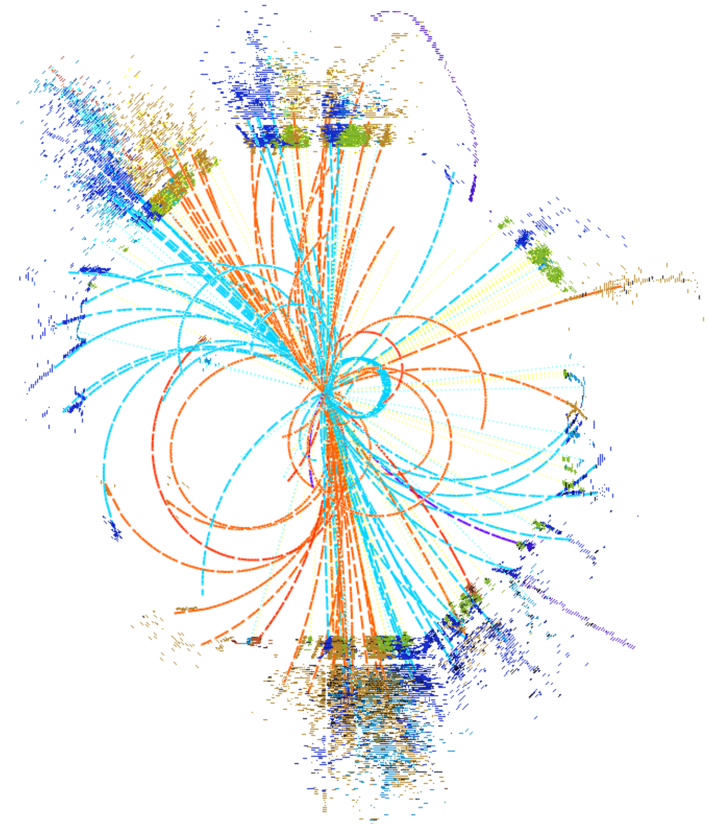
Physics case for ALIC



Philipp Roloff (CERN)

ALEGRO Workshop 2019

26/03/2019
CERN, Geneva

Introduction

- The Standard Model has been extremely successful (including prediction of the Higgs boson discovered at the LHC)

- However, it does not explain observations of:

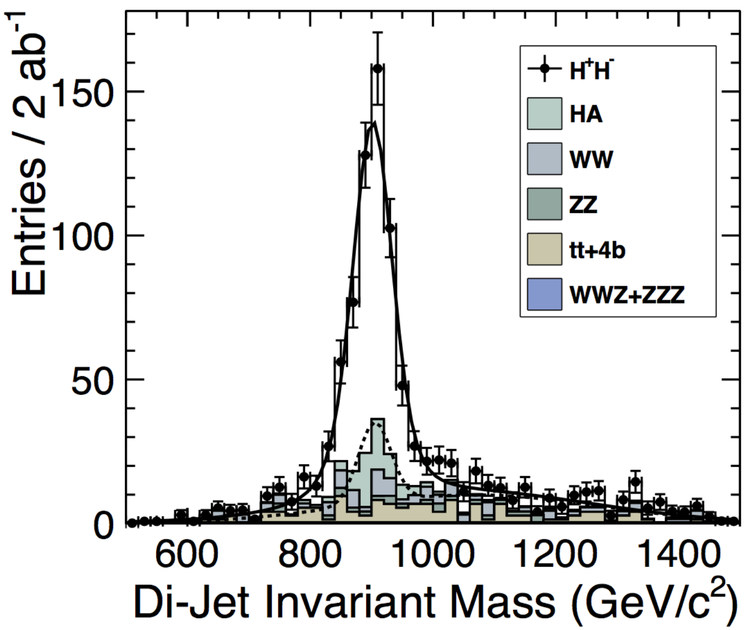
  - Dark Matter
  - The baryon-antibaryon asymmetry in the universe
  - Light neutrino masses and mixing

- Exploration of new territory motivates ambitious future colliders for particle physics

- **This talk:** potential of a very high-energy e^+e^- / $\gamma\gamma$ interactions of up to 30 TeV, many examples for 10 (and 3) TeV

How to search for new physics?

1.) Direct searches:
Looking for new particles
and unknown effects

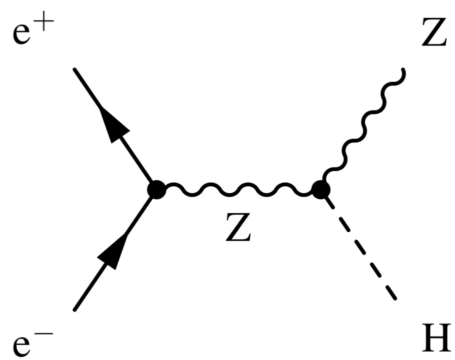


2.) Learning from SM processes:
Precision study of production and
decay properties of known SM particles

Modern approach:
Effective Field Theory (EFT):

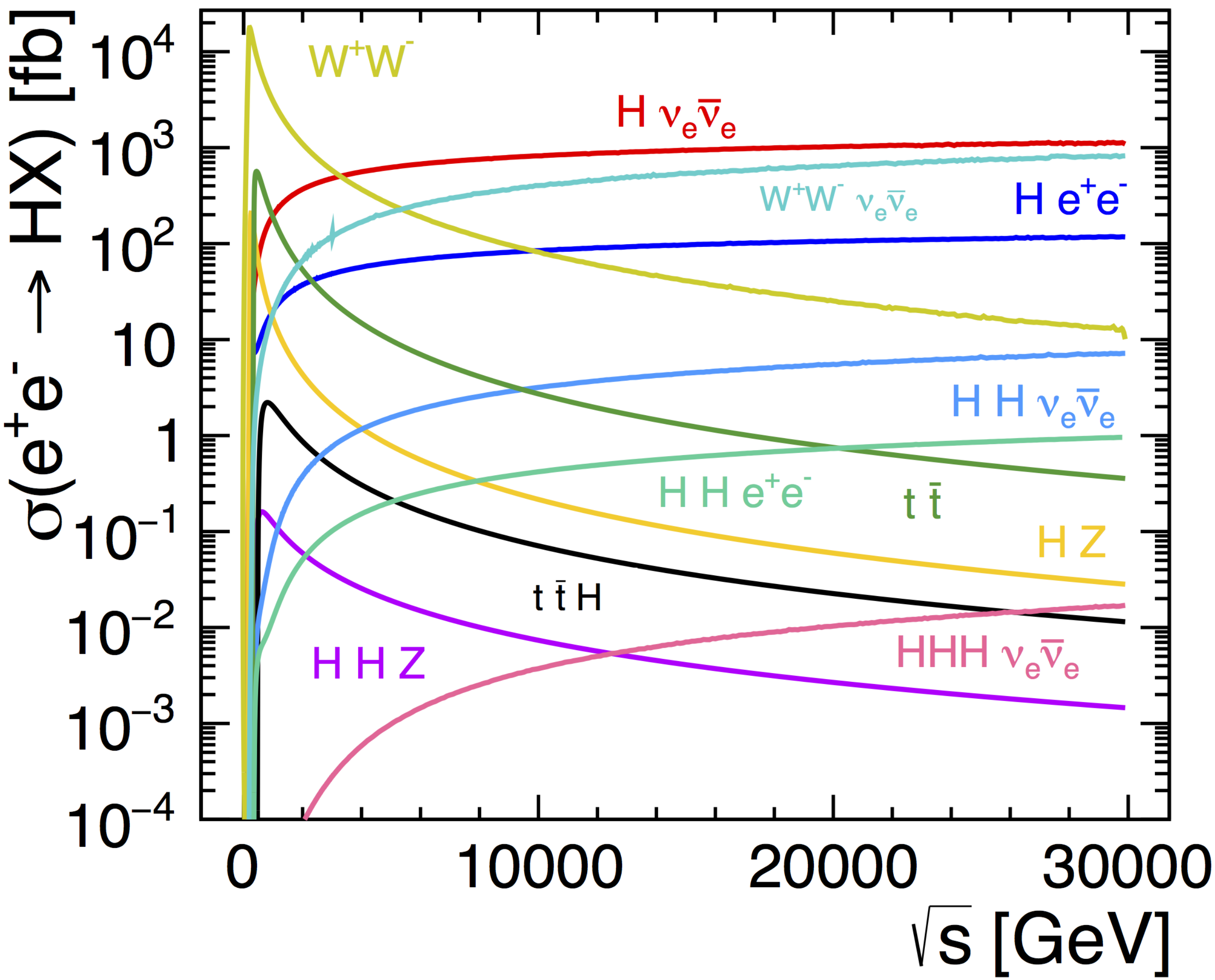
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

→ captures all heavy new
physics



→ Both approaches benefit from
the highest possible energies!

Standard Model processes



- Two-fermion production (e.g. $t\bar{t}$) scales as 1/s, similar for WW and ZH production
→ desired integrated luminosities increse with energy

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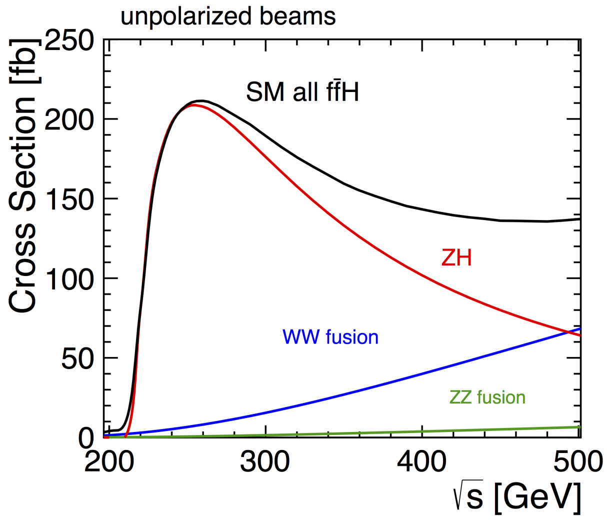
First stage?

