CLIC Physics Potential Working Group Report

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CERN & EPFL

CLICdp Collaboration Meeting
CERN, August 30, 2017

The Physics Potential Working Group

- **Conveners:** J.B. , J. Wells, A. Wulzer
- **Goals:**
  - Coordinate the theory community effort to assess the CLIC potential to discover cracks in the Standard Model. The physics picture that is emerging from the LHC results and the recent completion of the CLIC feasibility study and detector design, make this assessment particularly timely, in preparation of the forthcoming update of the European Strategy.
  - New physics might be discovered at CLIC either indirectly, through precise measurements showing departures from the Standard Model predictions, or via the direct observation of new particles. Both aspects will be investigated under several beyond-the-Standard Model perspectives.

The Physics Potential Working Group

Working Units

- **SM EFT** (F. Riva): Probing the SM EW-plus-Higgs sector with precise measurements.
- **Direct Searches** (R. Franceschini, M. Spannowsky): Assessing the direct discovery potential, its complementarity with indirect probes and the impact on BSM physics.
- **Light Flavours** (J. Zupan): Probing new physics through light quarks and leptons.

- **Webpage:** http://clicdp.web.cern.ch/content/wg-physics-potential
- **Mailing list:** clicdp-wg-physicspotential@cern.ch

The Physics at CLIC Workshop

Physics at CLIC

17-18 July 2017
CERN
Europe/Zurich timezone

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- Accommodation
- Directions to and inside CERN
- Videoconference Rooms

The physics picture that is emerging from the LHC results and the recent completion of the CLIC feasibility study and detector design, make an assessment of the CLIC physics potential particularly timely, in preparation of the forthcoming update of the European Strategy. A dedicated working group was recently set up at CERN, with the purpose of collecting and coordinating the theory community effort in this direction. This workshop is the kickoff meeting of this initiative. Topics include direct or indirect searches for new physics, from any beyond-the-SM perspective, that are relevant for the CLIC experimental program.

Starts 17 Jul 2017 07:25
Ends 18 Jul 2017 19:30
Europe/Zurich

Andrea Wulzer
James Wells
Jorge de Blas

https://indico.cern.ch/event/632228/

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Participant List

53 participants

First Name	Last Name	Affiliation
Admir	Greljo	University of Zurich
Aidan	Robson	University of Glasgow (GB)
Alberto	Mariotti	Vrije Universiteit Brussels
Alexander	Mitov	University of Cambridge
Alon	Faraggi	University of Liverpool

https://indico.cern.ch/event/632228/

The Physics at CLIC Workshop

Topics of the SM EFT/Indirect Searches Session

- -Top pair production - C. Englert
- -Higgs EFT at CLIC - J. Gu
- -Precision EW measurements: EWPT and Higgs couplings - G. Panico
- -EFT studies of hZ & hhZ production at ILC/CLIC - S. Bar-Shalom
- -Strong HH and VV prod. At CLIC - A. Thamm
- -Modelling VV Scattering at CLIC- W. Kilian
- -Seeking CLIC's competitive Advantages - J. Ellis

Topics of the Direct Searches Session

- -Accidental Matter - L. Di Luzio
- -SUSY @ CLIC - A. Mariotti
- -Extra Scalar Singlets: Higgses & PGB - F. Sala
- -Axion-like particles at e^+e^- colliders - K. Mimasu
- -(Dis) appearing tracks at CLIC - P. Schwaller
- -Testing the Twin Higgs Mech. at a L.C. - C. Verhaaren
- -Seesaw at a Lepton Collider - M. Mitra
- -Dark Sector at CLIC - M. Rauch

Topics of the Light Flavours Session

- -Charm Yukawa & New Physics - F. Bishara
- -Constraining $h \to ss$ at CLIC - M. Schlaffer
- -From B-anomalies to CLIC - A. Greljo

Topics of the Monte Carlo Session

- -WHIZARD for CLIC physics - J. Reuter

Selected topics: SM EFT/Indirect Searches Session

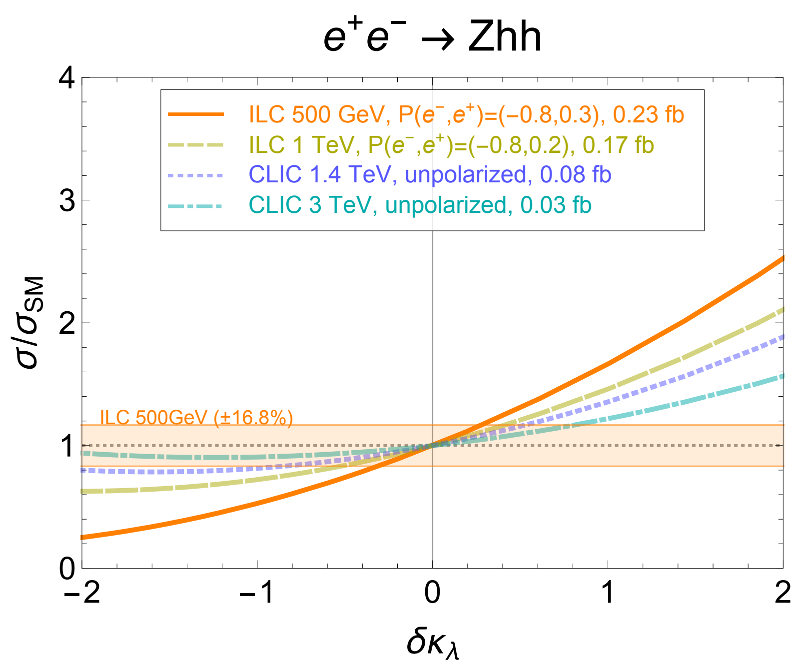
Selected topics: SM EFT/Indirect Searches Session

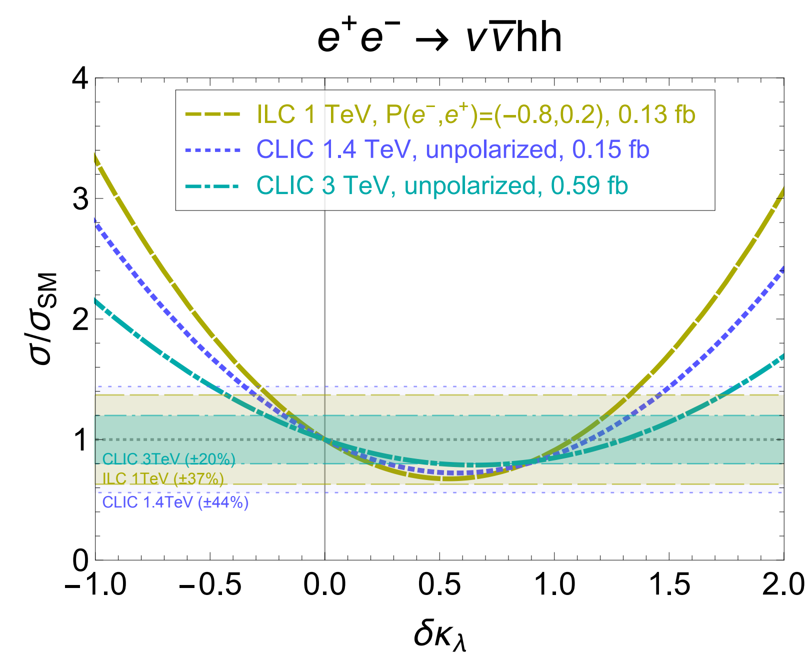
- **Di-Higgs production:** Measuring the Higgs self-interaction

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

G. Panico's talk

- ZHH gives stronger constraints on $\delta\lambda_3 > 0$
- $\nu\bar{\nu}$HH gives stronger constraints on $\delta\lambda_3 < 0$





- dependence on $\delta\lambda_3$ stronger at lower COM energy, maybe worth collecting more luminosity at 500 GeV and 1 TeV

