Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

AWAKE: Particle Physics Applications

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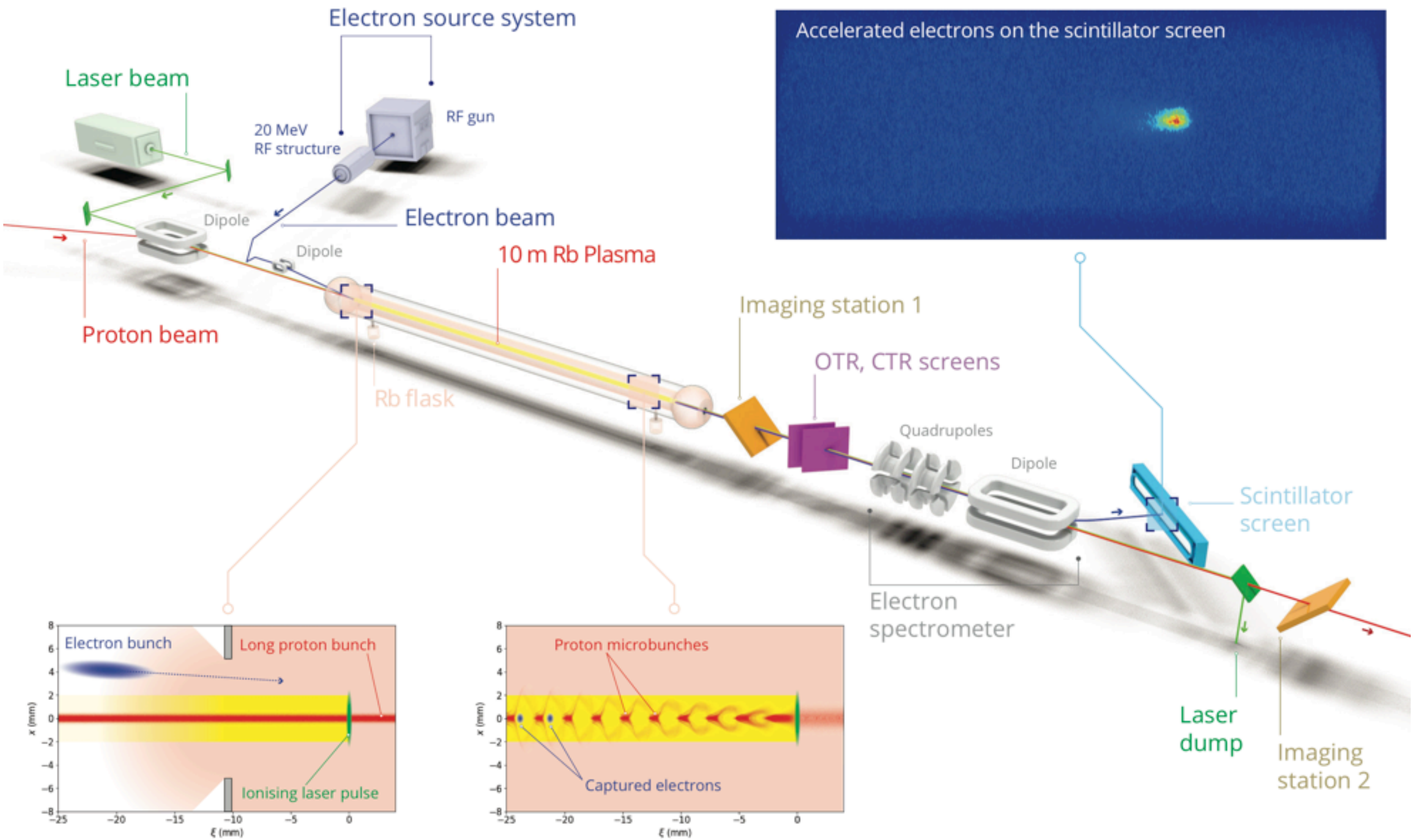
1. Beam Dump
2. Fixed Target
3. Collider applications
4. Other applications

CLIC Workshop - CERN - April 29, 2020

Run I (2016-2018) - summary

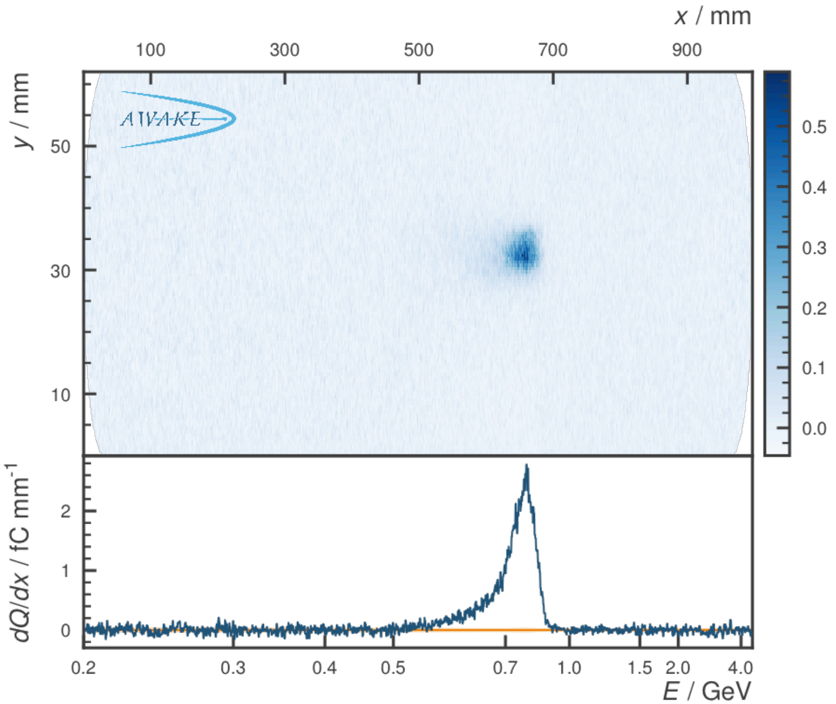
- **Phase 1: Understand the physics of self-modulation.**
- **Phase 2: Probe the accelerating wakefields with externally injected electrons.**

