Plasma Accelerator Applications I: Particle Physics

Marlene Turner
February 10th 2023, Bad Honnef, Heraeus Seminar

Outline

- **Introduction**
  - What is particle physics?
  - Big open particle physics questions?
- **How Could Plasma Wakefield Technology Serve Particle Physics?**
  - 1) Energy frontier collider
    - Injector, afterburner
    - Particle sources, beam dumps
  - 2) Dark matter experiment
  - 3) Strong-field quantum electrodynamic experiment
  - 4) Deep inelastic scattering experiment
- **Summary & Conclusions**

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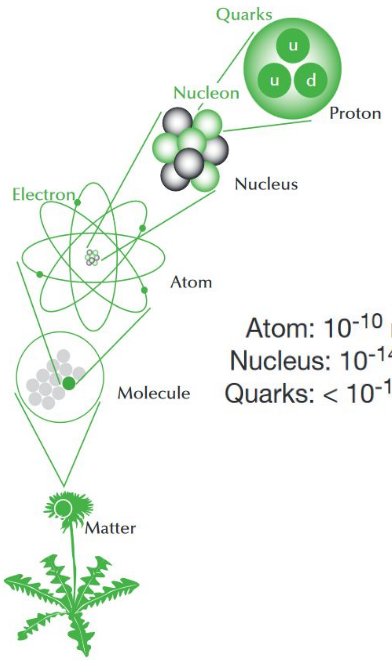
⇨ Why? How?
What are the challenges?

- **Summary & Conclusions**

What is Particle Physics?

Physics that deals with the properties, interactions and relationships of subatomic particles.

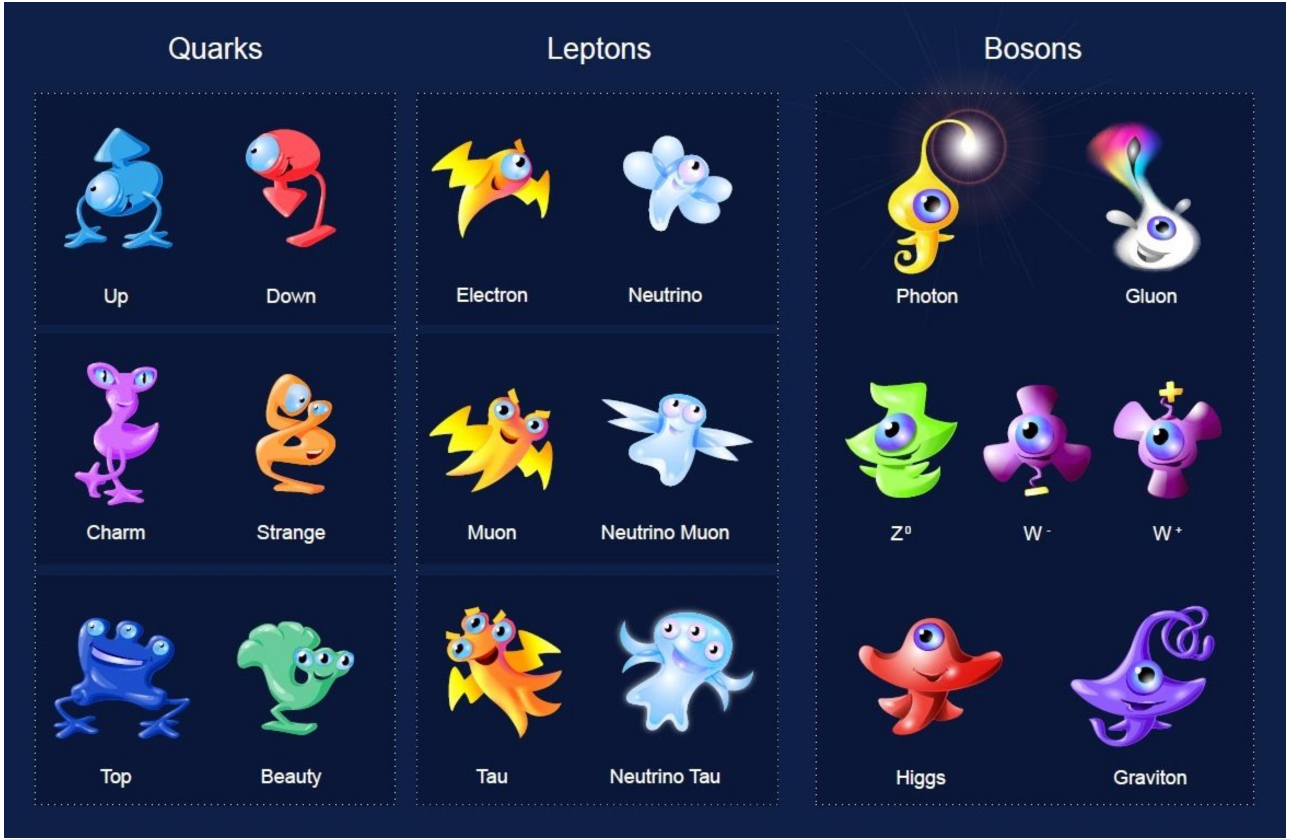


Atom: 10^{-10} m
Nucleus: 10^{-14} m
Quarks: < 10^{-19} m

Image from: LHC, the guide

- Waves do not scatter easily from small objects. To ‘see’ an object, the wavelength must be smaller than the object.
- Basics of quantum mechanics: all particles have wavelike properties.
  - EM waves (~eV,~10^{-6} m)
  - Particle beams $E=h\nu=hc/\lambda$ (1 TeV=10^{-18} m)
- So when we say that electrons and quarks have no deeper structure → at least on the scales of 10^{-19} m.
- Speculation that if you could magnify an electron or quark another 10^{18} times you would discover underlying morse code to be like strings.

The Particle Zoo



Particle quest sprites. *Source: André-Pierre Olivier.*

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The Particle Zoo

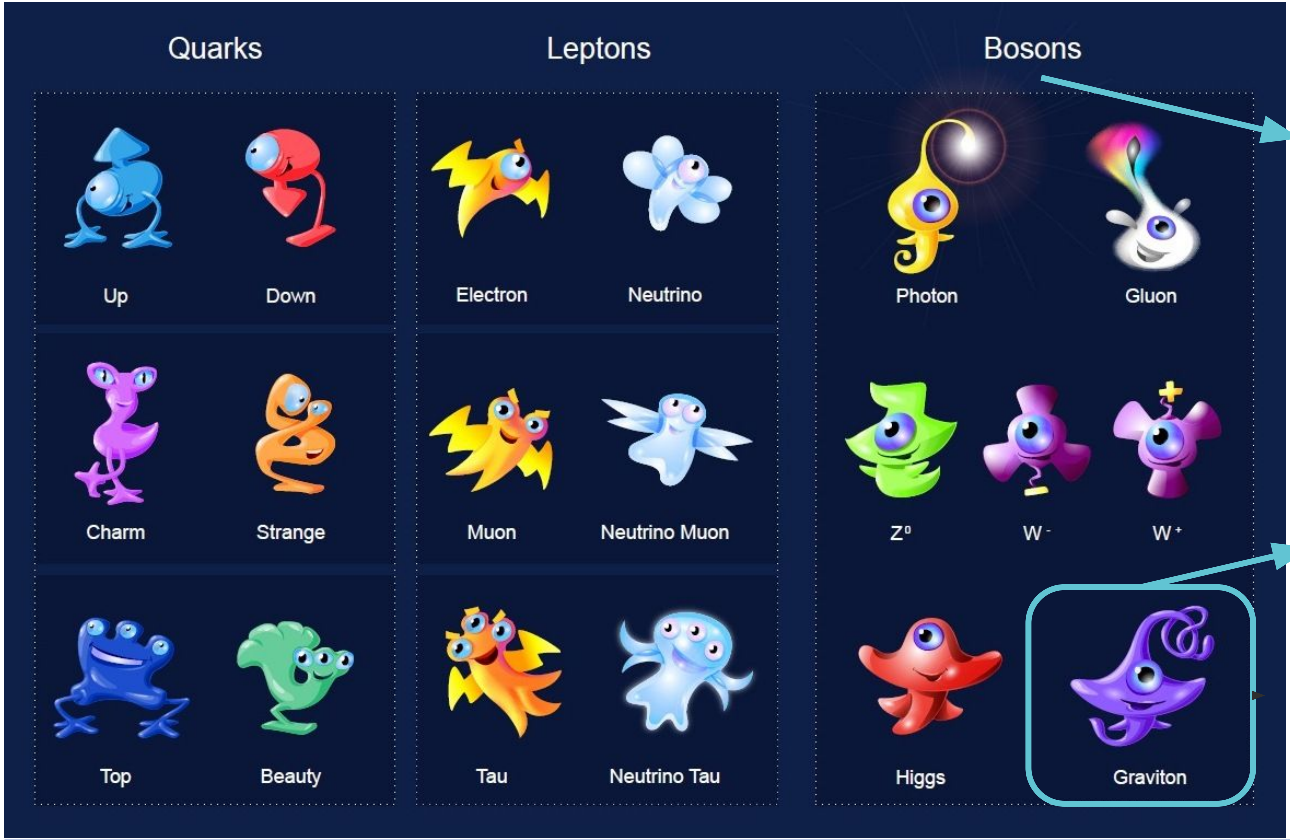
Make up everyday matter.

"These play no obvious role in the matter that we normally find on earth and it is not completely understood why nature uses them.

Answering such questions is one of the challenges currently facing us." (Quote from: Frank Close, A very short introduction to particle physics).

Particle quest sprites. *Source: André-Pierre Olivier.*

The Particle Zoo



- How forces manage to spread their effects through space.
- Existence implied by quantum theory.

Graviton:

- Hypothetical particle.
- Step towards a quantum mechanical description of gravity.
- Generally believed to be undetectable because they interact too weakly.

Particle quest sprites. *Source: André-Pierre Olivier.*

The Particle Zoo

Most scientists believe that we won't find the graviton *in the next 500 years*.

https://link.springer.com/article/10.1007/s10701-006-9081-9

There's a famous paper, which posits that:

- to detect a *single* graviton takes detector with the mass of more than **370 planet earths**
- it would take around **100 years**
- Detector would also need to be capable of distinguishing that single graviton from 10^{33} neutrinos

- How forces manage to spread their effects through space
- Implied by quantum theory

Graviton:

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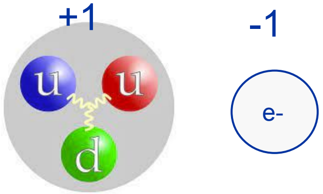
Some Particle Physics Questions

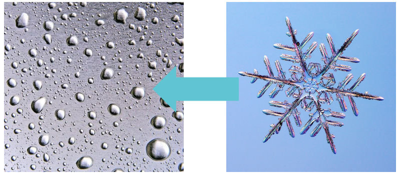


- **Inside the Atom:**
  - Electron: appears to be fundamental, if it has an inner structure we have yet to discover it
  - Proton: have internal structure → three quarks (+gluons)

  Electron and proton have miraculously identical opposite charges. Electrons and quarks are very similar (mass, size, spin).

