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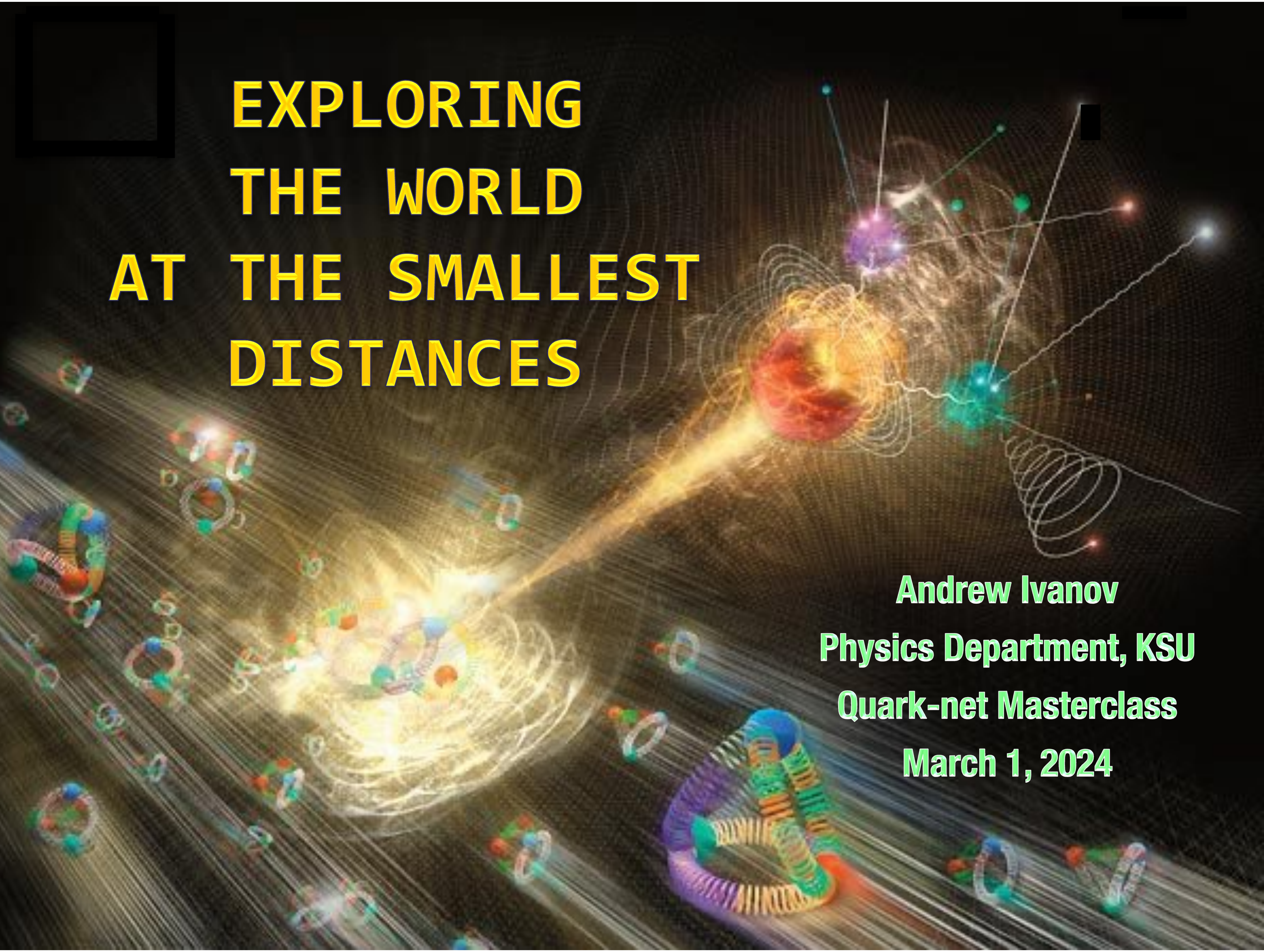
# EXPLORING THE WORLD AT THE SMALLEST DISTANCES



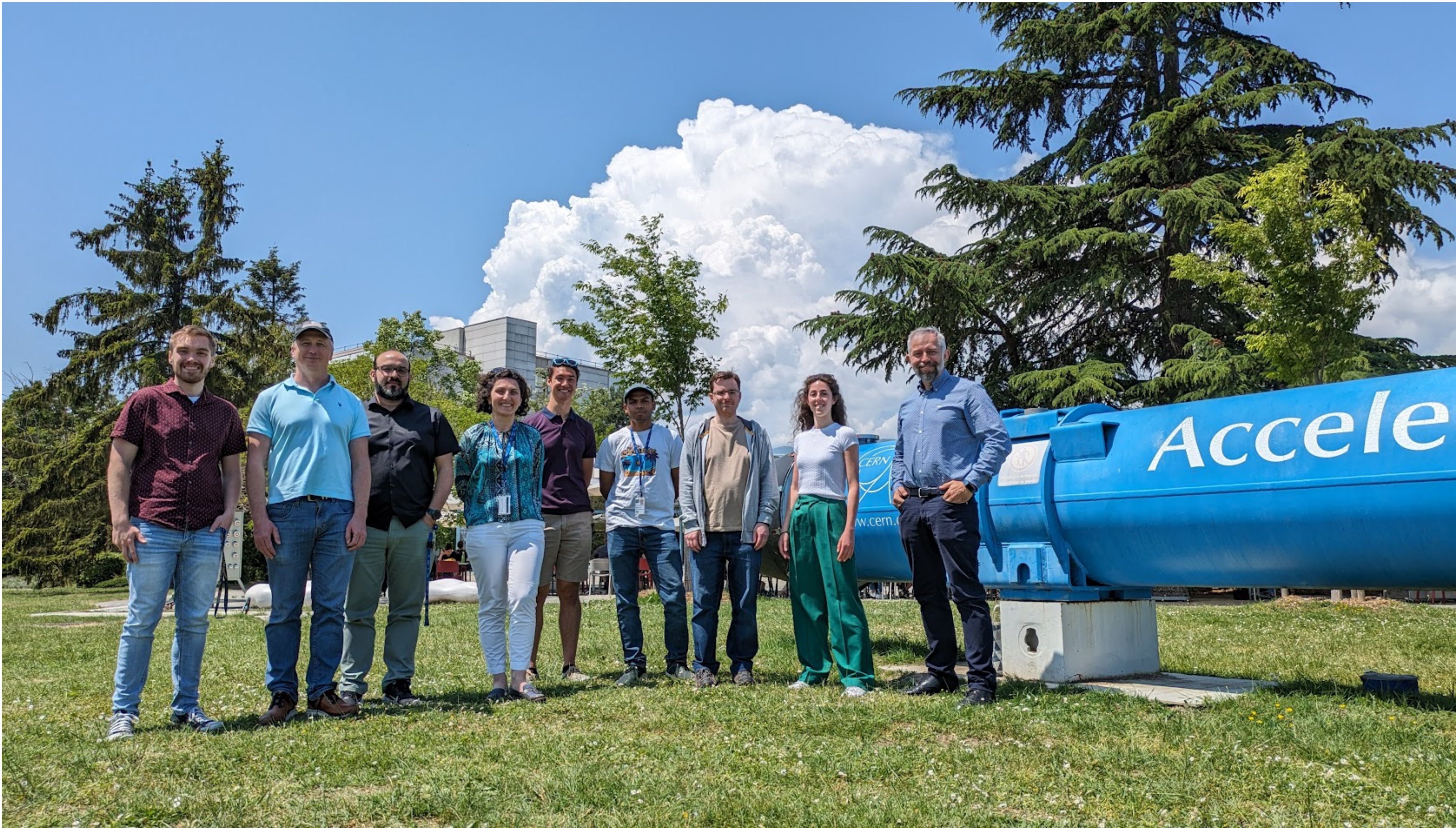
**Andrew Ivanov**

**Physics Department, KSU**

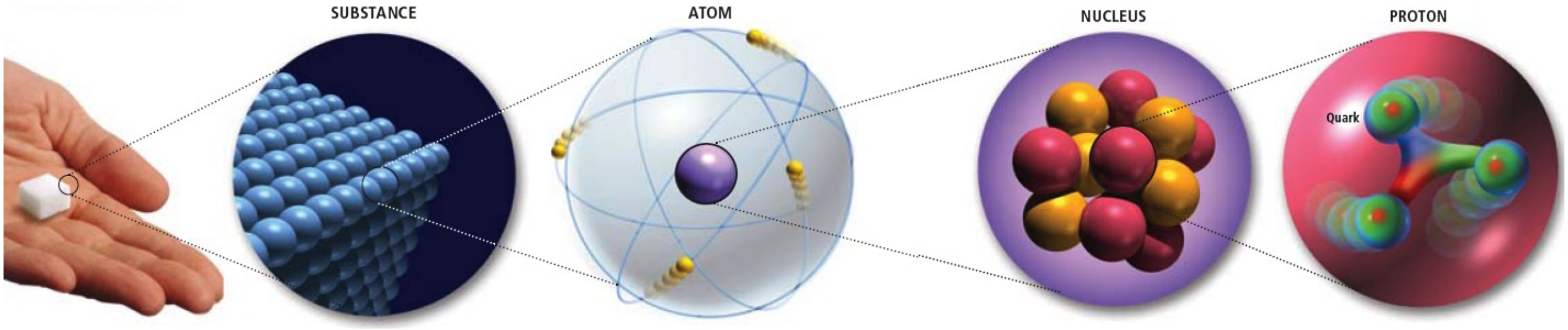
**Quark-net Masterclass**

**March 1, 2024**

# K-State High Energy Physics group at CERN

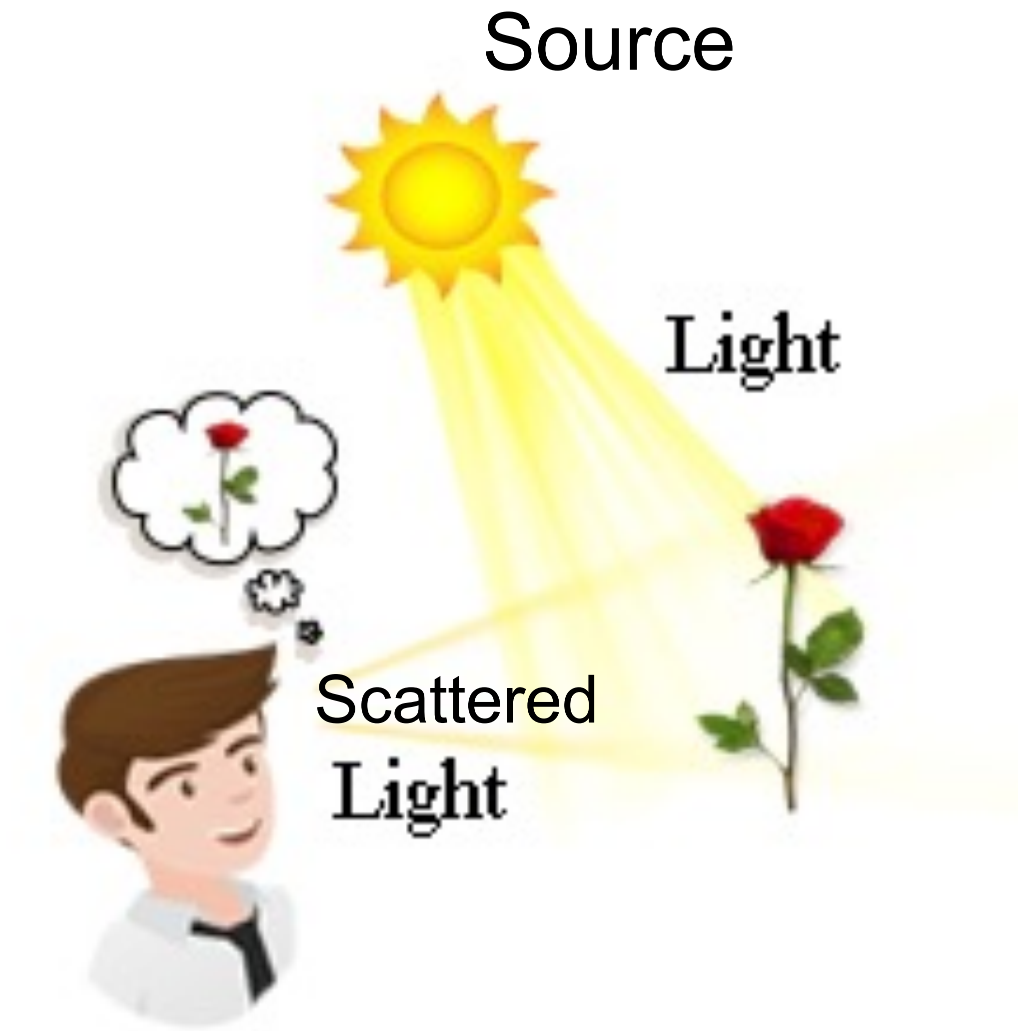


# What is High Energy Physics?



- High energy physics (elementary particle physics) studies the smallest pieces of matter and their interactions

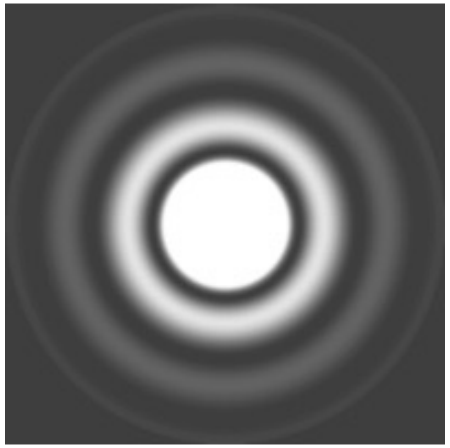
# How we see/study things?

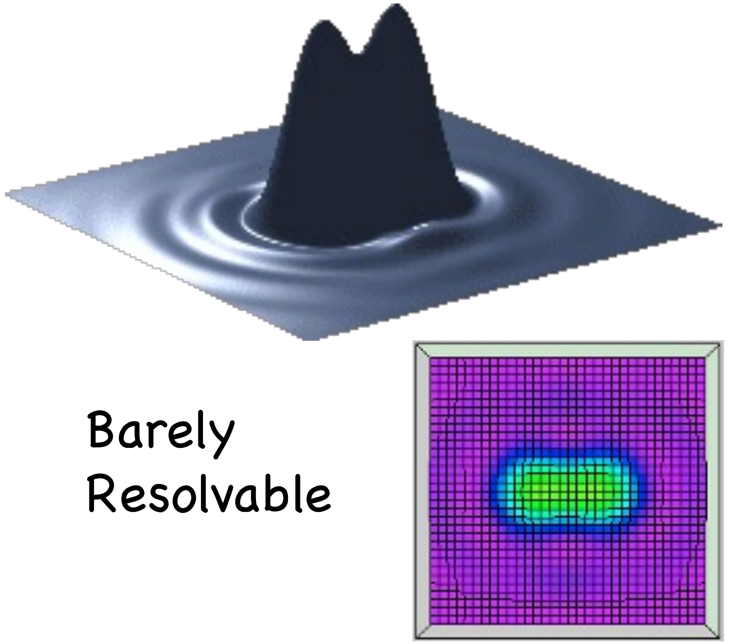


# How we see/study small things?

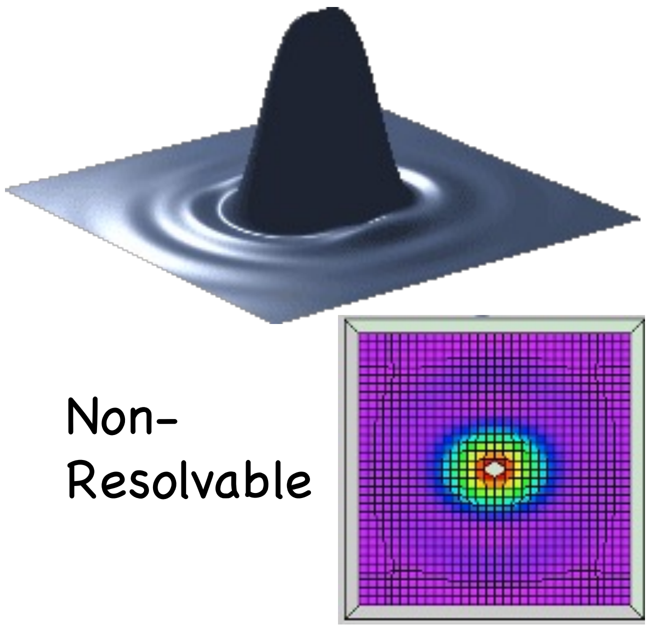
# Optical Microscope Limitations

- Due to diffraction effects every single point becomes ‘blurry circle’ with radius of ~λ





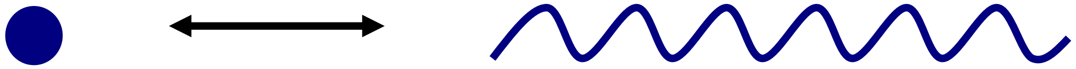
Barely Resolvable



Non-Resolvable

# Electron microscope

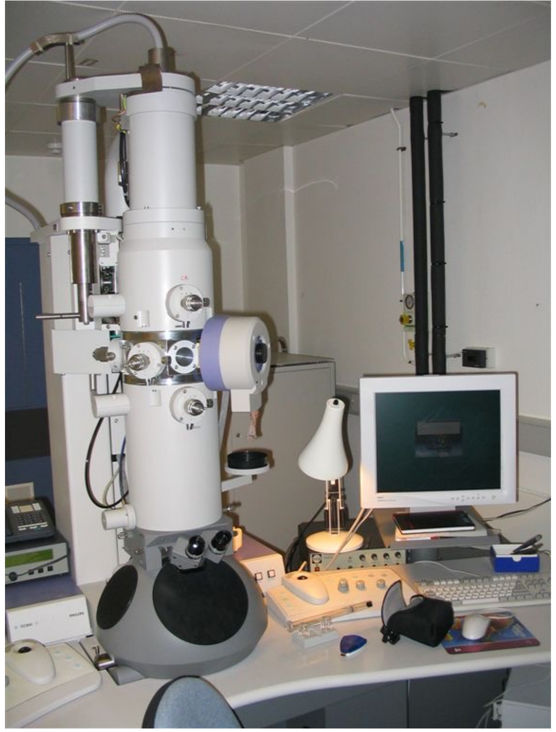
- Quantum mechanics tells us that particles behaves as a wave (and vice versa)



electron $\lambda = h/p$

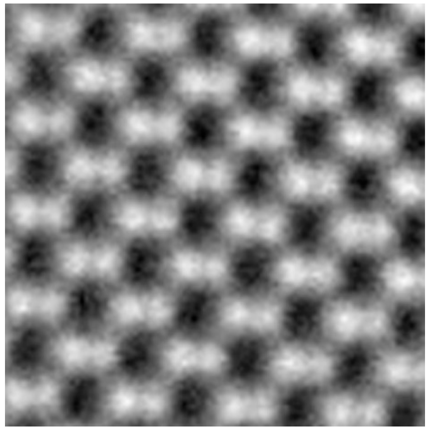
Louis de Broglie (1924)
De Broglie wavelength

  - The higher the energy of the particle – the smaller the wavelength and therefore, the smaller dimensions we can explore!