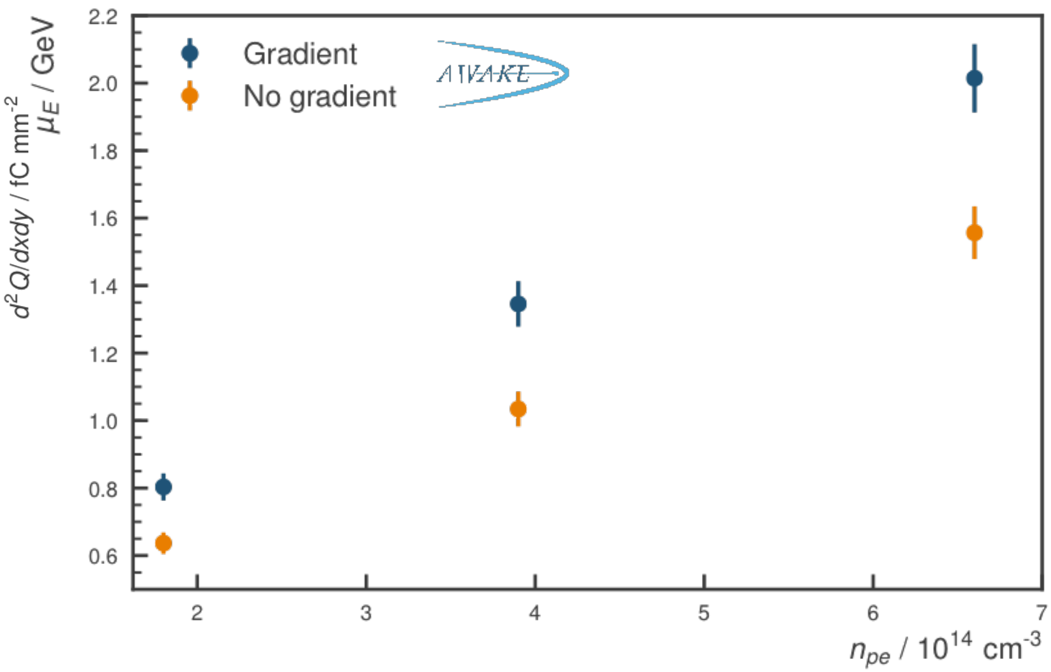


AWAKE

Electron Acceleration Results

E. Adli et al., AWAKE Collaboration, Nature **561,** 363 (2018)





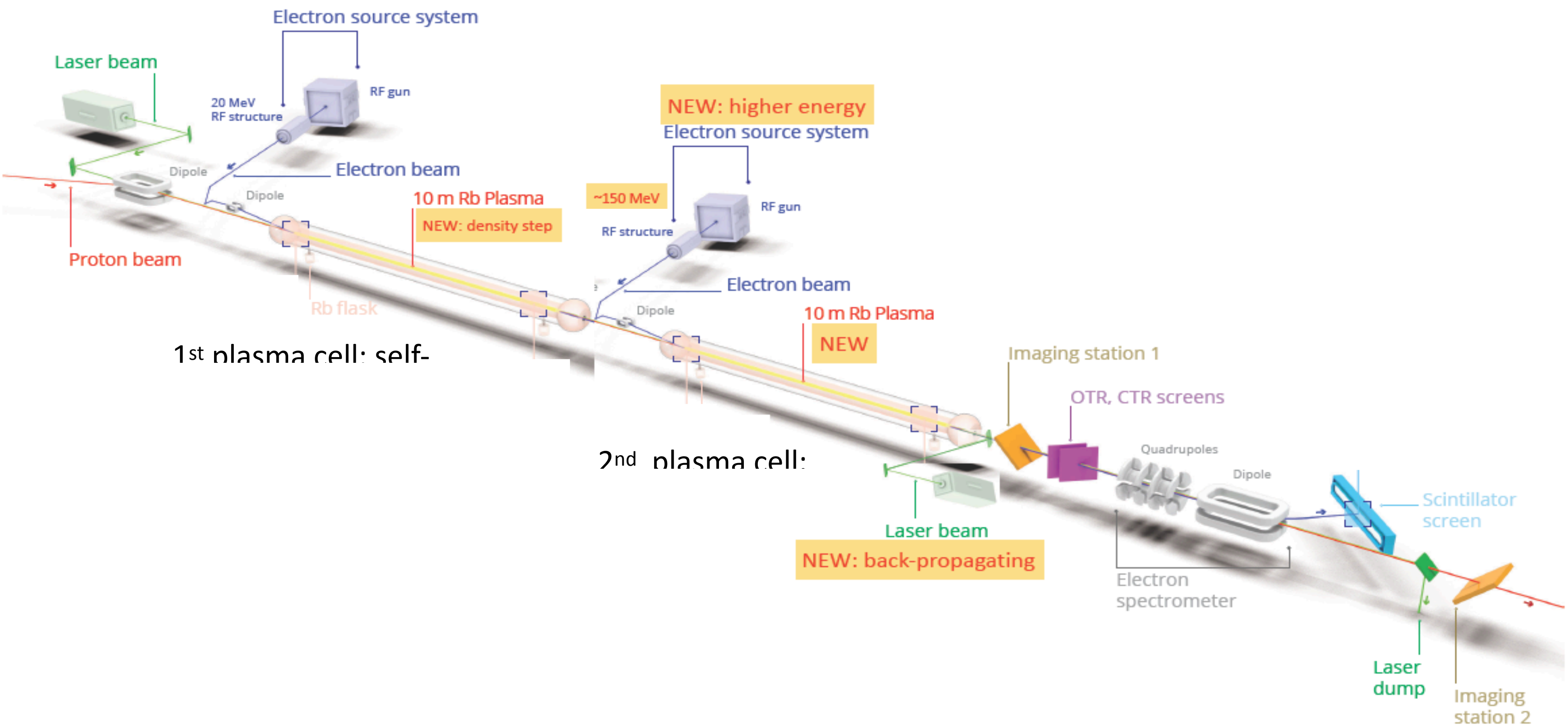
Note: we are accelerating 10 times more charge than previously thought (CLEAR calibration issue). Maximum accelerated charge ~100 pC (~20% of injected)

Electron acceleration in a proton-driven plasma wakefield works !

With todays existing proton bunches via seeded self-modulation!

Run II (2021-)

➔ Demonstrate possibility to use AWAKE scheme for high energy physics applications in mid-term future!



Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

Demonstrate scalable plasma source technology (e.g. helicon prototype)

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

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 !

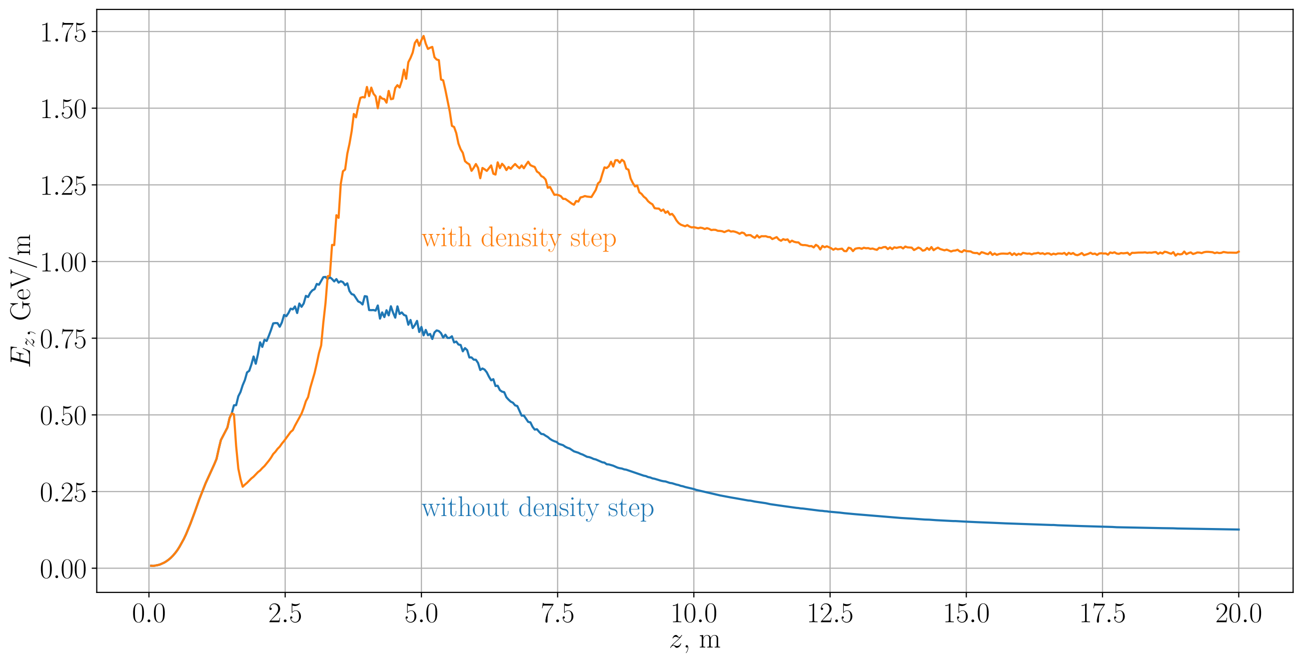
- **To be evaluated:**
  - AWAKE-like scheme with ions
  - acceleration of muons in LEMMA scheme
  - AWAKE-like scheme with FCC

We have just started to evaluate the particle physics potential of plasma acceleration. Need creative thinking !

Gradients

Proton-driven plasma wakefield acceleration such as from the AWAKE scheme could provide the highest energy electron beams for beam-dump, fixed-target and electron-proton/ion experiments (with LHC as driver).

From simulations of seeded, self-modulated proton beams, gradients in excess of 1 GV/m can be achieved and maintained with a density step in the plasma. To be demonstrated in AWAKE run II



Here: SPS beam
3 10^{11} protons
n = 7 10^{14} cm^{-3}

Potentially higher with LHC beam parameters (have not been investigated since 2011).

Single beams

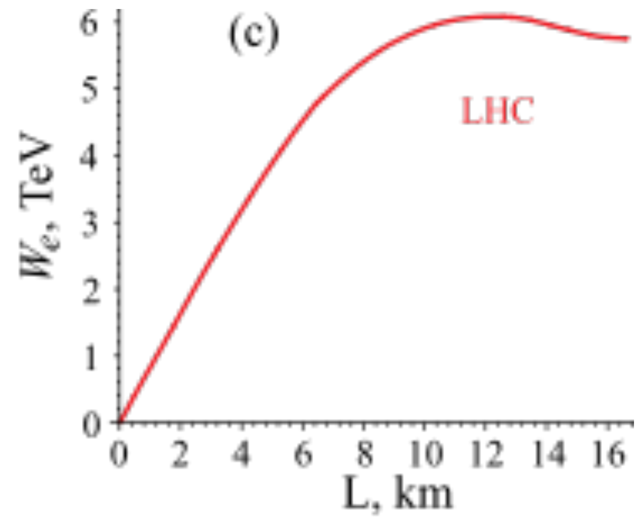
From simulations of seeded, self-modulated proton beams:

Energy reach using the SPS <= 100 GeV

Energy reach using the LHC <= 6 TeV

Physics of Plasmas **18**, 103101 (2011);
A. Caldwell and K. V. Lotov

Here: 1.15 10^{11} protons assumed. Gradients could be larger

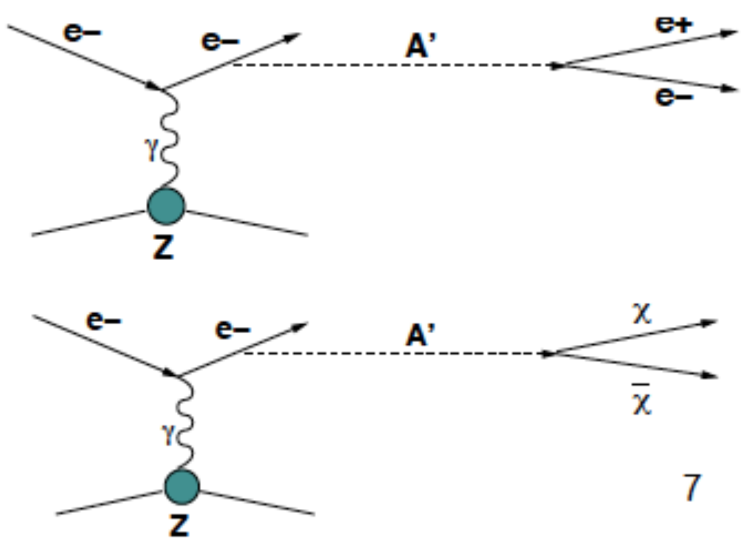


Number of protons will depend on SPS or LHC cycle time, availability for beam dump experiments, etc.

