Title: Collider Experiment

Speakers: Manuella Vincter

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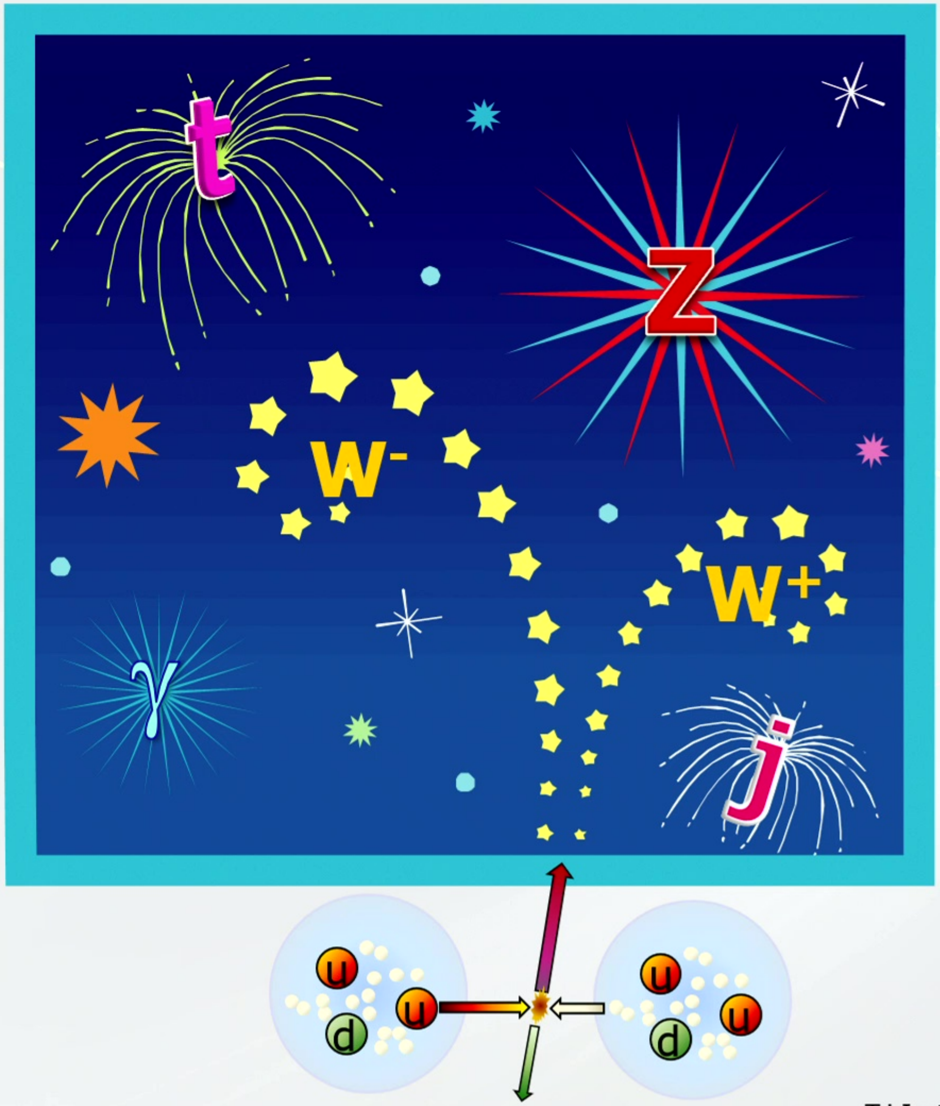


ATLAS EXPERIMENT

Collider physics at the LHC … mostly

(and some other stuff)

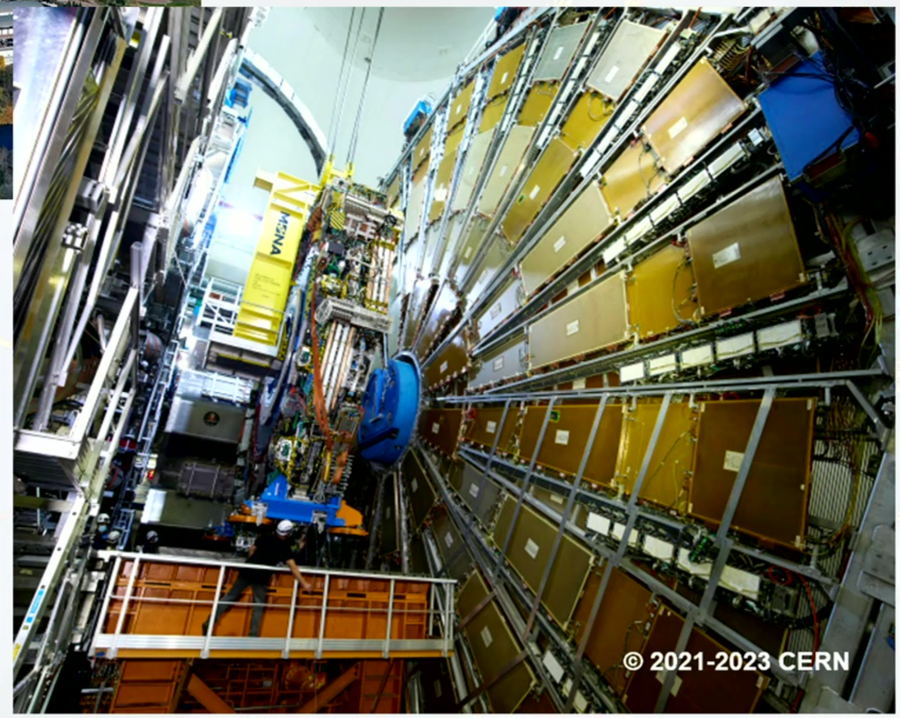
Manuella G. Vincter (Carleton University)

Tri-Institute Summer School on Elementary Particles (TRISEP) / June 2023

Carleton
UNIVERSITY

Manuella Vincter

- Professor at Carleton University in Ottawa, Canada
- Experimental Particle Physicist
- Deputy Spokesperson of the ATLAS Collaboration at the CERN Laboratory in Switzerland



ATLAS
EXPERIMENT

CERN

This is what motivates me!

3

The Universe is beautiful!

Neurons derived from human embryonic stem cells, around 10 micrometres
Russo E. (2005) Follow the Money—The Politics of Embryonic Stem Cell Research. PLoS Biol 3(7): e234. doi:10.1371/journal.pbio.0030234

Horsehead nebula 1,500 light years away
By Pablo Carlos Budassi - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=94313357

and the distance scales characterising the Universe are mind boggling...

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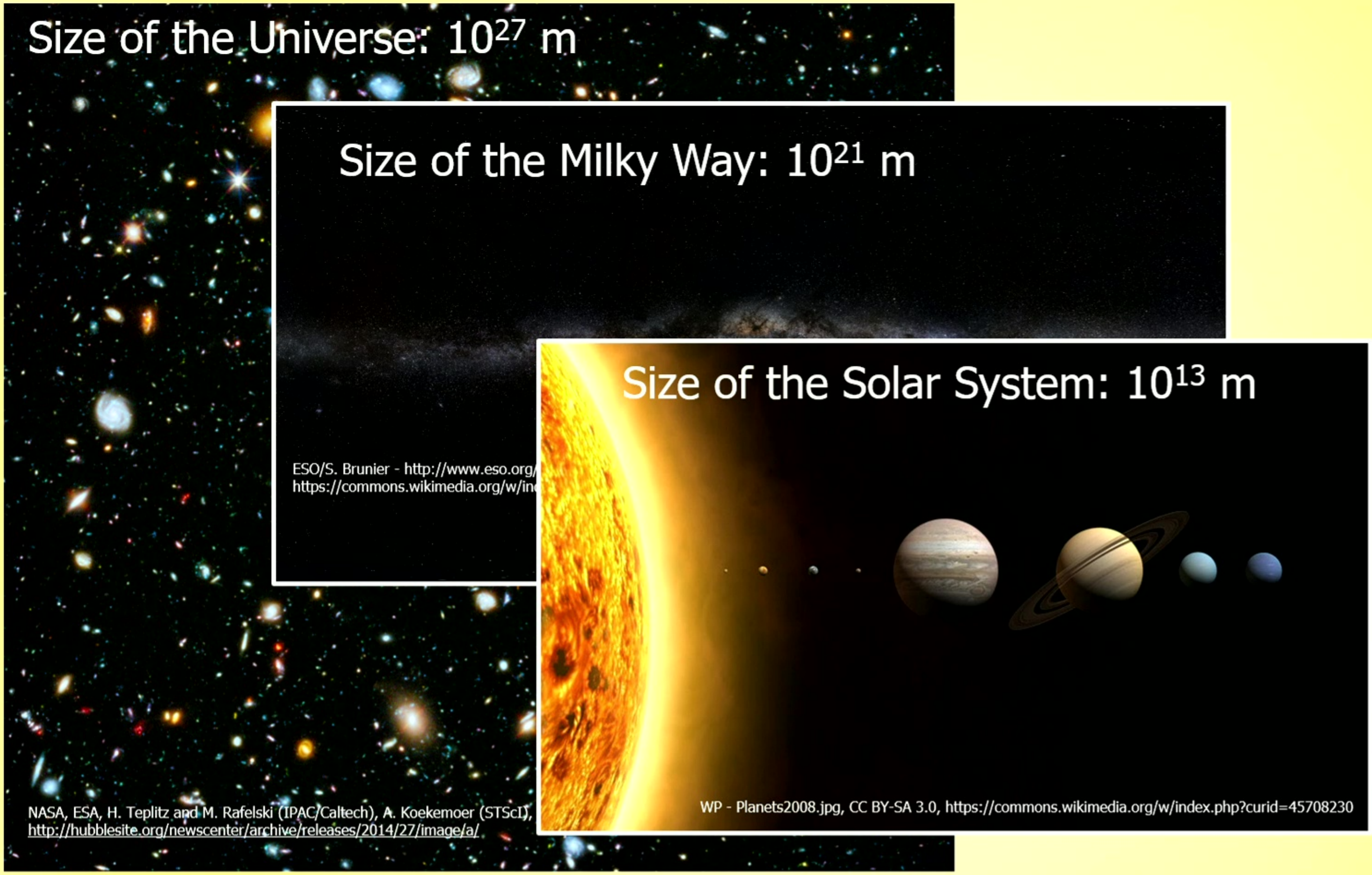
Size of the Universe: 10^27 m
Size of the Milky Way: 10^21 m
Size of the Solar System: 10^13 m
ESO/S. Brunier - http://www.eso.org/
https://commons.wikimedia.org/w/in
NASA, ESA, H. Teplitz and M. Rafelski (IPAC/Caltech), A. Koekemoer (STScI),
http://hubblesite.org/newscenter/archive/releases/2014/27/image/a/
WP - Planets2008.jpg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=45708230


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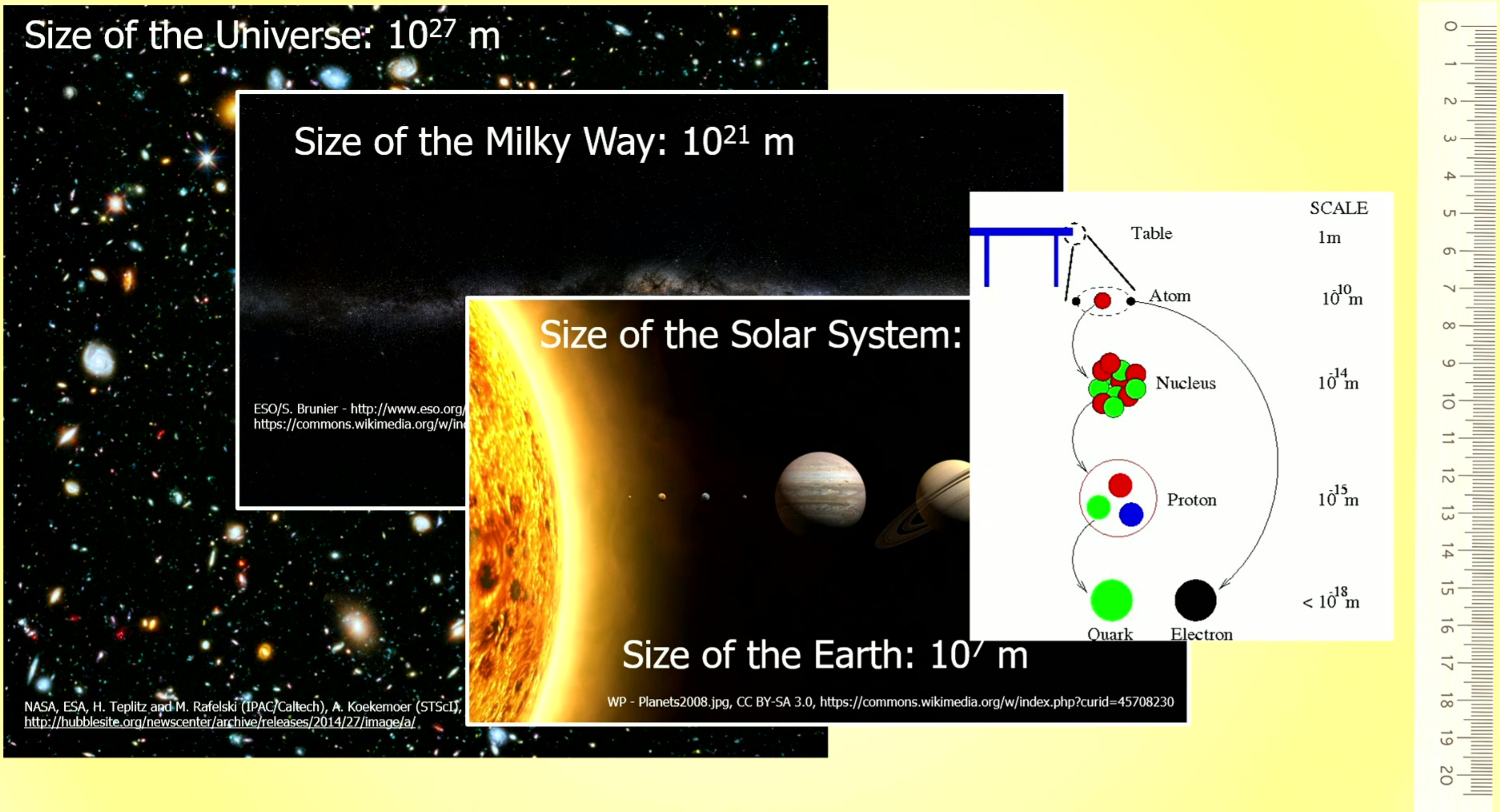
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http://hubblesite.org/newscenter/archive/releases/2014/27/image/a/
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https://commons.wikimedia.org/w/in
Size of the Solar System:
Size of the Earth: 10^7 m
WP - Planets2008.jpg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=45708230
SCALE
Table
1m
Atom
10^{-10} m
Nucleus
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Proton
10^{-15} m
Quark
Electron
$< 10^{-18}$ m

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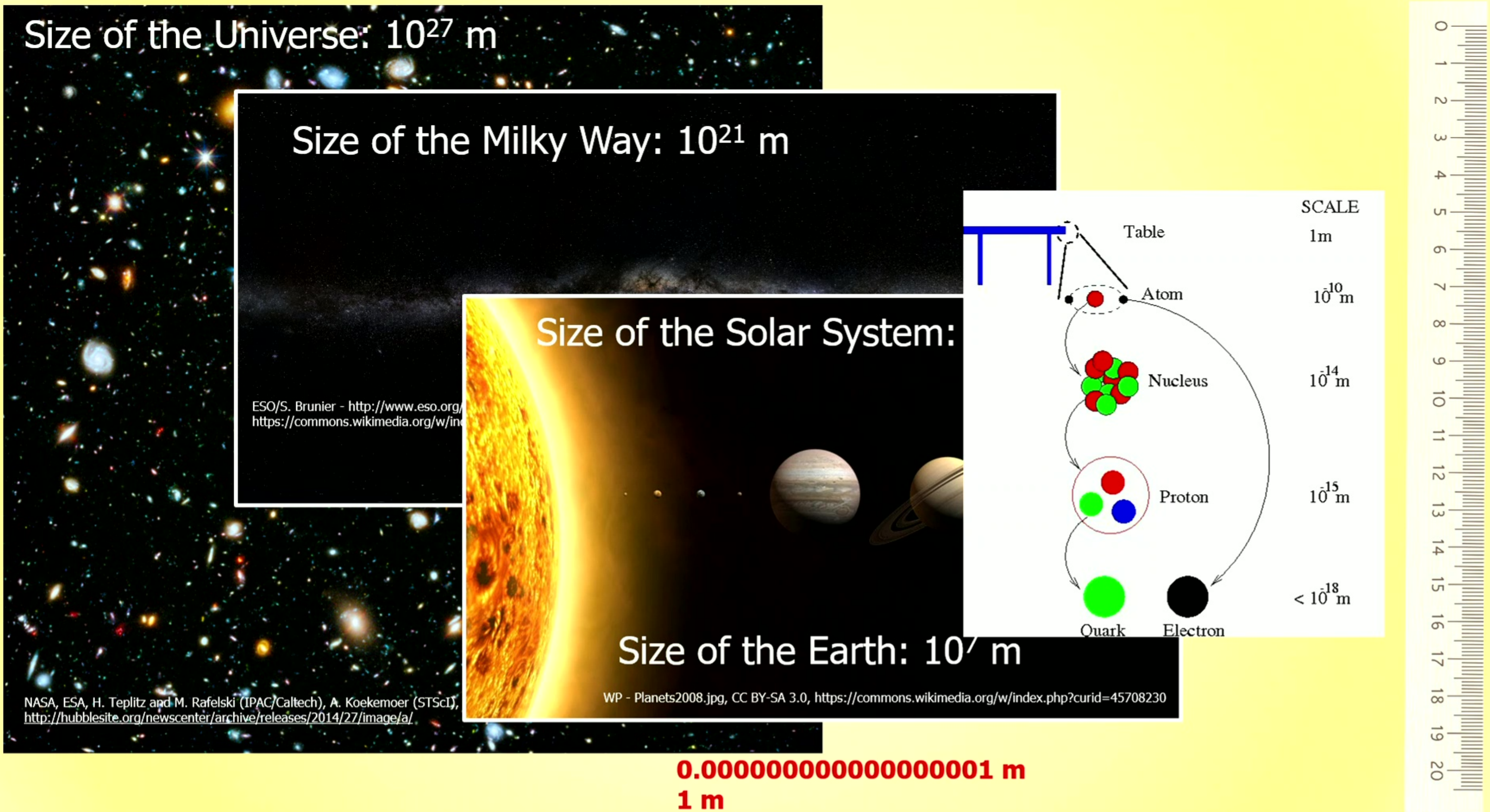

0.000000000000000001 m
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1000000000000000000000000000 m

