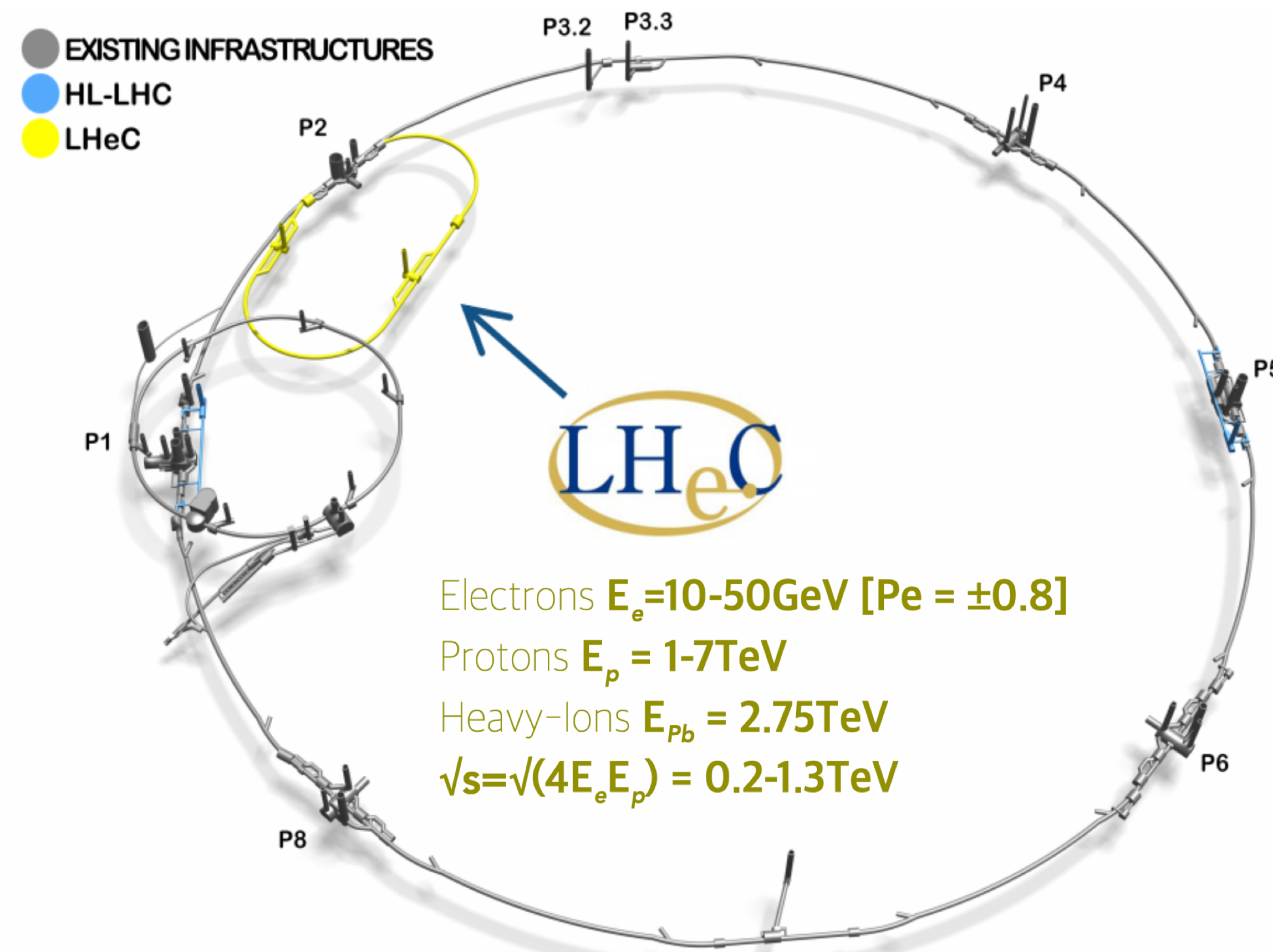
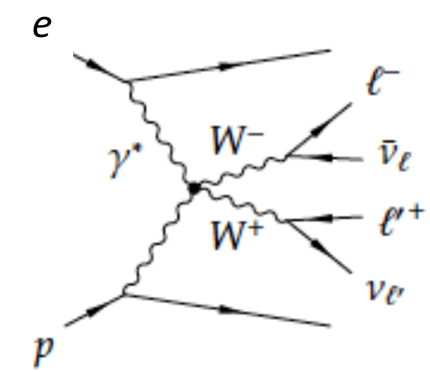
High Energy $\gamma\gamma$ Interactions at the LH*e*C
(and FCC-*eh*)

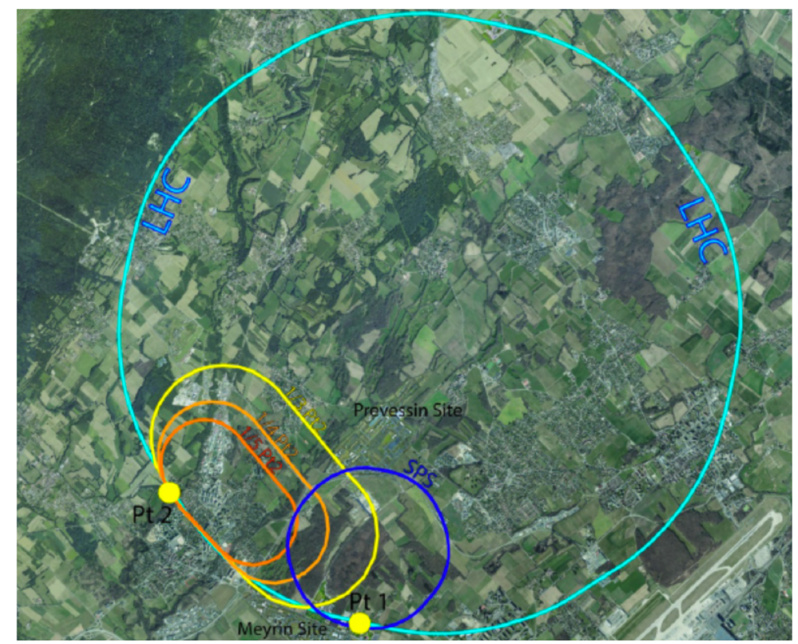
Krzysztof PIOTRZKOWSKI

AGH University of Science and Technology, Kraków

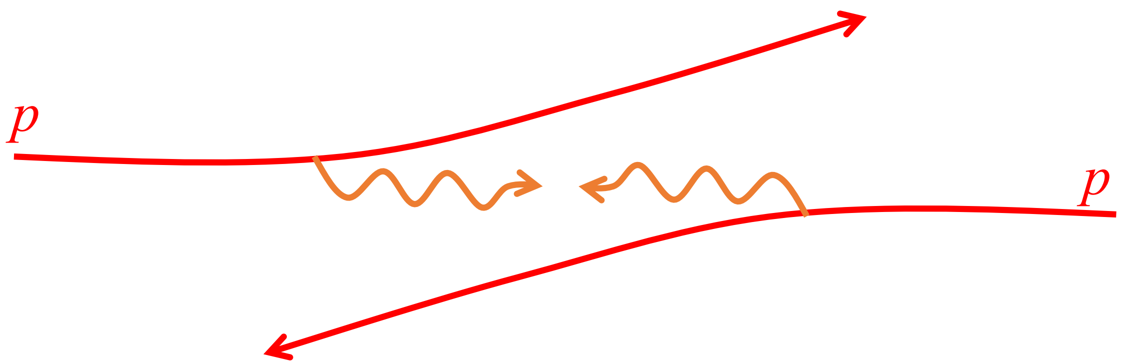


Electrons E_e=10-50GeV [Pe = ±0.8]
Protons E_p = 1-7TeV
Heavy-Ions E_{Pb} = 2.75TeV
$\sqrt{s}=\sqrt{(4E_eE_p)}$ = 0.2-1.3TeV





As an Introduction: **LHC as 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

Highlights:

- **$\gamma\gamma$ 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**

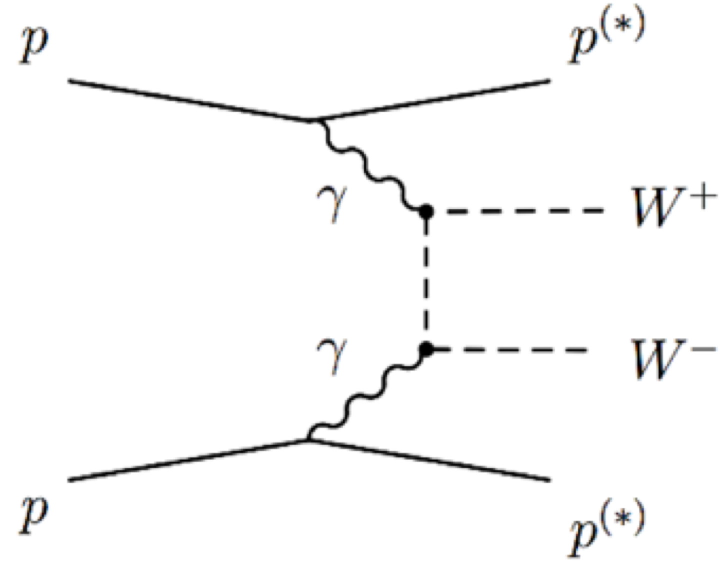
LHC as $\gamma\gamma$ collider: pair production

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,

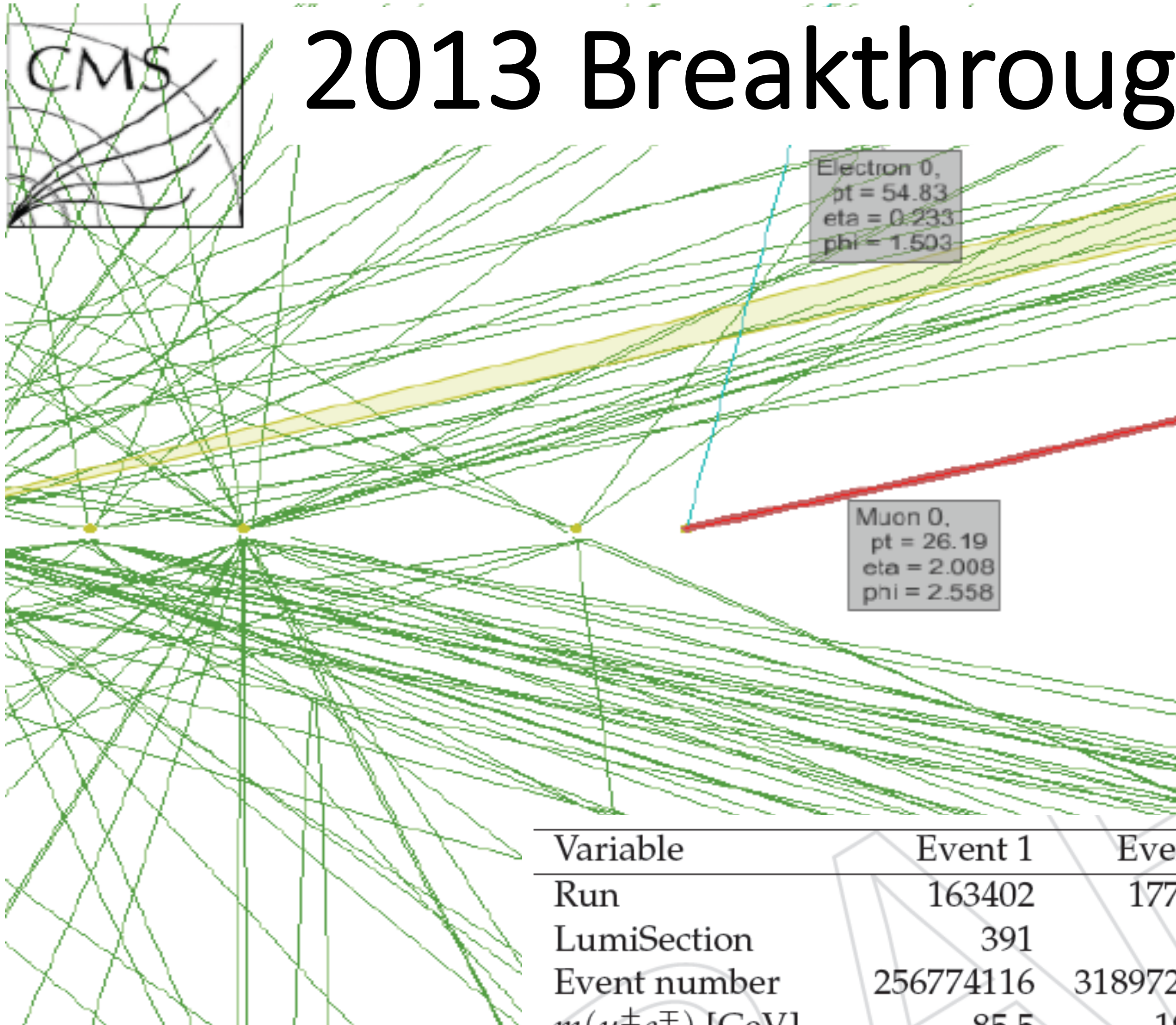
$\gamma\gamma \to WW$ pair production has a very sizable cross-section at the LHC of ~100 fb, and at least × 4, if inelastic production included (p^*)!

