Experimental Physics at Hadron Colliders

CERN Summer Students Lectures, July 17-21, 2023 - Lecture 1/4

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CERN Summer Student Lecture Program 2023

- Particle World - David Tong
- Detectors - Wernes Ziegler
- From Raw Data to Physics Results - Paul Laycock
- Accelerator Technology Part I - Susana Bermudez
- The Standard Model - Christophe Grojean
- Foundation of Statistics - Glen Cowan
- Particle Accelerators - Foteini Avesta
- Nuclear Physics at CERN - Magdalena Kowalska
- Theoretical Concepts in Particle Physics - Tim Cohen
- Future High Energy Collider Projects - Barbara Dalena
- Cosmology - Valerie Domcke
- Heavy Ion Physics - Francesca Bellini
- Accelerator Technology Part 2 - Walter Delsolaro
- **Experimental Physics at Hadron Colliders - Markus Klute**

- Flavour Physics - Mark Williams
- Physics and Medical Applications - Manuela Cirilli
- Accelerator Technology Part 3 - Francesc Pujol
- Astroparticle Physics - Bradley Kavanagh
- Predictions at Hadron Colliders - Alexander Huss
- Lepton Colliders - Frank Simon
- Antimatter in the Laboratory - Jack Devlin
- Physics Beyond the Standard Model - Tevong You
- Electronics, DAQ and Trigger - Tommaso Colombo
- What is String Theory? - Timo Weigand

https://indico.cern.ch/event/1254879/timetable/

Learning Objectives

- Understanding basics concepts of experimental particle physics at hadron colliders
- Knowledge of the broad and diverse LHC Physics program, including the vast number of opportunities at the LHC

What will I learn ?

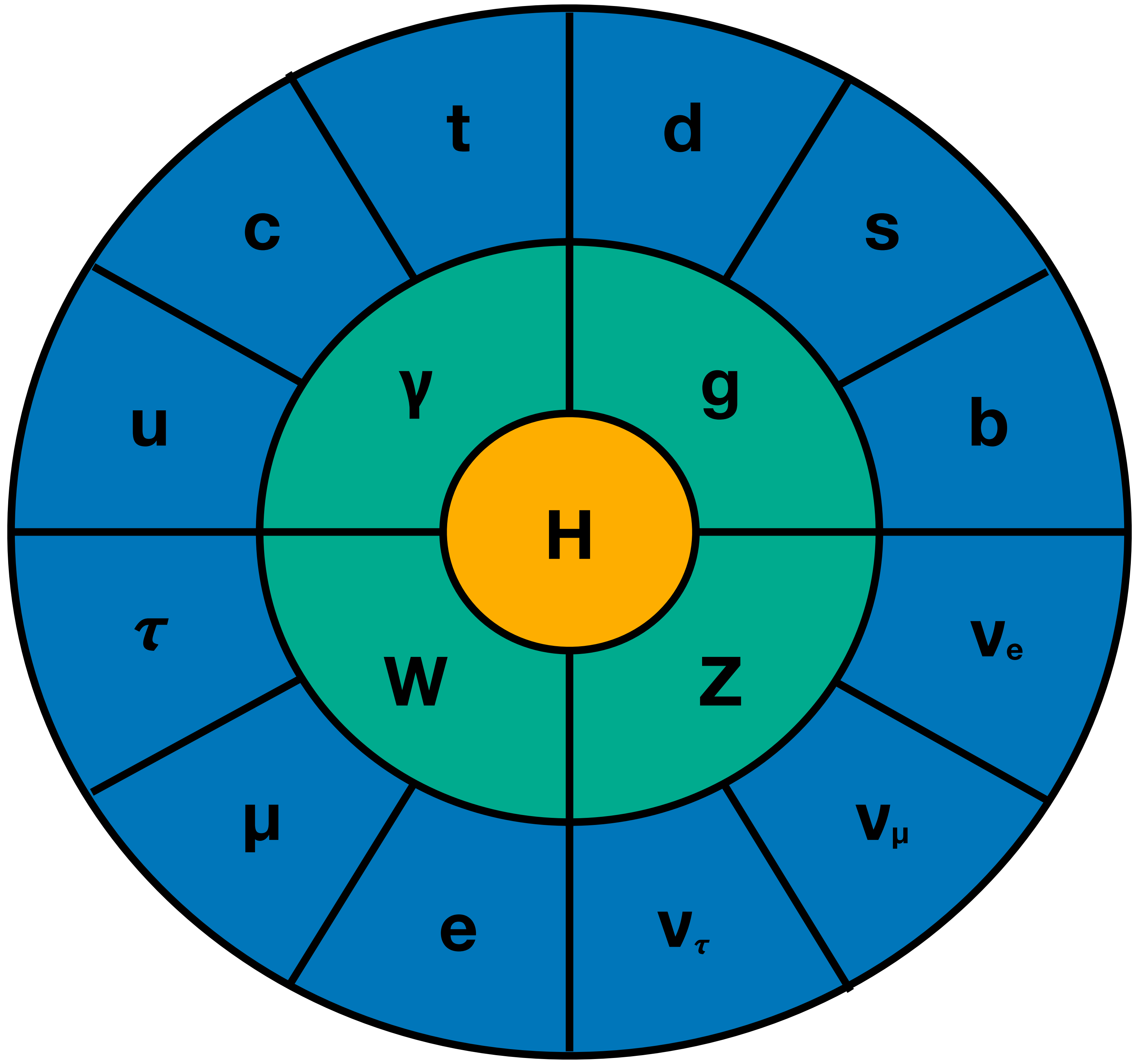
How do I learn?

Particle Physics at Colliders

- The objective of particle physics is to uncover the fundamental laws of nature and gain a comprehensive understanding of the universe at its most fundamental level.

- High-energy particle collisions enable
  - Discovery of new and massive particles
  - Probing the structure of matter
  - Exploring fundamental forces of nature
  - Recreating the early universe

Standard Model of Particle Physics

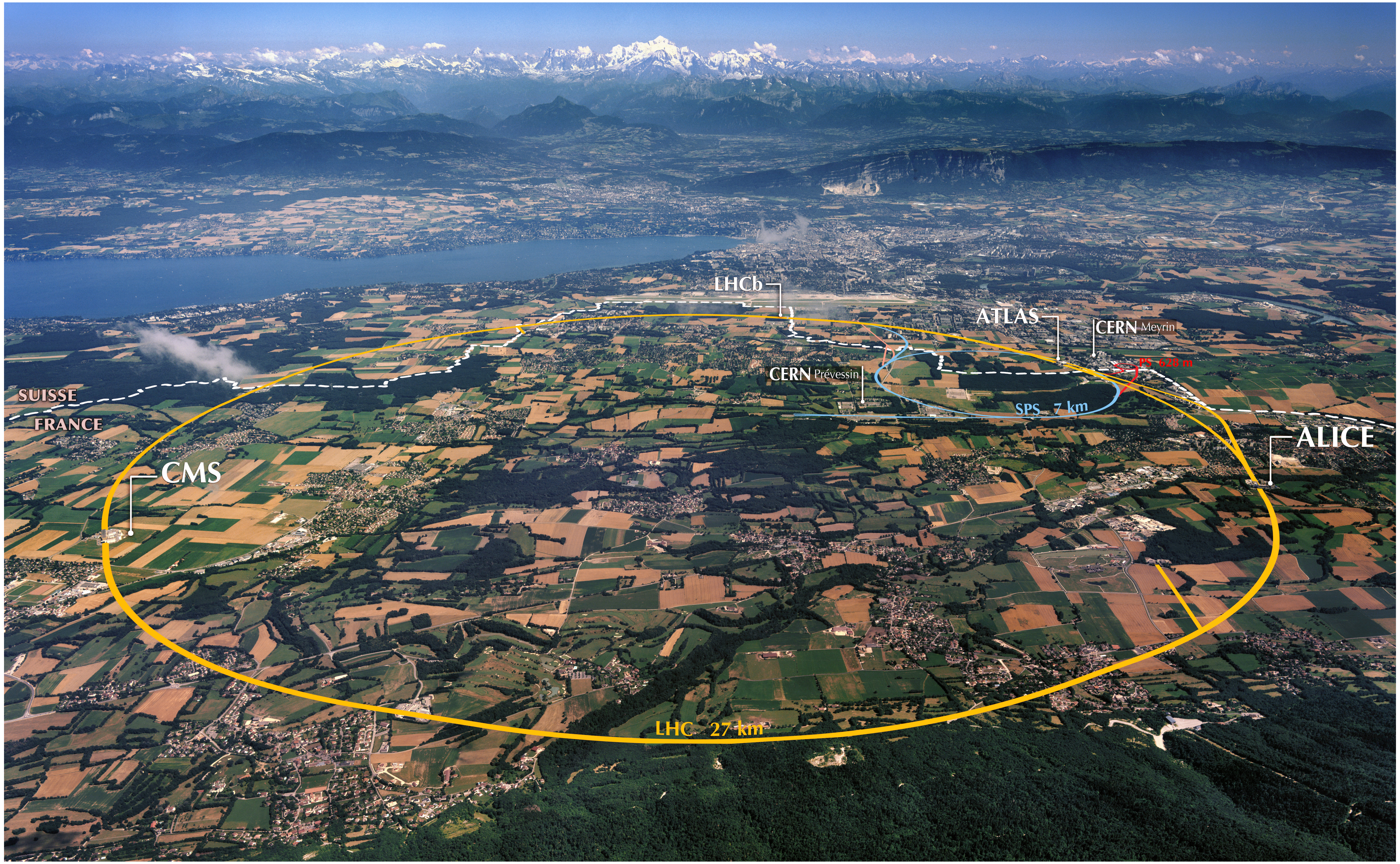


Work Plans

- Lecture 1: Introduction, fundamentals, cross sections
- Lecture 2: Standard model measurements
- Lecture 3: Higgs physics
- Lecture 4: Searches for new physics

Following the Protons @ CERN

https://videos.cern.ch/record/2020780
https://home.cern/science/accelerators/accelerator-complex



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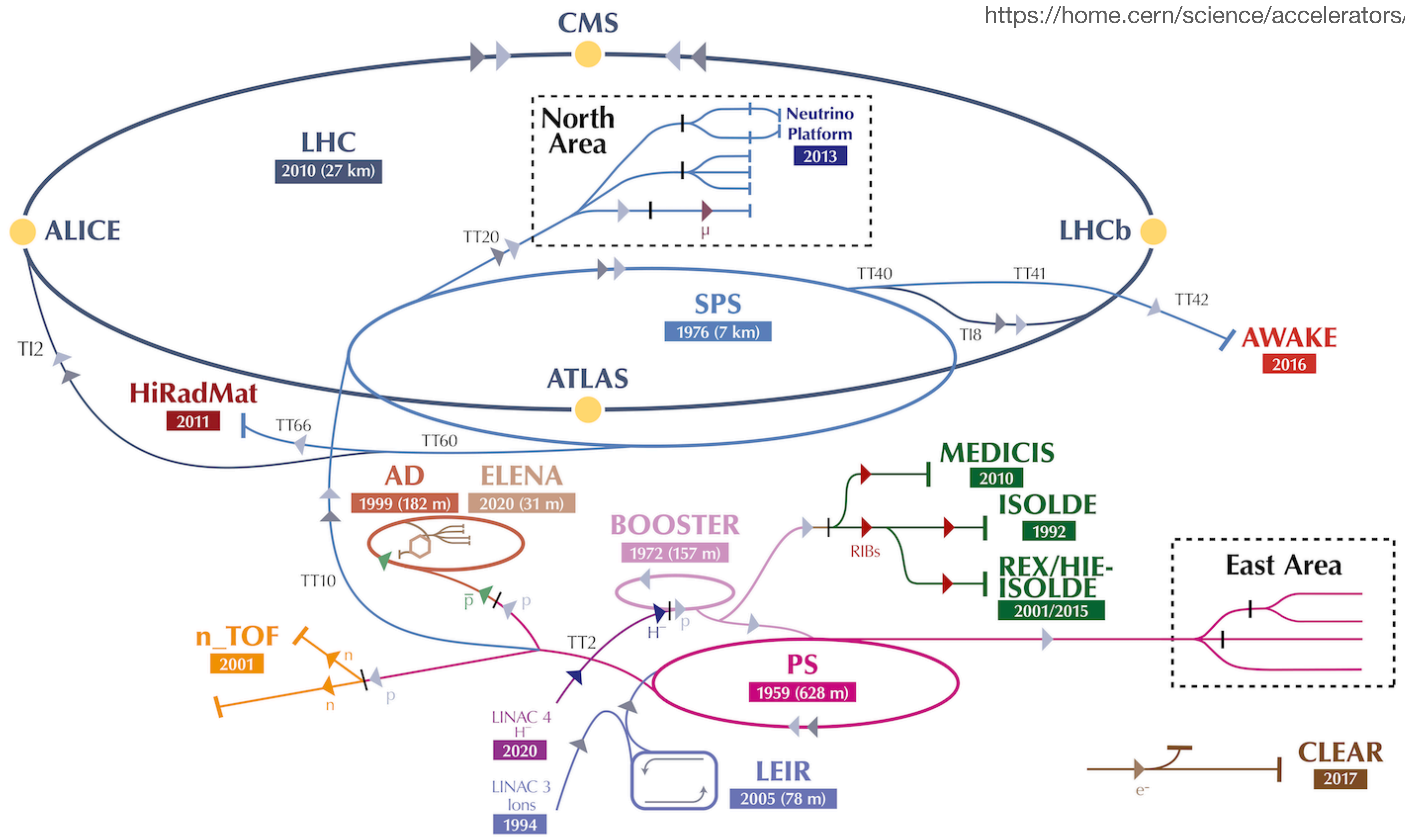

Following the Protons @ CERN

- Linear accelerator 4 (Linac 4) accelerates negative hydrogen ions (H-) to 160 MeV

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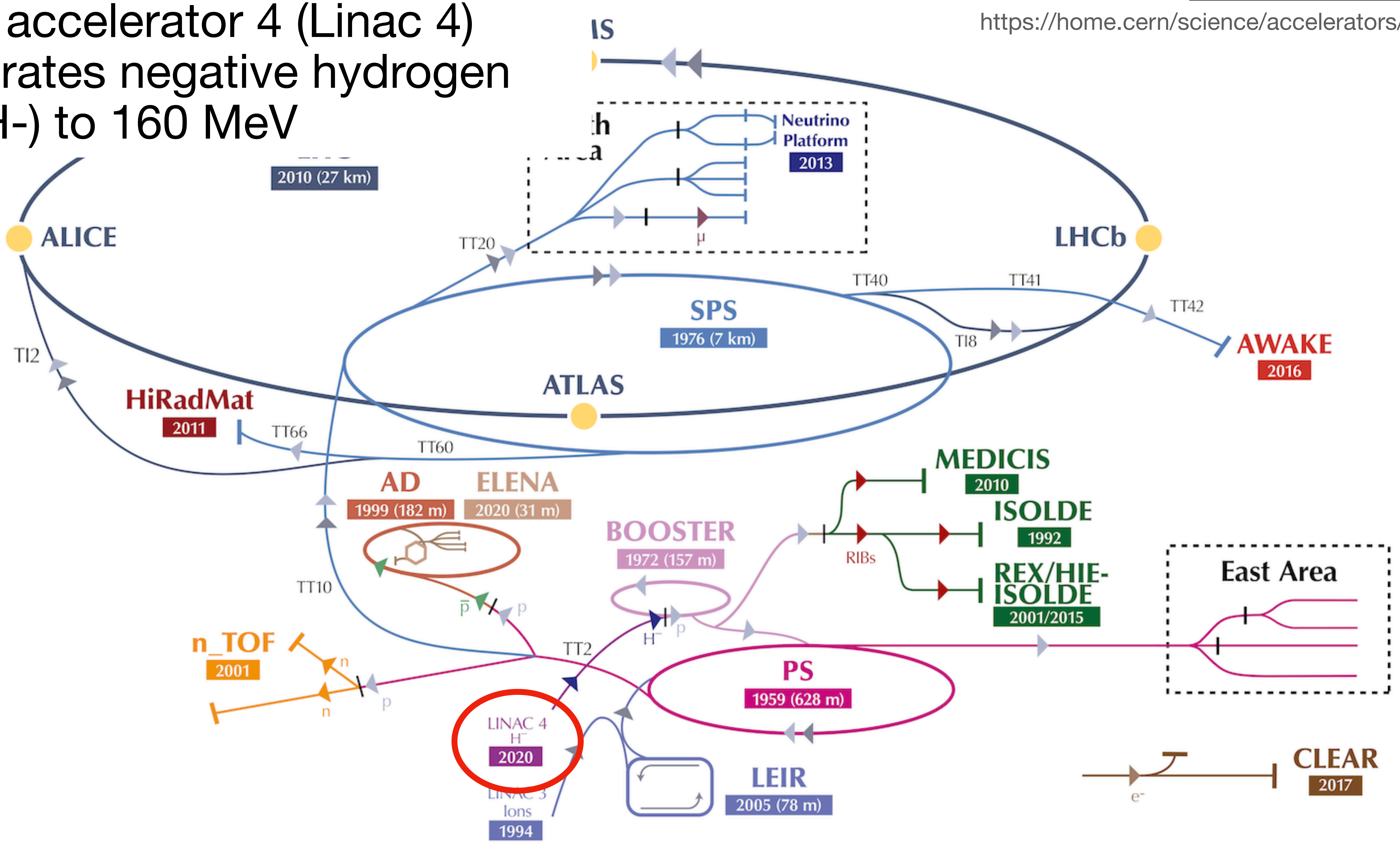

Following the Protons @ CERN

- Linear accelerator 4 (Linac 4) accelerates negative hydrogen ions (H-) to 160 MeV
- Ions are stripped of their two electrons during injection into the Proton Synchrotron Booster
- Booster is using four superimposed synchrotron rings to accelerate to 2 GeV

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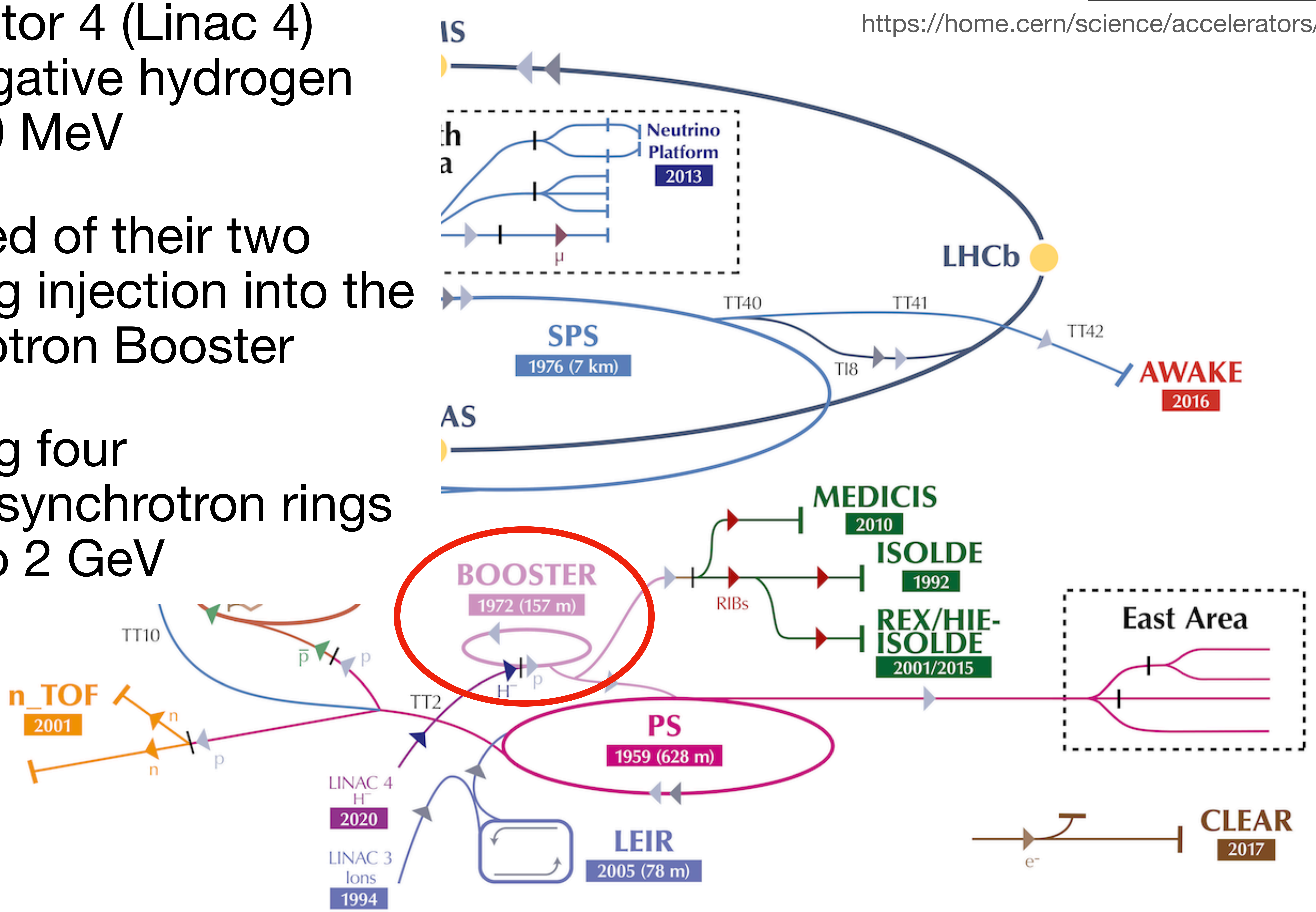

