Mid-term Particle Physics Applications

with

Plasma Acceleration

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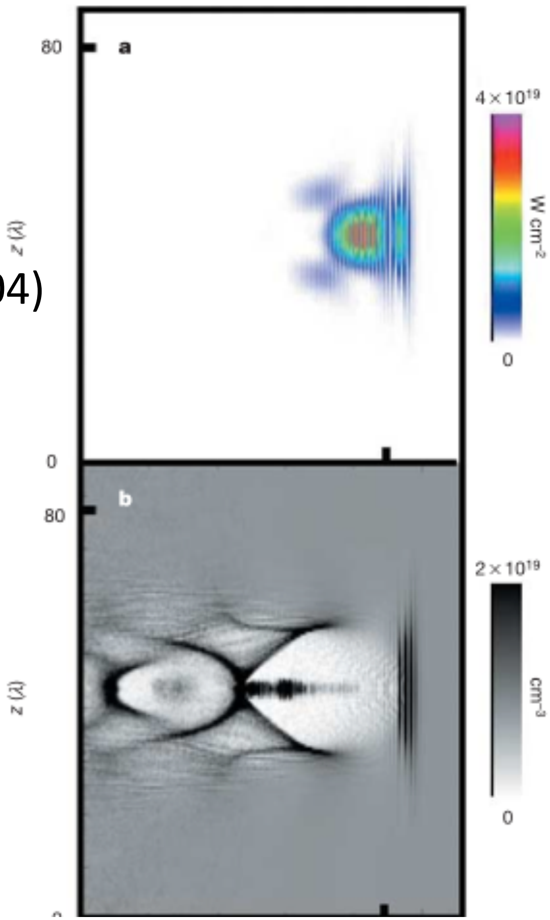
Plasma Wakefield Acceleration

Original Proposal: T. Tajima and J. W. Dawson, *Phys. Rev. Lett.* **43** (1979) 267.

Figure from
J. Faure et al.,
Nature **43** (2004)



Plasma frequency depends only on density

$$\omega_p^2 = \frac{4\pi n_p e^2}{m}$$

$$k_p = \frac{\omega_p}{c}$$

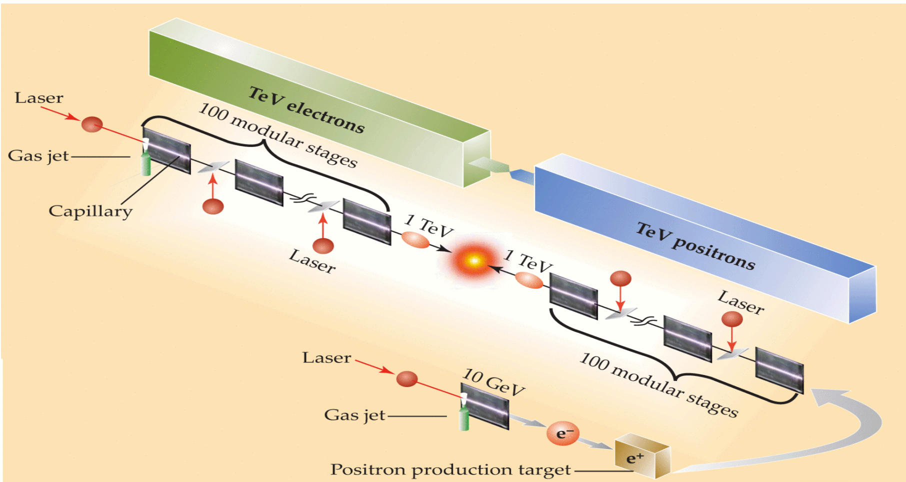
$$\lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1\cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$$

Produce an accelerator with mm (or less) scale ‘cavities’

100 GeV/m acceleration demonstrated !

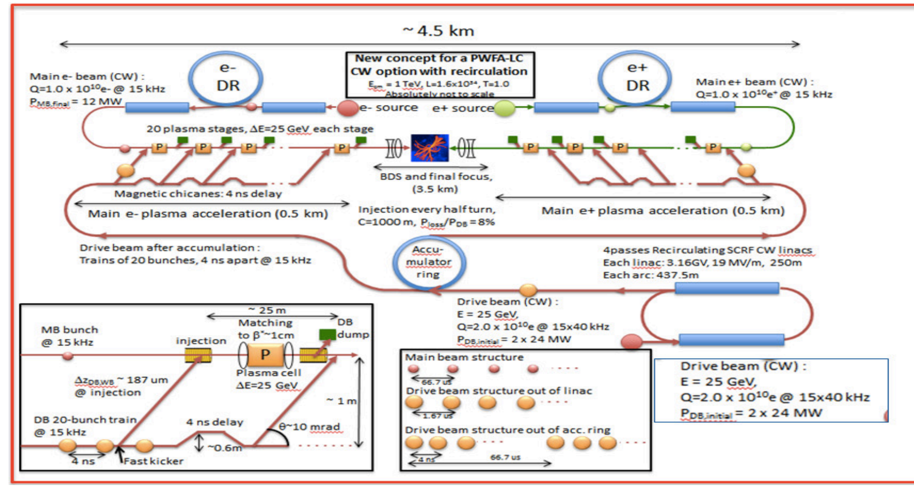
Staging Concepts

Laser Driven



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

Electron Driven



E. Adli et al. arXiv:1308.1145,2013

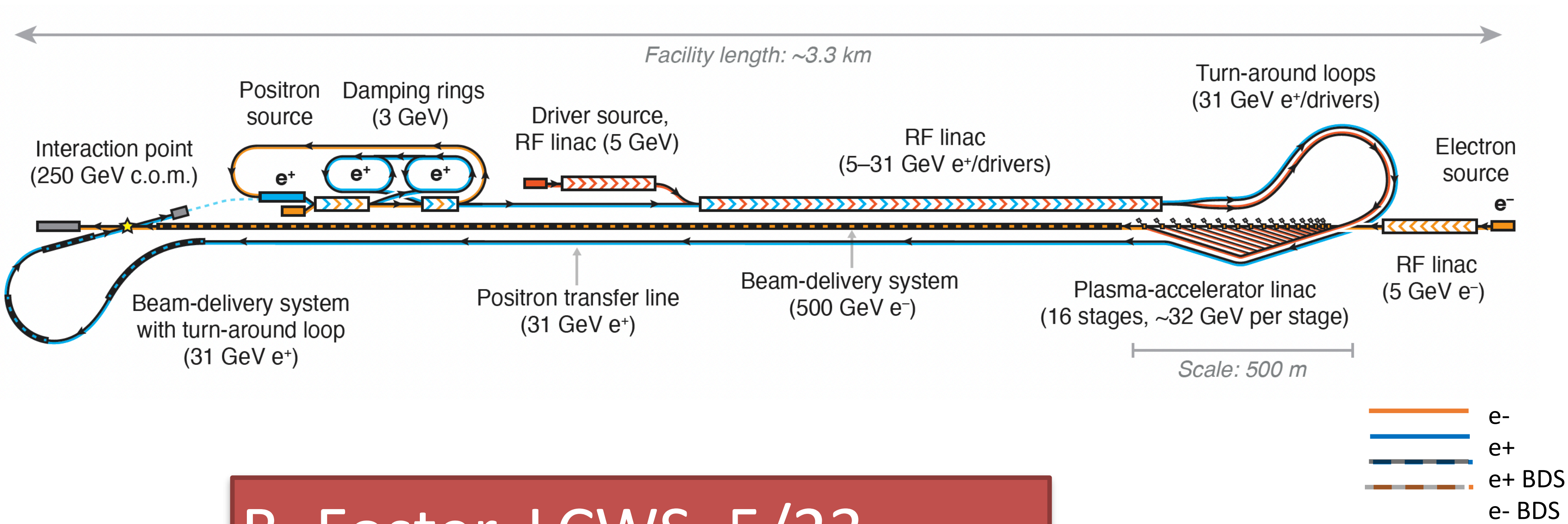
Proton Driven (AWAKE) - no staging ?

