TH-phenomenology highlights

Michelangelo Mangano
CERN TH

Thanks to the

Theory programme committee

- Ayres Freitas
- Janusz Gluza
- Christophe Grojean
- Sven Heinemeyer
- Michelangelo Mangano
- Matthew Mc Cullough
- Lian Tao Wang

Several talks reflected progress more focused on purely TH aspects.

For this short summary of the TH/pheno sessions, I will highlight contributions that have a most direct impact on the FCC planning, and which are more in need of being brought to the attention of the experimental colleagues who could not follow the TH sessions

PS I assume <u>everyone</u> attended the joint TH/EXP sessions, so will give those less prominence

Aside: factor-of-2 improvements can matter!

Search for $K_L \to \pi\pi$

ANNALS OF PHYSICS: 5, 156–181 (1958)

Long-lived Neutral K Mesons*

M. Bardon, K. Lande, and L. M. Lederman

Columbia University, New York, New York, and Brookhaven National Laboratories, Upton, New York

and

William Chinowsky

Brookhaven National Laboratories, Upton, New York

set an upper limit <0.6% on the reactions

< 0.6%

$$K_2^0 \to \begin{cases} \mu^{\pm} + e^{\mp} \\ e^+ + e^- \\ \mu^+ + \mu^- \end{cases}$$

and on $K_2^0 \to \pi^+ + \pi^-$.

Volume 6, Number 10 PHYSICAL REVIEW LETTERS May 15, 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3% for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our

< 0.3%

"At that stage the search was terminated by administration of the Lab."

[Okun, hep-ph/0112031]

Volume 13, Number 4 PHYSICAL REVIEW LETTERS 27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

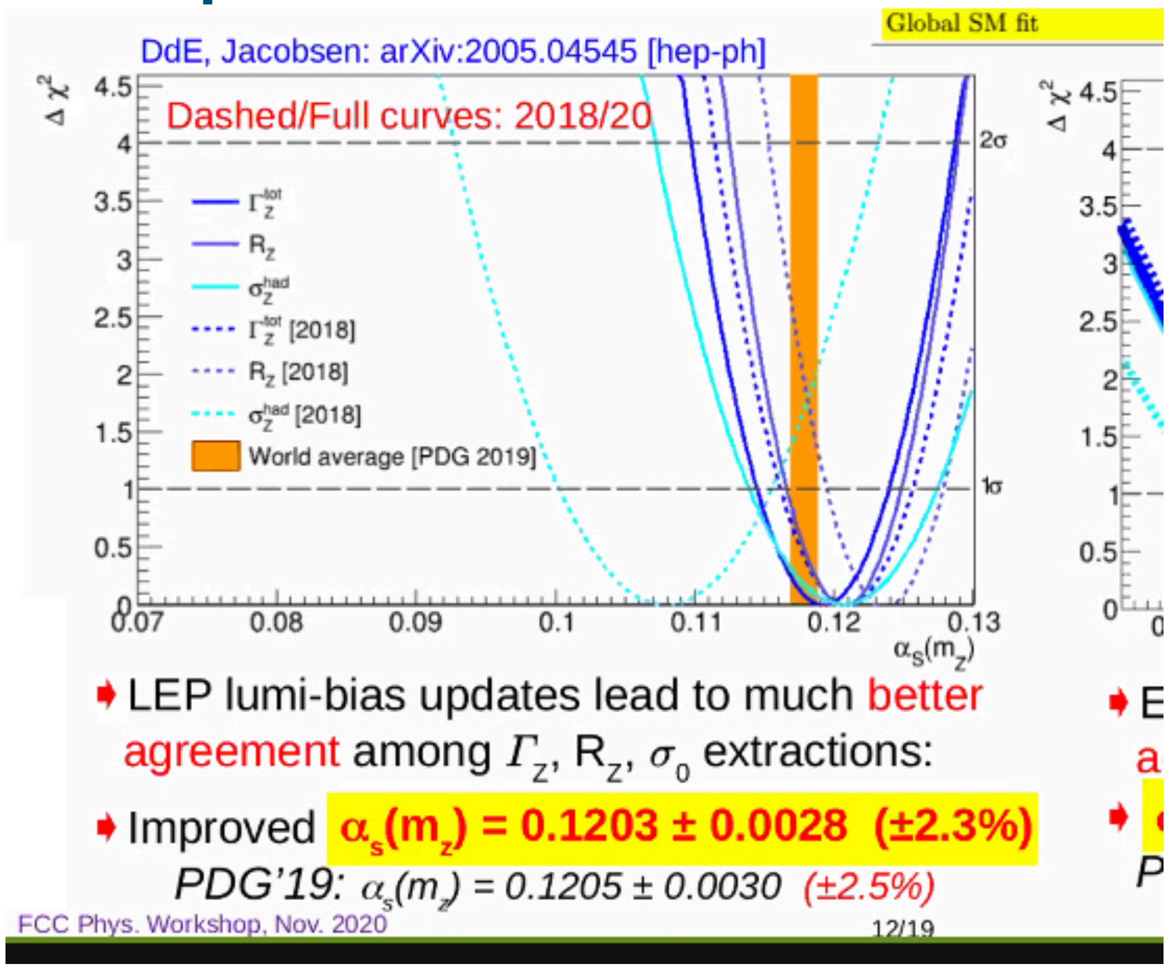
J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