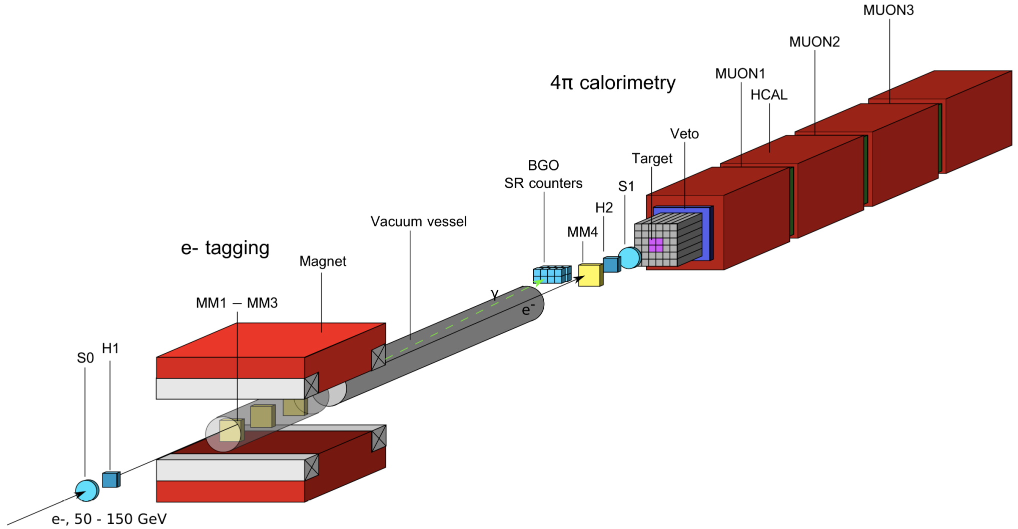
Number of electrons/proton estimated ~5% for SPS. Not yet studied for the LHC

Beam Dump

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



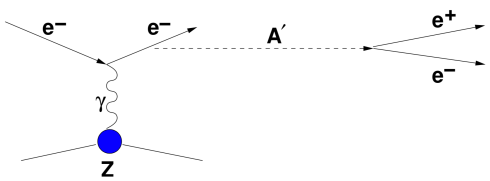
Decaying dark photons: into visible or invisible mode. For invisible mode - need to track individual electrons. How to do this in a bunched beam?

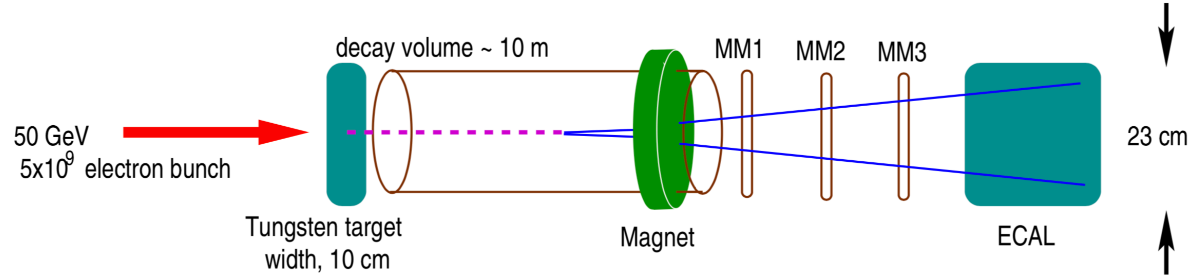


see: arXiv:1812.11164v1 [physics.acc-ph] 22 Dec 2018

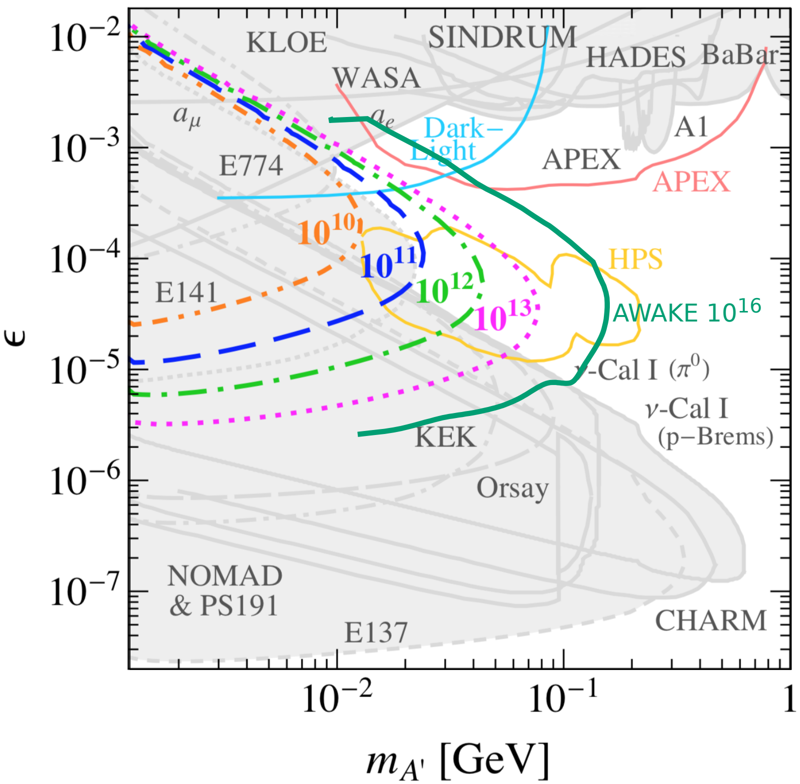
Beam Dump

AWAKE based scheme:

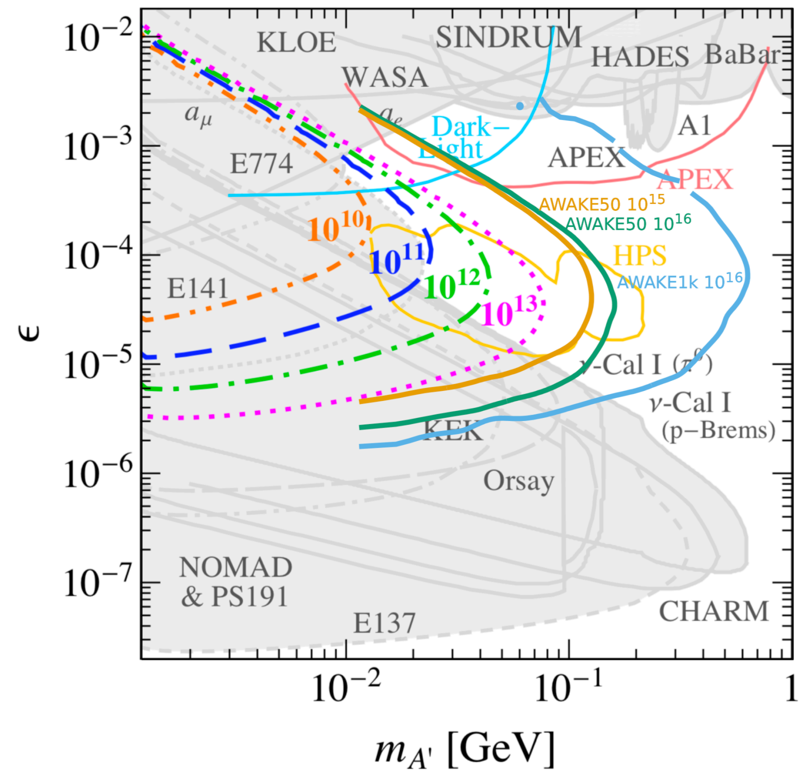




Expectation for 3 month run



Expectation for 10^{16} 1 TeV electrons



A. Hartin, UCL

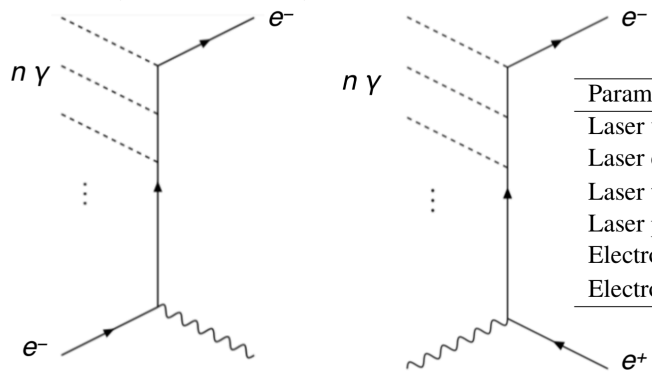
Strong Field QED

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

high power laser

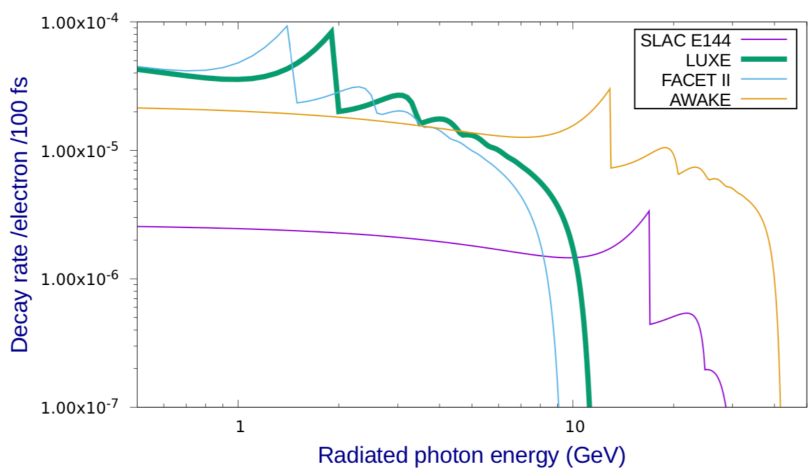
e.g.,

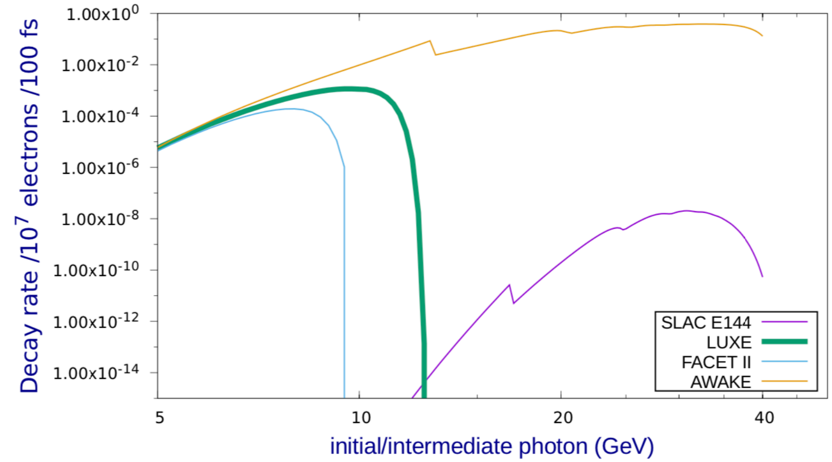
$e^- + n\gamma \rightarrow e^- + \gamma$ $\quad$ $\gamma + n\gamma \rightarrow e^+ + e^-$



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 from AWAKE beams would be a great benefit

Fixed Target

Presumably not much to gain from SPS driver.

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

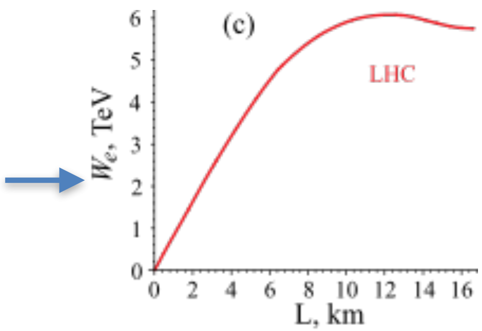
Advantage: luminosity achieved via the target
Disadvantage: very forward geometry for experiment. Exclusive states may be difficult to reconstruct. Pile-up if have `thick' target.

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

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

for E_e=100-6000 GeV   LHC Driver

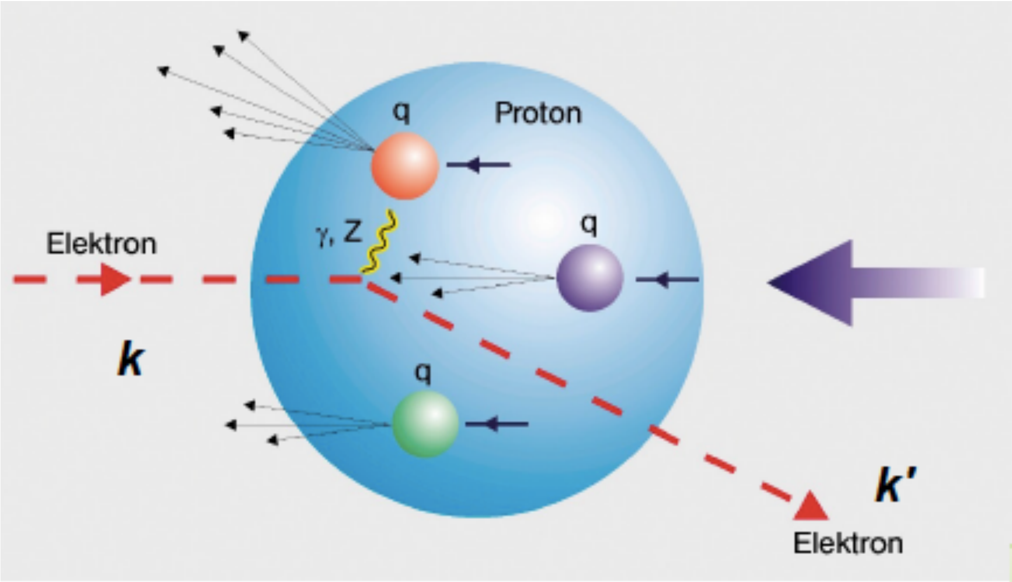


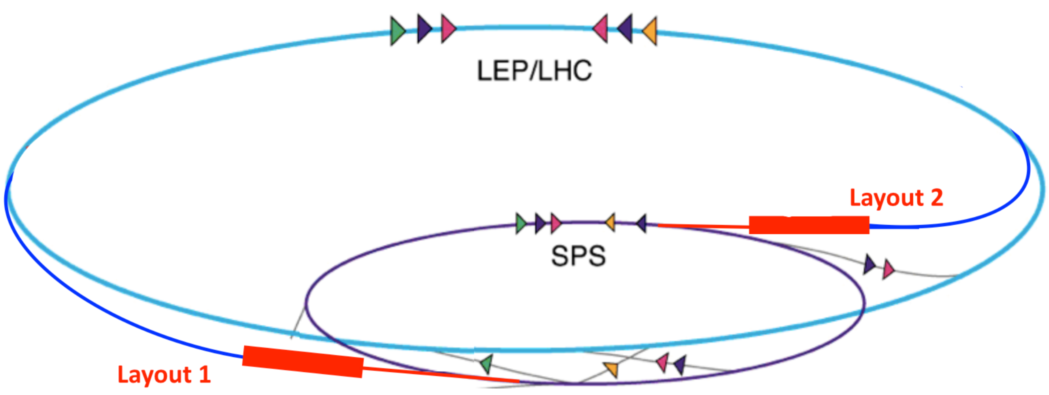
Compass: ~20 GeV
EIC: 15-140 GeV

LHeC-like Collider

Focus on QCD:

- Large cross sections – low luminosity (HERA level) enough
- Many open physics questions !
- Consider high energy ep collider with Ee up to O(50 GeV), colliding with LHC proton; e.g. Ee = 10 GeV, Ep = 7 TeV, √s = 530 GeV already exceeds HERA cm energy.