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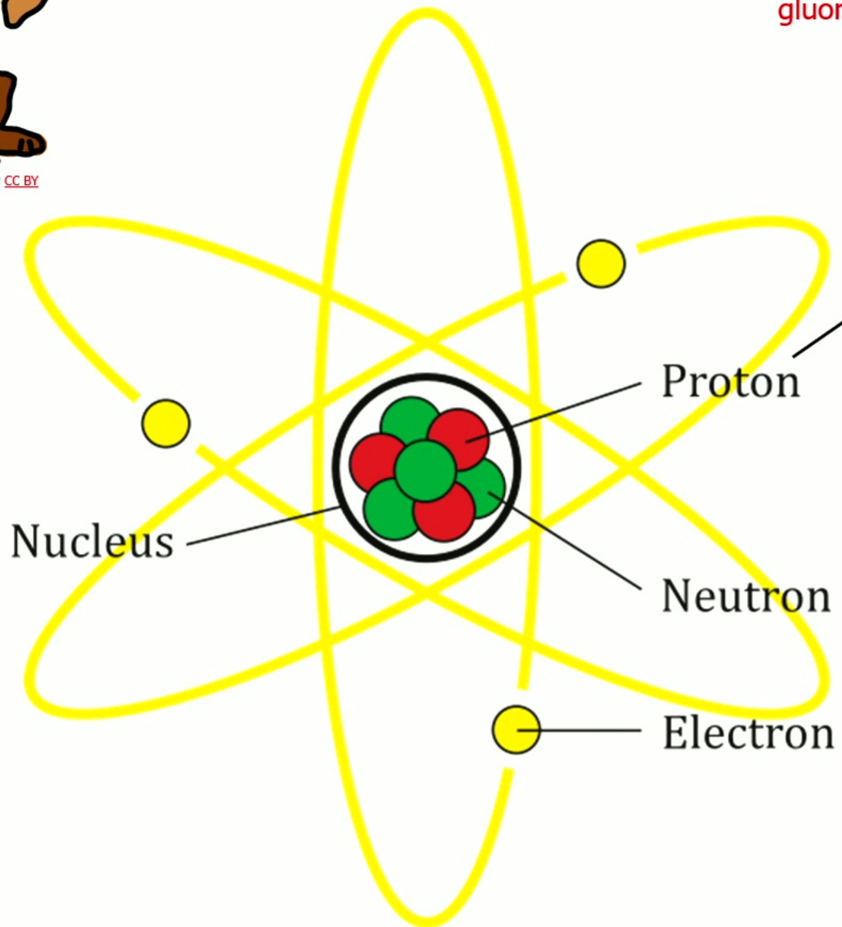
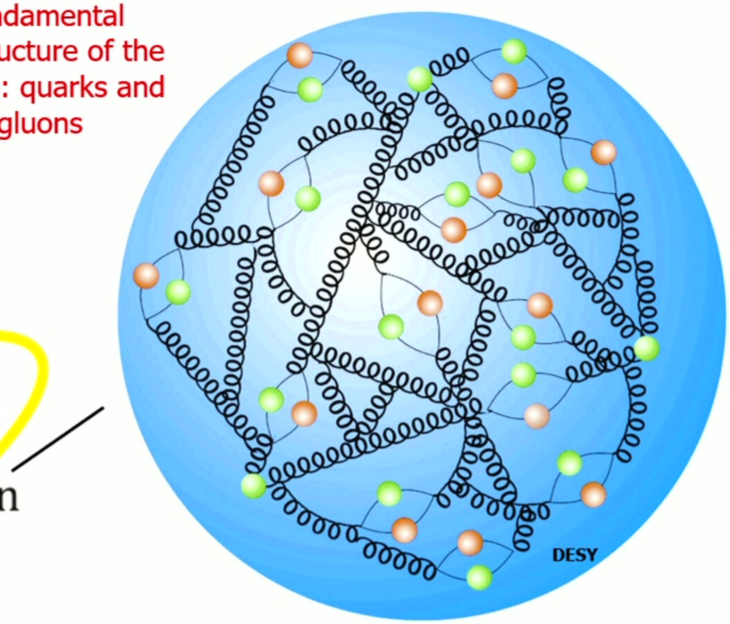


Fundamental substructure of the proton: quarks and gluons



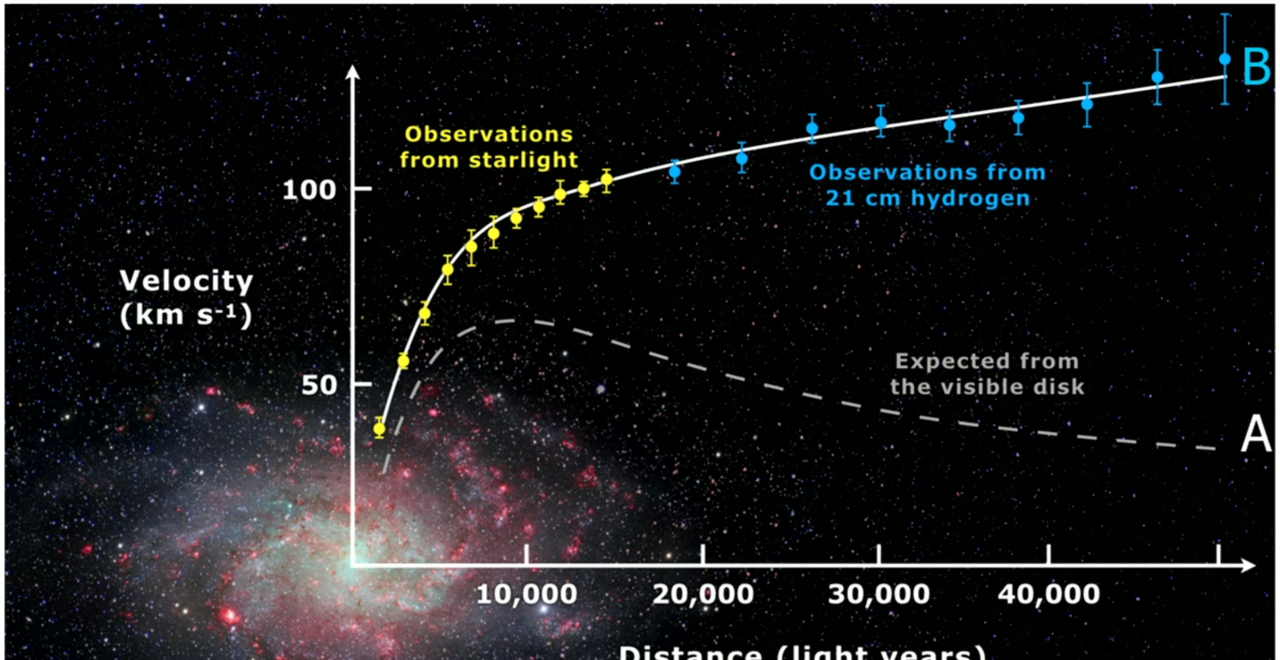
All of the Universe is made up of atoms (protons, neutrons, electrons)...

AG Caesar https://bar.wikipedia.org/wiki/Datei:Atom_Diagram.svg

Where is all the matter in the universe?

- Louise Volders (1959) measured that galaxy M33 did not spin according to expected laws of motion
- Orbital velocity of stars&gas (observed matter) in galaxy vs. distance from centre
  - Newtonian mechanics: decreases with distance (see A)
  - Observation: increasing! (see B)

- Galaxies are rotating at such speeds that the gravity generated by the observed matter cannot possibly hold them together:
  - Galaxies should have ripped apart a long time ago!
- Possible explanation:
  - missing matter in the galaxy



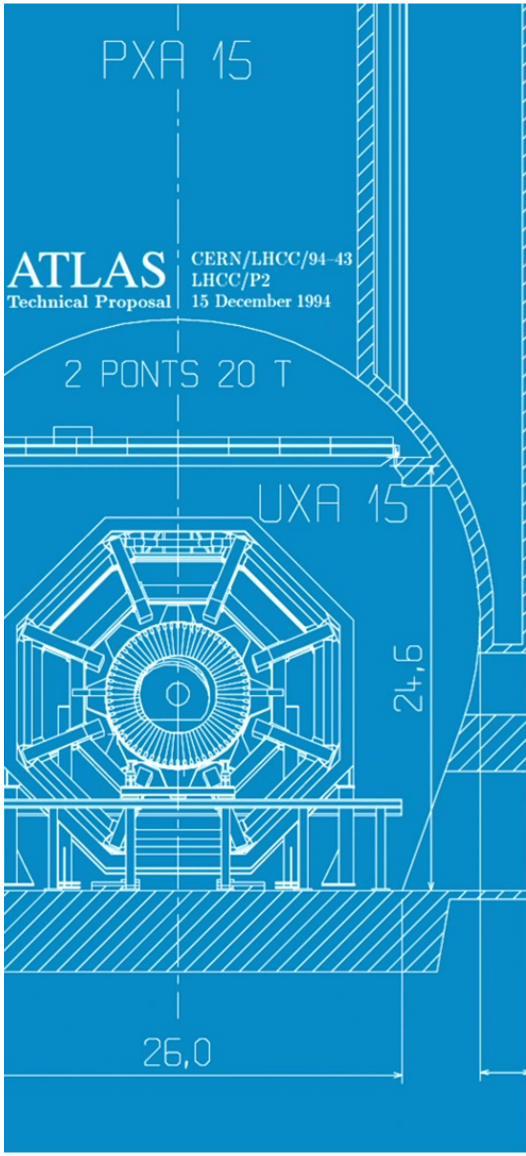
What is dark matter?

Can I find it in the universe?

If not, can I make it in a lab?

The Standard Model is beautiful, but not the last word!

- As we will see, agreement of measurements with the SM is amazing!
  - What is does predict, it does so very well indeed!
- SM leaves some questions completely unanswered e.g. Dark Matter
- **I know that there is something out there beyond the SM!** How will we see it?


PXA 15
ATLAS
Technical Proposal
CERN/LHCC/94-43
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15 December 1994
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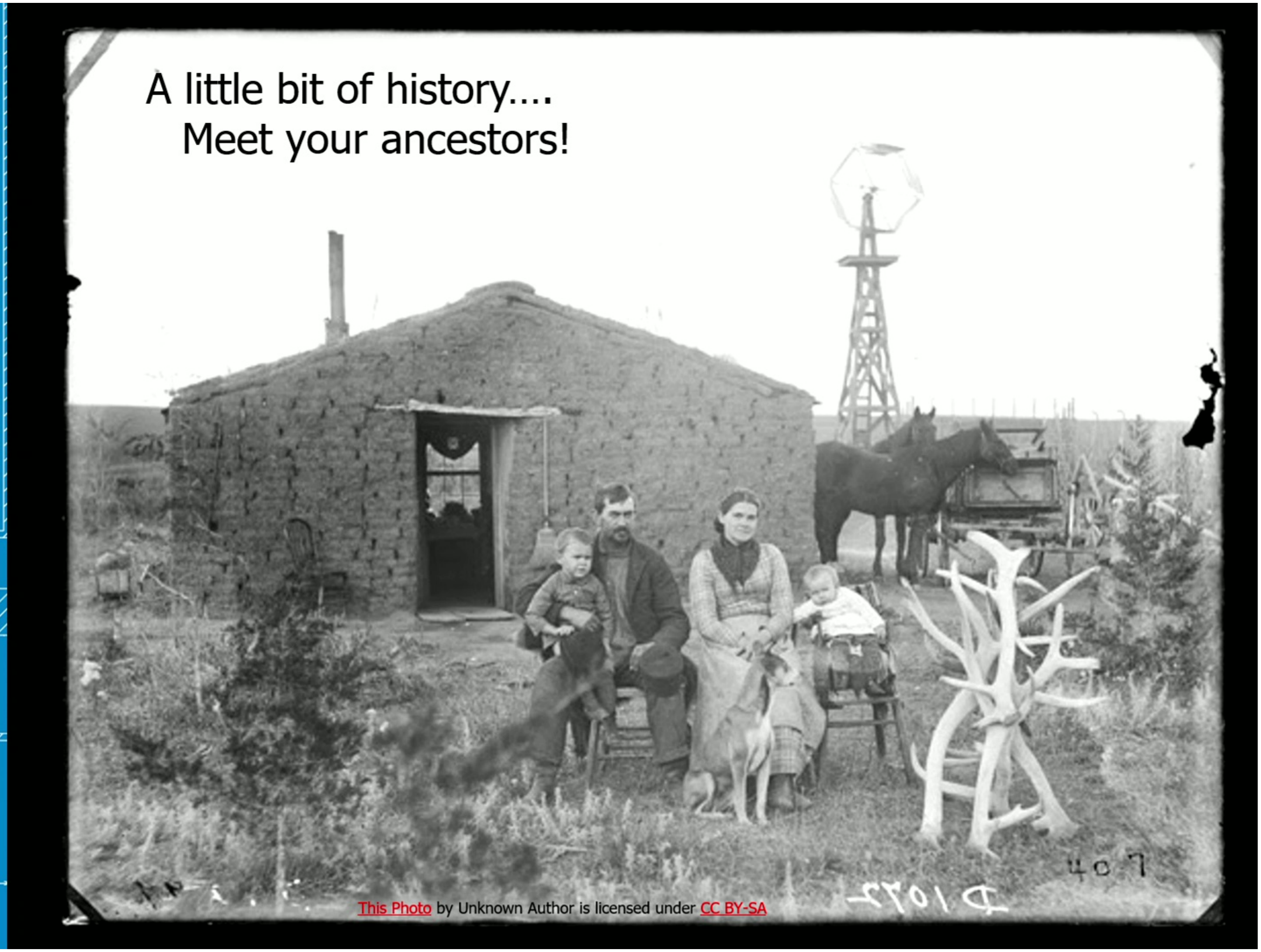
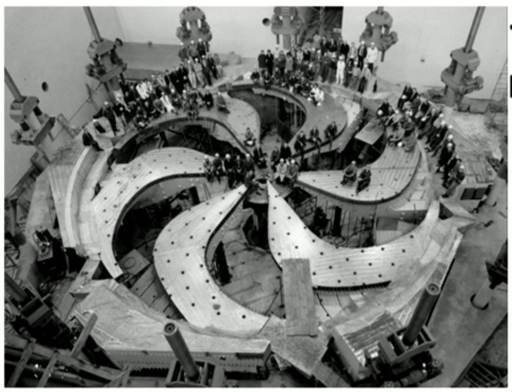

A little bit of history….
Meet your ancestors!
This Photo by Unknown Author is licensed under CC BY-SA

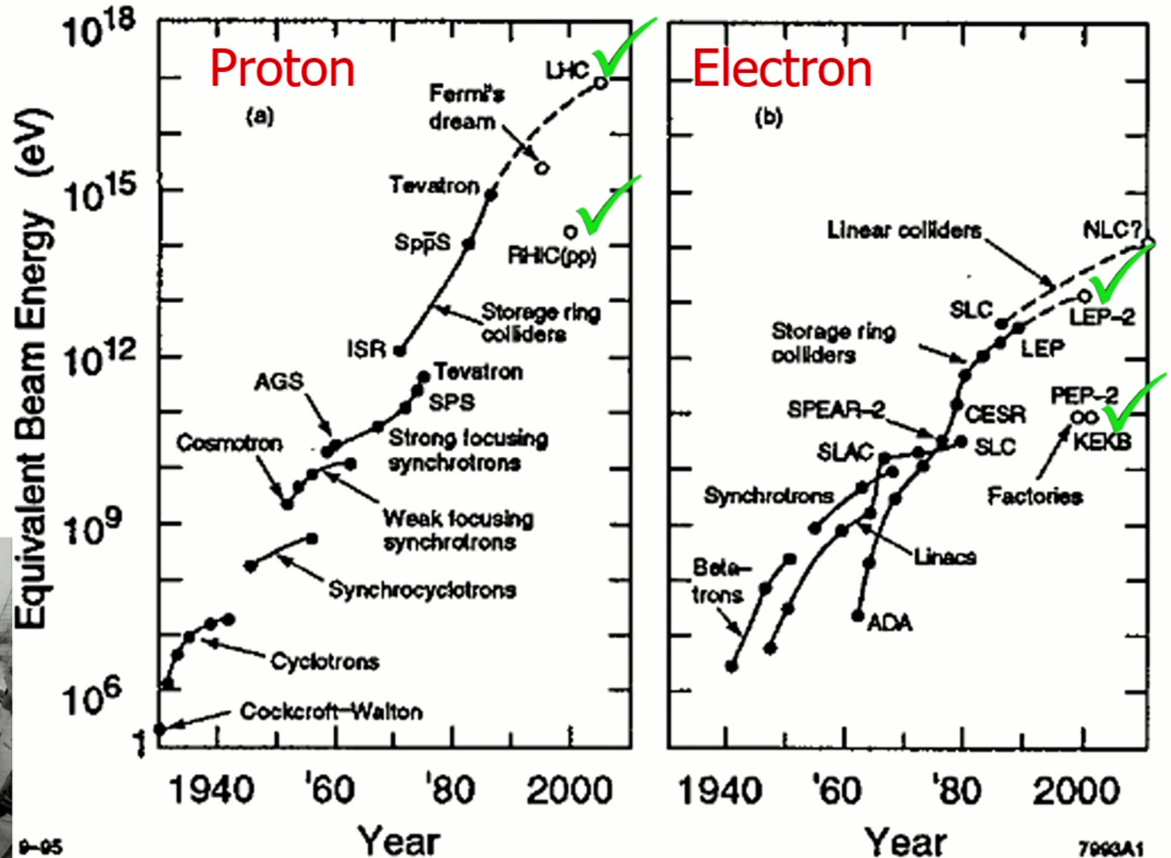
A wee history on accelerators

- Energy increase was exponential for many decades!

A Cockcroft-Walton generator in the National Science Museum in London, England, built in 1937

TRIUMF cyclotron magnet 1972





Equivalent energy of particles (assuming beam is hitting stationary proton targets) vs time when accelerator was built. Open circle: not yet in existence in 1995. SLAC-PUB-95-6947

- Many exciting discoveries as we probed the structure of matter and its interactions with the fundamental forces…

	KEKB (KEK)	PEP-II (SLAC)
Physics start date	1999	1999
Physics end date	2010	2008
Maximum beam energy (GeV)	e^-: 8.33 (8.0 nominal) e^+: 3.64 (3.5 nominal)	e^-: 7–12 (9.0 nominal) e^+: 2.5–4 (3.1 nominal) (nominal Ecm = 10.5 GeV)
Luminosity (10^{30} cm^{-2}s^{-1})	21083	12069 (design: 3000)
Time between collisions (μs)	0.00590 or 0.00786	0.0042
Full crossing angle (μ rad)	$\pm 11000^{\dagger}$	0
Energy spread (units 10^{-3})	0.7	e^-/e^+: 0.61/0.77
Bunch length (cm)	0.65	e^-/e^+: 1.1/1.0
Beam radius (μm)	H: 124 (e^-), 117 (e^+) V: 0.94	H: 157 V: 4.7

	LEP (CERN)
Physics start date	1989
Physics end date	2000
Maximum beam energy (GeV)	101 in 1999 (105=max. foreseen
Luminosity (10^{30} cm^{-2}s^{-1})	24 at Z^0 100 at > 90 GeV
Time between collisions (μs)	22
Crossing angle (μ rad)	0
Energy spread (units 10^{-3})	0.7→1.5
Bunch length (cm)	1.0

Canadian involvement at many of these facilities

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)				LHC† (CERN)	
Physics start date	1992	1987	2001	2000	2004	2002	2009	2010
Physics end date	2007	2011	—				—	
Particles collided	ep	$p\bar{p}$	pp (pol.)	Au Au	Cu Cu	d Au	pp	Pb Pb
Maximum beam energy (TeV)	e: 0.030 p: 0.92	0.980	0.25 34% pol	0.1 TeV/n	0.1 TeV/n	0.1 TeV/n	7.0 (3.5)	2.76 TeV/n (1.38 TeV/n)
Luminosity (10^{30} cm^{-2}s^{-1})	75	402	85 (pk) 55 (ave)	0.0040 (pk) 0.0020 (ave)	0.020 (pk) 0.0008 (ave)	0.27 (pk) 0.14 (ave)	1.0×10^4 (170)	1.0×10^{-3} (1.3×10^{-5})
Time between collisions (ns)	96	396	107	107	321	107	24.95 (49.90)	99.8 (1347)
Full crossing angle (μ rad)	0	0	0				≈ 300	≤ 100 (0)
Energy spread (units 10^{-3})	e: 0.91 p: 0.2	0.14	0.15	0.75	0.75	0.75	0.113 (0.116)	0.11
Bunch length (cm)	e: 0.83 p: 8.5	p: 50 $\bar{p}$: 45	55	30	30	30	7.55 (5.87)	7.94 (5.83)
Beam radius (10^{-6} m)	e: 280(H), 50(V) p: 265(H), 50(V)	p: 28 $\bar{p}$: 16	90	135	145	145	16.6 (45)	15.9 (45)

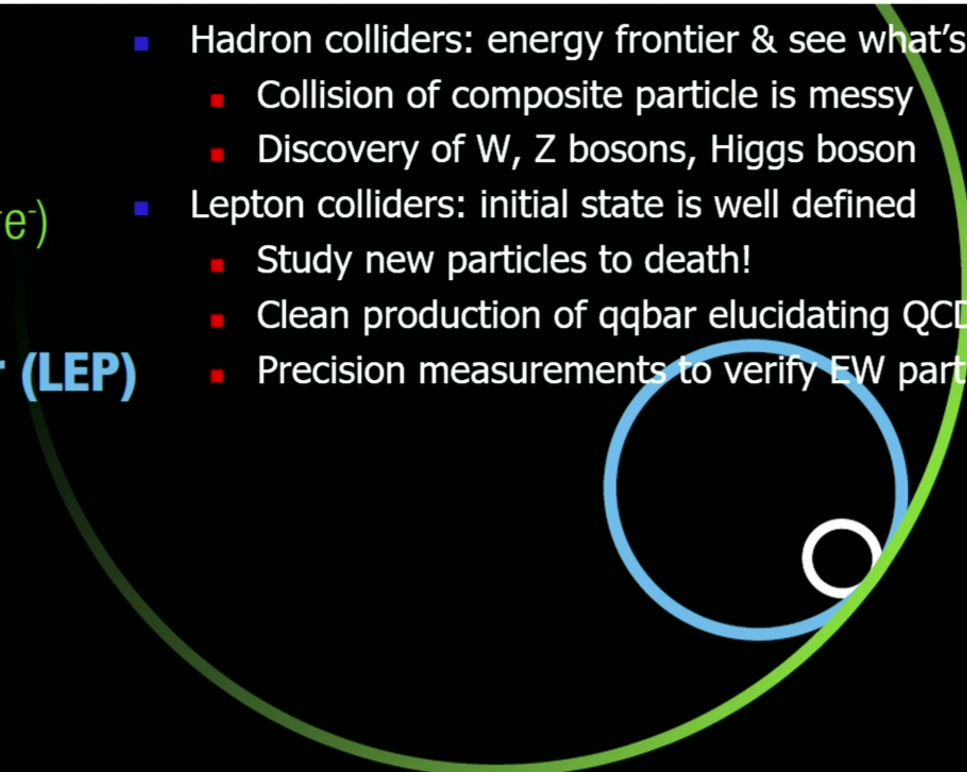
Why the back and forth between hadron and lepton colliders?