- **Grand Unified Theory:**
  - Electromagnetic and weak force can be unified (two sides of the same coin)
  - Hints that the strong force can also be unified at high temperatures

  No sign that gravity also fits into the picture.



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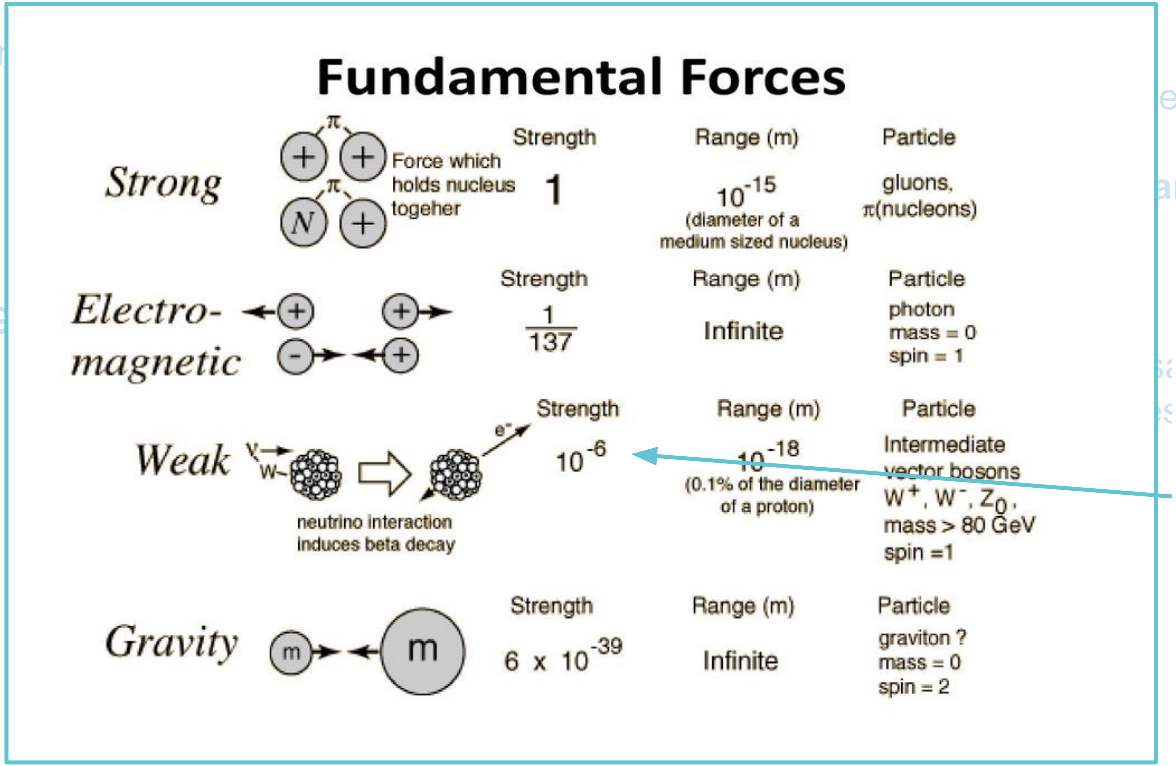

Weak force:

- The weak interaction changes one flavor of quark into another
- Transmutation p -> n so that deuterium can form and deuterium fusion
- The rate is crucial to the structure of the universe

Image taken from: https://slideplayer.com/slide/12885073/

Some Particle Physics Questions

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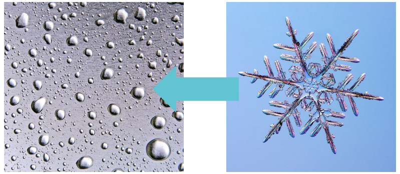


- **Extra Dimensions:**
  - Could explain why gravity much weaker than all other forces. E.g. because it's only leaking into our dimensions. → we only feel the effect of the unified forces that have leaked into our dimension.

    Are there extra dimensions?

Some Particle Physics Questions

- **Dark Matter:**
  - Primary evidence from calculations showing that many galaxies would behave quite differently if they did not contain a large amount of unseen matter.
  - Some galaxies would not have formed at all and others would not move as they currently do.
  - Observations in gravitational lensing and the cosmic microwave background.
    What is dark matter and dark energy?

- **CP Violation:**
  - Production of equal amounts of matter and antimatter at the big bang
  - Why does today (14 billions years later) the universe appears to be primarily made out of matter and there is no evidence for any antimatter in bulk anywhere at all
    This asymmetry is critical to us being here, the origin of it is one great unsolved problem.

  - …

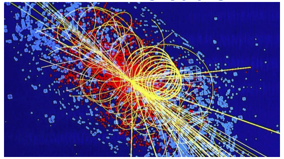
Particle Physics Experimental Approach

Smash

Credit: Getty Images

E

Credit: CERN



Heat

Image:
https://science4fun.info/heat/

E = kT
1eV~10^4K

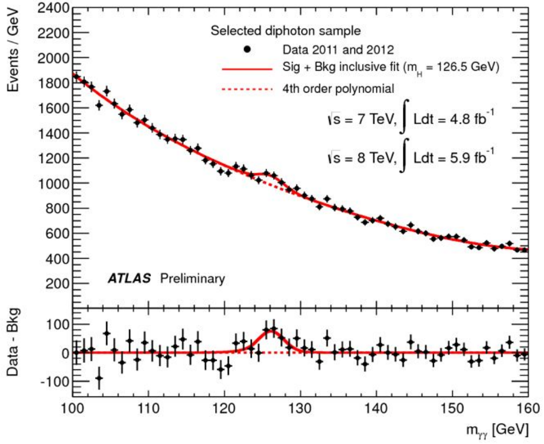
All three connected

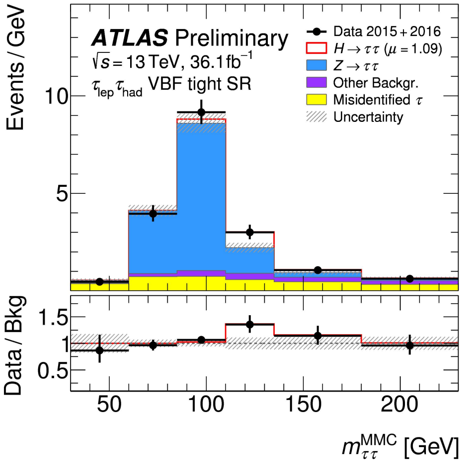
Look

E = hν = hc/λ
1eV ~ 1200 nm

By discovering new particles and phenomenon we can find answers to aforementioned questions.

Unravelling new Physics by Comparing Experimental Results with Theoretical Predictions





Compare theoretical predictions to experimental data

- The invariant mass from pairs of photons selected in the Higgs to γγ(left) Higgs to tau-pair (right) and analysis.
- The excess of events over the background prediction around 125 GeV is consistent with predictions for the Standard Model Higgs boson.

(Images: ATLAS Collaboration/CERN)

Plasma Accelerator Applications for Particle Physics

1

Particle Collider

(at the Energy Frontier)

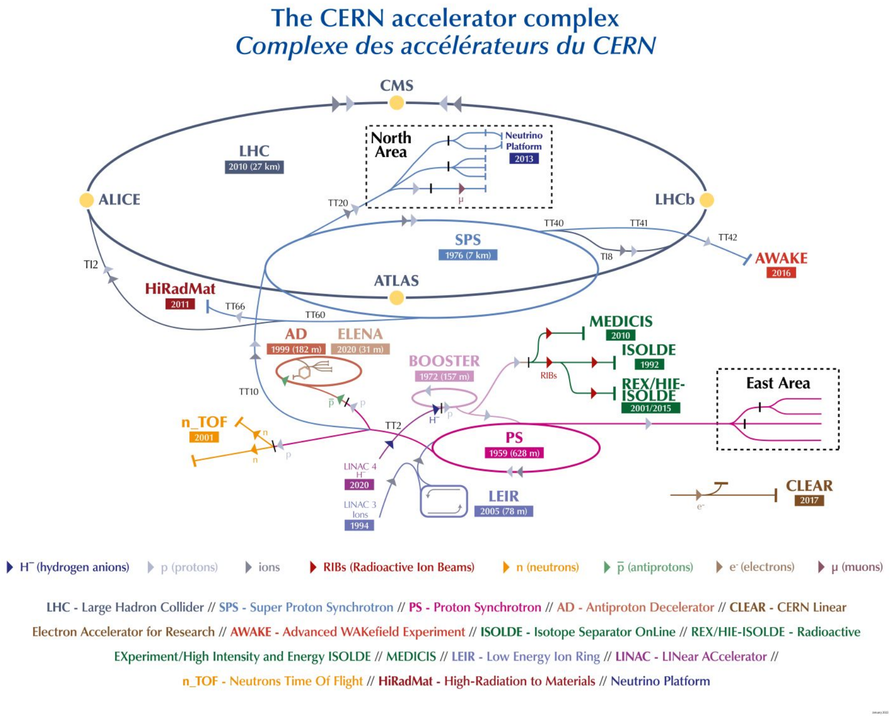
CLIC,
3 TeV,
e+e-
collider,
42 km long

Image source: https://home.cern/science/accelerators/compact-linear-collider

Claim:
High gradient acceleration in plasmas could significantly reduce the length of a future linear collider.

The Highest Energy Collider To-Date: CERN LHC

All accelerators in the LHC chain are based on conventional RF technology



- Proton-proton collider
- Collision energy ~14 TeV

- Luminosity: $L = 10^{34}$ cm$^{-2}\cdot$ s^{-1}
- HiLumi LHC→ increase instantaneous luminosity by a factor of ~5

- Power consumption: CERN complex ~200 MW

Image source: https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.rf_cavities

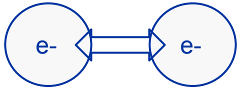
Next Particle Physics Collider Options

E

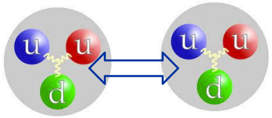
Collision energy defines what can you discover

Lepton or hadron collisions

Precision machine



Discovery Machine



L

Luminosity defines how likely you are to discover

Number of collisions are produced (per cm^2 and per second).