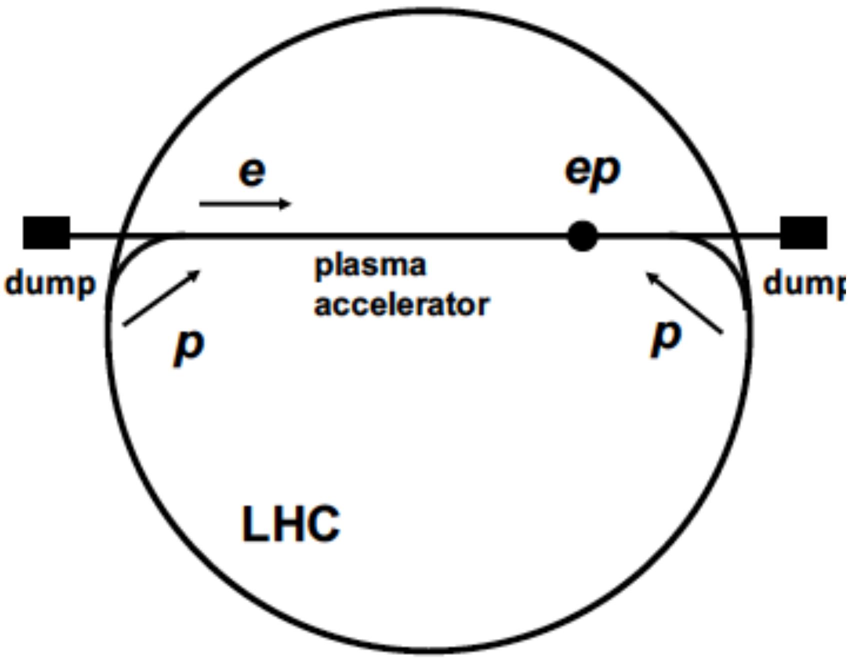
G. Xia et al., Nucl. Instrum. Meth. A 740 (2014) 173.

Create ~50 GeV beam within 50−100 m of plasma driven by SPS protons and have an LHeC-type experiment.

Clear difference is that luminosity currently expected to be $< 10^{30}\ cm^{-2}\ s^{-1}$.

VHEeP

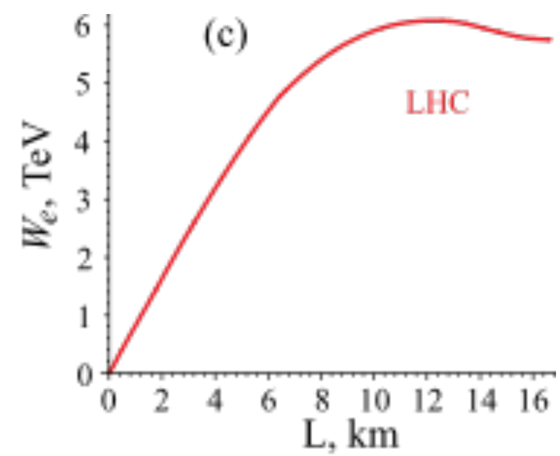
(Very High Energy electron-Proton collider)



One proton beam used for electron acceleration to then collide with 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



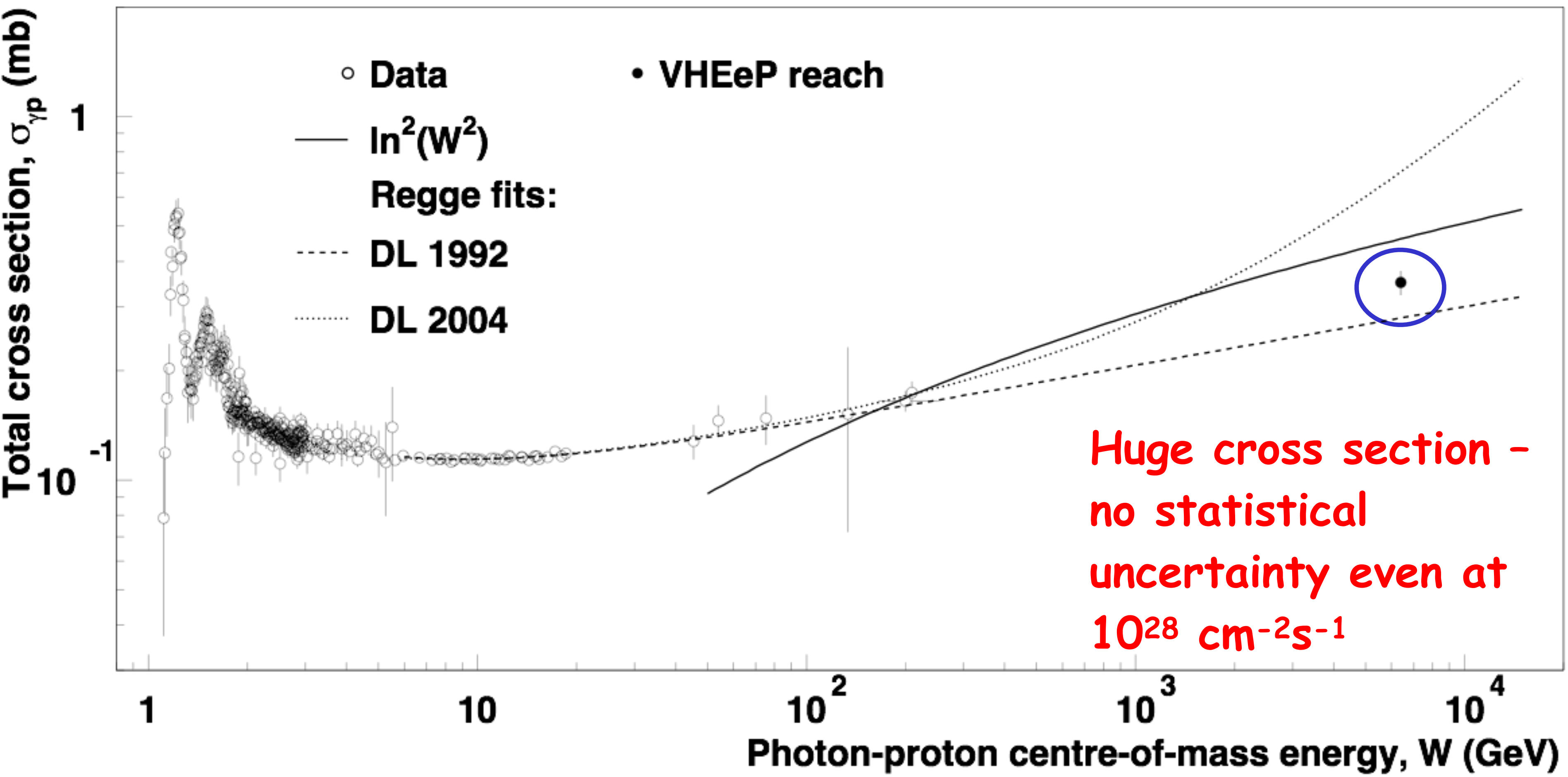
A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

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

- Centre-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

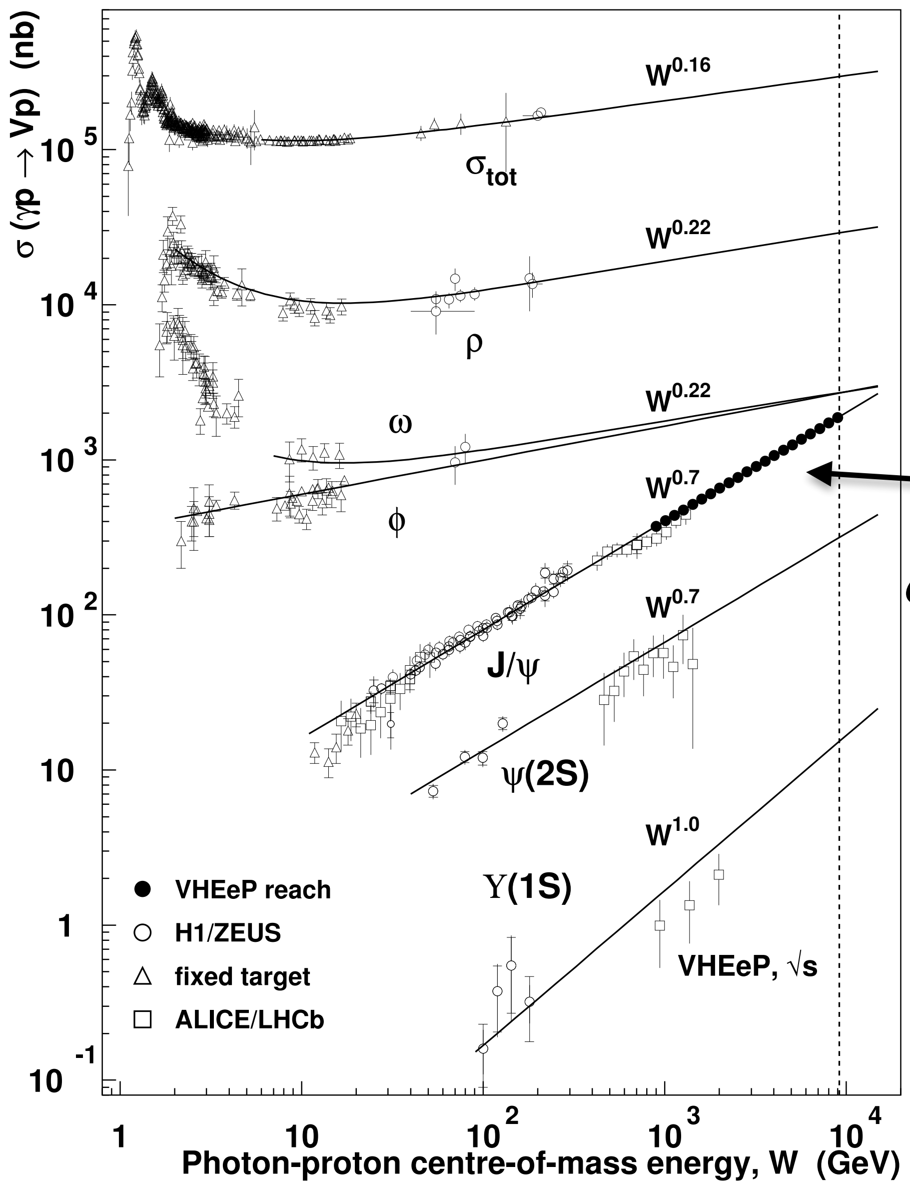
VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

