Probing Hadron Structure at the Electron-Ion Collider, ICTS

Hadron Structure in Experiments

Sanghwa Park
(Jefferson Lab)

Outline of the lectures

In three lectures, my plan is to discuss the followings:

- Part 1:
  Basics of hard scattering experiments

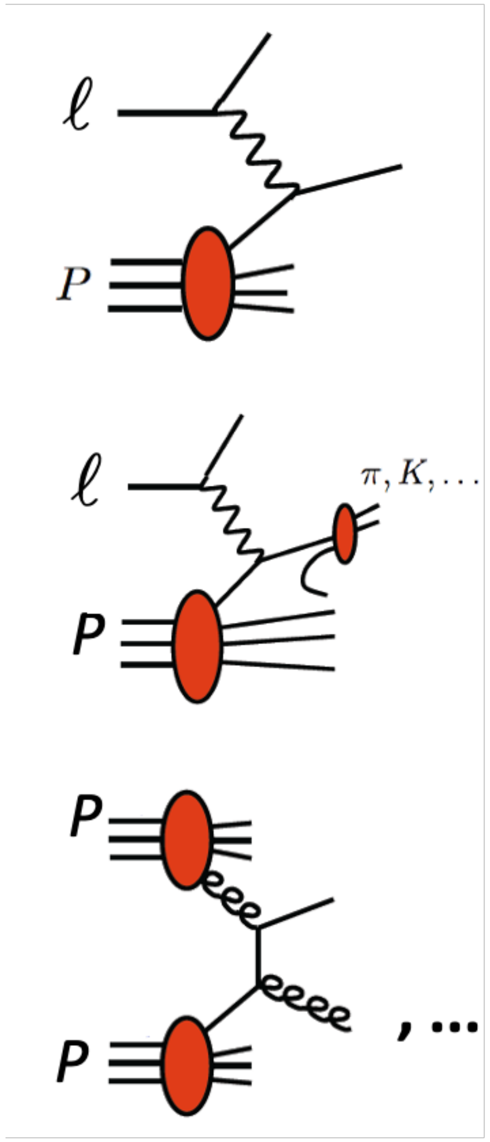
- Part 2:
  Collinear observables and measurements

- Part 3:
  Beyond collinear, Future facilities and experiments

Hadron Structure

- Experiments to study color (strong) interaction are done with hadrons, not with the quarks and gluons
  - Need to describe the hadron in terms of its constituent partons (quarks and gluons)
  - Experimental technique that allows us to determine the partonic structure of hadrons: Deep Inelastic Scattering
  - Increasing attention to the 3D imaging of the nucleon structure

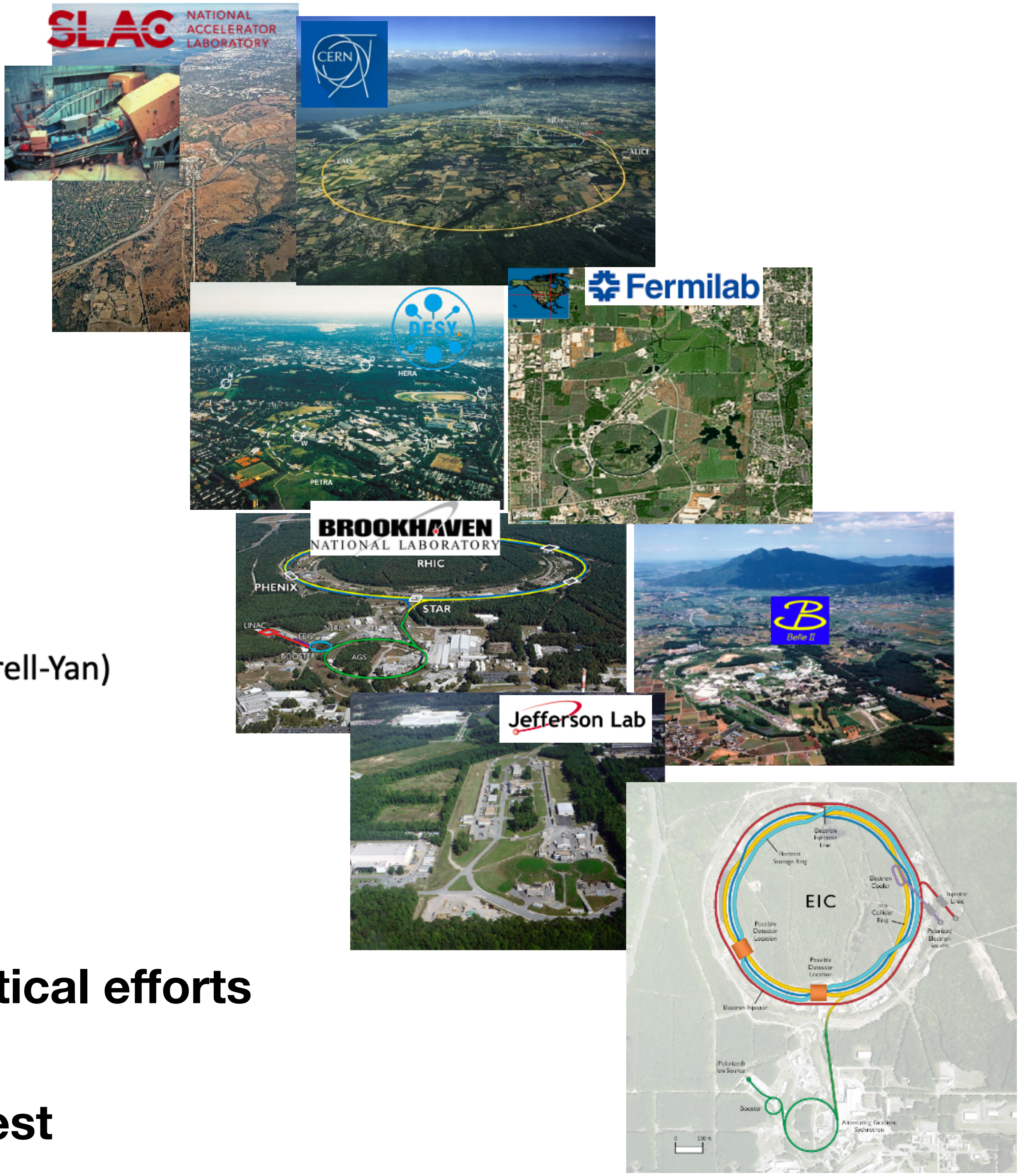
Decades of nucleon structure…



Inclusive spin-dependent DIS:
CERN, SLAC, DESY, Jlab
$\Delta q + \Delta \bar{q}$, Δg

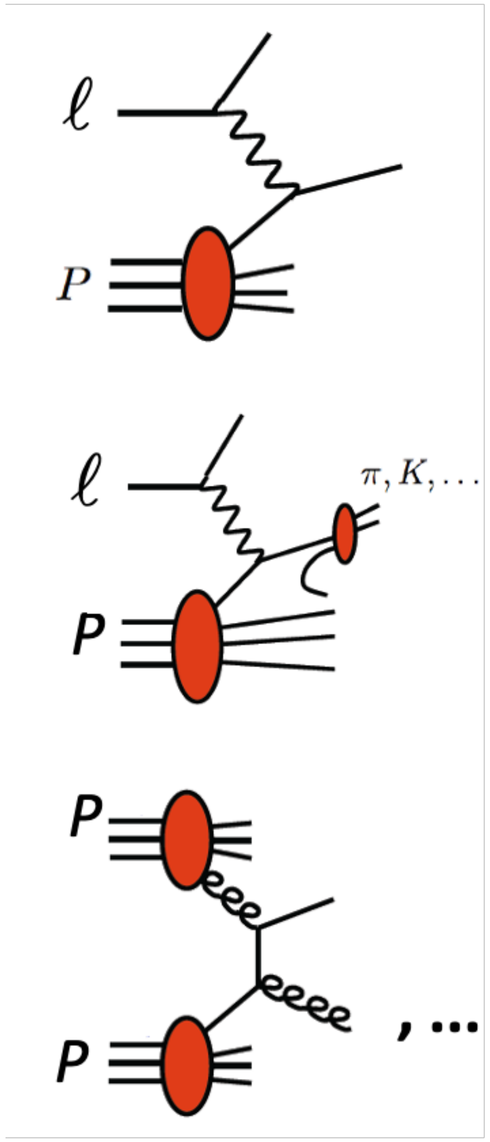
Semi-inclusive DIS:
SMC, COMPASS, HERMES, Jlab
$\Delta q + \Delta \bar{q}$, Δg

Polarized pp:
RHIC: PHENIX & STAR, FNAL (pol Drell-Yan)
$\Delta q + \Delta \bar{q}$, Δg (RHIC)



- **Decades of experimental and theoretical efforts**
- **Complementary datasets**
- **QCD factorization and Universality test**

Decades of nucleon structure…



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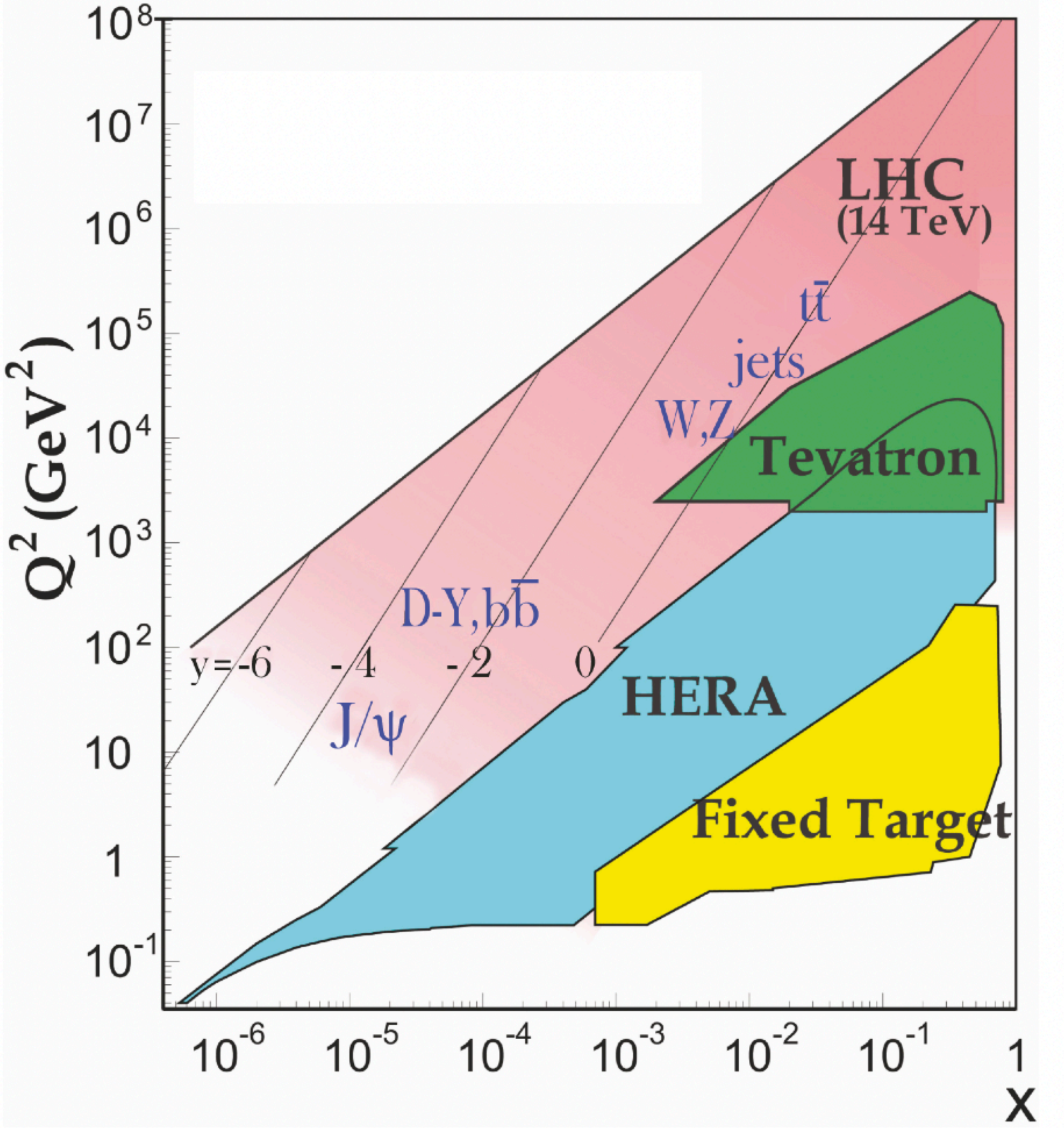
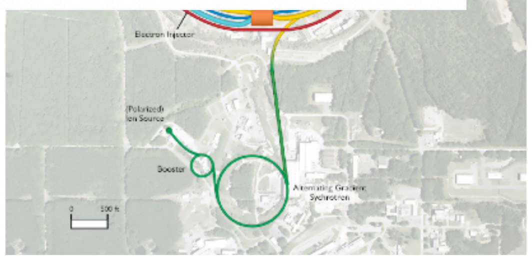
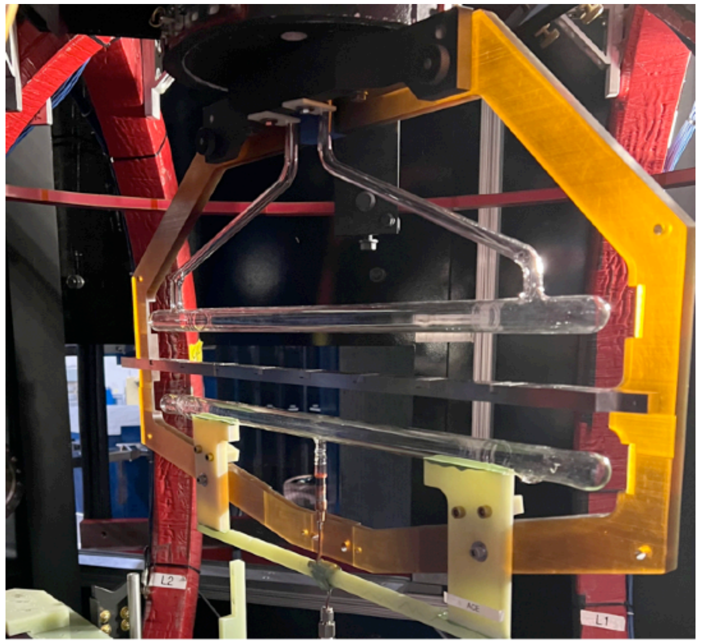


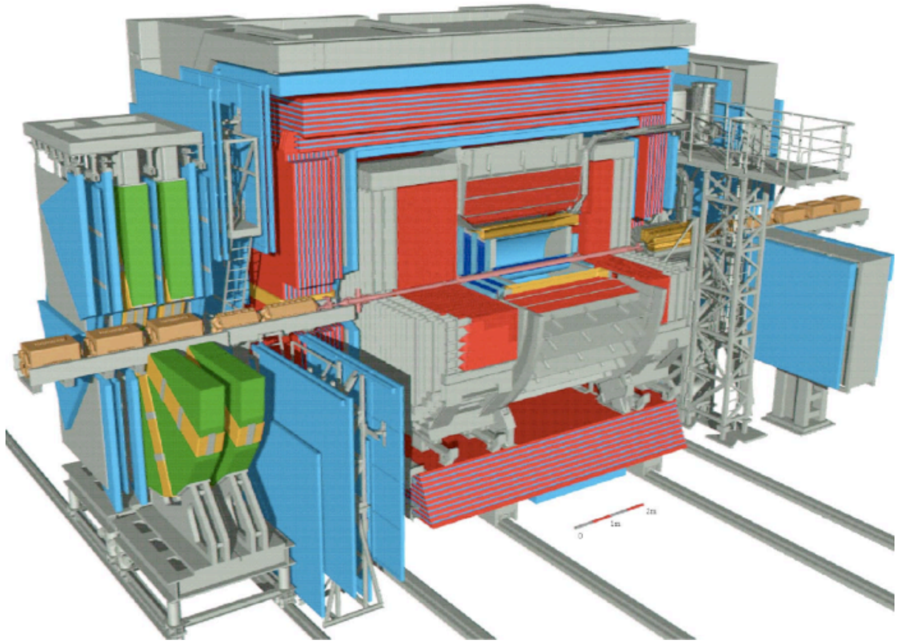


- Decades of experimental and theoretical efforts
- Complementary datasets
- QCD factorization and Universality test

Basic Components of Hadron Structure Experiments

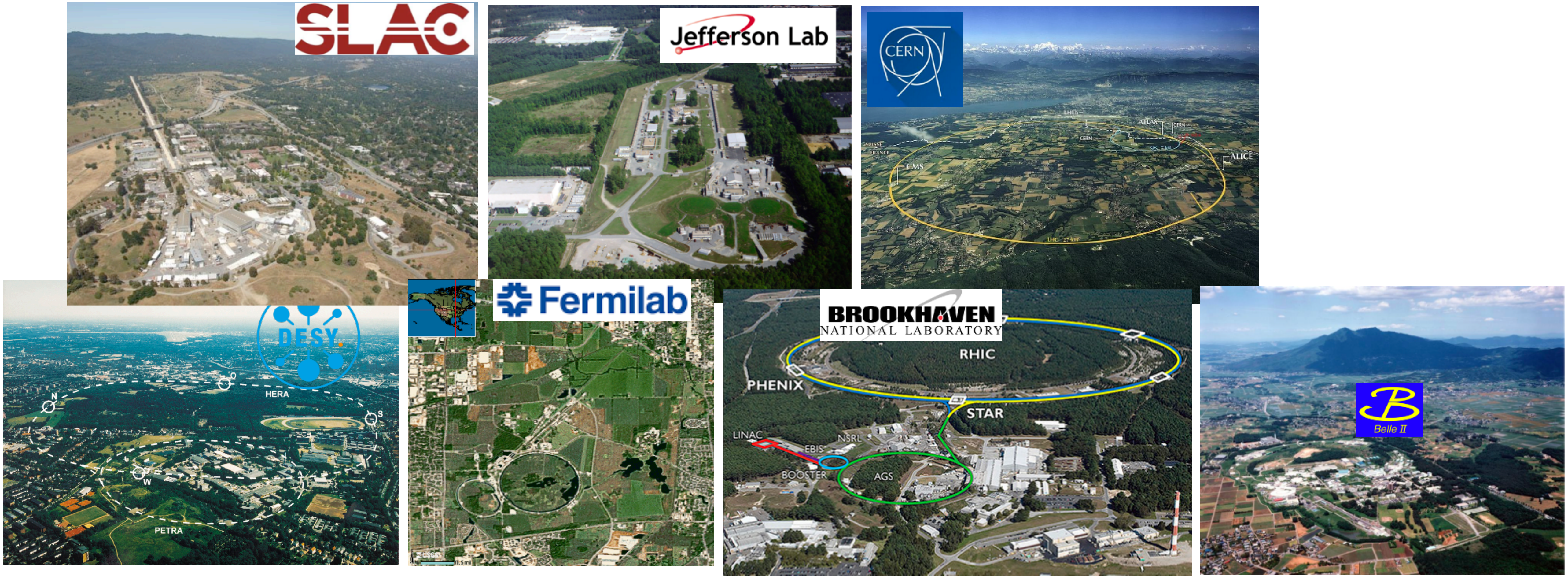
- Beam: probe, lepton or hadron beam
- Target: can be another beam or fixed target
- Detector: detect/analyze what's produced from the collisions





Accelerators

- There are different types of accelerators. The list of the particle accelerators goes long.
- Facilities that are relevant to our topic:

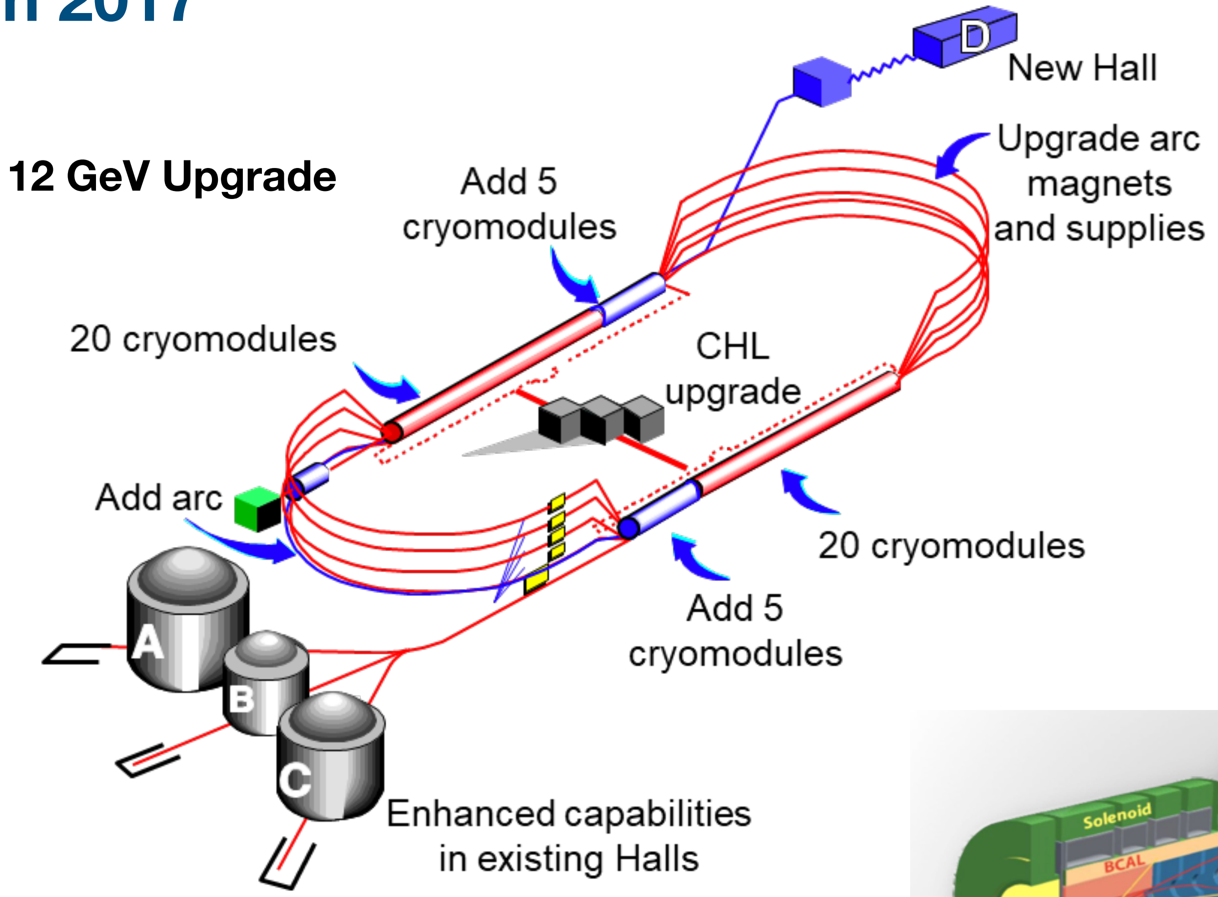


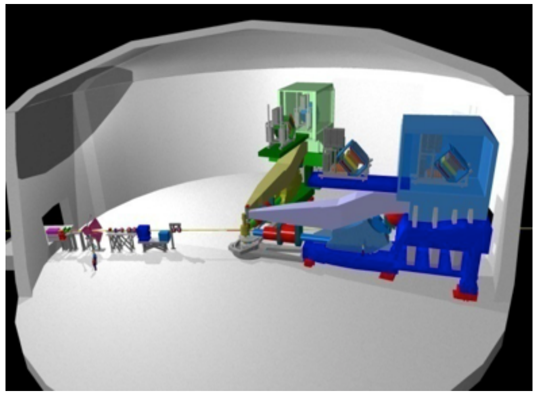
SLAC

- 3km long linear accelerator, e+e- collider
- Major physics outcome:
  1967, evidence of quark structure inside the proton (Novel prize, 1990)
  1974, discovery of charm quark (1976, shared with BNL's independent discovery)
  Discovery of tau lepton (1995)

