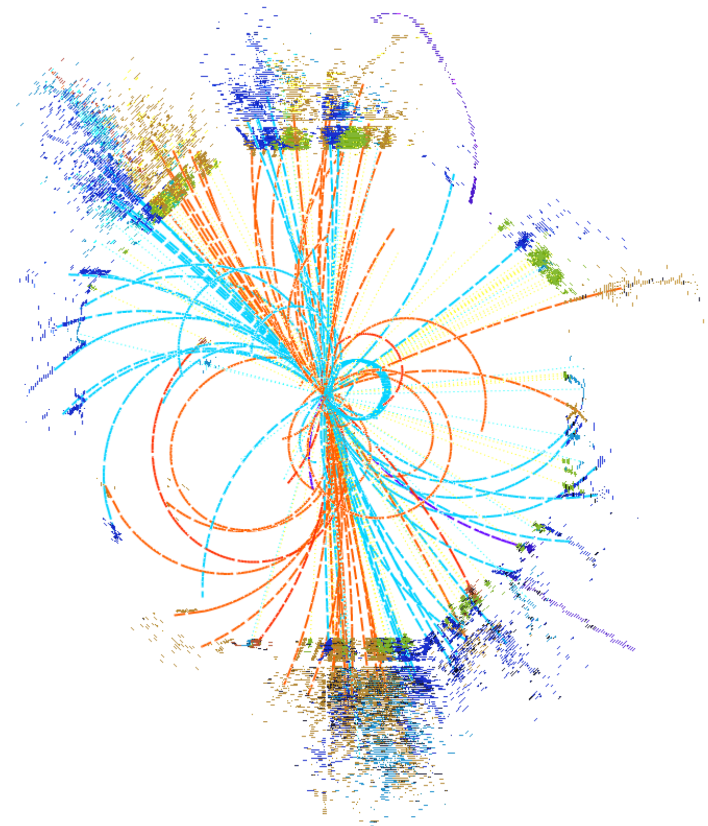
Update on physics considerations in view of novel accelerator techniques



Philipp Roloff (CERN)

CLICdp general meeting

14/05/2018
CERN, Geneva

Reminder: CLIC working group on novel accelerator techniques

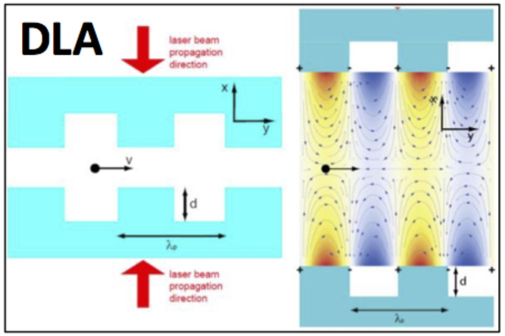
• The working group is mandated to consider how an initial CLIC machine can be extended in energy using novel accelerating schemes

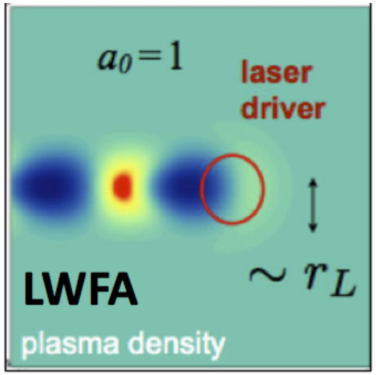
• Provide a report well in time for the CLIC implementation plan to be submitted to the next European Strategy process

• Current members: Erik Adli (chair), Daniel Schulte, Patric Muggli, Steinar Stapnes, Walter Wünsch, Alexej Grudiev, Igor Syratchev, Roberto Corsini, Steffen Doebert, Andrea Latina, Jürgen Pfingstner, Rogelio Tomas, Philipp Roloff, Edda Gschwendtner, Massimo Ferrari, Jens Osterhoff

• Open meetings (every 3-7 weeks) on Fridays at 9:00: http://indico.cern.ch/category/8905/

Novel accelerator techniques (1)





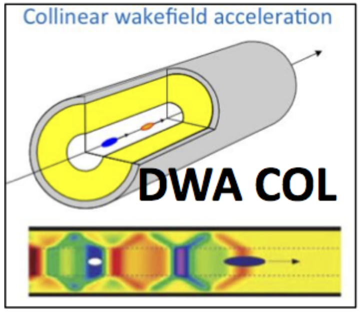
<u>Materials with higher damage threshold</u>:
- ✧Dielectrics (~GV/m)
- ✧Plasmas (10-1000GV/m)

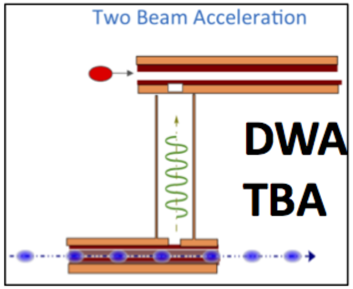
<u>Systems powered/driven by:</u>
- ✧Laser pulse(s)*
- ✧Relativistic, charged particle bunch(es)

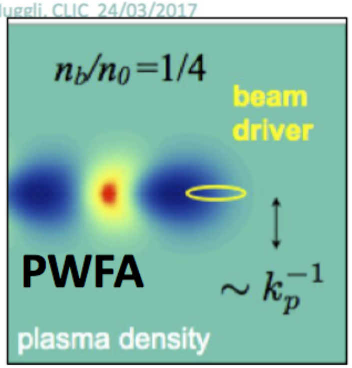
Driver \ Medium	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Dielectric Wakefield Accelerator DWA	Plasma Wakefield Accelerator PWFA

© P. Muggli *do not include laser vacuum/direct acceleration

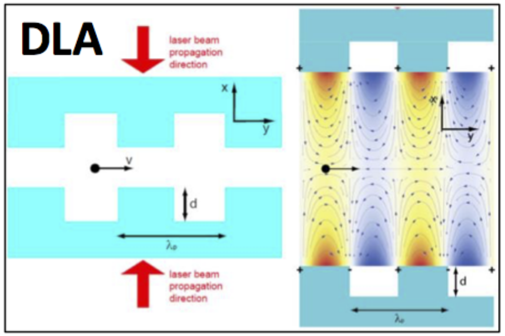
P. Muggli, CLIC 24/03/2017

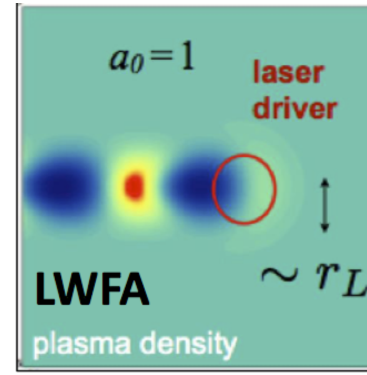






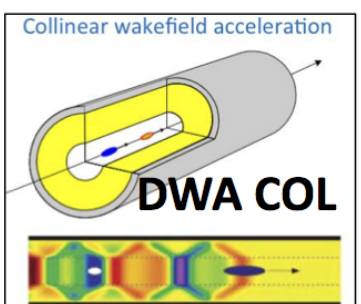
Novel accelerator techniques (2)

