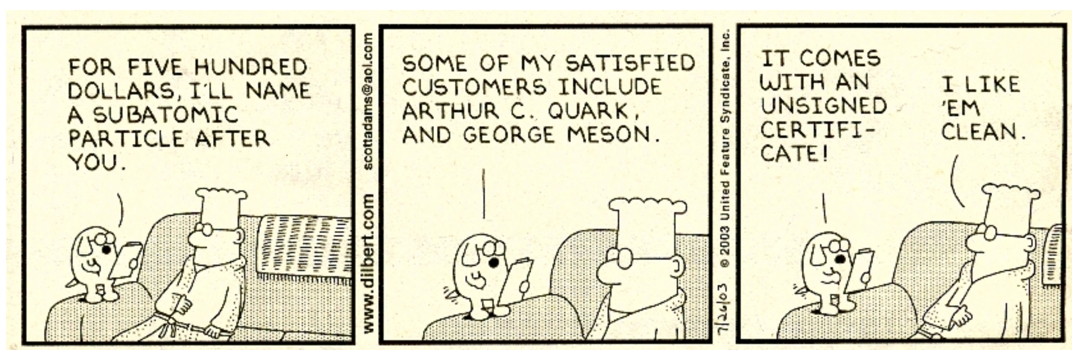
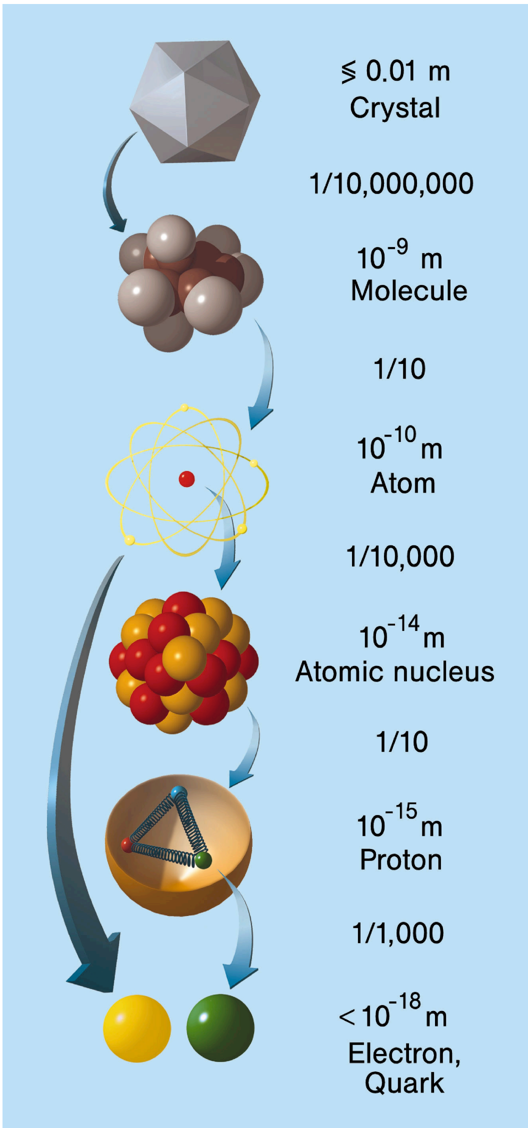
PHYS120 Part 1:

Particle/Nuclear Physics

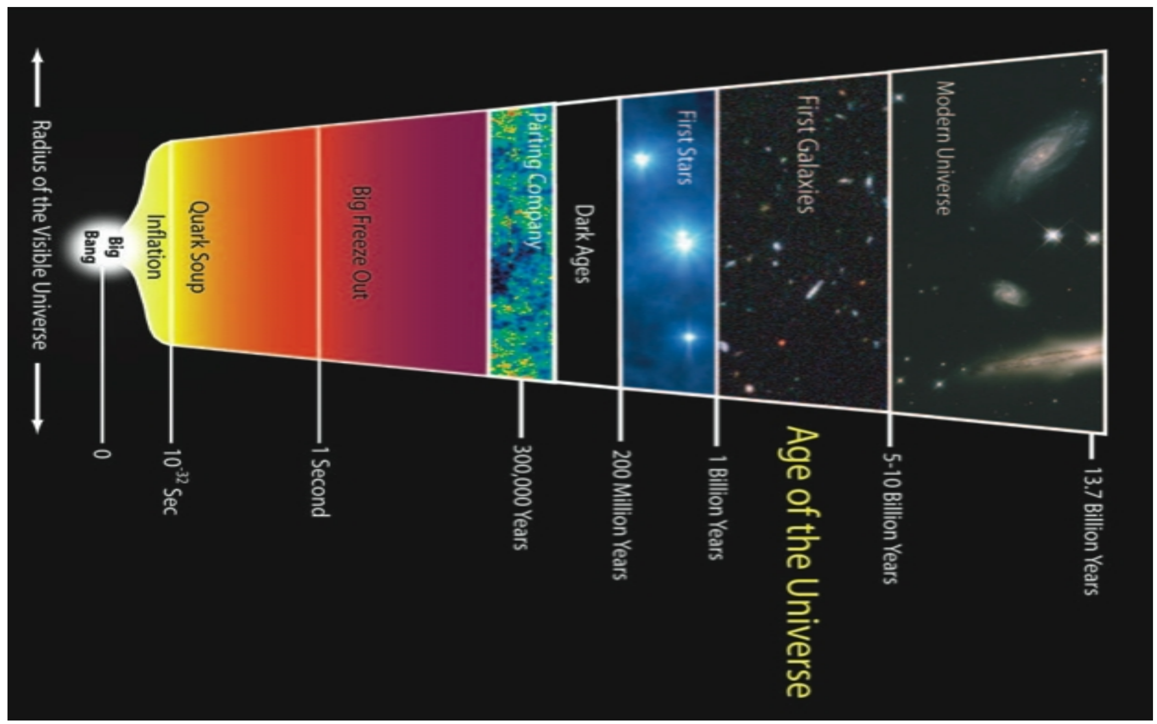
Sebastian Kuhn



The Structure of Matter

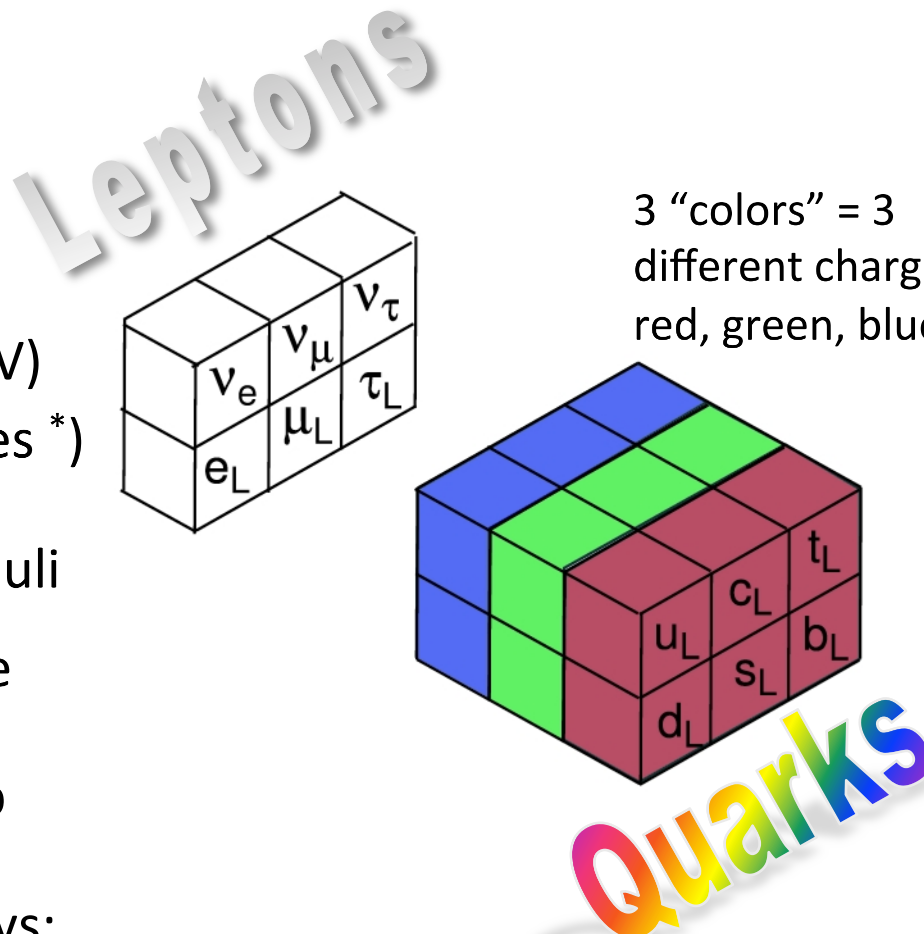


- What is the Universe made off?
- What are the most fundamental objects in Nature?
- What particles where there in the beginning (right after the big bang)?
- How do they interact?
- How do they form composite objects?



Matter Particles

- Make up visible matter
- Pointlike (<10^{-18} m), Fundamental *)
- Have mass (from < ½ eV to 178,000,000,000 eV = 178 GeV)
- Distinct from their antiparticles *)
- Fermions (Spin ½) ⇒ they "defend" their space (Pauli Principle) and can only be created in particle-antiparticle pairs
- Can be "virtual", but make up matter being (nearly) "real"
