PHYS 7363 - Experimental Particle Detection and Detectors I

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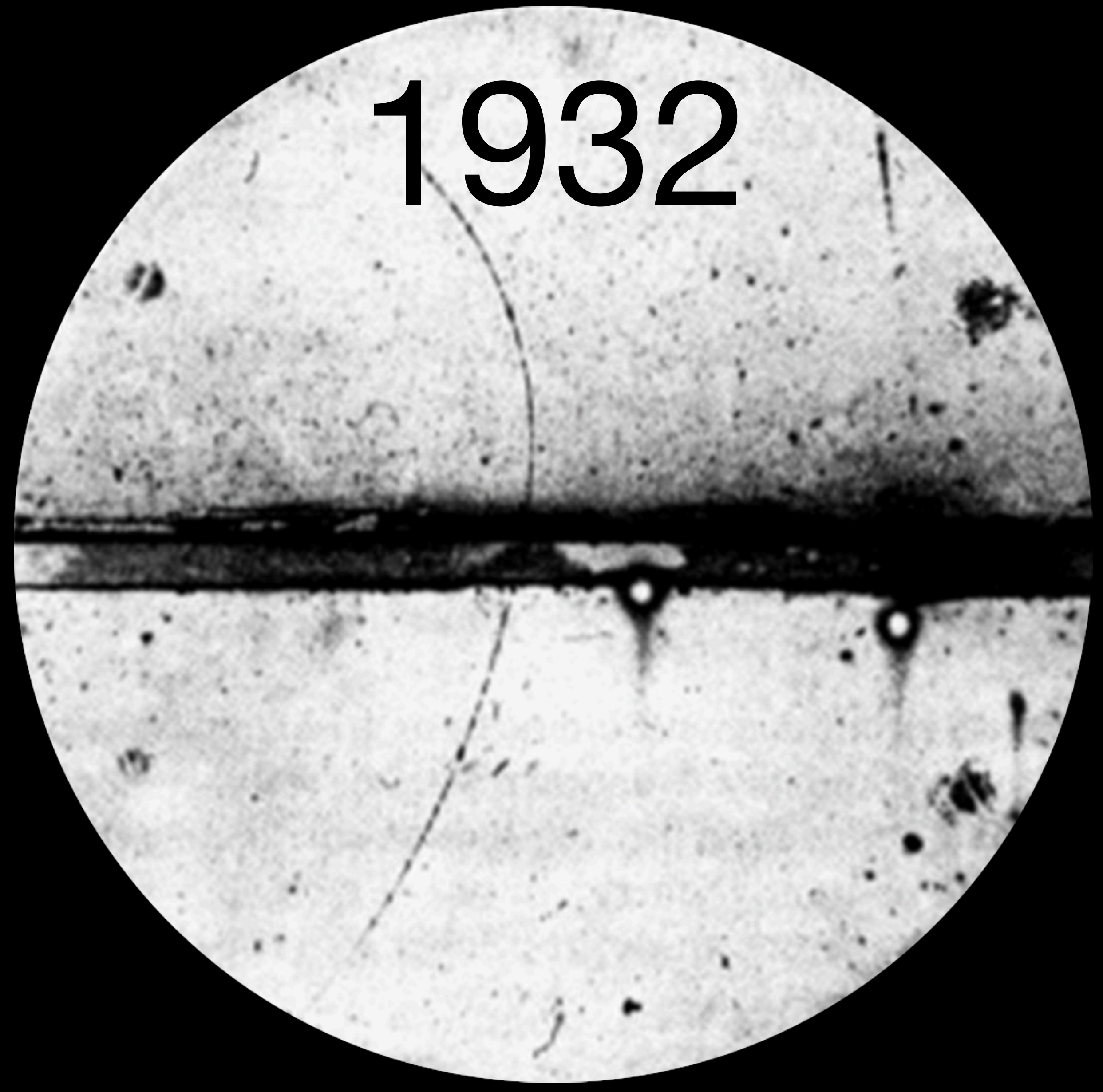
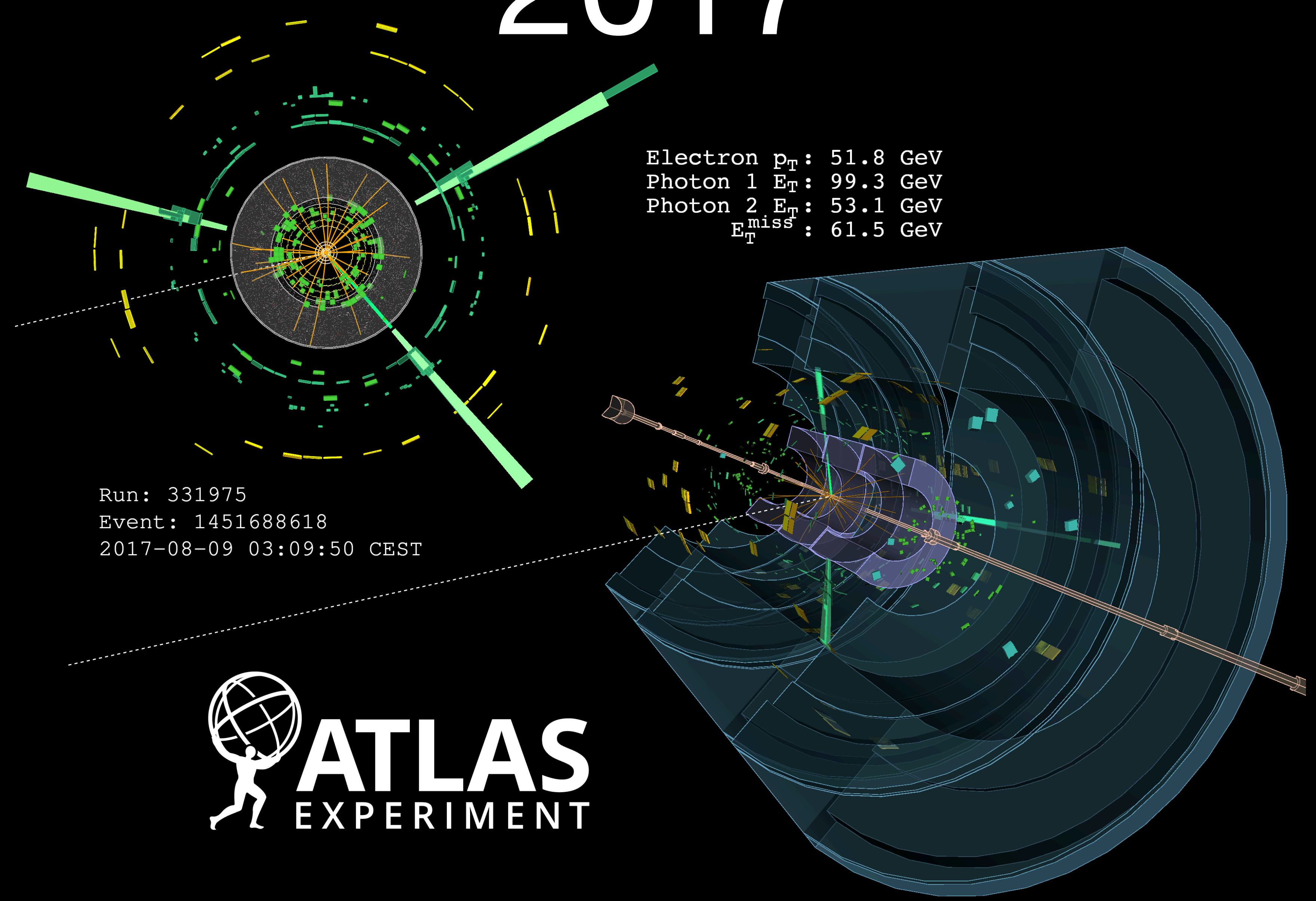
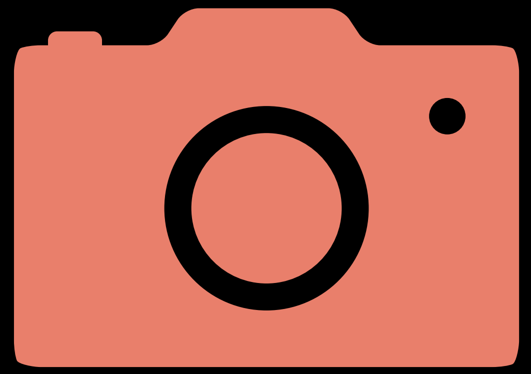


2017

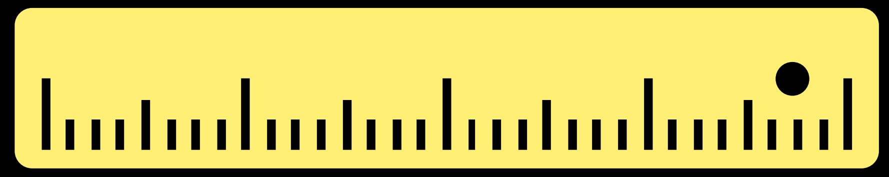


Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection* and *identification*, examine the intricate designs of modern detectors, and learn how machine learning is being harnessed to push the boundaries of detector design. If you're intrigued by how we “see” subatomic particles, this course is for you!



Detect

Identify



Measure

To discuss prerequisites (and any questions on the content of the course), please contact me: saptaparnab@smu.edu

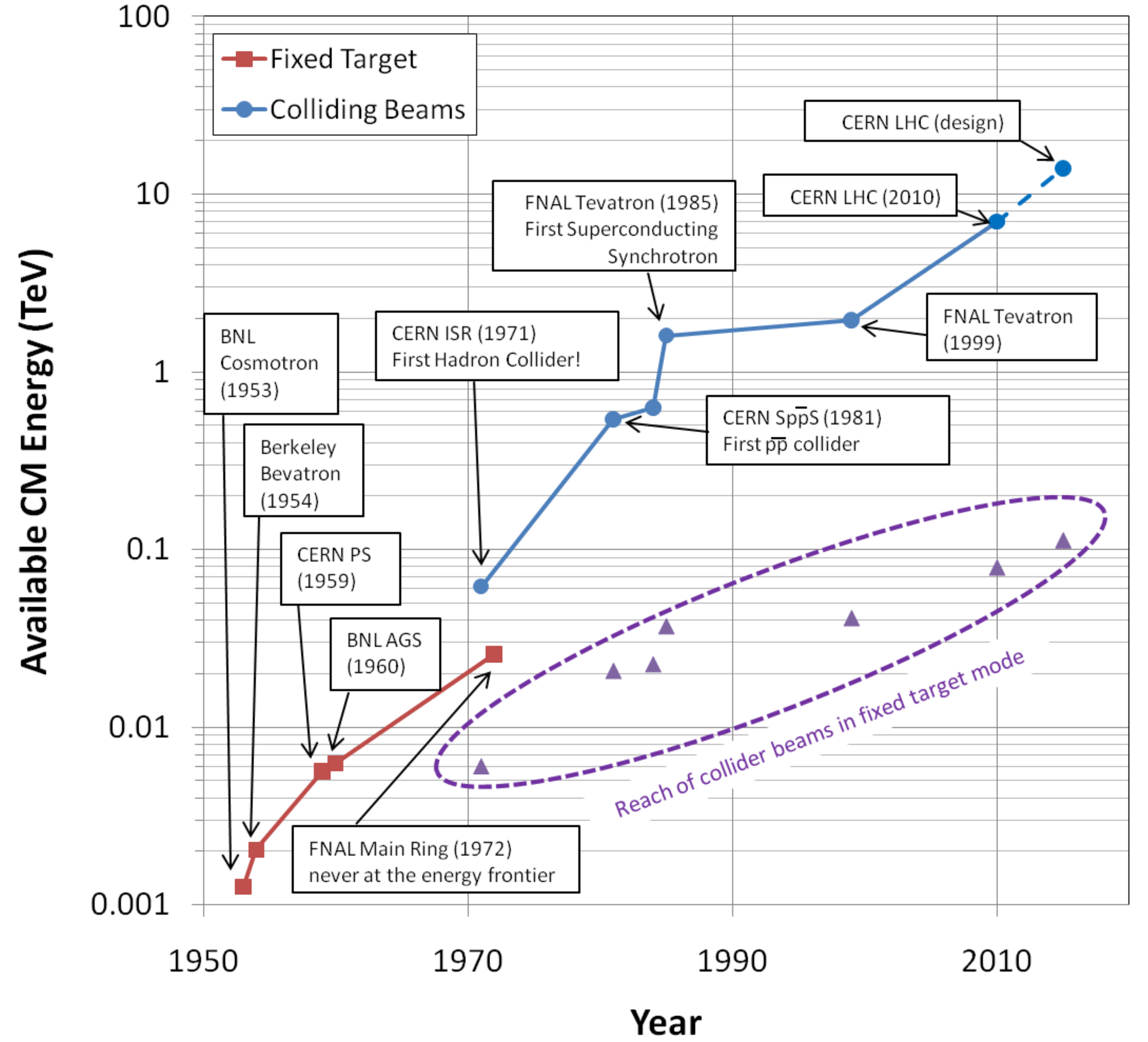
Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
October	6 ✅ 1.5 hours	7	8 ✅ 1.5 hours	9	10	11	12
	13 ✅ 1.5 hours	14	15 ✅ 1.5 hours	16	17 ✅	18	19
	20	21	22	23 ✅ 1.5 hours	24 ✅ 1.5 hours	25	26
	27: Midterm	28	29 ✅ 1.5 hours	30	31 ✅ 1.5 hours	1	2
November	3 ✅ 1.5 hours	4	5 ✅ 1.5 hours	6	7 ✅ 1.5 hours	8	9
	10 ✅ 1.5 hours	11	12 ✅ 1.5 hours	13	14 ✅ 1.5 hours	15	16
	17 ✅ 1.5 hours	18	19 ✅ 1.5 hours	20	21 ✅ 1.5 hours	22	23
	24 ✅ 1.5 hours	25	26	27	28	29	30
December	1 ✅ 1.5 hours	2	3	4	5 ✅ 1.5 hours	6	7
	8 ✅ 1.5 hours	9	10	11	12	13	14

A few important topics…

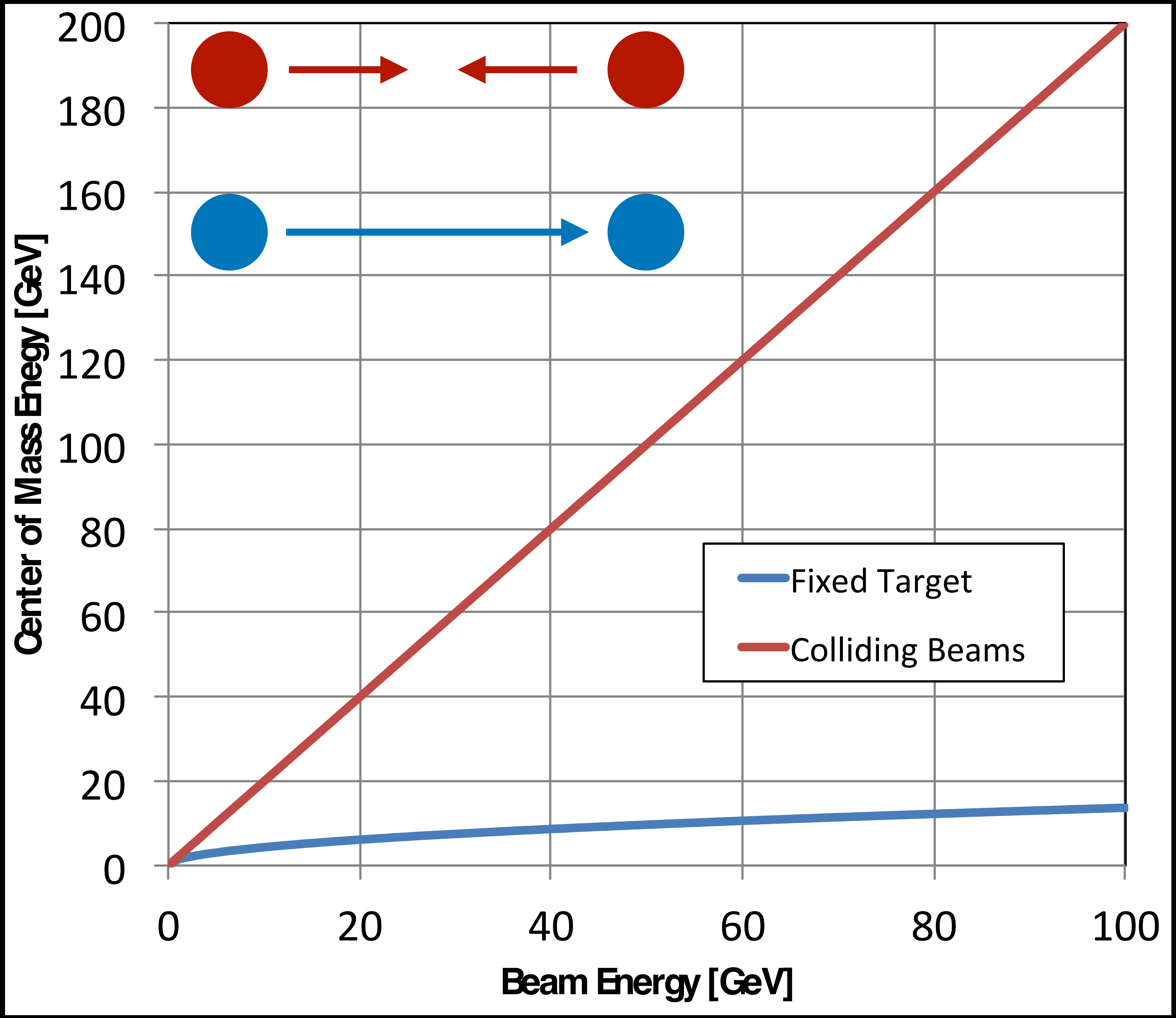
- In this lecture, I will cover a few important topics that we did not cover during the rest of the course:
  - LHC fill structure and pileup
  - Emittance and $\beta*$
  - Structure of electric field: some math
  - Calculate the limiting factor in raising energies in accelerators