Following the Protons @ CERN

- Linear accelerator 4 (Linac 4) accelerates negative hydrogen ions (H-) to 160 MeV
- Ions are stripped of their two electrons during injection into the Proton Synchrotron Booster
- Booster is using four superimposed synchrotron rings to accelerate to 2 GeV
- Proton Synchrotron (PS) uses conventional electromagnets and accelerates to 26 GeV

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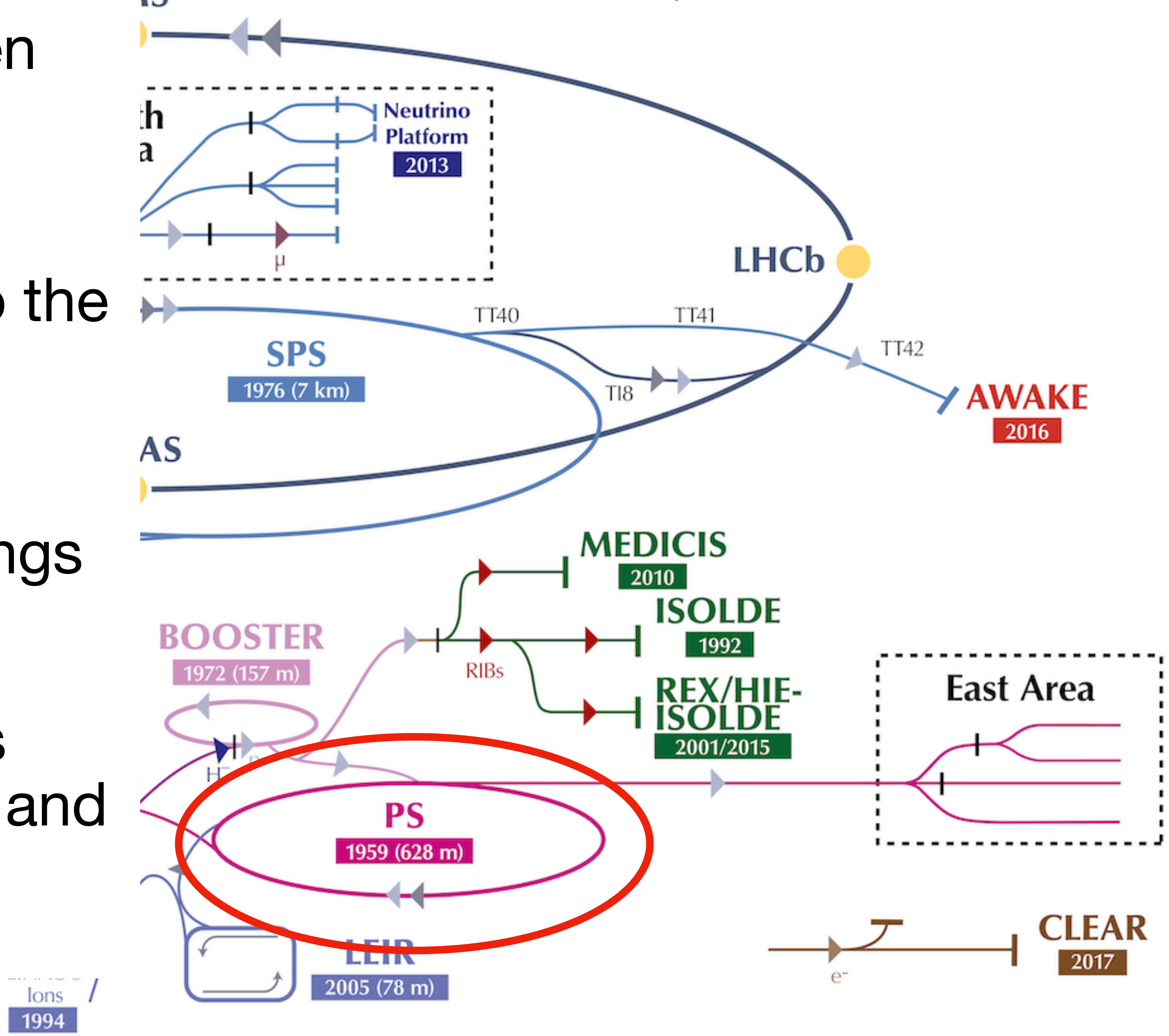

Following the Protons @ CERN

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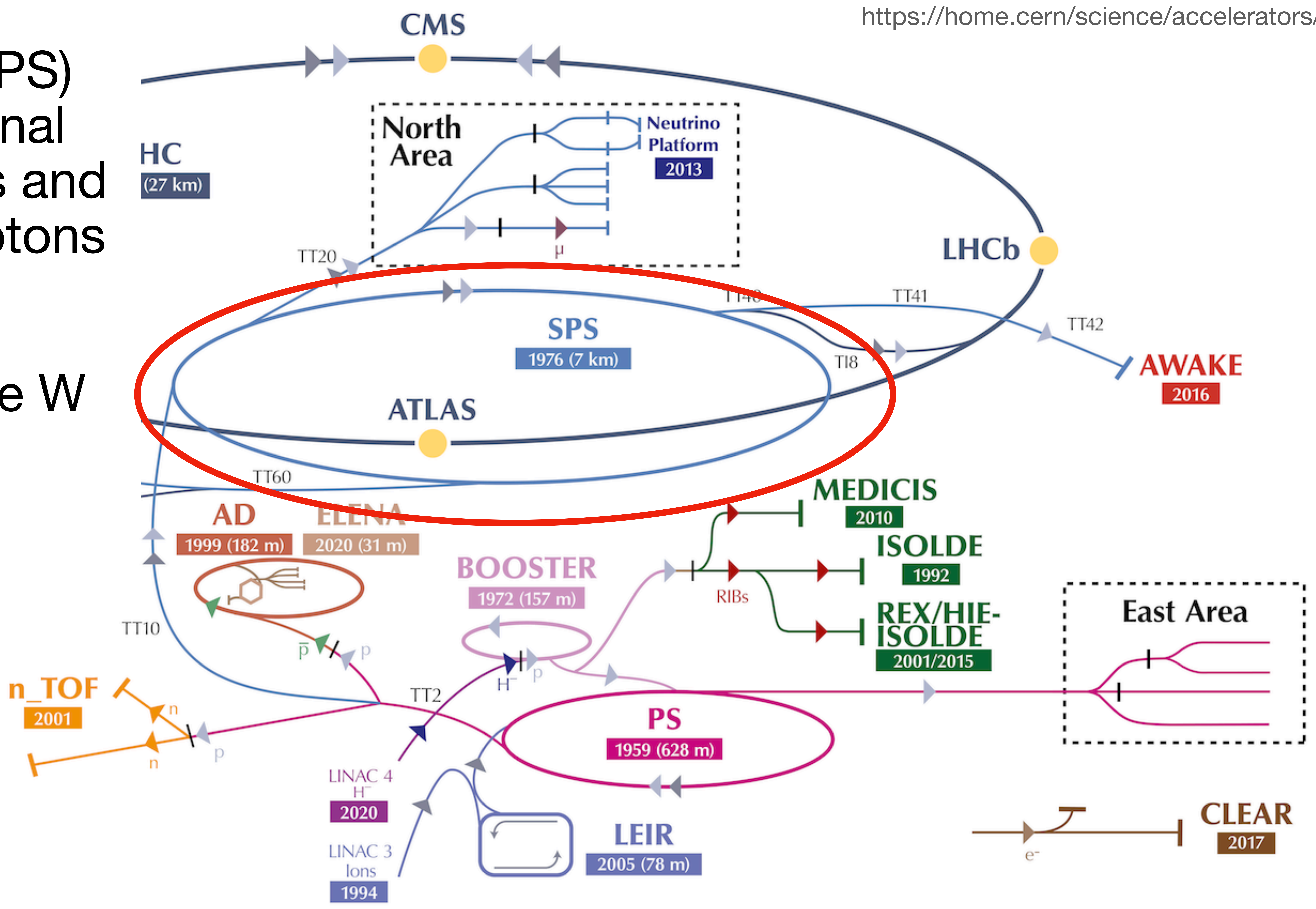
- Super Proton Synchrotron (SPS) uses conventional electromagnets and accelerates protons to 450 GeV
- Discovery of the W and Z boson in 1983.



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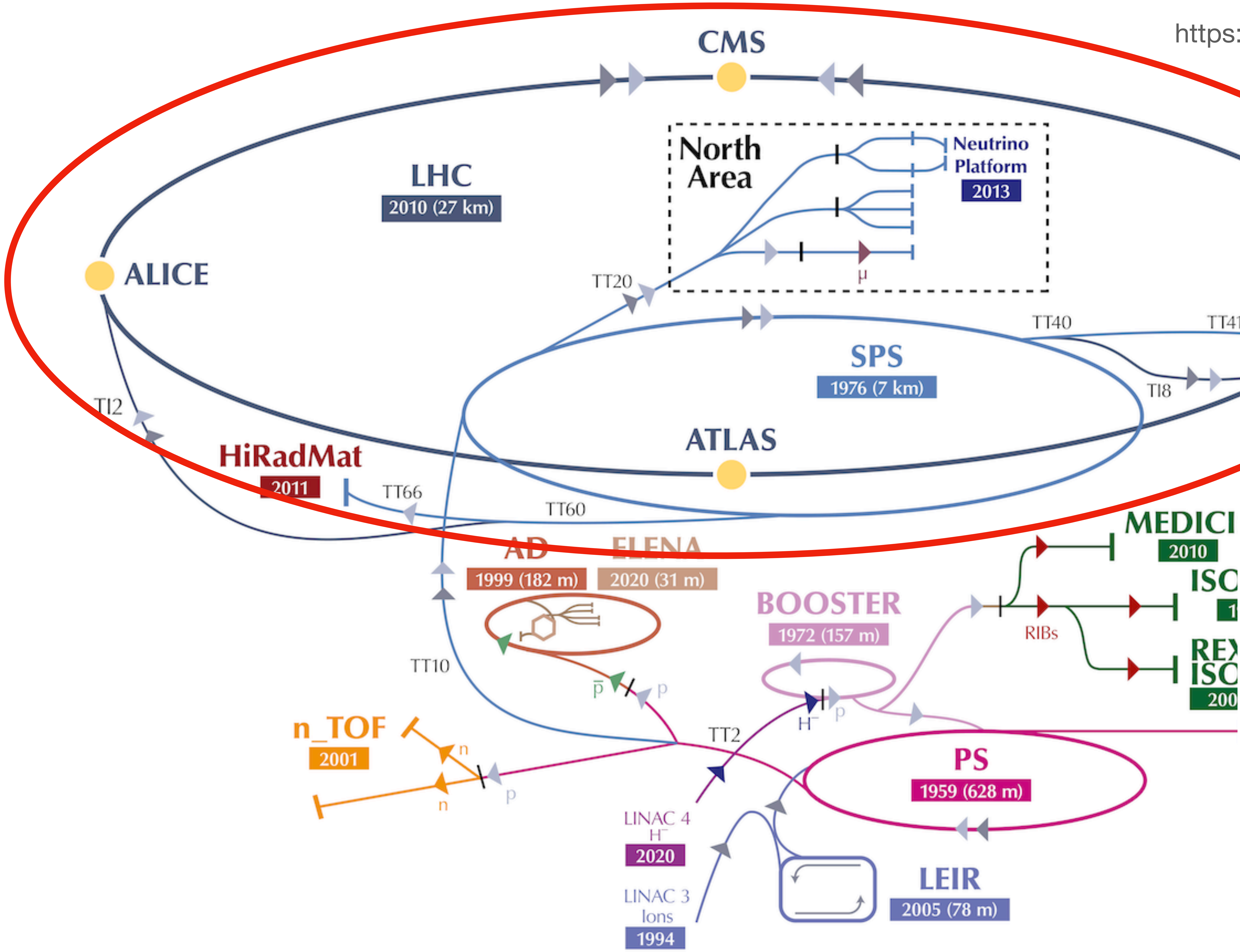

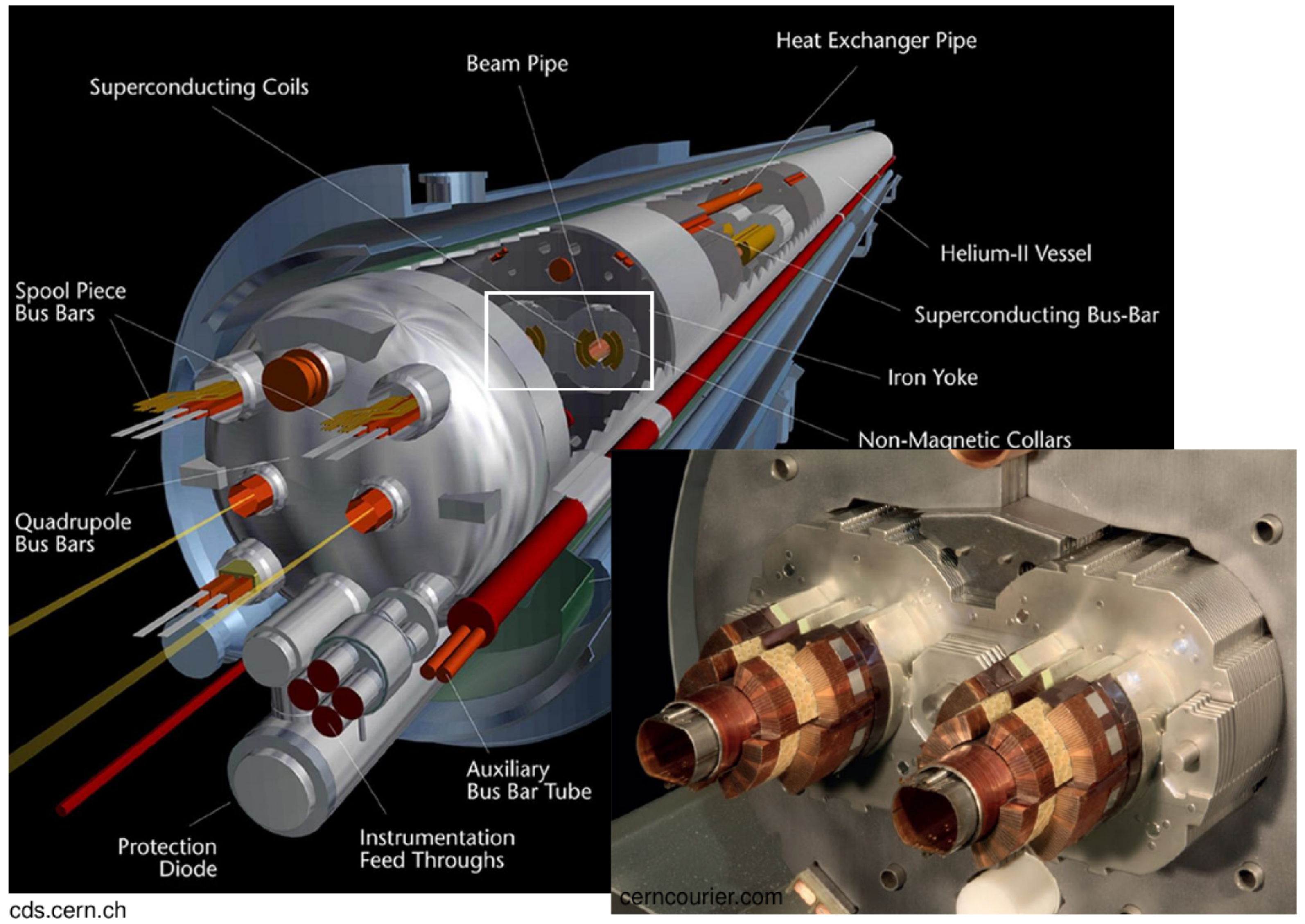

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Following the Protons @ CERN

- LHC: 8 arcs and 8 straight sections
- Proton-proton collisions at 13.6 TeV, also pA and AA collisions
- ARCs (2.45km)
  - 23 arc ‘cells’ with main dipoles, quadrupoles and other multipoles
- Straight sections (528m)
  - Experiments, beam injection, RF acceleration, beam dump

https://videos.cern.ch/record/2020780

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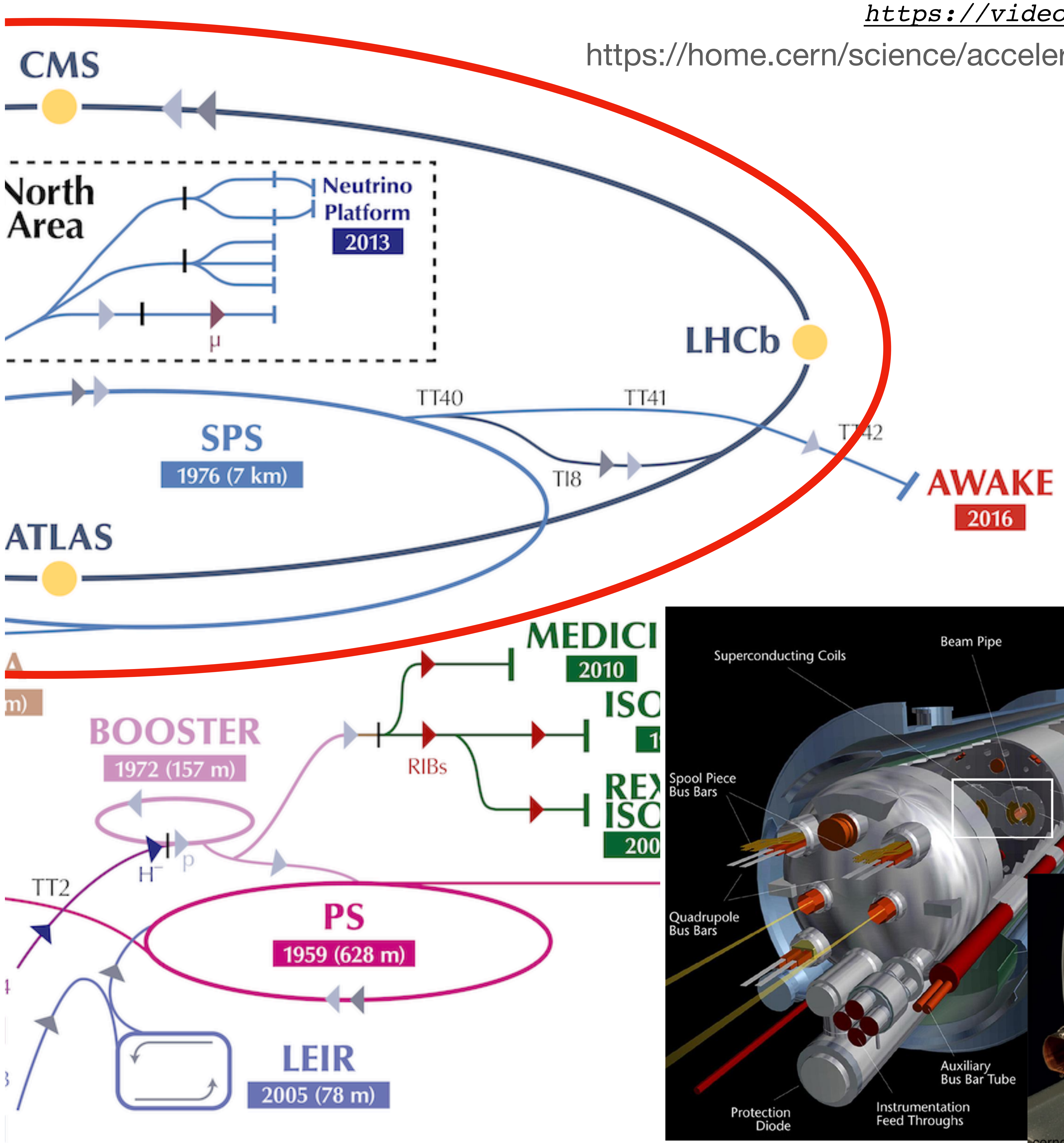