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} .$$

⇒ Cross section: probability of that a particular event occurs

- (Challenge: most lepton cross sections decrease with increasing collision energy)

Future Particle Physics Collider Options

proton - proton
lepton - lepton
ɣ-ɣ

Higgs Factory

- Lepton collider (precision machine)
- Collision energy ~ 250 GeV
- Shovel ready designs exist (ILC)
- Plasma technology not yet mature enough to compete with other designs…

Few TeV lepton collider

- Most mature concept is CLIC
- No indications of exciting physics from LHC

10+ TeV constituent-center-of-mass-collider

- ~100 TeV proton-proton collider or ~10-15 TeV lepton collider
- On the table:
  - FCC, CEPC
  - Muon Collider
  - Plasma Based Collider

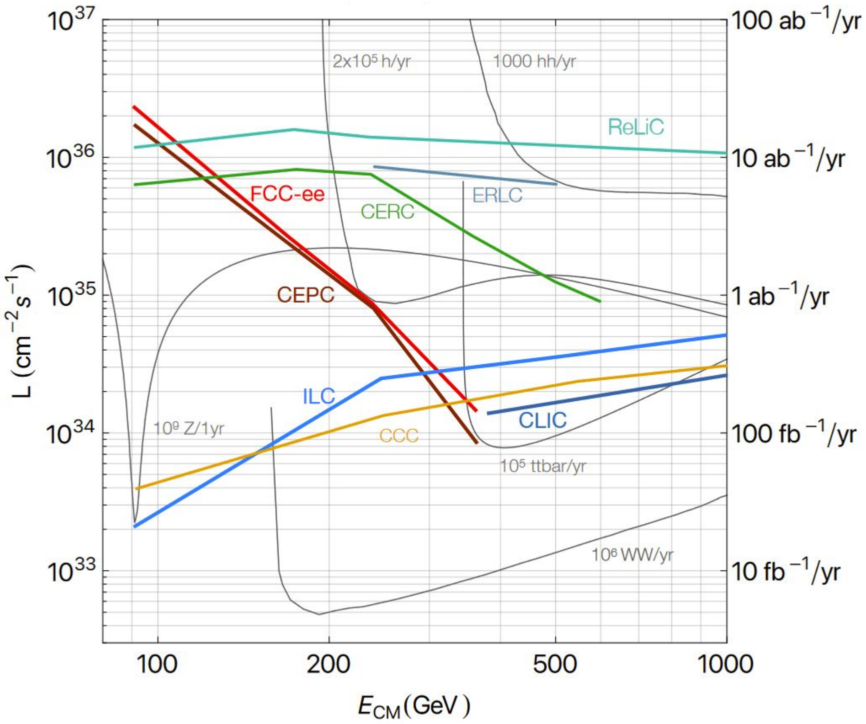
Circular machines

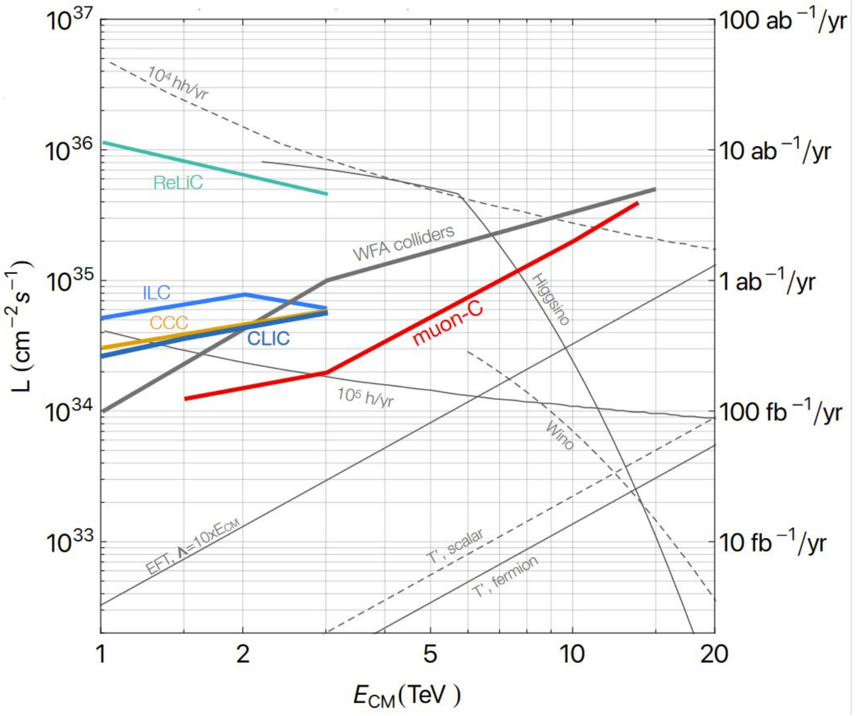
- None of the proposals is shovel ready, extensive R&D required for all options
- Different proposals have different challenges

Next collider: environmental impact may be a big decision factor

https://www.symmetrymagazine.org/article/energy-consumption-cost-considerations-could-shape-future-of-accelerator-rd

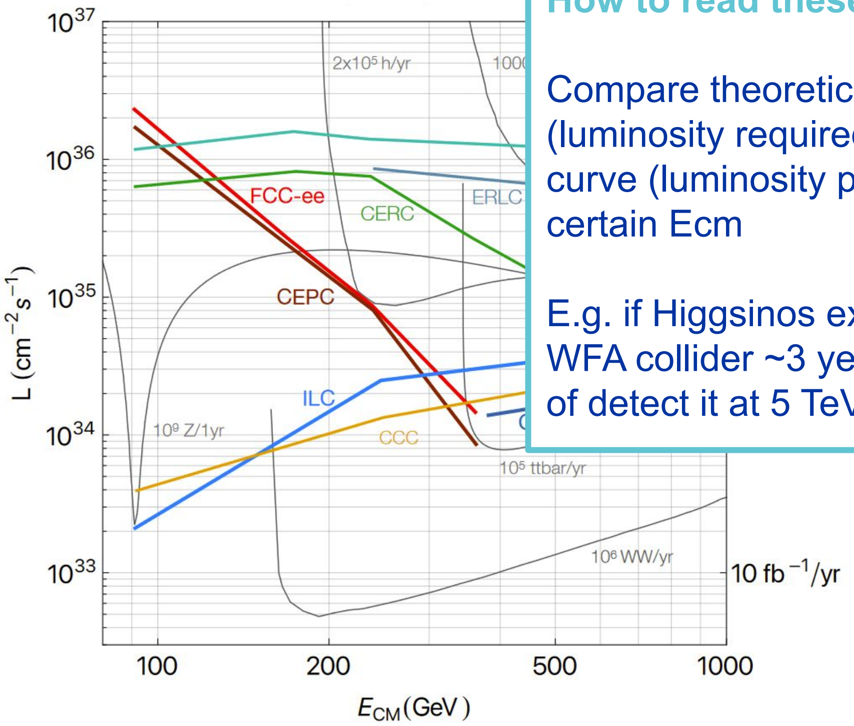
Future Particle Physics Collider Options

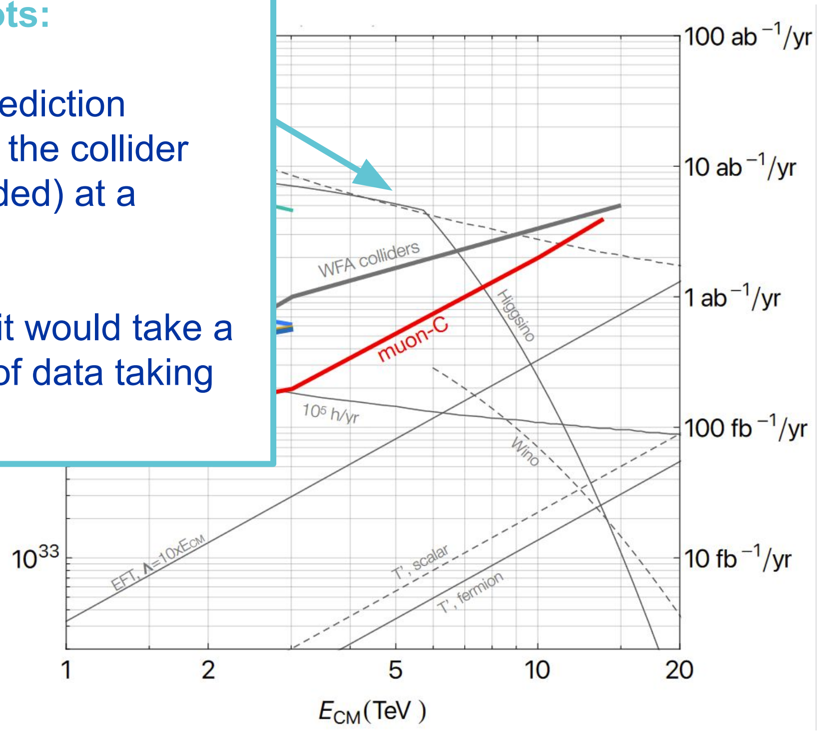




- Not seen in these plots: maturity of the concept and design, cost, timescale, R&D required…

Future Particle Physics Collider Options





How to read these plots:

Compare theoretical prediction (luminosity required) to the collider curve (luminosity provided) at a certain Ecm

E.g. if Higgsinos exist, it would take a WFA collider ~3 years of data taking of detect it at 5 TeV.