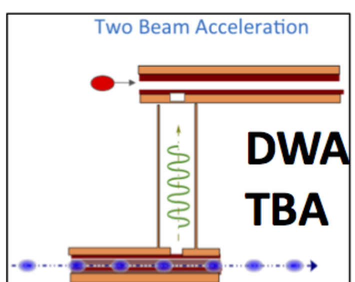




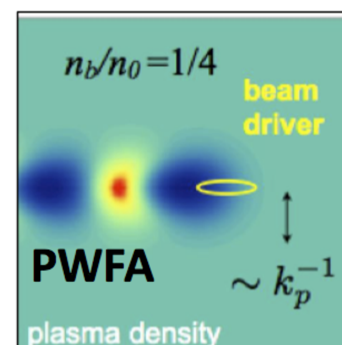
Charge symmetric
- same acceleration mechanism for e- and e+

Charge asymmetric in the non-linear regime (blow-out)
- e-: promise of good emittance preservation during acceleration
- e+: less clear





Patric Muggli, 23/03/2017
Erik Adli, 21/04/2017



Overview: physics considerations

Previous talk during the CLICdp general meeting on 15/05/2017 (http://indico.cern.ch/event/591066/):

- Physics at an e^+e^- collider above 3 TeV
- Comparison to e^-e^- and γγ collisions (mainly for a Higgs factory)
- Impact of asymmetric collisions

Main topics of this presentation (in response to questions by the accelerator experts):

- How much luminosity is needed at 10 (and 30) TeV?
(Direct searches, double/triple Higgs, precision measurements)
- Is there a physics case for a very high-energy photon colldier?

Current benchmark parameters

First iteration of benchmark parameters:

1.) e^+e^- collider at 10 TeV with options:

- $L = 2 \cdot 10^{33}$ cm^{-2}s^{-1}
- $L = 10^{34}$ cm^{-2}s^{-1} (default)
- $L = 5 \cdot 10^{34}$ cm^{-2}s^{-1}
- $L = 10^{34}$ cm^{-2}s^{-1}, 80% electron beam polarisation

Assuming 10 years of running including ramp-up in the first years:

→ L_{int} = 150 fb^{-1}, 750 fb^{-1} (default) and 4 ab^{-1}

NB: 1 year = 10^7 seconds

2.) γγ collider at 10 TeV:

photon energy spectra provided by Edu Marin Lacoma

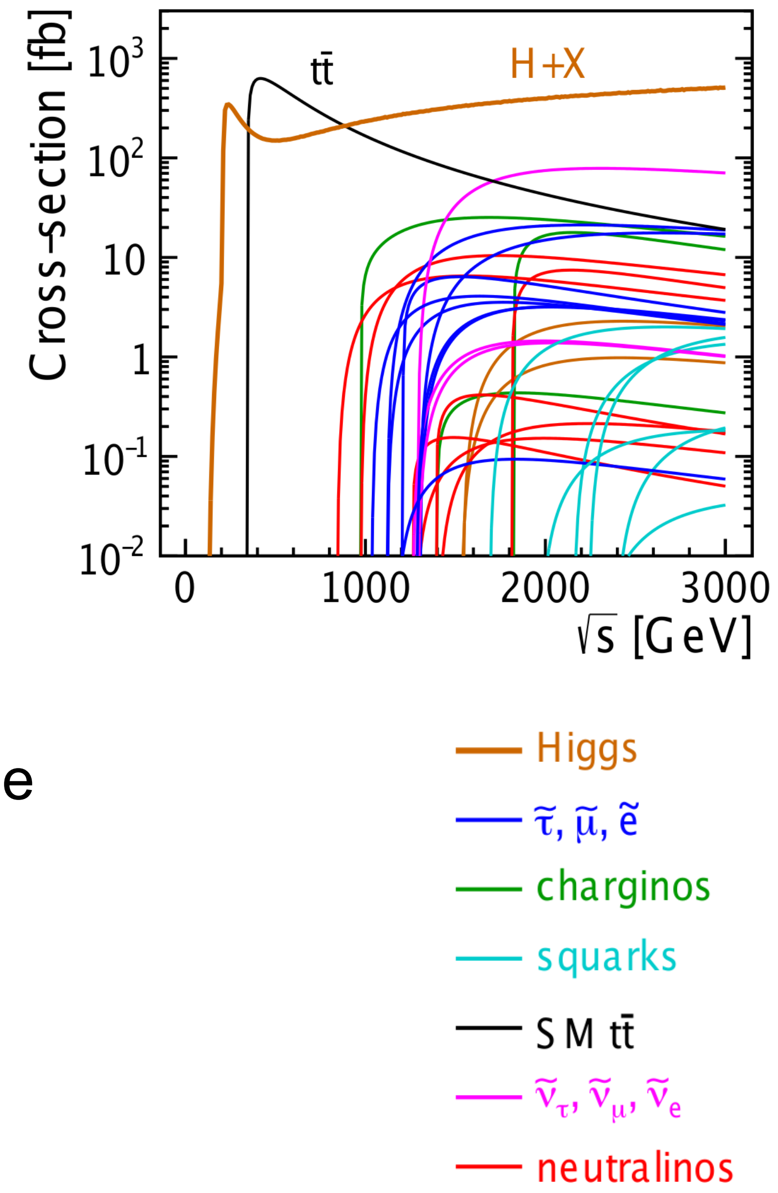
Direct searches for new physics in e^+e^- collisions

- Direct observation of new particles coupling to $\gamma^*/Z/W$
→ precision measurement of new particle masses and couplings