SPS@CERN 20kJ/bunch
LHC@CERN 300 kJ/bunch

Witness:
10^{10} particles @ 1 TeV ≈ few kJ

But low rep rate

Hybrid Concept



B. Foster, LCWS, 5/23

Hybrid solution: avoid e^+ acceleration via plasma, asymmetric collider

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 !

- **Physics with an electron-positron collider**
  - Higgs Factory

Hybrid concept as mid-term project

- **Other ideas**
  - Accelerate Muons?
  - Accelerate protons?

AWAKE vs Protons on Target

work in progress: indicative

Protons on target:

- continuous energy spectrum
- large transverse emittance
- slow extraction: unbunched

AWAKE-like:

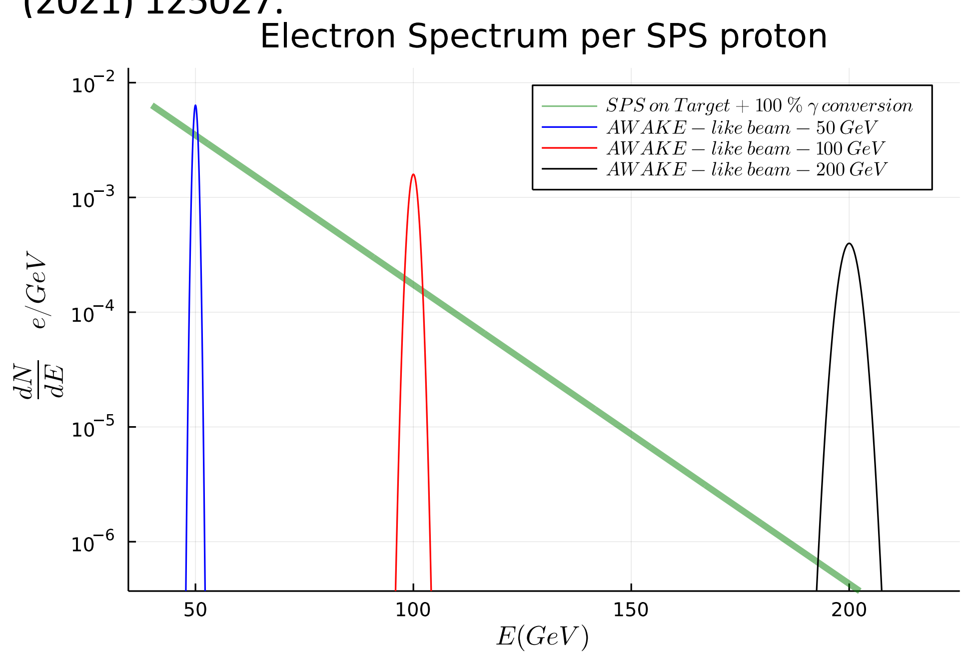
- % level energy spread
- mm-mrad level transverse emittance
- bunched beams

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

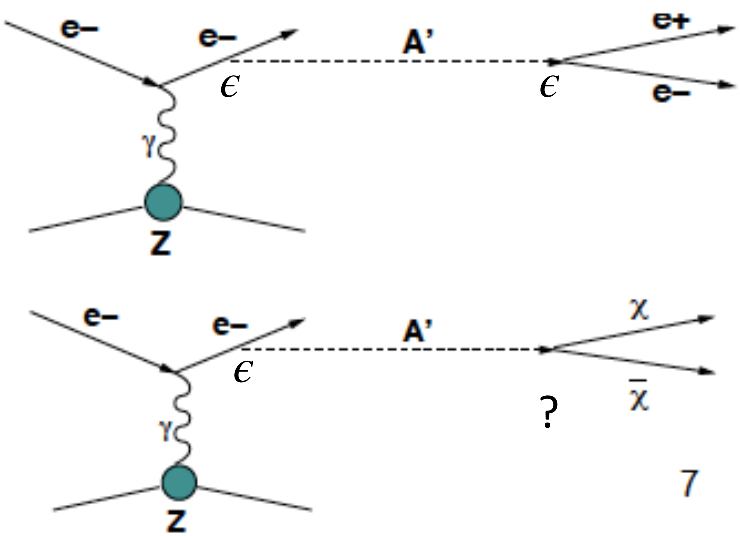
Compared to electrons accelerated to given energy, 1% energy spread, 0.01 electrons accelerated/proton

