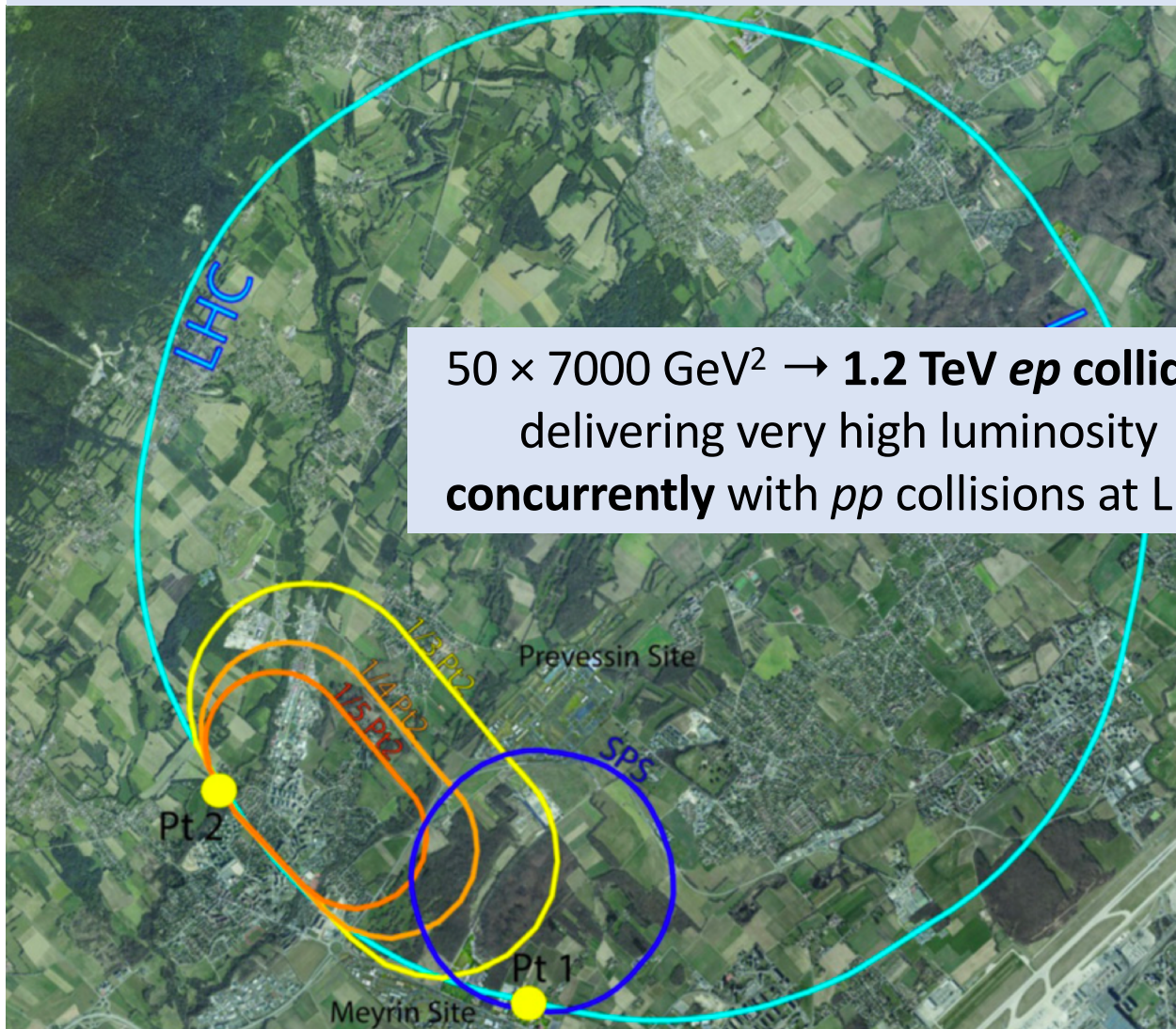


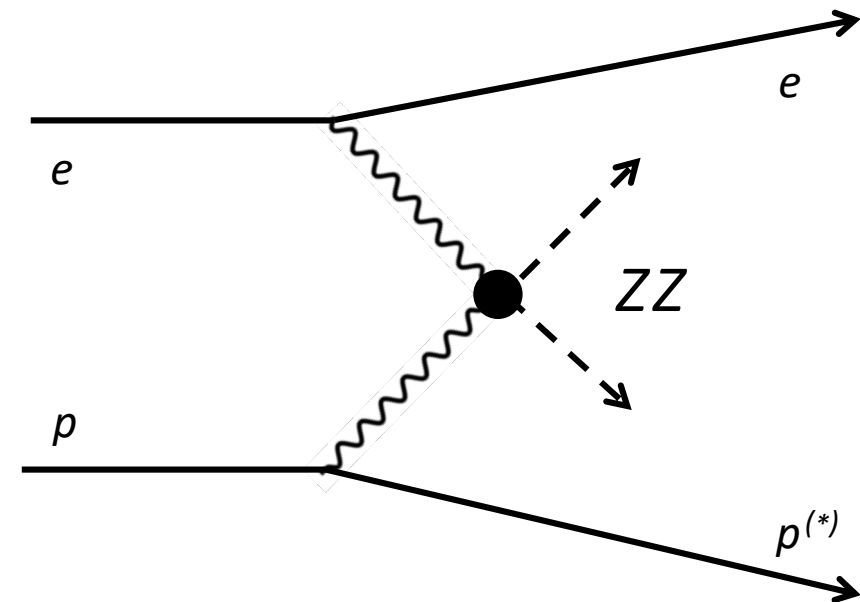
High energy photon-photon interactions at the LHeC (and FCC-*eh*)



$50 \times 7000 \text{ GeV}^2 \rightarrow 1.2 \text{ TeV } ep \text{ collider}$
delivering very high luminosity
concurrently with pp collisions at LHC

Krzysztof PIOTRZKOWSKI
(AGH Kraków)

Yuji YAMAZAKI
(Kobe Univ.)



XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects

Santiago de Compostela, 2-6 May 2022

Large Hadron *electron* Collider

ERL, or the on-going revolution in high energy electron acceleration techniques

Energy Recovery Linac
technology resulted in
the major breakthrough
for the LHeC:

> 20 luminosity increase

Large Hadron *electron* Collider

ERL, or the on-going revolution in high energy electron acceleration techniques

Machine Parameters and Operation - ep

arXiv:2007.14401

Parameter	Unit	LHeC			
		CDR	Run 5	Run 6	Dedicated
E_e	GeV	60	30	50	50
N_p	10^{11}	1.7	2.2	2.2	2.2
ϵ_p	μm	3.7	2.5	2.5	2.5
I_e	mA	6.4	15	20	50
N_e	10^9	1	2.3	3.1	7.8
β^*	cm	10	10	7	7
Luminosity	$10^{33} \text{ cm}^{-2} \text{ s}^{-1}$	1	5	9	23

Energy Recovery Linac

technology resulted in
the major breakthrough
for the LHeC:

> 20 luminosity increase

Large Hadron electron Collider

LHeC is NOT a super-HERA “only”!

LHeC is not just a **DIS super-collider**—it is much more:

New **very powerful lab** for electroweak & Higgs physics

+

Sensitivity to **new BSM signatures**

+

High energy eA collider (**very complementary** to EIC)

Large Hadron electron Collider

LHeC is NOT a super-HERA “only”!

