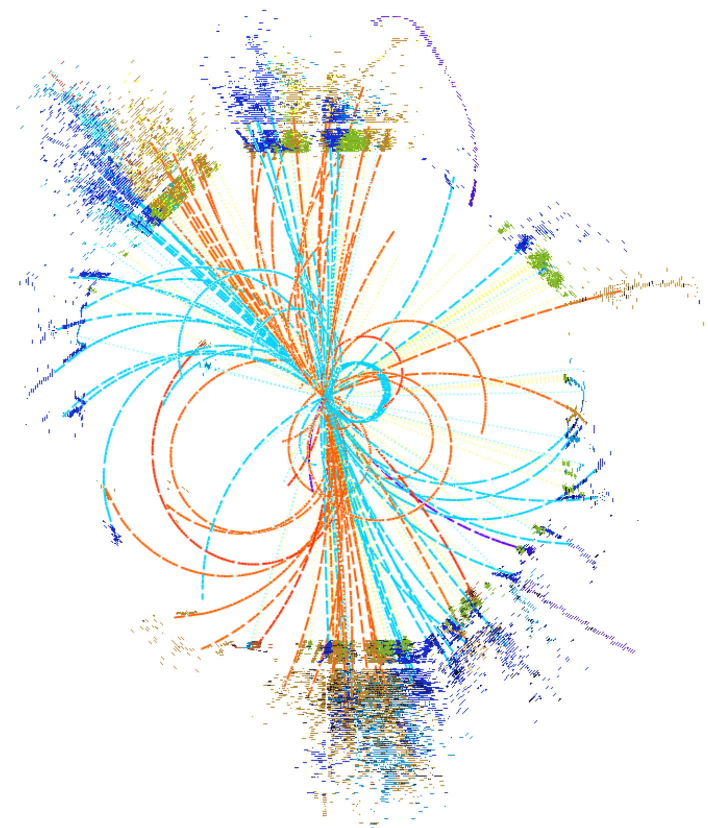
Multi-TeV γγ colliders

Philipp Roloff (CERN)

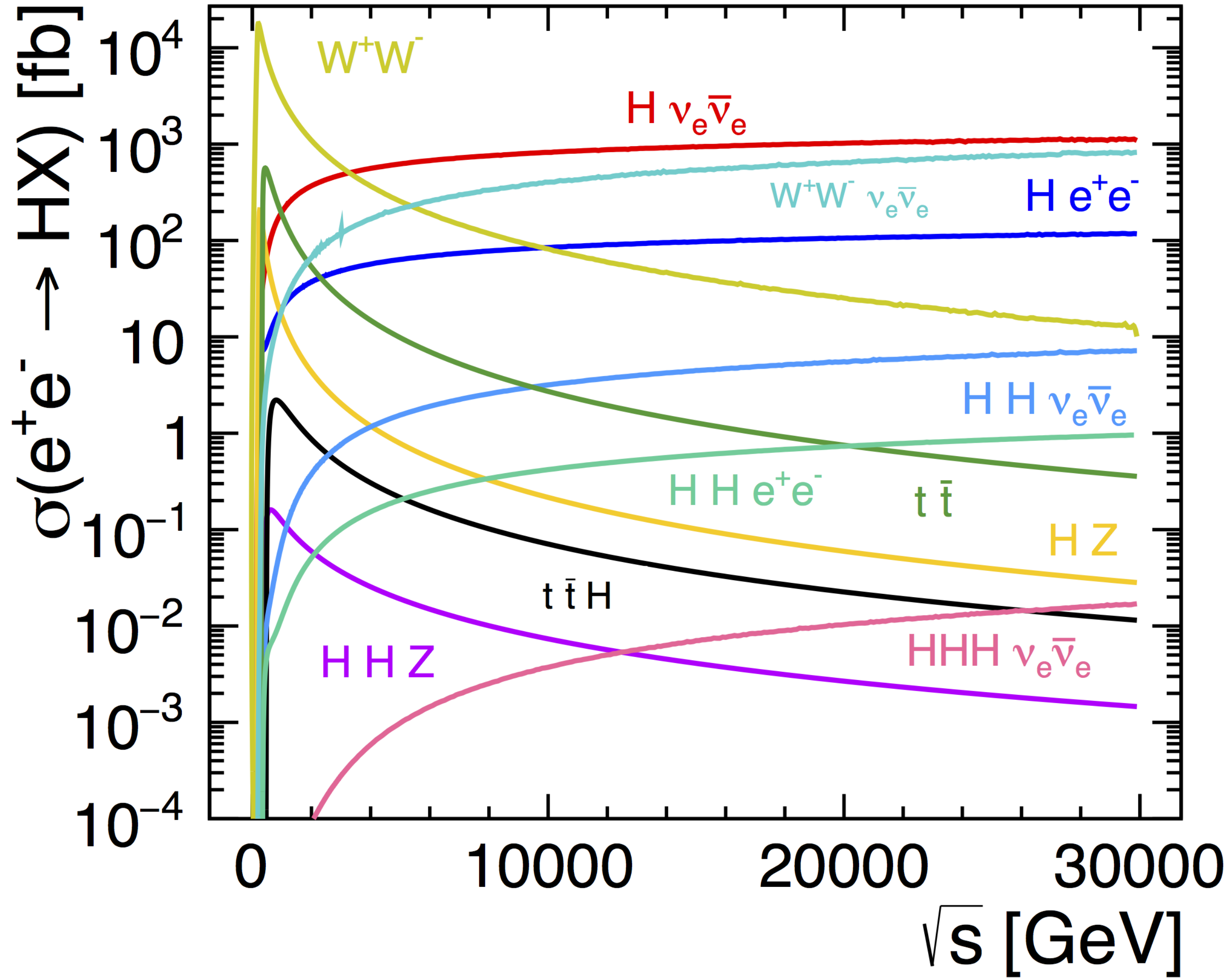
CLIC workshop 2019
Accelerator session



23/01/2019
CERN, Geneva

First, a few words on an e^+e^- collider at 10 TeV...

