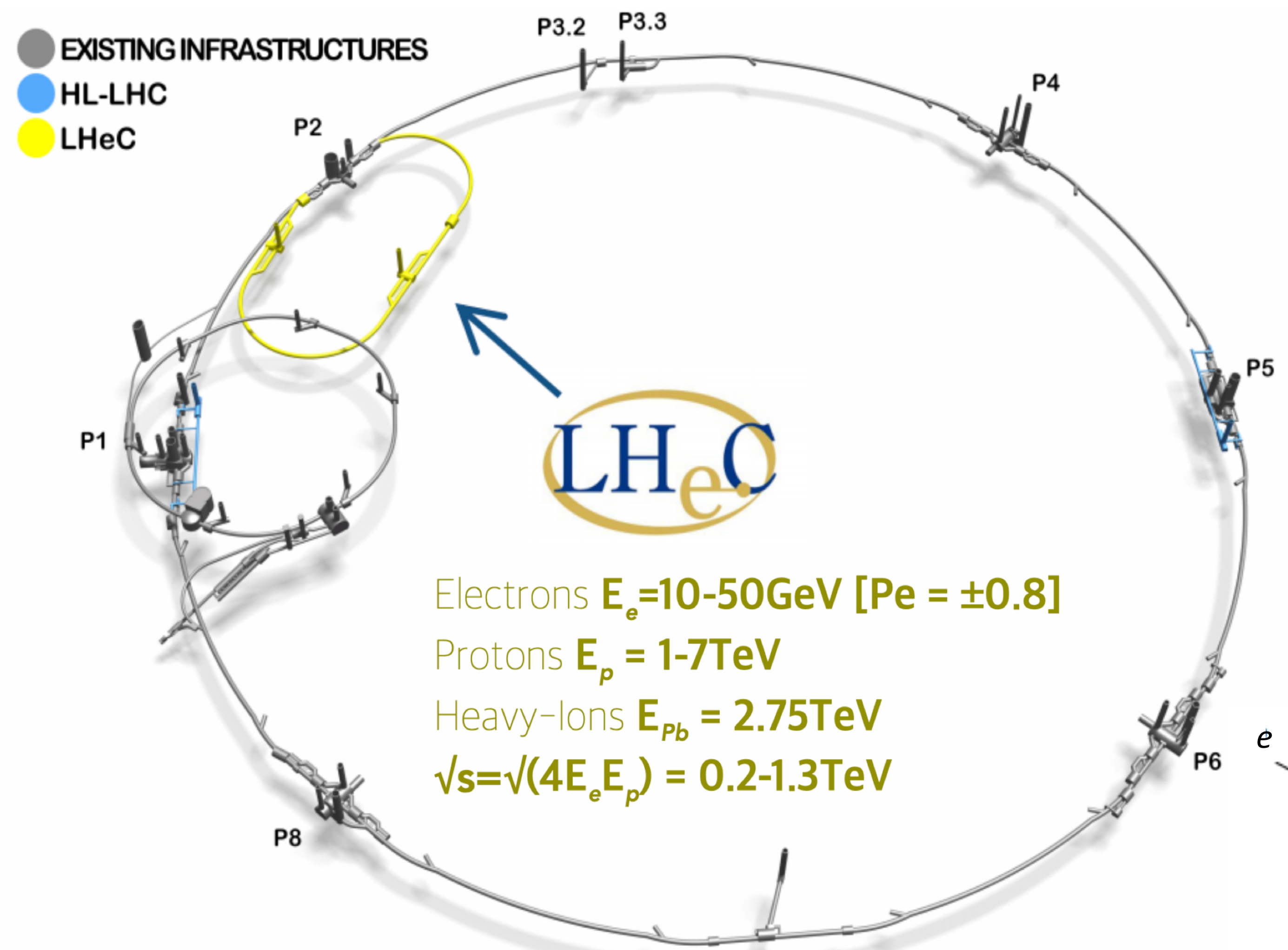
Photon and Diffractive Physics with the LHeC/FCC-*eh*

Krzysztof PIOTRZKOWSKI

AGH University of Science and Technology, Kraków

(on behalf of the LHeC and FCC-*eh* study groups)

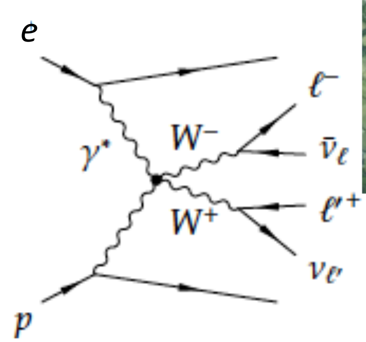


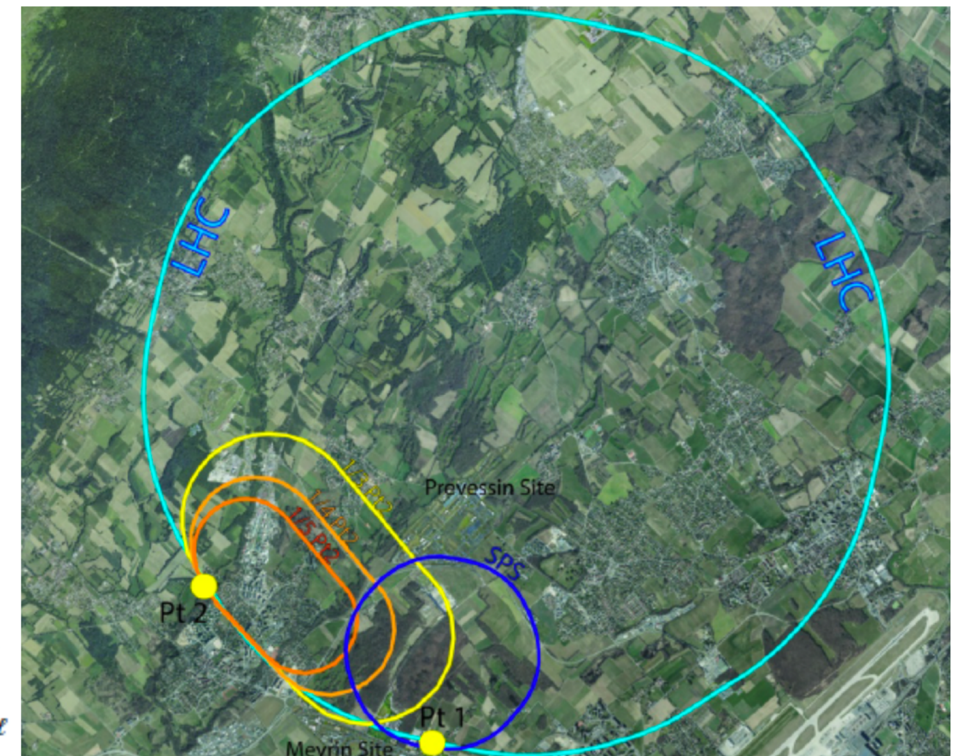
Electrons **E_e=10-50GeV [Pe = ±0.8]**

Protons **E_p = 1-7TeV**

Heavy-Ions **E_{Pb} = 2.75TeV**

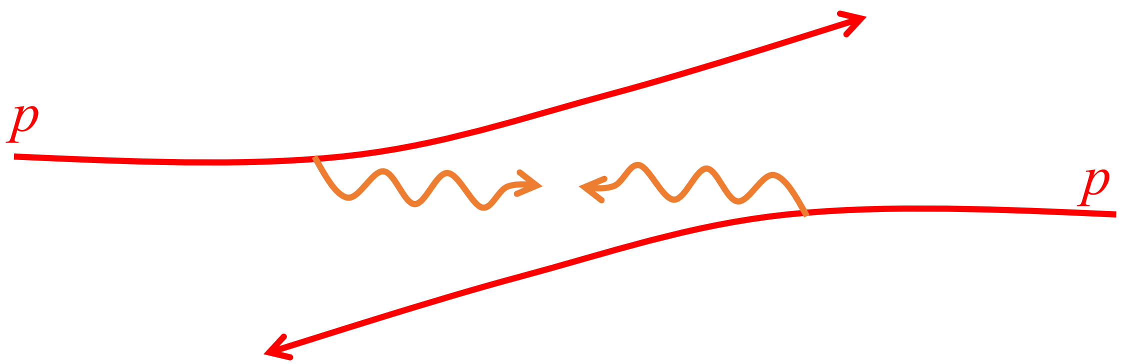
$\sqrt{s}=\sqrt{(4E_eE_p)}$ = 0.2-1.3TeV





FCC-*eh*: $\sqrt{s_{ep}}$ = 3.5 TeV

As an Introduction: **LHC as a High Energy $\gamma\gamma$ Collider**



Phys. Rev. **D63** (2001) 071502(R)
hep-ex/0201027

Initial observation:
Provided efficient measurement of very forward-scattered protons one can study high-energy $\gamma\gamma$ collisions at the LHC

<u>Highlights</u>:

- **$\gamma\gamma$ CM energy *W* up to/beyond 1 TeV (and under control)**
- **Large (quasi-real) photon flux *F* therefore significant (effective) $\gamma\gamma$ luminosity**
- **Complementary (and "clean") physics to *pp* interactions, e.g. studies of exclusive production of heavy particles might be possible ➡ opening new field of high energy $\gamma\gamma$ physics**

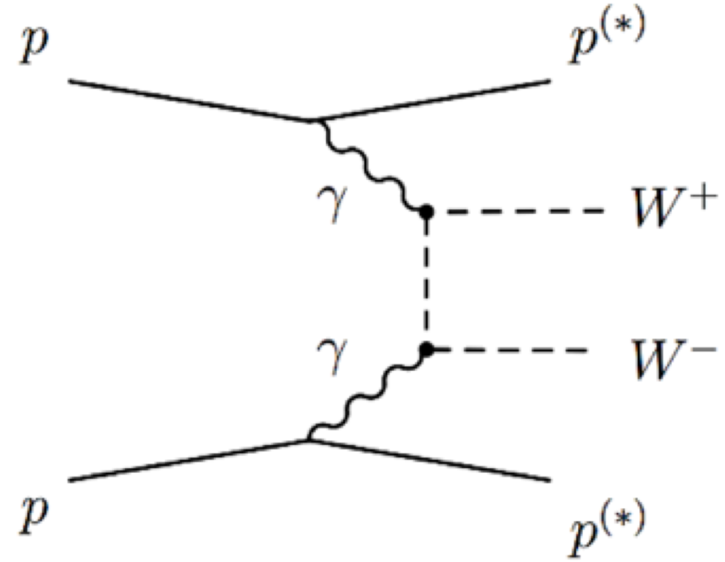
LHC as a $\gamma\gamma$ collider: pair production

At high energies two-photon exclusive pair production cross-section is given by:

particle **charge, mass and spin**

for given mass and charge it is largest for vector particles, then for fermions,

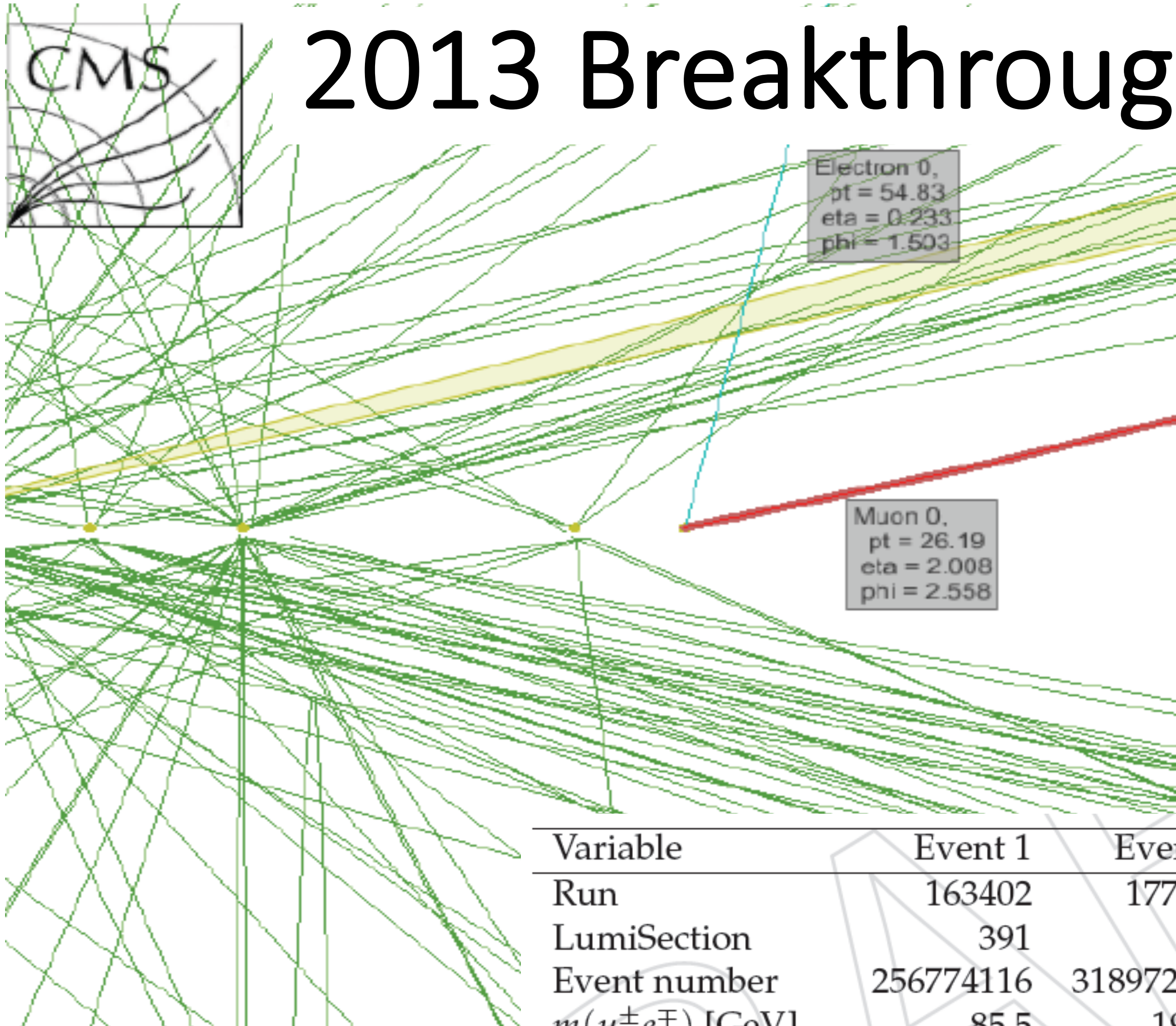
$\gamma\gamma \to WW$ pair production has a very sizable cross-section at the LHC of ~100 fb, and at least × 4, if inelastic production included (p^*)!