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

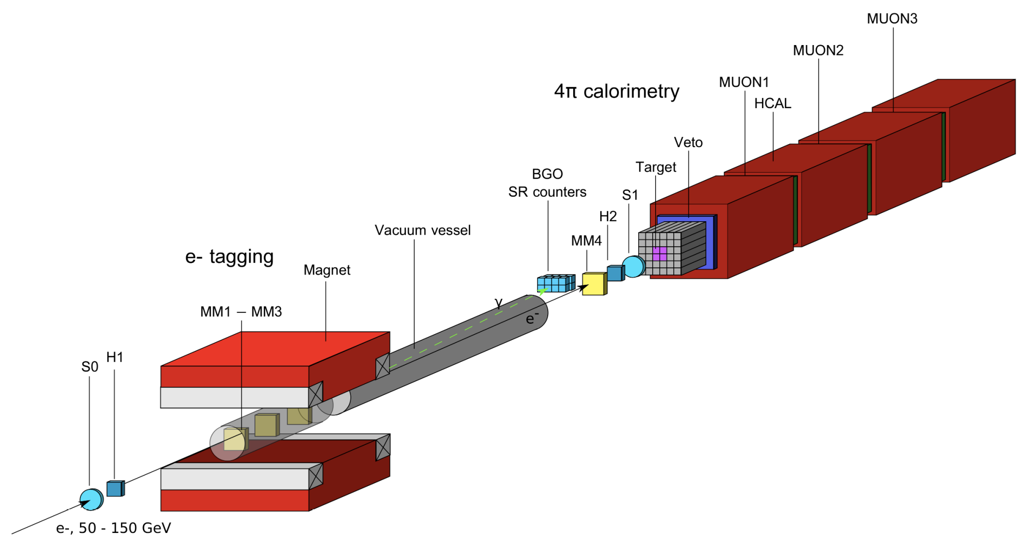


Beam Dump

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

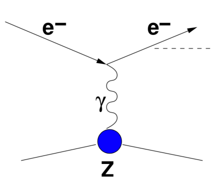


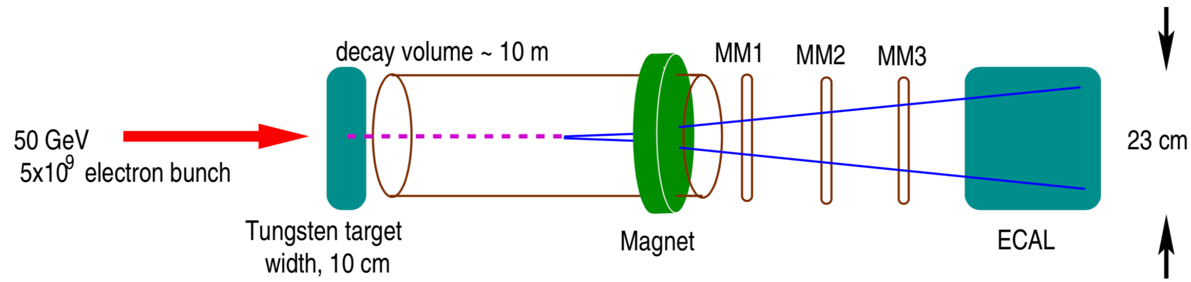
Decaying dark photons: into visible or invisible mode. For invisible mode - need to track individual electrons. How to do this in a bunched beam?



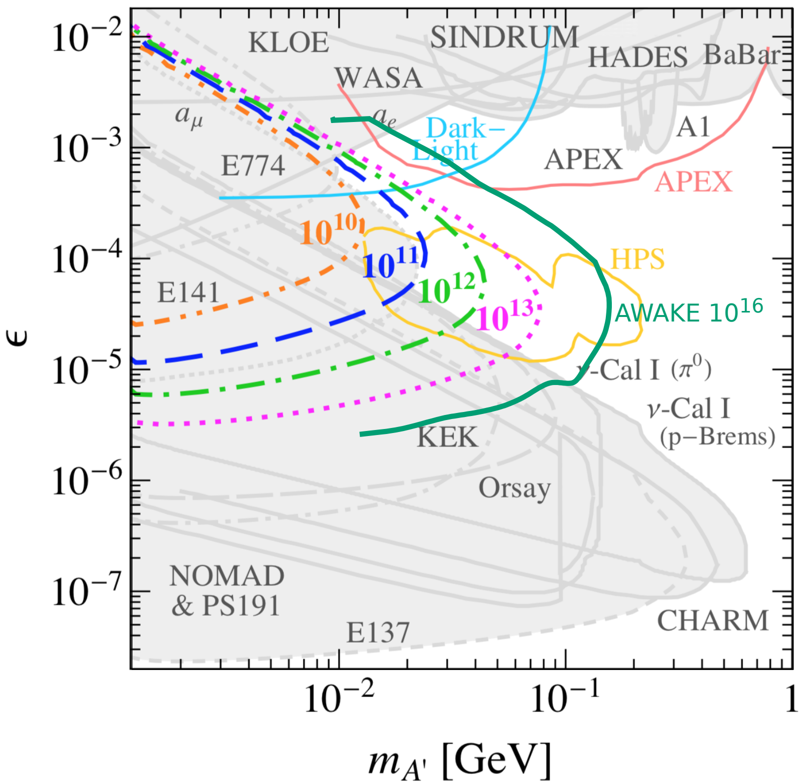
See e.g.: https://arxiv.org/pdf/2005.01515.pdf. 'The Physics of the Dark Photon'