Development



Accelerator basics — the collider

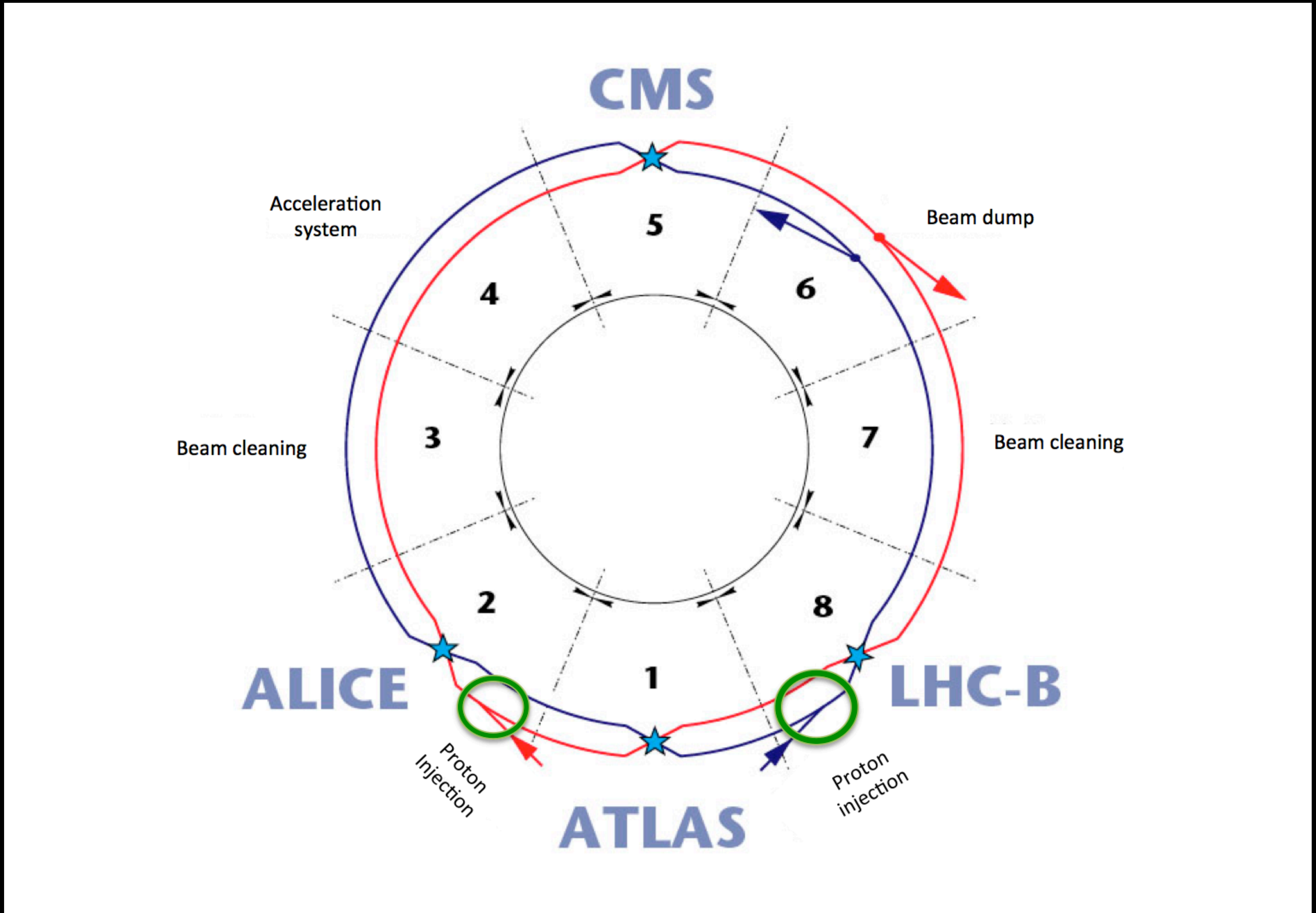
- If the beam hits a stationary proton, the center of mass energy is:
  - $E_{CM} = \sqrt{2E_{beam}m_{target}c^2}$
  - $E_{CM} = 2E_{beam}$
- To get the 14 TeV CM design energy of the LHC with a single beam on a fixed target would require that beam to have an energy of 100,000 TeV!
  - Would require a ring 10 times the diameter of the Earth!!
- We have to collide beams!



Some quick math

- To get the 14 TeV CM design energy of the LHC with a single beam on a fixed target would require that beam to have an energy of 100,000 TeV!
  - Would require a ring 10 times the diameter of the Earth!!
- Repeat this calculation!

LHC beam circulation



- Beam dumps are responsible for the safe absorption of the Large Hadron Collider (LHC) particle beams
- Beam cleaning: The system has primary, secondary, and tertiary collimators that progressively catch off-momentum and off-amplitude particles

- LHC filling scheme can be viewed here: https://lpc.web.cern.ch/cgi-bin/filling_schemes.py

LHC beam circulation

- LHC kicker systems:
  - Purpose of the LHC injection kicker systems is to quickly “kick” (deflect) incoming proton beams onto the correct central orbit within the main accelerator ring. This requires a magnetic field pulse with a precise shape
  - **Fast Rise Time**: The magnetic field must rise to its peak strength in the time between two successive beam “batches” to avoid deflecting circulating particles. The target rise time is less than 900 nanoseconds
  - **Flat Top**: The pulse must then maintain a constant (flat) magnetic field strength for a duration of up to 7.86 microseconds, corresponding to the length of the injected beam batch.

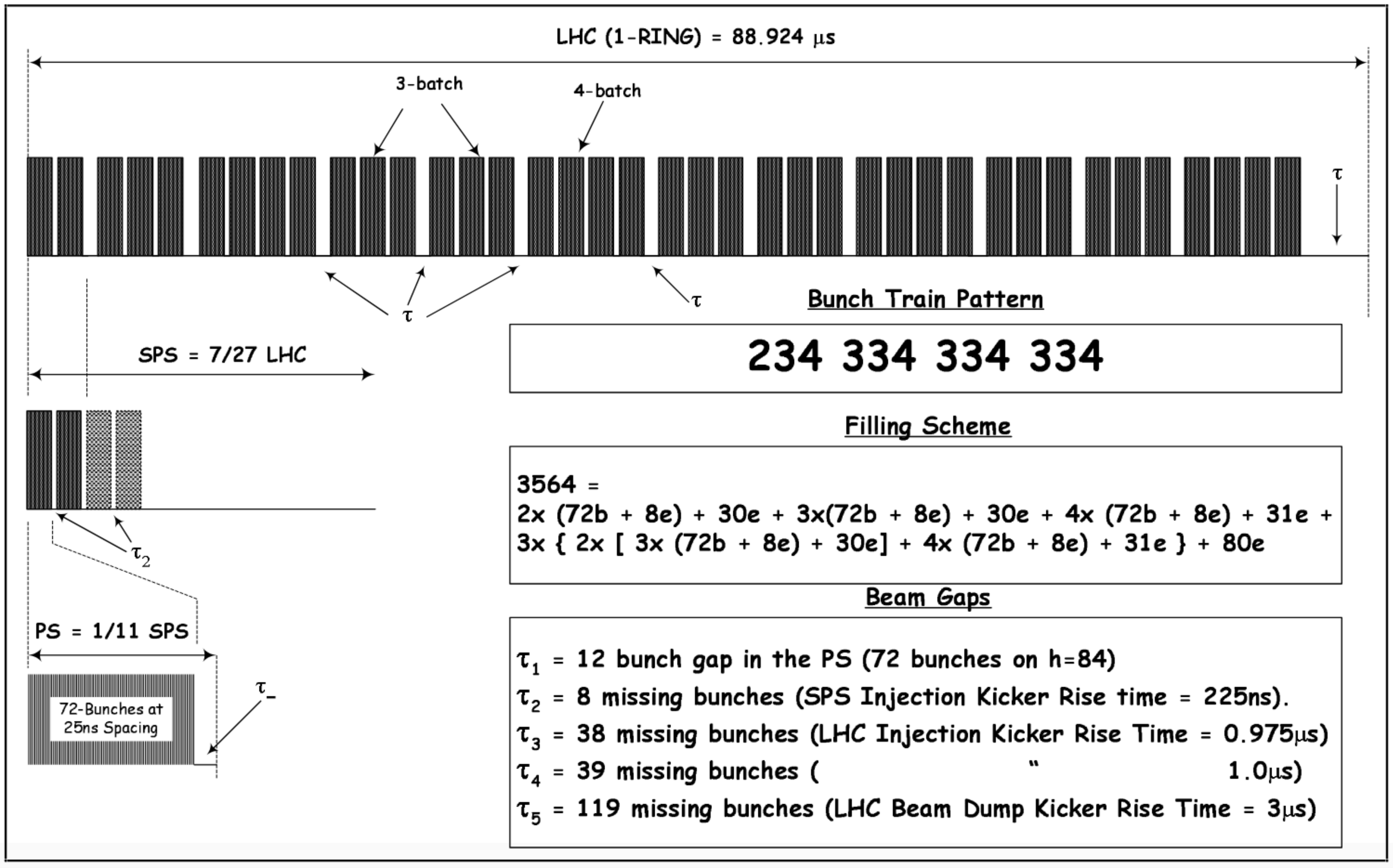
LHC filling scheme

- At the LHC, bunches of protons are injected every 25 ns
  - This is called the nominal proton bunch filling scheme
    - Widely used as baseline and adopted in 2000
  - The scheme lays out how many slots there are and how the bunches are injected into the ring
- All LHC filling schemes must respect:
  - A beam dump gap of 3 μs to allow for the dump kicker rise time (time for magnetic field to rapidly grow)
  - The space between adjacent batches injected into the LHC must be greater than the rise time of the LHC injection kickers (0.95 μs)
    - The LHC is equipped with two kicker systems installed at the injection points (near points 2 and 8) where the particle beams coming from the SPS are injected into the accelerator’s orbit
  - The LHC injection kicker flat top cannot exceed 7.86 μs
  - Minimize PACMAN bunches: bunch to bunch differences introduced by missing beam-beam interactions

LHC filling scheme

- In the 25 ns filing scheme, the beam is arranged in the form of 39 batches of 72 bunches
  - The bunches in each batch are spaced at 25 ns
  - Between the batches are gaps to allow for the SPS and LHC kicker rise times
  - Makes a total of 2808 bunches per LHC ring

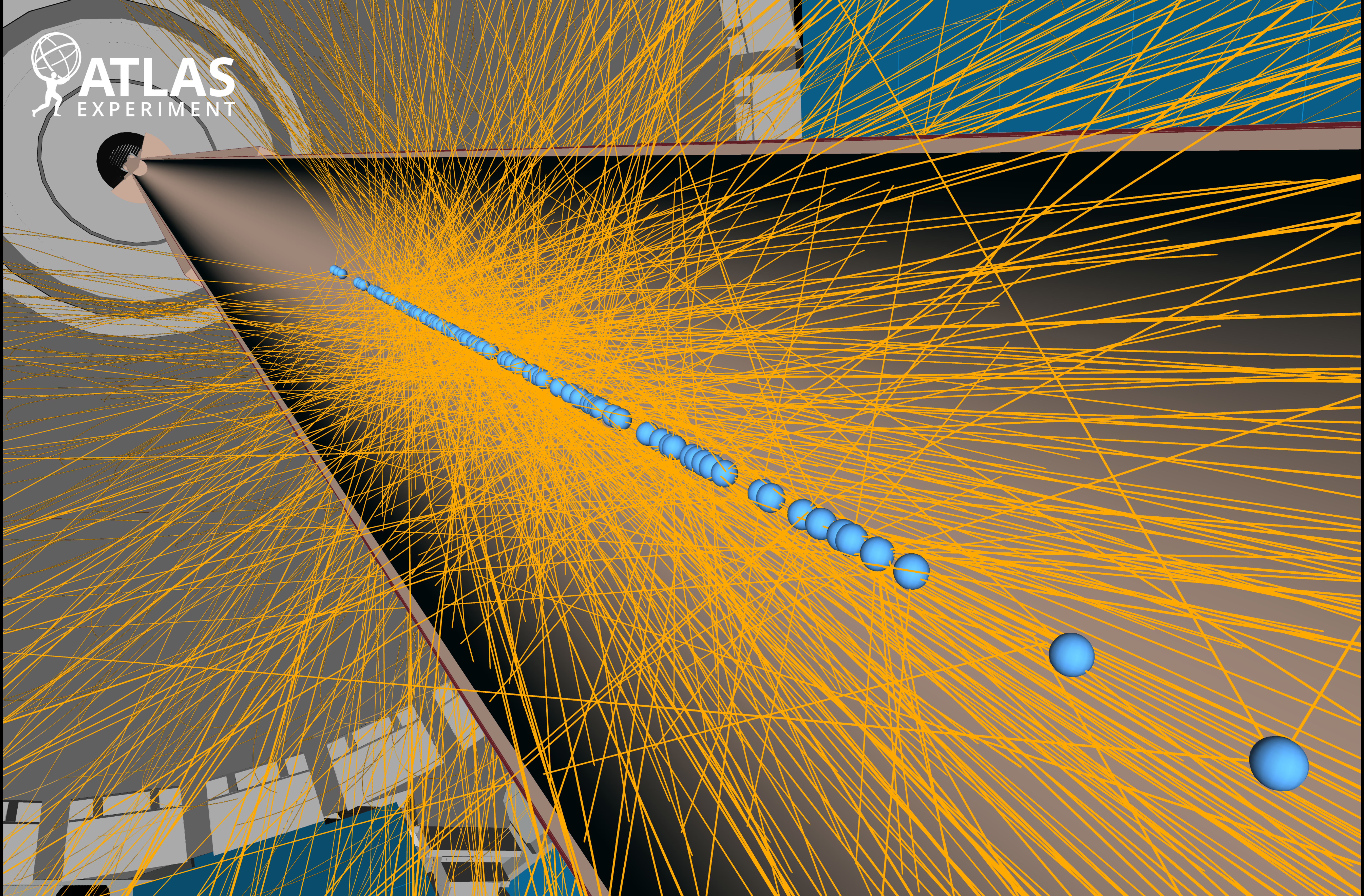
$$3564 = [2x\,(72b + 8e) + 30e] + [3x\,(72b + 8e) + 30e] + [4x\,(72b + 8e) + 31e] +$$
$$3x\,\{2x\,[3x\,(72b + 8e) + 30e] + [4x\,(72b + 8e) + 31e\,]\} + 80e$$



Pileup

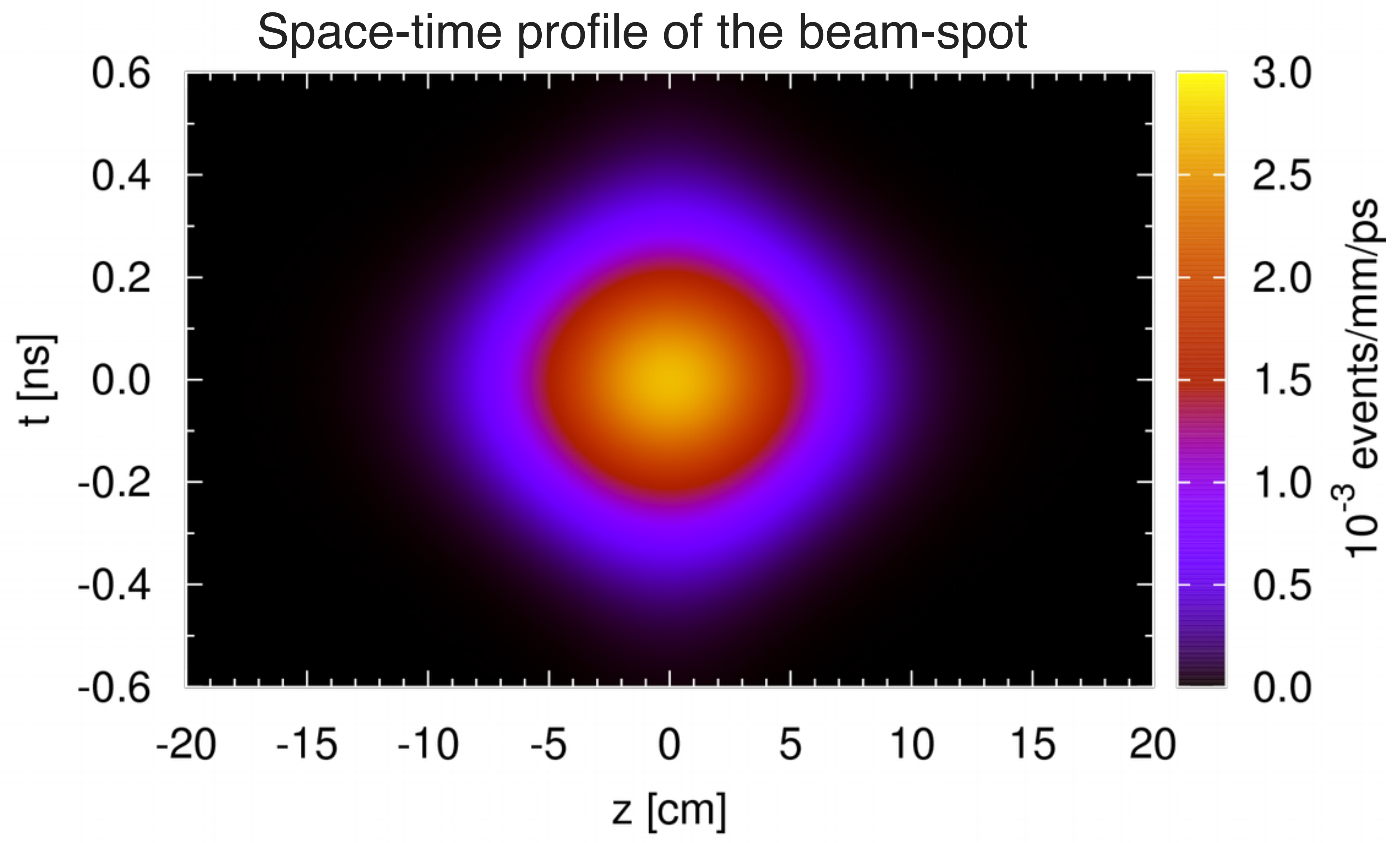
- LHC filling schemes dictate how protons are injected
  - causing pile-up, which is the multiple simultaneous collisions per bunch crossing
- What is pileup:
  - It is the phenomenon where multiple proton-proton (or ion) collisions occur within the same bunch crossing interval at the interaction points
    - These collisions can be grazing collisions
  - Measured as average events per bunch crossing, it is vital for high instantaneous luminosity but when it is too high, it overwhelms detectors
- Filling scheme and its impact on pileup:
  - Shorter spacing (e.g., 25ns) allows more bunches but increases pile-up; longer spacing (e.g., 50ns) reduces pile-up but lowers luminosity
  - Schemes use specific patterns, like placing bunches (b) separated by empty buckets (e), e.g., "8b+4e" or "24b+2e," to manage collisions and beam stability