Unique and guaranteed physics case for an e^+e^- collider in the energy range from 240 - 380 GeV:

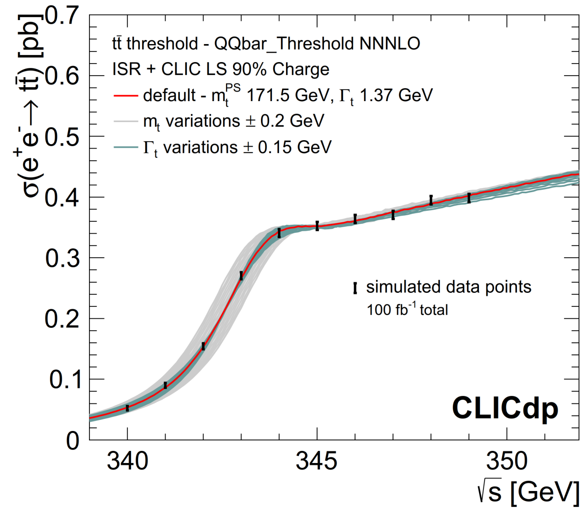


Higgs boson ($\sqrt{s}$ > 240 GeV):

- Model-independent measurement of Higgs width and couplings possible using $e^+e^- \rightarrow ZH$ (not possible at multi-TeV energy alone)

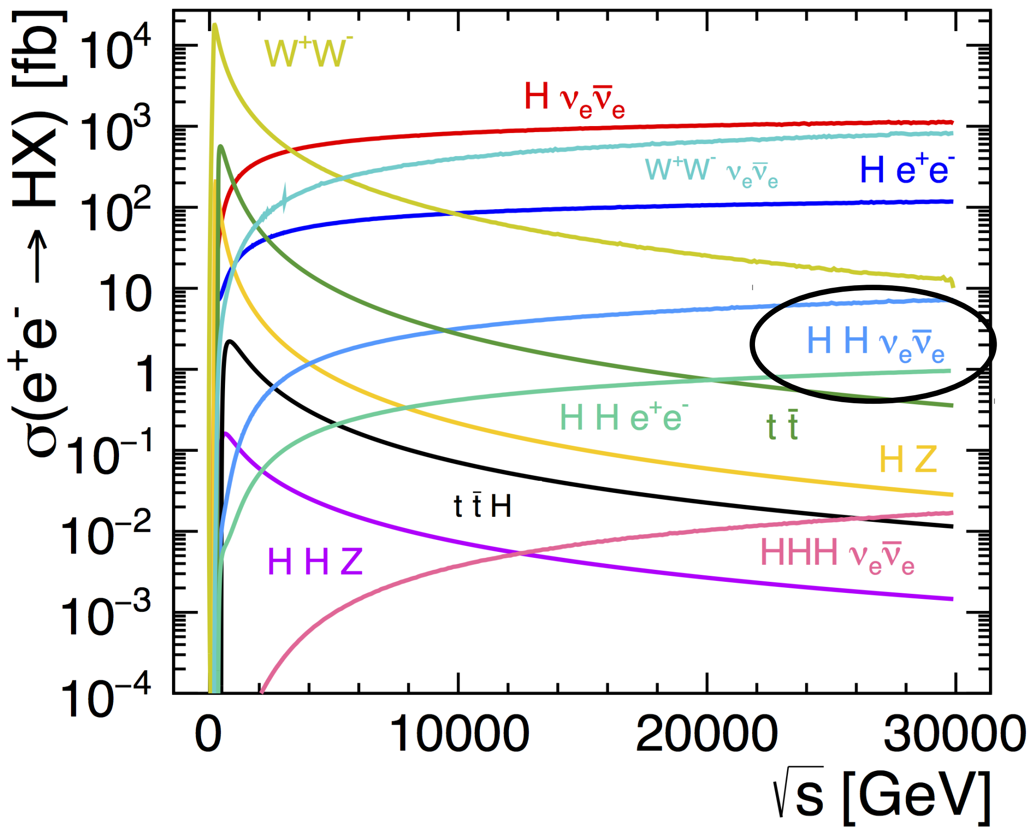
Top-quark ($\sqrt{s}$ > 350 GeV):

- Not studied in e^+e^- interactions so far
- Threshold scan is the best approach to measure its mass



→ ALIC would be a natural upgrade of a linear collider in this energy range

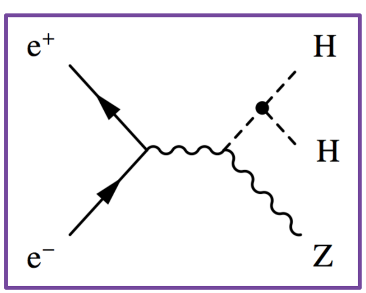
Double Higgs production

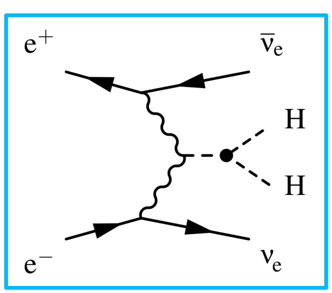


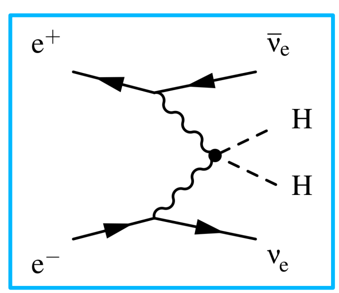
$e^+e^- \rightarrow HH\nu_e\bar{\nu}_e$:

Most important process for the measurement of the Higgs self-coupling at high energy

- Cross section 4.1 times larger at 10 TeV compared to 3 TeV



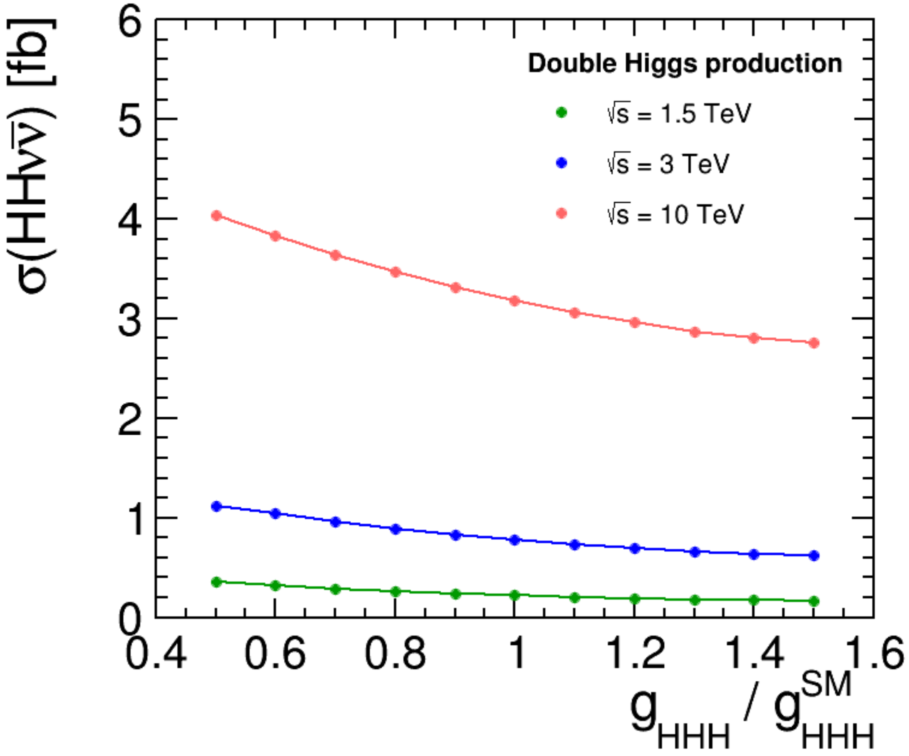




Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^{a}$ $-15\,\%^{b}$
NMSSM	$-25\,\%$

Phys. Rev. D 88, 055024 (2013)

Higgs self-coupling at 10 TeV



Some degradation in sensitivity for larger energies, e.g.:

$\Delta g_{HHH}/g_{HHH}$ = 1.5 • Δσ/σ at 3 TeV
$\Delta g_{HHH}/g_{HHH}$ = 2.5 • Δσ/σ at 10 TeV

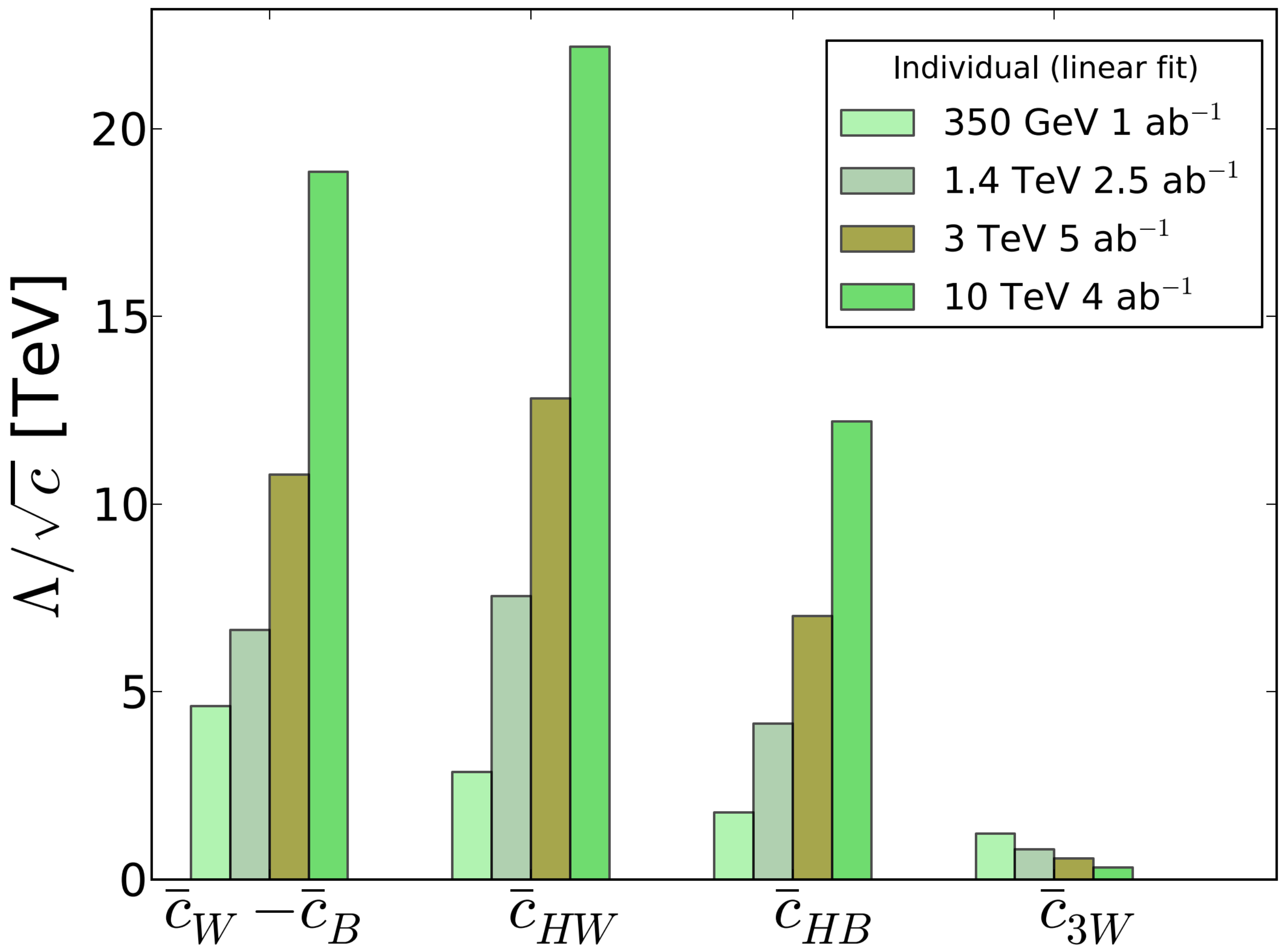
→ Impact smaller than rise of cross section