= 0.2 ± 0.04 %

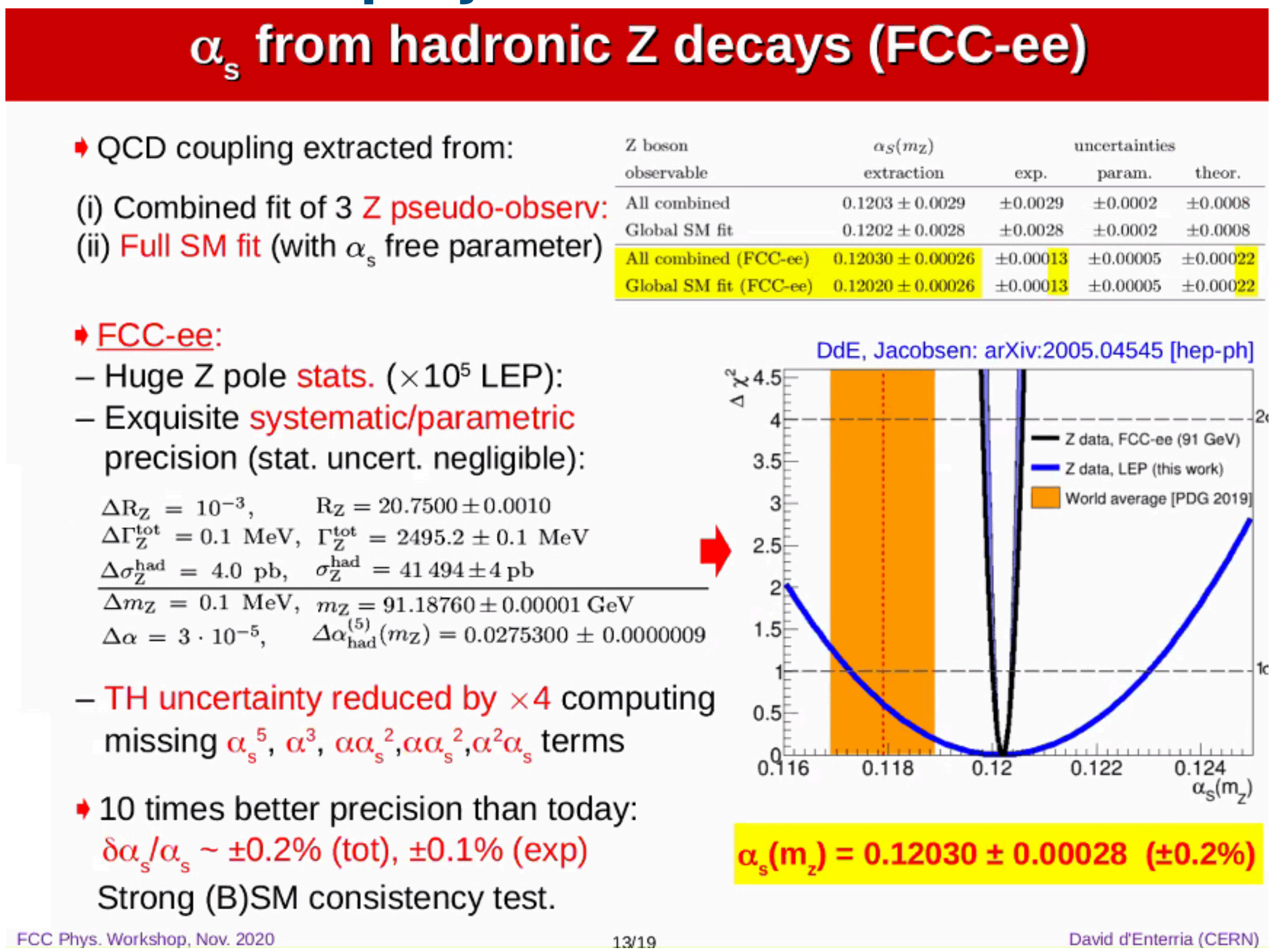
We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As empha-

The path to precision: α_S

LEP update



FCC-Z projection



± 2.3% → ± 0.2%

At this level of precision, independent measurements of similar precision are required to validate central value and uncertainties: will α_S be dominated by global hadronic rates @Tera-Z, or will the other extractions (event shapes, lattice, τ decays, DIS, …) evolve and remain competitive?

FCC programme's diversity ⇒ robustness

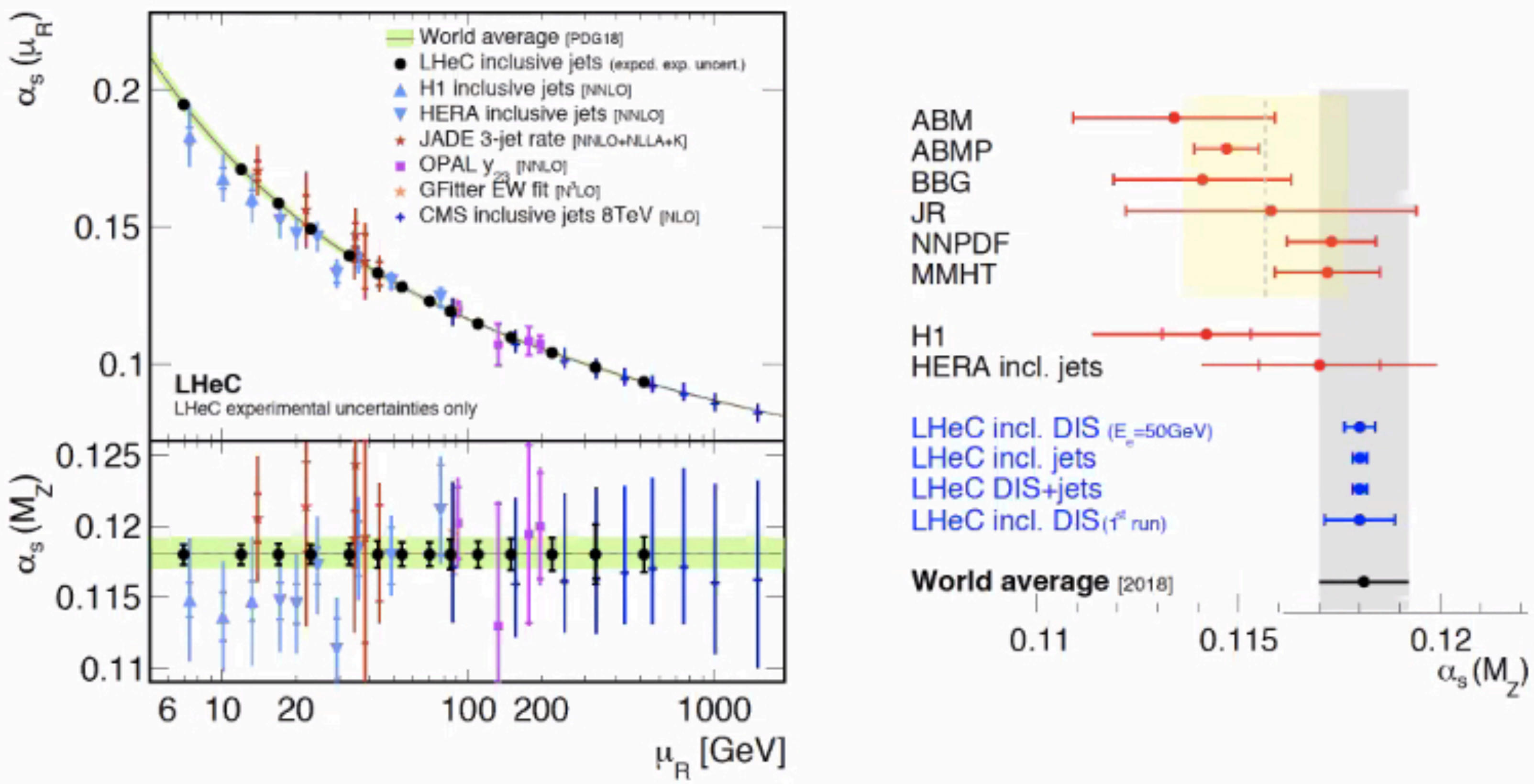
D.D'Enterria

FCC-WW, W→hadrons global obs: precision similar to Z→hadrons ± 0.2%

DIS at FCC-eh

D.Britzger, C. Schwanenberger

Before concluding.... Strong coupling determination



Future ep colliders offer a unique opportunity to determine α_s with high precision (simultaneous determination of α_s and PDFs)

Note: also a low luminosity run will already improve significantly the precision

Direct determination at low Q^2 → important also for small x

$$\boxed{\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00019_{(\text{exp+PDF})}}$$

FCC-eh

± 0.2%

New ideas to extend discriminating power for different QCD final states, better control over resummation of higher-orders for dedicated jet observables, etc

