Particle Physics Applications

with

AWAKE Technology

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Motivation-AWAKE

Energy Budget

Witness:

10^{10} particles @ 1 TeV ≈ few kJ

Drivers:

PW lasers today, ~40 J/Pulse

FACET (e beam, SLAC), 30J/bunch

SPS@CERN 20kJ/bunch

LHC@CERN 300 kJ/bunch

Dephasing

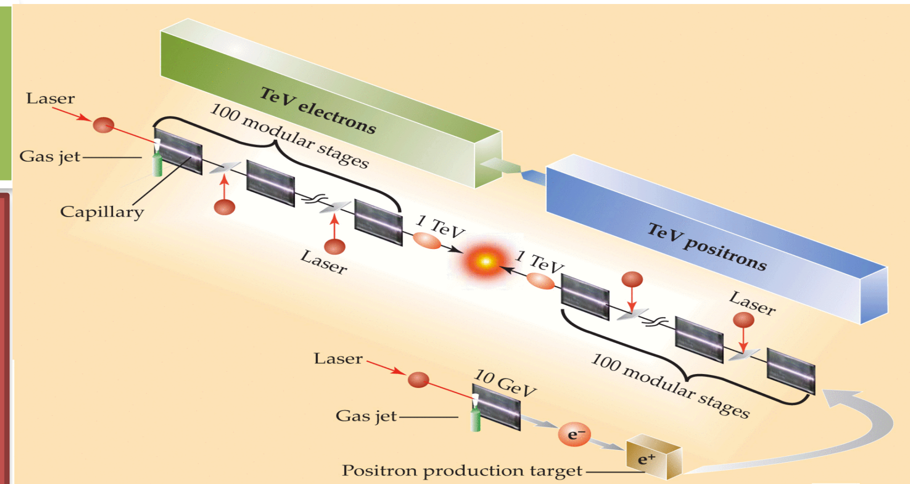
$$\delta \approx \frac{\pi L}{\lambda_p} \frac{1}{\gamma^2}$$

SPS: ~100m,

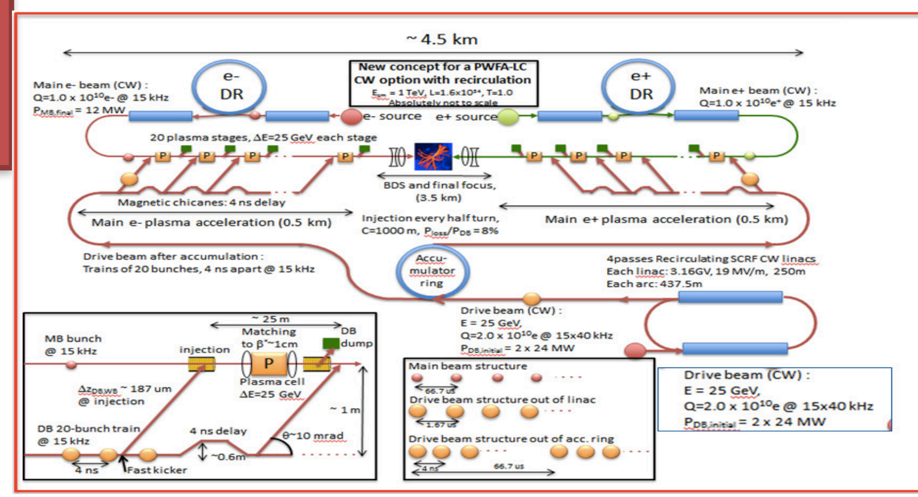
LHC: ~few km

FCC: ~ ∞

Staging Concepts



Leemans & Esarey, Phys. Today ***62 #3*** *(2009)*



E. Adli et al. arXiv:1308.1145,2013

Particle Physics Applications

- **Physics with a high energy electron beam**
  - search for dark photons in beam dump experiments
  - Fixed target experiments in new energy regime
  - Probe non-linear QED

Energy & Flux important - luminosity determined by target properties. Much more relaxed parameters for plasma accelerator

- **Physics with an electron-proton or electron-ion collider**
  - Low luminosity version of LHeC
  - Very high energy electron-proton, electron-ion collider

New energy regime means new physics sensitivity even at low luminosities !

o E. Gschwendtner et al. (AWAKE Coll.), The AWAKE Run 2 programme and beyond, Symmetry, 14 (2022) 1680

o A. Caldwell et al., Particle physics applications of the AWAKE scheme, arXiv: 1812.11164

o M. Wing, Particle physics experiments based on the AWAKE acceleration scheme, Phil. Trans. R. Soc. A 377 (2019) 20180185

AWAKE vs Protons on Target

Protons on target:
- continuous energy spectrum
- large transverse emittance
- slow extraction: unbunched

AWAKE-like:
- % level energy spread
- mm-mrad level transverse emittance
- bunched beams