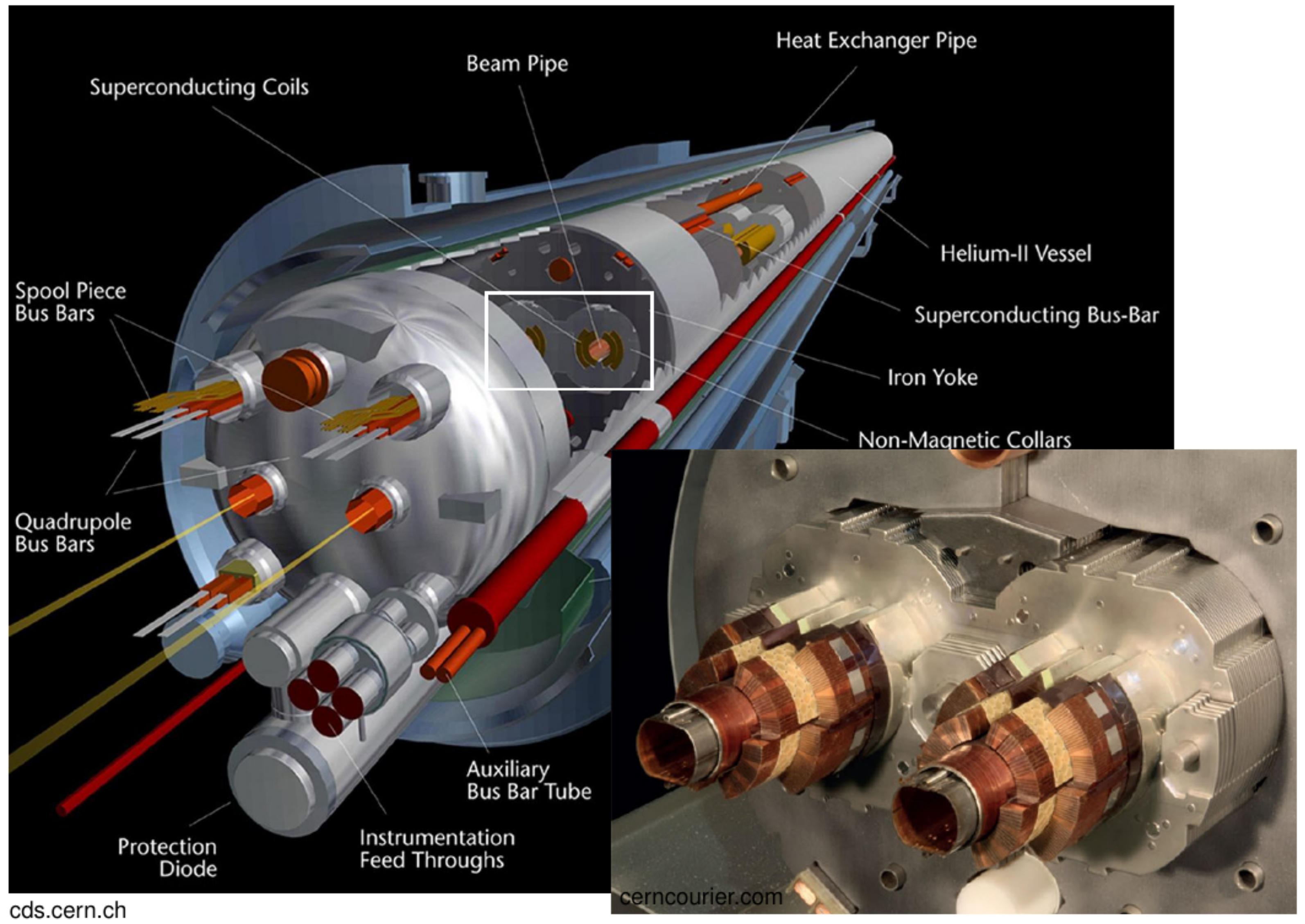

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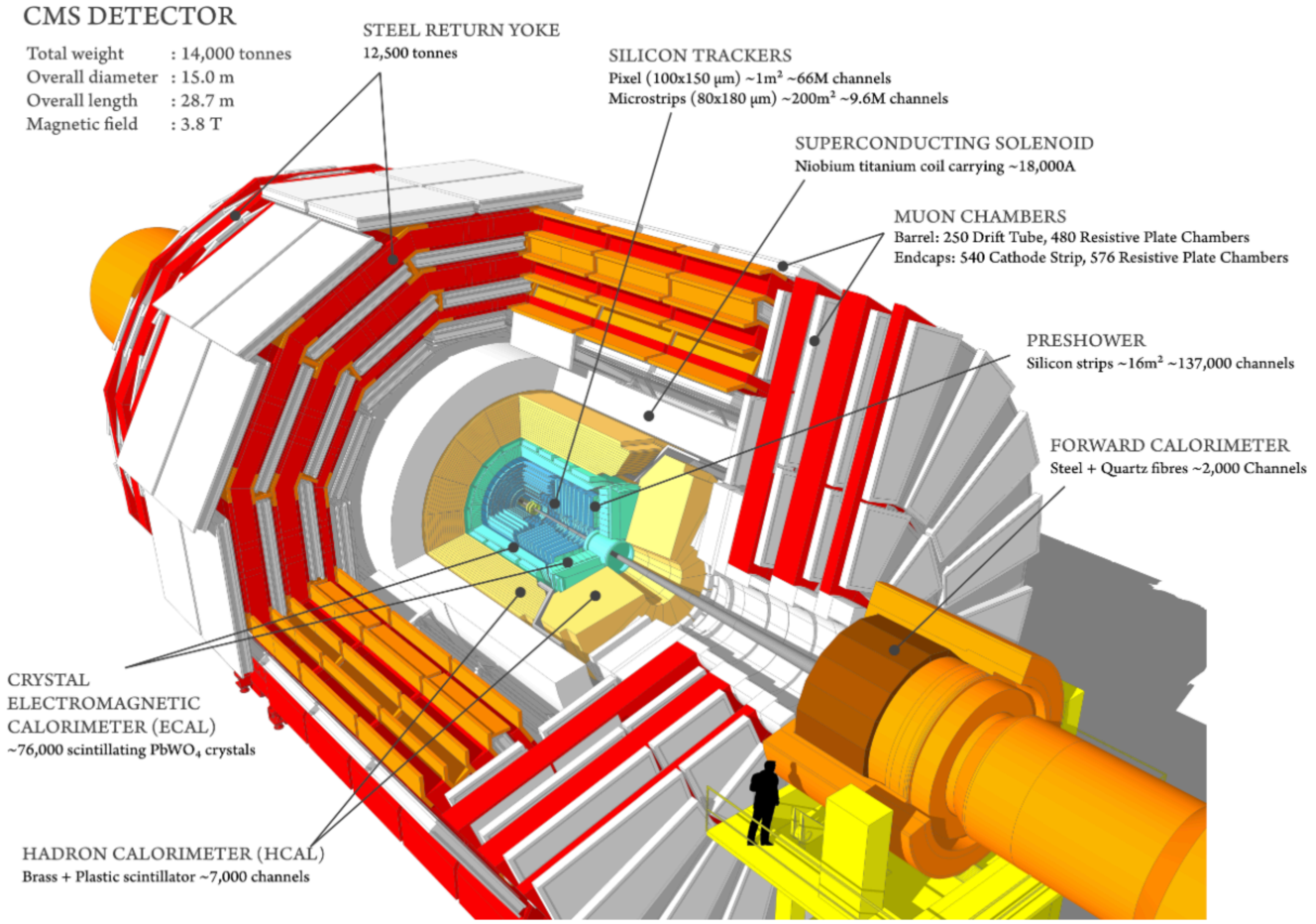

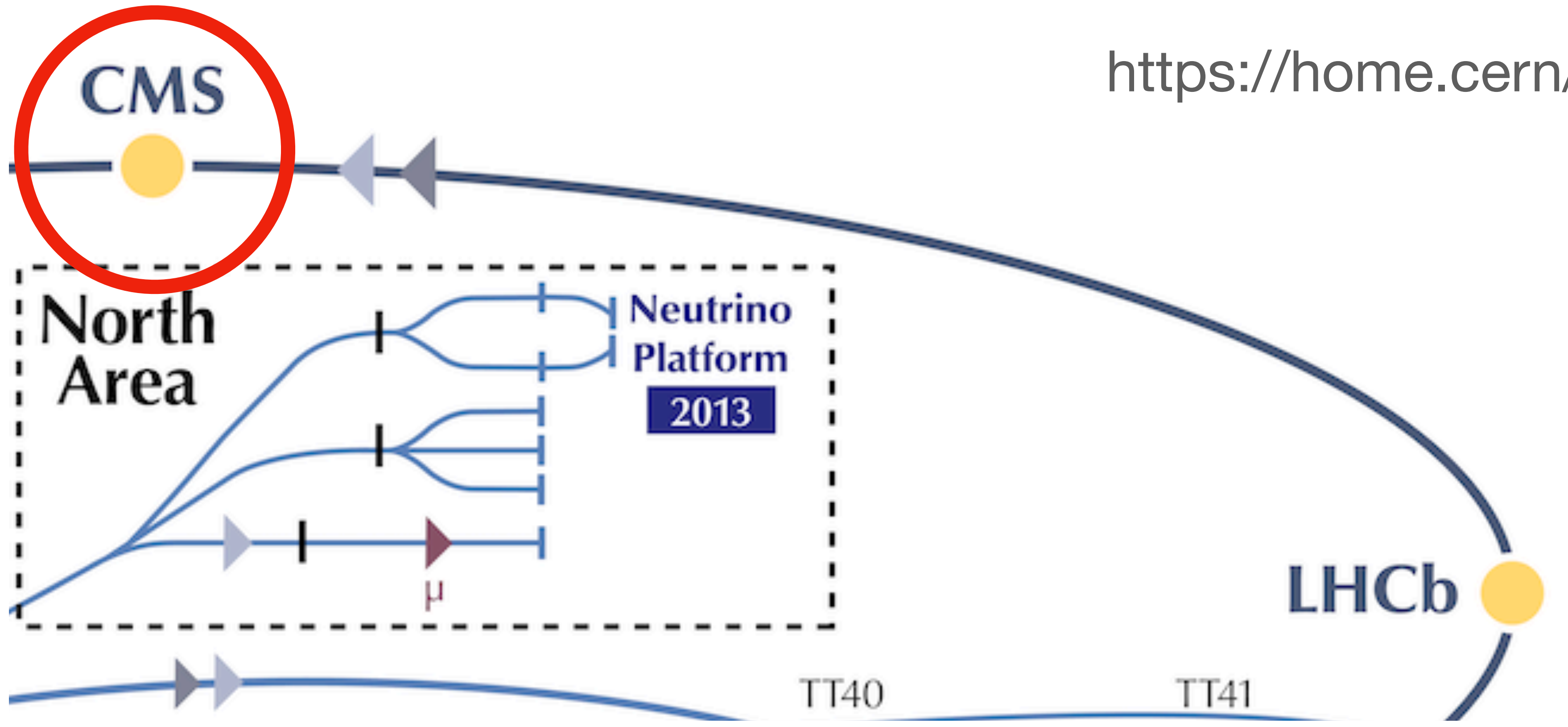

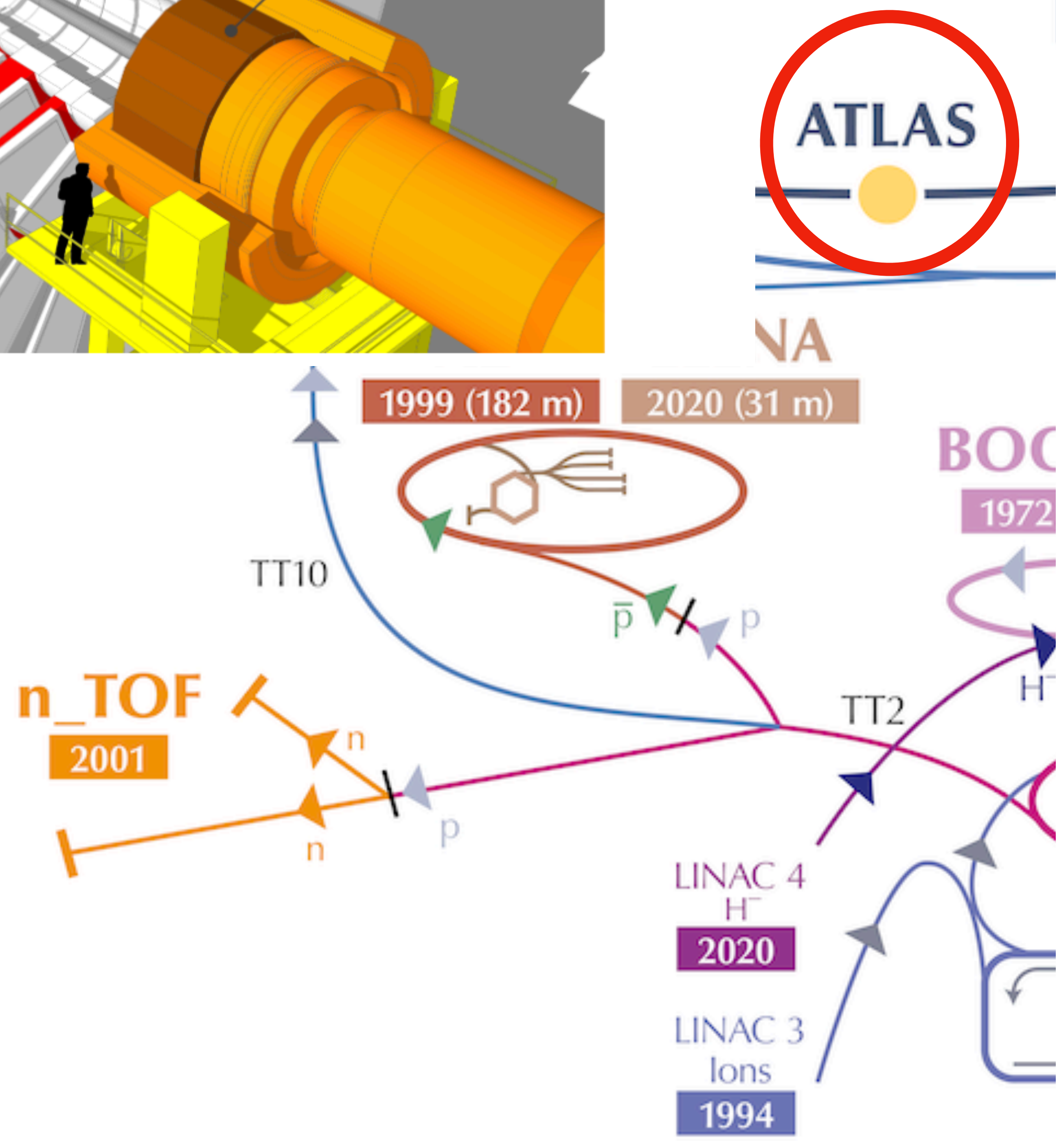

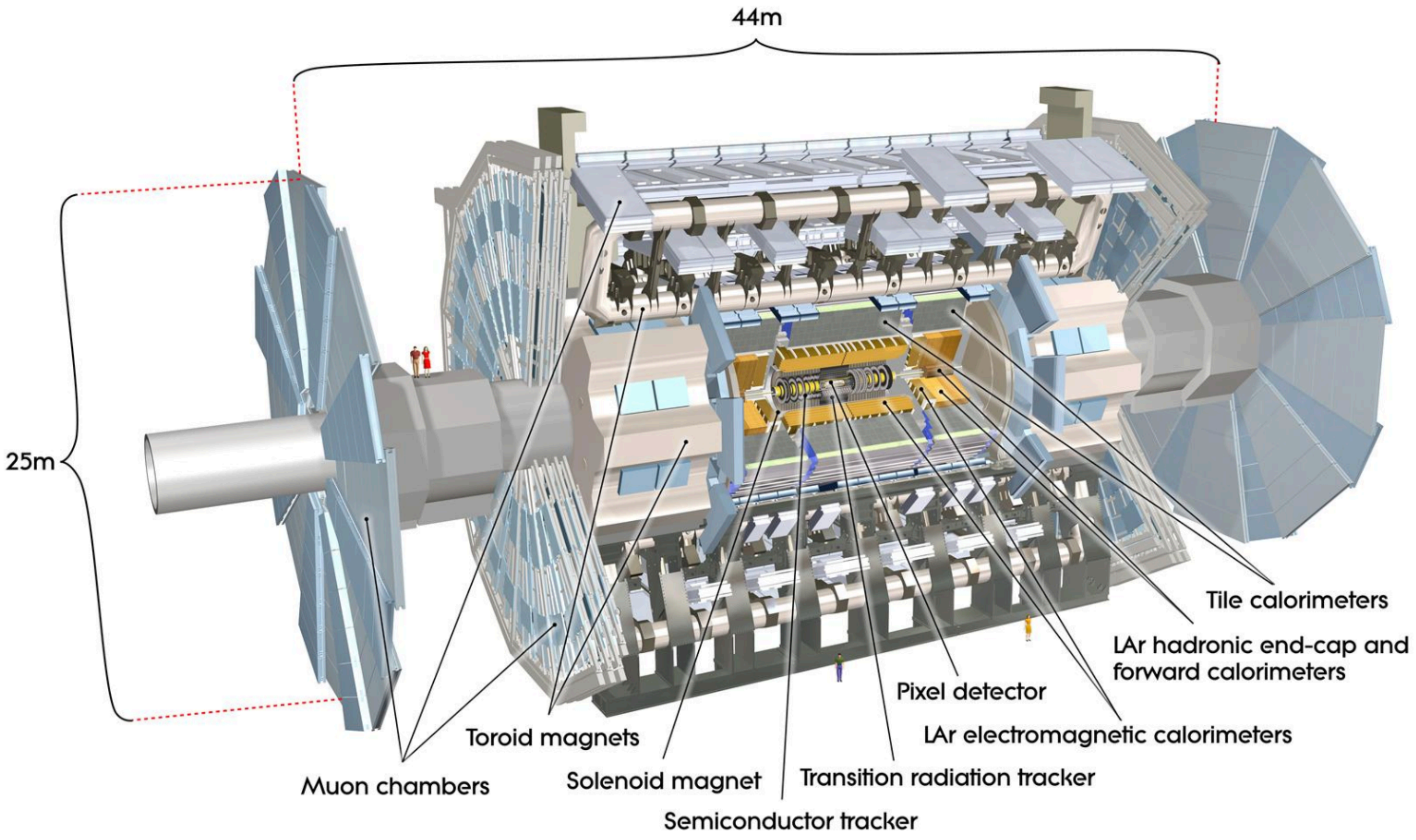

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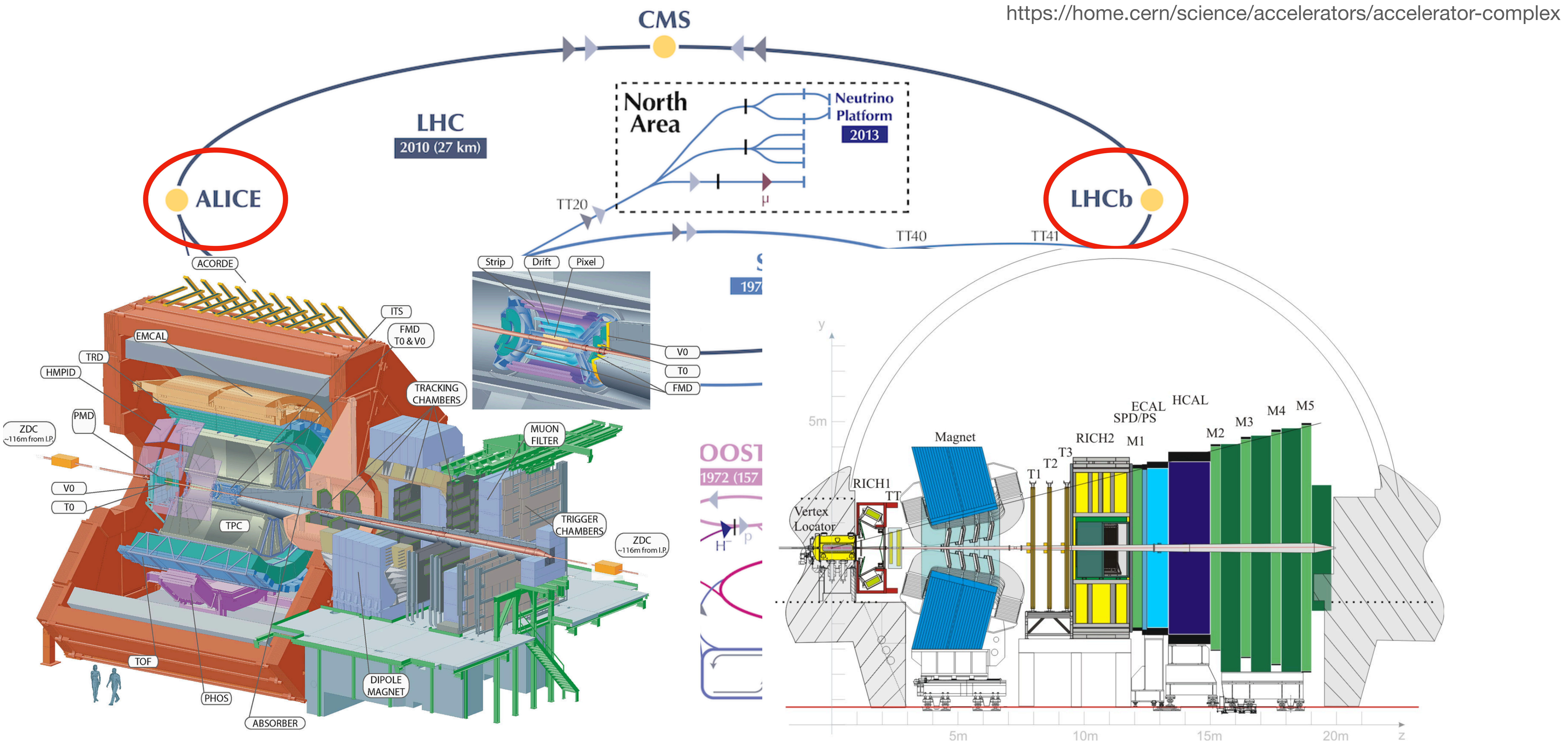