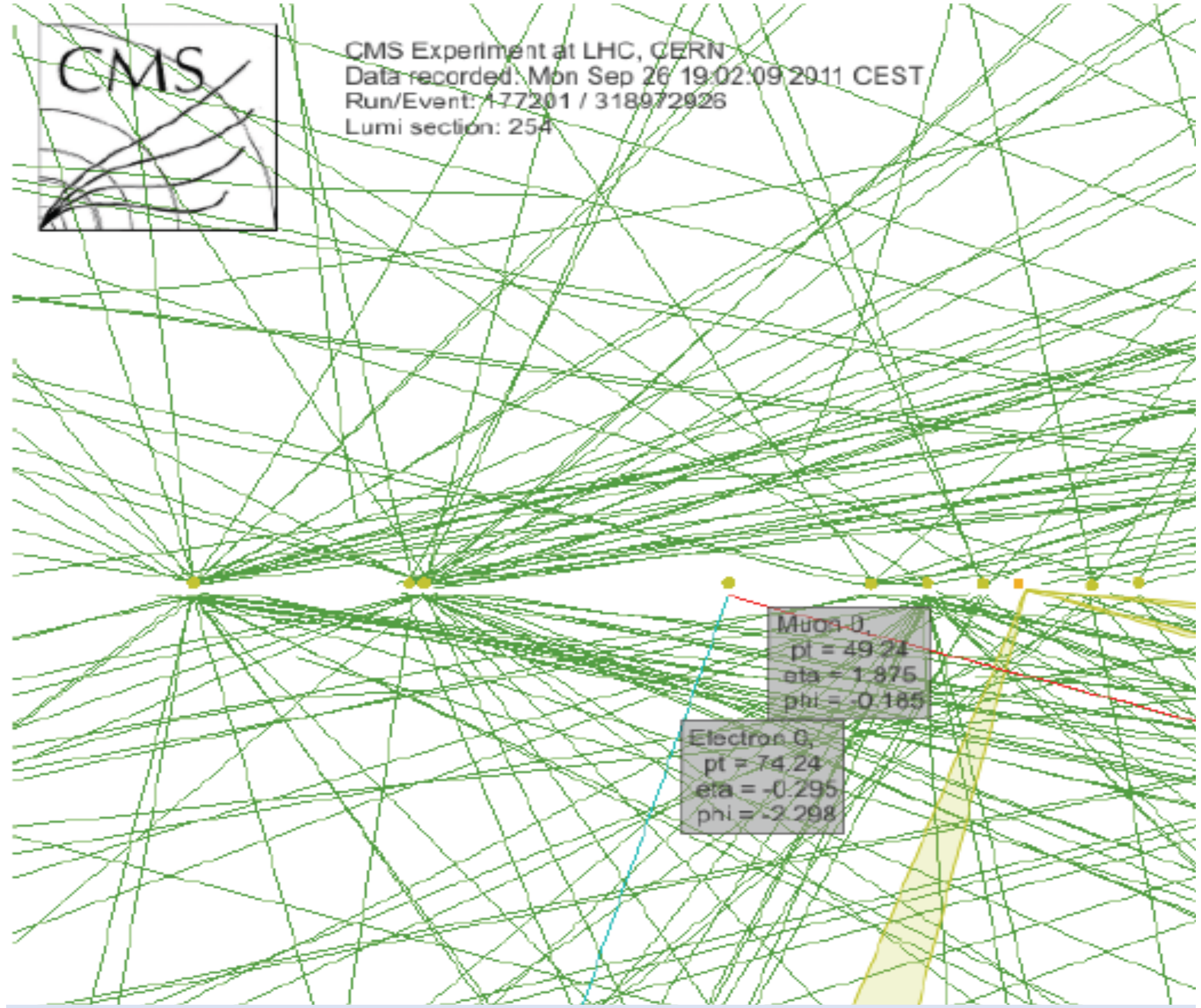


Massive fermions have sizable $\gamma\gamma$ cross-sections up to about 200 GeV masses, for scalars cross-sections are about 5 times smaller, but there is H^{++} case, for example

$\sigma \propto Z^4 \Rightarrow \sigma \times 16$!

2013 Breakthrough





Variable	Event 1	Event 2
Run	163402	177201
LumiSection	391	254
Event number	256774116	318972926
$m(\mu^{\pm}e^{\mp})$ [GeV]	85.5	190.3
$1 - \lvert\Delta\phi(\mu^{\pm}e^{\mp})/\pi\rvert$	0.66	0.33
$p_{\mathrm{T}}(\mu^{\pm})$ [GeV]	26.2	49.2
$E_{\mathrm{T}}(e^{\pm})$ [GeV]	54.8	74.2
$\eta(\mu^{\pm})$	2.01	1.88
$\eta(e^{\pm})$	0.23	-0.30

First ever $\gamma\gamma \rightarrow WW$!

(at CL > 90%)

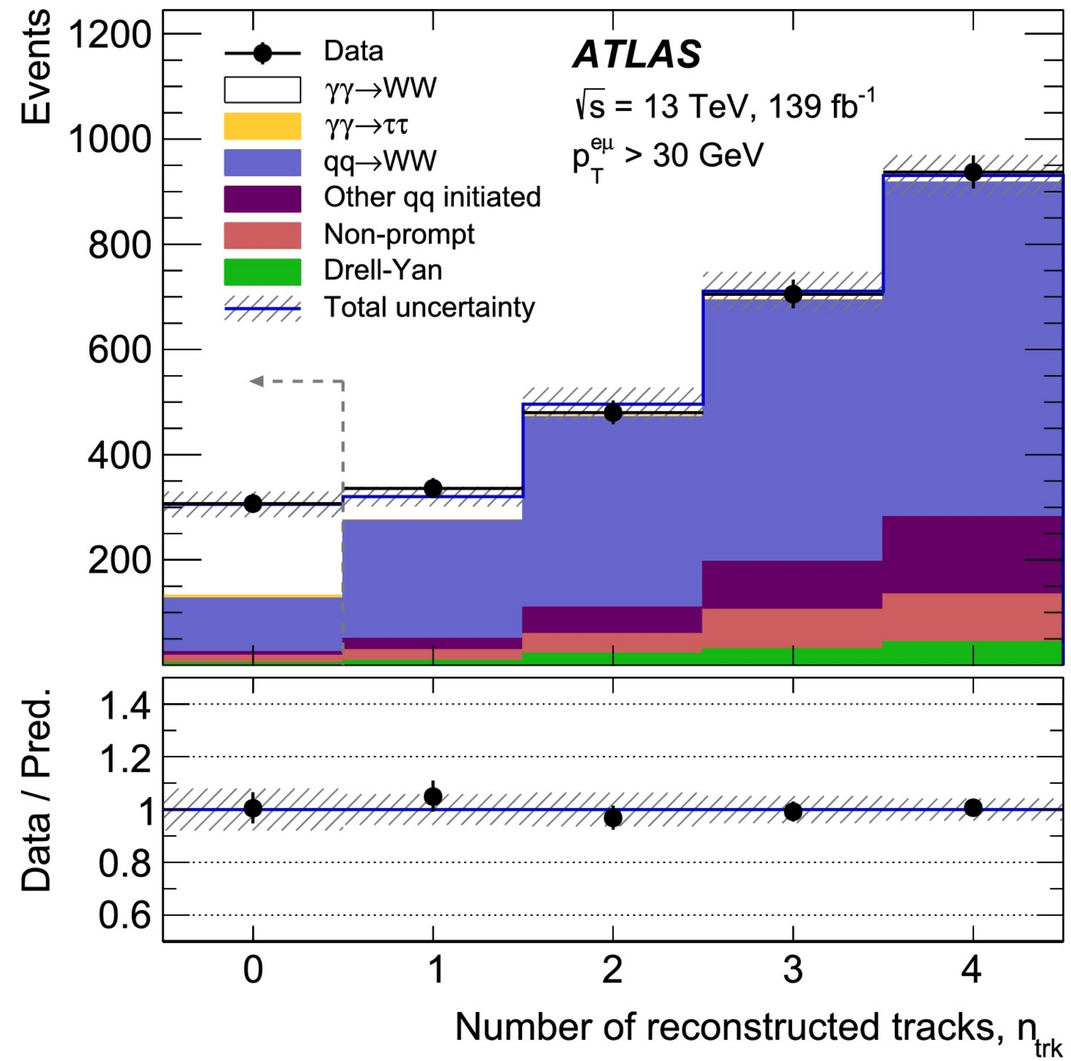
LHC as a high energy $\gamma\gamma$ collider: **recent results**

exclusive $W^+W^- \rightarrow e^\pm\nu\mu^\mp\nu$

ATLAS Run 2 final result at 13 TeV (average event **PU ≈ 34**):

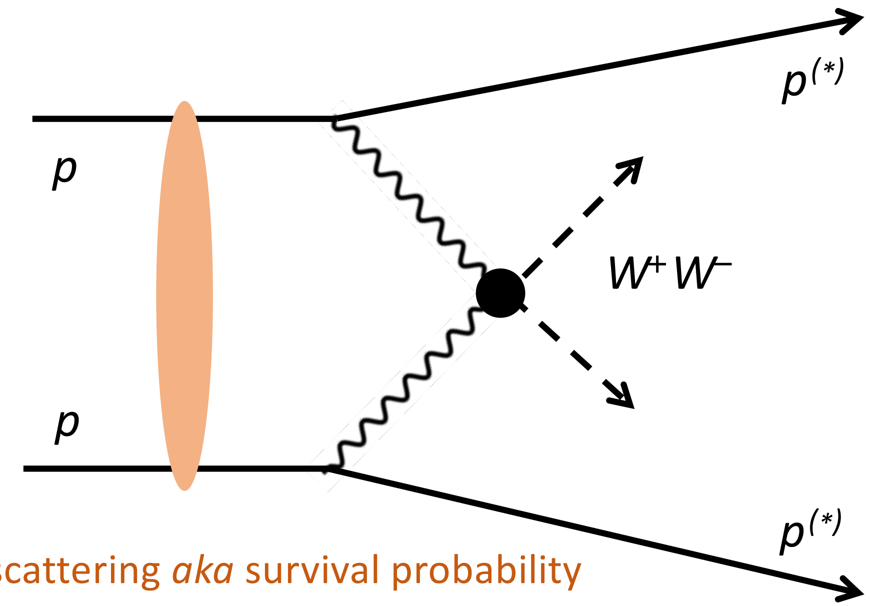
"The data yield in the signal region is 307, compared with 132 background events predicted by the best-fit result. [...] This measurement constitutes **the observation of photon-induced *WW* production in *pp* collisions**, a process for which only evidence was previously reported."

doi: 10.1016/j.physletb.2021.136190



Note: in spite of almost 5 times bigger PU, a similar S/B was achieved, as for Run 1 analyses, thanks to improved tracking/ vertexing **and** significantly higher $S_{\gamma\gamma}$ at 13 TeV.