Comparison

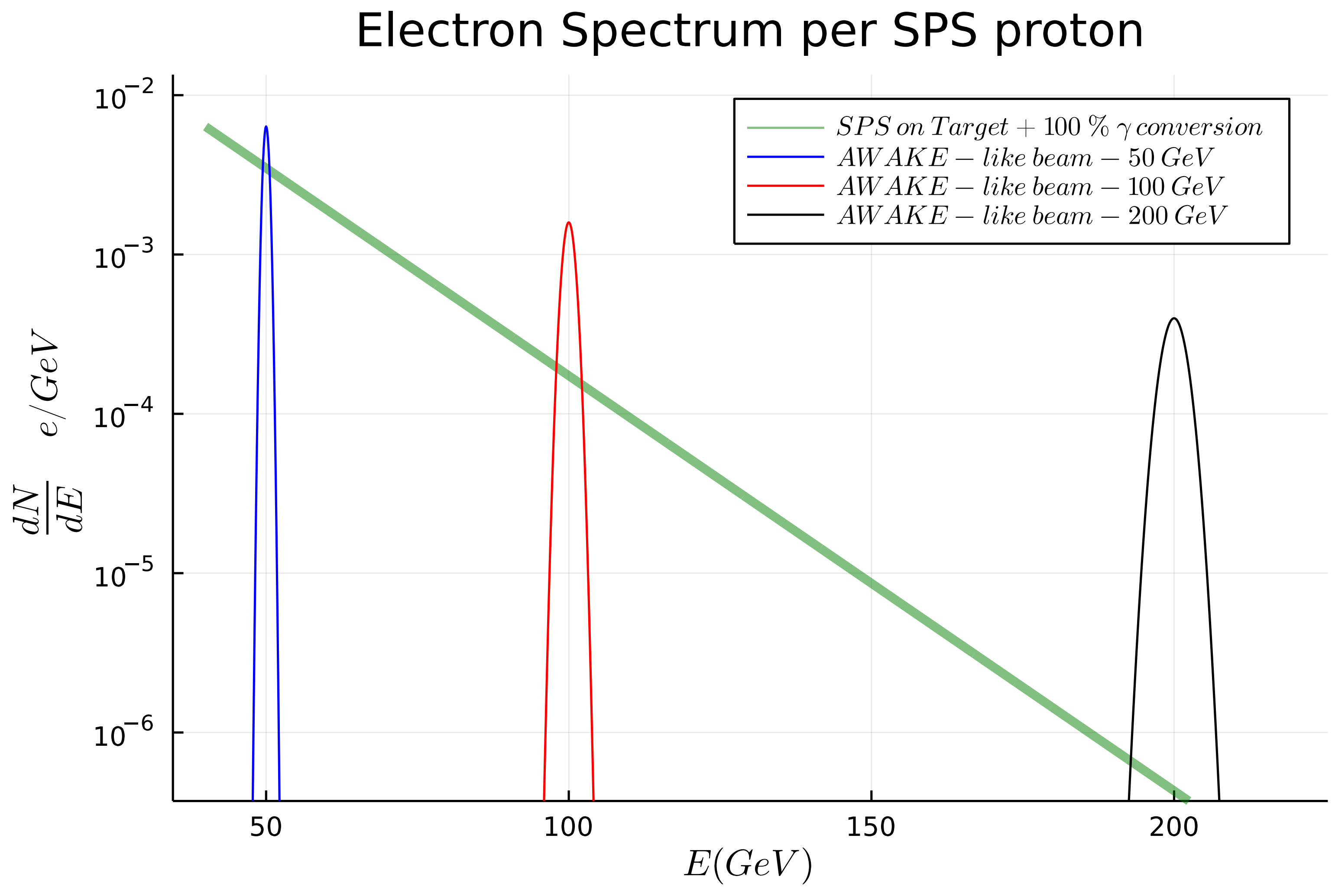
D. Cooke, UCL, calculated the γ spectrum achievable with the SPS. Spectrum approximated with exponential.

Converted to electron energy spectrum assuming 100% conversion to e^+e^-, electron get 50% of energy

Compared to electrons accelerated to given energy, 1% energy spread, 0.01 electrons accelerated/proton

Maximum energy for SPS driver $\sim 200\ \mathrm{GeV}$, K.V. Lotov and P.V. Tuev, Plasma Phys. Control. Fusion, **63**,(2021) 125027.

work in progress: indicative



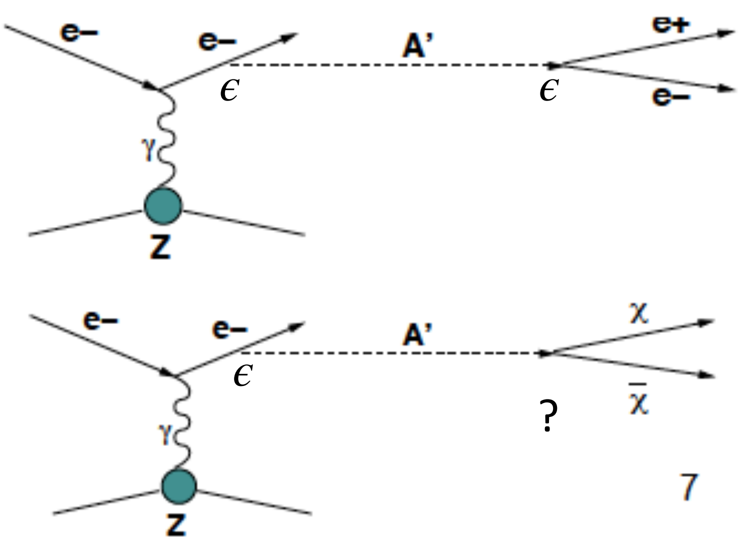
Notes:

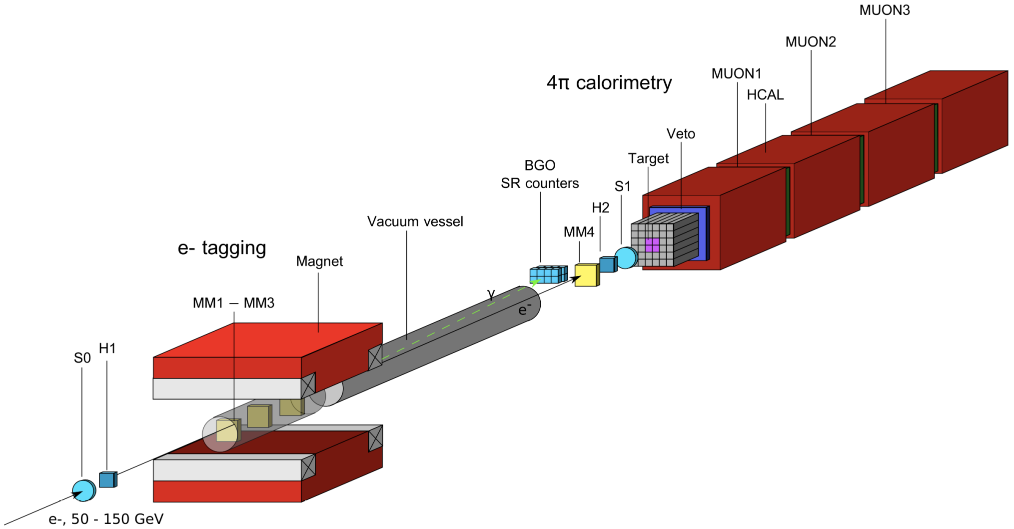
- acceptance of electrons from target production not taken into account
- Handling of AWAKE-produced beam discussed in J. Farmer *et al.*, arXiv:2203.11622

Beam Dump

Example: Dark photon search a la NA64. Currently: secondary electron beam from SPS. Provides 10^6 electrons/s, E=100 GeV

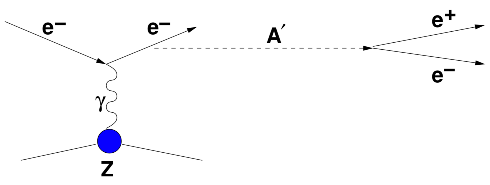
Decaying dark photons: into visible or invisible mode. For invisible mode - need to track individual electrons. How to do this in a bunched beam?

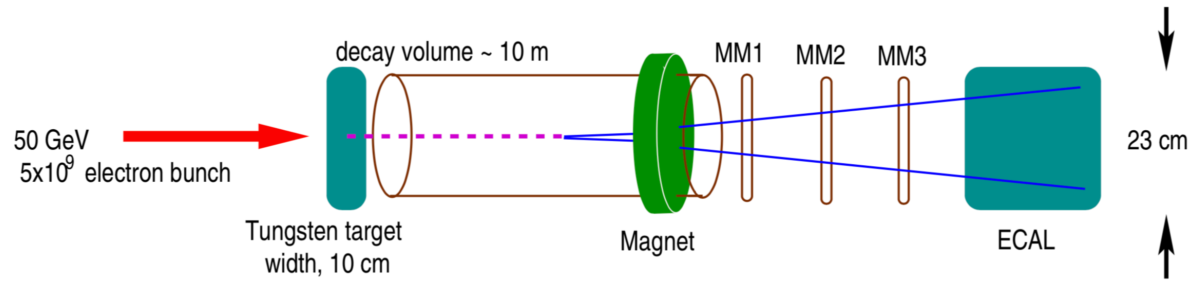




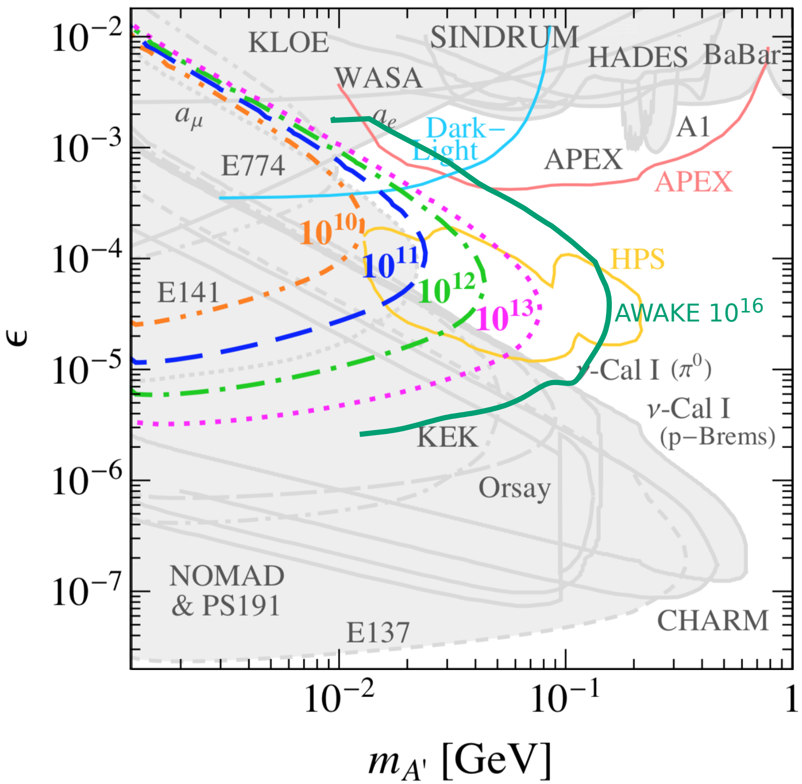
See e.g.: https://arxiv.org/pdf/2005.01515.pdf. ‘The Physics of the Dark Photon’