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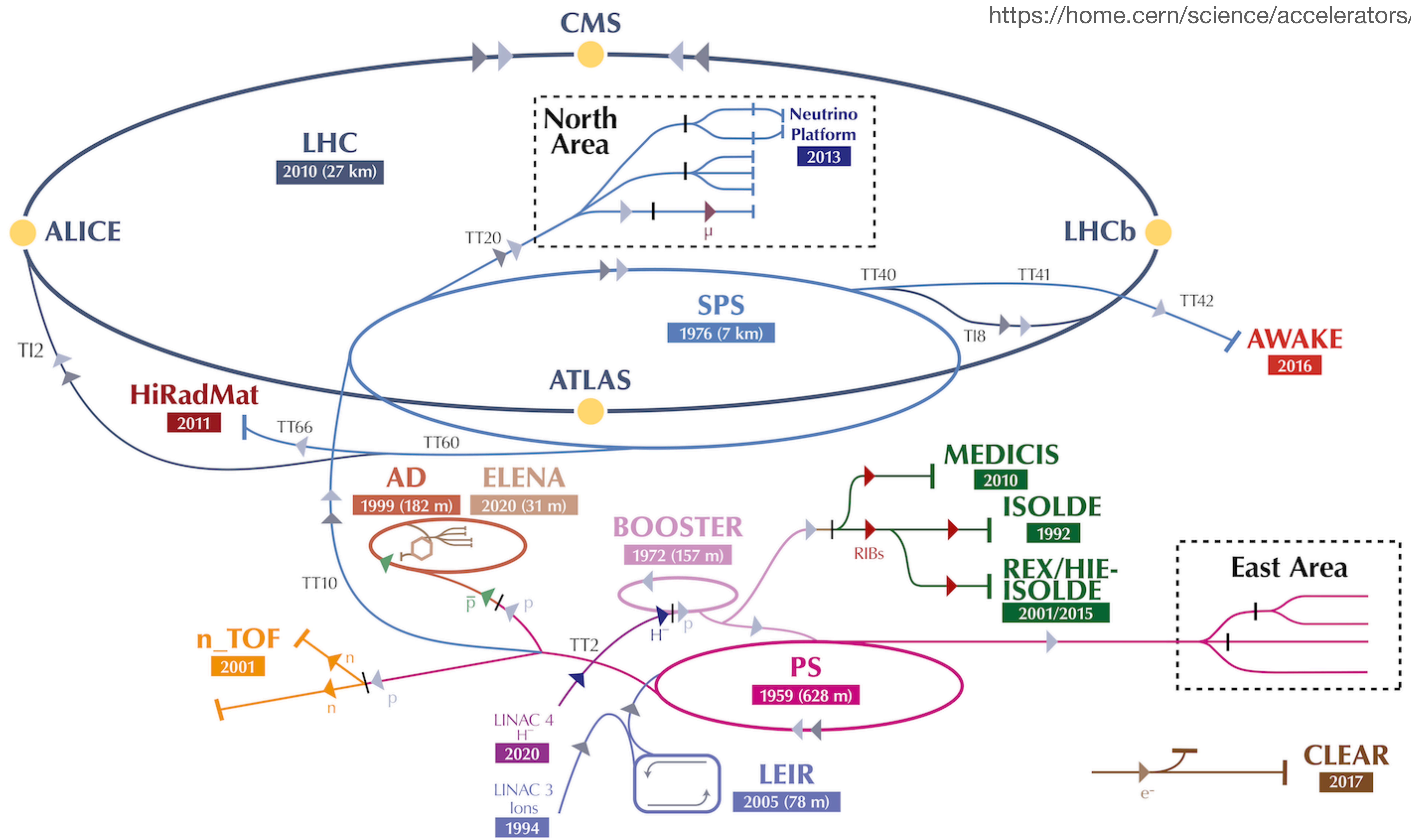
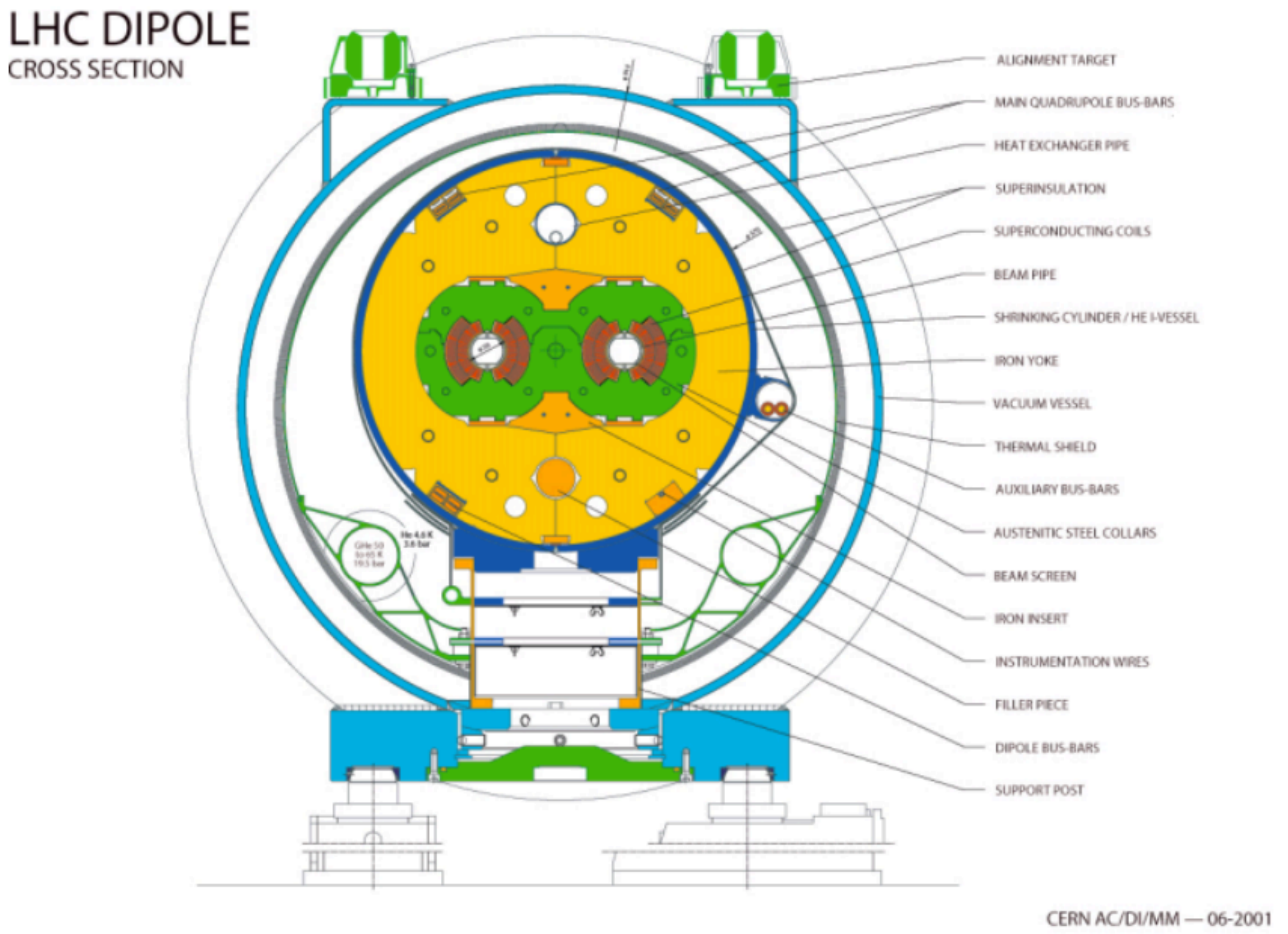


Why Protons and not Electrons?

- Energy loss by Bremsstrahlung ultimately limits the center-of-mass energy of circular lepton colliders
  - LEP reached 209 GeV with an energy loss per of 3.5 GeV
  - Energy loss per turn for the LHC is 7 keV
- Hadron collider limitation is the bending power
  - LHC effective radius is 2.7 km requiring a field of 8.5 T
  - At LEP (209 GeV) only about 0.1T was required.

Energy loss: $\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$

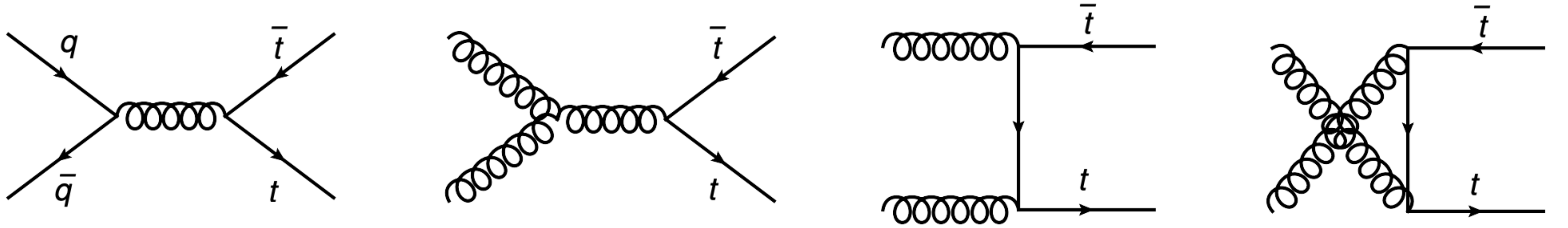
$$\frac{\Delta E(e)}{\Delta E(p)} = \frac{P(e)}{P(p)} = \left(\frac{m_p}{m_e}\right)^4 \simeq 10^{13}$$

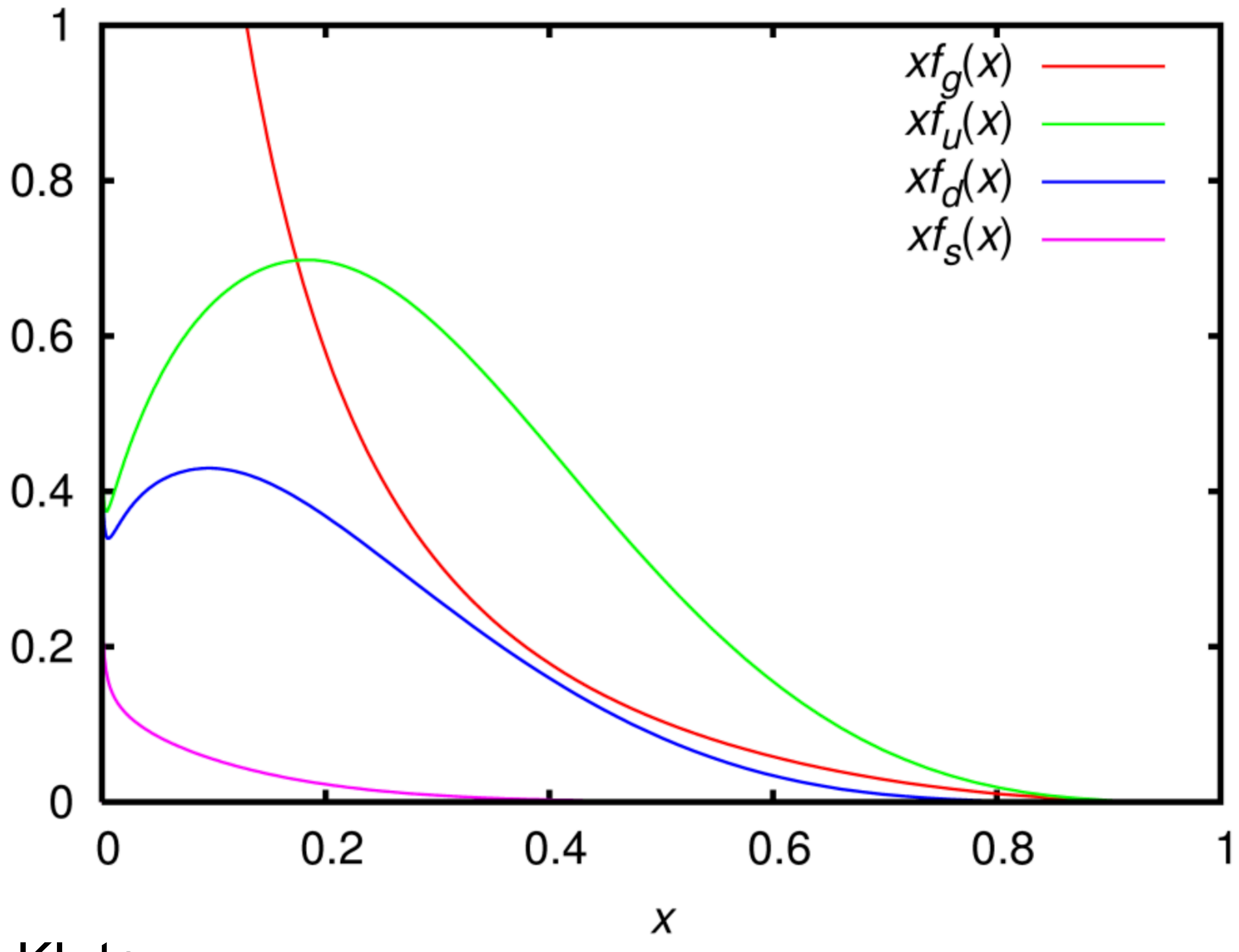


?

Why not Protons on Anti-Protons?

- Producing an anti-protons beam is challenging
- Studying collisions of proton constituents, i.e. quarks and gluons
- The probability to find a Parton with momentum fraction x is captured in parton distribution functions (PDFs)
  - PDFs are measured in experiments
  - Q^2 evolution is calculated with Altarelli-Parisi equations
  - Example: top pair production





Momentum sum rule

$$\sum_i \int_0^1 dx\, x f_i(x, Q^2) = 1$$

Flavour conservation sum rules

$$\int_0^1 (f_u(x, Q^2) - f_{\bar{u}}(x, Q^2))dx = 2$$

$$\int_0^1 (f_d(x, Q^2) - f_{\bar{d}}(x, Q^2))dx = 1$$

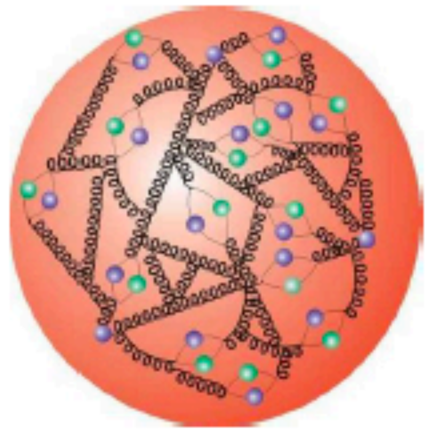
$$\int_0^1 (f_s(x, Q^2) - f_{\bar{s}}(x, Q^2))dx = 0$$

Hadron Collider History

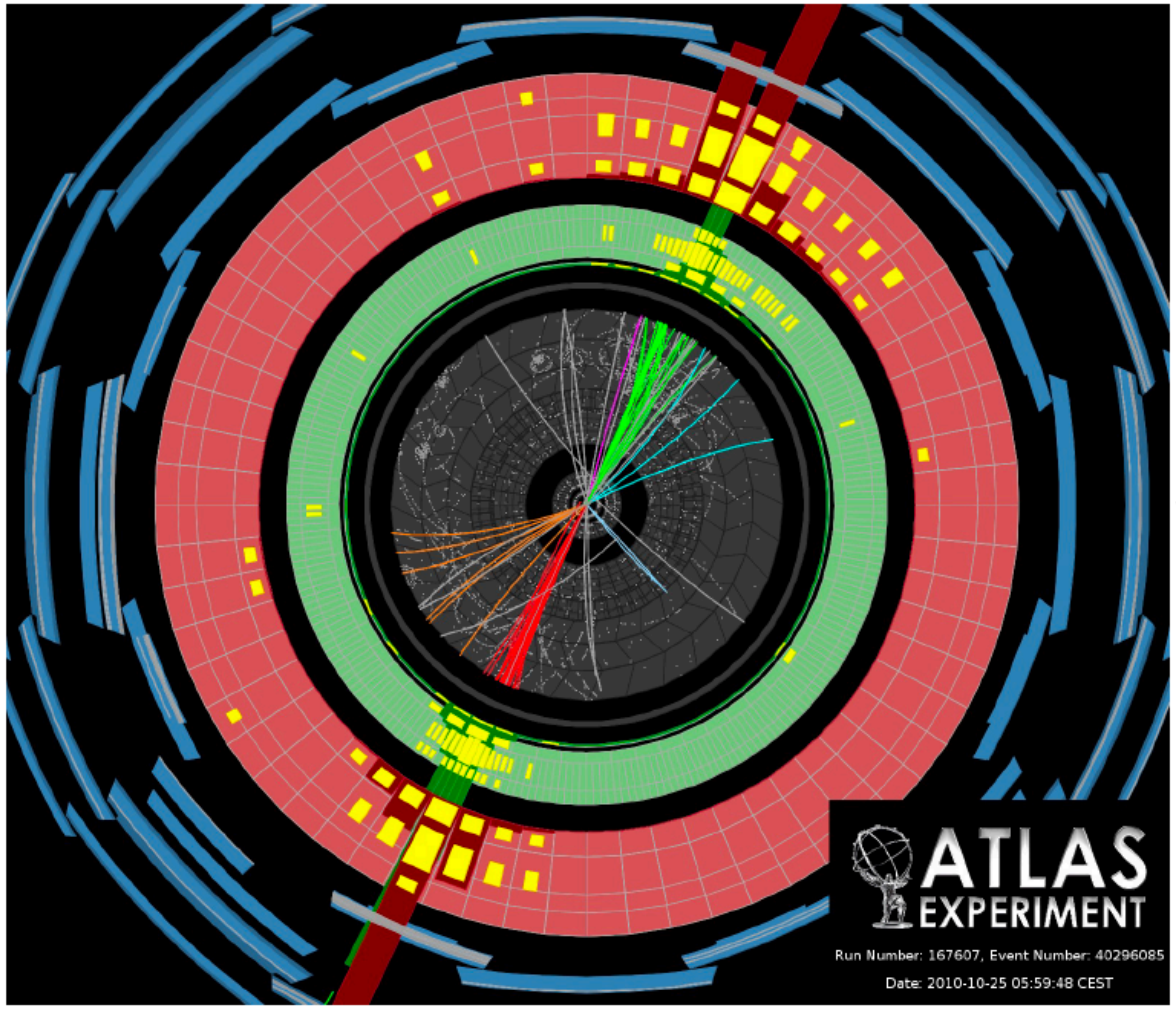
Collider	Location	Operating	Dimensions	Beam Energy	Type	Luminosity	Legacy
ISR	CERN	1971-84	~1km	31 GeV	pp	$2*10^{31}cm^{-2}s^{-1}$	First of its kind
SPS	CERN	1981-93	~6.9km	450 GeV	p-anti-p	$5*10^{30}cm^{-2}s^{-1}$	W and Z boson
HERA	DESY	1992-2007	~6.3km	920 GeV	ep	$5*10^{31}cm^{-2}s^{-1}$	PDFs
Tevatron	FERMILAB	1992-2011	~6.2km	980 GeV	p-anti-p	$4*10^{32}cm^{-2}s^{-1}$	Top quark discovery
SSC	Texas	Never completed	~87km	20 TeV	pp	$10^{33}cm^{-2}s^{-1}$	-
RHIC	Brookhaven	Since 2000	~3.8km	100 GeV	pp, pA, AA	$10^{32}cm^{-2}s^{-1}$	Quark-gluon plasma
LHC	CERN	Since 2008	LEP tunnel ~27km	6.8 TeV	pp, pA, AA	$2*10^{34}cm^{-2}s^{-1}$	Higgs boson discovery
EIC	Brookhaven	~2032	RHIC infrastructure	275 GeV	ep, eA	$10^{34}cm^{-2}s^{-1}$	-
FCC-hh	CERN	~2060	FCC-ee tunnel	50 TeV	pp, pA, AA	$3*10^{35}cm^{-2}s^{-1}$	-