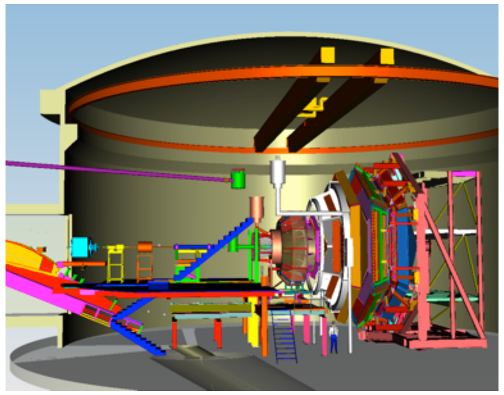
CEBAF at Jefferson Lab

Successfully completed 12 GeV upgrade in 2017

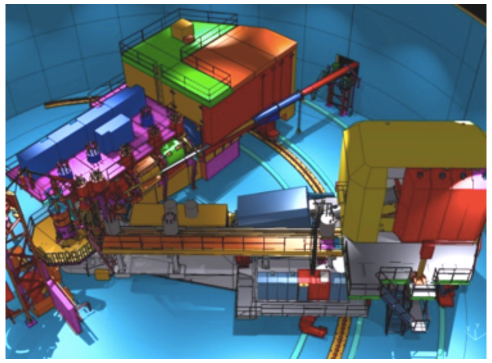




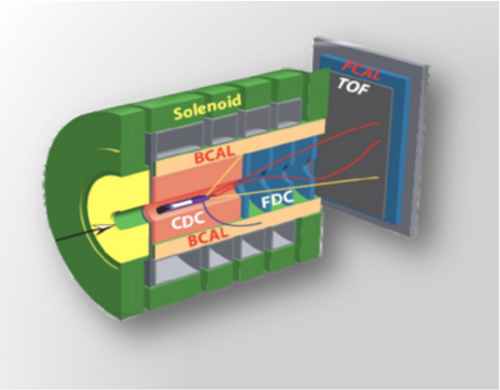
Hall A: SRC, form factors, future new experiments (MOLLER, SoLID)



Hall B: understanding nucleon structure (GPDs and TMDs) CLAS12



Hall C: precision determination of valence quark properties of nucleons and nuclei

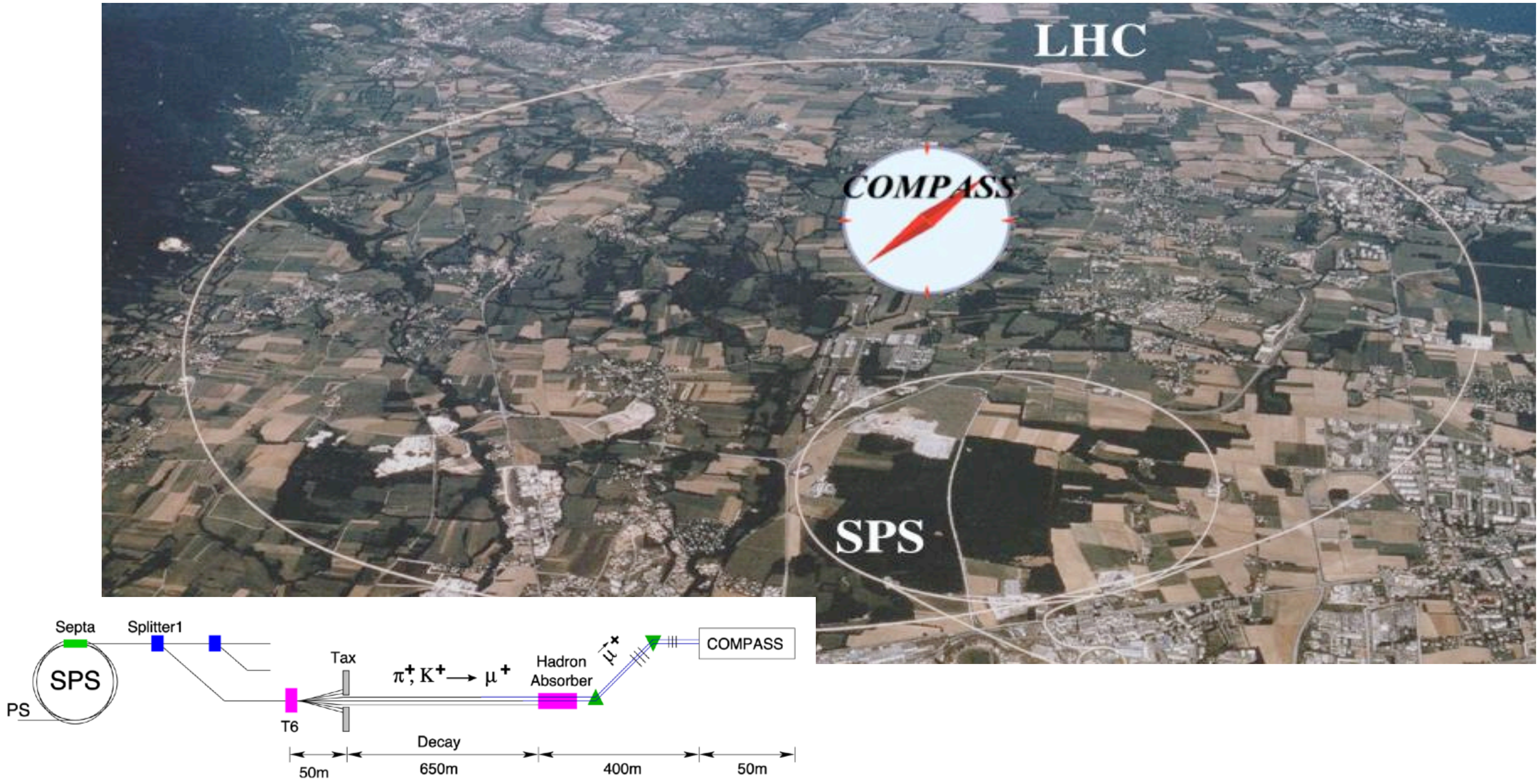


Hall D: exploring origin of confinement by studying exotic mesons

HERA @ DESY

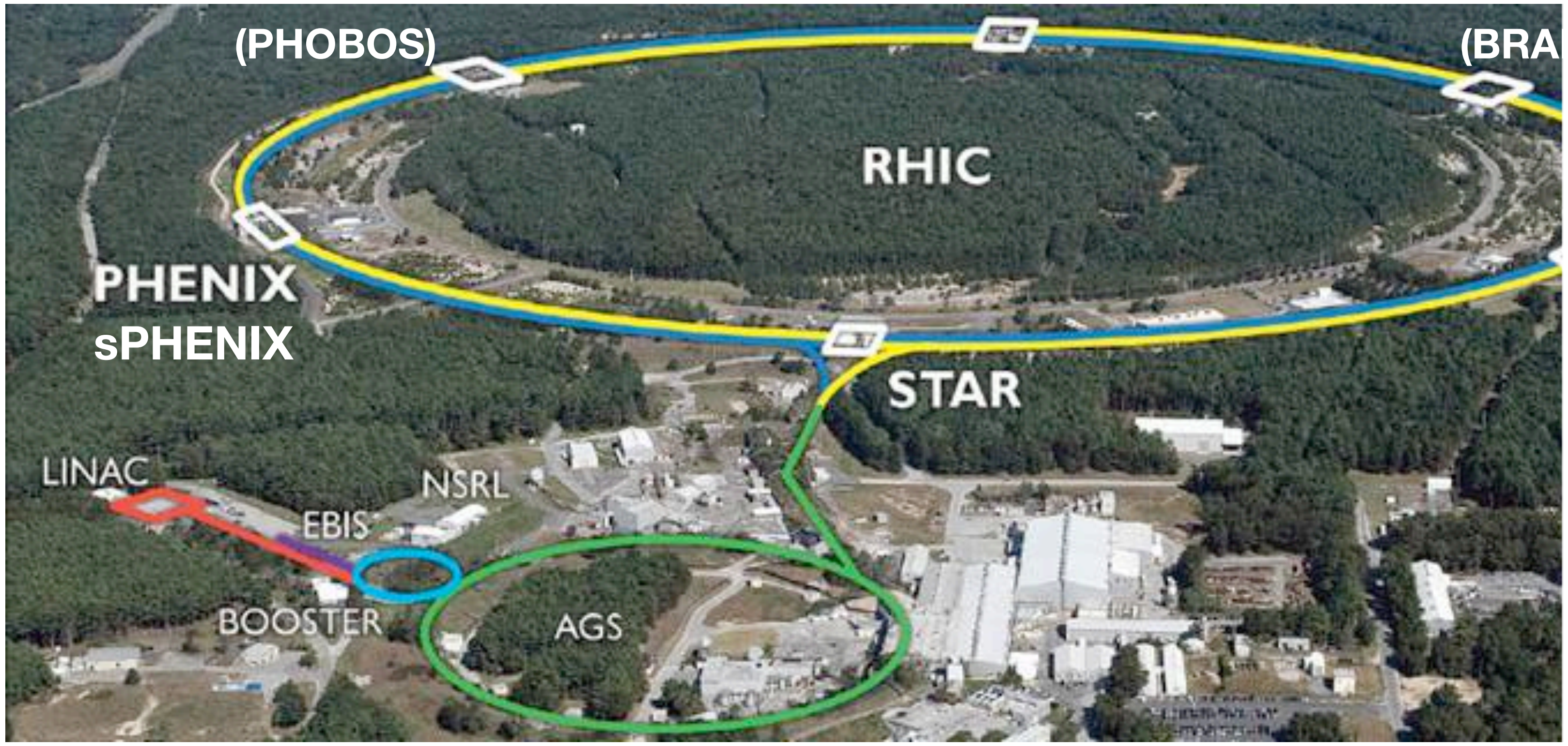
- Operated 1992-2007
- Two collider experiments: H1, ZEUS
- Two fixed target experiments: HERMES ($e^{\pm}$ beam), HERA-B (p)
- Two 6.3km circumference rings
  - Proton energy 460-920 GeV
  - Electron/positron energy 27.5 GeV
- Lepton beam polarization: ~60%
  - Solokov-Ternov effect: slow build-up of self-polarization (~30min)

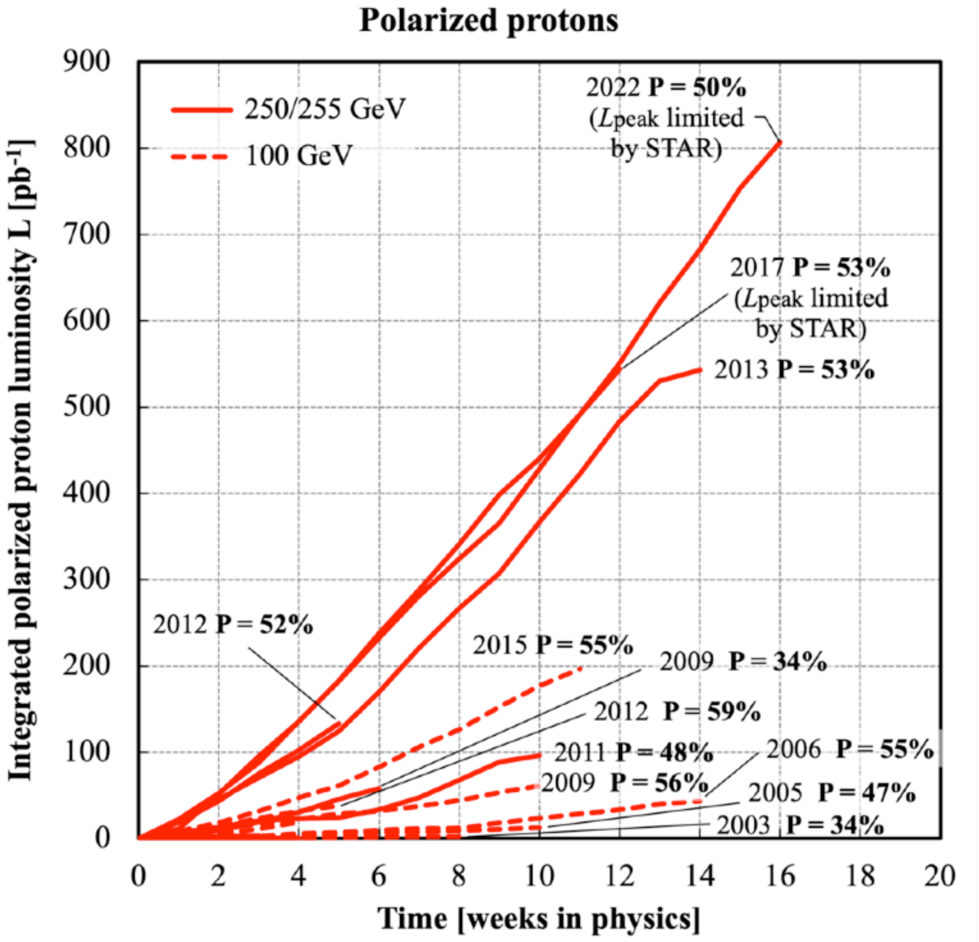
SPS @ CERN



- M2 beamline from SPS (Super Proton Synchrotron):
  - primary proton beam (400 GeV) on Be target produces secondary hadrons
- COMPASS experiment
  - Polarized gas targets
  - Spin structure of the nucleon

RHIC @ BNL

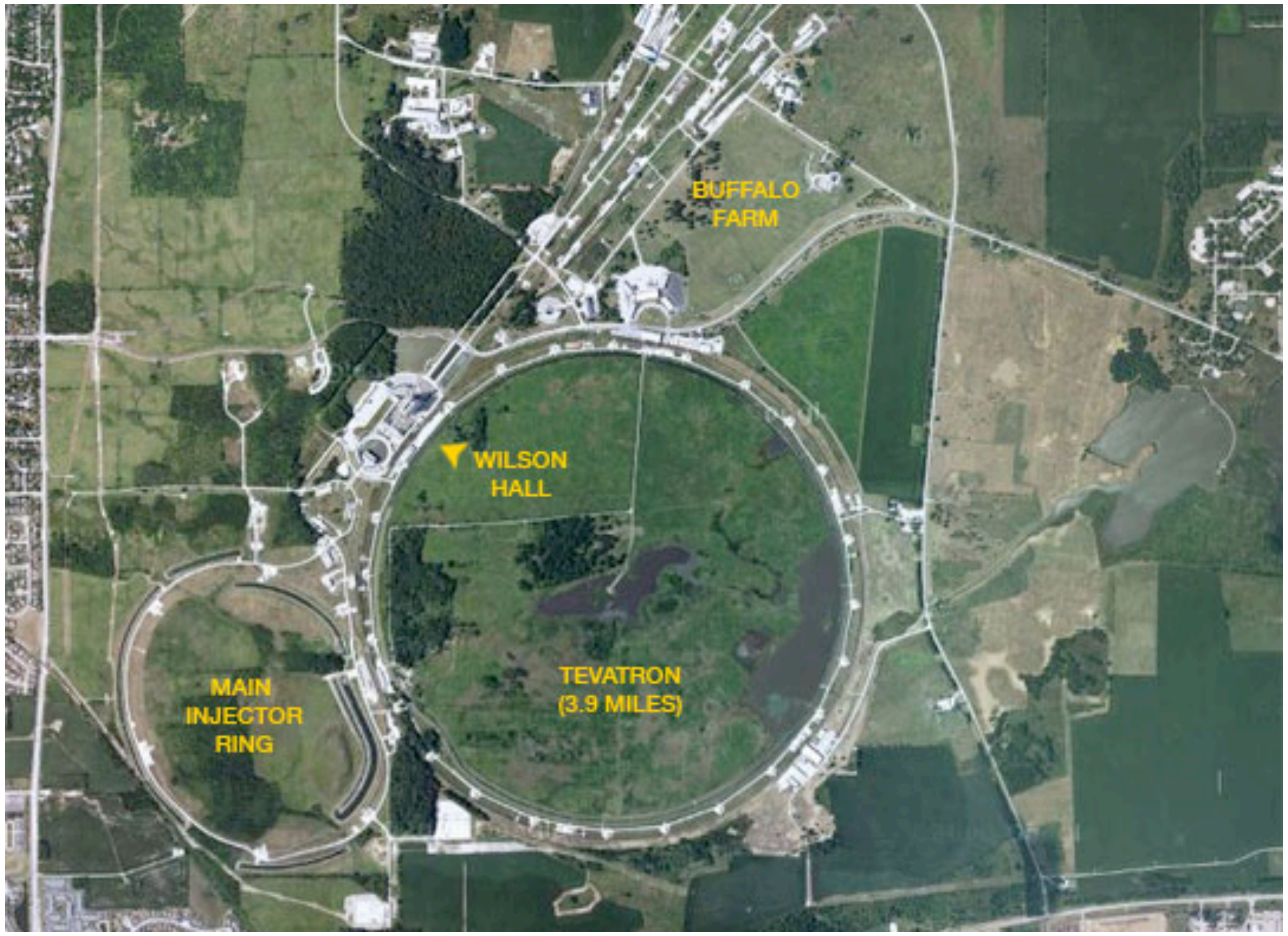




- (Transversely/Longitudinally) Polarized p+A collisions

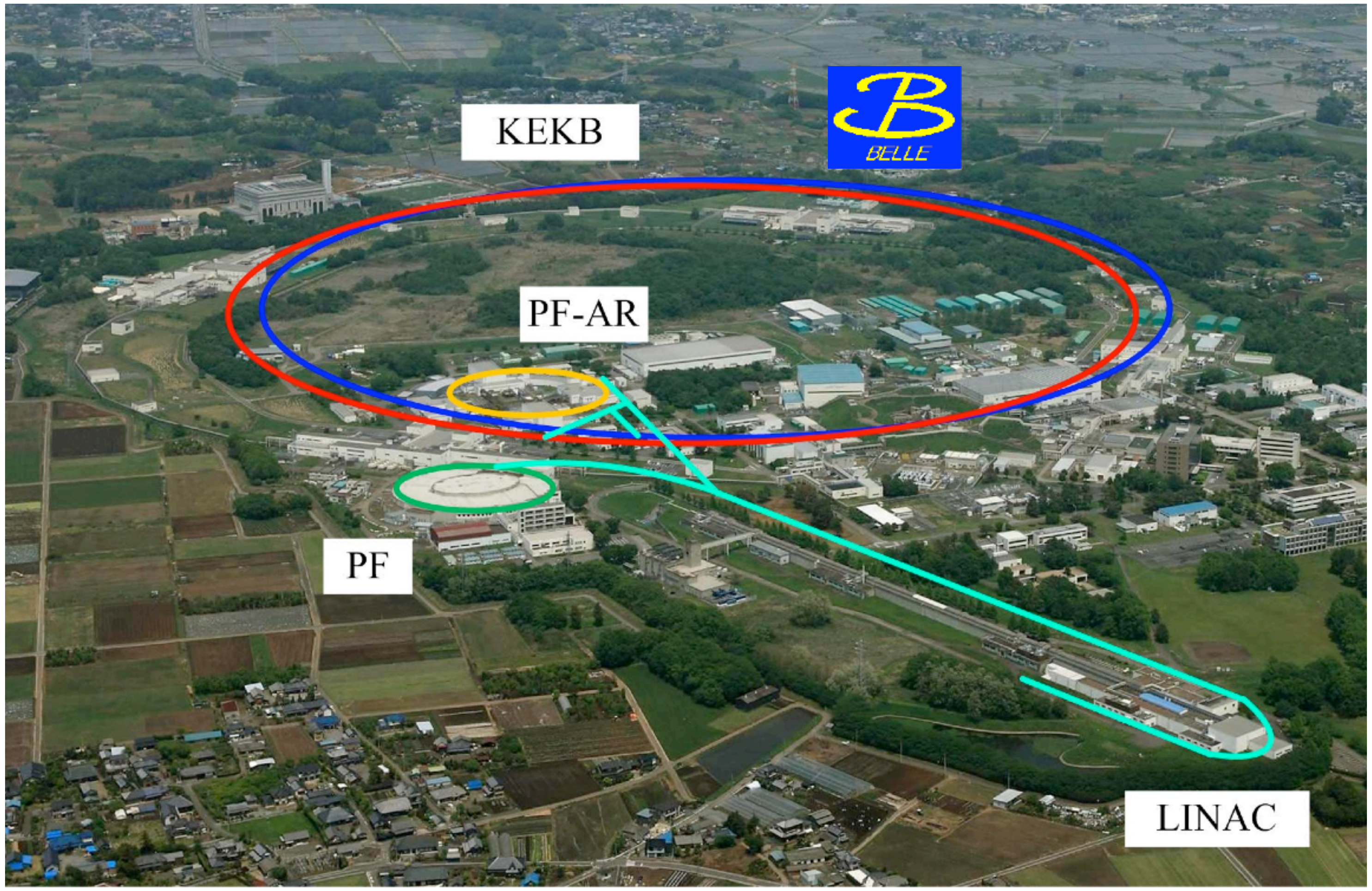
- Proton beam polarization ~55%
- Two main experiments: PHENIX, STAR
- RHIC Cold QCD program: helicity PDFs, transverse spin physics

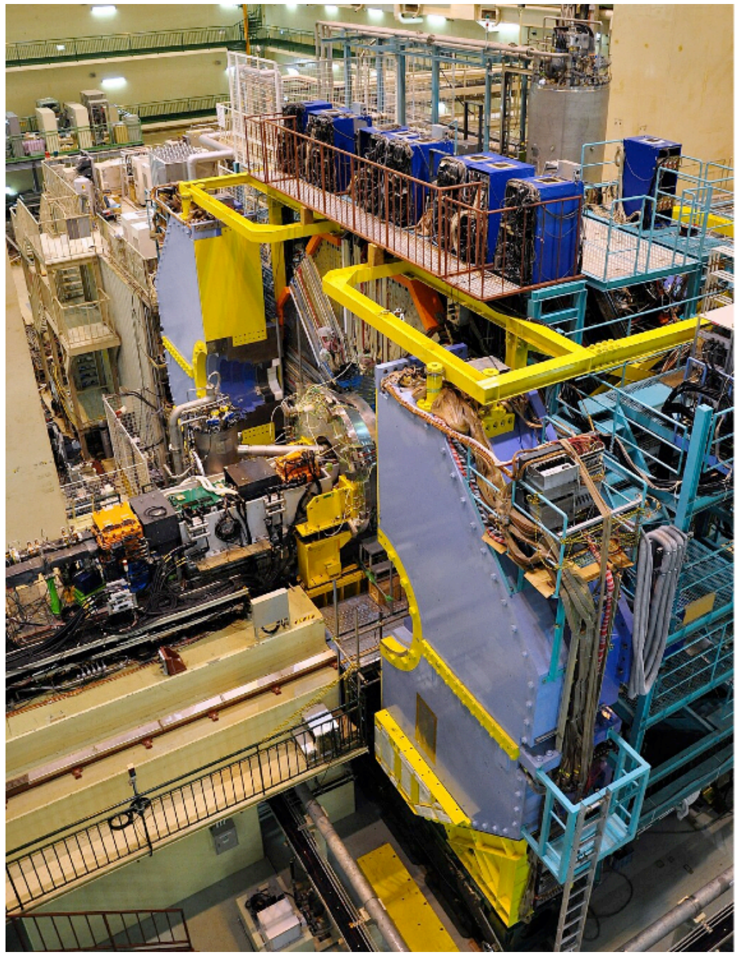
FNAL accelerator



- Tevatron: 6.28 km Proton and antiproton rings, with beam energy up to 1 TeV (highest energy until 2009)
- Discovery of top quarks (CDF, D0)
- Also produces beams for fixed target and neutrino experiments
- E866 and SeaQuest: lepton pair production to study light sea quarks
- Spin Quest: polarized sea TMDs

