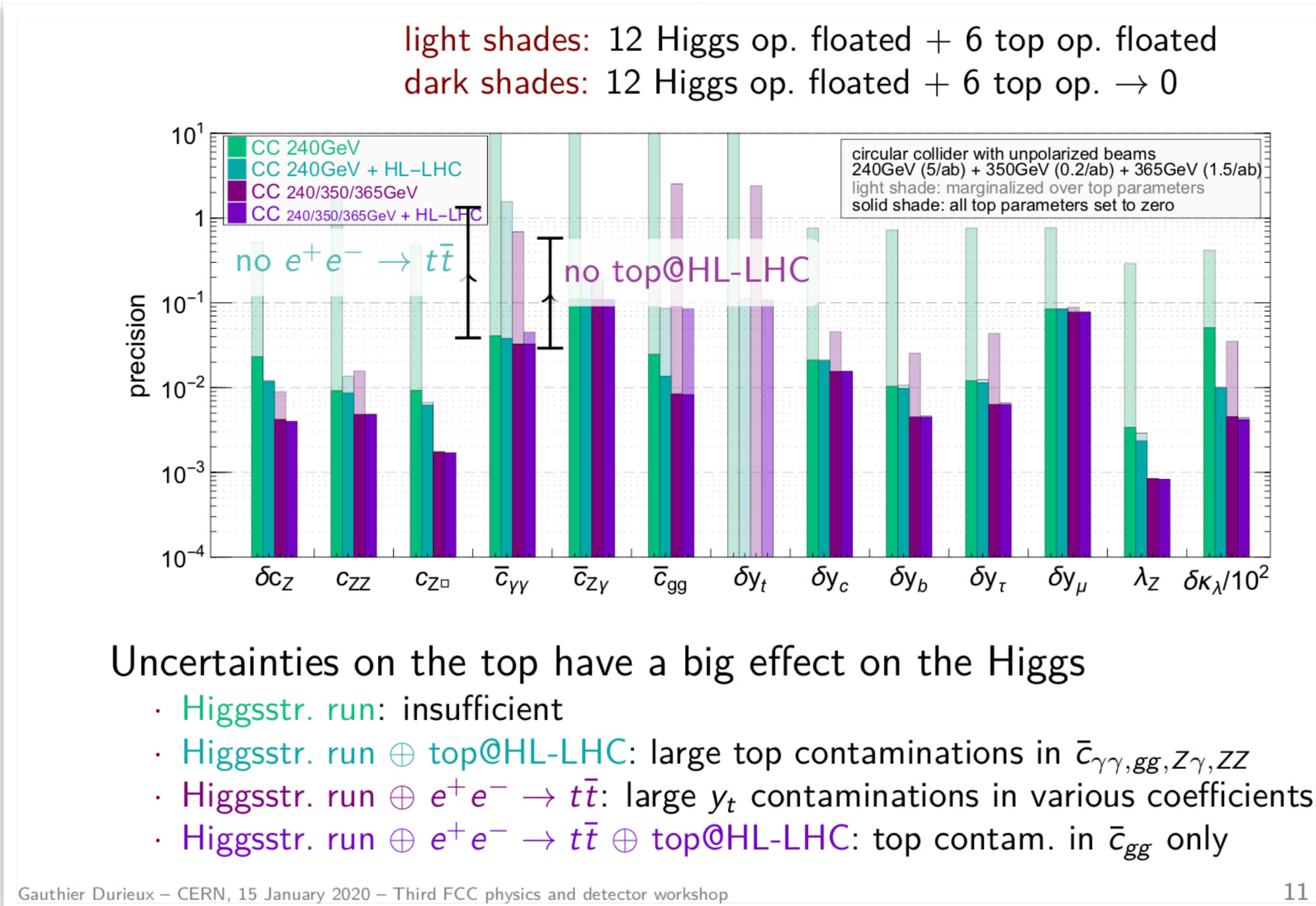


Blobs: *individual operators.*
Bars: *global fits, 12 Higgs + 6 top operators floated*

The importance of probing top EW couplings

G. Durieux, Impact of top-quark loops for Higgs precision measurements (see also arXiv:1809.03520)

Q2: Do top uncertainties impede precise Higgs measurements?