Implications for precision QCD measurements and for searches

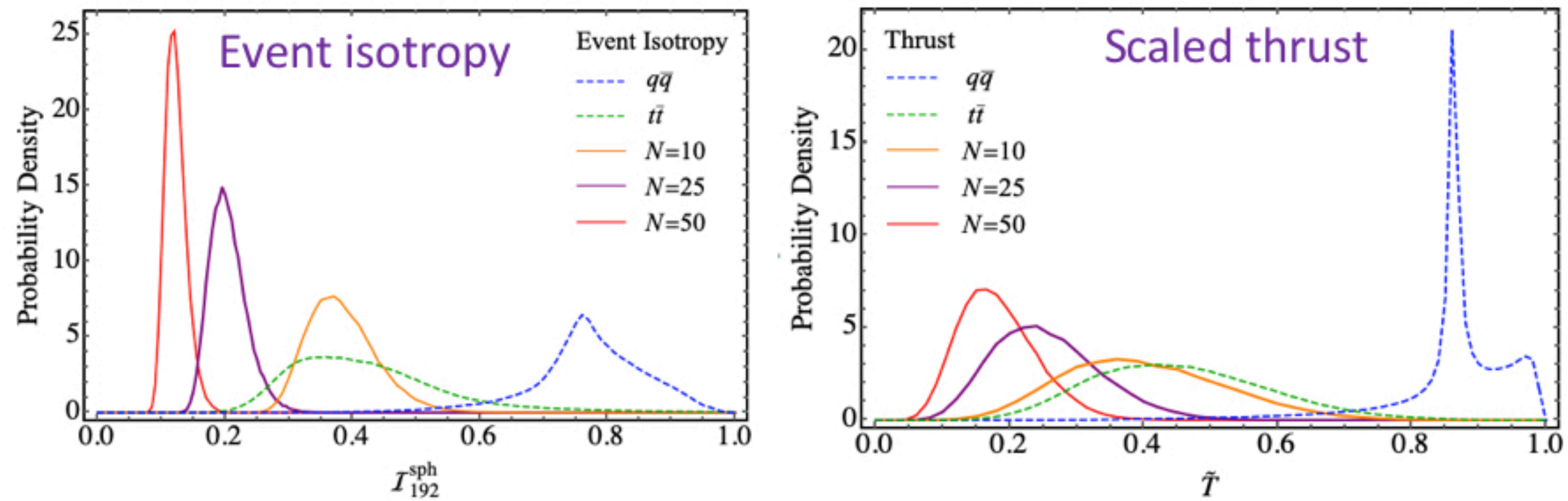
C.Cesarotti, T.Liu

Event Isotropy:

“distance” of an event from a uniform radiation pattern

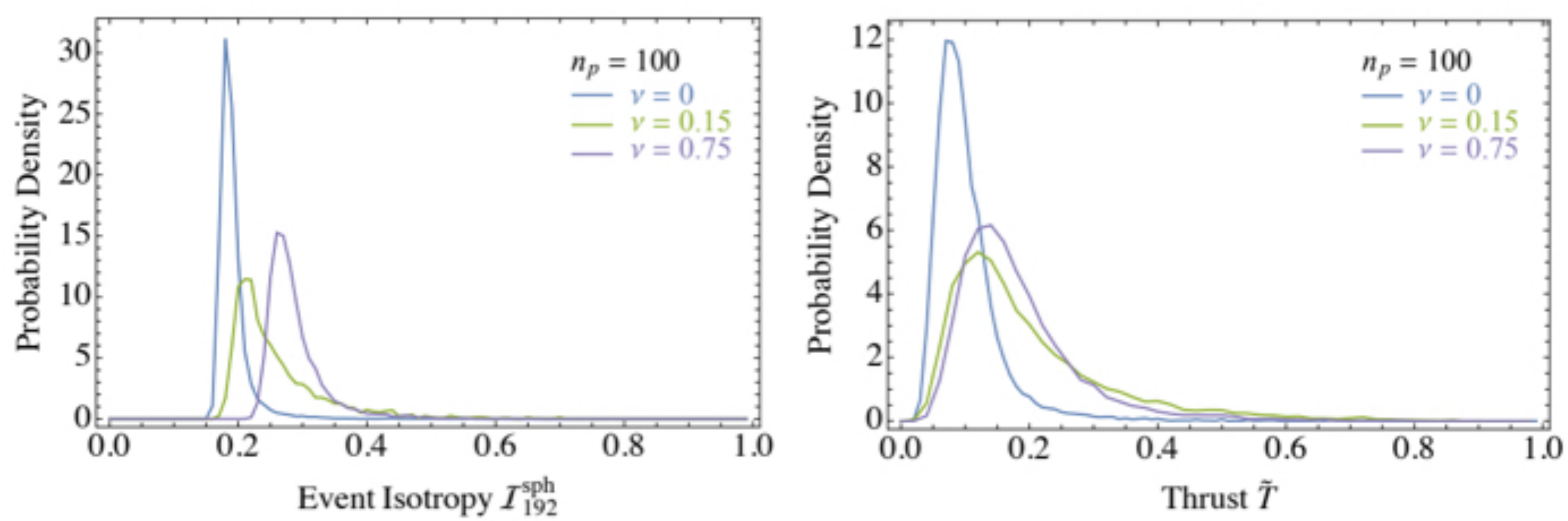
CC, J. Thaler, 2004.06125

Discriminating N = {10, 25, 50}-body samples



5d massive scalars ⟺ infinite towers of 4d modes (ν ⟷ m_{5d})

CJC, M. Reece, M. Strassler (2009.08981)

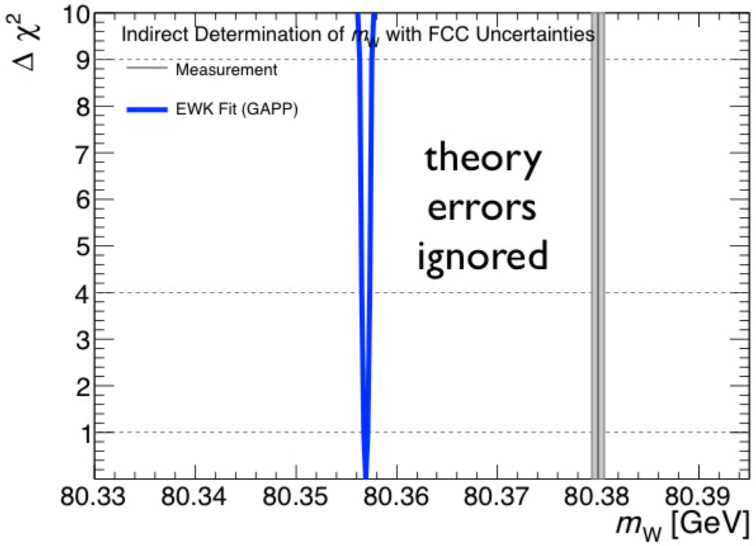


Are the detector designs optimized to fully exploit the potential of new ideas about jet structure and reconstruction, ML q/g separation, tagging, etc ?