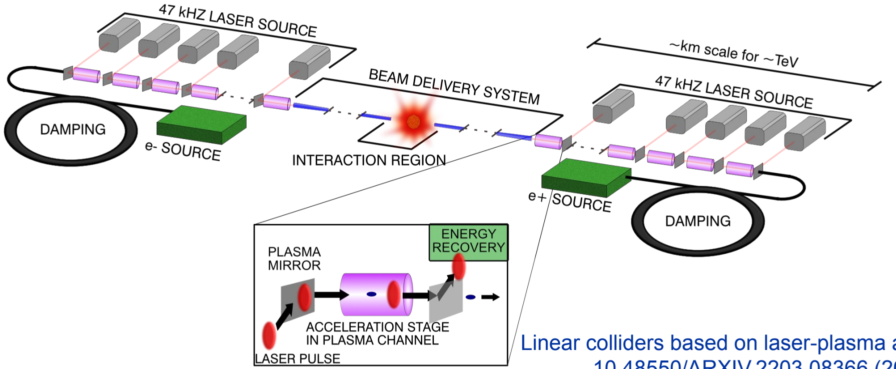
- Not seen in these plots: maturity of the concept and design, cost, timescale, R&D required…

Image: Holy grail from Monthy Python

Challenges of Plasma Based Particle Colliders

Straw-person design based on:

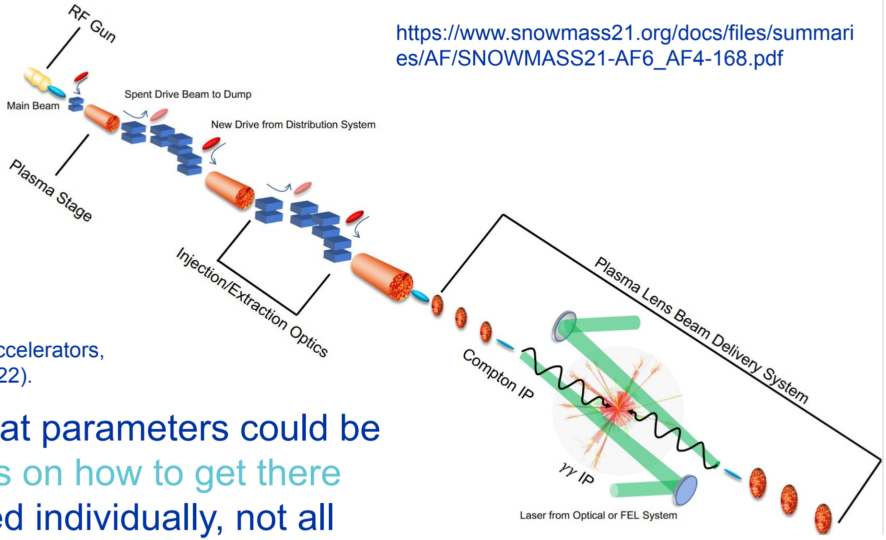
Laser-driven plasma wakefield acceleration



Linear colliders based on laser-plasma accelerators, 10.48550/ARXIV.2203.08366 (2022).

Beam-driven plasma wakefield acceleration

https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF6_AF4-168.pdf



- There is a set of *desired* parameters, estimating what parameters could be achieved with plasma wakefield technology → ideas on how to get there
- Many parameters/concepts have been demonstrated individually, not all together (either simulations or experiments) → long-timescale R&D work required
- Likely need a demonstrator between first applications (GeV scale) and final machine (TeV scale). (https://arxiv.org/abs/2203.08425)

$e^- - e^+$
$e^- - e^-$
γ-γ

Currently Ongoing: Towards a Self-Consistent Parameter Set

Grand challenges:

- Beam quality preservation over hundreds of stages
  - Emittance preservation, alignment tolerances, staging (in/out coupling of beams and pulses),
- Reaching the desired luminosity,
  - Squeezing beams tightly at the IP
  - Final focus design,
- Power consumption and efficiency,
- Positron acceleration and production of short dense positron bunches,
- …

https://indico.fnal.gov/event/54953/sessions/20614/attachments/156153/205983/ITFreportDRAFT-July19.pdf

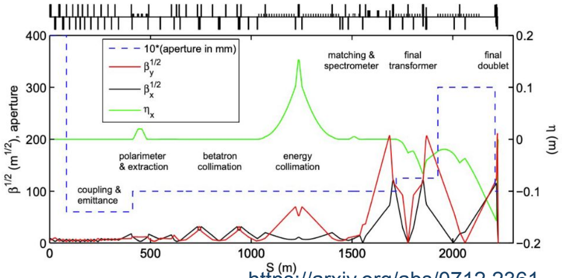
Currently Ongoing: Towards a Self-Consistent Parameter Set

Technology	PWFA	PWFA	PWFA	SWFA	SWFA	SWFA	LWFA	LWFA	LWFA
Aspect Ratio	Flat	Flat	Round	Flat	Flat	Round	Flat	Flat	Round
CM Energy	1	3	15	1	3	15	1	3	15
Single beam energy (TeV)	0.5	1.5	7.5	0.5	1.5	7.5	0.5	1.5	7.5
Gamma	9.78E+05	2.94E+06	1.47E+07	9.78E+05	2.94E+06	1.47E+07	9.78E+05	2.94E+06	1.47E+07
Emittance X (mm mrad)	0.66	0.66	0.1	0.66	0.66	0.1	0.1	0.02	0.1
Emittance Y (mm mrad)	0.02	0.02	0.1	0.02	0.02	0.1	0.01	0.007	0.1
Beta* X (m)	5.00E-03	5.00E-03	1.50E-04	5.00E-03	5.00E-03	1.50E-04	2.50E-02	1.40E-02	1.50E-04
Beta* Y (m)	1.00E-04	1.00E-04	1.50E-04	1.00E-04	1.00E-04	1.50E-04	1.00E-04	1.00E-04	1.50E-04
Sigma* X (nm)	58.07	33.53	1.01	58.07	33.53	1.01	50.55	9.77	1.01
Sigma* Y (nm)	1.43	0.83	1.01	1.43	0.83	1.01	1.01	0.49	1.01
N_bunch (num)	5.00E+09	5.00E+09	5.00E+09	3.13E+09	3.13E+09	3.13E+09	1.20E+09	1.20E+09	7.50E+09
Freq (Hz)	4200	14000	7725	11000	36000	19800	46856	46856	3435
Sigma Z (um)	5	5	5	40	40	40	8.4	8.4	2.2
Beamstrahlung parameter	15	78	6590	1	6	515	2	37	22466
n_γ	1.5	1.5	5.7	2.2	2.2	8.4	0.8	1.5	5.7
Single Beam Power (MW)	1.7	16.8	46.4	2.8	27.0	74.4	4.5	13.5	31.0
Two Beam Power (MW)	3.4	33.6	92.8	5.5	54.1	148.7	9.0	27.0	61.9
Geometric Lumi (cm^{-2} s^{-1})	1.01E+34	1.01E+35	1.50E+36	1.03E+34	1.01E+35	1.51E+36	1.05E+34	1.13E+35	1.50E+36
Beamstrahlung lumi	1.99E+34	1.99E+35	1.52E+36	2.03E+34	2.00E+35	1.52E+36	2.09E+34	2.17E+35	1.52E+36
Wall plug to drive laser/beam eff	0.4	0.4	0.4	0.774	0.774	0.774	0.4	0.4	0.5
Laser/beam drive to main eff	0.375	0.375	0.375	0.42	0.42	0.42	0.2	0.2	0.12
Wall plug to main beam eff	0.15	0.15	0.15	0.32508	0.32508	0.32508	0.08	0.08	0.06
Site power Wall to main only (MW)	22	224	619	17	166	457	113	338	1032
Lumi/Power (1e34/MW)	0.04	0.04	0.08	0.06	0.06	0.11	0.01	0.03	0.05
GUINEA-PIG Total Lumi	1.83E+34	1.85E+35	4.2E+37	2.08E+34	2.13E+35	4.2E+36	1.53E+34	2.58E+35	6E+36
GUINEA-PIG Lumi 1% (20%)	6.86E+33	6.23E+34	5E+35	8.49E+33	6.14E+34	5E+35	1.03E+34	8.72E+34	5E+35
GP Total Lumi/Power	0.08	0.08	6.79	0.12	0.13	0.92	0.01	0.08	0.58
GP Lumi 1%/Power (20%)	0.03	0.03	0.08	0.05	0.04	0.11	0.01	0.03	0.05
Length of 2 Linacs (km)	1	3	14	5	15	75	0.44	1.3	6.5
Length of Facility	14	14	14	8	18	90	3.5	4.5	9.5

Challenges for Any Multi-TeV Linear Collider

Beam delivery system

ILC final focus design



https://arxiv.org/abs/0712.2361

To achieve high luminosity at reasonable beam power→ small transverse beam size (~1-100 nm).

CLIC (3 TeV) BDS is ~3 km long.

Designs have sub-percent level energy acceptance.

DOI:10.1051/epjconf/20149503022

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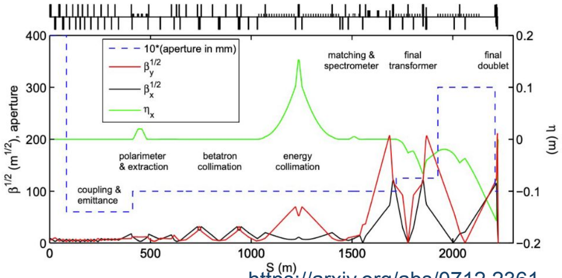

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Efficiency / Power consumption

Estimated:

- CLIC ~580 MW
  - ~10% wall plug to beam energy transfer efficiency.

Can plasma acceleration be more efficient?

Energy recovery?

How efficient can the drivers be?

Round vs. flat beams?

E.g. PWFA LC-15 TeV
206.28 MW vs 1121.52 MW

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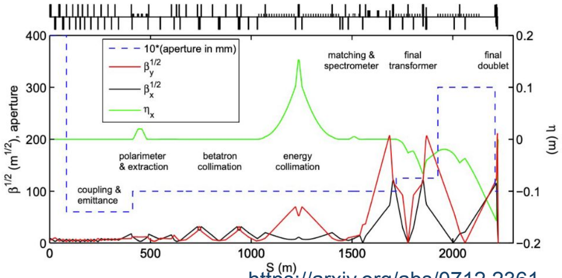

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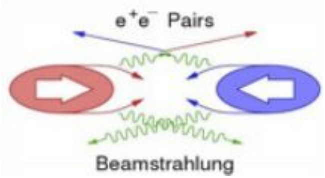
Beamstrahlung

small bunch sizes required to achieve high luminosity give rise to strong electromagnetic (synchrotron) radiation, so-called beamstrahlung, from the electron and positron bunches in the high field of the opposite beams.



$$\delta E \propto \frac{N^2 \gamma_L}{(\sigma_x + \sigma_y)^2 \sigma_z},$$

→ Reducing luminosity per energy, detector background

DOI:10.1051/epjconf/20149503022

What About Providing one of the Subsystems, Rather than a Whole Collider?