Standard model processes



- Two-fermion production (e.g. $t\bar{t}$) scales as 1/s, similar for WW production → desired integrated luminosities exceed baseline CLIC stages

- A few ab^{-1} at 10 TeV would improve the knowledge the Higgs self-coupling compared to 3 TeV → see talk by Ulrike Schnoor in the afternoon

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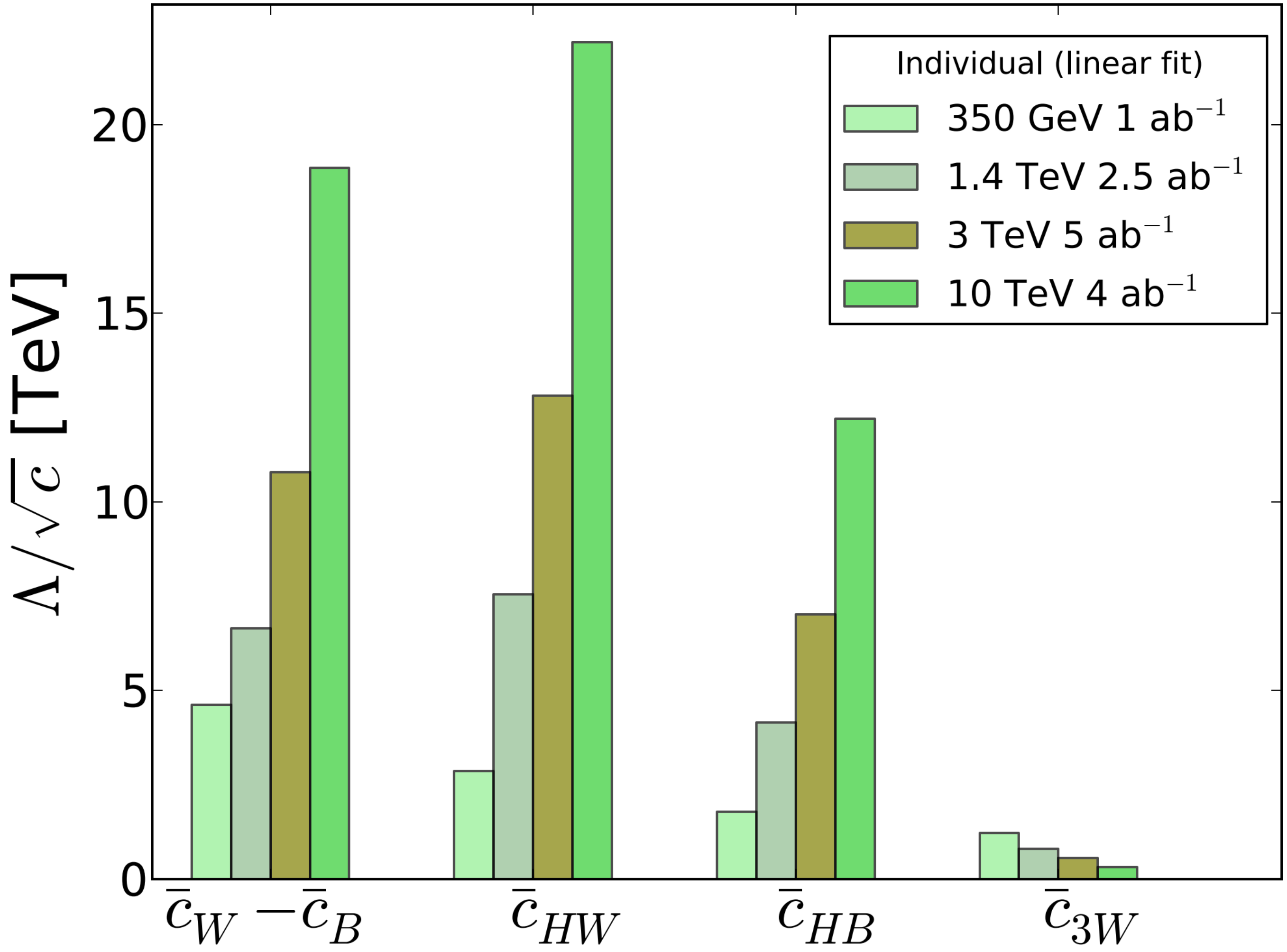
Update: Higgs and WW production in 10 TeV e^+e^- collisions

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



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

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

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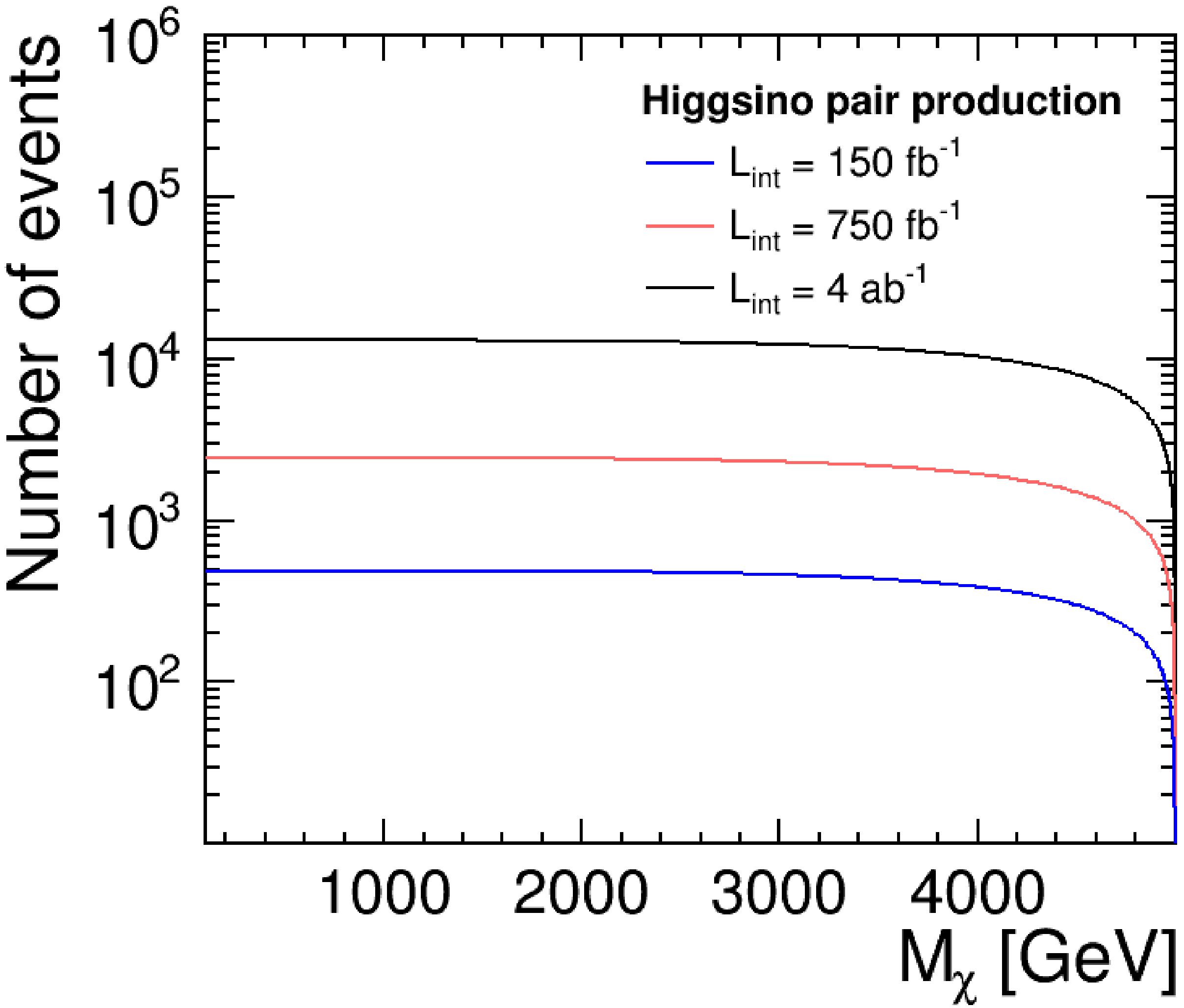
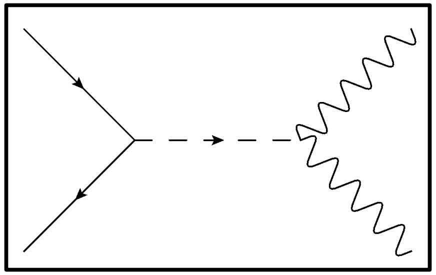
Heavy states