Beam Dump

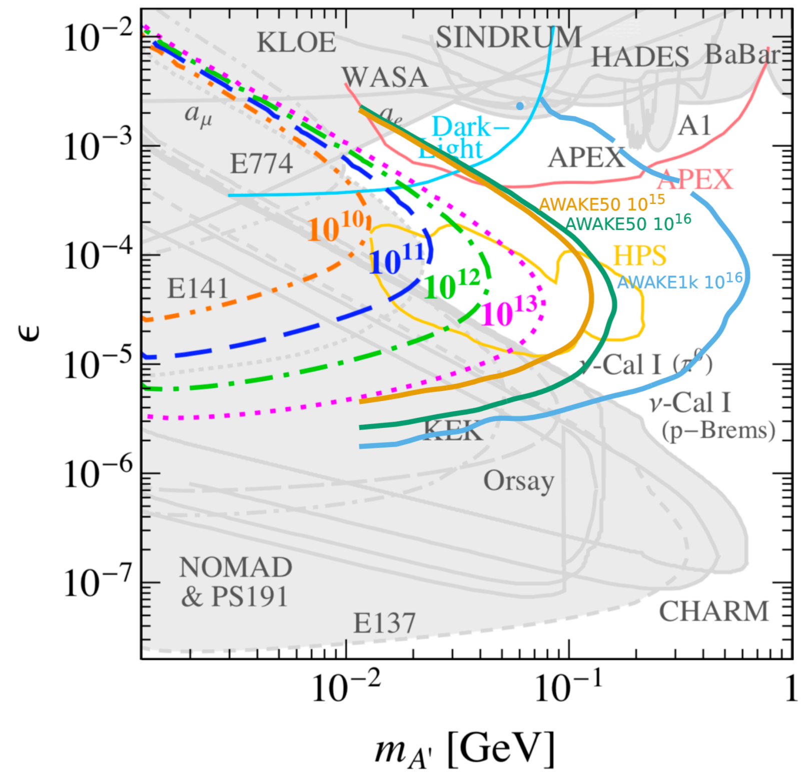




Expectation for 3 month run



Expectation for 10^{16} 1 TeV electrons



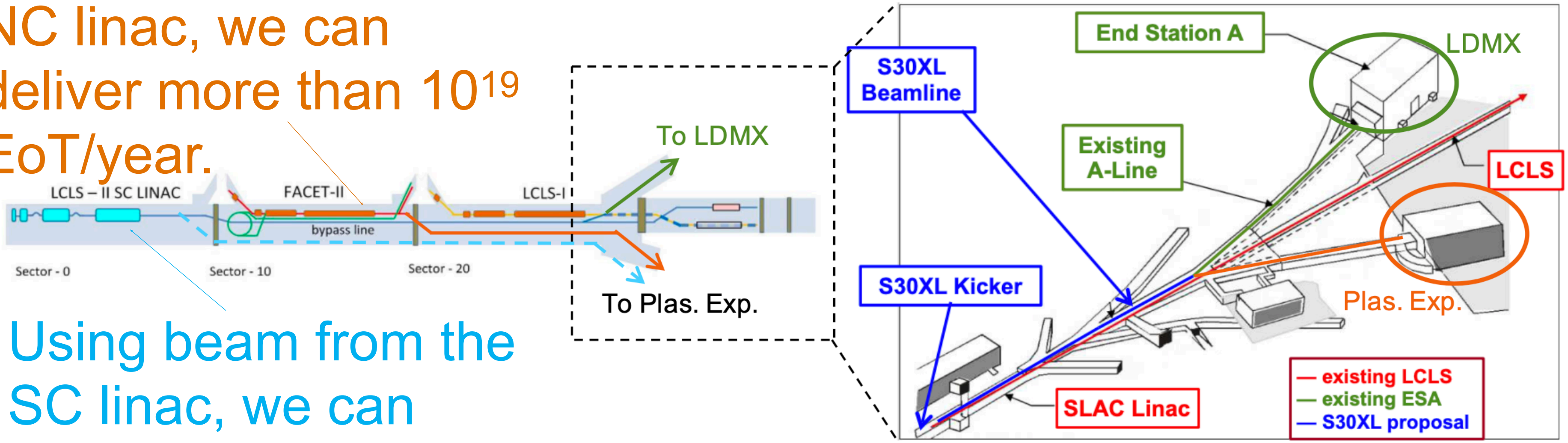
A. Hartin, UCL

From S. Gessner, SNOWMASS 2020

Concept @ SLAC

SLAC

Using beam from the NC linac, we can deliver more than 10^{19} EoT/year.



Using beam from the SC linac, we can deliver more than 10^{21} EoT/year.

Accelerator	Linac Energy	After Plasma	Bunch Charge	Rate	Current	EOT/year
NC to ESB	10 GeV	20-50 GeV	$0.2\text{-}2.0\times10^{10}$	120 Hz	19-190 nA	$0.4\text{-}4\times10^{19}$
SC to ESB	8 GeV	16-40 GeV	$0.3\text{-}3.0\times10^{9}$	1-62.5 kHz	0.5-30 μA	$0.1\text{-}6.0\times10^{21}$

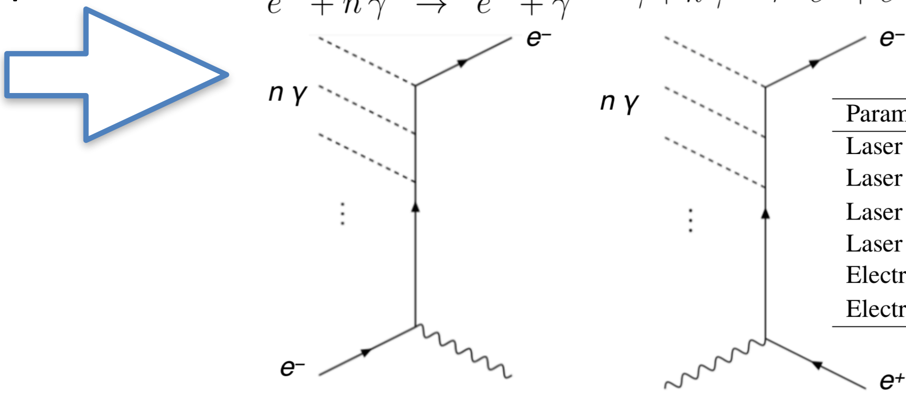
Strong Field QED

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

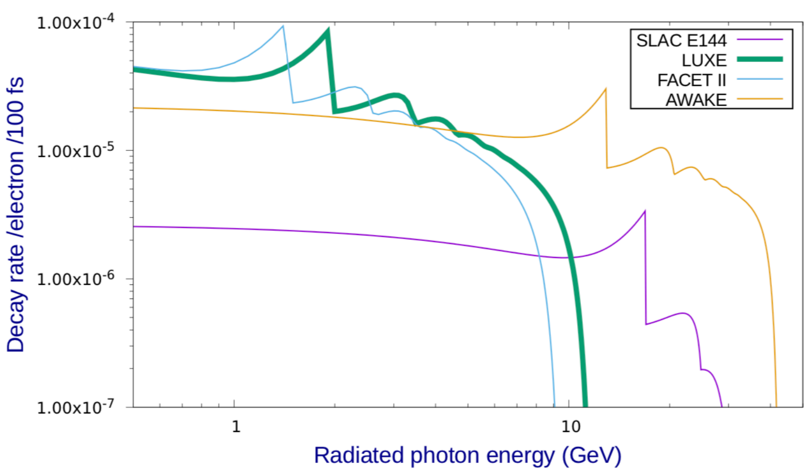
e.g.,

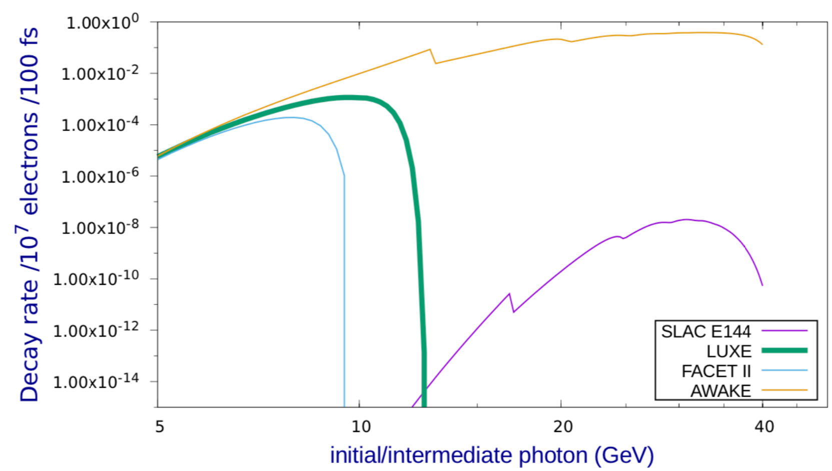
$$e^- + n\gamma \rightarrow e^- + \gamma \qquad \gamma + n\gamma \rightarrow e^+ + e^-$$



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

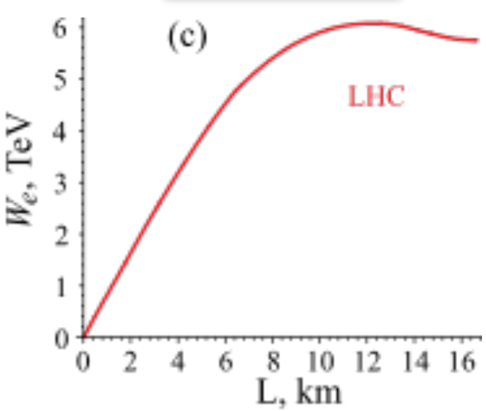
Fixed Target

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

LHC Driver



A. Caldwell and K. V. Lotov, Phys. Plasmas **18,** 103101 (2011)

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

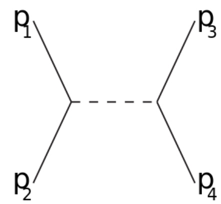
for E_e=100-6000 GeV

Compass: ~20 GeV	EIC: 15-140 GeV

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

General Considerations-Colliders

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



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

Power!