Selected topics: SM EFT/Indirect Searches Session

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CLIC 1.4 TeV ($1.5\,\mathrm{ab}^{-1}$) + 3 TeV ($2\,\mathrm{ab}^{-1}$), unpolarized beams, $e^+e^- \to \nu\bar{\nu}hh$

bounds on $\delta\kappa_\lambda$	68%CL		95%CL	
	full	linear	full	linear
1.4 TeV	$[-0.35,\ 1.51]$	± 0.45	$[-0.60,\ 1.76]$	± 0.90
3 TeV	$[-0.26,\ 0.49]$ & $[0.82,\ 1.57]$	± 0.31	$[-0.46,\ 1.77]$	± 0.62
combined	$[-0.22,\ 0.35]$ & $[0.91,\ 1.46]$	± 0.25	$[-0.39,\ 1.64]$	± 0.51

Final precision at CLIC ~25% (combining 1.4 TeV and 3 TeV runs)

… but inclusive measurements at CLIC can not resolve the additional minimum at $\delta\lambda_3 \sim 1$

Ways out:

- ✦ add information from lower-energy machines (eg. ILC 500 GeV, gives precision ~27% [Dürig, PhD thesis '16])
- ✦ consider differential distributions

G. Panico's talk

Jorge de Blas
INFN - University of Padova

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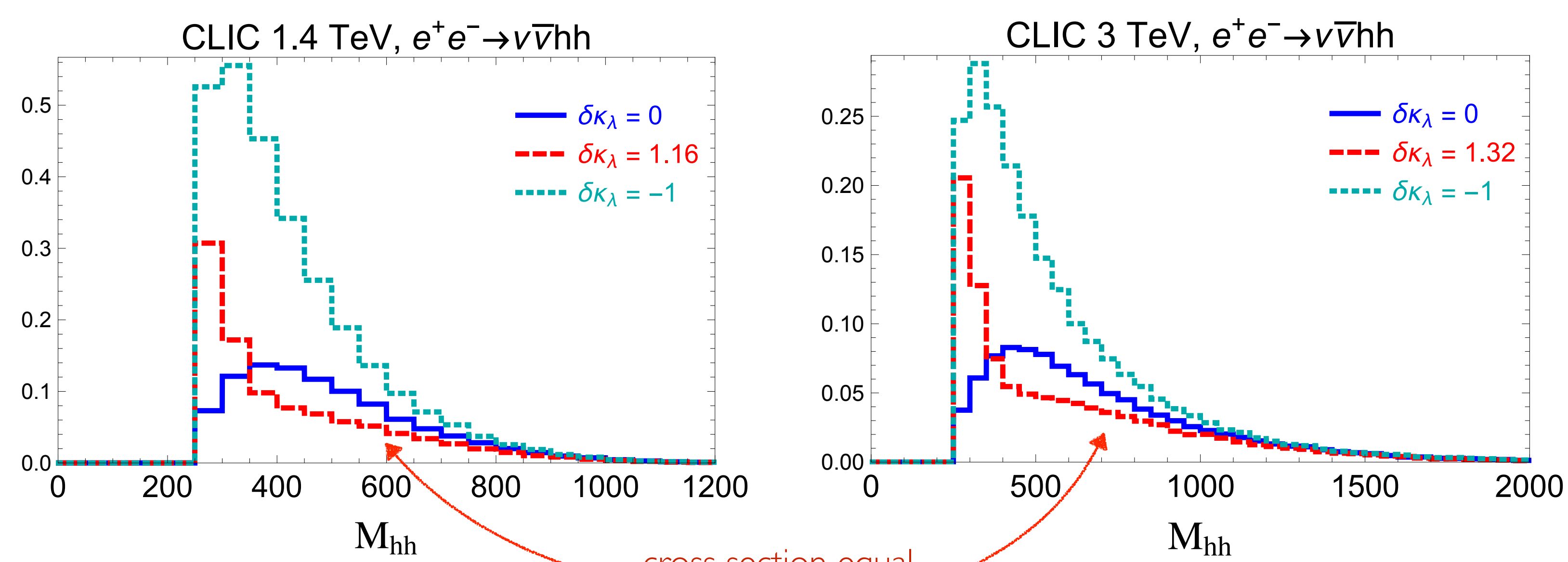
- **Di-Higgs production:** Measuring the Higgs self-interaction

$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

The Higgs trilinear coupling strongly modifies the distributions



	signal ev.	bkg. ev.
CLIC 1.4 TeV	~ 20	~ 40
CLIC 3 TeV	~ 60	~ 100

- differential analysis can probe the second minimum

$$\delta\lambda_3 \in [-0.17, 0.26]$$

G. Panico's talk

The Physics at CLIC Workshop

Selected topics: SM EFT/Indirect Searches Session

- **Sensitivity to universal new physics in $e^+e^-\to f\bar{f}$:**

✦ **CLIC** bounds: 1 TeV $|W|, |Y| \lesssim 0.5 \times 10^{-4}$

3 TeV $|W|, |Y| \lesssim 0.15 \times 10^{-4}$

Recast from [CLIC Design Report '12]

✦ Low-energy lepton machines not competitive with HL-LHC

	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	2×10^7 Z	0.3/ab	3/ab	10/ab	10^9 Z	10^{12} Z	10^{10} Z	3/ab	1/ab	1/ab
W $\times10^4$	$[-19,3]$	±0.7	±0.45	±0.02	±4.2	±1.2	±3.6	±0.3	±0.5	±0.15
Y $\times10^4$	$[-17,4]$	±2.3	±1.2	±0.06	±1.8	±1.5	±3.1	±0.2	$\sim\pm0.5$	$\sim\pm0.15$

FCC 100 would give much stronger bounds

[Farina, GP, Pappadopulo, Rudermann Torre, Wulzer '16]

Only muon channel

⇒ Combine different channels (leptonic, hadronic and top) to obtain global sensitivity to W & Y

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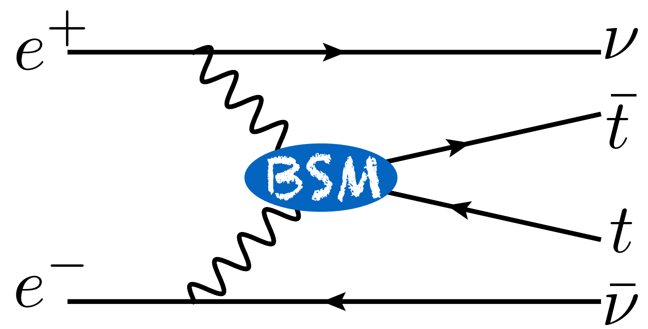
Selected topics: SM EFT/Indirect Searches Session

- **Sensitivity to Top Yukawa in $WW \to t\bar{t}$ production:**

C. Grojean's Introductory talk

$$H^\dagger \overleftrightarrow{D}_\mu H \bar{\Psi}^3 \gamma^\mu \Psi^3$$



$$\sim c_{H\Psi^3} \frac{E^2}{M^2}$$

?