KEKB e^+e^- collider and Belle experiment



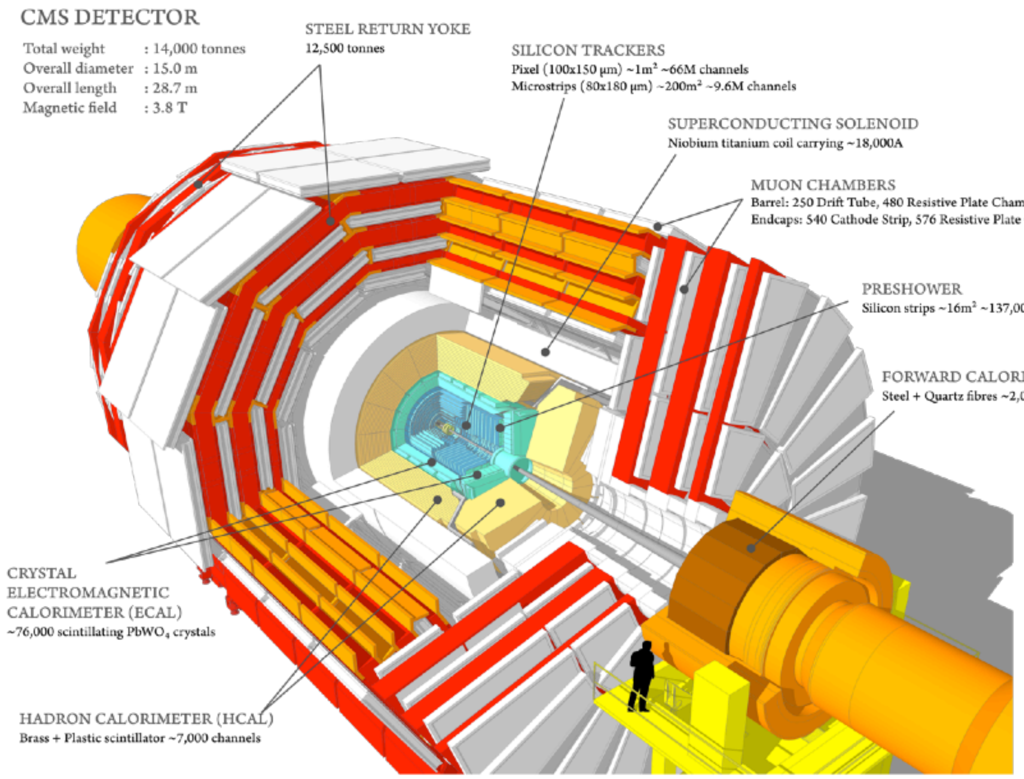


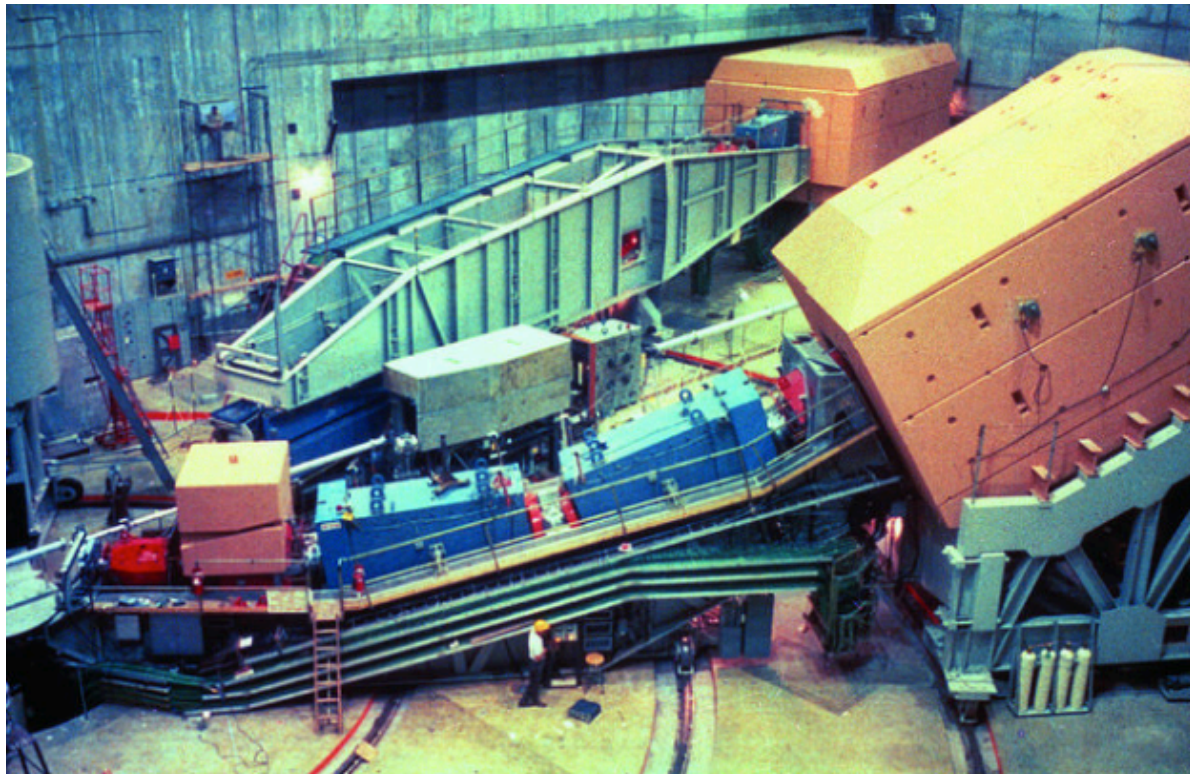
- electron and positron beams with circumference 3.016 km
- Asymmetric energies in e^- (8 GeV) and e^+ (3.5 GeV) rings
- KEK B-factory:
    - b quark hadrons to study CP violation
    - fragmentation functions

The Physics of B Factories (Belle and BaBar)
European Physical Journal C, 74:3026

Type of experiments:
Collider vs Fixed-Target

- Main differences: collision energy and luminosity
- Need to consider the detector configuration differently as well





- Two beams
- Higher energy
- Experimental apparatus surrounding the interaction point

- Single beam with fixed-target
- High rate, good for precision measurements
- Experimental apparatus covering boosted region (asymmetric collisions)

Center-of-mass energy

- Total four-momentum square of the system: invariant in any frame of reference

  In the lab frame:

  $$s = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 c^2$$
  $$= m_1^2 + m_2^2 + 2(E_1 E_2 - \overrightarrow{p_1} \cdot \overrightarrow{p_2})$$

  In the center-of-mass frame: $\sum_i \vec{p}_i^{\,*} = 0$,

  $$s = E^{*2} = m_1^2 + m_2^2 + 2(E_1 E_2 - \overrightarrow{p_1} \cdot \overrightarrow{p_2})$$

$$\sqrt{s} \approx \sqrt{2E_1E_2}$$

- ▸ Collider (head-on symmetric collisions):

  $m_1 = m_2, \overrightarrow{p_1} = -\overrightarrow{p_2}$

  $\sqrt{s} \approx 2E_1 \approx 2E_2$

- ▸ Fixed target:

  For target particle: $(E_2, \overrightarrow{p_2}) = (m_2, 0)$

  $\sqrt{s} \approx \sqrt{2E_1 m_2}$

Center-of-mass energy

- Total four-momentum square of the system: invariant in any frame of reference

  In the lab frame:

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  In the center-of-mass frame: $\sum_i \vec{p}_i^* = 0,$

  $$s = E^{*2} = m_1^2 + m_2^2 + 2(E_1 E_2 - \overrightarrow{p_1} \cdot \overrightarrow{p_2})$$

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- Fixed target:

  For target particle: $(E_2, \overrightarrow{p_2}) = (m_2, 0)$

  $\sqrt{s} \approx \sqrt{2E_1 m_2}$

- Example 1: RHIC p+p collider

  proton beam energy of 250 GeV $\sqrt{s} = ?$

- Example 2: HERA e+p collider

  Ee = 27.5 GeV Ep = 920 GeV, $\sqrt{s}$= ?

  For the same $\sqrt{s}$ from the fixed target experiment (electron beam on proton target), what beam energy do we need?

Luminosity

- Scattering rate: $\frac{dN}{dt} = L\sigma$

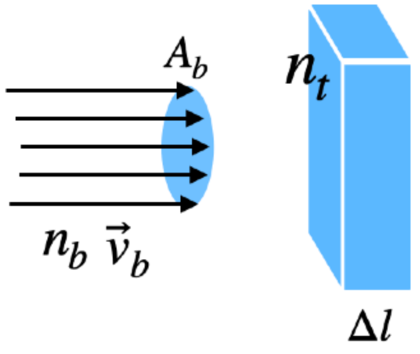
  given by physics

  given by experiment setup

- Basically, more beam and target particles -> high luminosity

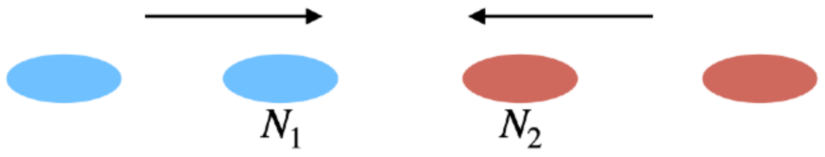
- Fixed-target:

  L = (incoming beam flux)
  x (target number density)
  x (target thickness)
  = $n_b v_b A_b n_t \Delta l$

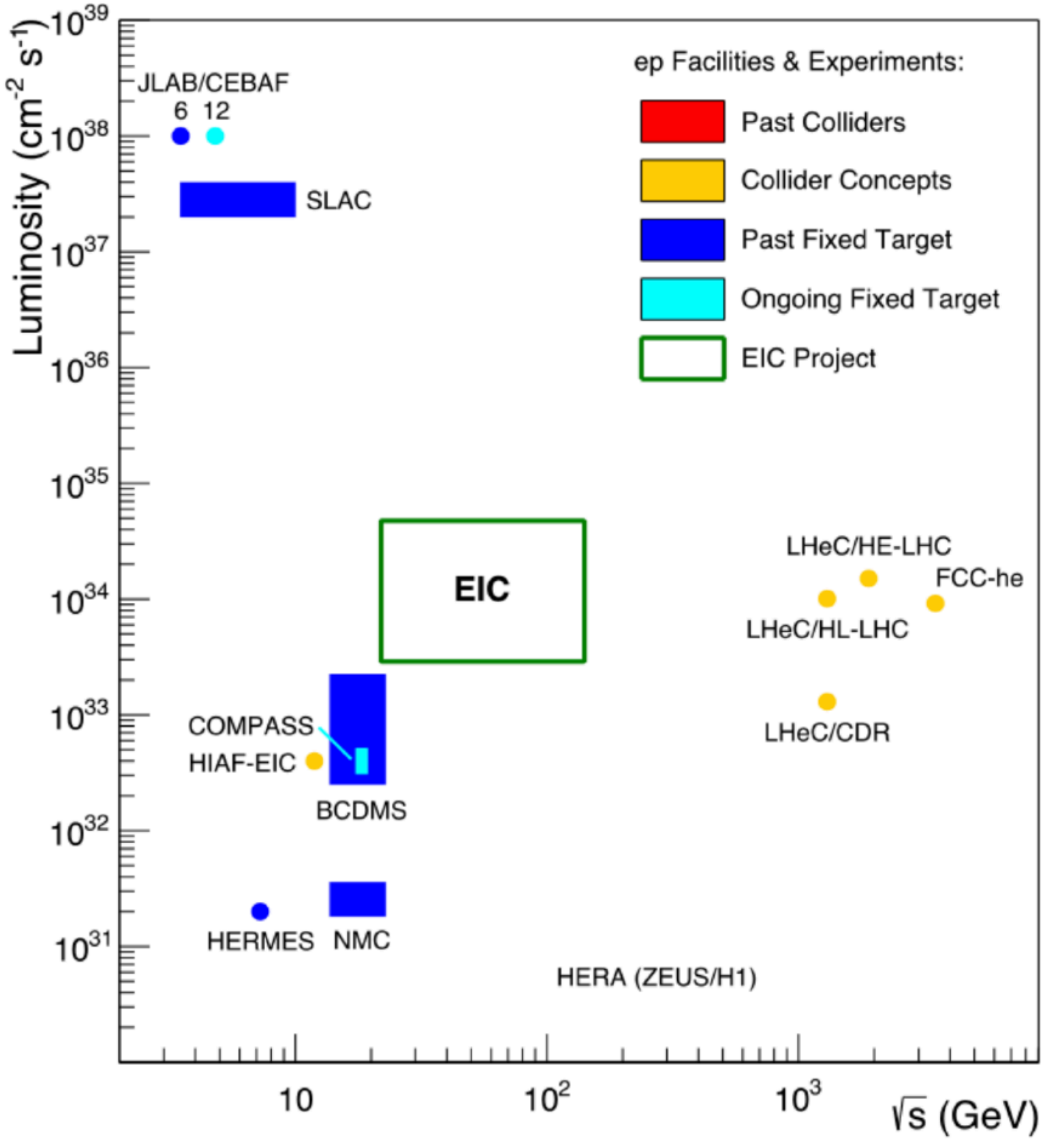


- Collider:

  L = $\frac{nN_1N_2f}{A}$



$N_{1(2)}$: number of particles per bunch
n: number of bunches
f: revolution frequency
A: beam transverse profile



Rapidity and Pseudo-rapidity

- Convenient variables to define in the collider physics is called rapidity:

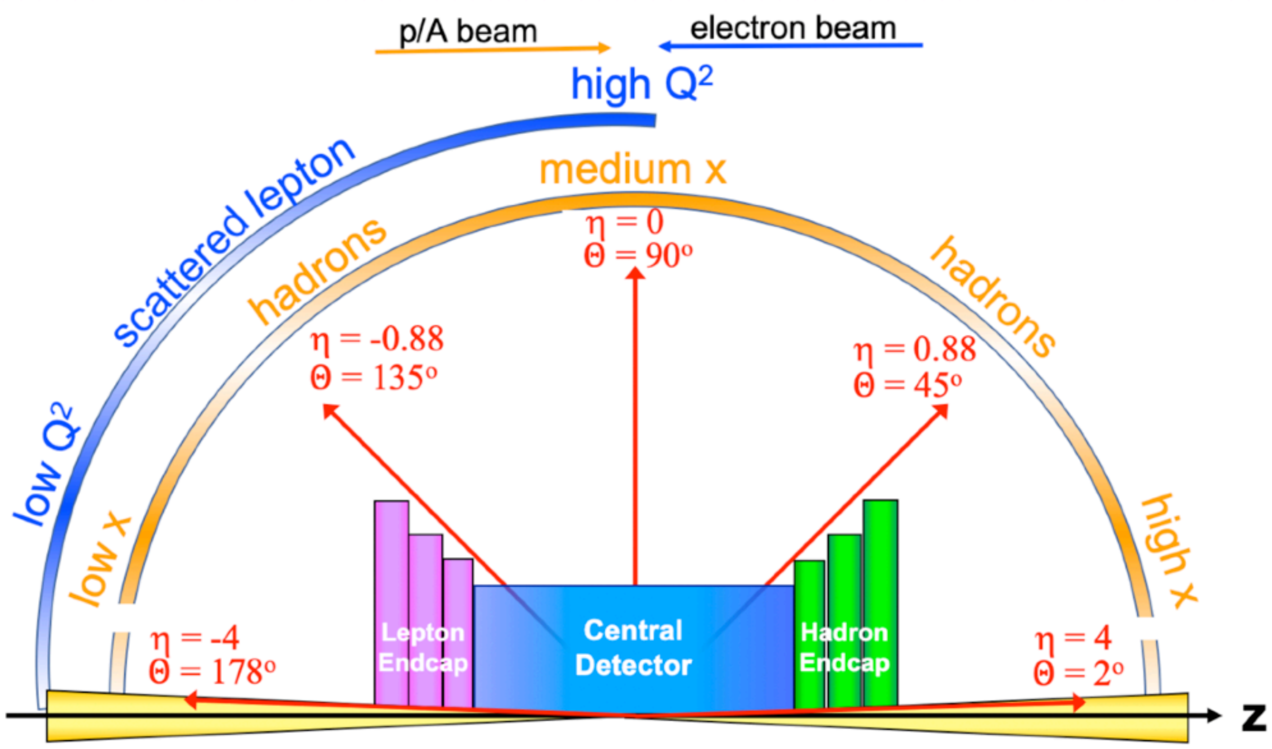
  $$y = \frac{1}{2} ln\left(\frac{E + p_z c}{E - p_z c}\right)$$

  For high energy collisions of particles traveling along the z-axis, Δy is invariant under boosts along the z-axis.

  But, more commonly we define the pseudo-rapidity:

  $$\eta = -\, ln\, tan\left(\frac{\theta}{2}\right)$$

  which is good approximate to y in high energy while easy to measure, and more directly related to the detector configuration.



Detector Considerations

- **Inclusive measurements:**

Need to detect the scattered electron or full scattered hadronic debris

- **Semi-inclusive measurements:**

Scattered electron and hadron(s) in coincidence

- **Exclusive measurements:**

All particles in the reaction

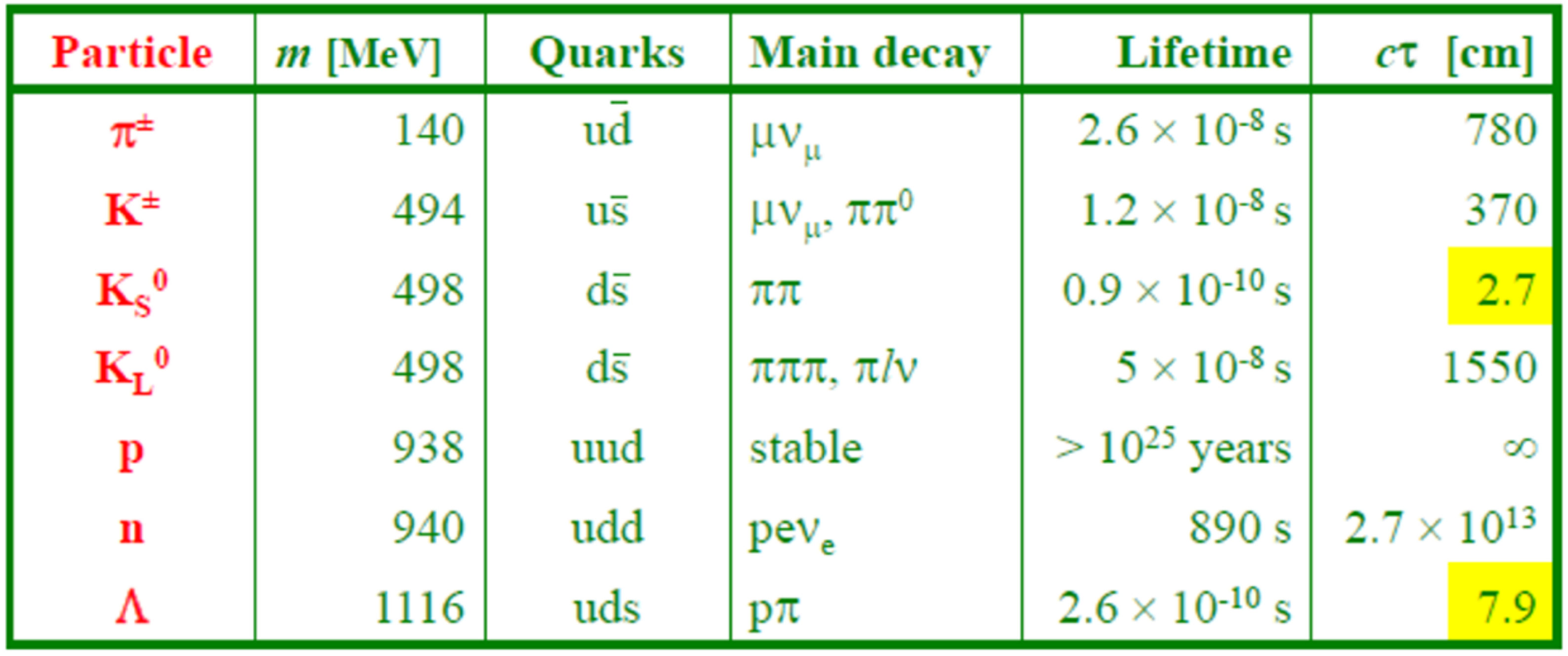
electron ID, excellent energy/momentum and angular resolution

hadron ID (pi/K/p) over a wide kinematic range, full azimuthal coverage

Large rapidity coverage, detect recoil and target remnants, neutron detection

Basis of particle detectors: Particle interaction with matter

- Information (energy, momentum, position, type) on the produced particles can be measured from their interactions with matter (material of the detectors)
- Short-lived particles: measure the decay products
- Undetected particles: missing mass/energy reconstruction



Particle	m [MeV]	Quarks	Main decay	Lifetime	$c\tau$ [cm]
$\pi^\pm$	140	$u\bar{d}$	$\mu\nu_\mu$	2.6×10^{-8} s	780
$K^\pm$	494	$u\bar{s}$	$\mu\nu_\mu$, $\pi\pi^0$	1.2×10^{-8} s	370
K_S^0	498	$d\bar{s}$	$\pi\pi$	0.9×10^{-10} s	2.7
K_L^0	498	$d\bar{s}$	$\pi\pi\pi$, $\pi l\nu$	5×10^{-8} s	1550
p	938	uud	stable	$> 10^{25}$ years	∞
n	940	udd	$pe\nu_e$	890 s	2.7×10^{13}
Λ	1116	uds	$p\pi$	2.6×10^{-10} s	7.9

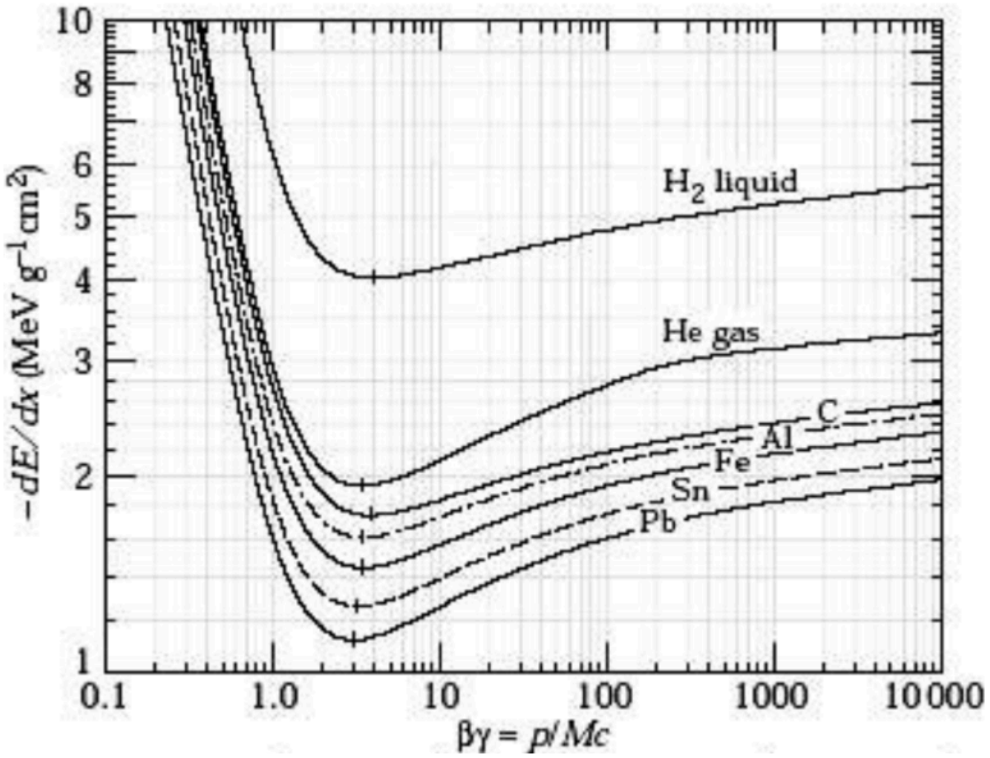
π^0 : $\tau \sim 85$ attoseconds (10^{-18}s)