HL-LHC as a high energy $\gamma\gamma$ collider: **challenges**



re-scattering *aka* survival probability

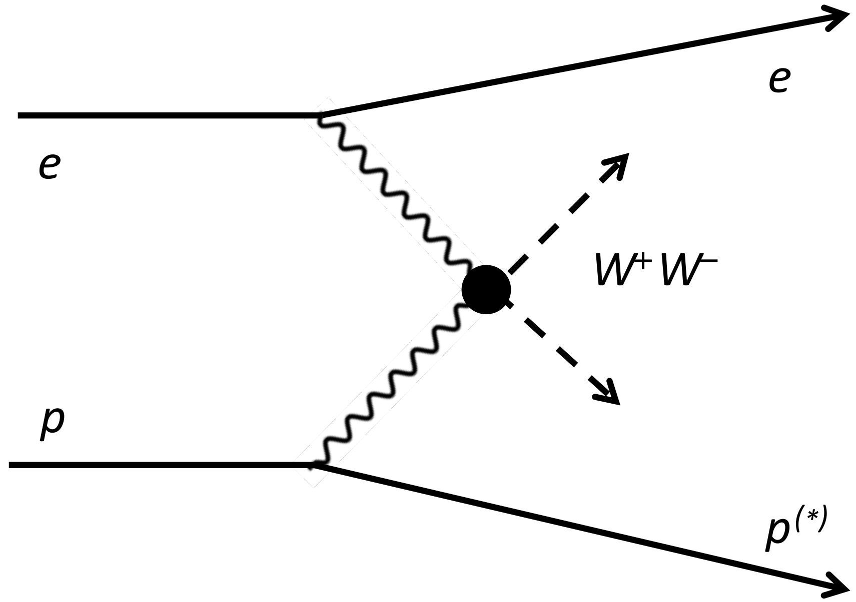
HL-LHC will provide 10 times bigger integrated *pp* luminosity, but:

- $S_{\gamma\gamma}$ luminosity only marginally higher, thanks to 13 → 14 TeV increase
- Event pileup yet 4 times higher (≈ 140) than for Run 2
- Very high event pileup will make tagging with forward protons even more tricky – **ps resolution timing detectors** are a must – however, the problem of overall efficiency loss still persists
- New ps timing in central detectors could provide much needed handle to more suppress accidental coincidences

Major challenges for the HL-LHC $\gamma\gamma$ collider:

- **Only** tracks can be used for the selection of (quasi-)exclusive production
- **Only** exclusive charged dilepton states could be successfully measured so far (after 10-year efforts)
- And, the **re-scattering suppression** is large and uncertain, especially at very large invariant mass $W_{\gamma\gamma}$

LHeC as a high energy γγ collider



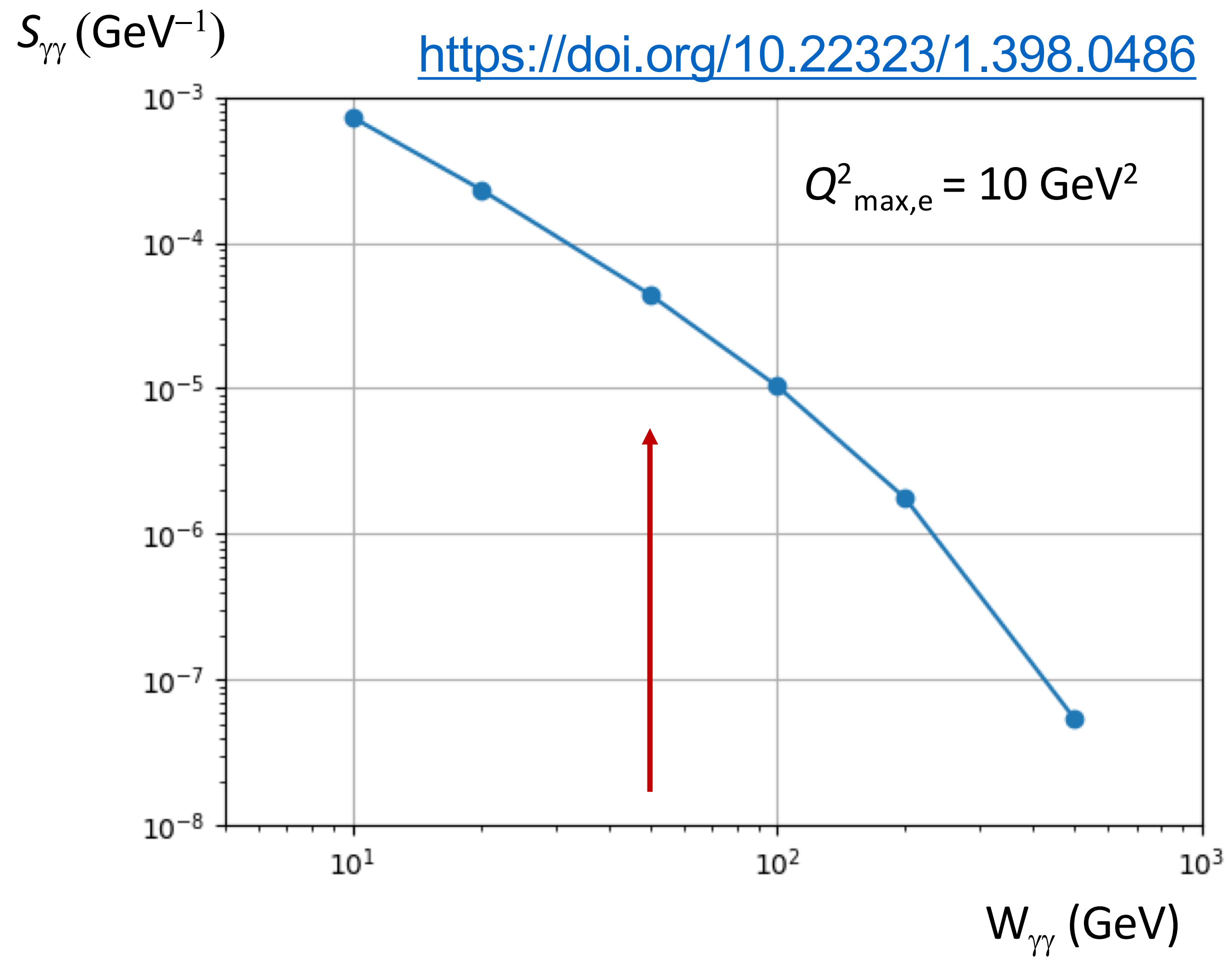
Very high LHeC luminosity is the key here ⇒ about **1 ab^{-1}** (= 1000 fb^{-1}) is expected for *ep* collisions.

Electrons will have "only" 50 GeV, but **stronger** photon flux, and approximately:

$$S_{\gamma\gamma} \propto \ln(Q^2_{max,e}/Q^2_{min,e})\ln(Q^2_{max,p}/Q^2_{min,p})$$

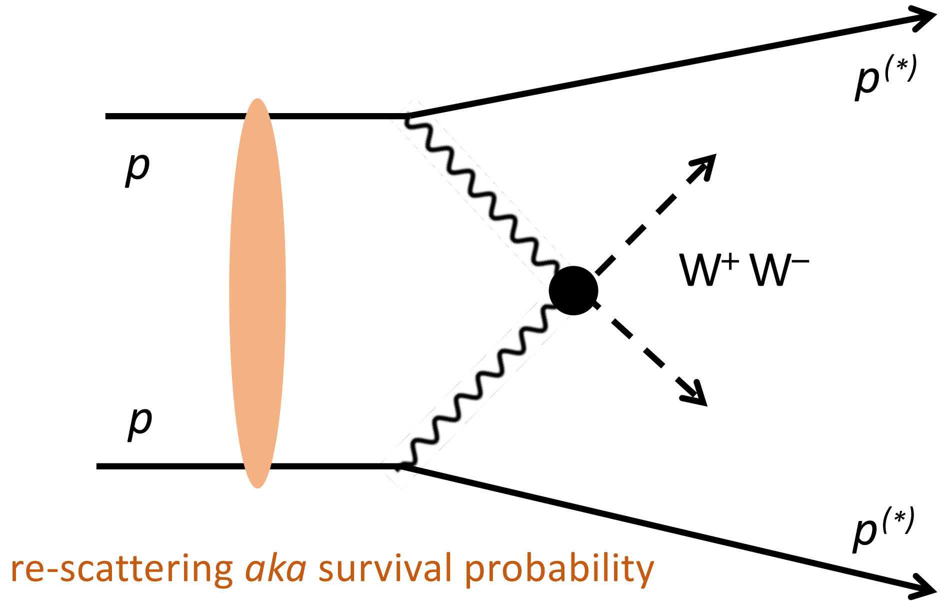
where $Q^2_{min} \propto m^2$, and $Q^2_{max,e}$ can be very high

https://doi.org/10.22323/1.398.0486

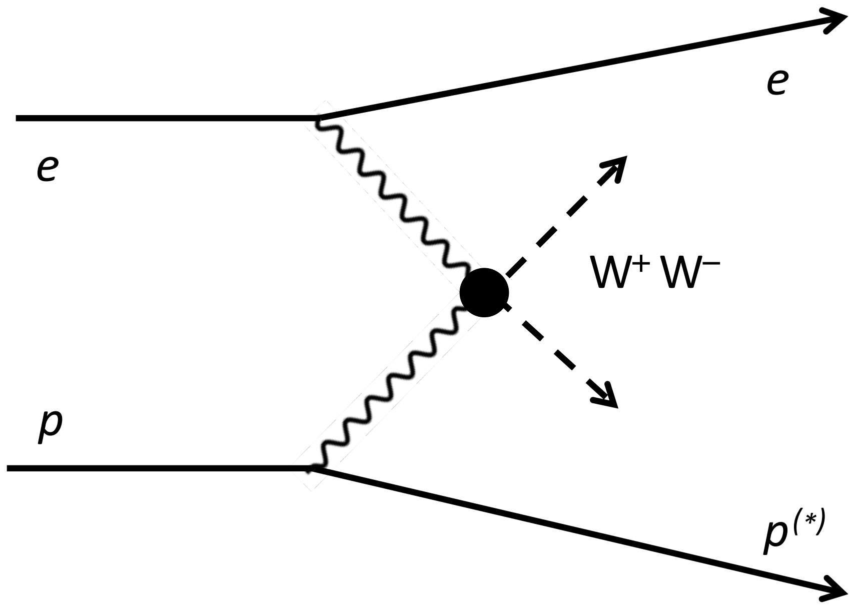


For $W_{\gamma\gamma}$ < 50 GeV the *fully* exclusive **γγ luminosity spectrum** is **higher** at the LHeC than at the HL-LHC!

HL-LHC vs. LH*e*C as high energy $\gamma\gamma$ colliders



vs.

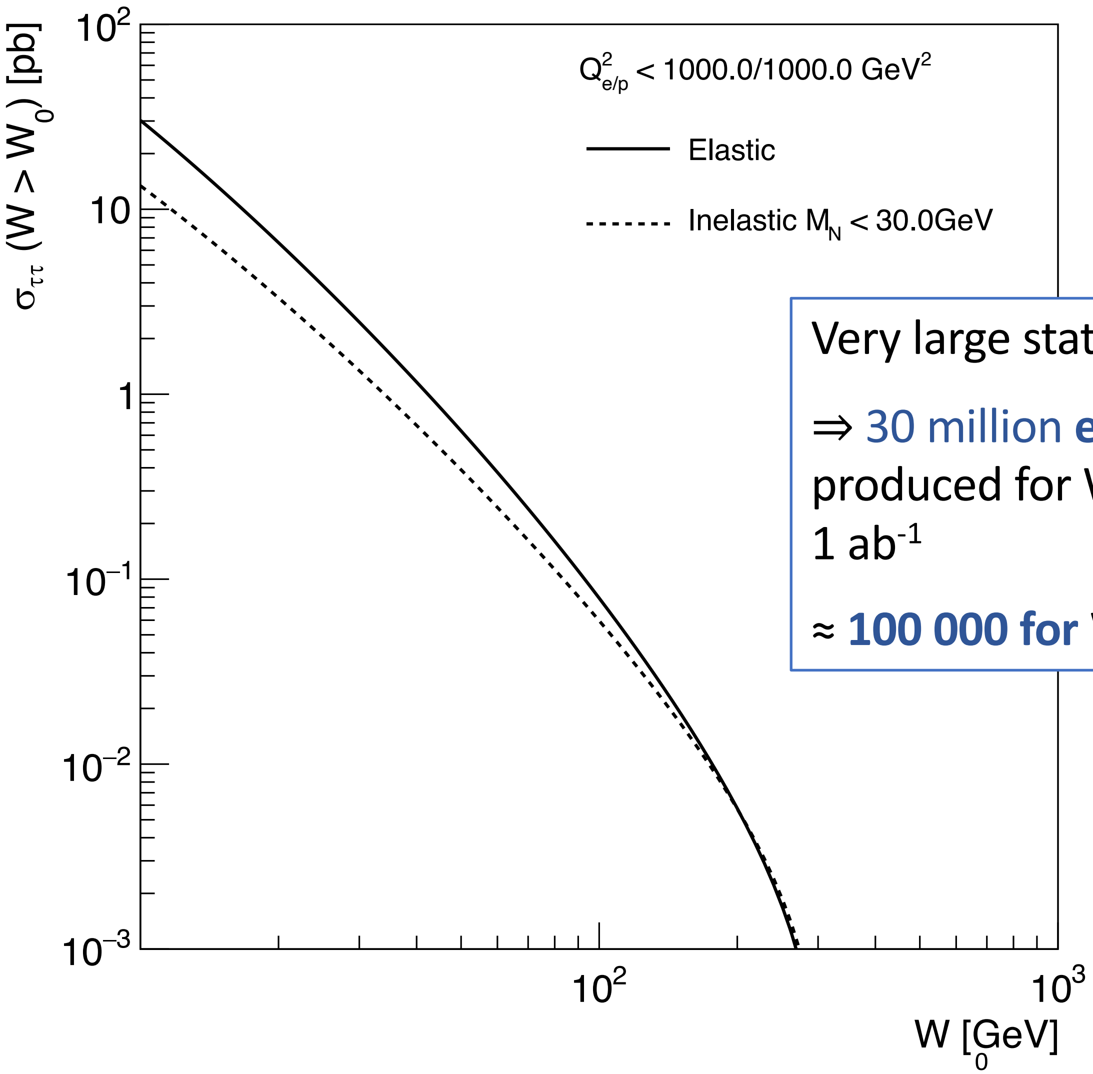


Energy reach for $\gamma\gamma$ interactions is higher at the LHC, however at the highest $W_{\gamma\gamma}$ tagging is not possible and the suppression due to re-scattering becomes large.

Event **pileup is very low at the LH*e*C** – it is **only 5 %** at the highest *ep* luminosity of $\mathbf{2 \times 10^{34}\ cm^{-2}s^{-1}}$.

This is not only allowing to **use calorimetry for the selection and reconstruction** of exclusive production, but will also significantly **increase** detection efficiencies, including $\gamma\gamma$ tagging, and will be used to **suppress** backgrounds!