Pileup



Mitigation of pileup — LHC timing detectors

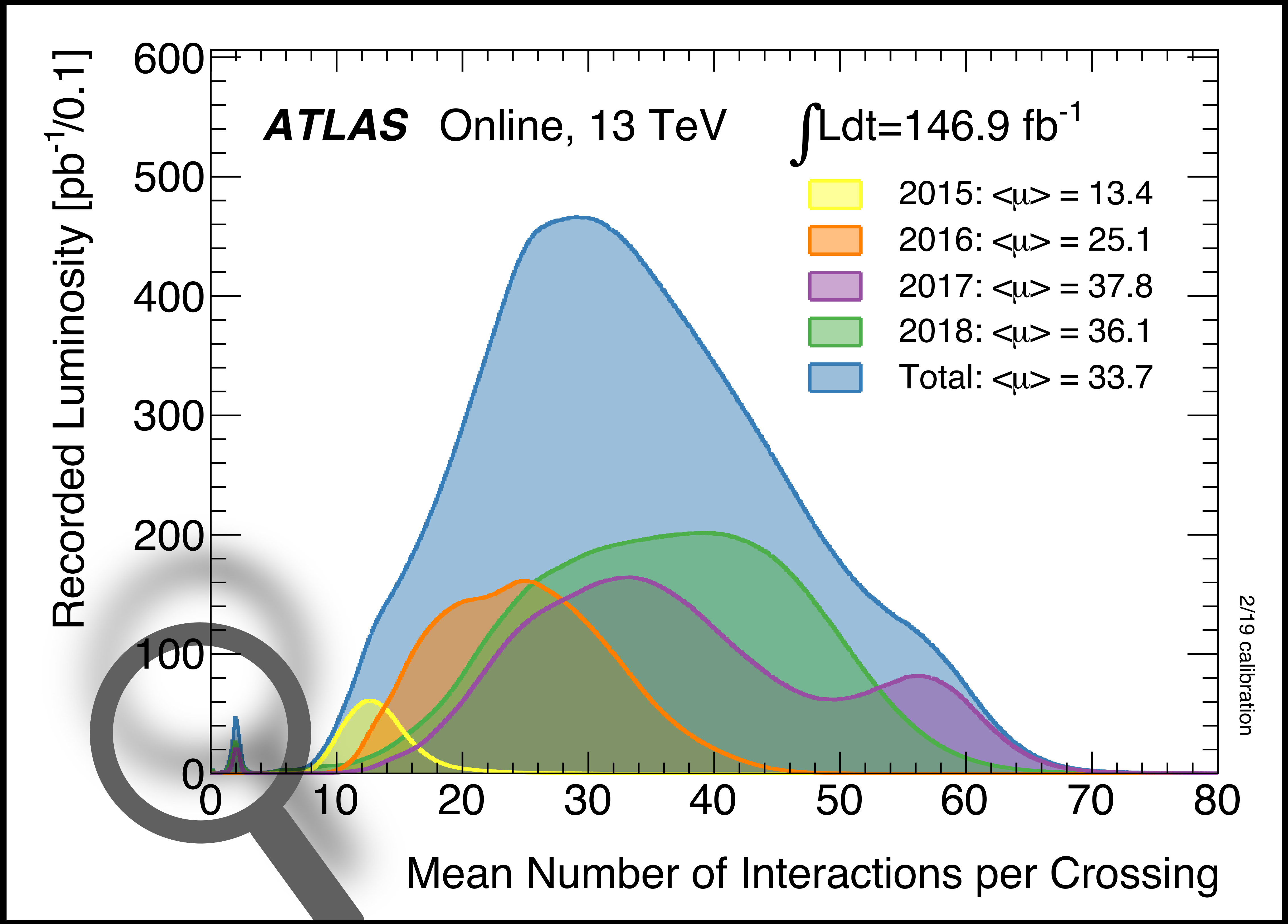
- Interactions at the LHC are spread over 100-200 ps in time
- HGCAL is capable of providing timing information associated with each recHit
- Time information can be used to distinguish between overlapping showers in space (from pile-up)



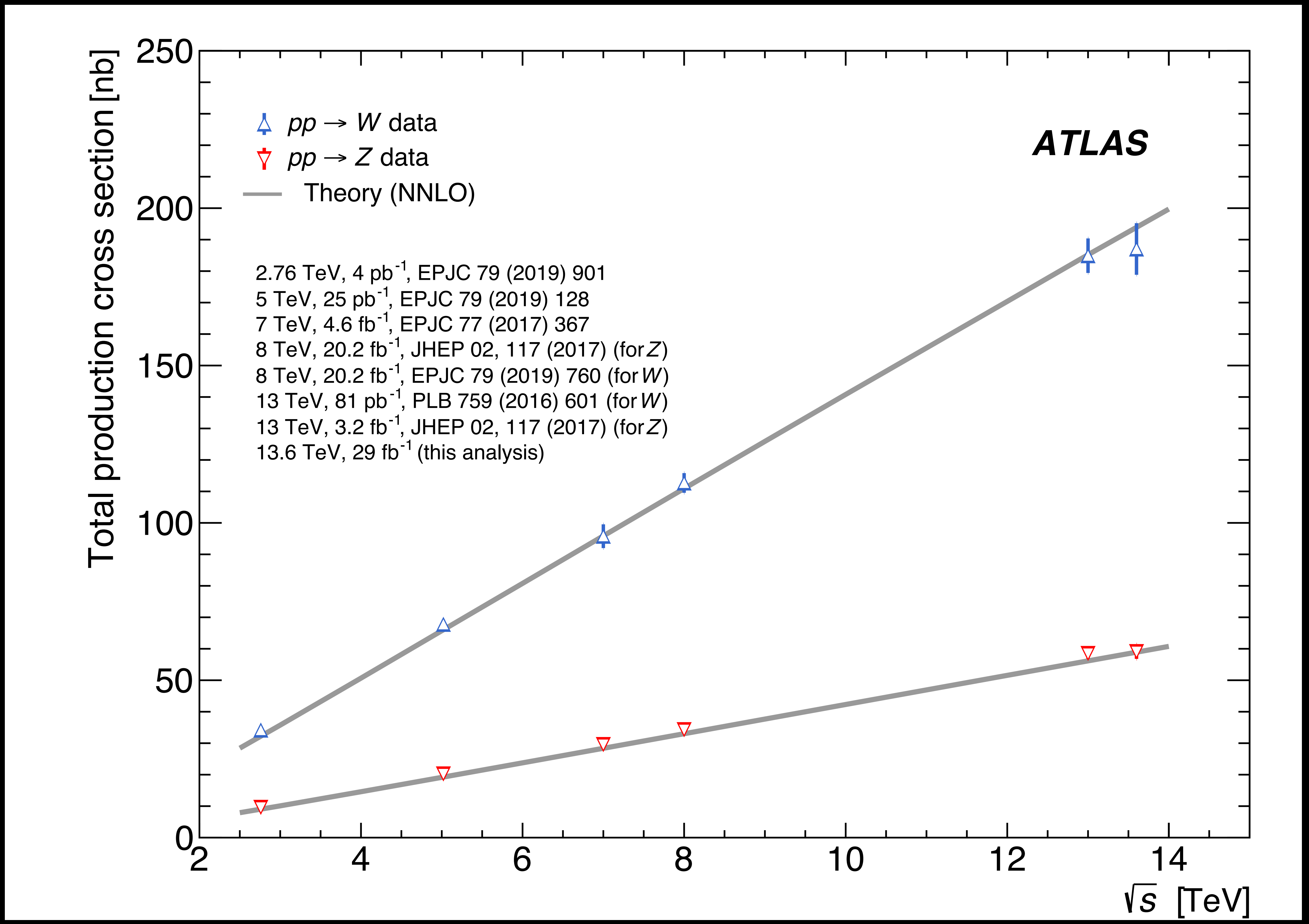
Case for low pileup: Single Boson Measurements

- Billions of W and Z bosons produced at the LHC
  - Enables precision tests of the electroweak theory
- To get to percent-level precision → multi-year effort
  - Low pileup runs are specially useful

- Cross section measured at $\sqrt{s}$ = 5.02, 13 and 13.6 TeV



Cross sections across several $\sqrt{s}$



Luminosity

- The relationship of the beam to the rate of observed physics processes is given by the "Luminosity"
  - $Rate = L\sigma$
- Standard unit for Luminosity is $cm^{-2}s^{-1}$
- Standard unit of cross section is "barn"=10^{-24} cm^2
- Integrated luminosity is usually in $barn^{-1}$, where $b^{-1} = (1\ \text{sec}) \times (10^{24}\text{cm}^{-2}\text{s}^{-1})$
- $nb^{-1} = 10^9\ b^{-1}$, $fb^{-1}=10^{15}\ b^{-1}$
- L is often expressed as $10^{\text{large exponent}}$ like 34, 10^{34} collisions per cm^2

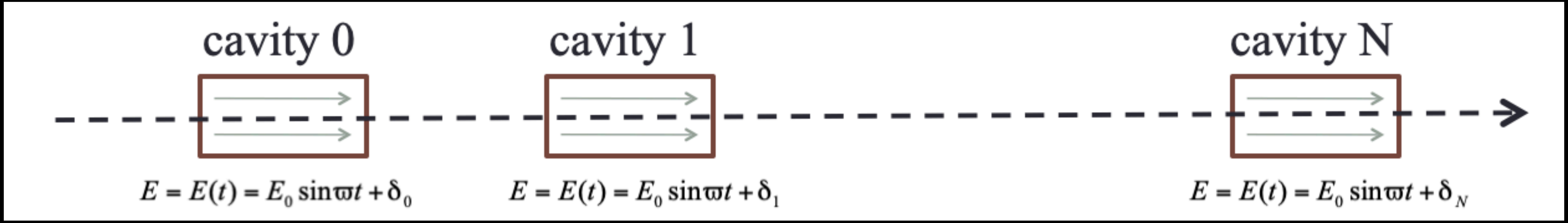
Luminosity of colliding proton beams

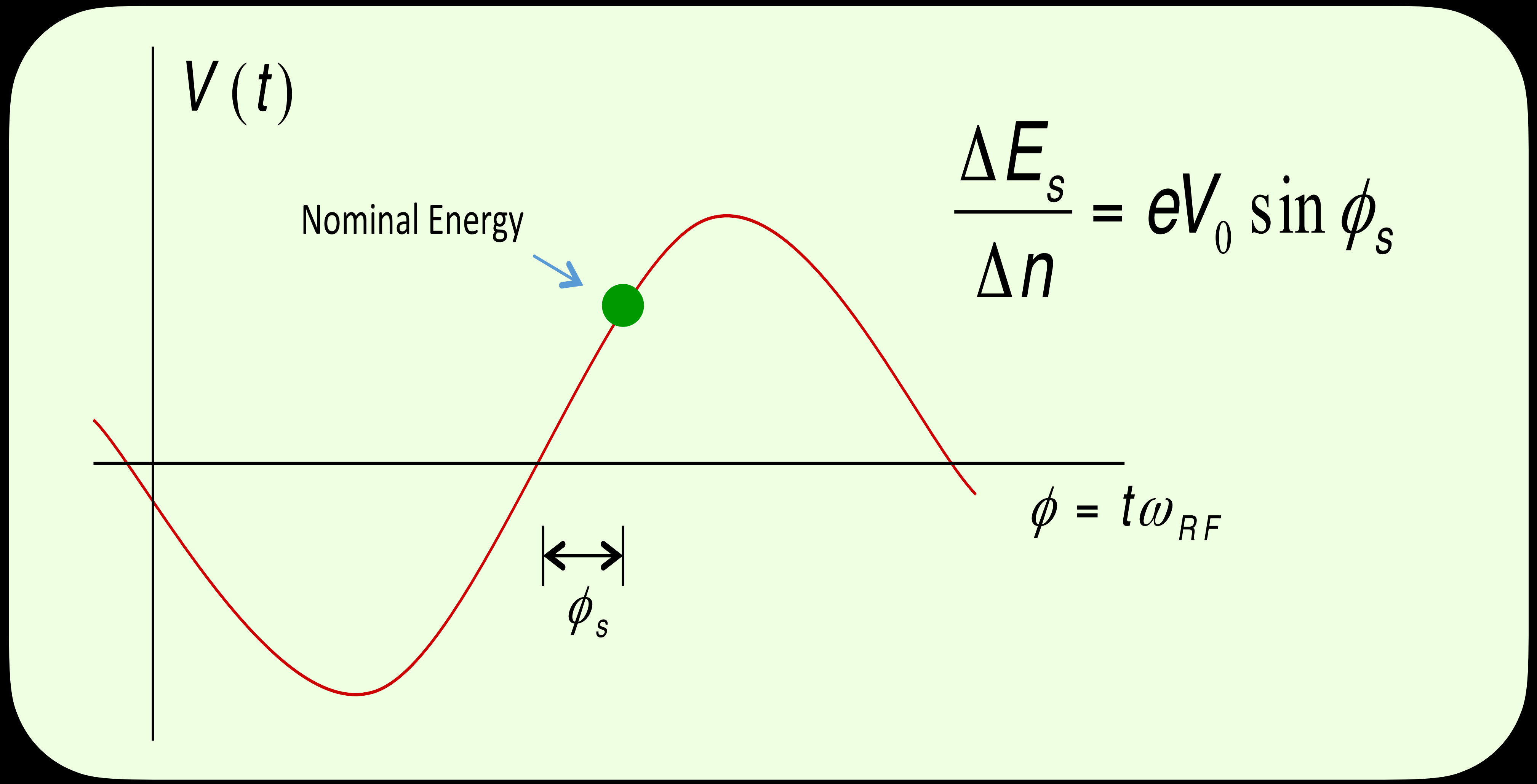
- For equally intense Gaussian beams
  - Collision frequency:
    - $L = f \frac{N_b^2}{4\pi\sigma^2} R$
    - f = collision frequency
    - N_b = particles in a bunch
    - R = geometrical factor (crossing angle)
    - σ = Transverse size (RMS)
  - Using $\sigma^2 = \frac{\beta^* \epsilon_N}{\beta\gamma} \approx \frac{\beta^* \epsilon_N}{\gamma}$
    - $L = f_{\text{rev}} \frac{1}{4\pi} n_b N_b^2 \frac{\gamma}{\beta^* \epsilon_N} R$
      - f_{rev} = collision frequency
      - n_b = number of bunches
      - β^* = betatron function at collision point, low values preferred