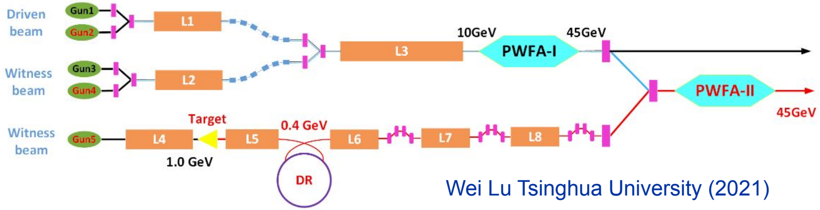
- Plasma-based injector
- Plasma booster / afterburner
- Particle production
- Beam dumps

Plasma-Based Injector

Idea: high-energy circular accelerators require a minimum injection energy

- typically defined by the field accuracy of the magnets

Feasibility Study: Using a 10m scale plasma accelerator to boost the energy of the injector to about 45 GeV? (120-180 GeV)



Wei Lu Tsinghua University (2021)

Parameter	Symbol	Unit	Requirement	Achieved(in sim.)
Energy	E_e	GeV	45.5	45.3(e-) / 45.2(+)
Energy Spread	σ_e		< 0.2%	0.2%(e-) / 0.14%(e+)
Frequency	f_{rep}	Hz	100	100
Bunch Charge	N_e	nC	> 1.0	1
Emittance	ε_r	nm·rad	< 30	1.89(e-) / 1.0(e+)
Bunch Length	σ_l	mm	< 3	0.3(e-) / 0.3(e+)
Energy Stability			< 0.2%	
Longitudinal Stability		mm	< 2	
Orbit Stability		mm	< 5(H) / 3(V)	

Plasma-Booster/Afterburner

Idea: ⇒ double the incoming beam energy

Conventional Linac + Plasma at the end

Challenges:

- When drive beam is split → reduction in accelerated charge linacs
- Positron- acceleration
- Requires short bunches!

Possibility of a multibunch plasma afterburner for linear colliders, R. Maeda, T. Katsouleas, P. Muggli, C. Joshi, W. B. Mori, and W. Quillinan, Phys. Rev. ST Accel. Beams **7**, 111301

Energy doubler for a linear collider, S. Lee, T. Katsouleas, P. Muggli, W. B. Mori, C. Joshi, R. Hemker, E. S. Dodd, C. E. Clayton, K. A. Marsh, B. Blue, S. Wang, R. Assmann, F. J. Decker, M. Hogan, R. Iverson, and D. Walz, Phys. Rev. ST Accel. Beams **5**, 011001

Particle Source

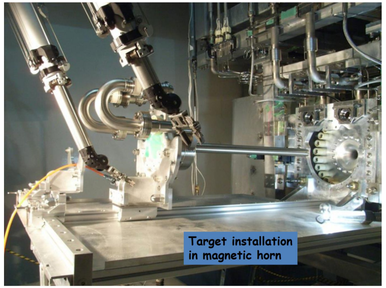
Assembly of the target prototype before installation (Image: Julien Ordan/CERN)

Why?

Particle physics experiments require production of particle beams for experiments.
Typical: protons, antiproton, electrons, positrons, muons, neutrinos, ions, or photons..

To be considered: flux, spectra, brilliance, polarisation (when desired),...

Our starting point: Helium Cooled T2K Target



DEEP UNDERGROUND NEUTRINO EXPERIMENT Chris Densham 6 Rutherford Appleton Laboratory

Particle Production Methods

Direct

E.g. proton beam from the LHC, is a bottle of hydrogen gas connected to a machine called a duoplasmatron.

Photocathodes, electron emitters (thermionic, field emission): ionisation of material, typically choose material with low ionisation potential

Typical for: protons, electrons, ions,..

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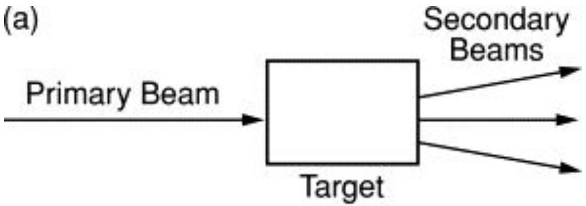
Secondaries (interaction with target)



Spray of secondary particles. Broad spectrum and divergence, select particles. Low yield→ need high intensities

Typical for: positrons, antiprotons, muons (decay from Pions and Kaons),neutrinos..

Challenge: low yields, broad distributions,..

Particle Production Methods

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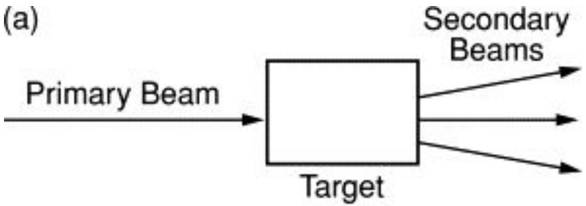

Spray of secondary particles. Broad spectrum and divergence, select particles. Low yield→ need high intensities

Typical for: positrons, antiprotons, muons (decay from Pions and Kaons),neutrinos..

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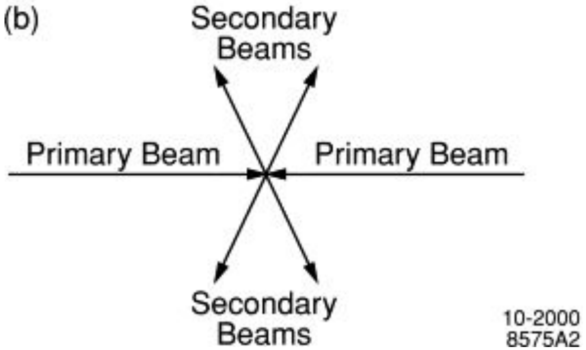
Interaction of two beams



Electron - photons→ positrons or muons

Advantage: collimated beams

Challenge: low yield, complicated setups,..

Plasma Wakefield Based Particle Sources

Advantages: compactness, potentially all-optical, potentially high brightness (high fields),..

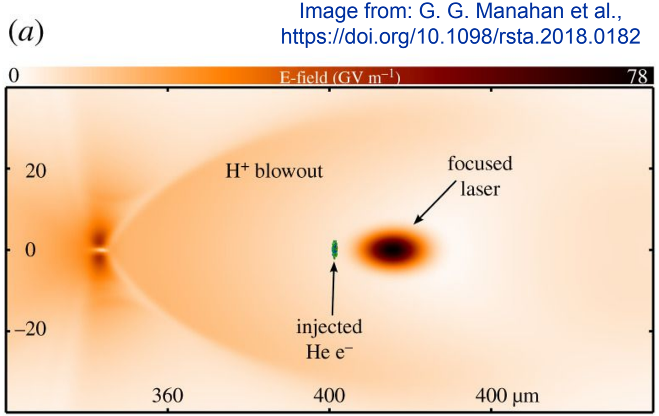
Electrons:

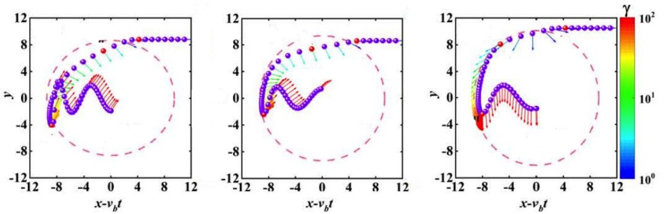
- Plasma photocathode:

  Based on injection and trapping of background plasma electrons in wakefields

  → idea: ionize and trap electrons from small phase space. e.g. Trojan Horse Injection or Two-Color ionisation injection.

Image from: G. G. Manahan et al., https://doi.org/10.1098/rsta.2018.0182





H. C. Fan, et al., "Control of electron beam polarization in the bubble regime of laser-wakefield acceleration," (2022), arXiv:2201.02969 [physics.plasm-ph].

→ ideas on how to produce polarized bunches

M. Wen, et al., Physical Review Letters 122, 214801 (2019). Zan Nie,et al., Phys. Rev. Lett. 126, 054801 (2021).H. C. Fan, et al., (2022), arXiv:2201.02969

M. Fuchs et al., Snowmass Whitepaper AF6: Plasma-Based Particle Sources arXiv:2203.08379 [physics.acc-ph]

Plasma Wakefield Based Particle Sources

Advantages: compactness, potentially all-optical, potentially high brightness (high fields),..

Positrons & Muons

Idea: Provide the primary beam (compactly compared to RF structures) that interacts with the target or the photon beam.

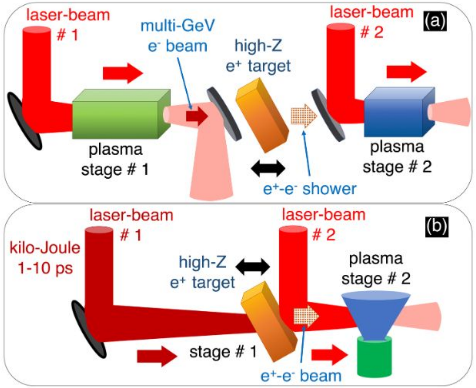
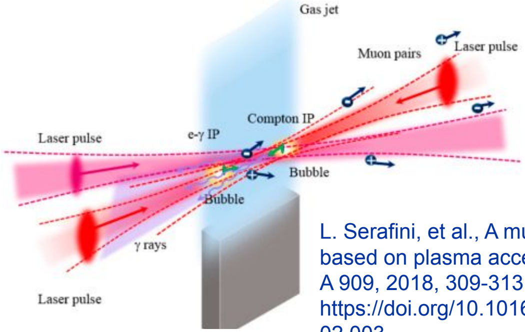


Image from : Aakash A. Sahai, Phys. Rev. Accel. Beams 21, 081301 (2018).

Alejo, A., Walczak, R. & Sarri, G. Laser-driven high-quality positron sources as possible injectors for plasma-based accelerators. *Sci Rep* **9**, 5279 (2019).