LHeC: $\gamma\gamma \longrightarrow \tau\tau$ and $\gamma\gamma \longrightarrow W^+W^-$

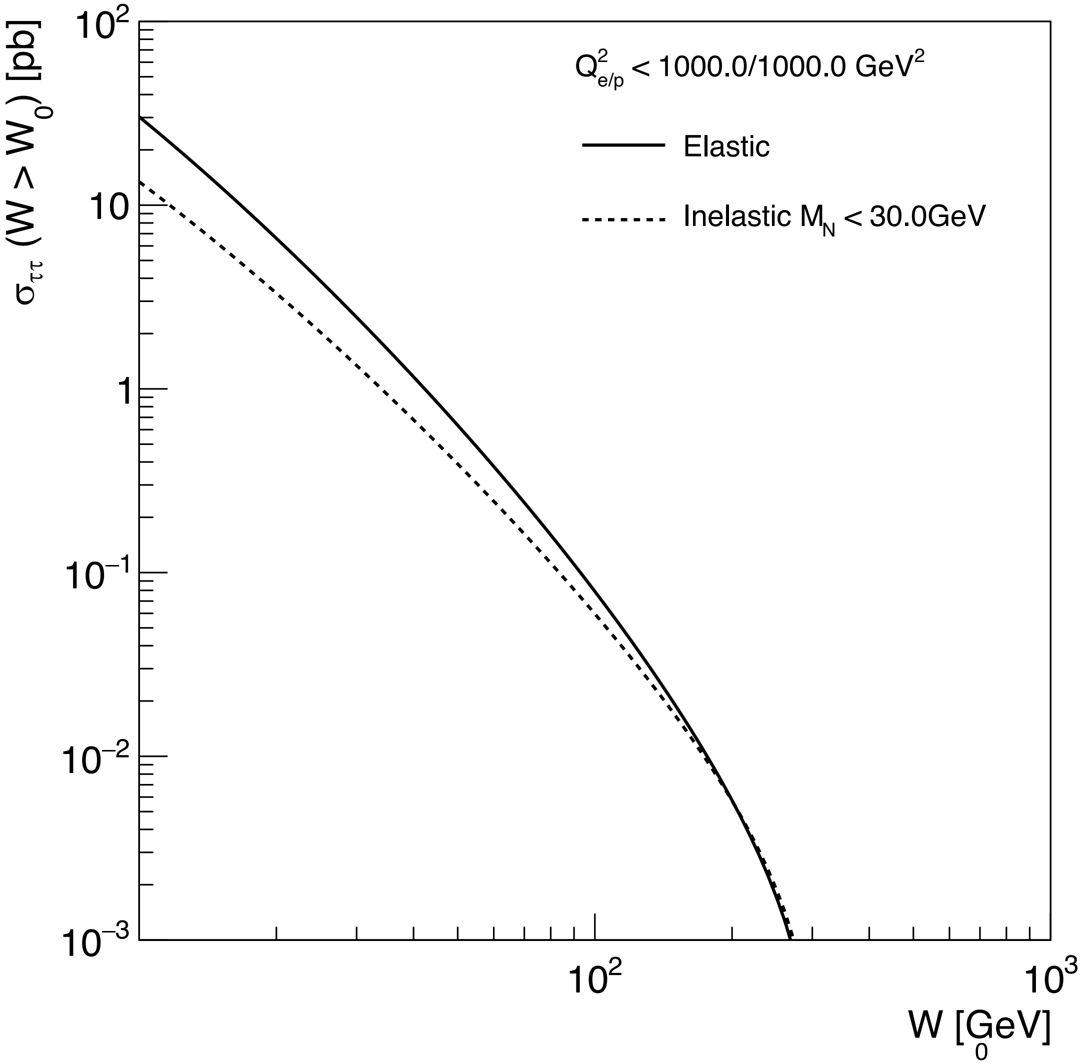


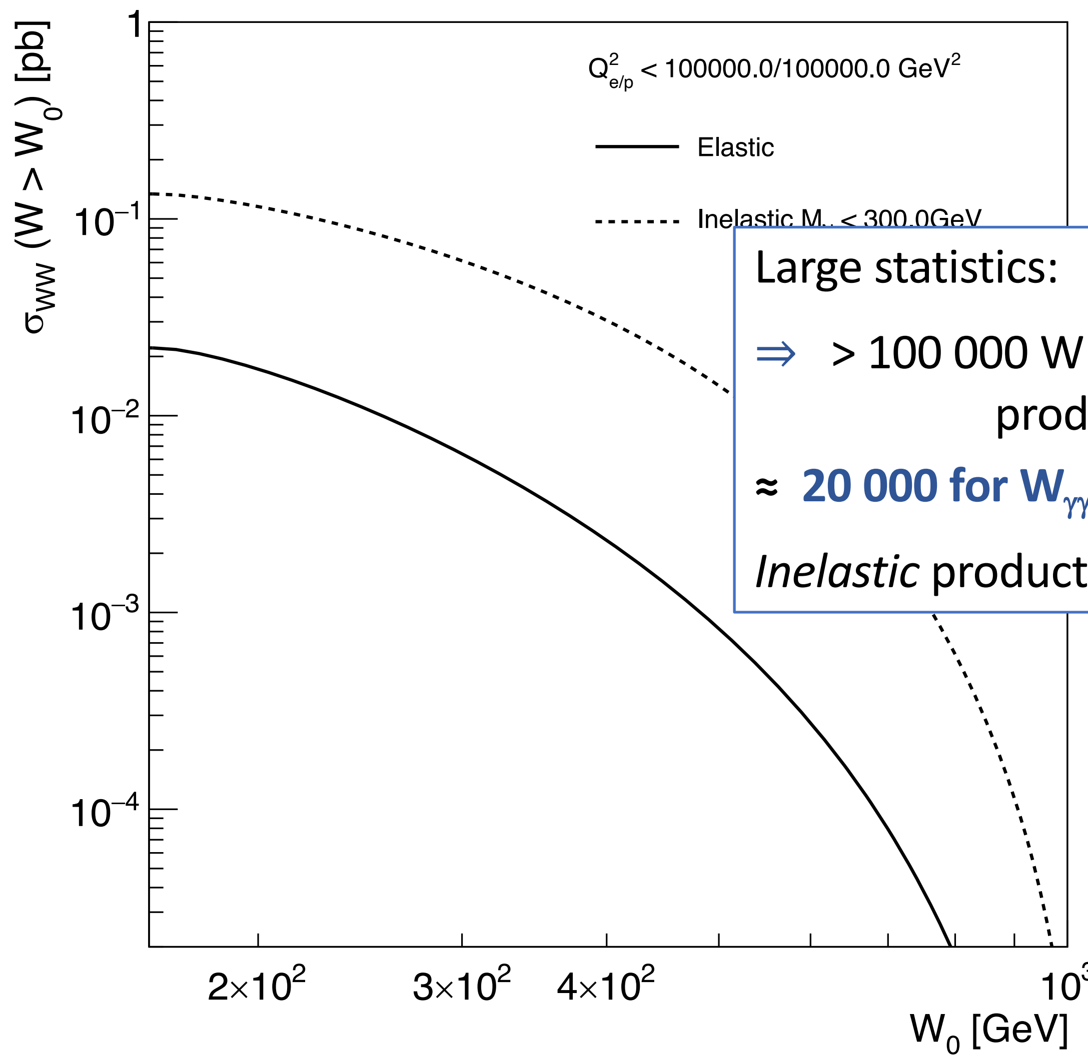
Very large statistics:

⇒ 30 million **elastic** $\tau\tau$ pairs produced for $W_{\gamma\gamma}$ > 10 GeV at 1 ab^{-1}

≈ **100 000 for** $W_{\gamma\gamma}$ **> 100 GeV**

LHeC: $\gamma\gamma \longrightarrow \tau\tau$ and $\gamma\gamma \longrightarrow W^+W^-$





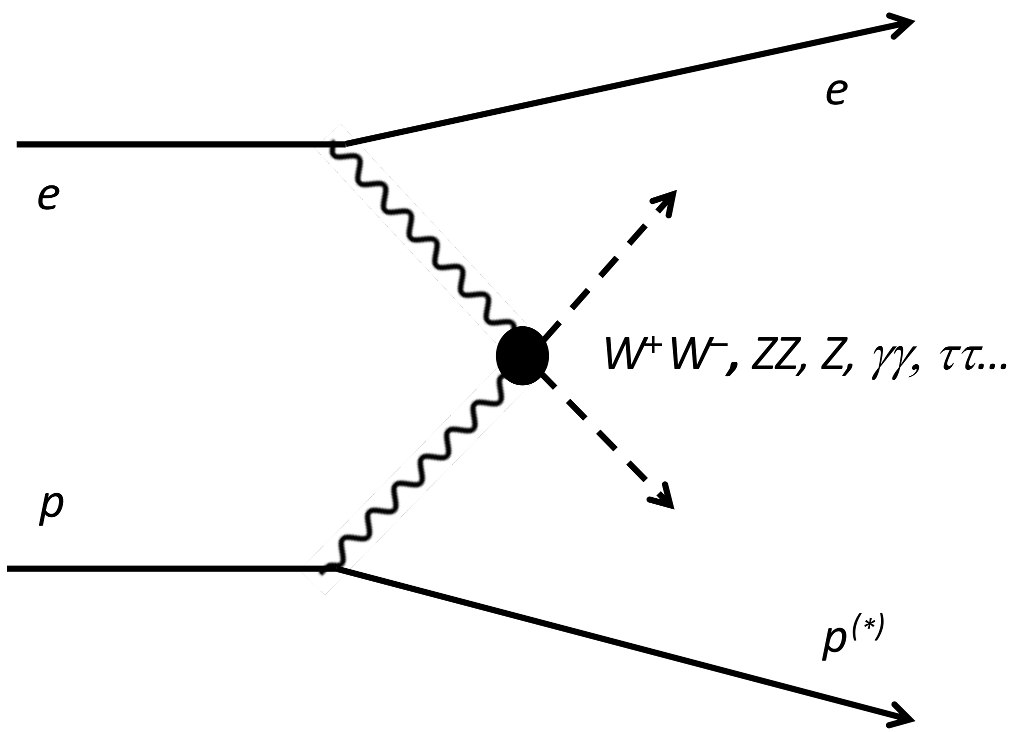
Large statistics:

⇒ > 100 000 W boson pairs produced at 1 ab^{-1}

≈ **20 000 for $W_{\gamma\gamma}$ > 500 GeV**

Inelastic production dominant

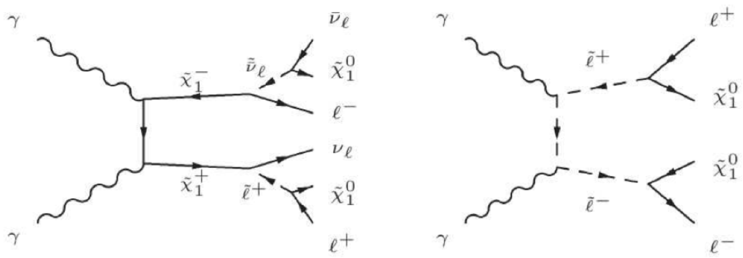
LH*e*C as a unique "generic" high energy $\gamma\gamma$ collider



Wide spectrum of $\gamma\gamma$ processes will be studied at the LHeC (and FCC-*eh*):

- $\gamma\gamma \to \tau^+\tau^-$: orders of magnitude higher statistics than for UPC at the HL-LHC, at higher pair invariant mass, and with $\gamma\gamma$ tagging $\Rightarrow$ new decay modes + better reconstruction of kinematics
- $\gamma\gamma \to Z$: search for the anomalous single Z boson exclusive production
- $\gamma\gamma \to ZZ$: possibility of first ever detection + stringent limits on anomalous quartic gauge couplings (aQGCs) using semi-leptonic decay modes, ZZ $\to l^+l^-jj$
- $\gamma\gamma \to W^+W^-$: measurements of semi-leptonic decay modes, $W^+W^- \to l\nu jj$, will allow for a use of Optimal Observable methods (even with single $\gamma\gamma$ tagging) for probing aQGCs; yet high statistics (≈ as at the HL-LHC) is expected for fully leptonic W^+W^- decays with tagging
- $\gamma\gamma \to \gamma\gamma$: *light-by-light* scattering at large invariant masses

SUSY?



Detection of two-photon exclusive production of supersymmetric pairs at the LHC

Nicolas Schul[a] * and Krzysztof Piotrzkowski[a]

[a]Université catholique de Louvain, Center for Particle Physics and Phenomenology (CP3), Louvain-la-Neuve, Belgium

The detection of pairs of sleptons, charginos and charged higgs bosons produced via photon-photon fusion at the LHC is studied, assuming a couple of benchmark points of the MSSM model. Due to low cross sections, it requires large integrated luminosity, but thanks to the striking signature of these exclusive processes the backgrounds are low, and are well known. Very forward proton detectors can be used to measure the photon energies, allowing for direct determination of masses of the lightest SUSY particle, of selectrons and smuons with a few GeV resolution. Finally, the detection and mass measurement of quasi-stable particles predicted by the so-called sweet spot supersymmetry is discussed.

