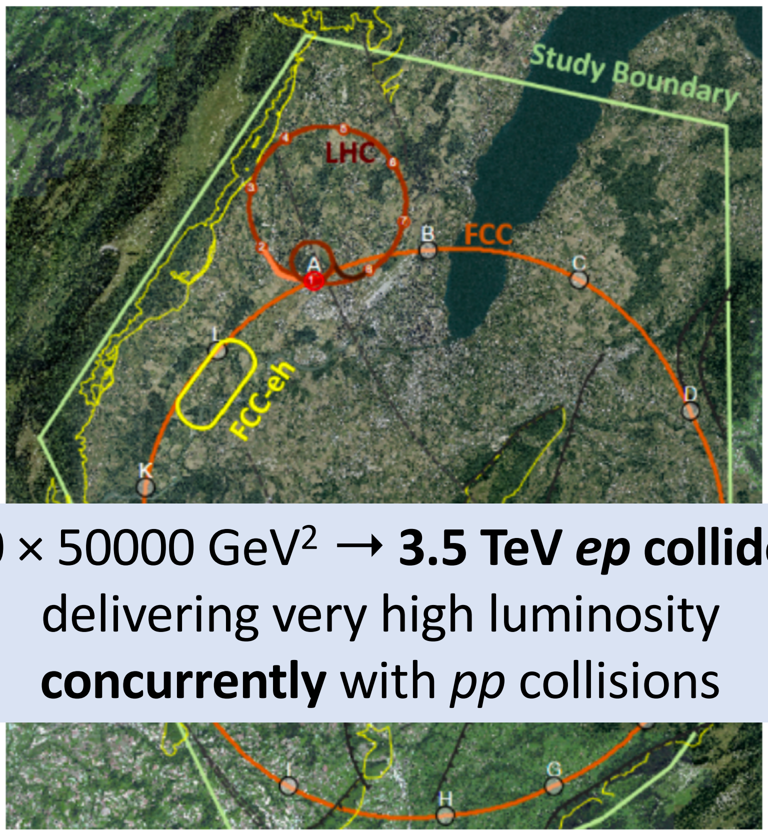
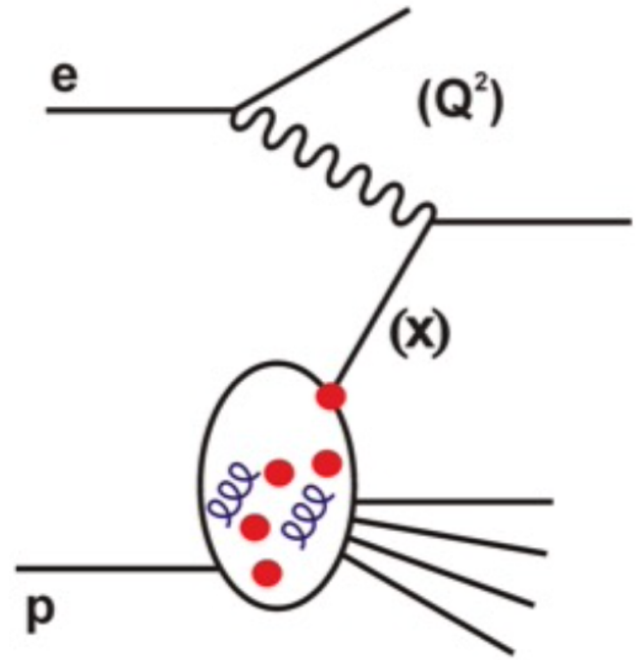
Partons, QCD and *eA* + forward physics @ FCC-*eh*



60×50000 GeV^2 → **3.5 TeV *ep* collider**
delivering very high luminosity
concurrently with *pp* collisions

Krzysztof PIOTRZKOWSKI
(Kraków)

on behalf of the FCC-eh study group



Reminder of "milestone references"

Eur. Phys. J. C (2019) 79:474
https://doi.org/10.1140/epjc/s10052-019-6904-3

Review

FCC Physics Opportunities

TOPICAL REVIEW • OPEN ACCESS

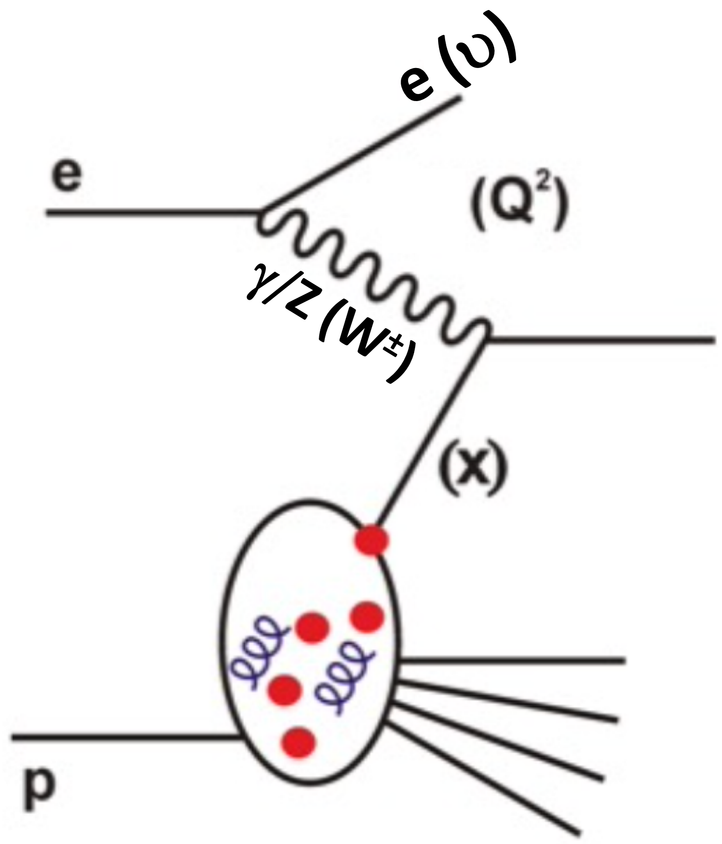
The Large Hadron–Electron Collider at the HL-LHC

P Agostini[1], H Aksakal[2], S Alekhin[3,4], P P Allport[5], N Andari[6], K D J Andre[7,8], D Angal-
S Antusch[11], L Aperio Bella[12], L Apolinario[13] + Show full author list

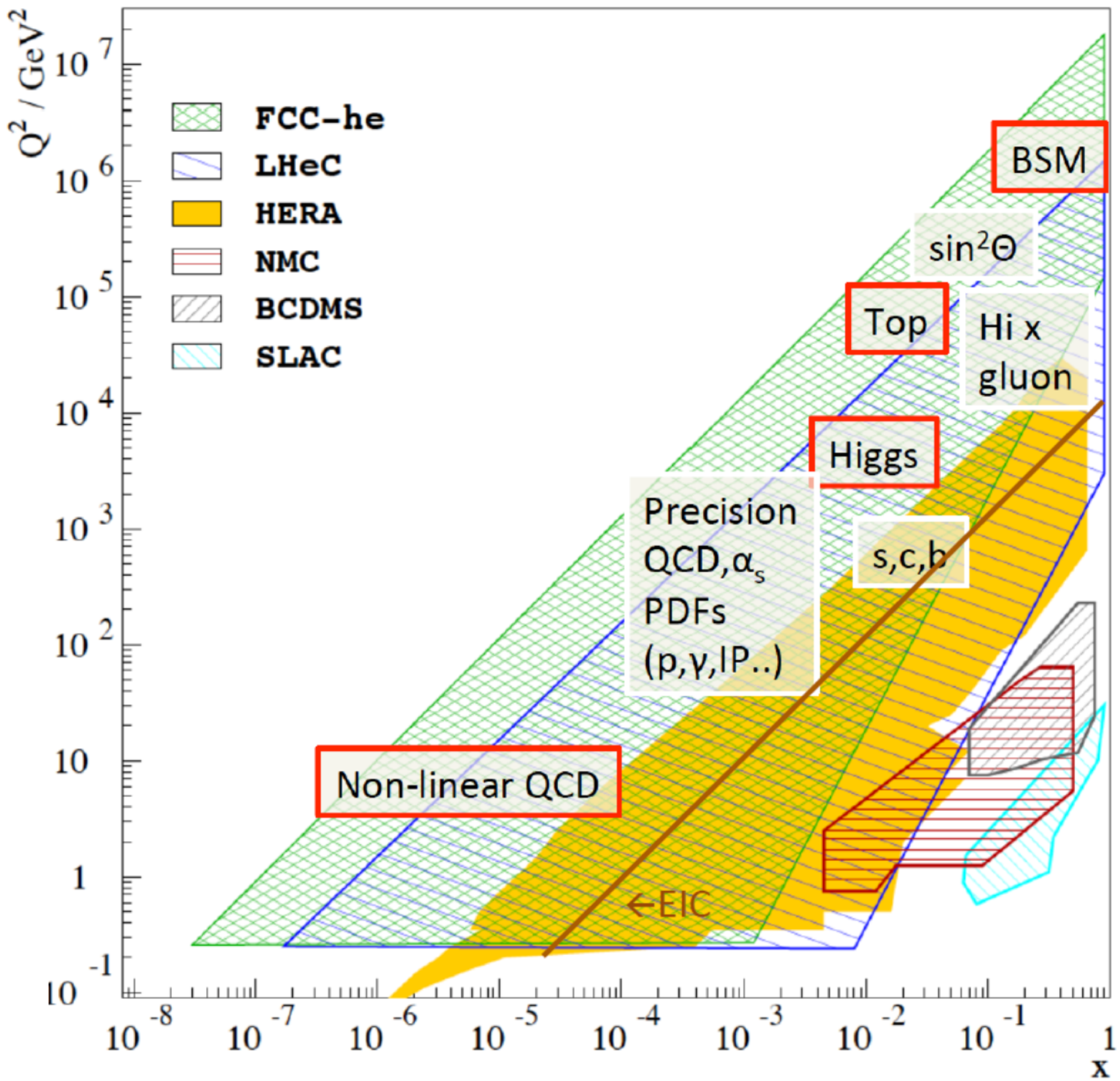
Published 20 December 2021 • © 2021 The Author(s). Published by IOP Publishing Ltd
Journal of Physics G: Nuclear and Particle Physics, Volume 48, Number 11