- Number of events almost independent of mass
- A few ab^{-1} needed for precision measurements

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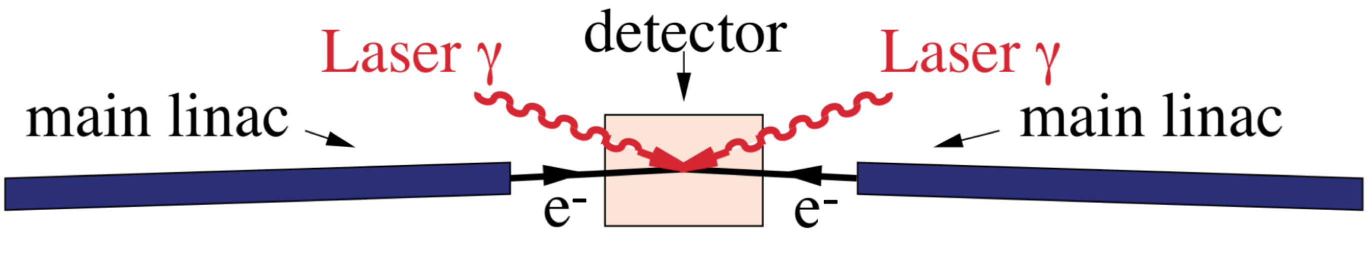
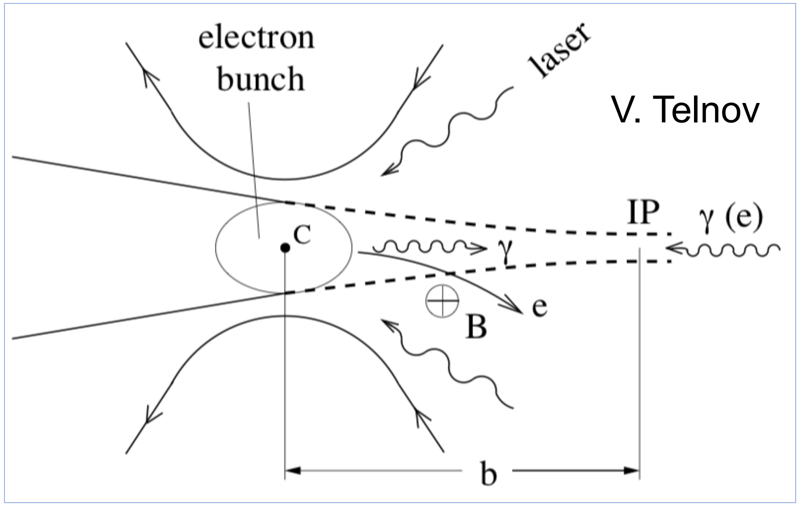
γγ colliders

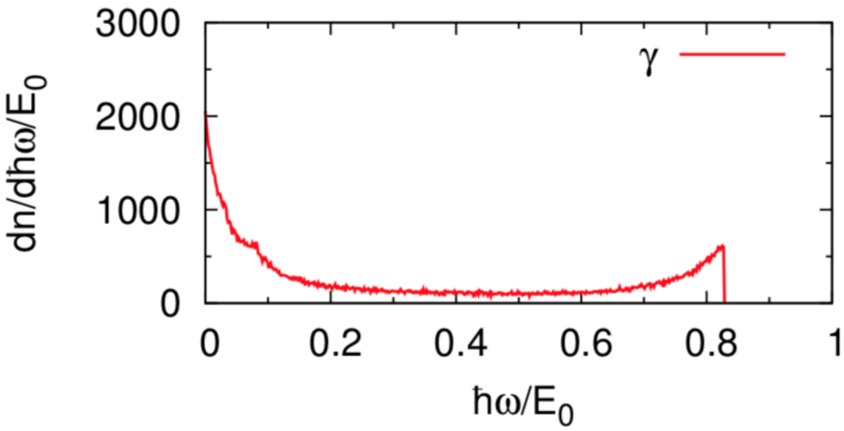
- An e^+e^- collider requires high-gradient, high-efficient positron acceleration
- **Possible alternative:** γγ collider
- Discussed in the past as possible upgrade to a linear collider