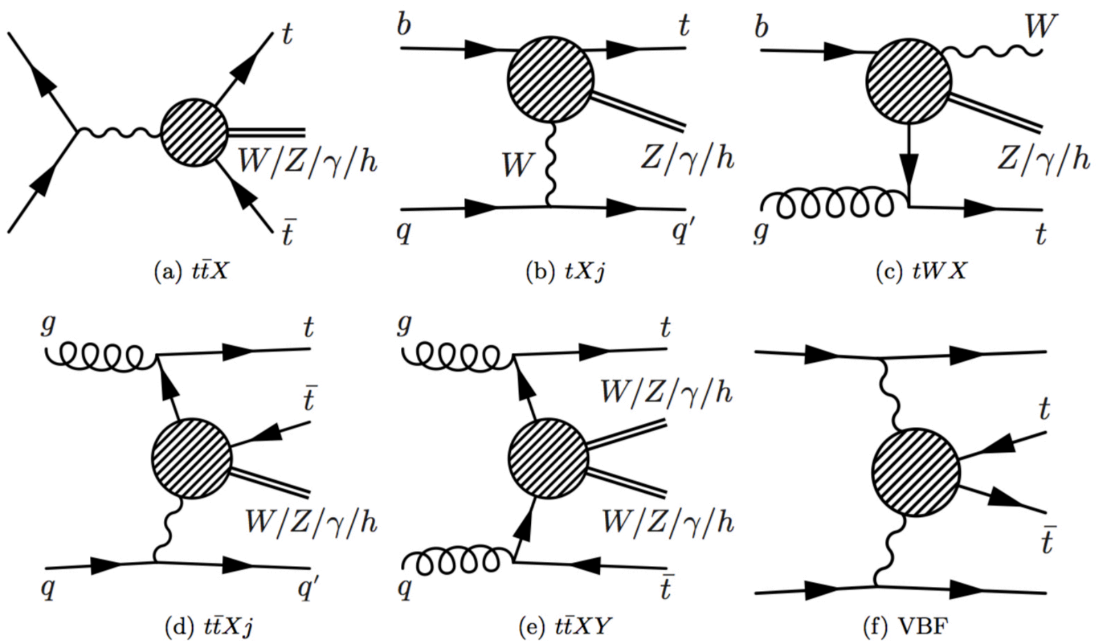


The importance of probing top EW couplings

K. Mimasu, Top quark EW interactions at high energy (see also arXiv:1904.05637)

Energy growth of various EFT ops appearing in high-E top processes

Collider processes: rare, EW top production



gauge/higgs operators $\Longleftarrow$ $\Longrightarrow$ *top operators*

Energy-growing interference

single-top

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$bW \to tZ$	E	–	–	–	E	E^2	–	E^2	E^2	E	E^2	E	E^2
$bW \to t\gamma$	–	–	–	–	E	E^2	–	E^2	E^2	–	–	–	–
$bW \to th$	–	–	–	E	–	–	E	–	E^2	–	E^2	–	E^2

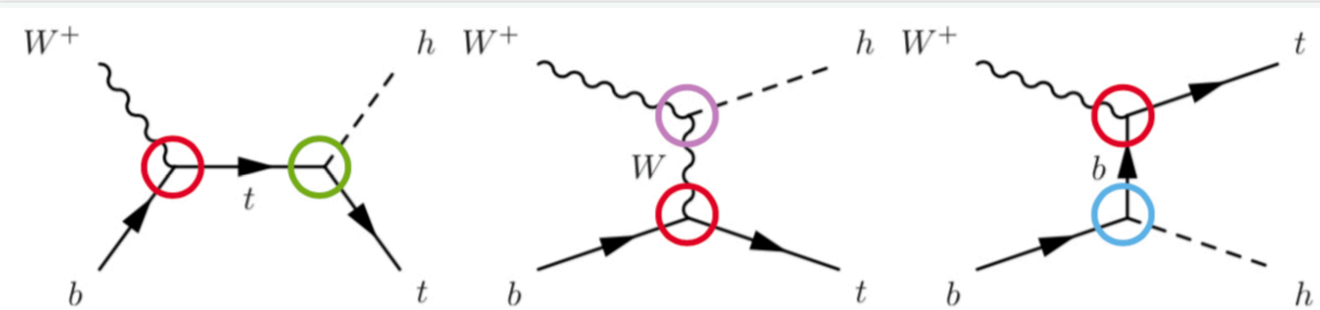
two-top w/o Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$
$tW \to tW$	E	E	–	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \to tZ$	E	E	E	E	E	–	E	E^2	E^2	E	E	E
$tZ \to t\gamma$	–	–	E	E	E	–	–	E^2	E^2	–	–	–
$t\gamma \to t\gamma$	–	–	E	E	E	–	–	E	E	–	–	–

two-top w/ Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$tZ \to th$	E	–	E	E	E	–	E	E^2	E^2	E^2	E^2	E^2	–
$t\gamma \to th$	–	–	E	E	E	–	–	E^2	E^2	–	–	–	–
$th \to th$	E	E	–	–	–	–	E	–	–	–	–	–	–