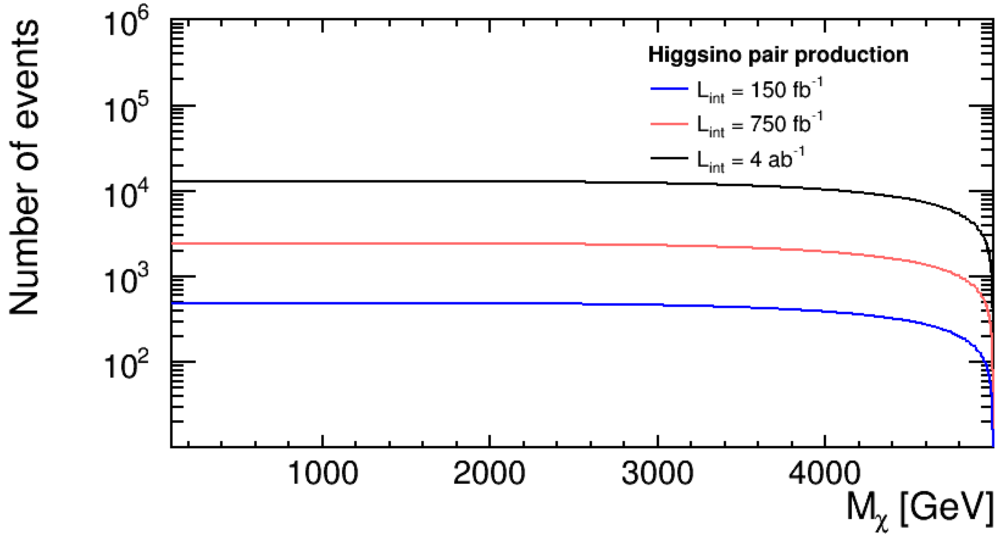
- The sensitivity often extends up to the kinematic limit
(e.g. $M \leq \sqrt{s}$ / 2 for pair production)

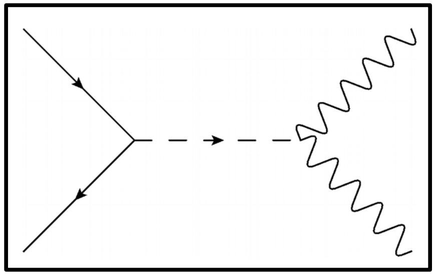
- Very rare processes accessible due to low backgrounds (no QCD)
→ Electron-positron colliders especially suitable for electroweak states

- Polarised electron beam and threshold scans might be useful to constrain the underlying theory



Electroweak states at 10 TeV

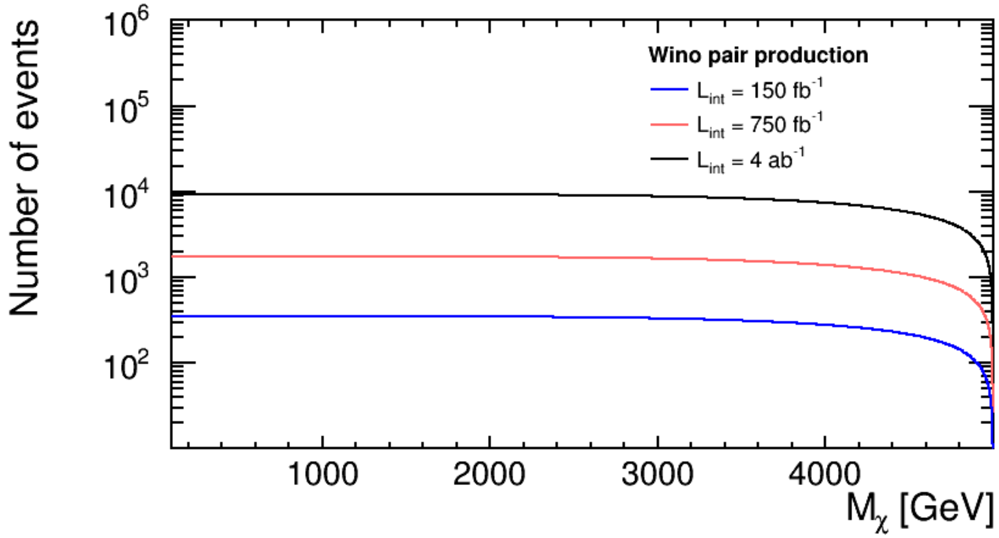




- Examples for electroweak pair production

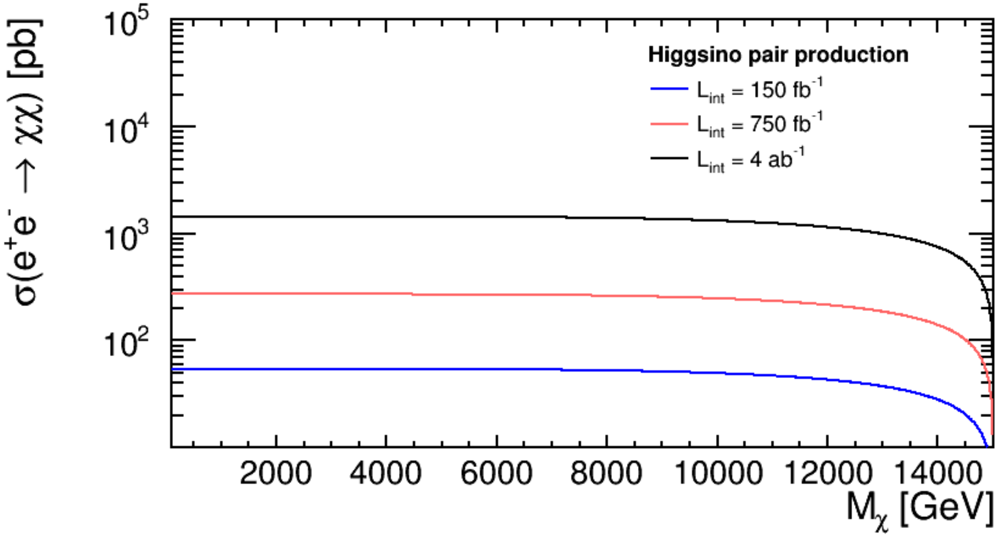
- **L = 4 ab^{-1}:** O(10’000) events → precision measurements of the new particle properties