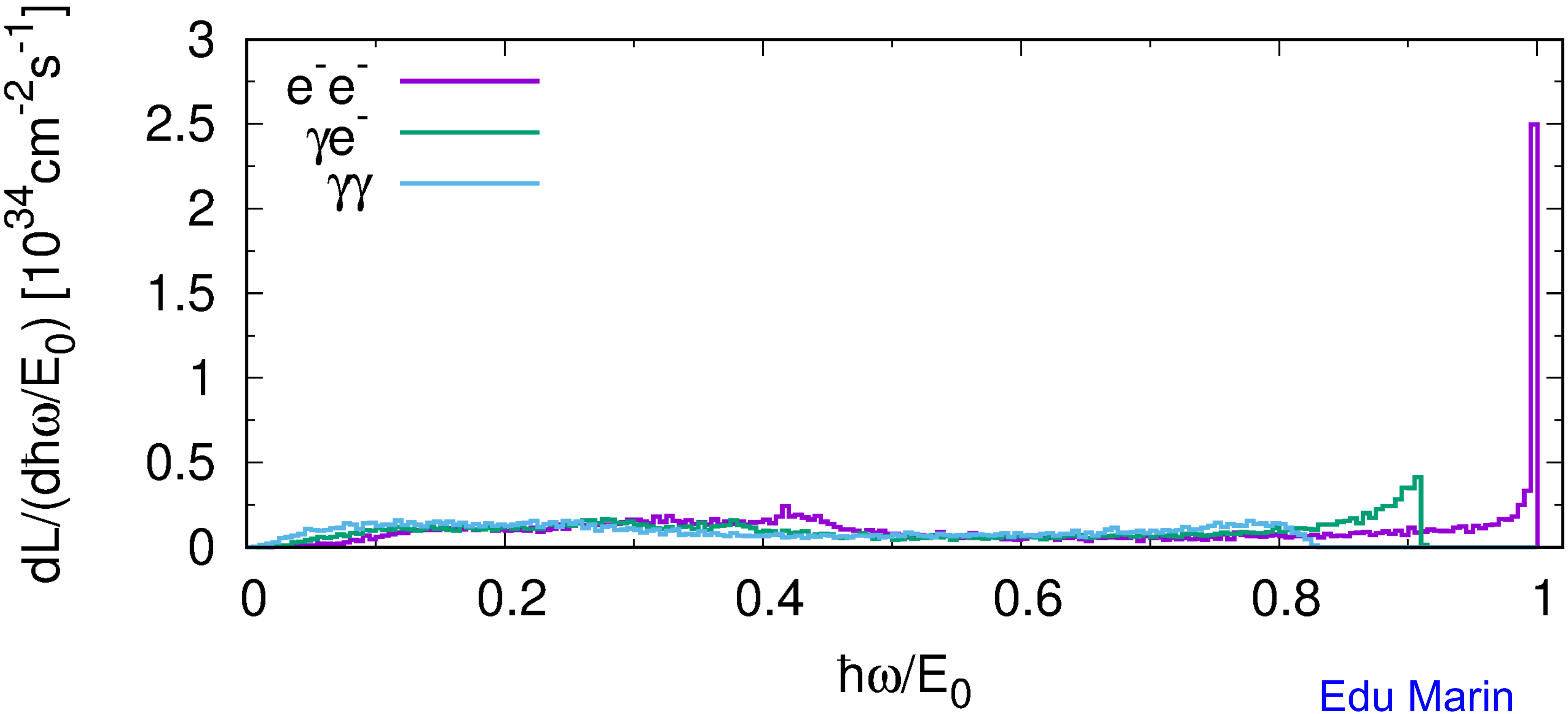
High-energy photons are produced by Compton back-scattering off TeV e^- beams