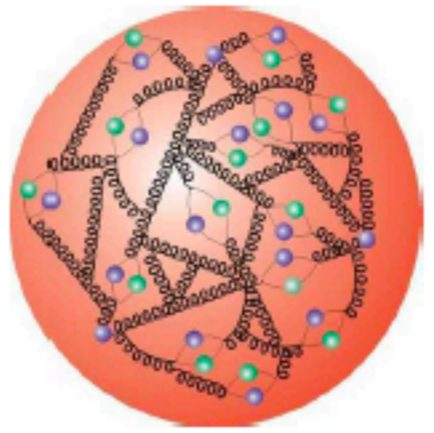
Hadron-Hadron Collision

Broadband beam of various parton types with various energies



Proton

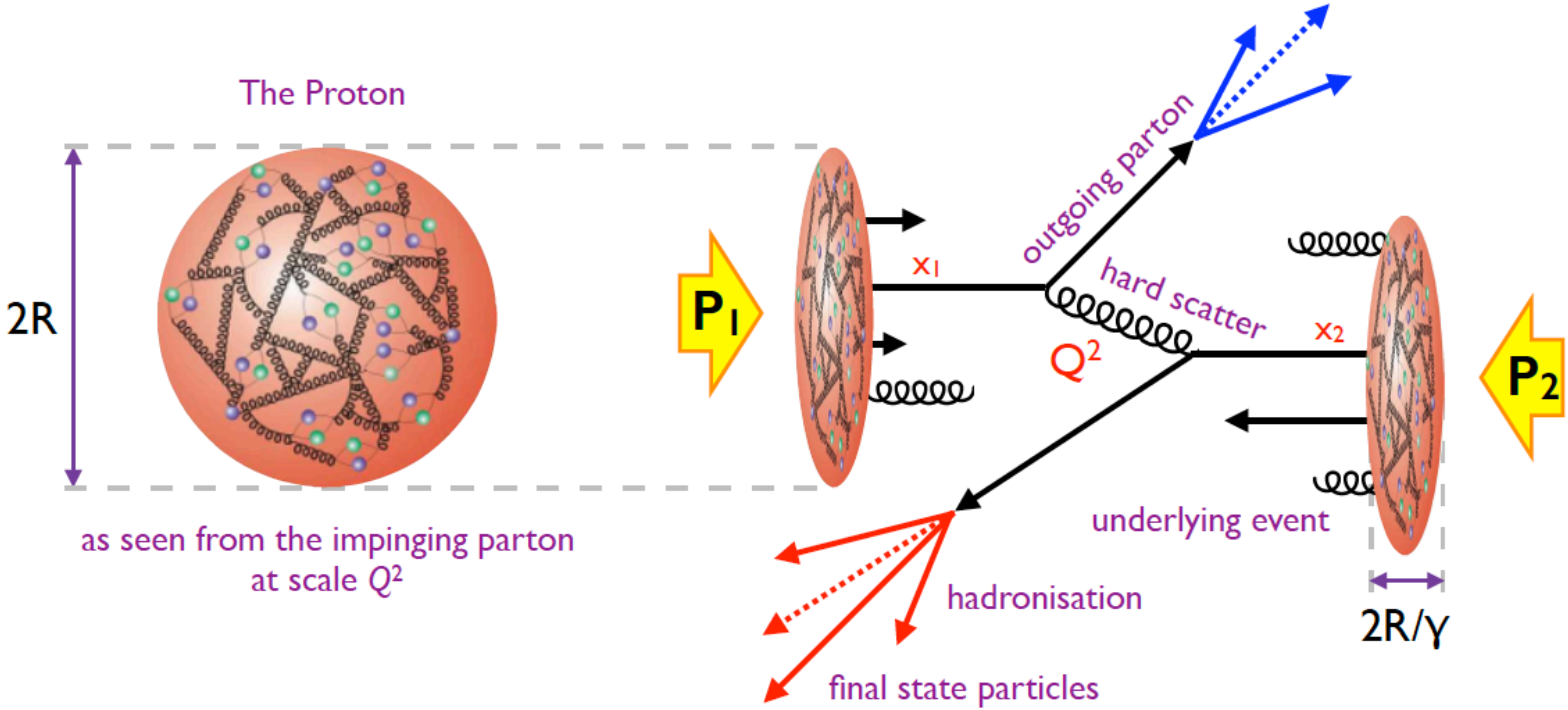




Proton

Challenge: reliable calculations of observables

Hadron-Hadron Collision



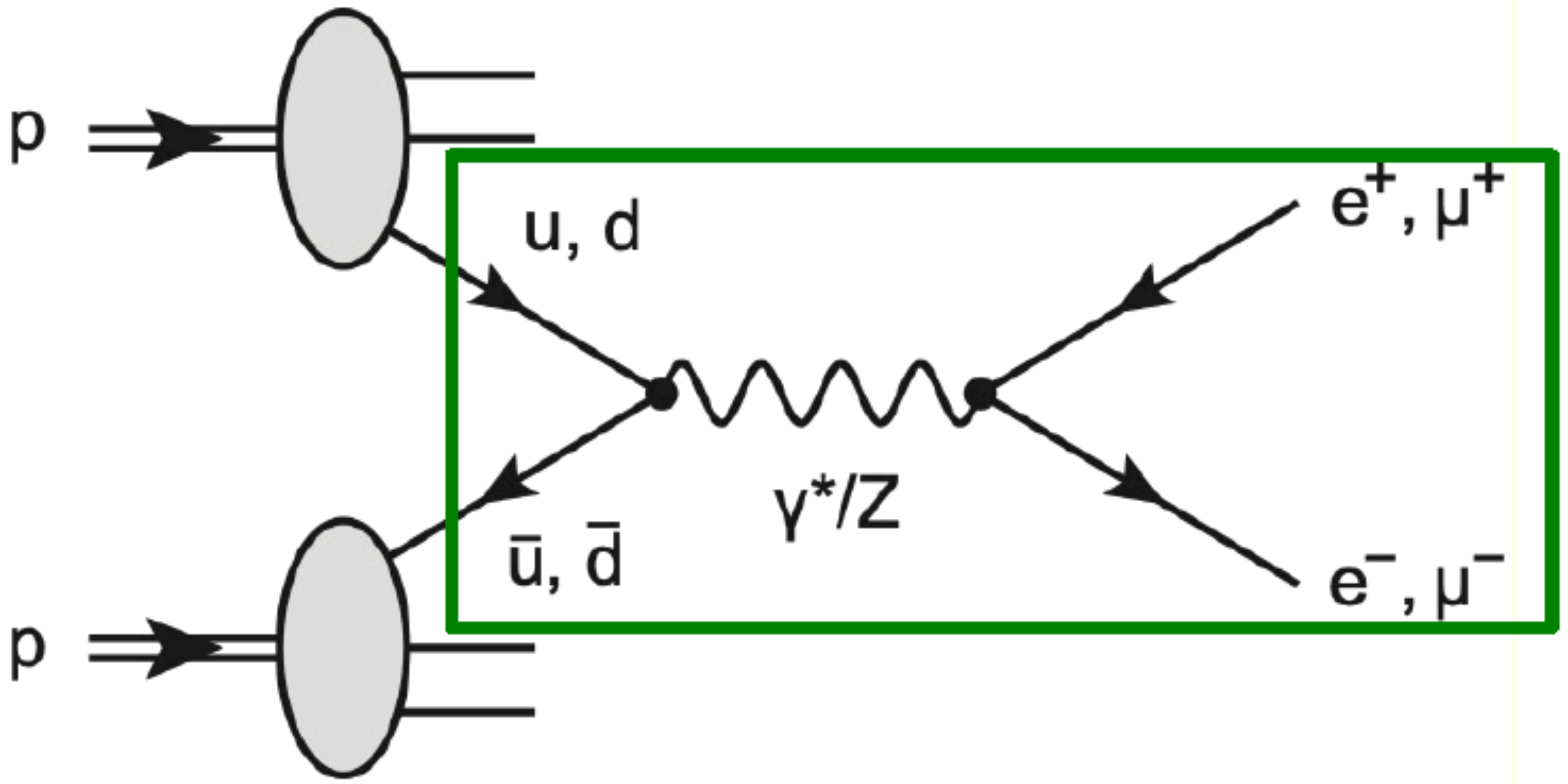
R = 0.8fm

$$\hat{s} = x_1 x_2 s$$

Prototype Process: Drell-Yan Production

$pp \to l^+l^- + X$

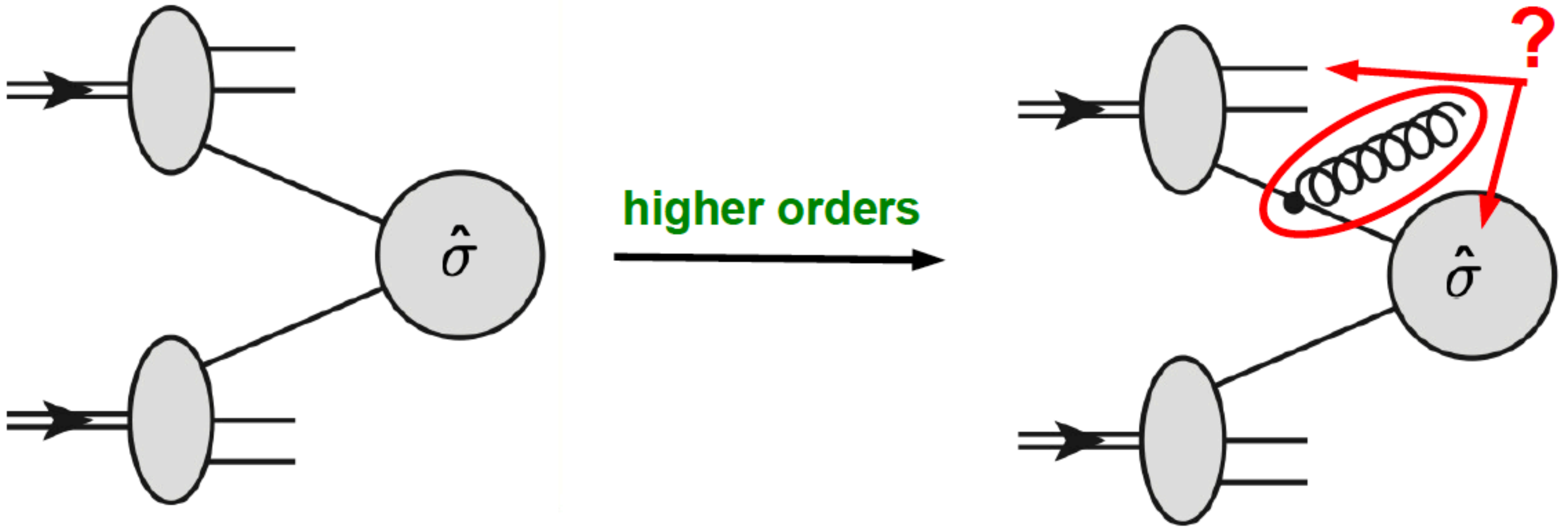
- Hadron production of lepton pairs
- Factorising "hard" and "soft" components
  - Calculate hard partonic subprocess
  - Weight cross section with probability to end parsons with momenta x1 and x2
  - Integrate over all possible parton momenta
  - Sum over all possible parton flavors



$$\sigma_{\mathrm{DY}} = \sum_{i,j} \int \mathrm{d}x_i \mathrm{d}x_j f_i(x_i) f_j(x_j) \cdot \hat{\sigma}(q_i q_j \to l^+ l^-)$$

Prototype Process: Drell-Yan Production

$pp \to l^+l^- + X$



Where does this belong to?

The PDF?

Or the parton process?

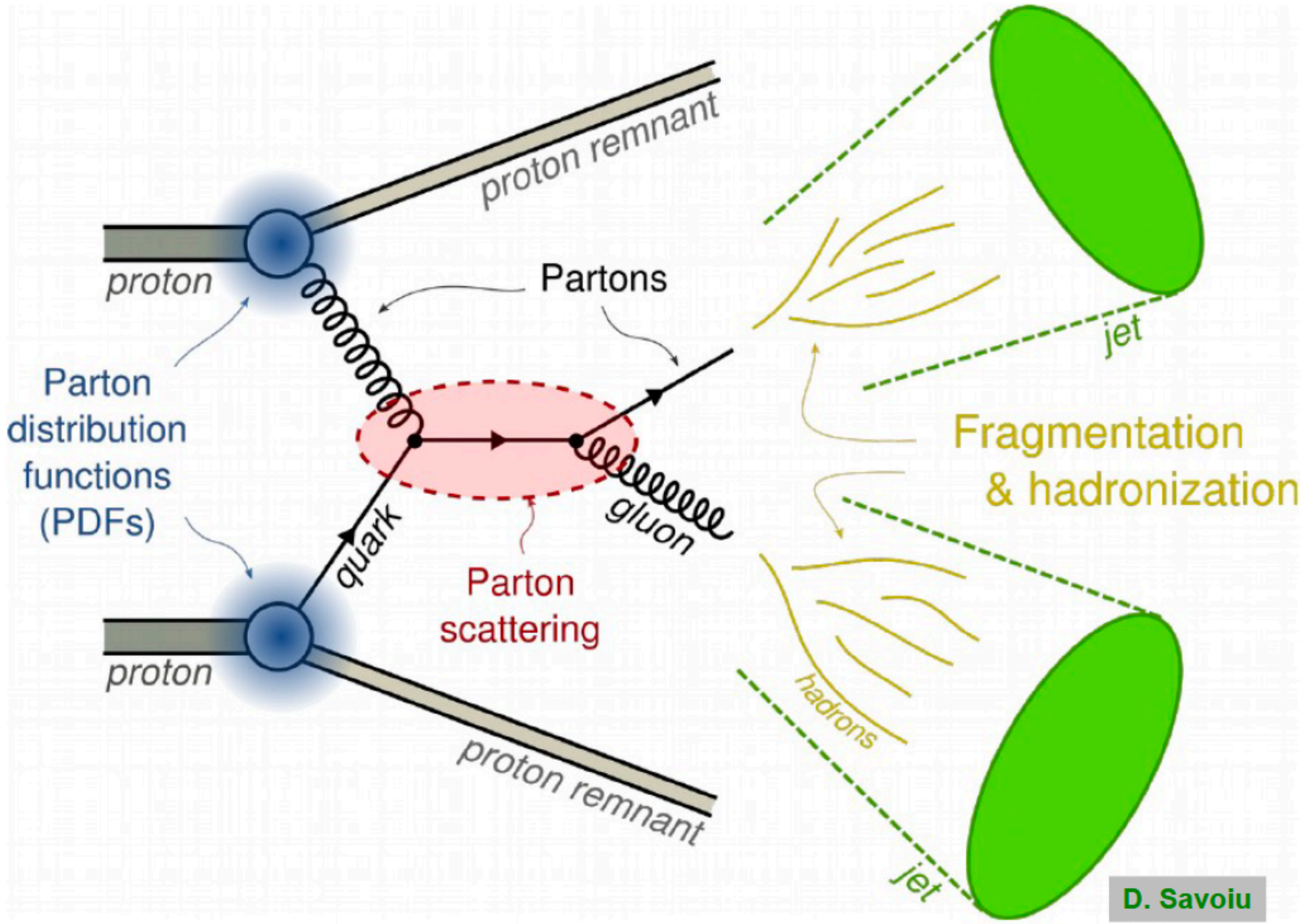
- Factorisation scale μ_f
- Attribution ambiguous
  - Leads to soft and / or collinear divergences (long-distance effects!)
  - Solution: introduce a new scale to separate short- and long-distance effects
  - Effects are absorbed into PDFs and determined experimentally

$$\hat{\sigma}_{ij}(x_i, x_j, \mu_r^2, \alpha_s(\mu_r^2)) \to \hat{\sigma}_{ij}(x_i, x_j, \mu_f^2, \mu_r^2, \alpha_s(\mu_r^2))$$

$$f_i(x_i) \to f_i(x_i, \mu_f^2)$$

Hadron-Hadron Cross Section

- Factorisation valid for more general final states, e.g. jet production



Luminosity

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \mathcal{L}(t)\sigma$$

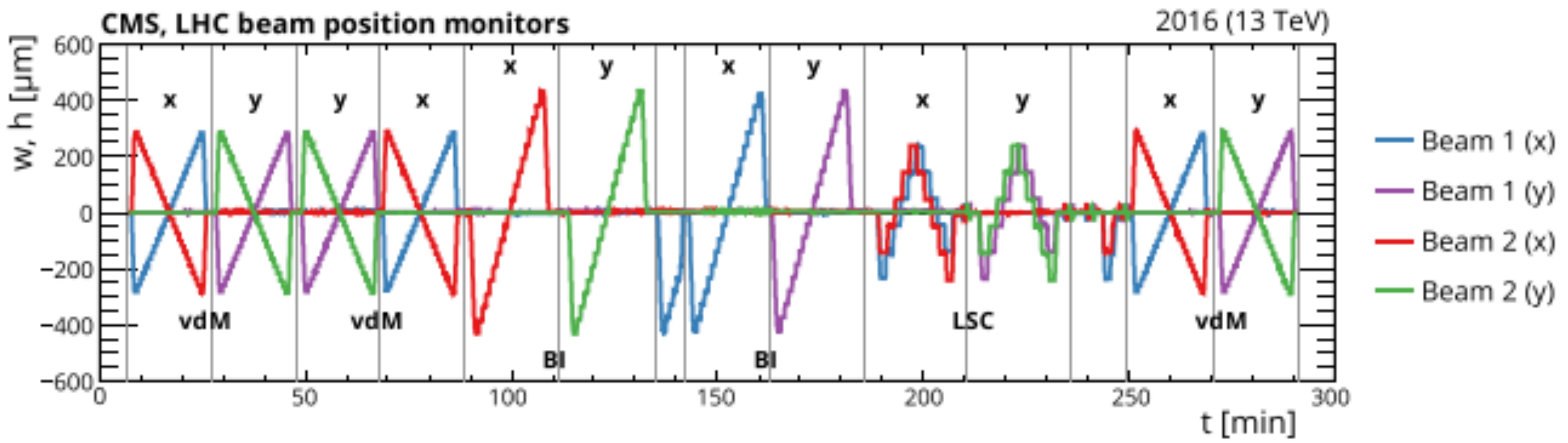
Events per second for a given cross section

Cross section in barn (10^{-24} cm^{-2})
Luminosity in cm^{-2}s^{-1}

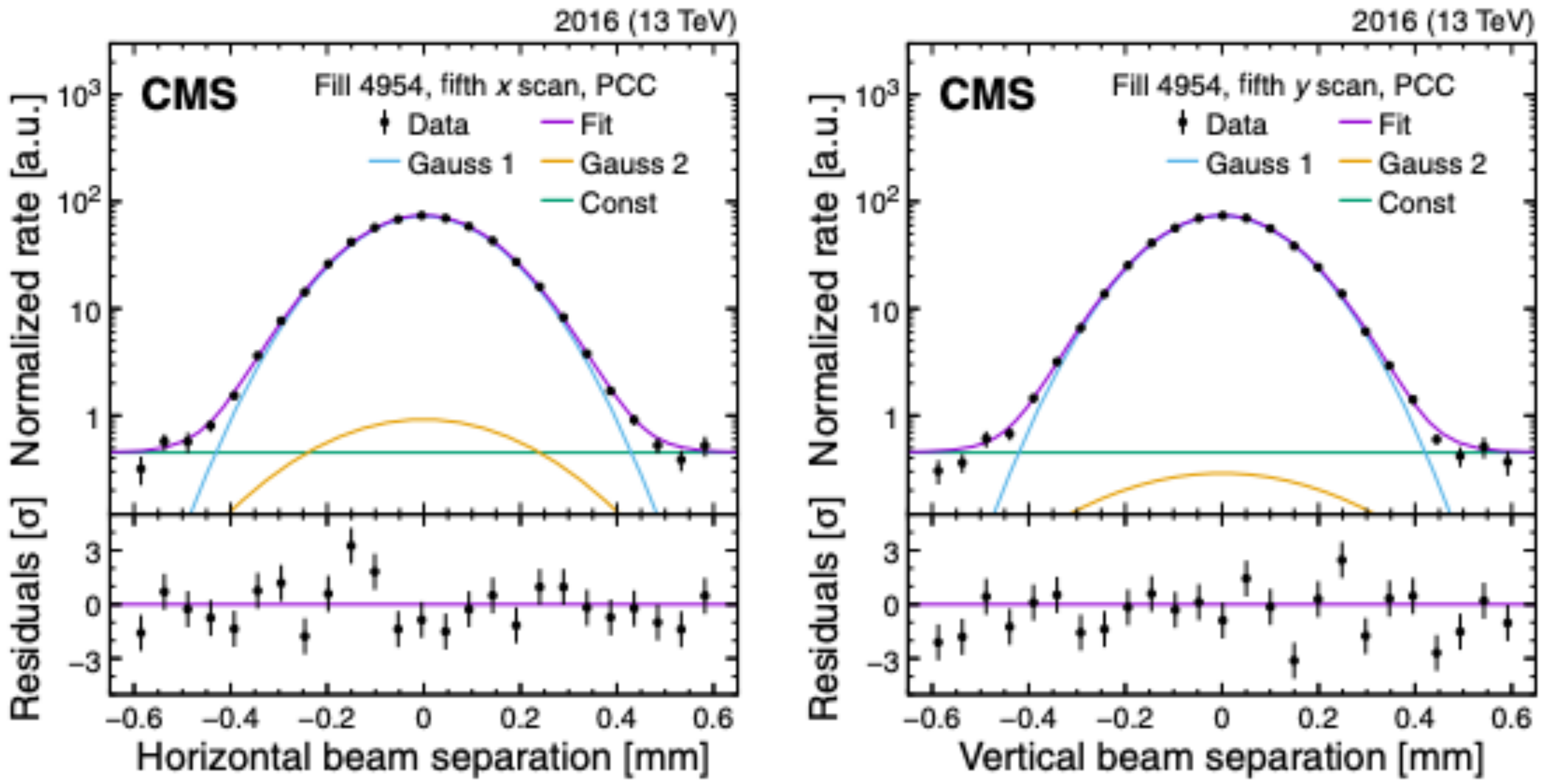
$$N = L\sigma \quad \text{with} \quad L = \int \mathcal{L}(t)\mathrm{d}t$$

- Luminosity depends on
  - Number of protons per bunch
  - Beam size at interaction point
  - Number of bunches

$$\mathcal{L} = \frac{N_p^2 f N_B}{4\pi \sigma_x \sigma_y}$$



- Luminosity measurements
  - Crucial for absolute cross section measurements or to set limits on physics beyond the SM
  - Calibration performed using “Van der Meer scans”
  - Uncertainty of order 1-2%