Total Photon-Proton Cross Section



Rises – as power of energy, or $\ln^2 s$ (Unitarity Constraint) ? Why ?
High energy behavior needed to understand cosmic ray interactions

Vector Meson Cross Section

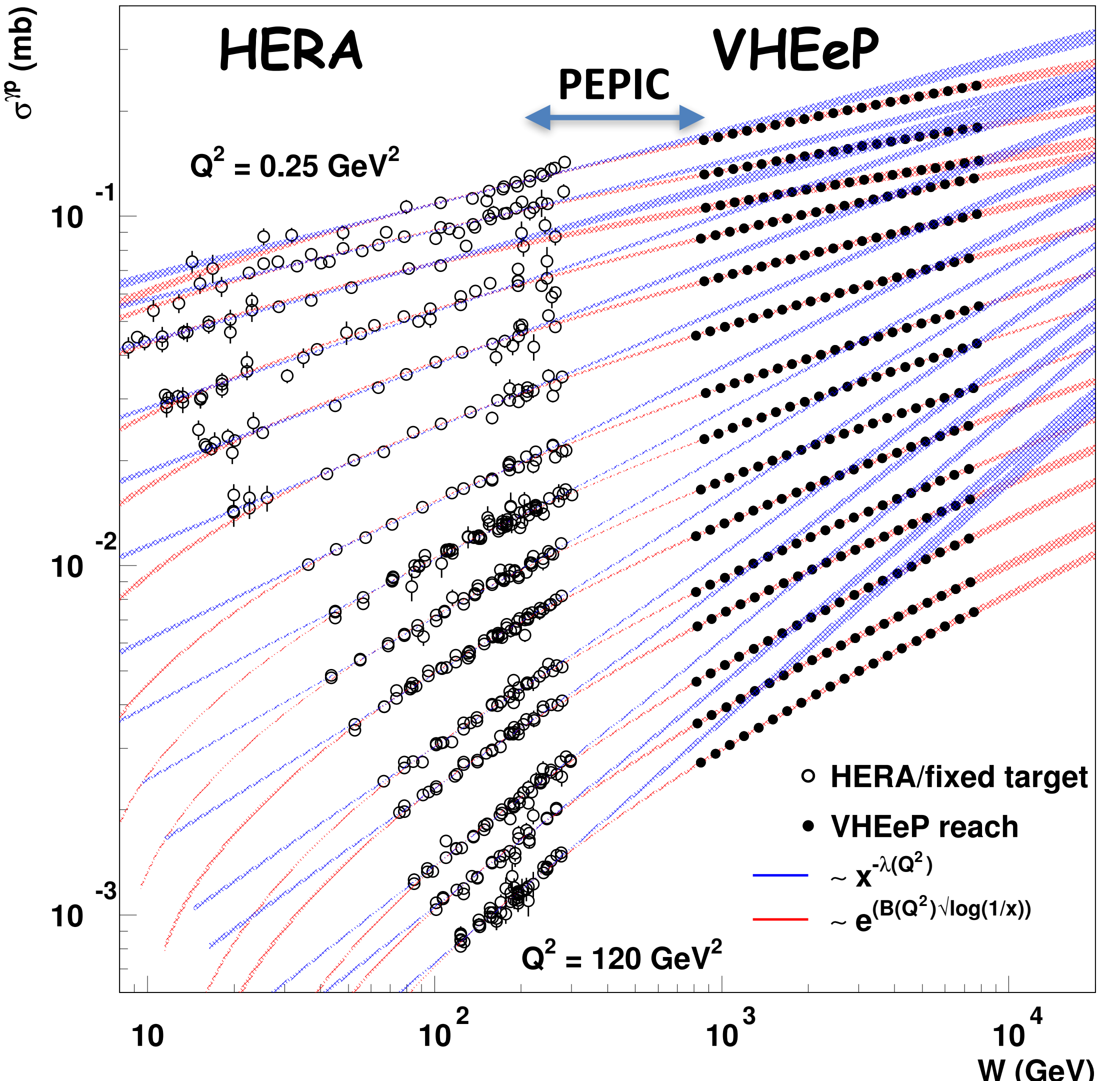


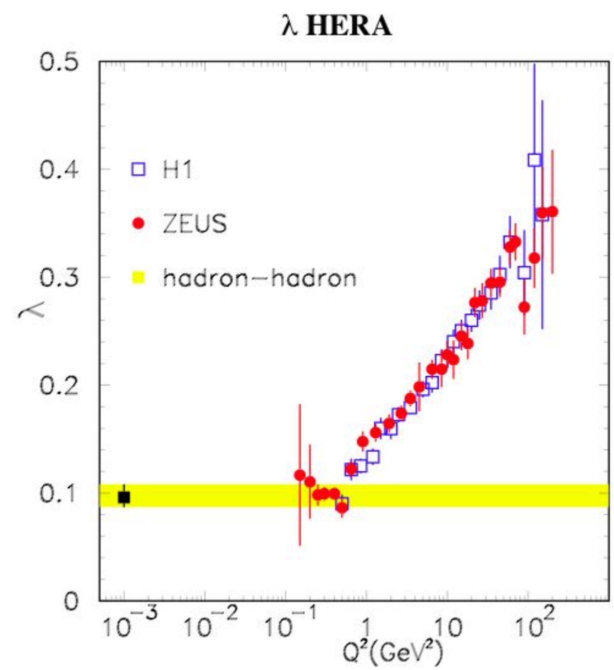
VHEeP W range

$$\sigma(\gamma p \to J/\psi p) \approx \sigma(\gamma p \to \rho p)????$$

Expect to see change in energy dependence

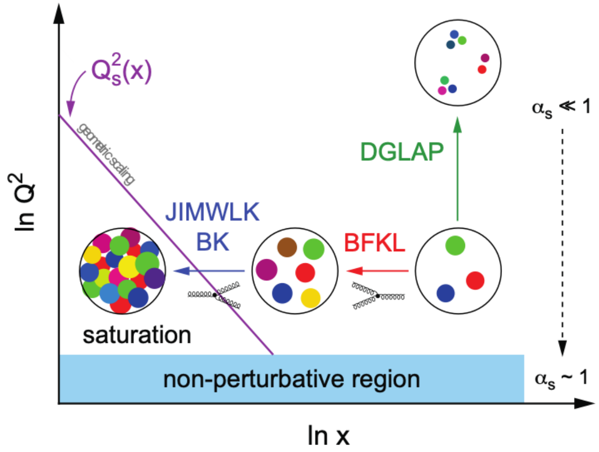
Virtual Photon-Proton Cross Section





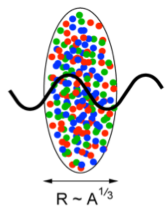
Cross sections increasing with energy -> do not require large luminosity to probe this physics. PEPIC & VHEeP will distinguish the important physics.