EW precision

J.Gluza

J.Erler



Global	$\Delta M_W = \pm\ 0.2$ MeV
FCC	$\Delta M_{top} = \pm\ 0.1$ GeV
EW fit:	$\Delta M_H = \pm\ 1.4$ GeV

(± 5.7 w. today's TH syst)

Leading Fermionic Three-Loop Corrections to EWPOs

L.Chen

	Current Theory	Main source	FCC-ee Exp
M_W[MeV]	4	α^3, $\alpha^2\alpha_s$	1
Γ_Z[MeV]	0.5	α^3, $\alpha^2\alpha_s$, $\alpha\alpha_s^2$	0.1
$\sin^2\theta^l_{eff}$	4.3×10^{-5}	α^3, $\alpha^2\alpha_s$	0.6×10^{-5}

	$\Delta\overline{M_W}$(MeV)	$\Delta sin^2\theta_{eff}$
O(α^3)	-0.389	1.34×10^{-5}
O($\alpha^2\alpha_s$)	1.70	1.31×10^{-5}
Add-up	1.311	2.65×10^{-5}

Lisong **Chen**, Ayres Freitas
arXiv:2002.05845

V.Yermolchyk

SANC/ARIeL framework

Planned 2-loop improvements

Implementation of the 2-loop (NNLO) QED results on RC to Bhabha and annihilation cross sections and comparison with existing works:

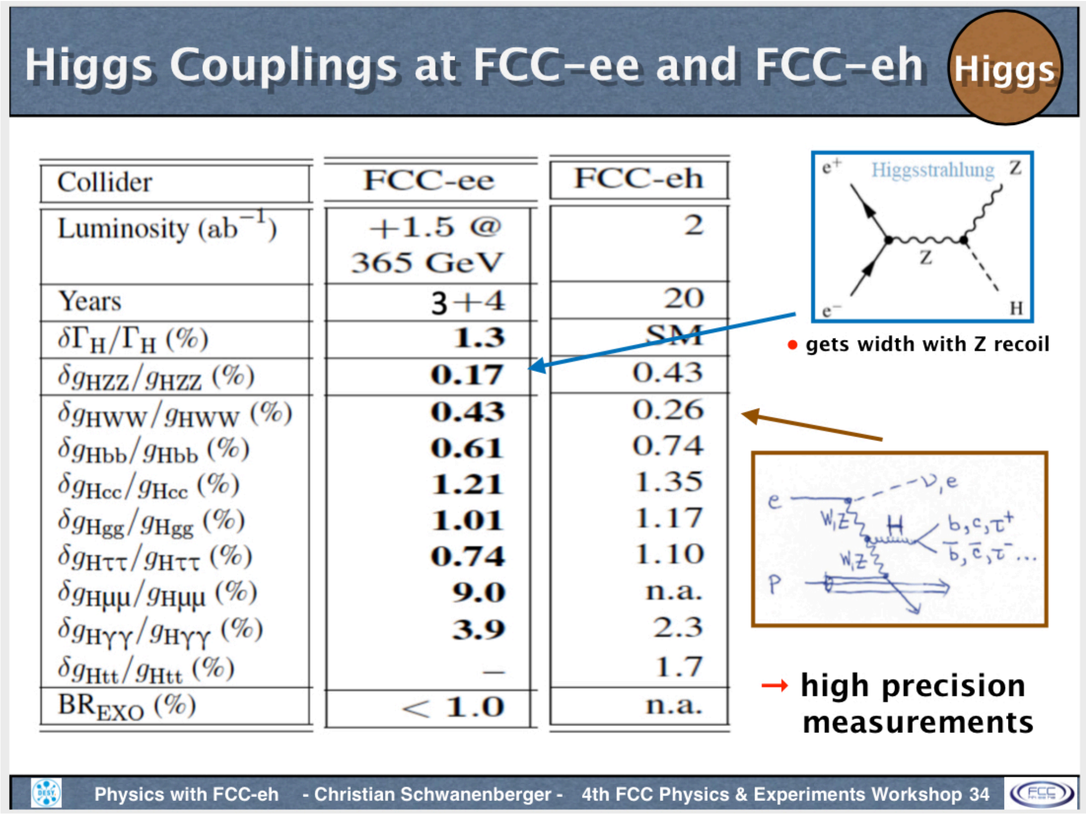
- J. Blümlein et al., "The $O(\alpha^2)$ initial state QED corrections to $e^+e^-\to\gamma^*/Z_0^*$", Nucl. Phys. B 956 (2020), 115055
- F. Campanario et al., "Complete QED NLO contributions to the reaction $e^+e^-\to\mu^+\mu^-\gamma$ ...", JHEP 02 (2014), 114
- C.M. Carloni Calame et al., "NNLO massive corrections to Bhabha scattering and theoretical precision of BabaYaga@NLO", Nucl. Phys. B Proc. Suppl. 225-227 (2012), 293
- C. Carloni Calame et al., "NNLO leptonic and hadronic corrections to Bhabha scattering ...", JHEP 07 (2011), 126
- S. Actis et al., "Virtual hadronic and leptonic contributions to Bhabha scattering", Phys. Rev. Lett. 100 (2008), 131602
- A. Penin and G. Ryan, "Two-loop electroweak corrections to high energy large-angle Bhabha scattering", JHEP 11 (2011), 081

Codes and evt generators undergoing continued improvements to match the formal TH progress