- Luminosity monitoring

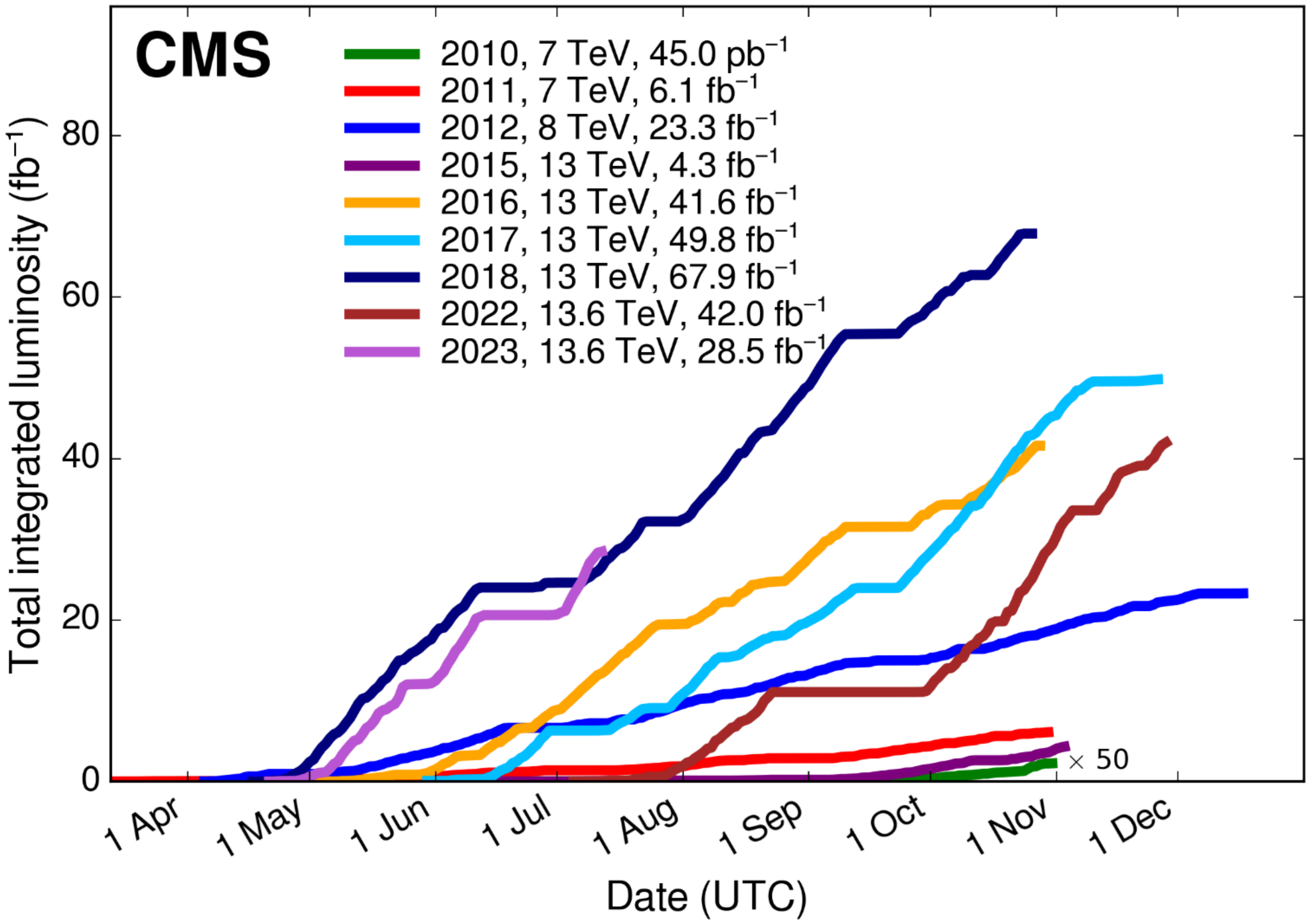
Luminosity

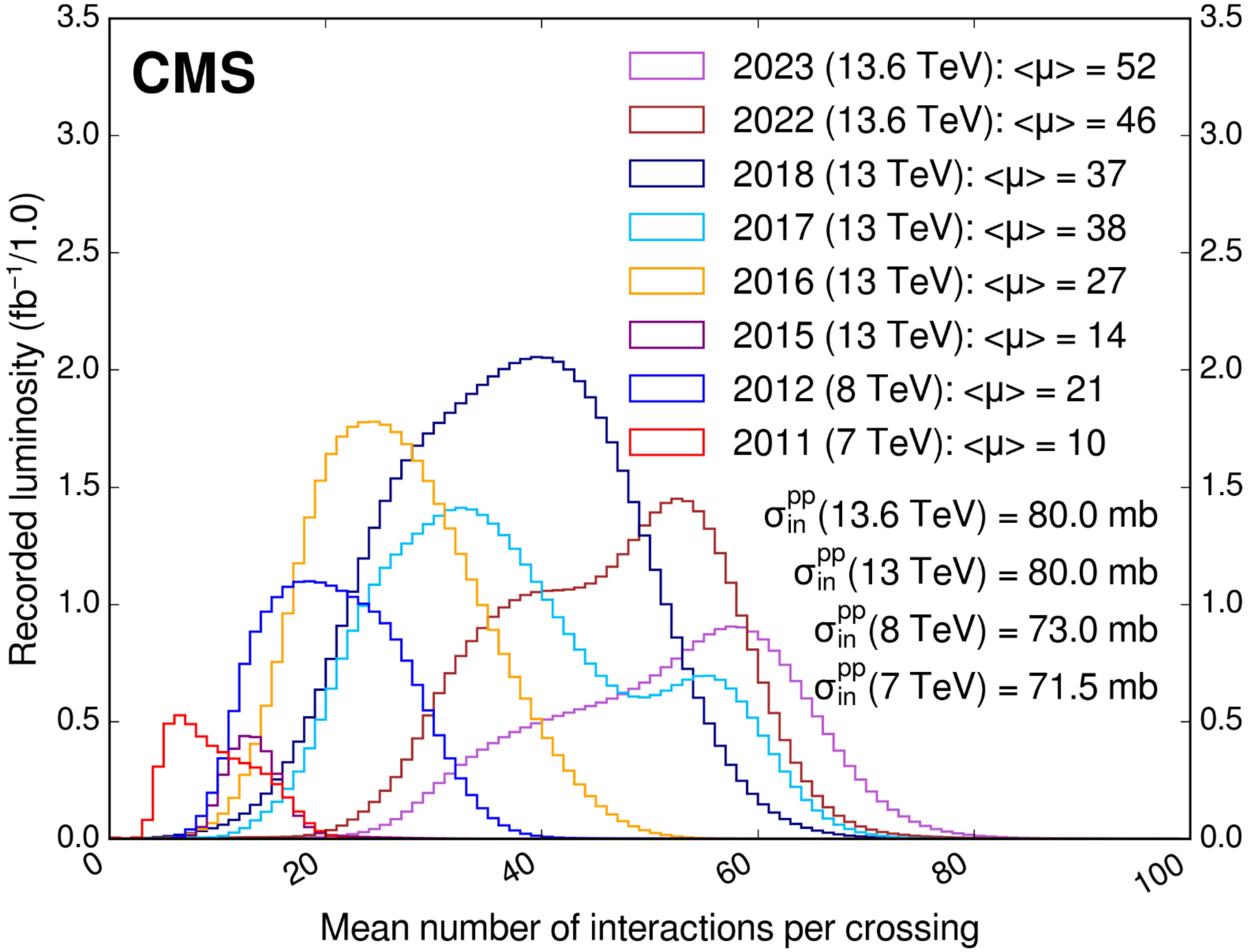
$$\mathcal{L} = \frac{N_p^2 f N_B}{4\pi \sigma_x \sigma_y} = \frac{N_p^2 f N_B \gamma F}{4\pi \beta^* \varepsilon_N}$$

Luminosity (beam size) expressed using beam parameters

Parameter	2010	2011	2012	2016	2017	2018	Nominal	HL-LHC
CoM Energy	7 TeV	7 TeV	8 TeV	13 TeV	13 TeV	13 TeV	14 TeV	14 TeV
N_p	$1.1\ 10^{11}$	$1.4\ 10^{11}$	$1.6\ 10^{11}$	$1.2\ 10^{11}$	$1.2\ 10^{11}$	$1.2\ 10^{11}$	$1.15\ 10^{11}$	$2.2\ 10^{11}$
Bunches k	368	1380	1380	2300	2450	2500	2808	2760
Spacing	150 ns	50 ns	50 ns	25 ns	25 ns	25 ns	25 ns	25ns
ε (mm rad)	2.4-4	1.9-2.3	2.5	2.6	2.3	2.6	3.75	2.5
β* (m)	3.5	1.5-1	0.6	0.4	0.3-0.4	0.4	0.55	0.15
L ($cm^{-2}s^{-1}$)	$2x10^{32}$	$3.3x10^{33}$	$\sim 7x10^{33}$	$1.5x10^{33}$	$2.0x10^{34}$	$2x10^{34}$	10^{34}	$8x10^{34}$
PU	~2	~10	~30	~30	~50	~50	~25	~130

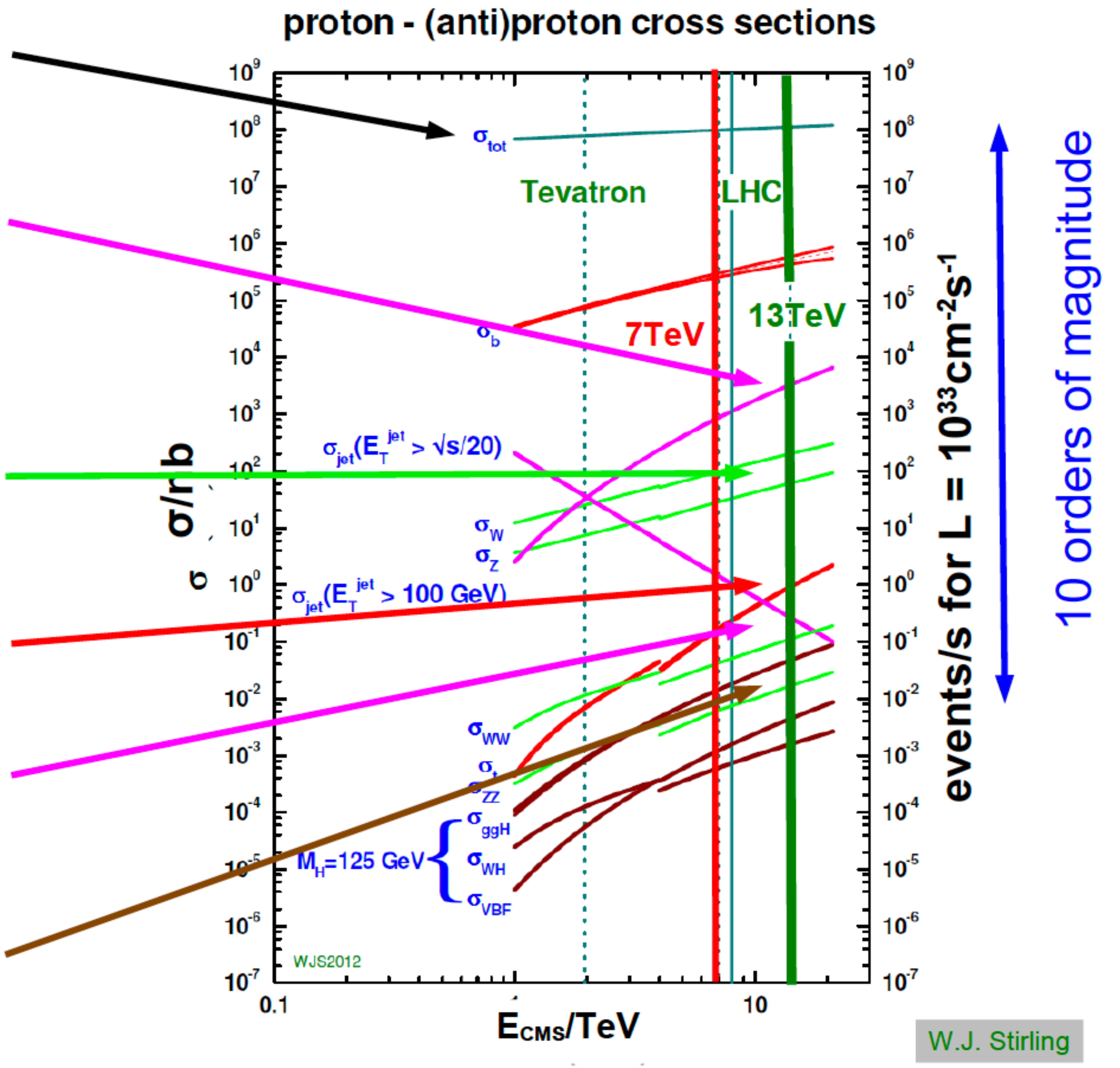
Integrated Luminosity and Pile-Up





Event rates at the LHC

- Total cross sections
  - ~1.6*10⁹ /s (80mb, $2*10^{34}cm^{-2}s^{-1}$)
  - Bunch crossing rate of 40MHz
- Jets (E_T^{jet} > 100 GeV)
  - ~40000 Hz
- W & Z bosons
  - ~4000 Hz, ~1000 Hz
- Top Quarks
  - ~20 Hz
- Jets (E_T^{jet} > 650 GeV)
  - ~6 Hz
- Higgs bosons
  - ~1 Hz (50pb, $2*10^{34}cm^{-2}s^{-1}$)

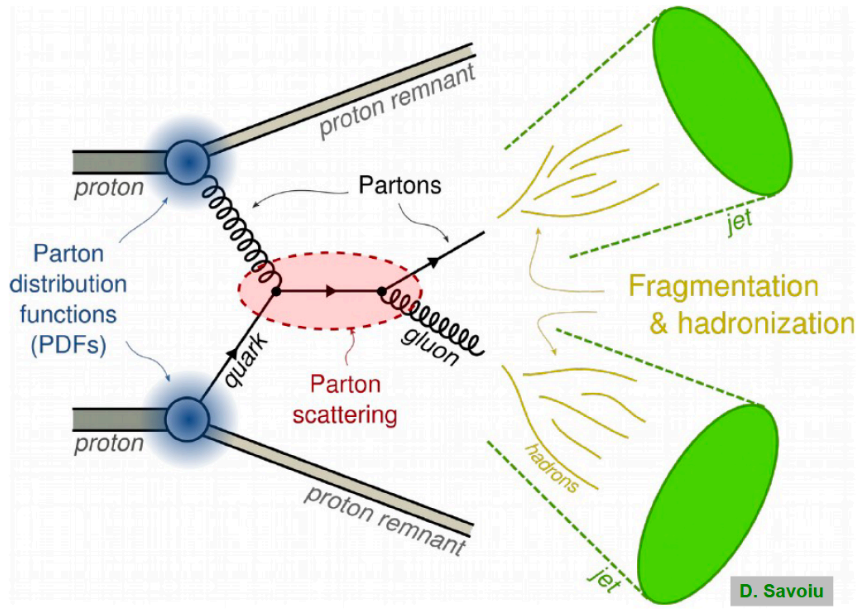


Data and Analysis Chain

Detector

On-detector Trigger Electronics

Theory



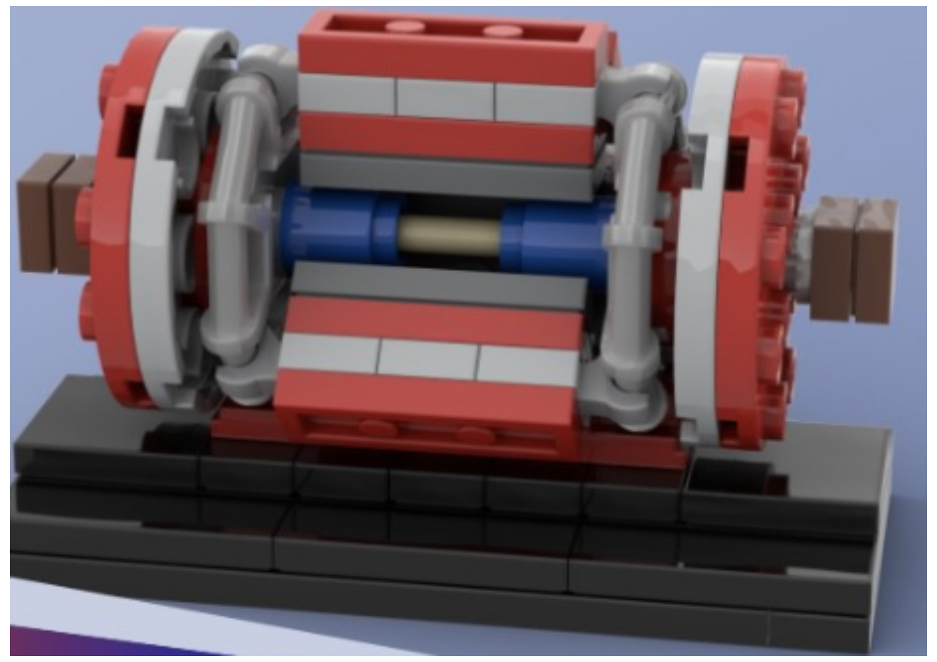
Calculation of physics processes including hadronization

Off-detector Trigger Computing farm

Collision Data

Calibration & alignment

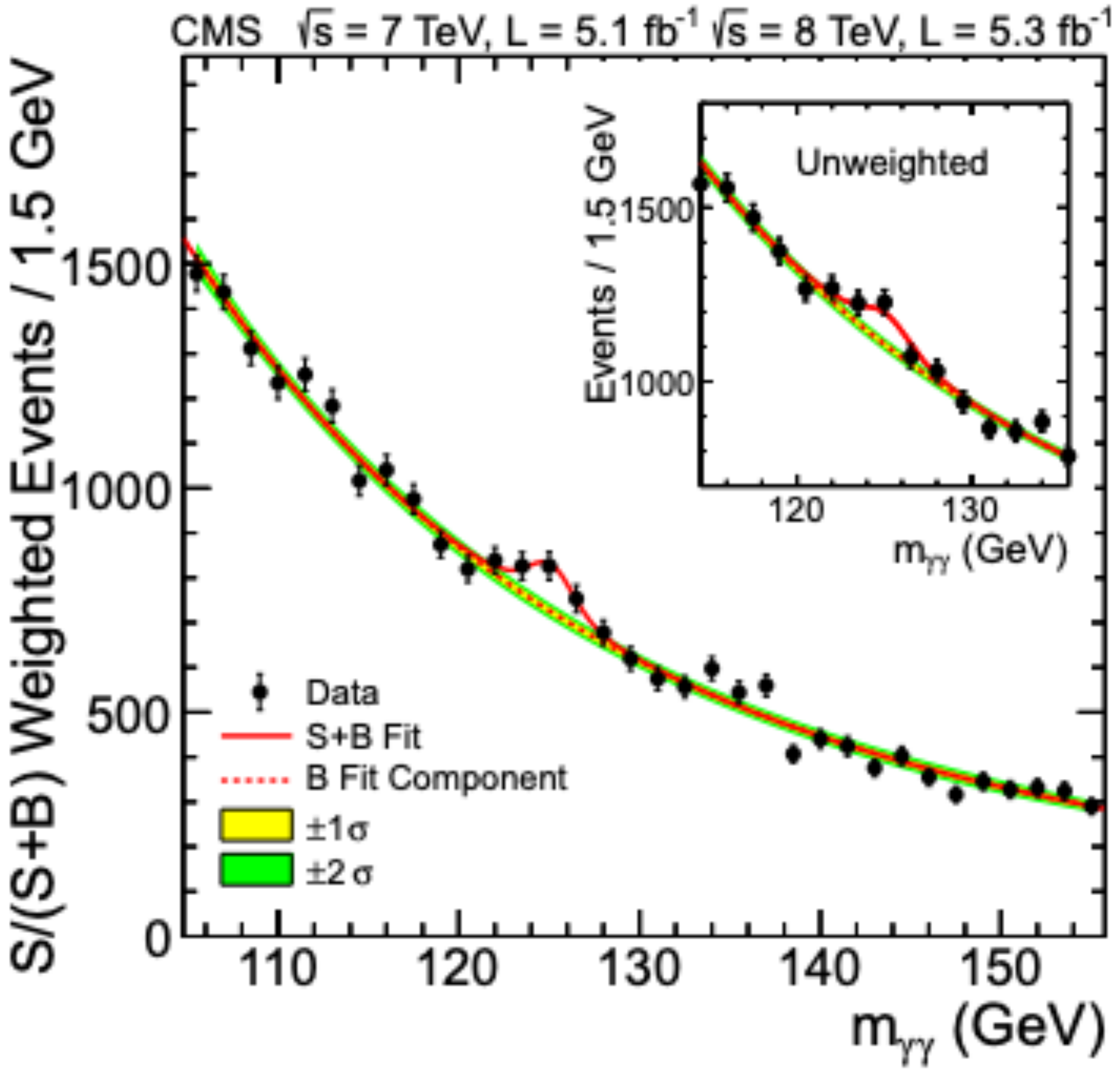
Digital twin (Simulation)