Evolution of gluon densities from QCD



Gluon saturation at scale $Q_s(x)^2$

Enhanced in nuclei



$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Search for saturation requires large densities and small coupling

- Need large enough Q², which requires large center of mass energies

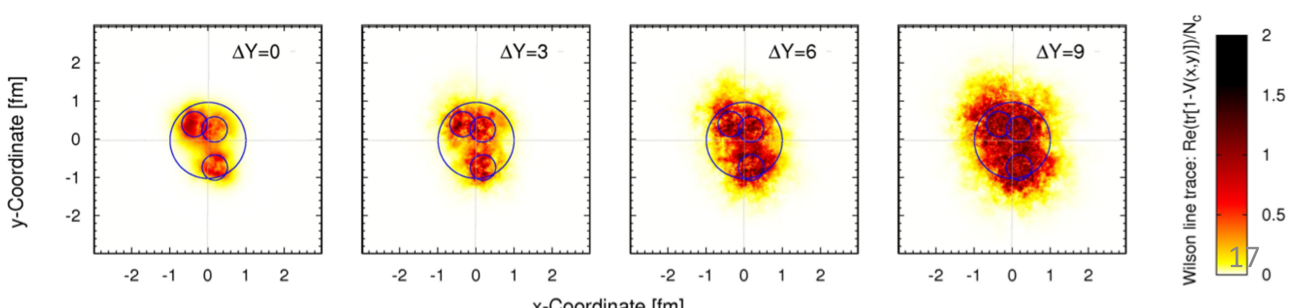
eA physics at very high energies

Heikki Mäntysaari

BROOKHAVEN NATIONAL LABORATORY

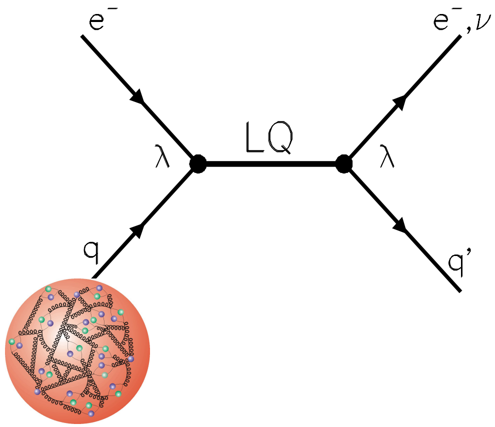
x evolution of the geometry

Small-*x* evolution (JIMWLK): proton growth and smoothening



Schlichting, Schenke, 1407.8458

Beyond the Standard Model



Leptoquarks are predicted in many models for Beyond-the-Standard-Model physics. Electron-proton colliders are the ideal tool to look for this kind of process.

Fixed mass of LQ means fixed x.

$$\sigma_{\mathrm{LQ}}^{\mathrm{NWA}} = (J+1)\frac{\pi}{4s}\lambda^2 q(x_0, M_{\mathrm{LQ}}^2)$$

Spin

coupling

Sensitivity depends mostly on CM energy

At the LHC

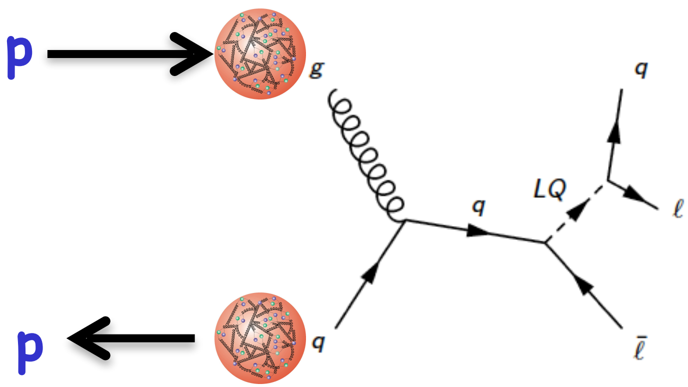


Figure 1: The s-channel resonant LQ production diagram.

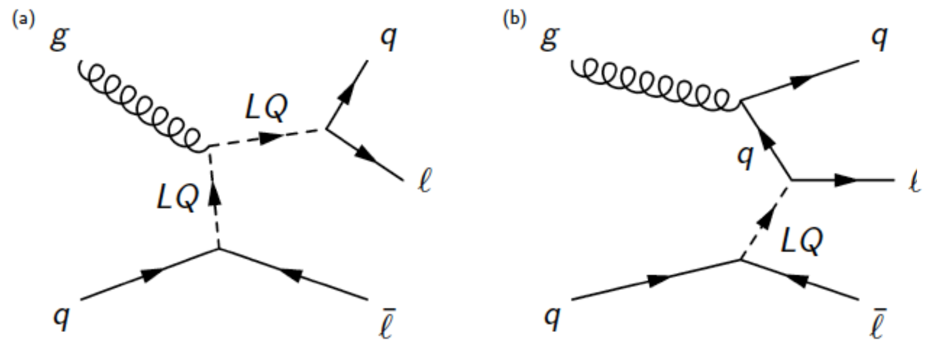
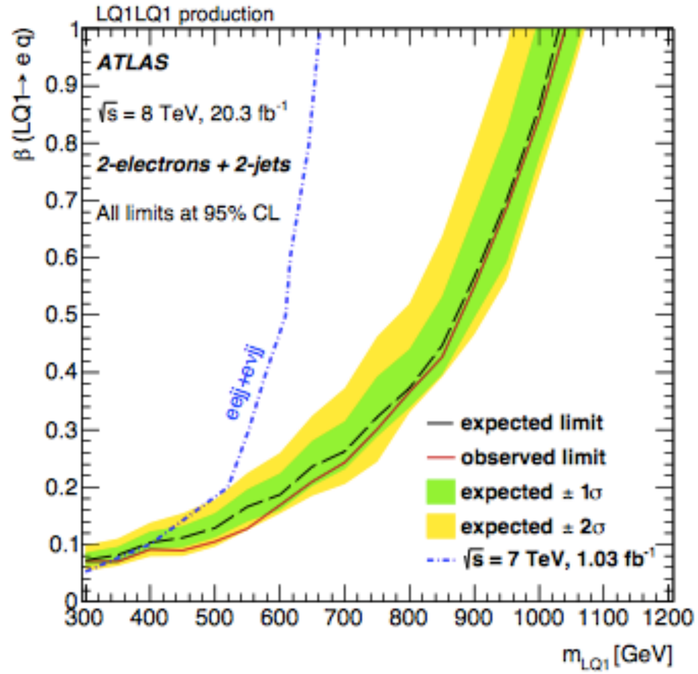
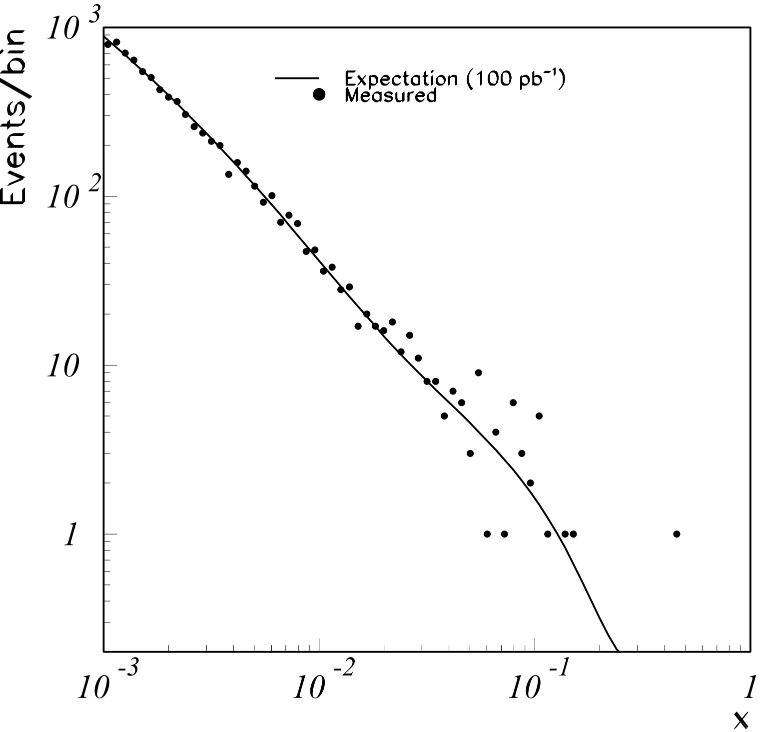


Figure 2: The t-channel LQ production diagrams with non-resonant components. The diagram



(b)