Beam Dump

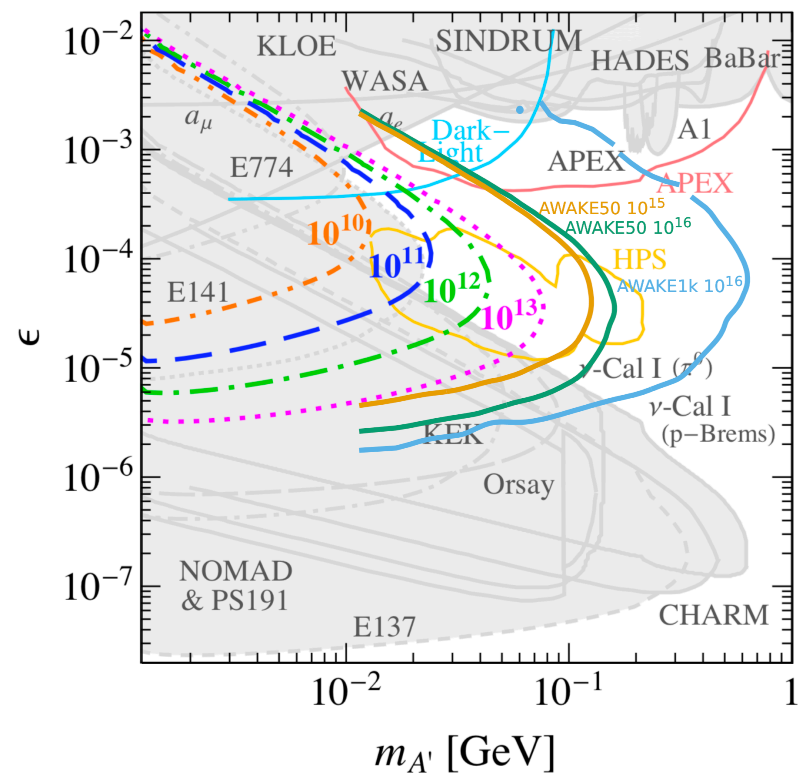




Expectation for 3 month run



Expectation for 10^{16} 1 TeV electrons



A. Hartin, UCL

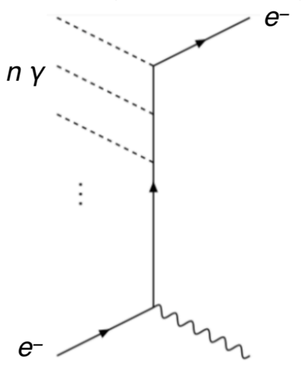
Strong Field QED

Idea: probe QED in the strong field regime (Schwinger critical field ~10^{18} V/m). Expect to see nonlinear effects in controlled laboratory environment.