LHeC luminosity $\approx 1000 \times \text{HERA}$

LHeC is not just a **DIS super-collider**—it is much more:

New **very powerful lab** for electroweak & Higgs physics

+

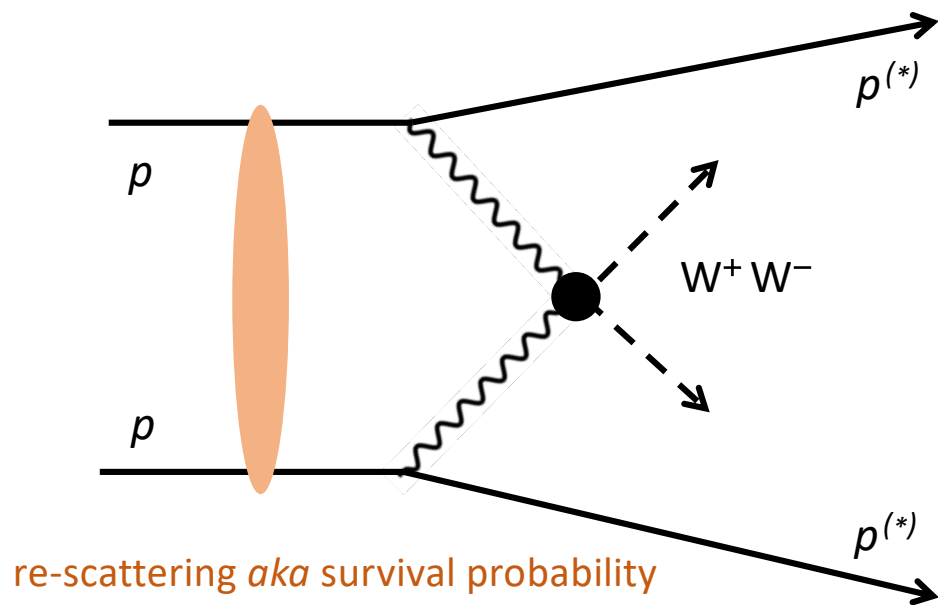
Sensitivity to **new BSM signatures**

+

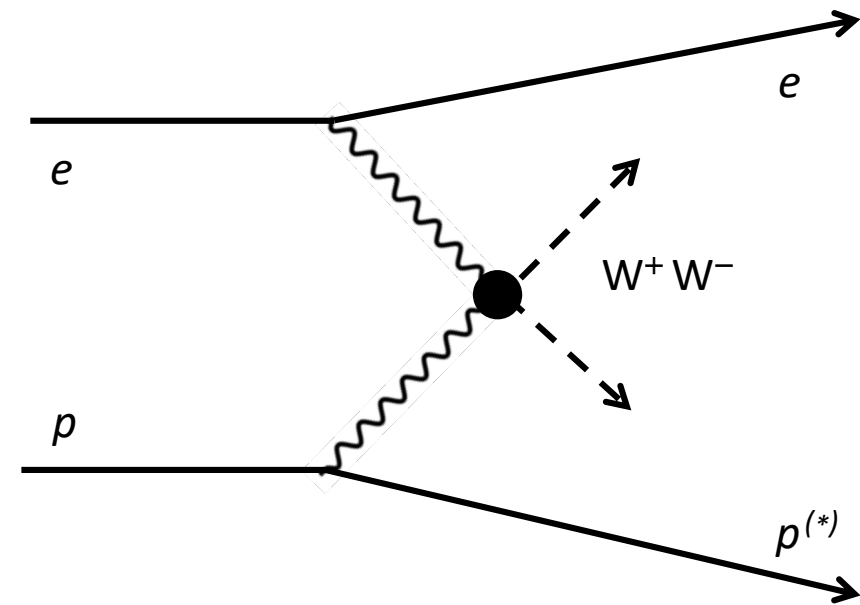
High energy eA collider (**very complementary** to EIC)

New aspect

HL-LHC vs. LHeC as high energy $\gamma\gamma$ colliders



VS.



Energy reach for $\gamma\gamma$ interactions is higher at the LHC, however tagging $\gamma\gamma$ events at the highest photon-photon CM energy (W) 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 $2.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

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

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

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

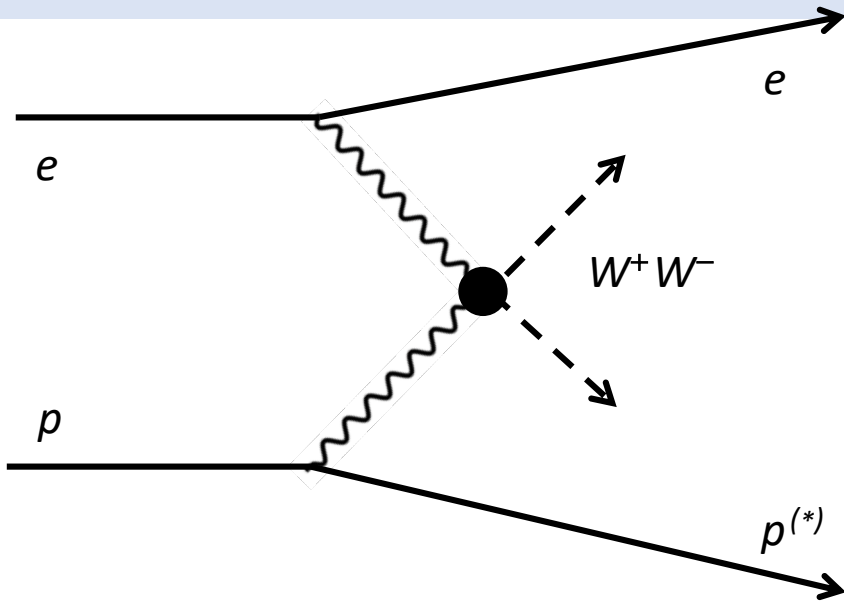
$$S_{\gamma\gamma} = \frac{2}{W} \int_{W^2/s}^1 dy_e \Phi_e(y_e) y_p \Phi_p(y_p)$$

EPA: Budnev *et al.* (1975)

$S_{\gamma\gamma}$ is analogous to the partonic luminosity, and its integral $\int_{W_0}^{\sqrt{s}} dW S_{\gamma\gamma}$ 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 $S_{\gamma\gamma}$

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

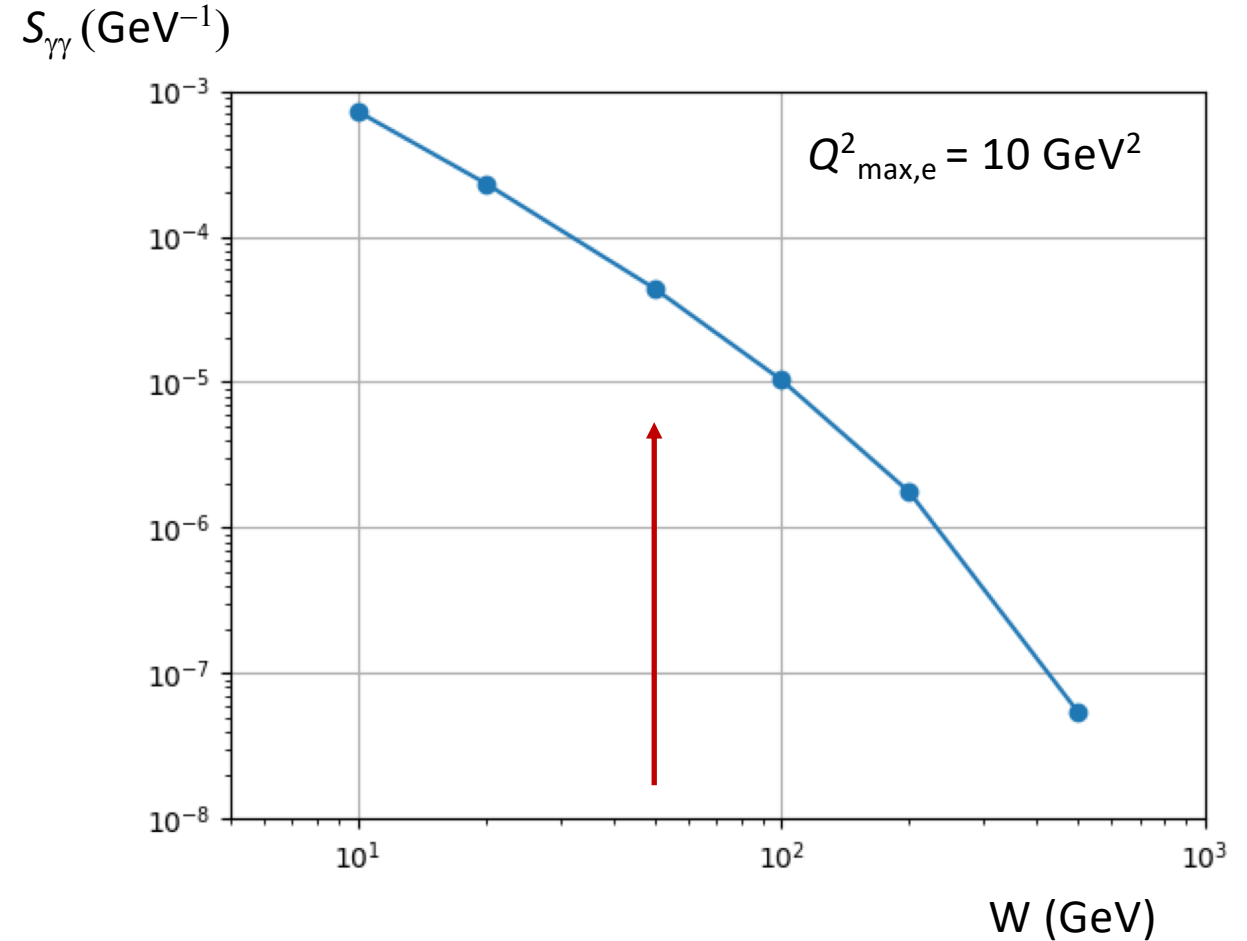


Very high LHeC luminosity is the key here \Rightarrow more than **1 ab⁻¹** (= 1000 fb⁻¹) is expected for ep collisions.