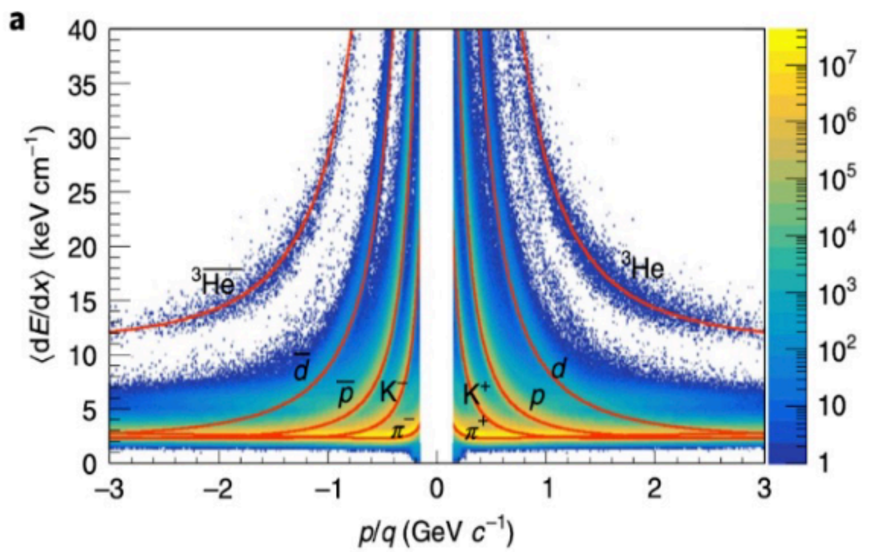
Basis of particle detectors: Particle interaction with matter

- Charged particles:
  - Ionization energy loss:
    - important for all charged particles
    - Dominant process is coulomb scattering from atomic electron
    - Bethe-Bloch formula:

$$\left\langle -\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2W_{\max}}{I^2}-\beta^2-\frac{\delta(\beta\gamma)}{2}\right]$$

- Minimum ionization value (MIP): most relativistic particles ~$2MeV \cdot g^{-1} \cdot cm^2$
- Use dE/dx for particle identification





Basis of particle detectors: Particle interaction with matter

- Charged particles:
  - Radiation energy loss:
    - E-field of nucleus -> accelerated/decelerated particles radiate photons. “Bremsstrahlung”
    - Particularly important for electrons and positrons
    - For relativistic electrons, average energy loss depends on the particle energy and radiation length

Basis of particle detectors: Particle interaction with matter

- **Energy loss of electrons and photons: basis of EM Calorimeter**

Dominant processes at high energies (E > few MeV) :

Photons : Pair production

$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right)$$

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm^2]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

X_0 = radiation length in [g/cm^2]

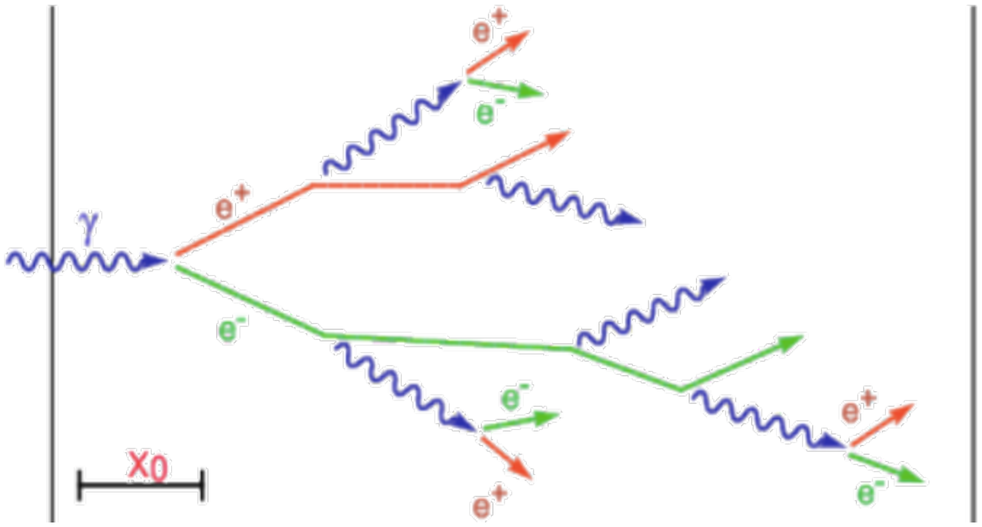
$$\boxed{X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}}$$

Electrons : Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A\,\frac{Z^2}{A}r_e^2\cdot E\,\ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow E = E_0 e^{-x/X_0}$$

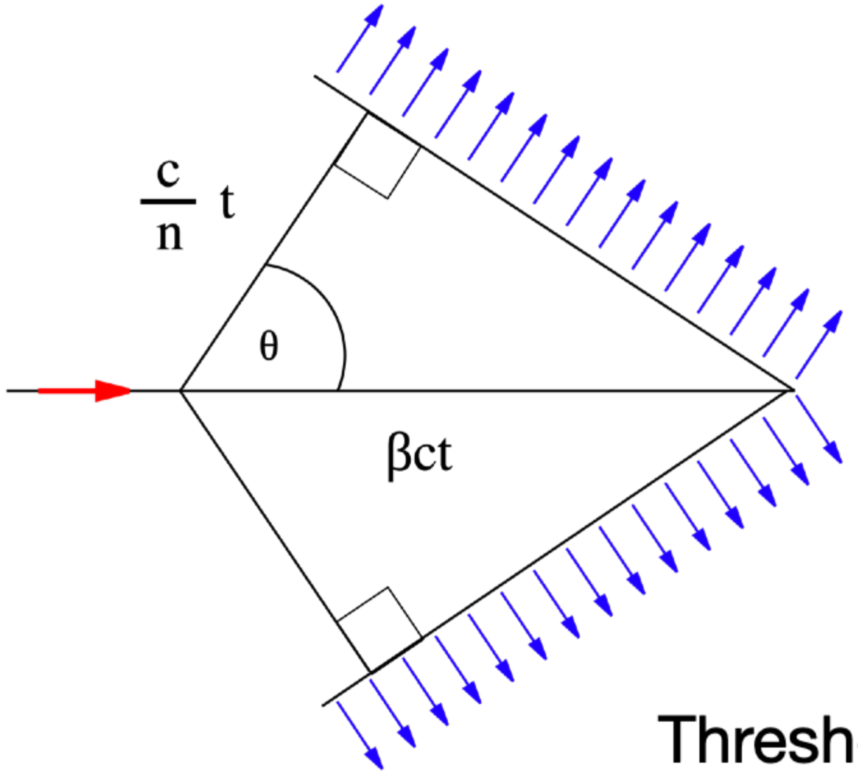
After passage of one X_0 electron has only (1/e)th of its primary energy ...
[i.e. 37%]



Particle Identification

- Velocity (β) measurement $E = m\gamma, p = m\gamma\beta$
- Important for measurements that need to indentify final state hardons
- Choose appropriate processes based on the detector arrangement and requirements
  - Cherenkov radiation
  - Time-of-Flight
  - Transition radiation
  - Ionization energy loss (dE/dx)

Cherenkov detector



Cherenkov radiation when

$v > c/n$ or $\beta > 1/n$

$$\boxed{p_{\mathrm{threshold}} = \frac{mc/n}{\sqrt{1-n^{-2}}}}$$

Cherenkov angle $$cos\theta = \frac{c}{nv} = \frac{1}{n\beta}$$

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha Z^2}{\lambda^2}(1 - \frac{1}{n^2\beta^2})$$

Threshold mode: Counting of number of photoelectrons

for ß < 1/n -> no Cherenkov photon emitted

Example) n=1.00062 (CF4)

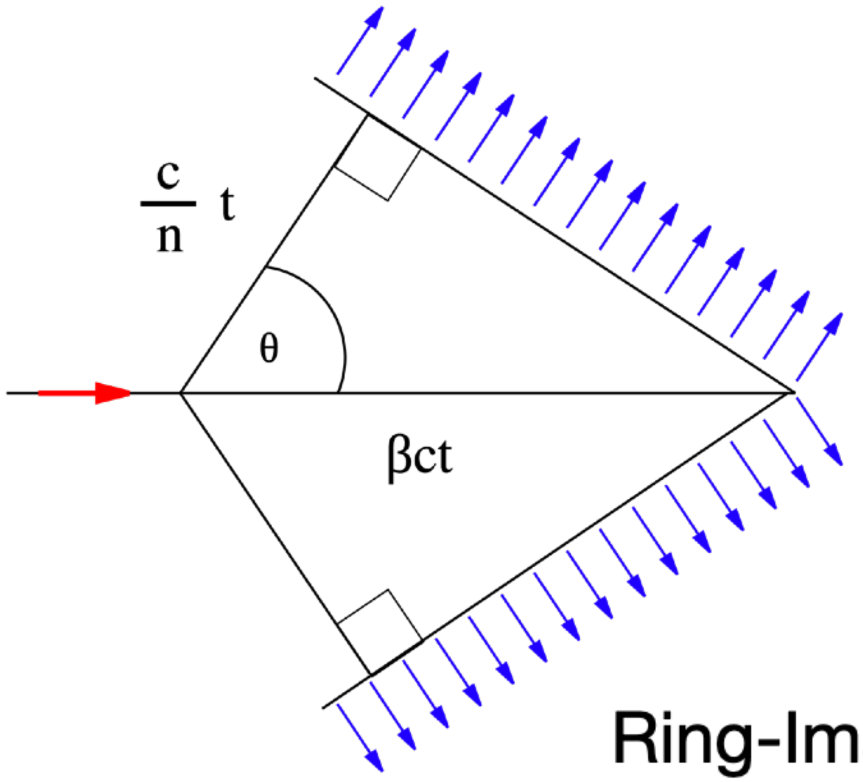
Pion threshold momentum ~4 GeV/c

Kaon threshold momentum ~14 GeV/c

Proton threshold momentum ~27GeV/c

Cherenkov detector

Medium with refractive index n



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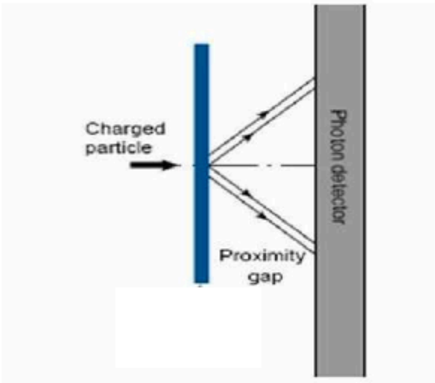
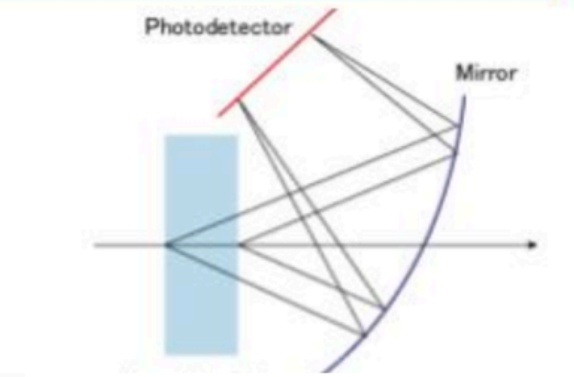
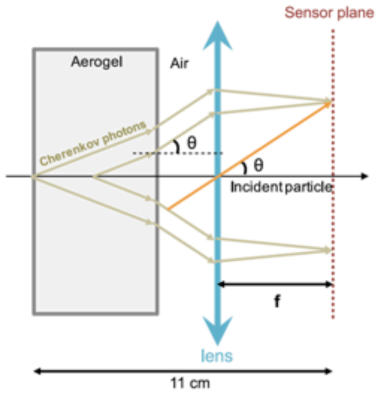
Ring-Imaging Cherenkov (RICH): momentum (tracking) and Cherenkov angle -> reconstruct particle mass



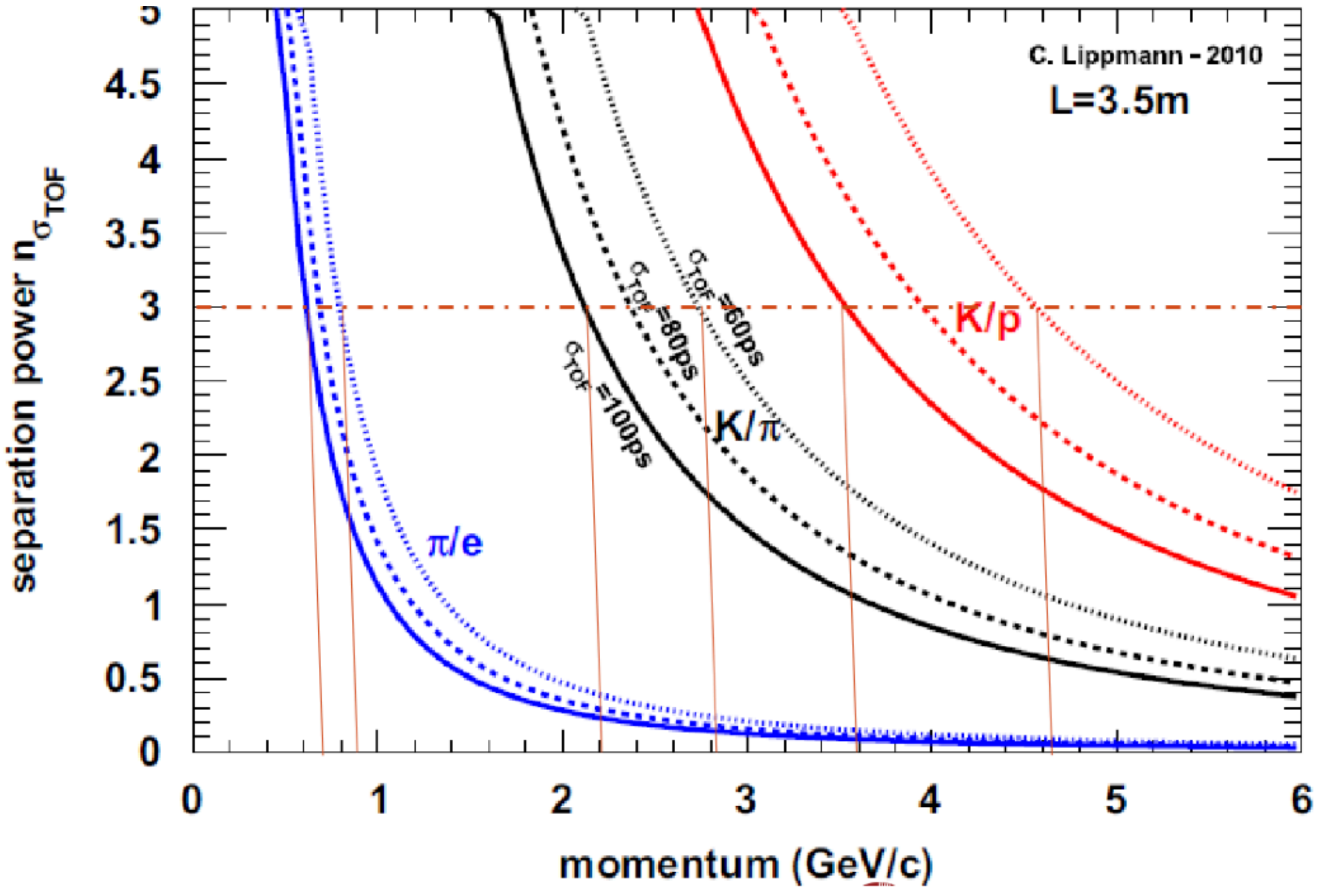


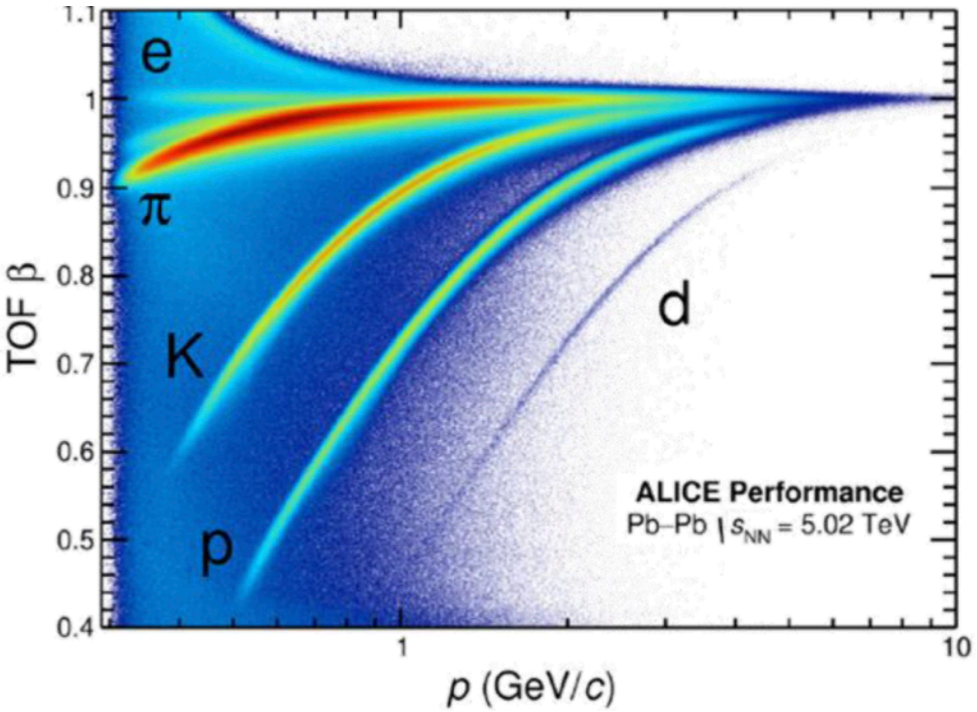


Time-of-Flight

- Particle identification can be done with TOF at low-moderate momentum range depending on the timing resolution of the detector
- Determine the mass from the velocity measurement ($d/c\Delta t$)

$$m^2 = p^2[(\frac{ct}{L})^2 - 1] \qquad \frac{\Delta M}{M} = \frac{\Delta p}{p} + \gamma^2[\frac{\Delta L}{L} + \frac{\Delta t}{t}]$$