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

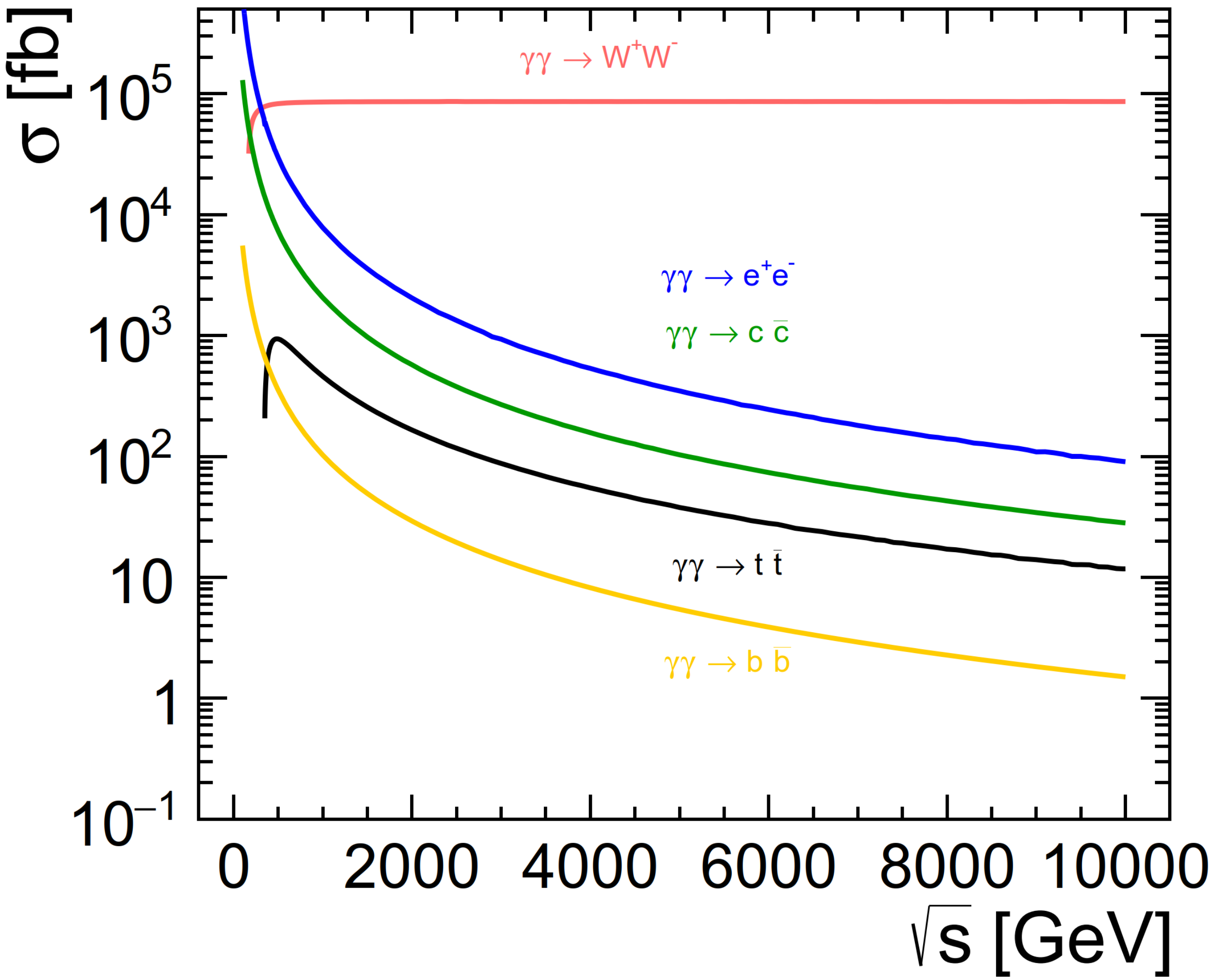


Luminosity spectra at 10 TeV



Edu Marin

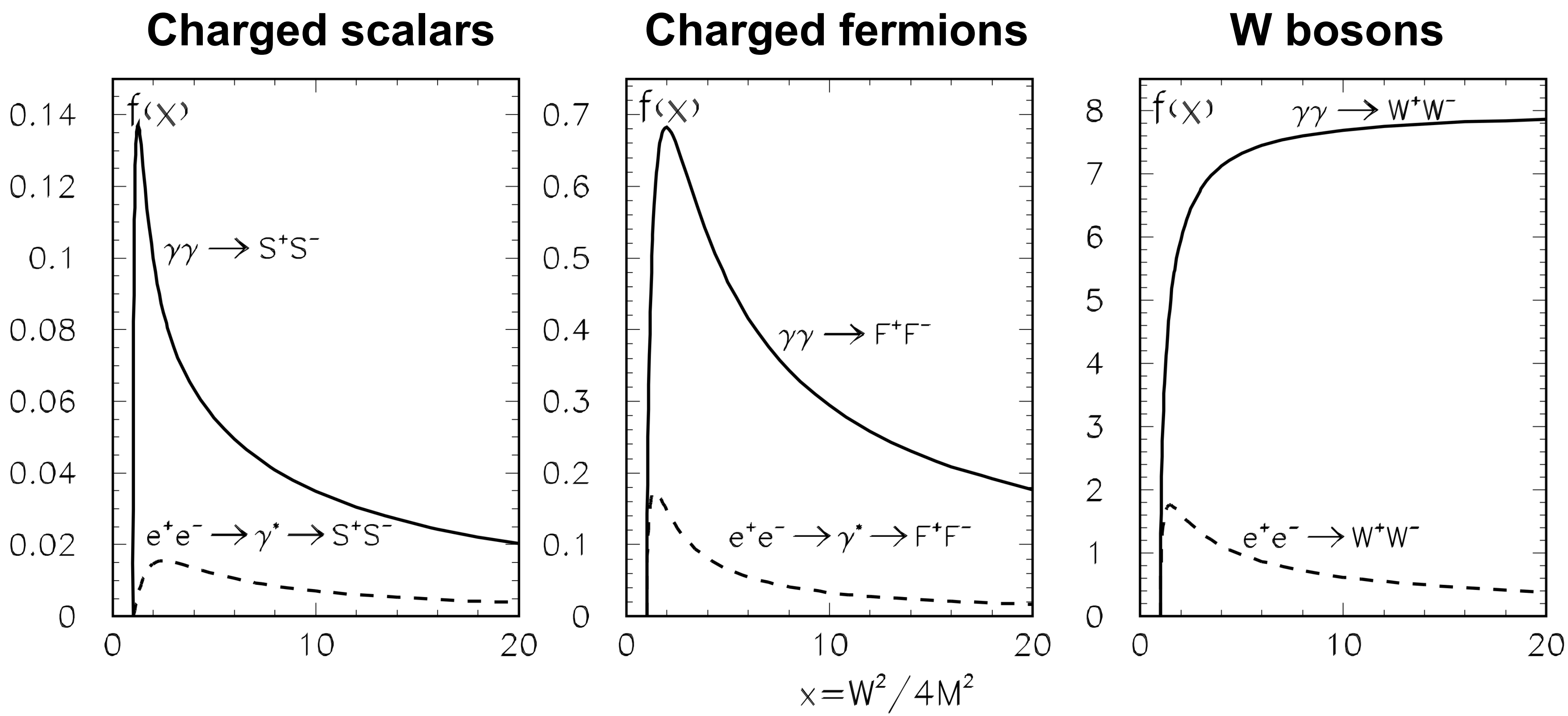
2-particle production in γγ collisions



no beam polarisation

- A photon collider is ideal to study electrically charged particles
- Large cross section W pair events

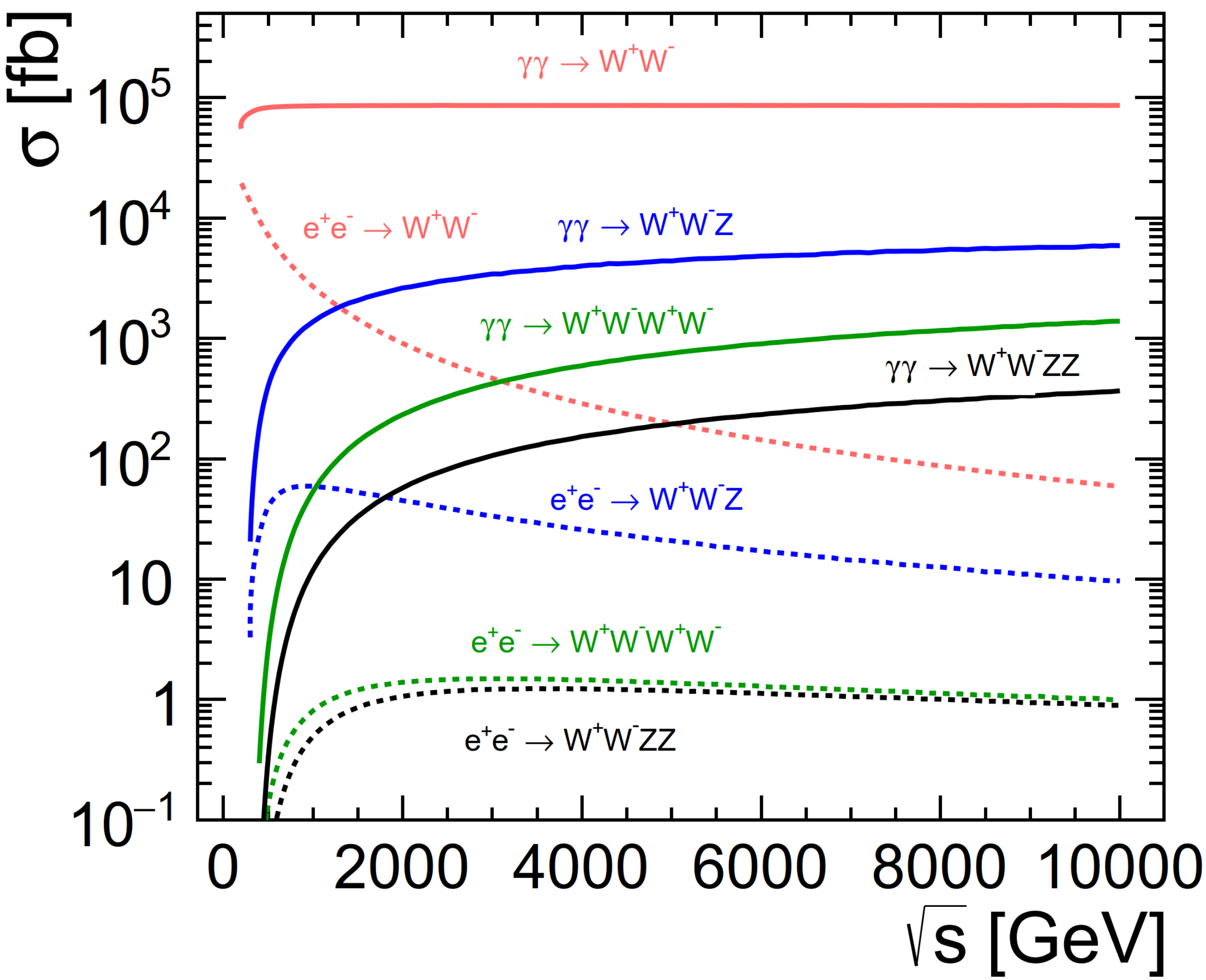
Comparison to e^+e^- collisions



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

no beam polarisation

Multi-boson production in γγ collisions



no beam polarisation

- **$\gamma\gamma \rightarrow W^+W^-$:** anomalous photon couplings to W boson λ_γ and $\Delta\kappa_\gamma$ (probably better than e^+e^-, under study)