- **Future Circular Collider (FCC)**
  Circumference: 90 -100 km
  Energy: 100 TeV (pp) 90-350 GeV (e^+e^-)

- **Large Hadron Collider (LHC)**
  Large Electron-Positron Collider (LEP)
  Circumference: 27 km
  Energy: 14 TeV (pp) 209 GeV (e^+e^-)

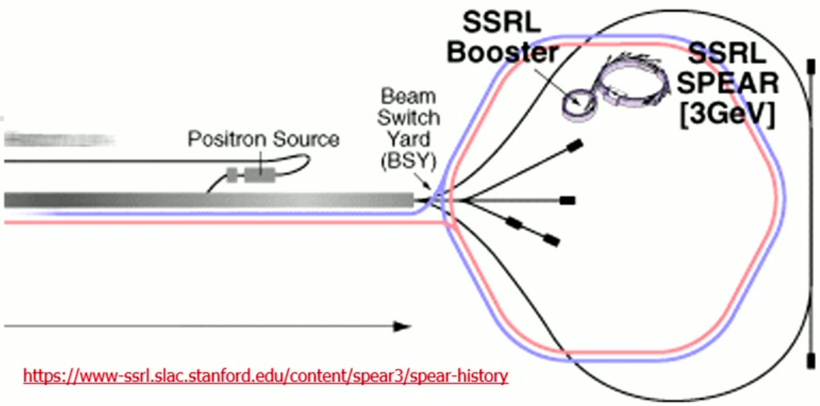
- **Tevatron**
  Circumference: 6.2 km
  Energy: 2 TeV ($p\bar{p}$)

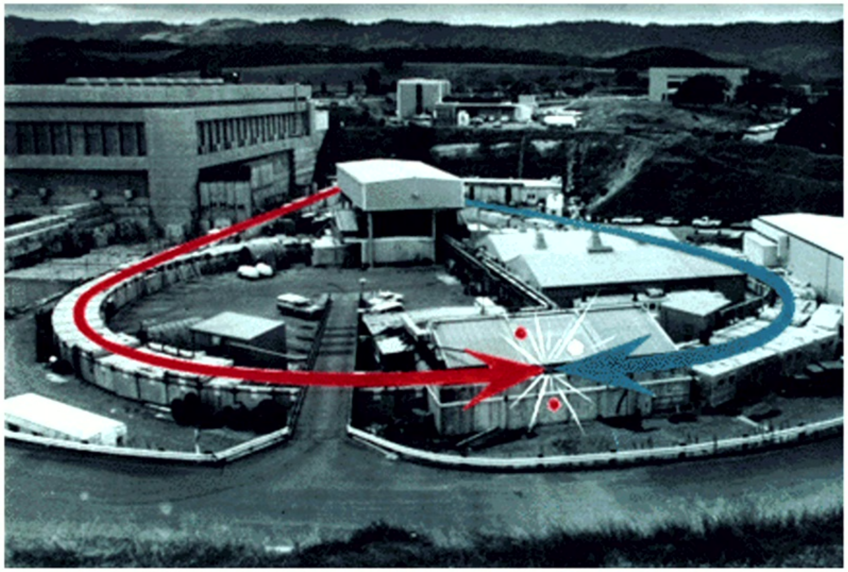
- Hadron colliders: energy frontier & see what's there
  - Collision of composite particle is messy
  - Discovery of W, Z bosons, Higgs boson
- Lepton colliders: initial state is well defined
  - Study new particles to death!
  - Clean production of qqbar elucidating QCD
  - Precision measurements to verify EW part of theory



Machines with key roles in SM: SPEAR at SLAC

- SPEAR (Stanford Positron Electron Asymmetric Rings)
- e^+e^- machine at SLAC, started in 1972
  - Single ~80m diam ring. Counter rotating e^+e^- up to 4 GeV
- Discovery of particles containing the charmed quark J/ψ and a number of other charmed particles
- Advances on quark model
- Also tau in 1977 by M. Perl with the LBL Magnetic detector





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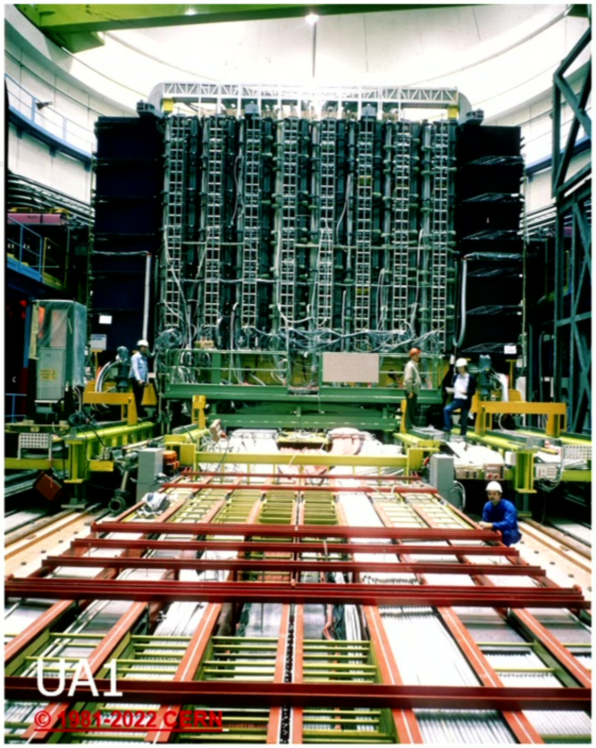
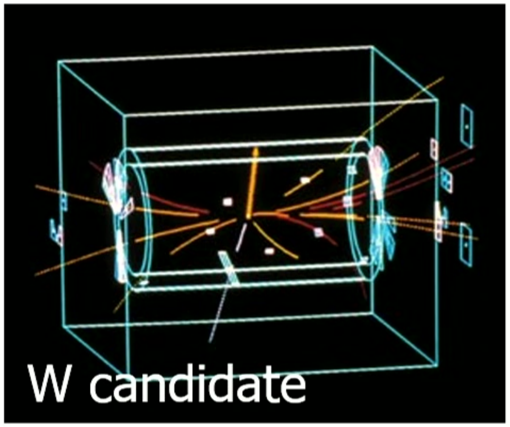
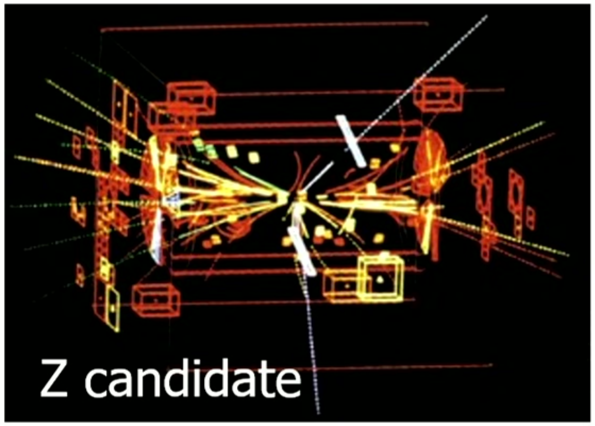
Machines with key roles in SM: ppbar collider at CERN

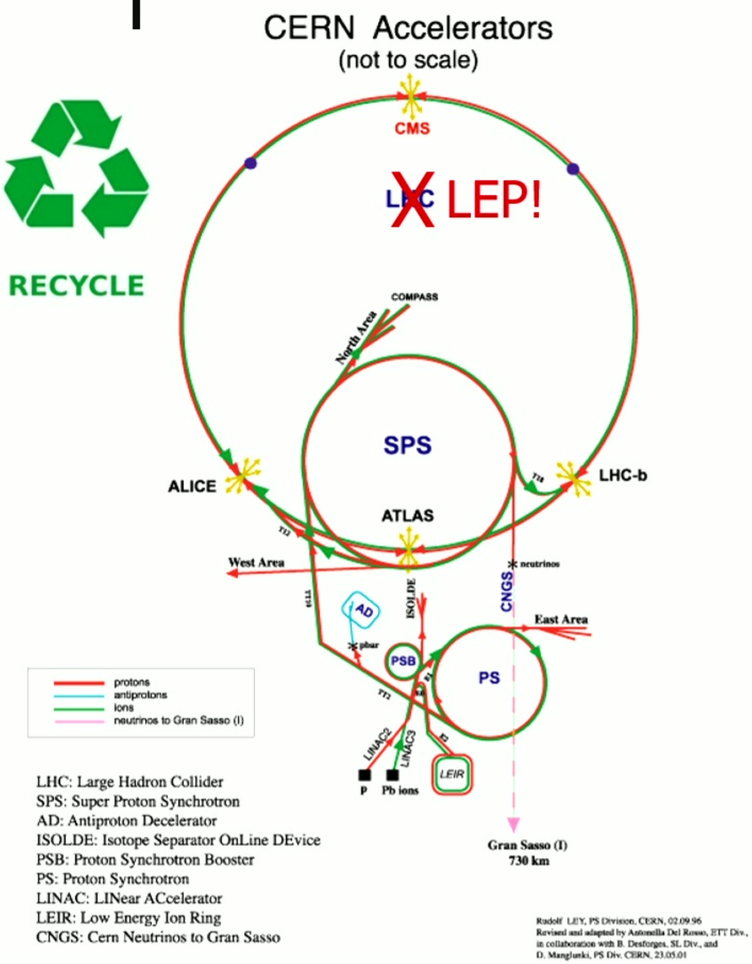
- Super Proton–Antiproton Synchrotron (Sp$\bar{\text{p}}$S) started in 1981
  - Accelerate a beam to 450 GeV, but mostly operated at 315 GeV centre-of-mass energy, to prevent overheating of magnets
- Key advances in terms of anti-proton cooling and accumulation.
  - Stochastic cooling: use electrical signals of charged particles in a feedback loop to reduce the tendency of individual particles to stray
- Two large experiments UA1, UA2 (and UA4, UA5, UA8)
- Discovered carriers of Weak force W and Z: predicted by theory



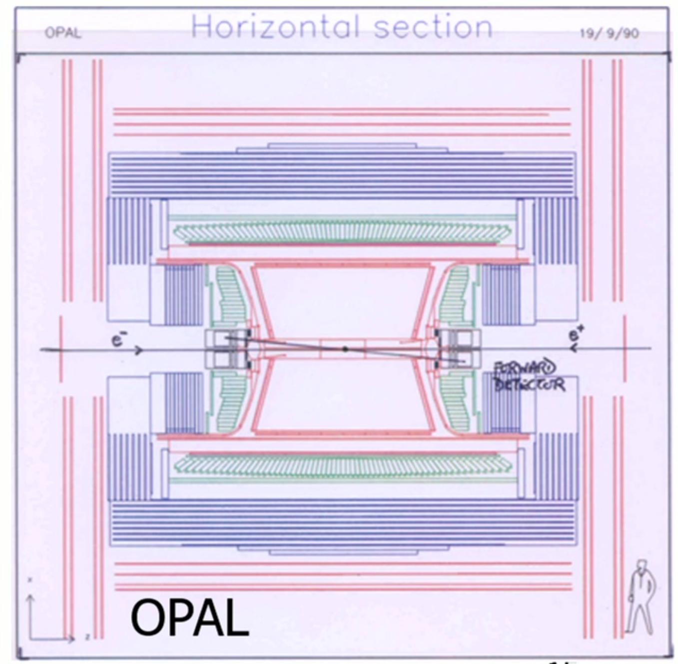




Machines with key roles in SM: LEP collider at CERN



- LEP Large Electron Positron collider stated in 1989
- 27 km circumference tunnel
  - Where the LHC is now!
- Low field magnets but with large amounts of RF power (Synchrotron losses)
- 4 experiments ALEPH, OPAL, DELPHI, L3
- Ran at Z peak (Z factory!) and above W^+W^- threshold
- Precision measurements of the Standard Model that are still the standards for today!
- Major Canadian participation in OPAL experiment



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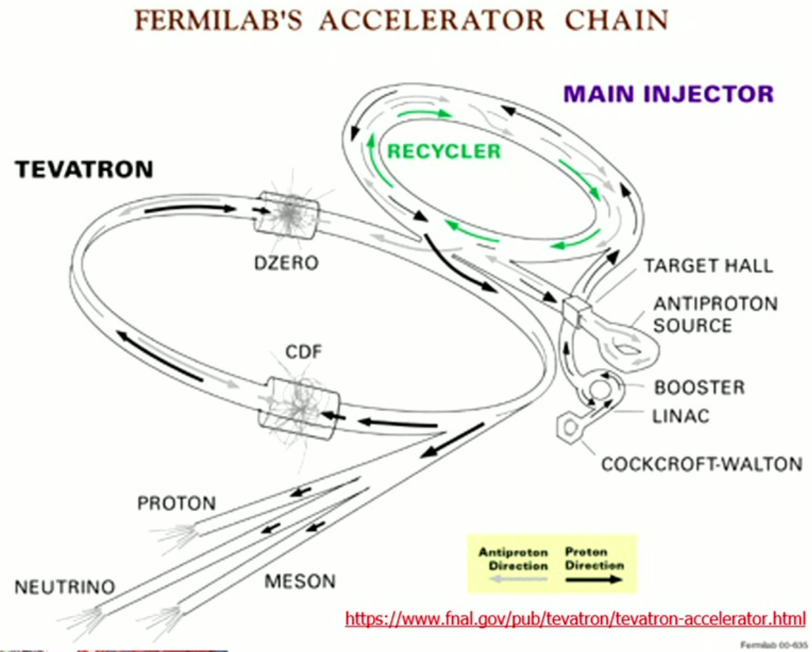
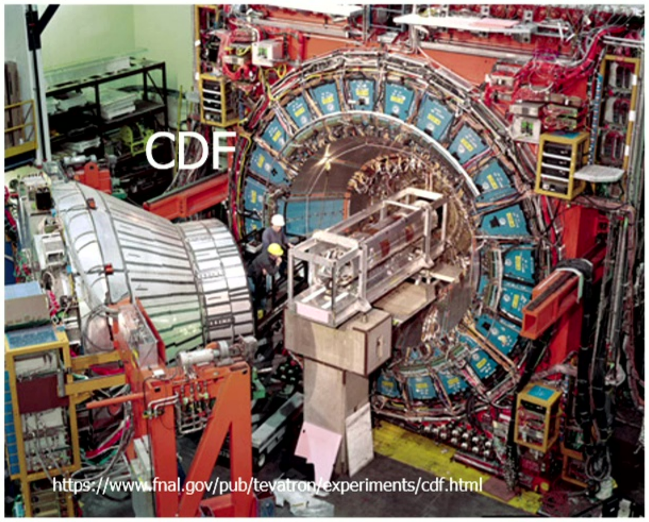
Machines with key roles in SM: Tevatron at Fermilab

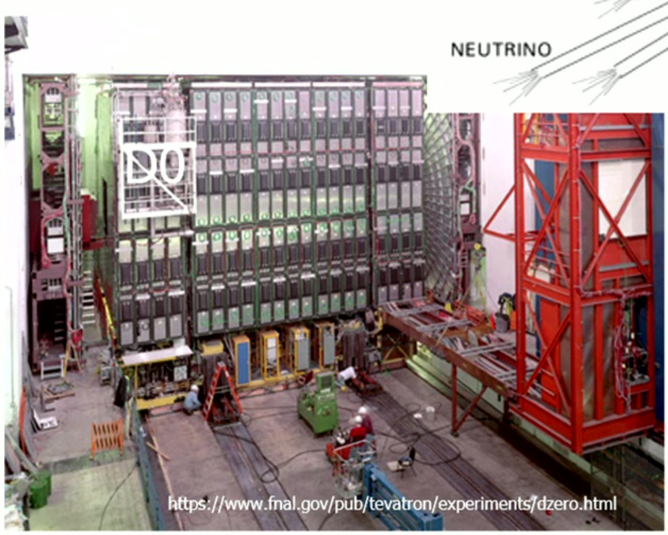
- Proton-anti-proton collider started in 1987
- Total centre-of-mass energy ~2 TeV
- Two experiments CDF and D0
  - Canadians contributed to both of these.
- Discovered top quark
  - Last quark of the three-family model!
- End of running in September 2011
  - Just as the LHC was taking off!



https://www.fnal.gov/pub/tevatron/tevatron-accelerator.html

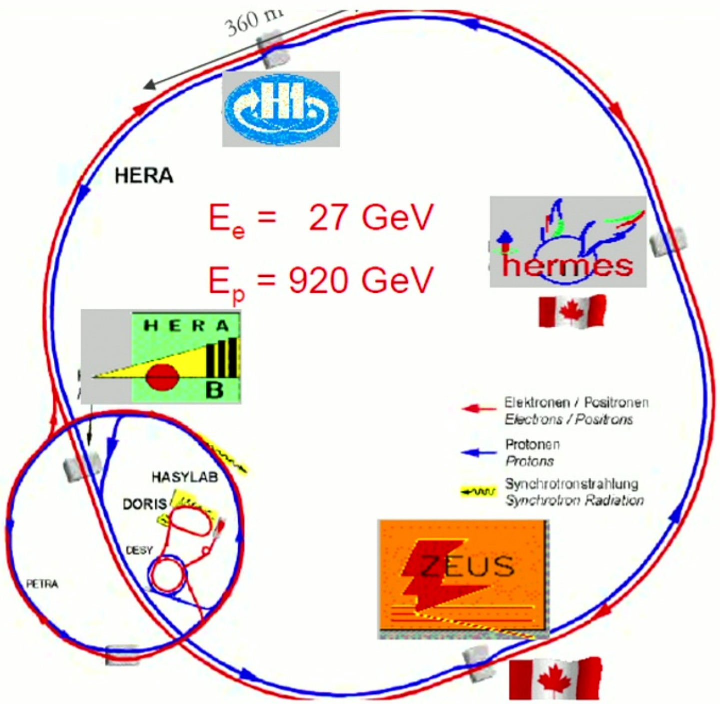


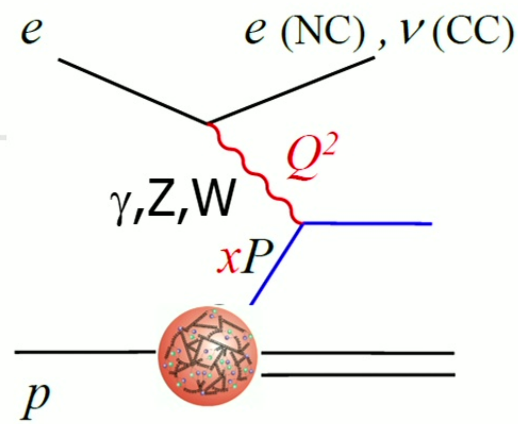
https://www.fnal.gov/pub/tevatron/experiments/cdf.html



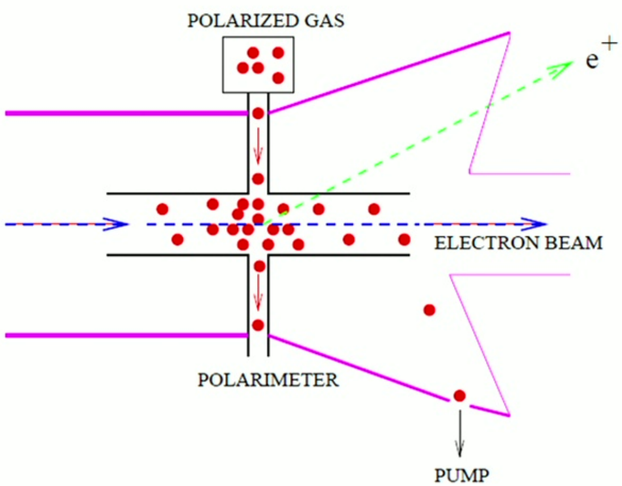
https://www.fnal.gov/pub/tevatron/experiments/dzero.html

Machines with key roles in SM: HERA (1992-2007) at DESY





It's all about nucleon structure!