Incident electrons will have “only” 50 GeV, but **higher** equivalent photon flux, as approximately:

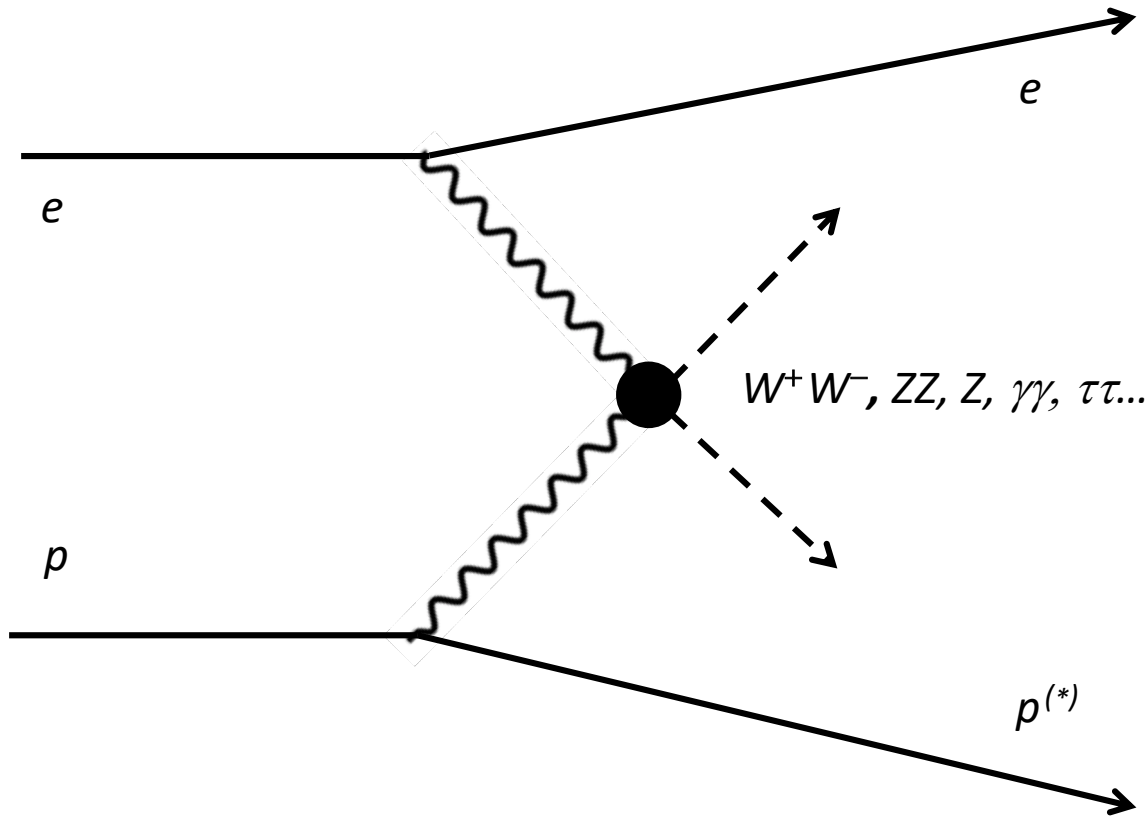
$$S_{\gamma\gamma} \propto \ln(Q_{\max,e}^2/Q_{\min,e}^2) \ln(Q_{\max,p}^2/Q_{\min,p}^2)$$

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



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

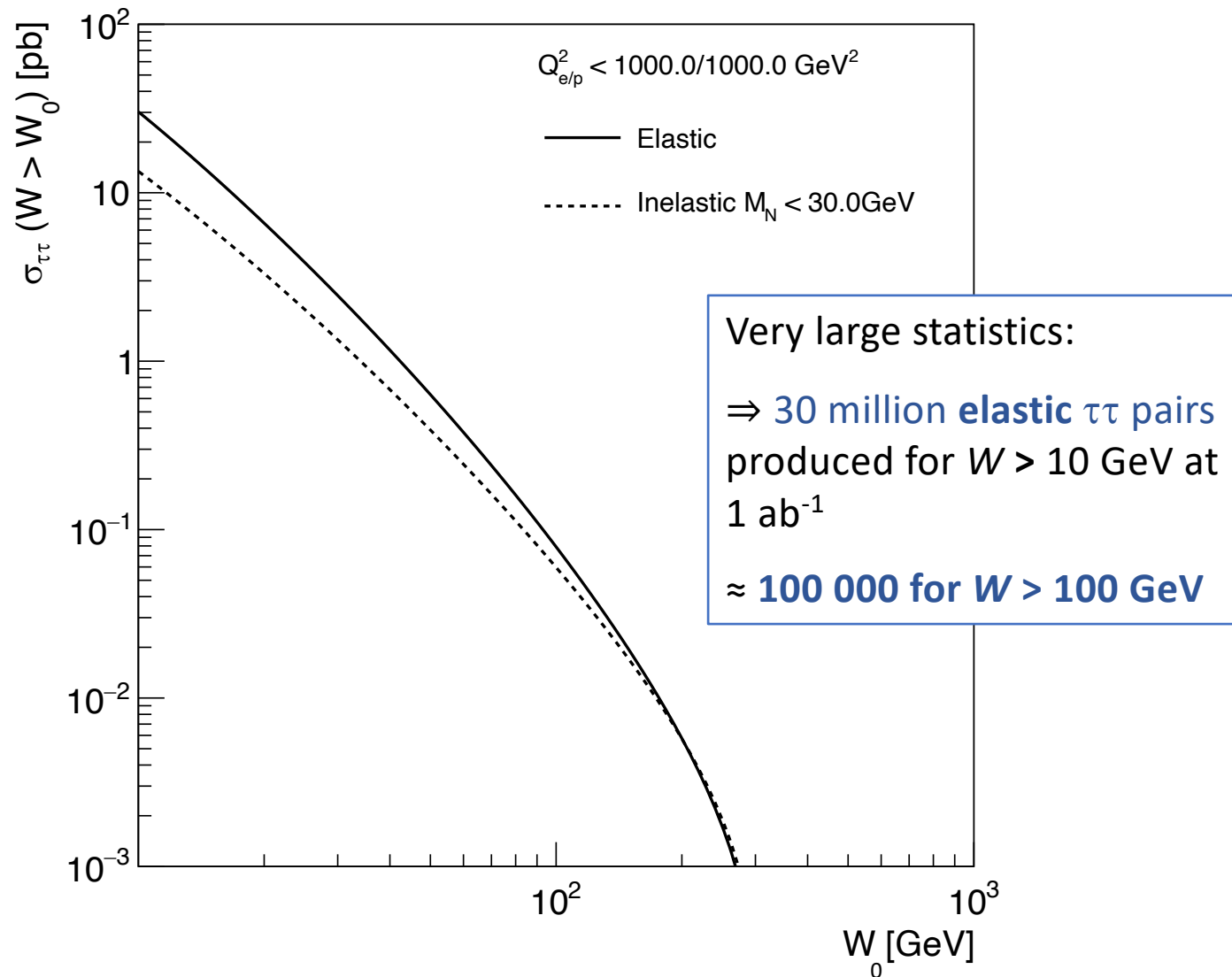
LHeC as a very unique, generic high energy $\gamma\gamma$ collider