Table 1
Cross sections for several examples of the exclusive two-photon pair production at the LHC. (F for fermion, S for scalar). [1]

Produced pairs	mass [GeV]	σ [fb]
W^+W^-	80	108.5
F^+F^-	100	4.064
F^+F^-	200	0.399
S^+S^-	100	0.680
S^+S^-	200	0.069

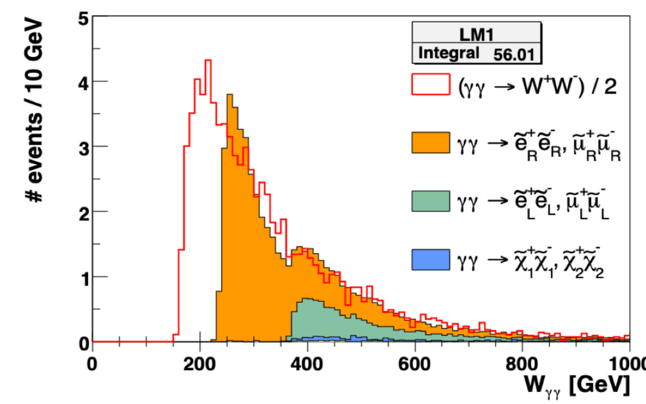


Figure 2. Distribution of two-photon invariant mass $W_{\gamma\gamma}$ for the LM1 benchmark and integrated luminosity L = 100 fb^{-1}. Two visible peaks are due to production thresholds of $\tilde{\ell}_R^+\tilde{\ell}_R^-$ and $\tilde{\ell}_L^+\tilde{\ell}_L^-$ pairs. Verious contribution are added cumulatively. The background distribution of WW pairs is shown separately,

SUSY?

"Compressed mass scenario" in SUSY and the renewed interest in $\gamma\gamma$ physics: a favored scenario (for DM) involves sleptons being 1 to tens of GeV above the neutralino mass:

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Search Strategy for Sleptons and Dark Matter Using the LHC as a Photon Collider

Lydia Beresford* and Jesse Liu†
Department of Physics, University of Oxford, Oxford OX1 3RH, United Kingdom

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We propose a search strategy using the LHC as a photon collider to open sensitivity to scalar lepton (slepton $\tilde{\ell}$) production with masses around 15 to 60 GeV above that of neutralino dark matter $\tilde{\chi}_1^0$. This region is favored by relic abundance and muon $(g-2)_\mu$ arguments. However, conventional searches are hindered by the irreducible diboson background. We overcome this obstruction by measuring initial state kinematics and the missing momentum four-vector in proton-tagged ultraperipheral collisions using forward detectors. We demonstrate sensitivity beyond LEP for slepton masses of up to 200 GeV for $15 \lesssim \Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \lesssim 60$ GeV with 100 fb^{-1} of 13 TeV proton collisions. We encourage the LHC collaborations to open this forward frontier for discovering new physics.

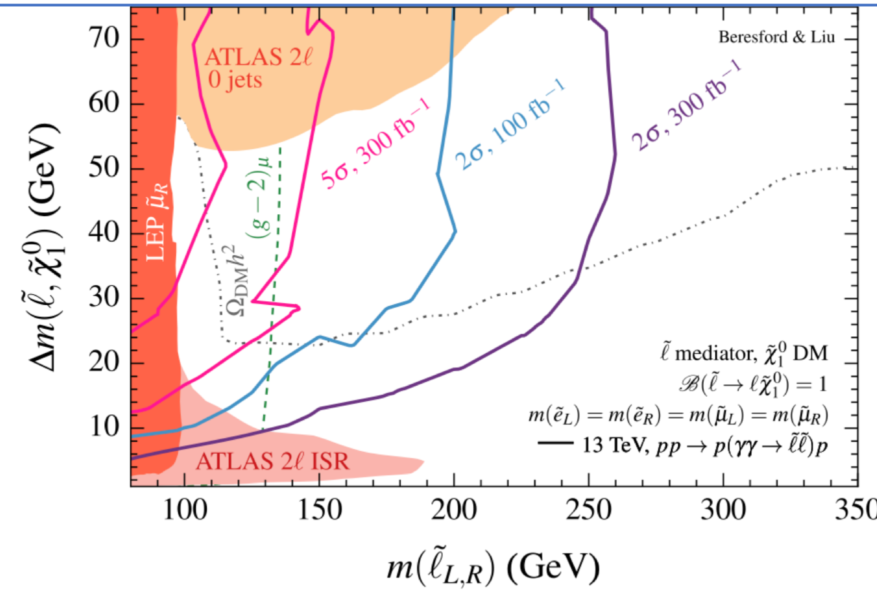
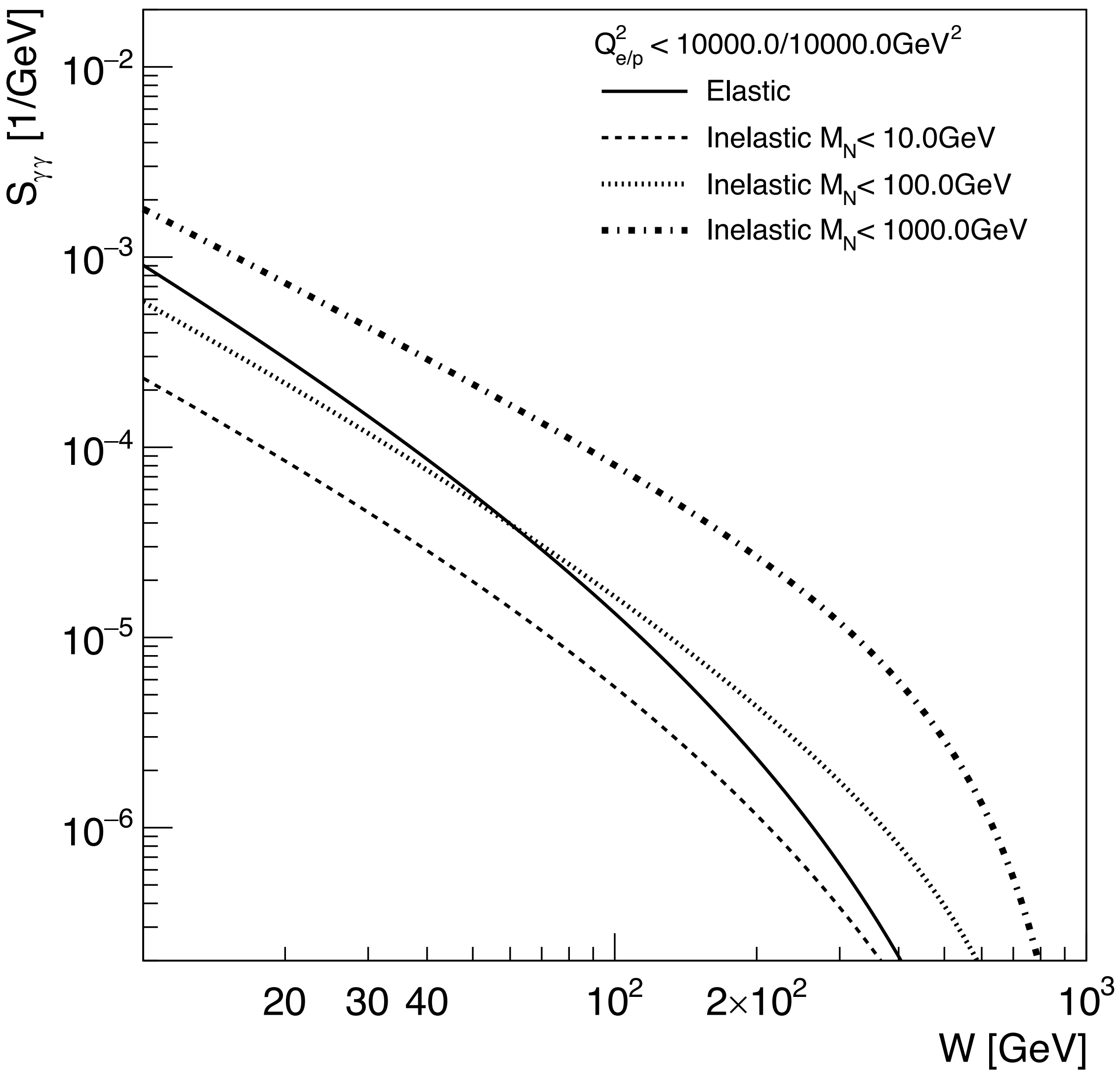
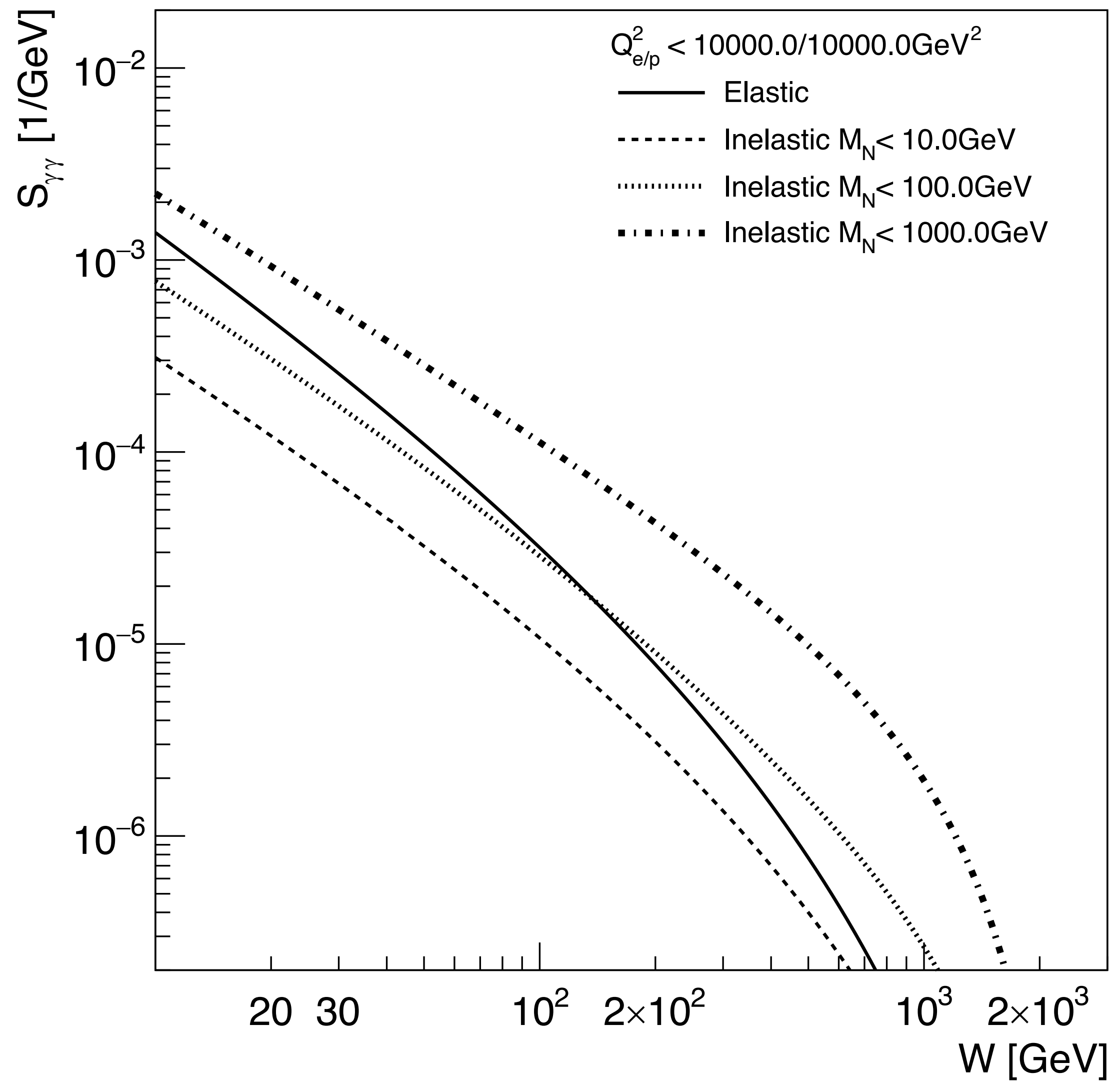


FIG. 3. Projected photon collider sensitivity of $\gamma\gamma \to \tilde{\ell}\tilde{\ell}$ using 13 TeV proton-tagged LHC collisions. Solid lines (this Letter) show the 2σ sensitivity contours for integrated luminosities of 100 fb^{-1} (blue) and 300 fb^{-1} (purple), along with 5σ at 300 fb^{-1} (pink). A simplified model of slepton mediators $\tilde{\ell}$ with a fourfold mass degeneracy decaying to neutralino DM $\tilde{\chi}_1^0$ is considered. Filled regions denote constraints from ATLAS 2ℓ 0 jets [11,12] (yellow), 2ℓ ISR searches [14] (pink), and LEP for partners of the right-handed muons $\tilde{\mu}_R$ [15–17] (orange). Dashed lines indicate parameter space favored by relic abundance $\Omega_{DM}h^2$ [4] (gray) and muon $(g-2)_\mu$ [8] (green) measurements, computed using MICROMEGAs [80].