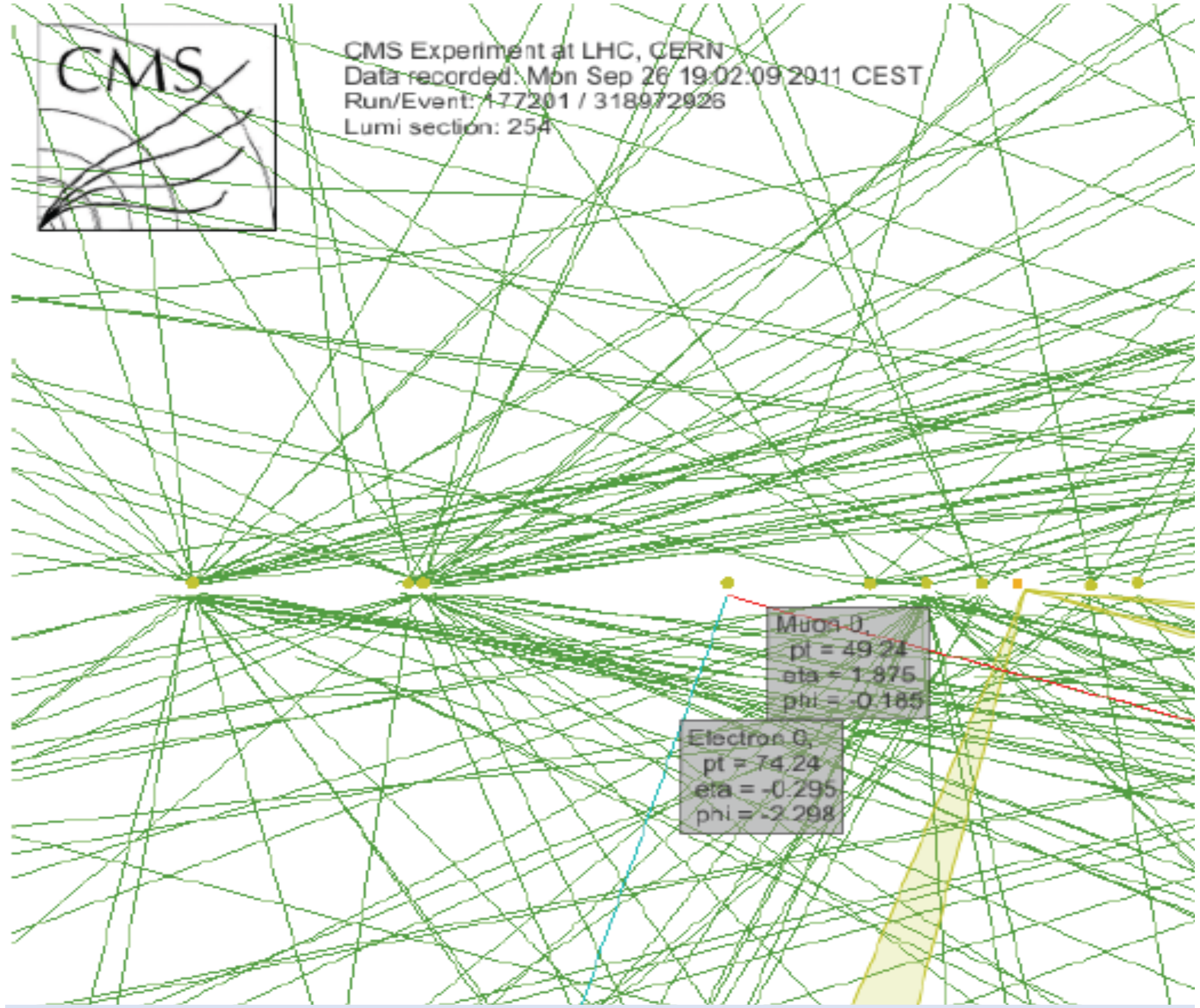


Massive fermions have sizable $\gamma\gamma$ cross-sections up to about 200 GeV masses, for scalars cross-sections are about 5 times smaller, but there is H^{++} case, for example

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

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
$p_{T}(\mu^{\pm})$ [GeV]	26.2	49.2
$E_{T}(e^{\pm})$ [GeV]	54.8	74.2
$\eta(\mu^{\pm})$	2.01	1.88
$\eta(e^{\pm})$	0.23	-0.30

First ever $\gamma\gamma \to WW$!

(at CL > 90%)

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

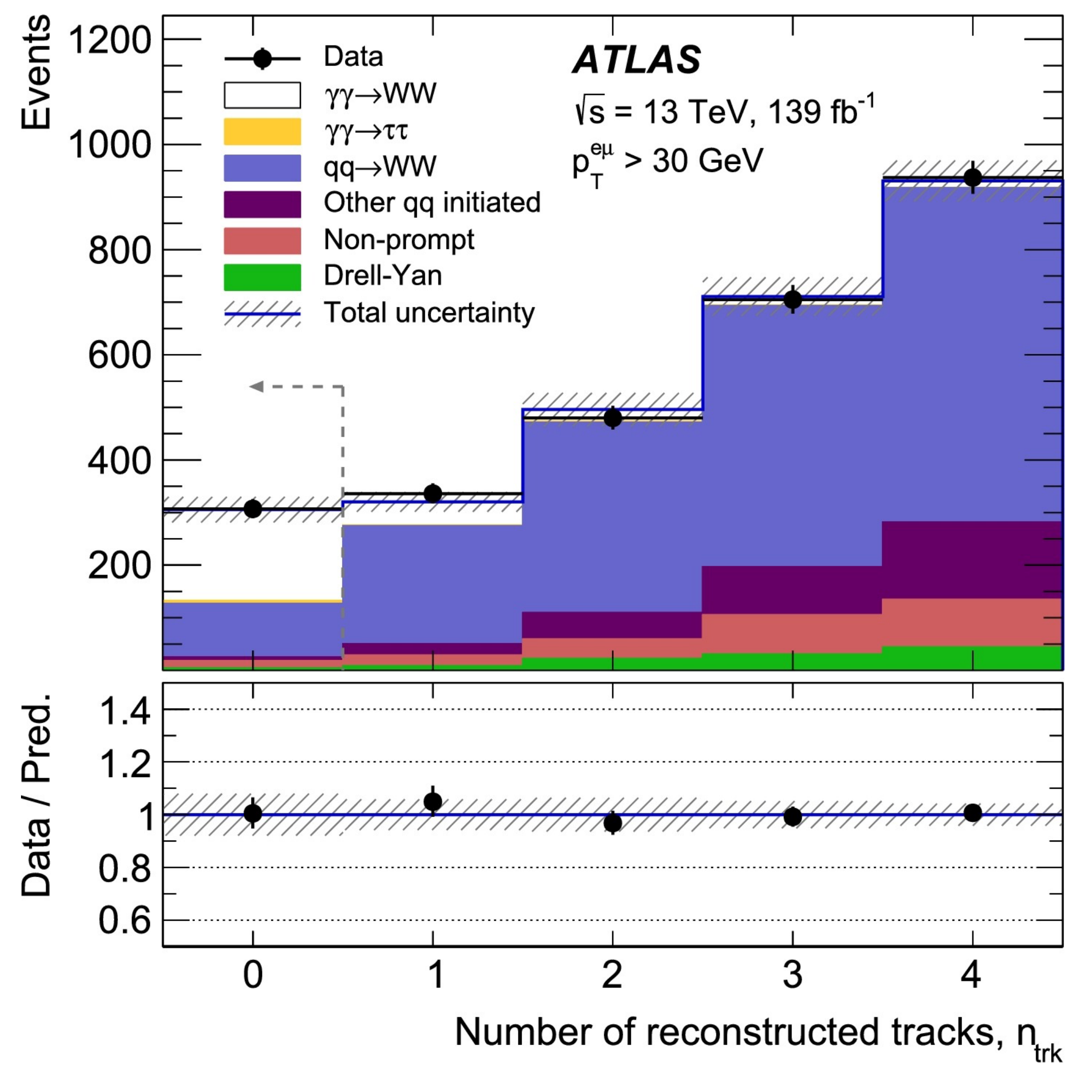
exclusive $W^+W^- \to e^\pm \nu \mu^\mp \nu$

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

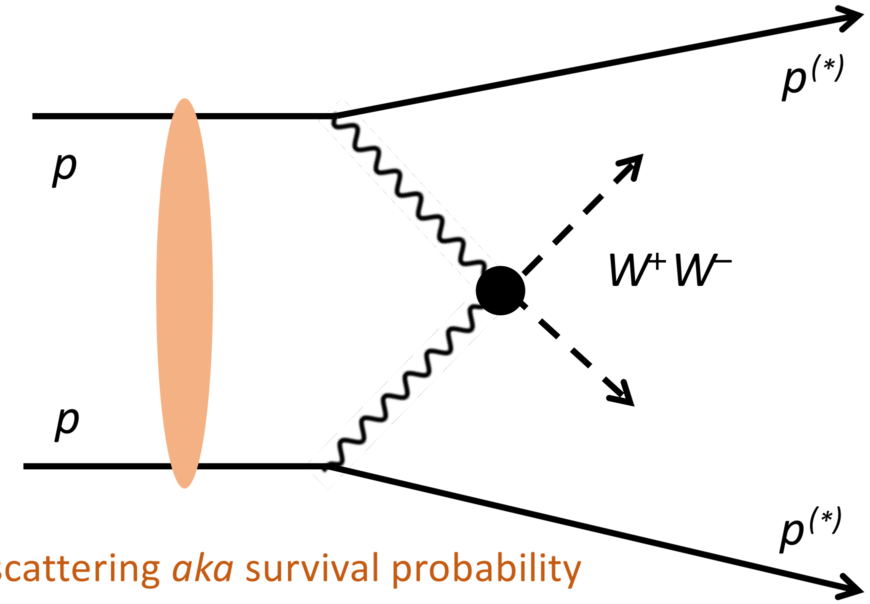
"The data yield in the signal region is 307, compared with 132 background events predicted by the best-fit result. [...] This measurement constitutes **the observation of photon-induced *WW* production in *pp* collisions**, a process for which only evidence was previously reported."