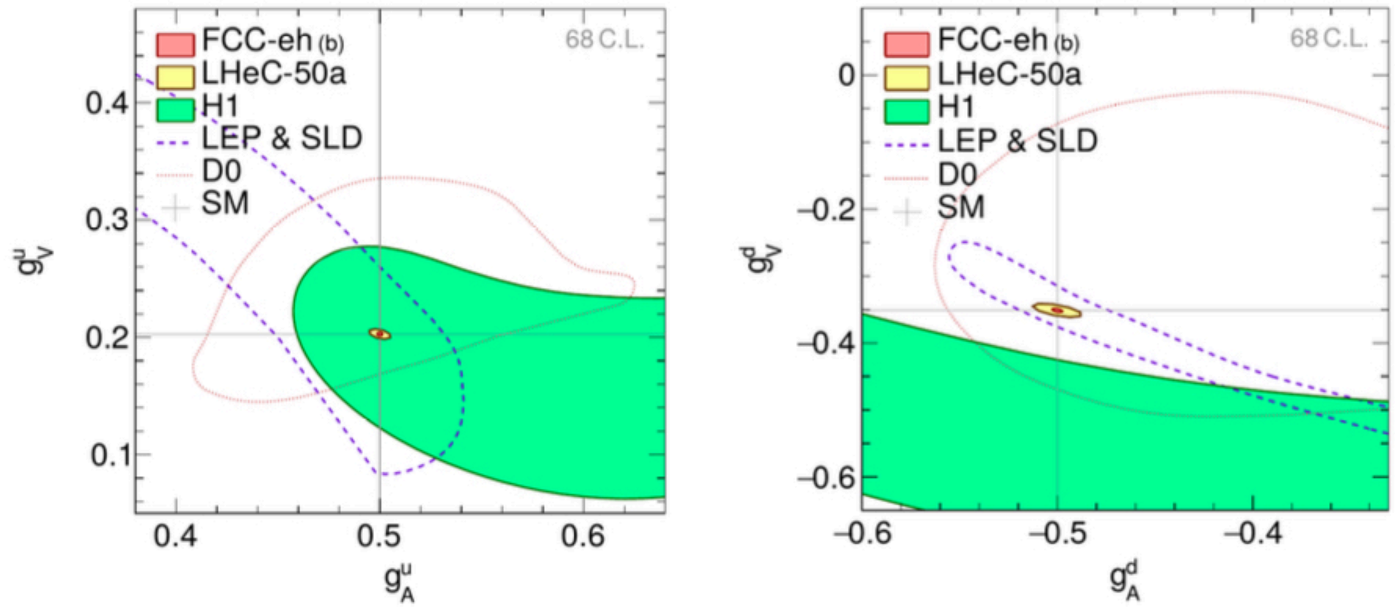
FCC-eh complementarity

C. Schwanenberger

Comparable precision, uncorrelated systematics

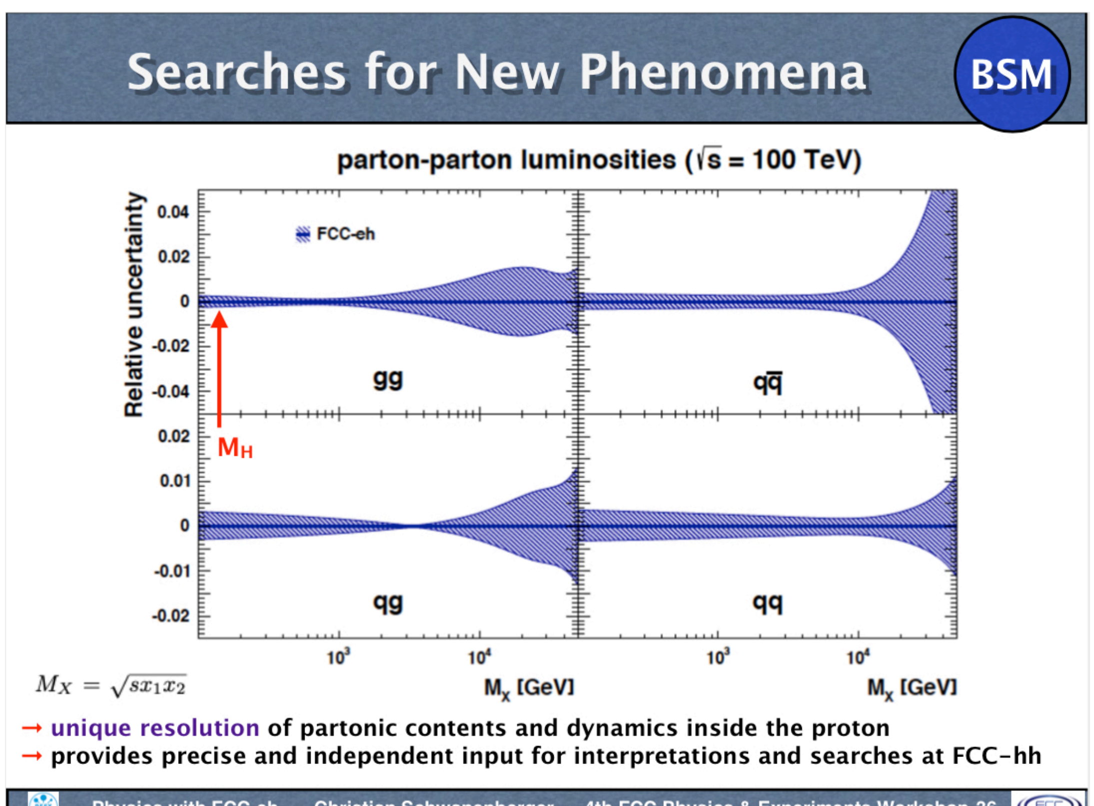


Complement the ee precision

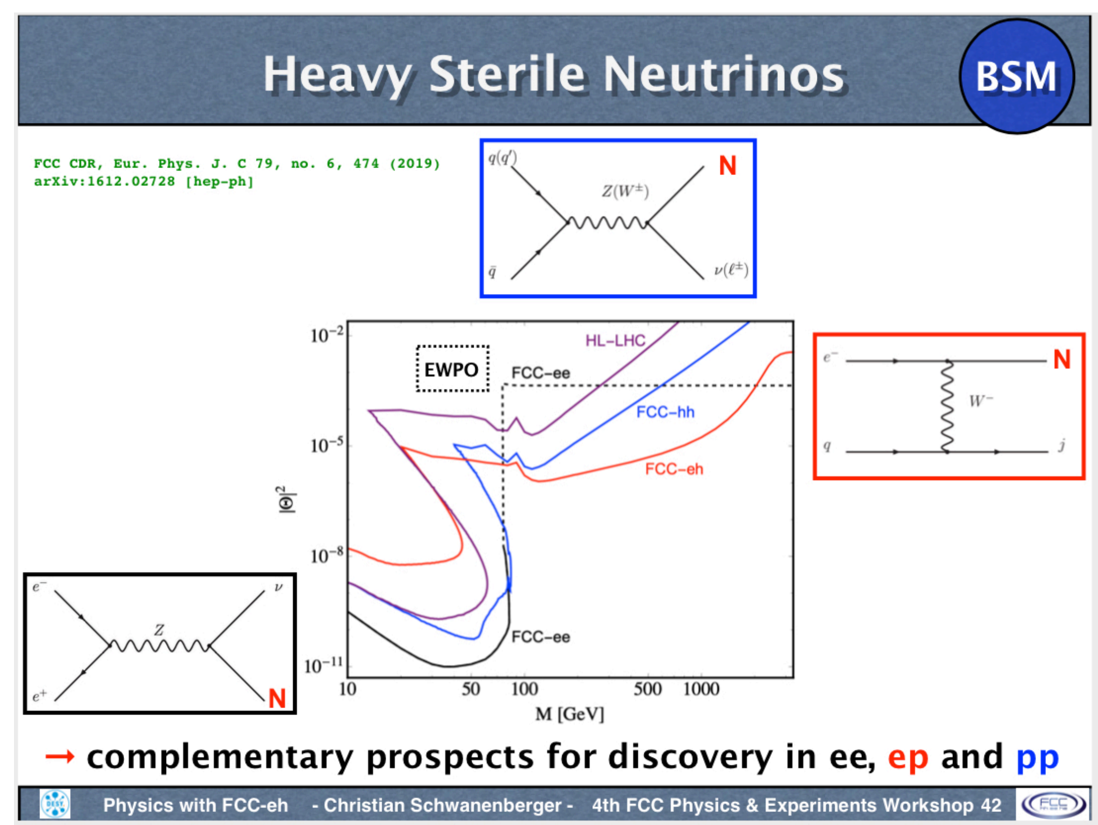


Independent measurement of u-type and d-type EW couplings

provide inputs to maximize FCC-hh precision

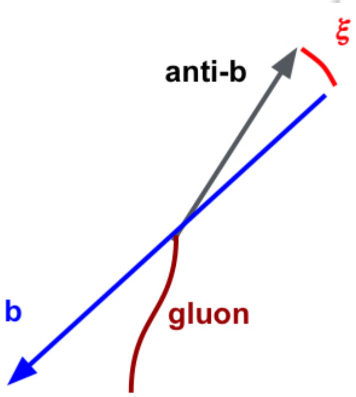


improved discovery reach for specific BSM scenarios



Helping TH make more robust predictions, reducing the absolute size of QCD corrections, and therefore of their syst:

Example: A_{FB}, focus on back-to-back b and bbar, to reduce impact of real QCD radiation, g→bb, etc