Grojean, Wulzer, You and Zhang 'in progress

Same process is also sensitive to $|H|^2 \bar{\Psi}^3_L H \Psi^3_R$ **(modifies Top Yukawa)**

⇒ ***$WW \to t\bar{t}$ vs $t\bar{t}H$*** **at High Energies?**

Comment by M. Mangano

Selected Topics: Direct Searches Session

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- **Accidental Matter:** Gauge quantum numbers of NP states preserve SM accidental symmetries and **adds accidental Z_2** ⇒ DM stability

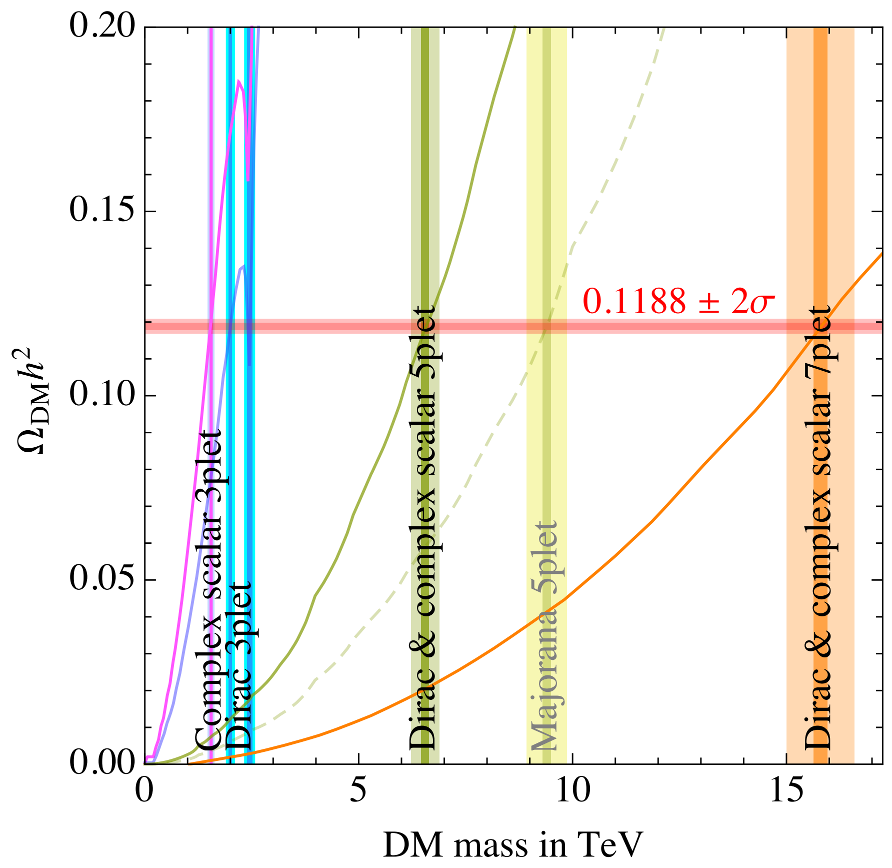
• A millicharge can effectively stabilise the DM: $\chi \sim (1, n, \epsilon)$

- n = 3, 5, 7, … thermal production via gauge interactions (and suppressed Z couplings)

- mass fixed by relic density

[Del Nobile, Nardecchia, Panci 1512.05353]

χ	$M_\chi^{(\mathrm{DM})}$ [TeV]
$(1,3,\epsilon)_{\mathrm{CS}}$	1.5
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0
$(1,3,0)_{\mathrm{MF}}$	3.0
$(1,5,\epsilon)_{\mathrm{CS,\,DF}}$	6.6
$(1,5,0)_{\mathrm{MF}}$	9.6
$(1,7,\epsilon)_{\mathrm{CS,\,DF}}$	16



- discovery potential of "minimal" DM at $\sqrt{s} = 3$ TeV (3rd phase of CLIC)

L. Di Luzio's talk

Selected Topics: Direct Searches Session

- **Accidental Matter:** Gauge quantum numbers of NP states preserve SM accidental symmetries and **adds accidental Z_2** ⇒ DM stability

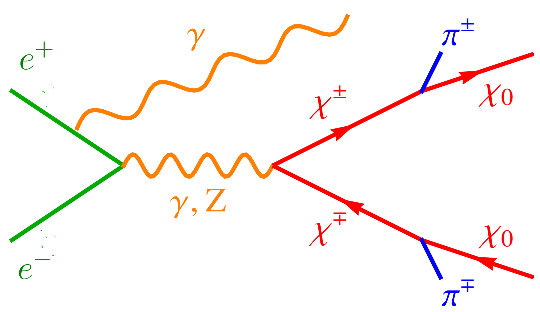
• Accidental EW multiplets with neutral LP

- can be potentially probed at CLIC up to the kinematical limit $\sqrt{s}/2$ (pair production)

$$\sqrt{s} = \{380 \text{ GeV}, 1.5 \text{ TeV}, 3 \text{ TeV}\}$$

- LEP-like chargino searches + disappearing tracks

[Barklow, Münnich, Roloff, "Measurement of chargino and neutralino pair production at CLIC", LCD-Note-2011-037, 2012, focus on jet + MET final states (relevant for Δm >> 1 GeV)]



- "Minimal" DM multiplet potentially testable

Mass fixed by relic density

χ	$M_\chi^{(\mathrm{DM})}$ [TeV]
$(1,3,\epsilon)_{\mathrm{CS}}$	1.5
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0
$(1,3,0)_{\mathrm{MF}}$	3.0
$(1,5,\epsilon)_{\mathrm{CS,\,DF}}$	6.6
$(1,5,0)_{\mathrm{MF}}$	9.6
$(1,7,\epsilon)_{\mathrm{CS,\,DF}}$	16

L. Di Luzio's talk

Selected Topics: Direct Searches Session

- **Disappearing tracks/Displaced vertices:** LLPs in many BSM models

  - Long lived particles appear in many BSM scenarios, often related to dark matter or baryogenesis (not discussed)
  - Unconventional collider signatures - dedicated searches can be very sensitive, background free
  - CLIC detector design looks very good:
    - no triggers
    - close to beam line
    - segmented calorimeters (also granular ecal?)
  - MC implementations available, for detailed studies!

  P. Schwaller's talk

Selected Topics: Direct Searches Session

- **Disappearing tracks:** LLPs in many BSM models

CLIC thoughts

- Disappearing tracks are essential for mass reach at hadron colliders
- For CLIC, the reach is probably close to $\frac{\sqrt{s}}{2}$
- No boost near threshold, bad for < cm lifetimes
- Tracklets to see all states, measure mass difference?
- Alternative? photon energy scan?
- How many tracker layers do we have to hit? dE/dx to discriminate from lighter charged tracks?
- Can we see the soft pion?