- "stable" (against strong decays; lifetimes from ∞ to 10^{-24} s)



x2 for R, x2 for antiparticles

*) Until further notice

Forces and Force Carriers

- Mediate Interactions (Forces) - form "Waves"
- Pointlike, Fundamental
- Massless *)
- Some are their own antiparticles (photon, Z^0, graviton)
- Spin 1, 2 -> Bosons (tend to cluster together, can be produced in arbitrary numbers)
- Can be real, but carry forces as virtual particles
- Some are absolutely stable (γ, gluons, gravitons)

*) See next slide

BOSONS force carriers spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

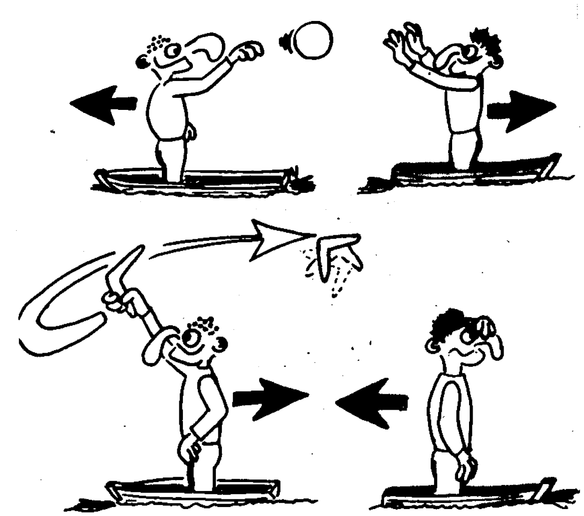
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

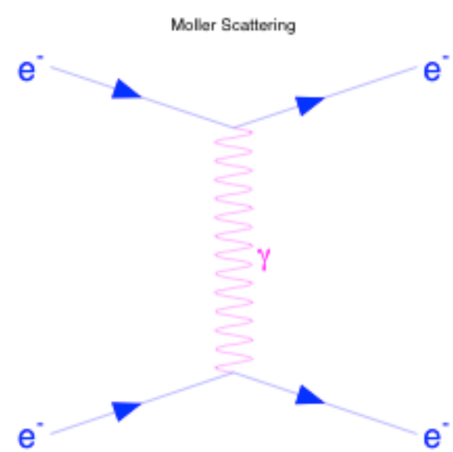
Gravitation spin = 2		
Name	Mass GeV/c^2	Electric charge
g graviton	0	0