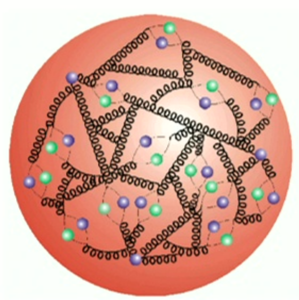


- HERA-I 1992-2000, HERA-II 2002-2007
- $e^{\pm}p$ collider (polarised $e^{\pm}$)
- At largest Q>200 GeV, can probe distance scales $<10^{-18}$ m
- Canada: ZEUS used $e^{\pm}p$, HERMES used $e^{\pm}$ on polarised/unpolarised fixed targets

Can't overstate the importance of HERA results to our understanding of particle physics!

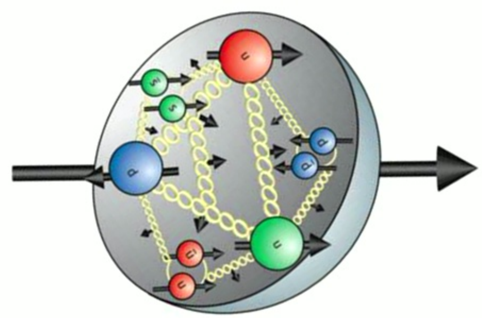
- ZEUS and H1 contributions to the understanding of proton structure unparalleled.
  - Provided solid foundations for LHC physics with proton collisions
- HERMES shed very bright light on spin structure of the proton
  - Detailed flavour decomposition of nucleon spin!
- Both had an incredibly rich programmes far beyond the flagship measurements

$e^{\pm}$



Inclusive deep-inelastic scattering

$e^{\pm}$



$= 1/2$

Semi-inclusive deep-inelastic scattering

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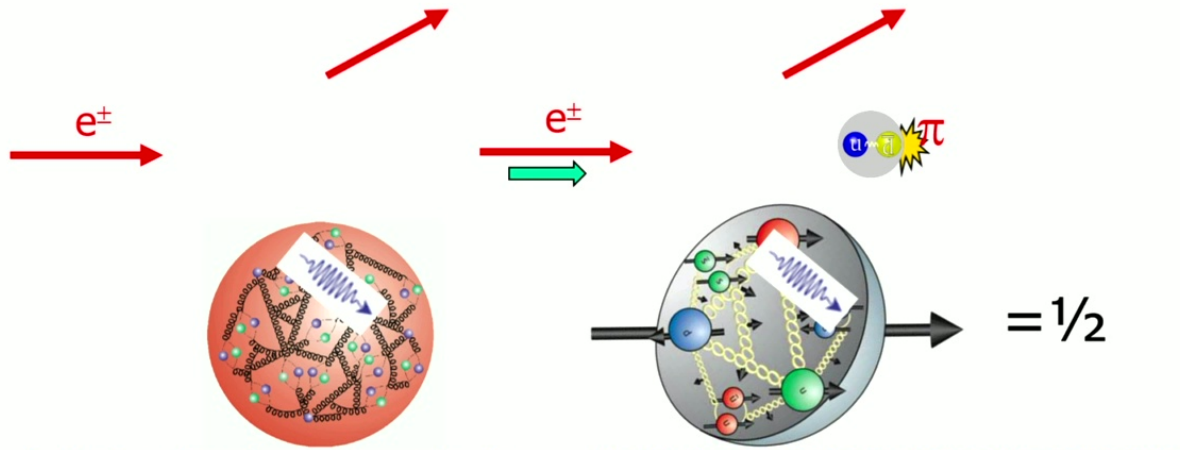

Inclusive deep-inelastic scattering   Semi-inclusive deep-inelastic scattering

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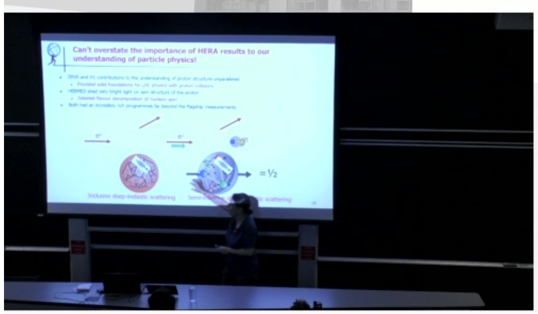


CHEER: a Canadian push for an ep collider!

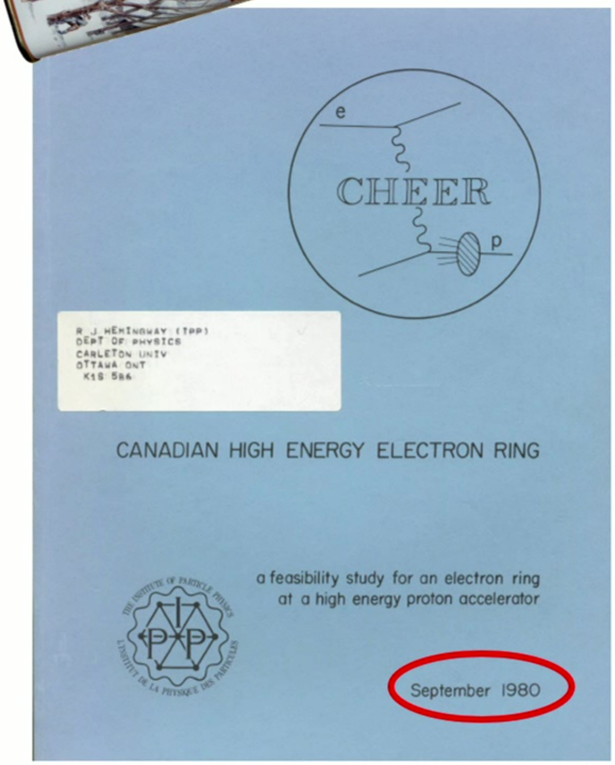
- 10 GeV electron synchrotron to collide "head on" with protons at Fermilab on the timescale of ~1985
- FERMILAB-PROPOSAL-0703 (June 1981)
  - IPP, Chalk River, Carleton, McGill, NRC, Saskatoon, Toronto, York, TRIUMF

Canadian High Energy Electron Ring

MACHINE PARAMETERS

Pre-Injector	300	MeV LINAC
Accumulator	300	MeV
Injector	2	GeV SYNCHROTRON
Storage Ring	10	GeV
Filling Time	3	seconds for e^-, 15 minutes for e^+
Electrons per bunch	10^{11}	

  - endorsed by NSERC PAC (Physics and Astronomy Committee) with some funding
  - well reviewed but ultimately not successful
- Funded by NSERC!
  - Canada does Big Science, gets Big $
- ➢ Established the reputation of Canadians on an international stage
- Led to Canadian involvement in:
  - HERA/ZEUS at DESY ($e^{\pm}p$)
  - LEP/OPAL at CERN (e^+e^-)

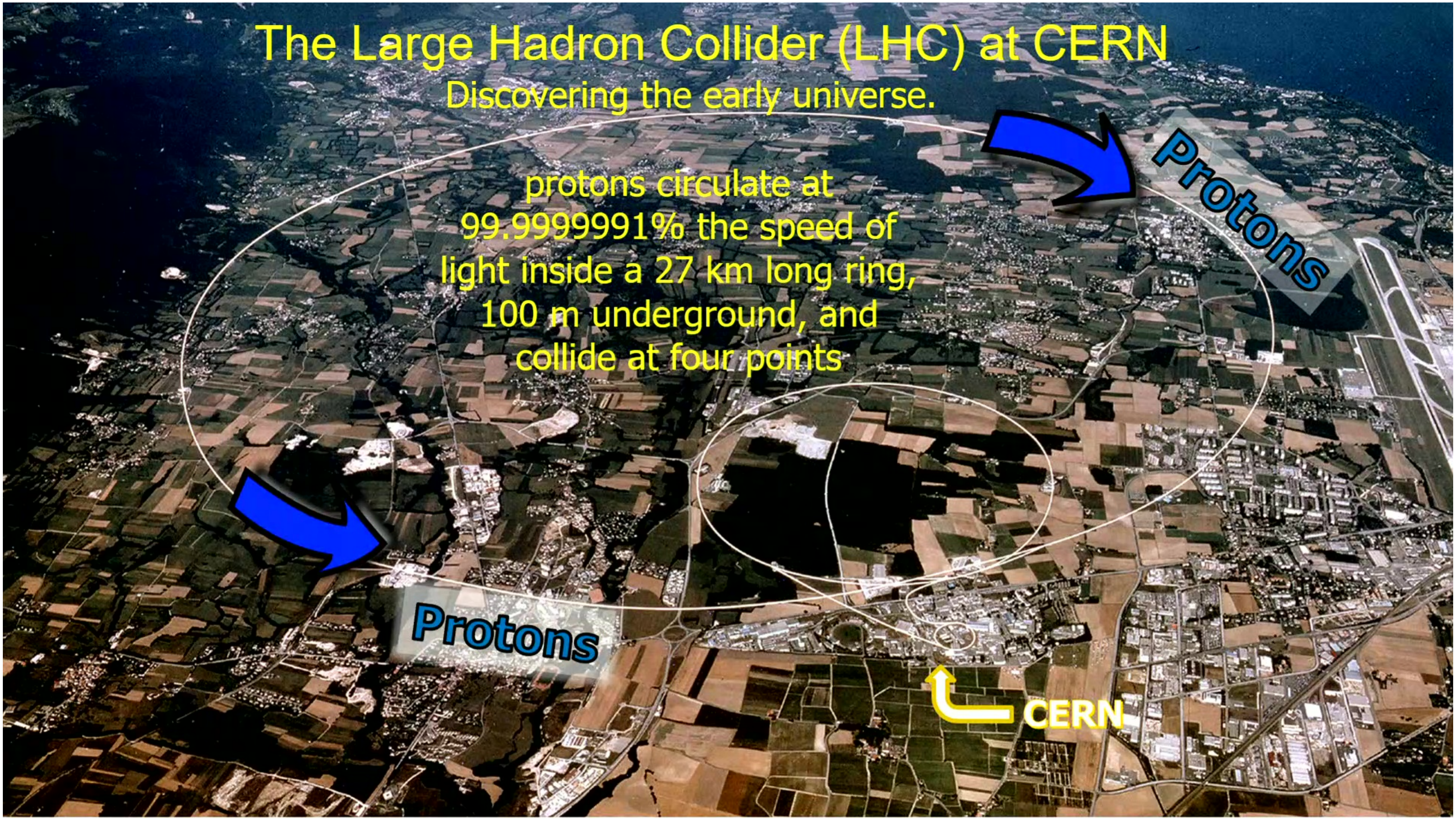


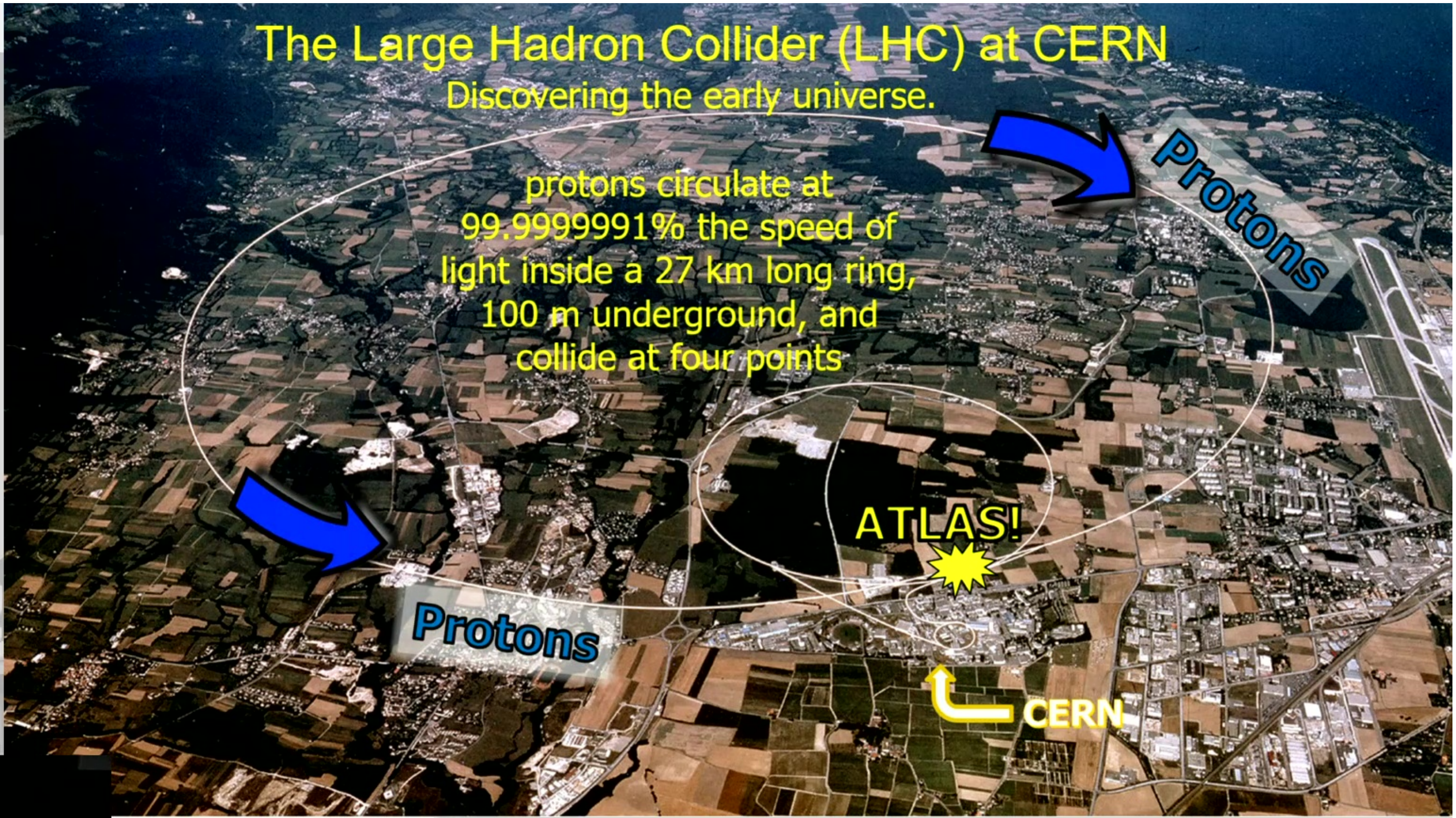
1980 IPP CHEER proposal

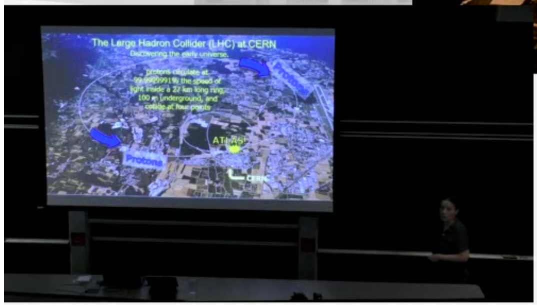
Summary: Colliding beam detectors

- Lepton-Lepton
  - BEPC BES
  - SPEAR MIII
  - DORIS ARGUS, CRYSTAL Ball
  - CESR CLEO, CUSB
  - PEP DELCO, HRS, MAC, MKII, TPC, PEP9
  - PETRA CELLO, JADE, MARK-J, TASSO, PLUTO
  - TRISTAN AMY, TOPAZ, VENUS
  - SLC MKII SLD
  - LEPI – II ALEPH, DELPHI, L3, OPAL
  - PEP II BABAR
  - KEKB BELLE and BELLE2
  - ILC, CLIC, FCC-ee Maybe some day ????
- Hadron-Hadron
  - SPPS UA1, UA2, UA5
  - TEVATRON CDF D0
  - SSC XXX CANCELLED
  - LHC ATLAS, CMS, LHCb, ALICE
  - HL-LHC To start in a few years… more later
  - FCC-hh Maybe some day????
- Lepton-hadron
  - HERA H1, ZEUS, HERMES, HERA-B

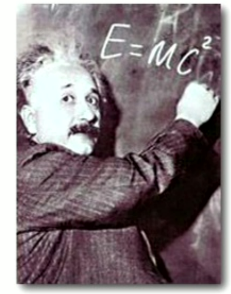
SSC: was to begin operations in 1999 in Waxahachie, Texas. Planned ring circumference was 87.1km, 20TeV per proton. Would have been nearly three times as powerful as the Large Hadron Collider at CERN. After ten years of planning and $2 billion in construction costs, US Congress pulled the plug on the project in 1993.


The Large Hadron Collider (LHC) at CERN
Discovering the early universe.
protons circulate at
99.9999991% the speed of
light inside a 27 km long ring,
100 m underground, and
collide at four points
Protons
Protons
CERN


The Large Hadron Collider (LHC) at CERN
Discovering the early universe.
protons circulate at 99.9999991% the speed of light inside a 27 km long ring, 100 m underground, and collide at four points
Protons
Protons
ATLAS!
CERN



Study interactions of matter by high energy collisions in a lab



$$E=mc^2$$

- The early universe was a HOT universe!
- Energy and mass are intimately related!

- High energy proton collisions provide the energy which can be converted to new massive objects!

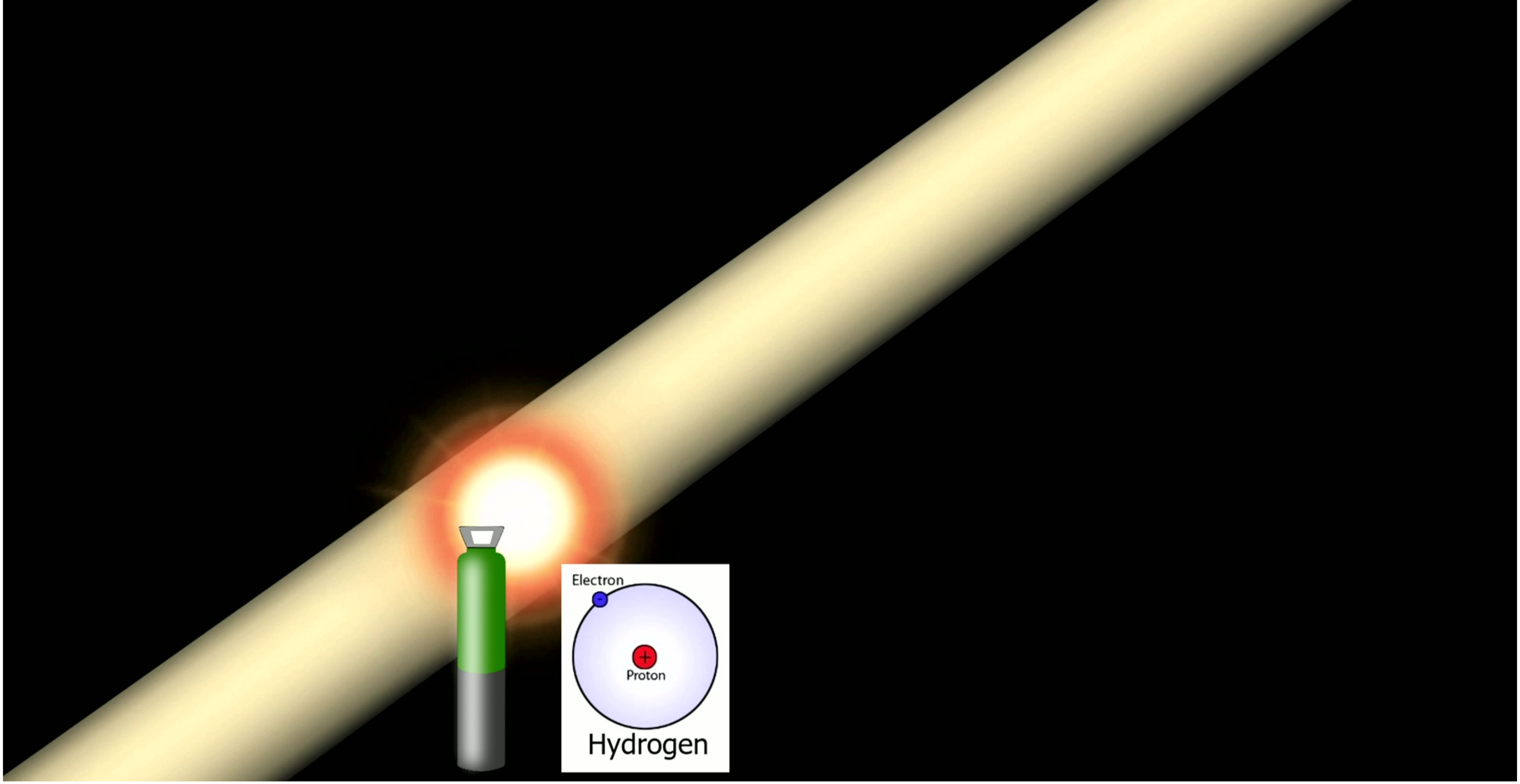
Matter → energy → new matter

- LHC: energy density of collisions like early universe less than a billionth of a second after Big Bang