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 high energy $\gamma\gamma$ collider: **challenges**



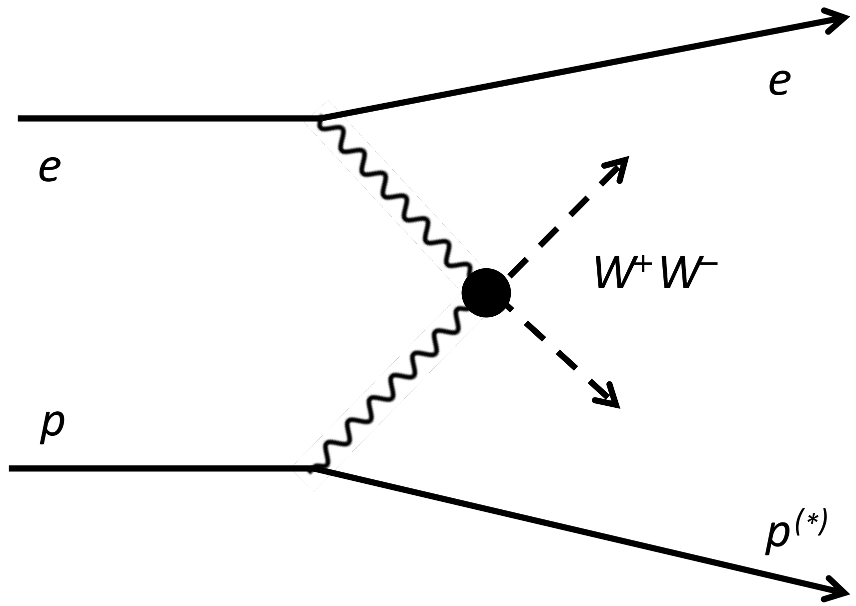
HL-LHC will provide 10 times bigger integrated luminosity, but:

- $S_{\gamma\gamma}$ only marginally higher (thanks to 13 → 14 TeV increase)
- PU yet 4 times higher (≈ 140) than for Run 2 – but new tracking exclusivity might be more performant
- 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 further suppress accidental coincidences!

Major challenges for the high luminosity 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 W

LHeC as a high energy $\gamma\gamma$ collider



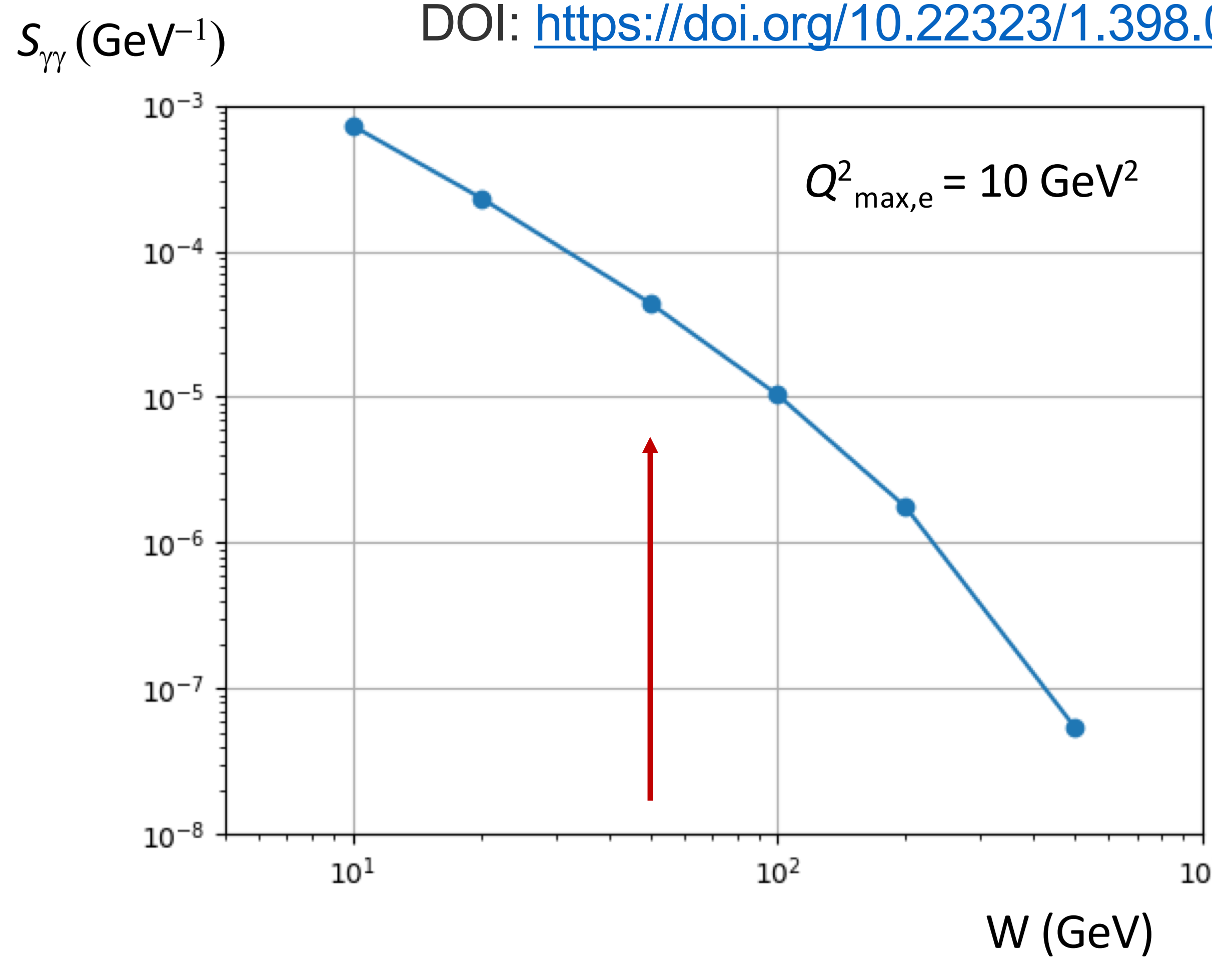
Very high LHeC luminosity is the key here ⇒ more than **1 ab^{-1}** (= 1000 fb^{-1}) is expected for *ep* collisions.

Electrons will have "only" 50 GeV, but **higher** photon flux, as approximately:

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

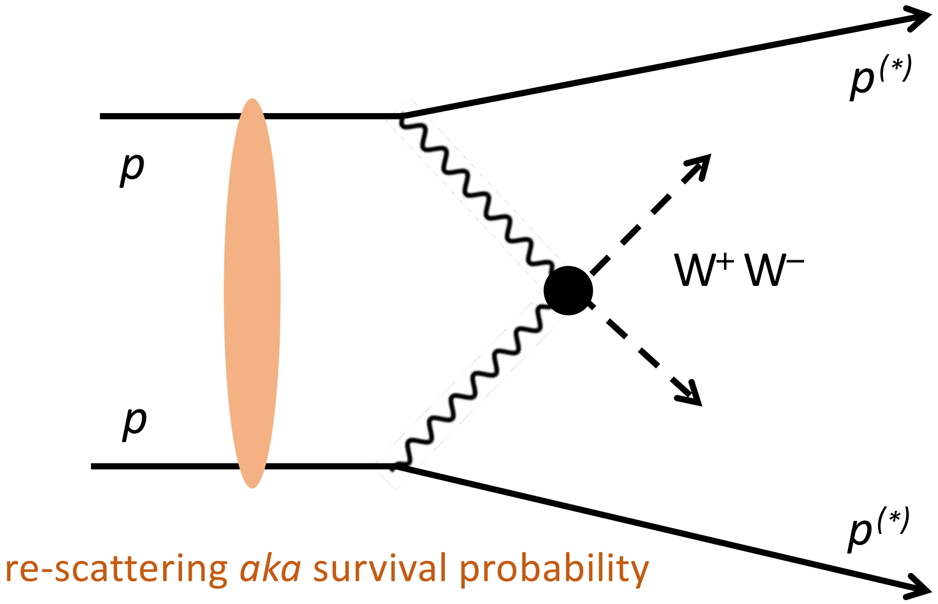
where $Q^2_{min} \propto m^2$, and $Q^2_{max,e}$ can be very high

DOI: https://doi.org/10.22323/1.398.0486

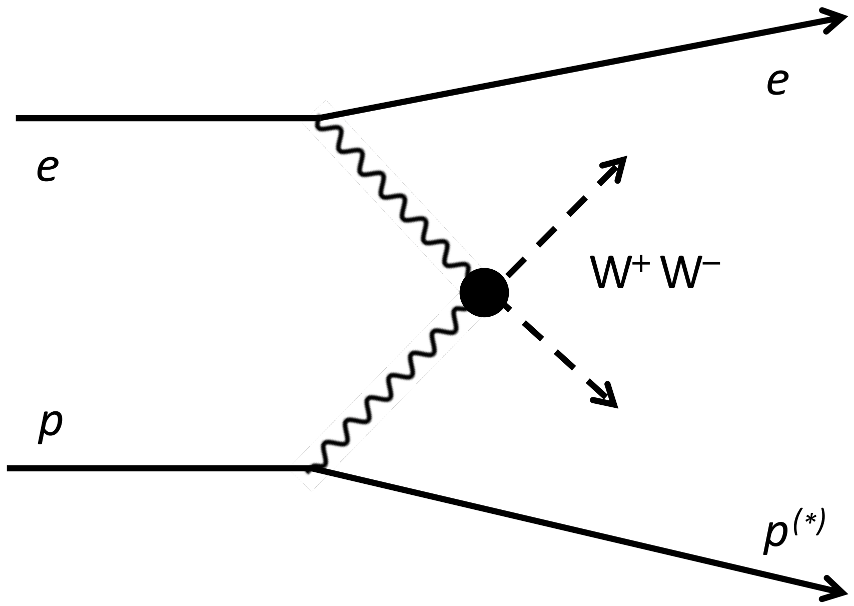


For $W < 50$ GeV the *fully* exclusive $\gamma\gamma$ luminosity spectrum is **higher** at the LHeC than at the HL-LHC!

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



vs.