QCD corrs.: adding uncertainties

- Detailed table of central values and uncertainties:

stat. unc. for $7\mathrm{x}10^7$ $Z \to b\bar{b}$ events

ξ_0 cut	Measured A_{FB}	$\Delta A_{FB}(\mathrm{stat})$	$\Delta A_{FB}(\mathrm{tune})$	$\Delta A_{FB}(\mathrm{theo.\ QCD\ corr})$
No cut	0.0998 ± 0.0004	0.00008	0.00014	0.00033
1.50	0.1003 ± 0.0003	0.00011	0.00014	0.00023
1.00	0.1011 ± 0.0002	0.00011	0.00010	0.00016
0.50	0.1023 ± 0.0002	0.00011	0.00010	0.00007
0.30	0.1030 ± 0.0002	0.00011	0.00010	0.00003
0.20	0.1033 ± 0.0001	0.00011	0.00005	0.00002
0.10	0.1035 ± 0.0002	0.00016	0.00005	0.00001

Table 9: Central values and components of the uncertainty in the measurement of the A_{FB} asymmetry with 7×10^7 $e^+e^- \to b\bar{b}(g)$ events at the Z pole, for different $\xi < \xi_0$ cuts at the reconstructed level.

$\lesssim$ 0.1% relative systematic uncertainties for $\xi \lesssim 0.3$

J. Alcaraz, 10 Nov 2020, QCD corrections to AFB(Q) revisited 19

Opportunities for flavour physics

- L. Li: Flavour studies at the Tera-Z factory
- Z. Ligeti: New physics in B meson mixing: future sensitivity and limitations
- A. Crivellin: Leptoquarks in Oblique Corrections and Higgs Signal Strength: Status and Prospects at FCC

More opportunities for flavour physics

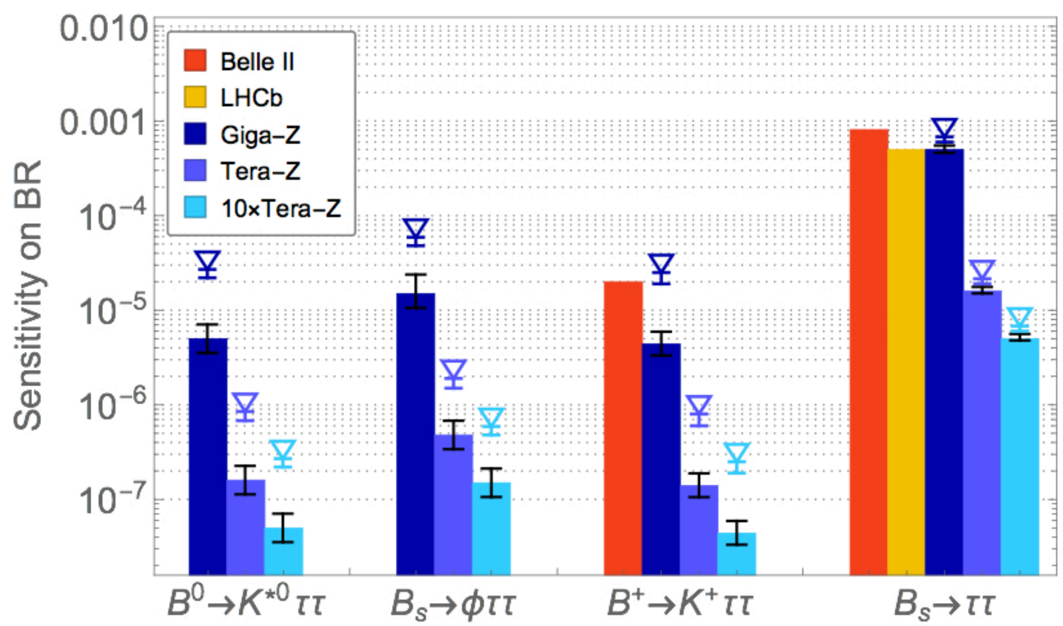
Current $b \to c\tau\nu$ anomalies indicate large LFUV in τ, thus enhancement of $b \to s\tau\tau$ rates. In some scenario, $\sim 10^3$ times larger than SM! [Capdevila et al.(2018)Capdevila, Crivellin, Descotes-Genon, Hofer, and Matias]

$\mathrm{BR}(b \to s\tau\tau) \sim \mathcal{O}(10^{-7})$ in SM

Result of $b \to s\tau\tau$ at Z Pole (Preliminary)

Work w/ Tao Liu, in preparation:

L. Li



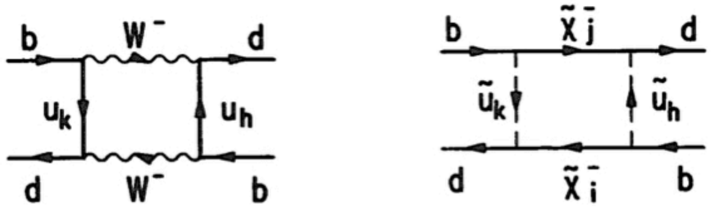
Traditional cut-based analysis: $\mathcal{O}(10^{-5} - 10^{-7})$ precision. Still affected by limited detector spacial resolution ($\sim 5 - 10\ \mu$m, "∇" symbols): Motivation for detector R&D!

Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

Probing BSM w. B mixing

Z.Ligeti

Meson mixing:



$\sim \frac{C_{\rm NP}}{\Lambda^2}$

General parametrization:

$M_{12} = M_{12}^{\rm SM} \times (1 + h\, e^{2i\sigma})$

NP parameters

If $h \ll 1$, then BSM $\ll$ SM

Bottlenecks

- Sensitivity does not improve as expected from Phase I to Phase II and Phase III

  Main bottlenecks: (i) $|V_{cb}|$ precision, (ii) mixing parameters from LQCD and η_B

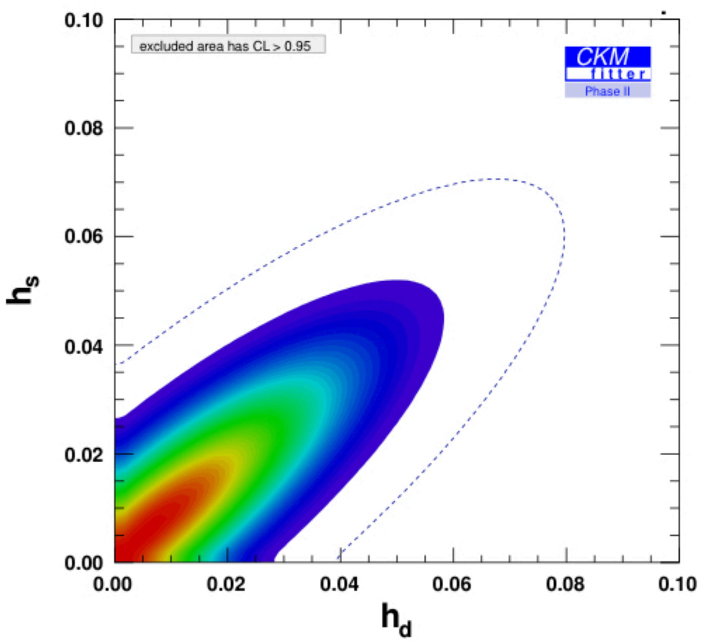
Phase I: LHCb 50/fb, Belle II 50/ab (late 2020s)