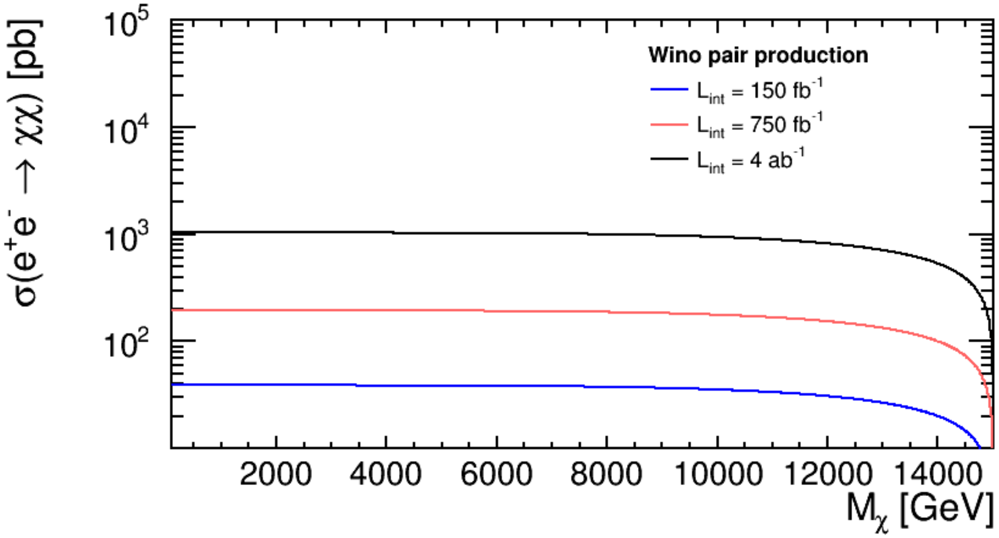
(NB: this corresponds to 4.5 less events than the 3 TeV SUSY studies in the CDR)

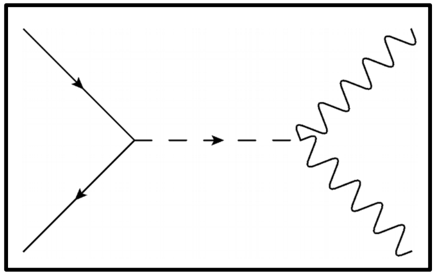


- **L = 150 fb^{-1}:** few hundred events → discoveries possible (depending on the scenario)

Electroweak states at 30 TeV

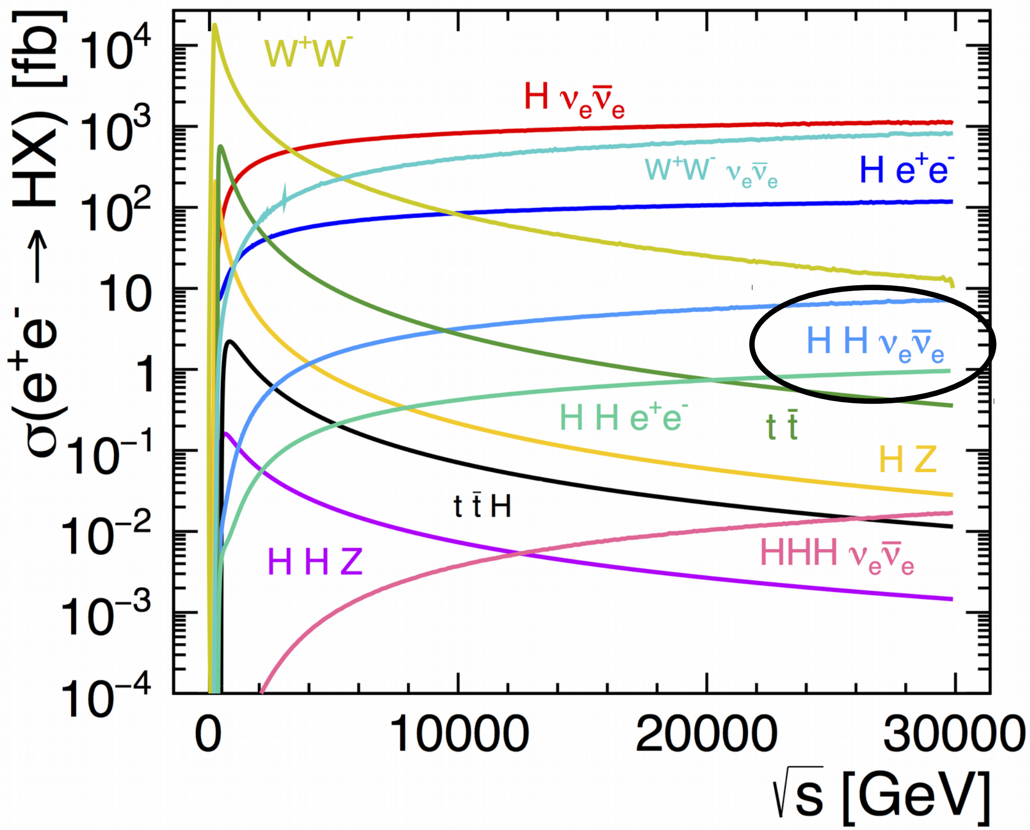






- Examples for electroweak pair production
- Precision studies would require tens of ab^{-1}
- Discoveries possible for about 1 ab^{-1}

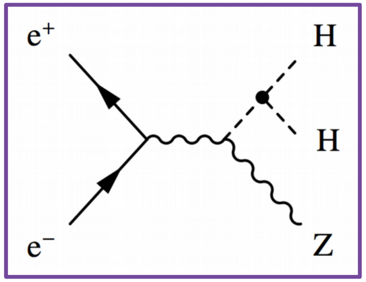
Double Higgs production

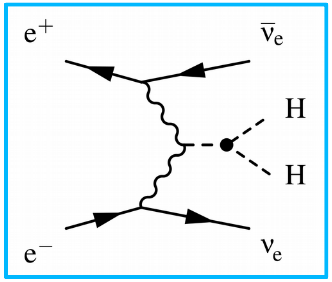


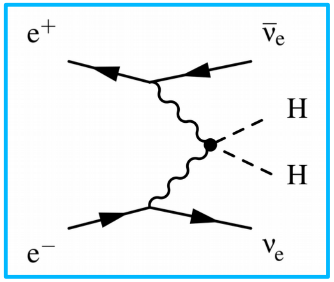
$e^+e^- \to HH\nu_e\bar{\nu}_e$:

- Allows simultaneous extraction of triple Higgs coupling, g_{HHH}, and quartic HHWW coupling
- Cross section 4.1 times larger at 10 TeV compared to 3 TeV

Phys. Rev. D 88, 055024 (2013)