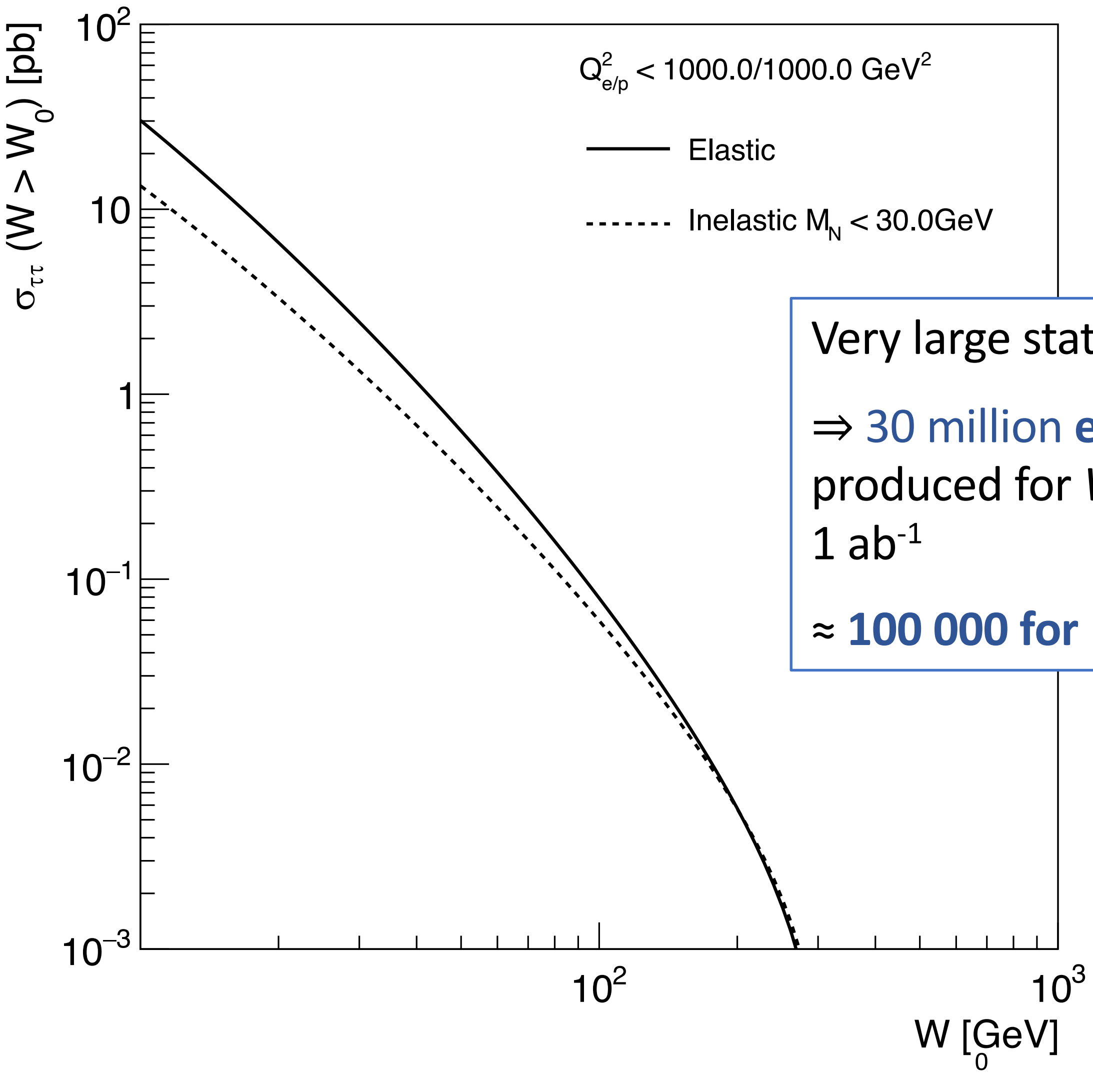
Energy reach for $\gamma\gamma$ interactions is higher at the LHC, however at the highest *W* tagging is not possible and the suppression due to re-scattering becomes large.

Event **pileup is very low at the LHeC** – it is **only 5 %** at the highest *ep* luminosity of **2×10^{34} cm^{-2}s^{-1}**.

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

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

with Y. Yamazaki



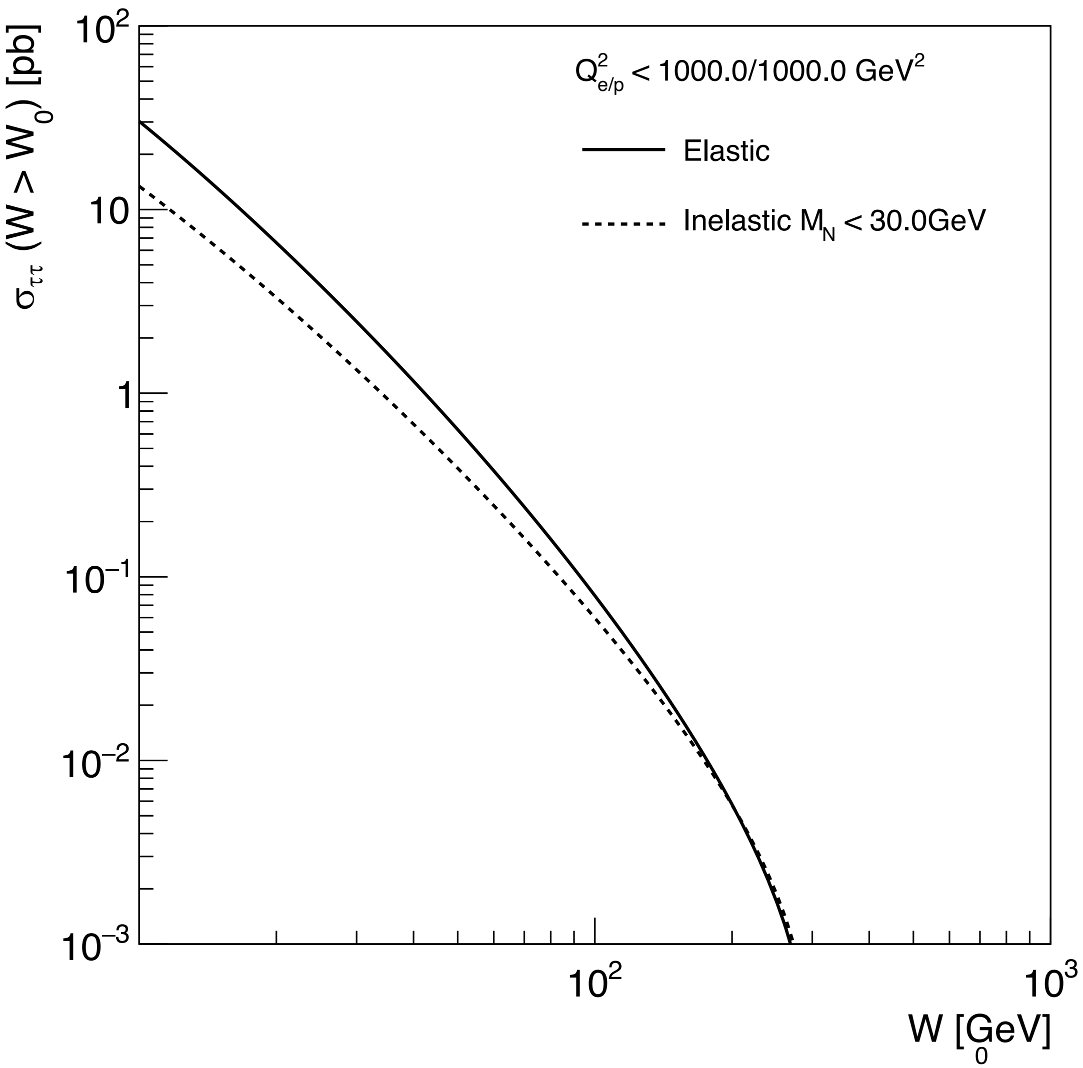
Very large statistics:

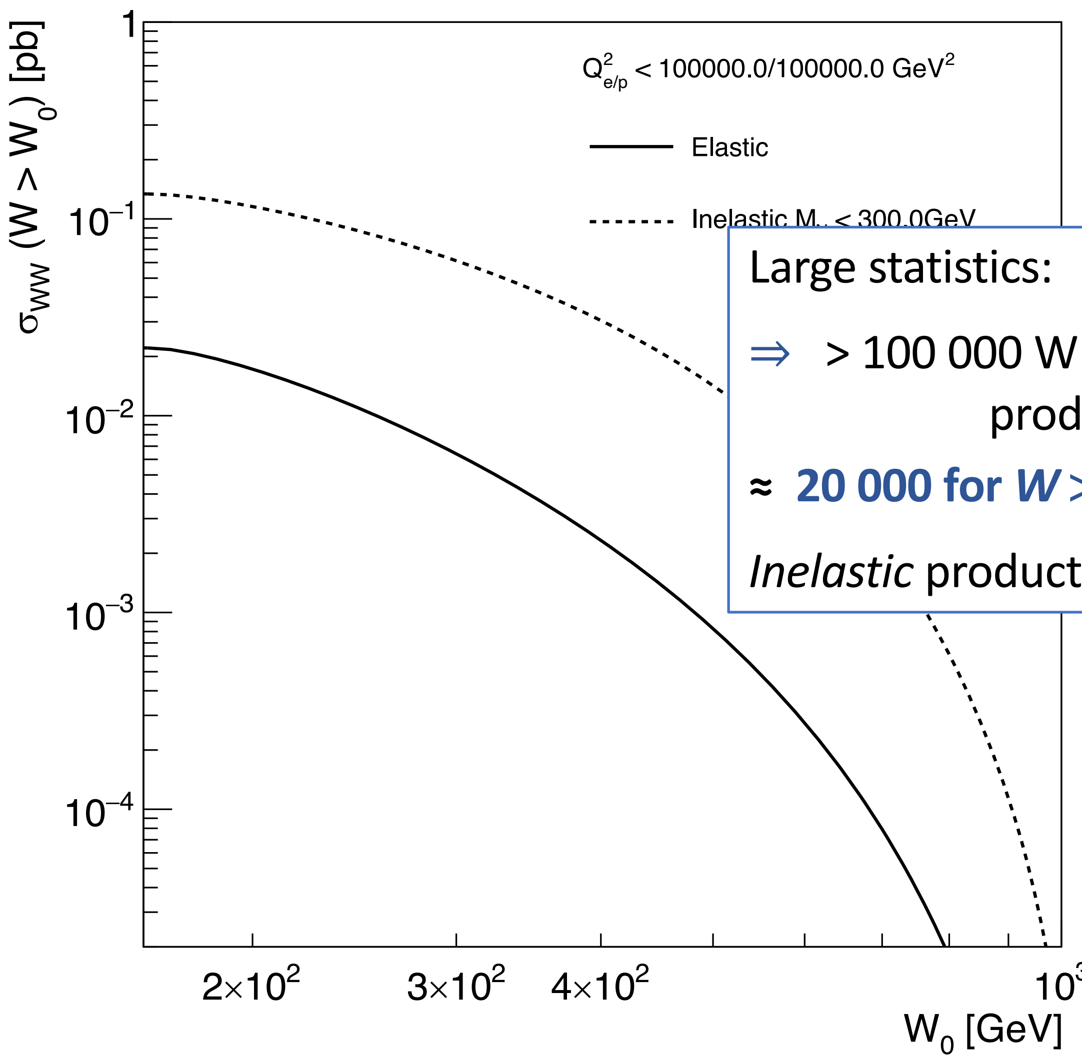
⇒ 30 million **elastic** $\tau\tau$ pairs produced for W **>** 10 GeV at 1 ab^{-1}