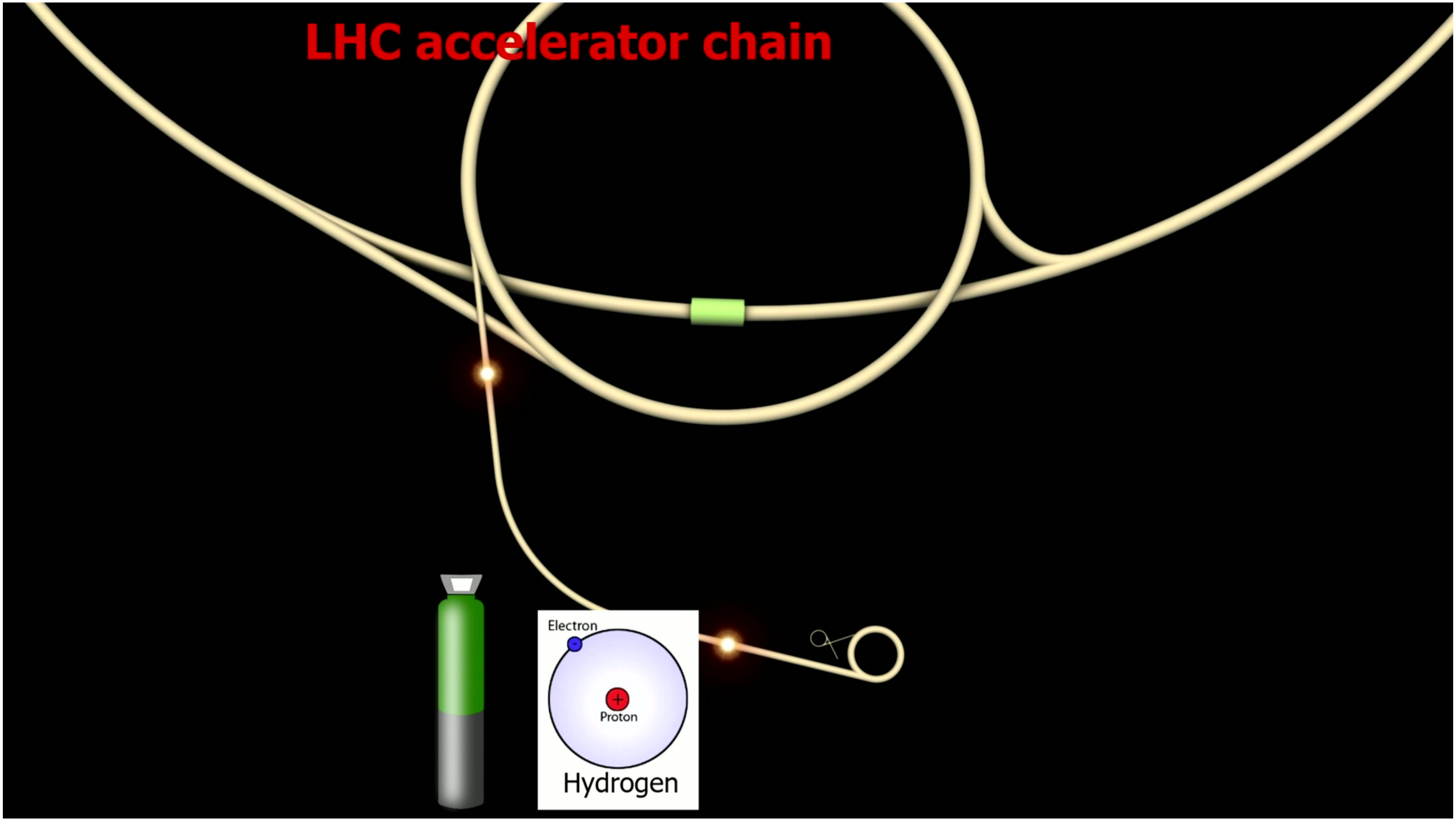
- Energy stored in each LHC beam: ~400 mega-joules
  - Kinetic energy: ~500 cars at 100 km/h
  - Chemical energy: ~80 kg of chocolate (count the calories!)
  - Thermal energy: enough to make "a tonne of tea"

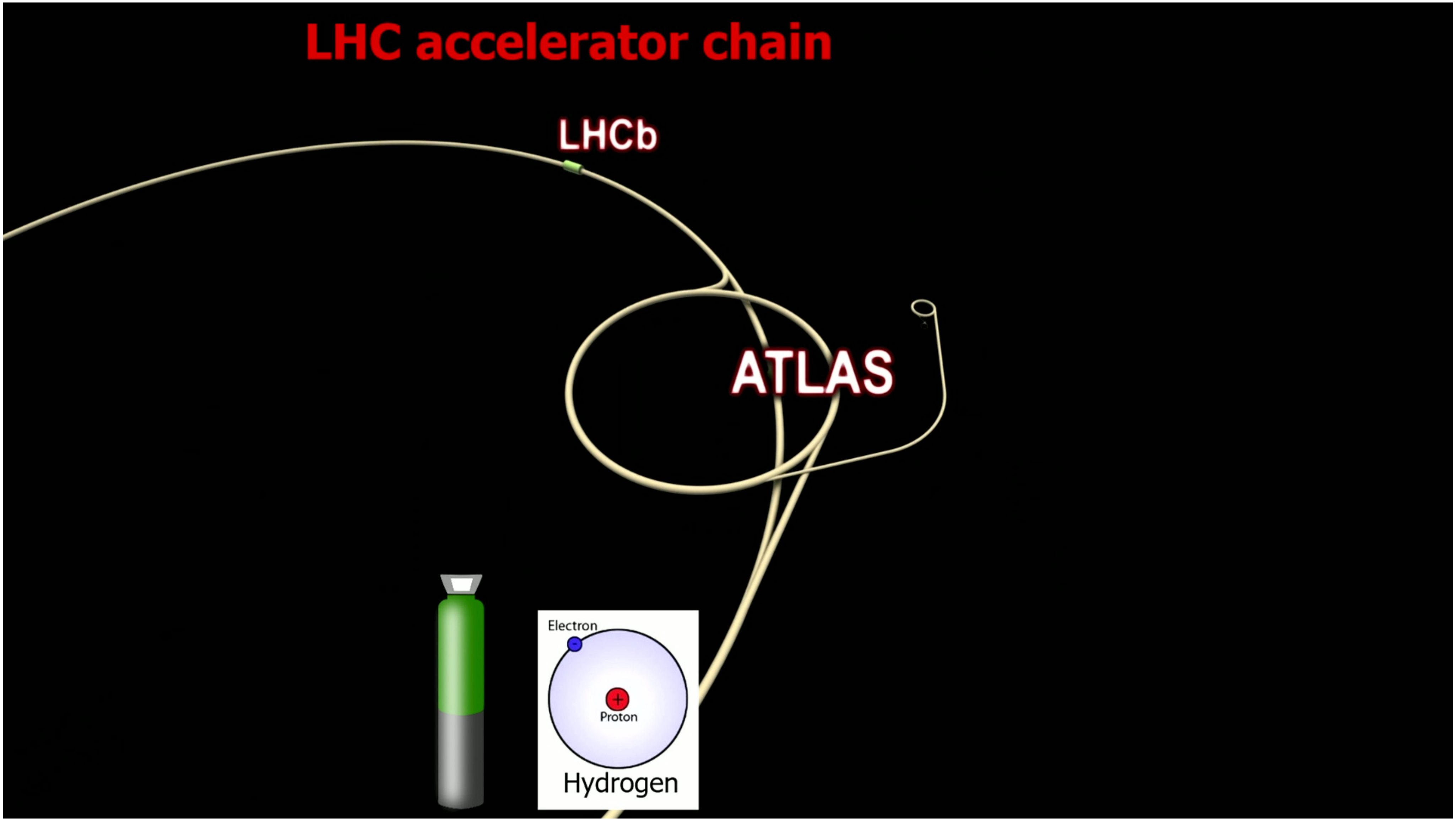
- Need "cameras" to record the passage of the collision products
  - Needs to take ~40 million pictures per second, for about 8 month every year!
- Four such "cameras" at the LHC
  - ATLAS, CMS, LHCb, ALICE

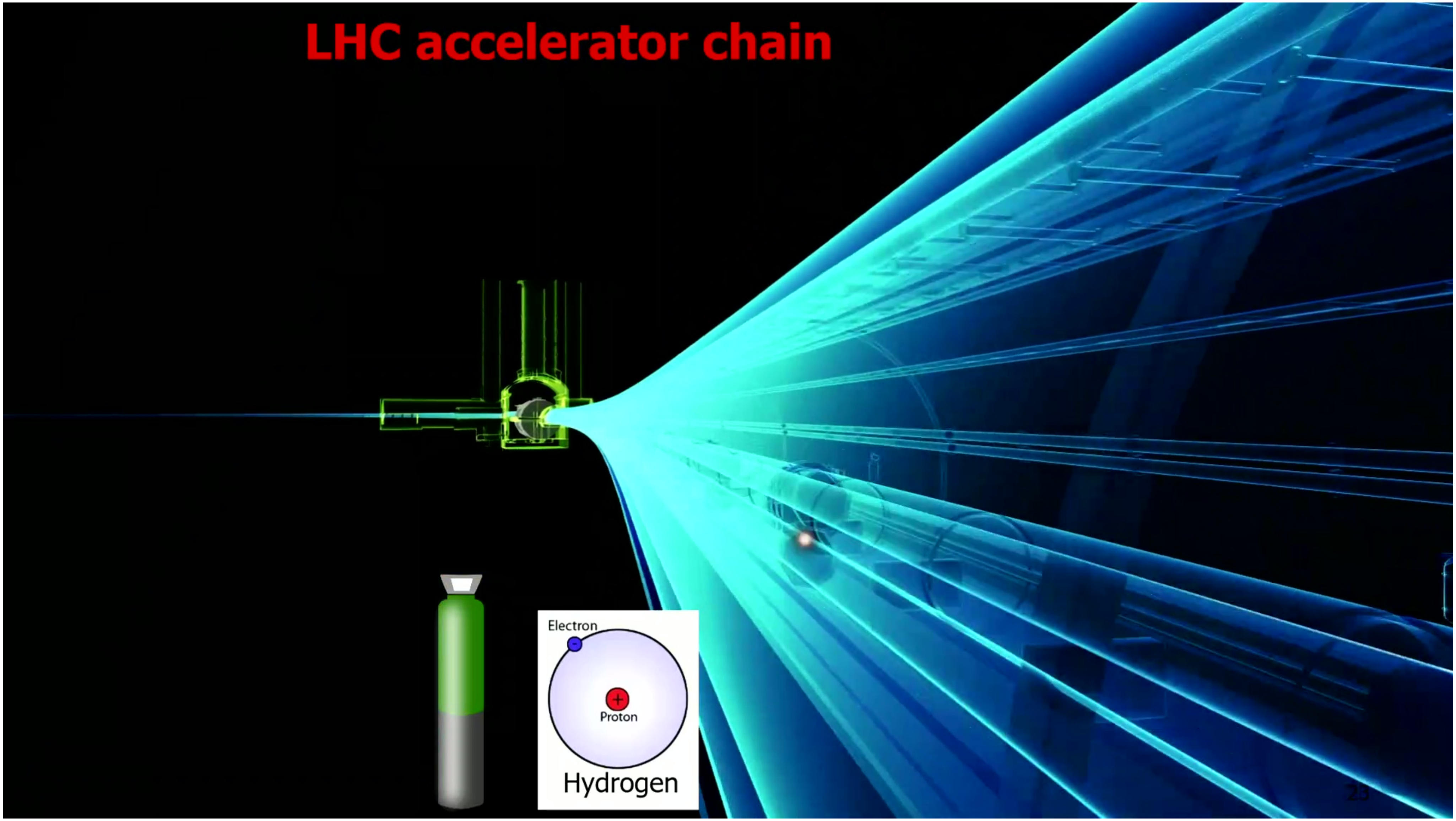
LHC accelerator chain

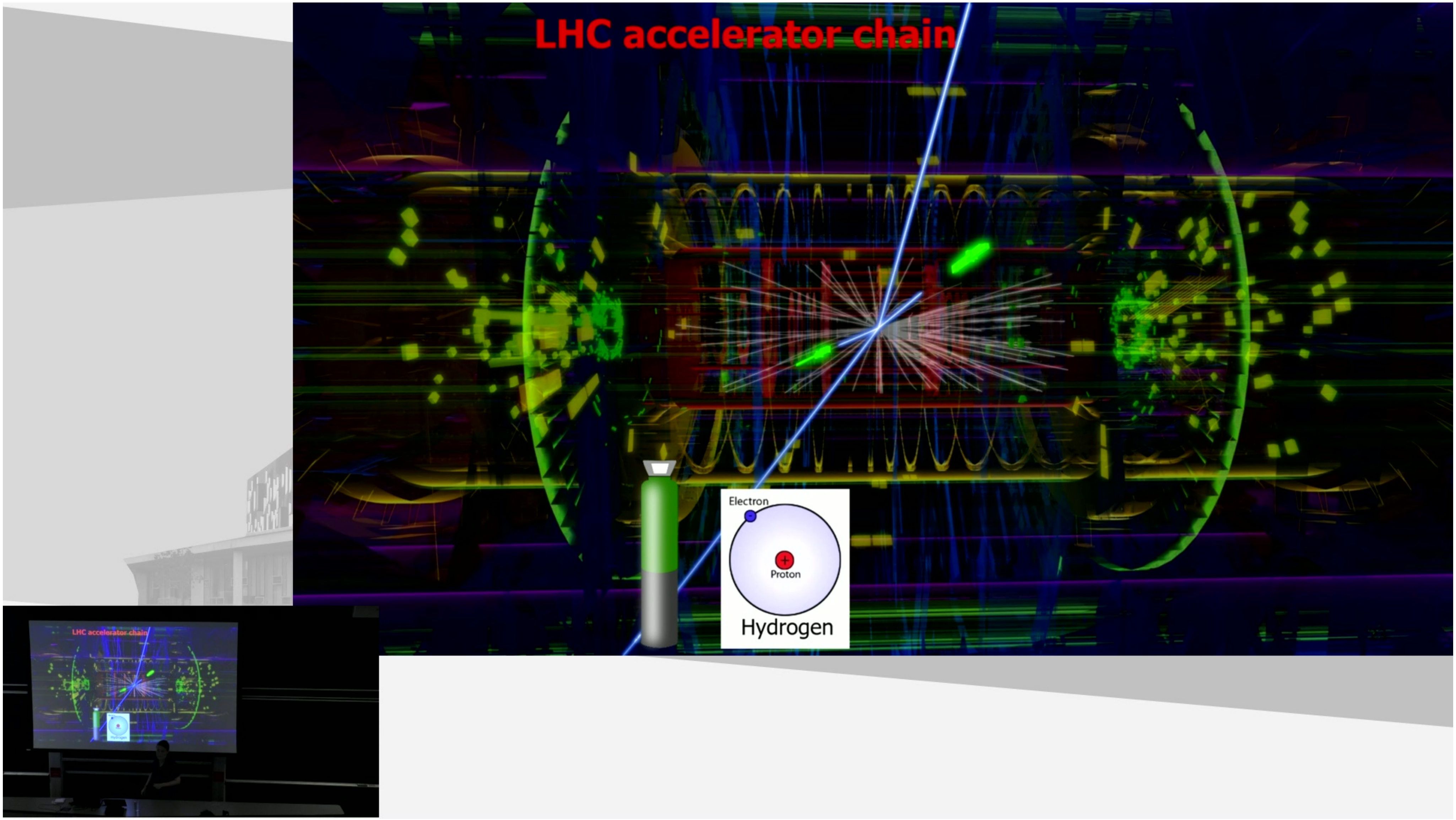


LHC accelerator chain



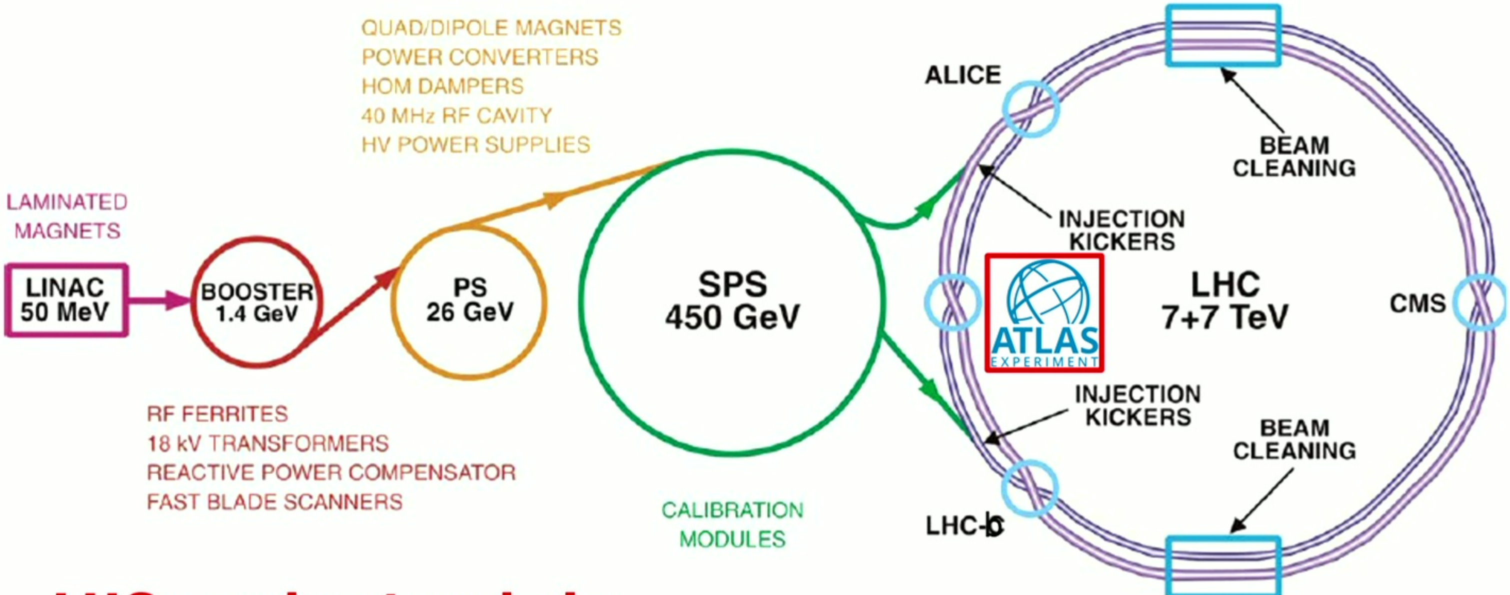

LHC accelerator chain
LHCb
ATLAS
Electron
Proton
Hydrogen


LHC accelerator chain
Electron
-
+
Proton
Hydrogen


LHC accelerator chain
Electron
Proton
Hydrogen

TRIUMF involvement in the LHC: ~1995-2005

- Upgrade of the injector: PS Conversion for LHC
  - provide proton beams with a factor two higher brightness, more strictly controlled emittance, and a different bunch spacing for the LHC operation.



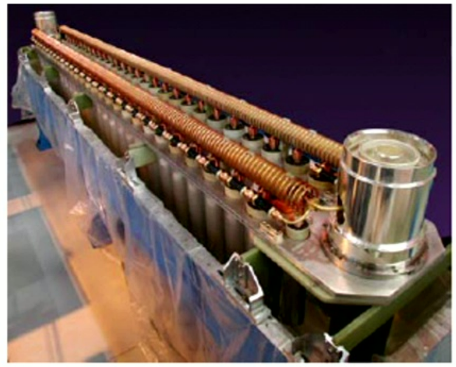
LHC accelerator chain

BEAM CLEANING STUDIES
TWIN APERTURE QUADRUPOLES
KICKER POWER SUPPLIES
KICKER PULSE FORMING NETWORKS
BEAM INSTRUMENTATION

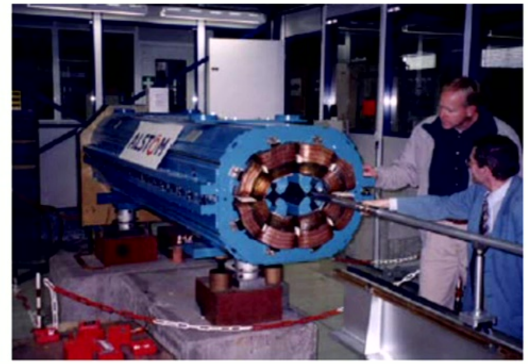
TRIUMF involvement in the LHC: ~1995-2005

The LHC itself

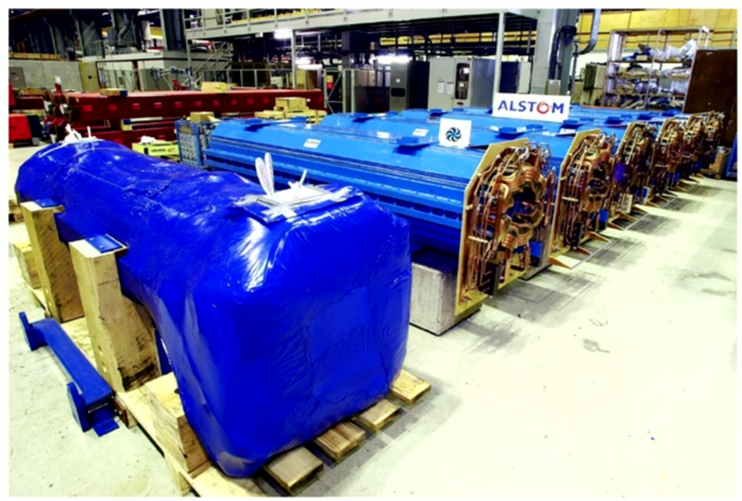
- prototype resonant charging power supply for injection kickers (in-house project)
- twin-aperture quadrupole magnets for the focusing elements of the beam cleaning insertions of LHC.
  - ALSTOM Canada (Tracy, Quebec) had contract for the prototype and series production
- full scope of involvement: production of 5 resonant charging supplies and 9 pulse forming networks for LHC injection and 52 of the quadrupole magnets
- $41.5M in Canadian upgrades: ~80% of contribution spent in Canada.