Includes discussion of FCC-eh physics (1.2 → 3.5 TeV)

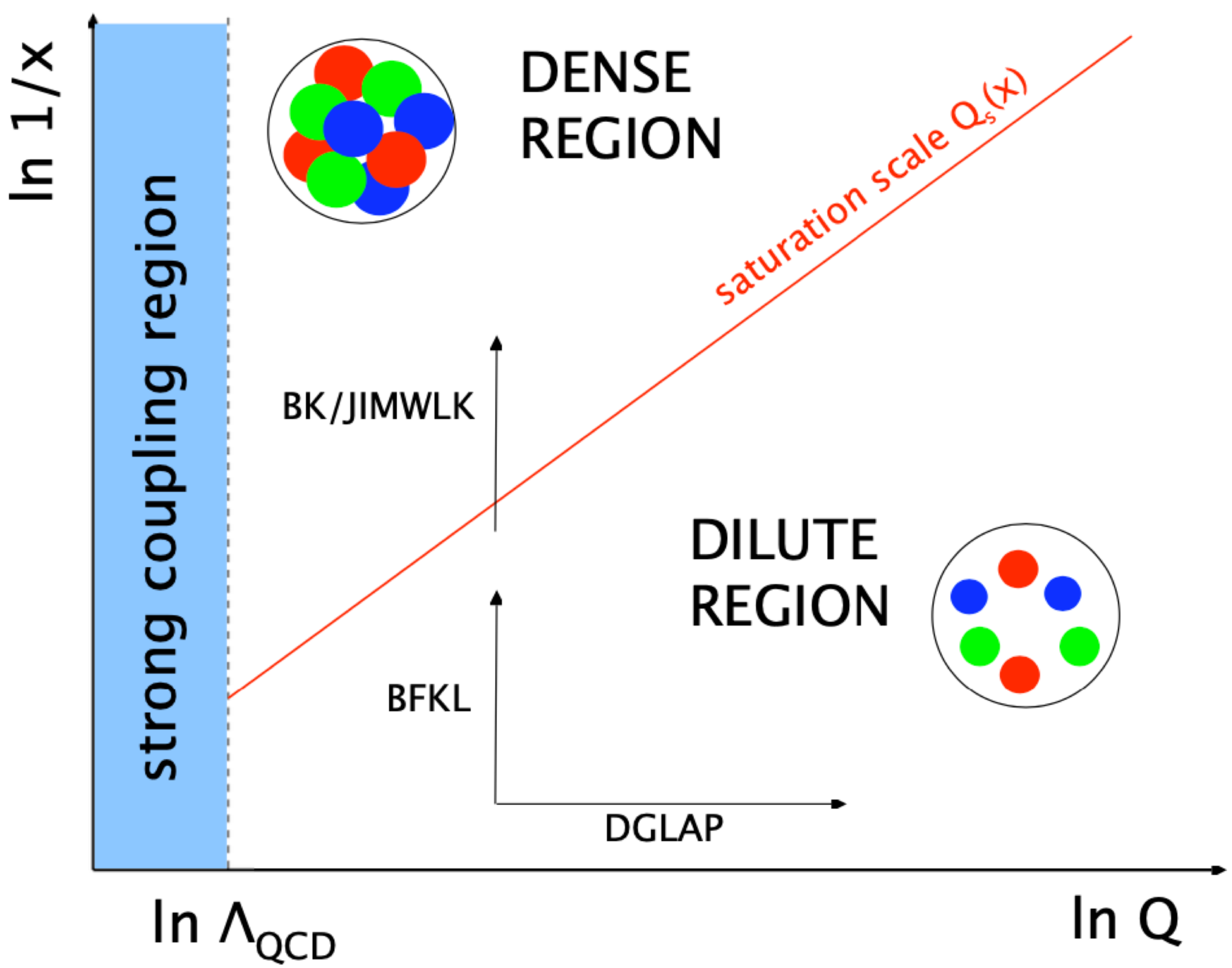
Parton Challenge: new, vast kinematical domain



NC vs. CC scattering ⇒ quark flavor sensitivity



Parton challenge: New dynamics vs. precision



At small x new phenomena may occur:

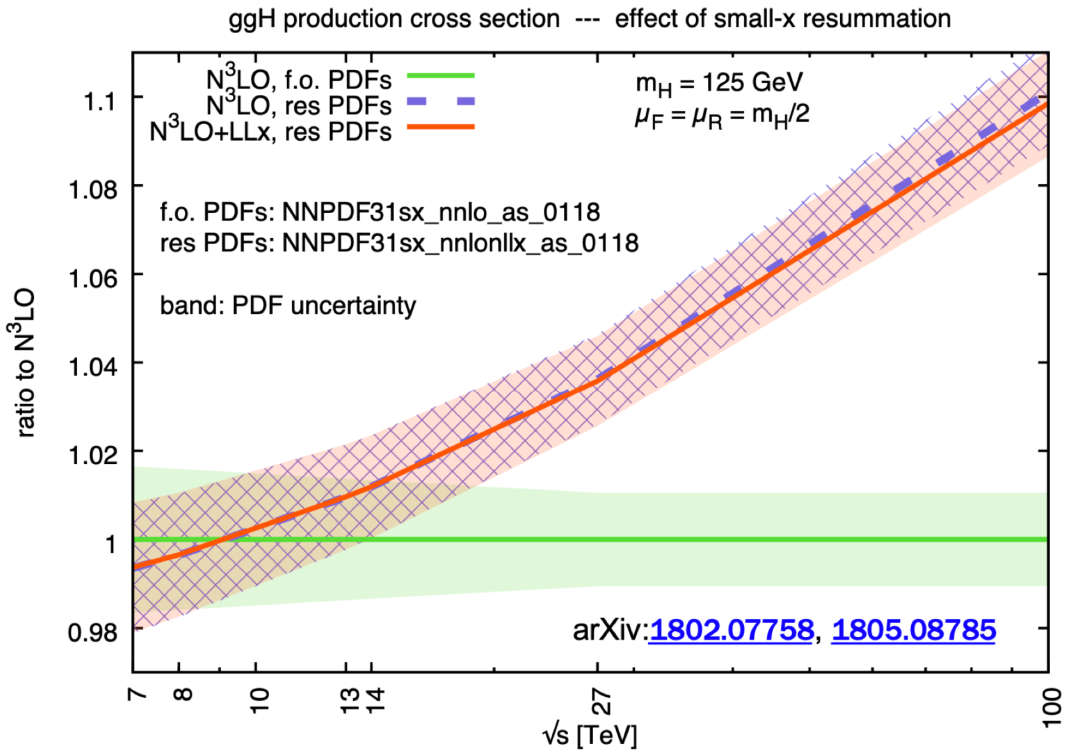
- need of re-summation of ln(1/x) terms (BFKL)
- gluon recombination → parton saturation and non-linear evolution

First signs visible at HERA below x = 0.001

Reminder, where $M_X = \sqrt{(s\, x_1\, x_2)}$:

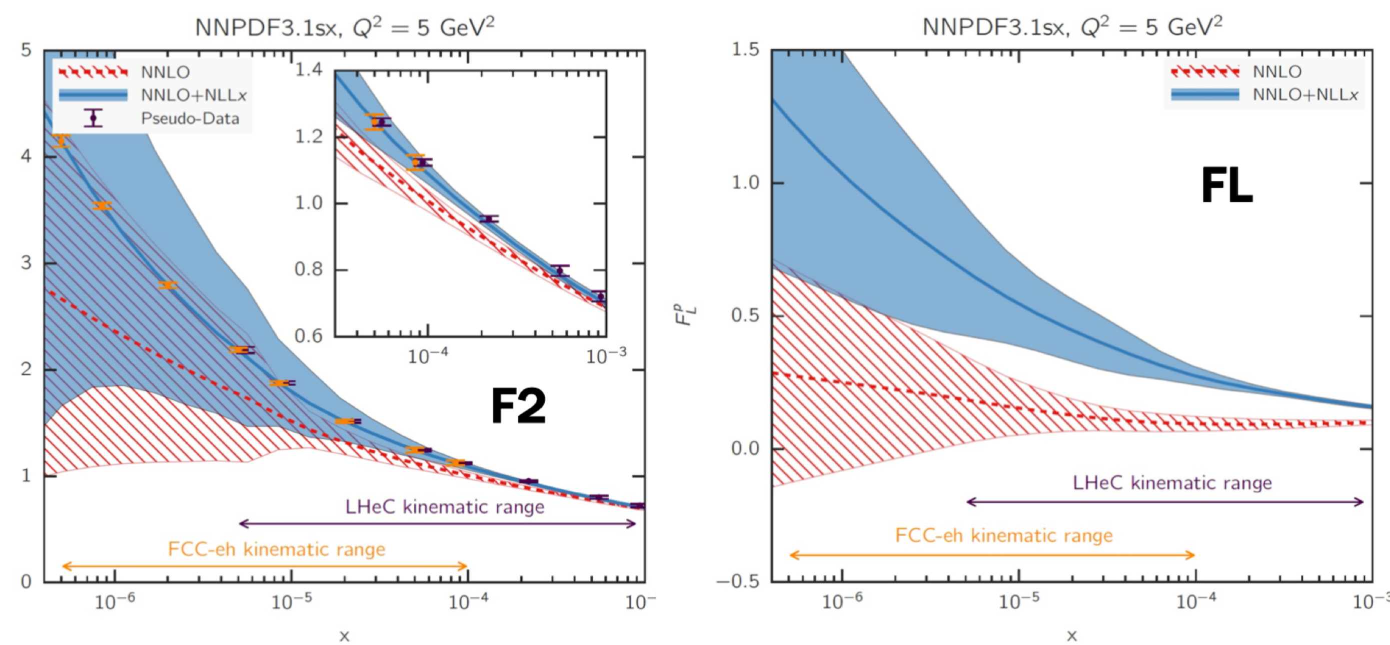
$\sqrt{(x_1 x_2)}$	Higgs	W/Z
HL-LHC	0.009	≈0.006
FCC-hh	0.0013	≈0.0009