Example: bW →tH



- tbW vertex: present in all diagrams → overall rescaling ~ E^0
- bbH vertex: ∝ m_b → 0
- HWW & ttH interactions: participate in a unitarity cancellation ~ v E

$$\mathcal{A}(b_L, W_L, t_R) \propto \sqrt{-t}\,(2m_W^2 \boxed{g_{th}} - \boxed{g_{Wh}}\, m_t)$$

Higgs selfcouplings, extended Higgs sectors, and the EW phase transition

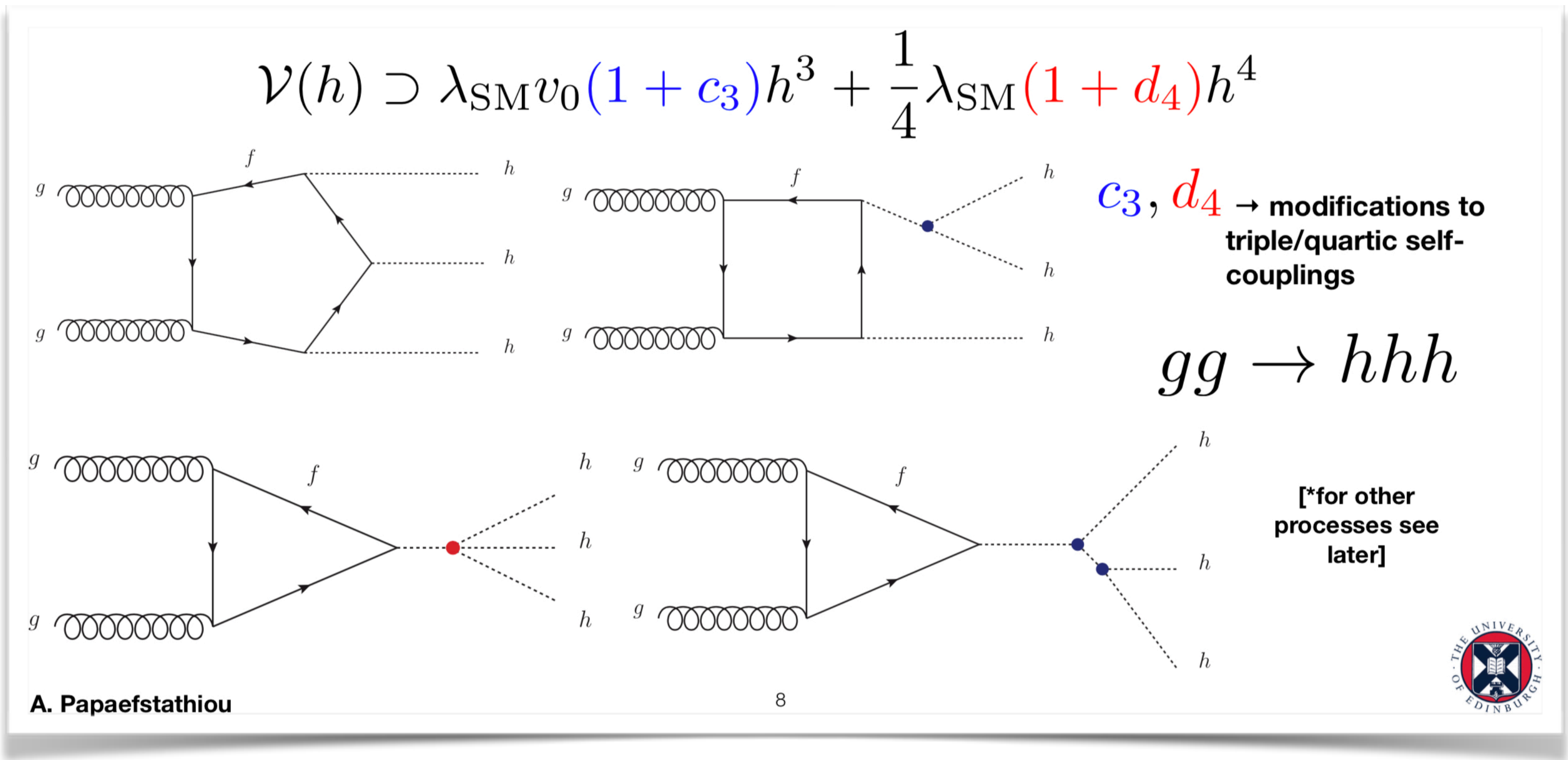
M. Ramsey-Musolf, *"The Electroweak Phase Transition: A Future Collider Target"*, arXiv:1912.07189
Z. Liu, "Electroweak Phase Transition meets Higgs Exotic decays" arXiv:1911.10206