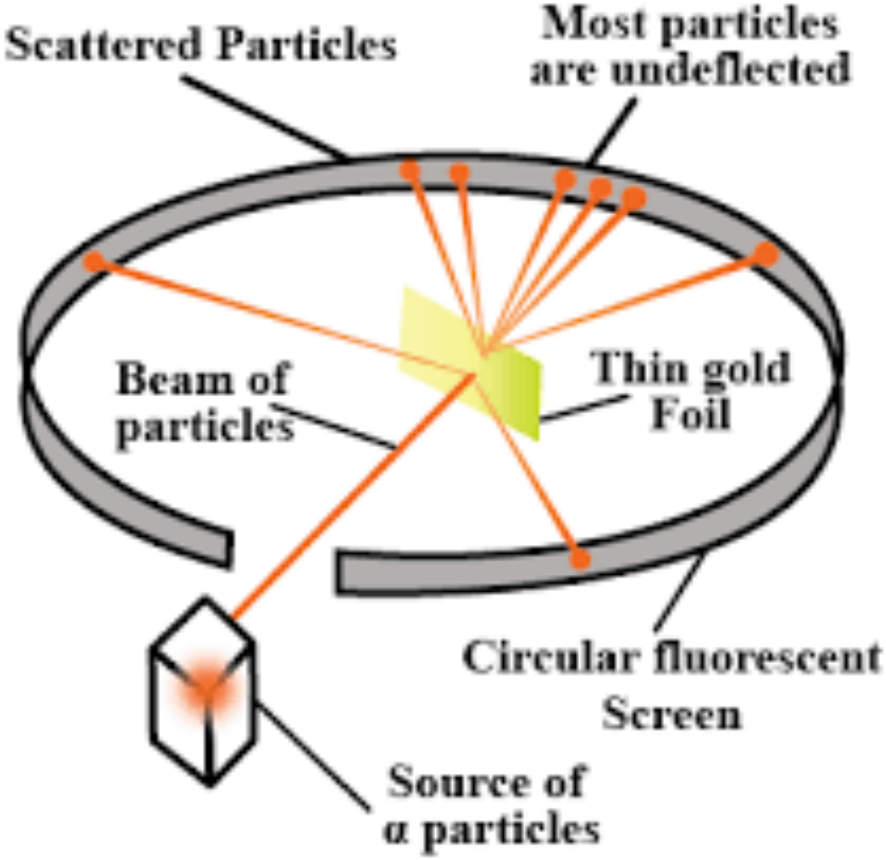
- Electron microscopes can explore tiny things with sizes of 50 pm ($5 \times 10^{-8}$ cm)
  - Two orders of magnitude better than optical microscopes…

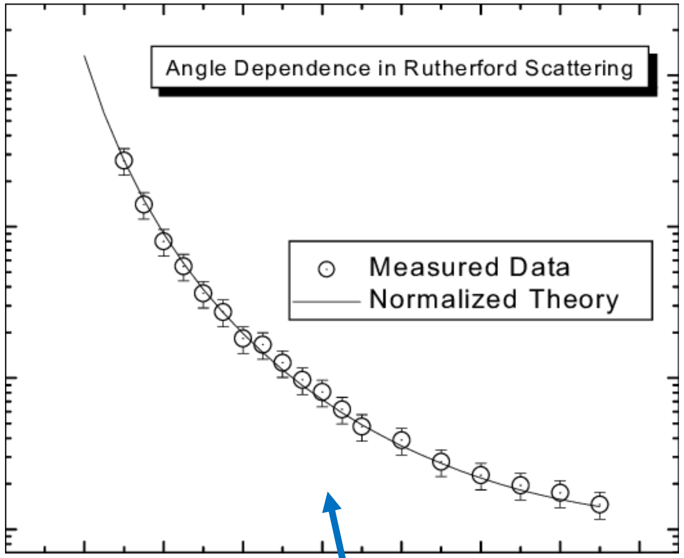
Image of GaN molecules separation is ~63 pm

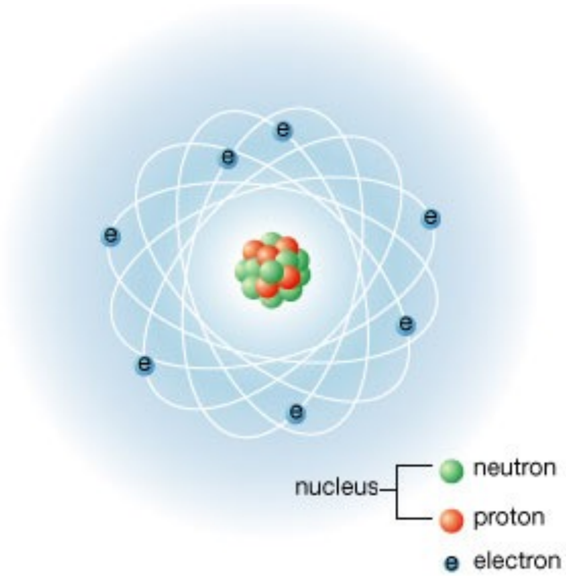


# Discovery of an atom

- 1919: Rutherford discovers atomic structure
  - Bombard very thin gold foil with $\alpha$-particles
  - Most of $\alpha$-particles went through: space is mostly empty!



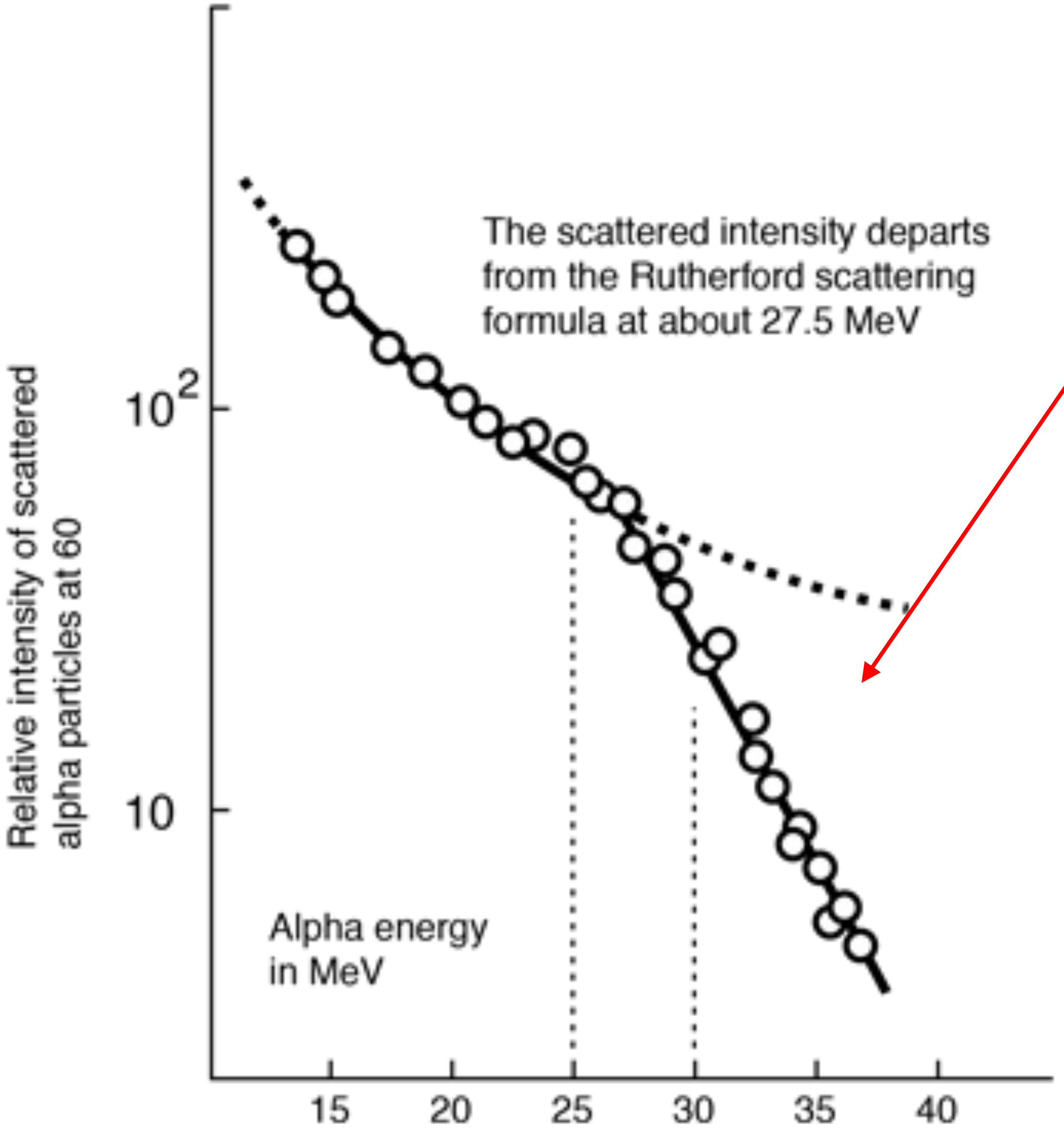




- Studying the number of scattered particles as a function of scattered angle tells us the information about the nature of interaction
  - This plot confirms a point-like Coulomb interaction
  - It is our tool for studying small pieces of matter

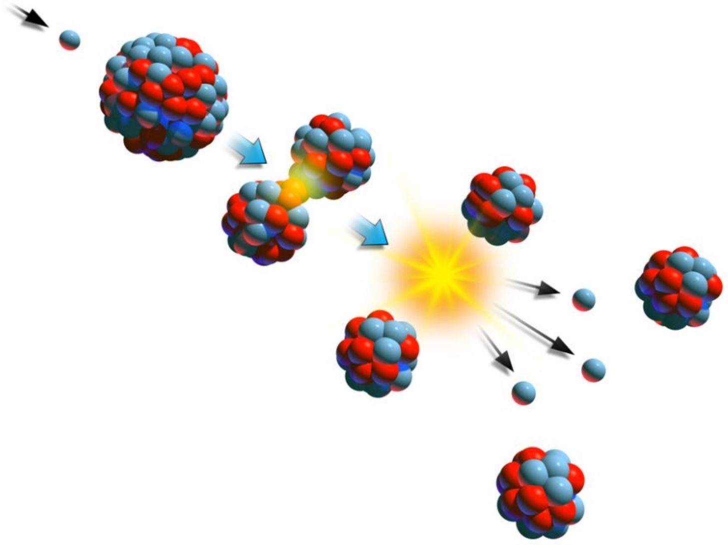
# Nucleus Structure

- What happens if we continue increasing energy of $\alpha$-particles?



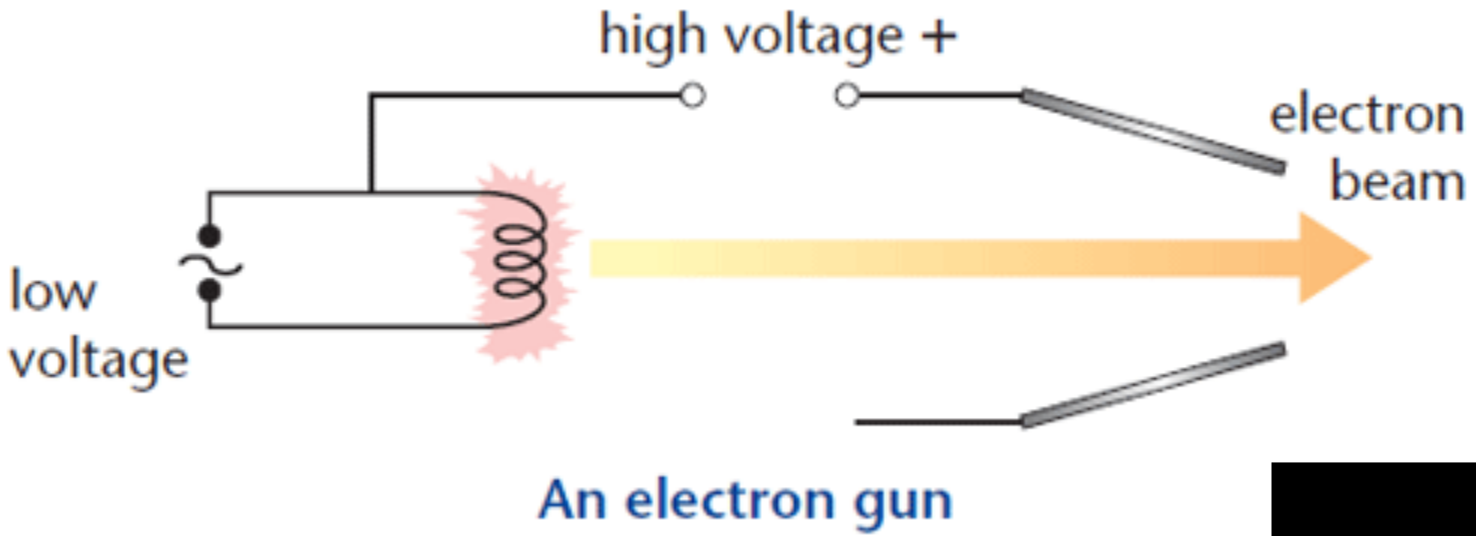
Energy

Nucleus breaks Into protons and neutrons



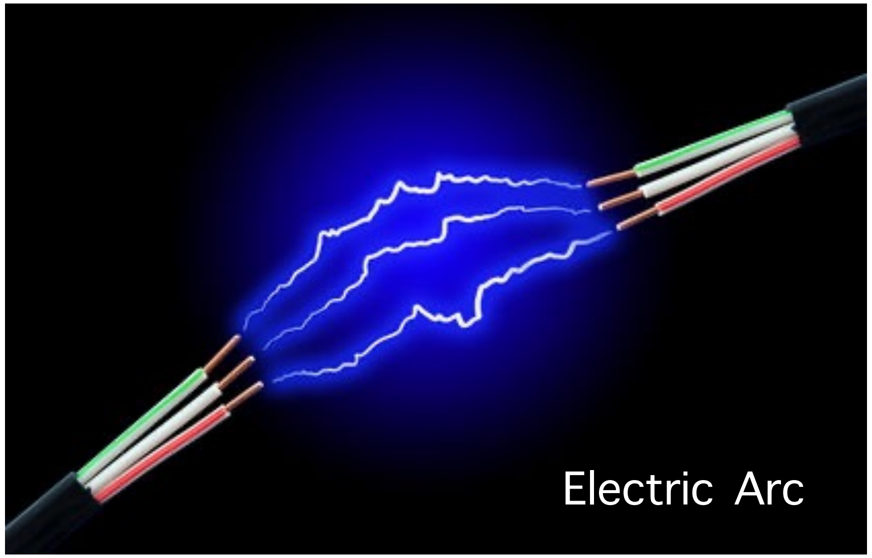
# How to accelerate a particle ?

- If it is charged, put into electric field !
  - But how high can we go ?



An electron gun

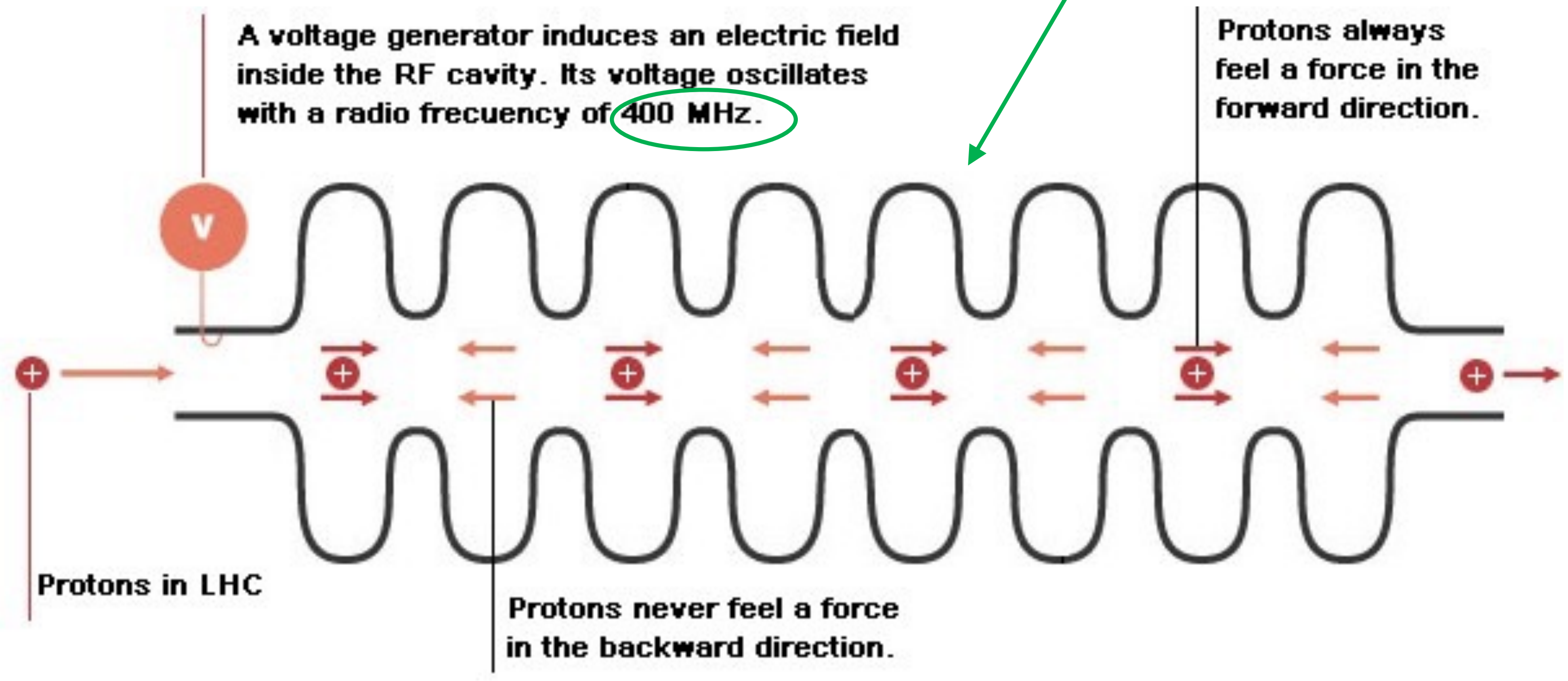
Electric discharge
in vacuum,
<~ 100 kV/cm