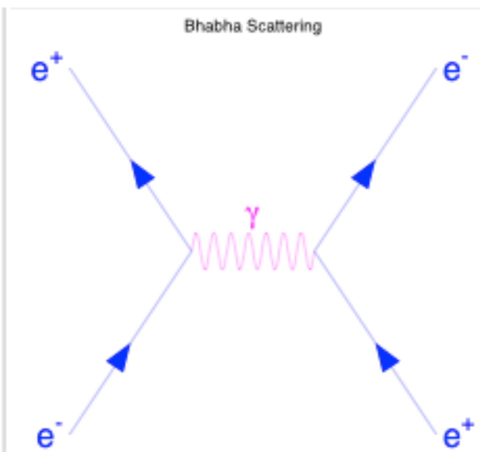
Note: gluons come in 8 possible combinations of color/anticolor (9th is "sterile" – doesn't exist)

Interactions

- Matter Particles interact with each other by exchanging Gauge Bosons
- Strength of Interaction determined by coupling ("charge": electromagnetic e, weak g, color α_S)
- Range of interaction determined by mass *) of gauge boson and Heisenberg uncertainty principle
- Examples:
  - e^- $e^{+/-}$ scattering (E&M)
  - neutron beta decay (weak)
  - quark-quark interaction (strong)
    - Confinement
    - Asymptotic freedom
    - Mesons, baryons…
    - Nπ interaction, NN interaction