Simulated Data

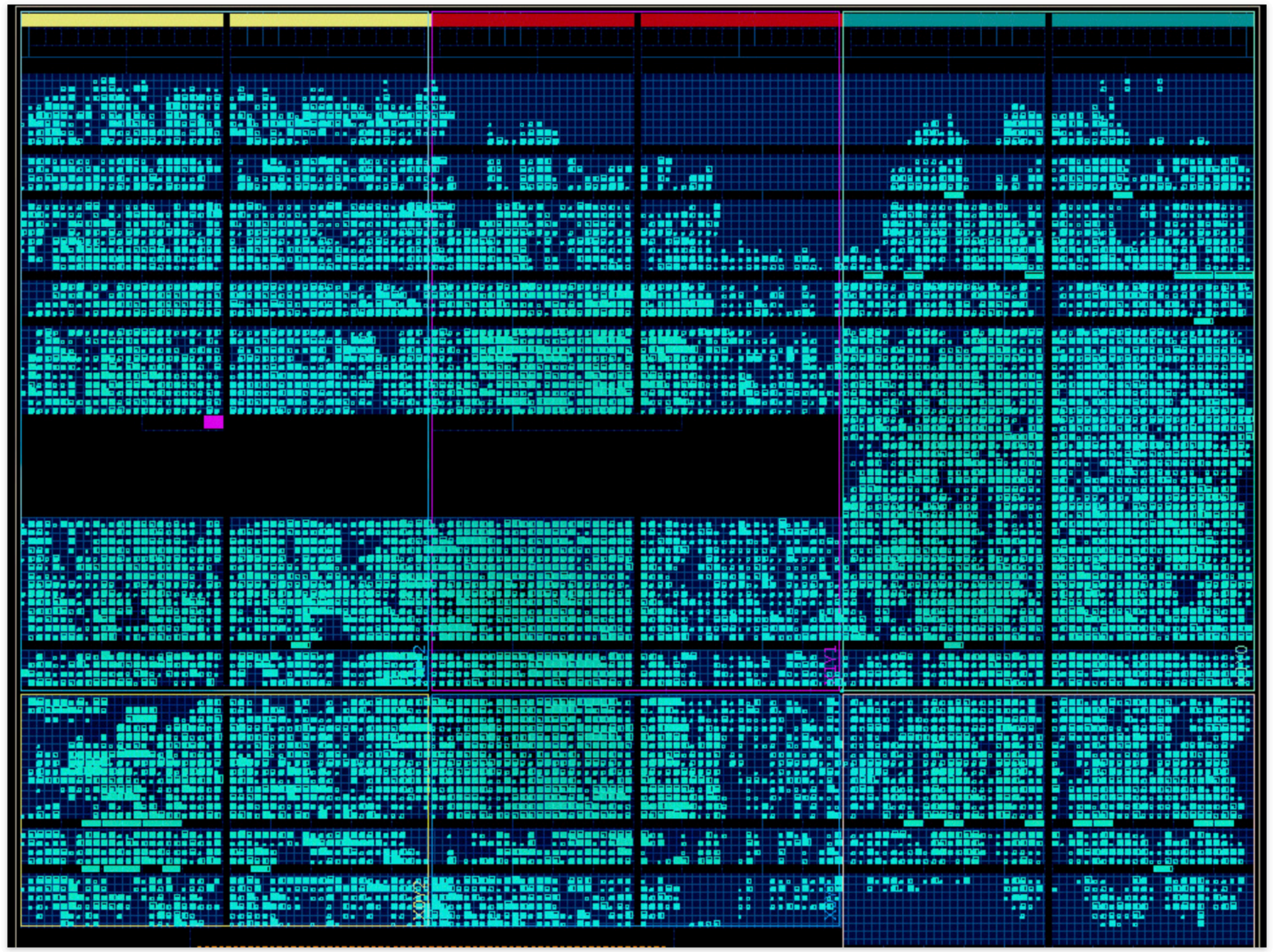
Reconstruction & Data reduction

Statistical analysis



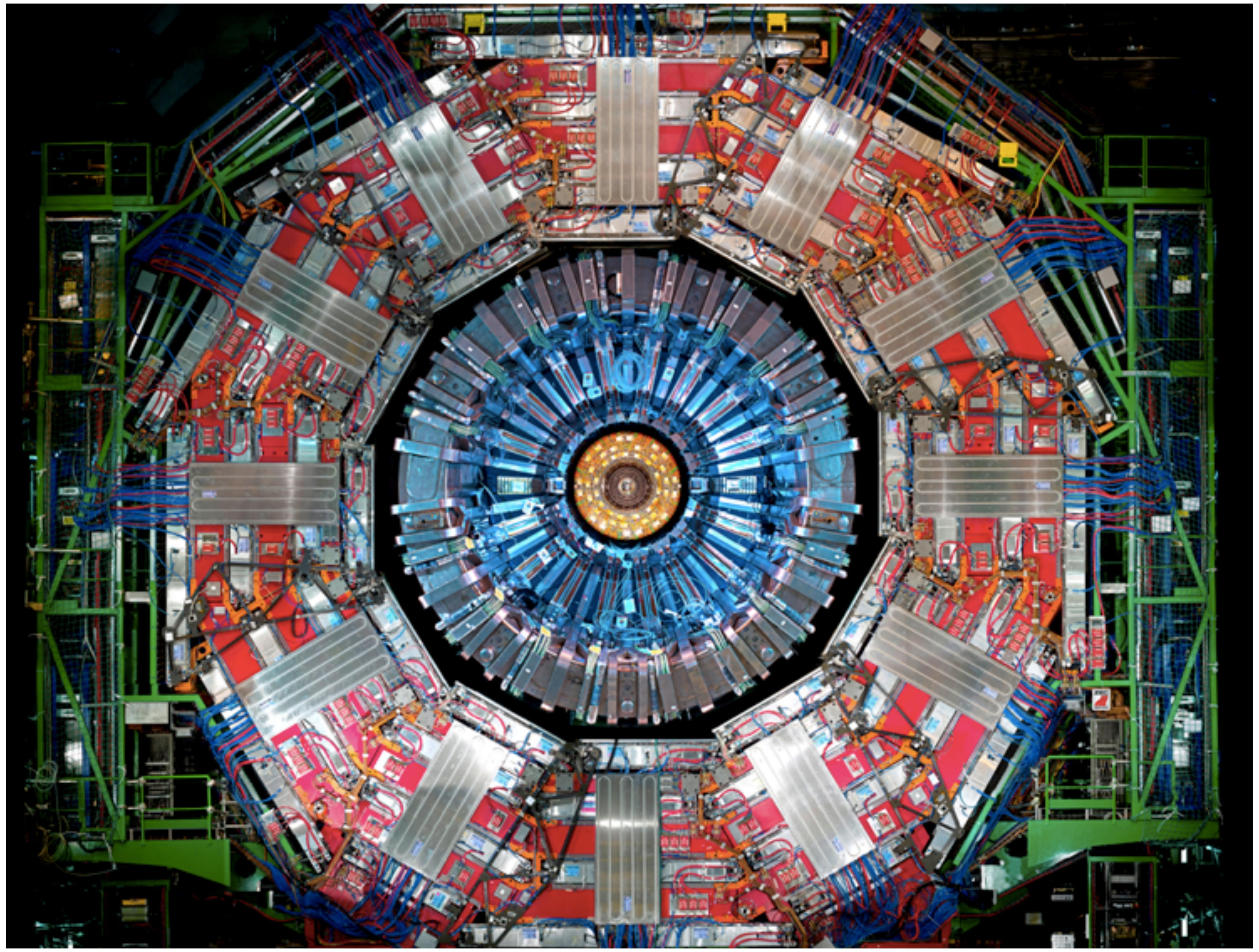
Software & Computing

- LHC computing scale
  - ~1 million cores fully occupied
  - ~1 EB (~500 PB disk, > 500 PB tape)
  - Global networking (~10-100Gbps)
  - ~140 Computing centres in 33 countries
- Challenges
  - Increasing data volume and complexity
  - Maintenance
- Opportunities
  - Heterogeneous computing resources
  - Applications of machine learning



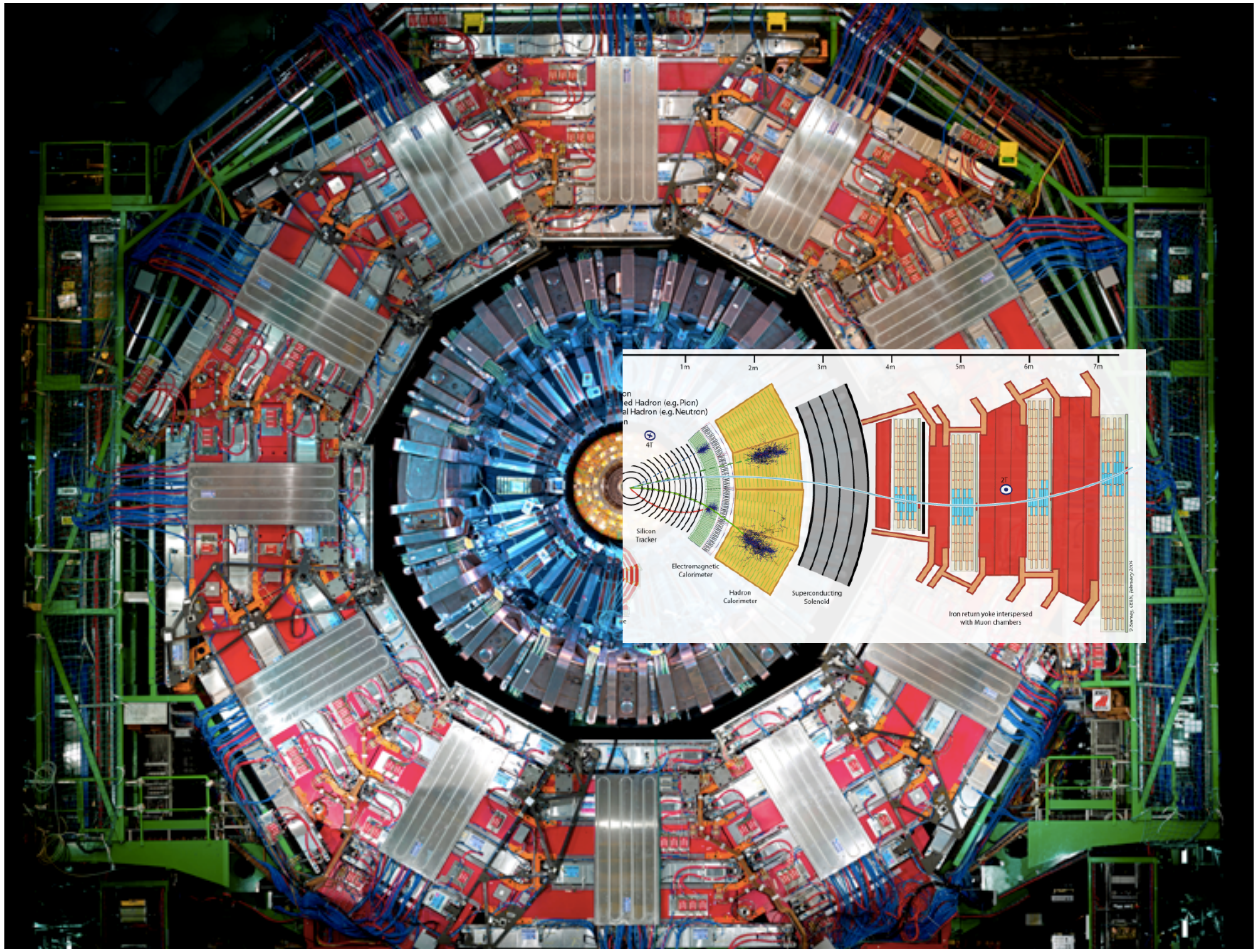
An ultra-compressed deep neural network on a field-programmable gate array. (Image: Sioni P. Summers)

What do we actually reconstruct from collisions?

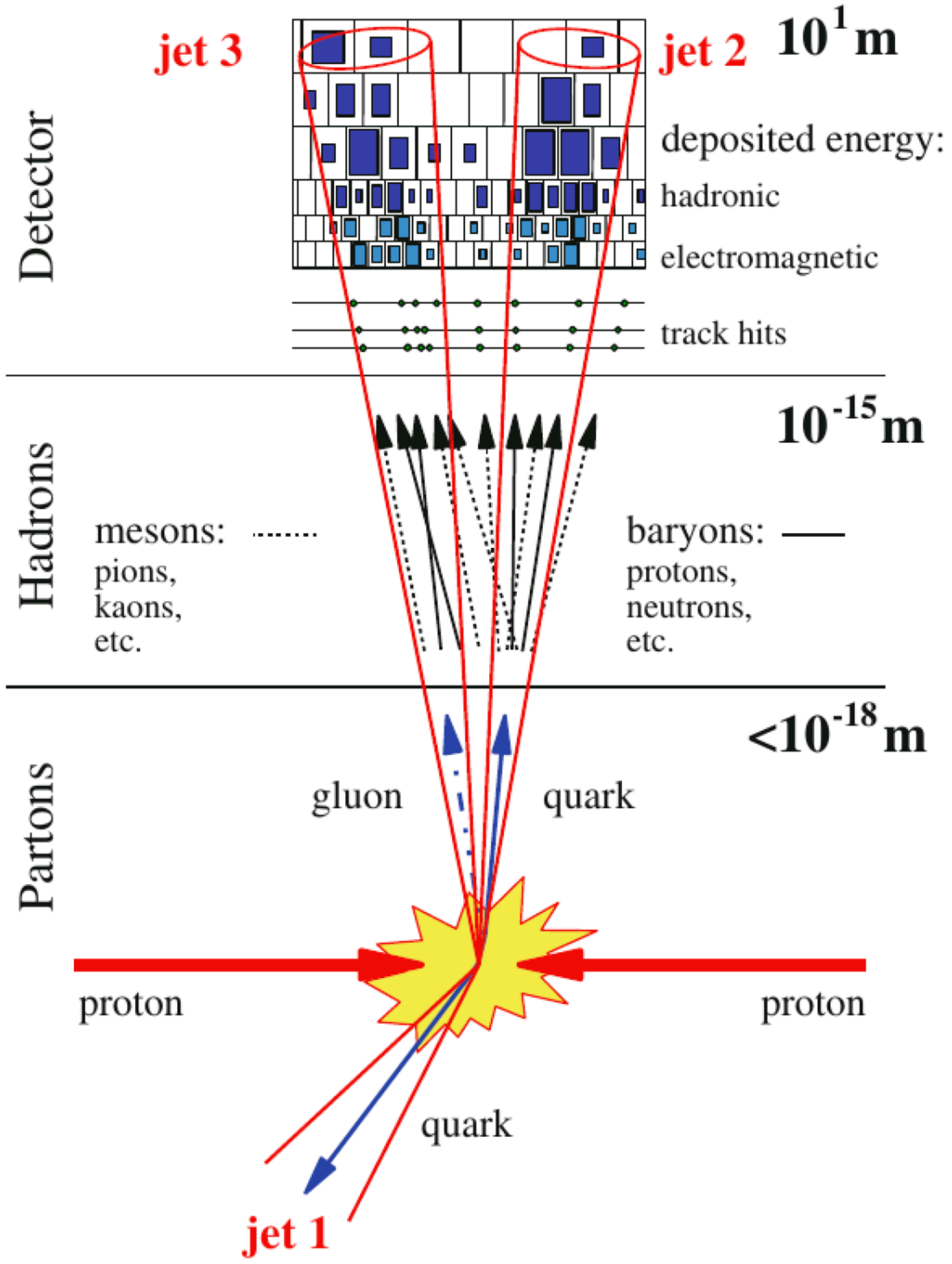


What do we actually reconstruct from collisions?

- Energy and momenta of “stable” particles
  - Electrons, positrons, muons, anti-muons, charged hadrons
  - Photons, neutral hadrons
- Identify particle species
  - Including reconstruction of “unstable” particles from decay products
- Assign proton-proton collision (pile-up removal)



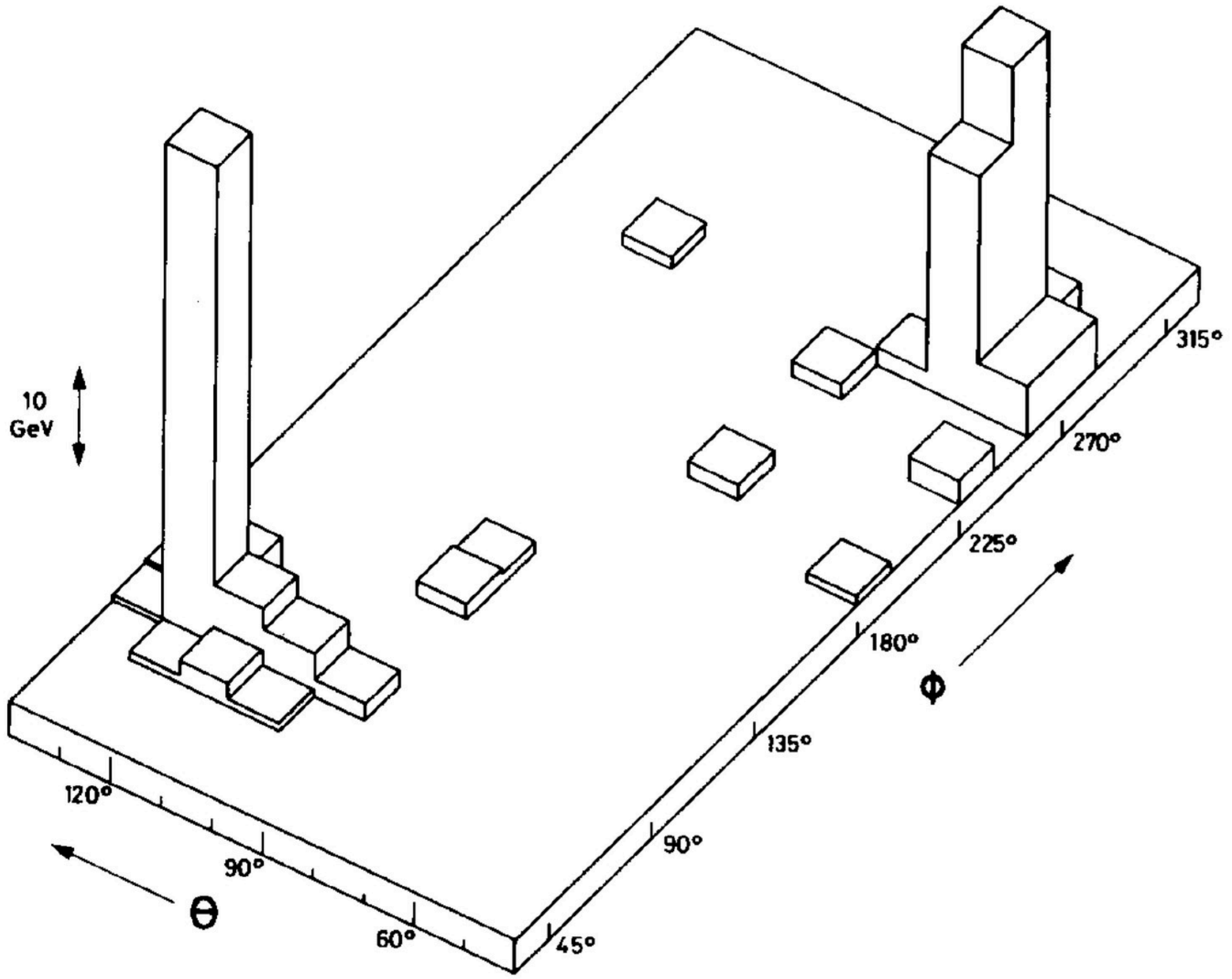
Jets at Hadron Collider



Jet History

- Di-jet events with clearly separated energy depositions
  - "Jet algorithm" based on cell structure of calorimeters (UA1 & UA2)
  - UA1 later also used a cone algorithm with