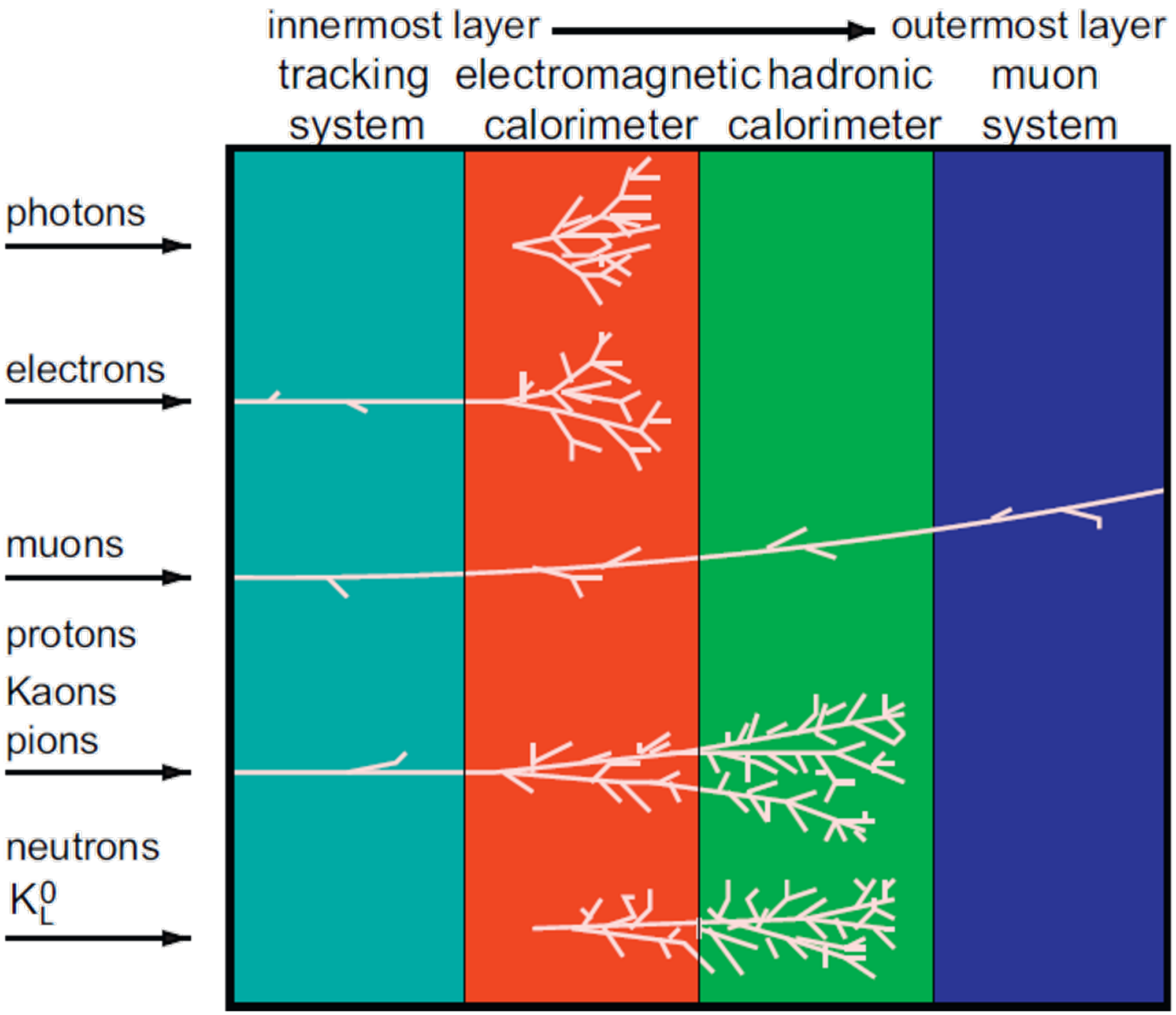
Detector Requirements

- What we measure: position, momentum, energy, charge and species

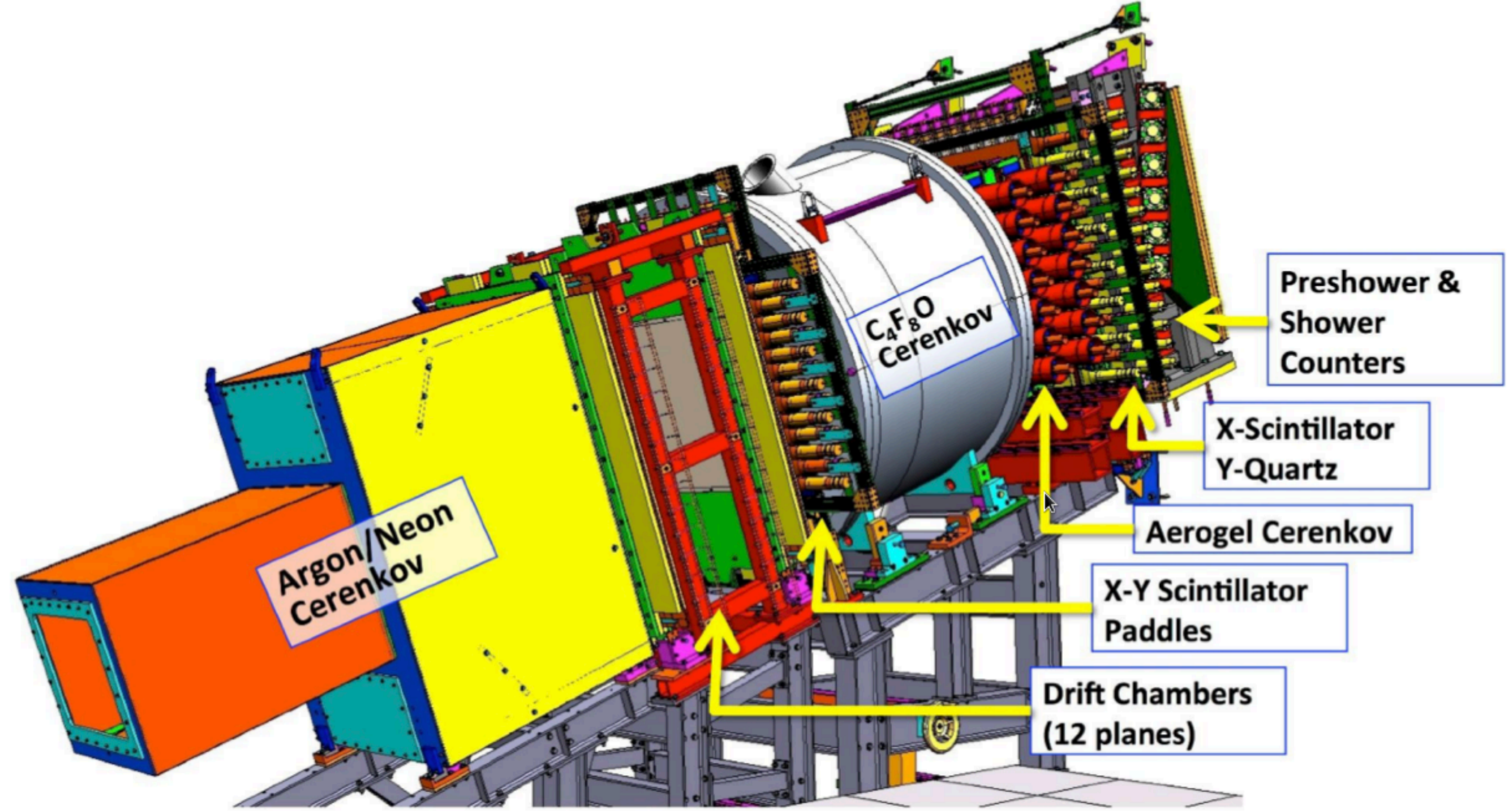
- **Traditional Experiments**

  Onion Structure

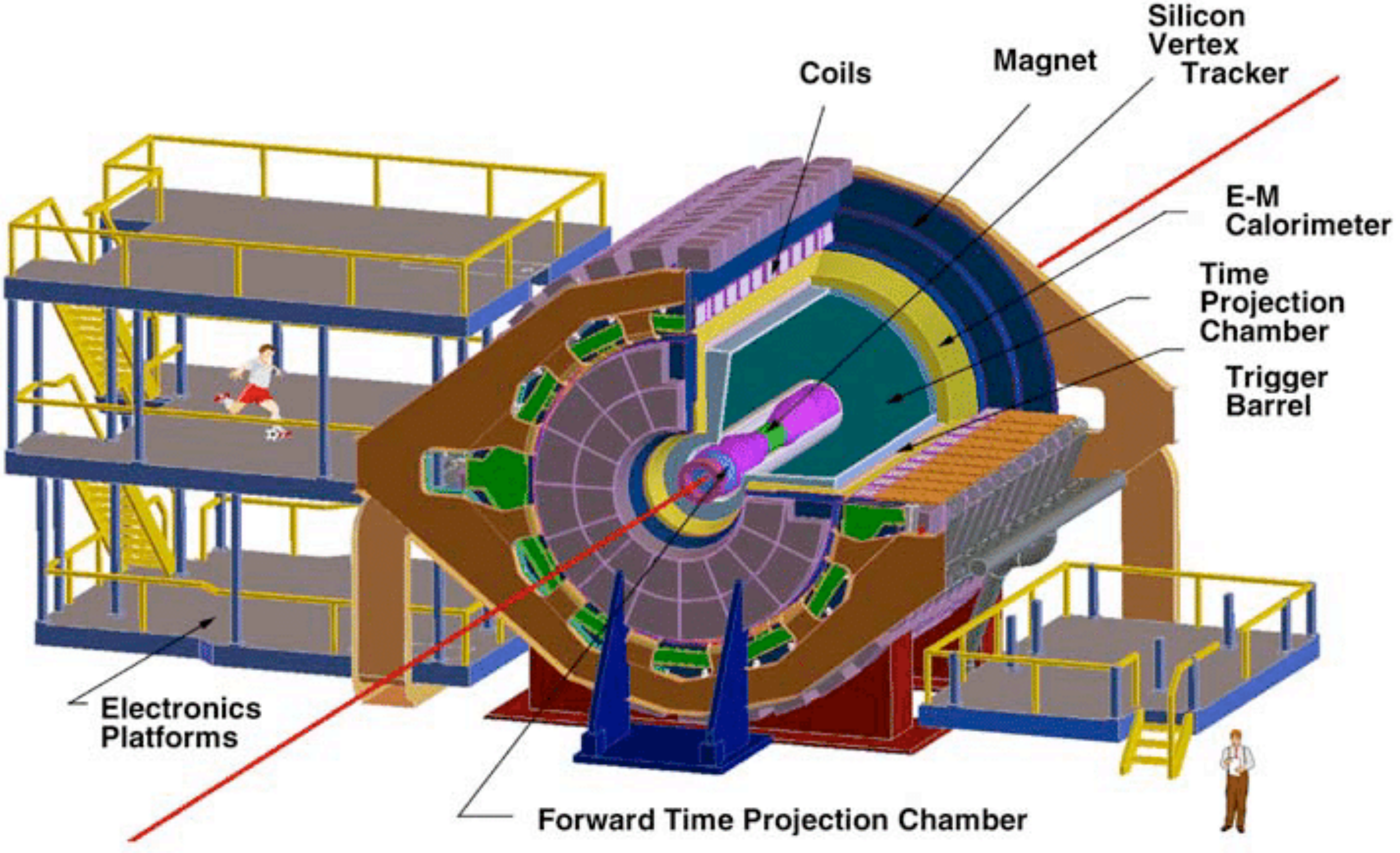
  - Trackers
    - Momentum measurement
    - Charge measurement
    - Non-destructive
  - Calorimeters
    - Detect neutral particles
    - Measure energy
    - Distinguish EM/Hadron interactions
    - Destructive
  - Others



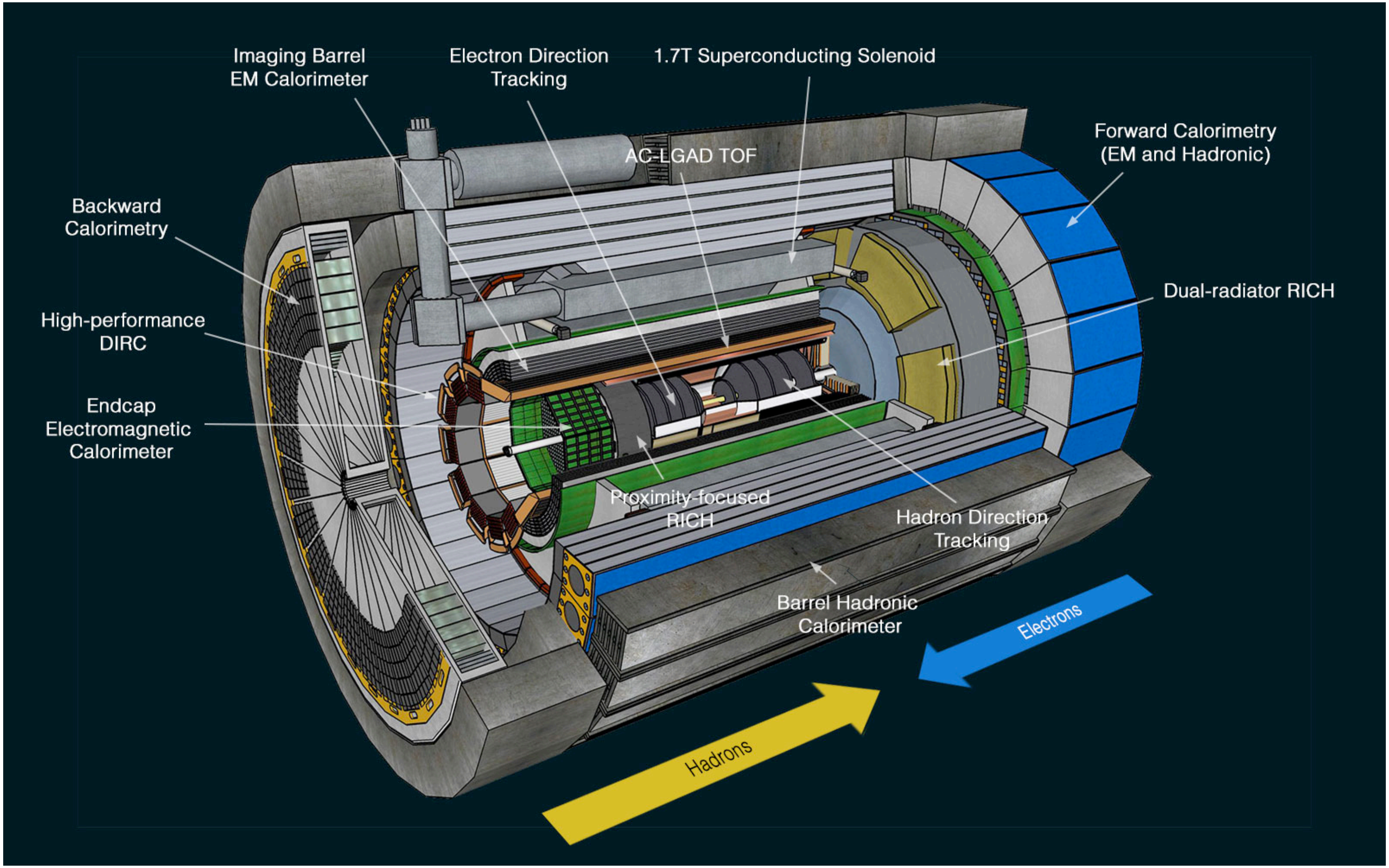
JLab HallC detector package



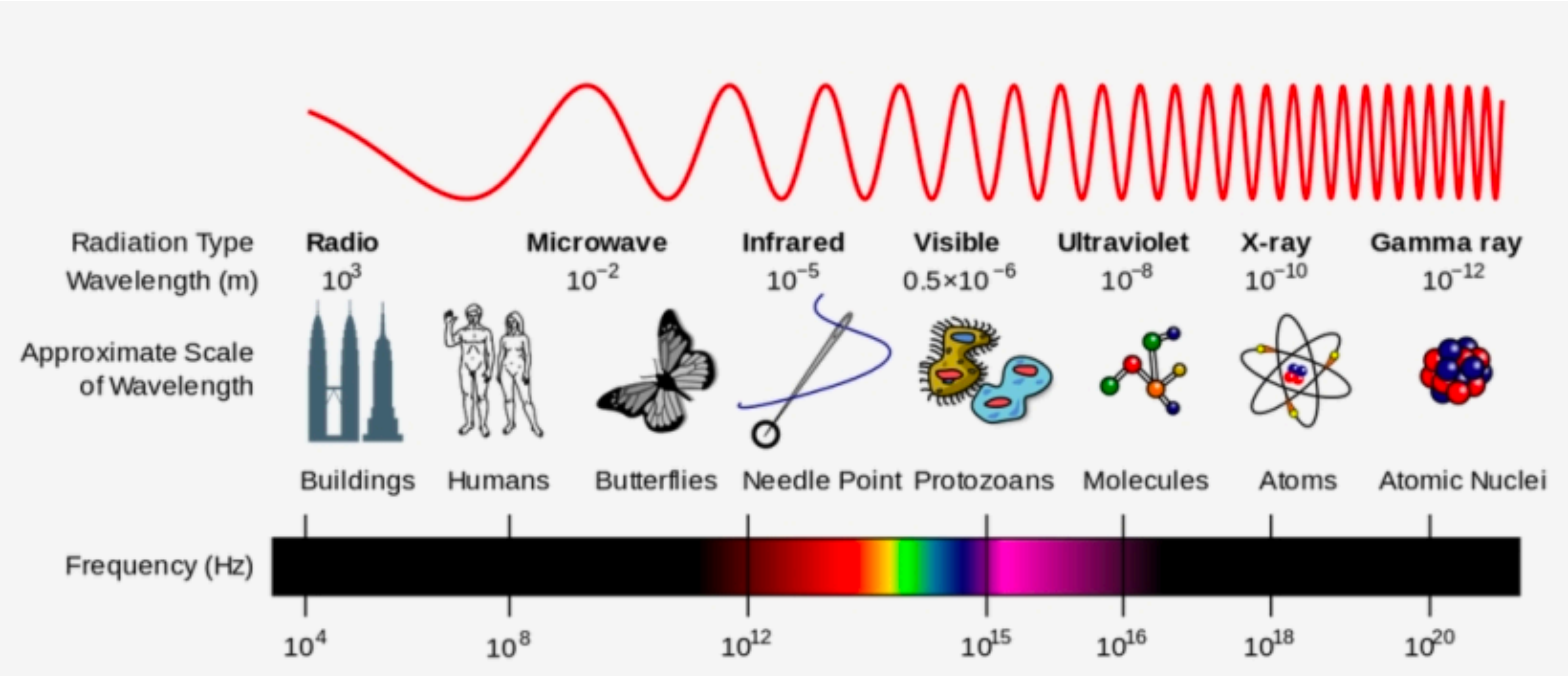
STAR detector

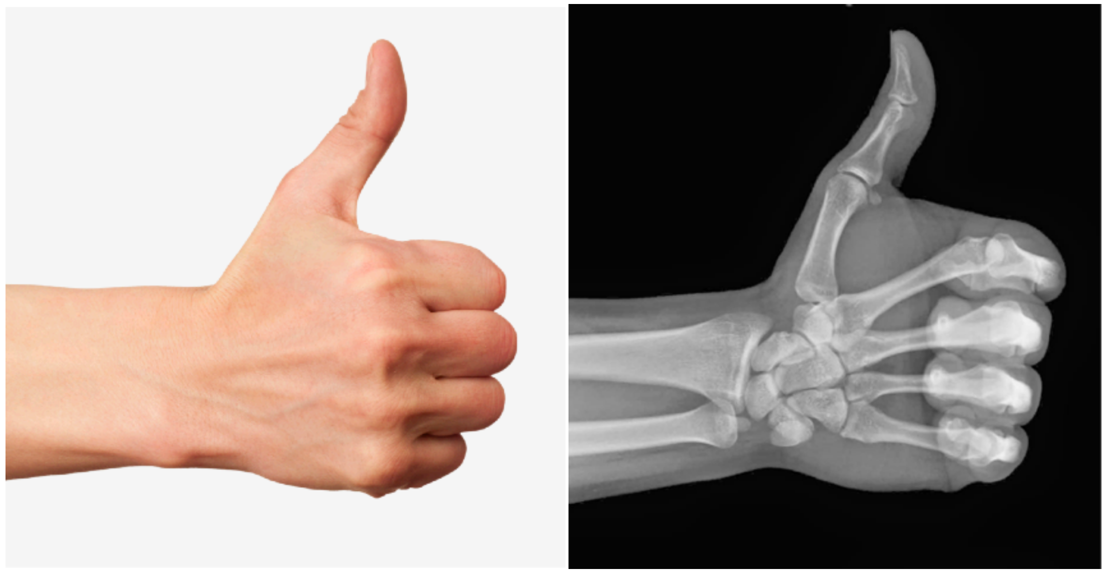


ePIC

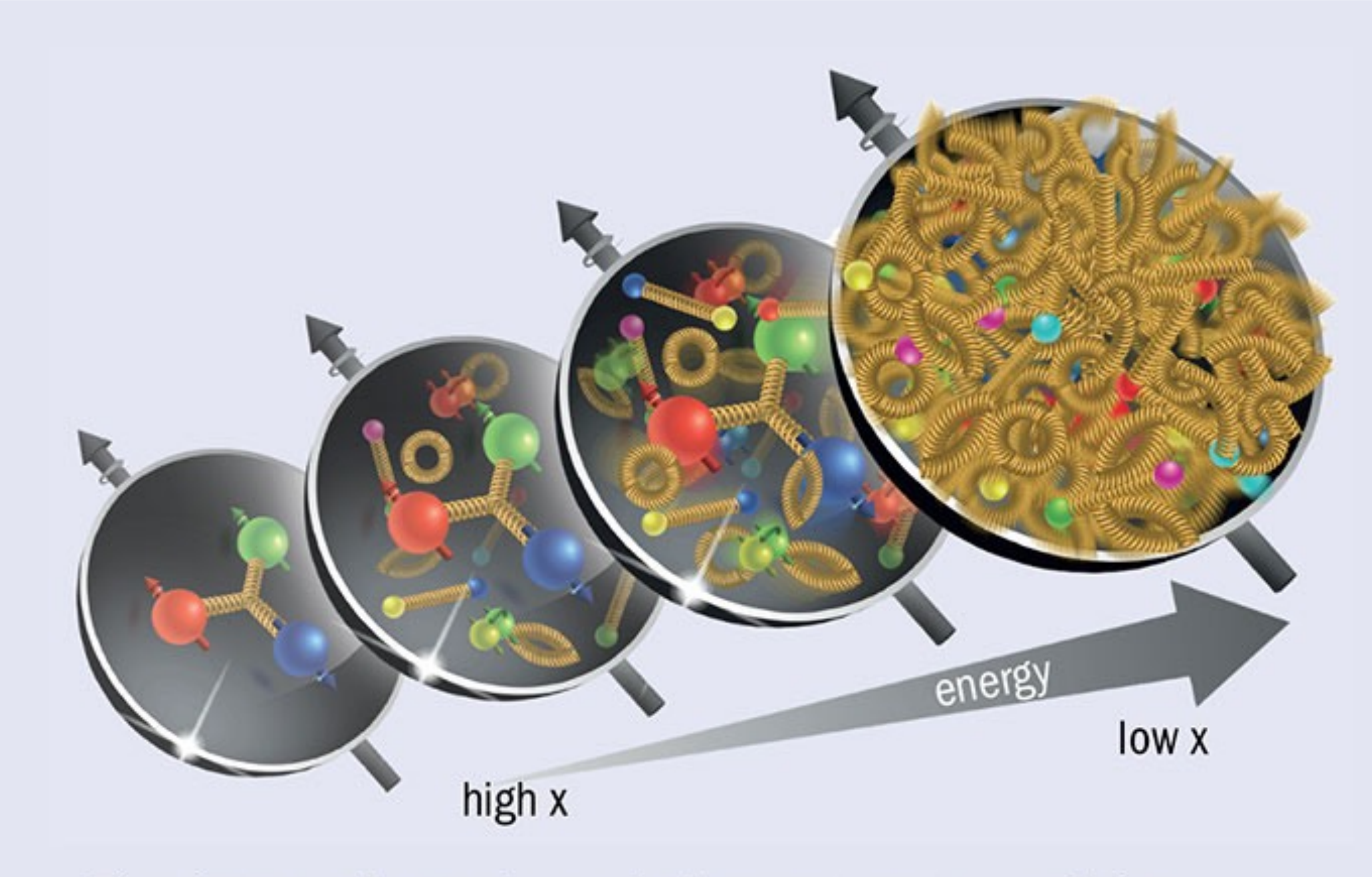

Imaging Barrel EM Calorimeter
Electron Direction Tracking
1.7T Superconducting Solenoid
AC-LGAD TOF
Forward Calorimetry (EM and Hadronic)
Backward Calorimetry
High-performance DIRC
Dual-radiator RICH
Endcap Electromagnetic Calorimeter
Proximity-focused RICH
Hadron Direction Tracking
Barrel Hadronic Calorimeter
Electrons
Hadrons

Understanding substructure depends on how we see

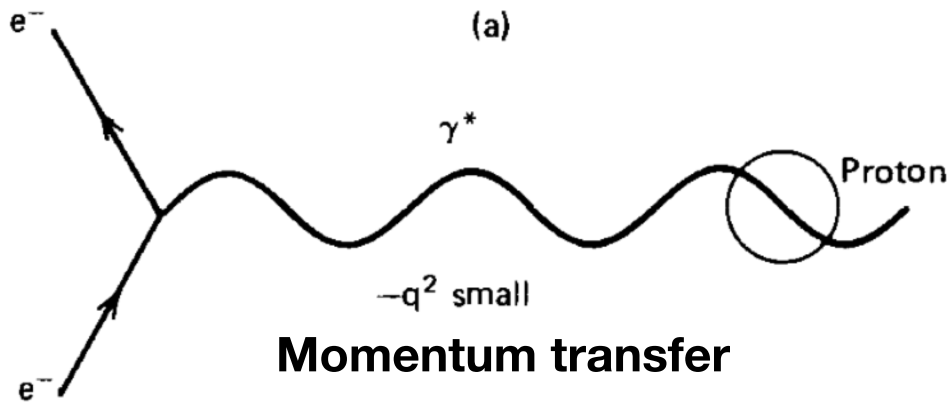




Understanding substructure depends on how we ~~see~~ hit it



Understanding substructure depends on how we ~~see~~ hit it



Momentum transfer

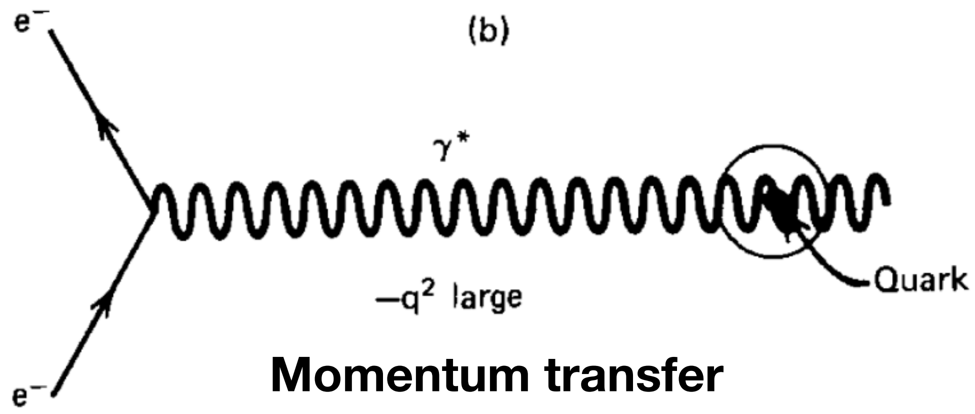
Elastic scattering

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{point} |F(q)|^2$$

$$F_p(Q^2) = \frac{1}{4\pi}\int d^3 r j_0(qr)\boxed{\rho_p(r)}$$

Charge density

—> Size of the proton



Momentum transfer

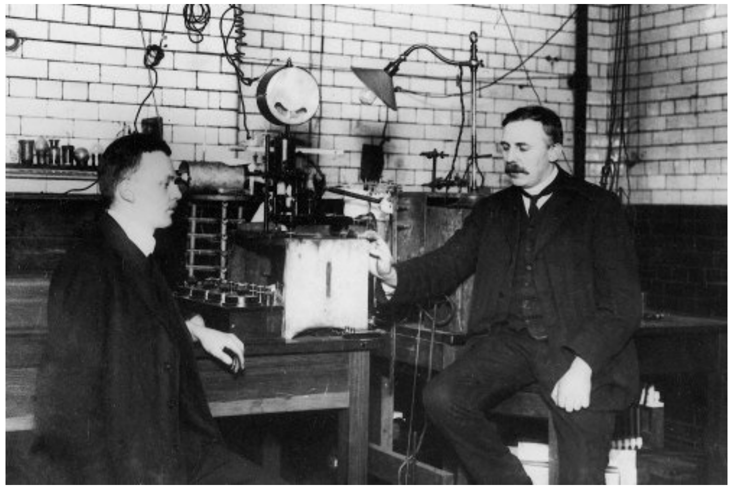
Inelastic scattering

$$\frac{d^2\sigma_{NC}}{dxdQ^2} \approx \frac{4\pi\alpha^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)\boxed{F_2} - \frac{y^2}{2}\boxed{F_L}\right]$$

Contain information of proton structure!