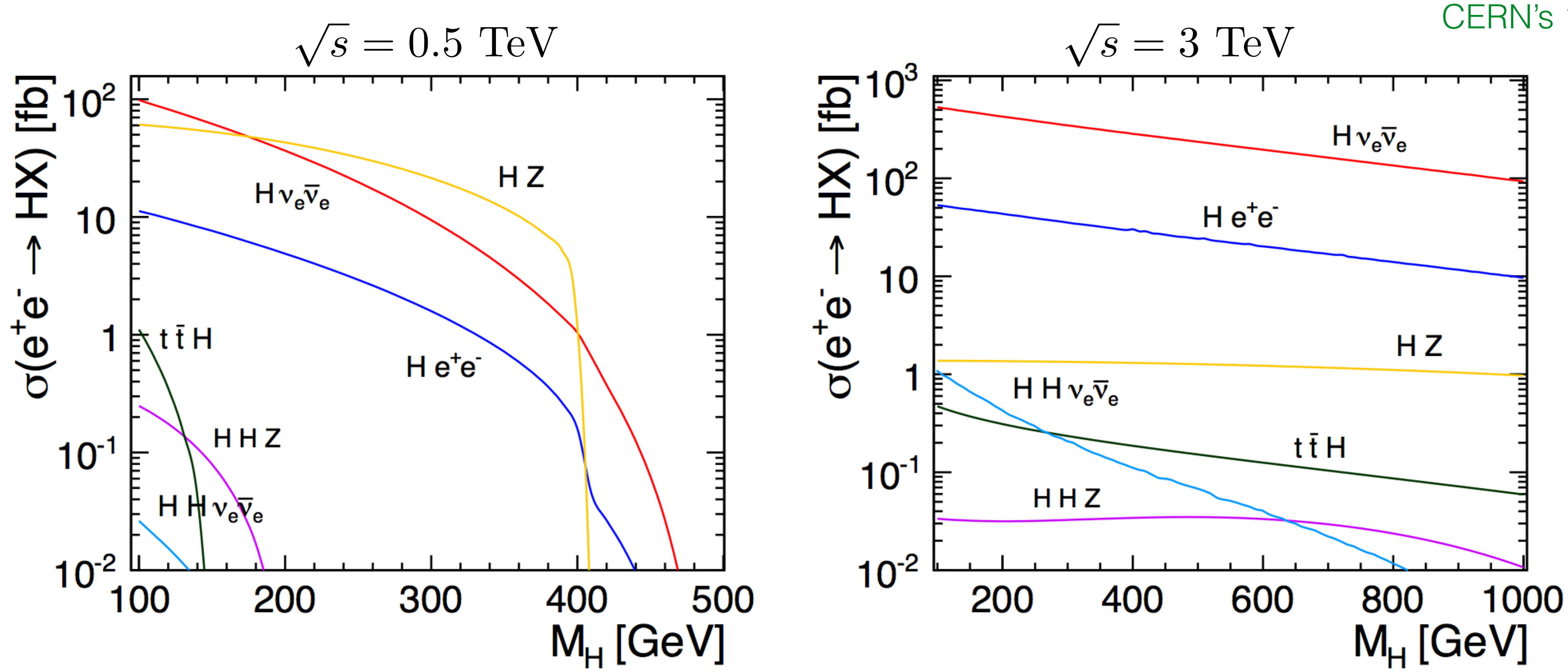
P. Schwaller's talk

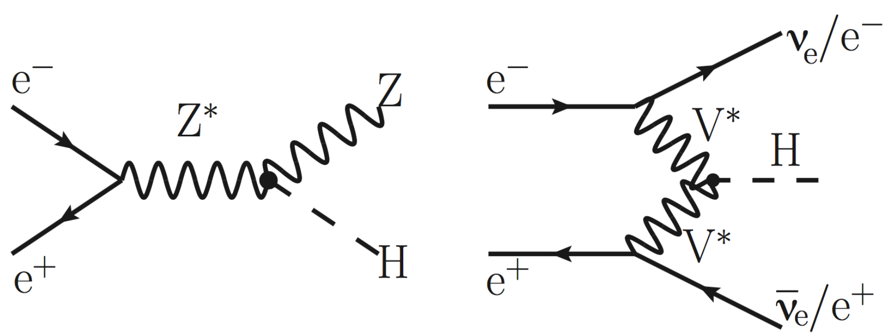
Selected Topics: Direct Searches Session

- **Extra Higgses:** reach for Higgs singlets at CLIC

Logic: suppose HL-LHC does not find them, what will CLIC have to say?

CERN's 1202.5940





Production of Higgs singlet =

these $\sigma \times \sin^2\gamma$

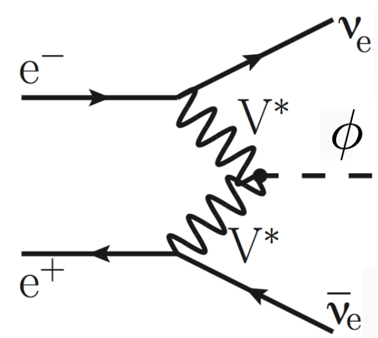
F. Sala's talk

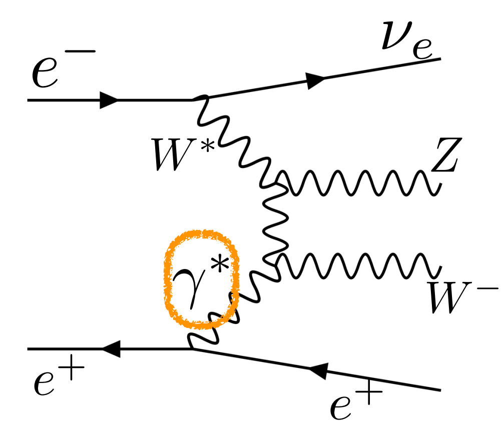
Selected Topics: Direct Searches Session

- **Extra Higgses:** reach for Higgs singlets at CLIC

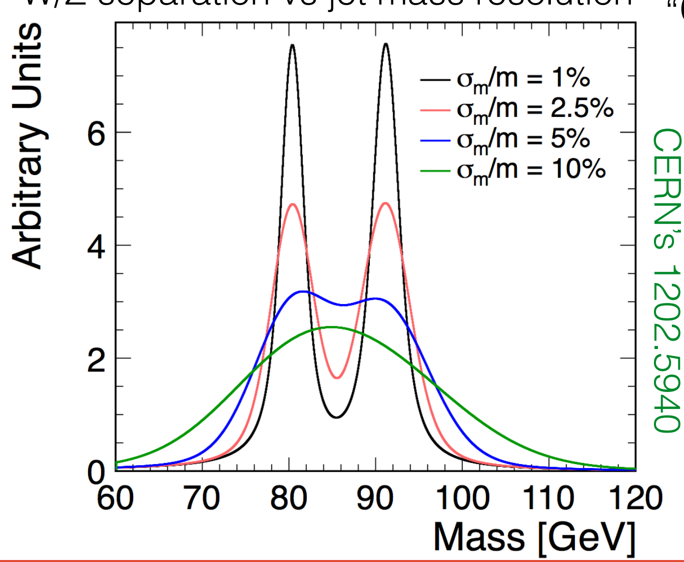
Initial exercise: focus on $\phi\nu\bar{\nu}$ @ CLIC 3 TeV, $\phi \to ZZ$

Final state	Dominant(?) backgrounds
$\nu\bar{\nu}\,4\ell$	$e^+e^- \to ZZ(4\ell)\nu\bar{\nu}$
$\nu\bar{\nu}\,2\ell\,2j$	$e^+e^- \to ZZ(2\ell\,2j)\nu\bar{\nu}$ $e\gamma \to W(jj)Z(2\ell)\nu$
$\nu\bar{\nu}\,4j$	$e^+e^- \to ZZ(4j)\nu\bar{\nu}$ $e\gamma \to W(jj)Z(2j)\nu$





W/Z separation vs jet mass resolution



CERN's 1202.5940

CERN's 1202.5940

"One goal for jet energy resolution [...] is that it is sufficient to provide discrimination between the hadronic decays of W and Z boson"

Is 3.5% realistic? $[\sim \sigma_m/m = 2.5\%]$

Dijet charge?

Other possible challenge: boosted dijets?

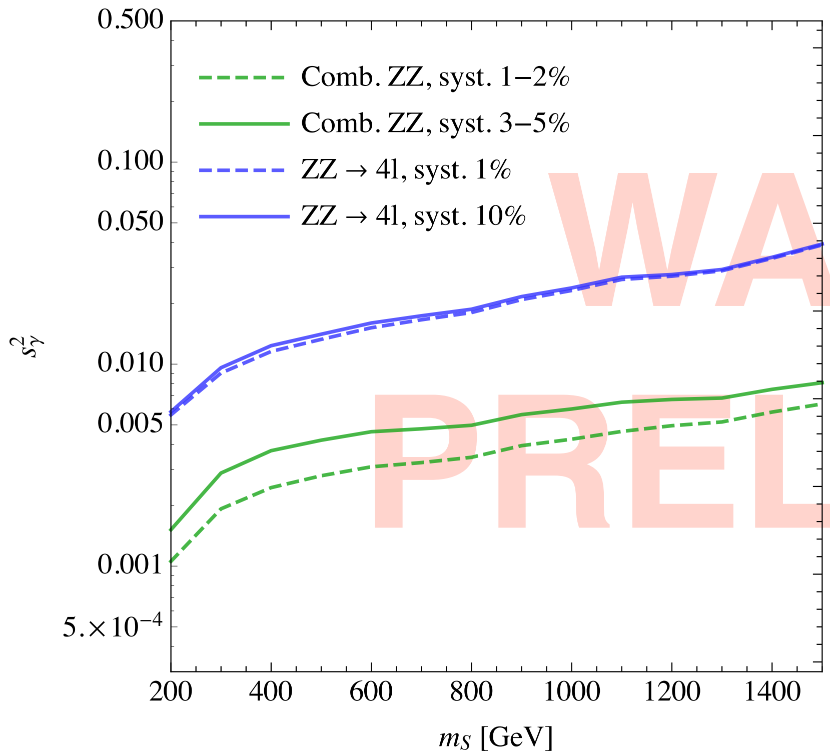
CMS already deals with them... CMS EXO-17-001-pas