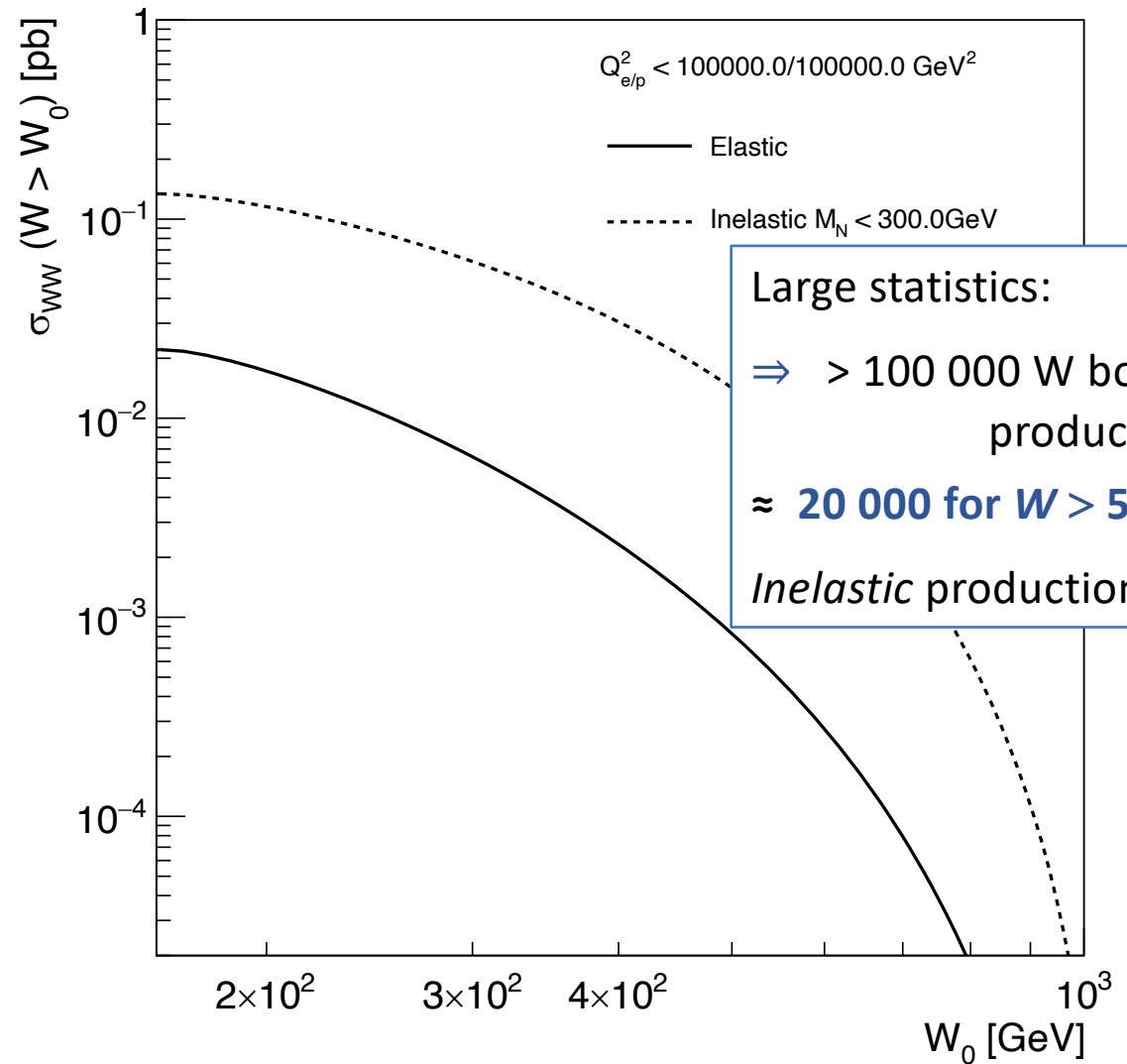
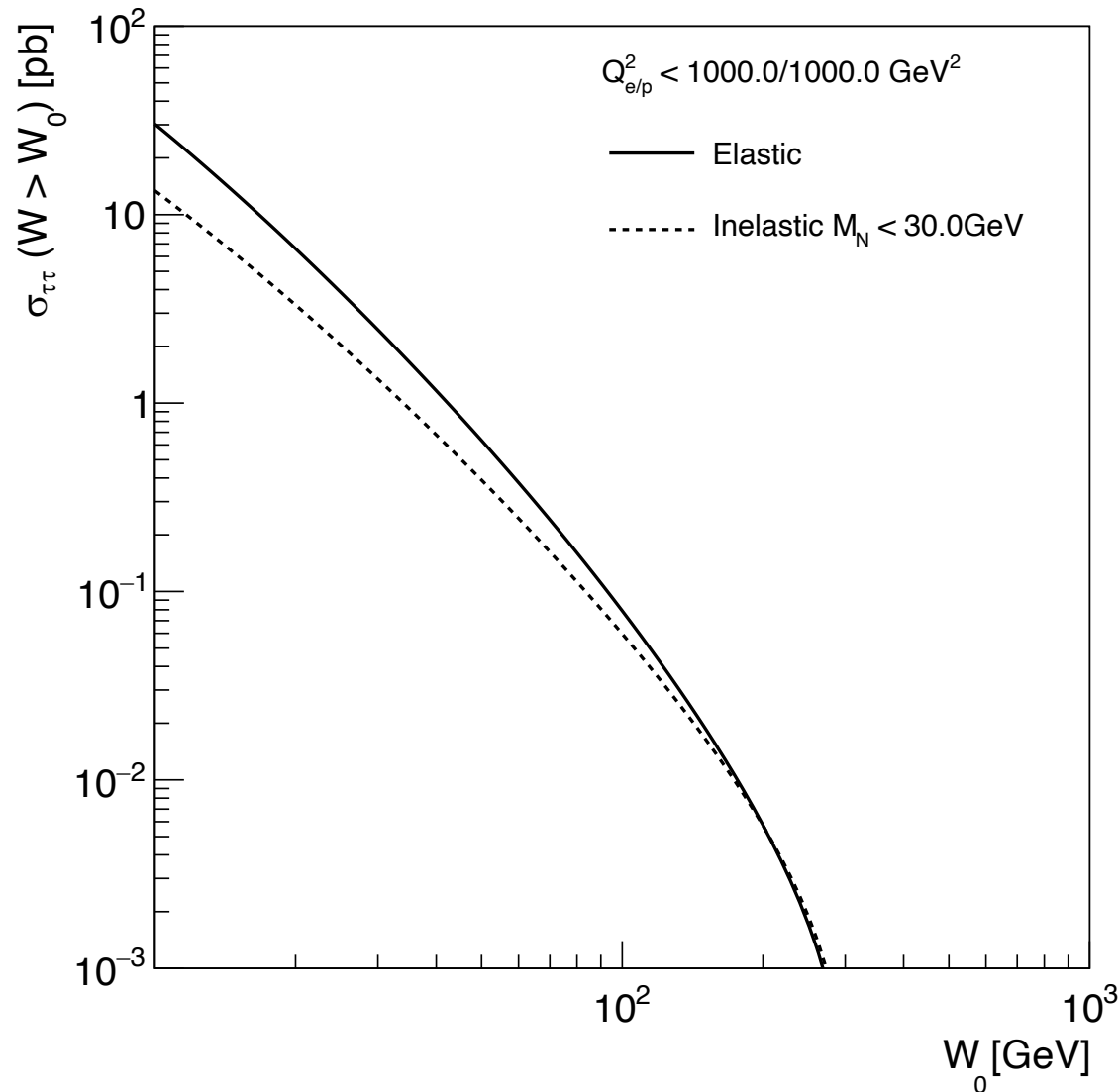
Wide spectrum of $\gamma\gamma$ processes will be studied at the LHeC:

- $\gamma\gamma \rightarrow \gamma\gamma$: orders of magnitude higher statistics than for $PbPb$ at the HL-LHC + $\gamma\gamma$ tagging \Rightarrow kinematic fitting
- $\gamma\gamma \rightarrow \tau^+\tau^-$: orders of magnitude higher statistics than for $PbPb$ at the HL-LHC + $\gamma\gamma$ tagging \Rightarrow new decay modes
- $\gamma\gamma \rightarrow Z$: search for the anomalous single Z boson exclusive production
- $\gamma\gamma \rightarrow ZZ$: possibility of first ever detection + stringent limits on anomalous quartic gauge couplings (aQGCs) using semi-leptonic decay modes, $ZZ \rightarrow l^+l^-jj$
- $\gamma\gamma \rightarrow W^+W^-$: measurements of semi-leptonic decay modes, $W^+W^- \rightarrow l\nu jj$, will allow for a use of Optimal Observable methods (even with single $\gamma\gamma$ tagging) for probing aQGCs; yet high statistics (\approx as at the HL-LHC) is expected for fully leptonic W^+W^- decays + tagging

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



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



Large statistics:

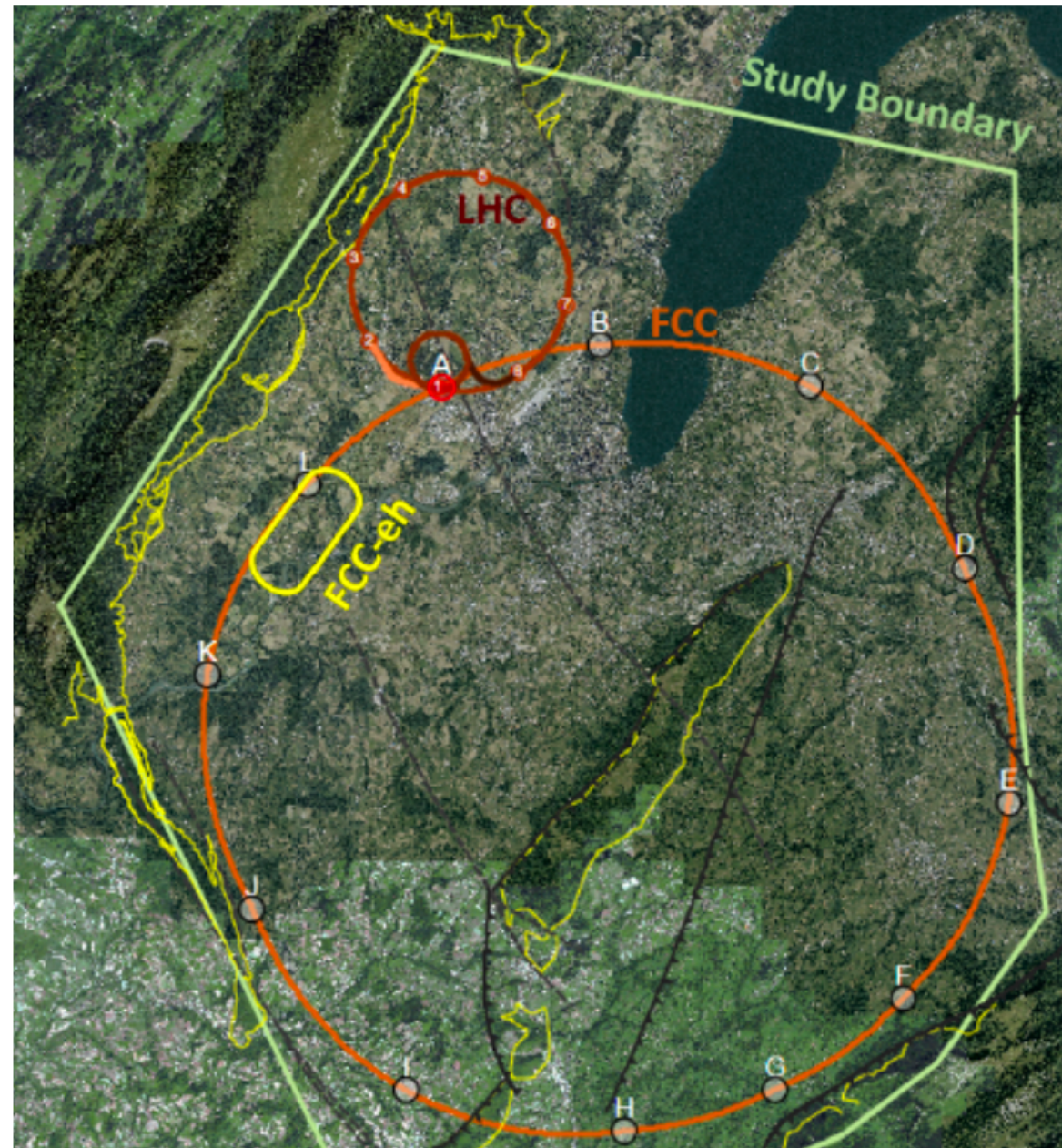
\Rightarrow > 100 000 W boson pairs
produced at 1 ab^{-1}

\approx **20 000 for $W > 500 \text{ GeV}$**

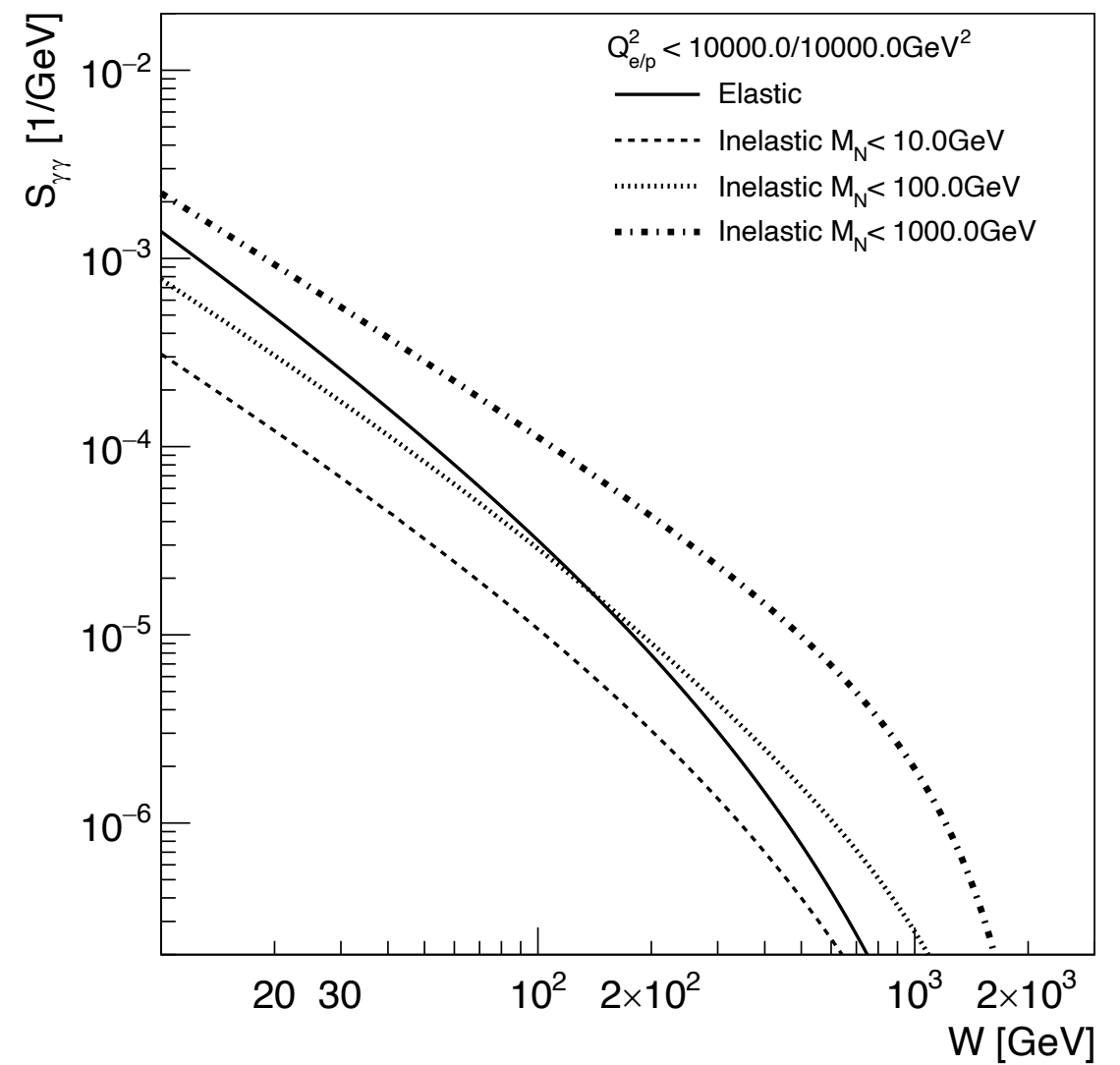
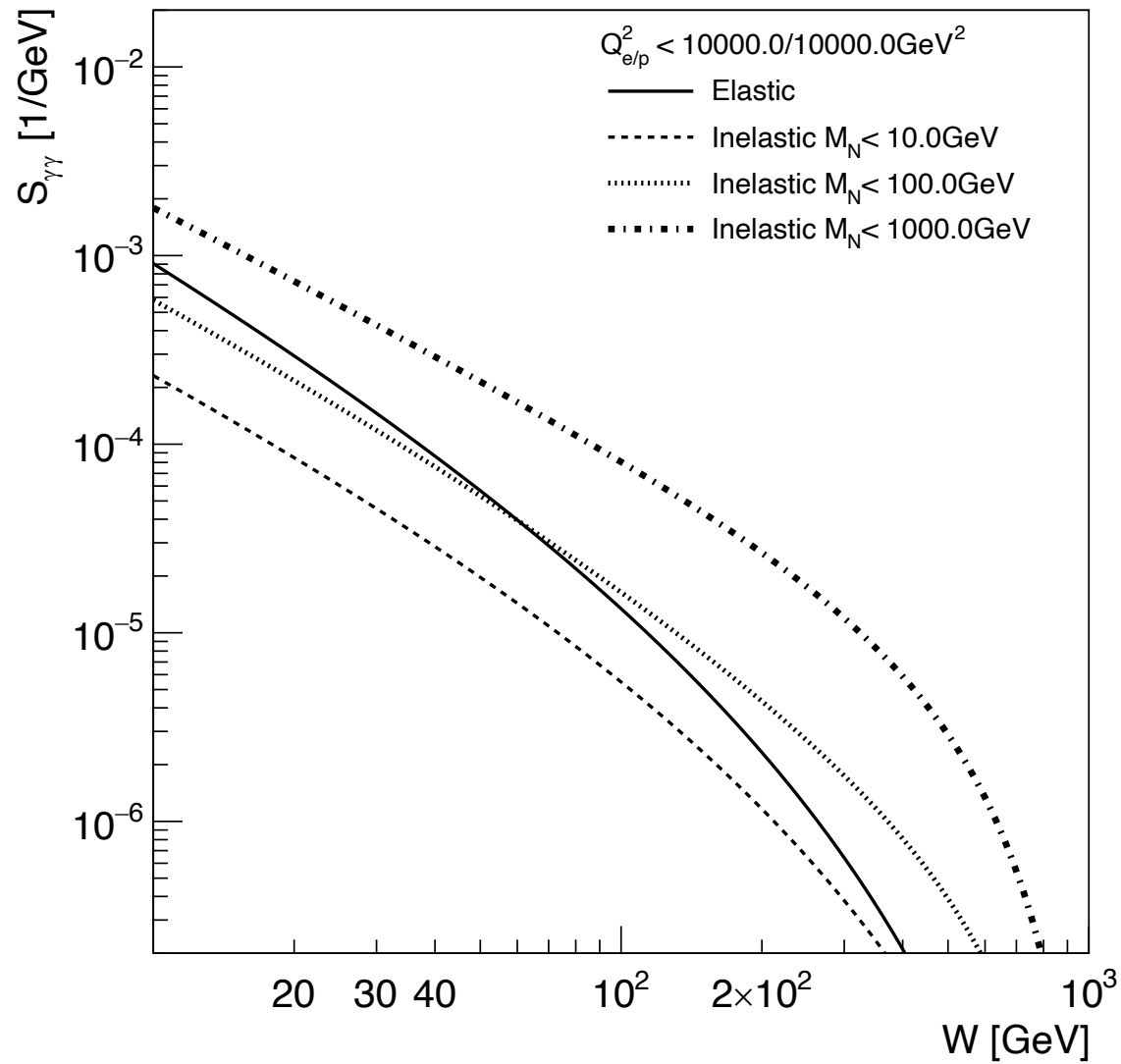
Inelastic production dominant