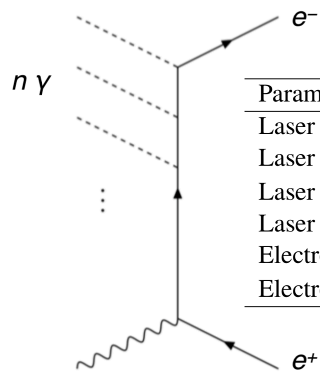
high power laser

e.g.,

$e^- + n\gamma \rightarrow e^- + \gamma$

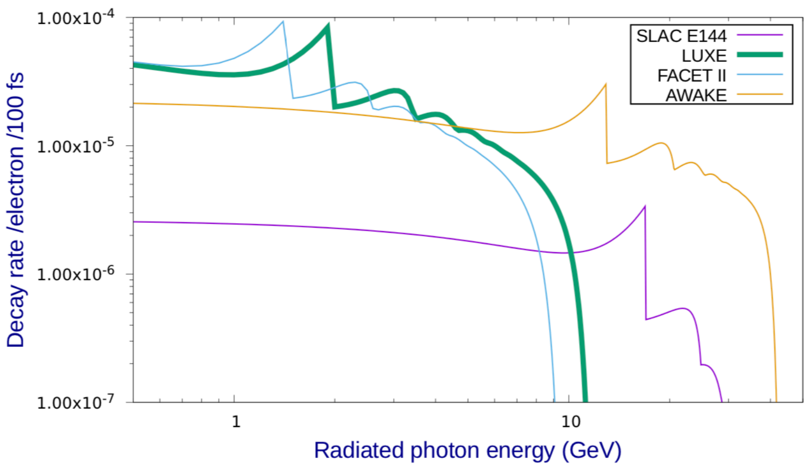


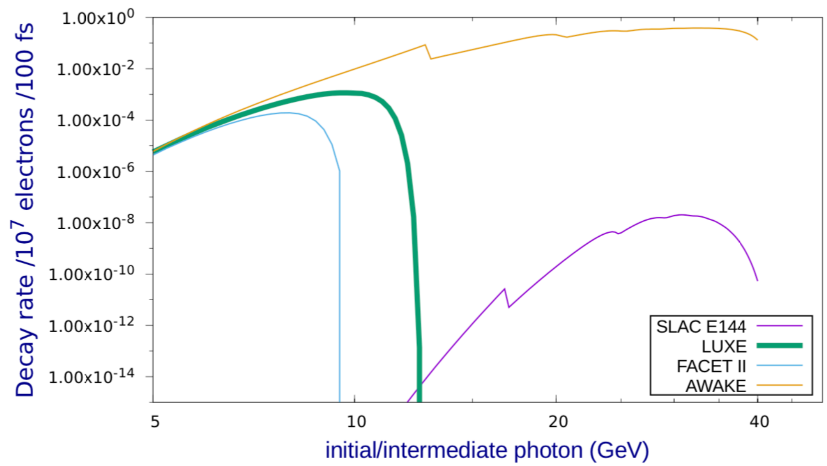
$\gamma + n\gamma \rightarrow e^+ + e^-$



Parameter	E144	LUXE	FACET II	AWAKE
Laser wavelength (nm)	527/1053	527/1053	527/800/1053	527
Laser energy (J)	2	2	1	1
Laser transverse size (μm^2)	50	100	64	64
Laser pulse length (ps)	1.88	0.05	0.04	0.04
Electron energy (GeV)	46.6	17.5	15	50
Electrons per bunch	5×10^9	6×10^9	5×10^9	5×10^9

high energy electron beam





higher energy beams would be a great benefit

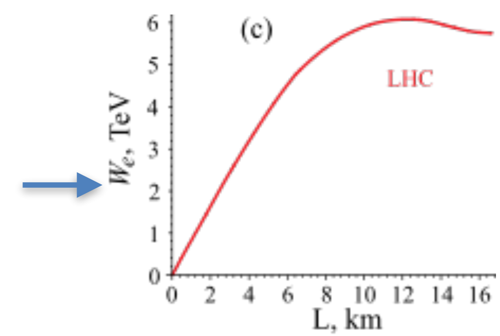
Fixed Target

Using LHC as driver, AWAKE style acceleration could reach energy regime that is comparable to the planned EIC at BNL in a fixed target mode.

Advantage: luminosity achieved via the target
Disadvantage: very forward geometry for experiment. Exclusive states may be difficult to reconstruct. Pile-up if have `thick' target.

Has not been studied … some part of the EIC program could be covered … to be investigated

Electron beam polarization maintained in blowout regime (J. Vieira et al., PRST-AB **14**, 071303(2011)
Needs investigation for AWAKE scheme



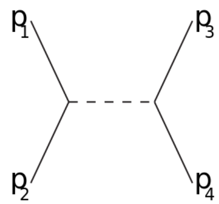
$$E_{\mathrm{CM}} = \sqrt{2 M_P E_e} = 14 - 110\ \mathrm{GeV}$$

Compass: ~20 GeV
EIC: 15-140 GeV

for E_e=100-6000 GeV   LHC Driver

General Considerations-Colliders

s-channel cross sections scale as $\sigma \propto \frac{1}{s}$



$n_{\text{fixed}} \implies \mathscr{L} \propto s$

Power!

very difficult to see today how high luminosity and high energy and affordability can be achieved in a linear collider:

LWFA - need high power AND high energy AND high efficiency laser …

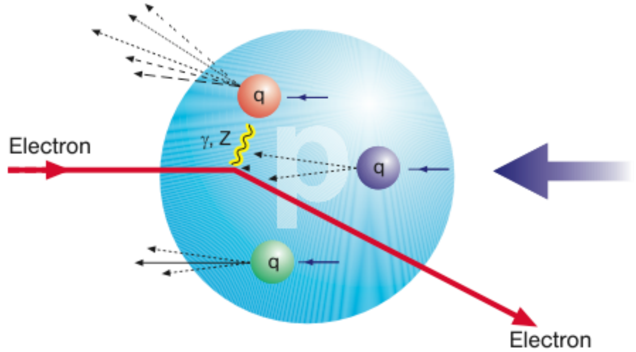
PWFA - electron driver will need many stages, emittance preservation, positrons (for s-channel), …

PWFA - proton driver. With LHC, many TeV foreseeable but low rep rate, dedicated short cycling time proton accelerator?

As intermediate step, think what physics we can get from low luminosity collider.