F. Sala's talk

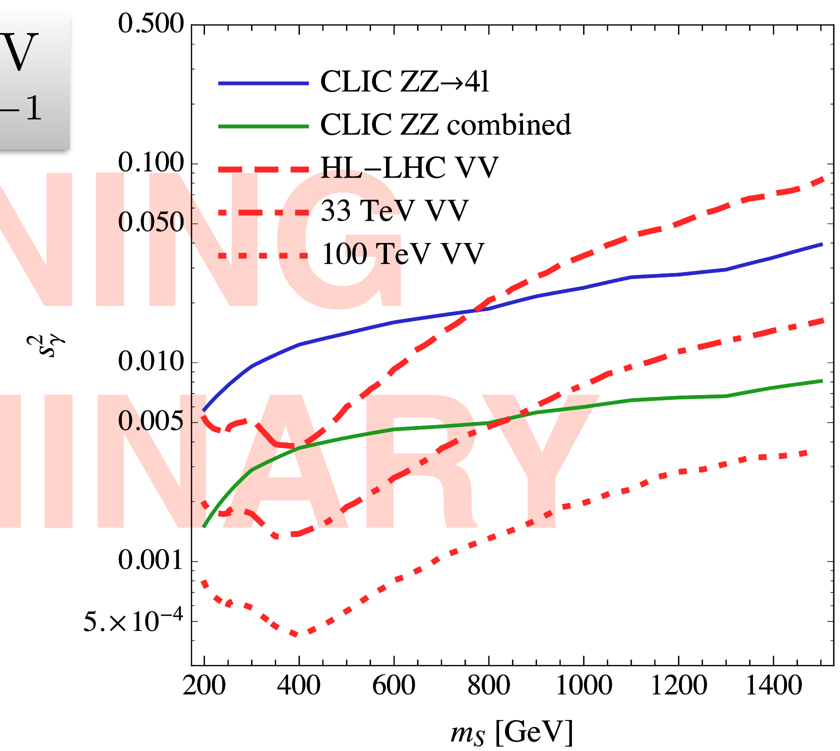
Selected Topics: Direct Searches Session

- **Extra Higgses:** reach for Higgs singlets at CLIC

Assume bkg from W's can be made subdominant: reach of $e^+e^- \to \nu\bar{\nu}ZZ$?



3 TeV
$2\ \mathrm{ab}^{-1}$



simple cut-and-count, just parton level

	4ℓ	$2\ell\,2j$	$4j$
ΔM_ϕ	2%	3%	7%

like ATLAS $\phi \to ZZ$ 1507.05930

Realistic for CLIC?

- → Cut flow still to be optimised
- → Minimisation of WW bkg to ZZ channel
- → WW & hh final states (2b & 4b become promising?)
- → Other production mechanisms
- → Polarisation of initial e^+e^-

....

F. Sala's talk

Selected Topics: Light Flavours Session

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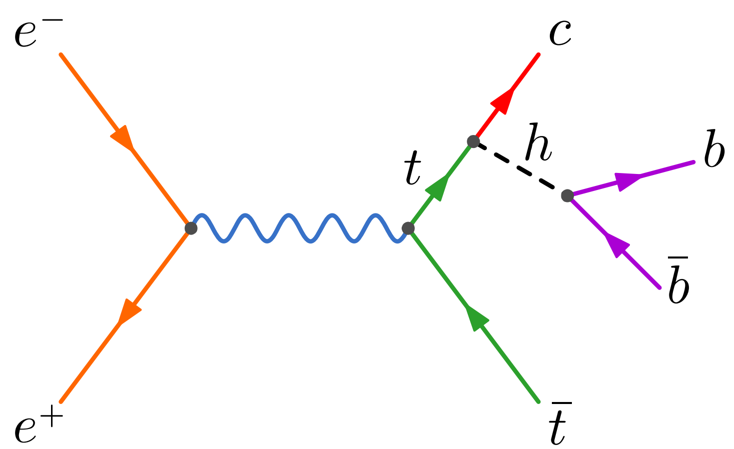
- **Charm quark and New Physics:** Rare top decays

F. Bishara's talk



- Rare decay in SM → smoking gun for NP
- CLIC study @ 380 GeV C.M. energy [Zarnecki: 1703.05007]

- Full detector simulation for H→ bb final state
- Limit: $\mathcal{B}(t \to hc) \times \mathcal{B}(h \to b\bar{b}) < 2.6 \cdot 10^{-4}$ with $\sqrt{s} = 380$ GeV, and 500 fb^{-1}

  1.6 A. F. Zarnecki's talk Yesterday

- This translates to $\kappa_{ct,tc} < 10^{-2}$

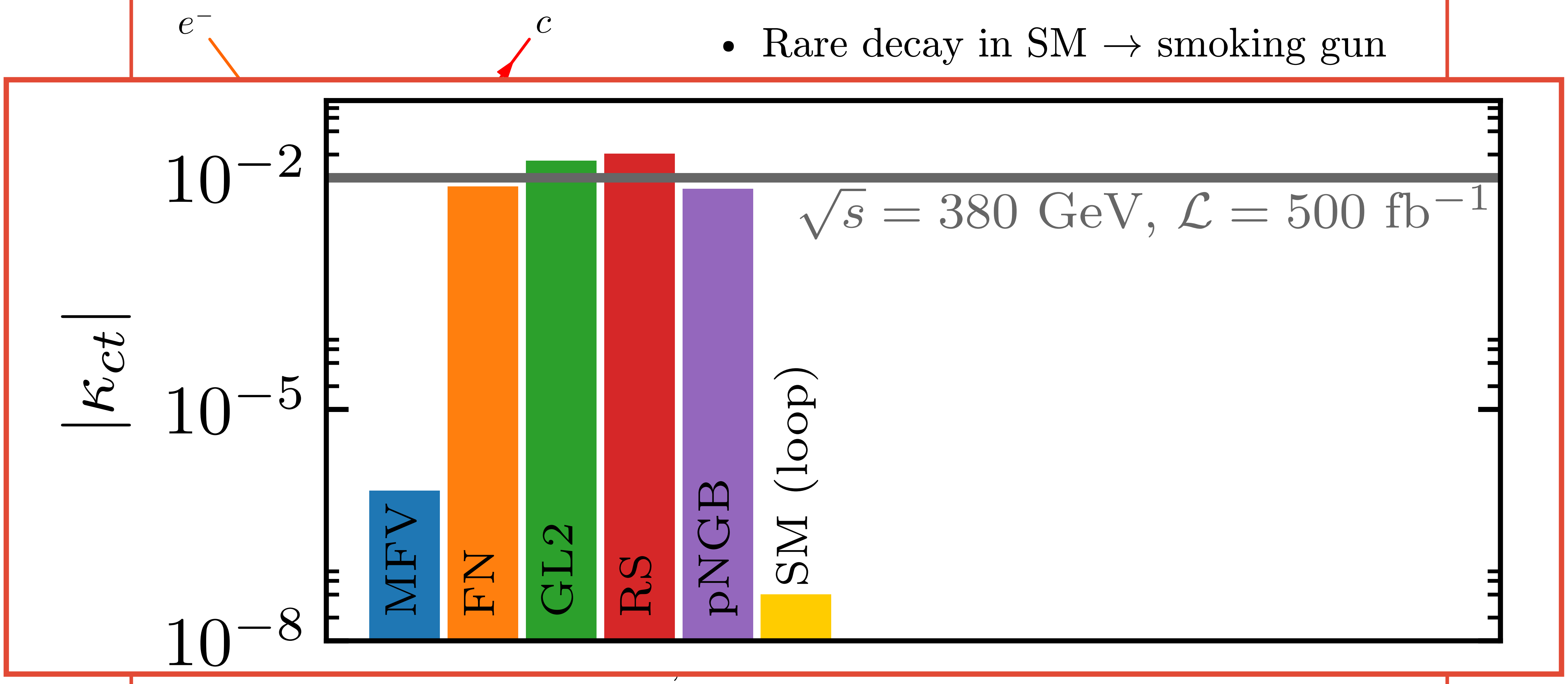
Improvement on this bound can cut into flavor model parameter space!