Extrapolation using 3 TeV CLIC study:

$\Delta g_{HHH}/g_{HHH} \approx$ 5% for 8 ab^{-1} at 10 TeV

(similar to 100 TeV FCC-hh)

EFT analysis of Higgs and WW production in 10 TeV e^+e^- collisions



→ New physics scales well beyond the centre-of-mass energy can be reached

The 10 TeV projections were scaled from CLIC at 3 TeV (assuming the same luminosity spectrum)

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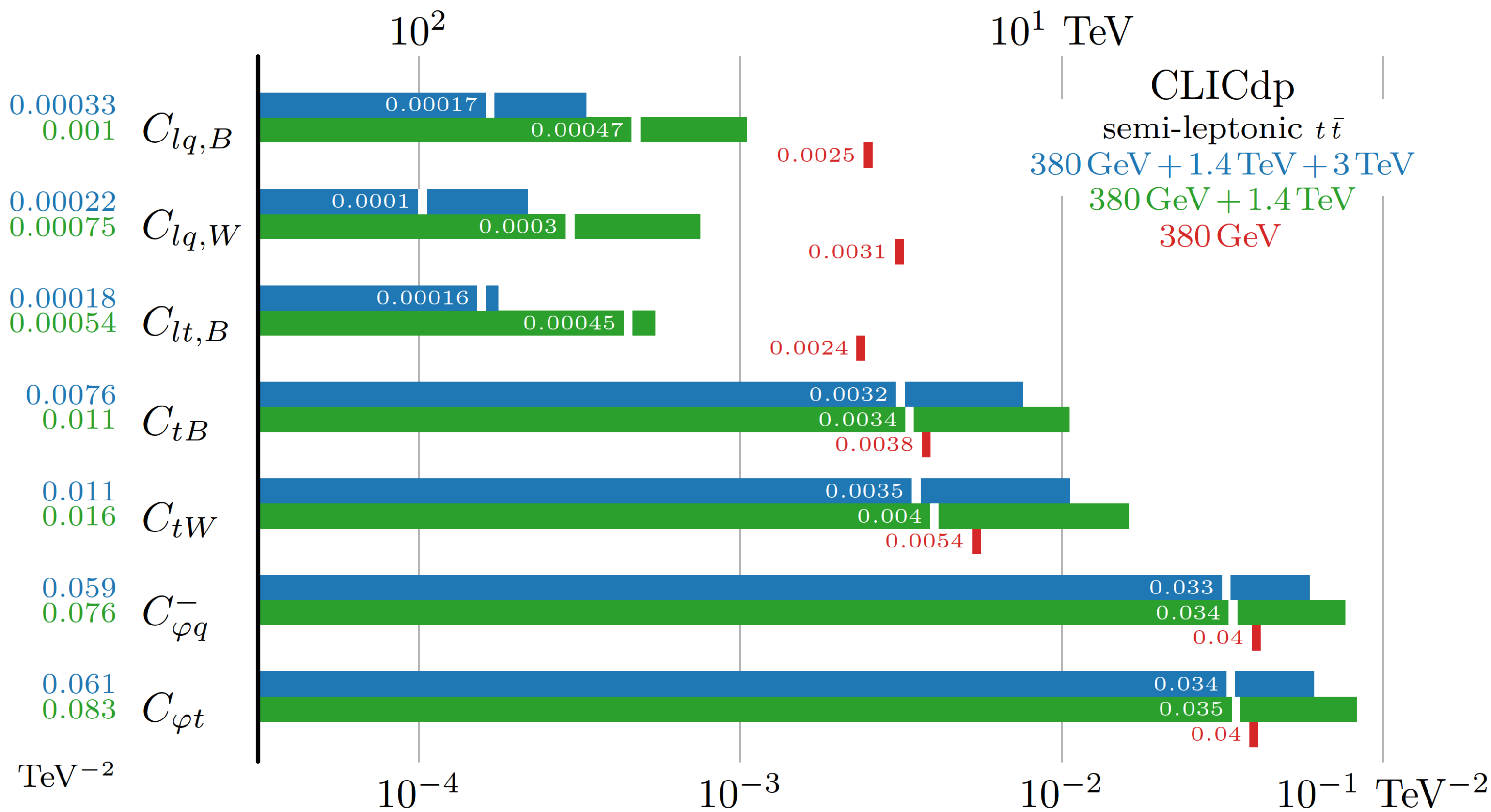
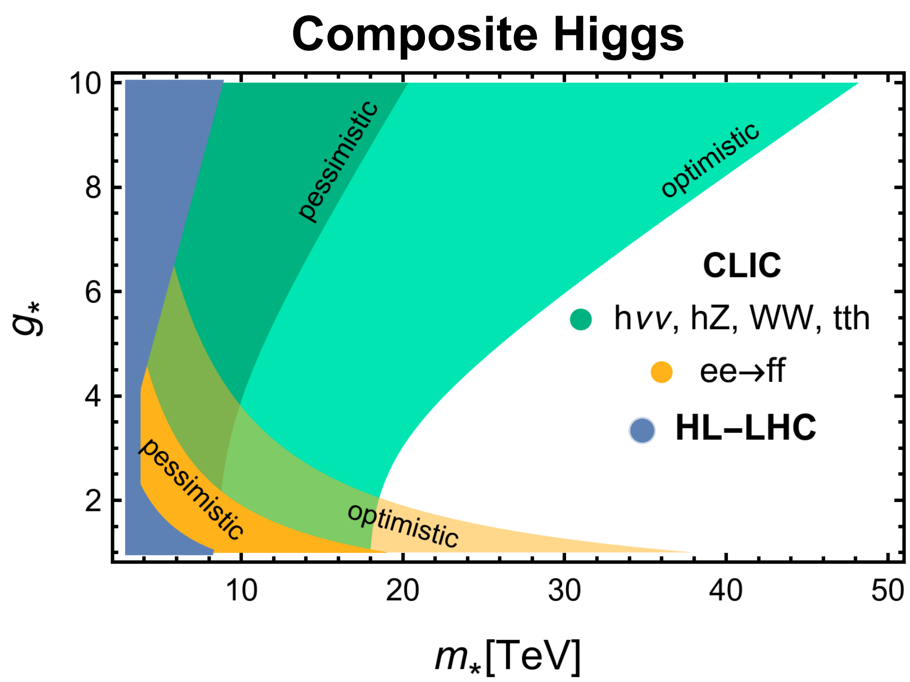
Top-quark pair production at CLIC

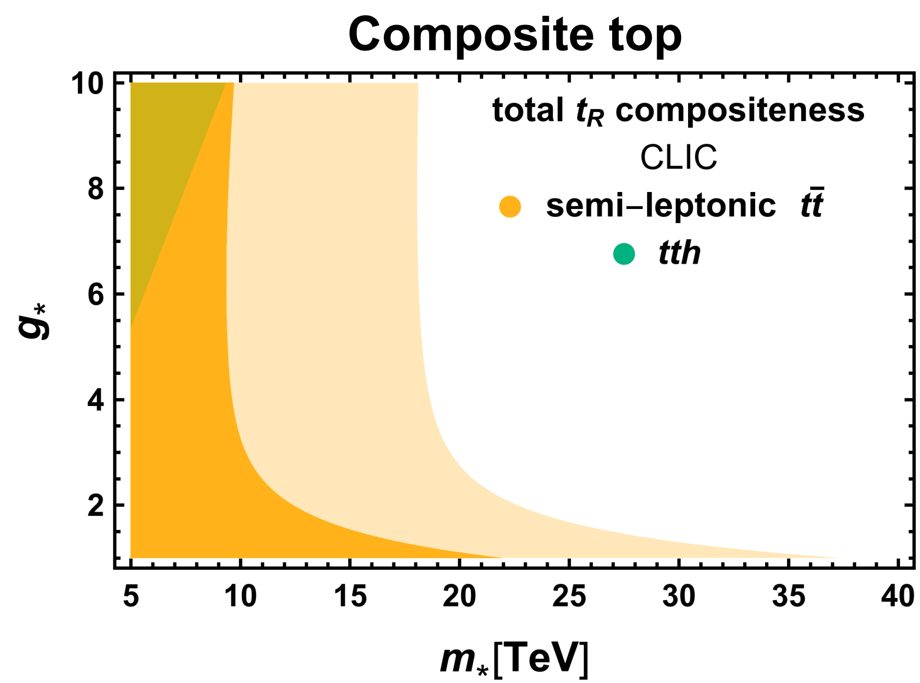


- A global fit requires at least one high-energy stage in addition to 380 GeV operation
- High-energy operation dramatically improves the sensitivity for certain ("four-fermion") operators
- Even higher energy would improve the reach further

arXiv:1807.02441

Compositeness at 3 TeV CLIC





m_*: compositeness scale

g_*:coupling strength of the composite sector

Discovery of Higgs compositeness scale up to 10 TeV (40 TeV for $g_* \approx 8$)

Discovery of top compositeness scale up to 8 TeV (20 TeV for small g_*)