Higher energies leading to discoveries

- Rutherford gold foil experiment (1910s):
  - 5 MeV beam of alpha particles, thin gold foil target, scintillation counter
  - Point-like positively charged region in the atom



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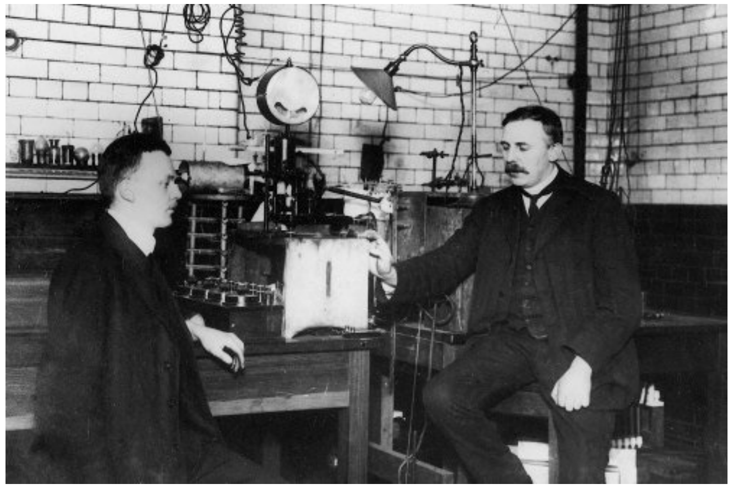
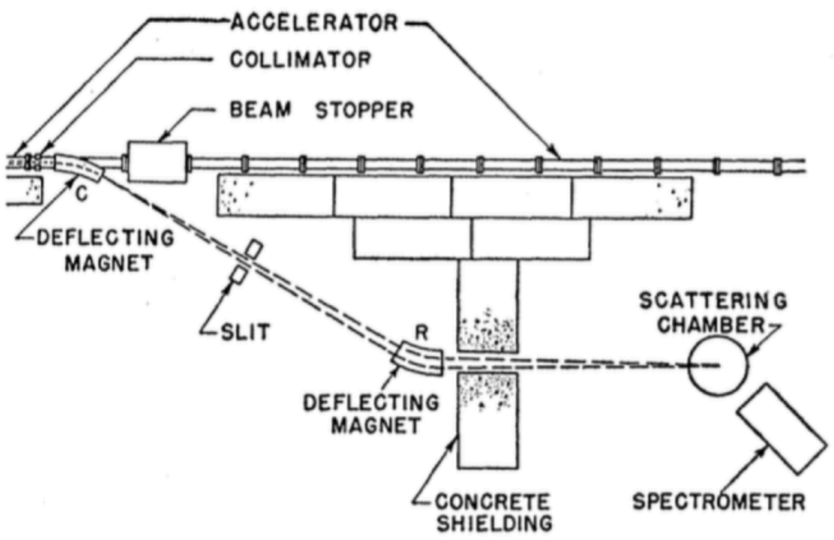


- Hofstadter (1954):
  - nuclear analogue of Rutherford scattering with ~200 MeV electron beam as a probe
  - Finite size of proton



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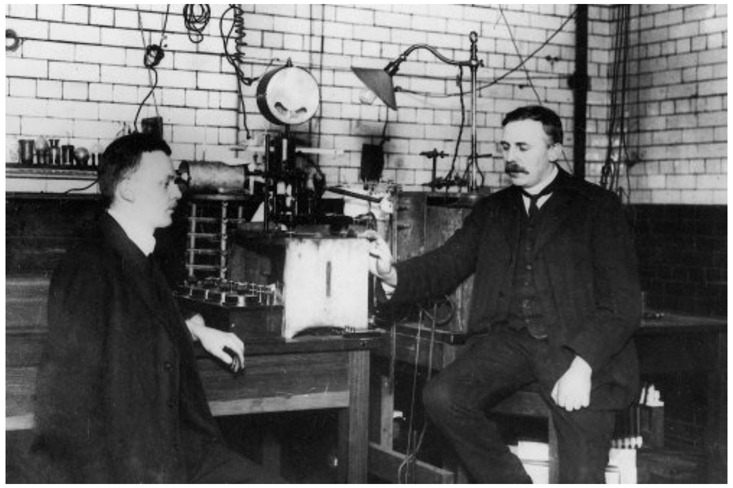

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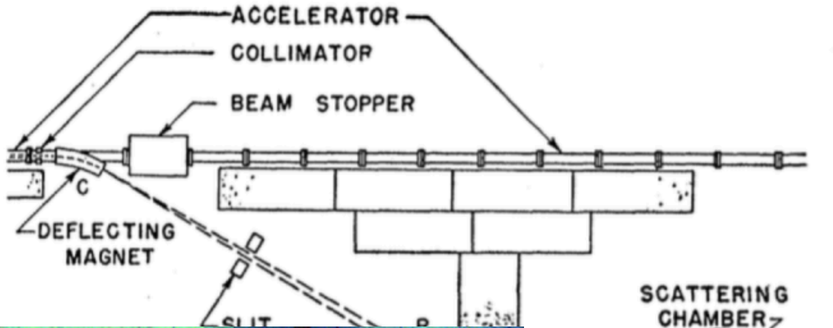
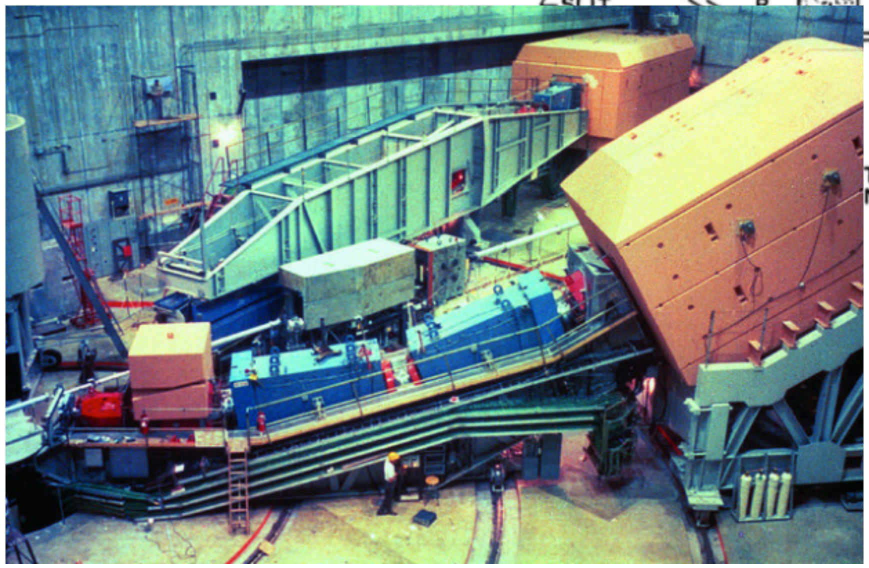
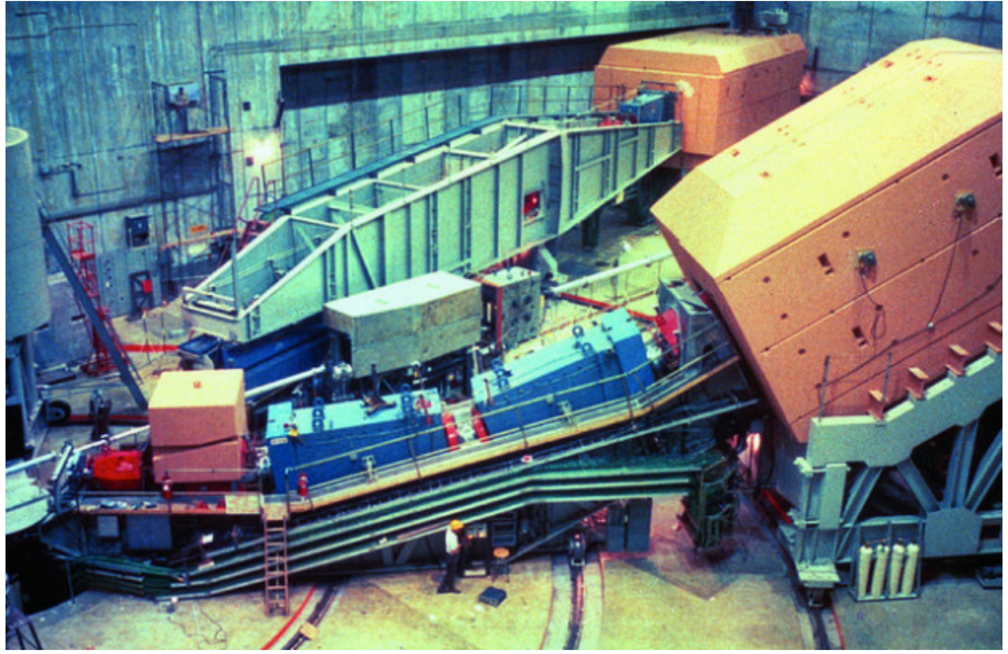


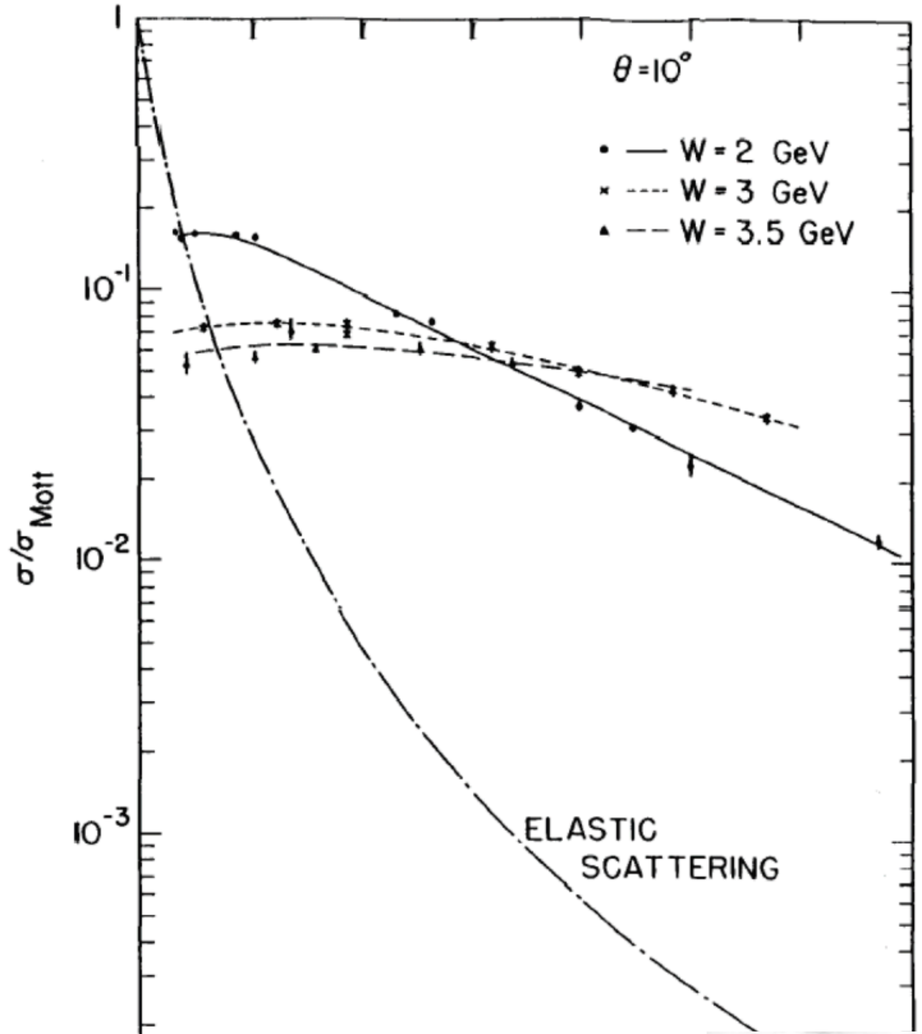
- Friedman, Kendall, Taylor (1967-73):
  - SLAC-MIT experiment
  - 4-21 **GeV** electron beam
  - Quark structure of the proton

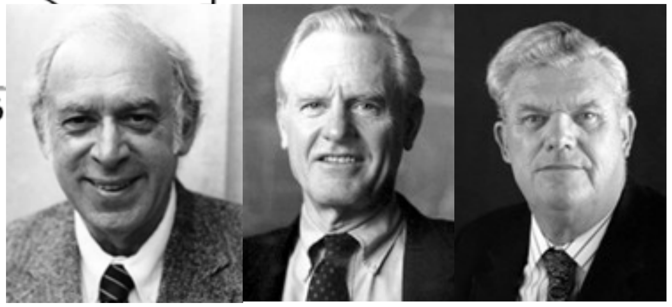


SLAC-MIT Experiments

- SLAC fixed-target DIS experiments

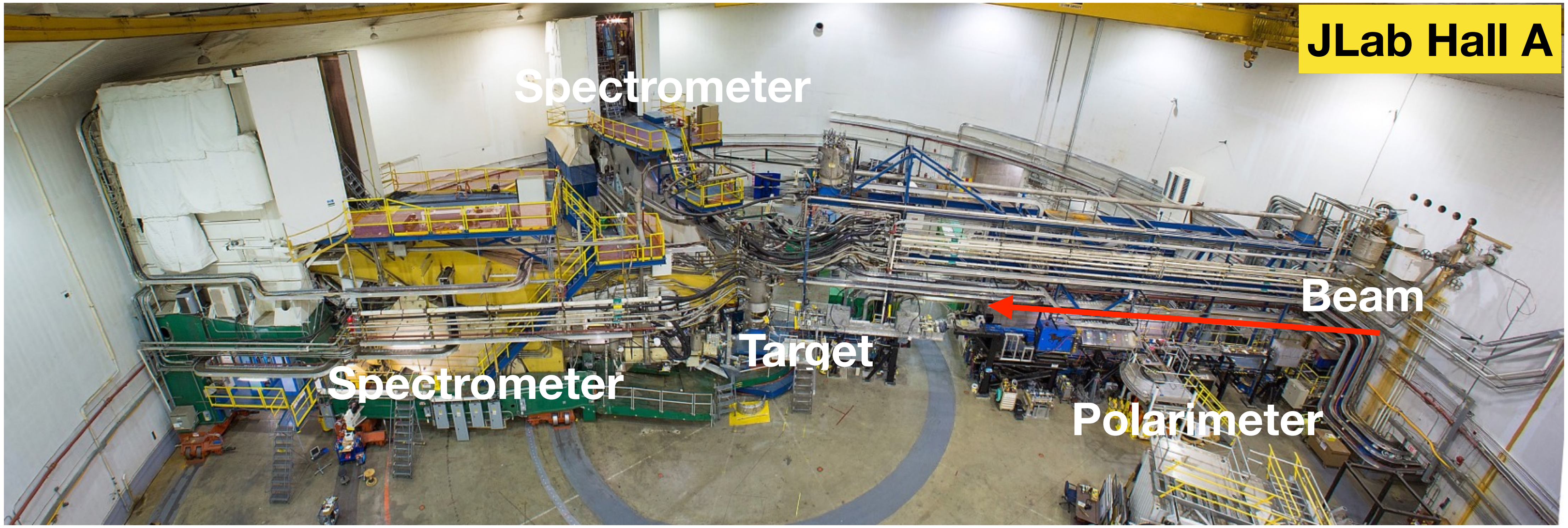


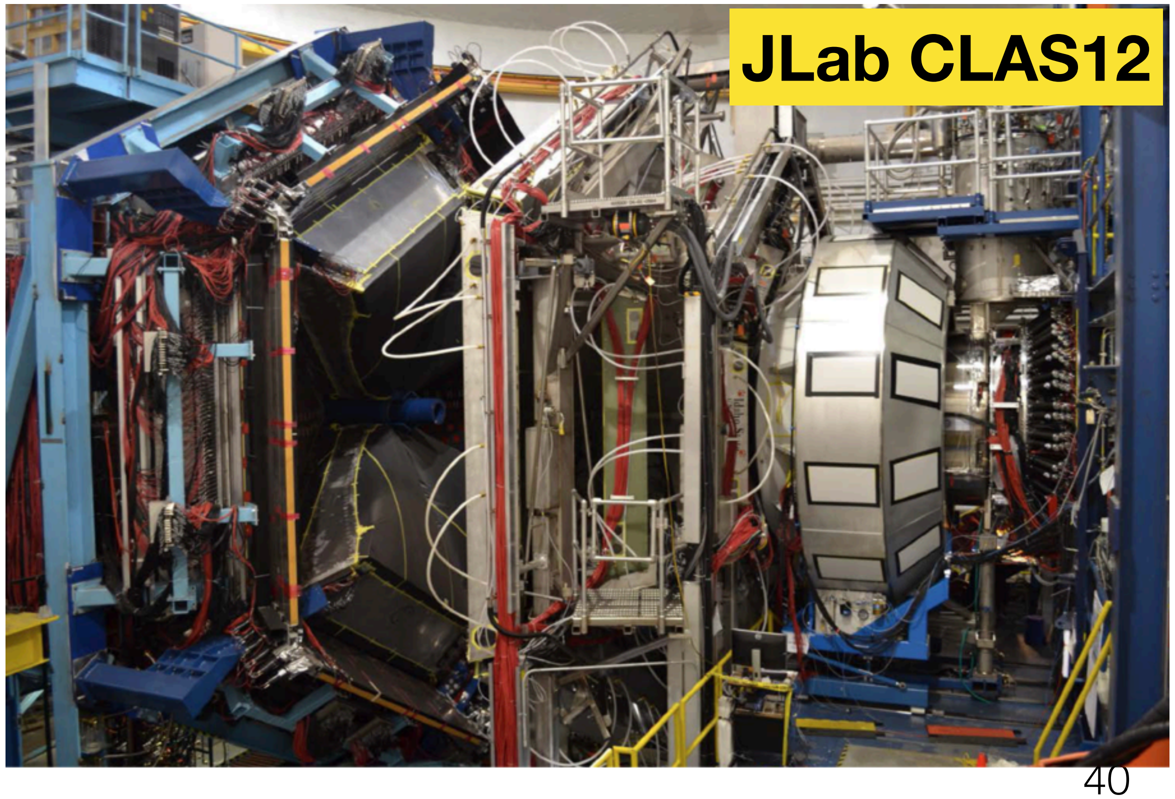


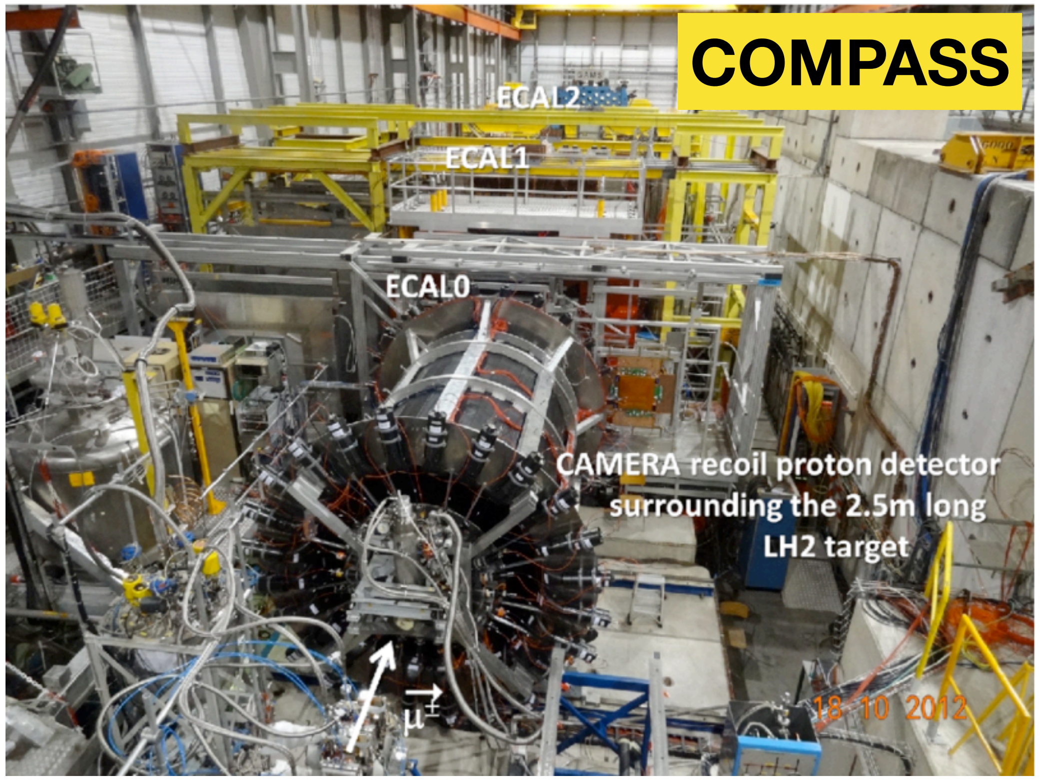


Friedman, Kendall, Taylor

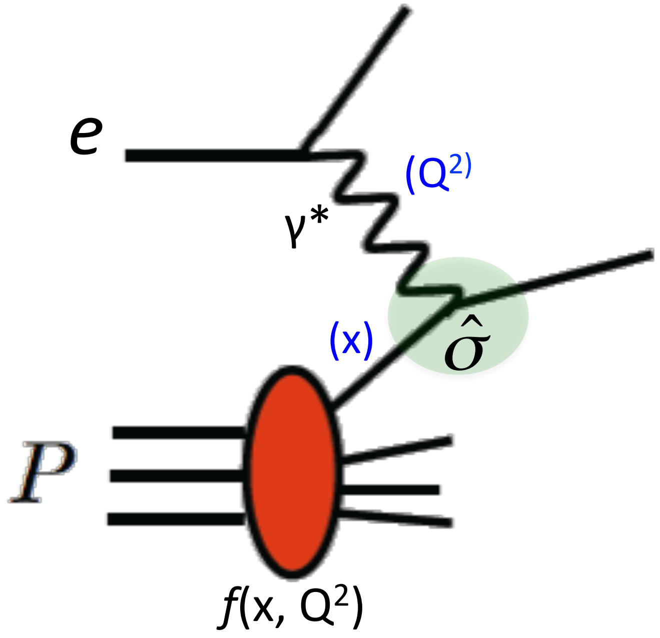
A bit more modern look?..