- *Determining the thermal history of EWSB is field theoretically interesting in its own right and of practical importance for baryogenesis and GW*
- *The scale T_{EW} → any new physics that modifies the SM crossover transition to a first order transition must live at M < 1 TeV*
- *Searches for new scalars and precision Higgs measurements at the LHC and prospective next generation colliders could conclusively determine the nature of the EWSB transition*

More Higgs selfcouplings at FCC-hh

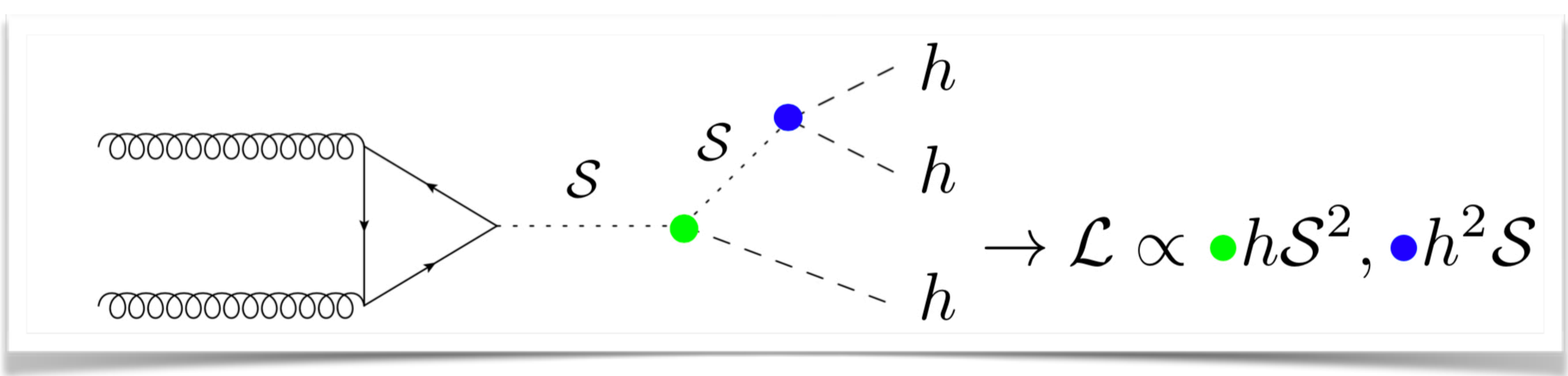
A. *Papaefstathiou, "Triple Higgs boson production at the FCC-hh", see also report* arXiv:1909.09166

Using HHH → 6 b and HHH → 4b γγ



In models with an additional scalar singlet (as eg considered for strong 1st order EW phase transition)

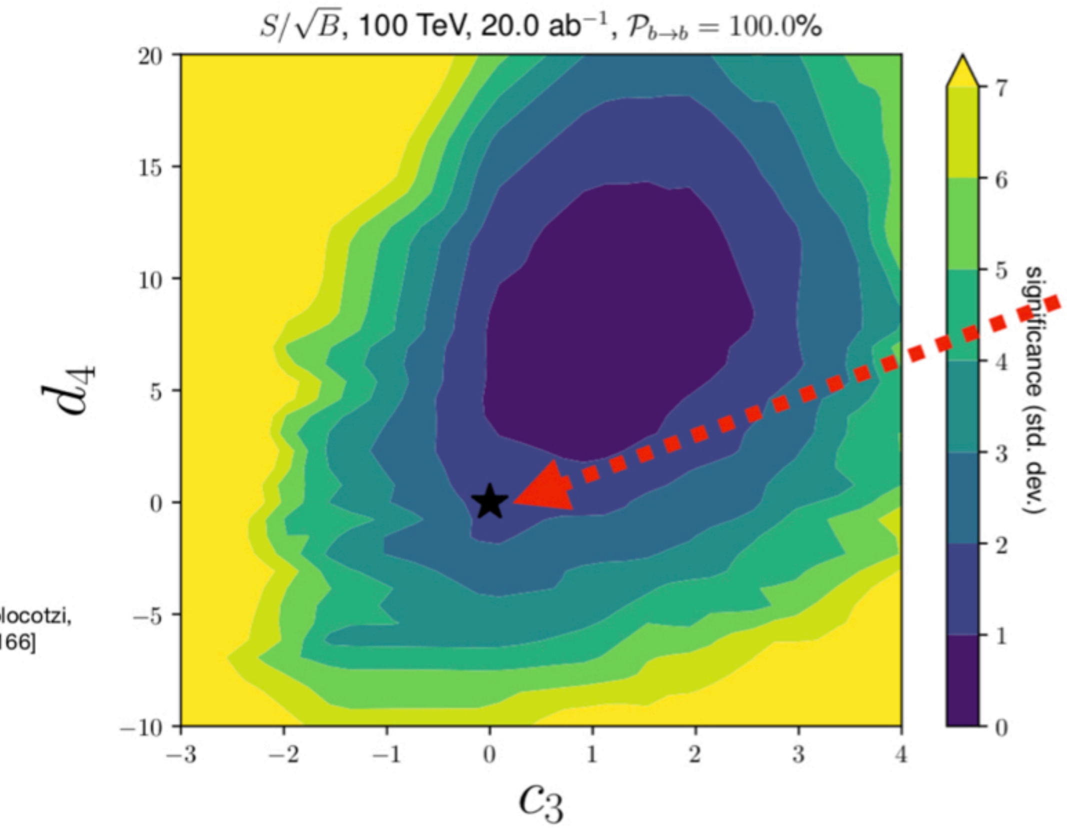
$$\mathcal{V}(H,S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$