ALIC at higher energy would increase the reach even further

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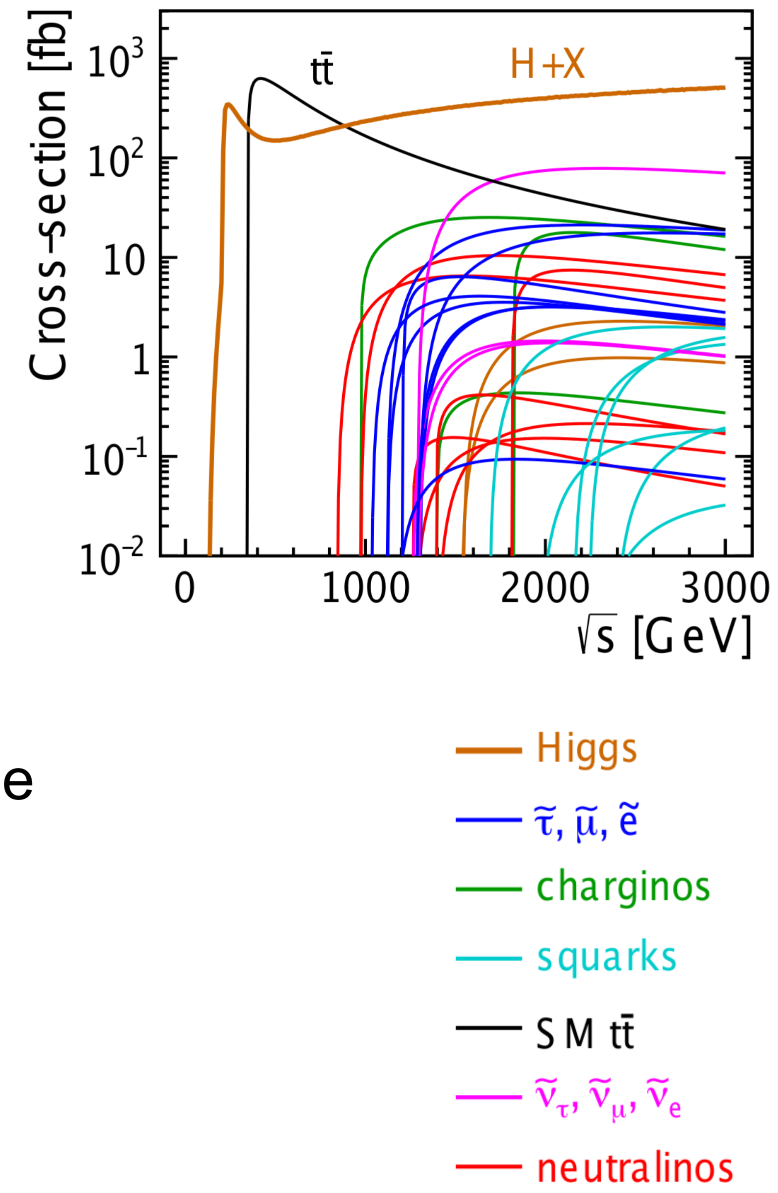
Direct searches for new physics in e^+e^- collisions

- Direct observation of new particles coupling to γ*/Z/W
→ precision measurement of new particle masses and couplings

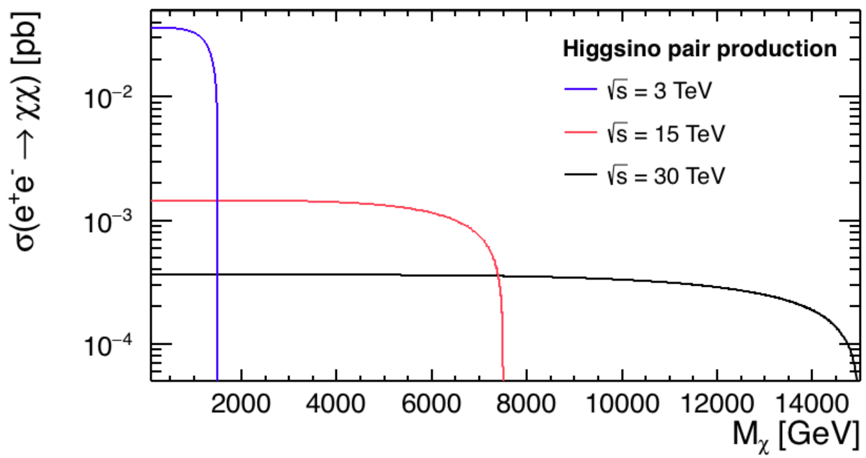
- The sensitivity often extends up to the kinematic limit
(e.g. M ≤ $\sqrt{s}$ / 2 for pair production)

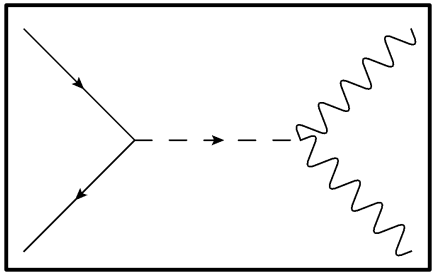
- Very rare processes accessible due to low backgrounds (no QCD)
→ Electron-positron colliders especially suitable for electroweak states

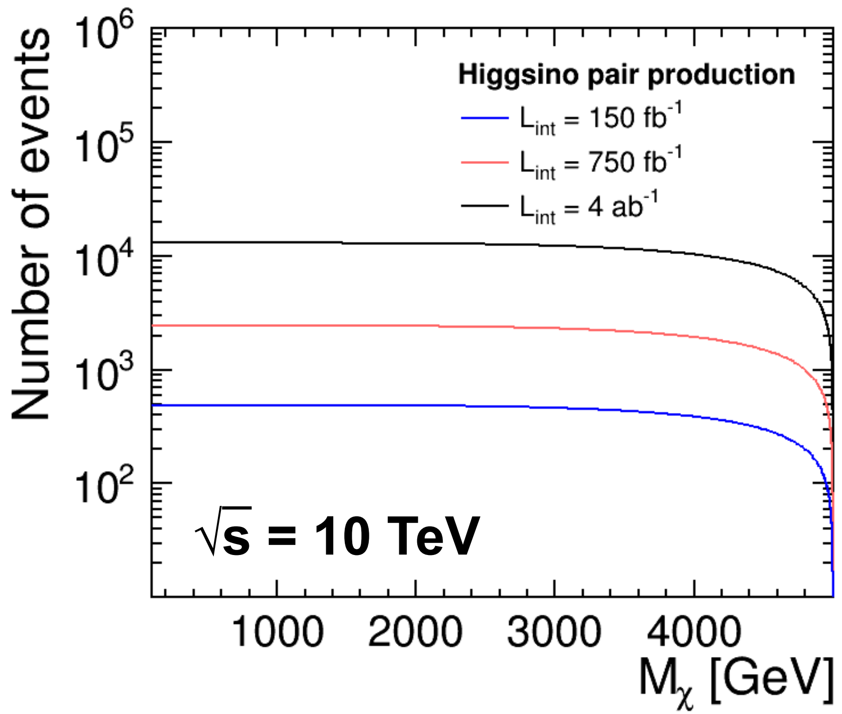
- Polarised beam(s) and threshold scans might be useful to constrain the underlying theory



Heavy electroweak states at high energy







- Number of events almost independent of mass (in contrast to hadron colliders)
- Precision measurements possible at 10 TeV using a few ab^{-1}

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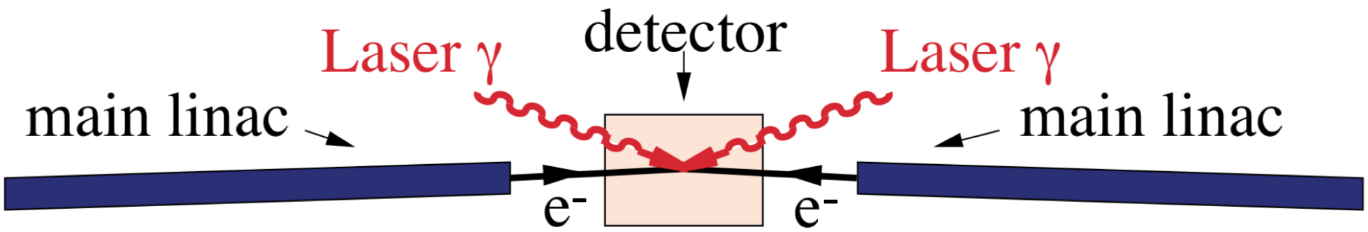
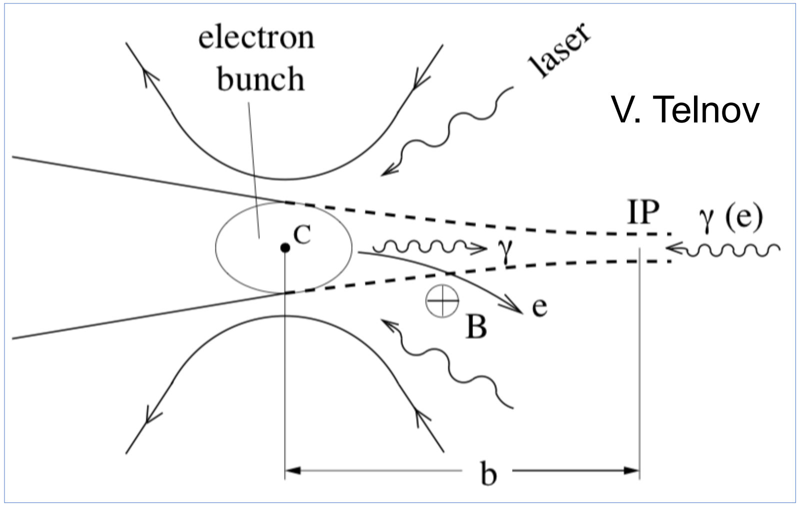
γγ colliders