≈ **100 000 for *W* > 100 GeV**

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

with Y. Yamazaki





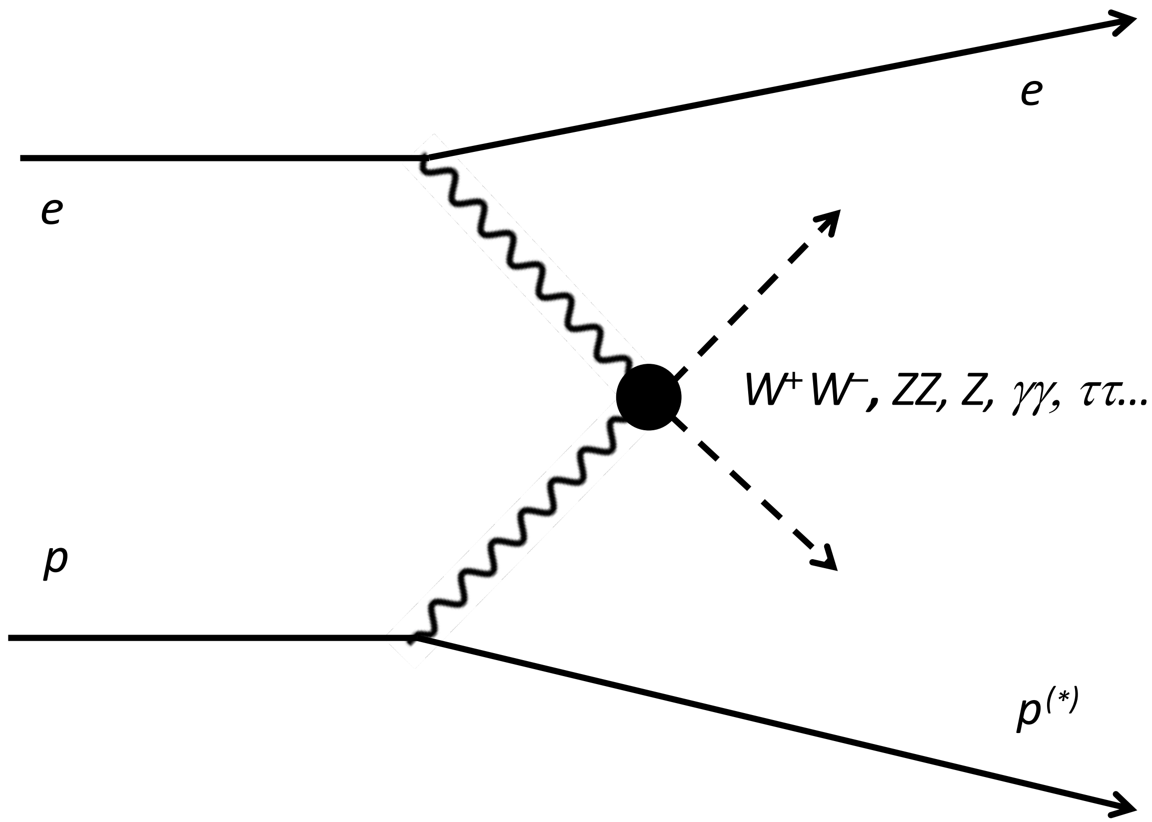
Large statistics:

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

≈ **20 000 for *W* > 500 GeV**

Inelastic production dominant

LH*e*C as very unique, generic high energy $\gamma\gamma$ collider

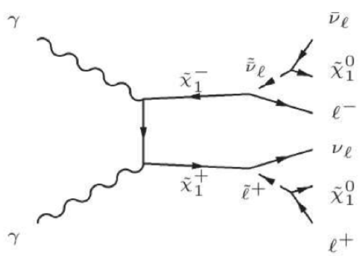


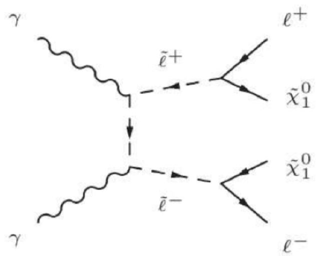
… and big surprises too??

Wide spectrum of $\gamma\gamma$ processes will be studied at the LHeC:

- $\gamma\gamma \to \gamma\gamma$: orders of magnitude higher statistics than for *PbPb* at the HL-LHC + $\gamma\gamma$ tagging ⇒ kinematic fitting
- $\gamma\gamma \to \tau^+\tau^-$: orders of magnitude higher statistics than for *PbPb* at the HL-LHC + $\gamma\gamma$ tagging ⇒ new decay modes
- $\gamma\gamma \to Z$: 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 → 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 + tagging

LH*e*C as high energy $\gamma\gamma$ collider: **new physics?**





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

Needs re-visiting for LH*e*C too…

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

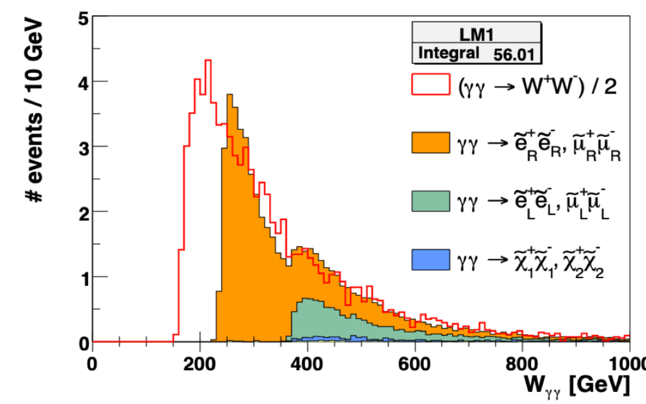
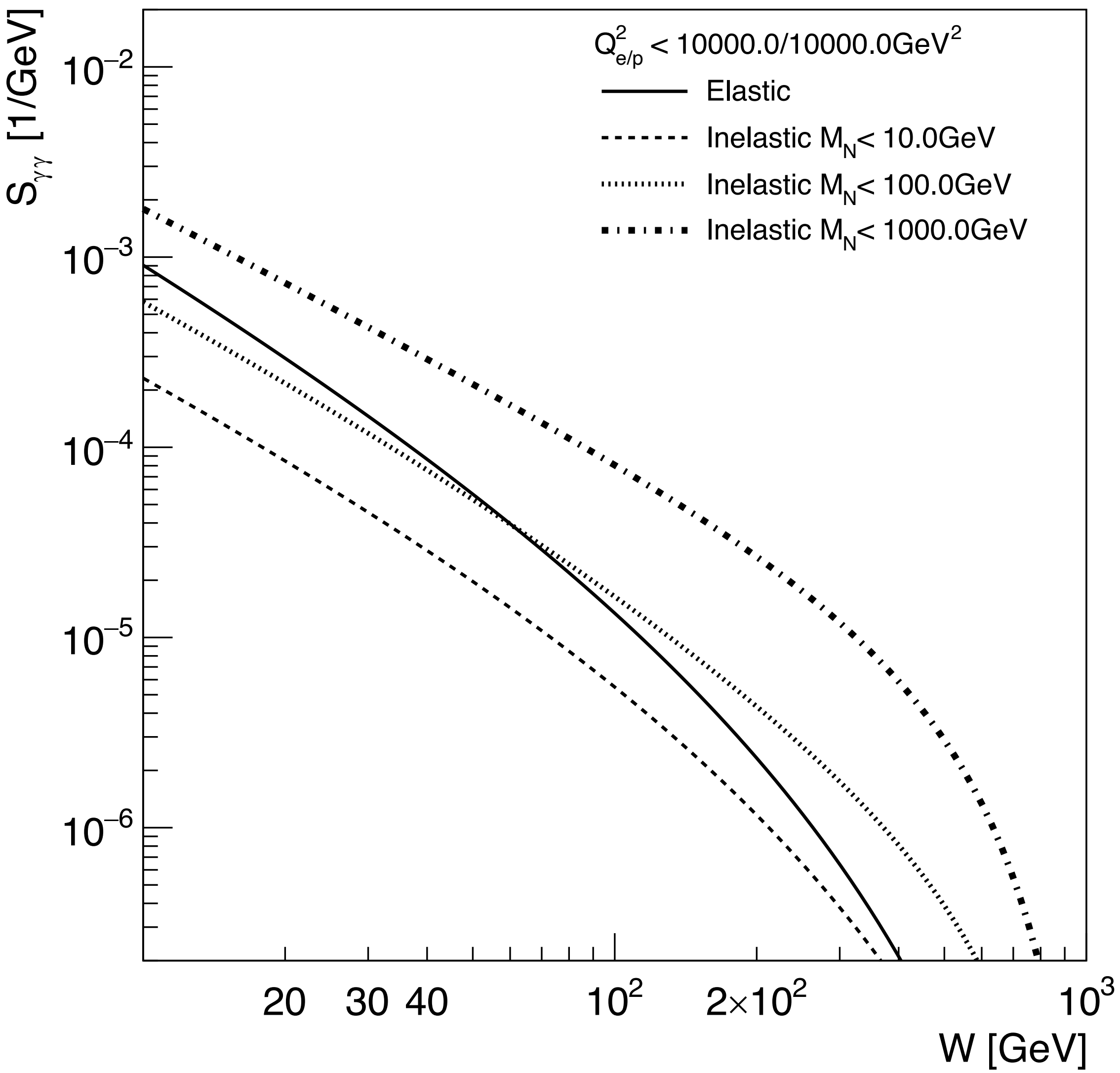
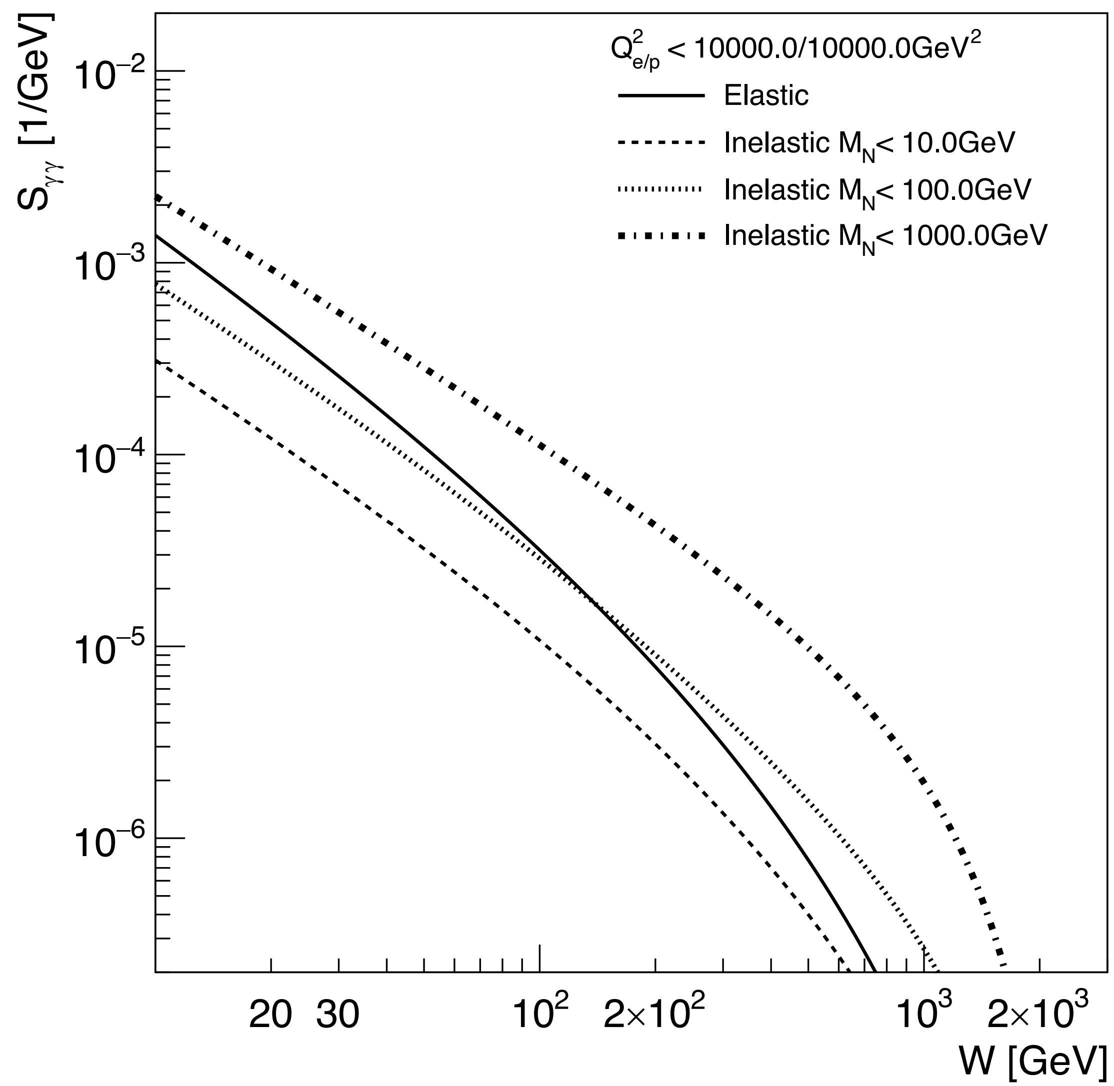