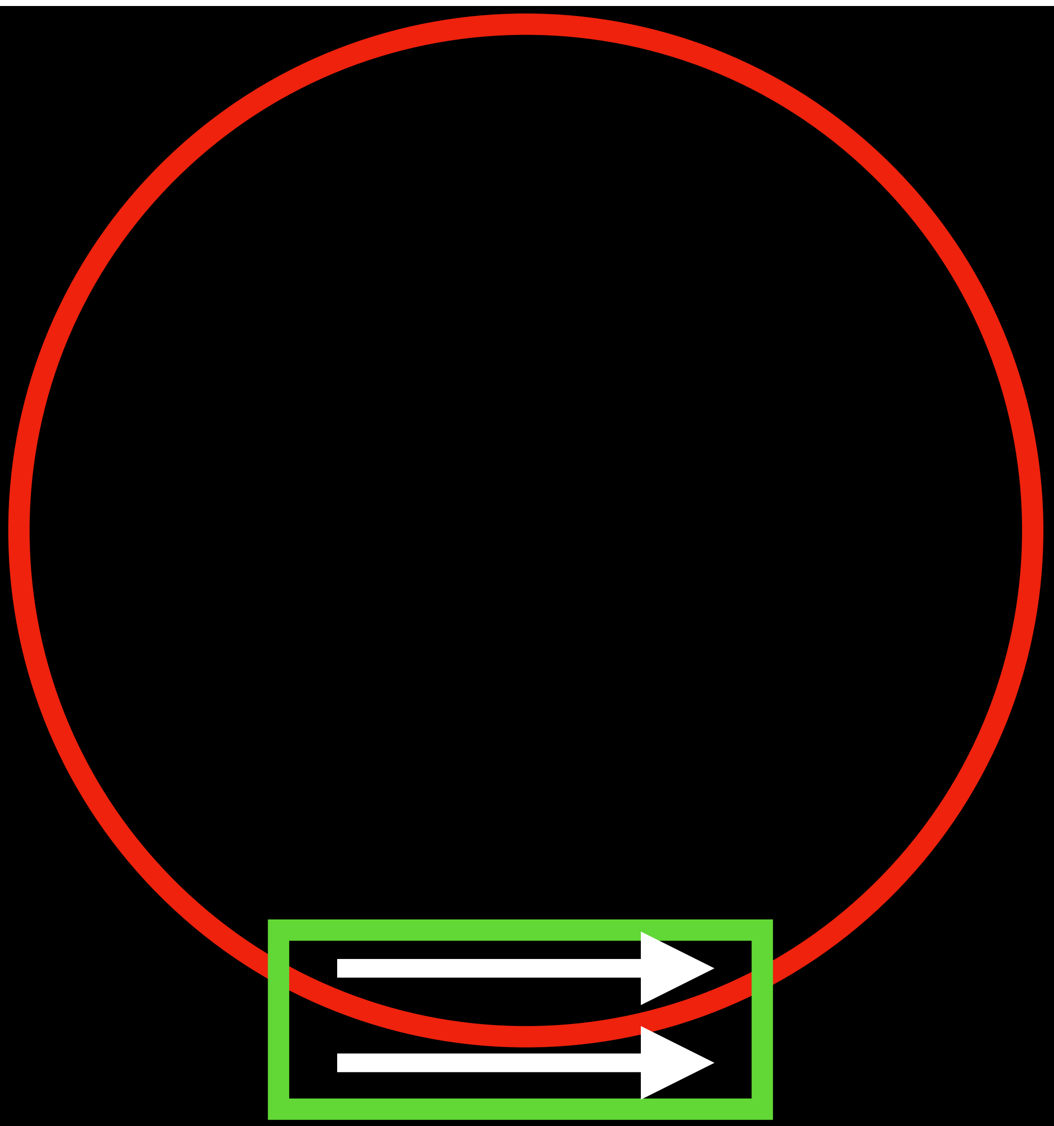
- $\sigma = \sqrt{\beta \cdot \epsilon}$, ϵ = geometric emittance, root mean square is a measure of the area occupied by the beam particles in a 2D phase space
- Normalized emittance: account for relativistic effects
  - $\epsilon_N = \beta_{rel} \cdot \gamma \cdot \epsilon$

Accelerator basics — the electric field

- Generally accelerate particles using structures that generate time varying electric fields (Radio Frequency cavities) either:
  - in a linear arrangement or
  - a circular ring







In both cases, phase the RF so a nominal arriving particle will see the same accelerating voltage and therefore get the same boost in energy

Equations of motion

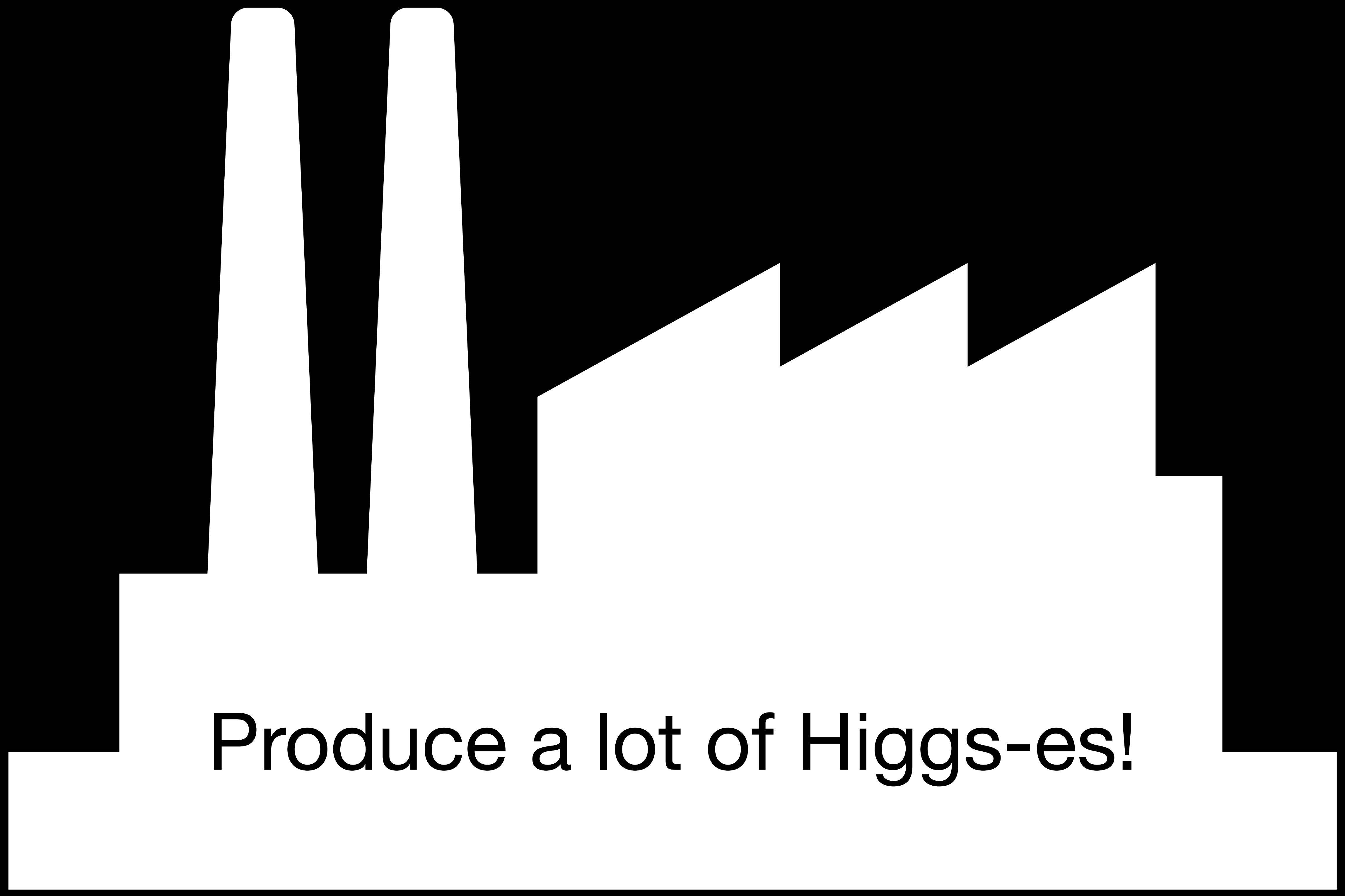
- Harmonic number:
  - Number of RF cycles per period: $V = V_0 \sin(\omega_{RF} t + \omega_0)$
  - $\omega_{RF} = 2\pi \frac{h}{\tau}$
  - Energy gain that a particle of the nominal energy experiences each turn is given by
    - $E_{n+1} = E_n + zeV_0 \sin \phi_s$
  - Phase evolution:
    - $\phi_{n+1} = \phi_n + d\phi$
  - $\Delta E_n \equiv (E_n - E_s)$
  - $\Delta \phi_n \equiv (\phi_n - \phi_s)$ or $\Delta t_n \equiv (t_n - t_s)$

Equations of motion

- $$\Delta\phi = \omega_{RF}\Delta t = \omega_{RF}\tau\eta\frac{\Delta p}{p} = 2\pi h\eta\frac{1}{\beta^2}\frac{\Delta E}{E}$$
- $$\phi_{n+1} = \phi_n + \frac{2\pi h\eta}{E_s\beta^2}\Delta e$$
- Derive this equation:
  - $$\frac{d^2\phi}{dn^2} = \frac{zeV_0 2\pi h\eta}{E_s\beta^2}(\sin\phi_n - \sin\phi_s)$$

Need Higgs Factories!

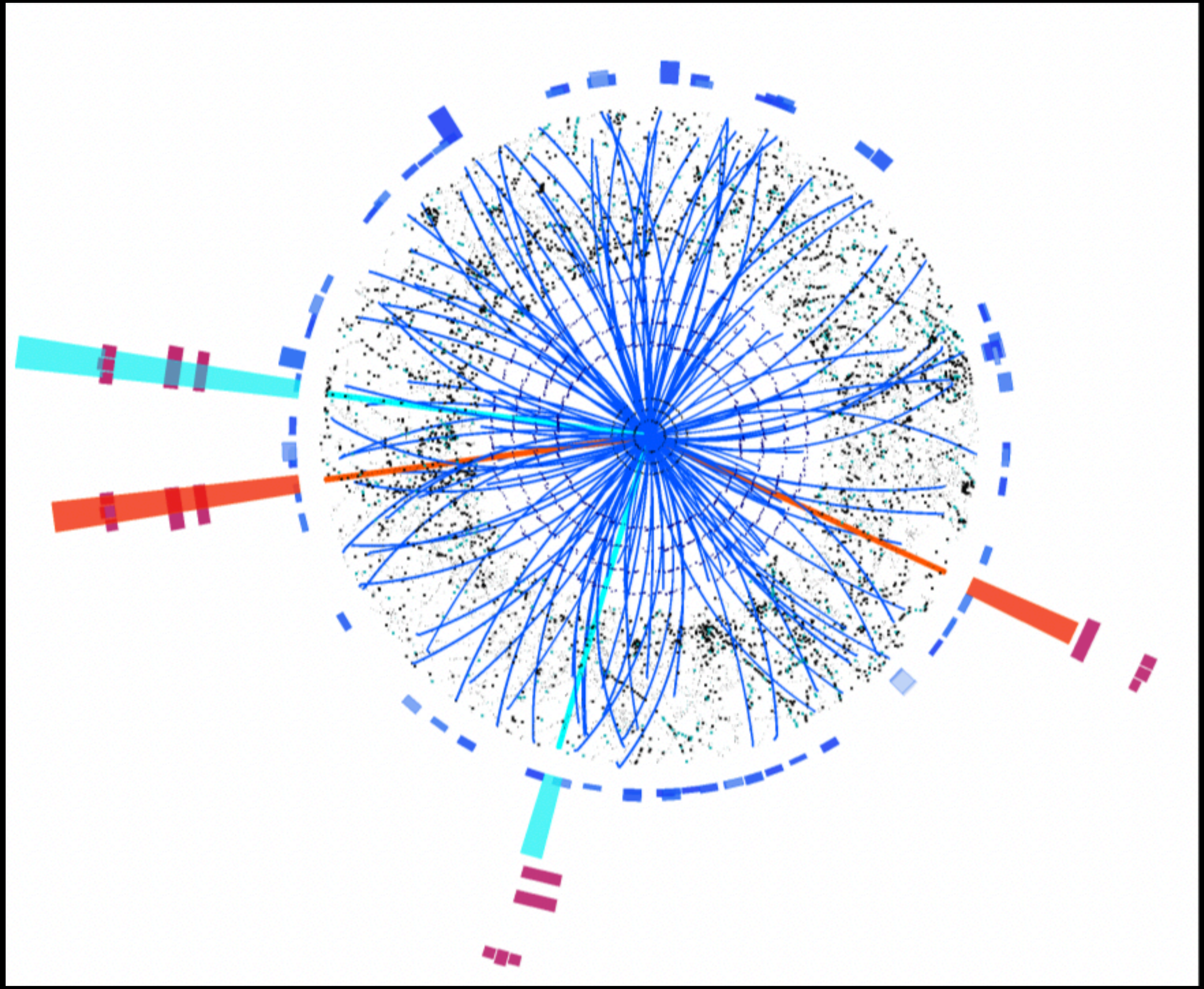
"The recently discovered Higgs boson is a form of matter never before observed, and it is mysterious. What principles determine its effects on other particles? How does it interact with neutrinos or with dark matter? Is there one Higgs particle or many? Is the new particle really fundamental, or is it composed of others? The Higgs boson offers a unique portal into the laws of nature."