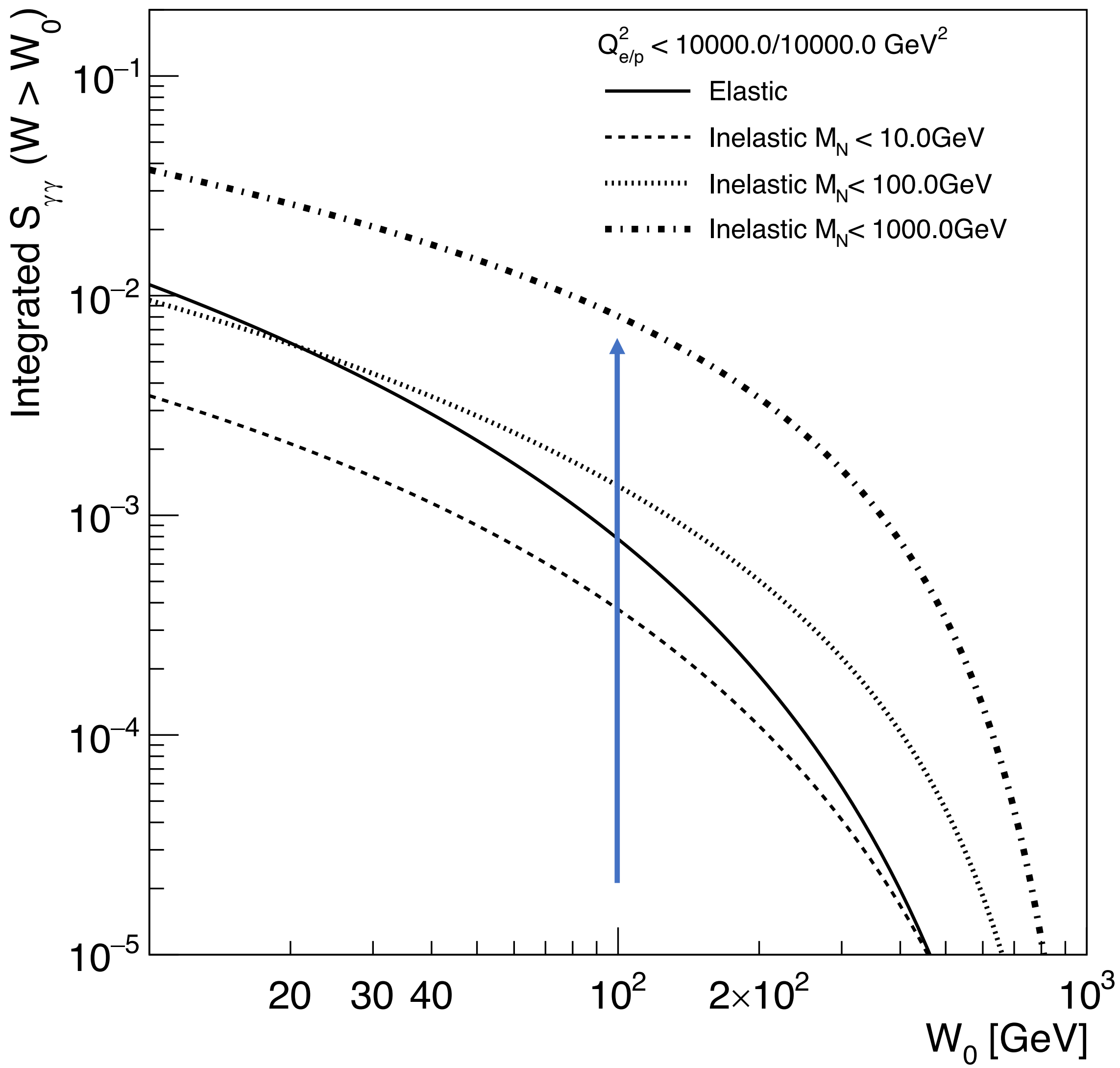
Needs re-visiting for the LH*e*C and FCC-*eh* cases

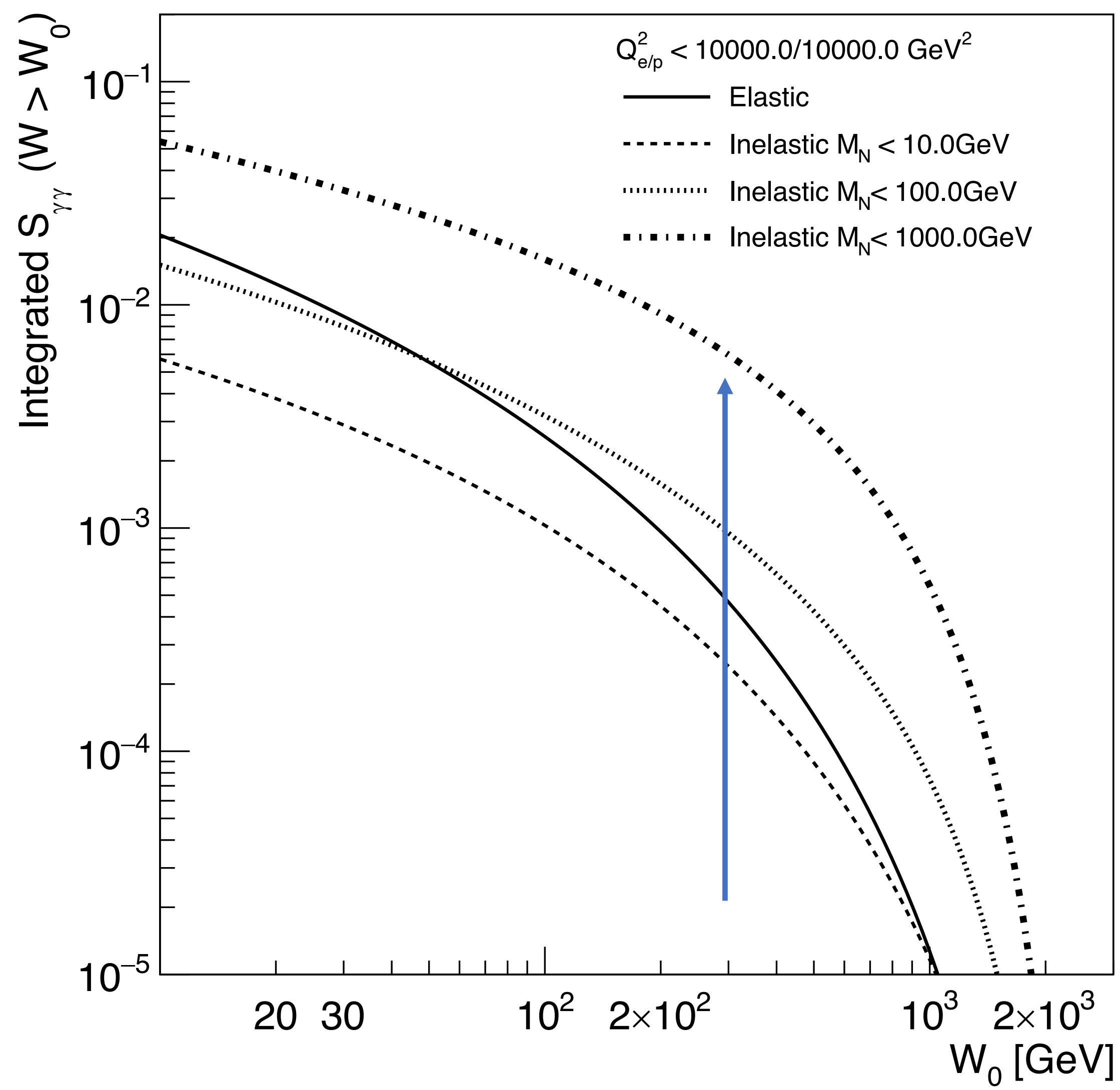
LHeC *vs.* FCC-*eh*





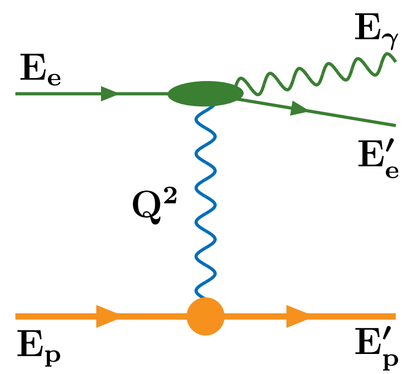
LHeC *vs.* FCC-*eh*

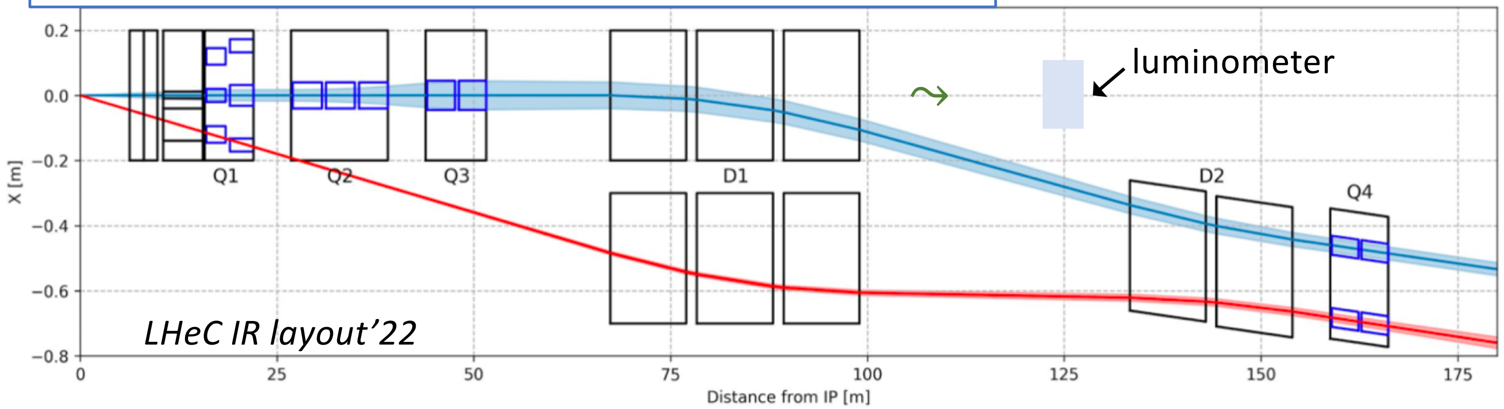


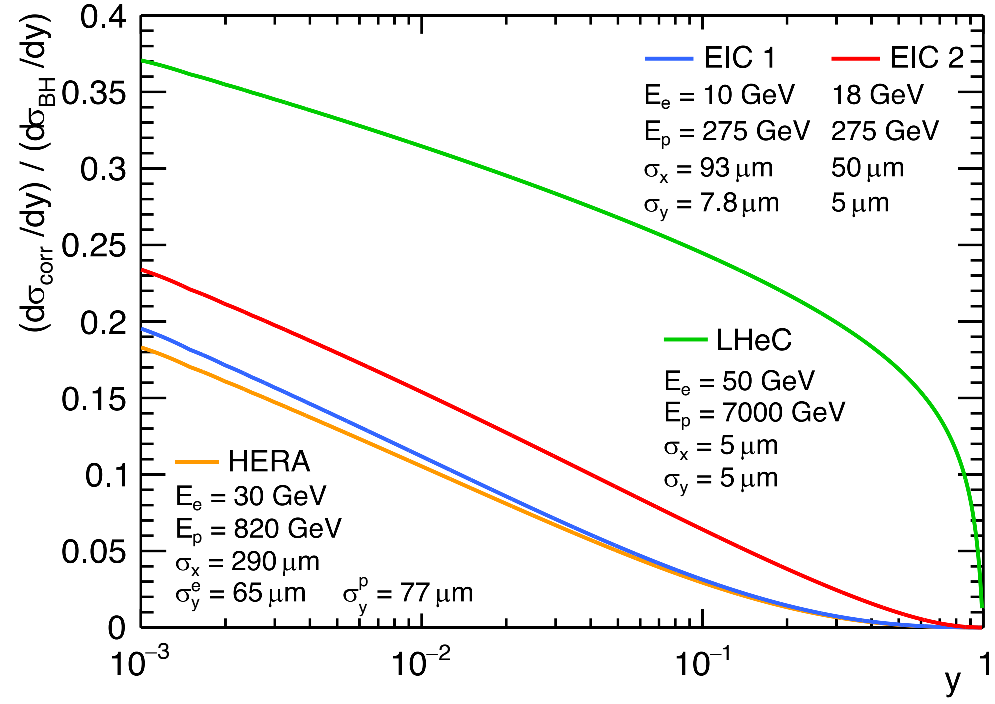


ep (& eA) luminosity

To get precise pdf/*parton* luminosities one needs to measure *ep* luminosity with high precision, at ≲ 1%. As was shown at HERA, *ep* bremsstrahlung is an excellent candidate for such a task.