For an electron beam similar to that proposed by the EuPRAXIA project (5 GeV, 100 pC), up to 5 × 10^6 positrons are generated in a energy range 1.00 ± 0.05 GeV, with a normalised emittance of 190π mm mrad.

electron–γ collider



L. Serafini, et al., A muon source based on plasma accelerators, NIM A 909, 2018, 309-313, https://doi.org/10.1016/j.nima.2018.02.003.

$$E_{cm} = 2\sqrt{\gamma m_e h\nu}$$

if energy in the center of mass of the system bigger than about 200 MeV

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

⇒ 1–100 muons/s at GeV energy

Applications

- Injectors for any accelerator or collider
- Test beams
  - Detector testing
  - Accelerator R&D

Connected to the source:

S. G. Rykovanov,et al., Phys. Rev. Lett. 114, 145003 (2015).
I. Andriyash, et al., Nature Commun 5, 4736 (2014).
S. Corde and K. Ta Phuoc, “ Physics of Plasmas 18, 033111 (2011)

- Plasma Wiggler for beam cooling:
  - Use transverse wakefields to force particles to radiate → reaccelerate
  - Damping time is inversely proportional to the square of the magnetic field of the damping device
    - → plasma wiggler generate order of magnitude larger effective magnetic fields than conventional wigglers → reduce the length of the damping units by a factor of hundred
    - Either insert in damping ring or in linear configuration (‘Plasma-accelerator-based linear beam cooling system’, C. Schroeder et al.,)

Beam Dumps

One of the two spare LHC's beam dumps is removed from the tunnel for upgrade work in preparation for Run 3 (Image: CERN)

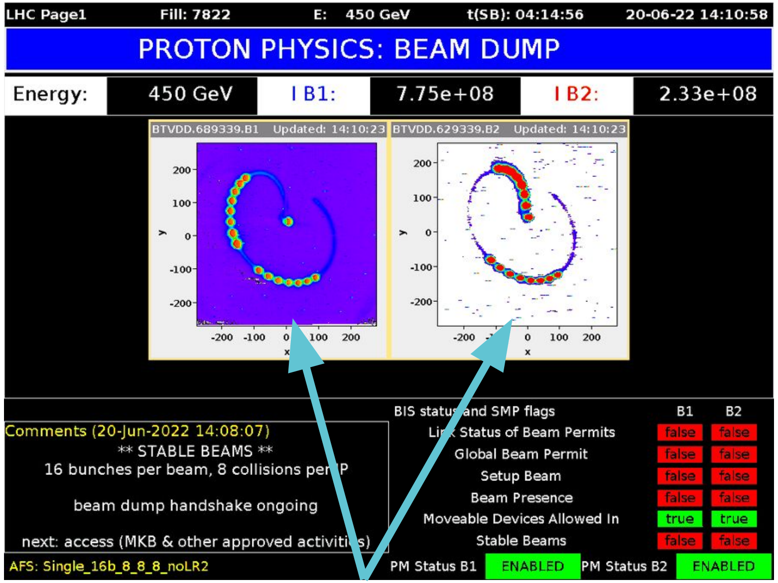
Particle beams for particle physics applications can carry significant amounts of energy that need to be deposited over a short amount of time in case of beam abort.

Must be reliable!

Conventional Particle Beam Dumps: Example LHC

Most common strategy to date:

Use materials (solids, liquids or gases) to stop the particles→ higher density, more compact



Fast magnet is used to separate the location of individual bunches on the beam dump

Beams can carry large amounts of energy:

$E_{total} = N\ N_b\ E_b\ eV_J$ ← Conversion factor: $1.6\ 10^{-19}$

Nr. of bunches   Particles / bunch   Particle Energy

E.g. for the LHC beam ~ 100 MJ.

(Equivalent to a TGV at full speed)

⇒ **Challenge:** thermal stress, fast cooling, production of radioactive isotopes by spallation from bremsstrahlung photons, reliability..

Plasma-Based Beam Dumps

Idea:
Beam deposits energy in plasma by driving wakefields; or use strong transverse forces to disperse.

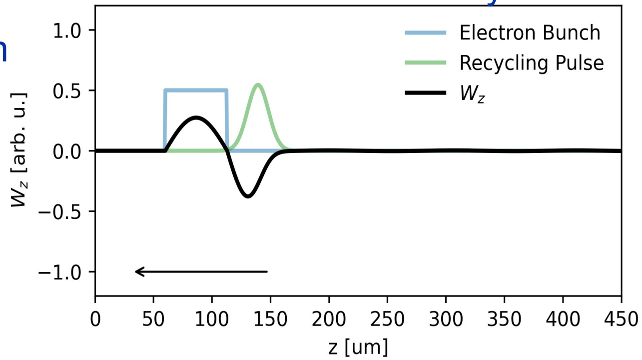
Advantages:

- High decelerating gradients with low density dump medium
- Possibility for energy recovery?

Challenge:

- Plasma has a low heat capacity
- Beam head does not deposit energy
- Reliability - active system
- Effectiveness depends on bunch parameters
  - bunch trains?

ER- Linear theory



C. B. Schroeder, et al., Efficiency considerations for high-energy physics applications of laser-plasma accelerators, AIP Conference Proceedings 1777, 020001 (2016); https://doi.org/10.1063/1.4965590

Recent work on low-energy plasma based beam dumps:

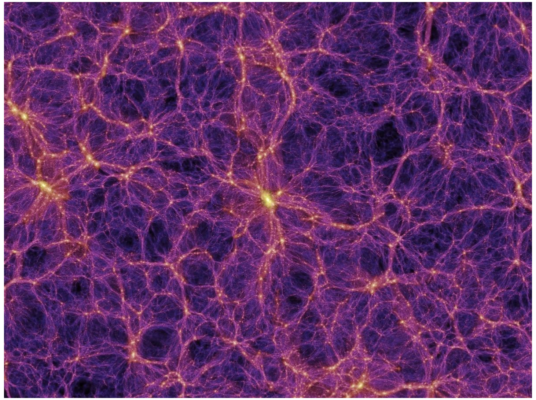
- Bonatto, A.; Nunes, R.P.; Nunes, B.S.; Kumar, S.; Liang, L.; Xia, G. An Active Plasma Beam Dump for EuPRAXIA Beams. *Instruments* **2021**, *5*, 24. https://doi.org/10.3390/instruments5030024
- Xia, G.; Bonatto, A.; Pizzato Nunes, R.; Liang, L.; Jakobsson, O.; Zhao, Y.; Williamson, B.; Davut, C.; Wang, X. Plasma Beam Dumps for the EuPRAXIA Facility. *Instruments* **2020**, *4*, 10. https://doi.org/10.3390/instruments4020010

Enough About Colliders and their Subsystems

Let's Move on to Experiments that may be realised within the Next Decade…

2

Dark Matter Experiment

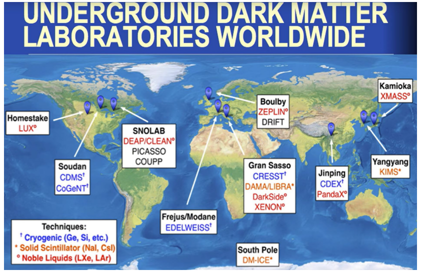


- Dark matter 5x more common than matter. No one has directly observed dark matter yet → must barely interact with ordinary matter and radiation except through gravity.
- The primary candidate for dark matter is some new kind of elementary particle that has not yet been discovered.
- Dark matter makes up most of the mass of galaxies.
  Dark energy, meanwhile, is the name we give the mysterious influence driving the accelerated expansion of the universe.

https://home.cern/news/news/knowledge-sharing/countdown-dark-matter-day

Dark Matter Detection

- Direct detection of dark matter faces several practical challenges. The theoretical bounds for the supposed mass of dark matter are immense, spanning from 10^{-21} eV to about that of a Solar Mass (~10^{57} eV).



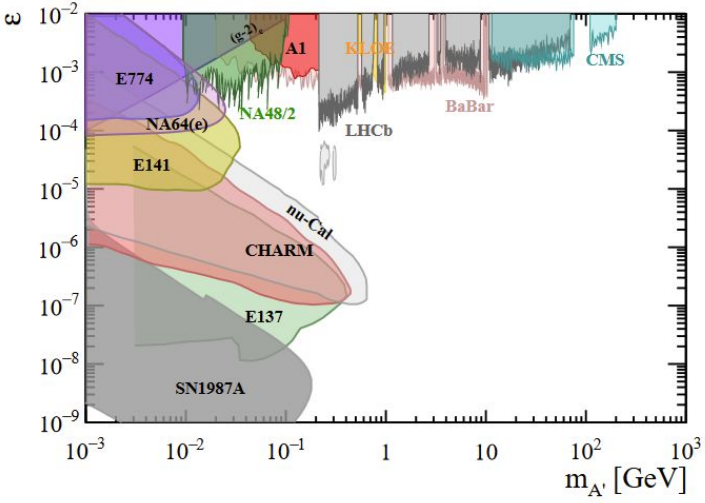
- Several strategies:
  - Direct detection: dark matter particle hits detector $\longrightarrow$ photon signal
    - Placed deep underground, challenging background subtraction and signal detection.
  - Collision of two dark matter particles may result in something we can detect e.g. gamma rays.
  - Production of dark matter particles at accelerators:
    - Covering the range of ~MeV to ~TeV

Dark Matter Detection

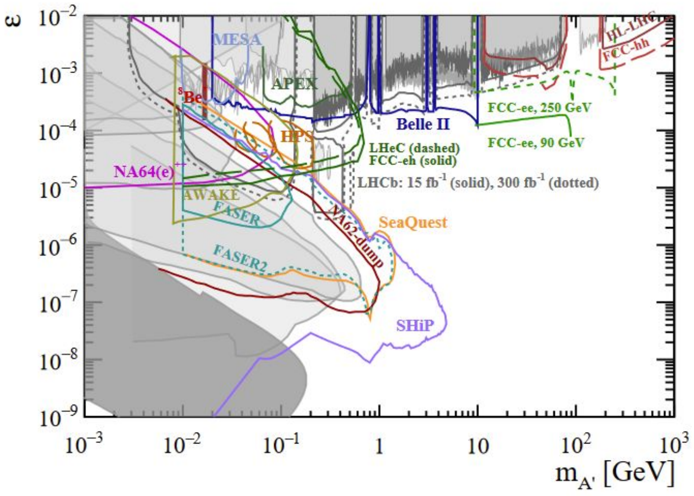
- Horizontal axis: mass of the dark matter particle (mA')
- Coupling / interaction strength with SM particles (ε)

Exclusion plots

Current State



Planned/Proposed Experiments



Dark Matter Detection: Detection of Visible Final States

- **Goal:** detect dark matter particle decay into visible final states (colliders+fixed target exp.)
    - E.g.: $e^+e^- \rightarrow \gamma A'$, $e^-Z \rightarrow e^-ZA'$, etc. and then $A' \rightarrow e^+e^-$, $A' \rightarrow \mu^+\mu^-$, etc…
    - Relevant for dark photons with masses above ~1 MeV (can decay to visible final states)
    - Experiments search for resonances over a smooth background

- Challenges:
    - Requires high luminosity or large fluxes
        - Dark photon detection rate is proportional to ε^4 (very suppressed for very feeble couplings)
            - Collider experiments are typically only sensitive to larger values of ε ($\varepsilon > 10^{-3}$)
            - Beam dump experiments which typically cover couplings ($\sim 10^{-7} < \varepsilon < \sim 10^{-3}$)

    - The smallness of the couplings implies that the dark photons are also very long-lived (up to 0.1 sec).
        - Long decay volumes followed by spectrometers with excellent tracking systems and particle identification capabilities.