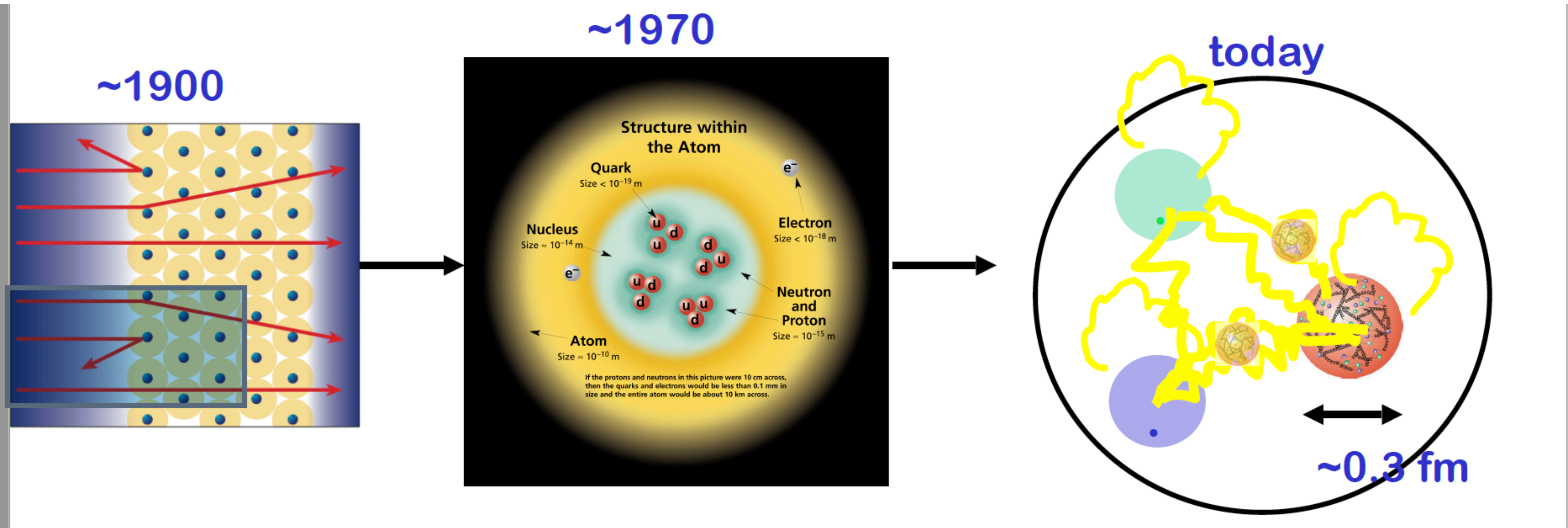
General Considerations-Colliders

QCD: fundamental studies do not need annihilation of beam particles - cross section grows with energy!



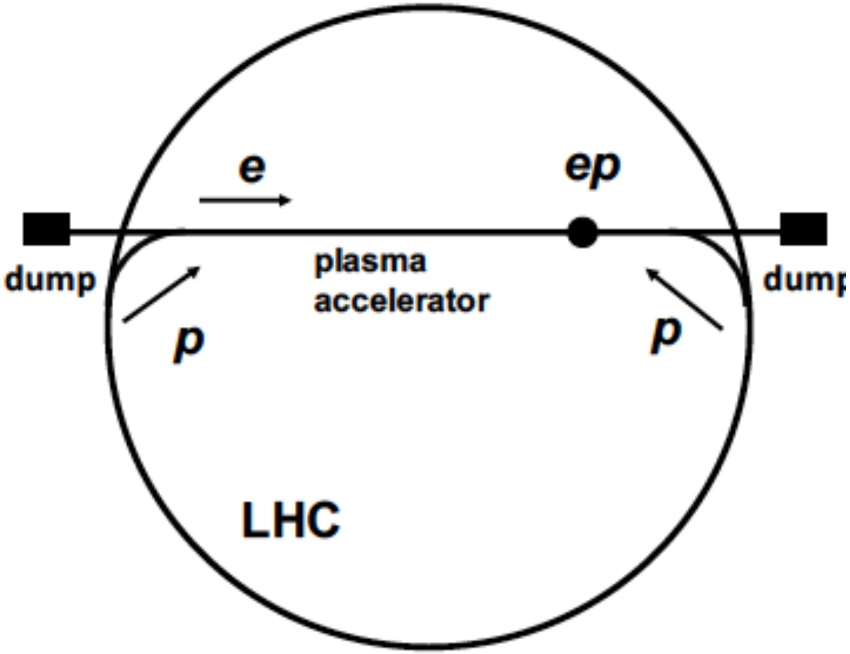
Effective fixed target parameters

McAllister, Hofstadter	Ee=188 MeV	r_{min}=0.4 fm
Bloom et al.	10 GeV	0.05 fm
CERN, FNAL fixed target	500 GeV	0.007 fm
HERA	50 TeV	0.7 am
VHEeP	35 PeV	0.02 am



VHEeP

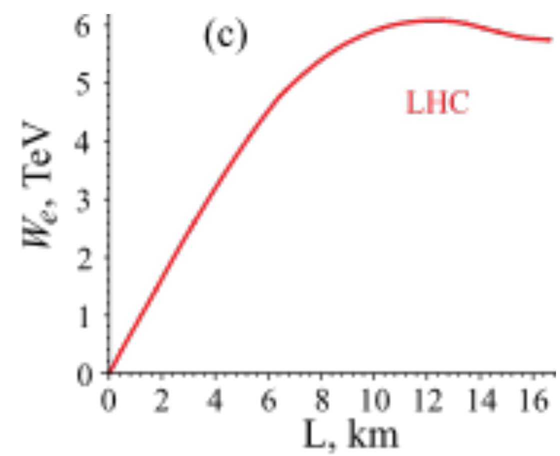
(Very High Energy electron-Proton collider)



One proton beam used for electron acceleration to then collide with one bunch from other proton beam

Luminosity ~ 10^{28} – 10^{29} cm^{-2} s^{-1} gives ~ 1 pb−1 per year.

Electron energy from wakefield acceleration by LHC bunch



Choose E_e = 3 TeV as a baseline for a new collider with E_p = 7 TeV yields √s = 9 TeV. Can vary.