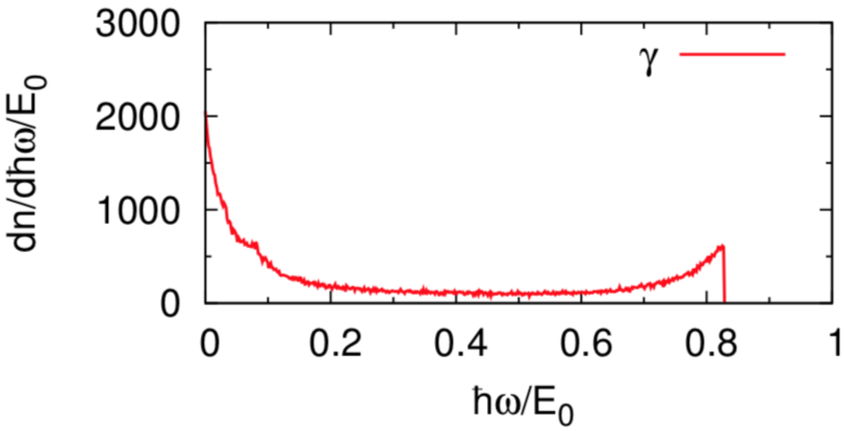
- An e^+e^- collider requires high-gradient, high-efficient positron acceleration
- **Possible alternative:** γγ collider
- Discussed in the past as possible upgrade to a linear collider



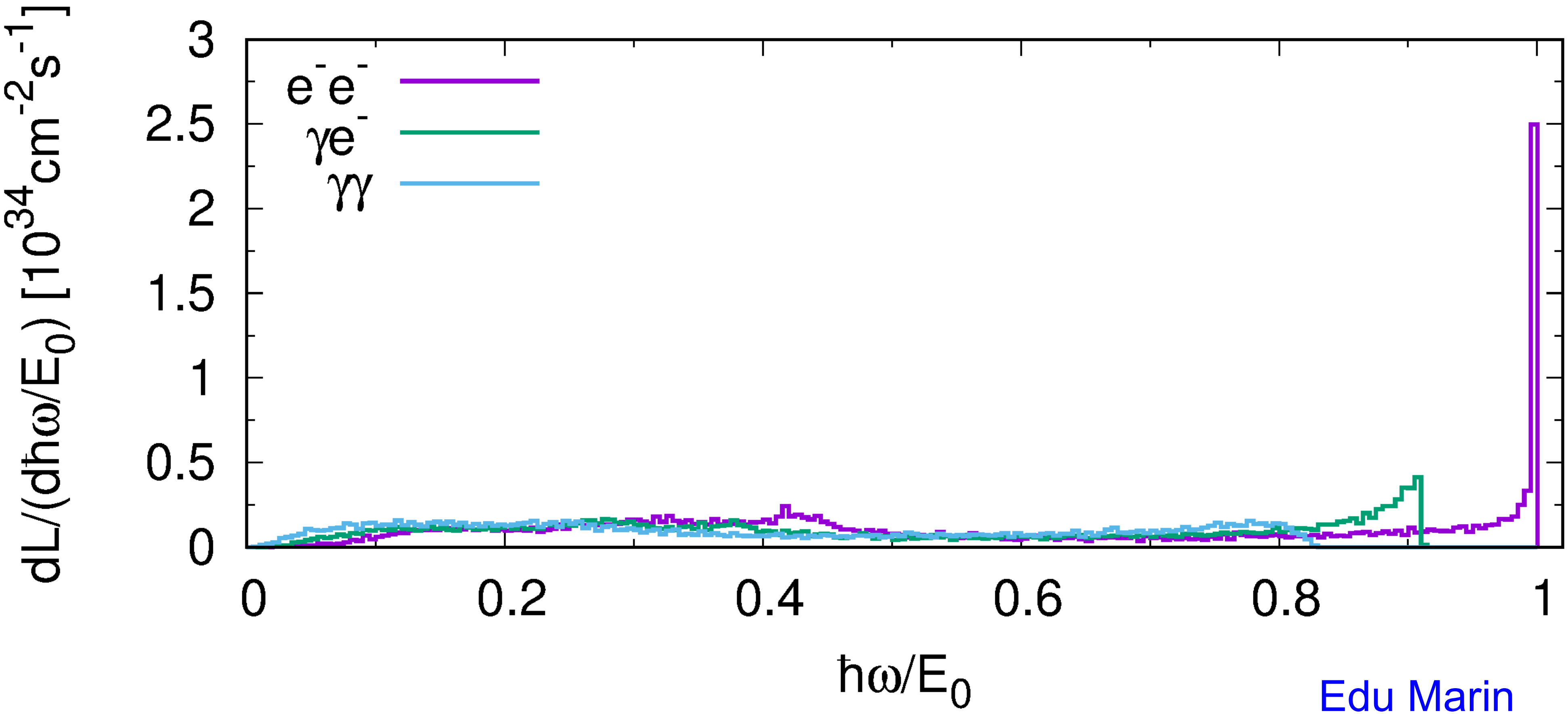
High-energy photons are produced by Compton back-scattering off TeV e^- beams



The photon spectrum has a peak near $0.8E(e^-)$

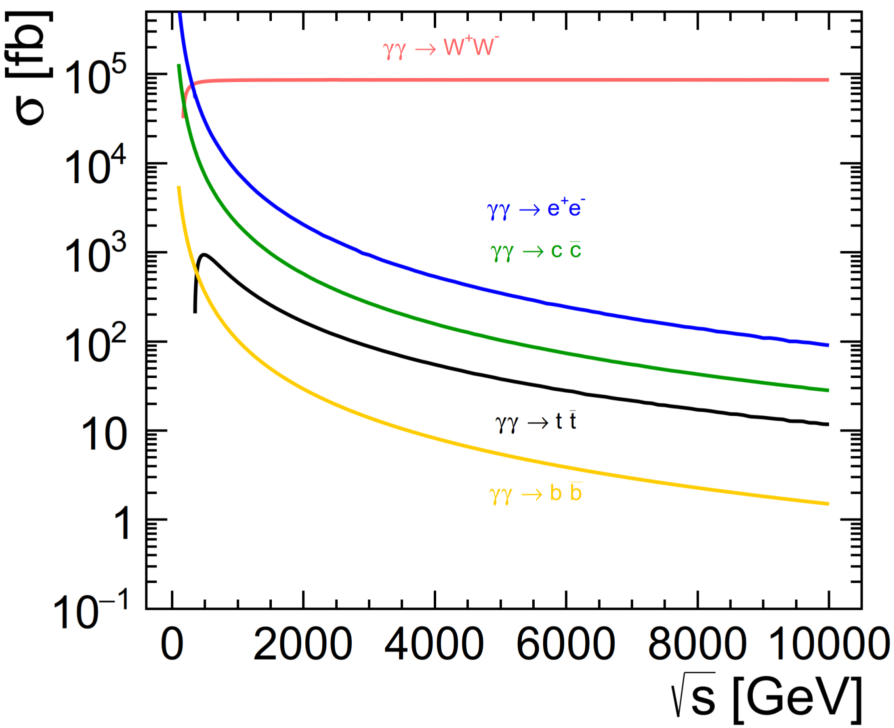


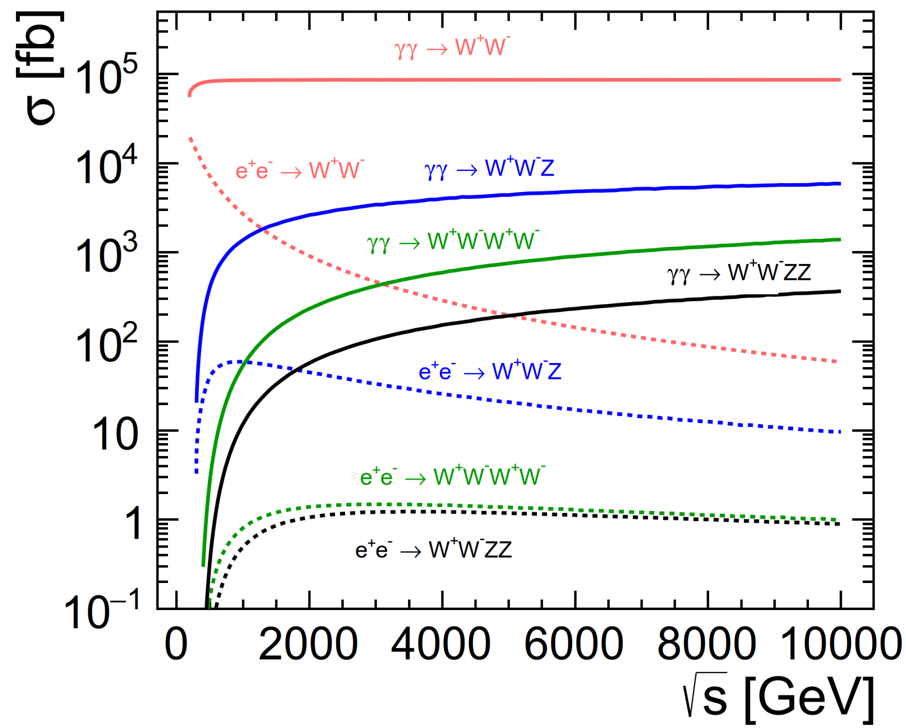
Luminosity spectra at 10 TeV



Edu Marin

Standard Model processes in γγ collisions





- A photon collider is ideal to study electrically charged particles

- **γγ→ W^+W^-:** anomalous photon couplings to W boson

- **γγ → $W^+W^-ZZ/W^+W^-W^+W^-$:** WW → WW and ZZ → ZZ scattering

no beam polarisation

“Higgs physics” at high energy

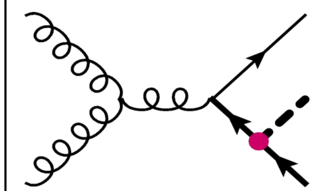
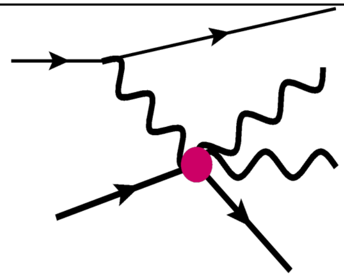
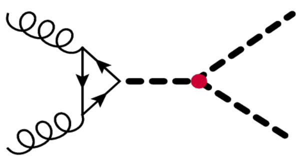
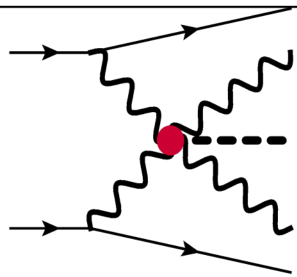
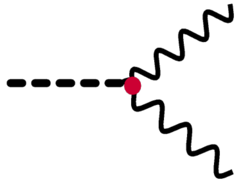
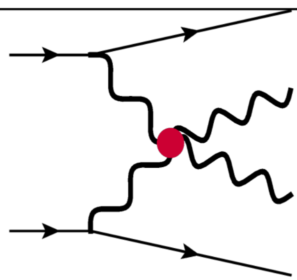
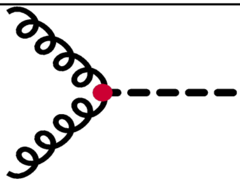
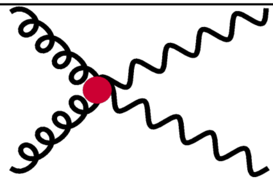
HC: Higgs coupling
HwH: High-energy process

• Higgs decays and high-energy processes probe the same operators

• Sensitivity of high-energy probes rises with energy

Very interesting!