Parton challenge: New dynamics vs. precision



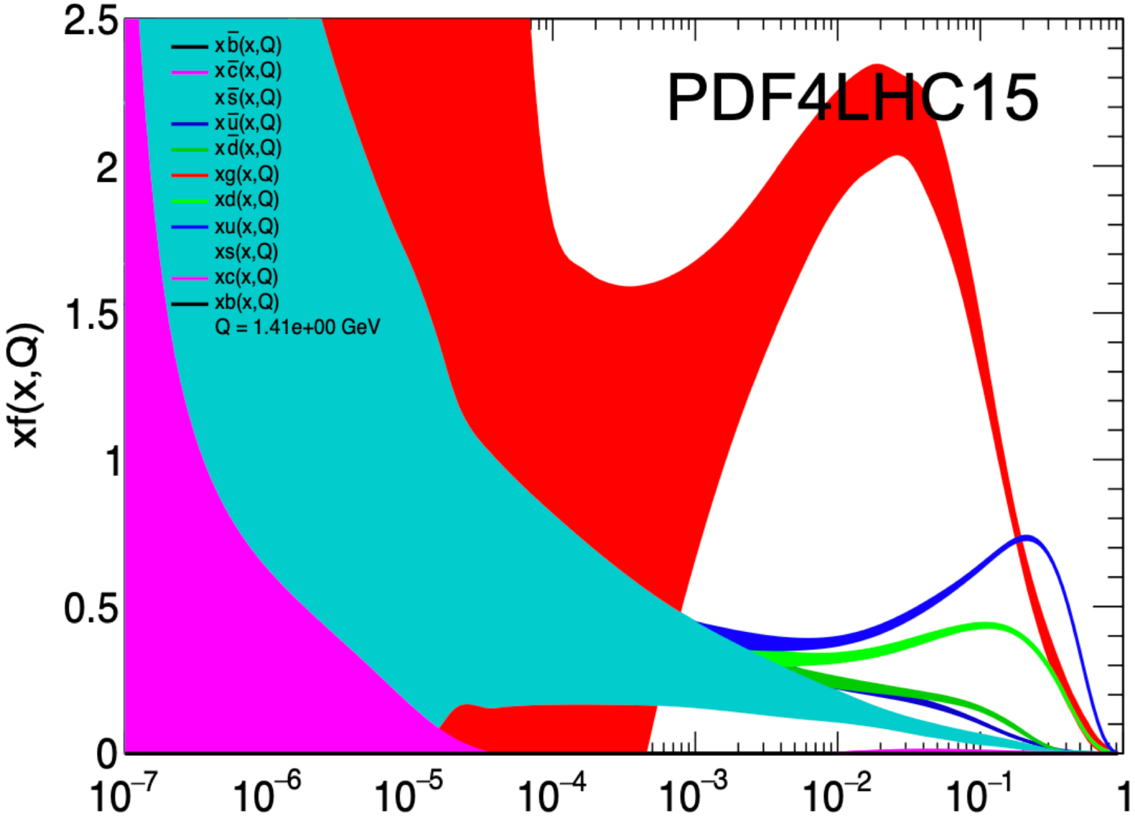
Significant impact, especially at very low x values probed at FCC (see also recent work on forward Higgs production, arXiv:2011.03193; other processes in progress)

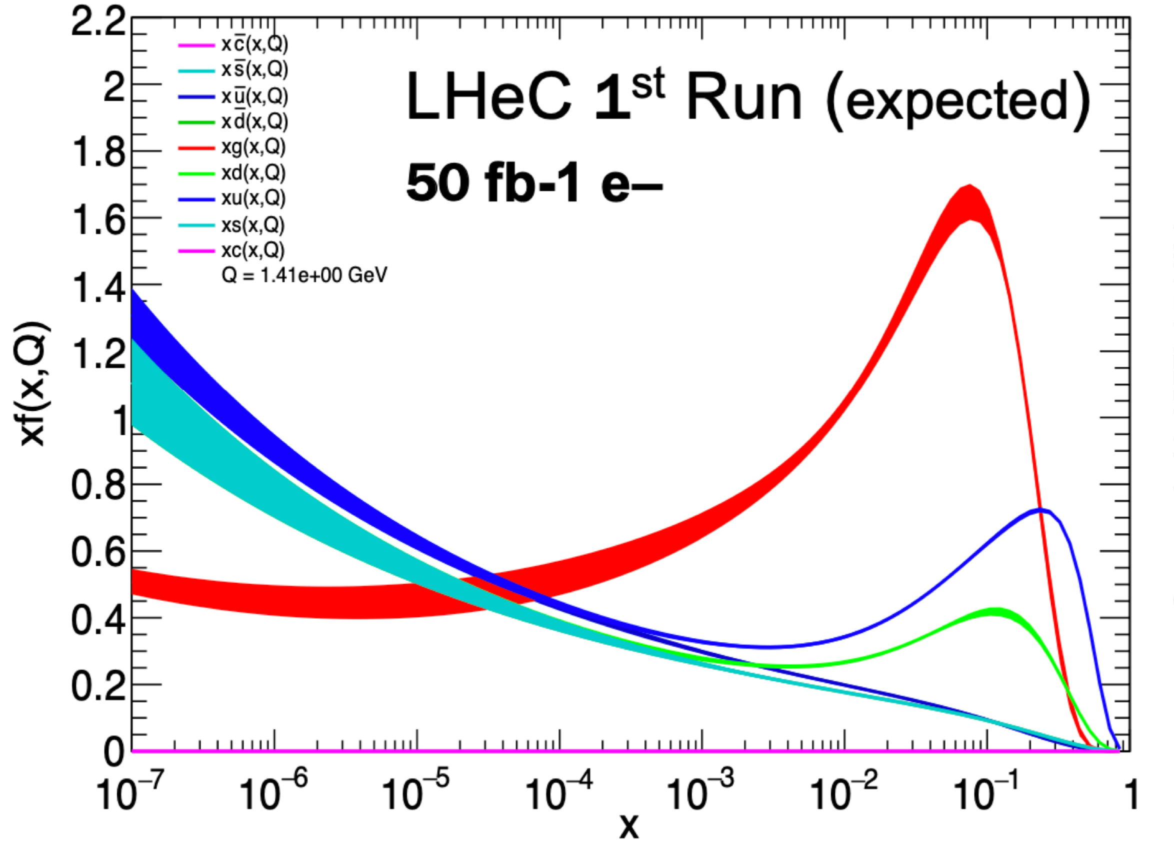
FCC-eh has large sensitivity and discriminatory power to pin down details of **small x QCD dynamics** and measurement of F_L has a significant role to play, arXiv:1802.04317



NC cross section: $\sigma_{r,\mathrm{NC}} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2) \qquad y = \frac{Q^2}{x\,s}$