Figure 2. Distribution of two-photon invariant mass $W_{\gamma\gamma}$ for the LM1 benchmark and integrated luminosity L = 100 fb^{-1}. Two visible peaks are due to production thresholds of $\tilde{\ell}^+_R\tilde{\ell}^-_R$ and $\tilde{\ell}^+_L\tilde{\ell}^-_L$ pairs. Various contribution are added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

LHeC *vs.* FCC-*eh*

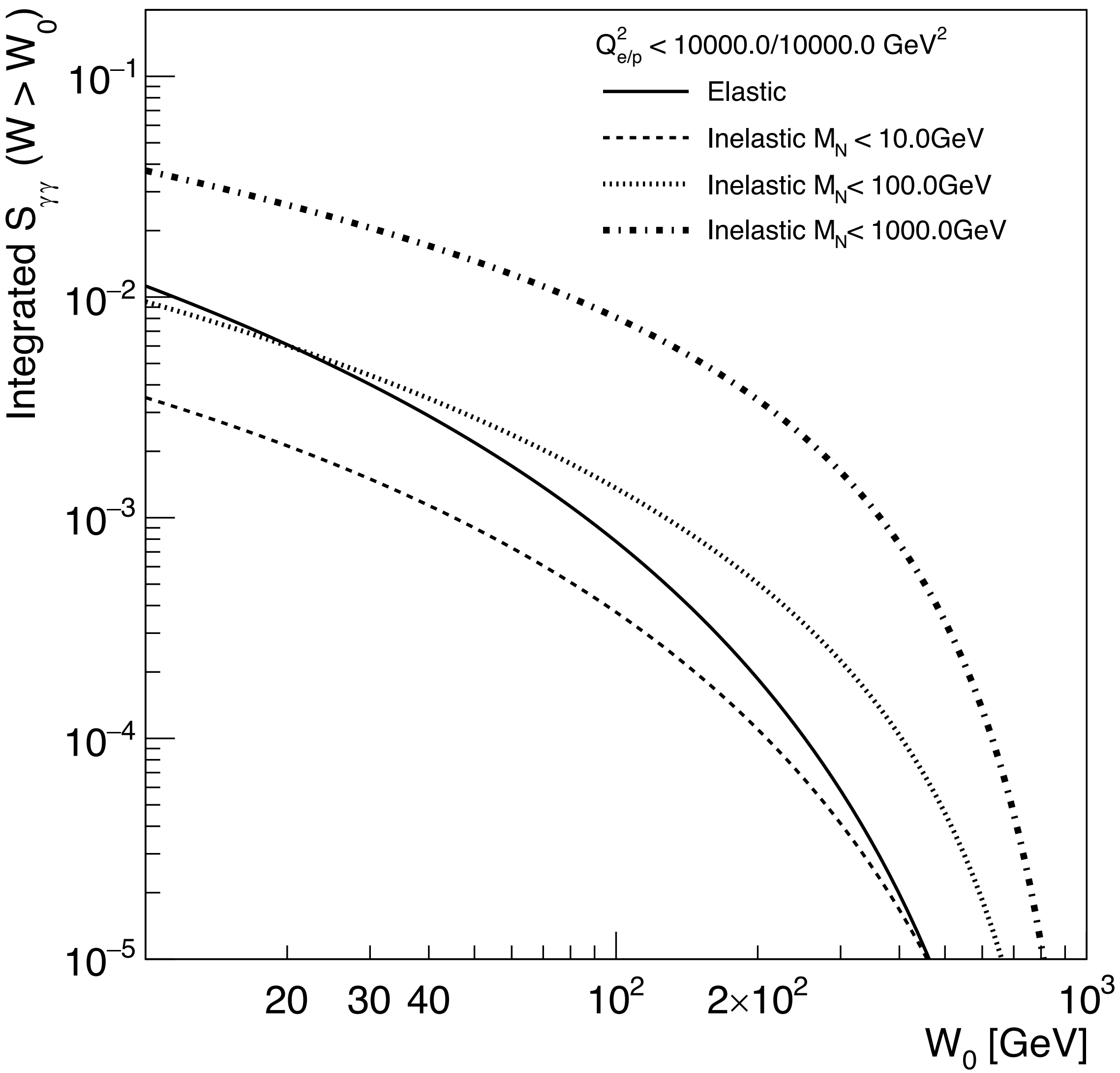
with Y. Yamazaki

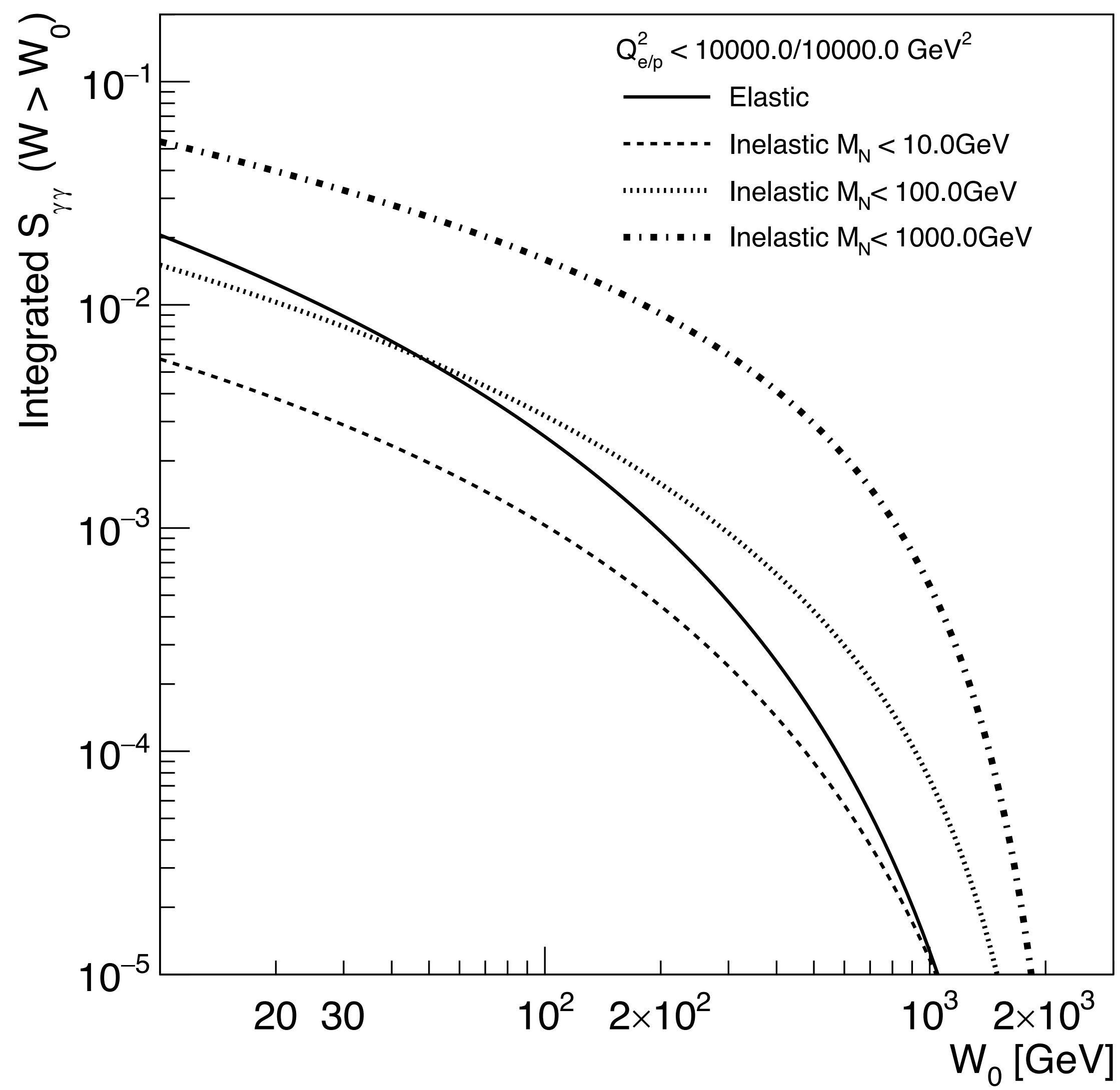




LHeC *vs.* FCC-*eh*

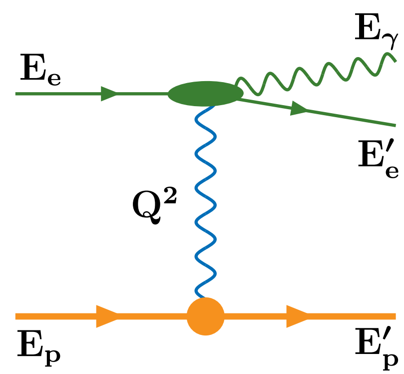
with Y. Yamazaki

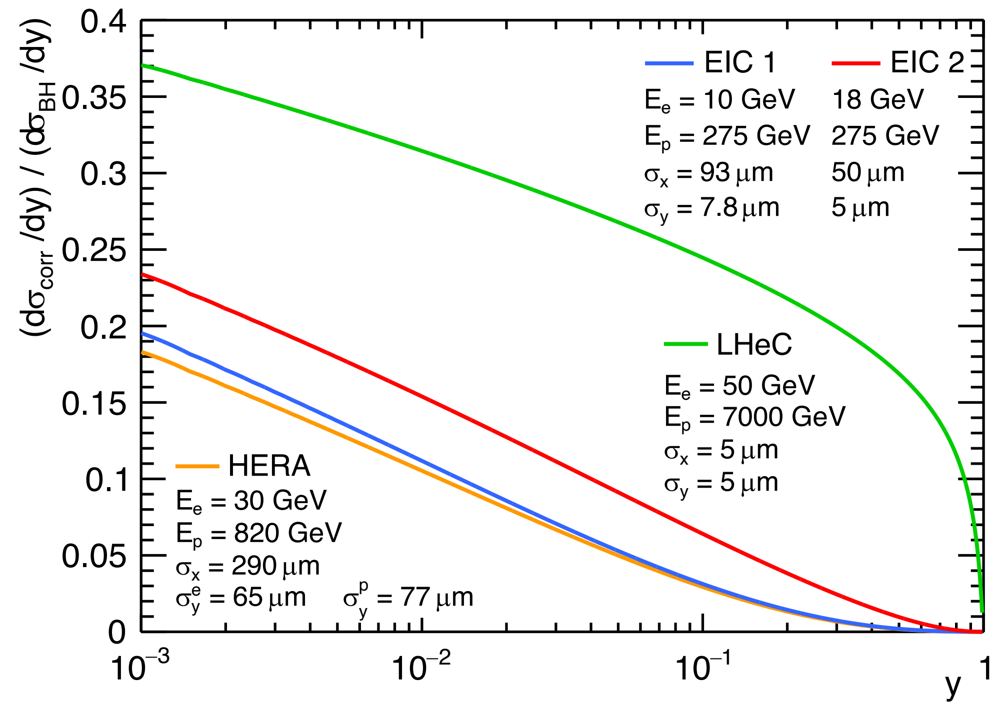


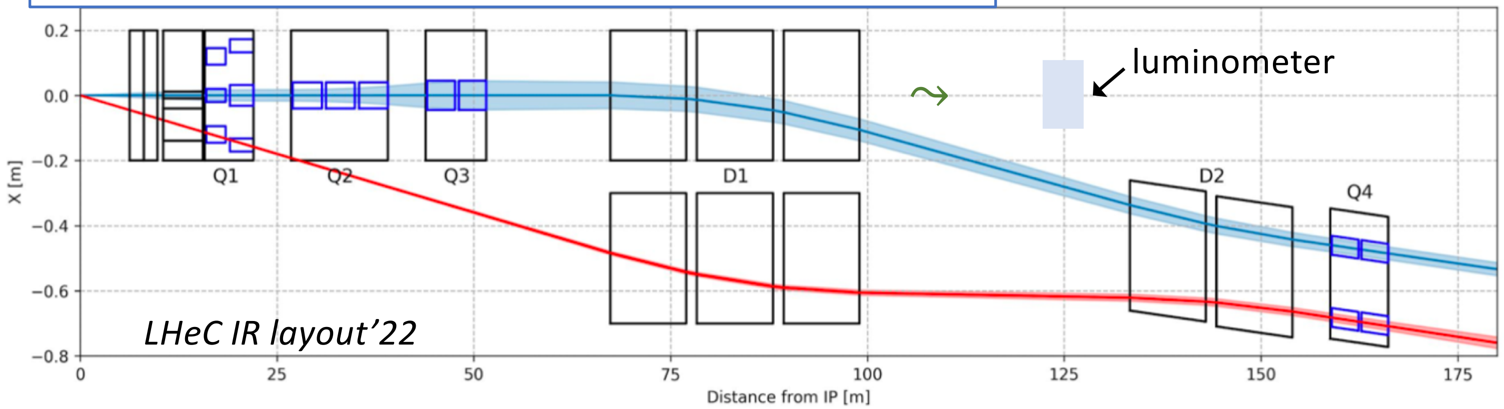


ep (& eA) luminosity

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 LH*e*C bremsstrahlung spectrum, where $y = E_\gamma / E_e$, will be strongly distorted over **entire** range of photon energies!
(see KP, M. Przybycien @ HEP-EPS'21)

However, rates of high energy bremsstrahlung will be extremely high at LH*e*C, 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 – further efforts are required.

See, for example:
https://iopscience.iop.org/article/10.1088/1748-0221/16/09/P09023

LH*e*C as an extraordinary $\gamma\gamma$ collider: summary & outlook

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

LH*e*C offers practically ideal conditions for studying high energy $\gamma\gamma$ interactions

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

Stay tuned!

Are there paper copies?

Thank you for attention!

High energy γγ 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)

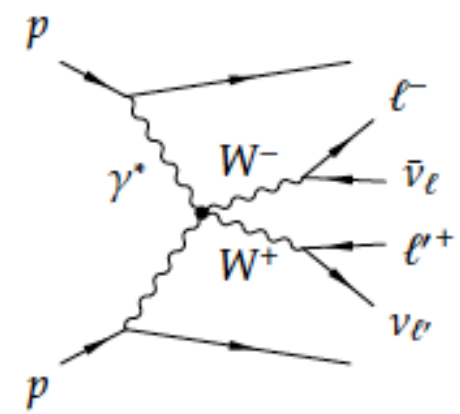
$S_{\gamma\gamma}$ is analogous to the partonic luminosity, and its integral $\int_{W_0}^{\sqrt{s}} \mathrm{d}W\, S_{\gamma\gamma}$ provides a fraction of the *pp* luminosity "available" for γγ collisions above *W_0*

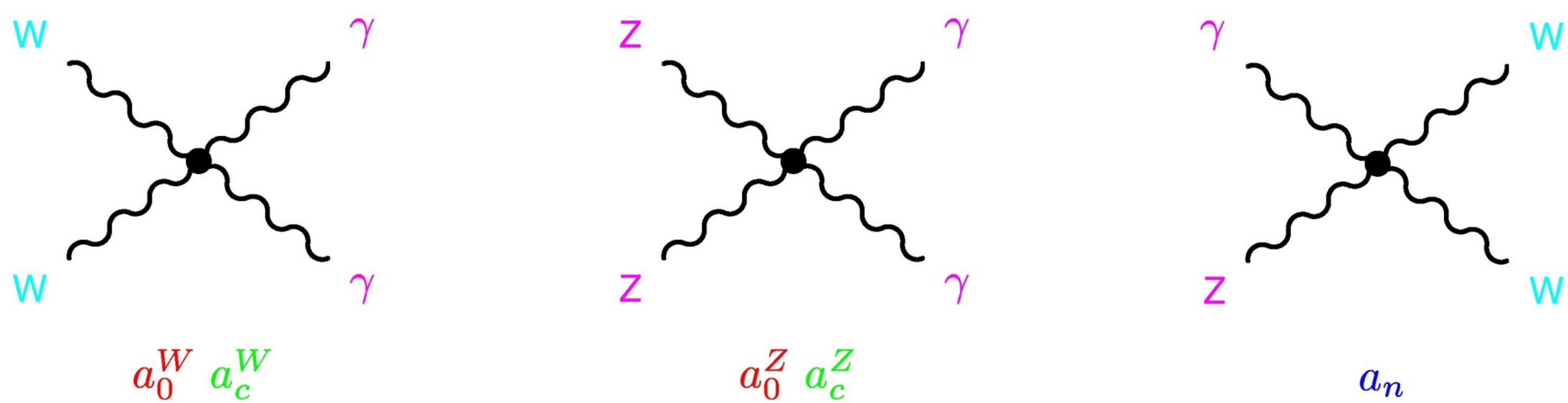
Note: There are *elastic* and *inelastic* (when the proton dissociates to p^*) contributions to $S_{\gamma\gamma}$