- **$\gamma\gamma \rightarrow W^+W^-ZZ/W^+W^-W^+W^-$:** WW → WW and ZZ→ZZ scattering (strong benefit from high energy, 3 TeV CLIC similar to HL-LHC, need to be studied)

“Higgs physics” at high energy

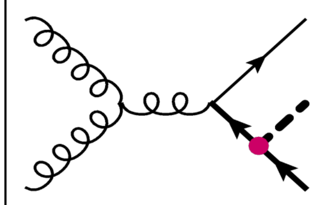
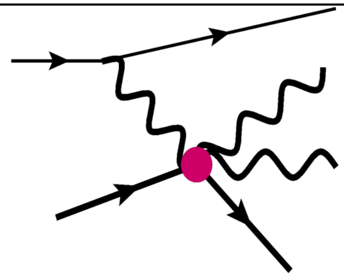
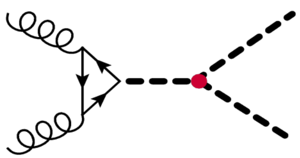
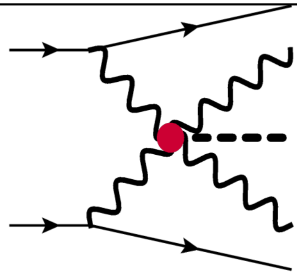
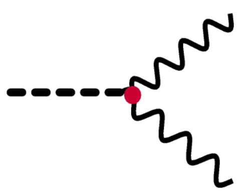
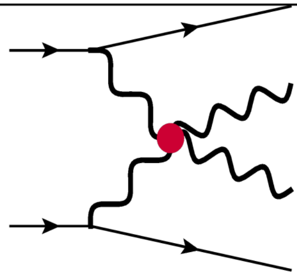
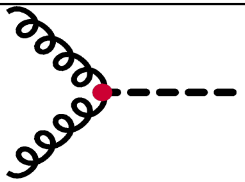
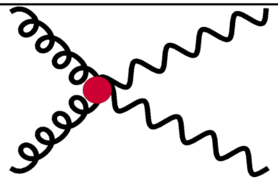
HC: Higgs coupling
HwH: High-energy process

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

• Sensitivity of high-energy Probes rises with energy

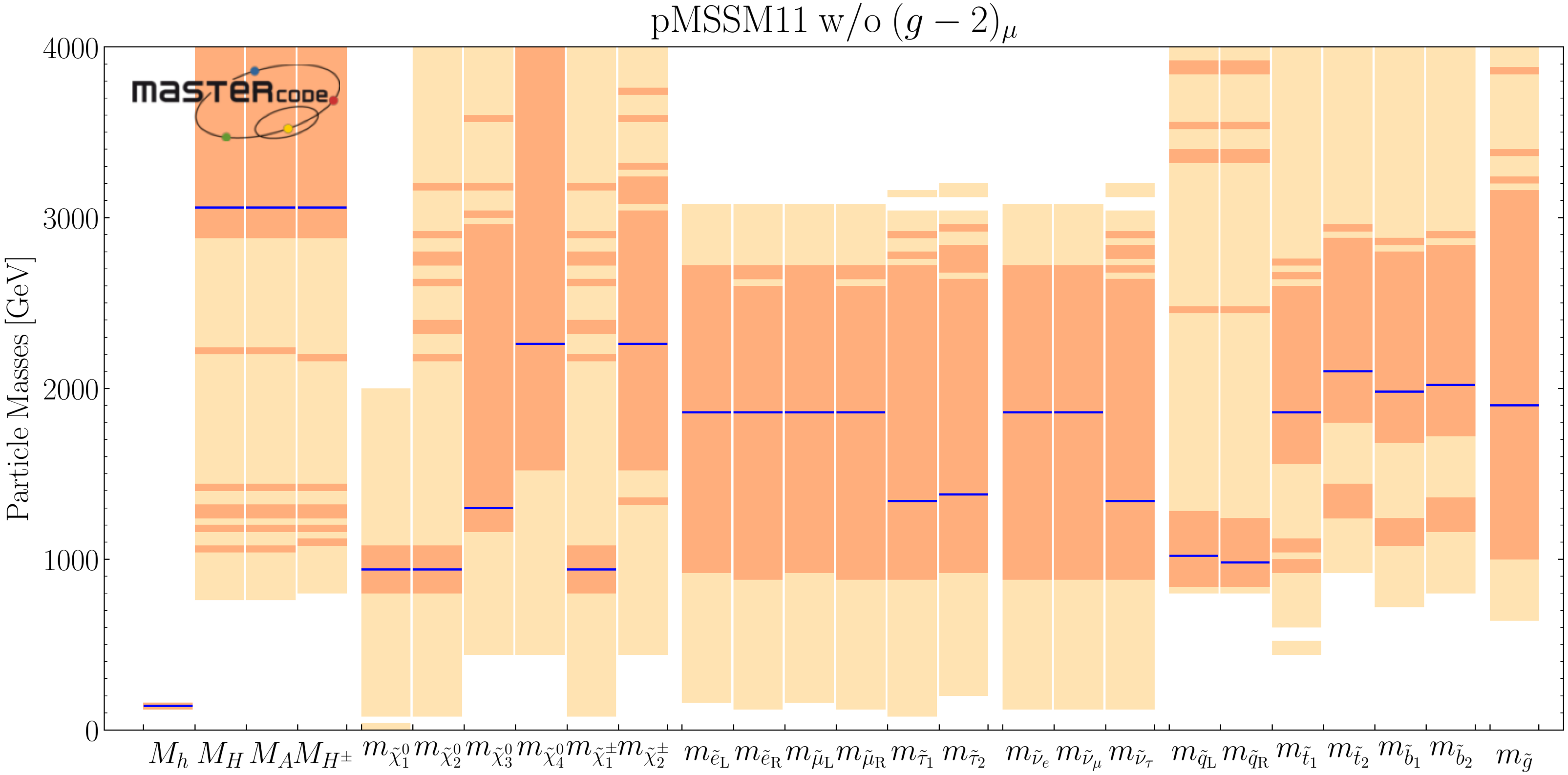
Very interesting!
To be studied...

arXiv:1812.09299

		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	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

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)

arXiv:1710.11091

e^+e^- vs γγ at 10 TeV (1)

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)

e^+e^- vs γγ at 10 TeV (2)