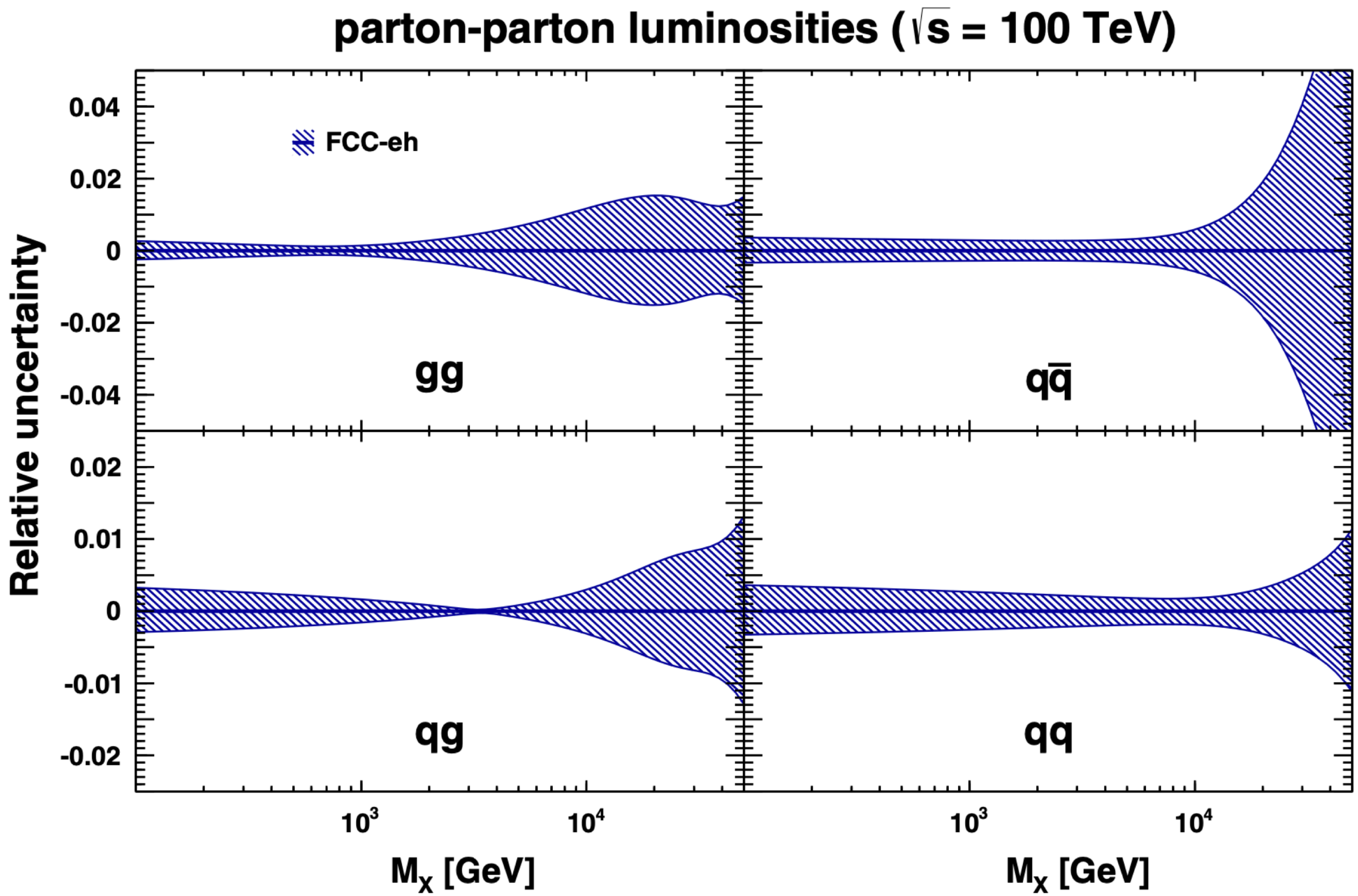
PDF exercise at LHeC...





situation today → after 1st LHeC Run

with further improvements after full running period, plus HQs, (DIS jets, …)



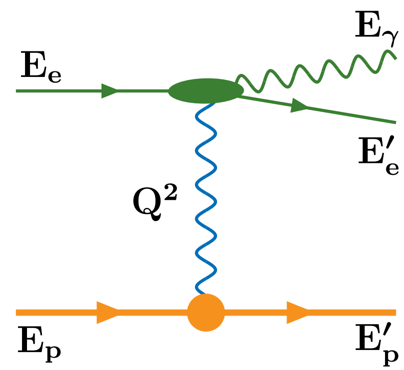
Under one condition....

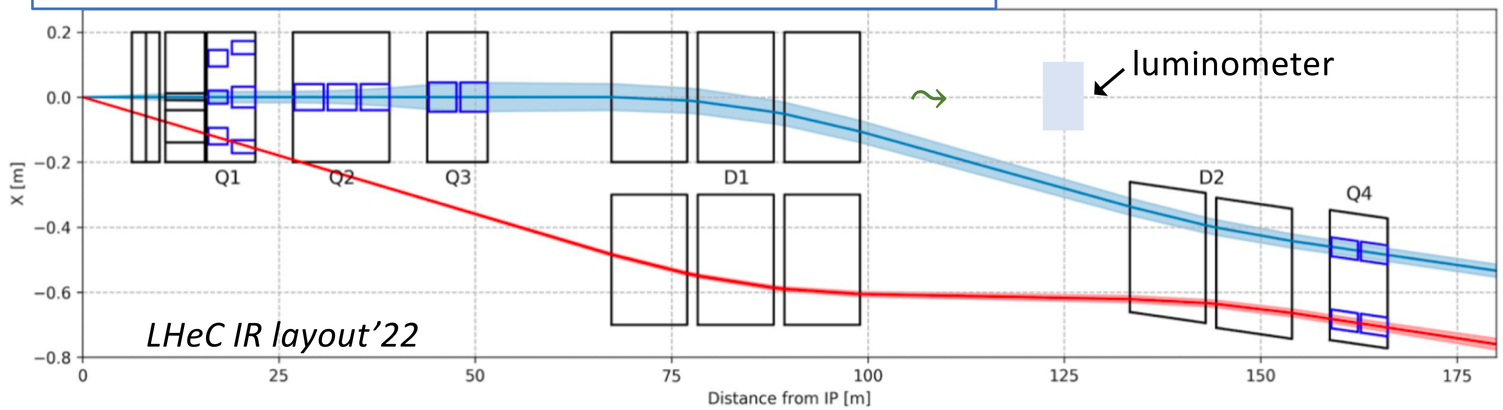
Fig. 1.4. Relative PDF uncertainties on parton-parton luminosities from the FCC-eh PDF set, as a function of the mass of the produced heavy object, M_X, at $\sqrt{s} = 100\,\text{TeV}$. Shown are the gluon-gluon (top left), quark-antiquark (top right), quark-gluon (bottom left) and quark-quark (bottom right) luminosities.

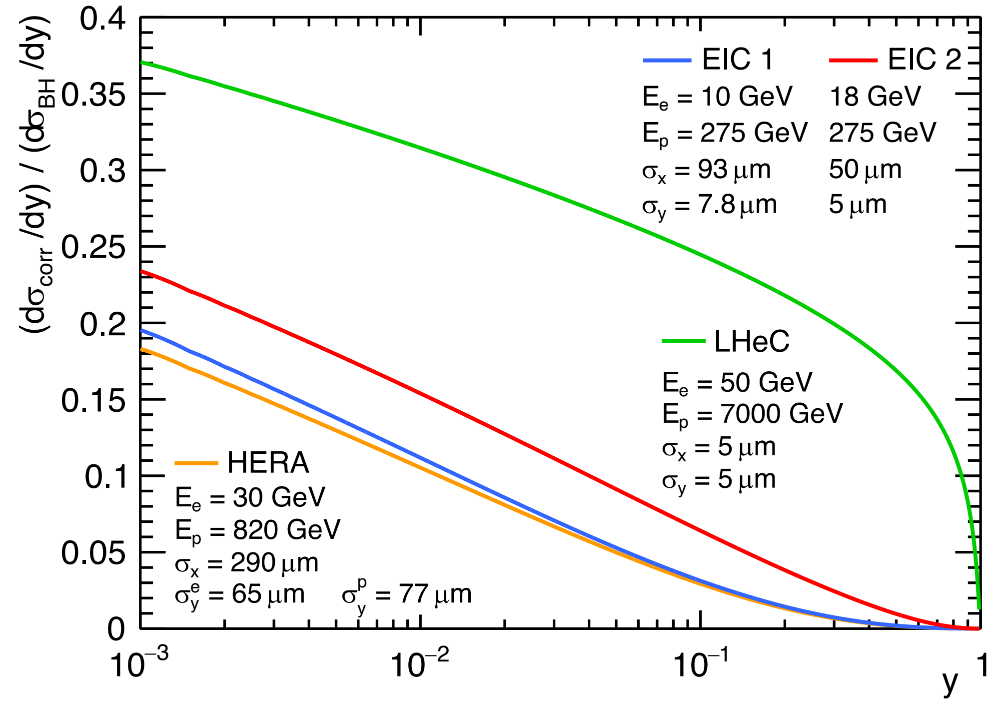
https://link.springer.com/article/10.1140/epjst/e2019-900087-0

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/FCC-eh* 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 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 = 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.