More Higgs selfcouplings at FCC-hh

A. Papaefstathiou

Constraints on the (c_3,d_4) plane

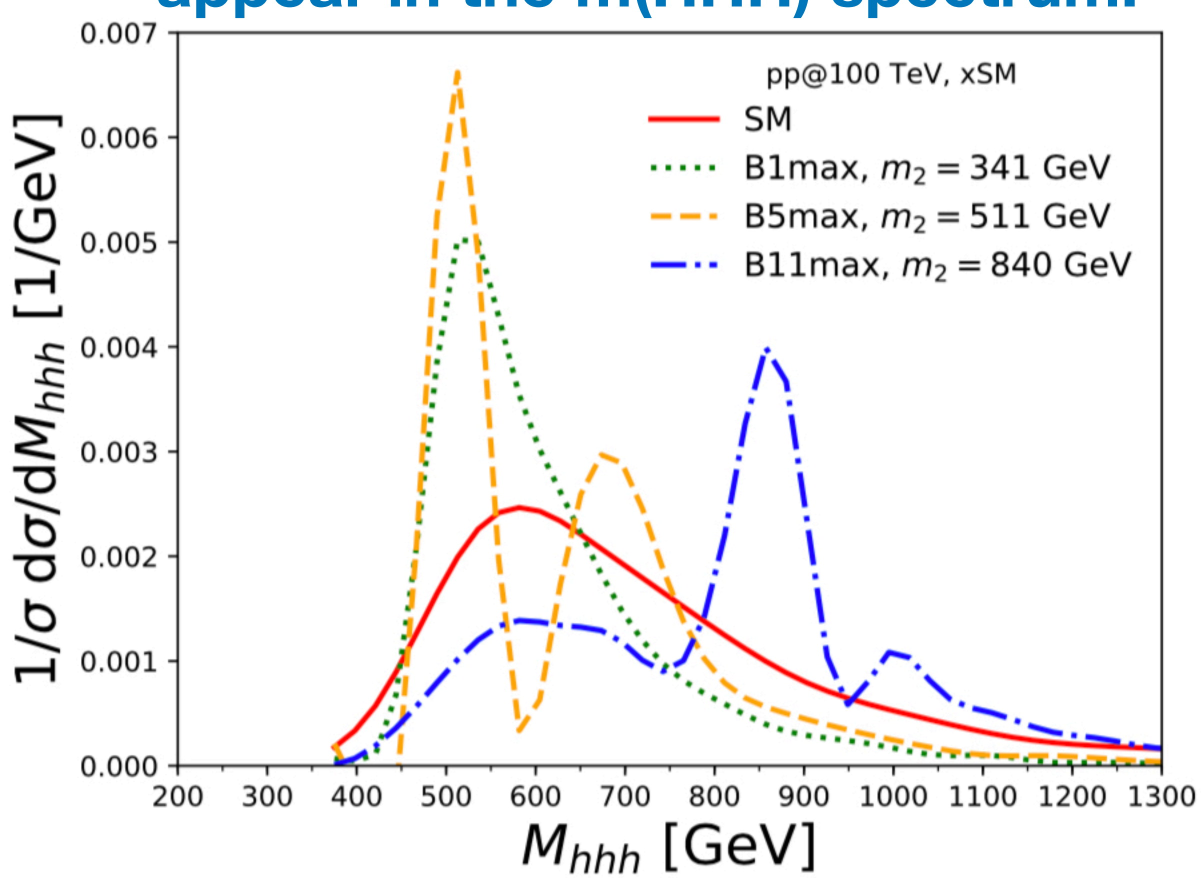


[AP, Tetlalmatzi-Xolocotzi, Zaro, 1909.09166]

SM significance ~ 1.7σ

& if $c_3 = 0 \Rightarrow d_4 \in [-1.7, 13.3]$ @ 95% C.L.