At LHeC (and FCC-*eh*) bremsstrahlung spectrum, where $y = E_\gamma / E_e$, will be strongly distorted over **entire** range of photon energies!
https://indico.desy.de/event/28202/contributions/104121/

However, rates of high energy bremsstrahlung will be extremely high at LHeC, well in excess of 1 GHz, and in addition strong **Beam-Size Effect** will take place – *effective* bremsstrahlung *suppression* at high energies due to small lateral beam-sizes of **both** colliding beams:

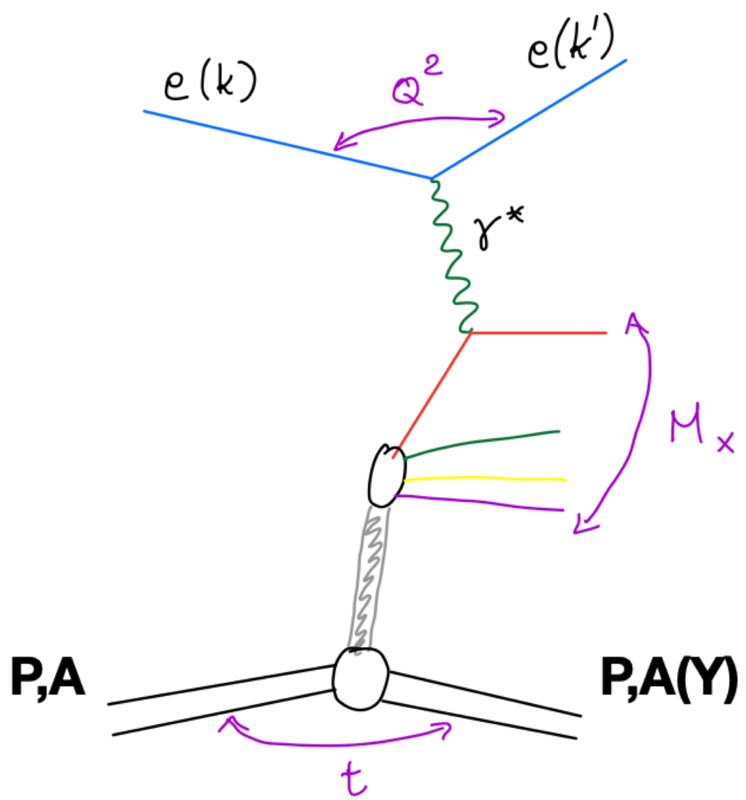
Event rate = Luminosity × cross section

where colliding particles are represented by PLANE waves – but this *assumption* **breaks down** if the lateral beam sizes are comparable to relevant impact parameter of a process. Its understanding can be deeply tested by measuring the bremsstrahlung spectrum while displacing a hadron beam:
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.103.L051901

Dedicated forward instrumentation is needed to cope with such challenges – see, for example:
https://iopscience.iop.org/article/10.1088/1748-0221/16/09/P09023

From $\gamma\gamma$ to $\gamma\mathbb{P}$ interactions

Inclusive Diffraction in e p(A)



t	4-momentum transfer squared
$x_{\rm Bj} = \frac{Q^2}{2p \cdot q}$	Bjorken x
$Q^2 = -q^2$	(minus) photon virtuality
$\xi \equiv x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$	momentum fraction of the Pomeron w.r.t hadron
$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$	momentum fraction of parton w.r.t Pomeron

$$x_{Bj} = x_{IP}\beta$$

From A. Staśto seminar

Rapidity gap $\ln 1/x_{IP}$

Inclusive diffraction: system X can contain anything (jets, heavy quarks),
Can learn about structure of the diffractive exchange

Diffractive structure functions

$$\frac{d^3\sigma^D}{dx_{IP}\,dx\,dQ^2} = \frac{2\pi\alpha_{\rm em}^2}{xQ^4} Y_+\,\sigma_r^{D(3)}(x_{IP},x,Q^2)$$

3 variables

$$Y_+ = 1 + (1-y)^2$$

Reduced diffractive cross section depends on two structure functions :

$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{Y_+} F_L^{D(3)}$$

Transverse photon polarization and longitudinal polarization

For y not to close to unity we have: $\sigma_r^{D(3)} \simeq F_2^{D(3)}$

From A. Staśto seminar

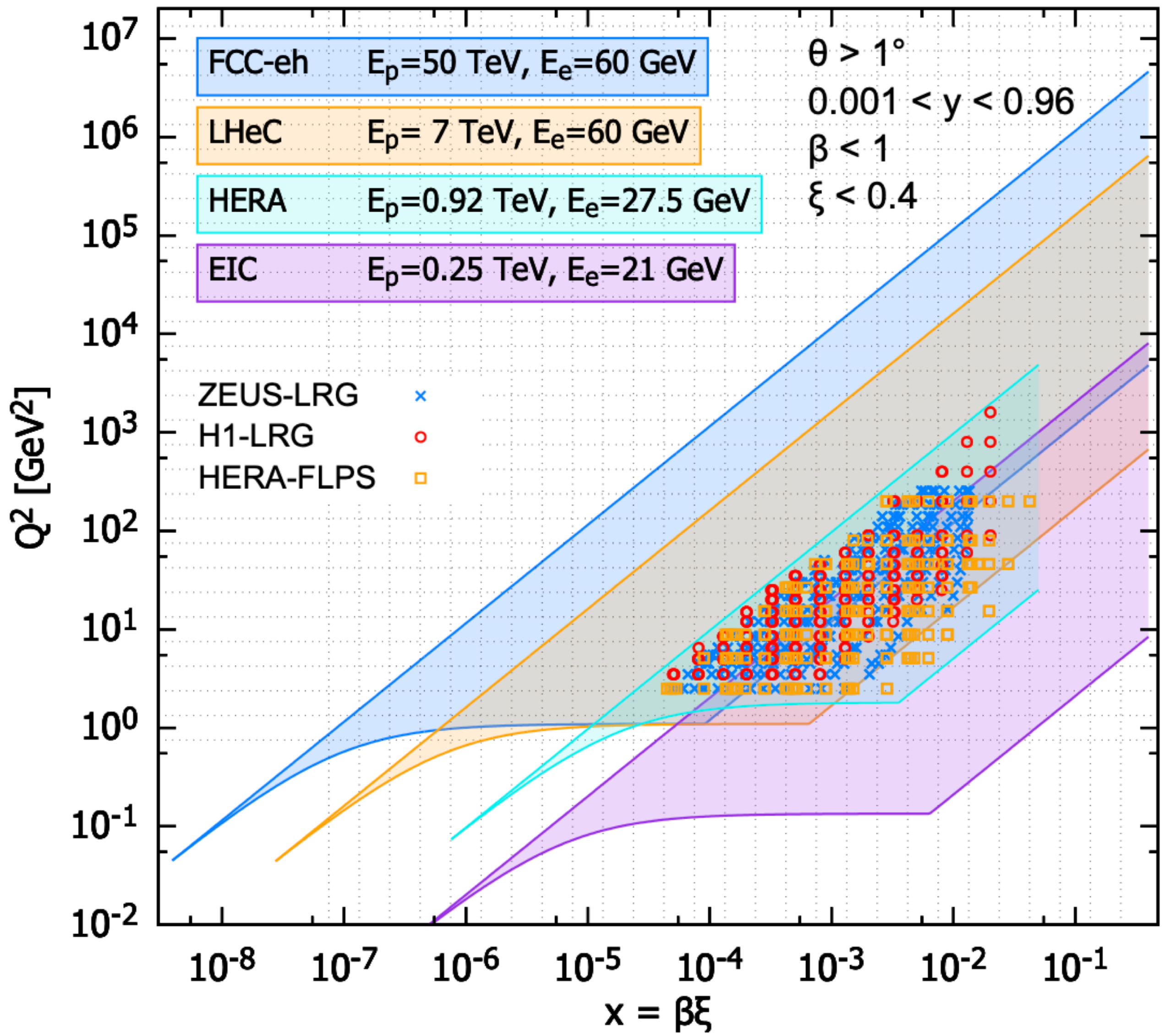
Integrated vs unintegrated structure functions over t:

$$F_{T,L}^{D(3)}(x,Q^2,x_{IP}) = \int_{-\infty}^{0} dt F_{T,L}^{D(4)}(x,Q^2,x_{IP},t)$$

4 variables

$$F_2^{D(4)} = F_T^{D(4)} + F_L^{D(4)}$$

Phase space of HERA and future colliders



EIC: large x, up by factor 10, small / moderate Q^2

LHeC: small x, xmin down by factor 20, wide range of Q^2, up by factor 100

From A. Staśto seminar

FCC-eh: very small x, down by factor 200, Q^2 up by factor 1000

LH*e*C as a $\gamma\mathbb{P}$ collider

“The precise measurement of **diffractive DIS over a wide kinematic range can provide unique insights into many facets of the strong interaction dynamics**. […] the mechanism through which a composite object [$\mathbb{P}$] interacts perturbatively can offer information about confinement and in general about emergent phenomena in strong interactions. It was established some time ago that the diffractive phenomena are closely related to low-*x* dynamics, and in particular to the partonic structure of the proton in this regime. Therefore, an **investigation of diffraction can offer unique insights into the role and importance of higher twists and nonlinear parton evolution**."

P. Agostini *et al., J. Phys. G* **48** 110501 (2021)

In addition to the inclusive diffraction, there are many exciting studies of exclusive and semi-exclusive diffraction, **both** for *ep* and *eA* interactions, as for example:

- Jets and HF in diffraction and testing the diffractive factorization
- Diffractive vector meson production and testing non-linear effects at very low-x

LH*e*C as a $\gamma\gamma$ and $\gamma\mathbb{P}$ collider: summary

LH*e*C will complete the HL-LHC science in a very profound and relevant way, both in the QCD and Electroweak/Higgs sectors

+

LH*e*C (and FCC-*eh*) offers practically ideal conditions for studying high energy $\gamma\gamma$ interactions

Scientific potential of $\gamma\gamma$ physics at the LH*e*C (and at the FCC), both in testing the electroweak theory and for New Physics searches, needs to be deeply explored

+

LH*e*C and FCC-*eh* offer huge extensions of the kinematical range for studying diffractive phenomena in *ep* **and** *eA* interactions

These investigations have only started, so stay tuned or consider joining!

Thank you for attention!

Basic research is what I am doing when I don’t know what I am doing.
-- *Wernher von Braun*

High energy $\gamma\gamma$ colliders: Equivalent Photon Approximation

$$\sigma_{ep} = \int dW\, S_{\gamma\gamma}\sigma_{\gamma\gamma}$$

$$S_{\gamma\gamma} = \frac{2}{W}\int_{W^2/s}^{1} dy_e \Phi_e(y_e) y_p \Phi_p(y_p)$$

EPA: Budnev *et al.* (1975)

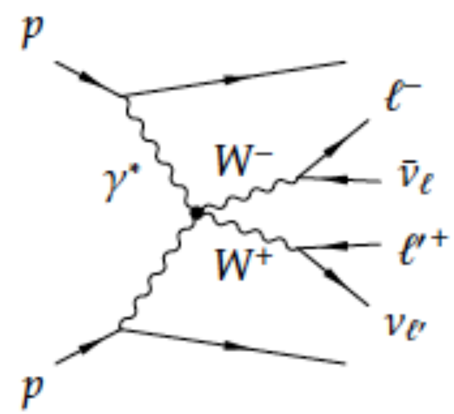
$S_{\gamma\gamma}$ is analogous to the partonic luminosity, and its integral $\int_{W_0}^{\sqrt{s}} \mathrm{d}W\, S_{\gamma\gamma}$ provides a fraction of the *pp* luminosity "available" for $\gamma\gamma$ collisions above W_0

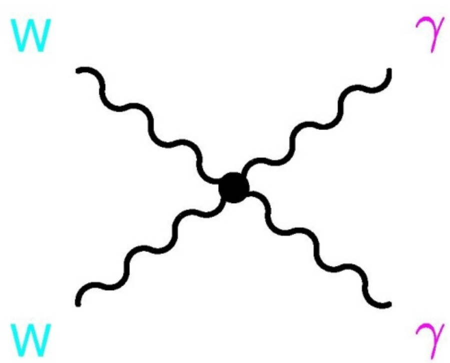
Note: There are *elastic* and *inelastic* (when the proton dissociates to p^*) contributions to $S_{\gamma\gamma}$

Physics with $\gamma\gamma \rightarrow$ WW (and ZZ)

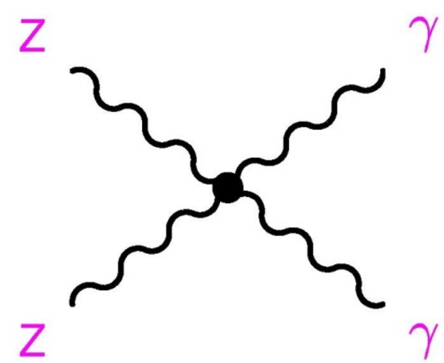
$\gamma\gamma \rightarrow$ WW and ZZ (=0 at tree level in SM) pairs as a powerful test bench for the gauge boson sector at the LHC

Search for anomalous quartic couplings

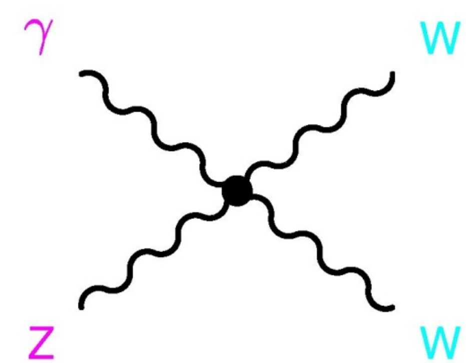




a_0^W a_c^W



a_0^Z a_c^Z



a_n

LHC PHYSICS

CMS sees first direct evidence for $\gamma\gamma \rightarrow WW$

In a small fraction of proton collisions at the LHC, the two colliding protons interact only electromagnetically, radiating high-energy photons that subsequently interact or "fuse" to produce a pair of heavy charged particles. Fully exclusive production of such pairs takes place when quasi-real photons are emitted coherently by the protons rather than by their quarks, which survive the interaction. The ability to select such events opens up the exciting possibility of transforming the LHC into a high-energy photon–photon collider and of performing complementary or unique studies of the Standard Model and its possible extensions.

The CMS collaboration has made use of this opportunity by employing a novel method to select "exclusive" events based only on tracking information. The selection is made by requesting that two – and only two – tracks originate from a candidate vertex for the exclusive two-photon production. The power of this method, which was first developed for the pioneering measurement of exclusive production of muon and electron pairs, lies in its effectiveness even in difficult high-luminosity conditions with large event pile-up at the LHC.

The collaboration has recently used this approach to analyse the full data sample collected at $\sqrt{s}$=7 TeV and to obtain the first direct evidence of the $\gamma\gamma \rightarrow WW$ process. Fully leptonic W-boson decays have been measured in final states characterized by opposite-sign and opposite-flavour lepton pairs where one W decays into an electron and a neutrino, the other into a muon and a neutrino (both neutrinos leave undetected). The leptons were required to have: transverse momenta p_T>20 GeV/c and pseudorapidity $|\eta|$<2.1; no extra track associated with their vertex; and for the pair, a total p_T>30 GeV/c. After applying all selection criteria, only two events remained – compared with an expectation of 3.2 events: 2.2 from $\gamma\gamma \rightarrow WW$ and 1 from background (figure 2).

The lack of events observed at large values of transverse momentum for the pair, which would be expected within the Standard Model, allows stringent limits on anomalous quartic $\gamma\gamma WW$ couplings to be derived. These surpass the previous best limits, set at the Large Electron–Positron collider and at the Tevatron, by up to two orders of magnitude (figure 3).