# Linear Accelerators (Linac)

- Modern superconducting linac component consists of several microwave cavities

5 MV/m



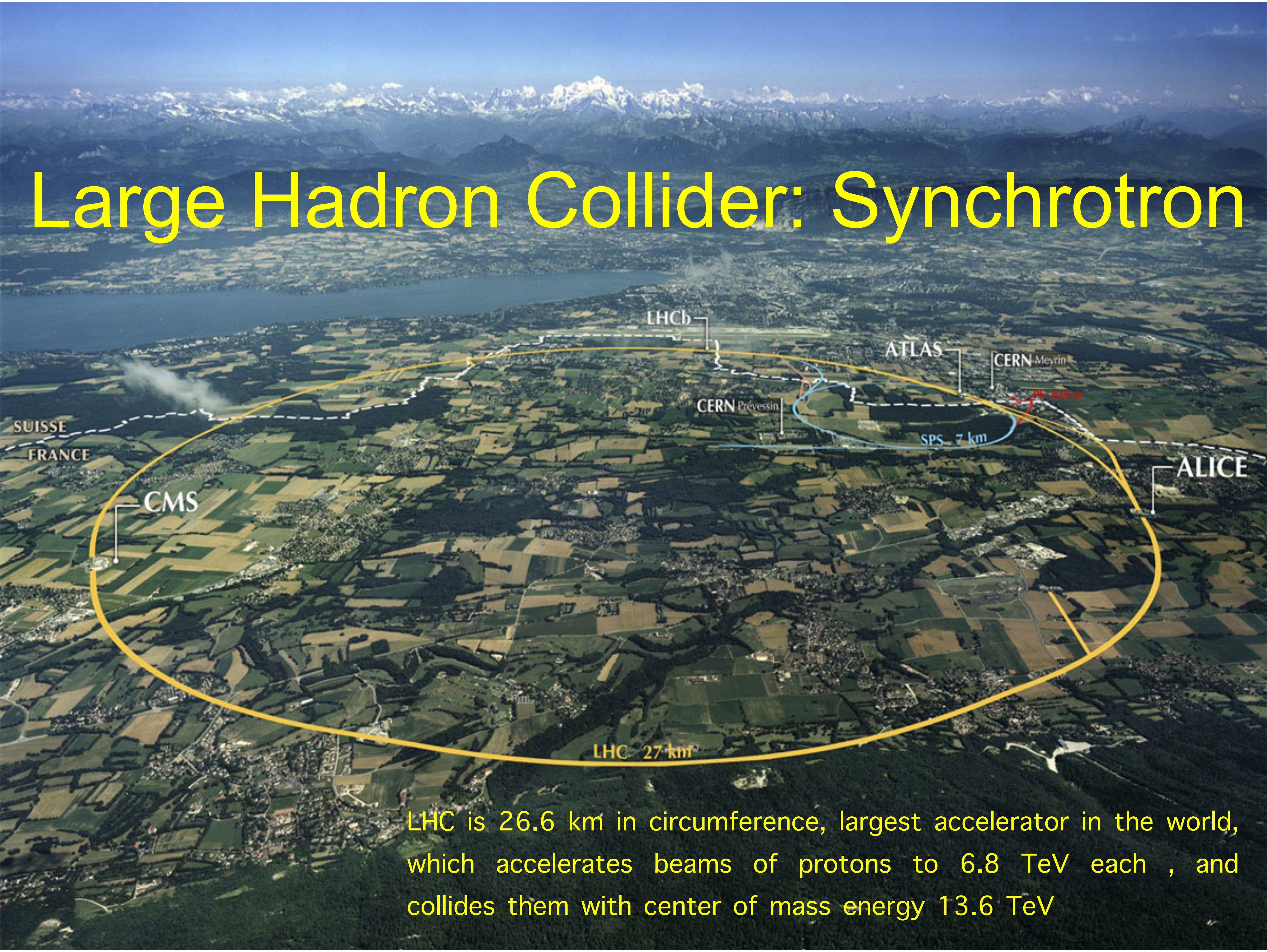
A voltage generator induces an electric field inside the RF cavity. Its voltage oscillates with a radio frecuency of 400 MHz.

Protons always feel a force in the forward direction.

Protons in LHC

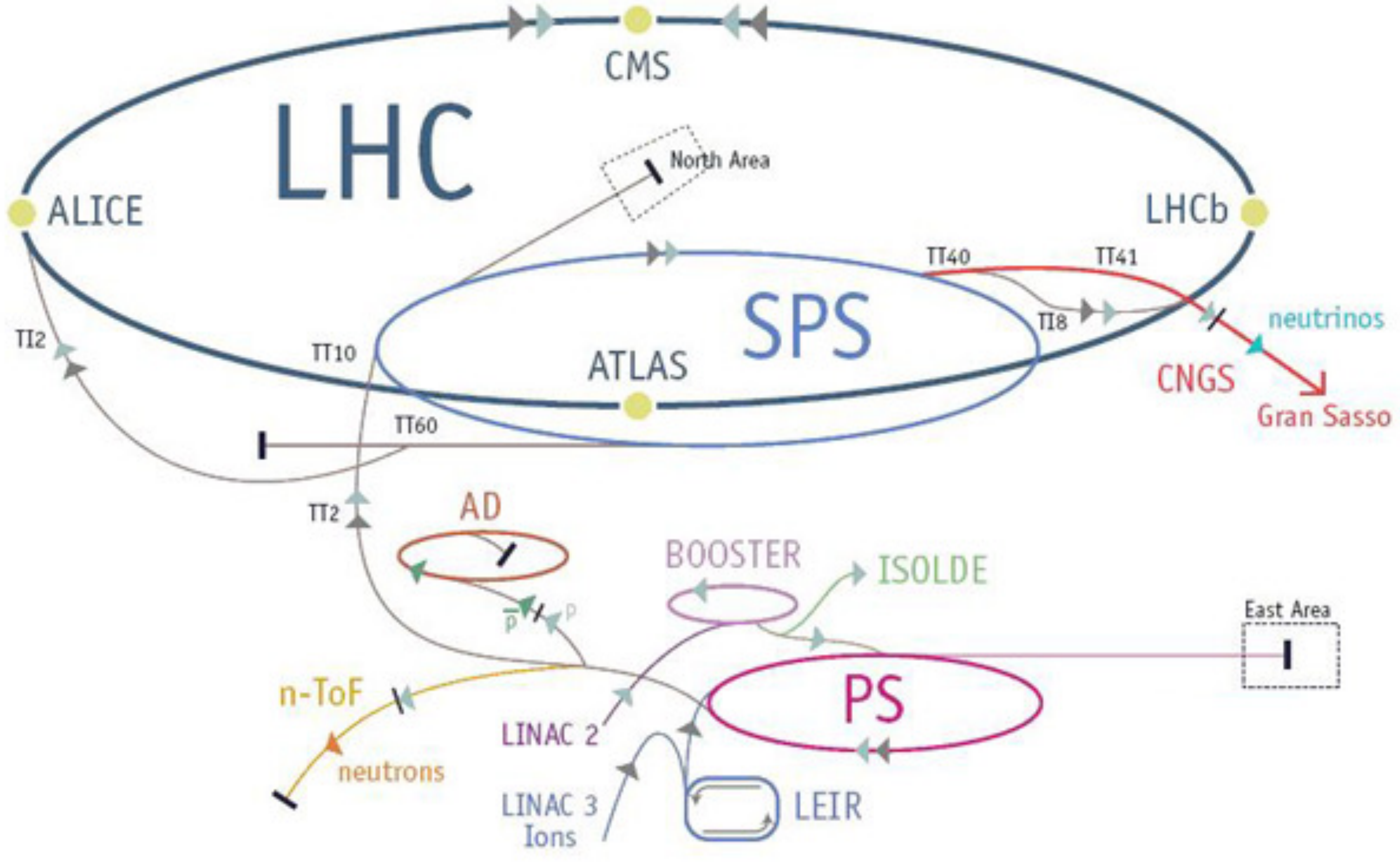
Protons never feel a force in the backward direction.

# Large Hadron Collider: Synchrotron

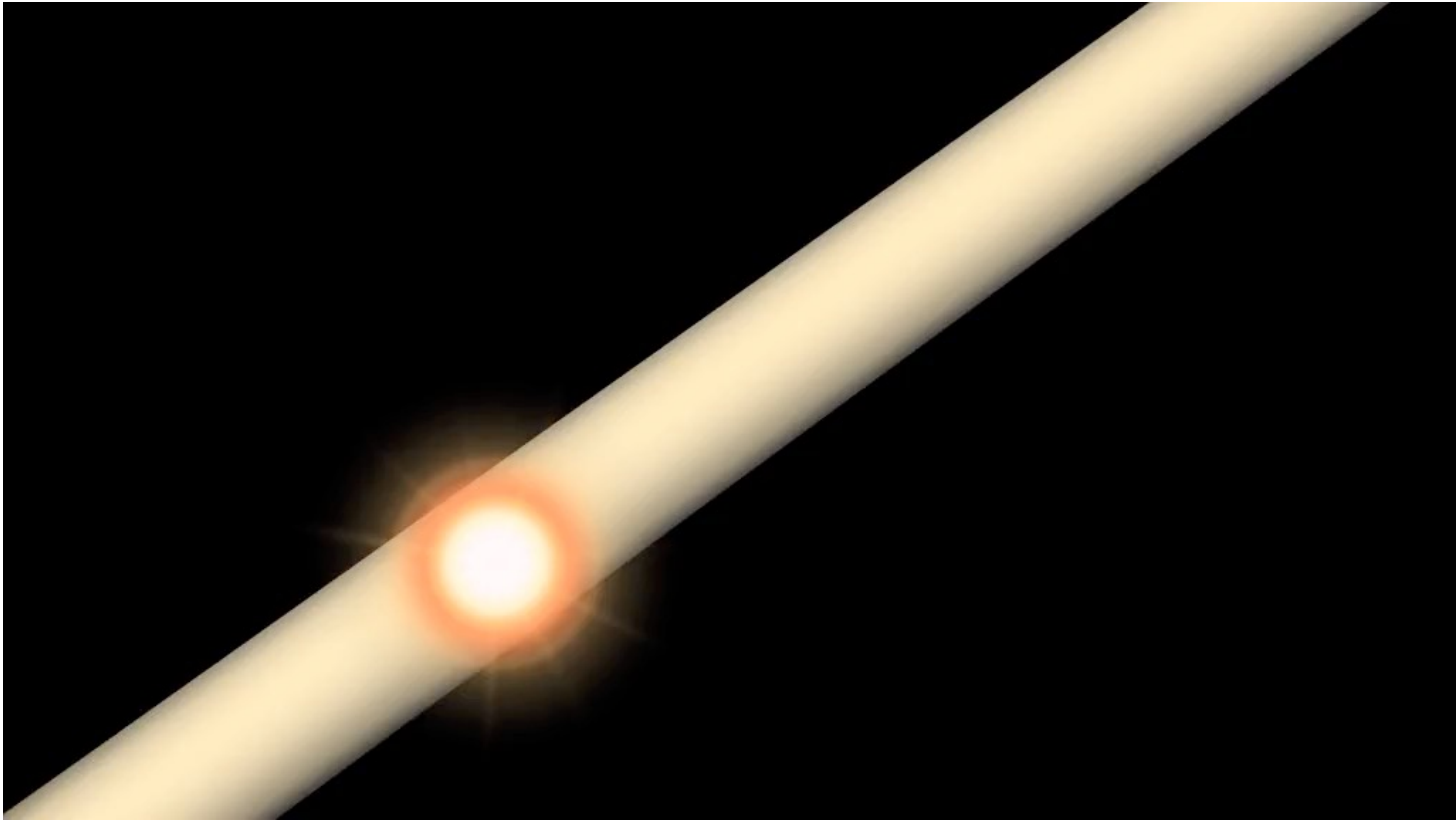


LHC is 26.6 km in circumference, largest accelerator in the world, which accelerates beams of protons to 6.8 TeV each , and collides them with center of mass energy 13.6 TeV

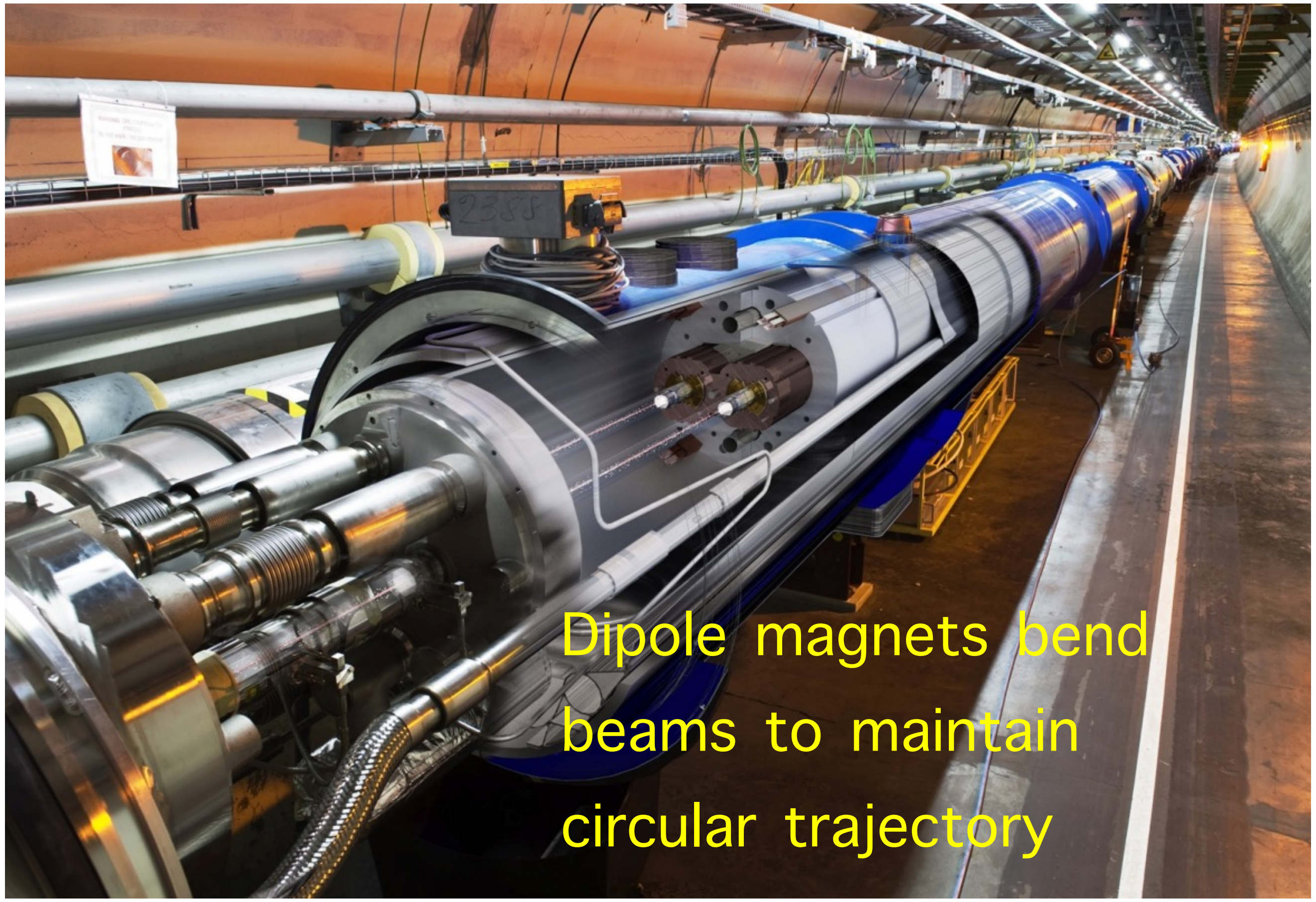
# CERN Accelerator Complex



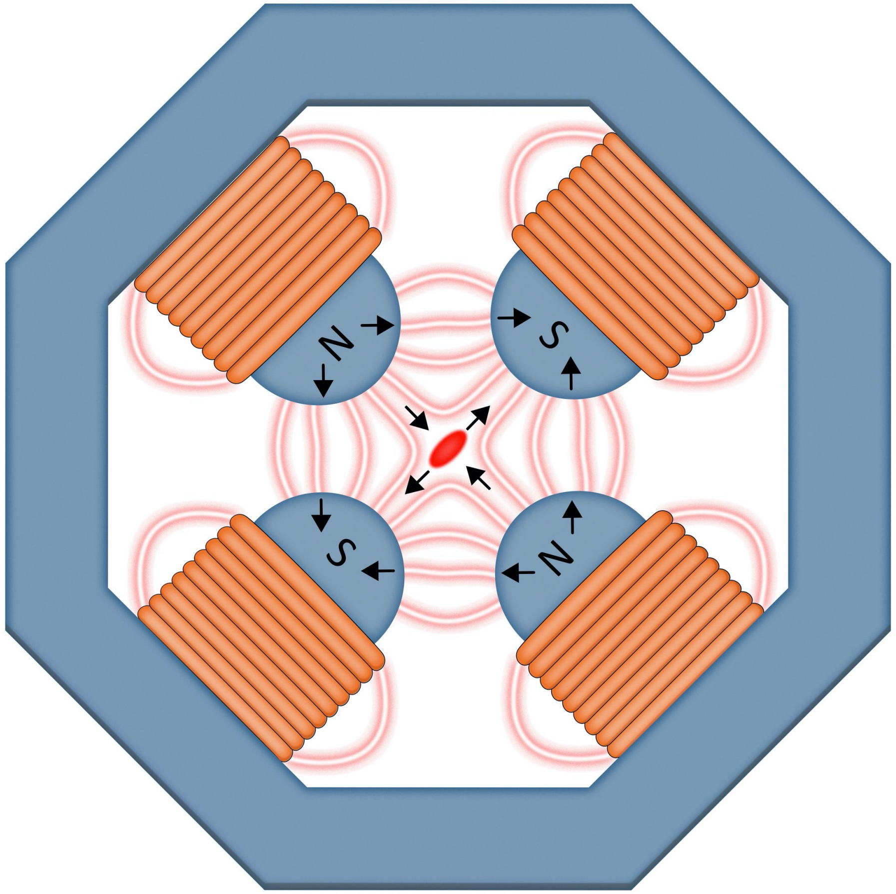
# CERN Accelerator Complex



# LHC Magnets



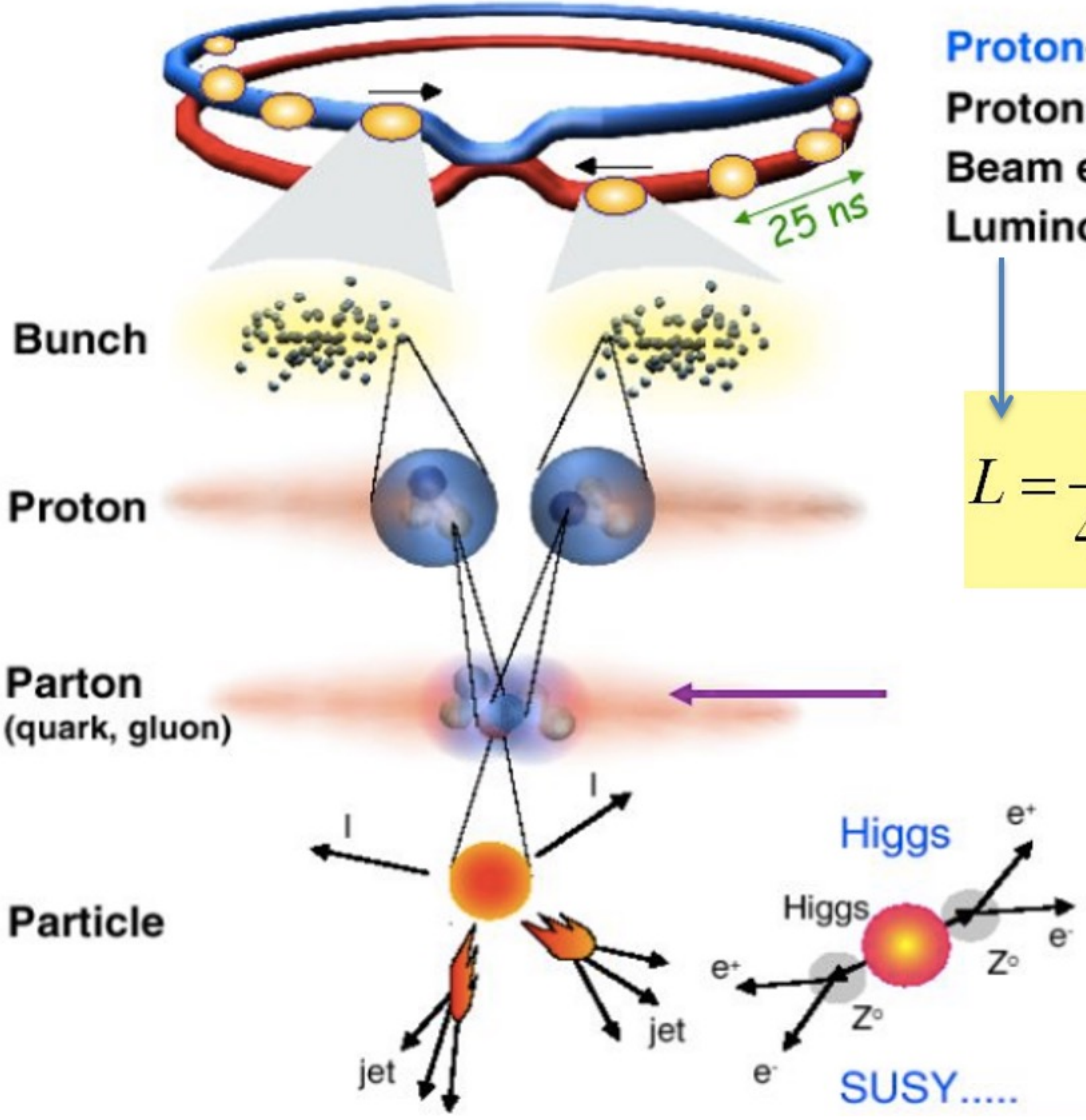
Dipole magnets bend beams to maintain circular trajectory