In singlet models, structures appear in the m(HHH) spectrum:

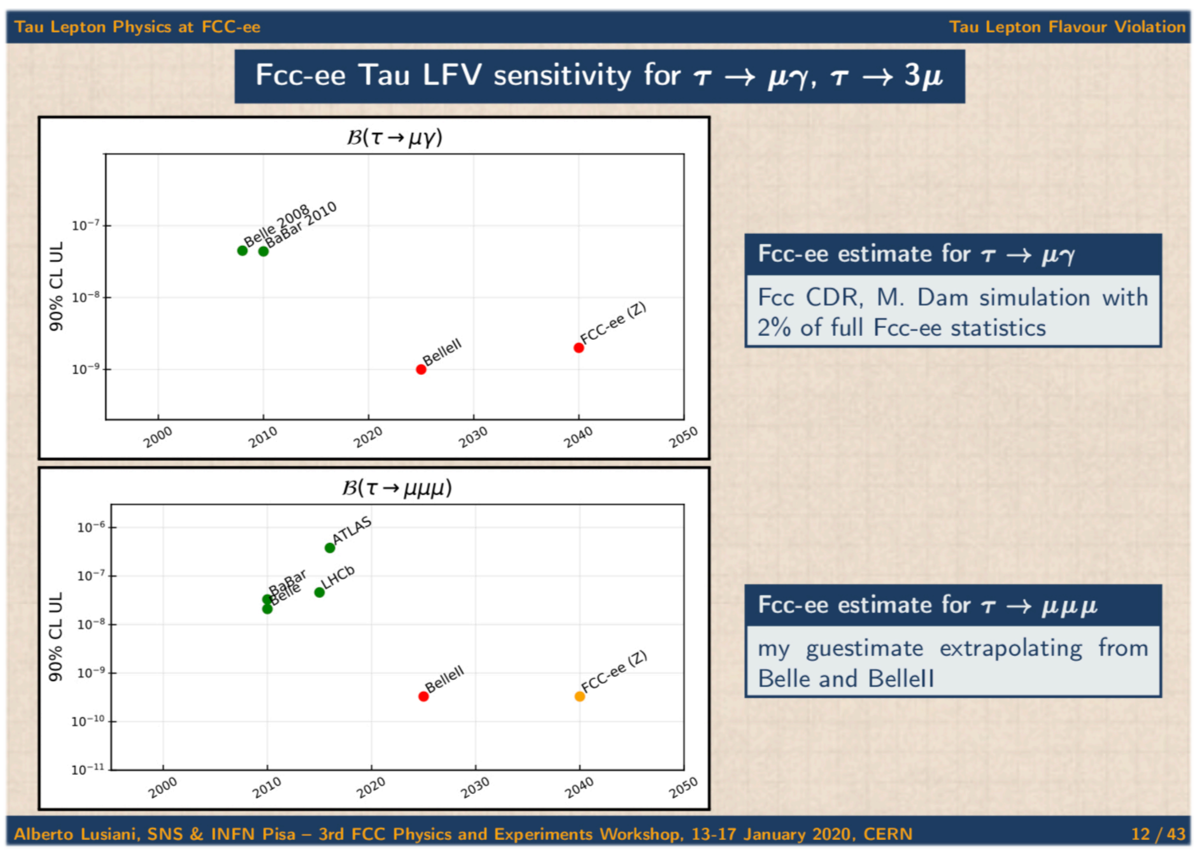


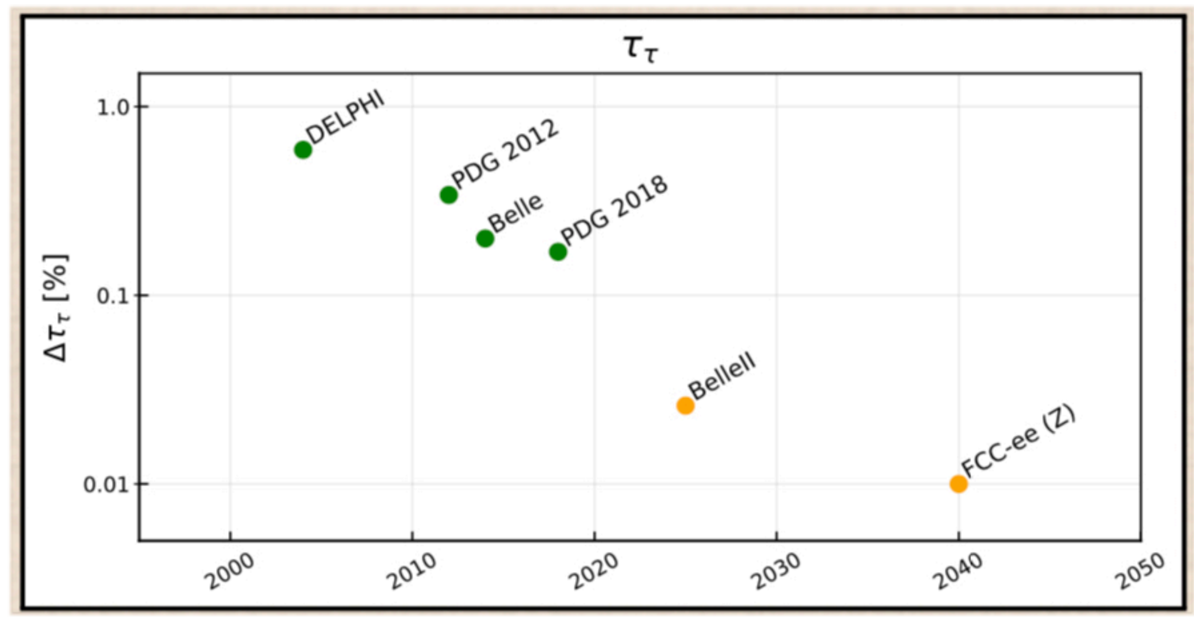
Benchmark models with strong 1st order PT