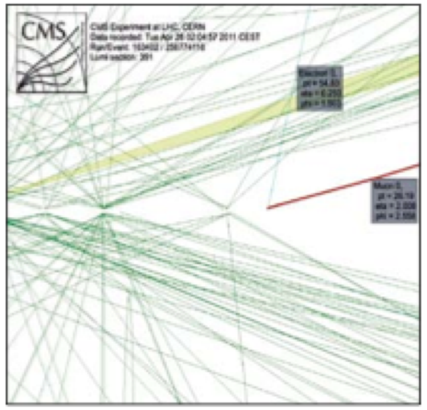


Fig. 1. Above: Proton–proton collisions recorded by CMS at $\sqrt{s}$=7 TeV, featuring candidates for the exclusive two-photon production of a W^+W^- pair, where one W boson has decayed into an electron and a neutrino, the other into a muon and a neutrino.

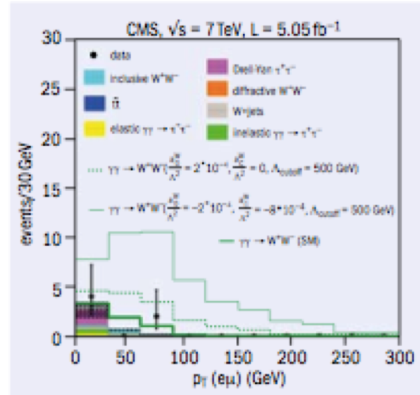


Fig. 2. Top right: The p_T distribution of eμ pairs in events with no extra tracks compared with the Standard Model expectation (thick green line) and predictions for anomalous quartic gauge couplings (dashed green histograms).

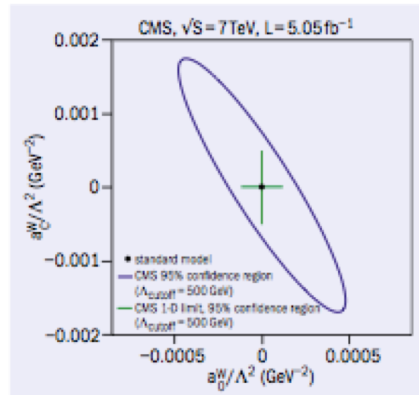


Fig. 3. Right: Limits on anomalous quartic $\gamma\gamma WW$ couplings.

Further reading

CMS collaboration 2013 arXiv:1305.5596 [hep-ex], submitted to *JHEP*.

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
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Hot news back in 2013…

LHC as a high energy $\gamma\gamma$ collider: **recent results II**

"The observation of forward proton scattering in association with lepton pairs ($e^+e^- + p$ or $\mu^+\mu^- + p$) produced via photon fusion is presented. The **scattered proton is detected by the ATLAS Forward Proton spectrometer**, while the leptons are reconstructed by the central ATLAS detector. Proton-proton collision data recorded in 2017 at a center-of-mass energy of √s = 13 TeV are analyzed, corresponding to an integrated luminosity of **14.6 fb⁻¹**."

doi: 10.1103/PhysRevLett.125.261801

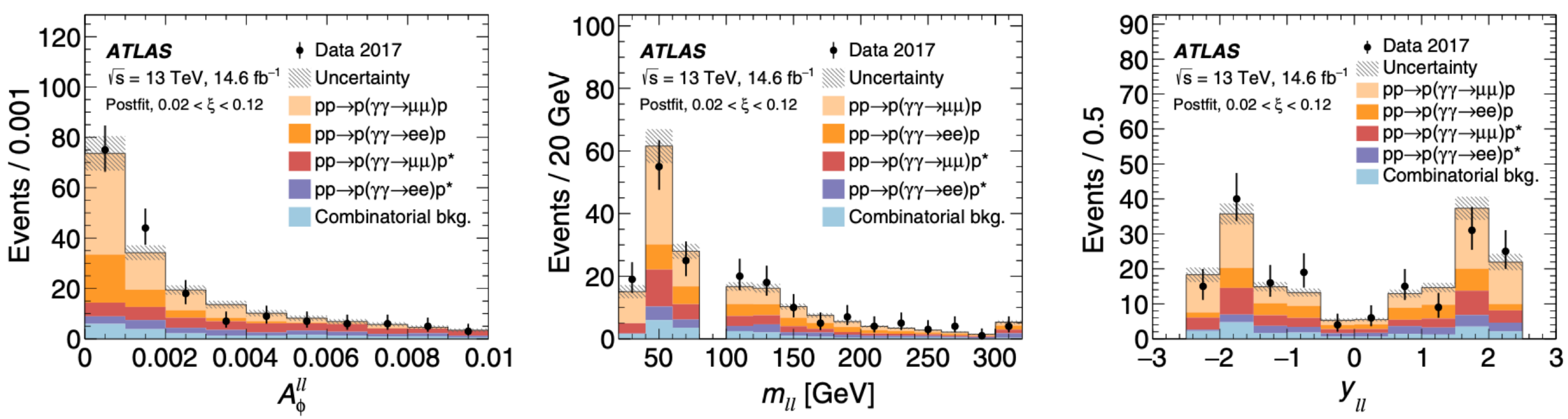


FIG. 3. Distributions of dilepton acoplanarity $A_\phi^{\ell\ell}$ (left), invariant mass $m_{\ell\ell}$ (center), rapidity $y_{\ell\ell}$ (right) satisfying $\xi_{\ell\ell}, \xi_{\rm AFP} \in [0.02, 0.12]$, and $|\xi_{\rm AFP} - \xi_{\ell\ell}| < 0.005$ for at least one AFP side. Events with $70 < m_{\ell\ell} < 105$ GeV are vetoed. The total prediction comprises the signal and combinatorial background processes, where p^* denotes a dissociated proton. The simulated predictions are normalized to data to illustrate the expected signal composition. The rightmost bin of the $m_{\ell\ell}$ distribution includes overflow. The hatched band indicates the combined statistical and systematic uncertainties of the prediction. Error bars denote statistical uncertainties of the data.

SUSY?

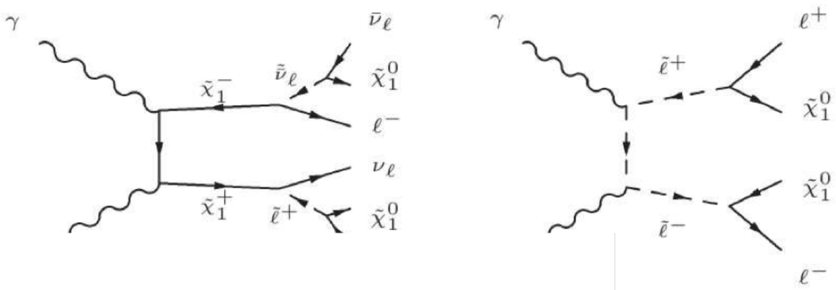
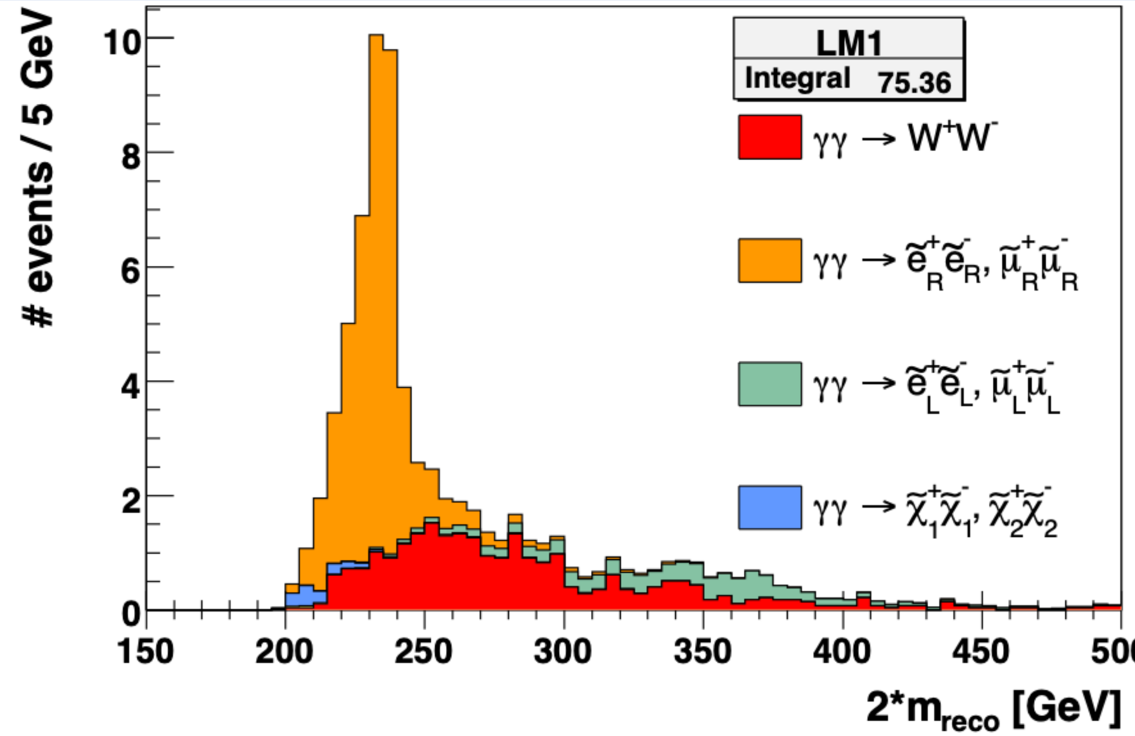


Table 3
LM1 signal and WW background cross sections before and after the acceptance cuts (including the flavor selection), and after the analysis cuts. Values are given in fb. ($\ell = e, \mu.\quad i = 1,2$).

Processes	σ	σ_{acc}	$\sigma_{acc+ana}$
$\gamma\gamma \to \tilde{\ell}^+_R \tilde{\ell}^-_R$	0.798	0.522	0.403
$\gamma\gamma \to \tilde{\ell}^+_L \tilde{\ell}^-_L$	0.183	0.135	0.089
$\gamma\gamma \to \tilde{\tau}^+_i \tilde{\tau}^-_i$	0.604	0.054	0.003
$\gamma\gamma \to \tilde{\chi}^+_i \tilde{\chi}^-_i$	0.642	0.043	0.014
$\gamma\gamma \to H^+ H^-$	0.004	/	/
$\gamma\gamma \to W^+ W^-$	108.5	3.820	0.255

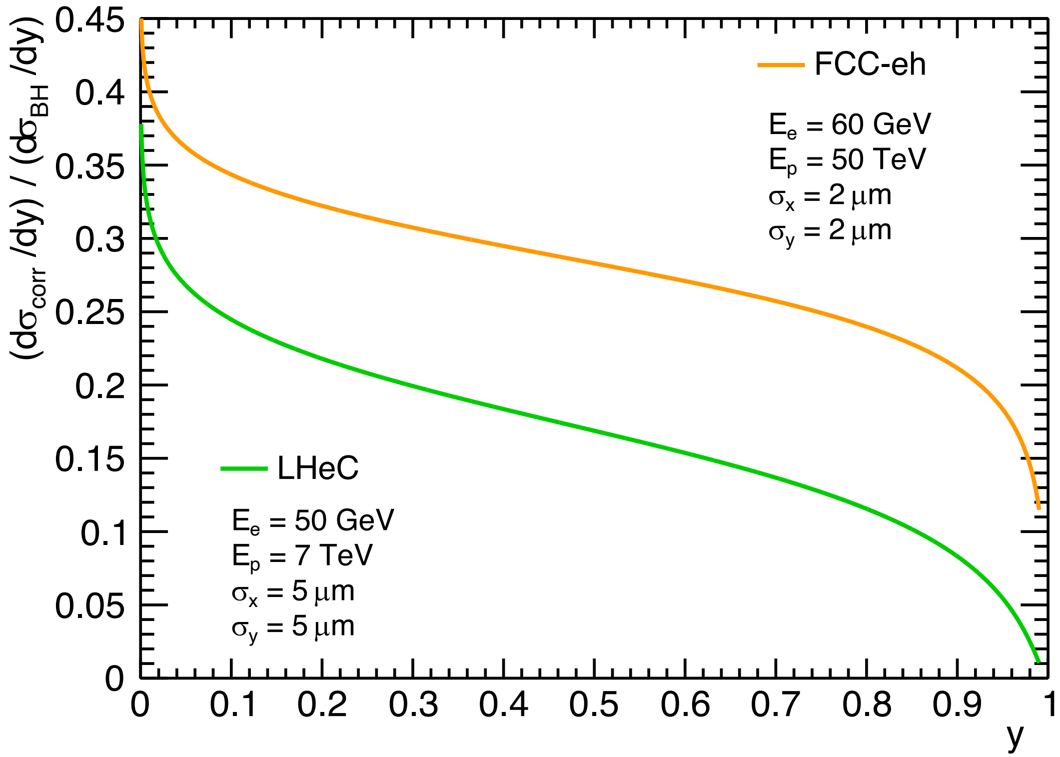


https://doi.org/10.1016/j.nuclphysbps.2008.07.036

Figure 6. Cumulative distributions of the reconstructed mass $2m_{reco}$ for the LM1 signal and the WW background for the intergrated luminosity L = 100 fb^{-1}.

At the *LHeC* and *FCC-eh* the bremsstrahlung spectrum will be strongly suppressed over the entire range of photon energies!

Both the beam sizes as well as beam alignment will have to be very well controlled.



From the DIS2022 Proceedings:
https://zenodo.org/record/7410748#.Y8j6IC8w06U