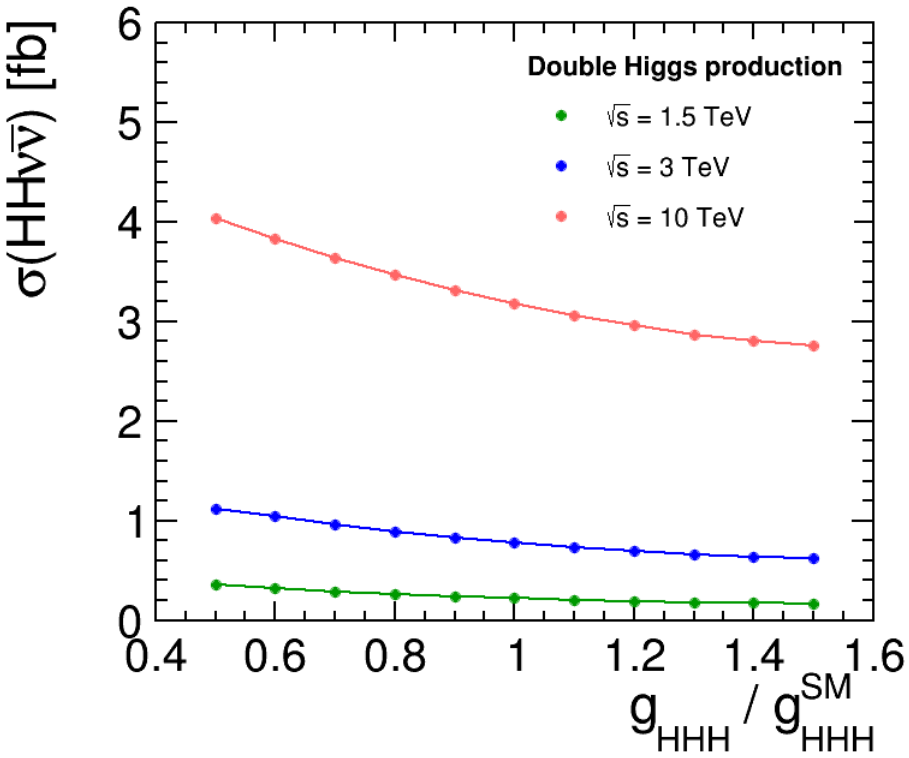






Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	−18 %
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	−25 %

Double Higgs production at 10 TeV



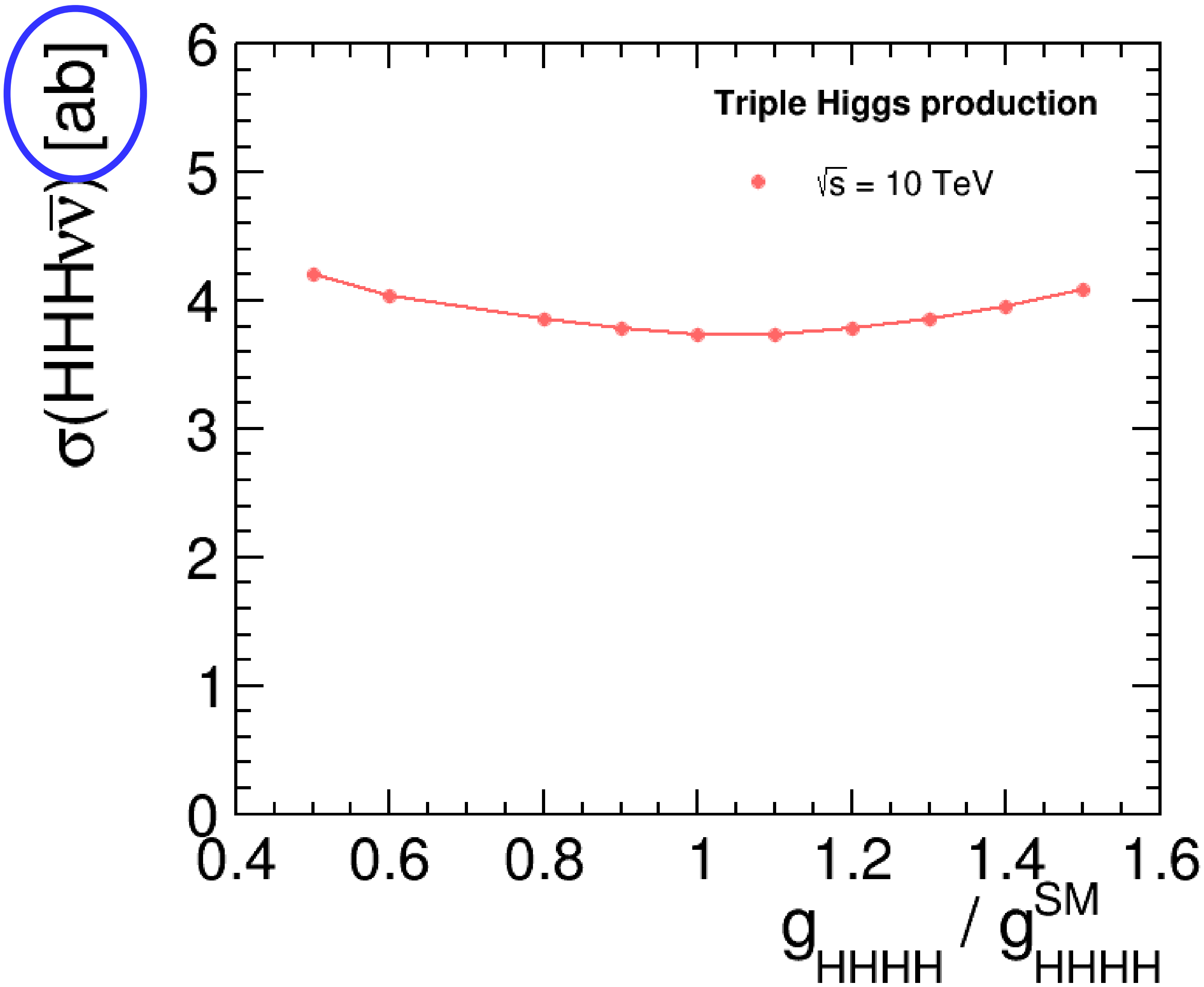
Collider	$\Delta g_{HHH}/g_{HHH}$
HL-LHC (3 ab^{-1})	50%?
CLIC 3 TeV (3 ab^{-1})	16% (from σ) ≈10% (templ. fit)
FCC-hh (30 ab^{-1})	3.5 - 5%

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

Conclusions:

- CLIC results extrapolated to 4 ab^{-1} at 10 TeV: $\Delta g_{HHH}/g_{HHH}$ = 11% from σ (7% from templ. fit?)
- Precision comparable to FCC-hh would require 8 - 16 ab^{-1}