VHEeP Study

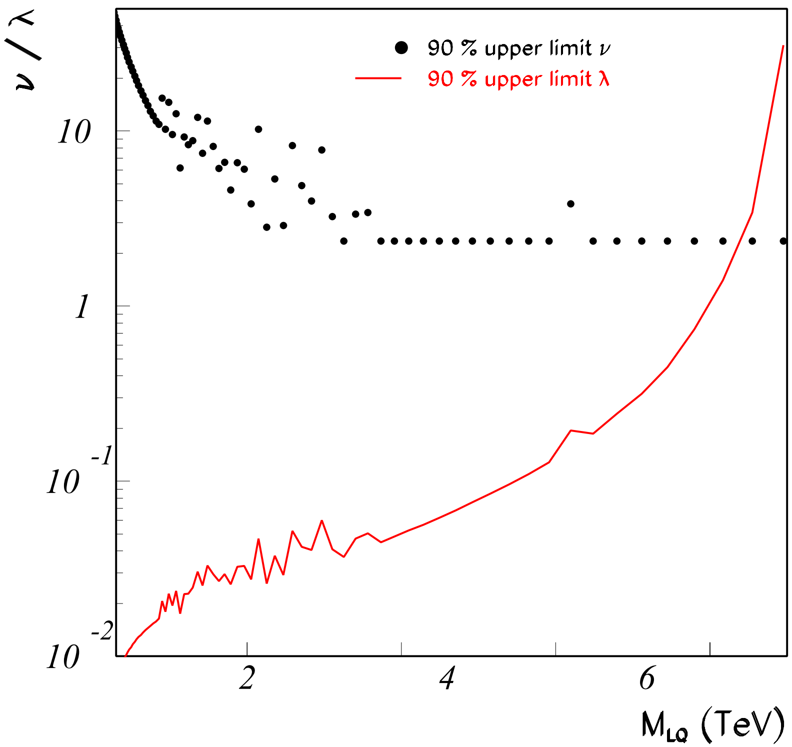


100 pb^{-1}

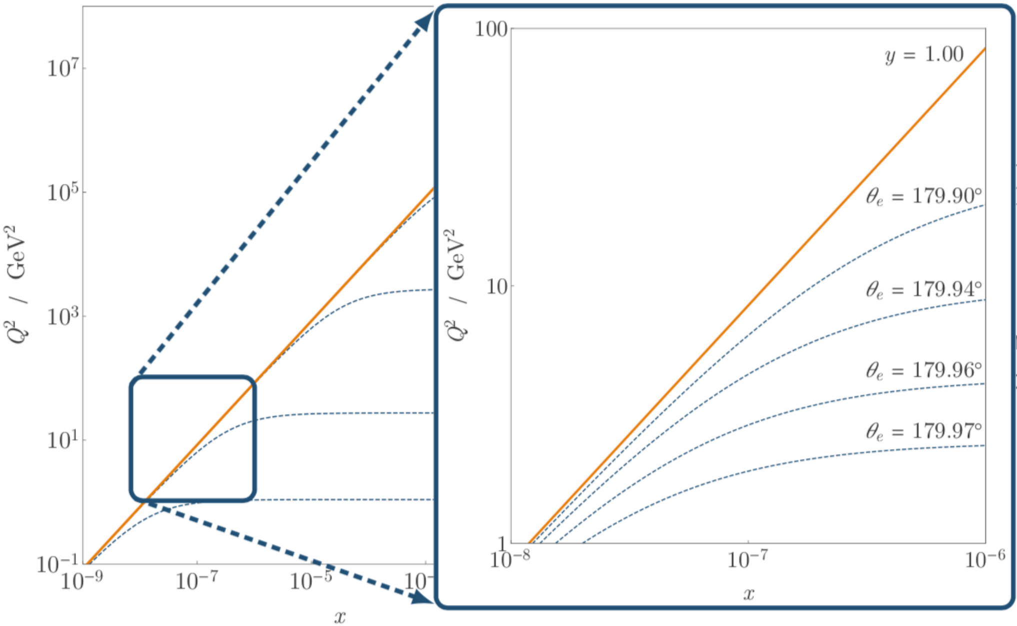
Require Q^2>10000 GeV^2 and y>0.1

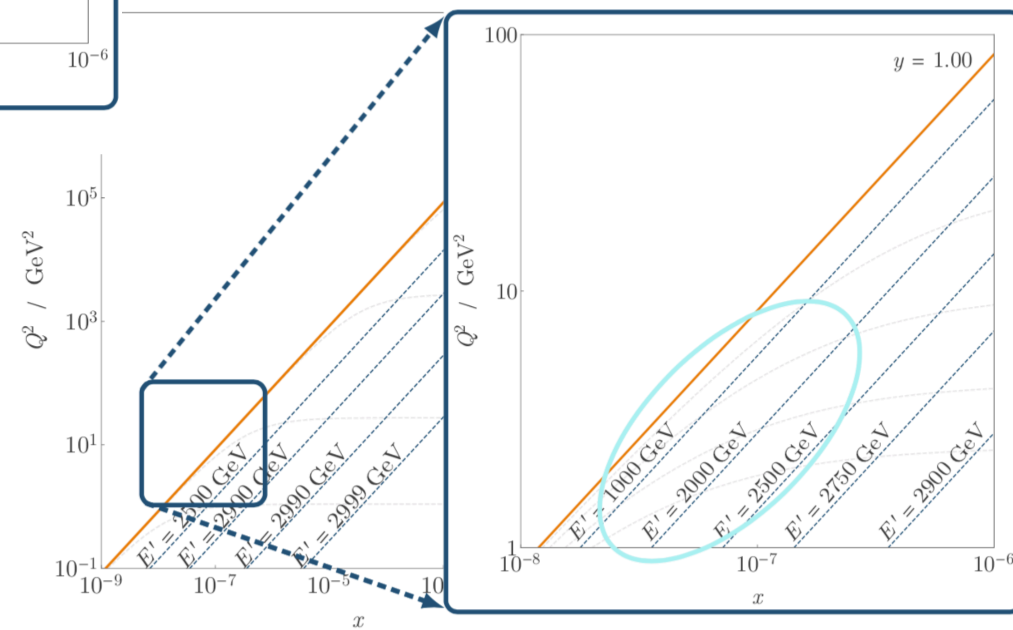
Use Standard Model prediction (no LQ)

Sensitivity goes far beyond what is expected to be reached at LHC. (Currently ~1 TeV, later 2-3 TeV)



There are detector challenges !



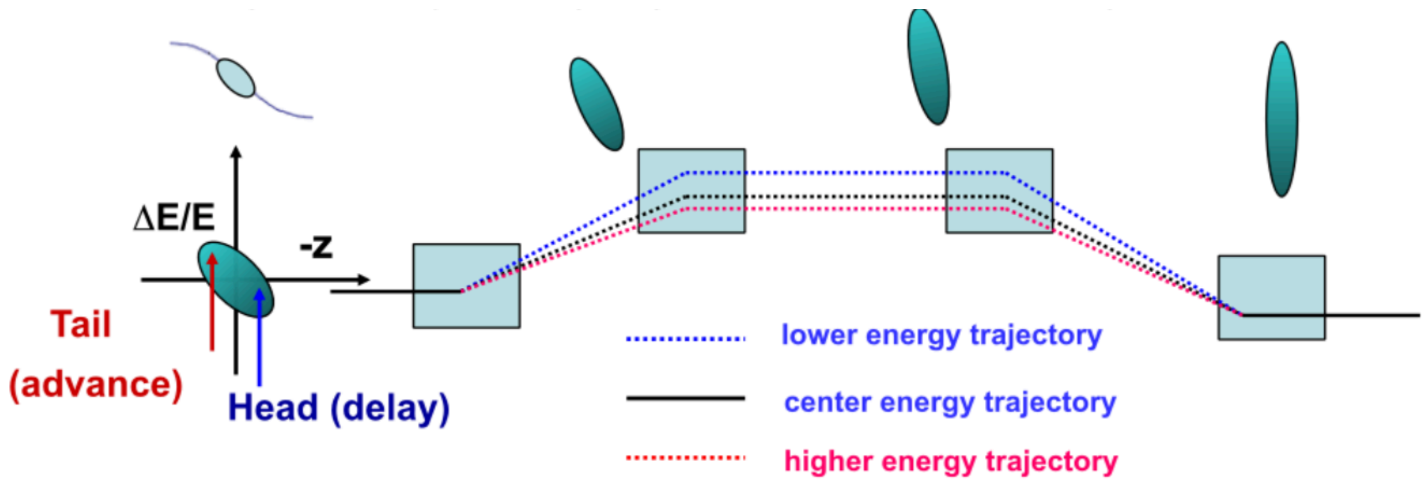


Very forward electron detector required.

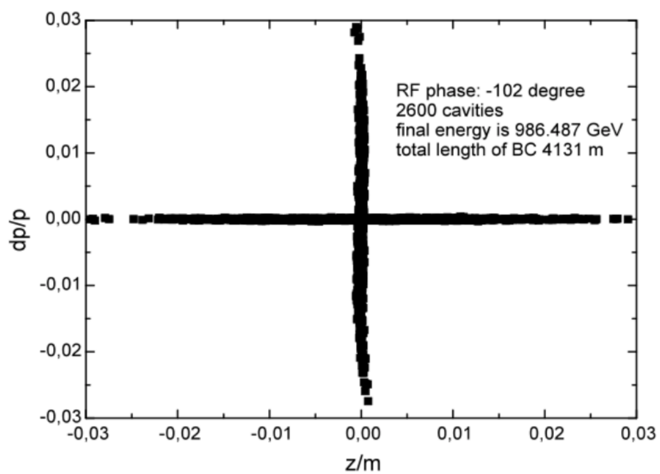
F. Keeble, UCL

- **To be evaluated:**
  - AWAKE-like scheme with ions
  - acceleration of muons in LEMMA scheme
  - AWAKE-like scheme with FCC

Phase Space Rotation



❑ **To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.**



It works - but it takes a lot of space & expensive

See A. Caldwell, G. Xia et al., Preliminary study of proton driven plasma wakefield acceleration, Proceedings of PAC09, May 3-8, 2009, Vancouver, Canada

Summary

AWAKE Scheme has the potential to allow single beam particle physics experiments in the mid-term future

Collider options with current proton drivers limited to large cross-section physics such as QCD. I.e., luminosity will not be large

Other applications likely

Studies are in their infancy …