Phase II: LHCb 300/fb, Belle II 250/ab (late 2030s)

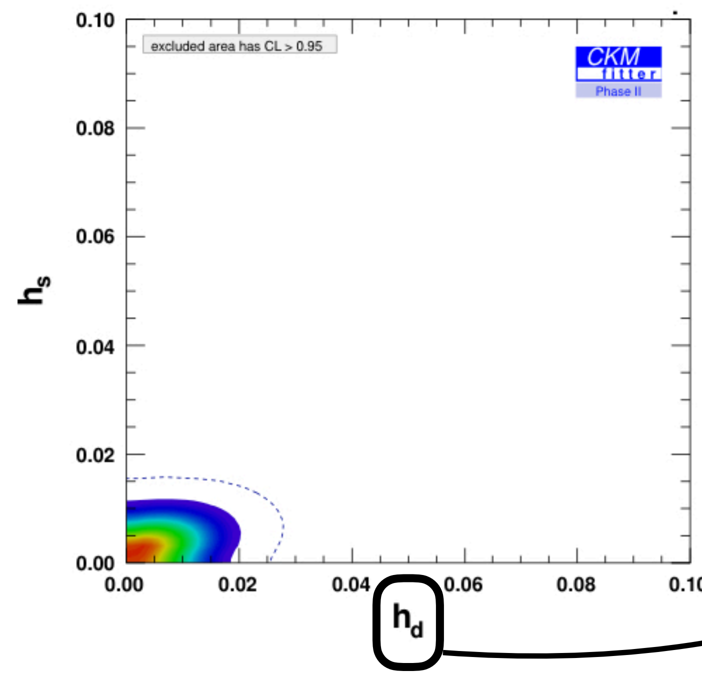
Phase III: Phase II + FCC-ee (5×10^{12} Z decays)

- The Phase II sensitivity, as an example:

Same plot as previous page



Set uncertainty of $|V_{cb}|$ and mixing param's $\to 0$



- WW threshold: $W \to b\bar{c}$ can give a qualitatively new determination of $|V_{cb}|$
  (Estimate 0.4% uncertainty, using 10^8 WW, independent of B measurements)

inspired by M-H Shune's talk at January FCC wshop

Detailed study: P.Azzurri, in the PID exptl session => 0.3% stat

BSM searches at FCC: why bother, in absence of guaranteed discoveries?

Because the questions addressed by the FCC BSM searches are foundational.

Not having identified an answer so far takes nothing away from their relevance, and from the need to keep pursuing them.

The questions covered during the Workshop

What is the origin of neutrino masses?

- Kulkarni: Exploring heavy neutrinos at FCC
- Das: Testing neutrino mass generation mechanism at the future colliders
- Mitra: Probing Low Scale Heavy Neutral Leptons at Colliders

Is the Higgs boson elementary or composite?

- Englert: EW Top Couplings, Partial Compositeness and Top Partner Searches
- Salvioni: Four tops for the future
- Deandrea: Composite scalar searches
- Csaki: A natural composite H via universal boundary conditions
- Choqque: Probing the top-H sector with composite H models at FCC-hh

What's the origin of its potential? What else in the Higgs sector and int's?

- Baglio & Shao: progress in the calculation of σ(HH)
- Selvaggi: Measuring the selfcoupling with HH at FCC-hh
- Heinrich: Exploring anomalous couplings in Higgs boson pair production through shape analysis
- Kanemura: Triple H couplings in BSM models at higher-orders
- Spannowski: Power meets Precision to explore the Symmetric Higgs Portal
- Su: 2HDM at 100 TeV collider
- Zurita: Exotic Higgs decays into long lived particles
- A. Crivellin: Leptoquarks in Oblique Corrections and Higgs Signal Strength: Status and Prospects at FCC

What is the nature EW phase transition?

- Ramsey-Musolf: Exotic H decays and EWPT
- Papaefstathiou: The EWPT at future colliders

What is Dark Matter?

- Doglioni, Suarez, Kulkarni: BSM at FCC: complementarity with astrophysics and non-collider experiments
- Ramsey-Musolf: Triplet scalar DM at FCC-hh
- Grzadkowski: DM spin effects

Anything else?

- Paul: Down type iso-singlet quarks at FCC
- Baum: Hunting scalar lepton partners

The agnostic perspective: EFT

- Banerjee: Ultimate differential SMEFT analysis
- Wulzer: Low- vs high-energy phenomena
- de Blas: incorporating diBoson/aTGC measurements into global SMEFT studies at future e+e- colliders
- Bishara: A New Precision Process at FCC-hh: the diphoton leptonic Wh channel
- Senol: Prospective constraints on anomalous Higgs boson interactions in an effective Lagrangian via diphoton production at FCC-h

In particular, the overarching question of <u>whether</u> and <u>how</u> the scale of weak interactions arises from a deeper theory was addressed in the highly inspiring talk by

M. Reece, "Naturalness at FCC"

The LHC found what looks like an elementary spin-0 Higgs boson. Still, ***we do not understand the weak scale***.

We need to make good use of the LHC, but also plan for the future. ***Important to emphasize the big-picture questions.***

Keep an eye out for important discoveries from beyond the world of colliders, like **EDM searches** or dark matter.

However, to really ***understand*** new physics:

Particle physics needs new energy-frontier colliders!

Big Tunnels: The Future of Our Field

New physics could be decisively ***discovered*** by an EDM experiment.

New physics can be thoroughly ***understood*** at a high-energy collider.

Precision vs energy reach

— — — —

Indirect vs direct probes

From A. Wulzer's concluding remarks

- High-Q^2 precision is promising, to be further explored

  At the LHC, in the first place.

  Design of observables, reduction of uncertainties, **analysis** techniques

- Arguably, easier BSM **characterisation** than low-energy:

  At low-energy, BSM will show up as an **intricate combination** of EFT operators [even if EFT is simple at cutoff, running will mess up].