PFNs for Kickers



Twin-Aperture Quads



Canada's involvement in LHC

- Thanks to Alan Astbury (1934-2014), R.M. Pearce Professor of Physics at UVic & TRIUMF Director

ATLAS-Canada founded in 1992

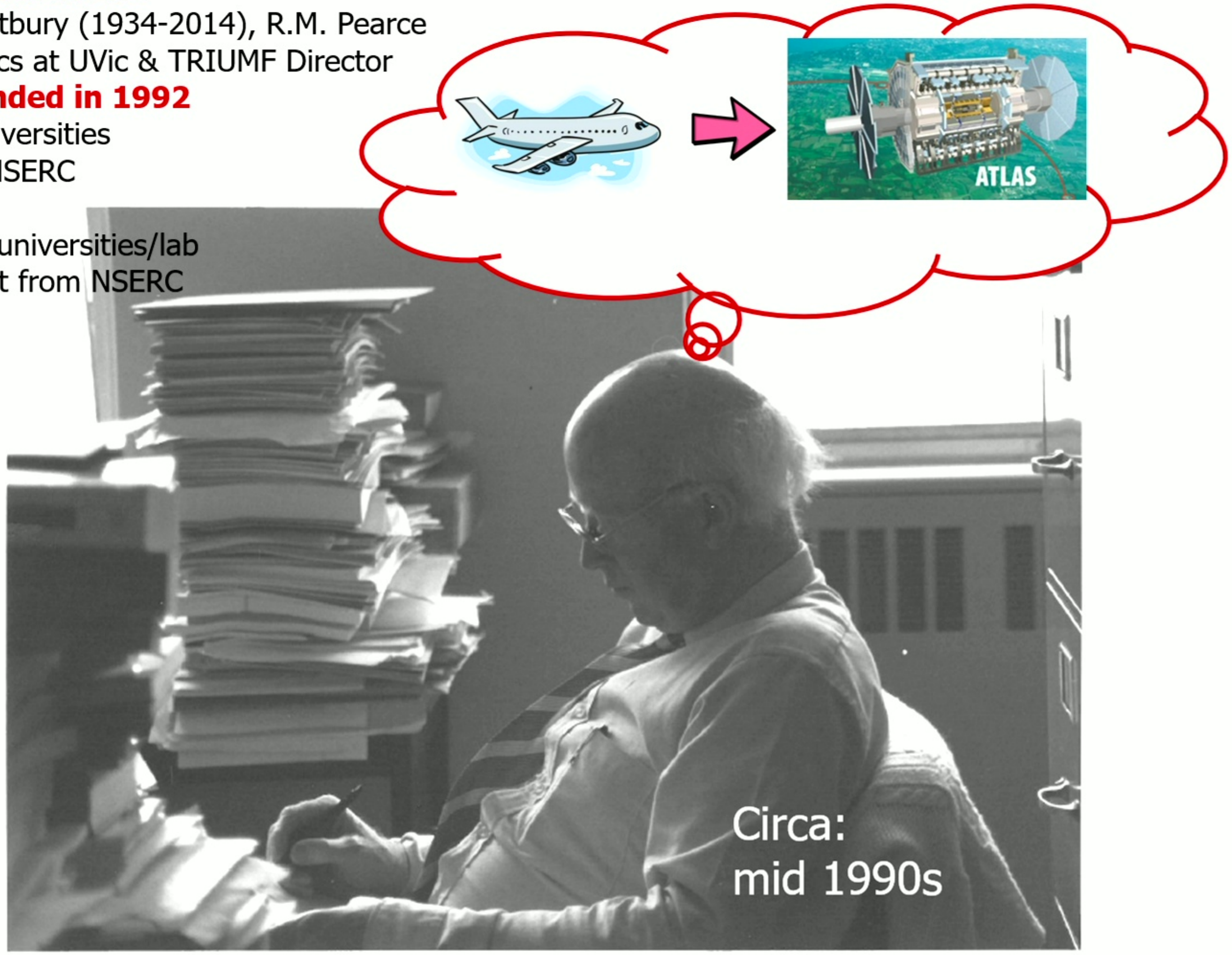
9 faculty/2 FTEs/2 universities

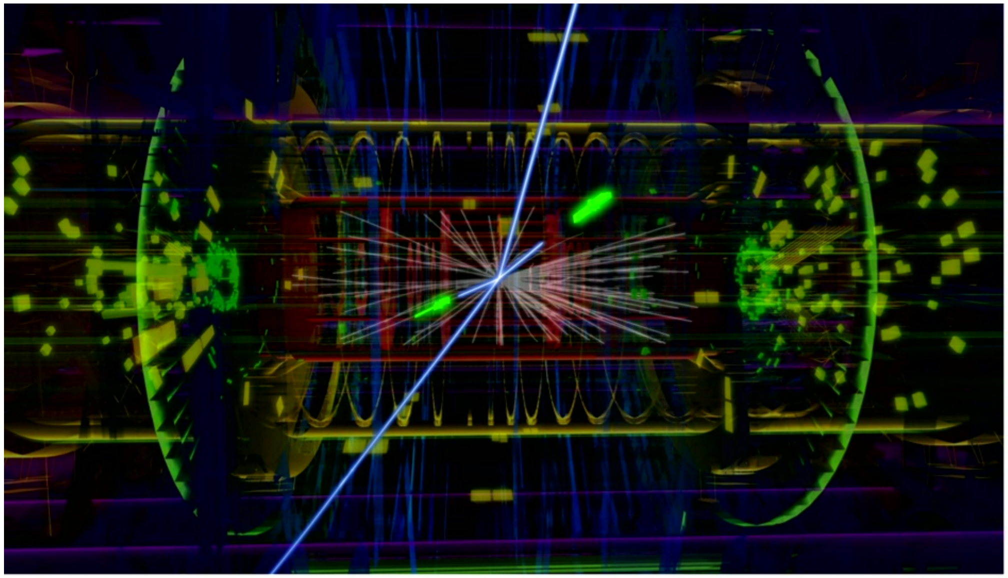
- $25k grant from NSERC

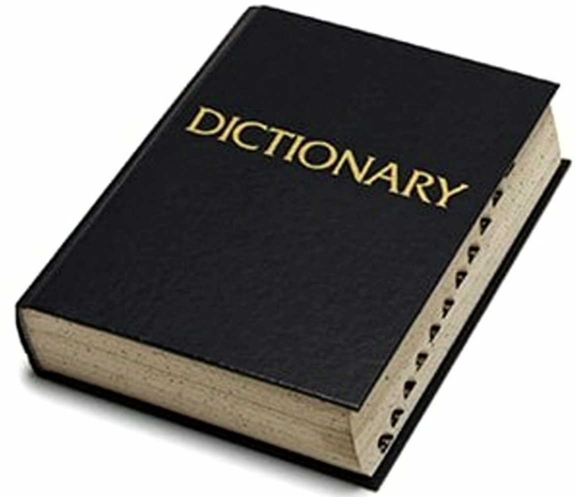
Now

40 faculty/35 FTE/10 universities/lab

- $6.5M yearly grant from NSERC







ESTABLISHING A COMMON LANGUAGE

Demystifying buzz words:

Pileup, luminosity, collision event, hard scattering, underlying event

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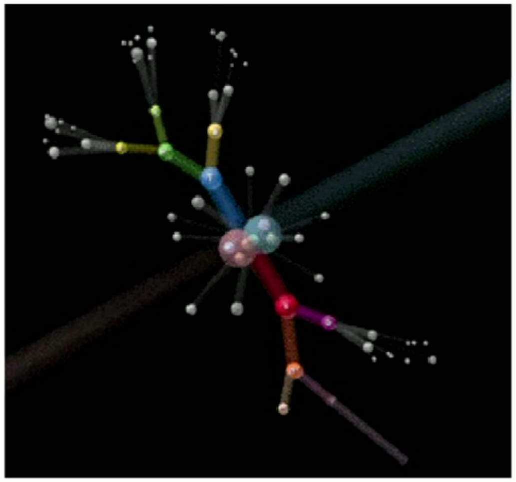
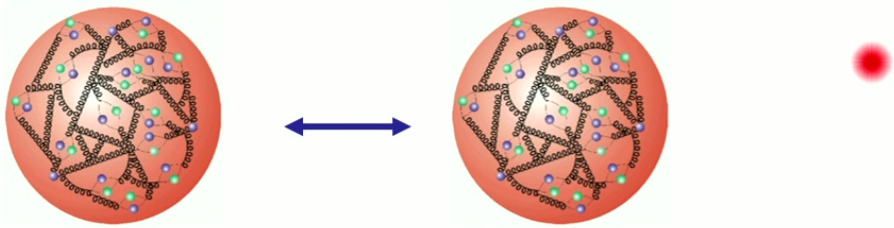
What do particle collisions at hadron colliders look like?

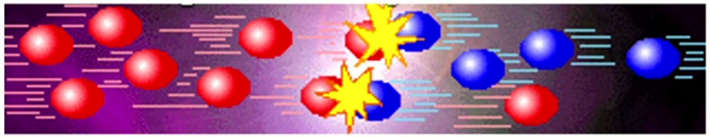


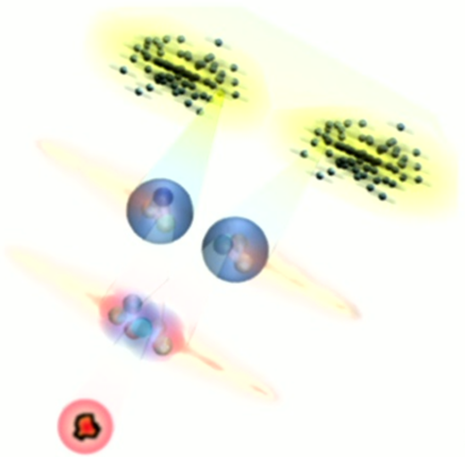
Particle collisions can be difficult to interpret!

- The protons themselves are not point like objects!



- The interactions of the proton constituents lead to the creation of new particles that can be unstable and decay to other particles (e.g. electrons, muons, pions, protons, etc…).
- Usually have many protons interacting simultaneously

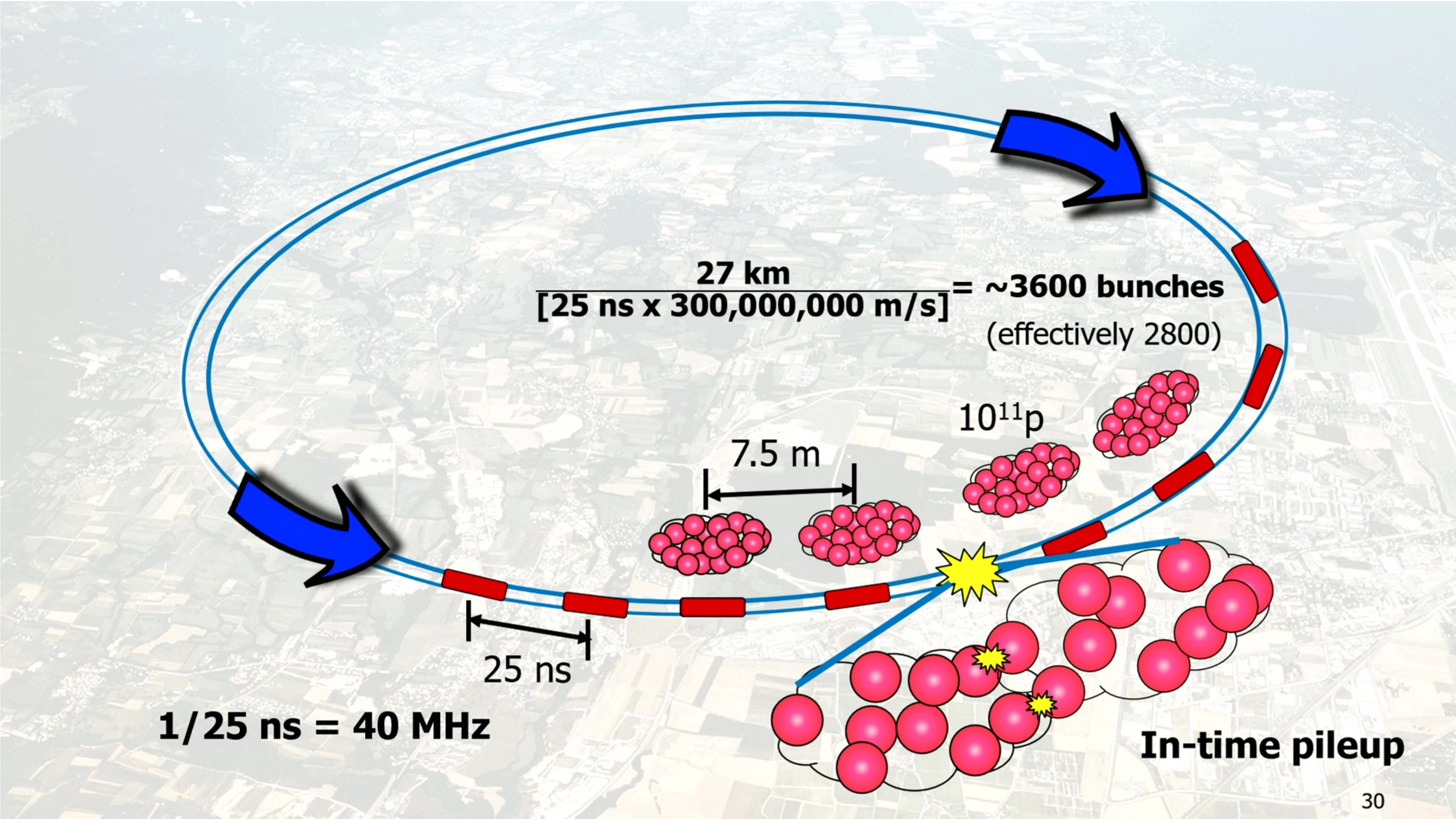




➡ Particle collisions can be messy!

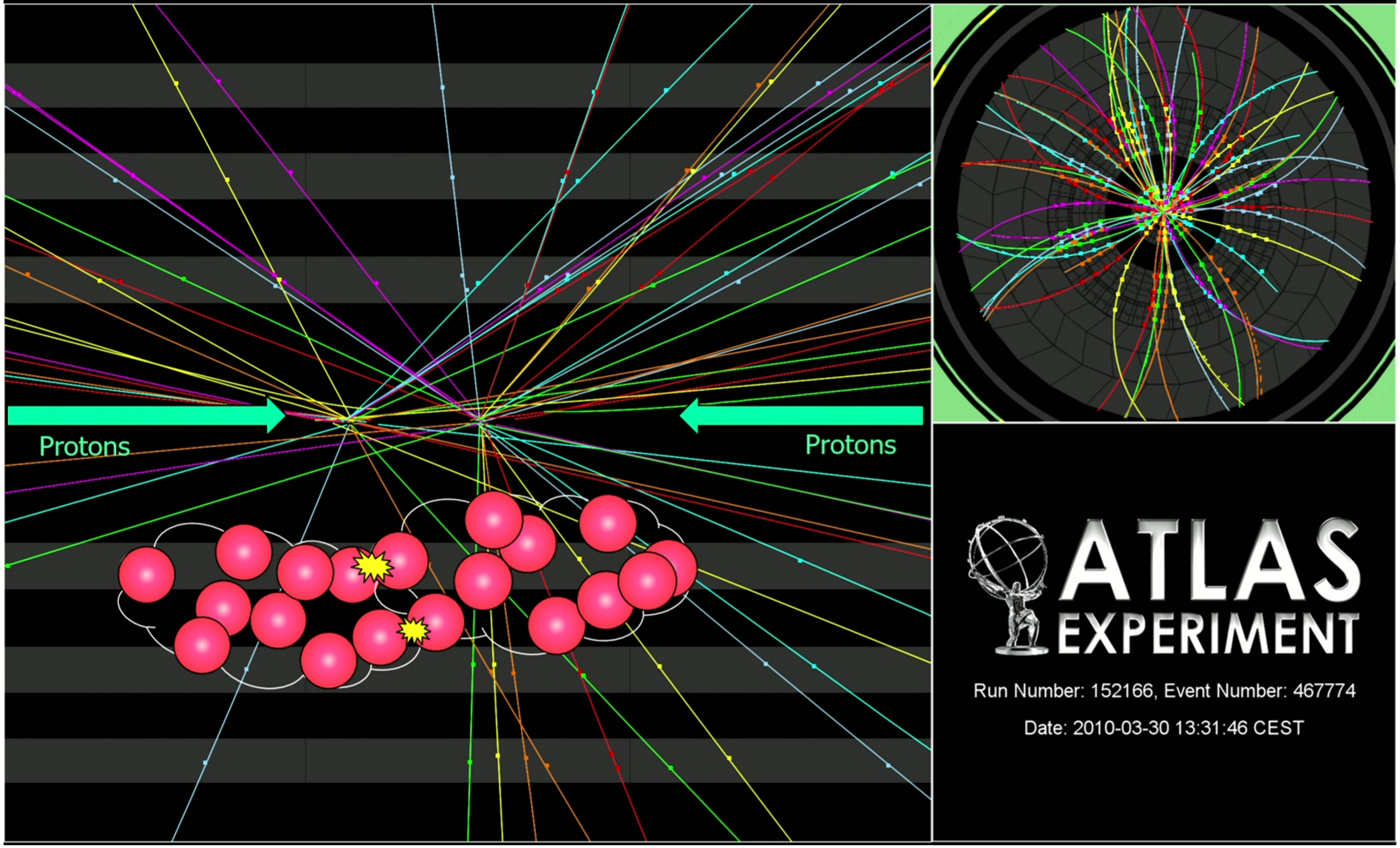
Buzz word #1

Pileup, μ!