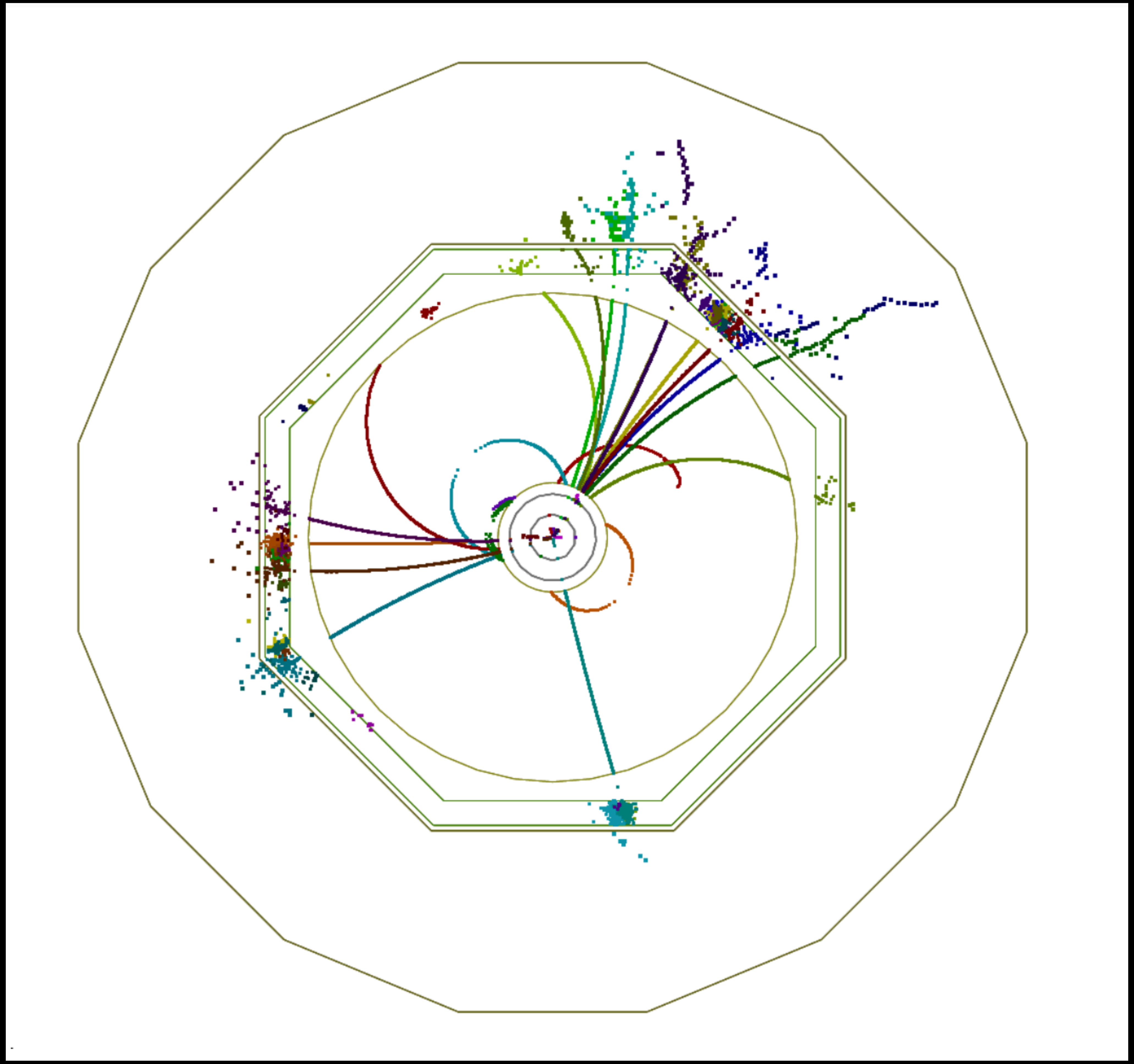
A precision machine

Let's collide e^+e^-

Event display — for comparison

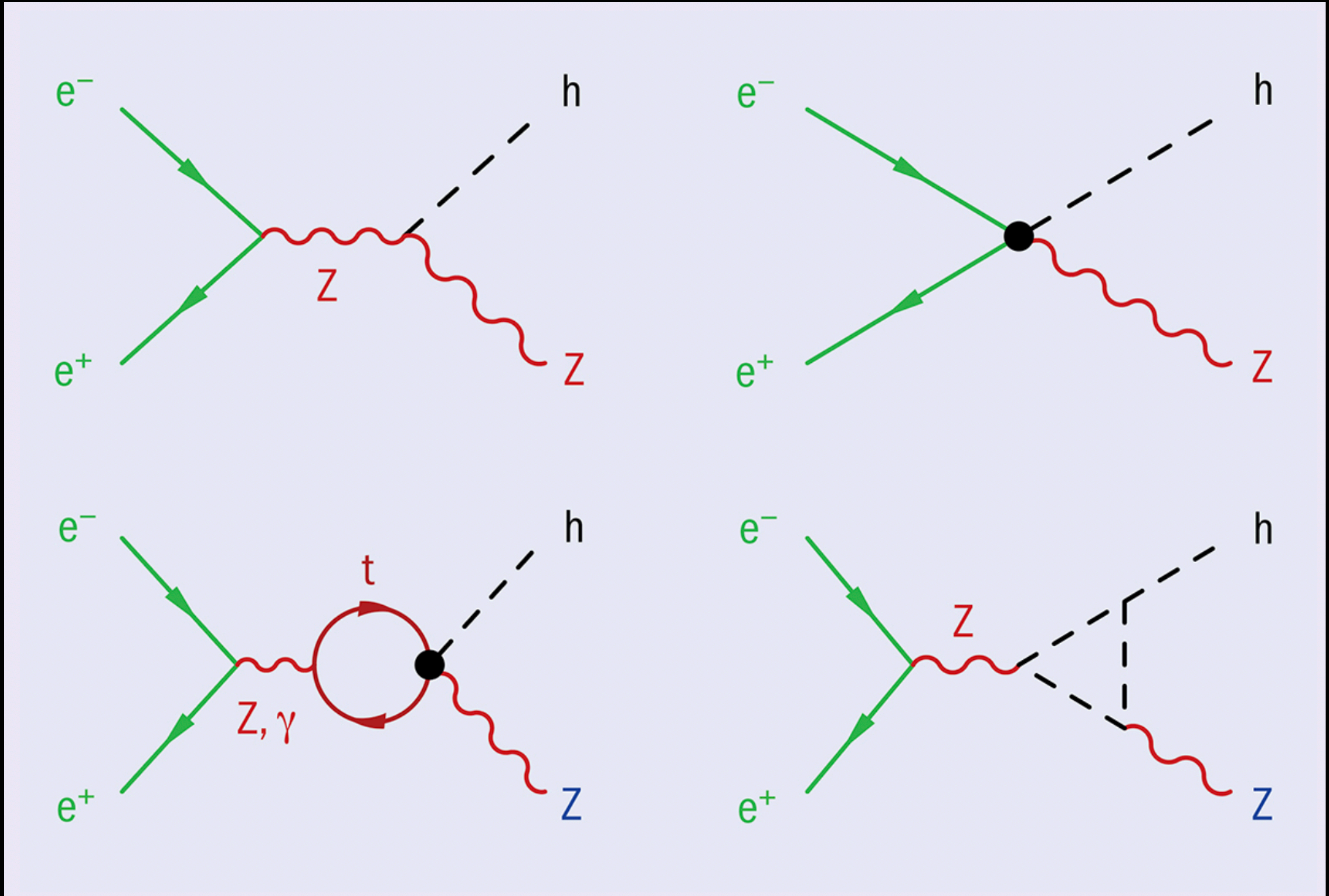


proton-proton collisions



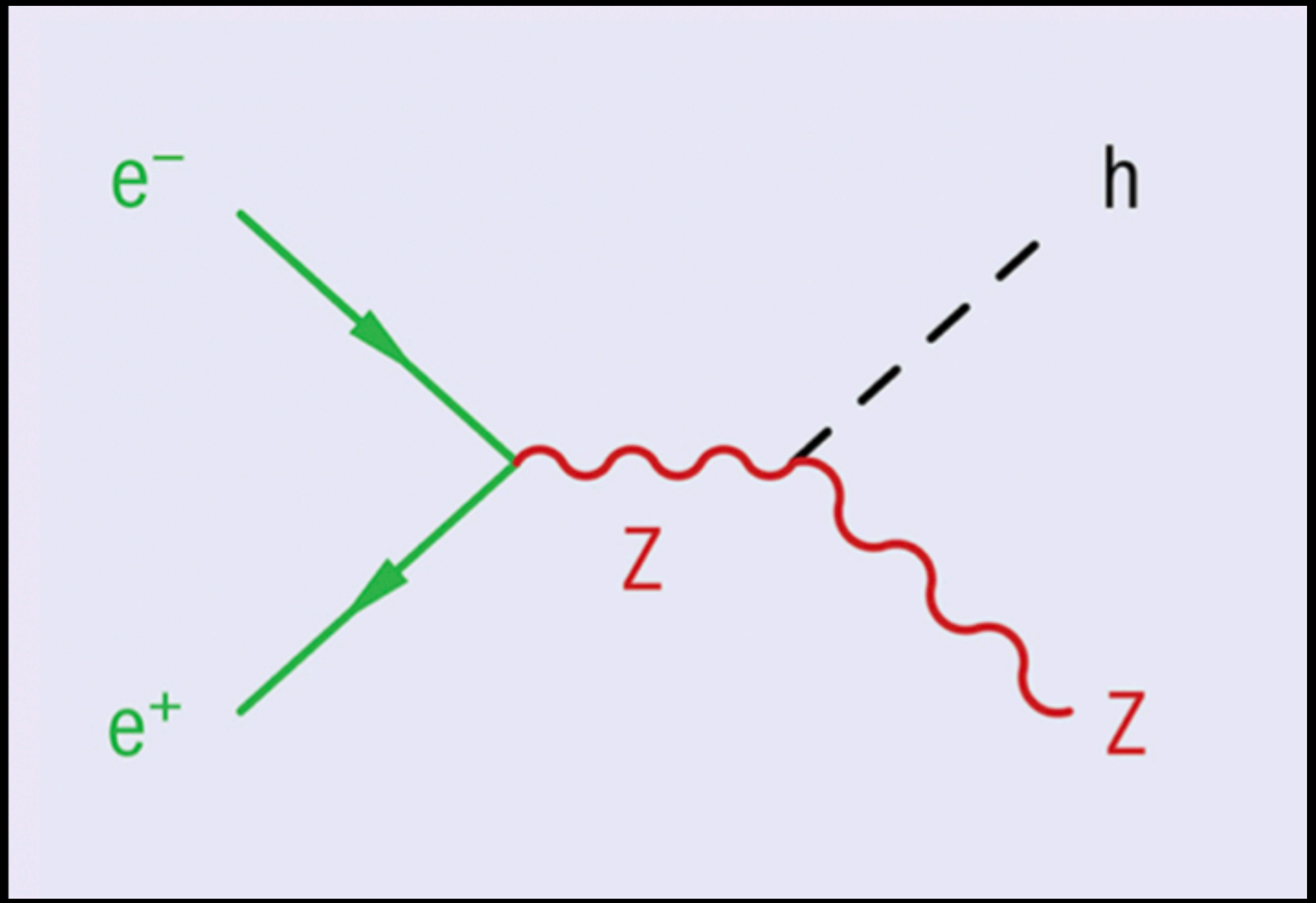
e^+e^- collisions

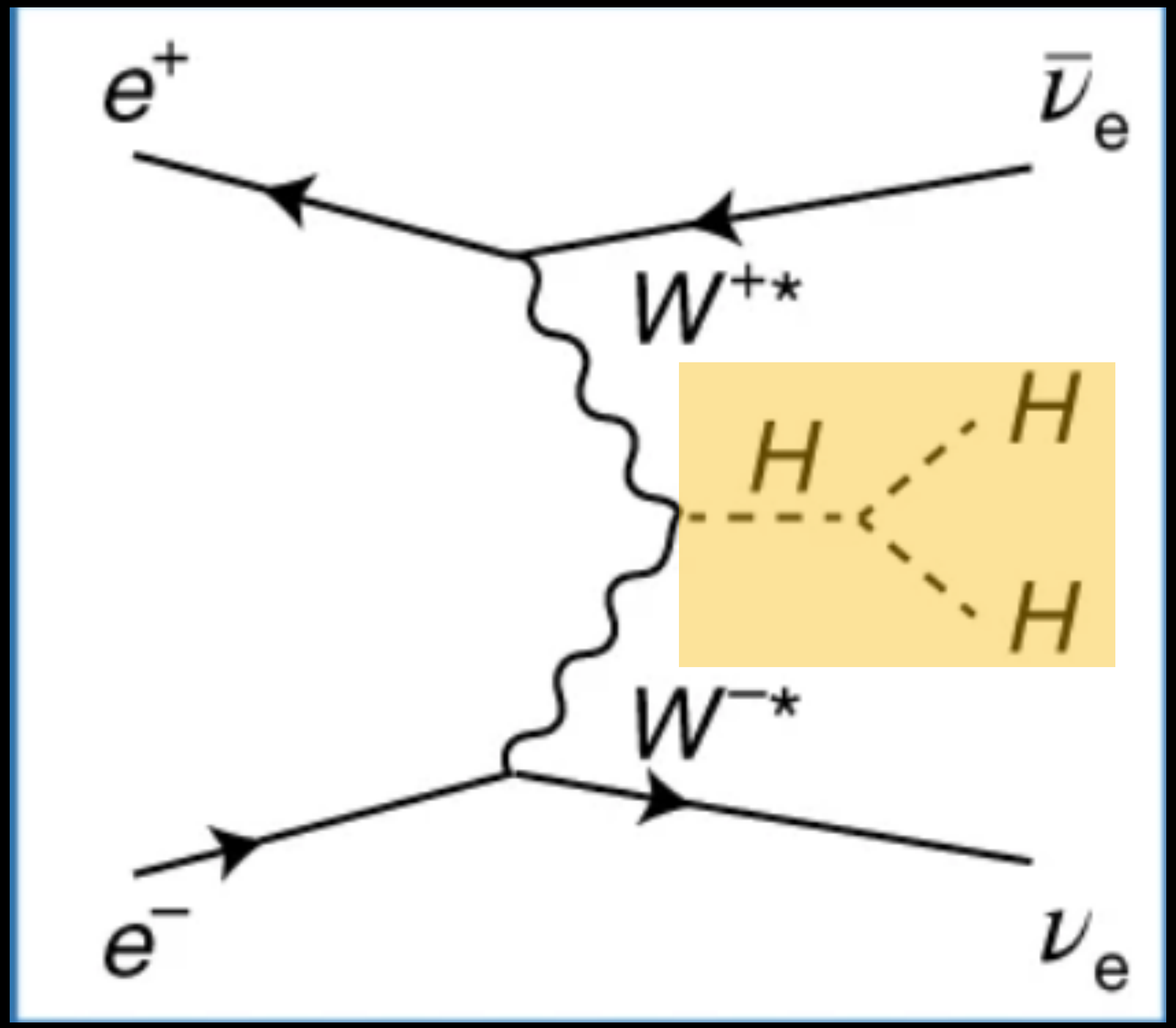
How will we produce Higgs at an e^+e^- collider?

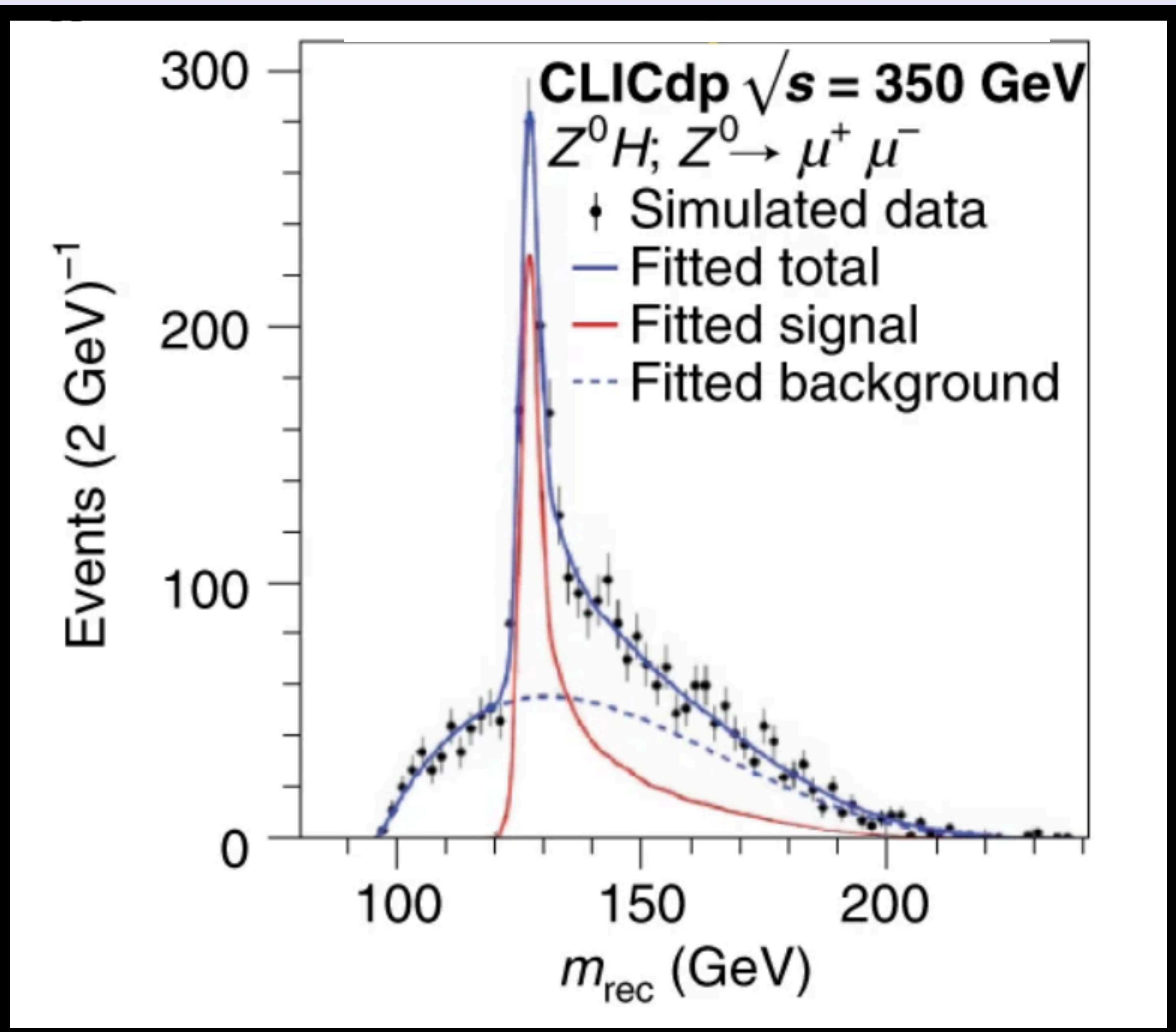


Process of interest

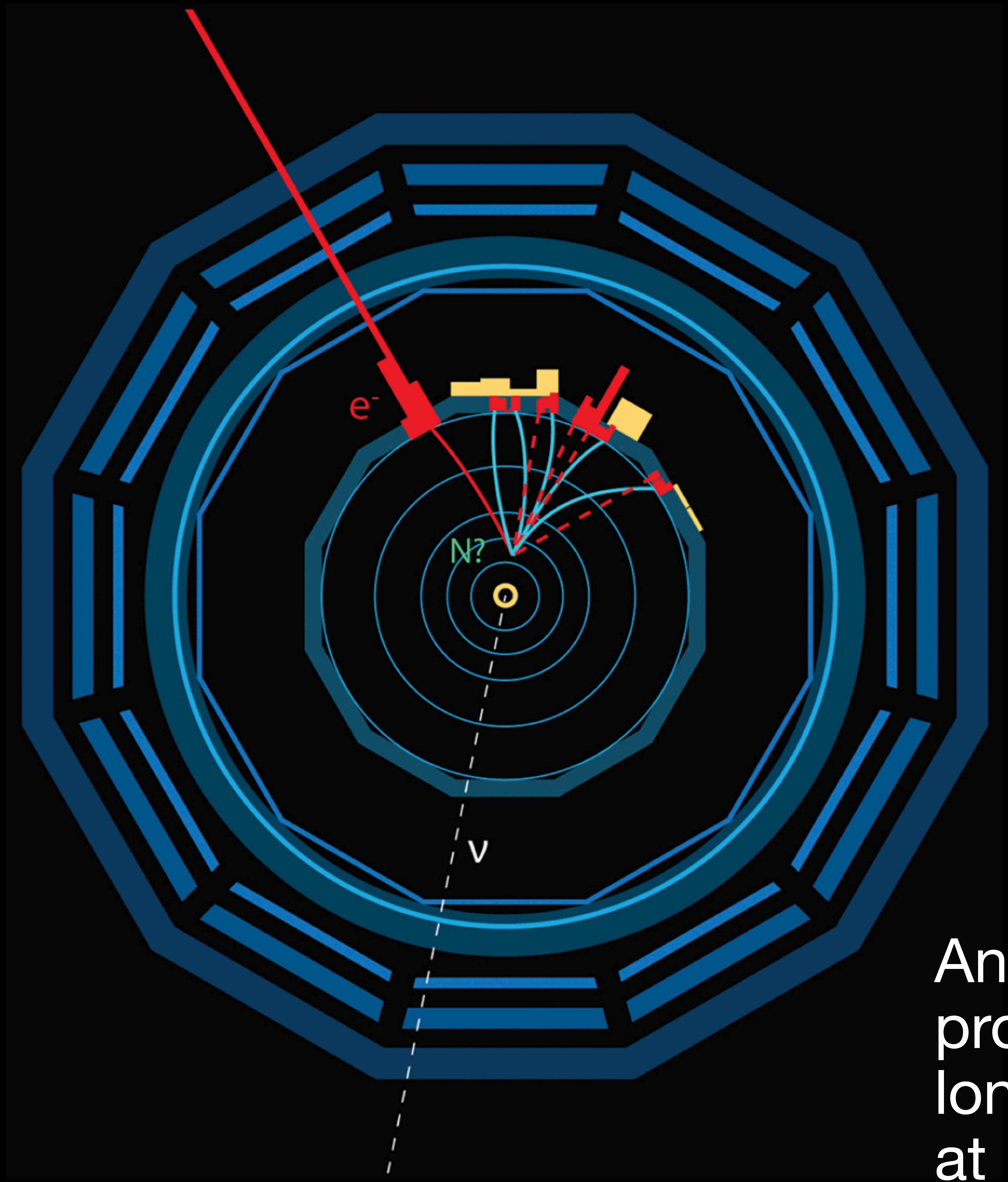
- Major production mode: Higgs boson produced with a Z
- Will recoil against the Z
- Can use this information to extract the Higgs boson mass and width
- Even access Higgs-self coupling