Dark Matter Detection: Missing Momentum Technique

- **Goal:** measuring missing momentum or energy carried away from the escaping invisible particle(s).
  - For fixed target reactions
  - E.g. , $e^{-}Z \rightarrow e^{-}ZA'$, $\rightarrow A' \rightarrow \chi\chi$
    - (e: electron, Z: nuclei atomic number, χ: dark matter particle)

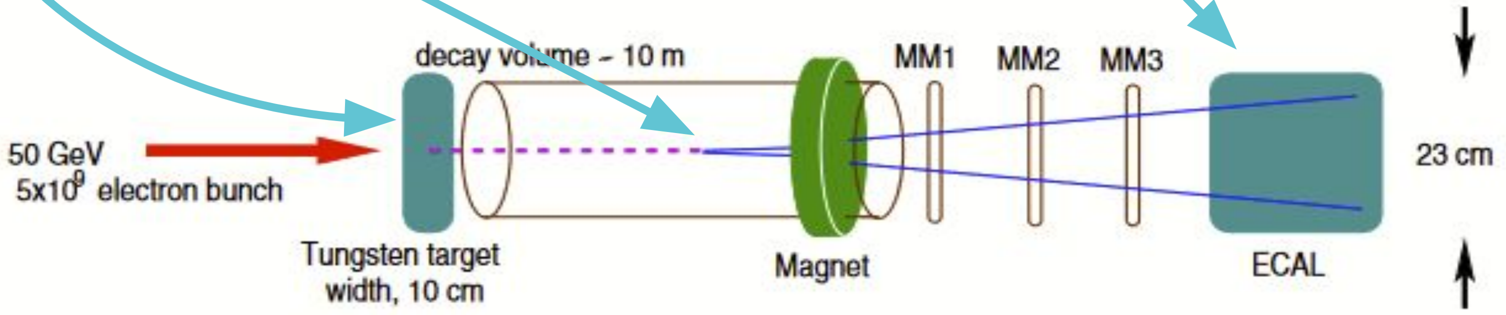
- Challenges:
    - exact knowledge of the initial and final state kinematics
      - Low particle rates preferred
    - very high background rejection, relying on the detector being hermetically closed
- Advantage:
  - Independent of the probability of decays and therefore only scales with ε^2.
    - provides better sensitivity for the same luminosity (compared to the detection of visible final states).

- Similar for Colliders: Missing Mass Technique ($e^{+}e^{-} \rightarrow A'\gamma$)

Plasma Wakefield Based Beam-Dump Experiment

- These experiments use the collisions of an electron beam with a fixed-target or a dump to generate the dark photon via Bremsstrahlung (electron and proton beams) or meson production.

- The products of the collisions are mostly absorbed in the dump and the dark photon is searched for as a displaced vertex with two opposite charged tracks in the decay volume of the experiment.

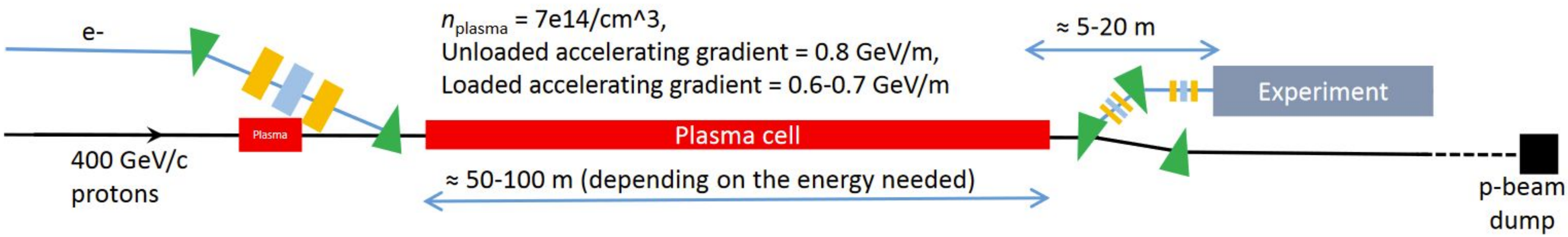


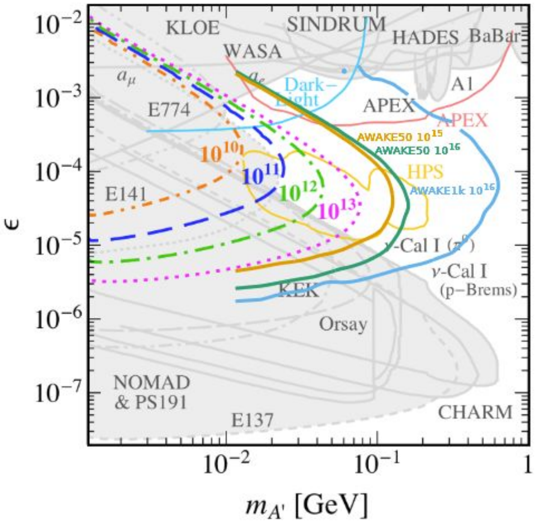
$e^- Z \rightarrow e^- Z A'$

$A' \rightarrow e^+e^-$, etc..

From Caldwell: https://arxiv.org/pdf/1812.11164.pdf

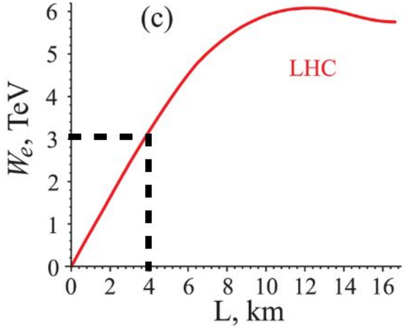
Plasma Based Experimental Based on the AWAKE Concept





- Assuming a bunch of 5×10^9 electrons and a running period of 3 months gives 10^{16} electrons on target to visualise the effect of the number of electrons on target (green curve).

- Expectation for 10^{15} electrons @50 GeV
- Expectation for 10^{16} electrons @50 GeV
- Expectation for 10^{16} electrons @1000 GeV

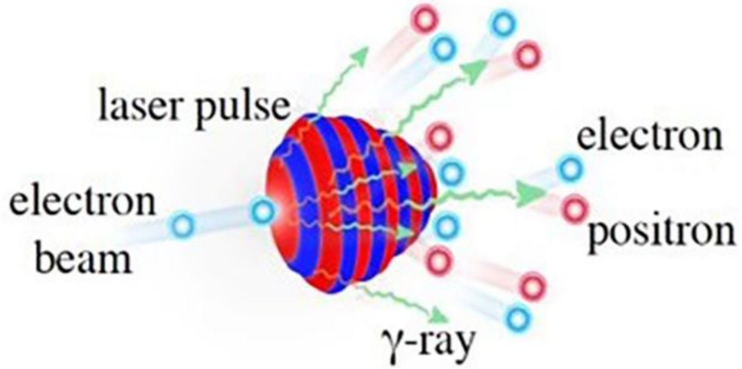


A. Caldwell & K. Lotov, Phys. Plasmas **18** (2011) 103101

Quantum electrodynamics (QED) is the relativistic quantum field theory of electrodynamics. It describes how light and matter interact.

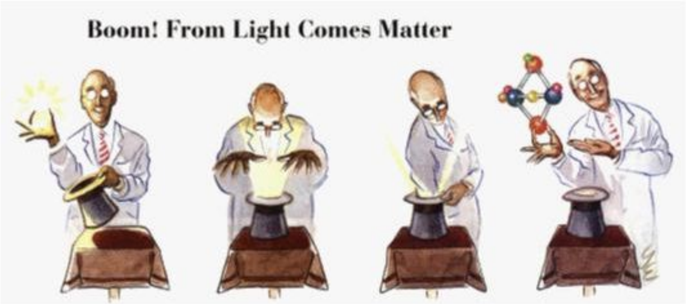
3

A Strong-Field Quantum-Electro-Dynamics Experiment

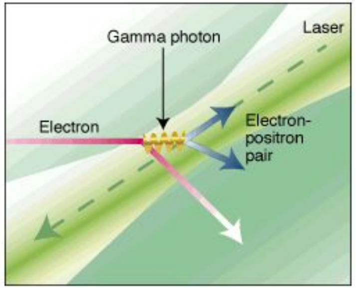


The dominant effects in SF-QED are the:

- Compton effect
  (photon emission by an electron)
- Breit-Wheeler effect
  (photon decay into an electron-positron pair)



3



A Strong-Field Quantum-Electro-Dynamics Experiment

An EM field is considered strong when it is of the order of the QED critical field:

$E_{crit} = 1.32 \times 10^{18}$ V/m or
$B_{crit} = 4.41 \times 10^{9}$ T

⇒ QED becomes non-linear

J. Schwinger, “On gauge invariance and vacuum polarization,” Physical Review, vol. 82, pp. 664–679, 6 1951.
F. Sauter, “¨Uber das Verhalten eines Elektrons im homogenen elektrischen Feld nach der relativistischen Theorie Diracs,” Zeitschrift f¨ur Physik, vol. 69, no. 11-12, pp. 742–764, 1931
W. Heisenberg and H. Euler, “Folgerungen aus der Diracschen Theorie des Positrons,”Zeitschrift f¨ur Physik, vol. 98, pp. 714–732, 1936.

Reaching the SF-QED Regime

Strong EM fields can be found in different environments:

- including in close proximity of compact astrophysical objects
  - (such as magnetars and black holes)
- high-Z nuclei
- dense particle beams
  (at the interaction point of high energy particle accelerators)
- and in the foci of high power lasers

⇒ Fields below E_{crit} can exceed E_{crit} in the reference frame of a sufficiently high energy particle.

Relativistic gamma of the particle

Nonlinear quantum parameter: chi

$$\chi = \gamma E / E_{cr} \sim> 1$$

At the current state-of-the-art, laboratory SF-QED experiments will require an interaction between energetic particles and EM fields.