LHC has1232 dipole and 392 quadrupole Nb-Ti magnets with magnetic field of 8.33 T

Quadrupole magnet acts like a lens, non-uniform magnetic fields focus the beams

# Collisions at LHC

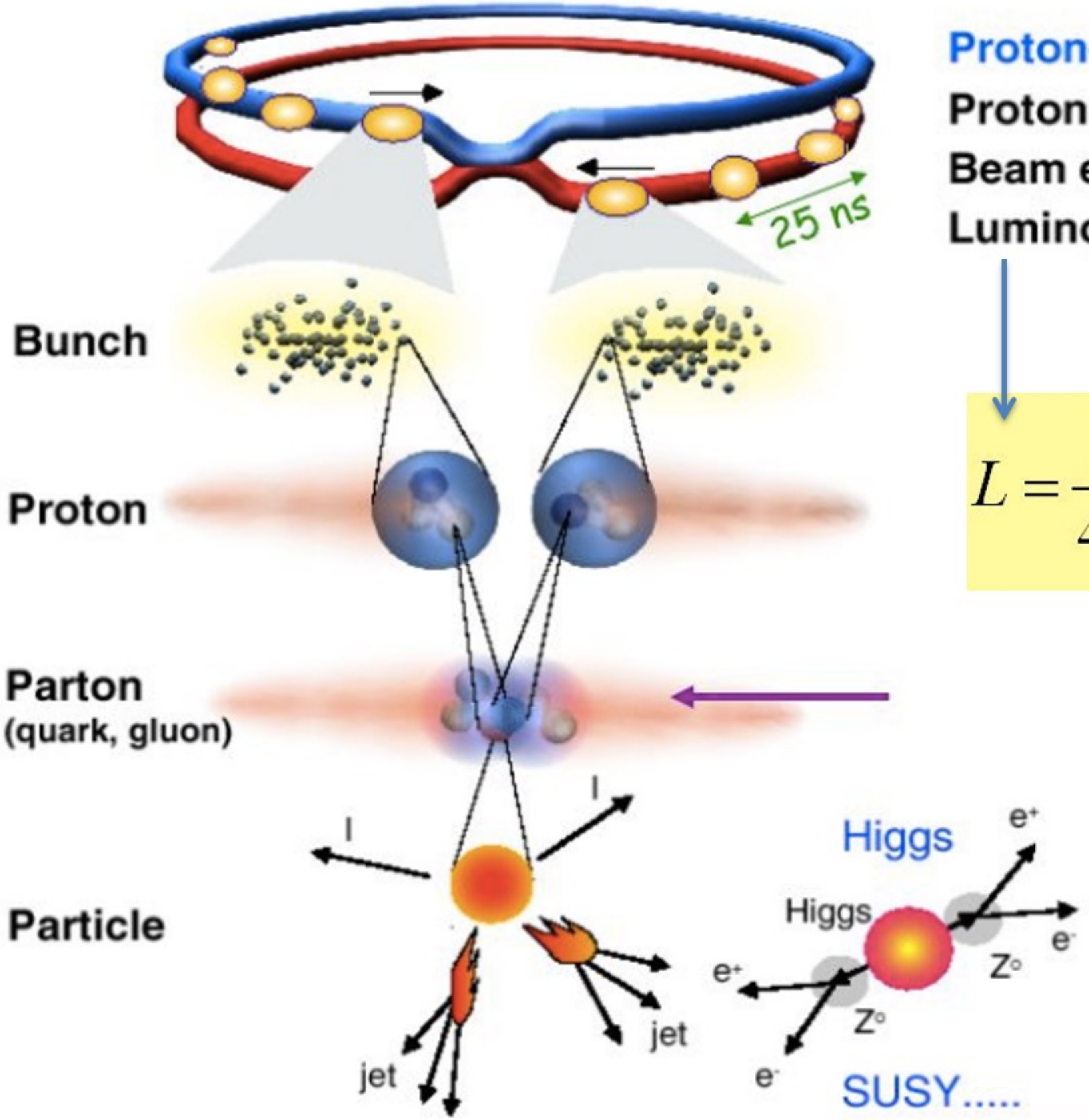


**Proton-Proton** Collisions every 25 ns

| | |
|---|---|
| Protons/bunch | $10^{11}$ |
| Beam energy | 13.6 TeV |
| Luminosity | $10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} = 10\ \mathrm{nb}^{-1}\mathrm{s}^{-1}$ |

$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}F$$

# Collisions at LHC



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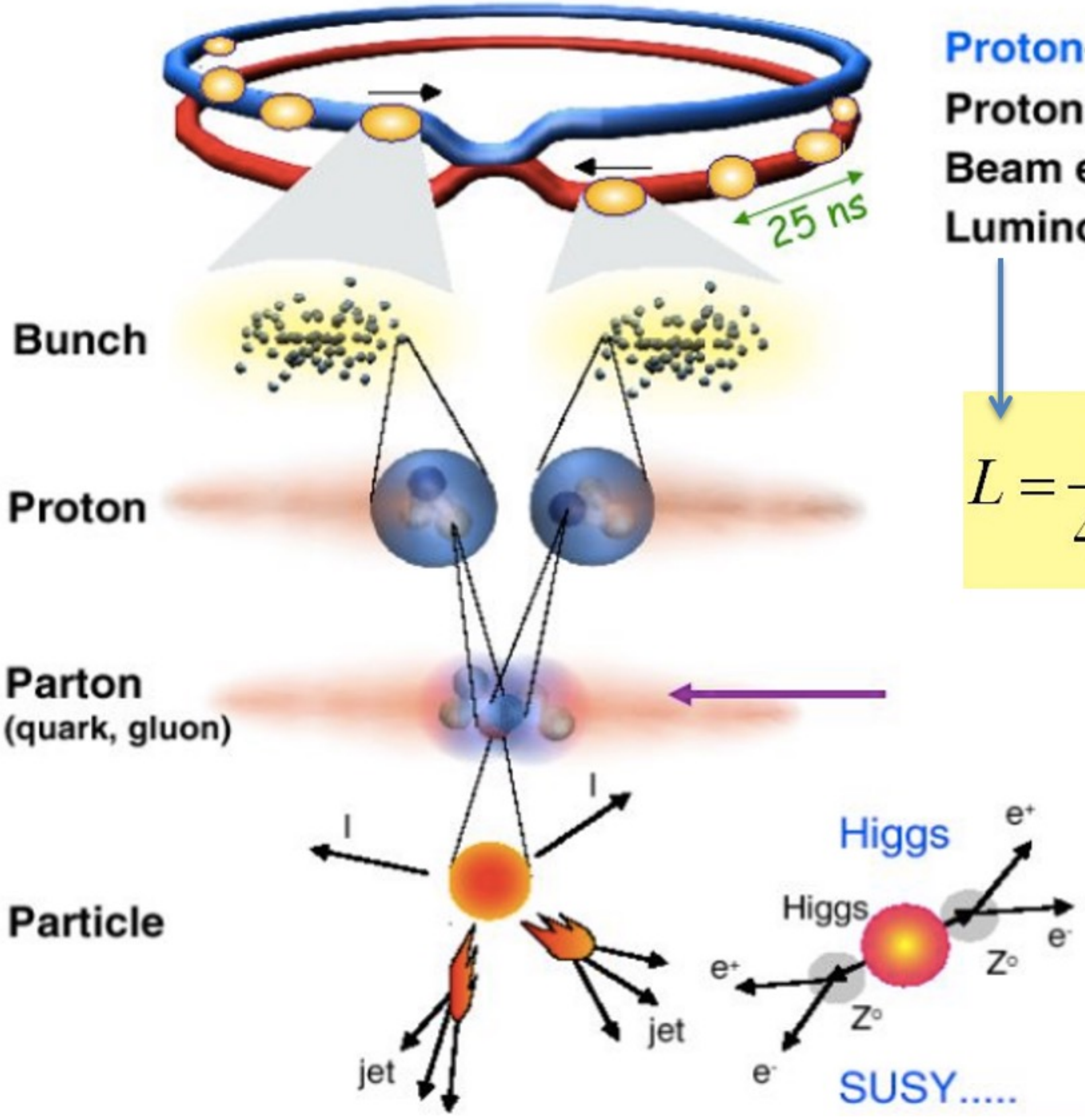

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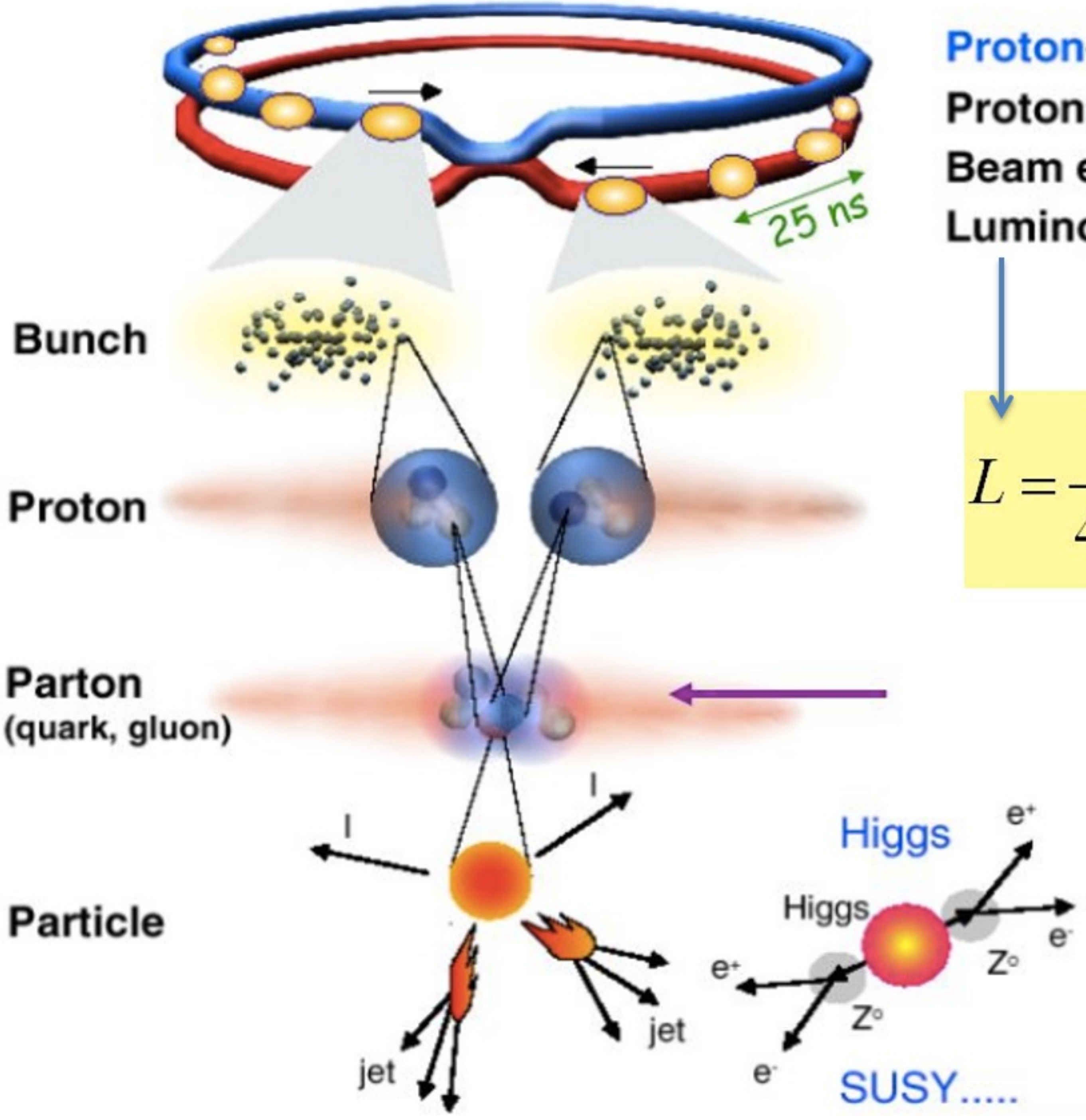
**# of colliding bunch pairs = 2808**

$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}F$$

# Collisions at LHC



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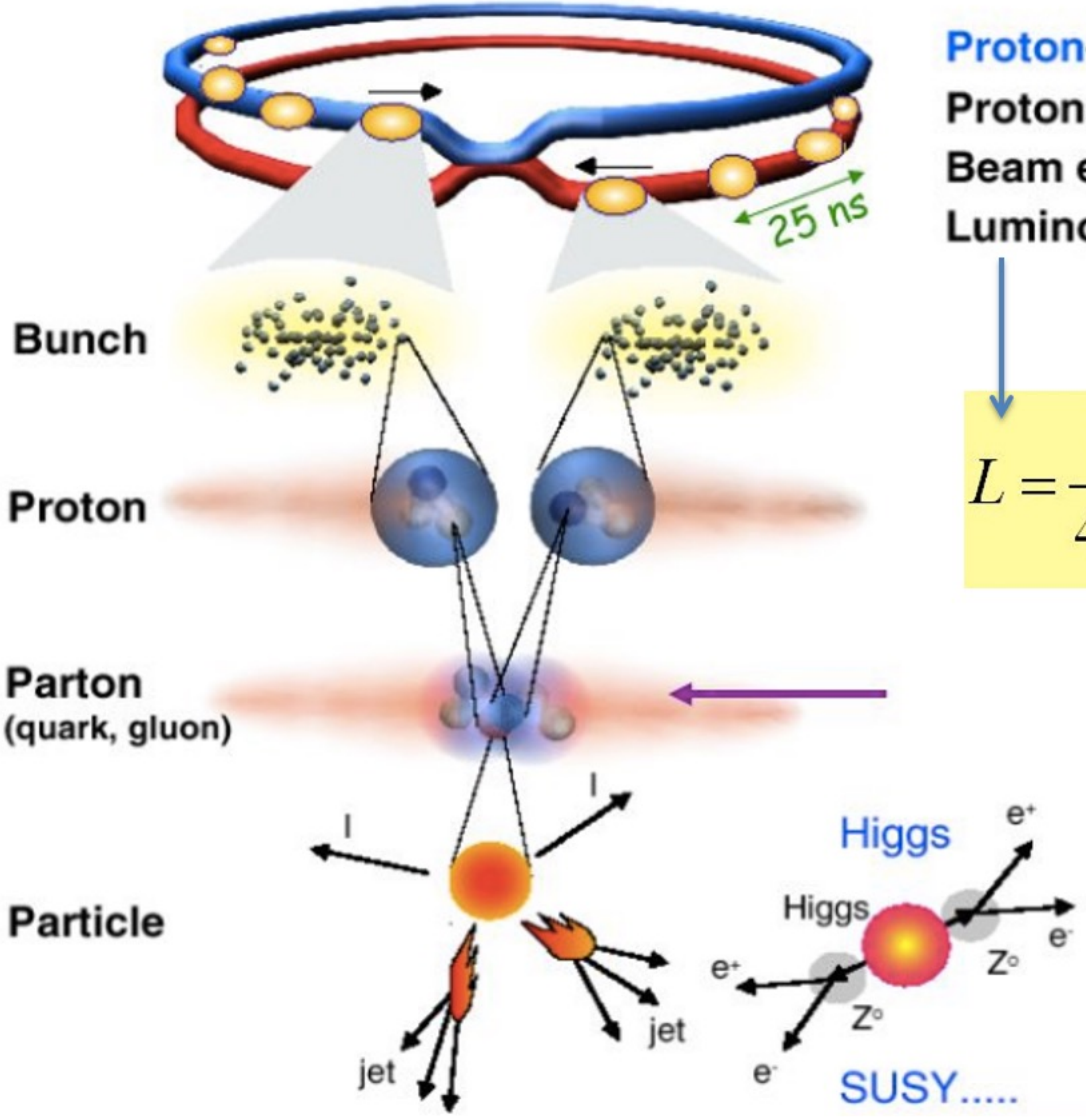
**Revolution Frequency = 11.245 kHz**