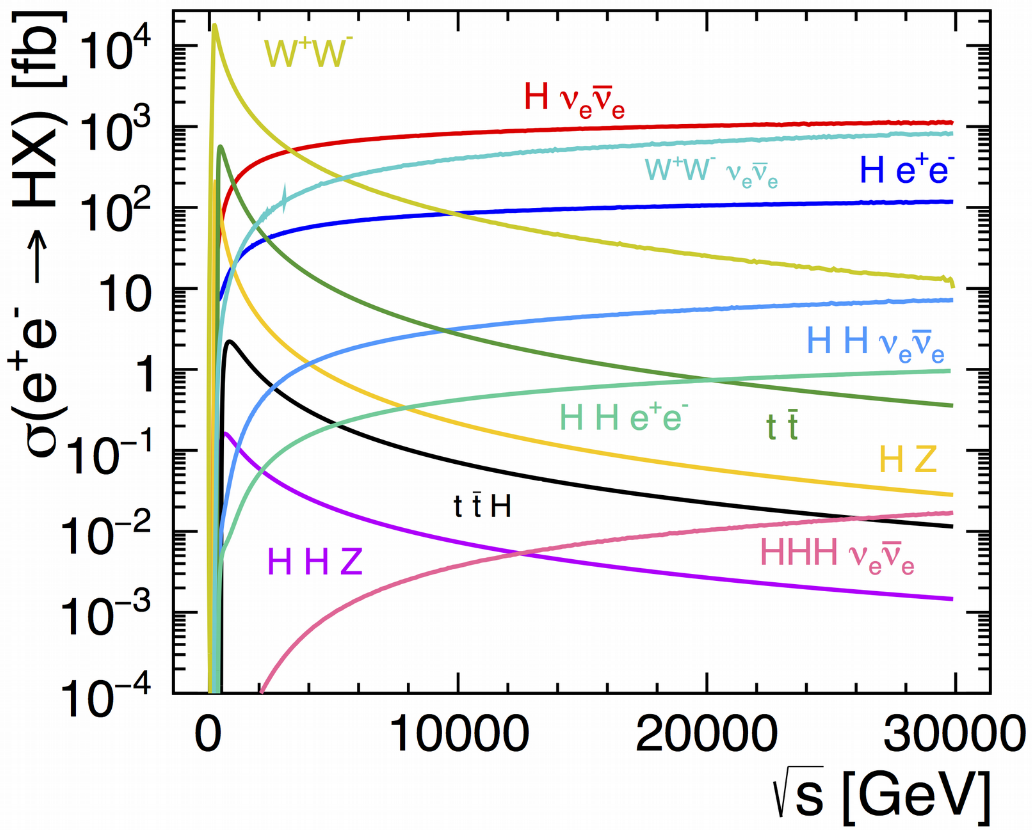
What about triple Higgs production?



- At 10 TeV the triple Higgs cross section is 3 orders or magnitude smaller compared to the double Higgs cross section!
- No measurement of g_{HHHH} even at 10 TeV

NB: New physics might enhance the cross section significantly (to be studied)

Single Higgs production



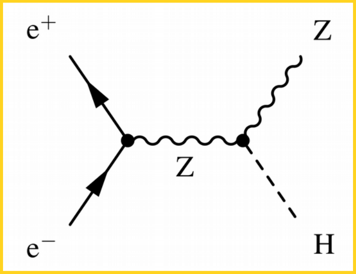
Higgsstrahlung: $e^+e^- \to ZH$

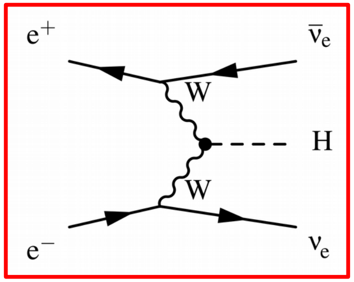
- $\sigma \sim 1/s$, dominant up to ≈ 450 GeV

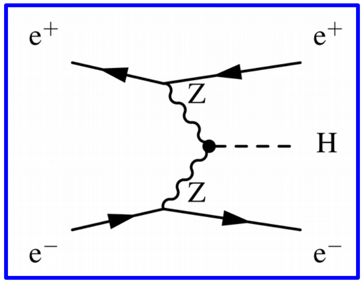
WW fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$

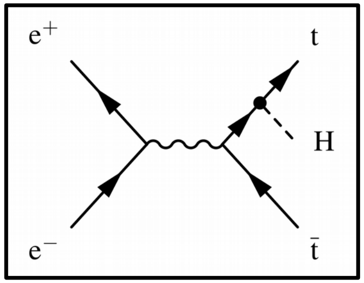
- $\sigma \sim \log(s)$, dominant above 450 GeV
- Large statistics at high energy
- Cross section 1.7 times larger at 10 TeV compared to 3 TeV

→ no significant gain expected in "kappa" framework from 3 to 10 TeV









BSM potential of Higgs production & $e^+e^- \rightarrow W^+W^-$

Effective Field Theory:

Standard Model

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

Dimension-6 operators

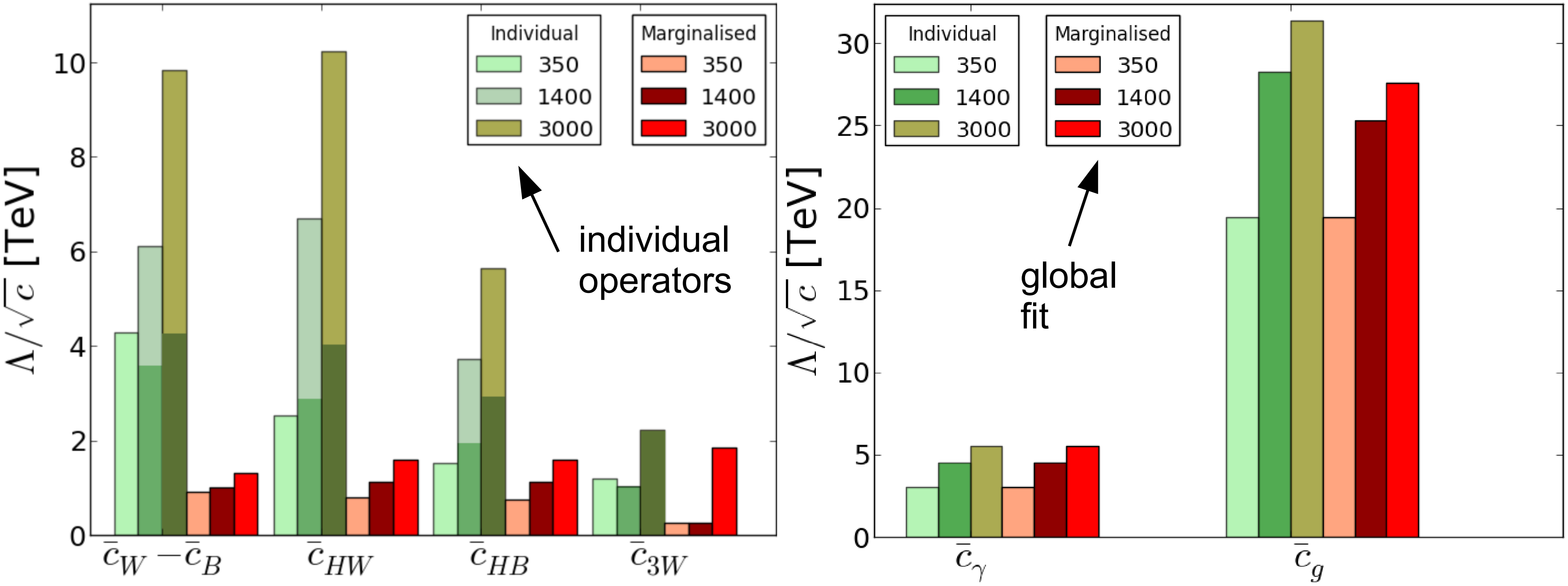
Scale of new decoupled physics

- Model-independent framework for probing indirect signs of new physics → very useful for comparison of future collider options

- **Input to fit:** Higgs measurements using WW-fusion and Higgsstrahlung, $e^+e^- \rightarrow W^+W^-$

CLIC sensitivities to dimension-6 operators

Individual CLIC energy stages



Sensitivity enhanced by higher centre-of-mass energy

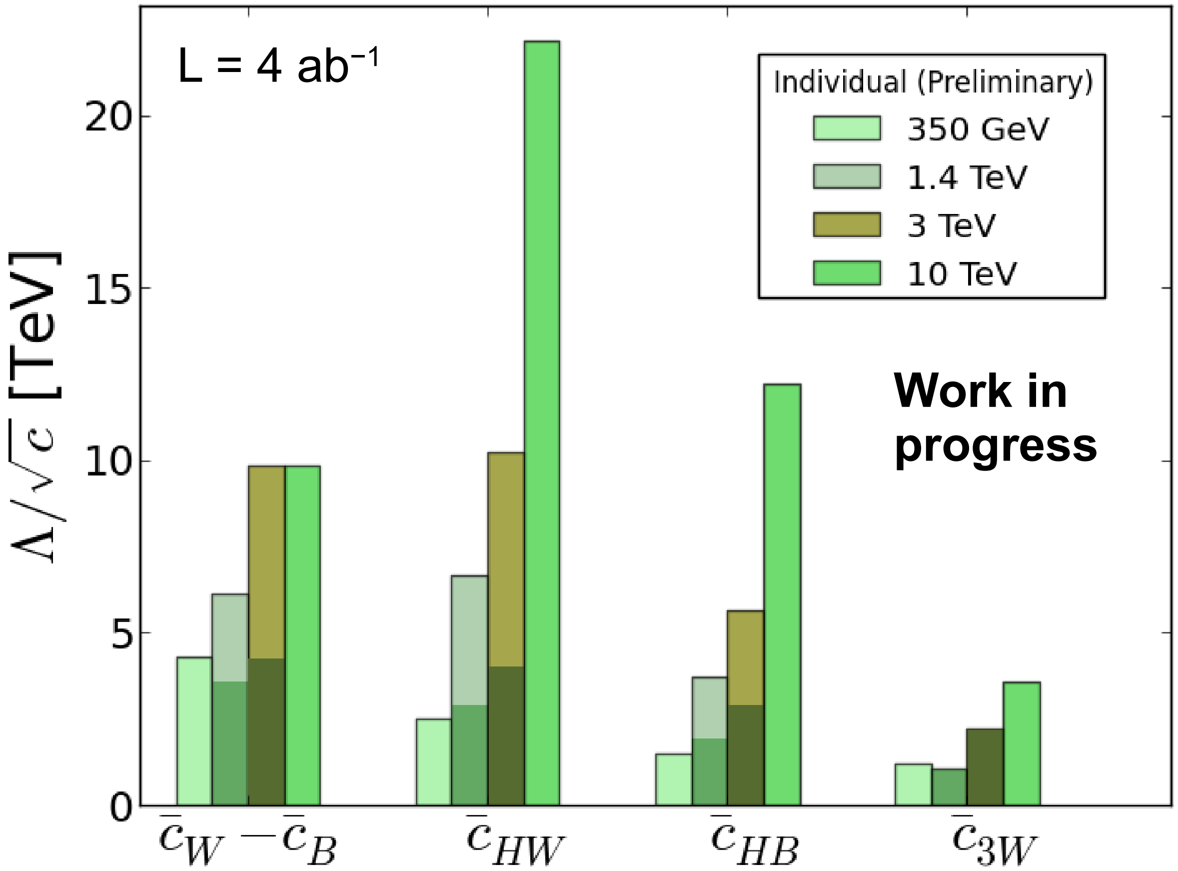
Ellis, PR, Sanz, You, JHEP 1705, 096 (2017)

Extrapolation to 10 TeV

- The 3 TeV CLIC projections for Higgs and WW production were extrapolated to 10 TeV (assuming the luminosity spectrum at 10 TeV has the same shape as at 3 TeV)

- Benefit of very high energy visible

- More results in progress



Light-by-light scattering ($\gamma\gamma \rightarrow \gamma\gamma$)