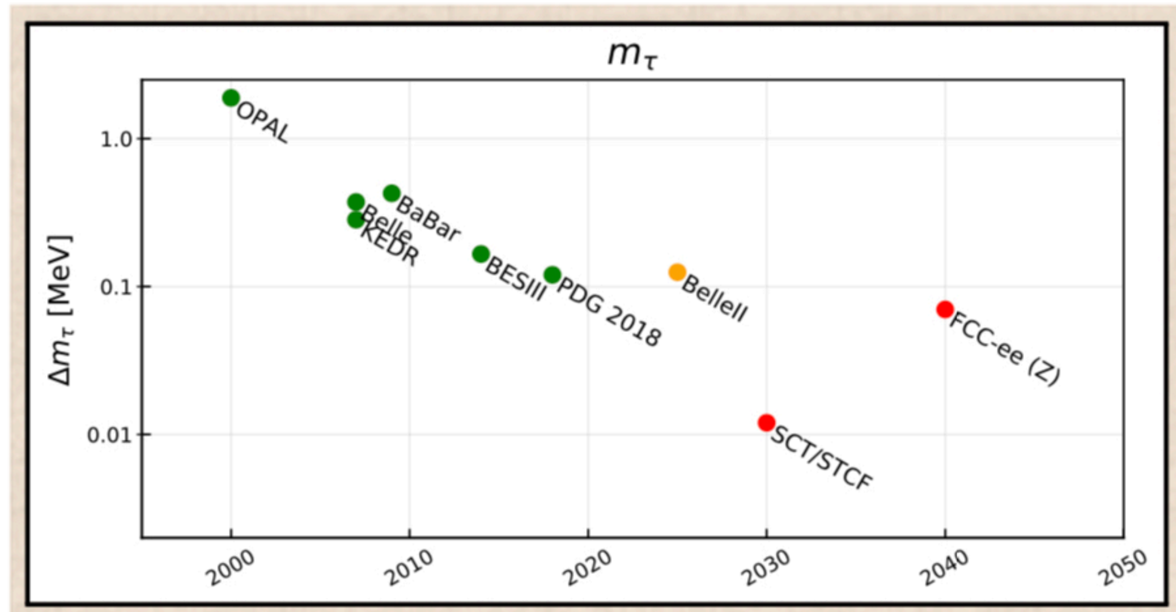
Benchmark	Significance (stdevs)
B1max	46.6
B2max	42.9
B3max	2.9
B4max	3.7
B5max	3.0
B6max	3.8
B7max	5.3
B8max	7.8
B9max	5.9
B10max	4.9
B11max	2.3