# Collisions at LHC



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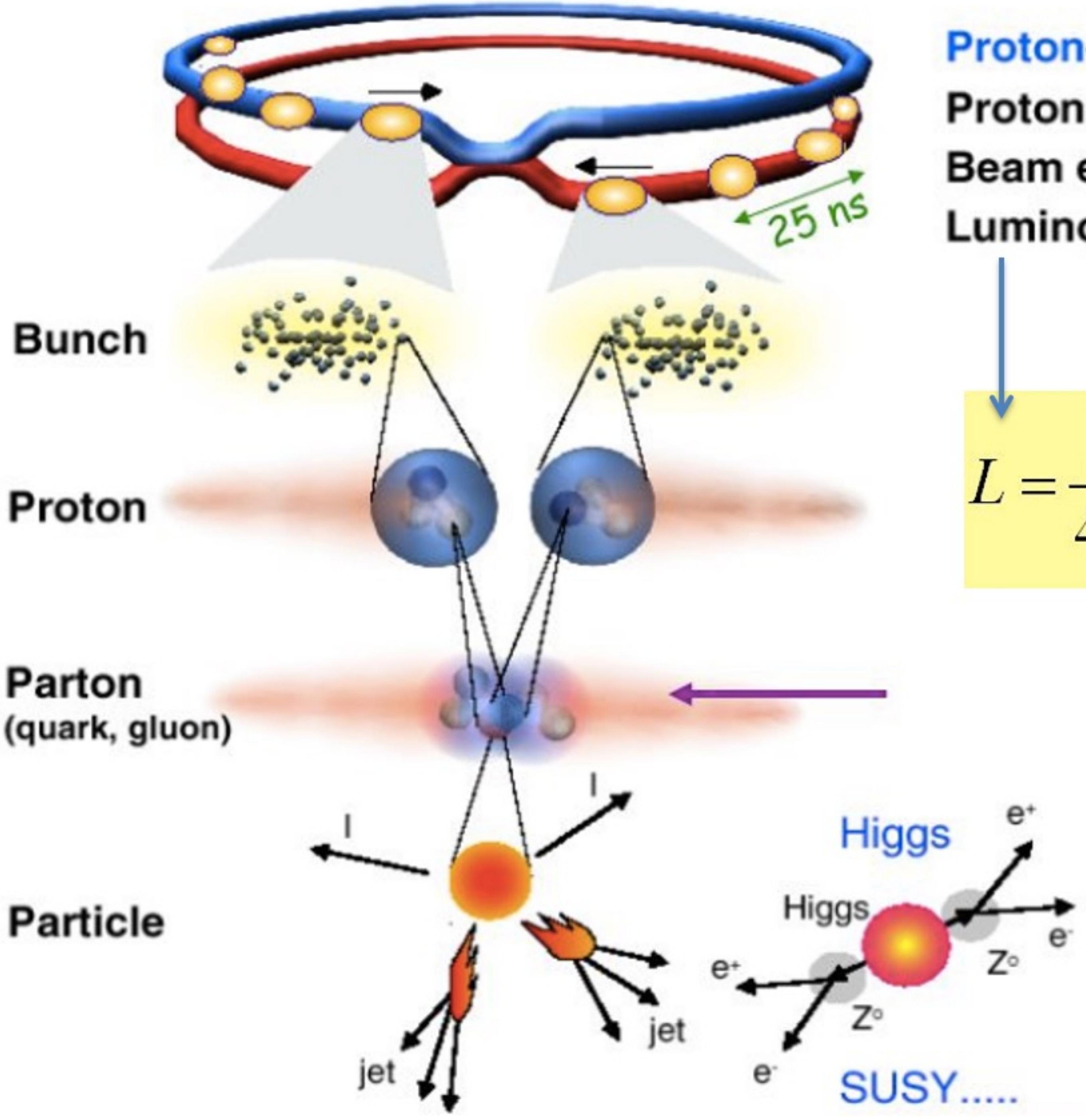
**Geometric loss Factor (~0.95)**

# Collisions at LHC



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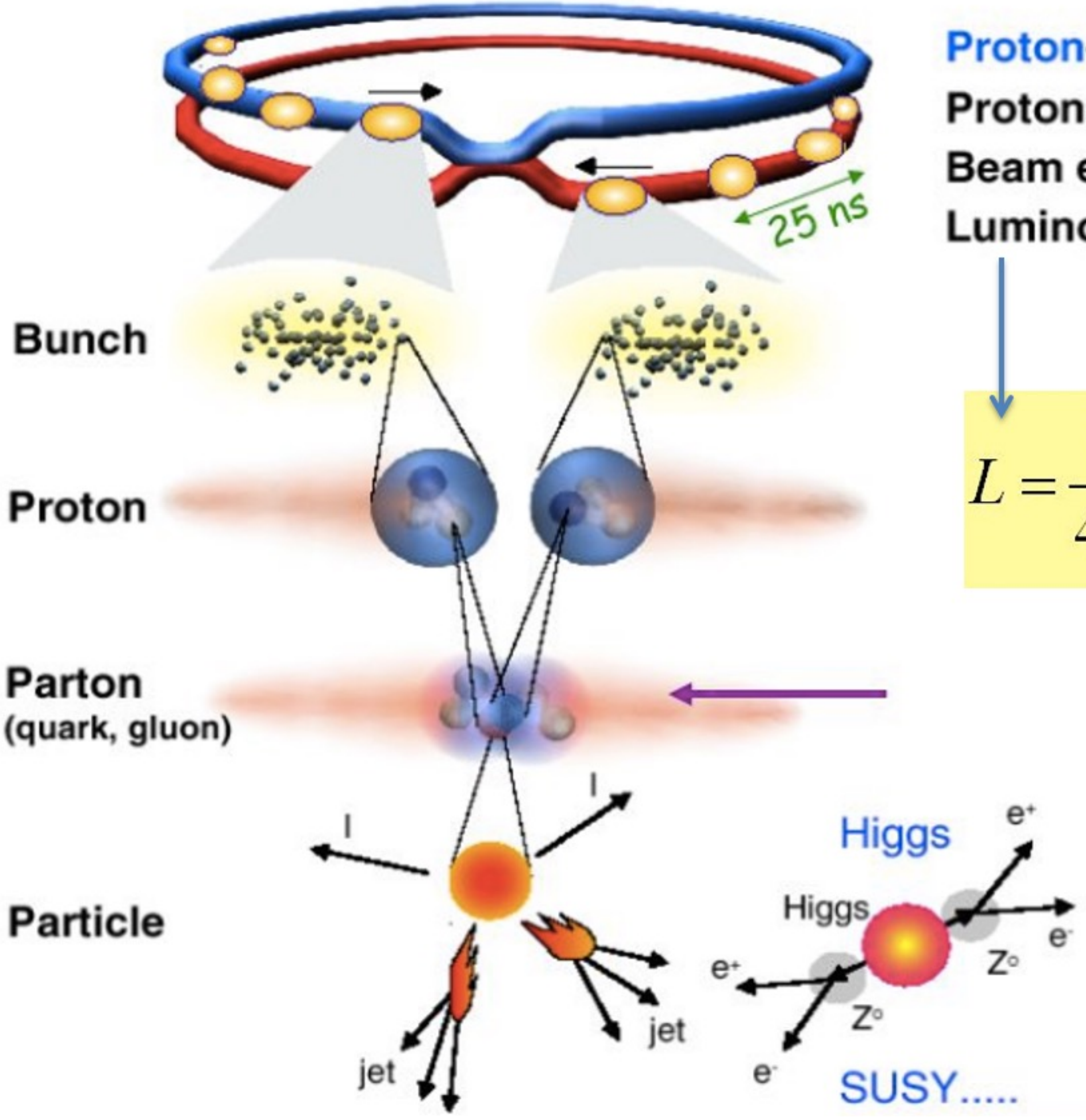
**Beam Size at Interaction Point = 16.6 μm**

# Collisions at LHC



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|---|---|
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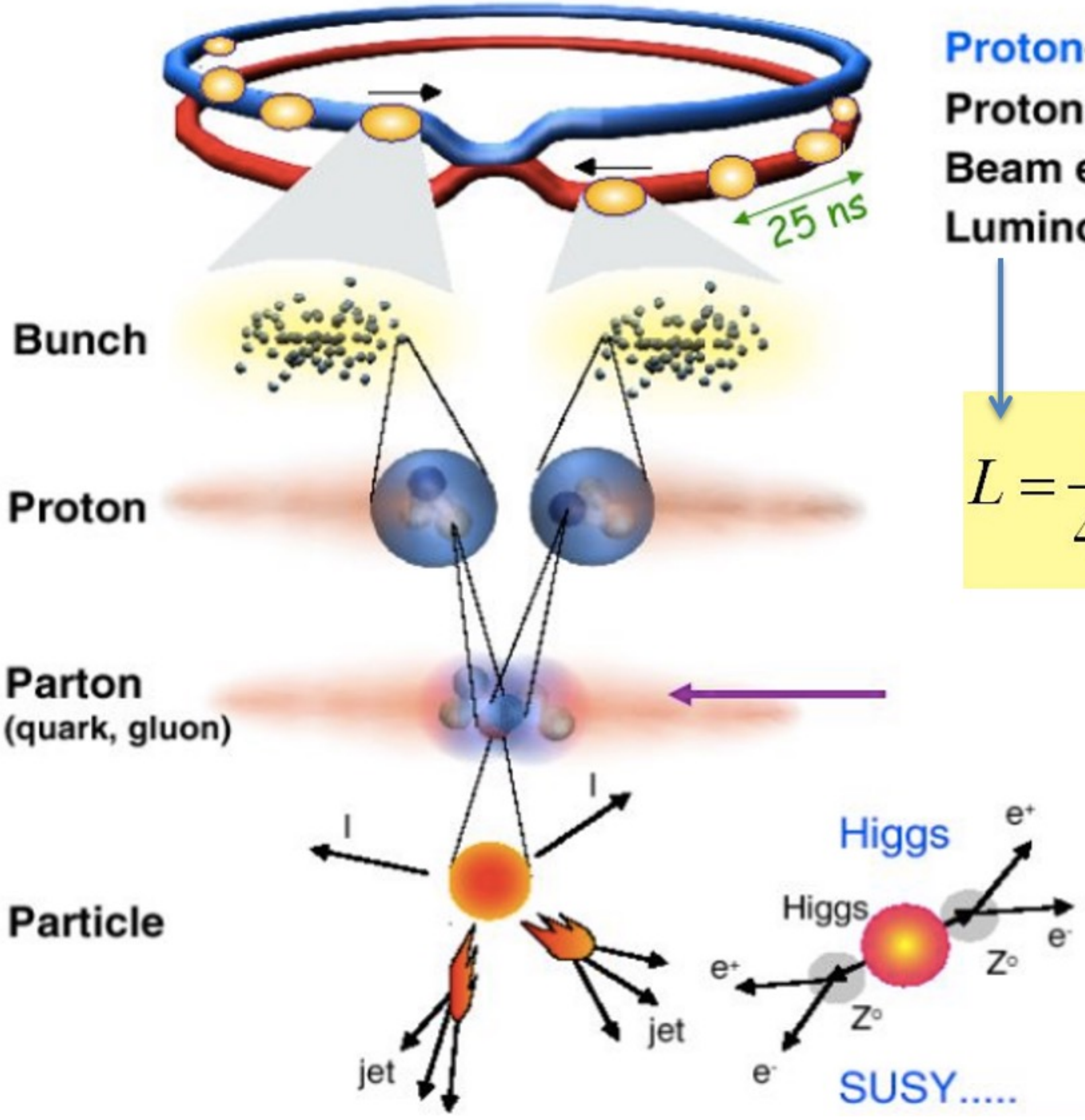
**Geometric loss Factor (~0.95)**

**Beam Size at Interaction Point = 16.6 μm**

$$L_{\text{int}} = \int L \, dt.$$

# Collisions at LHC



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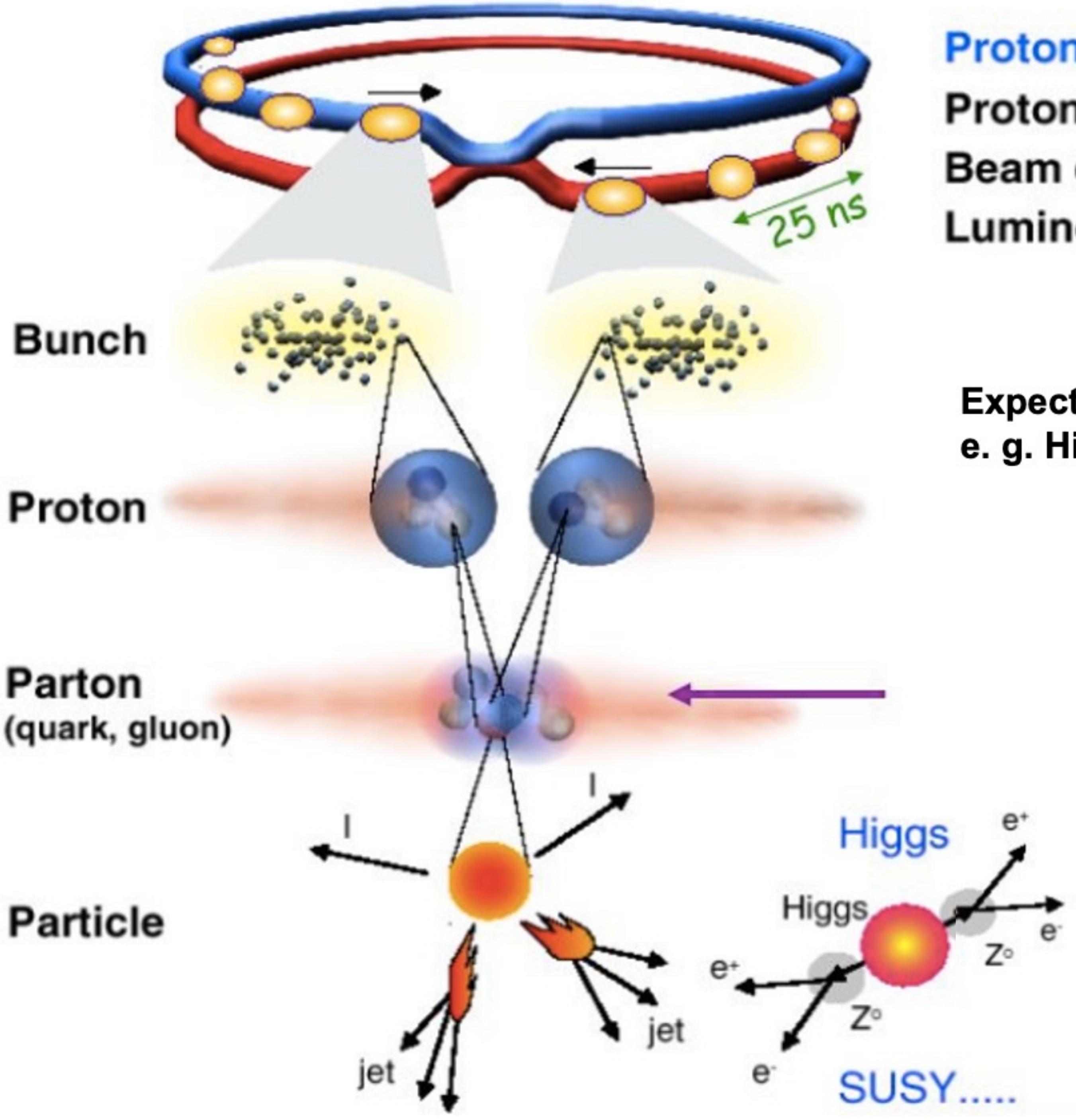
**Beam Size at Interaction Point = 16.6 $\mu$m**

$$N = \epsilon \cdot \mathcal{A} \cdot \sigma \cdot \int L dt$$

# Collisions at LHC



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**Expected Number of e. g. Higgs events**

**Integrated Luminosity**

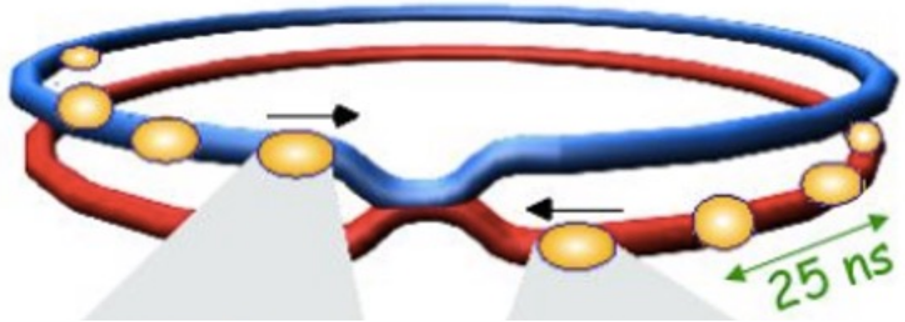
**Production Cross Section**

$$N = \epsilon \cdot \mathcal{A} \cdot \sigma \cdot \int L dt$$

**Efficiency**

**Acceptance**

# Collisions at LHC



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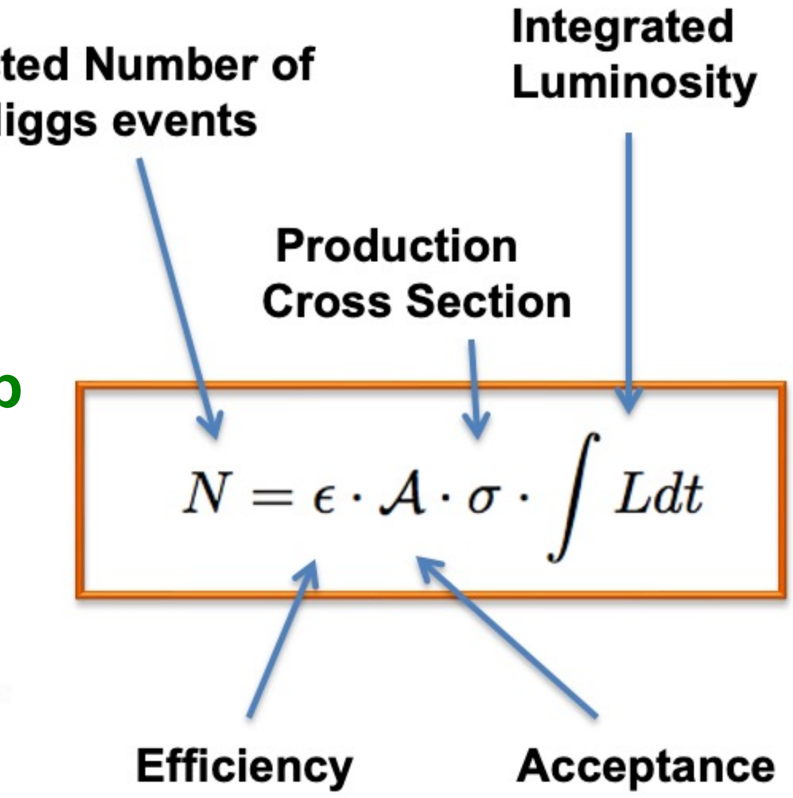
**Question :**
**How many H➔ γγ events were Produced in Run1 (2010-2012) ?**
**BR ( H➔ γγ )= $2.3 \times 10^{-3}$**

- **Integrated Luminosity = 10 fb$^{-1}$**
- **Higgs Production Cross Section @ 8TeV = 20 pb**