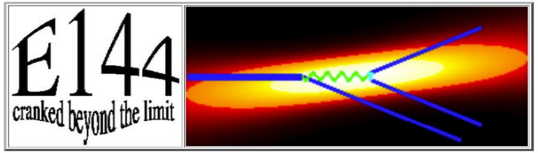
Verify SF-QED Theory and ɣ,e^+ Sources

- Classical and quantum electrodynamics have been **extensively and successfully** verified for almost all parameter ranges. Open questions remain for interactions in **strong** EM fields:
  - e.g. classical electrodynamics allows for the emission of photons with energy greater than the particle energy
    - addressed by switching to the quantum description
  - Need experiments to develop a complete experimental framework
    - previous experiments either operated in a parameter space where the nonlinear quantum parameter **χ was clearly below 1** or provided a limited set of data.

- Evaluate whether strong-field interactions may provide competitive ɣ-ray or low-divergence positron sources.

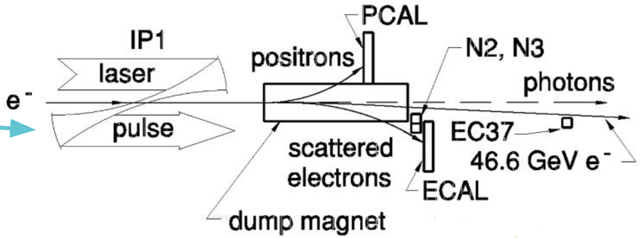
Previous SF-QED Experiments

χ~0.3



- E144 Experiment at SLAC (https://www.slac.stanford.edu/exp/e144/e144.html)

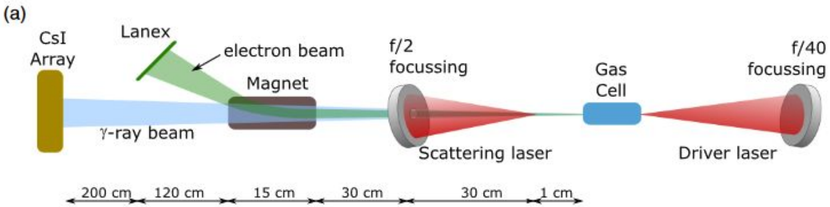
TW pulses



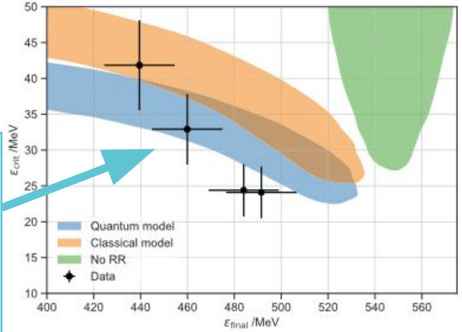
Key findings:

- Positron Production
  106 14 signal positrons, 22,000 laser pulses.
  (Phys. Rev. Lett., Vol. 79, p. 1626 (1997))
- Observation of Nonlinear Effects in Compton Scattering
  (Phys. Rev. Lett., Vol. 76, p. 3116 (1996))

- Based on LPA: Gemini Experiments at CLF (χ~0.2)



Experiments highlight discrepancies with theory.



M. Cole, et al., PRX, vol. 8, p. 01102 2018
K. Poder, et al., PRX, vol. 8, p. 31004, 3 2018

Planned Experiments (□>1)

- E320 experiment at SLAC
- LUXE experiment at DESY (conventionally accelerated 10 or 17.5 GeV electron beams in collision with tens of TW laser pulses
- The University of Michigan ZEUS facility will use two laser pulses (2.5 PW and 0.5 PW, one to accelerate electrons in a laser wakefield accelerator (LWFA) (to either ~ >10 GeV, or several GeV) and one to provide the EM field (with intensity 10^{21} W/cm^2, or 10^{23} W/cm^2)

- Other laser facilities with active SF-QED study programs include:
  - J-Karen in Japan
  - Apollon in France
  - CORELS in Korea
  - BELLA in Berkeley
  - CALA in Germany
  - ELI NP in Romania
  - ELI BL in Czech Republic
  - SEL in China
  - …

Studies ideal for LPAs.

Challenge:
- Reproducibility (conditions at focus)
- Detection of small signals (background subtraction)
- Challenging geometries

6

A Deep Inelastic Scattering Experiment

Deep inelastic scattering is the name given to a process used to probe the **insides** of hadrons, using electrons, muons and neutrinos.

A Deep Inelastic Scattering Experiment

"deep" refers to the high energy of the lepton, which gives it a very short wavelength and hence the ability to probe distances that are small compared with the size of the target hadron

"inelastic" means that the target absorbs some kinetic energy.

"scattering" refers to the lepton's deflection. Measuring the angles of deflection gives information about the nature of the process

History of Deep Inelastic Scattering Experiments

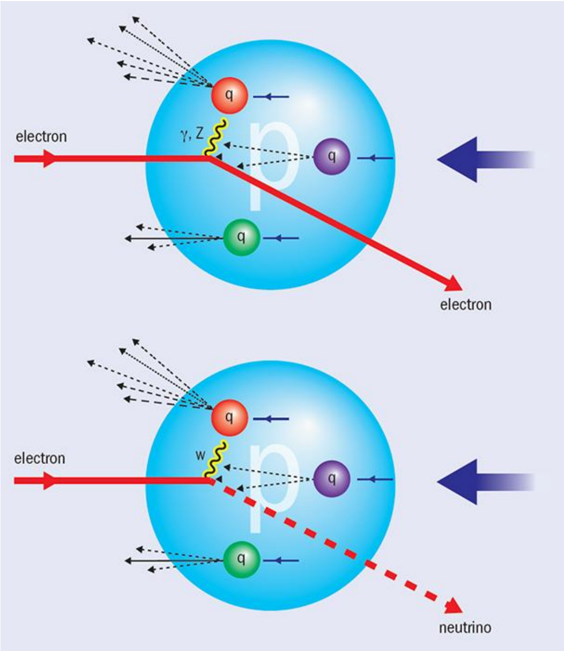
- Rutherford experiments were based on **elastic scattering**
  - fired alpha particles at atoms of gold proving that atoms have internal structure
    - small, massive, charged nucleus at their centre and a lot of empty space
  - Provided the first ides for detecting quarks
    - → use a small, penetrating particle, e.g. electrons

- In 1968, at the Stanford Linear Accelerator Center (SLAC), electrons were fired at protons and neutrons in atomic nuclei.
  - Analysis of the results led to the conclusion that hadrons do indeed have internal structure.

- HERA e ± p Collider : 1991-2007 (27.5 GeV electrons with 920 GeV protons)
- New: EIC (5-18 GeV electrons with 14-275 GeV protons), high luminosity, controlled polarization!

https://www.bnl.gov/eic/science.php, https://www.desy.de/forschung/anlagen__projekte/hera/index_ger.html

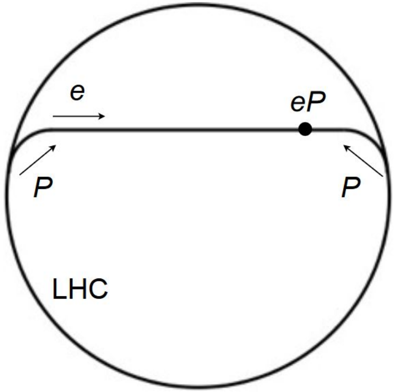
Plasma-Based Deep Inelastic Scattering Experiment: VHEeP



Diagrams of neutral-current (top) and charged-current (bottom) deep-inelastic electron–proton scattering processes.Image credit: DESY.

- Collide:
  - 50 GeV electrons with 7 TeV LHC protons
  - ~TeV electrons with 7 TeV LHC protons

Plasma-based collider design



Caldwell, A., Wing, M. VHEeP: a very high energy electron–proton collider. *Eur. Phys. J. C* **76**, 463 (2016). https://doi.org/10.1140/epjc/s10052-016-4316-1

Physics cases:

- Study of the sub-structure and spin structure of the proton and photon
- Determine if partons are fundamental point-like objects
- Clarifying the underlying physics leading to the energy dependence of cross sections
- Leptoquark production: hypothetical particles that would interact with quarks and leptons

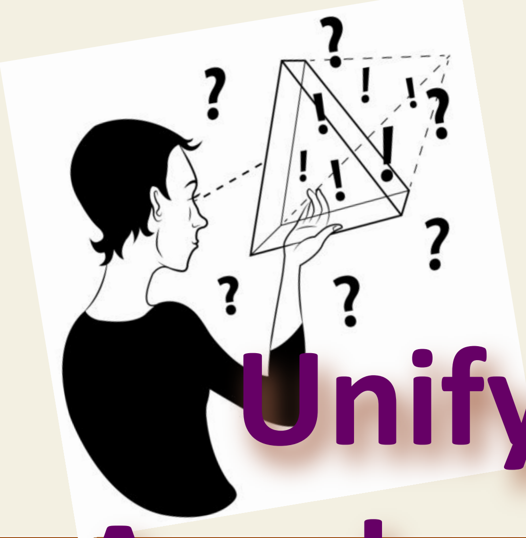
Summary & Conclusions

Summary and Conclusions

- Particle physics has **major open** questions
  - No clear or path/strategy to answering them
  - Hints may come from anywhere

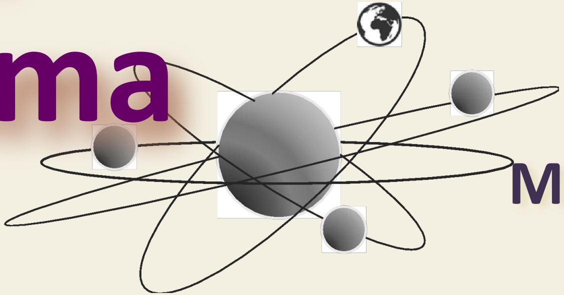
- Biggest (long-term) challenge for **plasma-based** concepts: 10+ TeV e^+e^- collider
  - Or provide one of the subsystems:
    - Beam dump, particle source
    - Energy booster/afterburner
    - Injector, Cooling
    - Test beams for detector and accelerator R&D

- Plasma wakefield acceleration may benefit particle physics in the **next decade**:
  - Dark Matter Experiment
  - Strong Field QED experiment
  - Deep inelastic scattering experiment



Unifying Physics of Accelerators, Lasers and Plasma

LHC sketches by Sergio Cittolin (CERN)



Andrei Seryi
Jefferson Lab
Marlene Turner
CERN

USPAS June 12-16 2023

References

- F. Close,
  - Book ‘A very short introduction to particle physics’ and his CERN summer student lectures: http://videolectures.net/cernstudentsummerschool09_close_ipp/
- A. Caldwell
  - arXiv:1812.11164
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