We can also look for new physics at e^+e^- machines



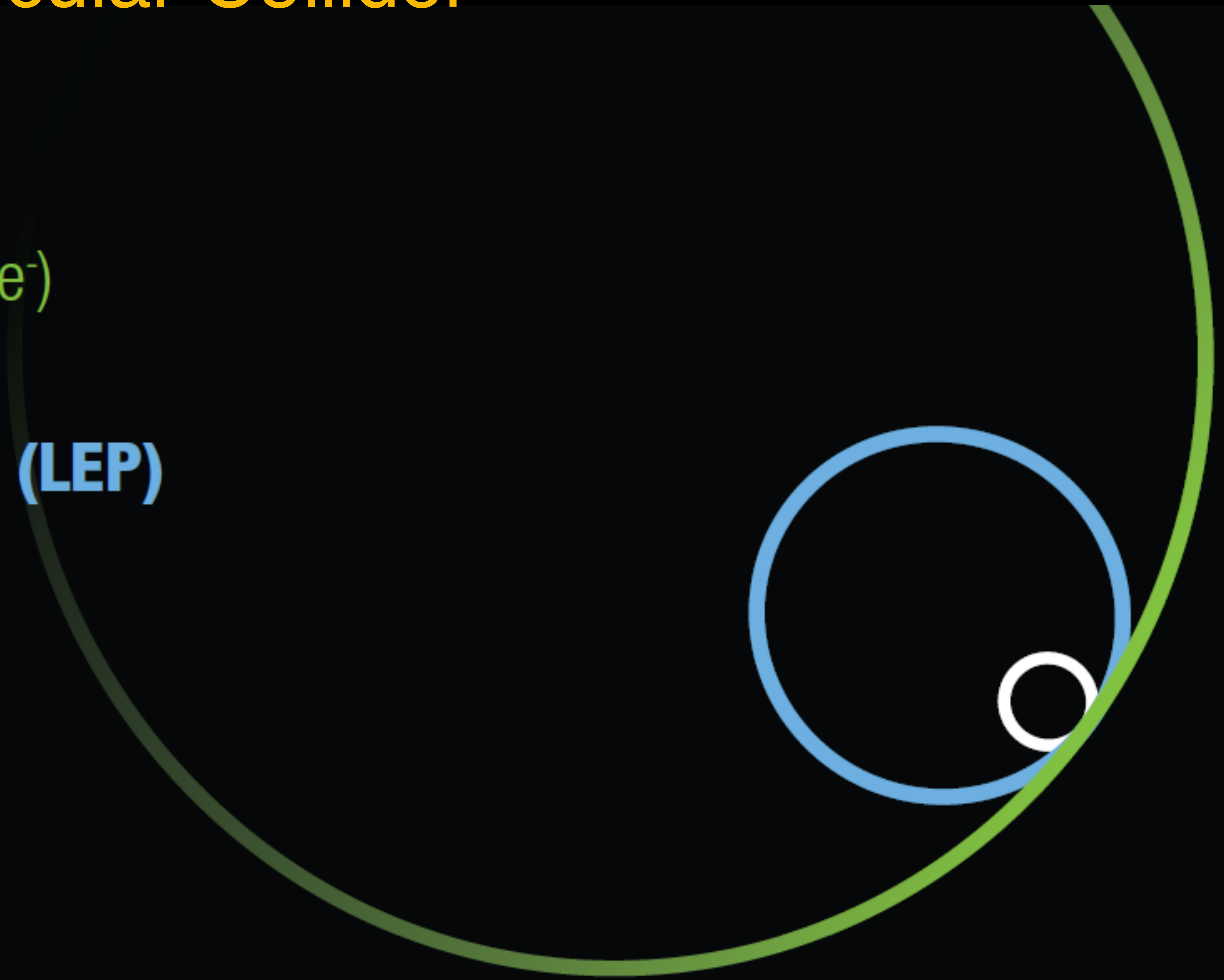
An artistic rendering of the production and decay of a long-lived heavy neutral lepton at FCC-ee

Future Circular Collider

- **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 ($p\bar{p}$)



Future Circular Collider — timeline

Multi pronged strategy

FCC
hh ee he

FCC-ee

Produce:

10^{12} Z bosons

10^{8} W bosons pairs

10^{6} Higgs bosons

4×10^{5} top-quark pairs

per year

FCC-hh

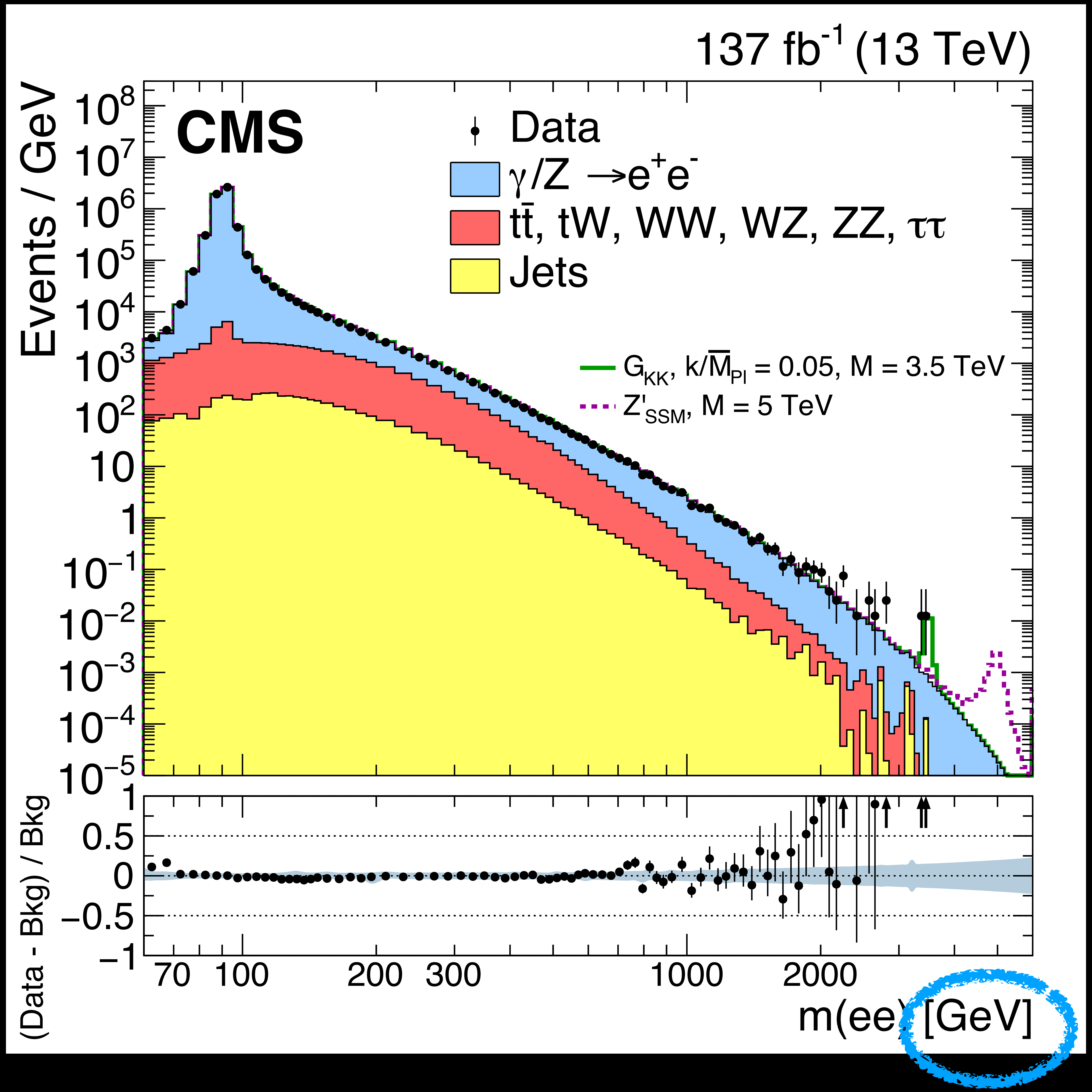
Discovery Machine (à la LHC)

Eightfold increase in energy

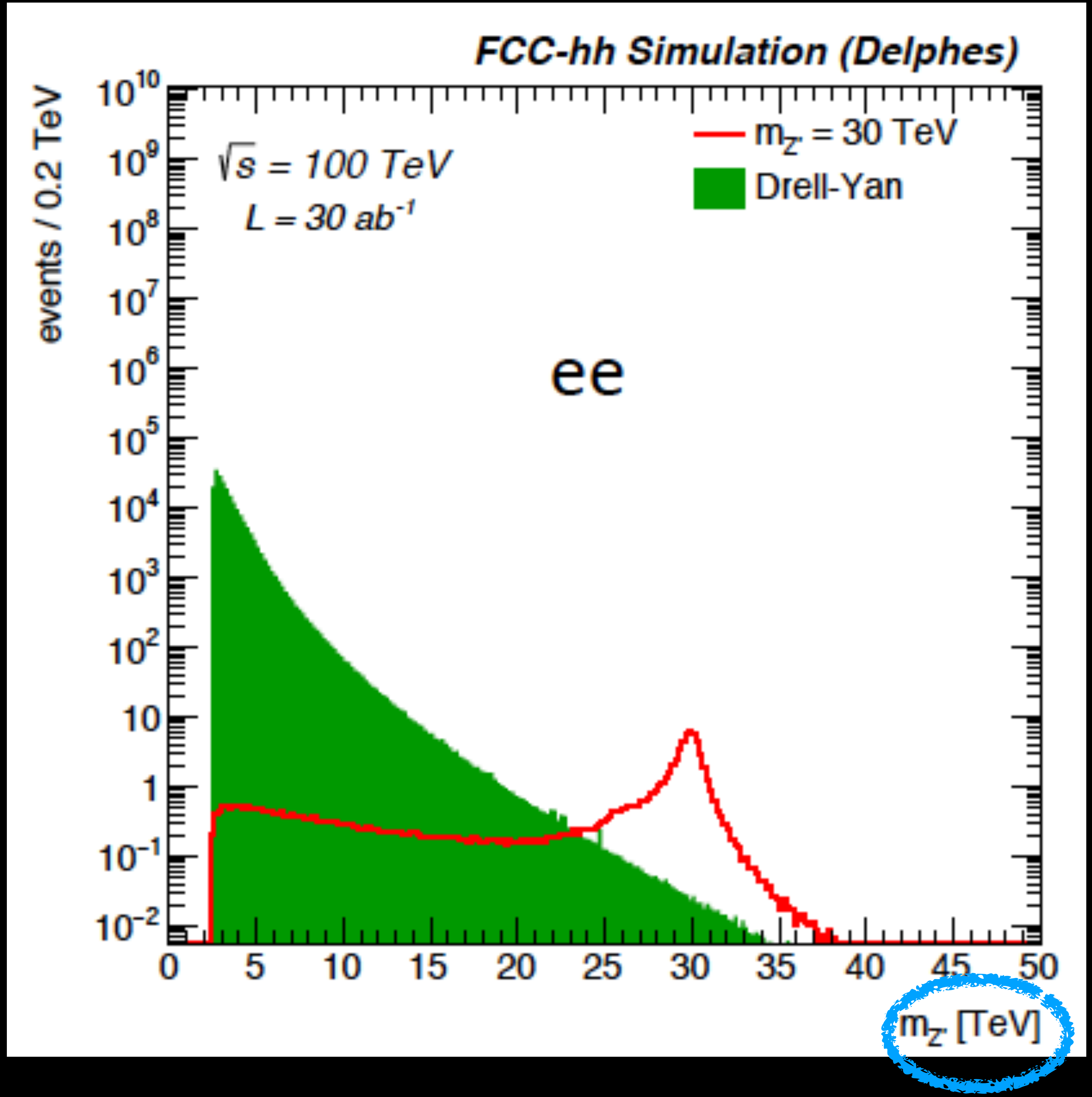
An energy machine

Let’s collide proton (p) - proton (p) but at higher energy

Pushing the limits of new physics searches



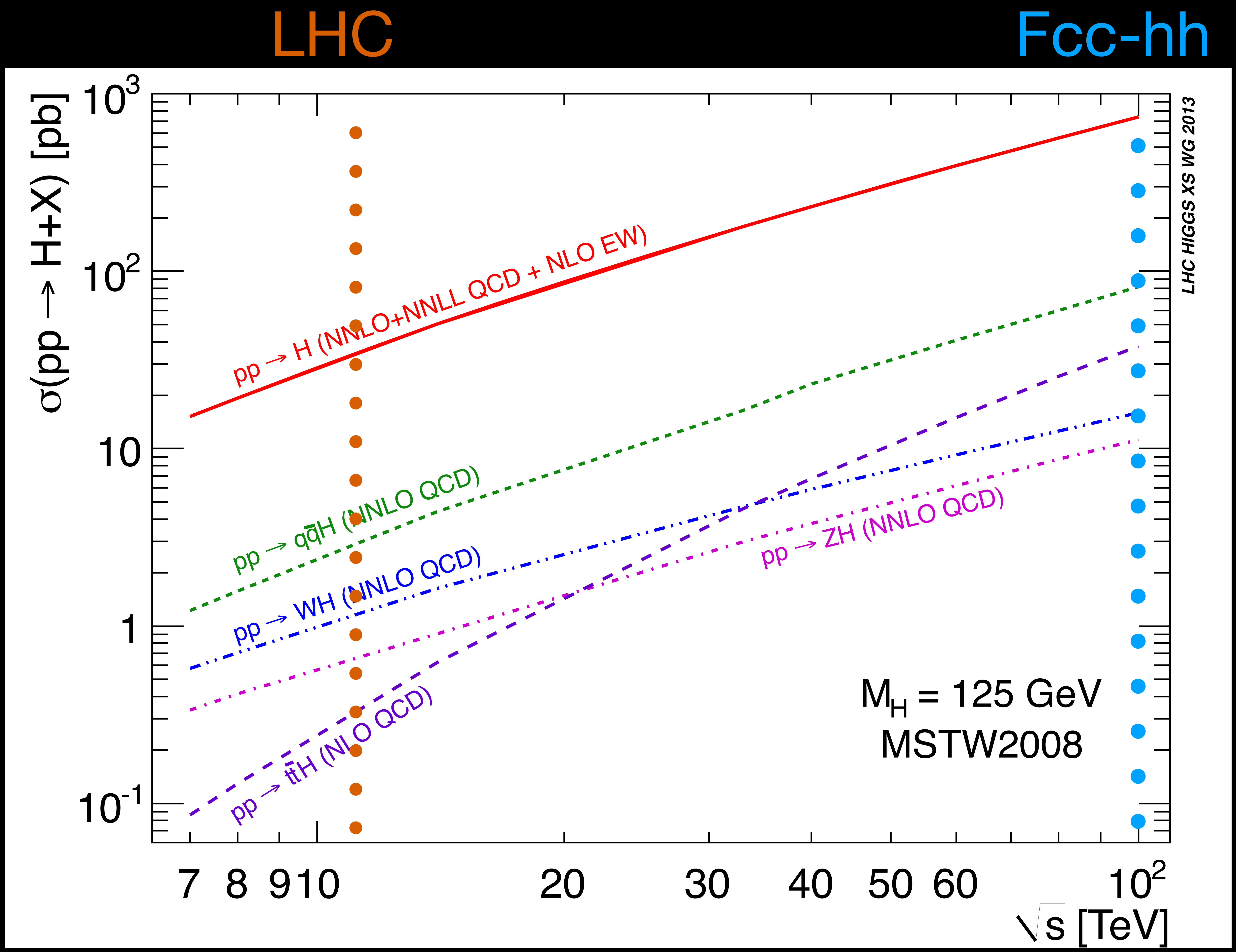
Current reach



Future reach

Higgs Reach at future hadron colliders

Process	rate(100 TeV)/rate(14 TeV)
W,Z	~7
WW, ZZ	~10
$t\bar{t}$	~30
H	~80
$t\bar{t}H$	~50
HH	~40
Super symmetric particle (stop, m= 1 TeV)	~1000