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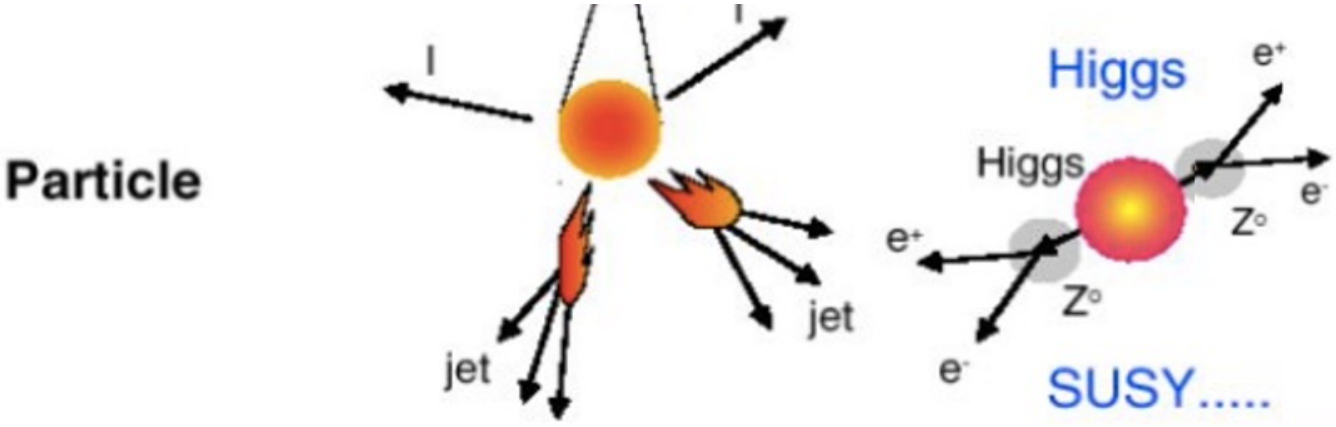
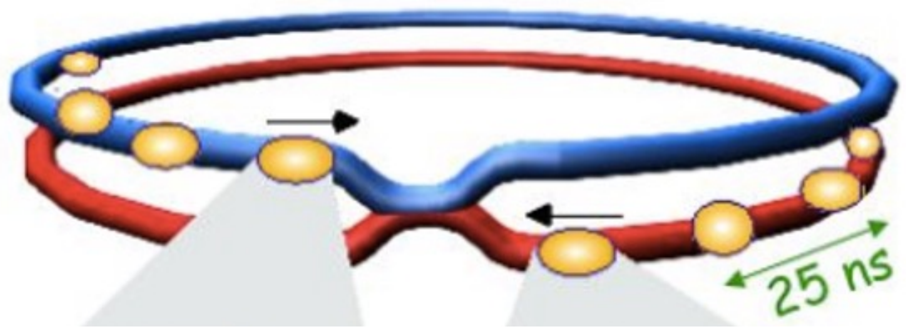


# Collisions at LHC



**Proton-Proton Collisions every 25 ns**

**Protons/bunch** $10^{11}$

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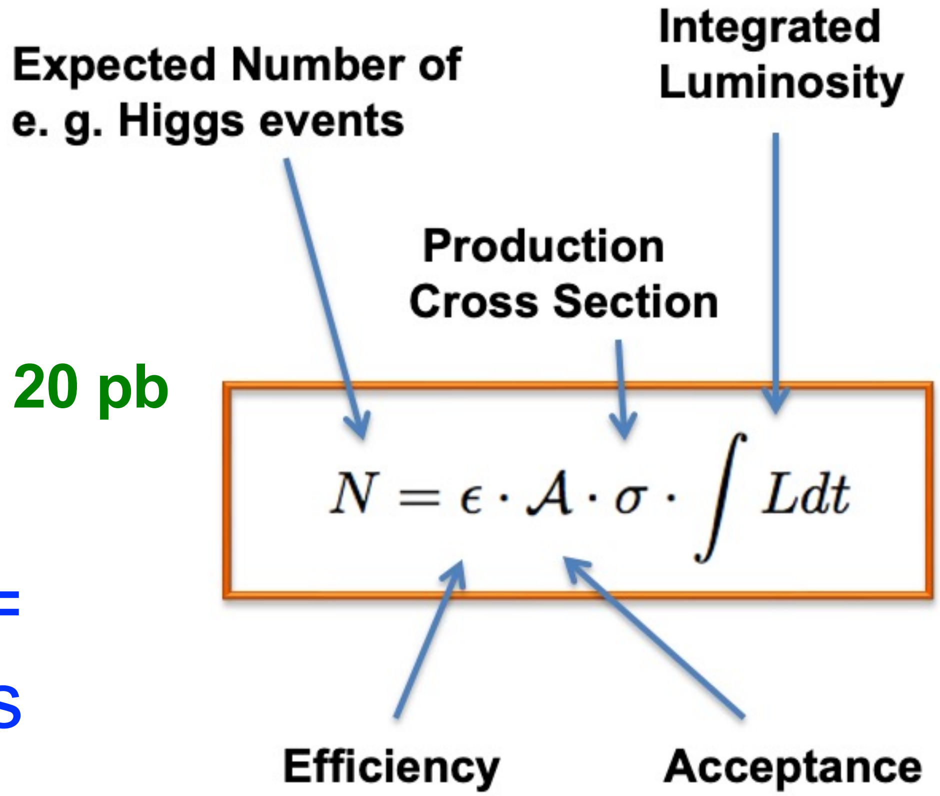
**BR ( H➔ $\gamma\gamma$ )= $2.3 \times 10^{-3}$**

- **Integrated Luminosity = 10 $\mathrm{fb}^{-1}$**
- **Higgs Production Cross Section @ 8TeV = 20 pb**

$$N = 20{,}000\ \mathrm{fb} * 2.3 * 10^{-3} * 10\ \mathrm{fb}^{-1} = 460\ \text{events}$$



**Expected Number of e. g. Higgs events**

**Integrated Luminosity**

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$$N = \epsilon \cdot \mathcal{A} \cdot \sigma \cdot \int L dt$$

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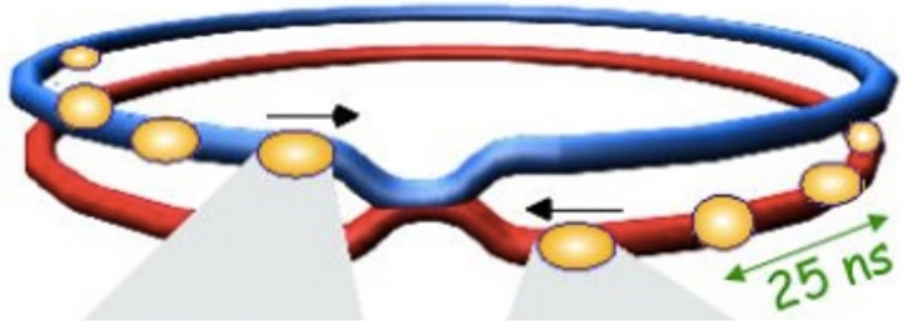
# Collisions at LHC



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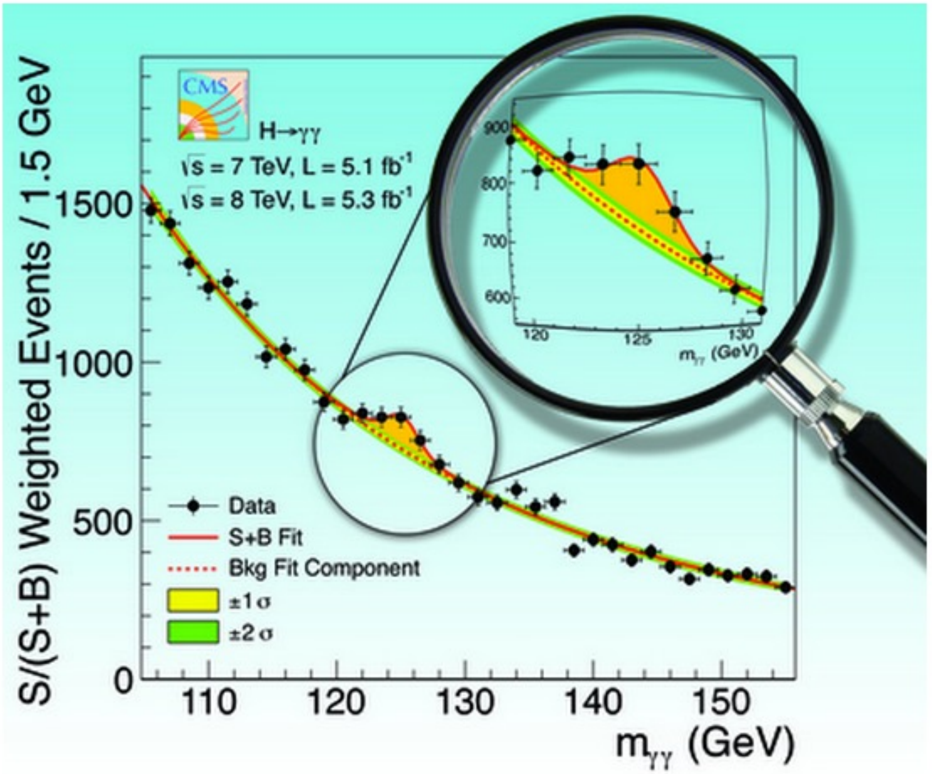
**Question :**
**How many H➔ γγ events were Produced in Run1 (2010-2012) ?**
**BR ( H➔ γγ )= 2.3 x $10^{-3}$**

- **Integrated Luminosity = 10 fb$^{-1}$**
- **Higgs Production Cross Section @ 8TeV = 2**

$$N = 20{,}000\ \text{fb} * 2.3 * 10^{-3} * 10\ \text{fb}^{-1} = 460\ \text{events}$$

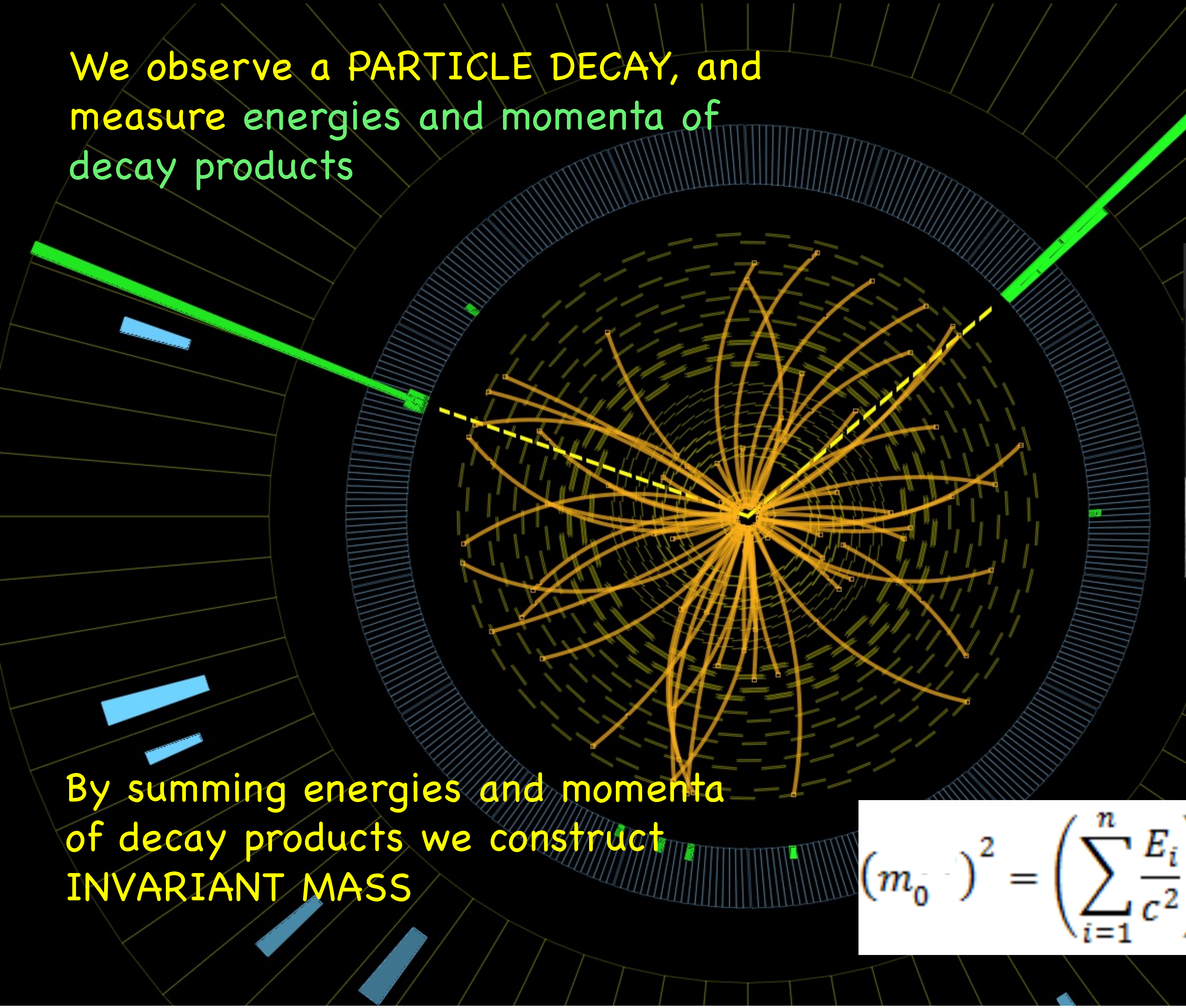
**Expected Number of e. g. Higgs events**

**Integrated Luminosity**

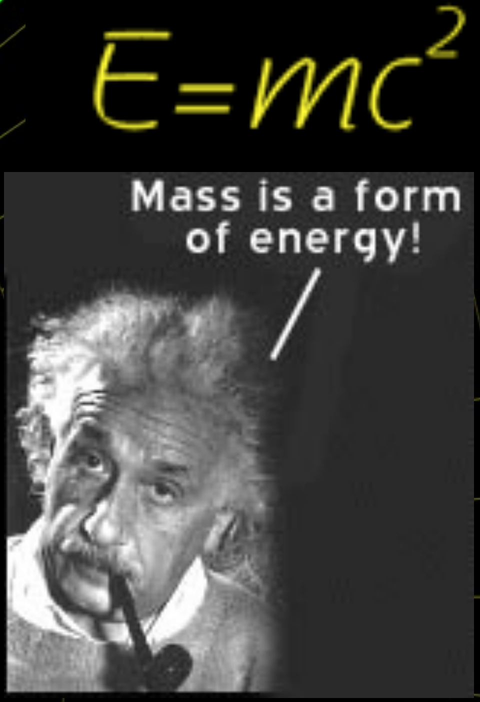


# Higgs Discovery, July 4, 2012

# How do we detect Higgs ?



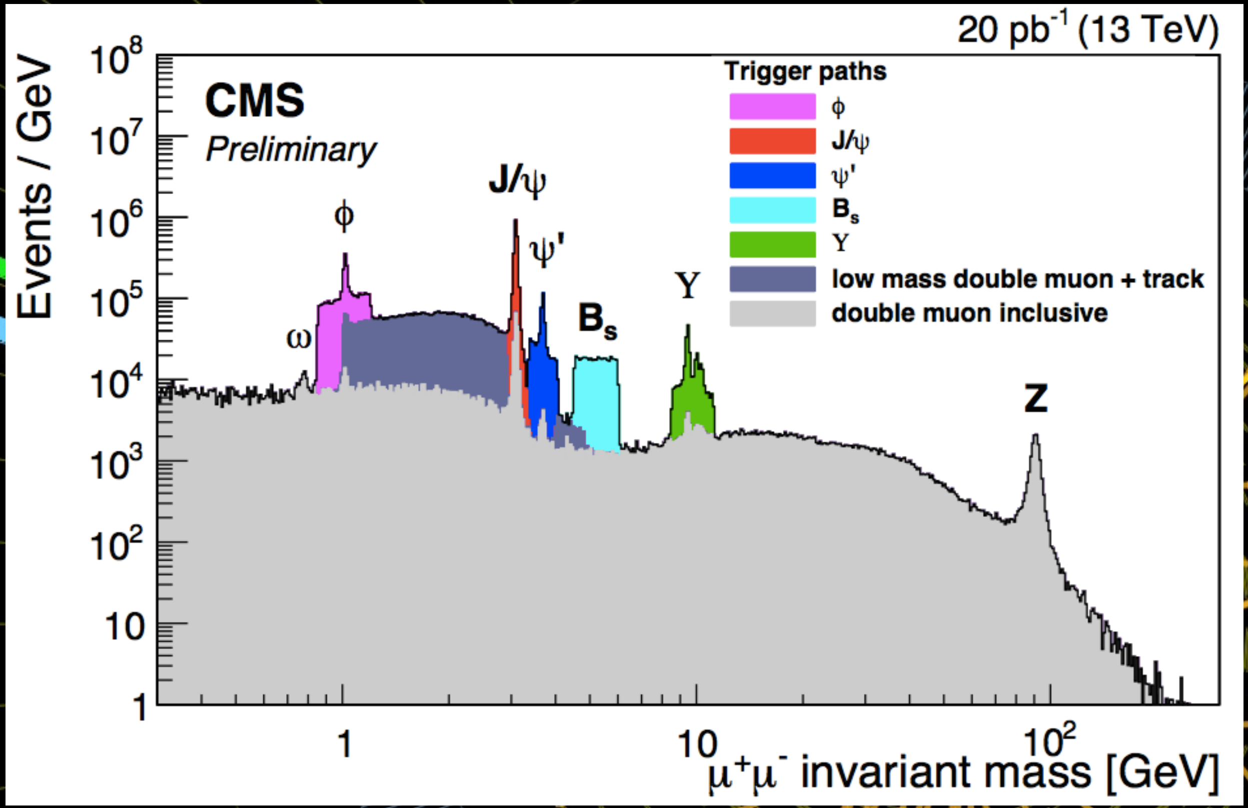
We observe a PARTICLE DECAY, and measure energies and momenta of decay products



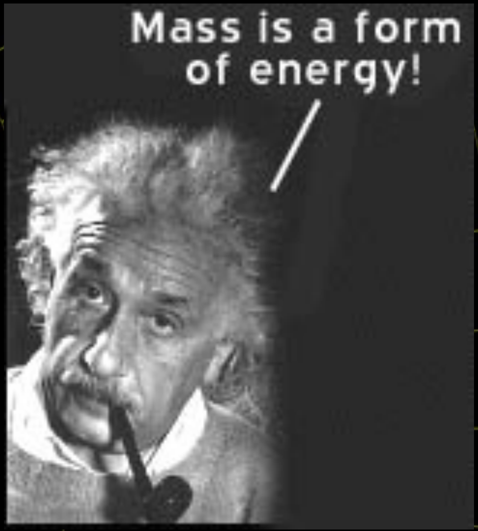
By summing energies and momenta of decay products we construct INVARIANT MASS