$\frac{27\ \text{km}}{[25\ \text{ns x}\ 300{,}000{,}000\ \text{m/s}]}$ = ~3600 bunches
(effectively 2800)
10^{11}p
7.5 m
25 ns
1/25 ns = 40 MHz
In-time pileup
30

Collision Event at 7 TeV with 2 Pile Up Vertices



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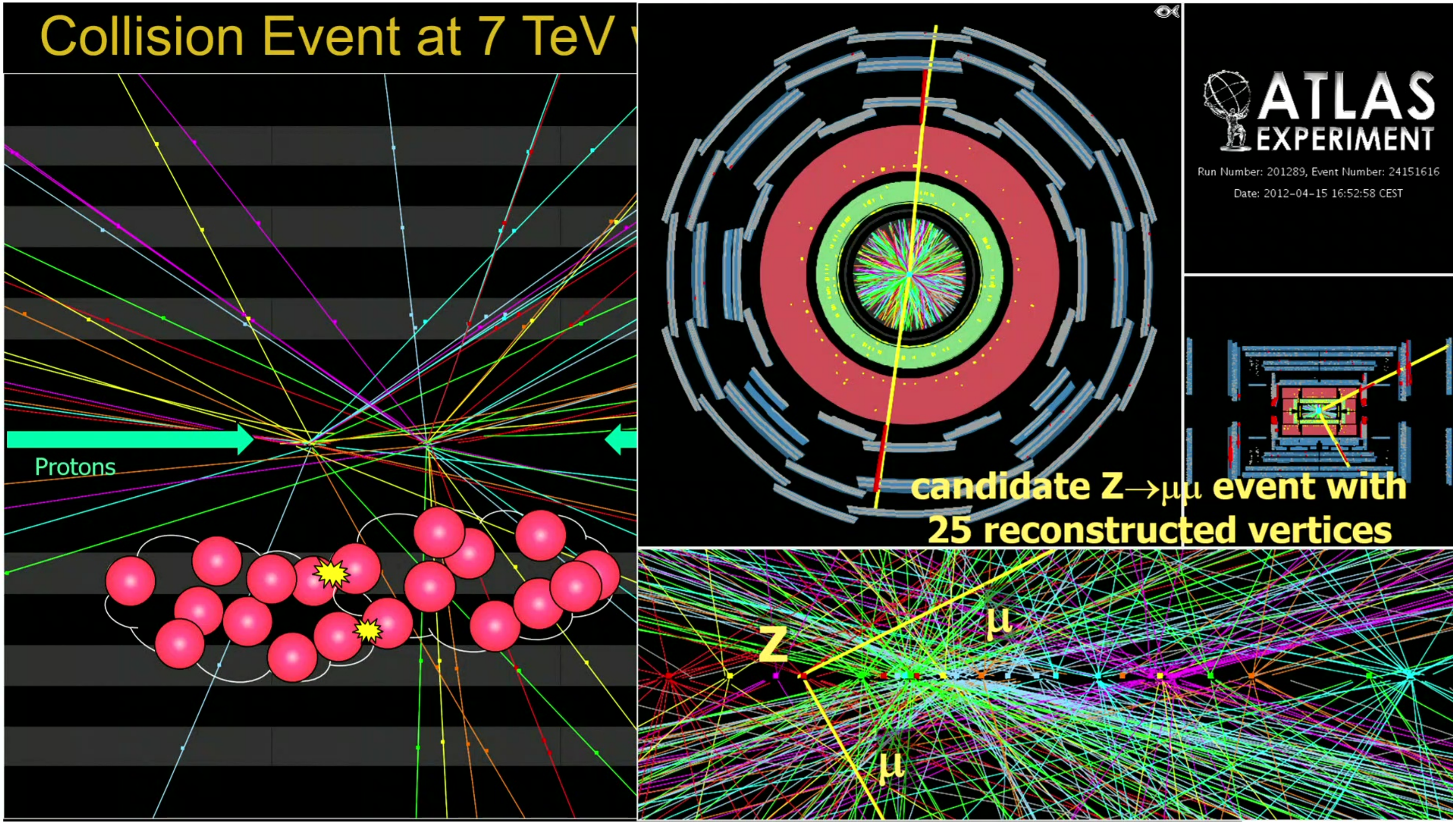
Collision Event at 7 TeV
Protons
ATLAS EXPERIMENT
Run Number: 201289, Event Number: 24151616
Date: 2012-04-15 16:52:58 CEST
candidate Z→μμ event with
25 reconstructed vertices
Z
μ
μ

Inelastic collisions per bunch crossing

- Extract number of inelastic collisions per bunch crossing (BC)

$$<\mu> \; = \; \sigma_{inel} \;\; x \;\; L \;\; x \;\; \Delta t \;\; / \; \varepsilon^{occupancy}{}_{bunch}$$

- LHC: $<\mu>$ = ~70-80 mb x (1-2 x 10^{34} cm^{-2} s^{-1}) x 25 ns / 0.8 = ~50
  - On average in LHC Run 2 (2015-2018), there were ~30-40 simultaneous collisions per bunch crossing
- Big change compared to recent machines:
  - LEP: Δt = 22 ms and $<\mu> << 1$
  - SppS: Δt = 3.3 ms and $<\mu> \approx 3$
  - HERA: Δt = 96 ns and $<\mu> << 1$
  - Tevatron: Δt = 0.4 ms and $<\mu> \approx 2$

Inelastic collisions per bunch crossing

- Extract number of inelastic collisions per bunch crossing (BC)

$$\langle\mu\rangle = \sigma_{inel} \times L \times \Delta t \,/\, \varepsilon^{occupancy}_{bunch}$$

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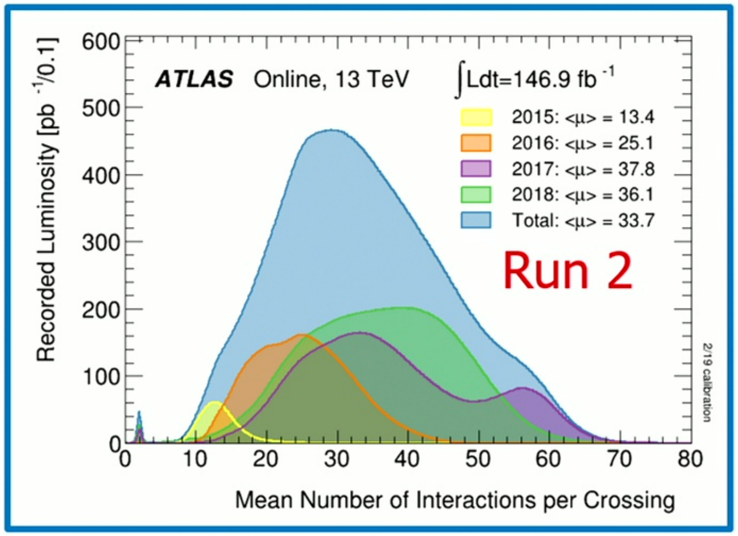
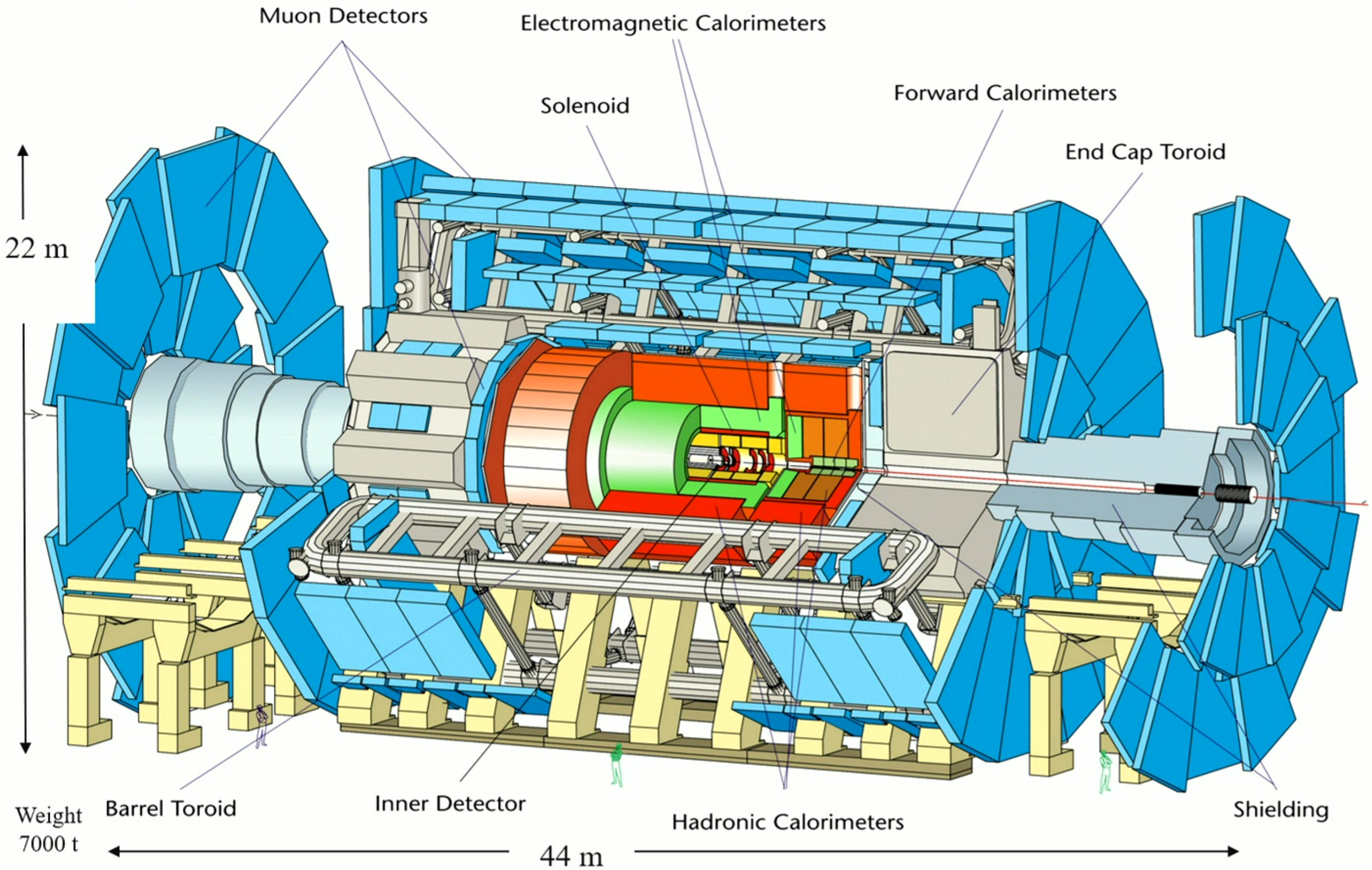


32

pile-up (out-of-time)

- Interactions every 25 ns …
  - In 25 ns particles travel 7.5 m



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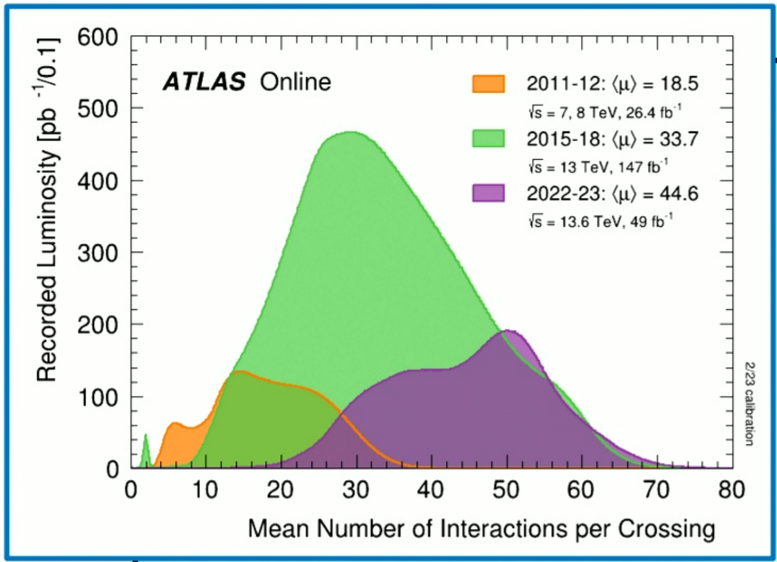


Deputy Data Preparation Coordinator

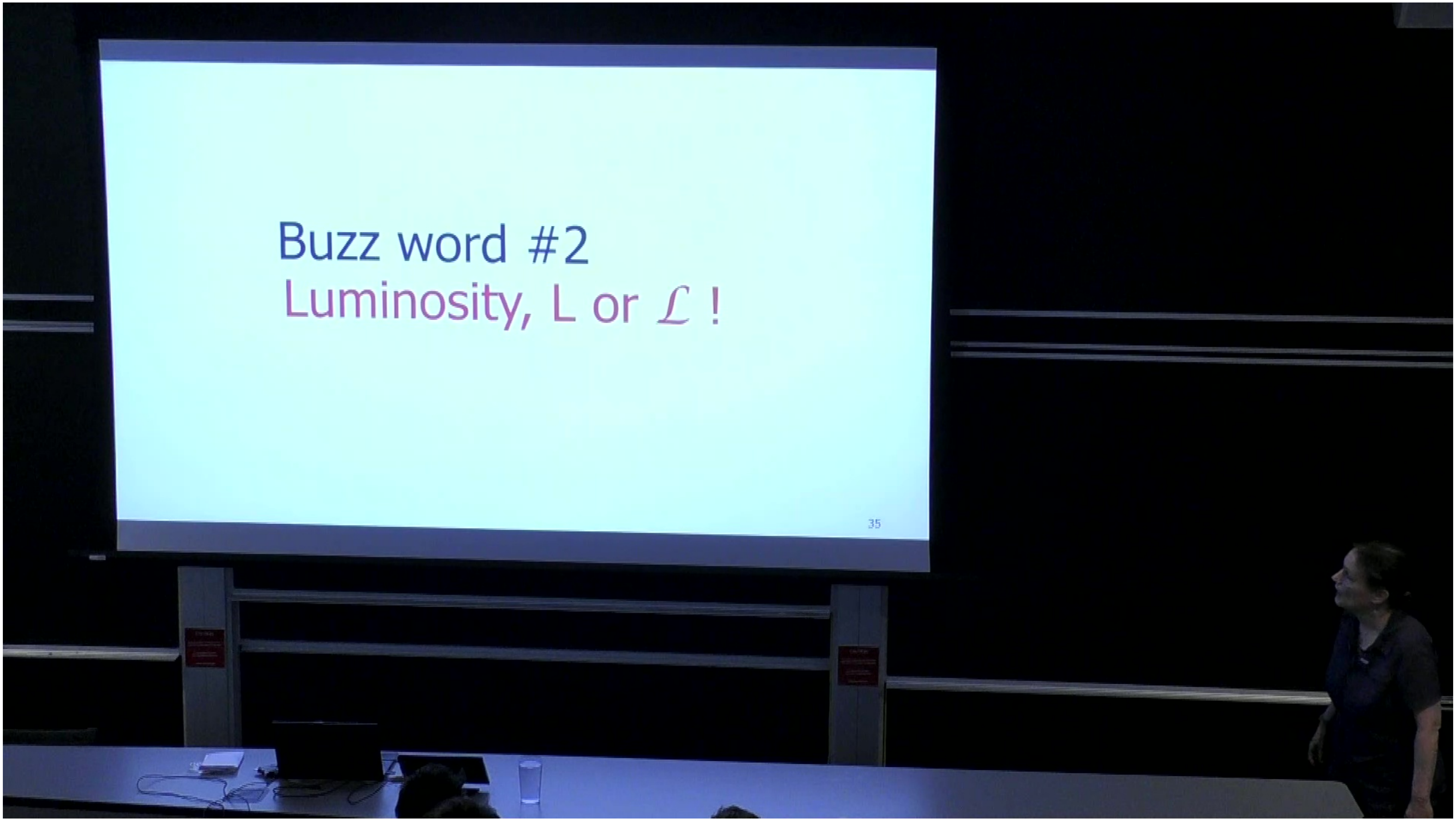
I am fascinated by trying to understand how nature works on the most fundamental level and, for me, the answer lies through particle physics experiments. I love the science and I also love the large and diverse group of people that I get to work with every day.

Heather Gray
Associate Professor at UC Berkeley and Faculty Scientist at LBNL (USA)

Buzz word #2

Luminosity, L or $\mathcal{L}$!

35


Buzz word #2
Luminosity, L or $\mathcal{L}$!
35

Properties of the LHC

Luminosity L: ratio of the number of events produced N within a time t to the interaction cross-section σ:

$$L = \frac{1}{\sigma}\frac{dN}{dt}. \qquad L \propto \frac{{N_b}^2\, n_b\, f_r}{beam\ pars}$$

$N_{tot} = L\,\sigma$

L depends on the beam parameters

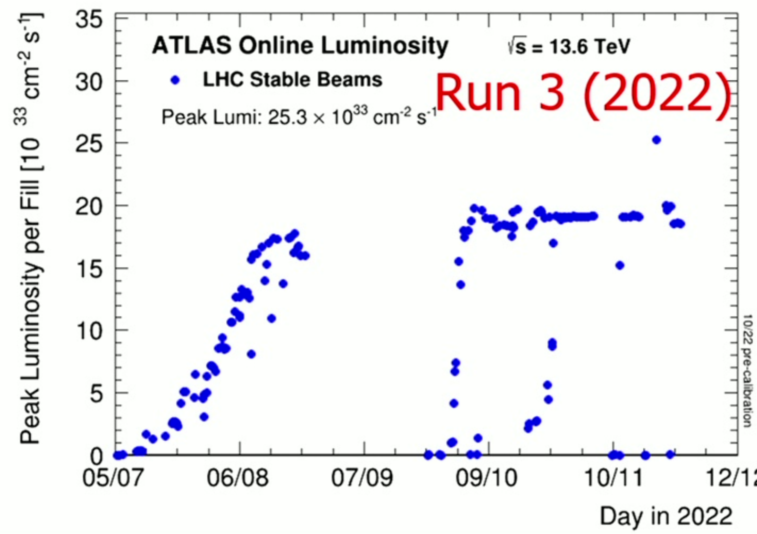
- N_b= number of particles per bunch ≈ 1.15 x 10^{11} protons
- n_b = number of bunches per beam ≈ 2800
  - 26659 m/7.5 m between bunches = 3550 bunches but need extra room to insert bunches etc… so effectively 2800
- f_r = revolution frequency of the accelerator ≈ $[26659\ m/3x10^8\ m/s]^{-1} \cong 11245$ Hz
- Parameters related to the size of the beam in the transverse plane

At full LHC design:

- Centre-of-mass energy of 14 TeV
  - Run 1: 7 TeV (2010/1), 8 TeV (2012)
  - Run 2: 13 TeV (2015-2018)
  - Run 3: 13.6 - ? TeV (2022-2025)
- Collisions every 25 ns
  - 50 ns (2010-12), 25 ns (since then)
- Peak luminosity of L = 1 x 10^{34} $cm^{-2}s^{-1}$
  - 2022: L = 2 x 10^{34} $cm^{-2}s^{-1}$

Integrated luminosity ∫Ldt delivered by LHC so far:

- ~28 fb^{-1} (2010-2012), ~155 fb^{-1} (2015-2018), ~40 fb^{-1} (2022)



How do you measure the luminosity? – Part I

Inelastic interactions per BC → μ

Bunch pairs colliding → n_b

LHC revolution frequency → f_r

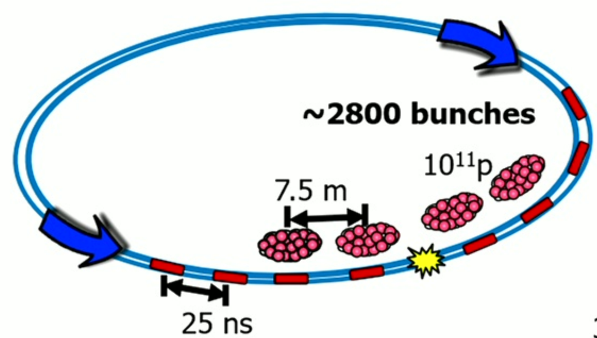
Measured quantity → μ_{vis}

- $L = \dfrac{\mu \, n_b \, f_r}{\sigma_{inel}} = \dfrac{\mu_{vis} \, n_b \, f_r}{\sigma_{vis}}$

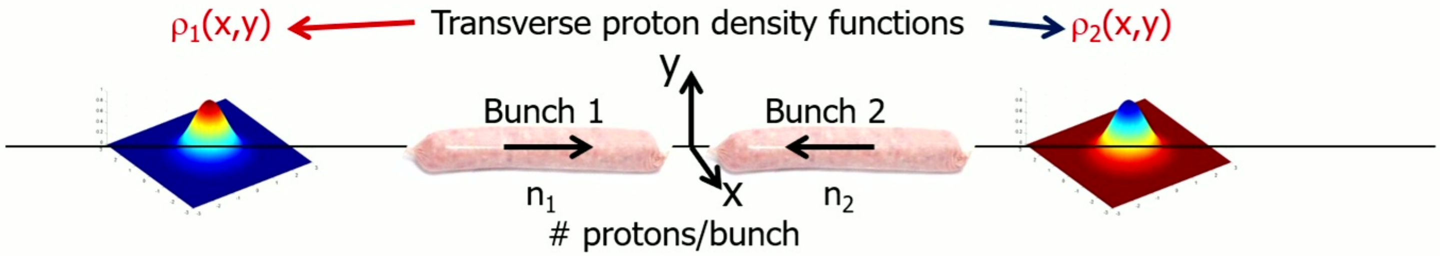
$\sigma_{vis} = \varepsilon \times \sigma_{inel}$
Needs to be calibrated!
van der Meer scan

Luminosity detectors:

- Bunch-by-bunch luminosity
  - Dedicated lumi monitors, count the number of primary vertices with tracking detectors
- Bunch blind:
  - Currents in the calorimeters
- Should all give consistent results!