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

$\gamma\gamma \to$ 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





LHC PHYSICS

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

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 $\gamma\gamma \to WW$ 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 $\gamma\gamma \to WW$ 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).

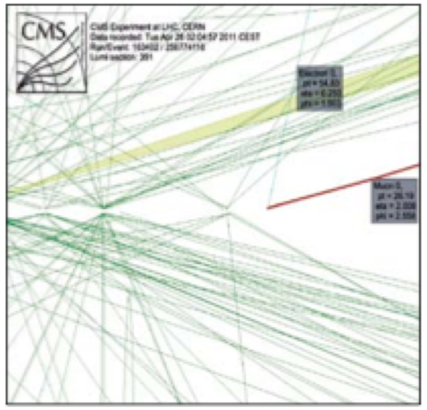


Fig. 1. Above: Proton–proton collisions recorded by CMS at $\sqrt{s}$=7 TeV, featuring candidates for the exclusive two-photon production of a W^+W^- pair, where one W boson has decayed into an electron and a neutrino, the other into a muon and a neutrino.

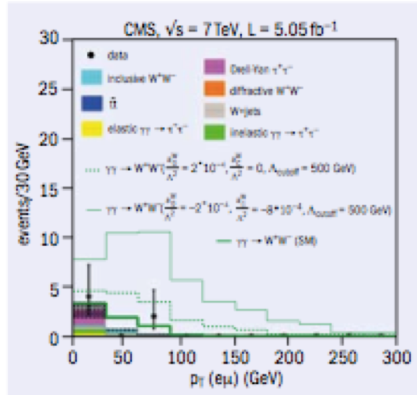


Fig. 2. Top right: The p_T distribution of eμ pairs in events with no extra tracks compared with the Standard Model expectation (thick green line) and predictions for anomalous quartic gauge couplings (dashed green histograms).

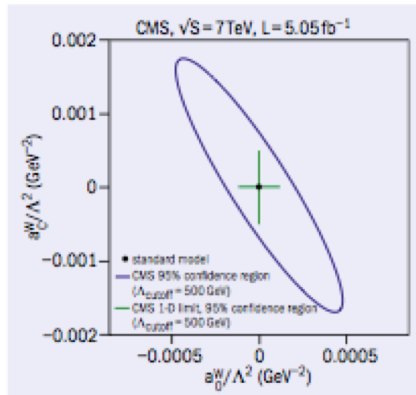


Fig. 3. Right: Limits on anomalous quartic $\gamma\gamma WW$ couplings.

Further reading

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

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
CERN COURIER
VOLUME 53 NUMBER 6 JULY/AUGUST 2013

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 $\sqrt{s}$ = 13 TeV are analyzed, corresponding to an integrated luminosity of **14.6 fb^{-1}**."
doi: 10.1103/PhysRevLett.125.261801

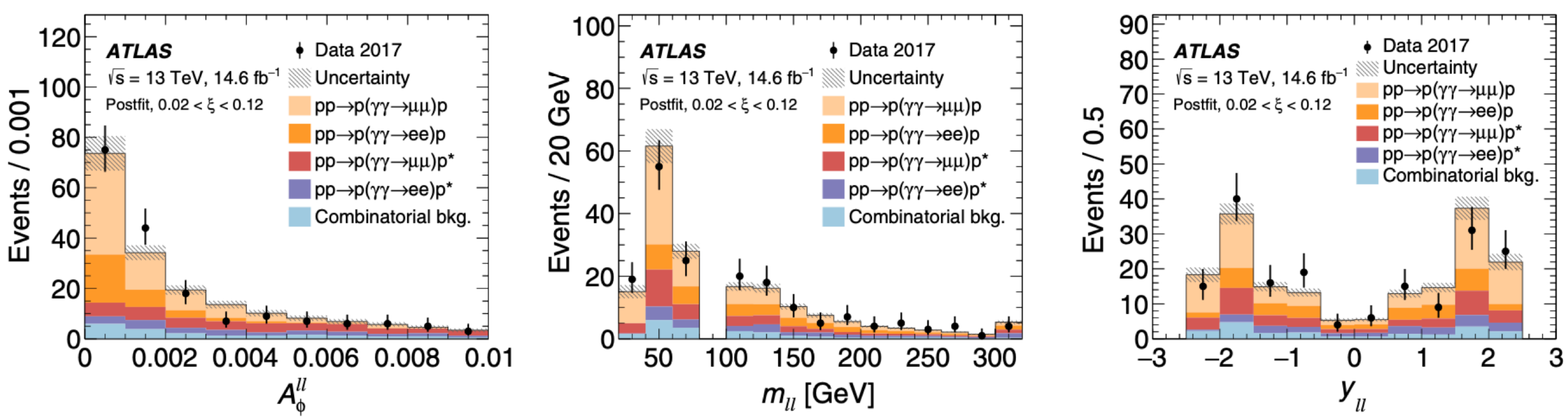


FIG. 3. Distributions of dilepton acoplanarity $A_\phi^{\ell\ell}$ (left), invariant mass $m_{\ell\ell}$ (center), rapidity $y_{\ell\ell}$ (right) satisfying $\xi_{\ell\ell}, \xi_{\mathrm{AFP}} \in [0.02, 0.12]$, and $|\xi_{\mathrm{AFP}} - \xi_{\ell\ell}| < 0.005$ for at least one AFP side. Events with $70 < m_{\ell\ell} < 105$ 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.