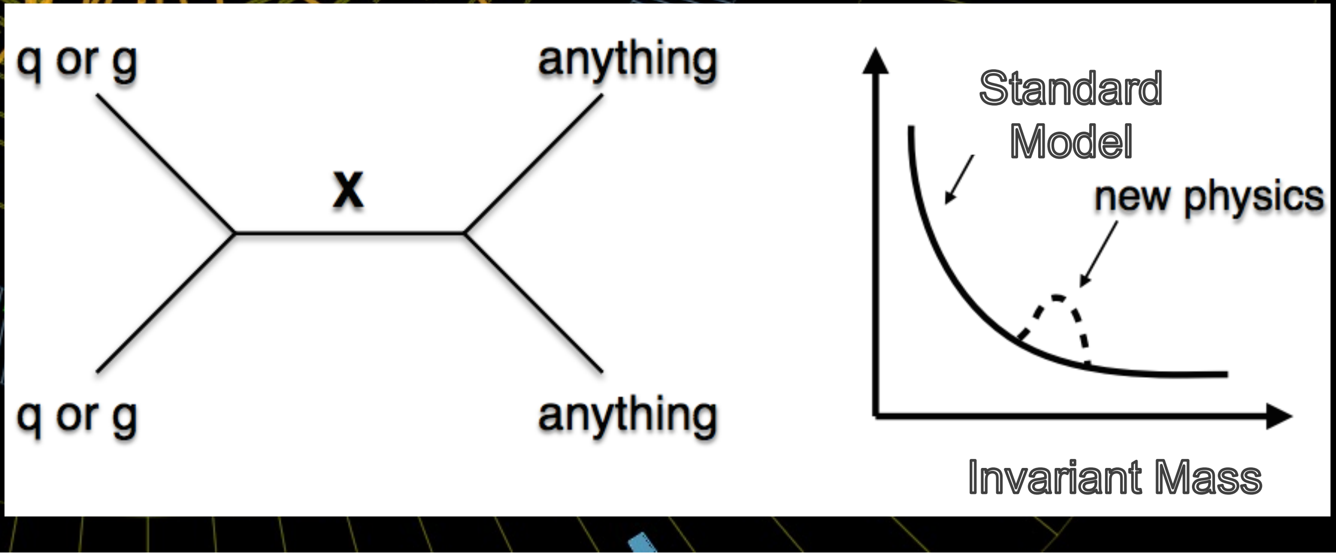
$$(m_0)^2 = \left(\sum_{i=1}^{n} \frac{E_i}{c^2}\right)^2 - \left(\sum_{i=1}^{n} \frac{\vec{p}_i}{c}\right)^2$$

# Search for Exotic Resonances



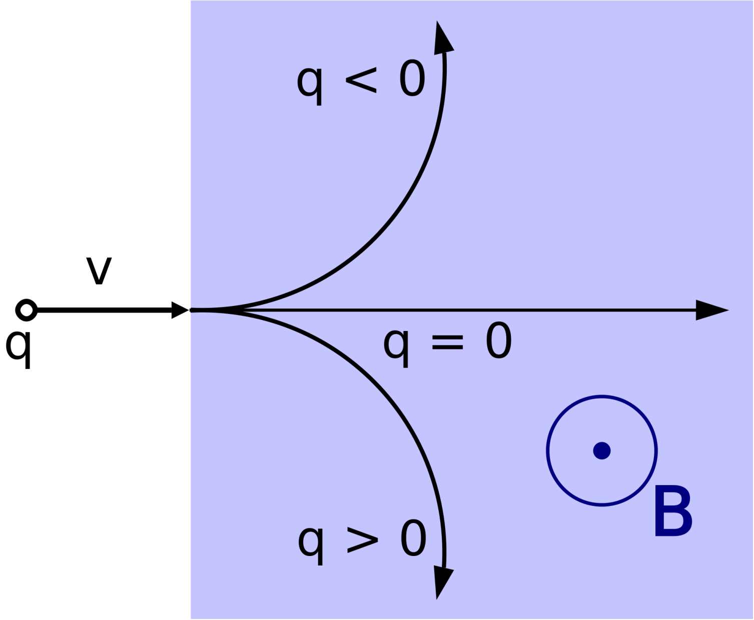
$E=mc^2$


Mass is a form of energy!



# Basic Principles of Particle Detection

- Charged particles leave a trace
- They curve in magnetic field, and by measuring the curvature we can measure the momentum of the particles



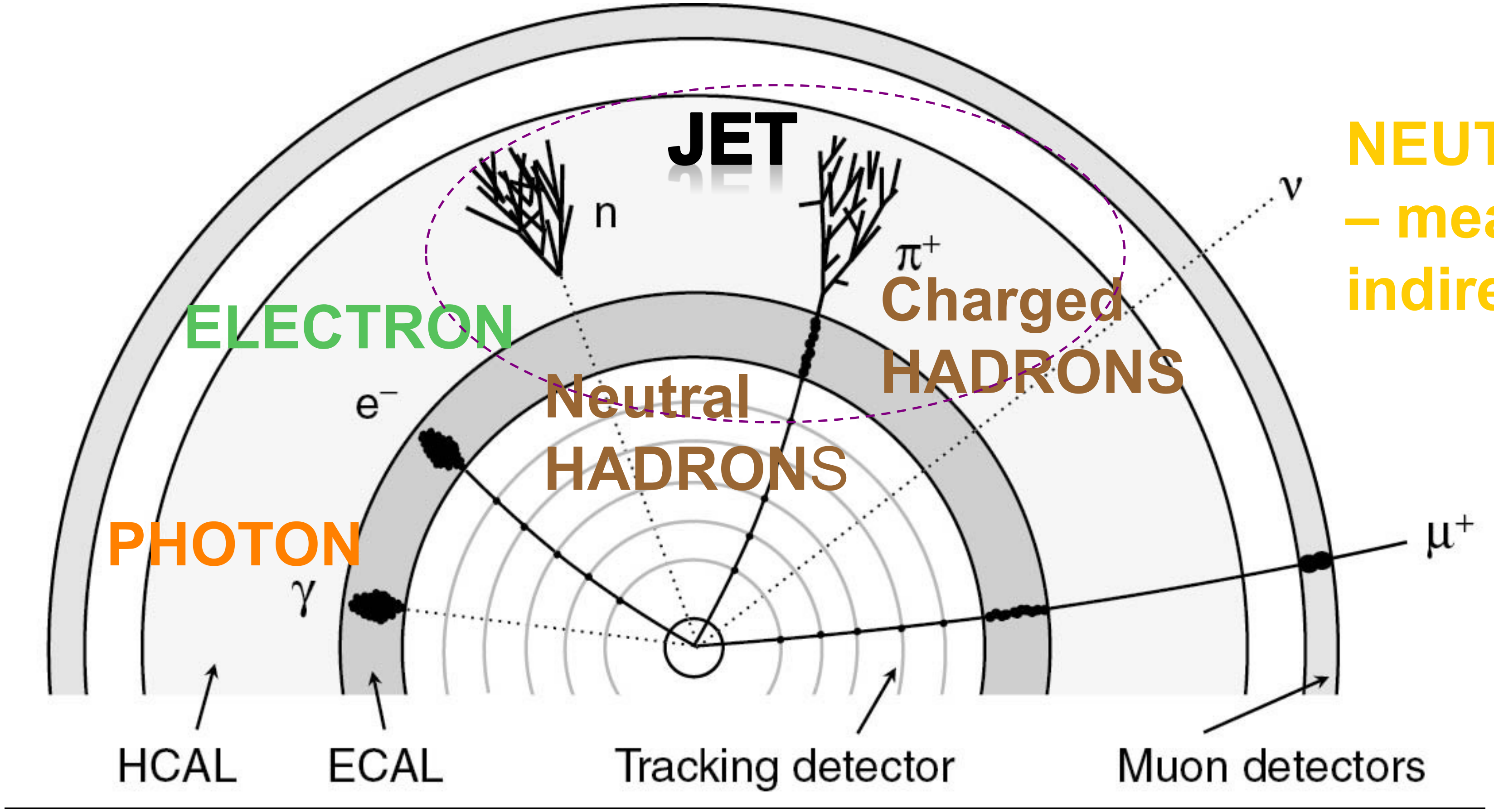
# Basic Principles of Particle Detection

- Propagation of particles through matter is similar to a football player running through the football field
- Player/particles loses energy due to collisions/interactions, and might be stopped completely

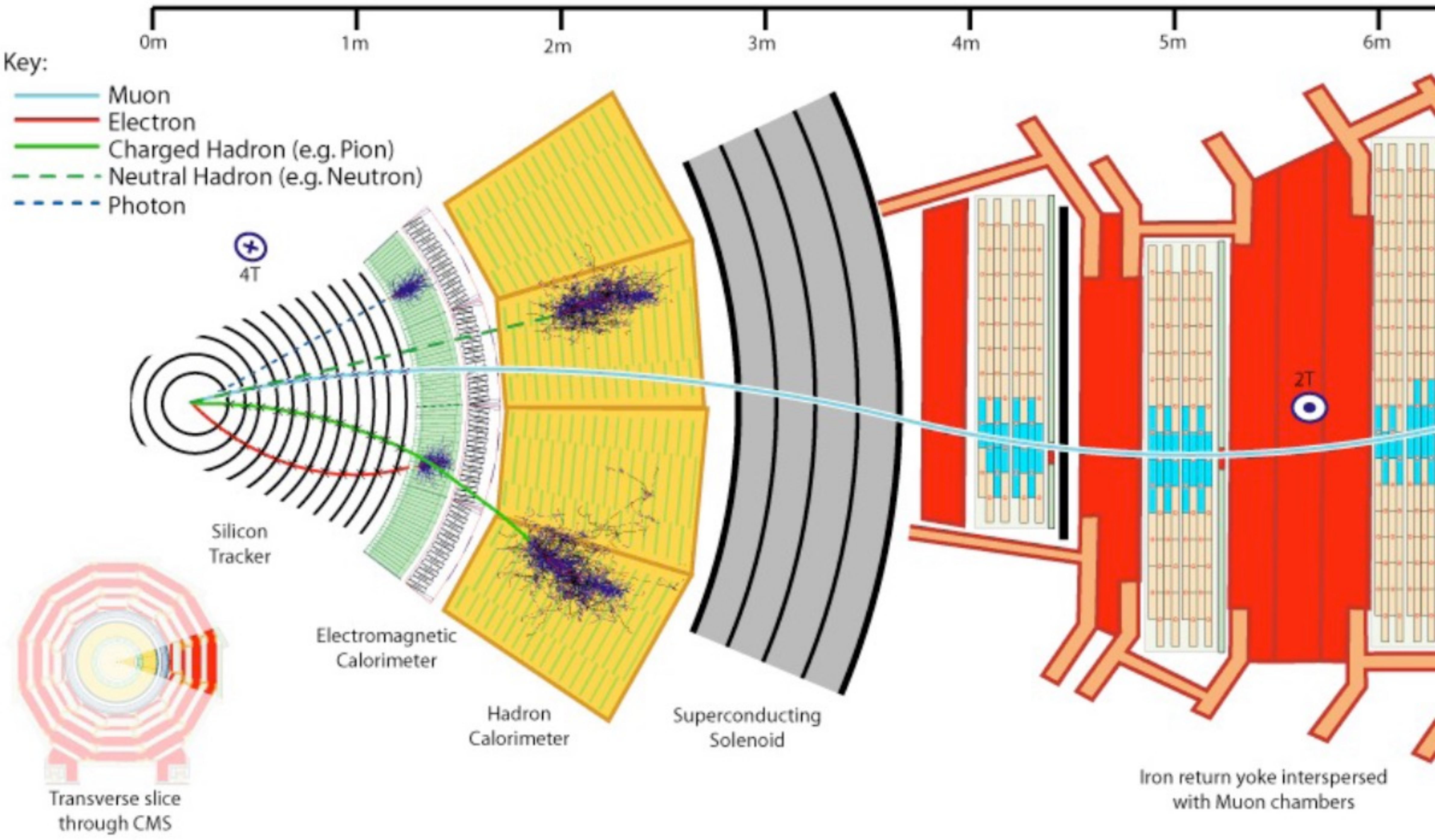
- By counting a number of collisions and energy loss, we can compute the original energy of the particle

# Basic Principles of Particle Detection

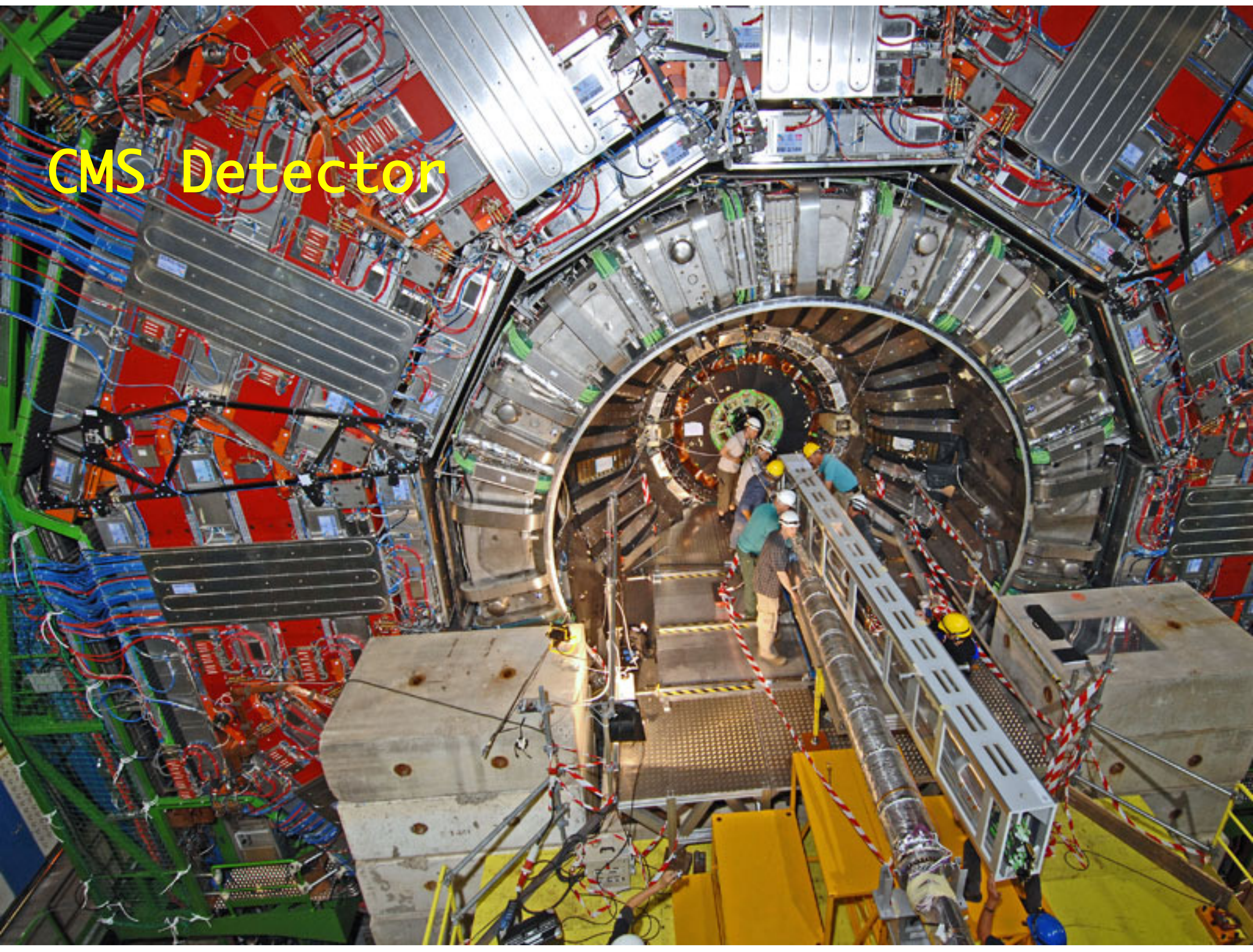
- We can measure energies and momenta of only long-lived particles, i.e. those that decay at measurable distances
- There are five main kinds of particles that we measure
- We categorize hard inelastic collisions by the number and momenta/energies of these "objects", and call it an event