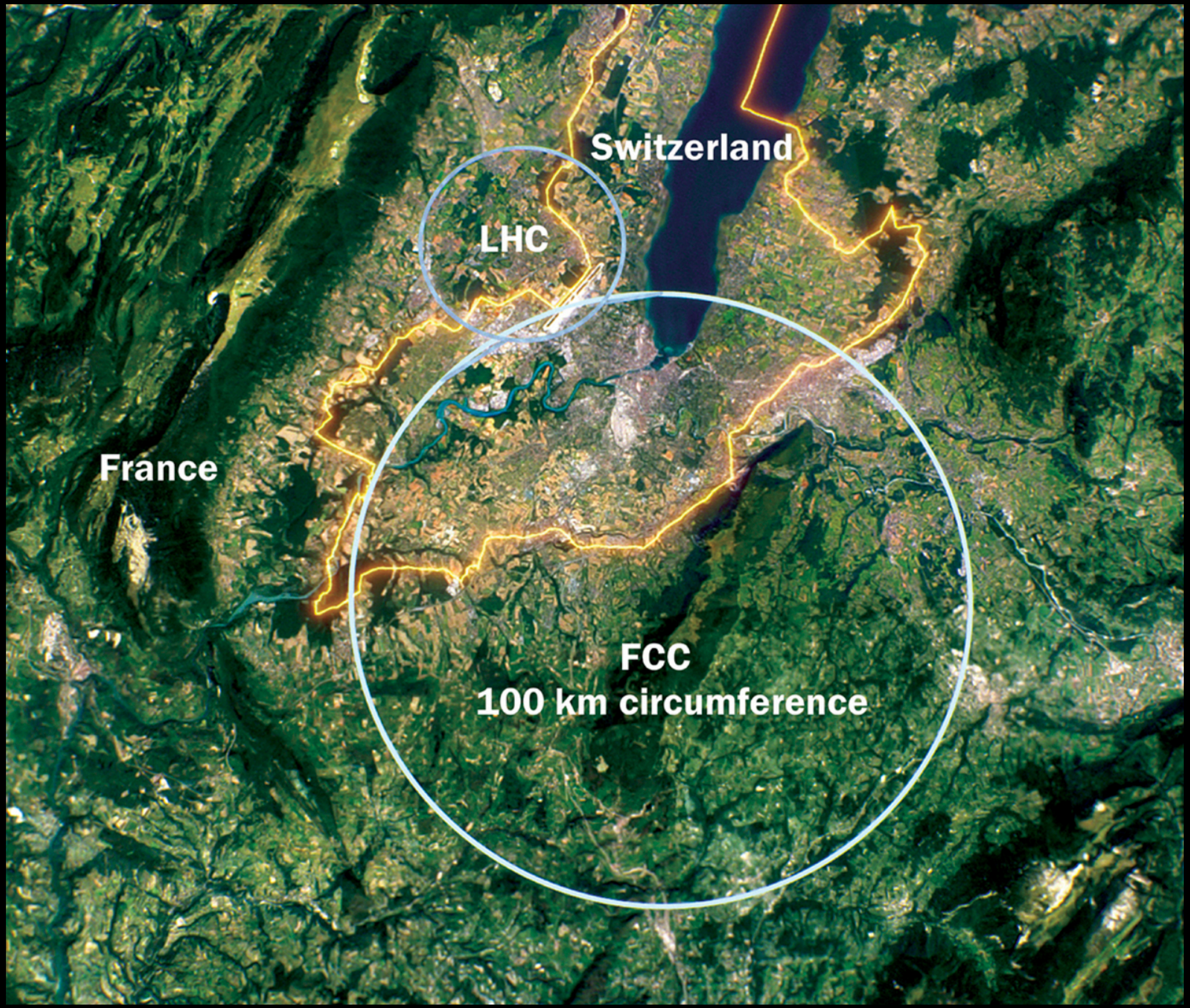
Key Parameters

Parameters	Tevatron	HL-LHC	Fcc-hh
Circumference	6.2 km	27 km	100 km
Beam energy	980 GeV	7 TeV	50 TeV
Stored proton beam energy	**2.1 MJ**	**732 MJ**	**8.4 GJ**
Bend field	4.2 T	8.3 T	16 T

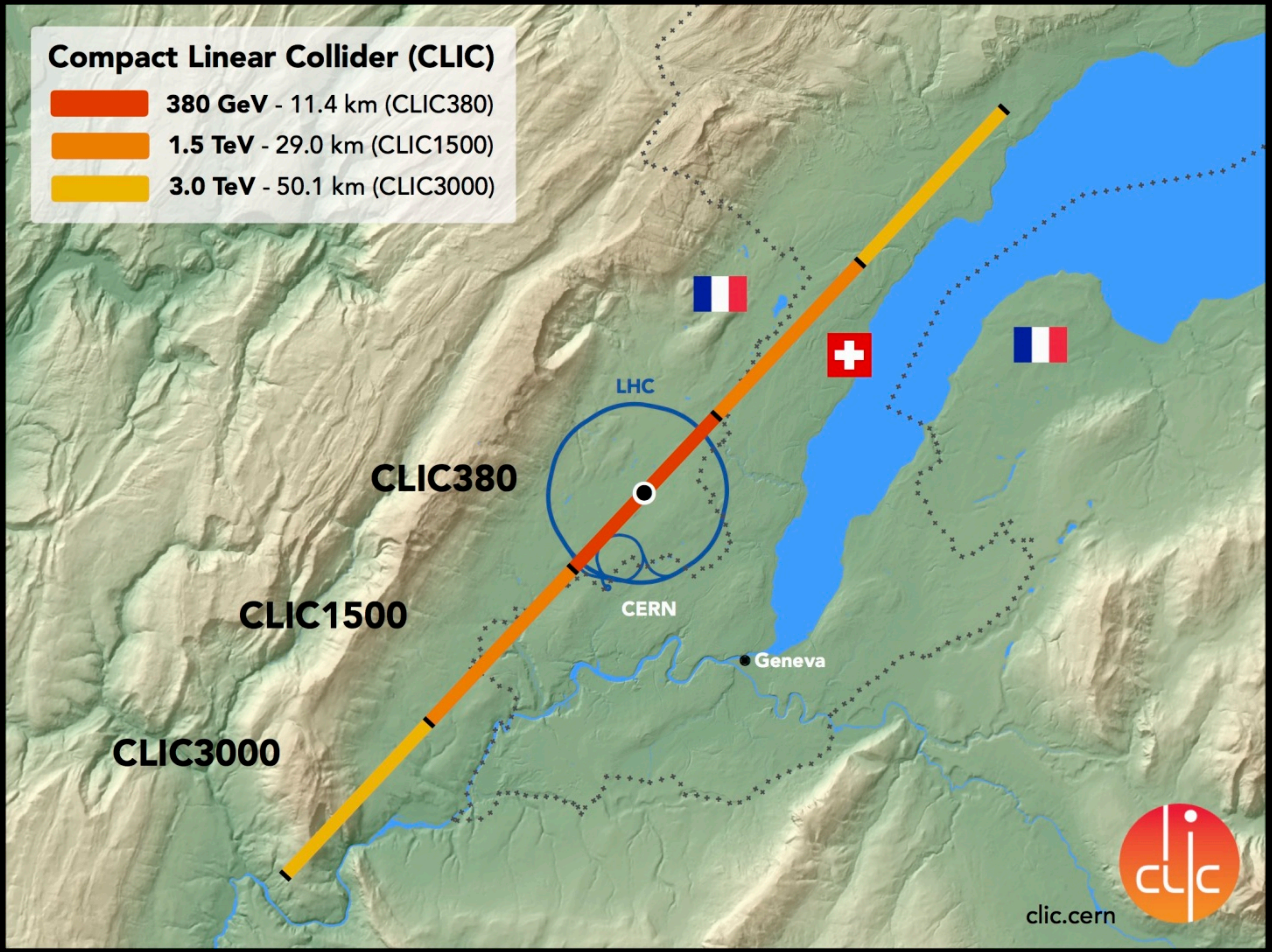
1 stick of dynamite releases 2.1 MJ of energy 🧨

Overview of the machines

Circular Collider



Linear Collider



Circular vs. Linear

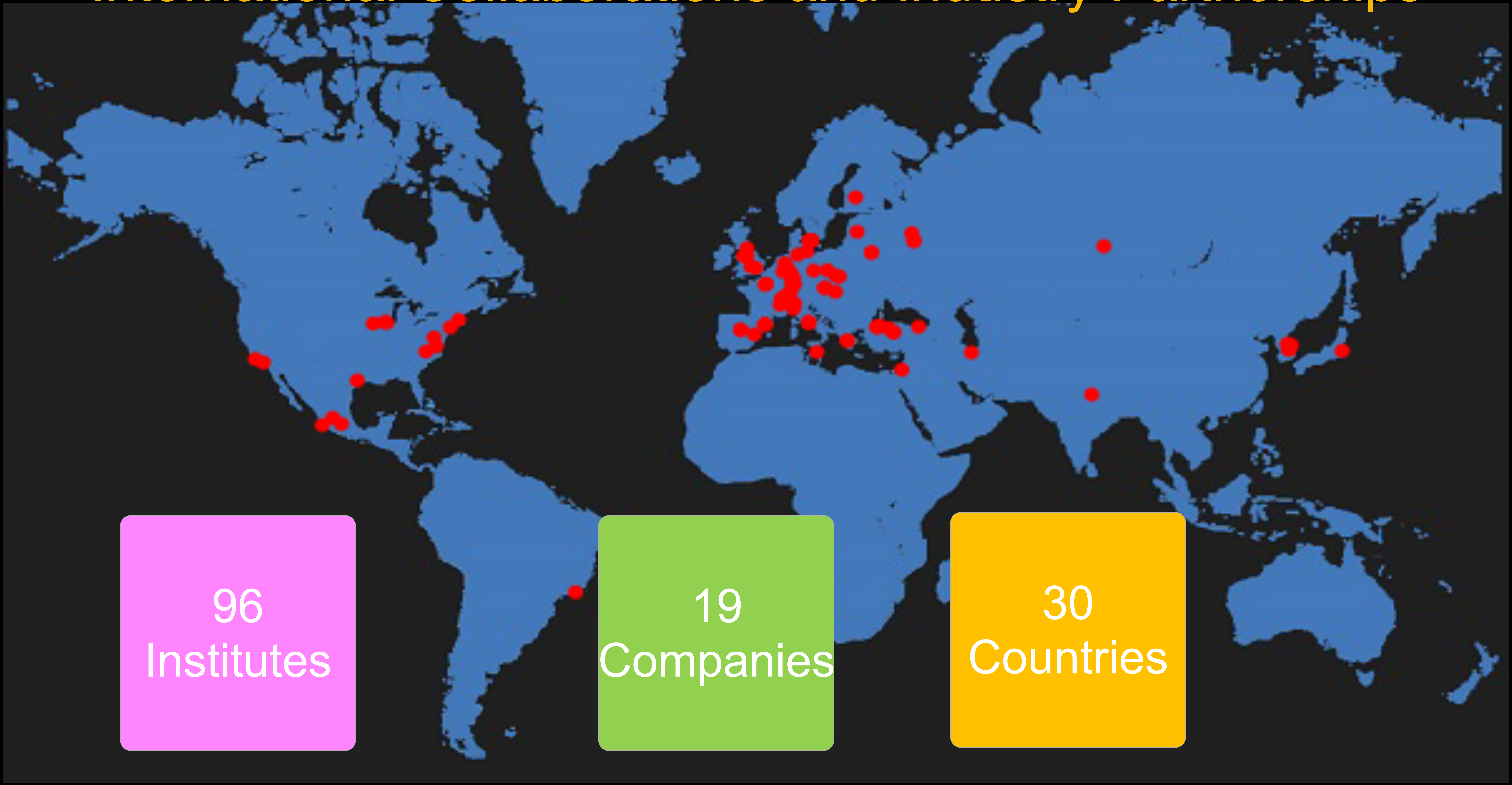
Circular

- Can achieve higher luminosities
- Several interaction points
- Limited by Synchrotron radiation

Linear

- Easier to polarize beams
- One impact parameter
- Large beamstrahlung

International Collaborations and Industry Partnerships



96
Institutes

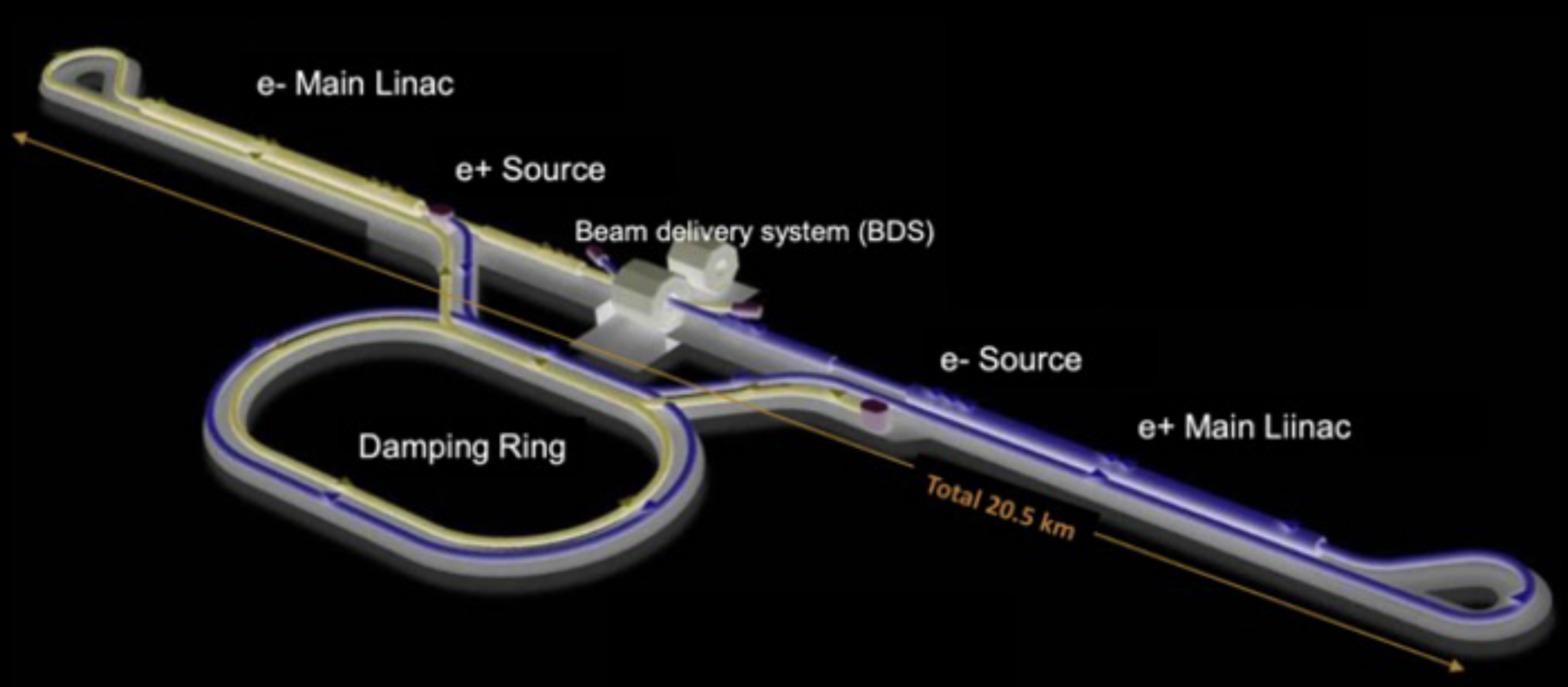
19
Companies

30
Countries

Overview of the machines in Asia

Chinese Circular Electron Positron Collider

International Linear Collider



Japan

Muon Collider — why collide $\mu^+\mu^-$?

- Electrons lose a lot of energy through radiation
- High power consumption associated with e^+e^- machines

The muon emits ~2 billion times less synchrotron radiation than the electron

Q & A

A Call for Courage as Physicists Confront Collider Dilemma

11

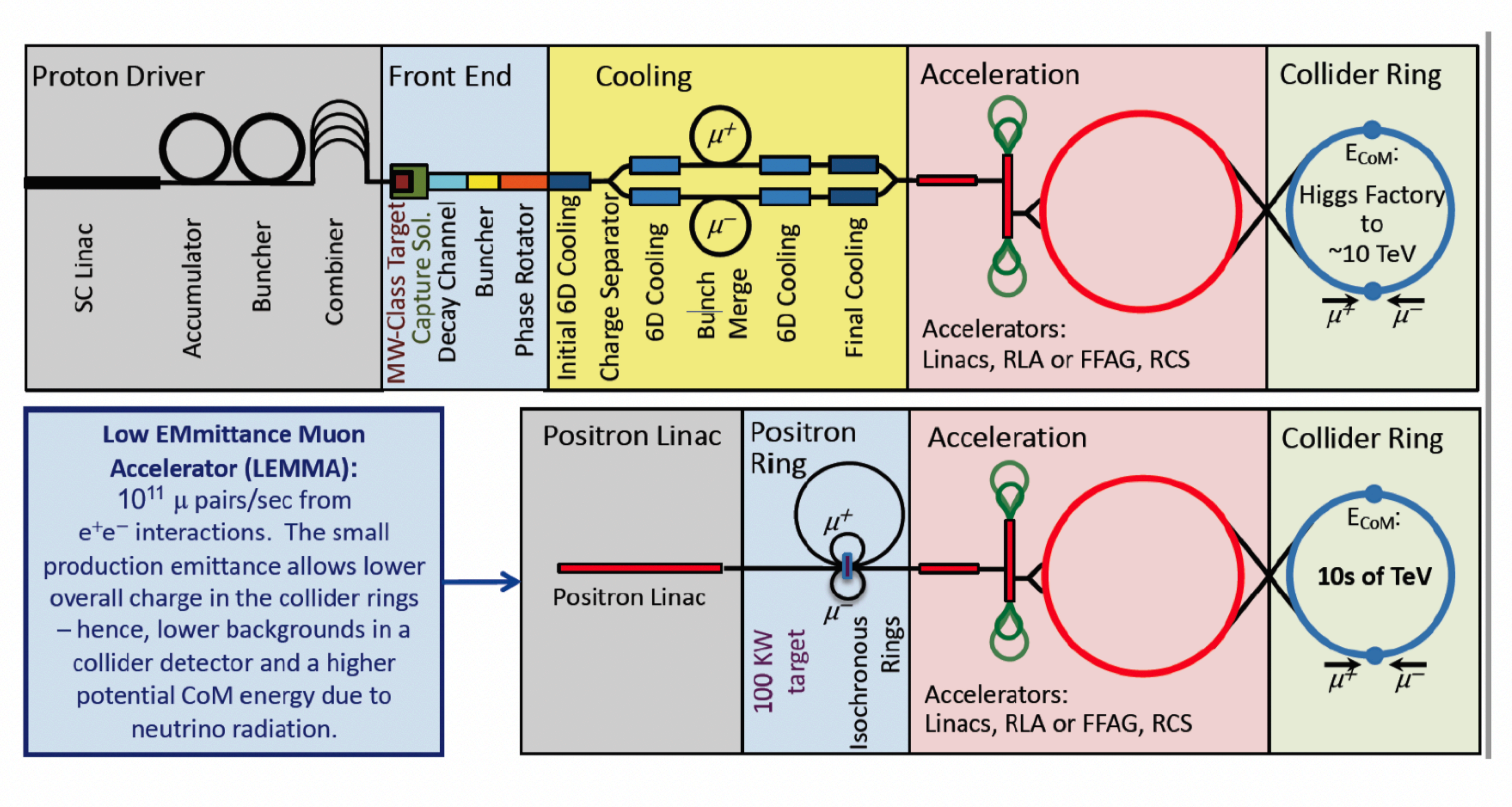
Carlo Rubbia, leader of the bold collider experiment that in 1983 discovered the W and Z bosons, thinks particle physicists should now smash muons together in an innovative "Higgs factory."