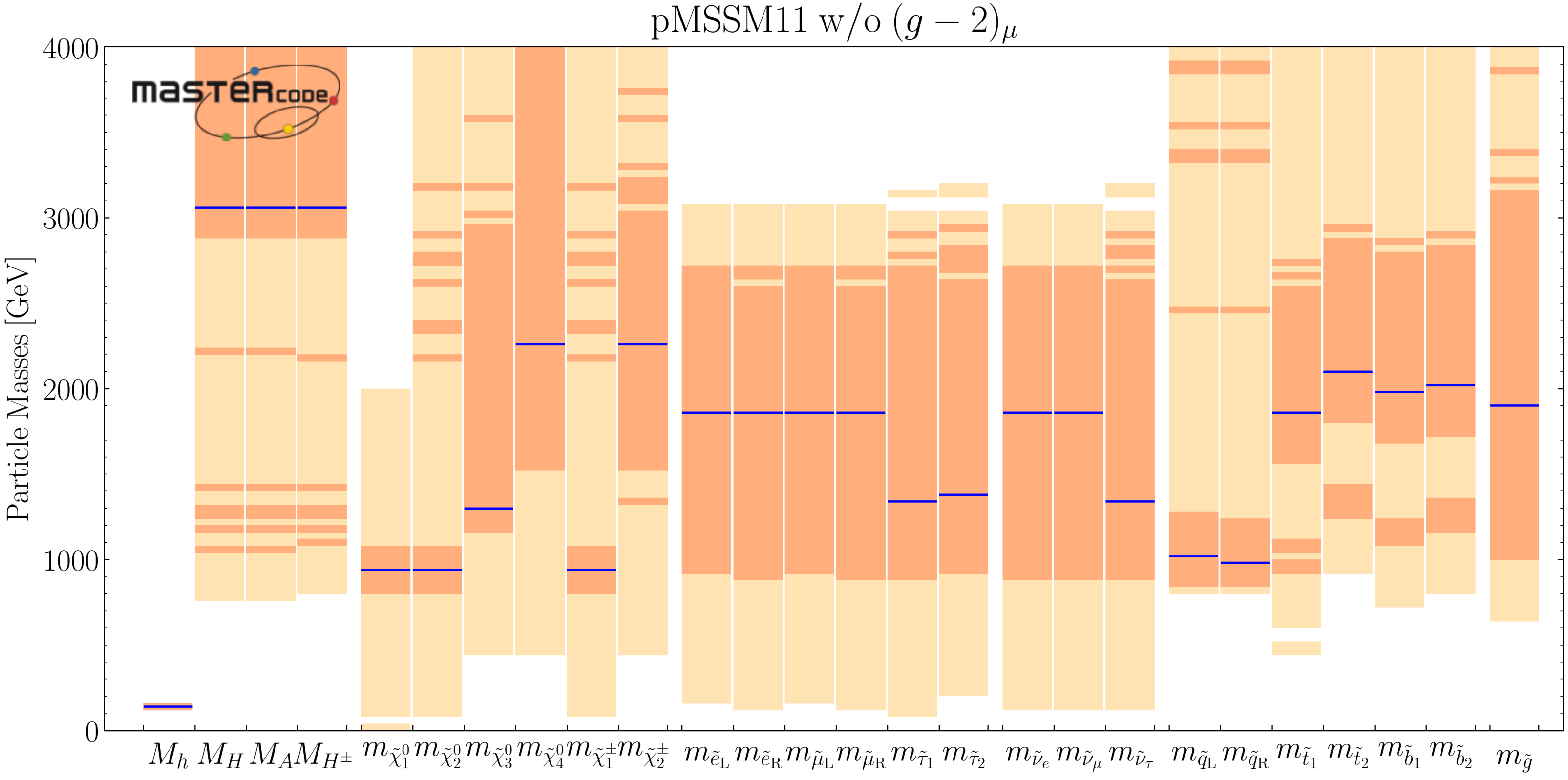
To be studied for ALIC...

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

arXiv:1812.09299

An example SUSY scenario

Example: Phenomenological MSSM with 11 parameters



Blue lines:
best fit values

Orange bands:
68% & 95%
CL ranges

- Global fit to current experimental data (LHC results, low-energy and flavour experiments, CDM measurements)

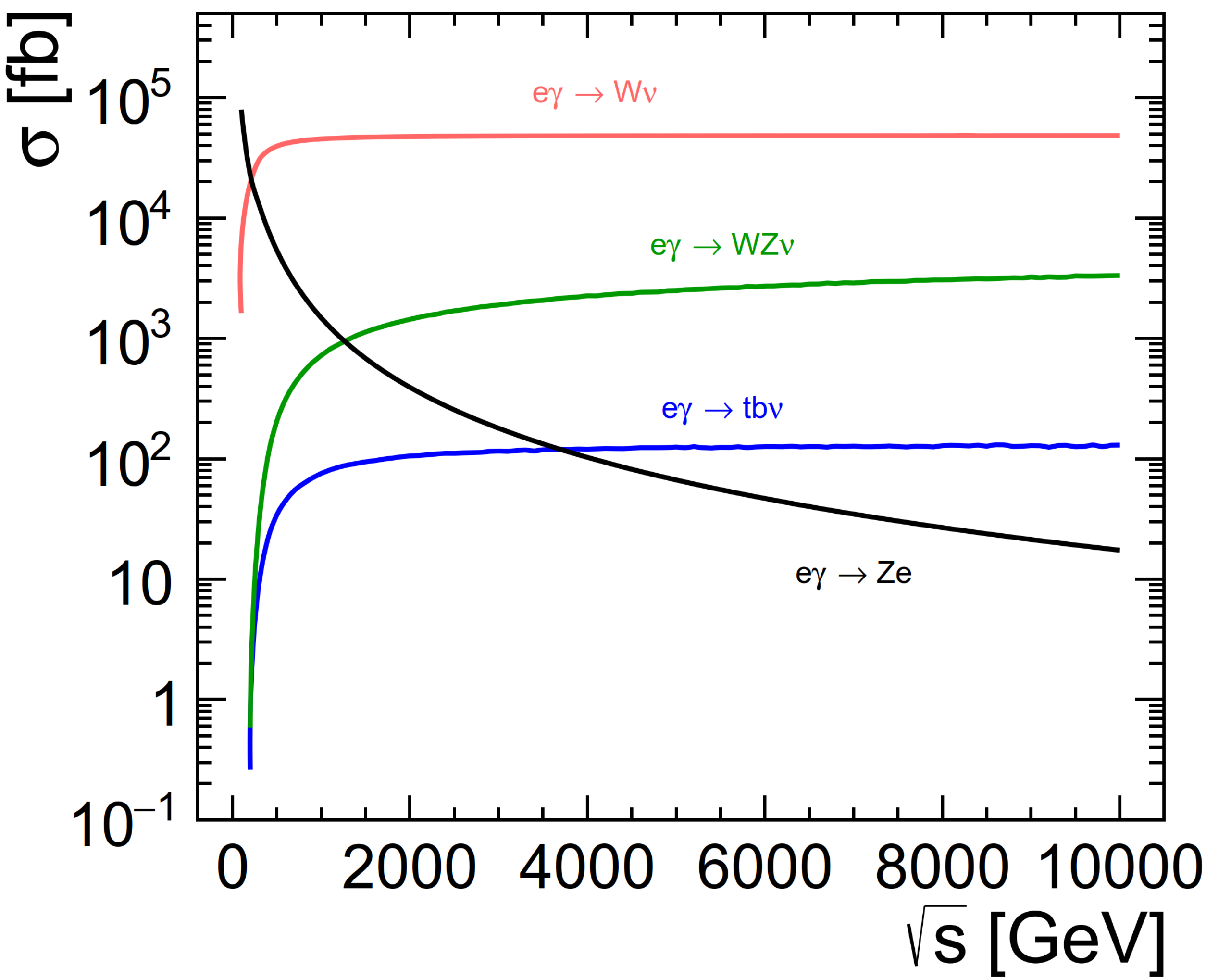
Eur. Phys. J. **C 78**, 256 (2018)

e^+e^- vs $\gamma\gamma$ at 10 TeV

Particle pair	Mass [GeV]	$\sigma(e^+e^- \to XX)$ [fb] Circe2 + ISR, unpol.	$\sigma(\gamma\gamma \to XX)$ [fb] Circe2, unpol.
$\tilde{d}_L\tilde{d}_L$	1009	0.61	0.07
$\tilde{u}_L\tilde{u}_L$	1006	0.89	1.2
$\tilde{s}_L\tilde{s}_L$	1009	0.61	0.07
$\tilde{c}_L\tilde{c}_L$	1006	0.89	1.2
$\tilde{b}_1\tilde{b}_1$	1997	0.19	0.01
$\tilde{t}_1\tilde{t}_1$	1866	0.28	0.22
$\tilde{e}_L\tilde{e}_L$	1869	0.95	0.37
$\tilde{\nu}_{eL}\tilde{\nu}_{eL}$	1867	4.6	/
$\tilde{\mu}_L\tilde{\mu}_L$	1869	0.25	0.37
$\tilde{\nu}_{\mu L}\tilde{\nu}_{\mu L}$	1867	0.11	/
$\tilde{\tau}_1\tilde{\tau}_1$	1328	0.30	0.93
$\tilde{\nu}_\tau\tilde{\nu}_\tau$	1364	0.15	/
$\tilde{d}_R\tilde{d}_R$	988	0.13	0.08
$\tilde{u}_R\tilde{u}_R$	989	0.53	1.2
$\tilde{s}_R\tilde{s}_R$	988	0.13	0.08
$\tilde{c}_R\tilde{c}_R$	989	0.53	1.2
$\tilde{b}_2\tilde{b}_2$	2032	0.07	0.01
$\tilde{t}_2\tilde{t}_2$	2108	0.26	0.16
$\tilde{e}_R\tilde{e}_R$	1856	1.4	0.38
$\tilde{\nu}_{\mu R}\tilde{\nu}_{\mu R}$	1856	0.21	0.38
$\tilde{\tau}_2\tilde{\tau}_2$	1365	0.31	0.86
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	954	≈ 0	/
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	954	≈ 0	/
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	955	2.7	1.4
$\tilde{\chi}_3^0\tilde{\chi}_3^0$	1294	1.1	/
$\tilde{\chi}_4^0\tilde{\chi}_4^0$	2262	0.53	/
$\tilde{\chi}_2^+\tilde{\chi}_2^-$	2262	1.3	1.3
H^0A^0	3046	0.04	/
H^+H^-	3046	0.10	0.08