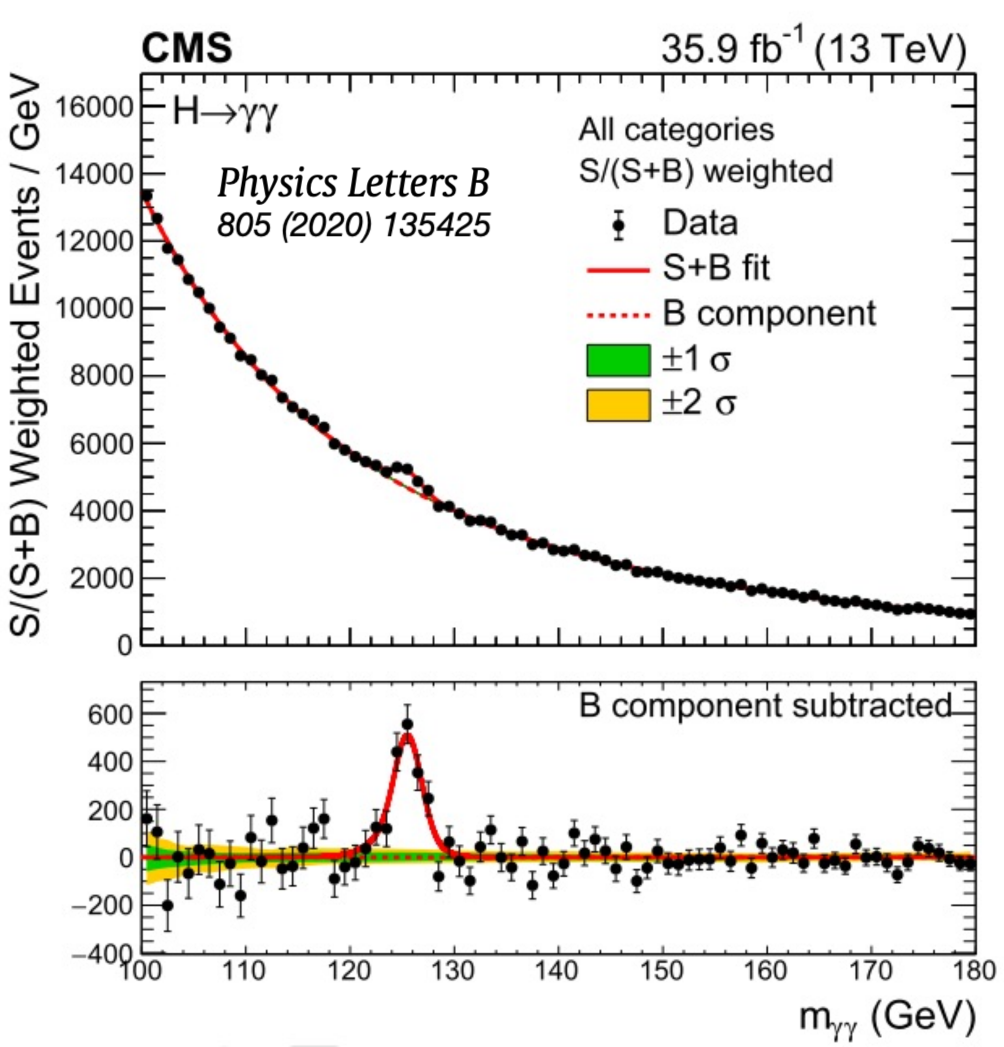
# Basics of CMS Subdetectors

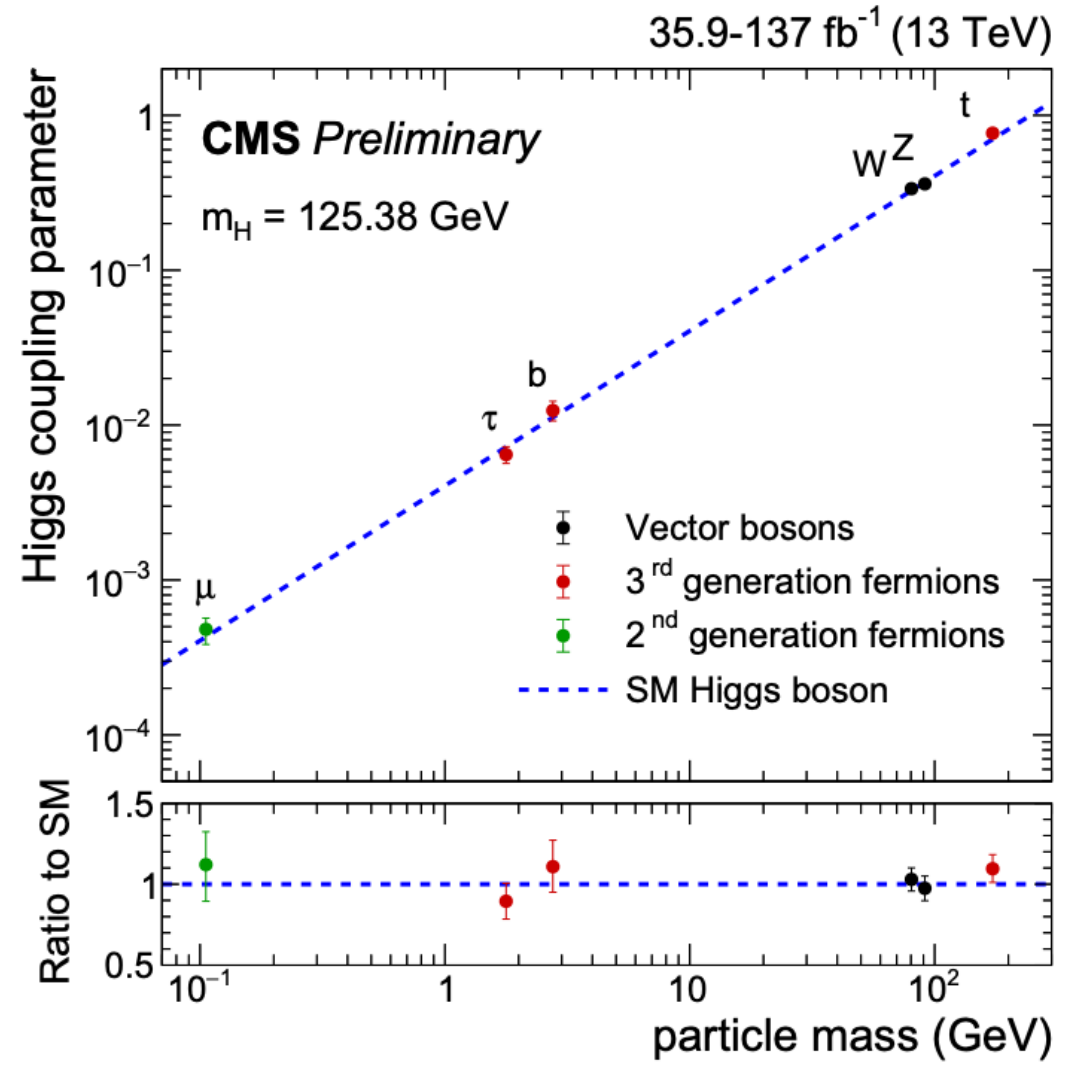


# CMS Detector



# We know the Higgs mass is 125.38±0.14 GeV

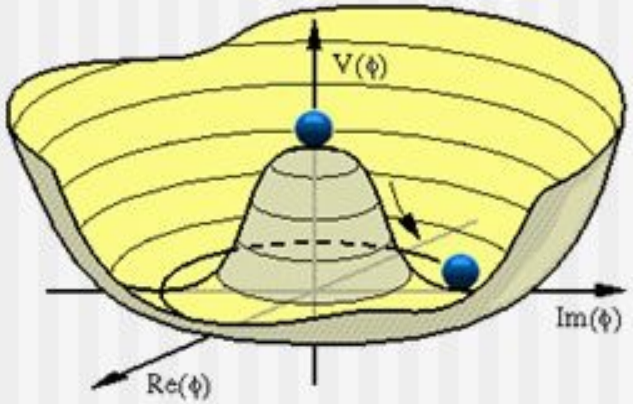




**Higgs couplings follow Standard Model expectations: proportional to mass**

# Higgs Potential

Higgs-Potential $U(\phi) = -\frac{1}{2}\mu^2\left(\phi^\dagger\phi\right) + \frac{1}{4}\lambda^2\left(\phi^\dagger\phi\right)^2$



Symmetric, but non-symmetric in the ground state.

$$v = \frac{\mu}{\sqrt{\lambda}} = \sqrt{\frac{1}{\sqrt{2}G_F}}$$

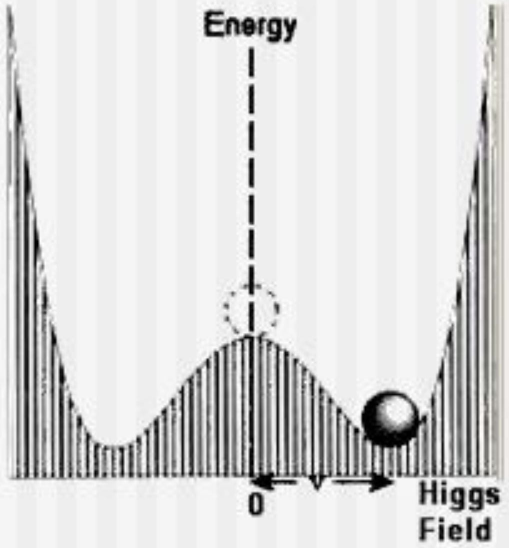
Non-zero vacuum expectation value:

$G_F = 1.166\,e^{-5}\ \mathrm{GEV}^{-2}$

$v = 246$ GeV

No constrain for λ
In the Higgs mass

$$M_{H^0} = \sqrt{2\lambda}\, v$$

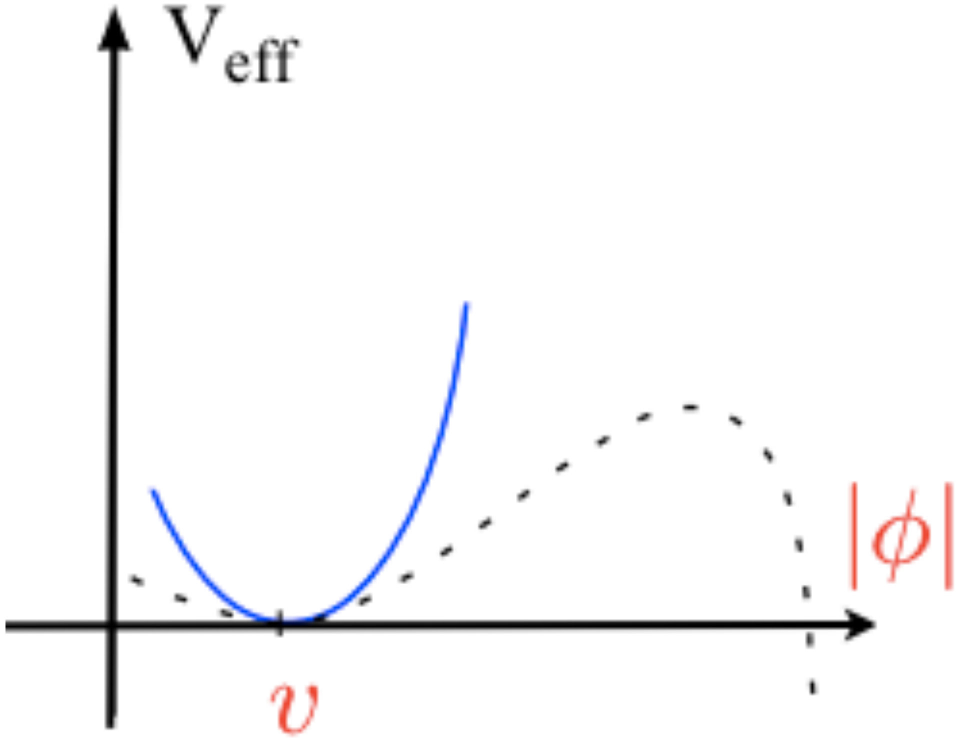


# Higgs Interactions

- We study that and confirm that all Higgs interactions agree with theory

- Studying Higgs self-interactions means searching and measuring properties of double Higgs production is now one of our main targets at the LHC

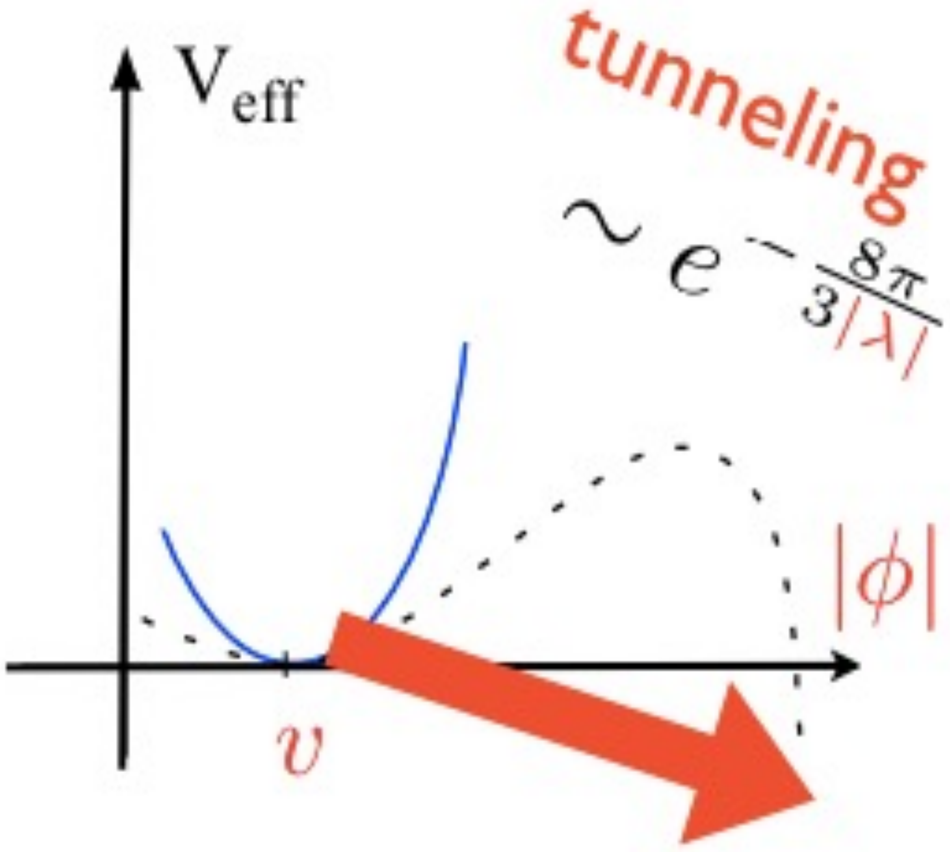
# Higgs Potential and Vacuum Stability



$$V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$$

- What happens if $\Phi \gg \lambda$ ?
- Quantum corrections from top can affect $\lambda$ of Higgs potential

# Higgs Potential and Vacuum Stability



$$V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$$

- What happens if $\Phi >> \lambda$ ?
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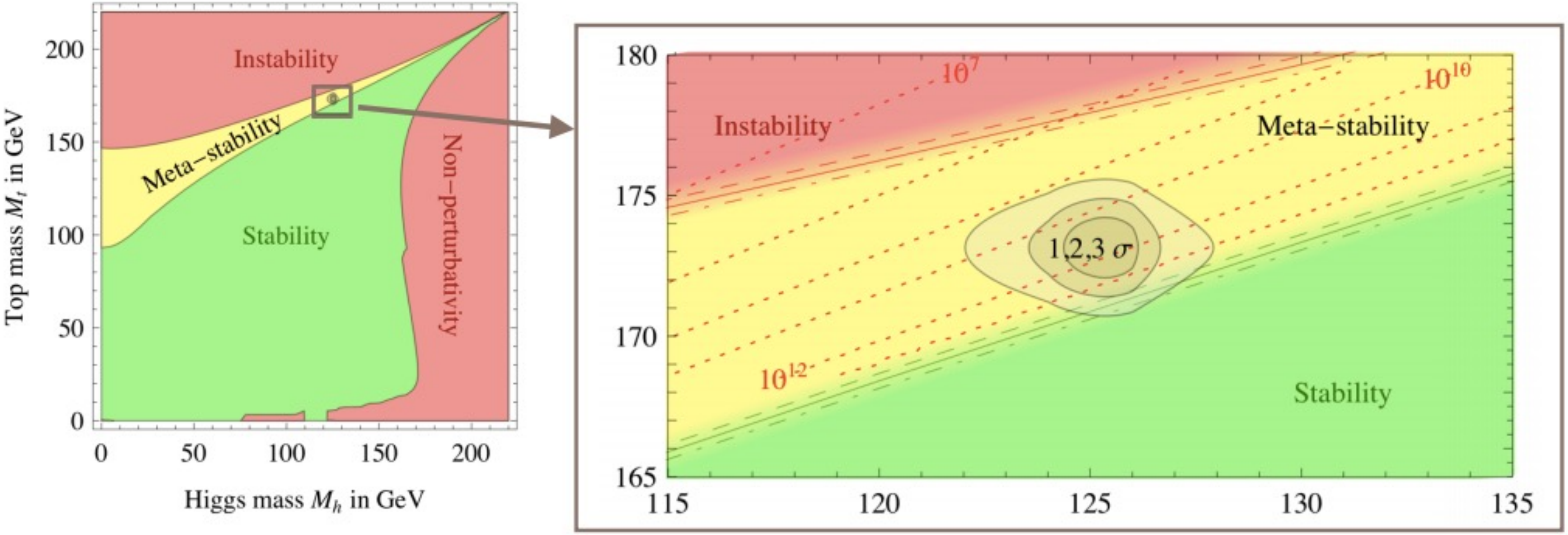
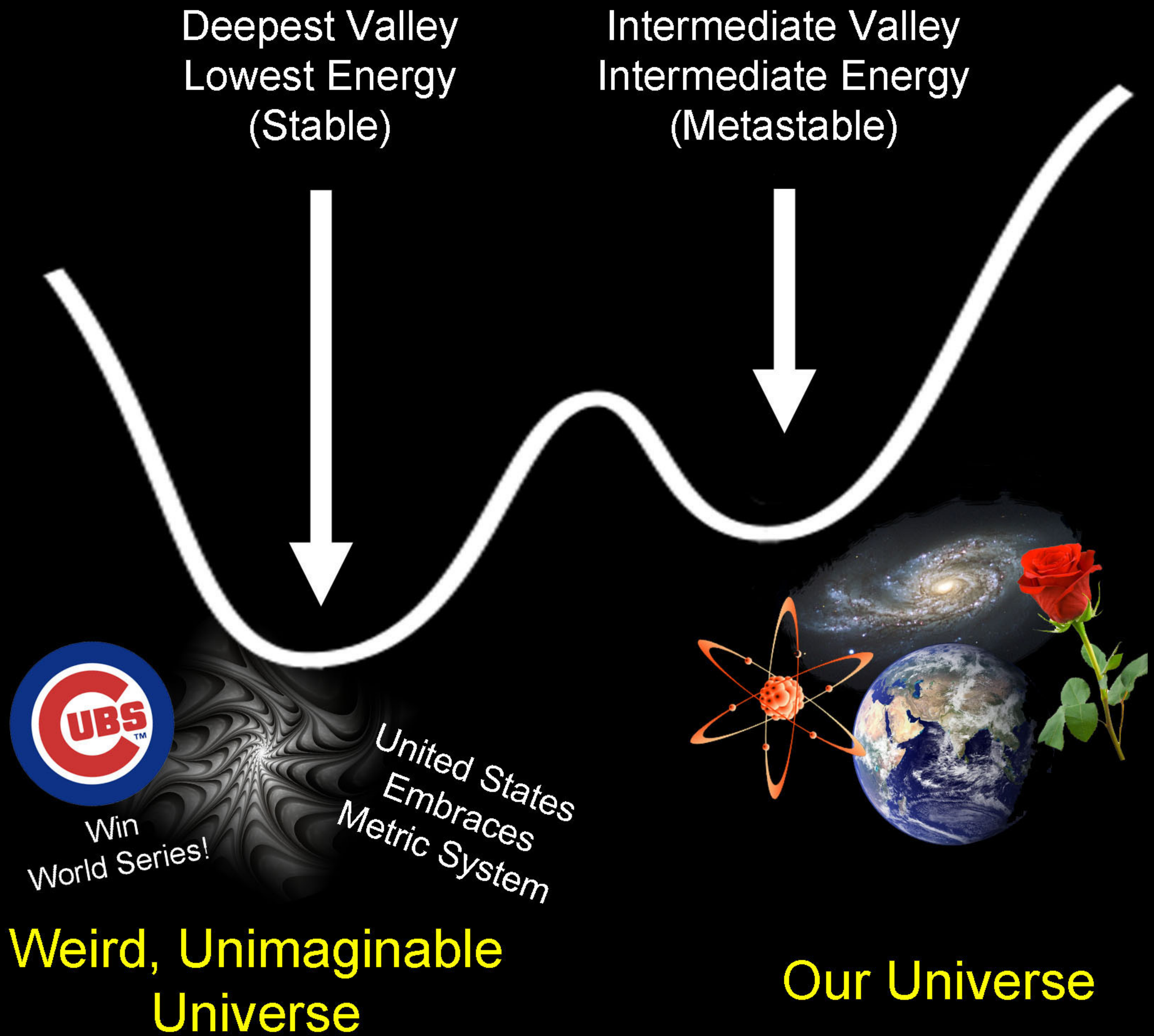
# Higgs Potential and Vacuum Stability





Deepest Valley
Lowest Energy
(Stable)

Intermediate Valley
Intermediate Energy
(Metastable)

Win
World Series!

United States
Embraces
Metric System

Weird, Unimaginable
Universe

Our Universe

# Thank you !