https://www.quantamagazine.org/carlo-rubbia-calls-for-courage-as-physicists-confront-collider-dilemma-20190807/

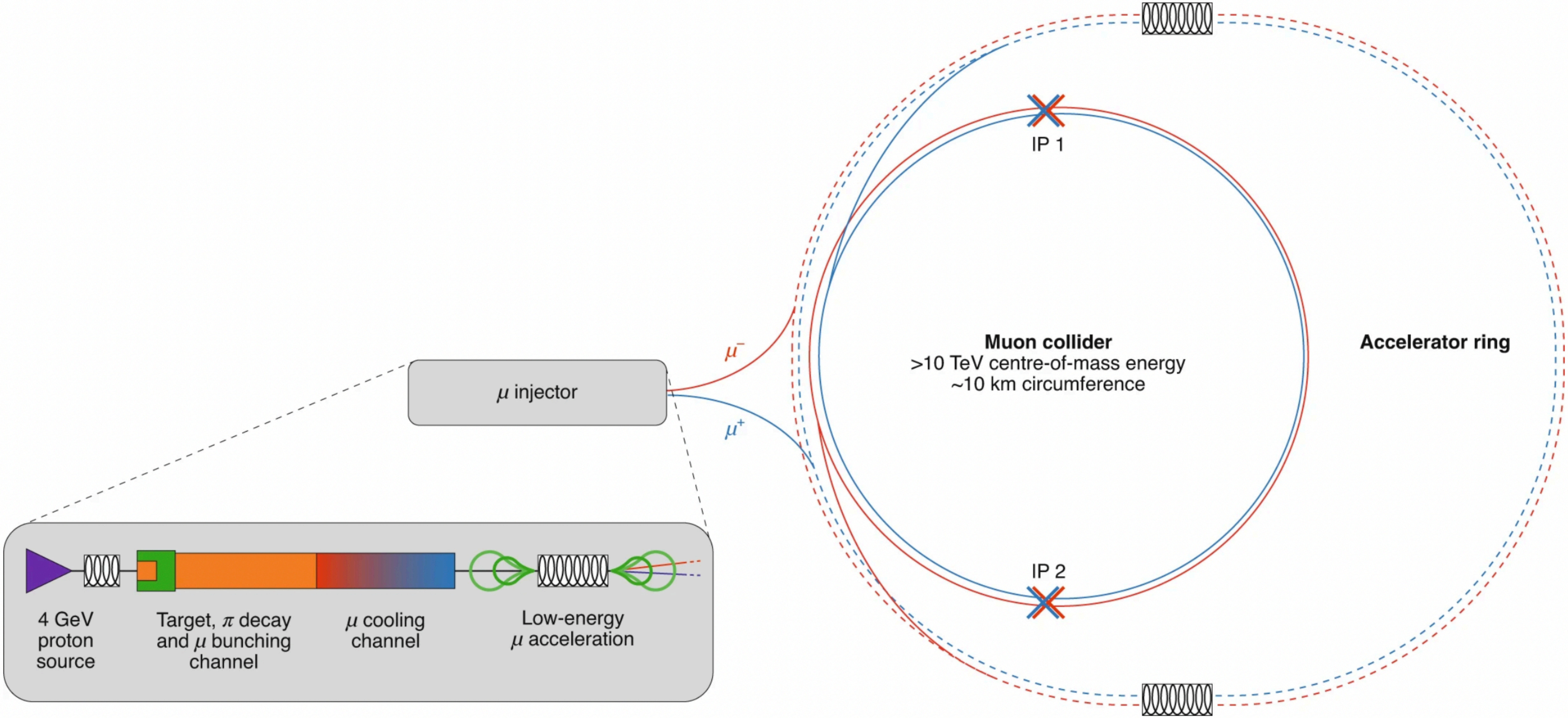
We even have t-shirts!

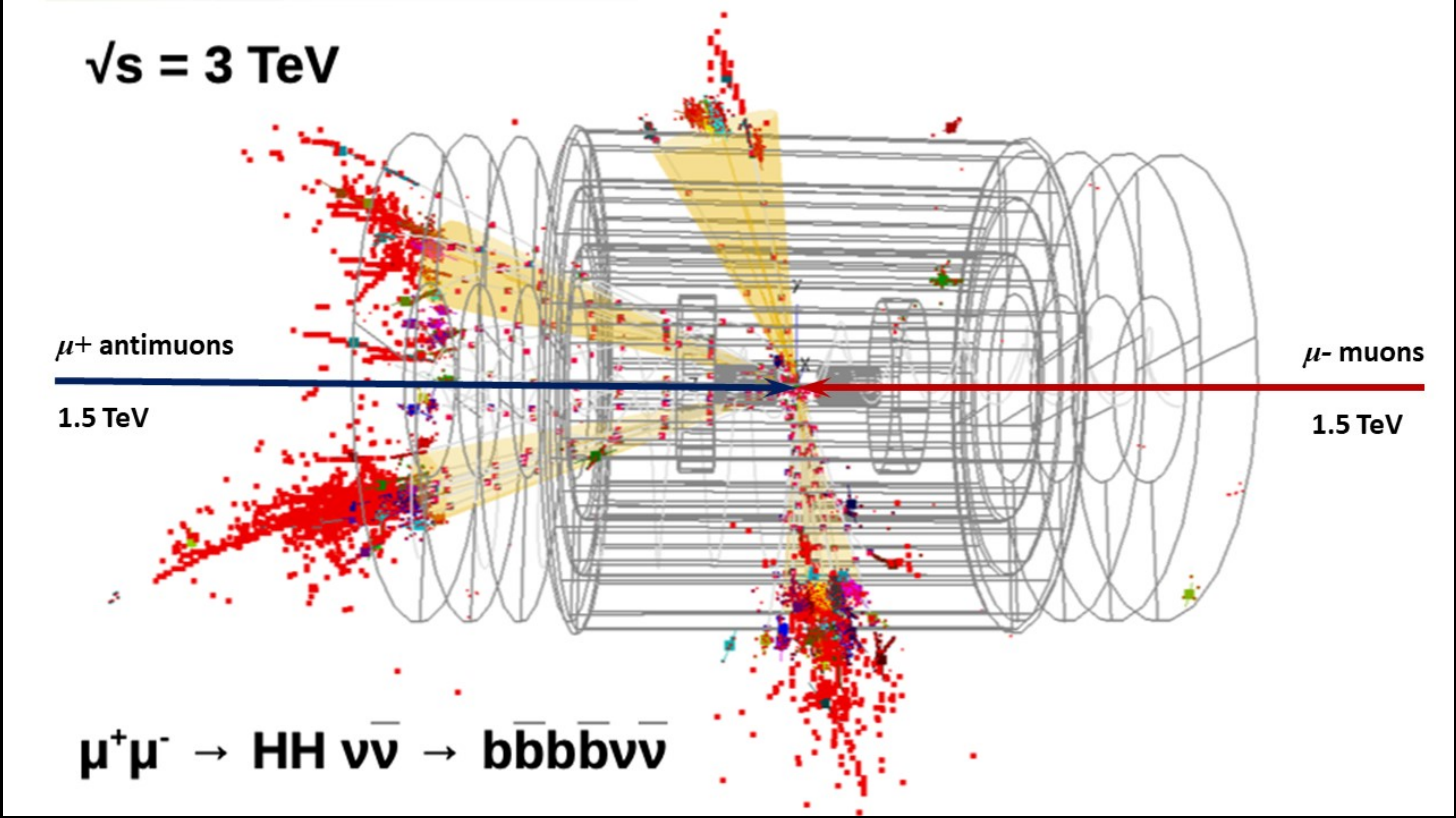
Muon Collider — Challenges

- Short muon lifetime — 2.2 μ second at rest
- Producing a large number of muons
- Mitigating beam background from the decay of muons

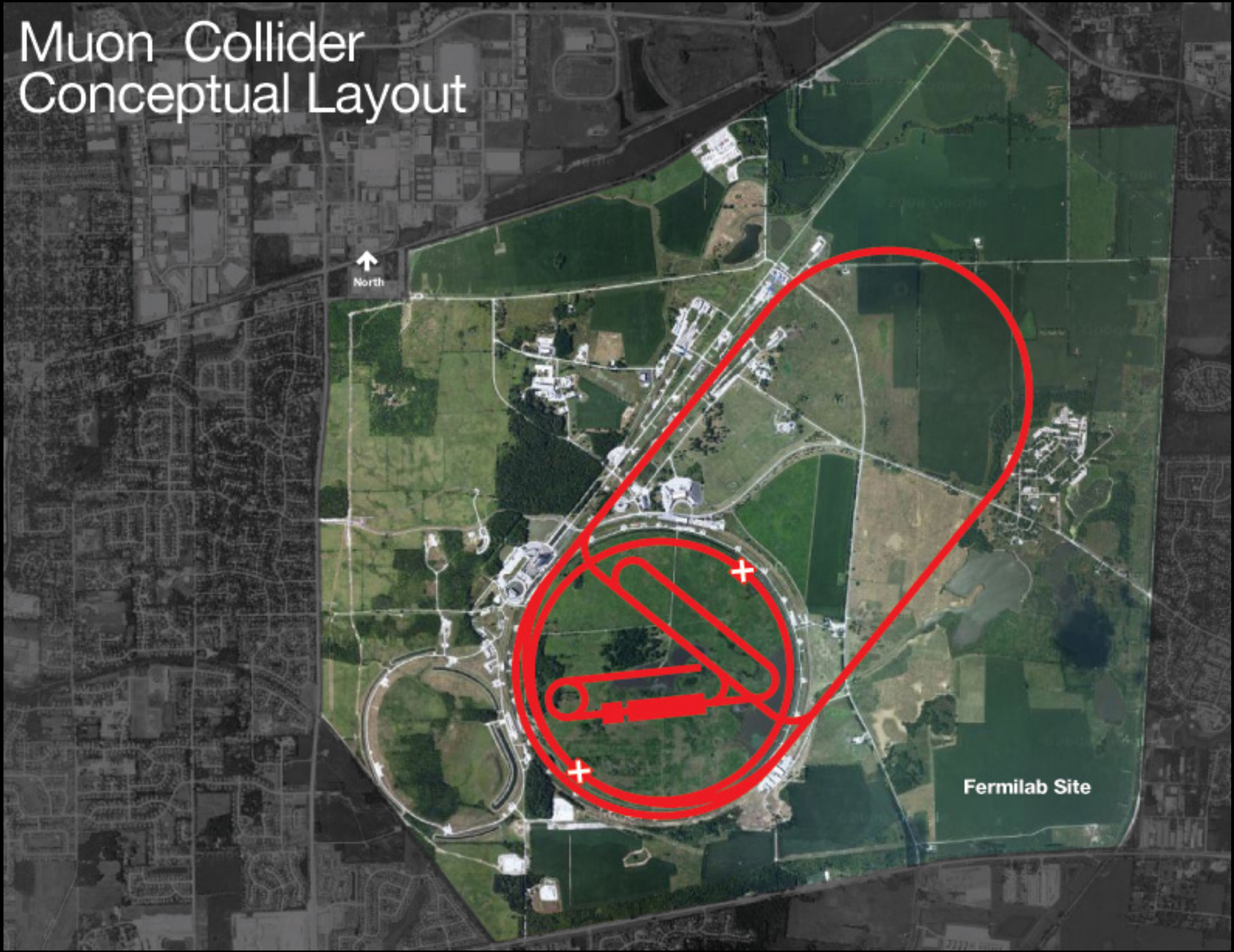


Muon Collider — Design




$\sqrt{s} = 3$ TeV
μ+ antimuons
1.5 TeV
μ- muons
1.5 TeV
$\mu^+\mu^- \rightarrow HH\ \nu\bar{\nu} \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$

A collider in the US?



Why should fundamental science be funded?

Senator Pastore: *Is there anything connected with the hopes of this accelerator that in any way involves the security of the country?*

Robert Wilson: *No sir, I don't believe so.*

Pastore: *Nothing at all?*

Wilson: *Nothing at all.*

Pastore: *It has no value in that respect?*

Wilson: *It has only to do with the respect with which we regard one another, the dignity of men, our love of culture. It has to do with are we good painters, good sculptors, great poets? I mean all the things we really venerate in our country and are patriotic about. It has nothing to do directly with defending our country except to make it worth defending.*

A collider in the US?

Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

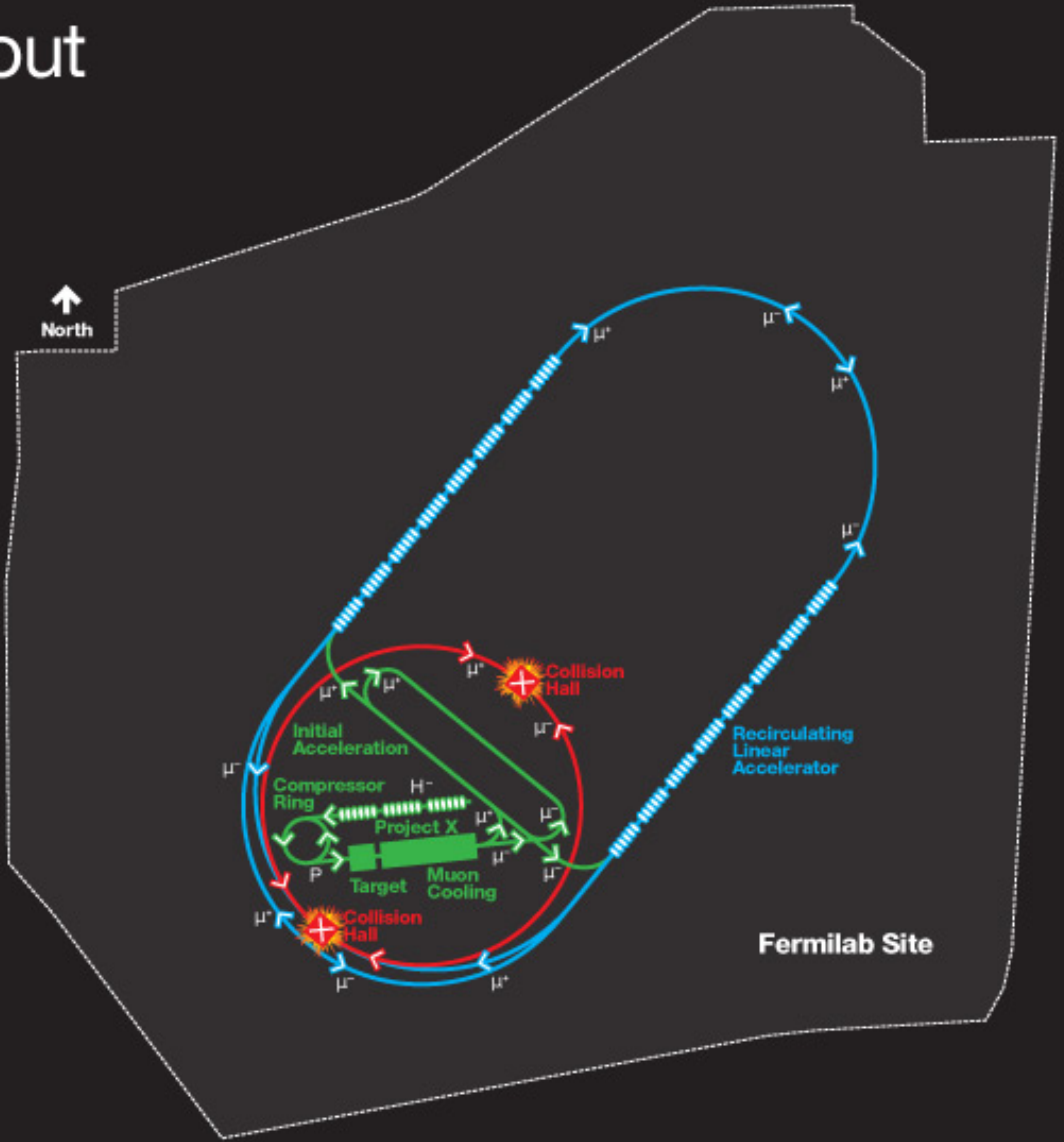
Target
Collisions lead to muons with energy of about 200 MeV.

Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.



It's as much about the *people* as it is about the particles

Particle Physicists
collaborate with industry leaders

Particle Physics trains
an AI-ready workforce

Rubric

Originality	Narrative	Quality of slides	Introduce background material	Delivery and time management
25%	15%	• Text vs. images: 15% • Quality of plots: 15%	20%	10%

- Notes on structure:
  - Follow a **logical and coherent structure**; the introduction, body, and conclusion should transition seamlessly and guide the audience through complex ideas