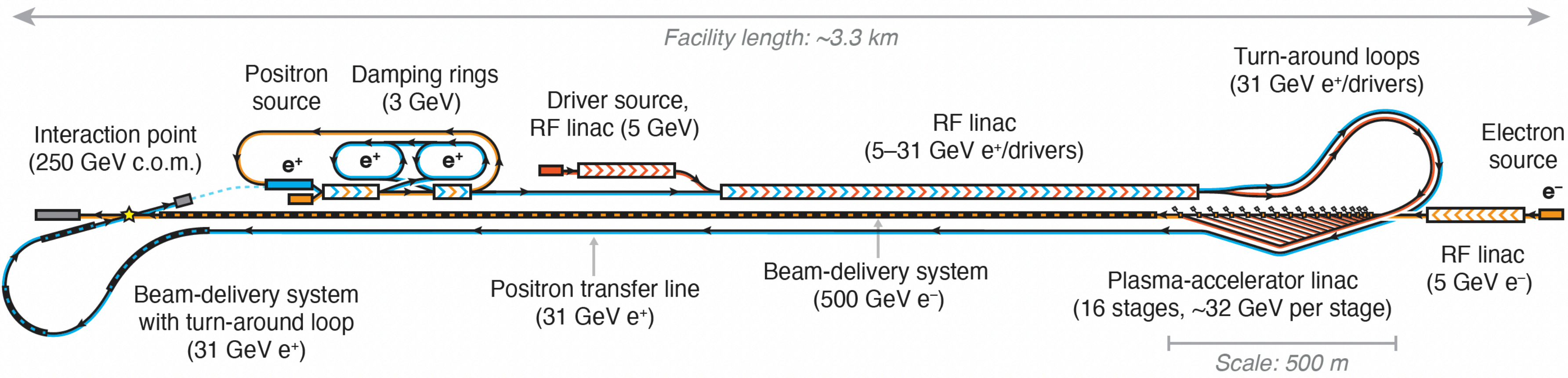
Challenge: high luminosity + high energy + affordability

LWFA - need high power + high energy + high efficiency laser

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

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

From B. Foster, LCWS 2023



Parameter	*Unit*	*HALHF*		*ILC*	*CLIC*
		e^-	e^+	e^-/e^+	e^-/e^+
Center-of-mass energy	GeV	250		250	380
Center-of-mass boost		2.13		-	-
Bunches per train		100		1312	352
Train repetition rate	Hz	100		5	50
Average collision rate	kHz	10		6.6	17.6
Average linac gradient	MV/m	1200	25	16.9	51.7
Main linac length	km	0.41	1.25	7.4	3.5
Beam energy	GeV	500	31.25	125	190
Bunch population	10^{10}	1	4	2	0.52
Average beam current	µA	16	64	21	15
Horizontal emittance (norm.)	µm	160	10	5	0.9
Vertical emittance (norm.)	µm	0.56	0.035	0.035	0.02
IP horizontal beta function	mm	3.3		13	9.2
IP vertical beta function	mm	0.1		0.41	0.16
Bunch length	µm	75		300	70
Luminosity	cm^{-2} s^{-1}	0.81×10^{34}		1.35×10^{34}	2.3×10^{34}
Luminosity fraction in top 1%		57%		73%	57%
Estimated total power usage	MW	100		111	168
Site length	km	3.3		20.5	11.4

Proton-driver for e-beam ?