Deep Inelastic Scattering: microscope to “see” inside the proton



Nucleon structure encoded in PDFs

Q^2: squared momentum transfer. Measure of resolution

x: Momentum fraction of the struck parton in a proton

Factorization and Universality

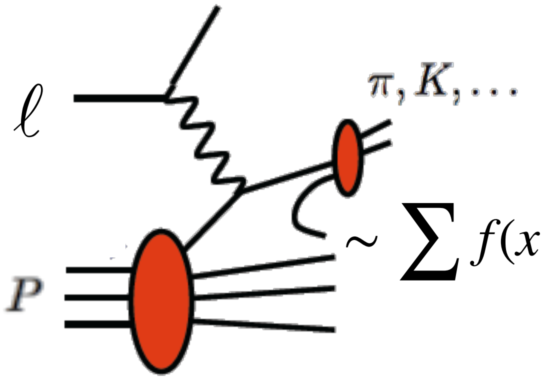
Separate cross section into the short-distance parton level scattering part and the universal parton distribution functions

$$\overset{\text{Inclusive}}{\sigma}_{\text{DIS}} \propto \sum f(x,Q^2) \otimes \hat{\sigma}$$

Determined from measurements

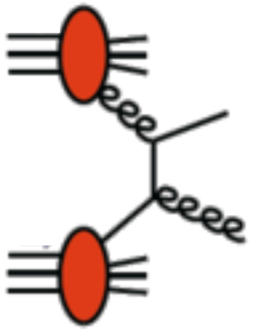
Can be calculated from perturbative QCD (pQCD)

Universality of PDFs - Predictive power of QCD



$$\sim \sum f(x,Q^2) \otimes \hat{\sigma} \otimes D^h$$

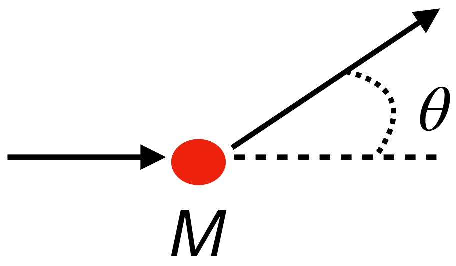
Use PDFs from DIS to predict the cross section in hadron collisions



$$\sim \sum f_a(x,Q^2) \otimes f_b(x,Q^2) \otimes \hat{\sigma} \otimes D^h$$

Deep Inelastic Scattering

- DIS experiments have been successful mapping out the momentum distributions of quarks and gluons



$$\frac{d^2\sigma}{d\Omega dE'} = \frac{8\alpha^2 cos^2(\theta/2)}{Q^4}[\frac{\boxed{F_2(x, Q^2)}}{\nu} + \frac{\boxed{2F_1(x, Q^2)}}{M} tan^2(\theta/2)]$$

Information of internal structure of target nucleon

Can directly link to parton distribution functions (PDFs)

In Quark parton model, $F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x, Q^2)$ $F_2(x, Q^2) = x\sum_i e_i^2 q_i(x, Q^2)$

- Polarized Structure Functions: $g_1(x, Q^2), \quad g_2(x, Q^2)$

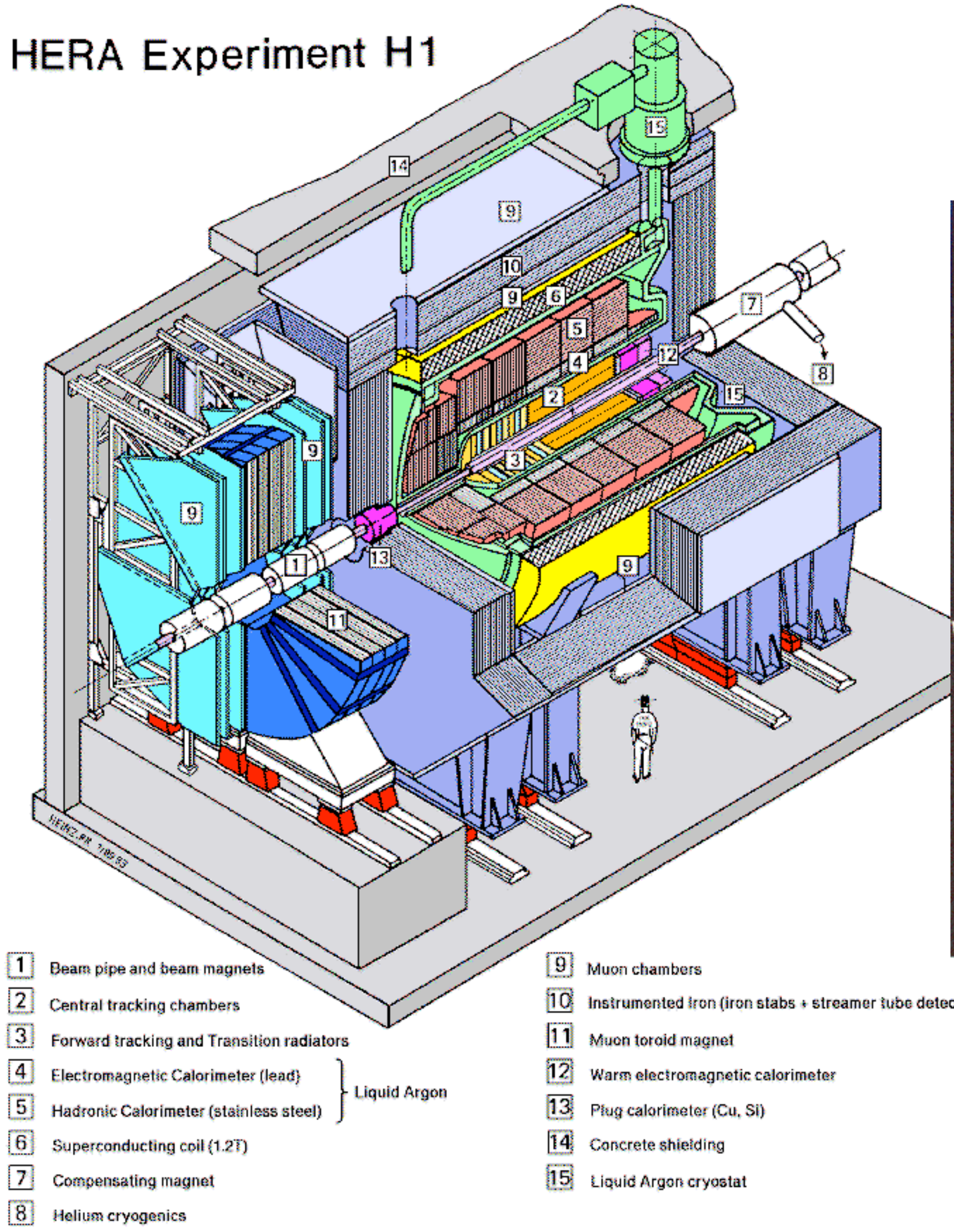
In Quark parton model, $g_1(x,Q^2) \sim \sum_q e_q^2 \Delta q(x,Q^2)$

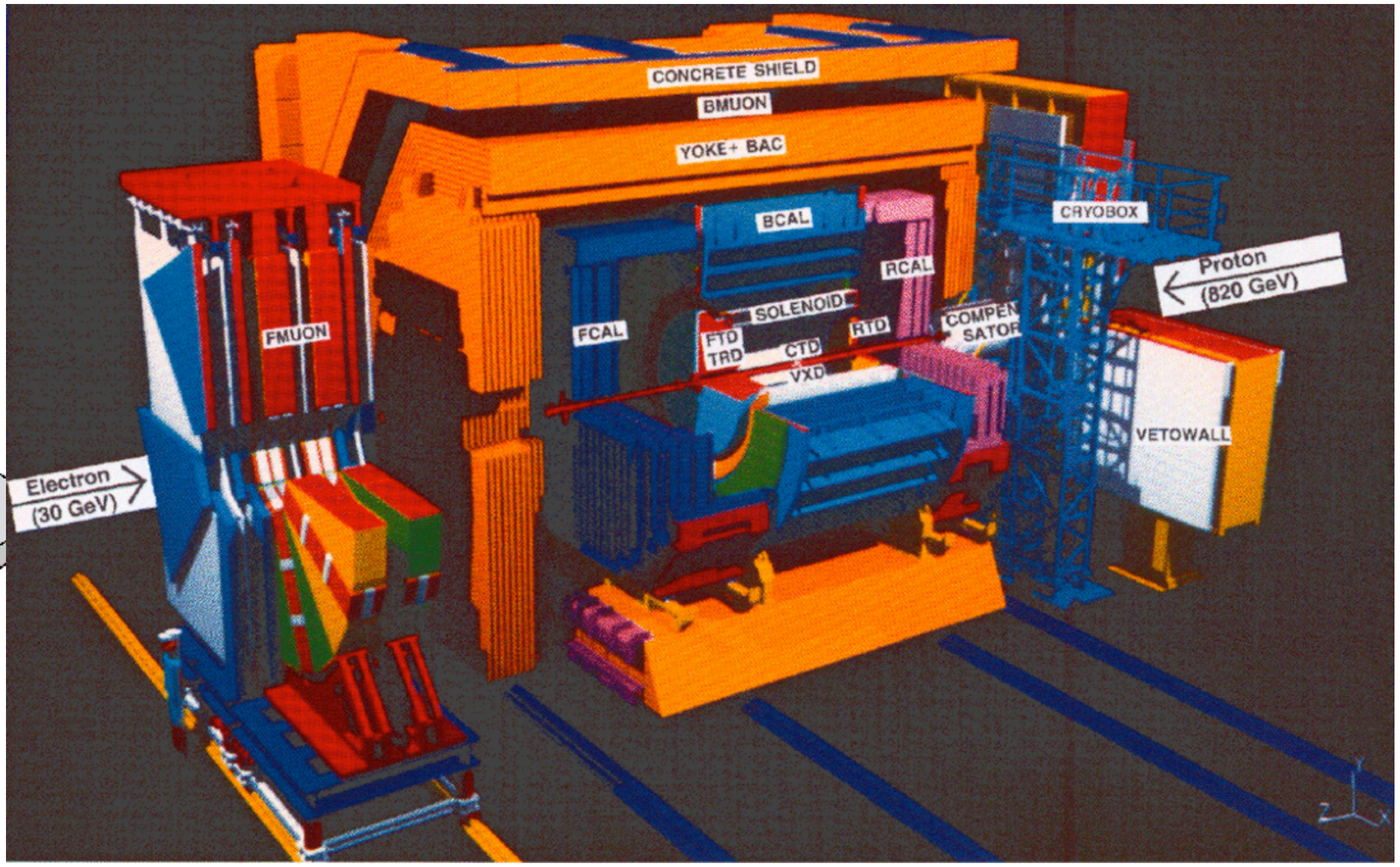
quark spin distribution

HERA @ DESY

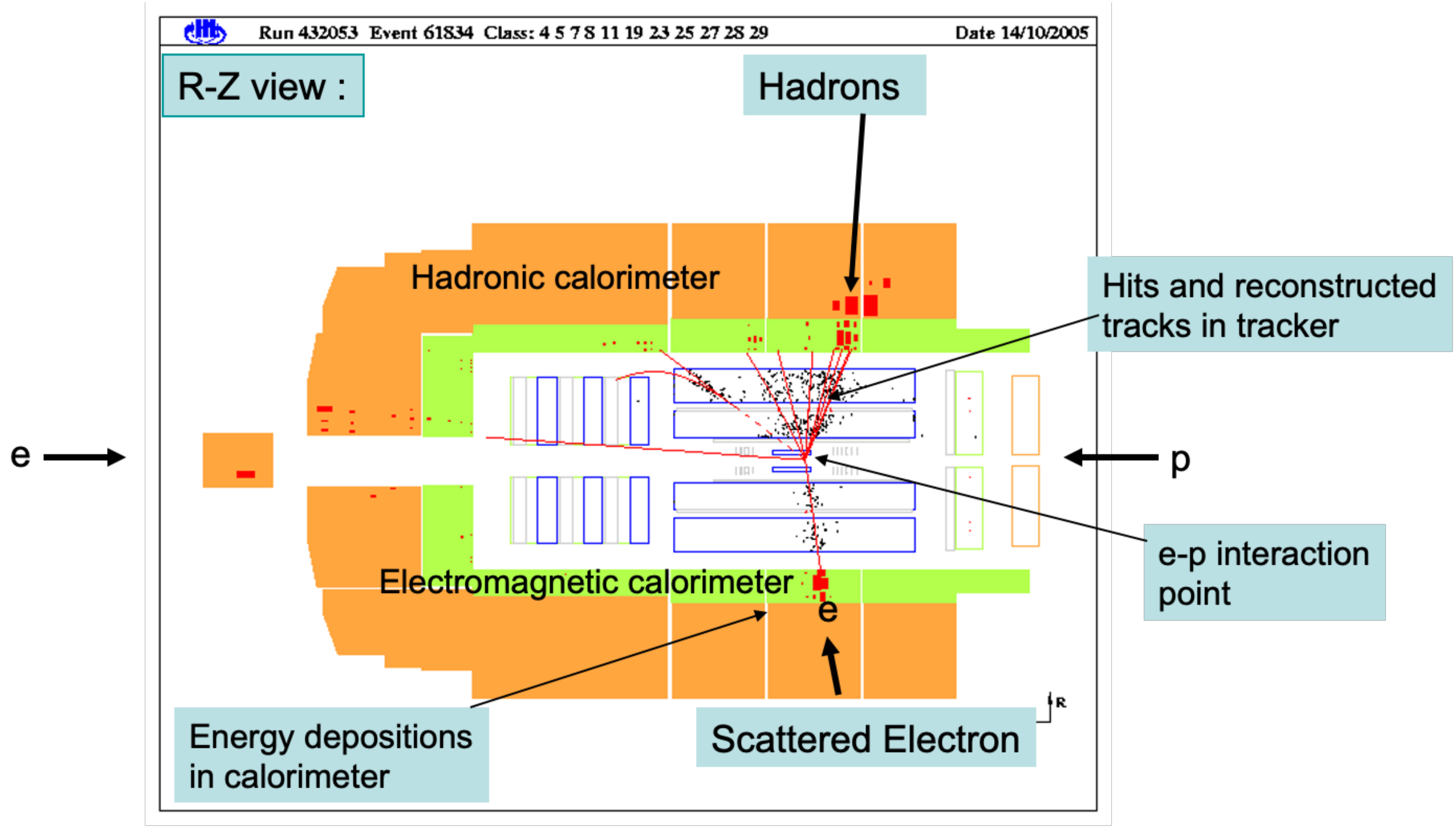
- Operated 1992-2007
- Two collider experiments: H1, ZEUS
- Two fixed target experiments: HERMES ($e^{\pm}$ beam), HERA-B (p)
- Two 6.3km circumference rings
  - Proton energy 460-920 GeV
  - Electron/positron energy 27.5 GeV
- Lepton beam polarization: ~60%
  - Solokov-Ternov effect: slow build-up of self-polarization (~30min)

H1 and ZEUS


HERA Experiment H1
14
15
9
10
9
6
5
4
2
3
12
7
8
15
9
9
13
1
11
9
1 Beam pipe and beam magnets
2 Central tracking chambers
3 Forward tracking and Transition radiators
4 Electromagnetic Calorimeter (lead)
5 Hadronic Calorimeter (stainless steel)
Liquid Argon
6 Superconducting coil (1.2T)
7 Compensating magnet
8 Helium cryogenics
9 Muon chambers
10 Instrumented Iron (iron stabs + streamer tube detectors)
11 Muon toroid magnet
12 Warm electromagnetic calorimeter
13 Plug calorimeter (Cu, Si)
14 Concrete shielding
15 Liquid Argon cryostat


CONCRETE SHIELD
BMUON
YOKE+ BAC
BCAL
RCAL
CRYOBOX
Proton
(820 GeV)
SOLENOID
FMUON
FCAL
FTD
TRD
CTD
VXD
RTD
COMPEN
SATOR
VETOWALL
Electron
(30 GeV)

e+p event at HERA



From H1 event tutorial by J. Meyer

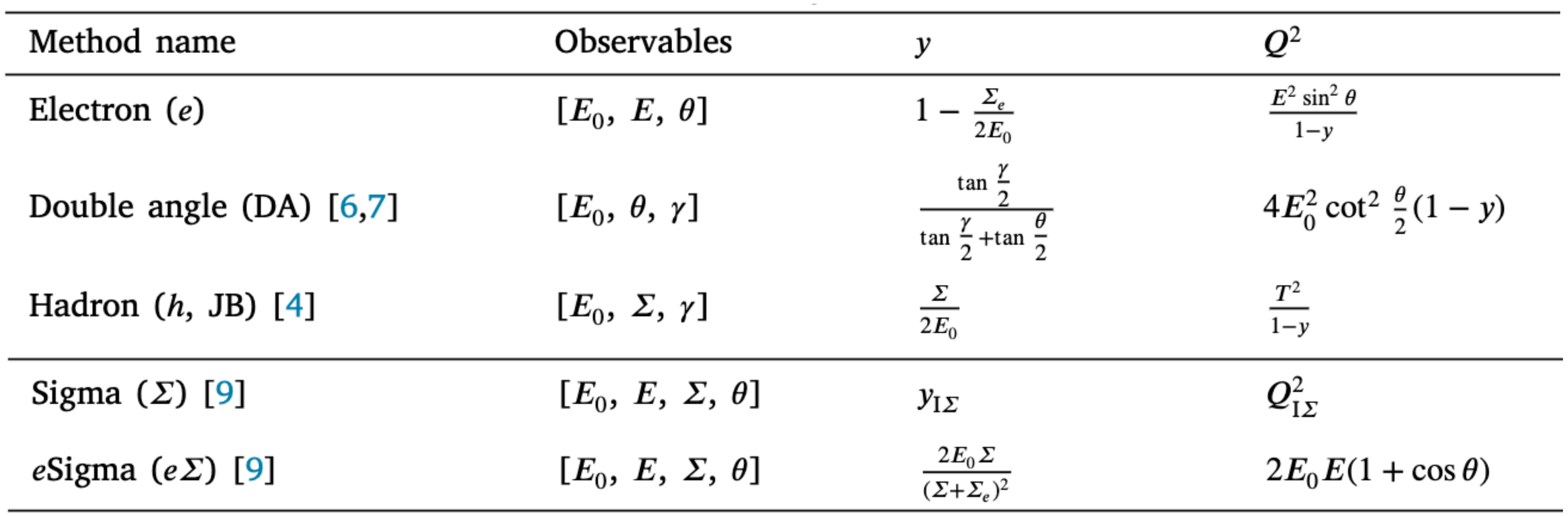
Kinematics reconstruction

- For inclusive events, the DIS kinematics can be reconstructed by
  - detecting the scattered electron
  - reconstructing hadronic recoil
- Several ways to reconstruct y, Q^2, x. Here we compare some of the methods used at HERA.
  - For detailed discussion: Bassler and Bernardi NIM A 426 (1999) 583-598
- One of the most simple methods: electron method
  - need to know the scattered electron energy and angle

$$Q^2 = 4EE' \cos^2\left(\theta_p^{e'}/2\right) \qquad y = 1 - \frac{E'(1-\cos\theta_p^{e'})}{2E} \qquad x = \frac{Q^2}{sy}$$

Reconstruction Methods

- Detector oriented variables (E,θ, Σ, γ) -> y, Q², x



Method name	Observables	y	Q^2
Electron (e)	$[E_0,\ E,\ \theta]$	$1-\frac{\Sigma_e}{2E_0}$	$\frac{E^2\sin^2\theta}{1-y}$
Double angle (DA) [6,7]	$[E_0,\ \theta,\ \gamma]$	$\frac{\tan\frac{\gamma}{2}}{\tan\frac{\gamma}{2}+\tan\frac{\theta}{2}}$	$4E_0^2\cot^2\frac{\theta}{2}(1-y)$
Hadron (h, JB) [4]	$[E_0,\ \Sigma,\ \gamma]$	$\frac{\Sigma}{2E_0}$	$\frac{T^2}{1-y}$
Sigma (Σ) [9]	$[E_0,\ E,\ \Sigma,\ \theta]$	$y_{\mathrm{I}\Sigma}$	$Q^2_{\mathrm{I}\Sigma}$
eSigma ($e\Sigma$) [9]	$[E_0,\ E,\ \Sigma,\ \theta]$	$\frac{2E_0\Sigma}{(\Sigma+\Sigma_e)^2}$	$2E_0E(1+\cos\theta)$

$$\Sigma = \sum_h (E_h - p_{z,h})$$

$$T = \sqrt{(\sum_h p_{x,h})^2 + (\sum_h p_{y,h})^2}$$

$$\gamma = 2tan^{-1}(\Sigma/p_{T,h})$$

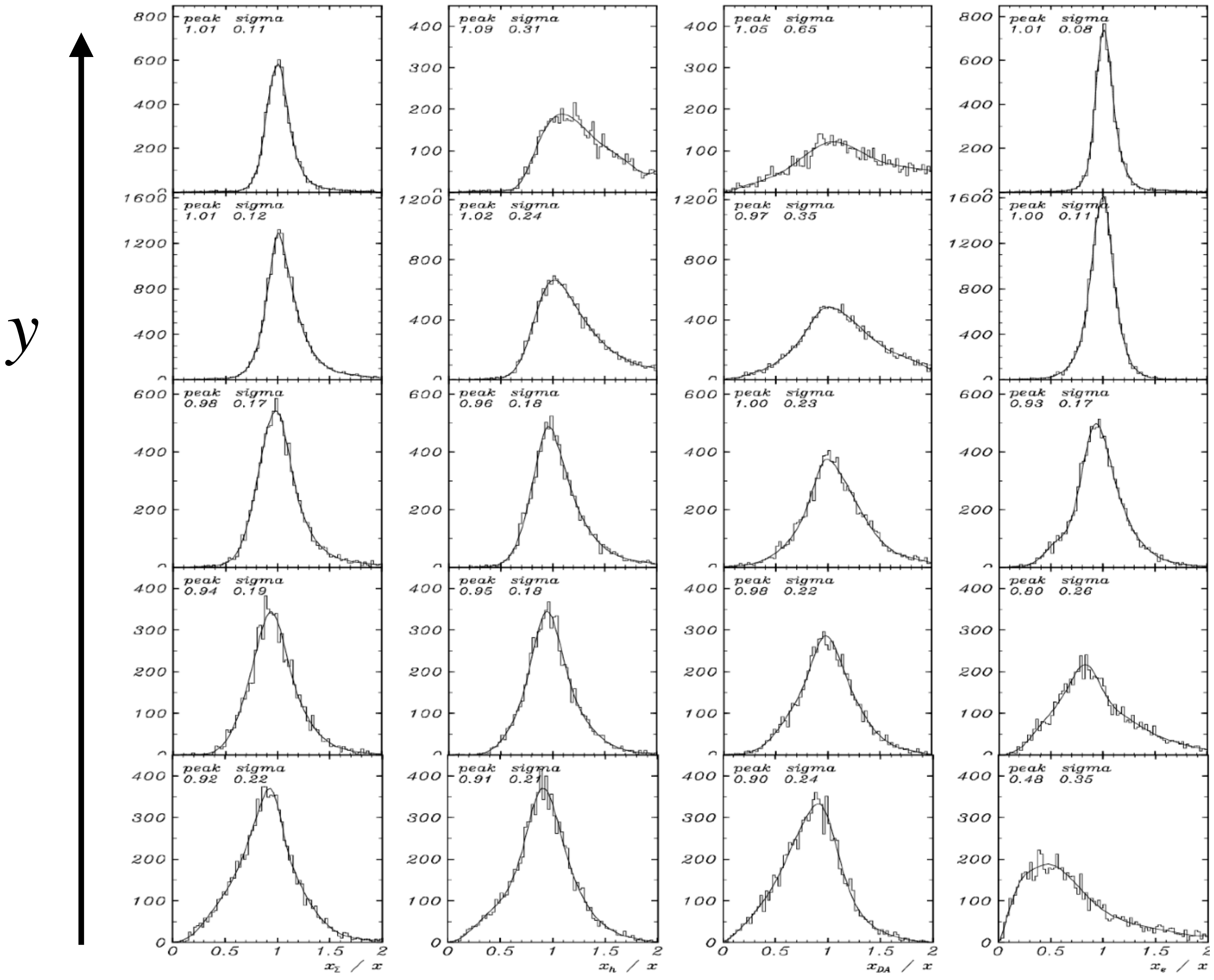
- Which one to use? Depends on kinematic regions and detector performance
  - ZEUS: good hadronic calorimeter - DA (low Q2) and PT (high Q2) methods
  - H1: better electron energy measurement - electron, eΣ methods
- Recently, using AI-ML approach has been developed:

DIS kinematics reconstruction using ML [M. Arratia et. al, NIM.A 1025 166164]

SIDIS event kinematics reconstruction using ML [Pecar, Vossen, arxiv.2209.14489]