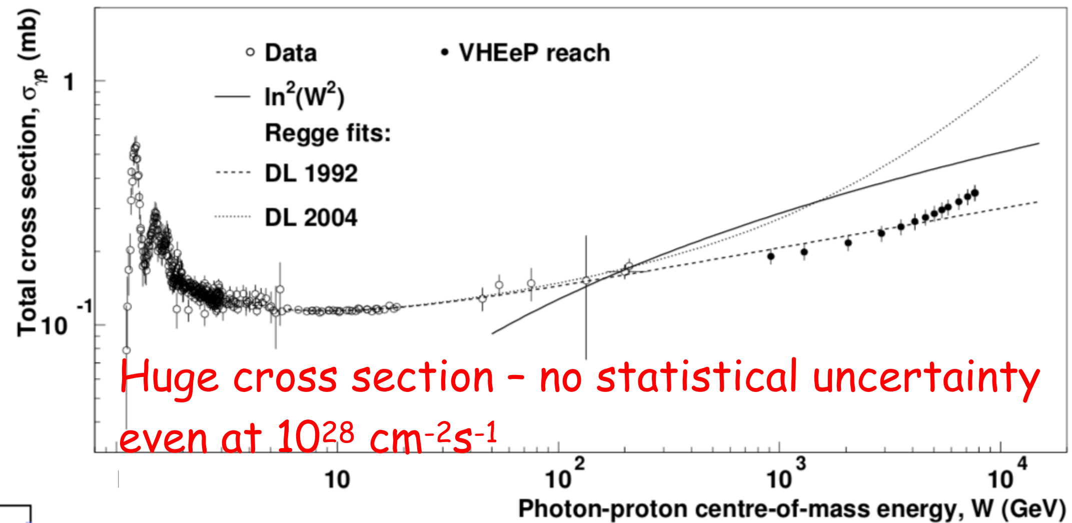
- Center-of-mass energy ~30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken x extended by ~1000 compared to HERA.
- Opens new physics perspectives

VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

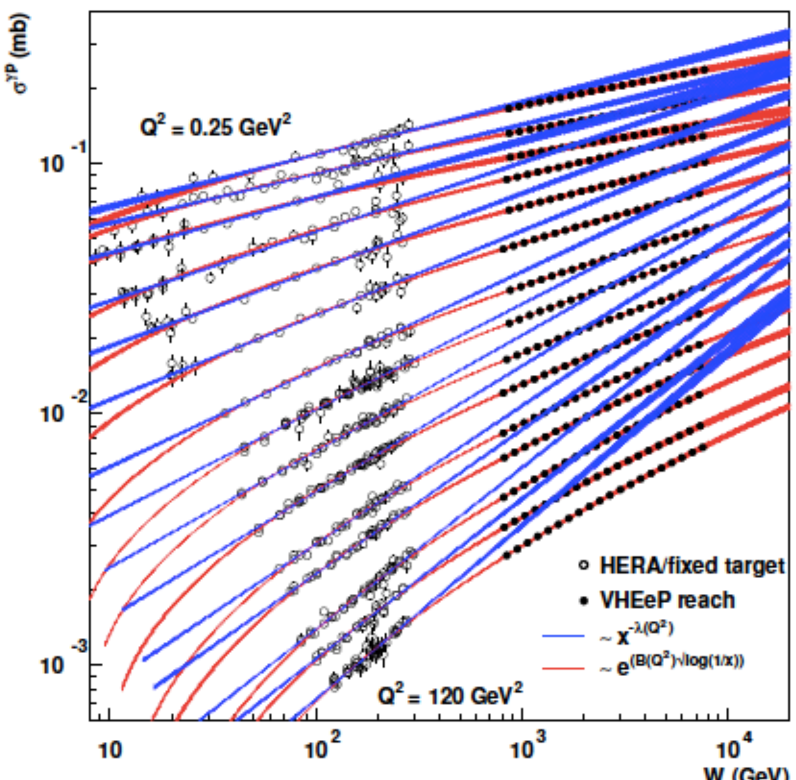
A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

Colliding 3 TeV electrons with LHC Protons

Total photoproduction cross section – energy dependence ?
See approach to Froissart bound ?
Impact on cosmic ray physics