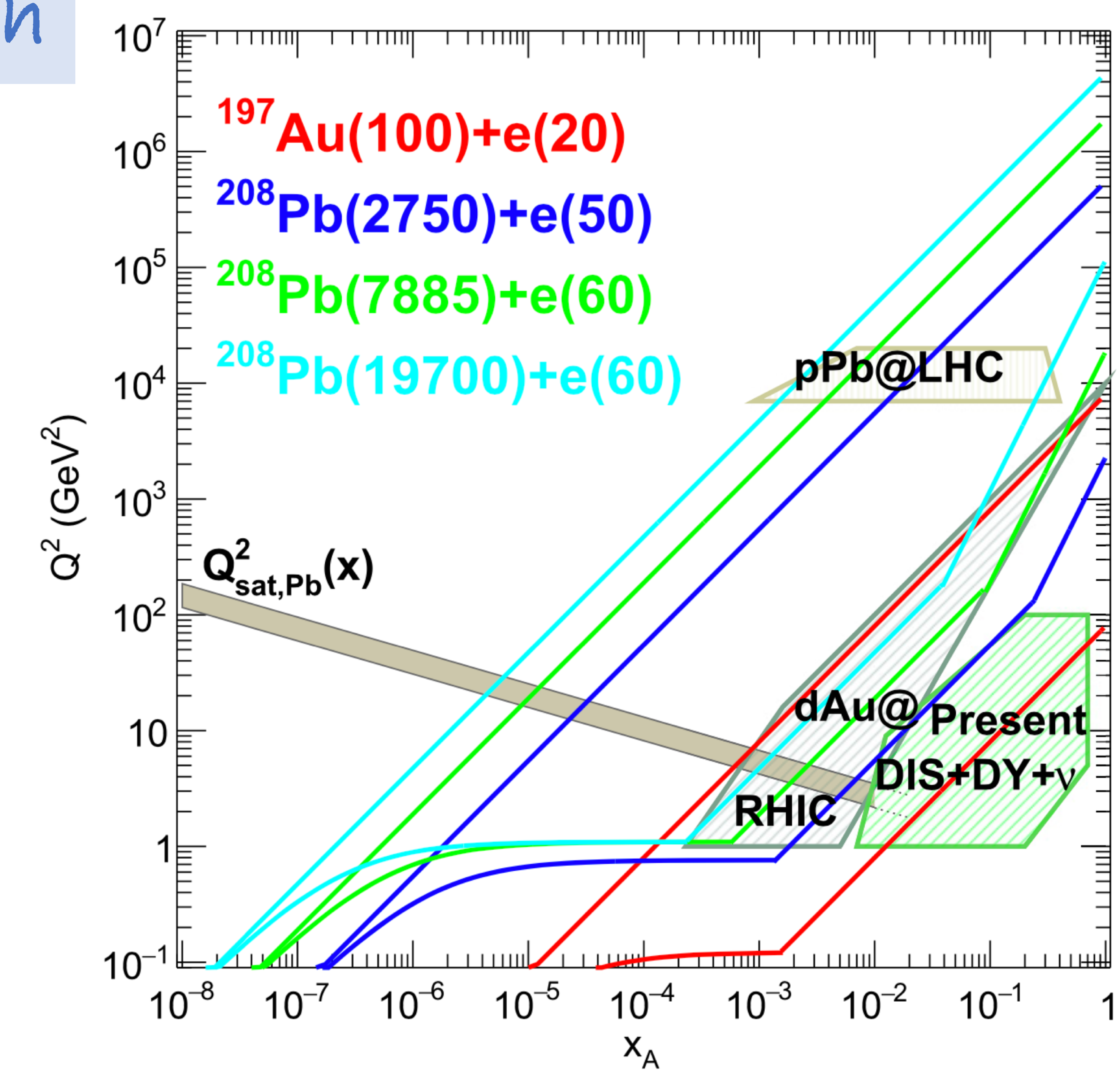
See, for example:
https://iopscience.iop.org/article/10.1088/1748-0221/16/09/P09023

eA scattering at FCC-eh

Unprecedented access to (x,Q^2) kinematic plane (in *eA*):

• coverage extended with respect to EIC by up to **3 orders of magnitude**

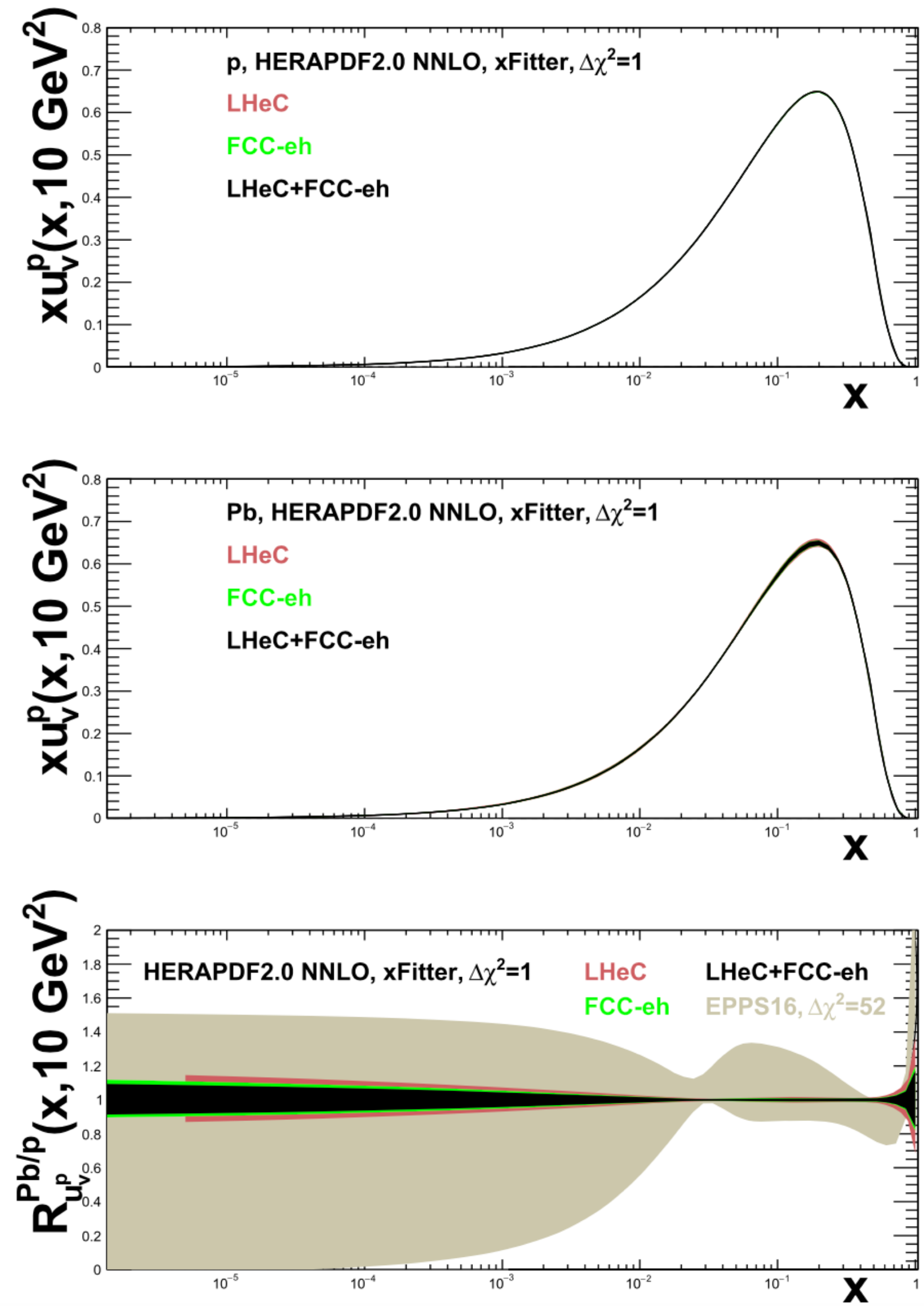
• DIS with nuclei down and below $x=10^{-6}$ in **perturbative** regime ⇒ saturation scale (non-linearities) in fully perturbative regime



Nuclear PDFs

"Precise [and direct] determination of nuclear parton densities for a single nucleus (lead, and eventually lighter ions) will be possible [in a single experiment!]. In particular, the current huge uncertainties in nuclear gluon and sea quark densities at low *x* will be dramatically improved using the data from the LHeC [FCC-eh]. In analogy to the proton PDF extraction described in previous sections, **full flavor de-composition** in the nuclear case could be achieved using both NC and CC data with HF identification."