Selected Topics: Light Flavours Session

- **Charm quark and New Physics:** Rare top decays

F. Bishara's talk

- Rare decay in SM → smoking gun



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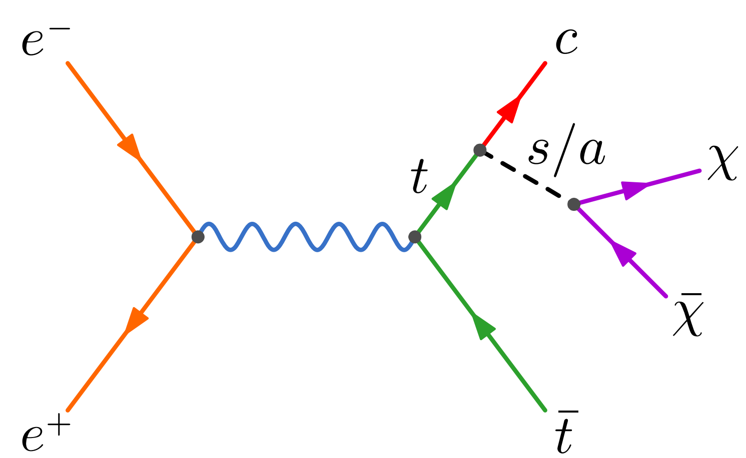
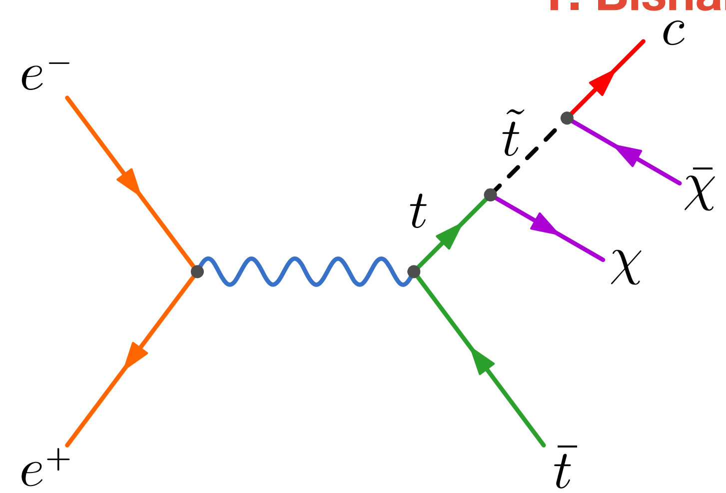




- Arises, e.g., in models of DM with a scalar/pseudoscalar with flavor structure [Isidori, Kamenik: 1103.0016], [Zupan, Kamenik: 1107.0623], [Andrea, Fuks, Maltoni: 1106.6199], [Blanke, Kast: 1702.08457] + many others
- Unique signature with charm + MET reconstructing m_t but presents other challenges (e.g., leptonic W decays?)
- Branching ratios vary by model, e.g.:

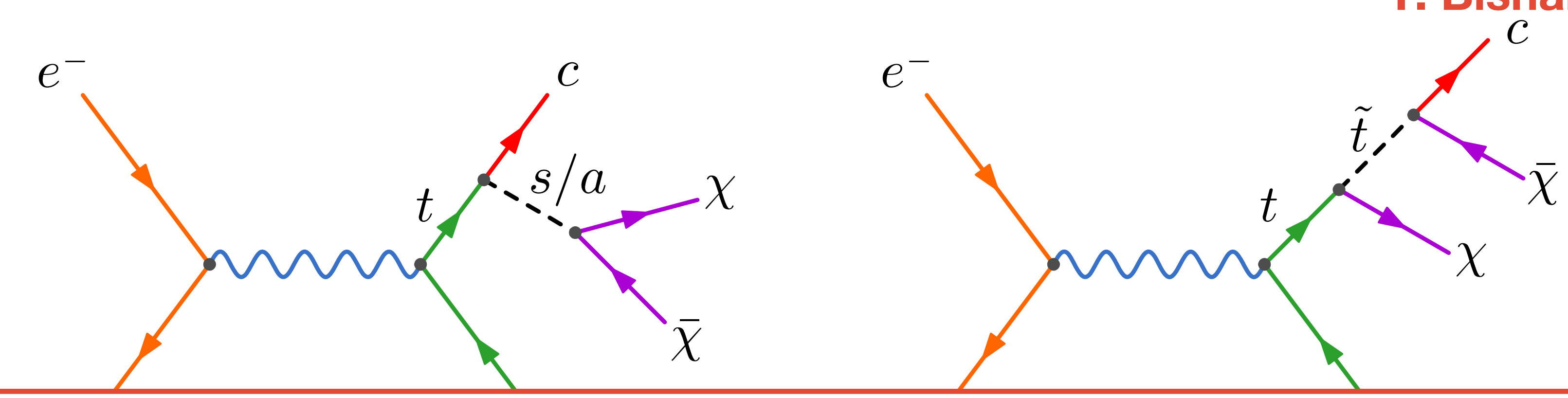
  Flavon: $\mathcal{B}(t \to ca) \sim 10^{-3}$ for $m_a = 100$ GeV [Bauer, Schell, Plehn: 1603.06950]

see also [Alvarado, Elahi, Raj: 1706.03081]

Selected Topics: Light Flavours Session

- **Charm quark and New Physics:** Rare top decays

F. Bishara's talk



- Many more channels to look in – e.g., t→Zc, t→γc, t→Vc, …

[Andrea, Fuks, Maltoni: 1106.6199], [Blanke, Kast: 1702.08457] + many others

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Selected Topics: Light Flavours Session

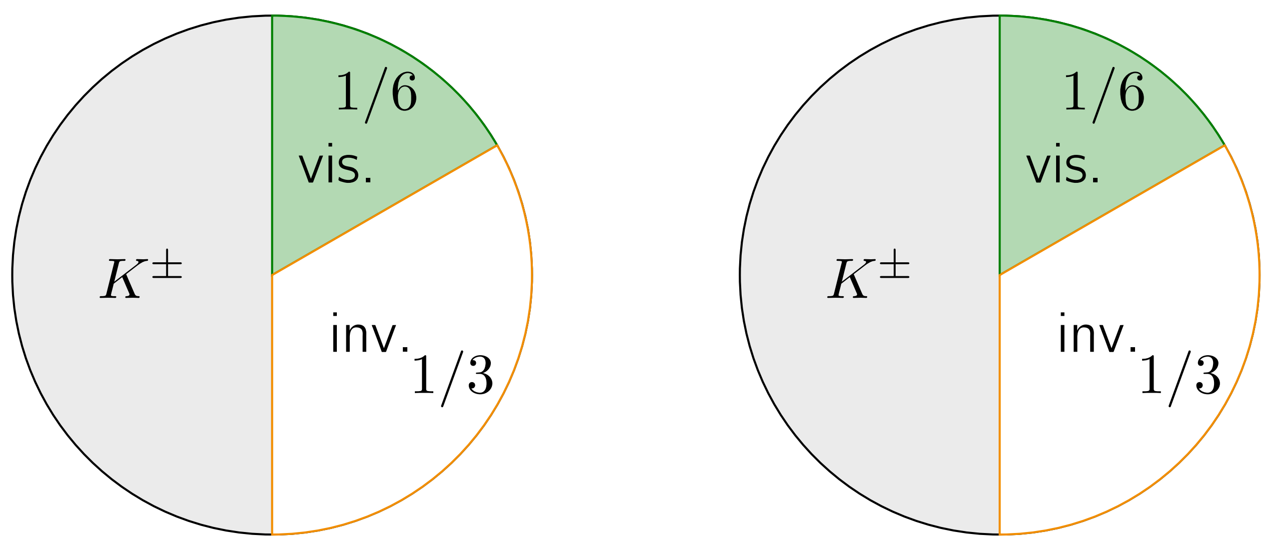
- ***H* $\to s\bar{s}$:** potential of s-tagging at CLIC

Setup for an s-tagger

M. Schlaffer's talk

Ansatz: s-jets dominantly contain a prompt kaon that carries a large fraction of the jet momentum.