FCC-eh case

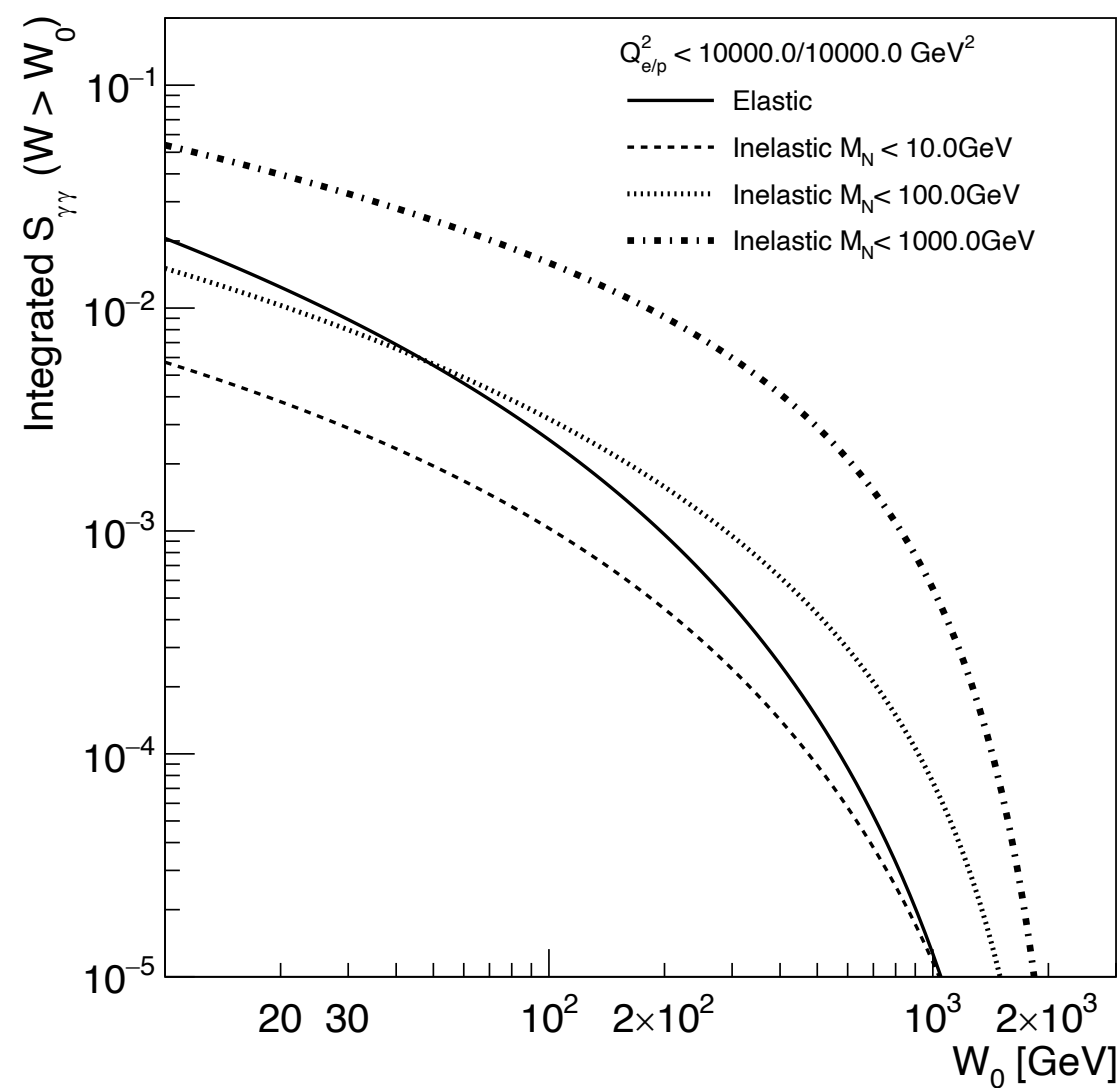
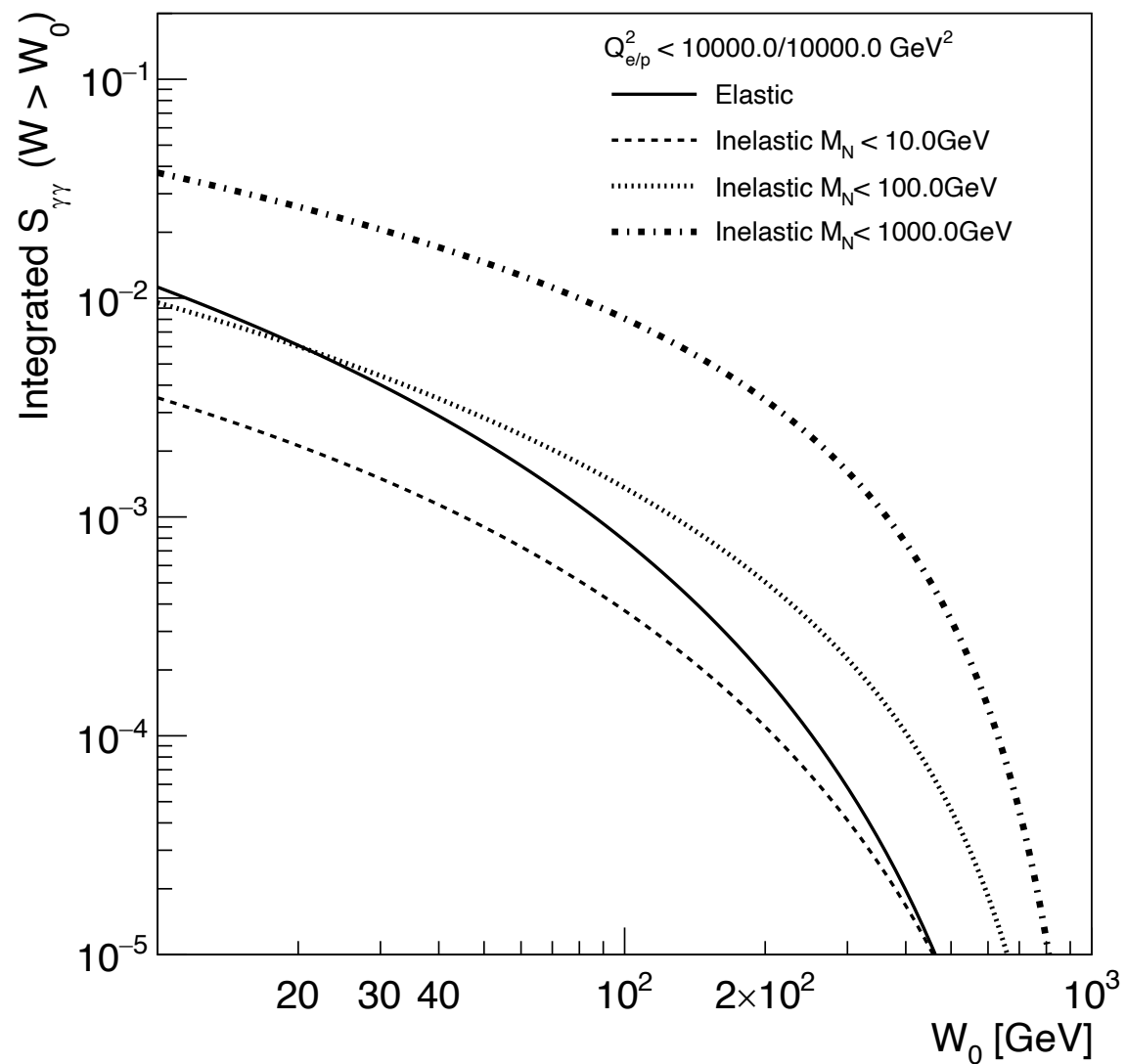
$60 \times 50000 \text{ GeV}^2 \rightarrow 3.5 \text{ TeV } ep \text{ collider}$
delivering very high luminosity
concurrently with pp collisions