https://iopscience.iop.org/article/10.1088/1361-6471/abf3ba

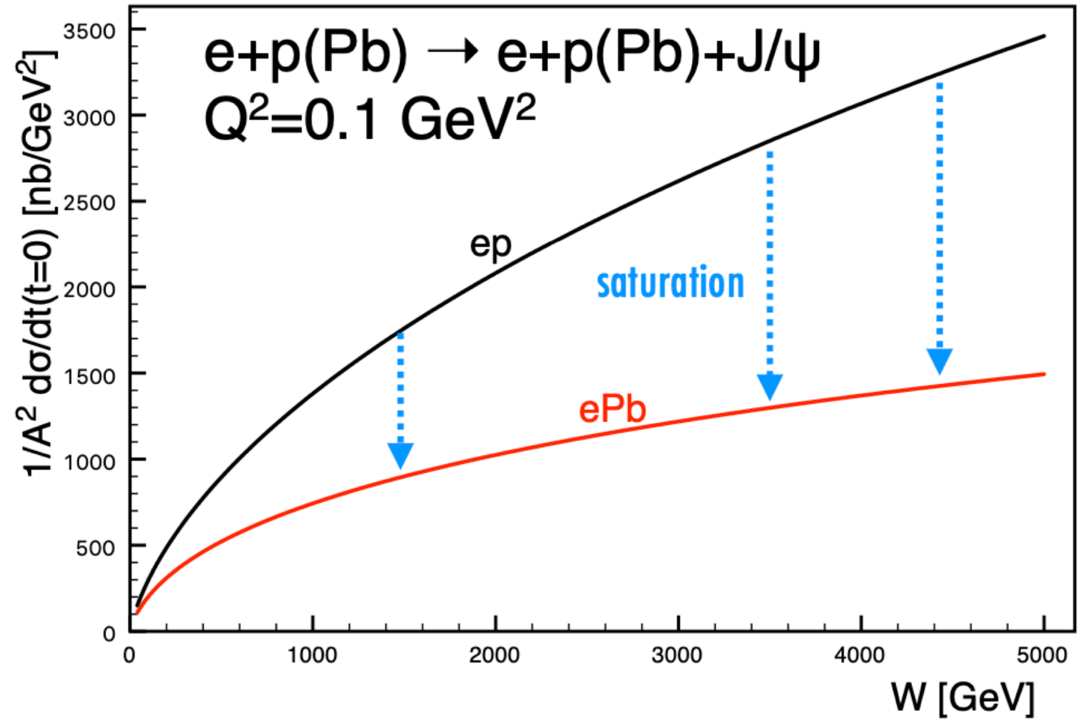


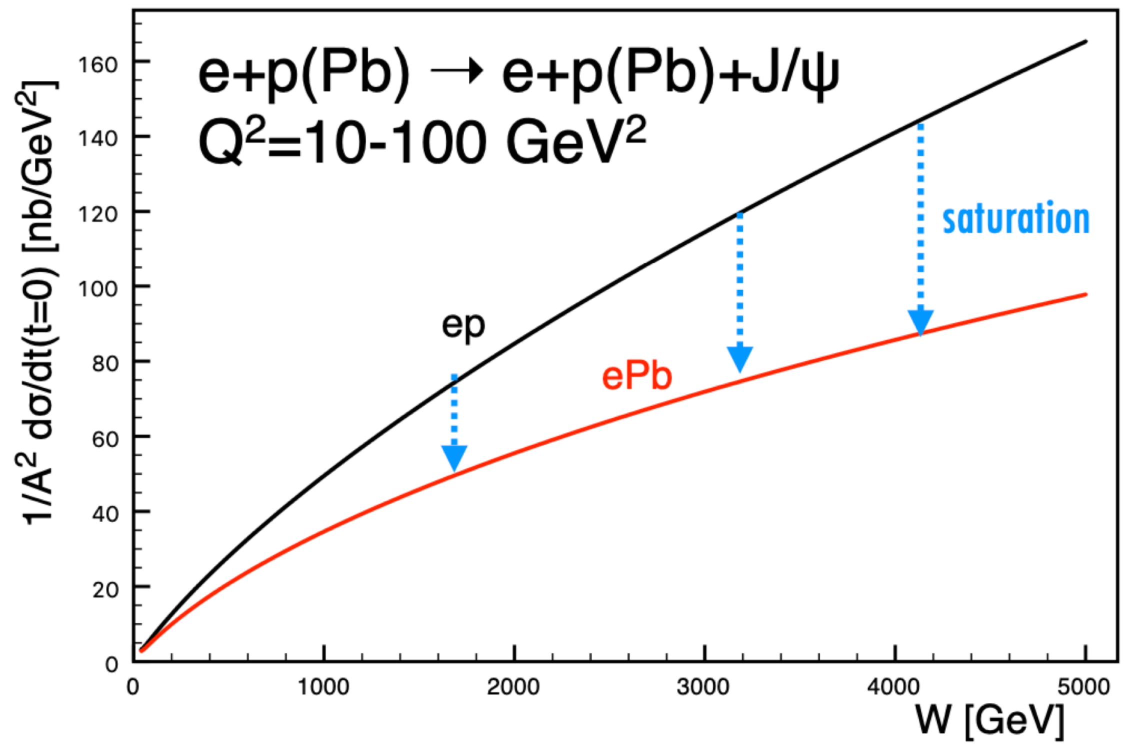
Nuclear particle physics with electron–ion scattering at the LHeC/FCC-eh

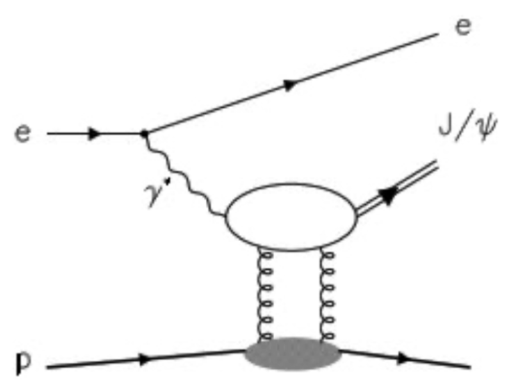
- "The LHeC [FCC-eh] will be able to test and establish or exclude the phenomenon of parton saturation at low *x* in protons and nuclei. […] The LHeC [FCC-eh] will be a unique machine with which to address both of their variations, such that the saturation concepts can be precisely tested."
- "LHeC [FCC-eh] machine in *e*A mode will have a huge impact on physics explored in *p*A and AA collisions, see section 9.7, where it provide vital input and constraints on the 'baseline' initial state in nuclear collisions and meawillsurements of the impact of a cold nuclear medium on hard probes and the effects of hadronisation. It will also explore the effect of the initial-state correlations on the final-state observables, which are relevant in order to understand collectivity in small systems explored in *pp* or *p*A collisions."
- "The measurements of diffraction of protons and nuclei as well as the inclusive structure functions in the nuclear case will allow us to explore the very important relation between nuclear shadowing and diffraction […]
- Similarly to the proton case, DVCS and exclusive vector-meson production will provide unique insight into 3D nuclear structure."

https://iopscience.iop.org/article/10.1088/1361-6471/abf3ba

Exclusive Vector meson production and saturation



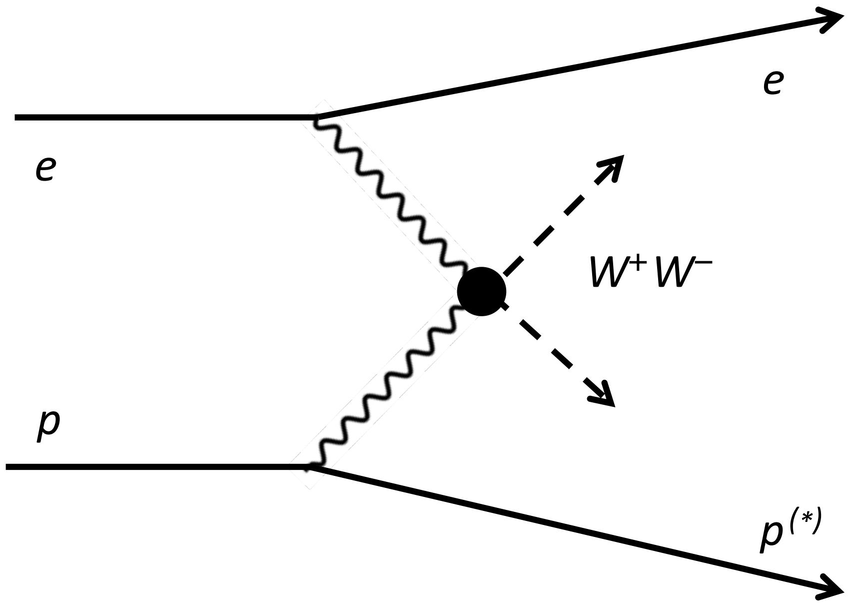




No color transfer ⇒ (at least) two-gluon exchange + meson mass provides hard scale

⇒ exclusive J/ψ production is very sensitive to nuclear effects and saturation

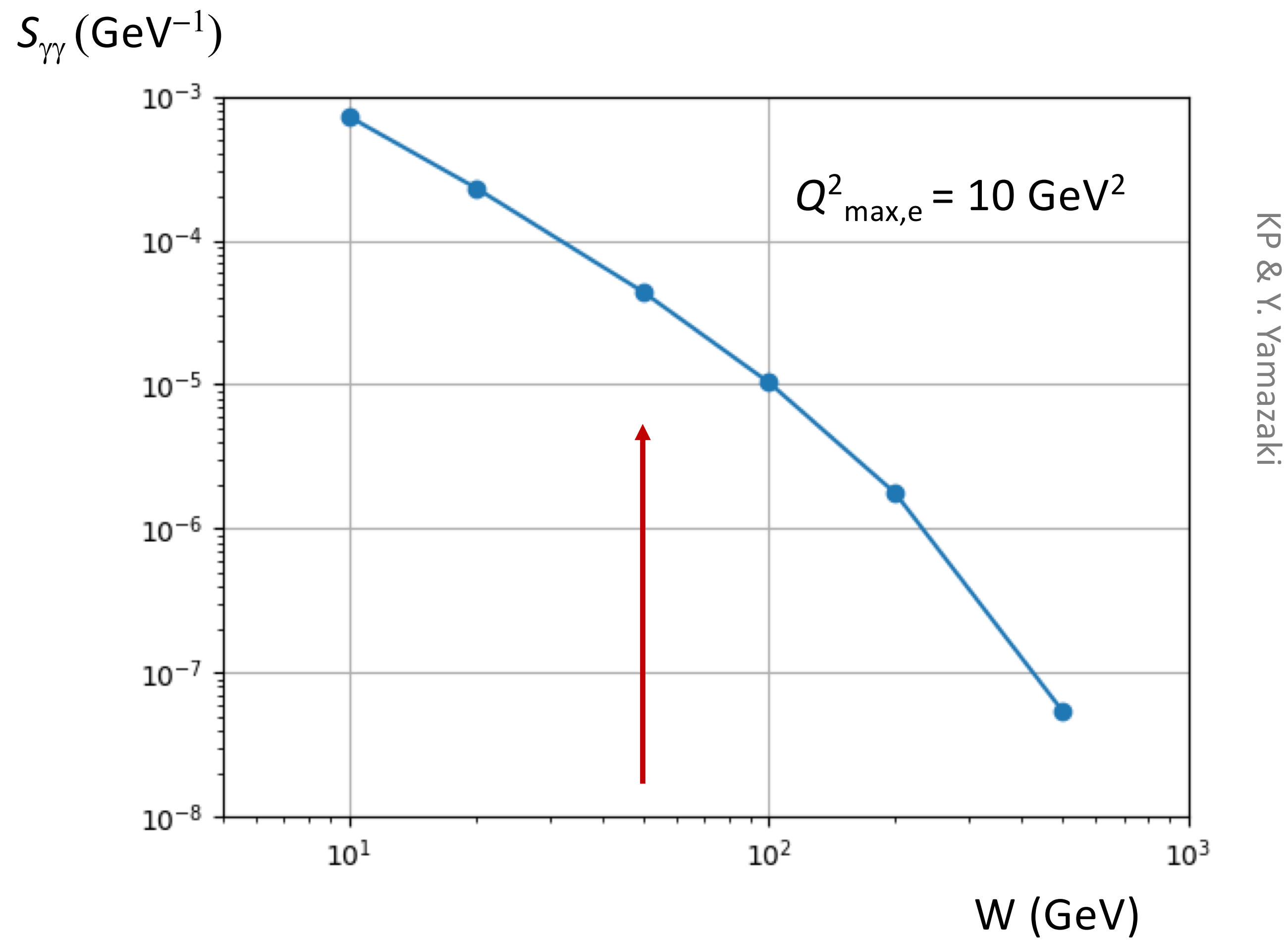
Exclusive production: FCC-eh as a high energy $\gamma\gamma$ collider