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

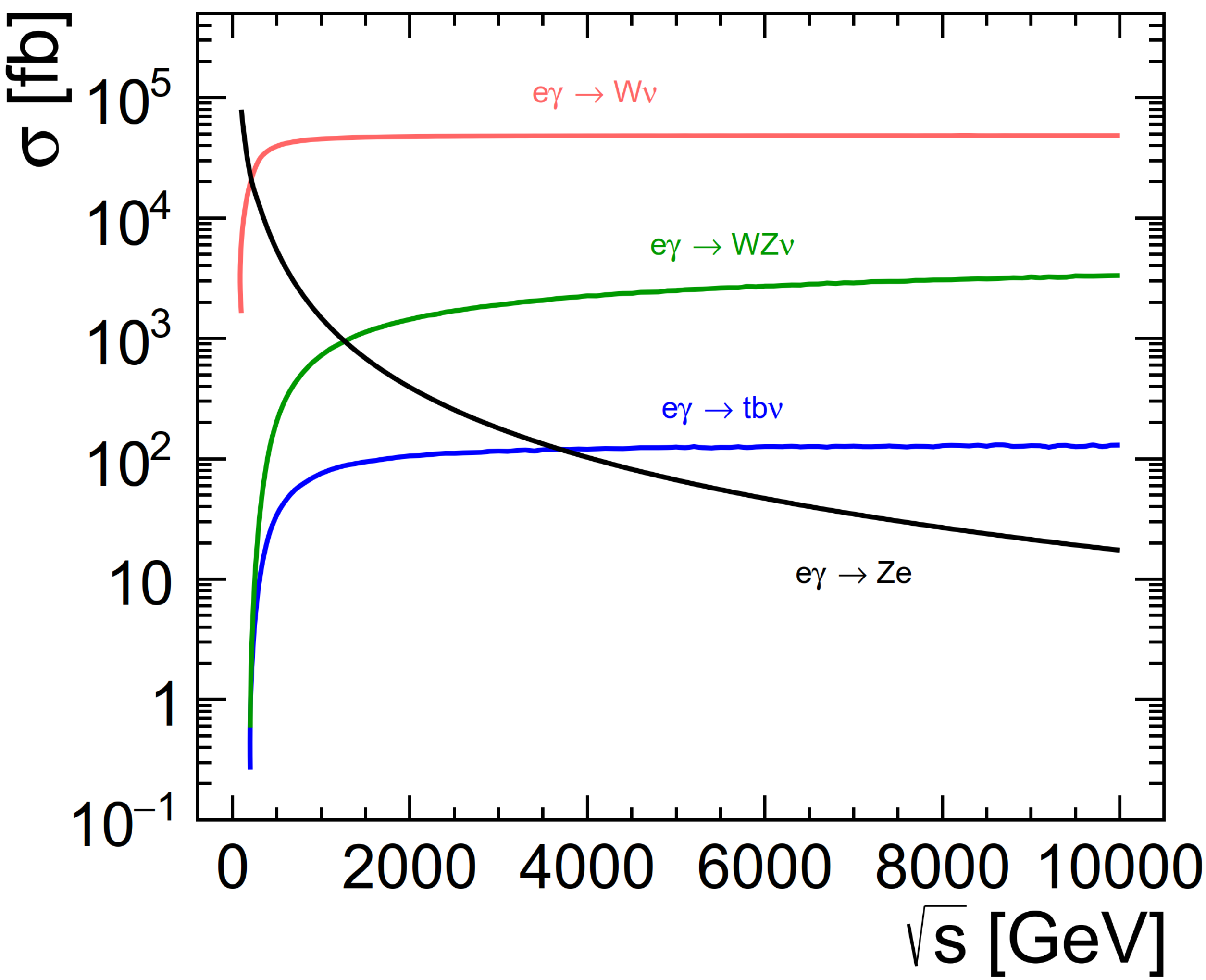
- Work in progress, need to include luminosity spectra for different photon helicity configurations

- Using 3 TeV luminosity spectrum scaled to 10 TeV for e^+e^-

→ A multi-TeV photon collider has discovery potential for squarks, sleptons and chargions with a few ab^{-1}

- A 10 TeV e^+e^- collider would cover the entire SUSY particle spectrum in this scenario

What about 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.:

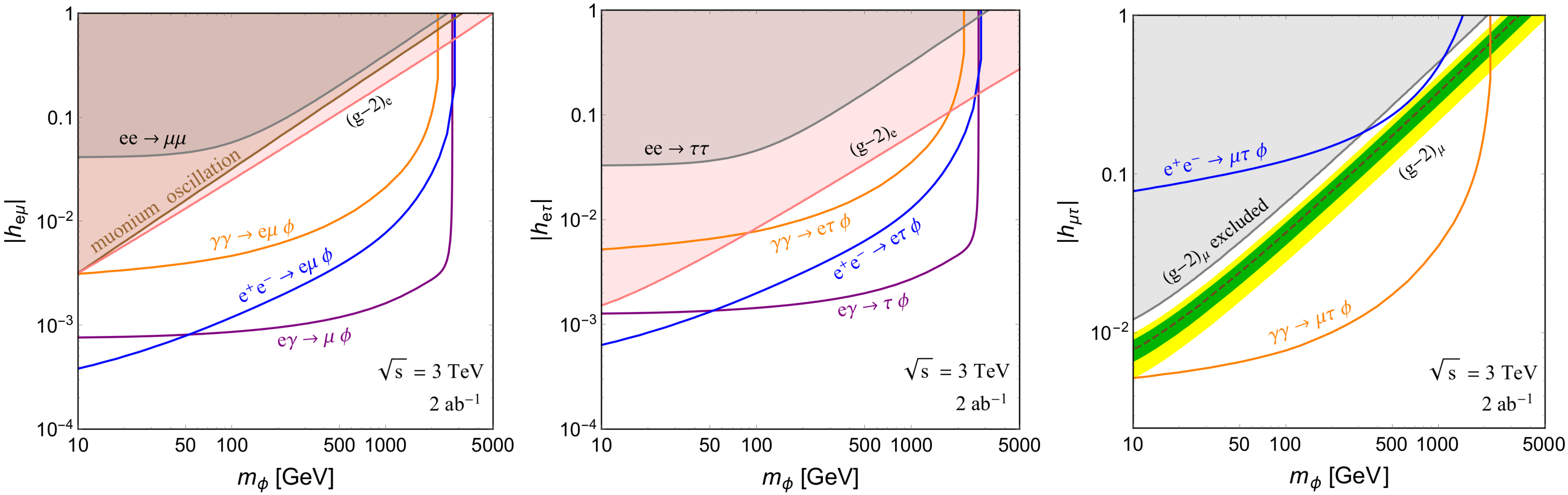
$$e\gamma \rightarrow \tilde{e}\,\tilde{\chi}^0_1$$

- eγ interactions would cause very difficult backgrounds for SUSY searches in γγ

- Ideally, operation with and without the electron beams at the IP?