In which kaons can a s quark hadronize?



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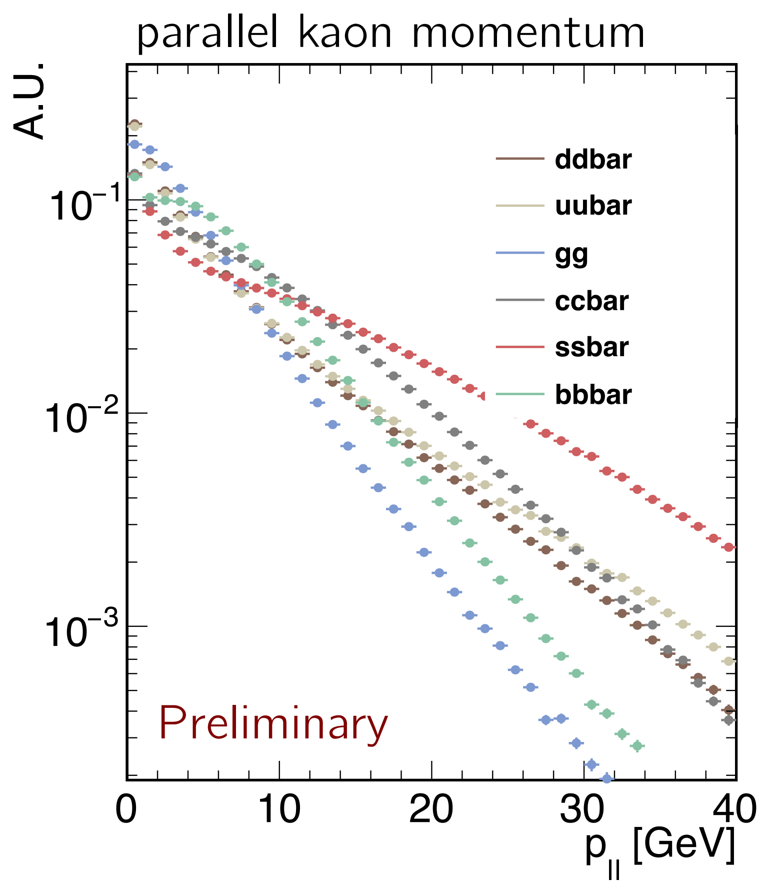
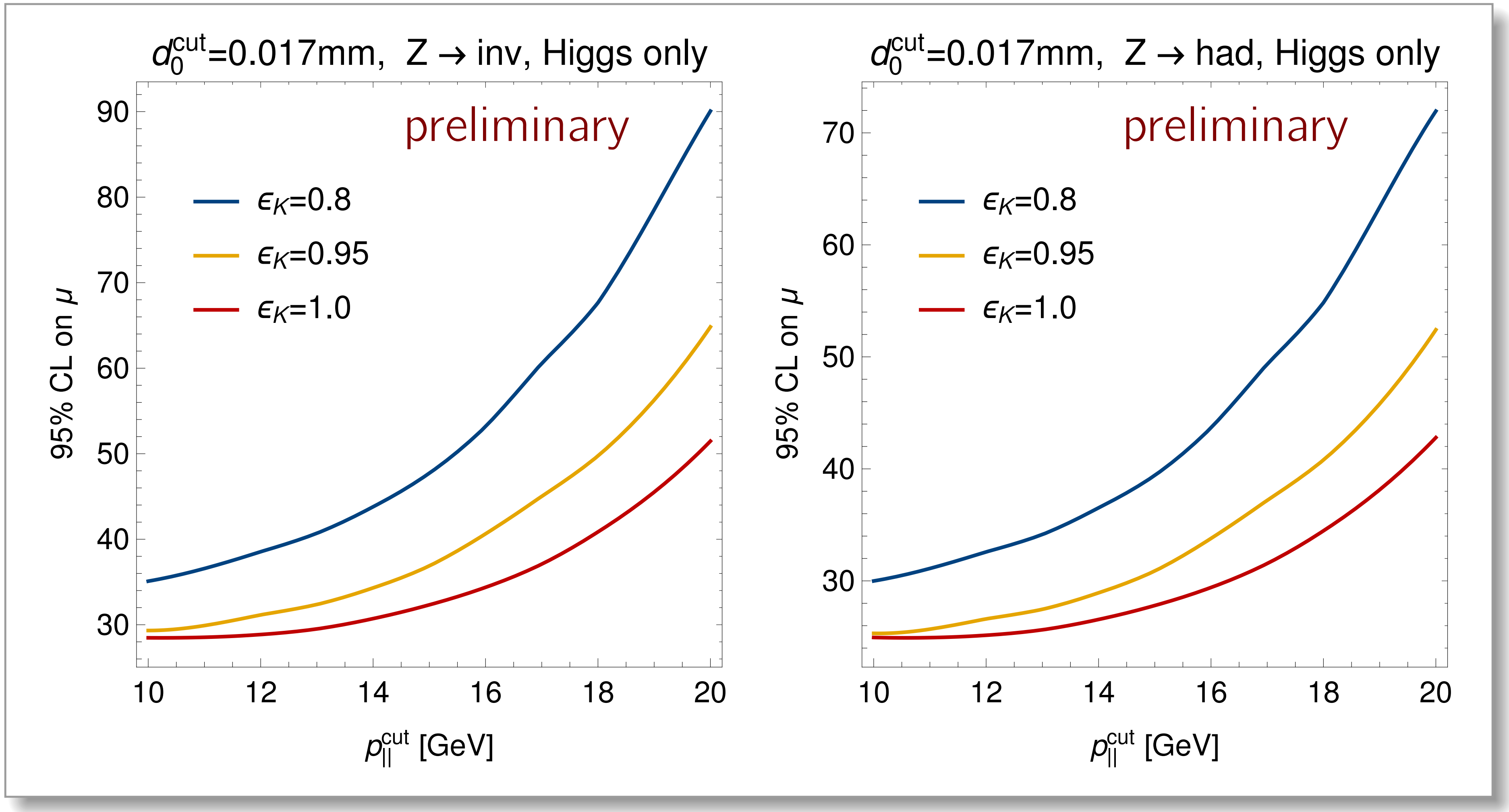


candidates from non-s-jets are soft, especially in g-jets

Selected Topics: Light Flavours Session

- $H \to s\bar{s}$: potential of s-tagging at CLIC



strange Yukawa testable with CLIC at $\mathcal{O}(10)$

M. Schlaffer's talk

Selected Topics: Light Flavours Session

- **LFV at CLIC:** LFV 4-Fermion interactions at high E

$$\mathcal{L}_\tau = \sum_{i,j=L,R} V_{ij}\,[\bar{e}\gamma^\mu P_i e]\,[\bar{\tau}\gamma_\mu P_j e] + h.c. \qquad \left(\begin{array}{c} \tau \to 3e \\ e^+e^- \to e\tau \end{array} \right)$$

> Background at CLIC: $e^+e^- \to \tau\nu_\tau e\nu_e$ and $e^+e^- \to \tau\tau$

> Use kinematics:
  - all energy used: $E_e > 0.9\sqrt{s}/2$
  - back-to-back: $\sqrt{\hat{s}} = (p_e + p_\tau)^2 > 0.9\sqrt{s}$

> Unpolarized beams with $\int \mathcal{L} = 1\ \mathrm{ab}^{-1}$:

$\sqrt{s}$ [GeV]	250	500	1000	3000
95% CL on $\lvert V_{LL}\rvert^{-1/2}$ [TeV]	8	12	18	35

> can be improved by tighter cuts and polarized beams

> However: BELLE II, improvement by $\mathcal{O}(10^2)$ on BR
  $\Rightarrow$ projection: $\lvert V_{LL}\rvert^{-1/2} \gtrsim 40$ TeV