Electrons will have "only" 60 GeV, but **higher** photon flux, as approximately:

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

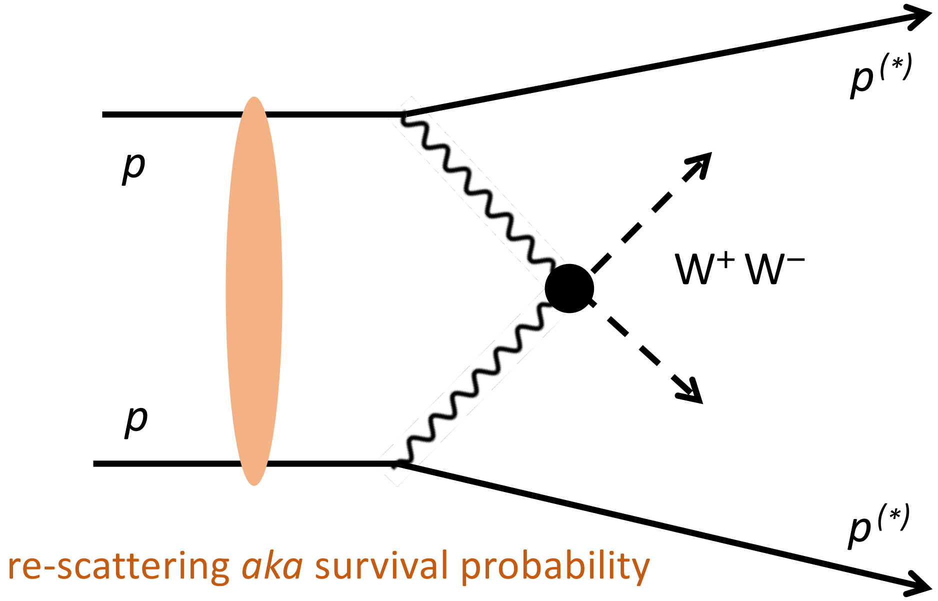
where $Q^2_{min} \propto m^2$, and $Q^2_{max,e}$ can be very high



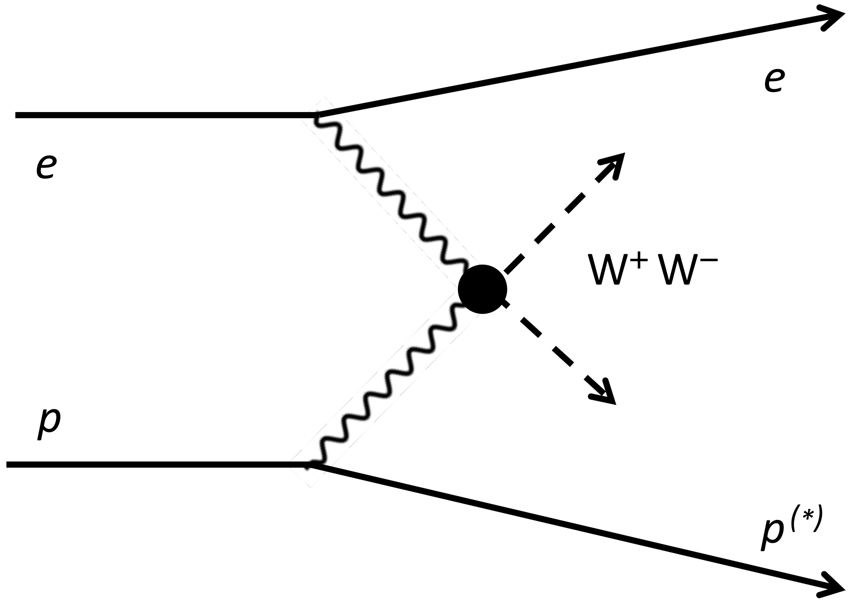
For W < 50 GeV the *fully* exclusive $\gamma\gamma$ luminosity spectrum is **higher** at the LHeC than at the HL-LHC!

https://arxiv.org/abs/2109.08001

FCC-hh vs. FCC-eh as high energy $\gamma\gamma$ colliders



vs.

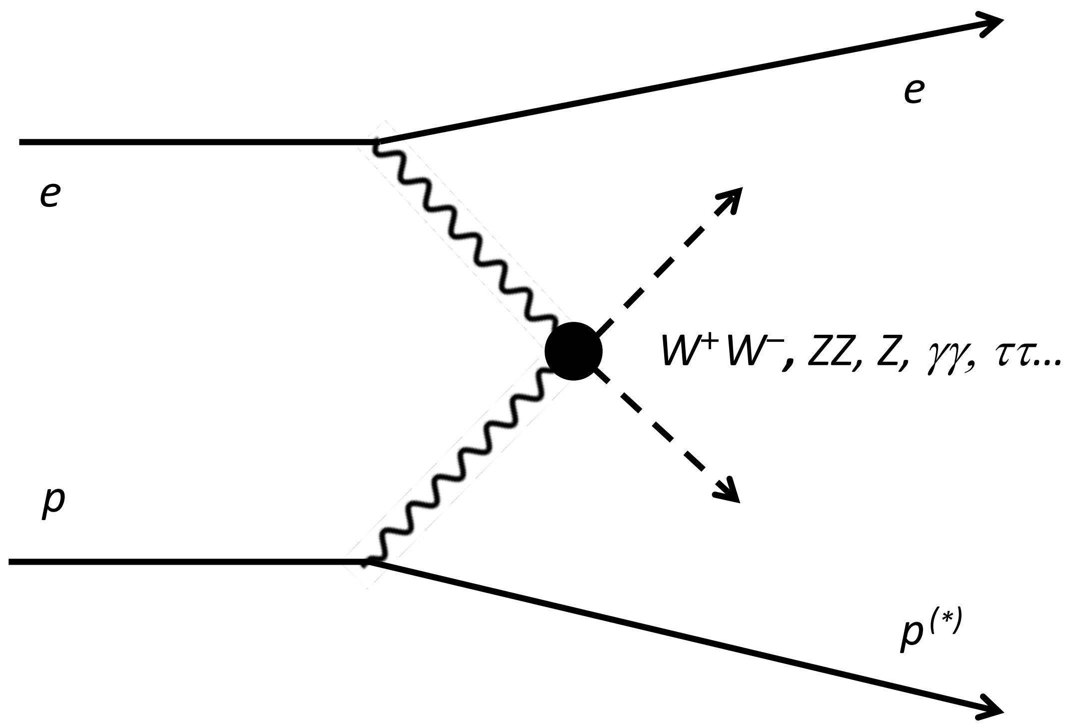


Energy reach for $\gamma\gamma$ interactions is higher at the LHC, however at the highest W tagging is not possible and the suppression due to re-scattering becomes large.

Event **pileup is very low at the FCC-eh** – of few percent at most

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!

FCC-eh as a very unique, generic high energy $\gamma\gamma$ collider



Wide range of $\gamma\gamma$ processes will be studied at FCC-eh:

- $\gamma\gamma \to \gamma\gamma$: orders of magnitude higher statistics than for *PbPb* at FCC-hh + $\gamma\gamma$ tagging ⇒ kinematic fitting
- $\gamma\gamma \to \tau^+\tau^-$: orders of magnitude higher statistics than for *PbPb* at FCC-hh + $\gamma\gamma$ tagging ⇒ new decay modes
- $\gamma\gamma \to Z$: search for the anomalous single Z boson exclusive production
- $\gamma\gamma \to ZZ$: 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 FCC-hh) is expected for fully leptonic W^+W^- decays + tagging

Summary** and outlook

- FCC-eh offers multiple and unique research directions in QCD, including nuclear phenomena
- Moreover, FCC-eh is mandatory if one wants to fully exploit the scientific potential of FCC-hh
- What HERA was for the proton DIS, FCC-eh will be for the *eA* DIS – opening a new era of research
- There are still new and exciting research directions being added to the FCC-eh physics menu