$$R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



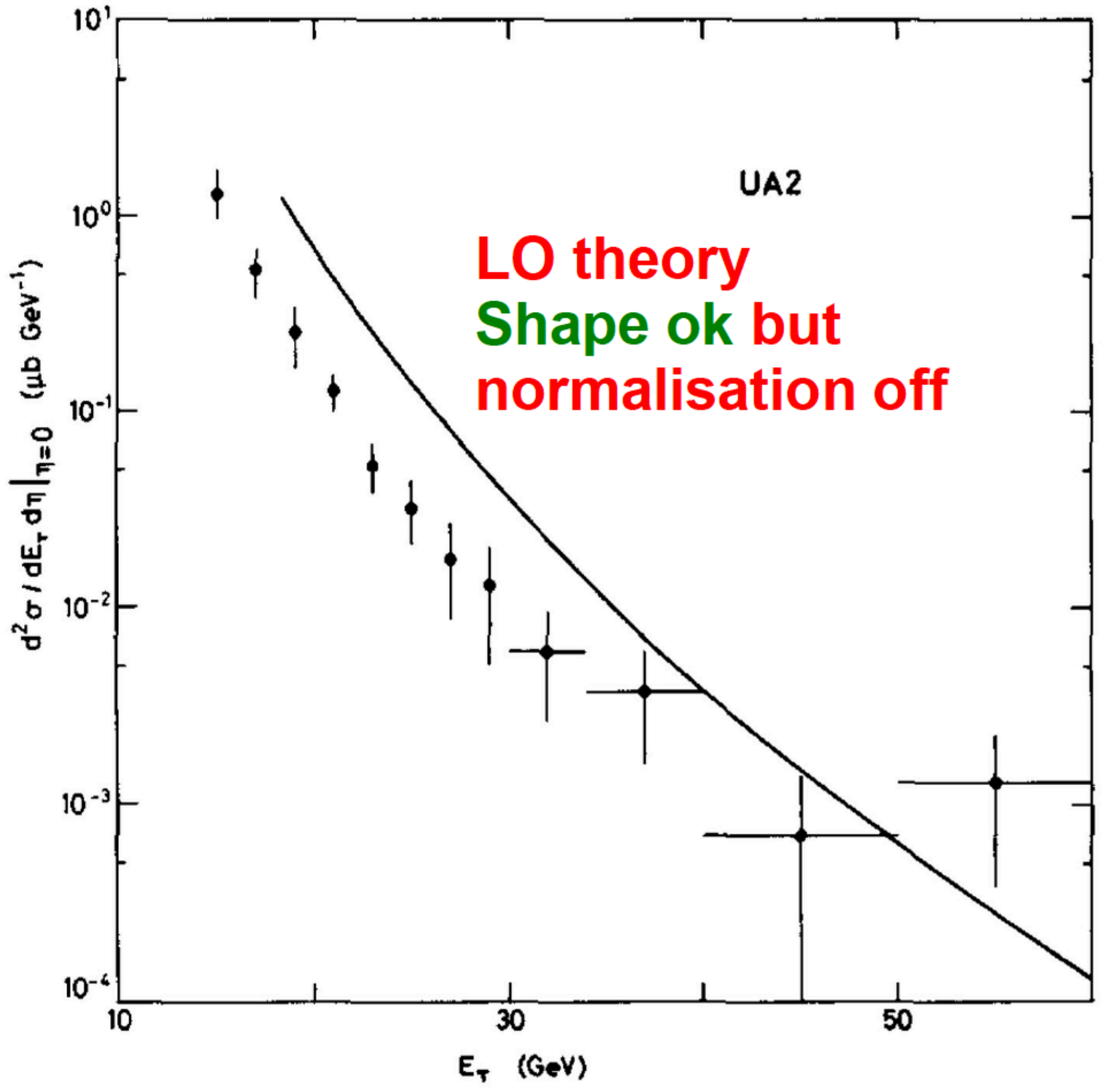
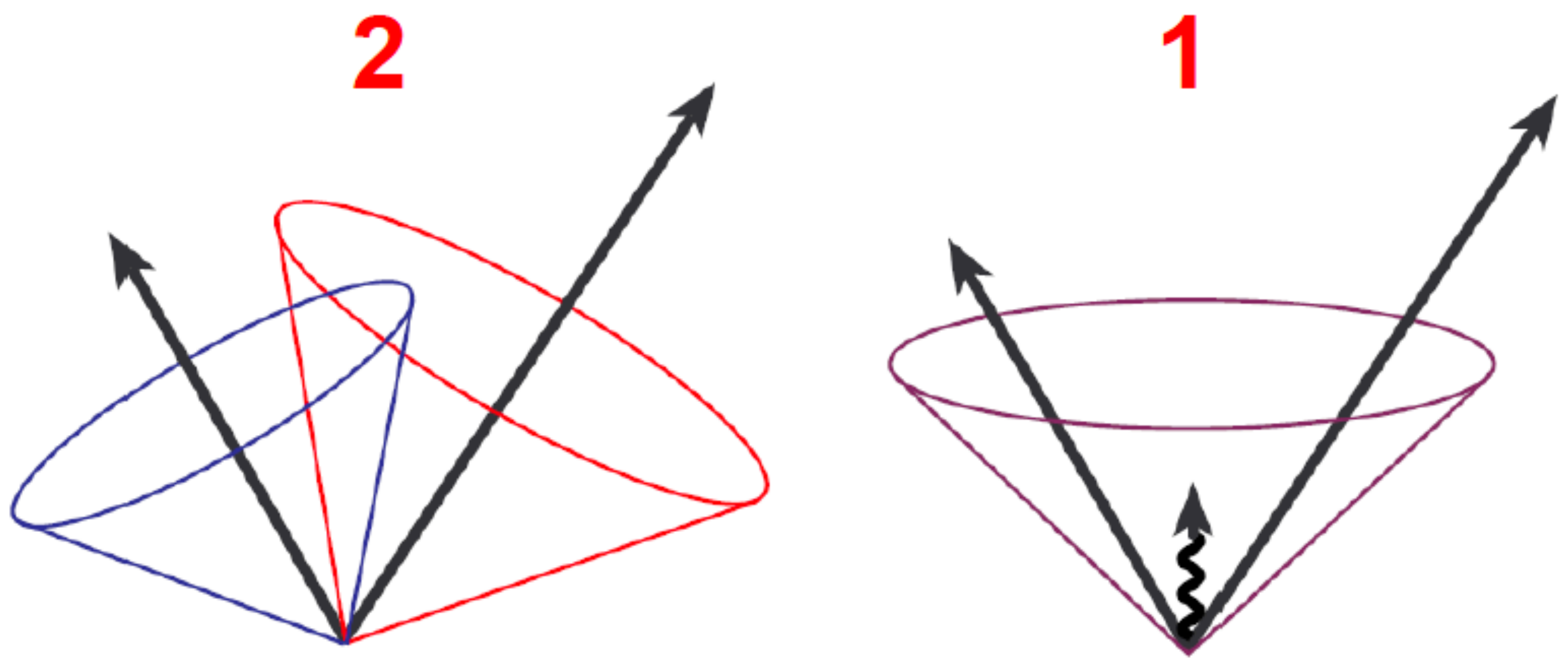


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

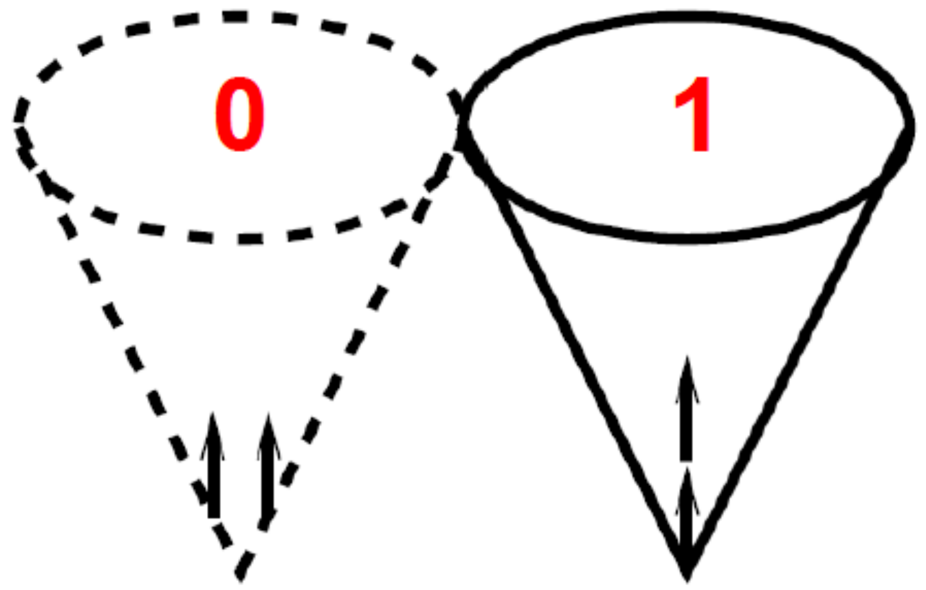
UA2, PLB 118 (1982).

Jets at Hadron Collider

- Primary goal is to find correspondence between
  - Detector measurements
  - Particles in final state
  - Hard partons
- Classes of algorithms
  - Cone algorithms
  - Sequential recombination
- Requirements
  - Infrared and collinear safe
  - Order independence
  - Ease of implementation



IR unsafe: Sensitive to the addition of soft particles



Coll. unsafe: Sensitive to the splitting of a 4-vector (seeds!)

Jets at Hadron Collider

- Primary goal is to find correspondence between
  - Detector measurements
  - Particles in final state
  - Hard partons
- Classes of algorithms
  - Cone algorithms
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- Requirements
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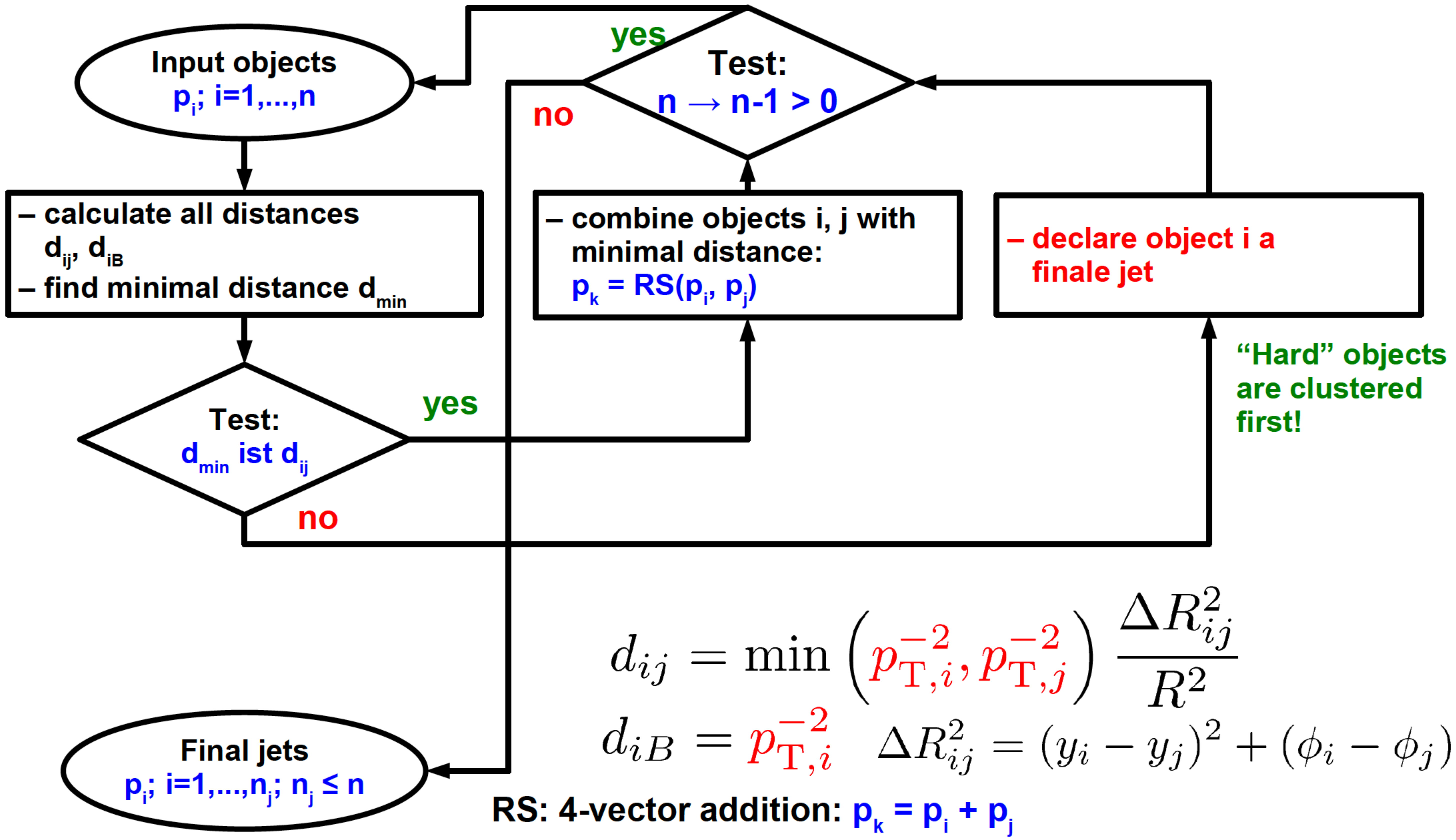
Anti-kT algorithm



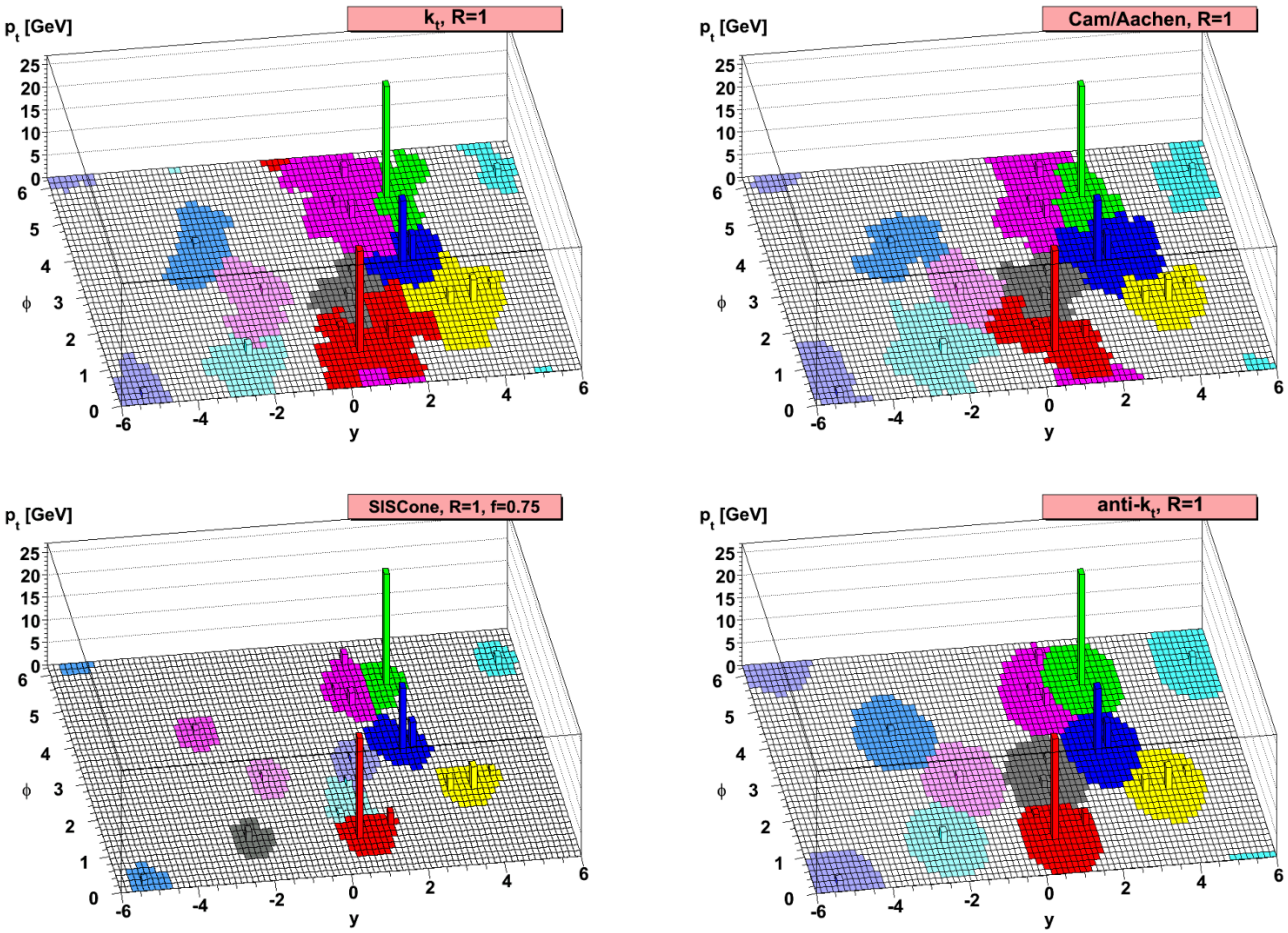
$$d_{ij} = \min\left(p_{\mathrm{T},i}^{-2}, p_{\mathrm{T},j}^{-2}\right) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{\mathrm{T},i}^{-2} \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

RS: 4-vector addition: $p_k = p_i + p_j$

Cacciari, Salam, Soyez, JHEP04 (2008).

Jets at Hadron Collider



$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p} ,$$

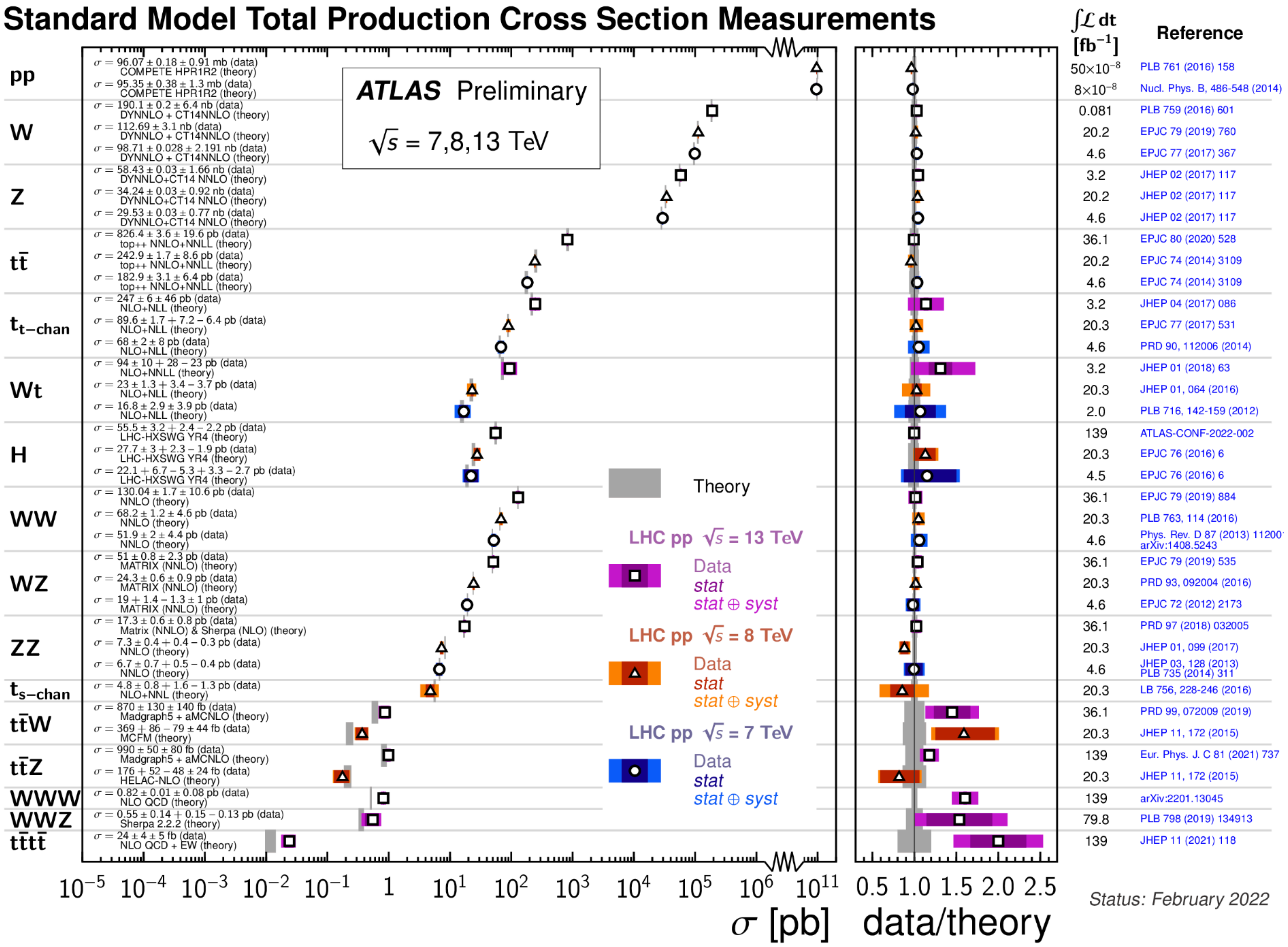
p=-1 anti-kT algorithm
p=0 Cambridge/Aachen
p=1 kt algorithm

Cross Section Measurements

$$\sigma = \frac{N_{sel} - N_{bkg}}{\int \mathcal{L}\, dt \cdot A \cdot \varepsilon}$$

- Luminosity
- Selection efficiency (objects, kinematics, binning)
- Acceptance (extrapolation from fiducial volume)
- Background estimation

Cross Section Measurements



Work Plans

- Lecture 1: Introduction, fundamentals, cross sections
- Lecture 2: Standard model measurements
- Lecture 3: Higgs physics
- Lecture 4: Searches for new physics

Quiz

- Why don’t we collide electrons and positrons or protons and anti-protons at the LHC?
- What is the minimal energy of a proton hitting a proton target at rest to produce an anti-proton?
- How many proton-proton collisions does the LHC produce per second?
- How can we estimated the expected number of pile-up events?
- How many Higgs Bosons have been produced in Run 2?
- If the hunt for the Higgs Boson can be compared to the search of a needle in the haystack, how big is the haystack?

References and further reading

- Textbooks
  - Modern Particle Physics by Mark Thomson
  - QCD at Colliders by Ellis, Stirling, and Weber
- Pictures
  - CERN Document Server
  - Wikipedia
  - Or reference on page
- References
  - Previous CERN Summer Lectures - https://indico.cern.ch/category/97/
  - MIT’s OCW 8.701 and 8.811
  - KIT’s Particle Physics master courses (you can contact me)
  - Or reference on page