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

CERN-2018-009-M

Summary and outlook

• Very first look at photon-photon collisions in the multi-TeV region

• Promising opportunities for precision measurements in multi-boson production (will be explored further)

• Direct discovery in pair production of charged particles, requirements on integrated luminosity same order of magnitude as for electron-positron collisions

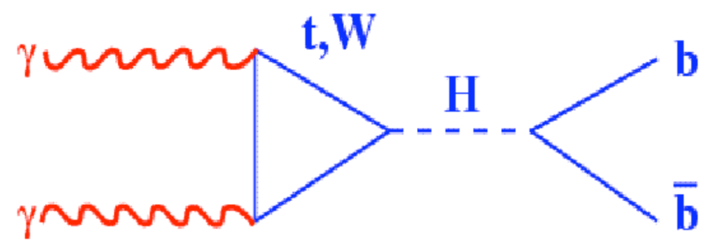
• Some unique opportunities in electron-photon interactions

• Interesting possibility: 380 GeV CLIC collider for Higgs & top, then multi-TeV γγ collider

Thanks a lot for help and / or discussions:
Jean-Jacques Blaising, Wolfgang Kilian, Francesco Riva, Ulrike Schnoor, Daniel Schulte

Backup slides

γγ collider as Higgs factory



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

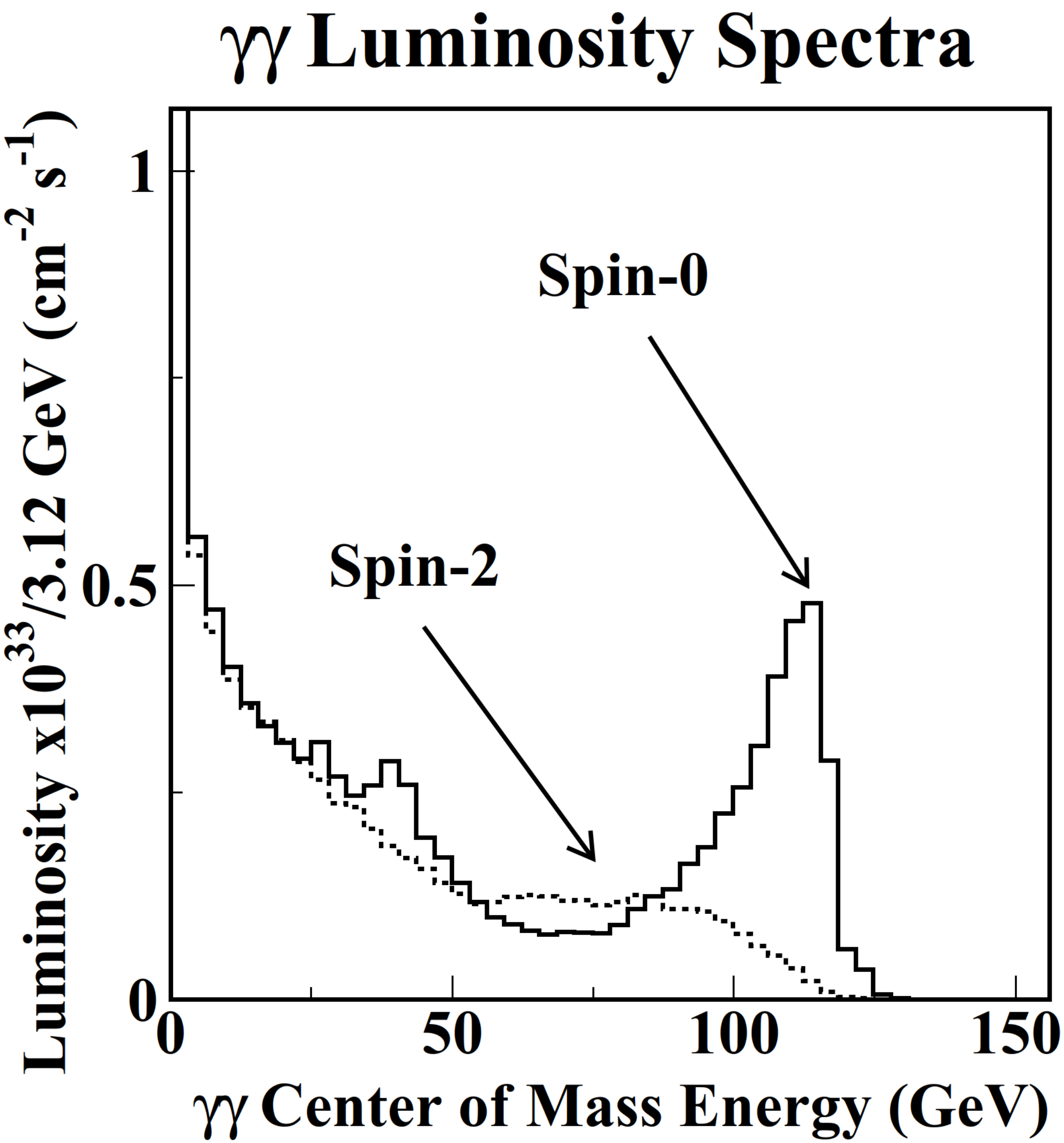
• However, some decays seem difficult in photon collisions: $H \to c\bar{c}$, $\tau^+\tau^-$, gg

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

• The optimal γγ collision energy for γγ → H* → 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

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

ARTICLES
PUBLISHED ONLINE: 14 AUGUST 2017 | DOI: 10.1038/NPHYS4208

nature physics

OPEN

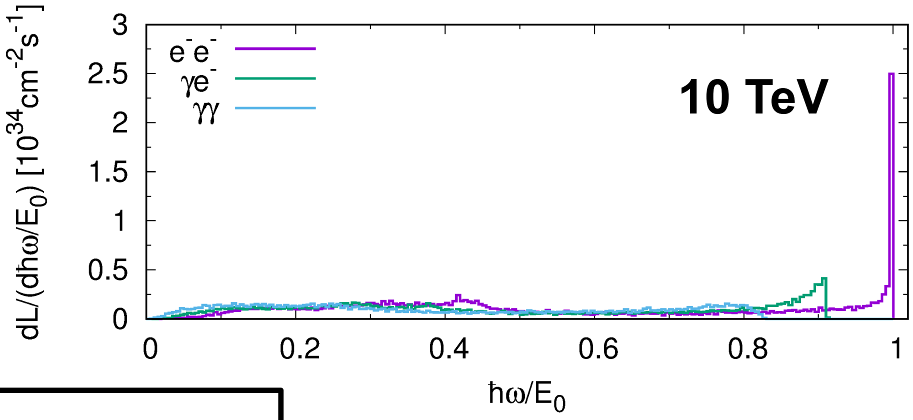
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

ATLAS Collaboration†

Light-by-light scattering ($\gamma\gamma \rightarrow \gamma\gamma$) 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 $Pb + Pb\,(\gamma\gamma) \rightarrow Pb^{(*)} + Pb^{(*)}\gamma\gamma$, 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