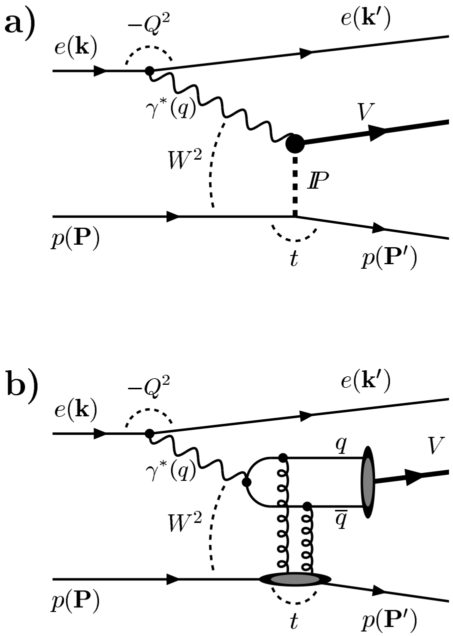


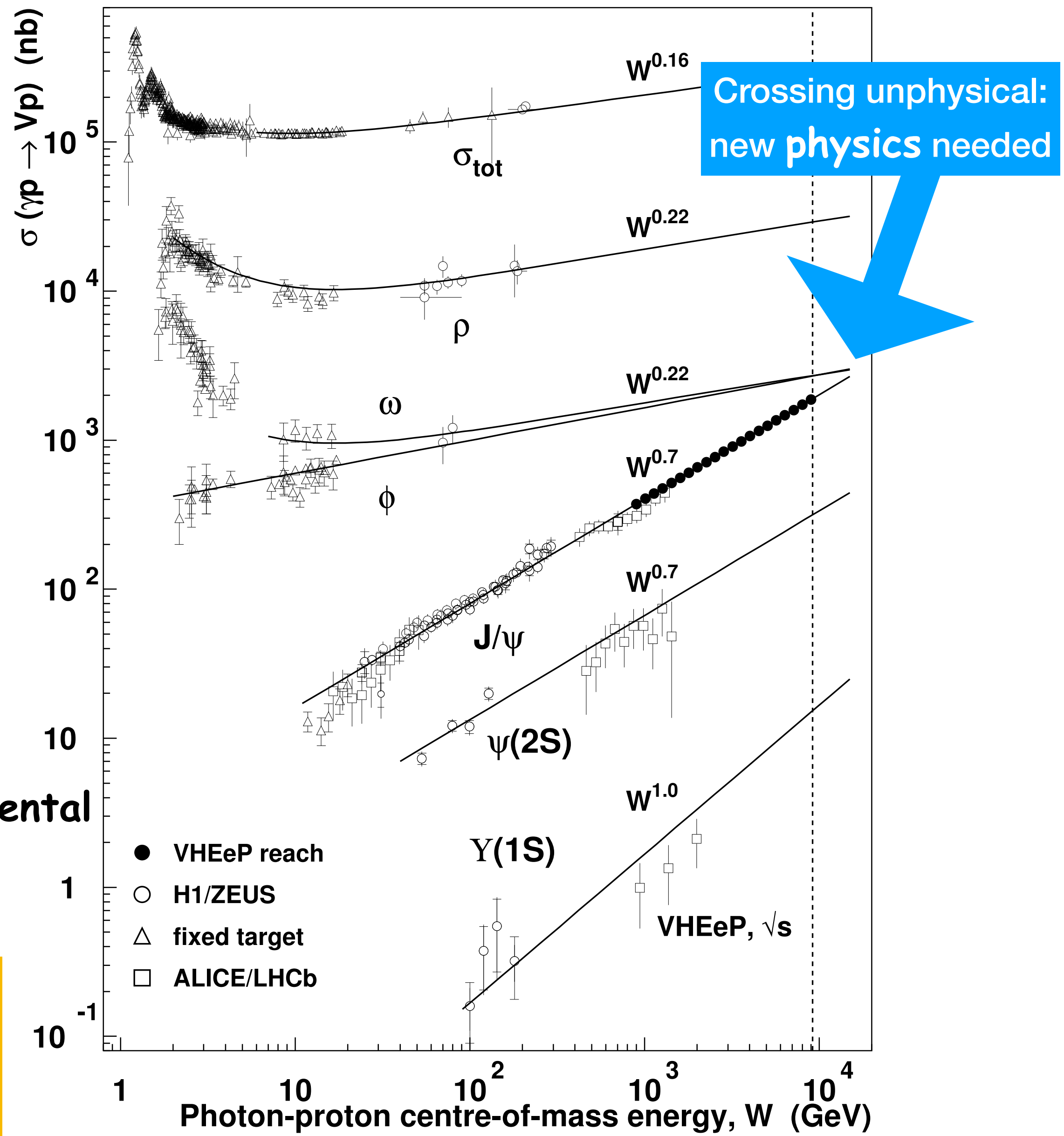
Huge cross section – no statistical uncertainty even at 10^{28} $cm^{-2}s^{-1}$



Virtual photon cross section: unphysical extrapolation of cross sections -> observation of saturation of parton densities ?

With the three orders of magnitude extension in the range at small-x, expect to see signs of the fundamental saturated regime.





Exclusive processes:

Sensitive to square of gluon density

Early signs of new saturated regime

Good opportunity to see the fundamental high-energy saturated state!

eA possibility will make this physics even more dramatic "oomph"-factor again

QCD and Gravity - universal physics

Classicalization and unitarization of wee partons in QCD and gravity: The CGC-black hole correspondence
G. Dvali, R. Venugopalan *Phys.Rev.D* **105** (2022) 5, 056026

We discuss a remarkable correspondence between the description of black holes as highly occupied condensates of N weakly interacting gravitons and that of color glass condensates (CGCs) as highly occupied gluon states. In both cases, the dynamics of "wee partons" in Regge asymptotics is controlled by emergent semihard scales that lead to perturbative unitarization and classicalization of 2→N particle amplitudes at weak coupling.

Message:

- the physics of QCD is universal physics
- QCD processes have very large cross sections: we do not need huge luminosities to measure the relevant qualities
- with AWAKE technology, can conceive of very high energy $e^{\pm}P$ colliders: clean and fundamental physics!

Conclusions

Mid-term:
AWAKE-like technology will allow **high** energy electron bunches for beam-dump and fixed target experimental programs + collisions with existing proton bunches and other studies

Long-term:
AWAKE-like technology will allow **very high** energy electron bunches for above.

The physics program made possible by these developments is very broad.

The new, fundamental, physics could well come from understanding 'condensed matter'-like systems in particle physics experiments: QCD studies are critical!