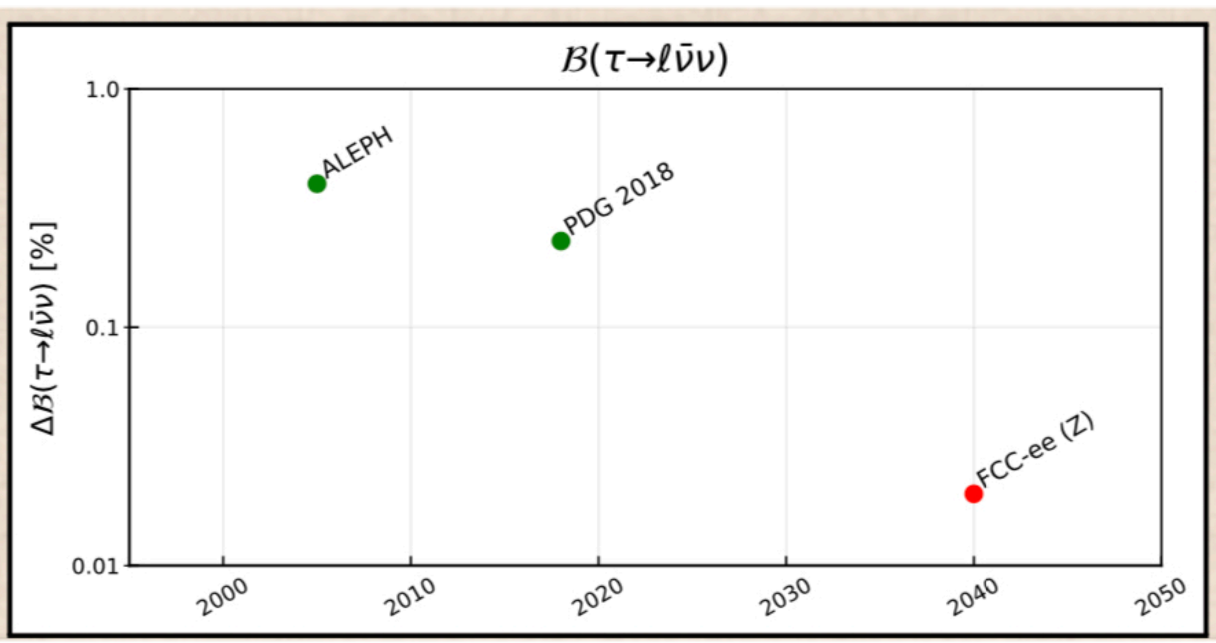
Flavour physics at TeraZ

"Tau lepton physics", A.Lusiani
"Charm physics", G.Hiller
"B physics", M-H Schune









- TeraZ facilities are the best for τ physics
- there are several interesting measurements to be improved
- fair share of systematics scale with luminosity
- identified possibly limiting systematics still allow large and interesting margins of improvement
- improvements on tau lifetime and leptonic BRs make desirable improvements on m_τ (SCTF?)

Flavour physics at TeraZ

"B physics", M-H Schune

Tracking and vertexing :
Momentum reconstruction down to 100 MeV
$\sigma(PV) = 3\ \mu m$
$\sigma(B\ vtx) = 7\ \mu m$
$\sigma(\tau\ vtx) = 5\ \mu m$

e/γ:
resolution : ~3%/$\sqrt{E}$ and granularity (transverse and longitudinal)
Low X0 detector before the ECAL

PID:
Electron/muon up to 45 GeV

π/K/p separation over the full kinematical range

G. Wilkinson's talk

V0s (K_s and Λ):
Good efficiency and precision important (CPV, B_s Λ_b)

Final remarks

- I left out a majority of the individual contributions, covering a broader set of processes and BSM scenarios I could consider
- The scope and detail in the definition of the physics potential are continuously growing
- Next steps (from Alain's Workshop conclusions):

Physics and Experiments studies

We started organizing ourselves in the last months towards the next steps

In particular physics and experiments studies should become more intense
-- towards detector conceptual designs and LOIs
-- engage community of users (experimenters and theorists)

Steps have been made towards broader reach, both by increasing the scope of our International advisory committee **FCC-IAC** and working within the framework of **ECFA**

Some upcoming tasks for P&E stemming from this workshop

1. establish a list of benchmark processes on which to compare detector solutions
   ex: σ ee→HZ, H→bb, cc, gg, R_l, R_b, m_W, tau lifetime, mass, polarization etc.
   need a little task force -- ILC&B-factory experts would be useful

2. discuss proposal
   to measure ee(ECM=30-90)-> hadrons (cross-section and event shapes)
   and compare with possibilities offered by e+e-(91 GeV)→ γ + hadrons($\sqrt{s}$=30-90)
   need also a little QCD task for these studies

People who would be honored to be asked, please manifest yourselves