M. Schlaffer's talk

Selected Topics: Light Flavours Session

- **LFV at CLIC:** LFV 4-Fermion interactions at high E

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> Background at CLIC: $e^+e^- \to \tau\nu_\tau e\nu_e$ and $e^+e^- \to \tau\tau$

> Use kinematics:

– all energy used: $E_e > 0.9\,\sqrt{s}/2$

- **Impact of polarized beams?**
- **Projections for other LFV processes ($e^+e^- \to \mu\tau$) and interactions (V_{ij})**

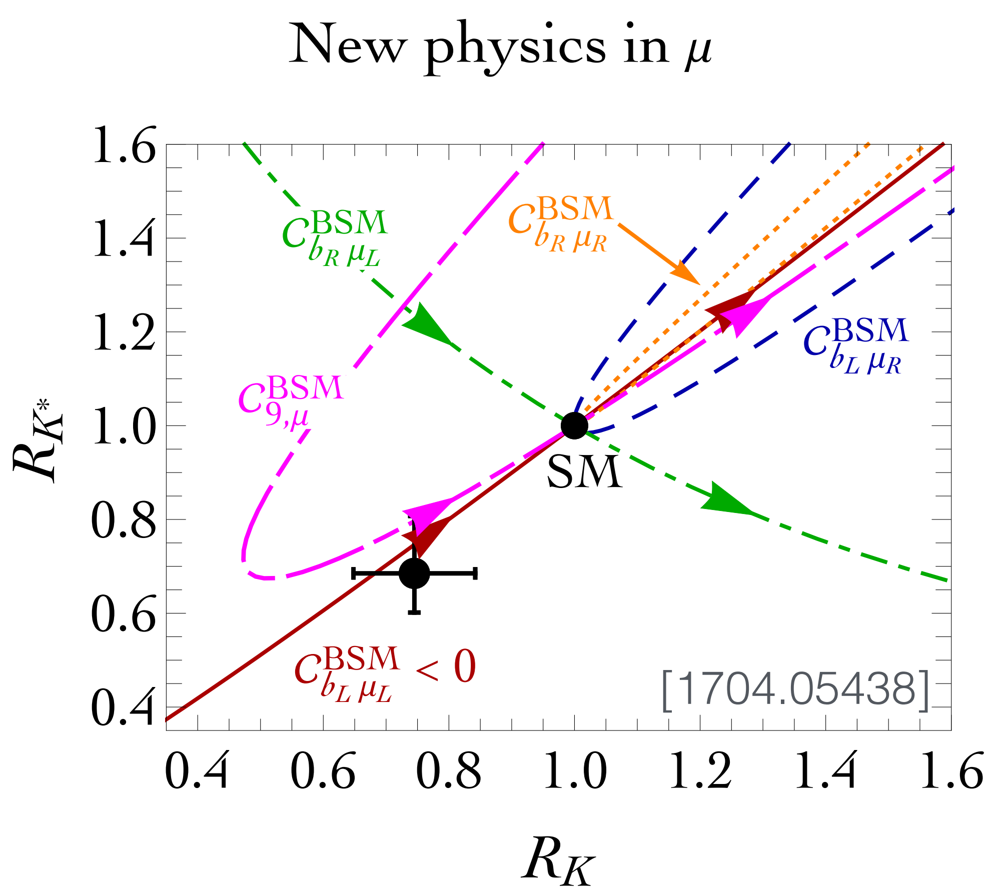
> can be improved by tighter cuts and polarized beams

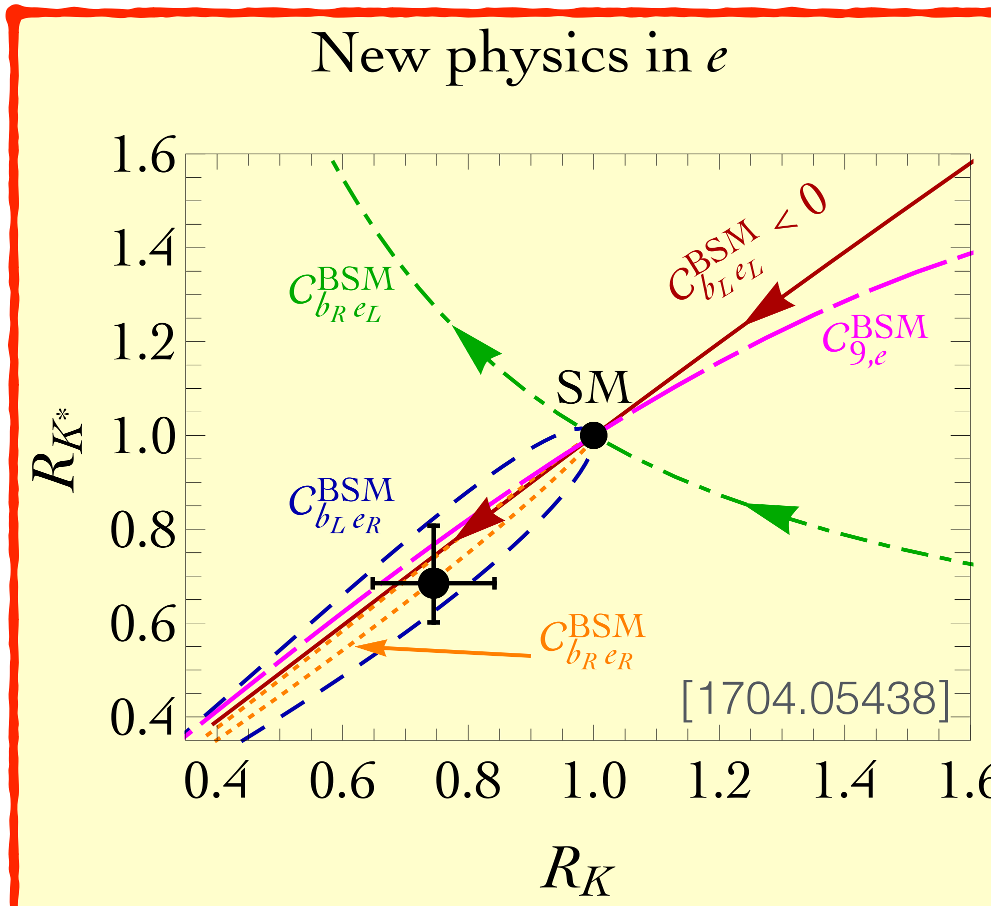
> However: BELLE II, improvement by $\mathcal{O}(10^2)$ on BR
$\Rightarrow$ projection: $|V_{LL}|^{-1/2} \gtrsim 40$ TeV

M. Schlaffer's talk

Selected Topics: Light Flavours Session

- **LFU at CLIC:** Hints of LFUV in B decays at the LHC (R_K & R_{K^*})





- *Can explain only LFUV anomalies!*

Same interactions enter in $e^+e^- \to bs$

More opportunities at CLIC!

A. Greljo's talk

Summary of Selected Topics from the Workshop

- Di-Higgs: optimize CLIC sensitivity to Higgs self-interaction? Differential Distributions, run at lower E, … (G. Panico et al. WiP)
- CLIC reach in models with Higgs singlets (F. Sala et al. WiP)
- $H \to s\bar{s}$ using s-tagging techniques (M. Schlaffer et al. WiP)

"To Do" list:

- $WW \to t\bar{t}$ sensitivity to modified Top Yukawa
- High Energy probes of universal new physics: Global $e^+e^- \to ff$ analysis
- Discovery potential of Accidental/Minimal DM multiplets at 3 TeV
- CLIC opportunities in searches for disappearing tracks/displaced vertices
- General LFV: High energy ($e^+e^- \to l\tau$) vs. rare decays ($\tau \to lee$), effect of polarization,…
- FCNC: $t \to c + X$, $e^+e^- \to tc$? Also $e^+e^- \to bs$ (in connection with LFUV in B decays?)

CLIC Physics: BSM Report

- Outcome of the WG studies, including the developments on the above-mentioned topics, to be included in a new CLIC Physics Document

  CLIC BSM Physics Report

- **Projected timeline:**

  - Studies to be finished before Summer 2018

  - Final document ready by Fall 2018

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