Reconstruction Methods

Σ method **JB** **DA** **Electron**



For $Q^2 > 7GeV^2$

$0.5 < y < 0.8$

$0.2 < y < 0.5$

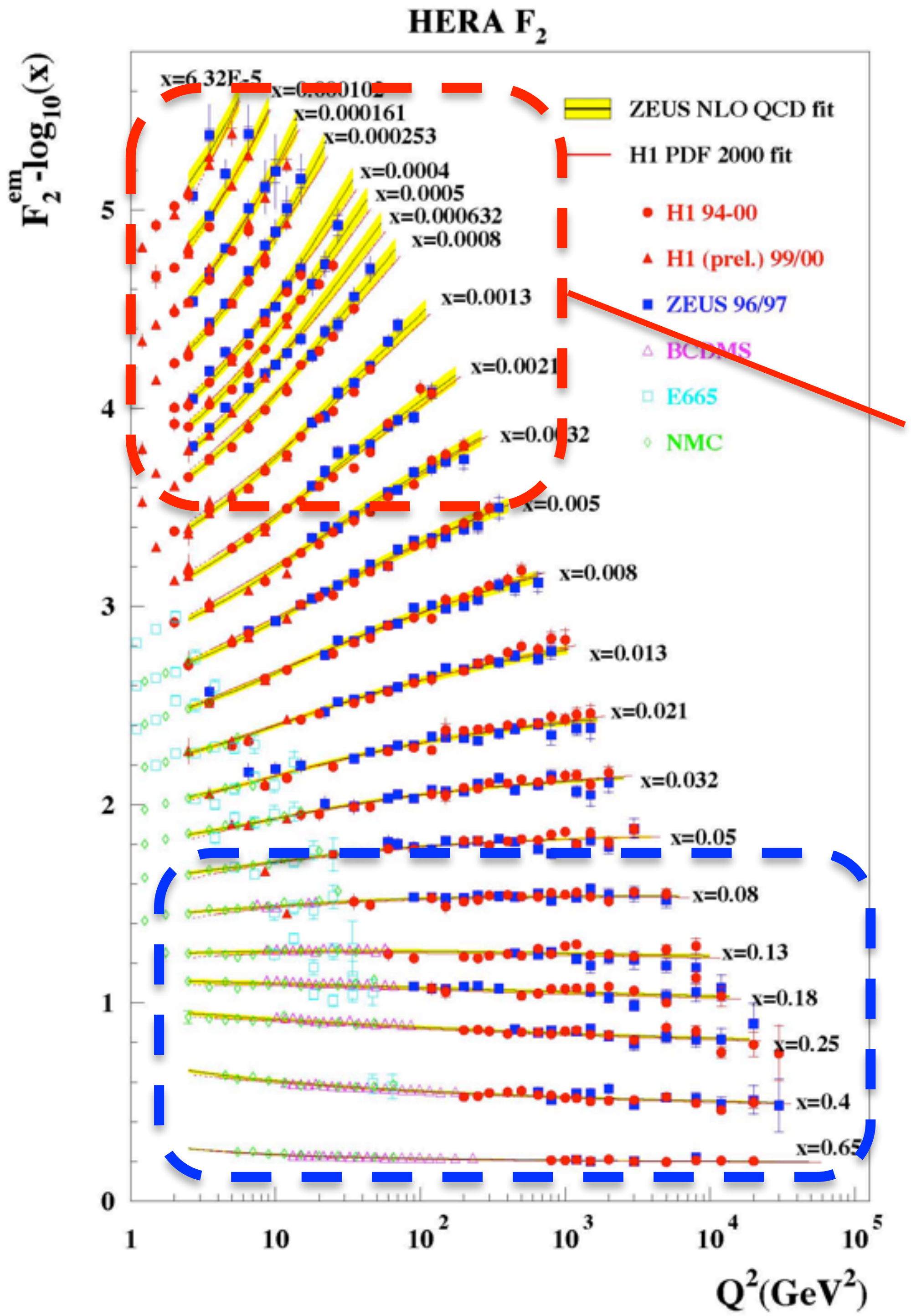
$0.1 < y < 0.2$

$0.05 < y < 0.1$

$0.01 < y < 0.05$

Bassler and Bernardi,
NIM.A. 361 (1995)
197-208

Structure functions



Structure function in terms of PDFs:

$$F_2(x,Q^2) = \sum_i e_i^2 x f_i(x,Q^2)$$

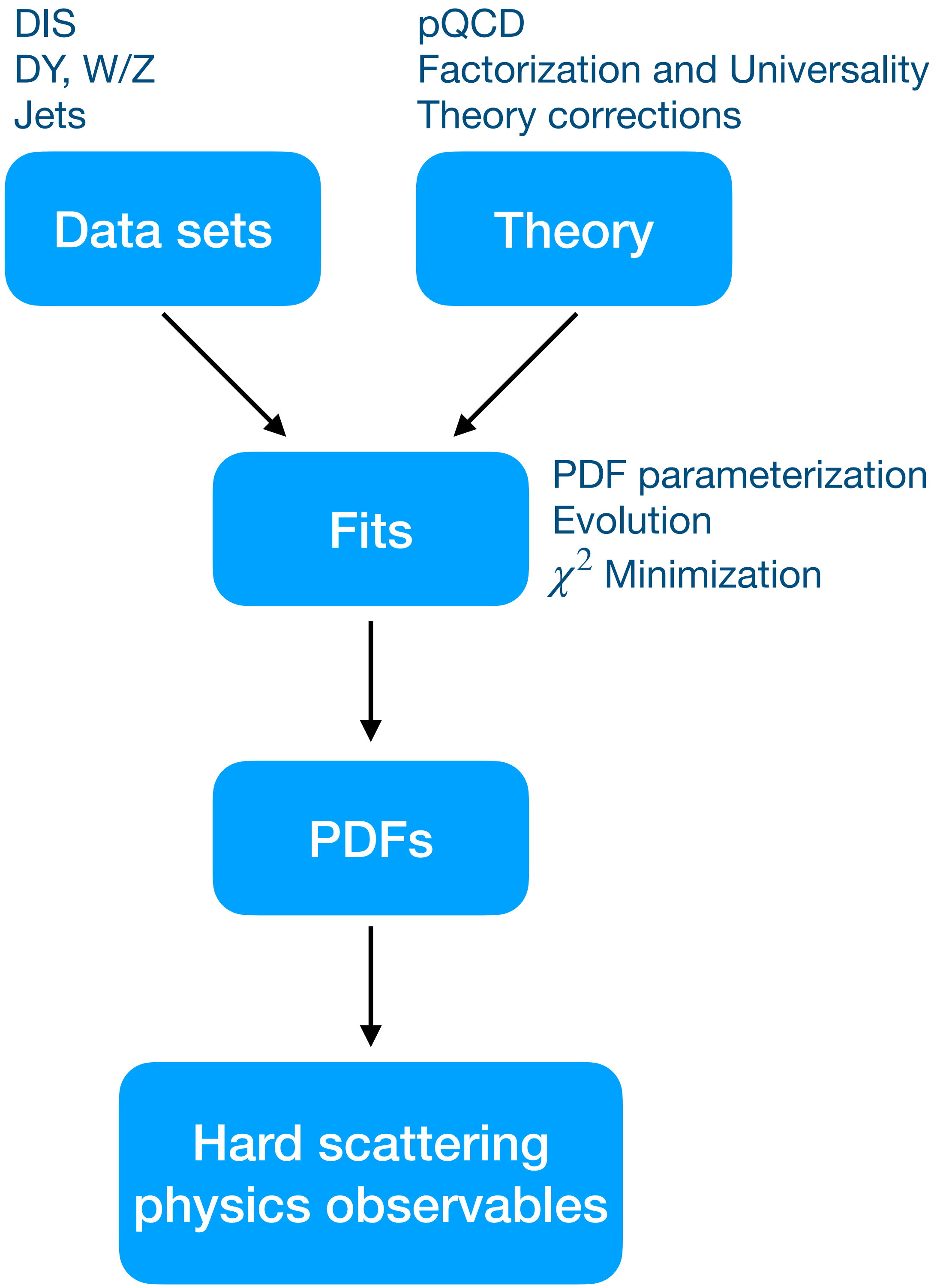
Scaling violation in low-x: Gluons!

Quark-gluon coupling:
PDFs evolve with the scale!

Scaling behavior of the structure function: $F_2(x,Q2) \rightarrow F_2(x)$

Global PDF analysis in practice

- Assume PDFs in a parameterized form at initial scale Q_0 → evolve to any other Q using DGLAP evolution
- Use the PDFs to calculate the chosen hard scattering processes
  - Data from a set of different hard scattering processes
- Repeat: varying the parameters and evolving the PDFs to obtain an optimized fit to a set of data



DIS
DY, W/Z
Jets

pQCD
Factorization and Universality
Theory corrections

Data sets

Theory

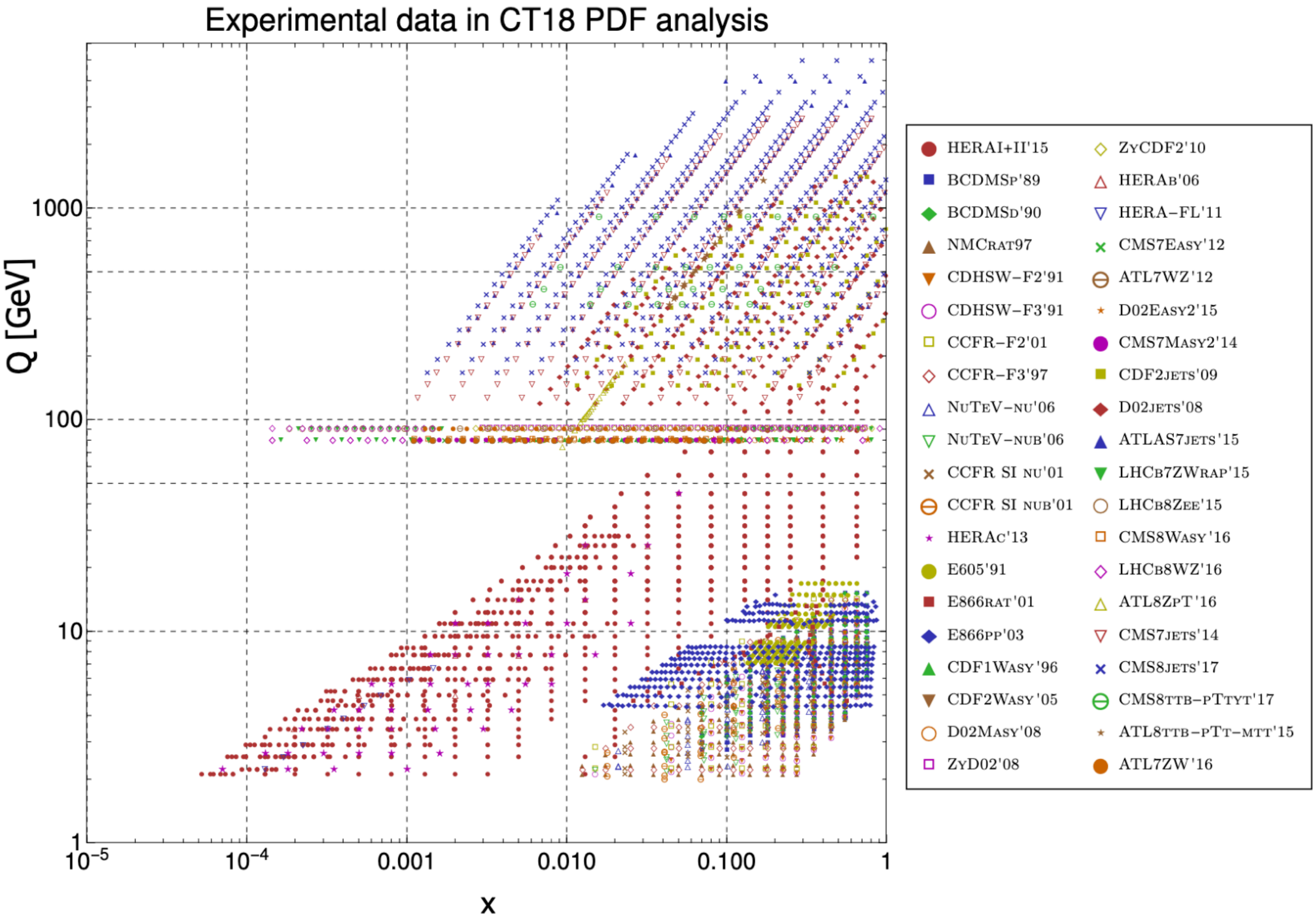
Fits

PDF parameterization
Evolution
χ^2 Minimization

PDFs

Hard scattering physics observables

World dataset for PDF analysis



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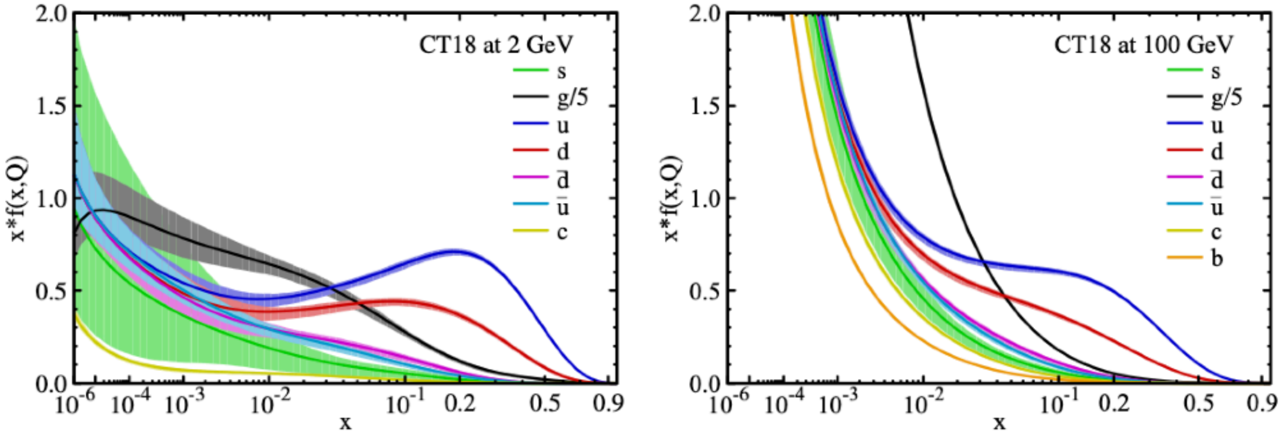
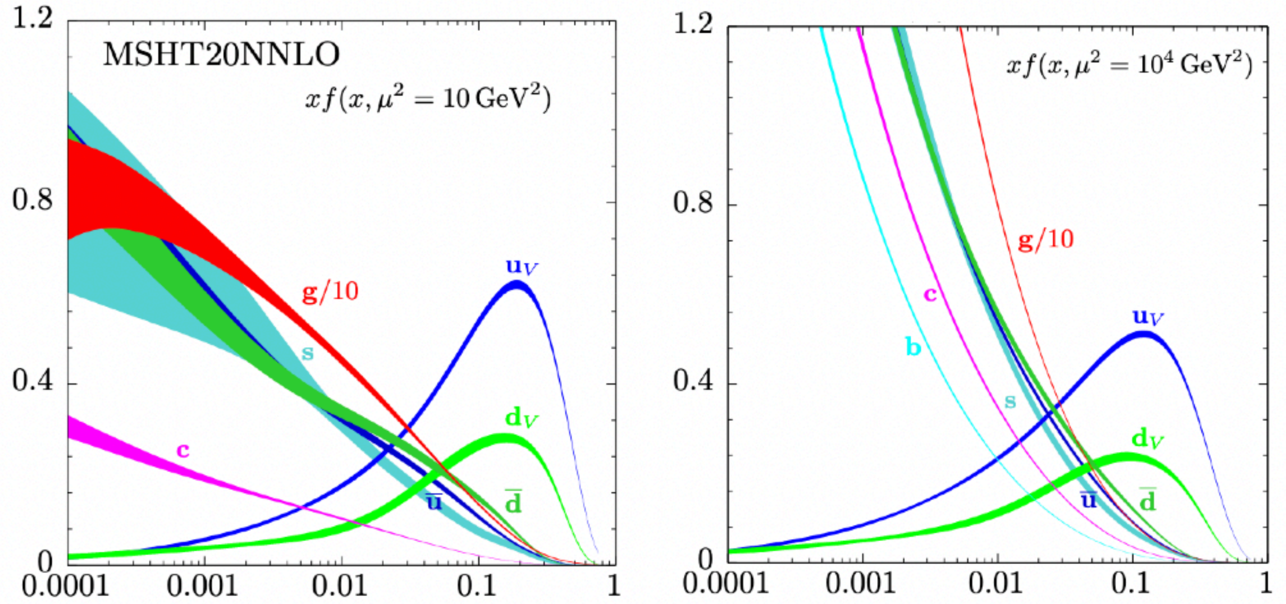
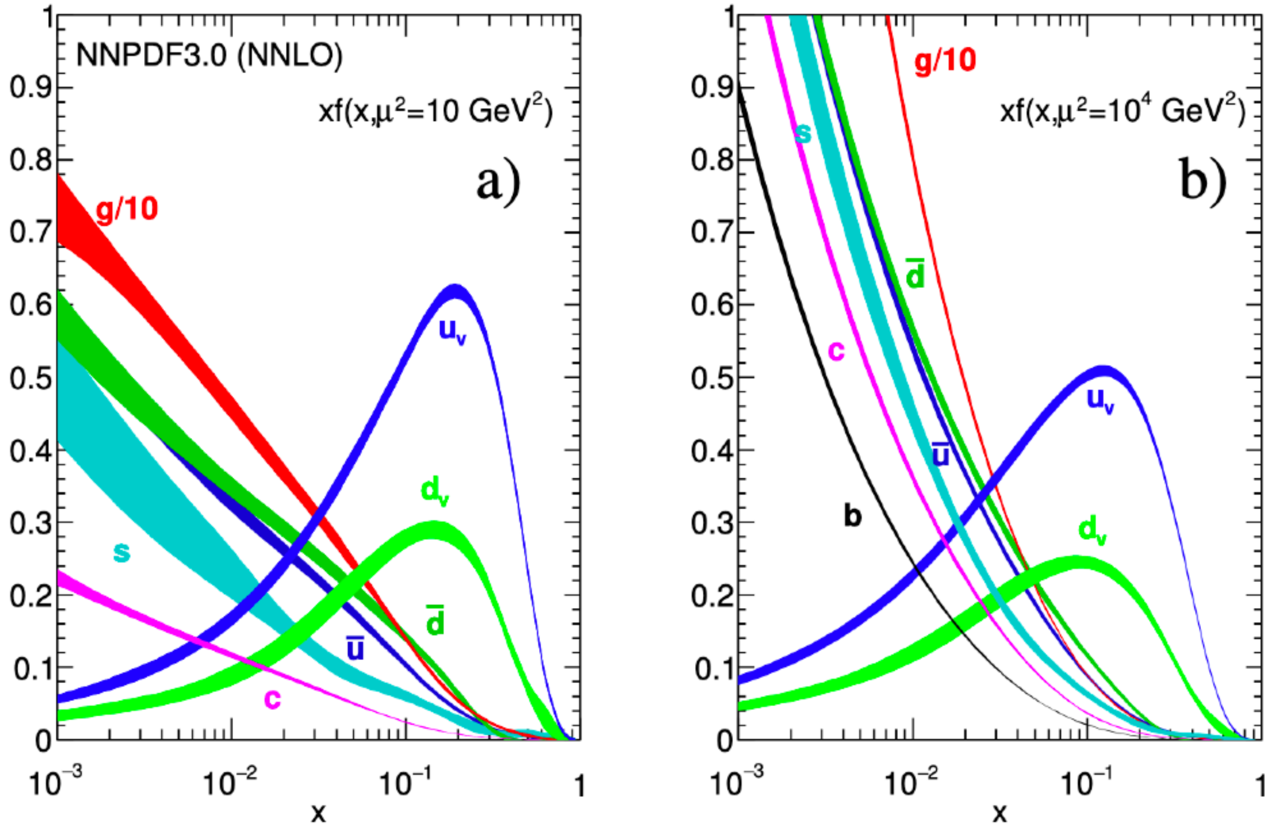
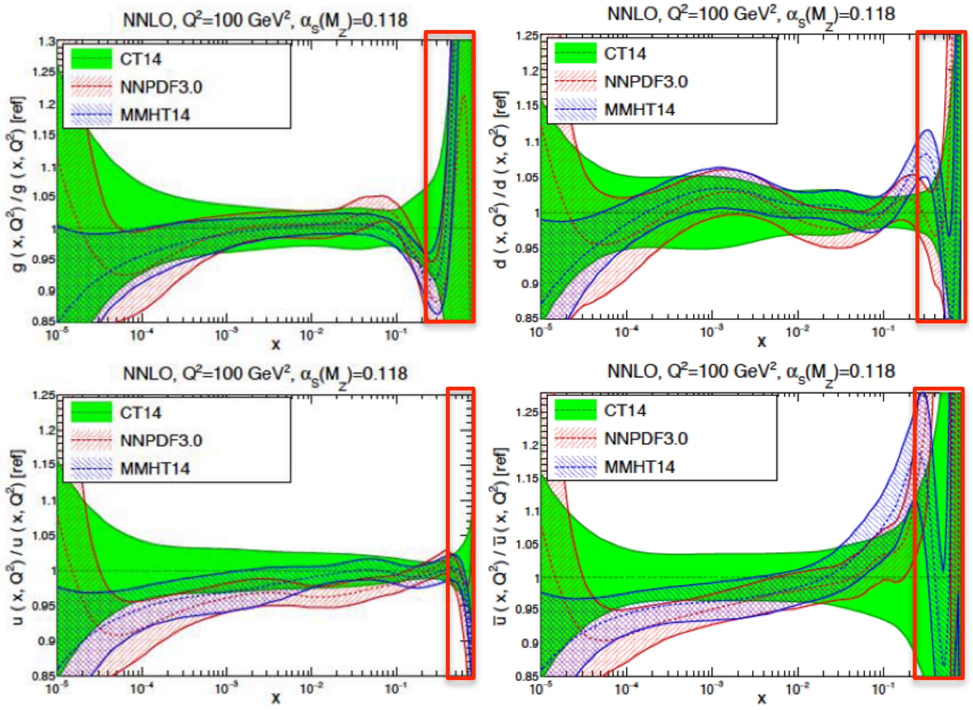
Global PDF analysis

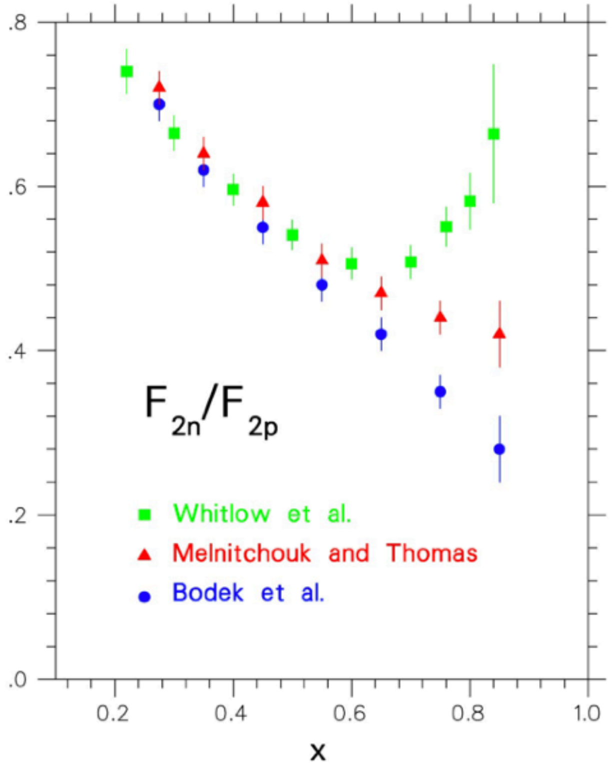


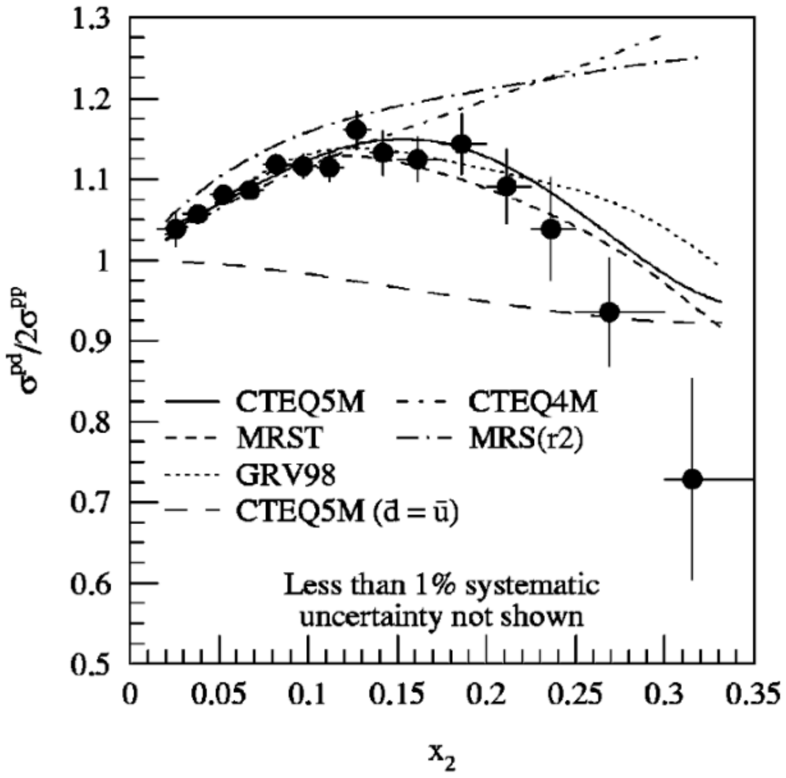




Not the end of the story







- Large-x distributions
- How about sea quarks?
- How about polarized structure?