How do you measure the luminosity? – Part II



- Beam-separation scan to get the absolute lumi calibration
- Peak luminosity is a convolution of the beam widths

$$\mathcal{L}_{peak} = f_r n_1 n_2 \iint \rho_1(x,y)\rho_2(x,y)dxdy$$

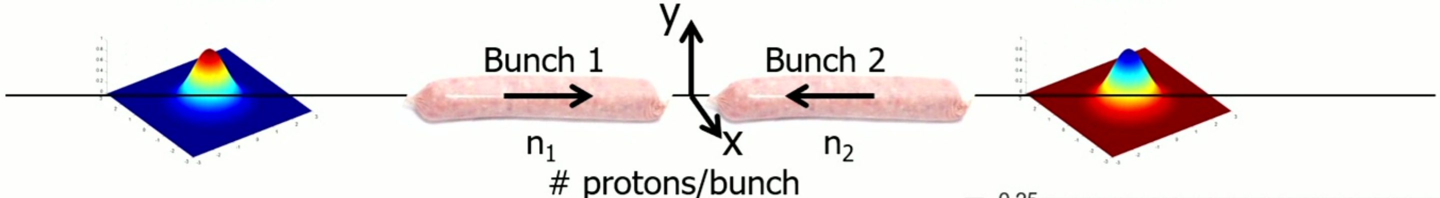
$$= f_r n_1 n_2 \frac{1}{2\pi\Sigma_x\Sigma_y}$$

Bunch population product

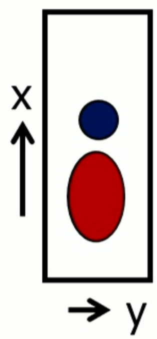
Convoluted beam widths

- Method assumed that you can factorise scan into x and y components
  - Not totally true

How do you measure the luminosity? – Part II



- Beam-separation scan to get the absolute lumi calibration
  - e.g. scan in x

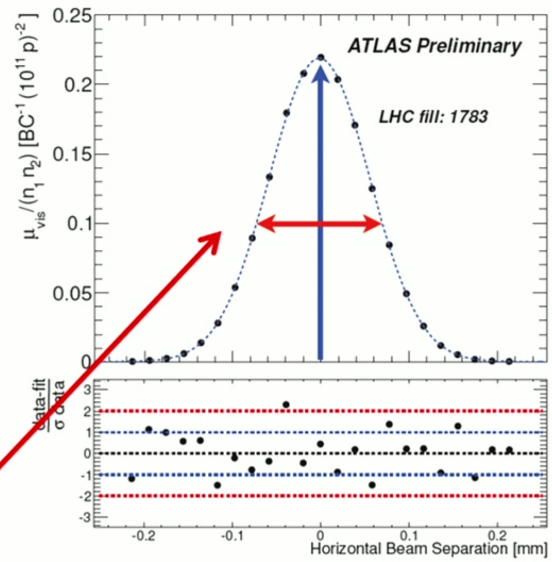


$$\sigma_{vis} = \mu_{vis}^{MAX} \frac{2\pi\Sigma_x\Sigma_y}{n_1 n_2}$$

Scan Widths

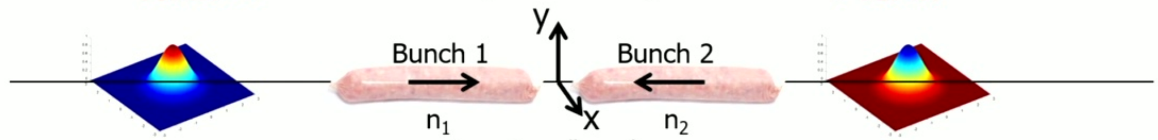
Peak Rate

Bunch Population



x-scan width

How do you measure the luminosity? – Part II



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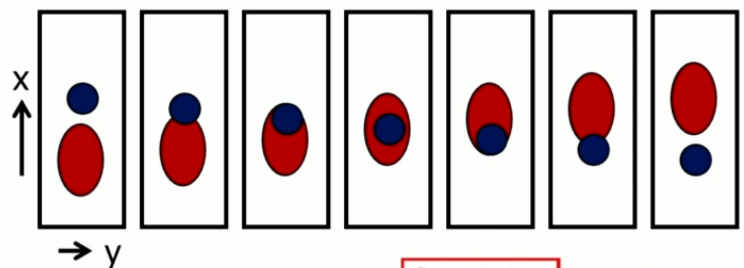
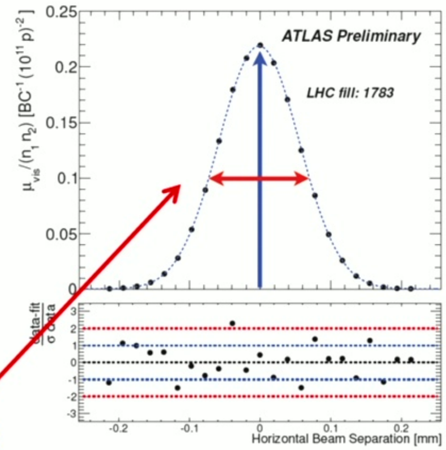




x-scan width

$$\sigma_{vis} = \mu_{vis}^{MAX} \frac{2\pi\Sigma_x\Sigma_y}{n_1 n_2}$$

Peak Rate

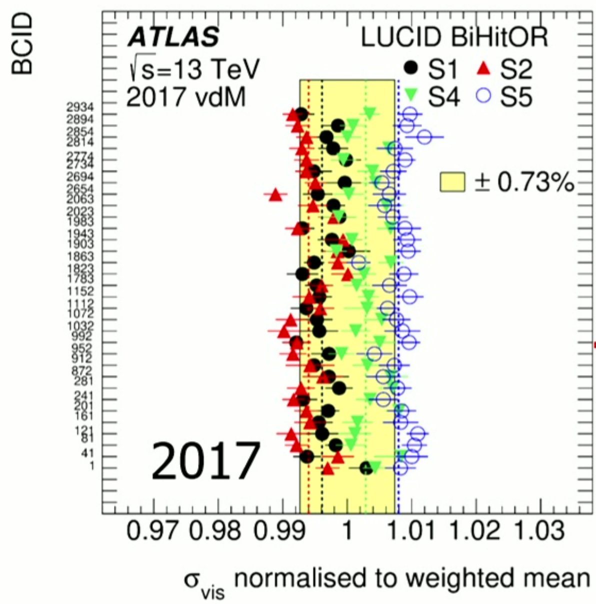
Scan Widths

Bunch Population

39

How do you measure the luminosity? – Part II

- Example of σ_{vis} measured in 2017 using the LUCID detector
  - Four scans as a function of which beam crossing (BCID) where you perform the scan



Data sample	2015	2016	2017	2018	Comb.
Integrated luminosity [fb^{-1}]	3.24	33.40	44.63	58.79	140.07
Total uncertainty [fb^{-1}]	0.04	0.30	0.50	0.64	1.17
Uncertainty contributions [%]:					
Statistical uncertainty	0.07	0.02	0.02	0.03	0.01
Fit model*	0.14	0.08	0.09	0.17	0.12
Background subtraction*	0.06	0.11	0.19	0.11	0.13
FBCT bunch-by-bunch fractions*	0.07	0.09	0.07	0.07	0.07
Ghost-charge and satellite bunches*	0.04	0.04	0.02	0.09	0.05
DCCT calibration*	0.20	0.20	0.20	0.20	0.20
Orbit-drift correction	0.05	0.02	0.02	0.01	0.01
Beam position jitter	0.20	0.22	0.20	0.23	0.13
Non-factorisation effects*	0.60	0.30	0.10	0.30	0.24
Beam–beam effects*	0.27	0.25	0.26	0.26	0.26
Emittance growth correction*	0.04	0.02	0.09	0.02	0.04
Length scale calibration	0.03	0.06	0.04	0.04	0.03
Inner detector length scale*	0.12	0.12	0.12	0.12	0.12
Magnetic non-linearity	0.37	0.07	0.34	0.60	0.27
Bunch-by-bunch σ_{vis} consistency	0.44	0.28	0.19	0.00	0.09
Scan-to-scan reproducibility	0.09	0.18	0.71	0.30	0.26
Reference specific luminosity	0.13	0.29	0.30	0.31	0.18
Subtotal vdM calibration	0.96	0.70	0.99	0.93	0.65
Calibration transfer*	0.50	0.50	0.50	0.50	0.50
Calibration anchoring	0.22	0.18	0.14	0.26	0.13
Long-term stability	0.23	0.12	0.16	0.12	0.08
Total uncertainty [%]	1.13	0.89	1.13	1.10	0.83

Beautiful example of accelerator + detector physics

- Then need to transport results to normal data-taking conditions
- Luminosity uncertainty 2011: 1.8%, 2012: 1.9%, 2015-2018: 0.83%

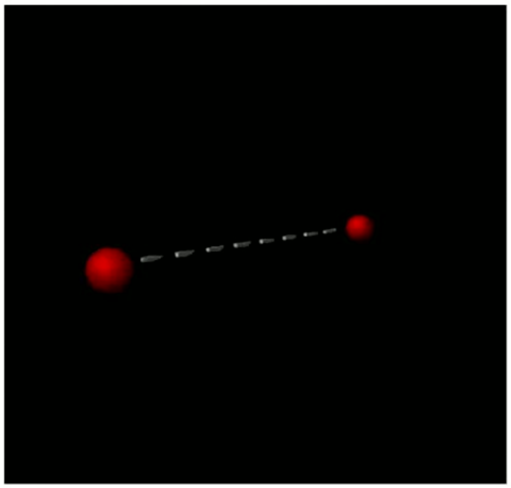
Buzz word #3

Collision event!

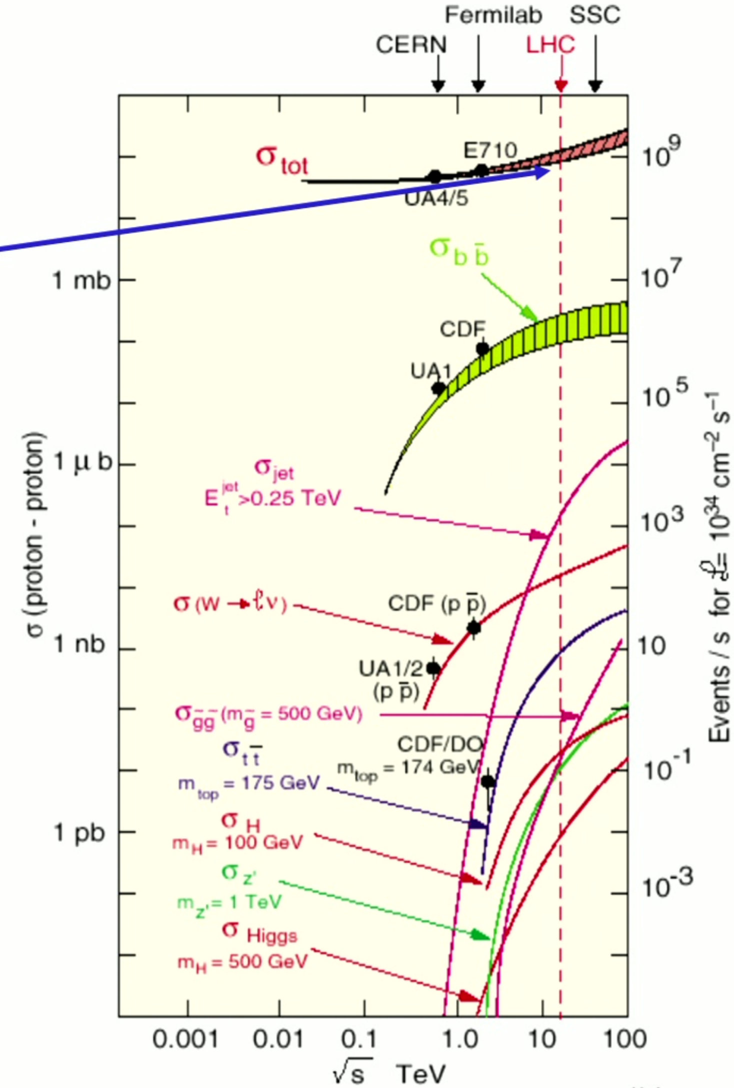
Proton-proton collisions

Proton-proton cross section:

- $\sigma^{pp}_{tot}(s) = \sigma_{elastic}(s) + \sigma_{inelastic}(s)$
- $\sigma^{pp}_{tot}(s) \approx 100$ mb at centre-of-mass energy $\sqrt{s} = 14$ TeV (design LHC):
  - Note: 1 millibarn (mb) = 10^{-31} m^2 = 10^{-27} cm^2 (i.e. units of area)



- Approximate event rates for various physics channels for L=10^{34} cm^{-2}s^{-1}:
  - $W \rightarrow l\nu$: 100 Hz, ttbar: 10 Hz, Higgs: 1 Hz
- Trigger is critical to get to the interesting events!
  - It makes **irrevocable** decisions!



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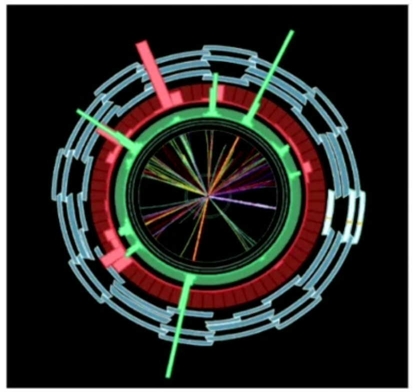

- Approximate event rates for various physics channels for $L=10^{34}$ cm^{-2}s^{-1}:
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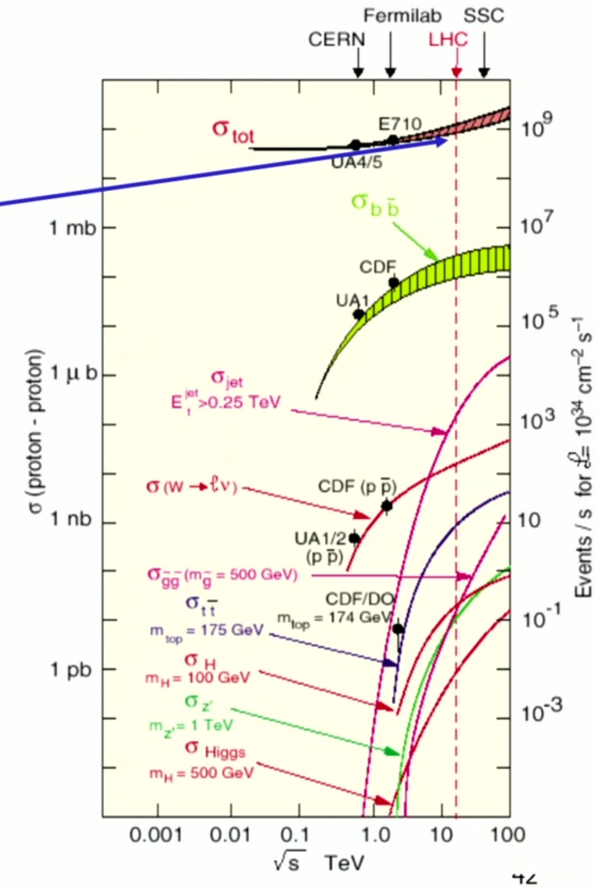

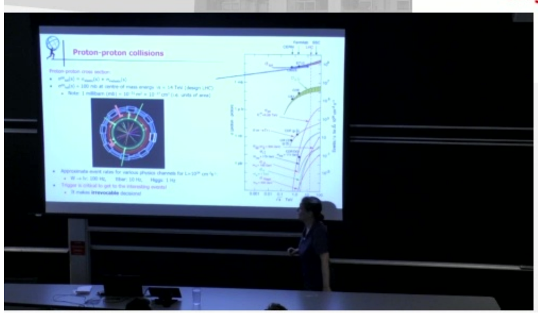

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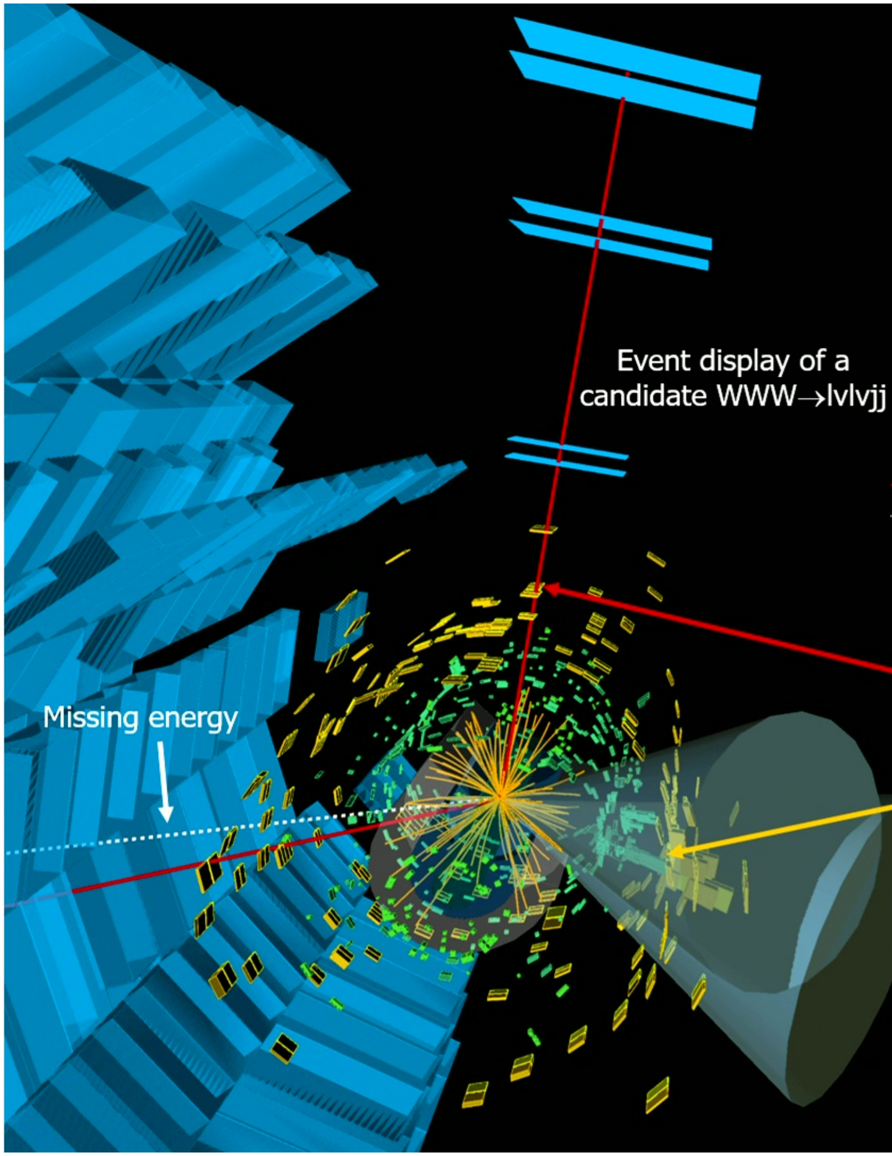


ATLAS Trigger/ Data Acquisition System

40 MHz → Level-1: 100 kHz → High-Level Trigger: 3 kHz (Run 3) → Stored

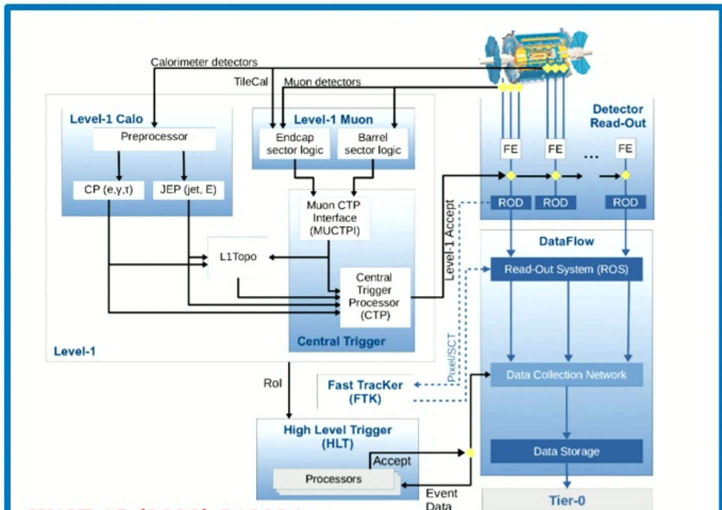
On-detector hardware.
Decision in 2.5 μs.

Muon

Jet of particles

Off-detector computing,
~50k processing apps.
Decision in <1/2 s.
More refined selection.

Recall: 1/25 ns = 40 MHz



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Deputy Trigger Coordinator

Everyday is something new and interesting. Working on ATLAS is like working on a giant puzzle where all the different pieces need to come together to deliver a very interesting physics picture. Working with so many different people to make sure everything comes together so that we can efficiently collect the data delivered from the LHC is a very rewarding experience.

Savanna Shaw
Research Associate, University of Manchester (UK)

A proton-proton collision event (cartoon)