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

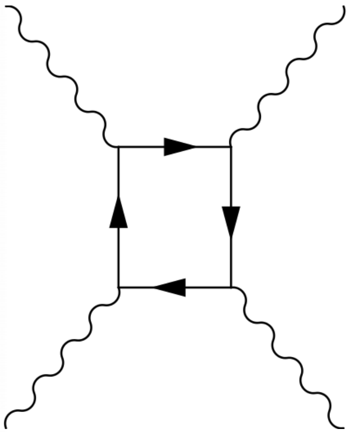
nature physics

OPEN

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

ATLAS Collaboration†

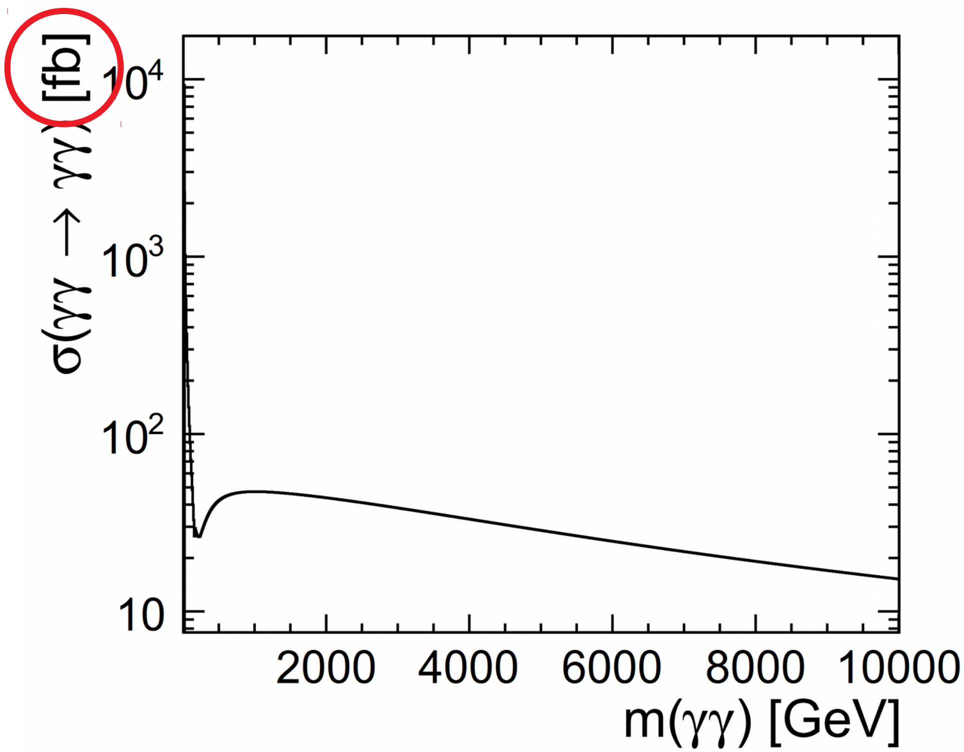
Light-by-light scattering ($\gamma\gamma \rightarrow \gamma\gamma$) is a quantum-mechanical process that is forbidden in the classical theory of electrodynamics. This reaction is accessible at the Large Hadron Collider thanks to the large electromagnetic field strengths generated by ultra-relativistic 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.

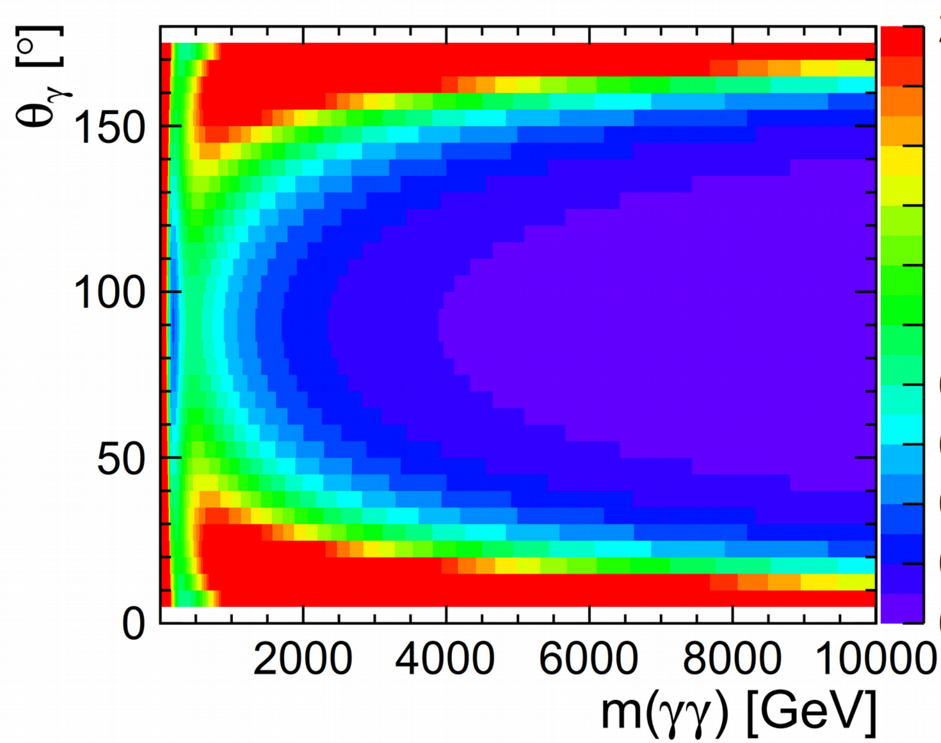


13 events!

Standard Model cross section

Cross section for γγ → γγ including W and top loops:





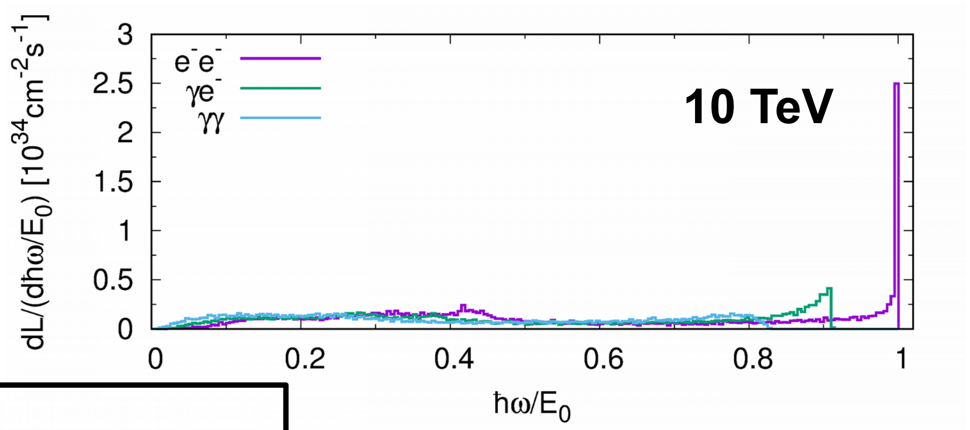
The photon angular distribution peaks in the forward/backward direction except near massive thresholds

Ellis, Mavromatos, Ph.R., You (in progress)

$\gamma\gamma \to \gamma\gamma$ at a 10 TeV photon collider

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

- Estimated the sensitivity to two dimension-8 operators c_1 and c_2:



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

- **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 (in progress)

For comparison: M > 100 GeV at ATLAS

arXiv:1703.08450

- Other models under study

Summary and outlook

- The reach of an e^+e^- collider for new phenomena increases strongly with the centre-of-mass energy
- The variation of the luminosity within the considered range has a large impact on the physics potential
- One opportunity for a 10 TeV photon collider was shown, more work is needed to understand the benefit of this option

NB: A yellow report on the CLIC BSM physics potential is being prepared collecting input from the theory community. We are suggesting to extend the studies beyond 3 TeV where appropriate.