- Luminosity spectra and ISR (for e^+e^-) included
- A 10 TeV e^+e^- collider would cover the entire SUSY particle spectrum in this scenario
- Neutral particles not accessible at (tree level) in $\gamma\gamma$ collisions
- A multi-TeV photon collider has discovery potential for squarks, sleptons and chargions (with a few ab^{-1})

What about the e⁻γ collisions?



no beam polarisation

- **eγ → Wν:** e.g. anomalous W couplings
- **eγ → tbν:** e.g. anomalous Wtb coupling
- Limited potential for direct searches, e.g.:

$$e\gamma \rightarrow \tilde{e}\,\tilde{\chi}_1^0$$

- eγ interactions would cause difficult backgrounds for physics in γγ collisions
- Ideally, operation with and without the electron beams at the IP?

Conclusions

- Very high-energy e^+e^- and $\gamma\gamma$ interactions provide unique physics opportunities

- The reach of an e^+e^- collider for new phenomena increases strongly with its centre-of-mass energy

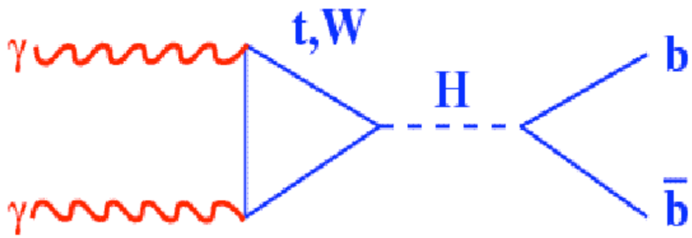
- Photon collider promising for precision measurements in multi-boson production and direct discovery in pair production of charged particles

- The desired integrated luminosity rises with energy, for example at least several ab^{-1} are desired at 10 TeV

- Interesting possibility: ILC or CLIC collider for Higgs & top, then ALIC in the same tunnel

Backup slides

γγ collider as Higgs factory



• A γγ collider with $\sqrt{s}_{\gamma\gamma}$ around 125 GeV allows to study the process $\gamma\gamma \rightarrow H$

• The previous proposals CLICHE (arXiv:0111056) and SAPPHiRE (arXiv:1208.2827) would provide 20000 Higgs bosons / year
→ comparable to first stage of CLIC at 350 / 380 GeV

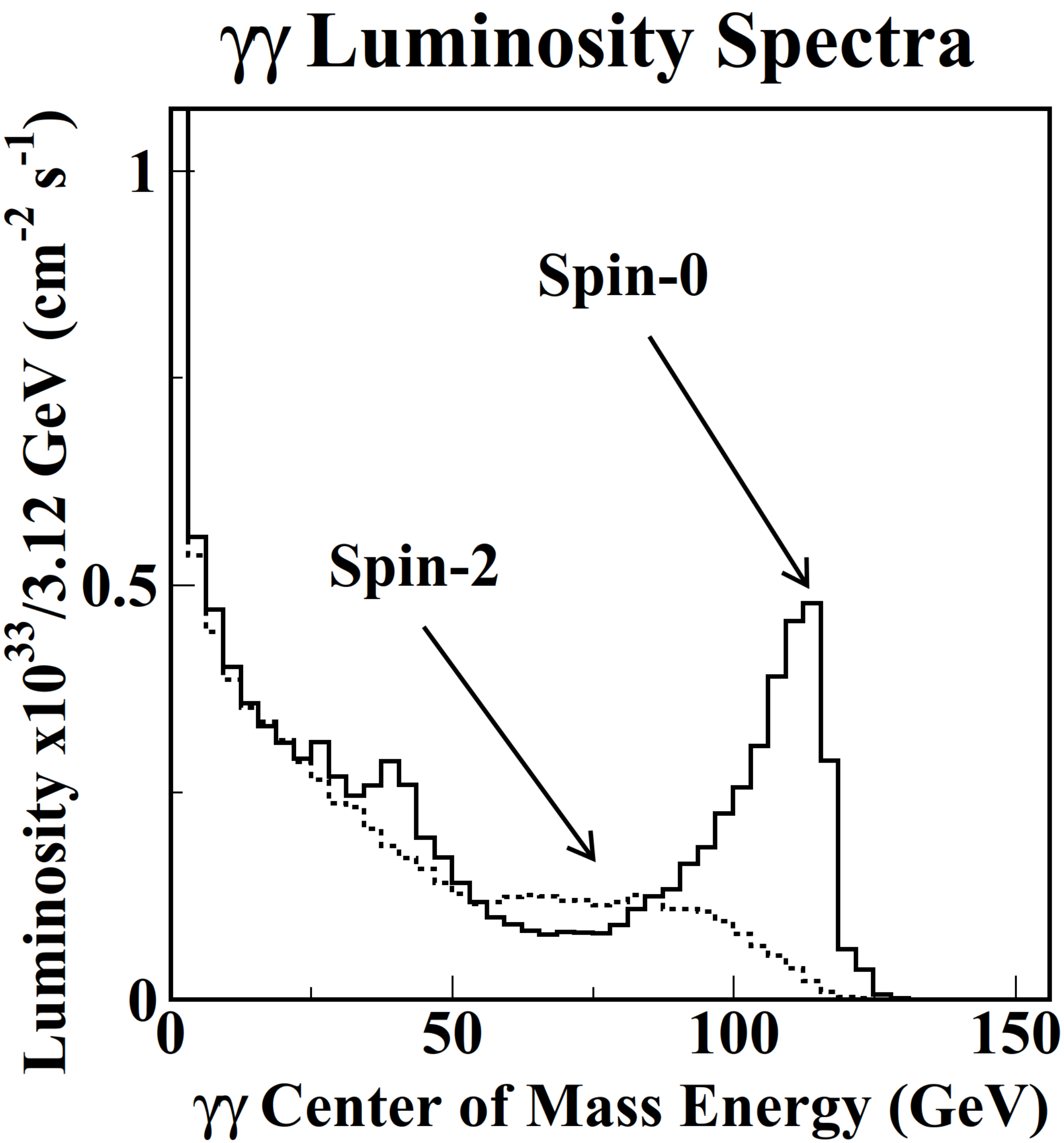
• However, some decays seem difficult in photon collisions: $H \rightarrow c\bar{c}$, $\tau^+\tau^-$, gg

• A fully model-independent interpretation of the results would require some input from an e^+e^- collider

• The optimal γγ collision energy for $\gamma\gamma \rightarrow H^* \rightarrow HH$ is a bit below 300 GeV (an ILC-based photon collider running for 5 years seems not competitive on with a high-energy e^+e^- collider for double Higgs production) arXiv:1205.5292