(HL-)LHC as a high energy $\gamma\gamma$ collider: **summary**

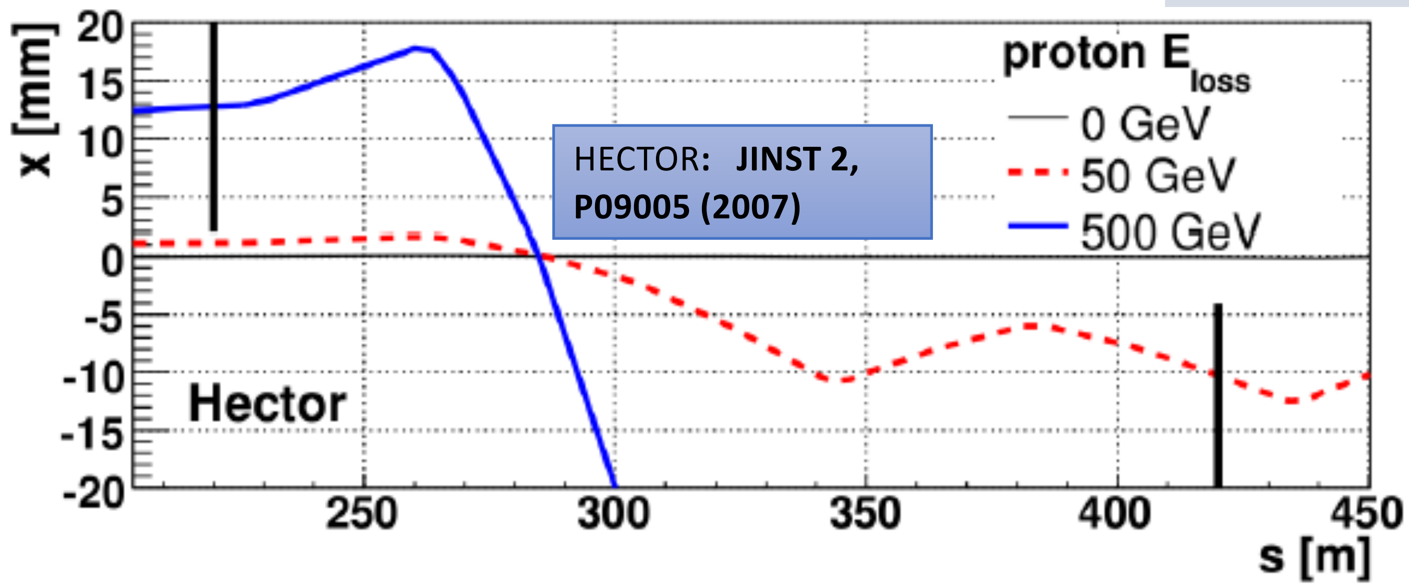
High energy $\gamma\gamma$ physics can be successfully studied at the LHC!

- Fundamental role of exclusive $\mu\mu$ (and *ee*) pairs – they serve as a **standard candle** in many ways: as a precise calibration tool & acceptance verification + a photon-flux-meter
- Use of very forward proton detectors is essential for full exploration of $\gamma\gamma$ physics at the LHC – perhaps new channels as semi-leptonic WW can be studied already in Run 3
- HL-LHC opens new horizons in this exploration – to properly profit from that, the development of **dedicated ps resolution timing detectors** is mandatory (+ studies of the potential impact of ps timing in central detectors)
- Precise studies of high-mass diffraction at the LHC are **crucial** for optimal extraction of the $\gamma\gamma$ signals using very forward proton detectors

Picosecond ToF detectors @ LHC

Use very fast ToF detectors to measure *longitudinal vertex position* by *z-by-timing* from forward proton arrival time difference:

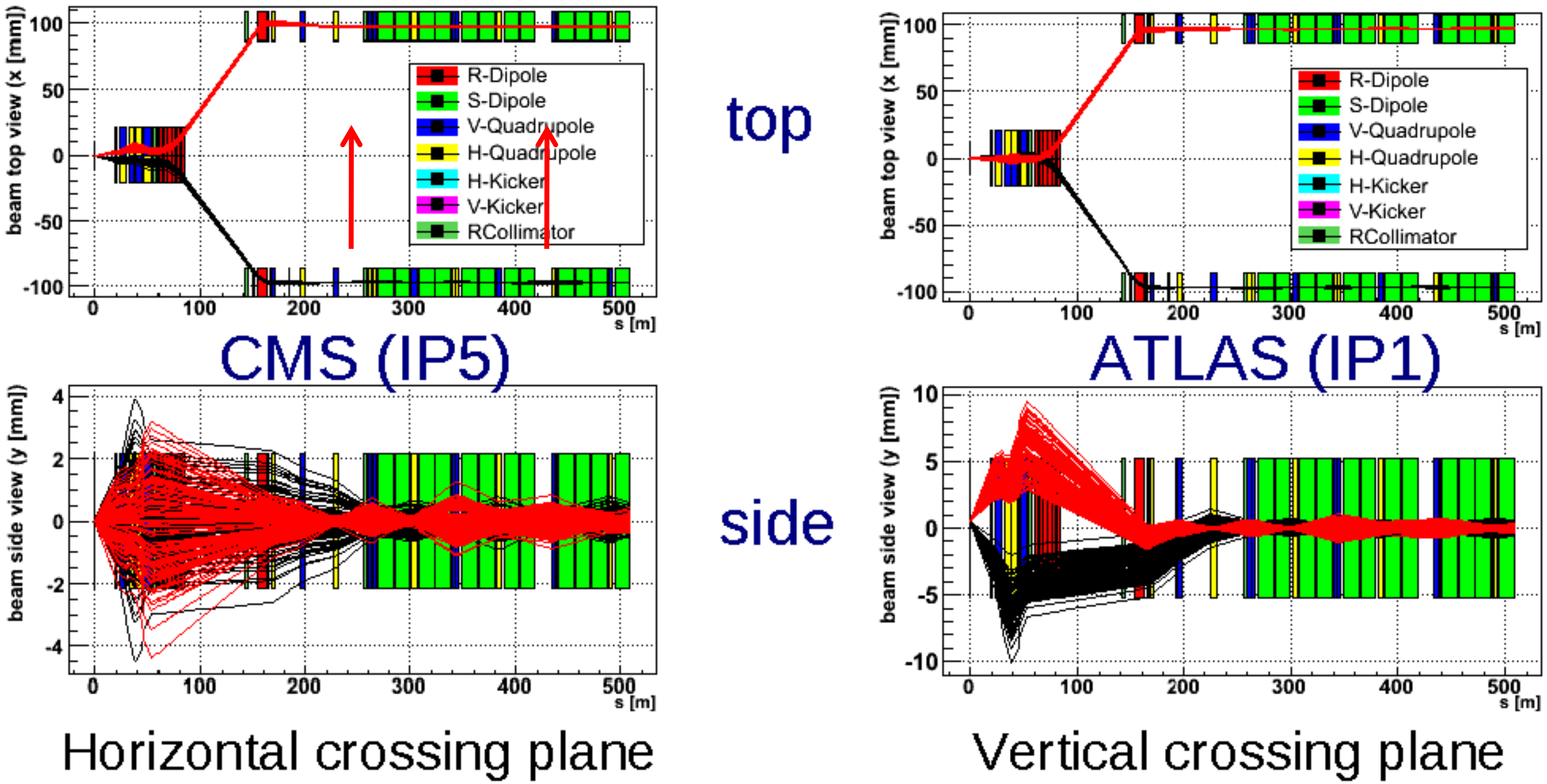
$z = (t_1 - t_2)/2c$



Path length differences are very small for forward protons at LHC, typically << 100 μm corresponding to sub-picosecond time differences.

Ultra fast timing detectors are essential for measuring the exclusive production at LHC, JINST 4 (2009) T10001

Optimal places for tagging Exclusive Production at LHC: @ 220/240m and 420m from IP



HECTOR: **JINST 2, P09005 (2007)**
For <u>nominal</u> low-β LHC optics

HL-LHC as a high energy γγ collider: new physics?

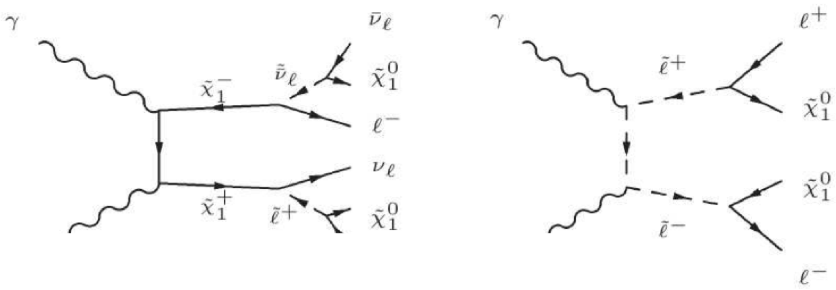
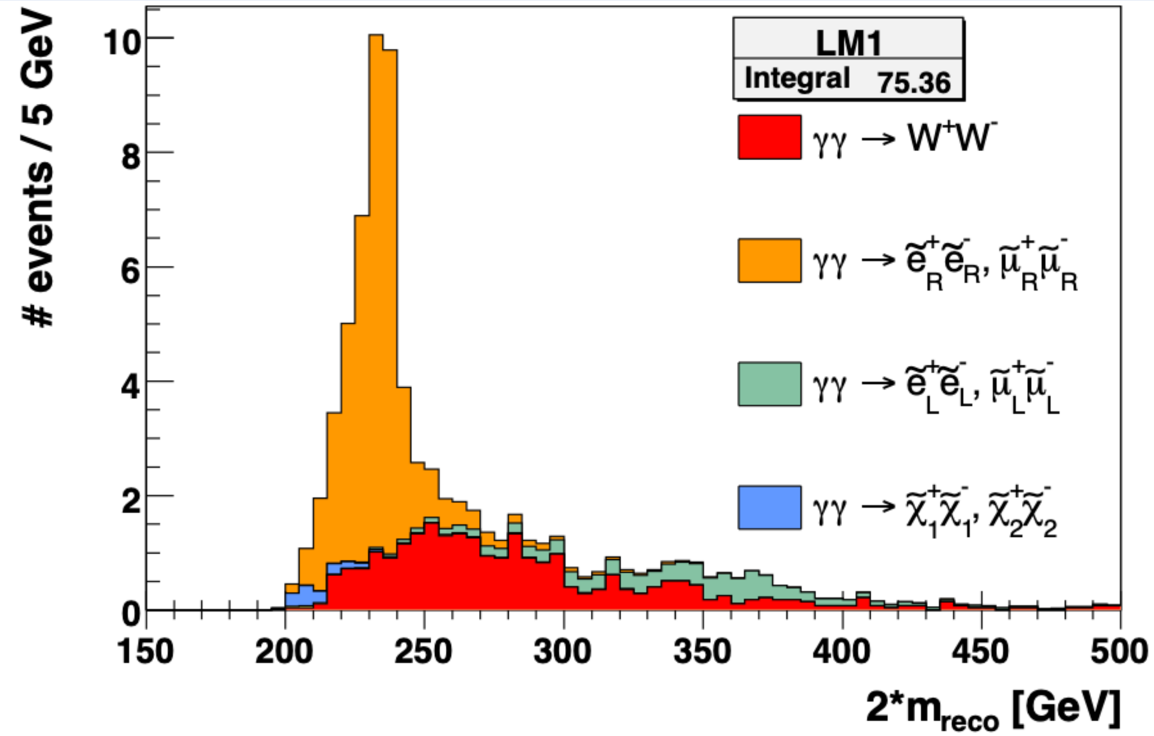


Table 3
LM1 signal and WW background cross sections before and after the acceptance cuts (including the flavor selection), and after the analysis cuts. Values are given in fb. ($\ell = e, \mu$. $i = 1, 2$).

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}.

Need updating for HL-LHC/recent BSM models