LHeC vs. FCC-eh

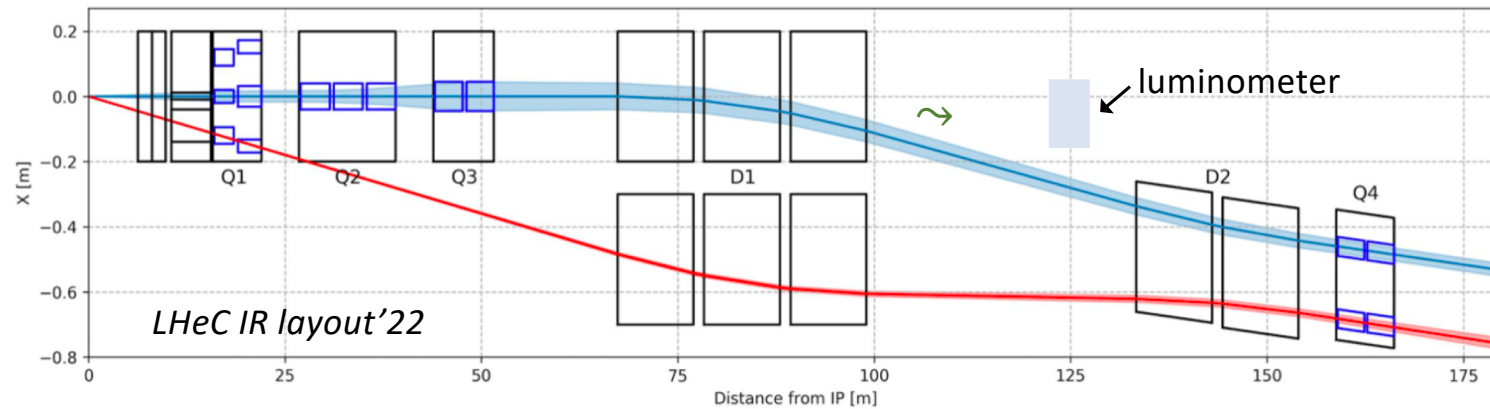
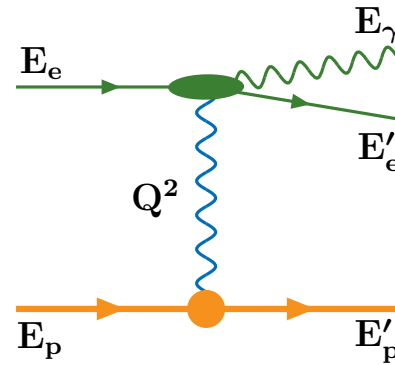


LHeC vs. FCC-eh



ep (& eA) luminosity

As was shown at HERA, *ep* bremsstrahlung can be used to measure *ep* luminosity with high precision, at $\lesssim 1\%$.



However, rates of high energy bremsstrahlung will be extremely high at the LHeC/FCC-*eh*, 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:

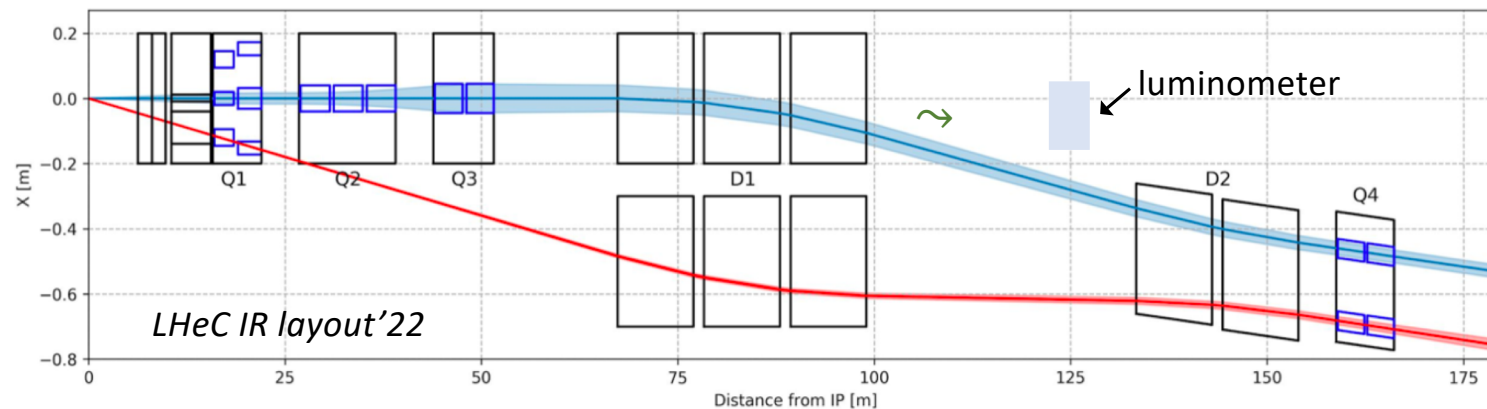
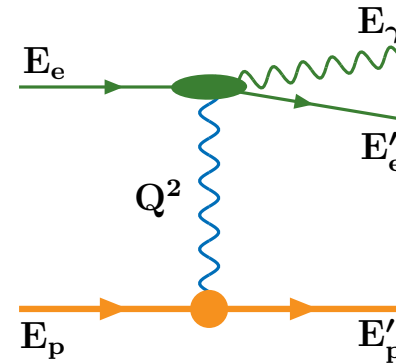
$$\text{Event rate} = \text{Luminosity} \times \text{cross section}$$

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>

ep (& eA) luminosity

As was shown at HERA, *ep* bremsstrahlung can be used to measure *ep* luminosity with high precision, at $\lesssim 1\%$.