→ e^+e^- seems to be the best option for Higgs physics

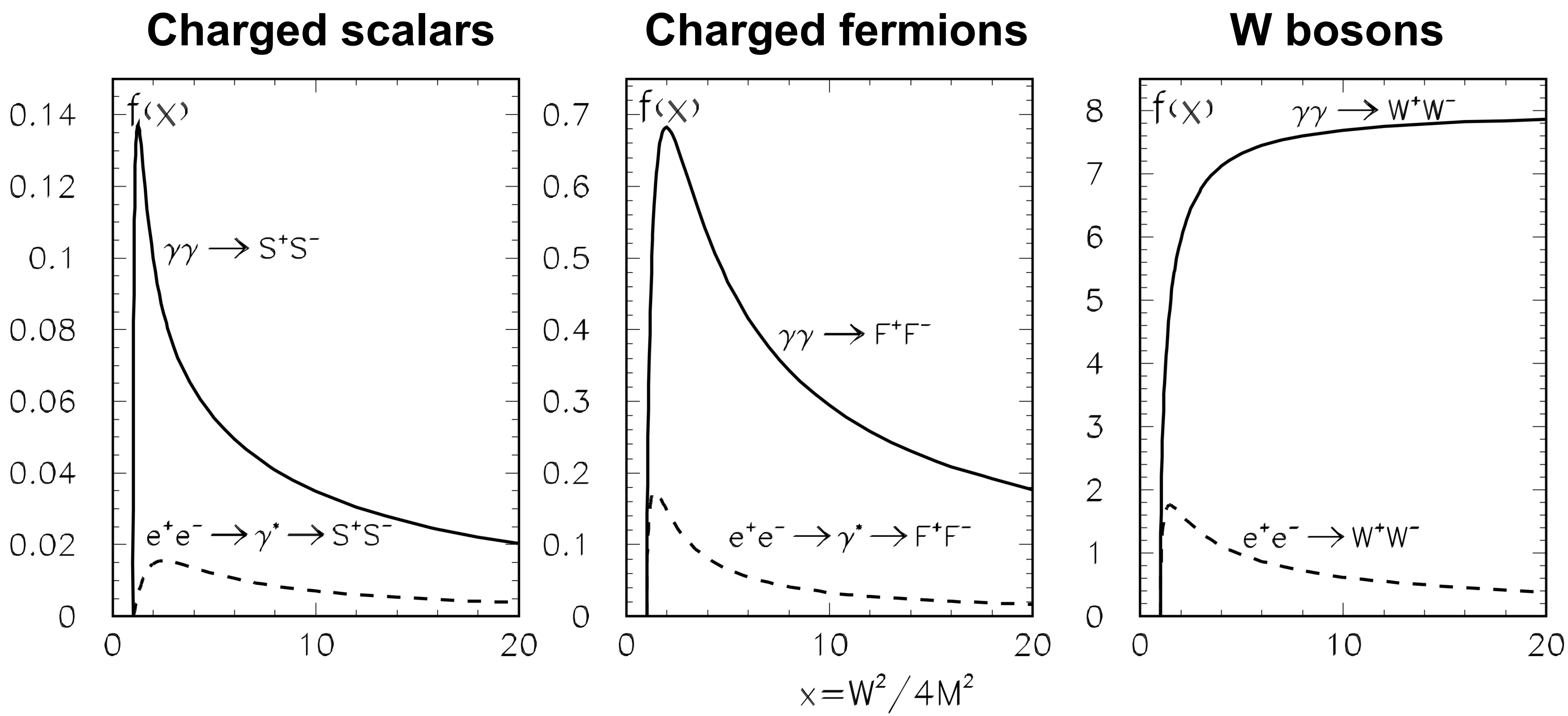
Helicity dependence



For discussion:
we also need these distributions for 10 TeV

arXiv:0111056

Comparison to e^+e^- collisions



$\sigma = (\pi\alpha^2/M^2)f(x)$

no beam polarisation

γγ at 10 TeV

Particle pair	Mass [GeV]	$\sigma(e^+e^- \to XX)$ [fb] unpol.	$\sigma(\gamma\gamma \to XX)$ [fb] unpol.	$\sigma(\gamma\gamma \to XX)$ [fb] $J_Z = 0$	$\sigma(\gamma\gamma \to XX)$ [fb] $J_Z = 2$
$\tilde{d}_L\tilde{d}_L$	1009	0.35	0.04	0.002	0.08
$\tilde{u}_L\tilde{u}_L$	1006	0.51	0.70	0.04	1.4
$\tilde{s}_L\tilde{s}_L$	1009	0.35	0.04	0.002	0.08
$\tilde{c}_L\tilde{c}_L$	1006	0.51	0.70	0.04	1.4
$\tilde{b}_1\tilde{b}_1$	1997	0.18	0.03	0.001	0.05
$\tilde{t}_1\tilde{t}_1$	1866	0.26	0.52	0.14	0.91
$\tilde{e}_L\tilde{e}_L$	1869	1.2	0.88	0.23	1.5
$\tilde{\nu}_{eL}\tilde{\nu}_{eL}$	1867	5.0	-	-	-
$\tilde{\mu}_L\tilde{\mu}_L$	1869	0.23	0.88	0.23	1.5
$\tilde{\nu}_{\mu L}\tilde{\nu}_{\mu L}$	1867	0.10	-	-	-
$\tilde{\tau}_1\tilde{\tau}_1$	1328	0.21	1.06	0.11	2.0
$\tilde{\nu}_\tau\tilde{\nu}_\tau$	1364	0.11	-	-	-
$\tilde{d}_R\tilde{d}_R$	988	0.08	0.04	0.002	0.09
$\tilde{u}_R\tilde{u}_R$	989	0.30	0.70	0.03	1.4
$\tilde{s}_R\tilde{s}_R$	988	0.08	0.04	0.002	0.09
$\tilde{c}_R\tilde{c}_R$	989	0.30	0.70	0.03	1.4
$\tilde{b}_2\tilde{b}_2$	2032	0.06	0.03	0.01	0.05
$\tilde{t}_2\tilde{t}_2$	2108	0.27	0.48	0.17	0.80
$\tilde{e}_R\tilde{e}_R$	1856	1.6	0.89	0.22	1.6
$\tilde{\nu}_{\mu R}\tilde{\nu}_{\mu R}$	1856	1.9	0.89	0.22	1.6
$\tilde{\tau}_2\tilde{\tau}_2$	1365	2.2	1.05	0.12	2.0
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	954	≈ 0	-	-	-
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	954	≈ 0	-	-	-
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	955	1.26	11	5.9	15
$\tilde{\chi}_3^0\tilde{\chi}_3^0$	1294	0.91	-	-	-
$\tilde{\chi}_4^0\tilde{\chi}_4^0$	2262	0.58	-	-	-
$\tilde{\chi}_2^+\tilde{\chi}_2^-$	2262	1.4	6.5	5.9	7.0
H^0A^0	3046	0.06	-	-	-
H^+H^-	3046	0.15	0.61	0.62	0.60

- Pair production using the best fit values for the masses
- Neutral particles not accessible at (tree level) in γγ collisions
- No ISR or beam spectra included
- J_Z = 2 preferred for sfermions (J_Z = 0 would be preferred at 5 TeV for the same model)

Reminder: Light-by-light scattering (γγ→γγ)

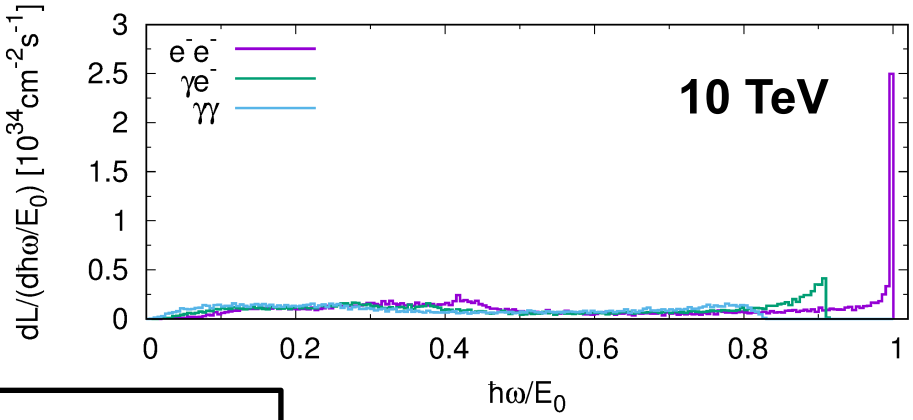
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

ATLAS Collaboration†

Light-by-light scattering ($\gamma\gamma \to \gamma\gamma$) is a quantum-mechanical process that is forbidden in the classical theory of electrodynamics. This reaction is accessible at the Large Hadron Collider thanks to the large electromagnetic field strengths generated by ultra-relativistic colliding lead ions. Using 480 μb^{-1} of lead–lead collision data recorded at a centre-of-mass energy per nucleon pair of 5.02 TeV by the ATLAS detector, here we report evidence for light-by-light scattering. A total of 13 candidate events were observed with an expected background of 2.6 ± 0.7 events. After background subtraction and analysis corrections, the fiducial cross-section of the process $Pb + Pb\,(\gamma\gamma) \to Pb^{(*)} + Pb^{(*)}\gamma\gamma$, for photon transverse energy $E_T > 3$ GeV, photon absolute pseudorapidity $|\eta| < 2.4$, diphoton invariant mass greater than 6 GeV, diphoton transverse momentum lower than 2 GeV and diphoton acoplanarity below 0.01, is measured to be 70 ± 24 (stat.) ±17 (syst.) nb, which is in agreement with the standard model predictions.

γγ → γγ at a 10 TeV photon collider

- A high energy photon collider would be ideal to study light-by-light scattering



$$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2 \hat{s}} \left(\hat{s}^2 + \hat{t}^2 + \hat{s}\hat{t}\right)^2 \left(48c_1^2 + 11c_2^2 + 40c_1c_2\right)$$

- **Example:** Born-Infeld theory (nonlinear extension of QED) $c_1 = -1/(32M^4)$, $c_2 = 1/(8M^4)$

95% CL limit: M > 12.2 / 13.6 / 15.1 TeV for 150 / 750 / 4000 fb^{-1}
→ only small dependence on integrated luminosity

Ellis, Mavromatos, Ph.R., You

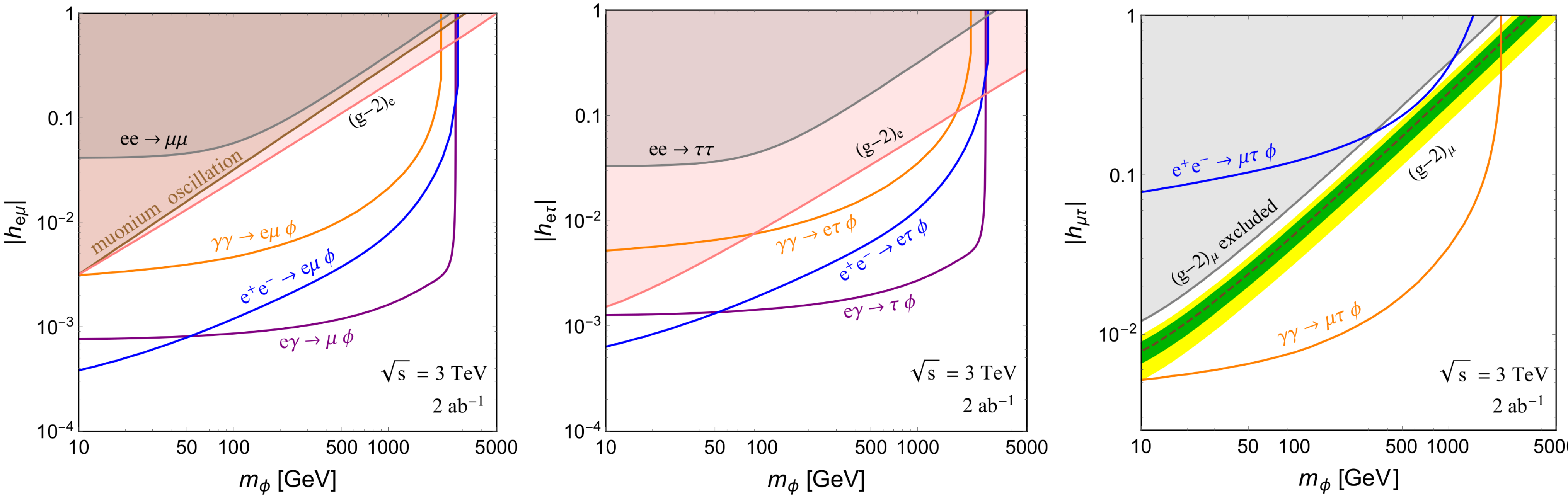
For comparison: M > 100 GeV at ATLAS

arXiv:1703.08450

- Other models under study

One more example: LFV couplings

Scenarios with Lepton Flavour Violation (LFV) and a heavy scalar ϕ
(connection to neutrino mass generation)



m_ϕ : mass of heavy scalar
$h_{\alpha\beta}$: LFV couplings

→ Complementarity of eγ- and γγ-collisions in this scenario

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