Drive beam: p^+

E=1 TeV, $N_p=10^{11}$

$\sigma_z=100$ µm, $\sigma_r=0.43$ mm

$\sigma_\theta=0.03$ mrad, ΔE/E=10%

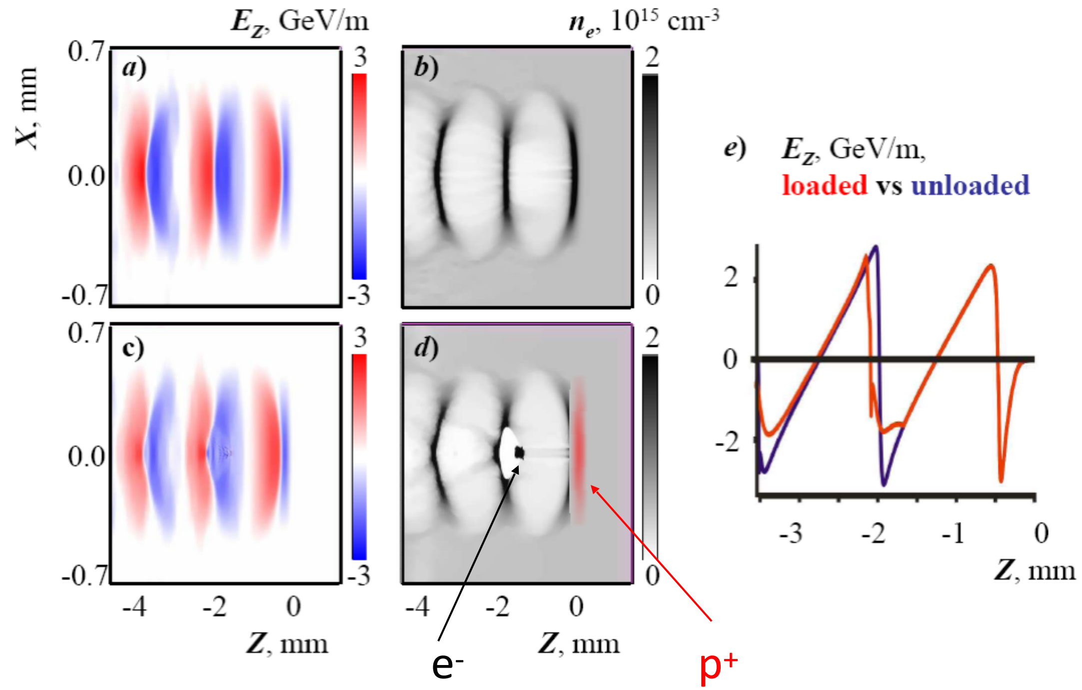
Witness beam: e^-

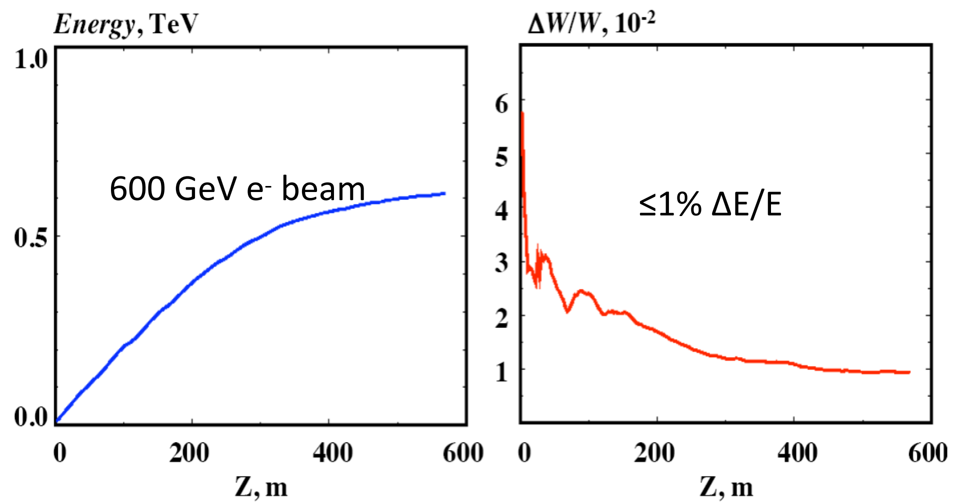
$E_0=10$ GeV,

$N_e=1.5\times10^{10}$

Plasma: Li^+

$n_p=6\times10^{14} cm^{-3}$

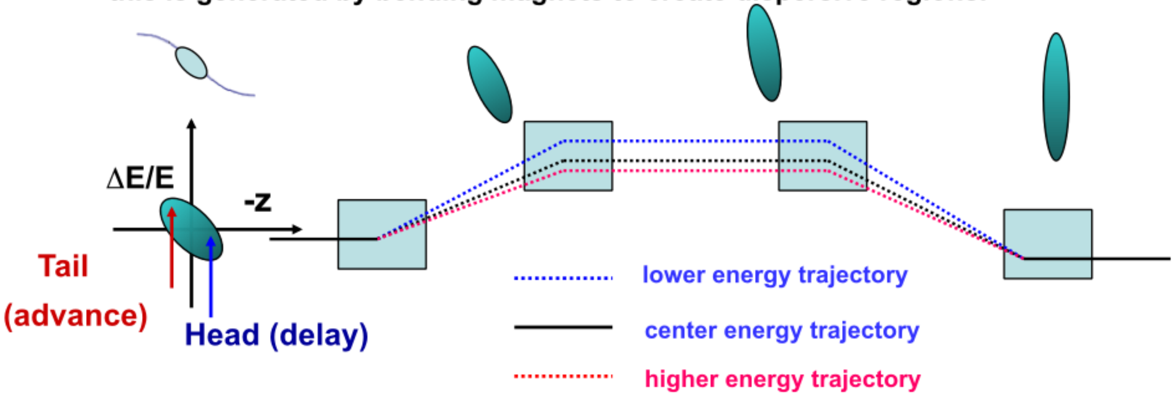




A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Nature Physics 5, 363 (2009).

Magnetic bunch compression (BC)

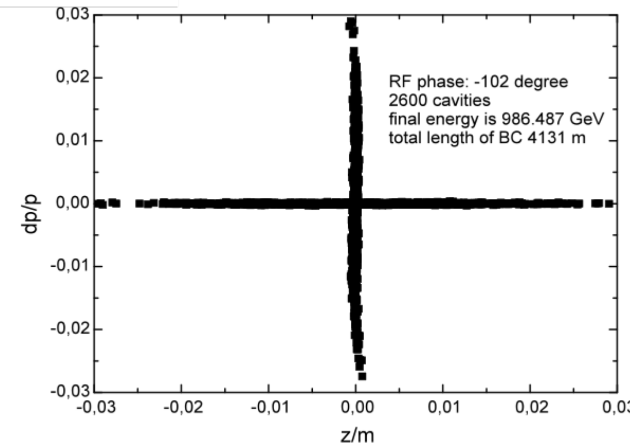
- **Beam compression can be achieved:**
  - **(1) by introducing an energy-position correlation along the bunch with an RF section at zero-crossing of voltage**
  - **(2) and passing beam through a region where path length is energy dependent: this is generated by bending magnets to create dispersive regions.**



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

Short proton bunches could be produced …

Luminosity issue: one electron bunch accelerated/proton bunch. Rep rate (for SPS, e.g., 15 Hz)



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

Parameter	*Unit*	*HALHF*		*ILC*	*CLIC*
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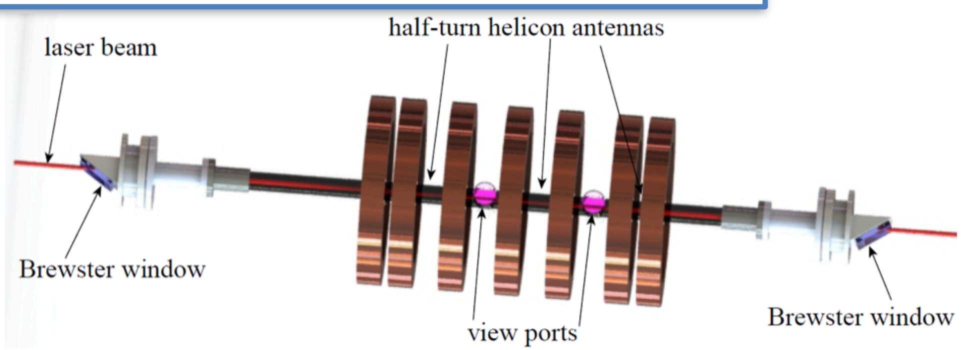
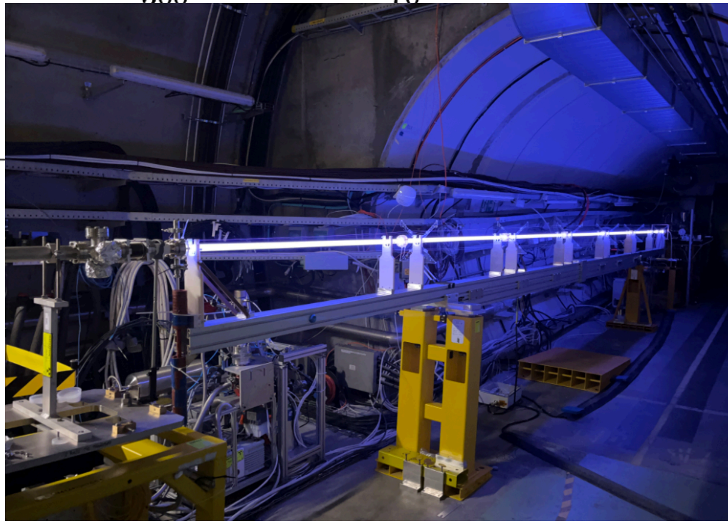
Bunch length	µm	75		300	70

Luminosity 3 orders of magnitude smaller with existing p accelerators … still interesting as PoP? Other challenges: e.g., long plasma cell. We're working on that …

Helicon plasma
B Buttenschön et al 2018 Plasma Phys. Control. Fusion **60** 075005