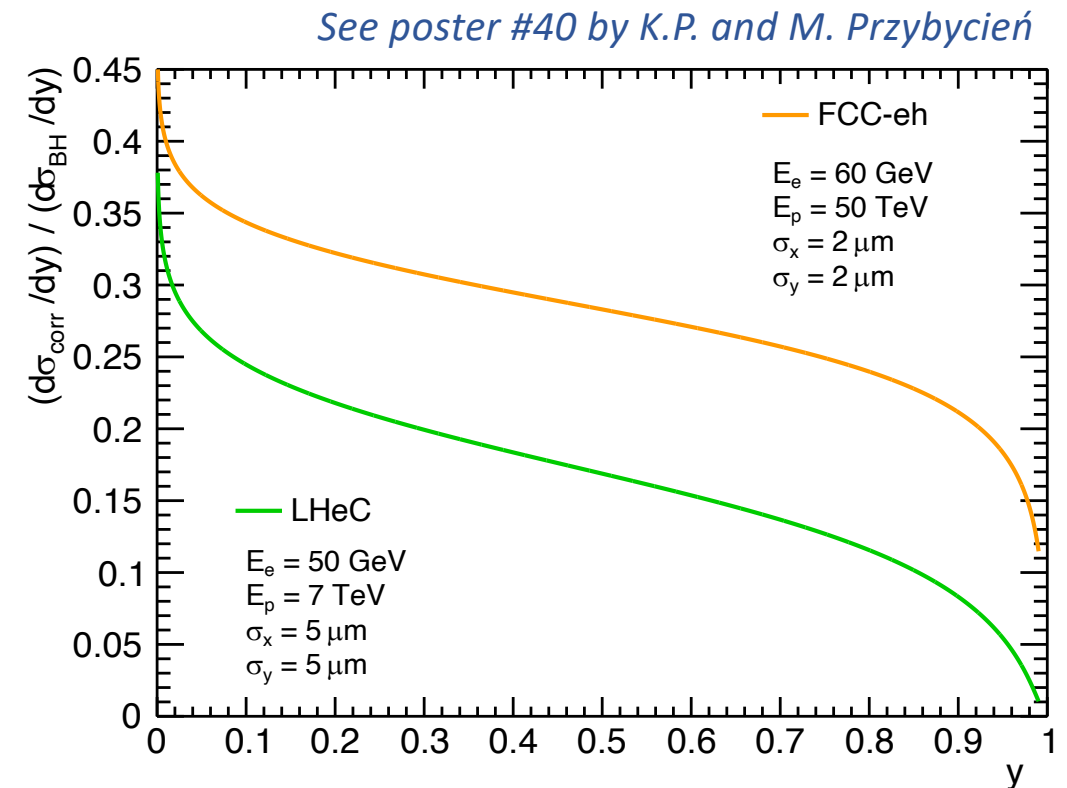


However, rates of high energy bremsstrahlung will be extremely high at the LHeC/FCC-*eh*, well in excess of 1 GHz, and in addition strong **Beam-Size Effect** will take place – *effective* bremsstrahlung *suppression* at high energies due to small lateral beam-sizes of **both** colliding beams:

Event rate \neq Luminosity \times 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>



At LHeC/FCC-*eh* bremsstrahlung spectrum, where $y = E_\gamma/E_e$, will be strongly distorted over **entire** range of photon energies!

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>

Summary and outlook

LHeC will complete the HL-LHC science in a very profound and relevant way, in the QCD and Electroweak sectors

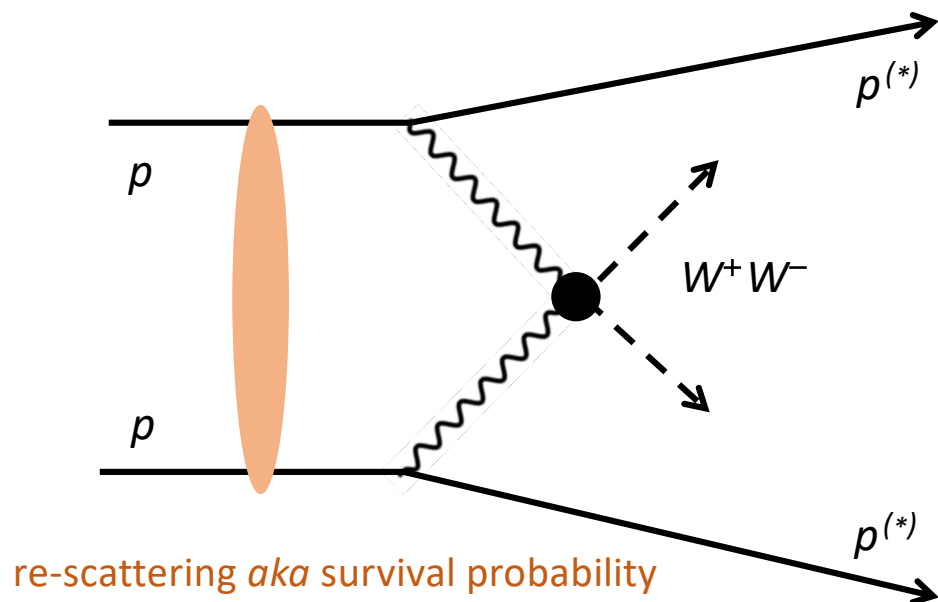
LHeC offers practically ideal conditions for studying high energy $\gamma\gamma$ interactions

Scientific potential of $\gamma\gamma$ physics at the LHeC, both in testing the electroweak theory and for searches of signals of New Physics, will be further explored

STAY TUNED!

Backup slides

HL-LHC (and FCC- hh) as a high energy $\gamma\gamma$ collider: challenges & limitations



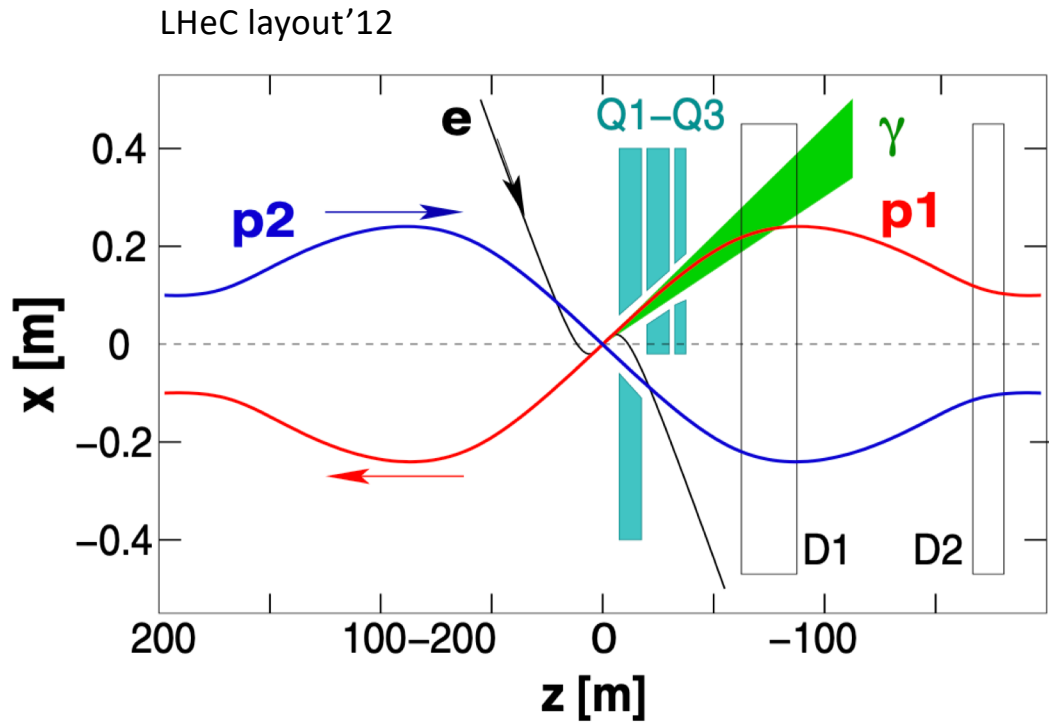
HL-LHC will provide 10 times bigger integrated luminosity, but:

- $S_{\gamma\gamma}$ only marginally higher (thanks to $13 \rightarrow 14$ TeV increase)
- PU yet 4 times higher (≈ 140) than for Run 2 – but new tracking **with** ps resolution timing should cope well with it
- Very high event pileup will make tagging with forward protons even more tricky – **ps resolution timing detectors** will help – however, the problem of overall efficiency loss still persists

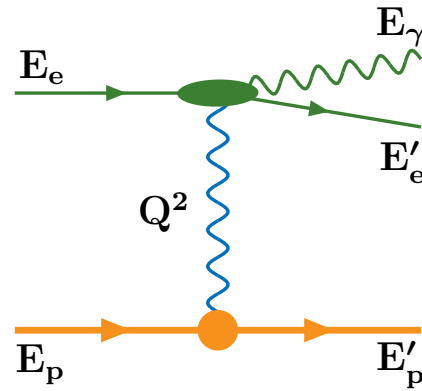
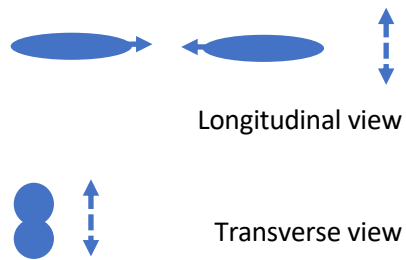
Major limitations for the high luminosity pp case of a $\gamma\gamma$ collider:

- **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

ep Luminosity



Using Van der Meer scans:



See poster #40 by K.P. and M. Przybycień