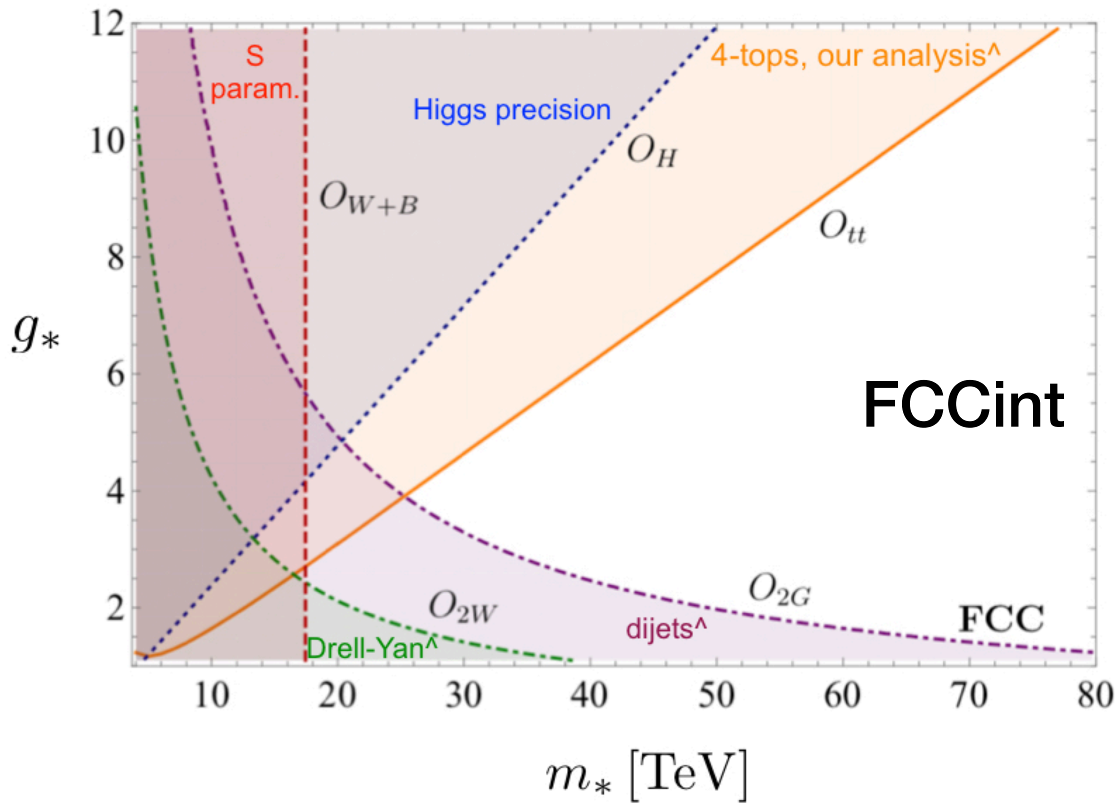
  Energy-growing BSM in one channel, instead, **uniquely associated** to specific EFT operators.

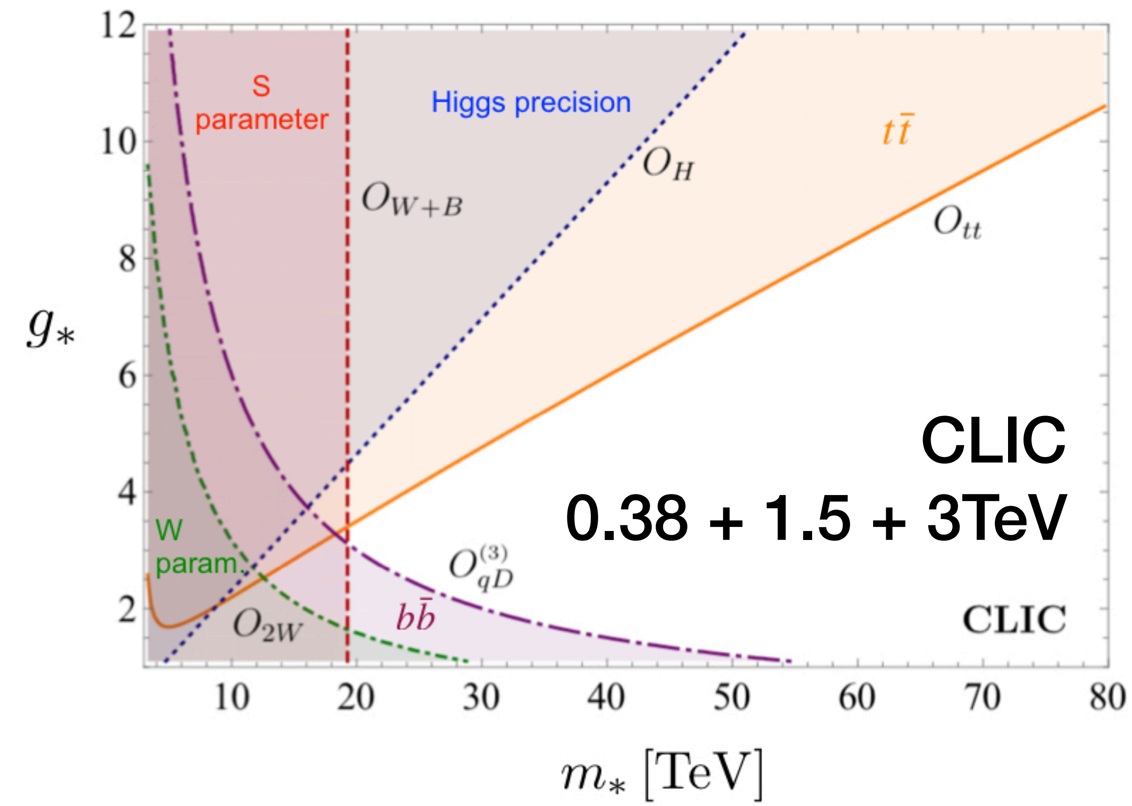
  Much more information in (multivariate) FCC-hh distributions than in FCC-ee observables. Opportunity to **disentangle** different operators.

  Could play essential role to **"give a name"** to FCC-ee discoveries, or to Direct discoveries at FCC-hh.

Salvioni

Examples: direct 4t vs indirect 2t probes of Higgs compositness

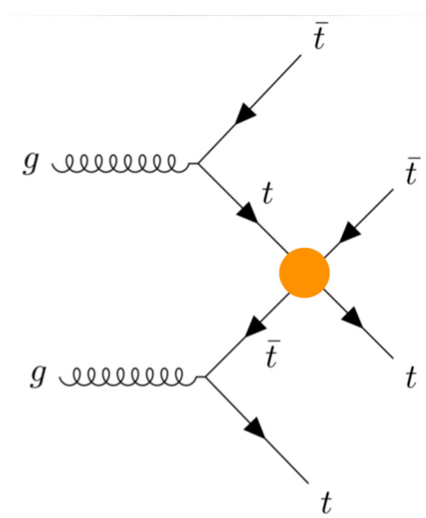




Higgs precision: $\dfrac{m_*}{g_*} > 4.2$ TeV

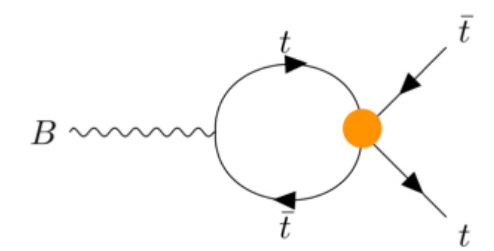
$pp \to t\bar{t}t\bar{t}$: $\dfrac{m_*}{g_*} > 6.5$ TeV

$$\frac{g_*^2}{m_*^2}(\bar{t}_R\gamma^\mu t_R)^2$$



Higgs precision: $\dfrac{m_*}{g_*} > 4.3$ TeV

$e^+e^- \to t\bar{t}$: $\dfrac{m_*}{g_*} > 7.7$ TeV



$$O_{tD} = (\partial^\mu B_{\mu\nu})(\bar{t}_R\gamma^\nu t_R)$$

What's more powerful between CLIC and FCC?

What's more effective in detecting SM deviations, direct or indirect probes?

My own remark & suggestion

I feel that these are not the right questions to ask, even though most often this is how the comparison among future facilities is reported.

Pheno studies should start moving from focusing on finding

what is the best way to find SM deviations induced by a given EFT operator

to asking

what is the best way to decode the origin of possible deviations

The "inverse problem" (reconstructing the origin of a new phenomenon) is very challenging, and answers to the above question will vary case by case. Still this approach might enhance the sometimes small differences in physics potential among different facilities