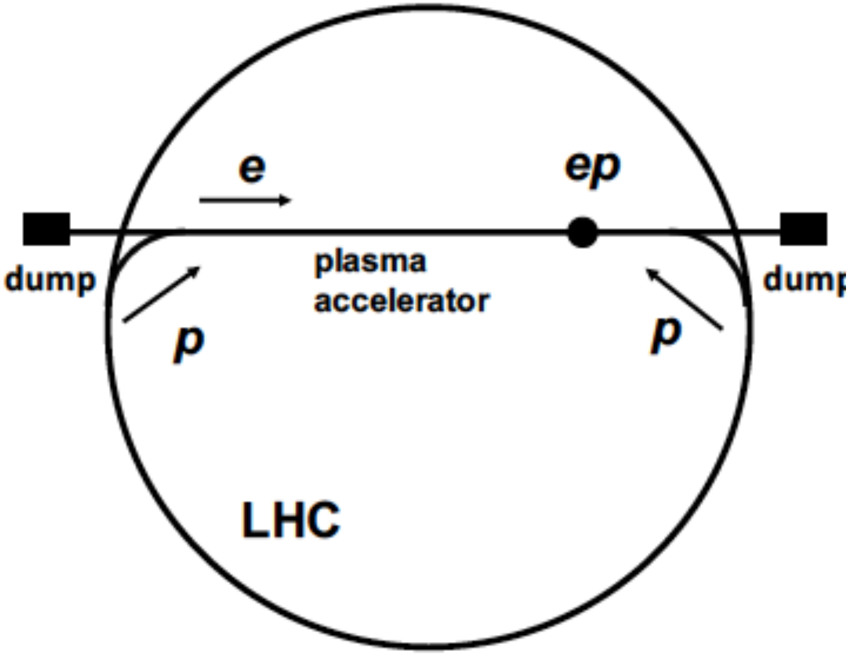




Discharge plasma under study @ CERN, IST - Lisbon, Imperial College, CERN

VHEeP

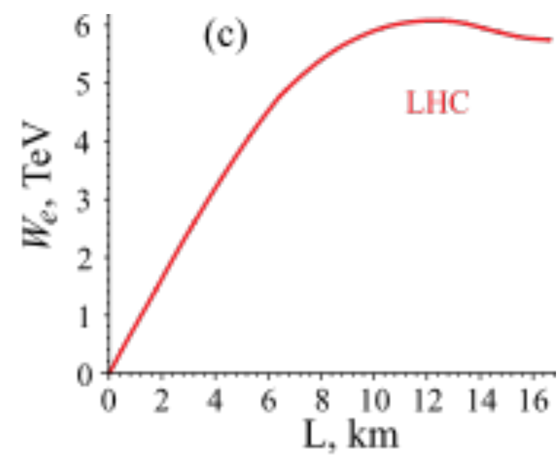
(Very High Energy electron-Proton collider)



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.

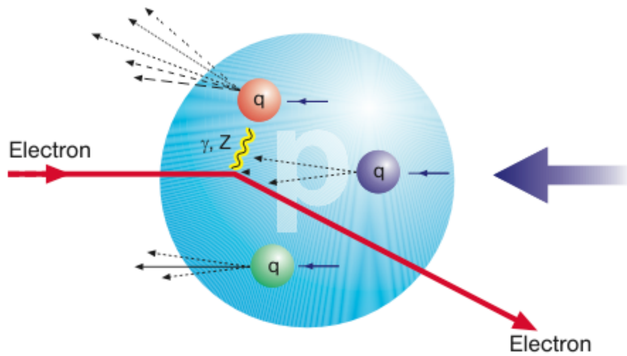
- Center-of-mass energy ~30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken x extended by ~1000 compared to HERA.
- Opens new physics perspectives