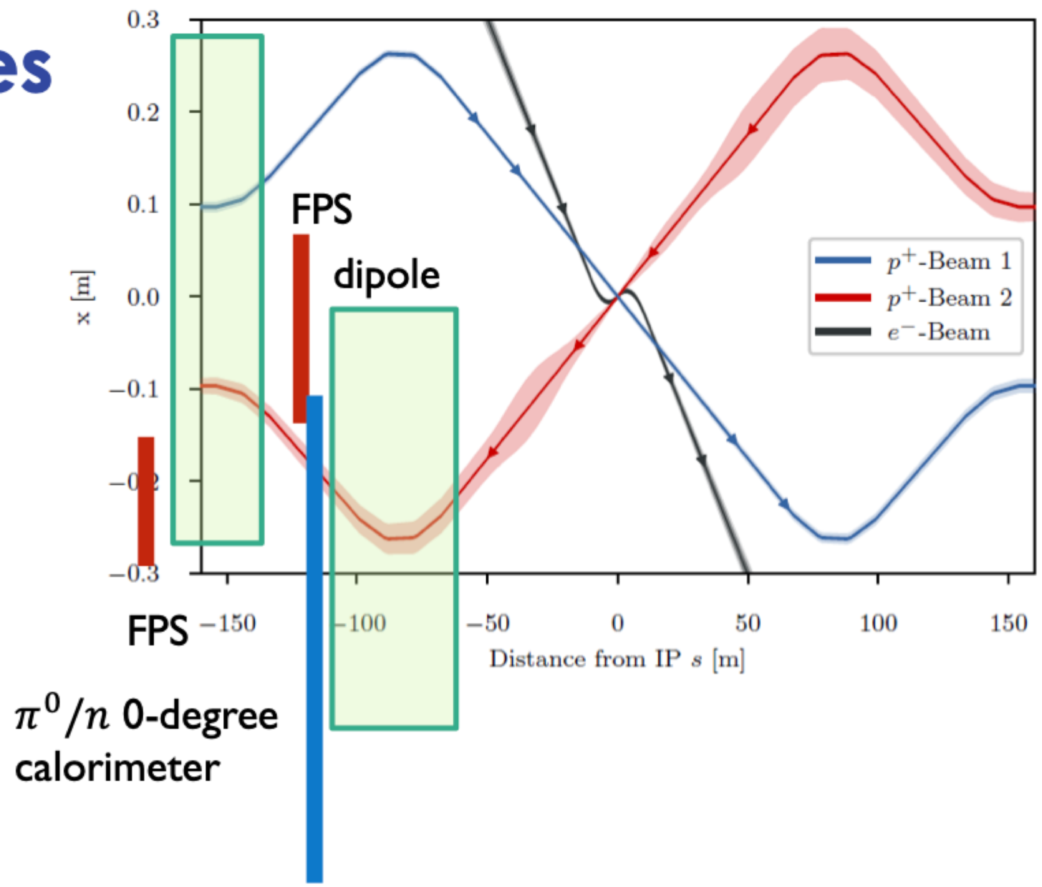
S T A Y   T U N E D !

**) Only a small fraction of all subjects from these vast fields of research could be mentioned here

Backup slides

Around zero-degrees

- Forward Proton spectrometer ~ following the LHC design apart from stations close to IP
- New IP design allows to place a ZDC
  - Transvers size ±30 cm shower leak moderate
  - Aperture ~ 0.35 mrad or 2.4 GeV in p_T
- Technology candidate: Si-W
  - Need < 1mm resolution for p_T resolution ≪ 100 MeV for 7 TeV neutron i.e. very fine segmentation (e.g. ALICE FoCal)
  - Radiation dose: O(10MGy) or more
    - Much less than LHC, possibility to use silicon sensors



Y. Yamazaki, ICHEP'20

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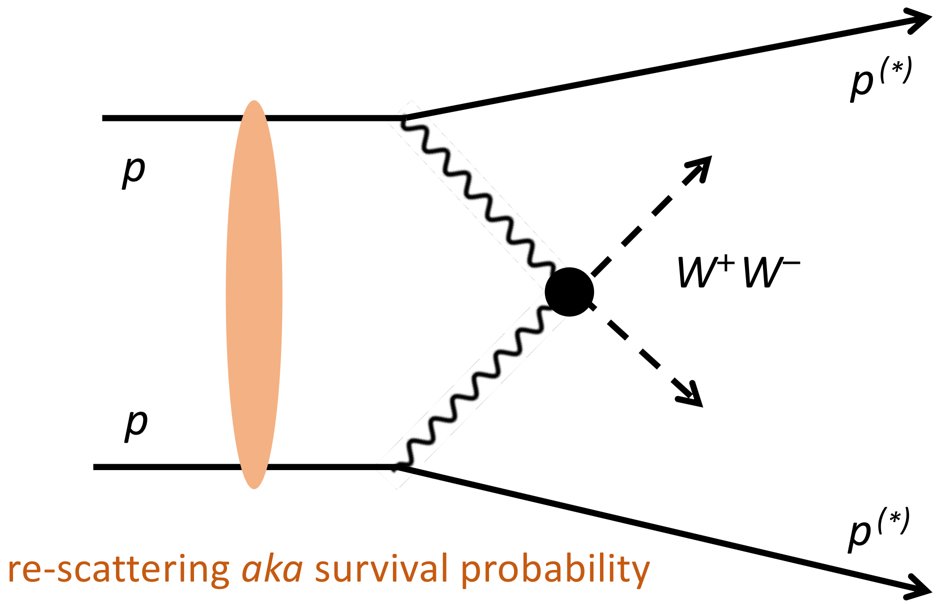
FCC-hh as a high energy $\gamma\gamma$ collider: **challenges & limitations**

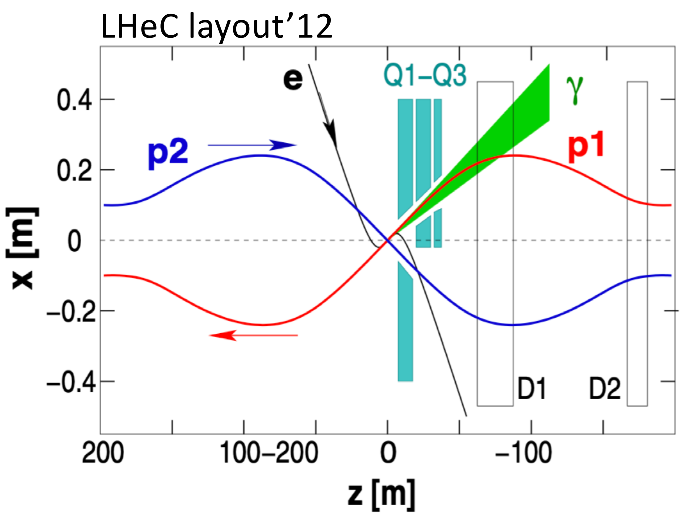


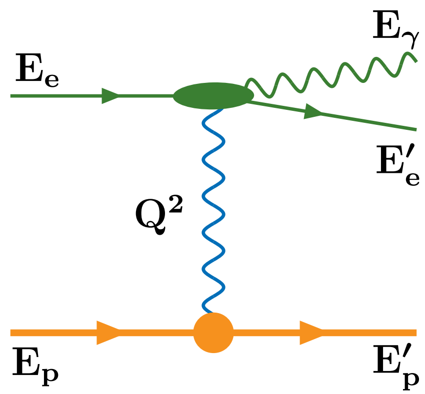
- Event pileup is very high – central tracking **with** ps resolution timing will mitigate it only partially; event pileup will make tagging with forward protons even very tricky – **ps resolution timing detectors** will help

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 at LHC so far (after 10-year efforts)
- And, the **re-scattering suppression** is large and uncertain, especially at very large W

ep Luminosity





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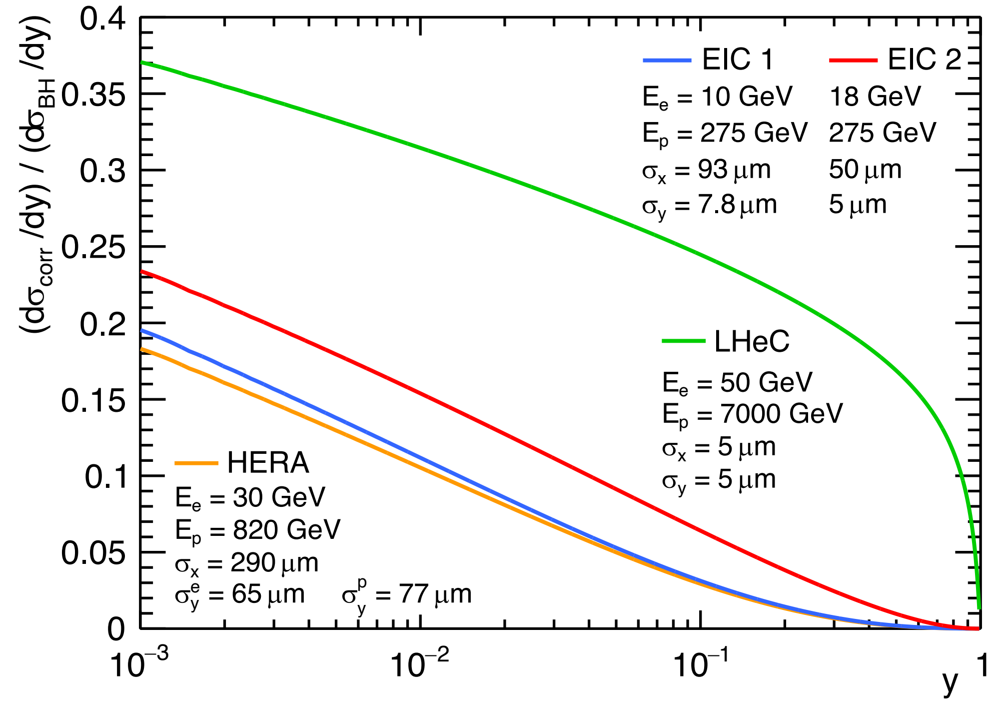

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