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

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

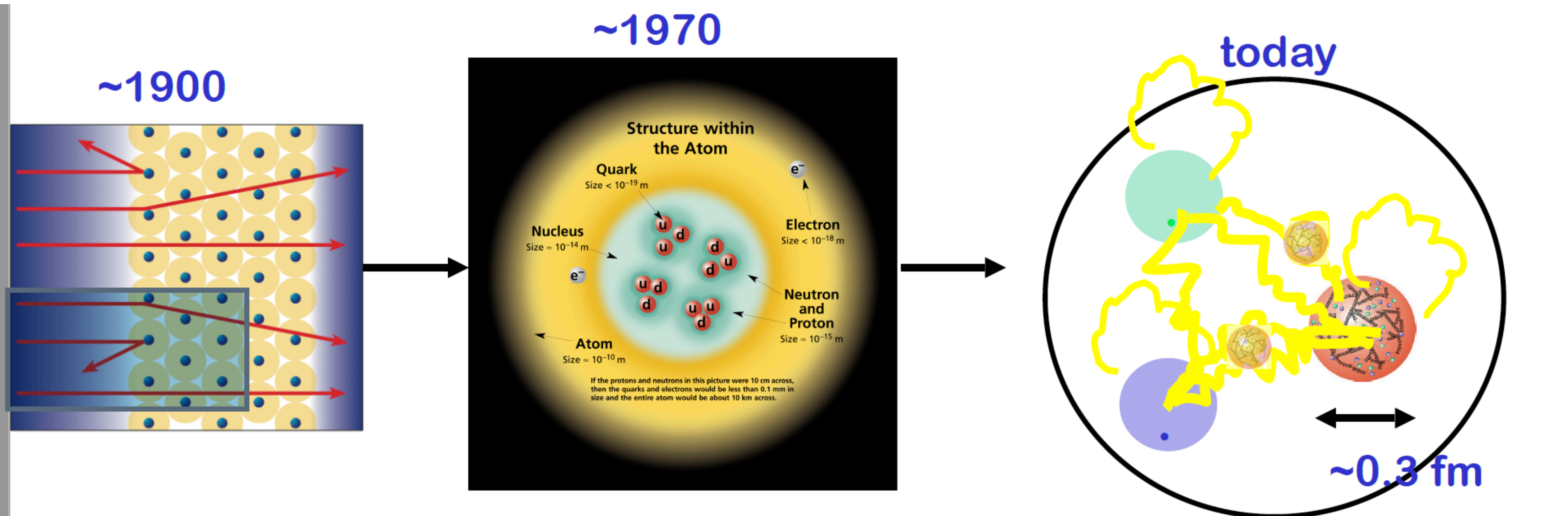
QCD is Fascinating

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



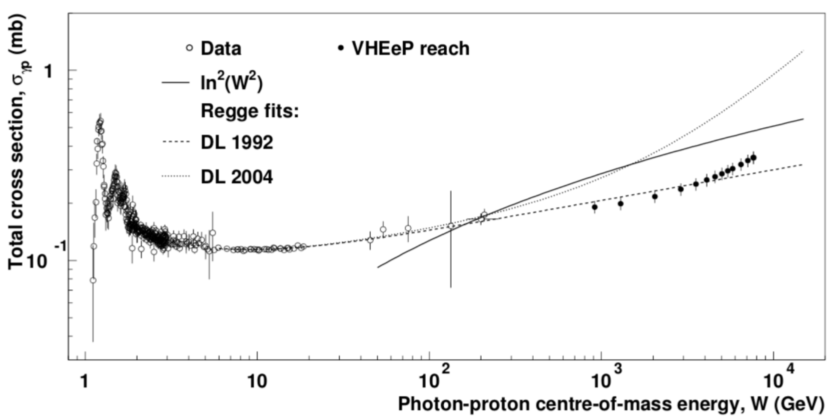
Effective fixed target parameters

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



Colliding 3 TeV electrons with LHC Protons

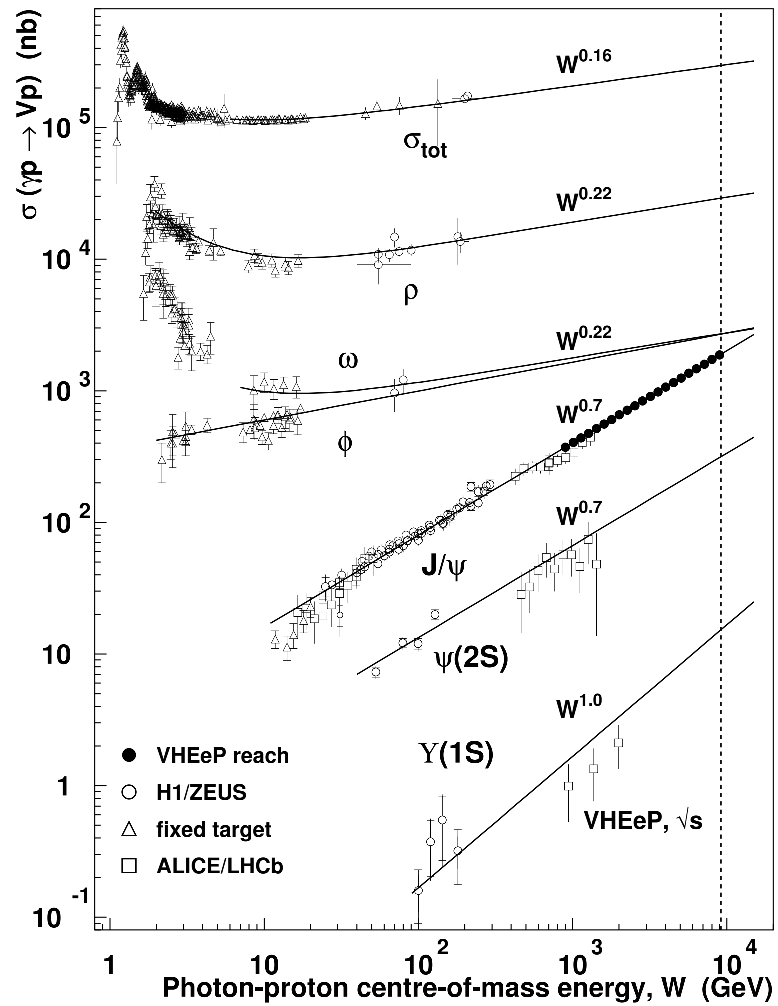
Total photoproduction cross section – energy dependence ? See approach to Froissart bound ?
Impact on cosmic ray physics



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

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

Exclusive processes:
Sensitive to square of gluon density
Early signs of new saturated regime



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!

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

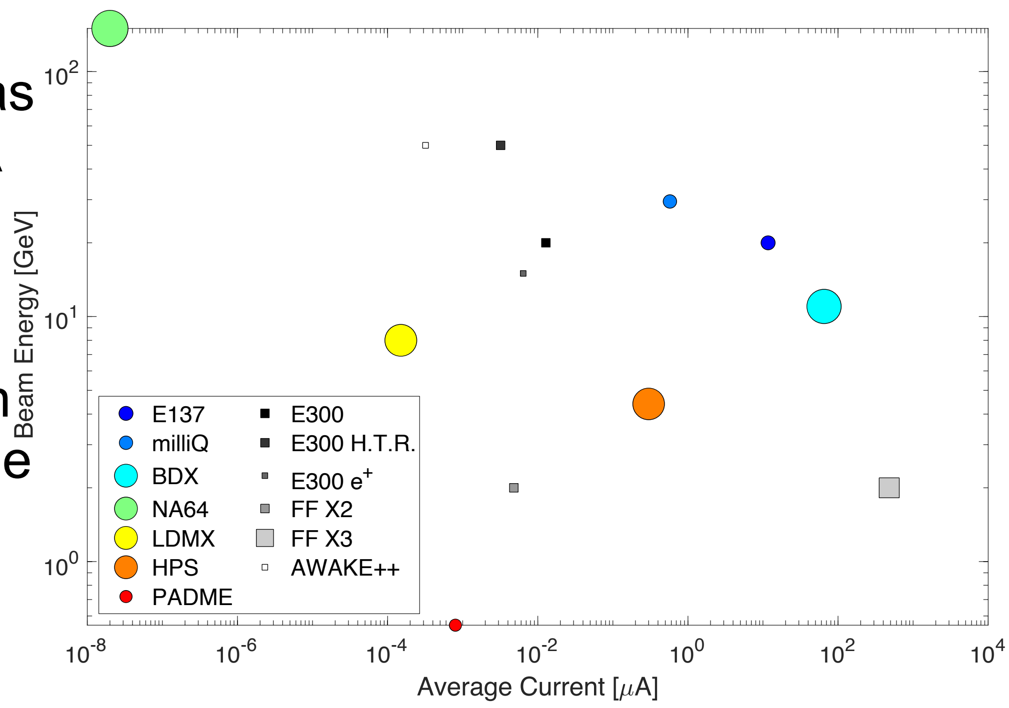
The new, fundamental, physics could well come from understanding ‘condensed matter’-like systems in particle physics experiments: QCD studies are critical!

Beam Characteristics

This plot shows past, current, and planned Dark Sector experiments as colored circles, and planned PWFA experiments as gray squares.

Plasma accelerators deliver high-charge, short-pulse bunches, which are good for suppressing out-of-time backgrounds in beamdump experiments.

In order to compete with other proposed beamdump (thick target) experiments, a plasma-based experiment should deliver 10^{19}-10^{21} electrons (or positrons) on target per year.



From S. Gessner, SNOWMASS 2020

Example Search: Millicharged Particles

As an example, we examine the exclusion curve from the SLAC MilliQ experiment and assume:

- 10x increase in EoT over milliQ
- 10x increase in detector sensitivity
- Beam energy scaled down to 20 GeV from 30 GeV for the 1998 experiment.

Achieving 10x increase in EoT requires 2 years of operation with NCRF linac at SLAC or a few weeks of operation with the new SCRF LCLS-II linac.