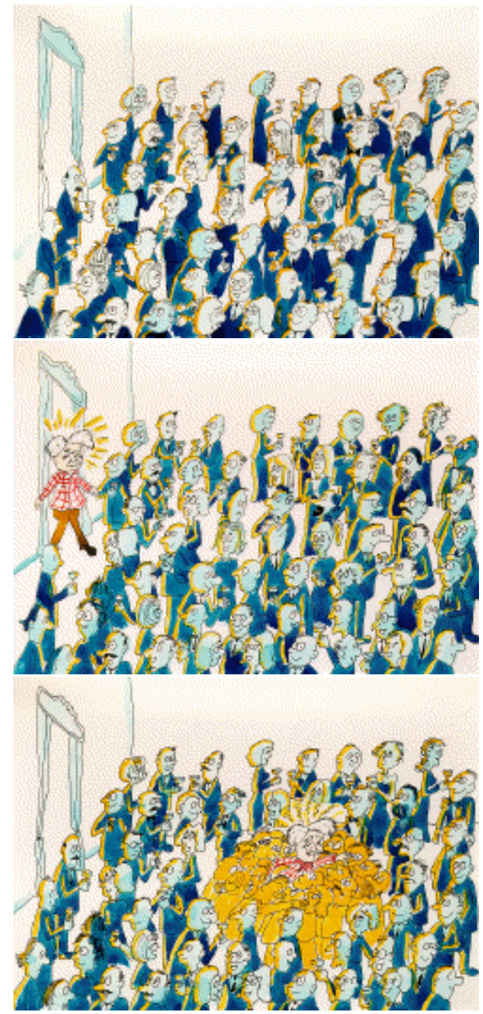




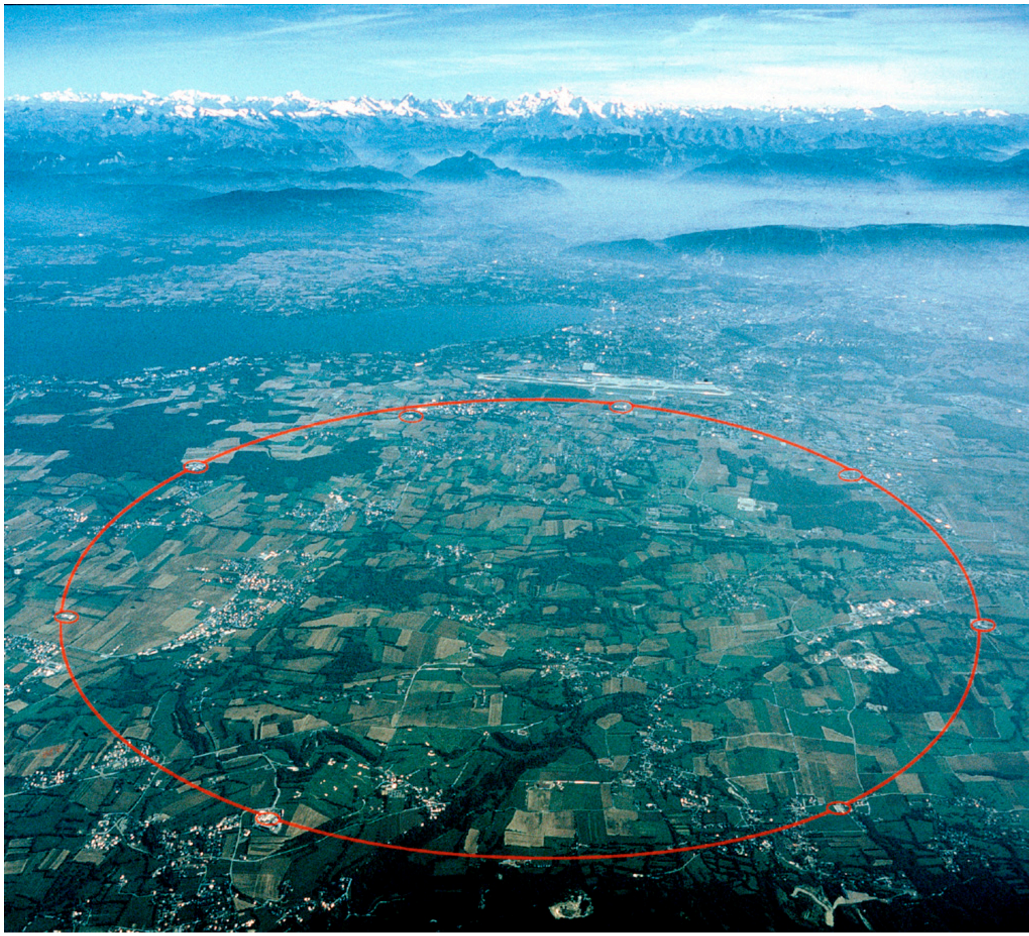
*) Huh? See next slide

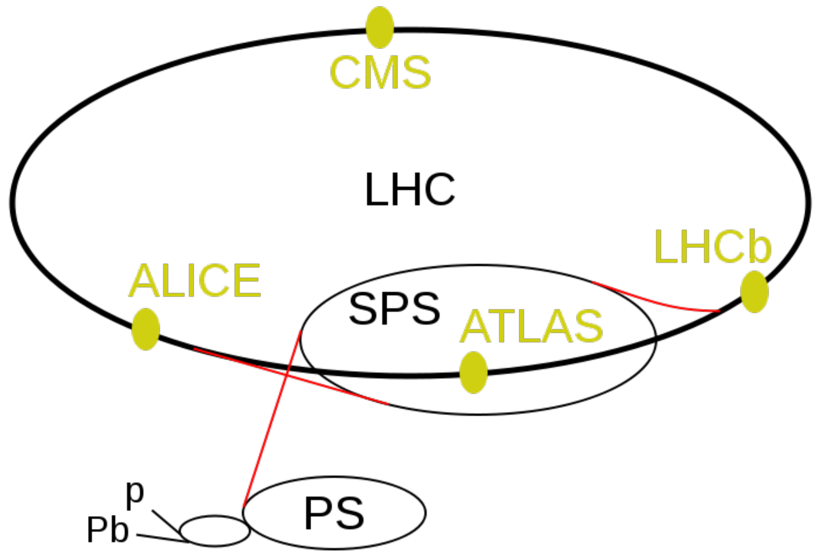
Higgs Field

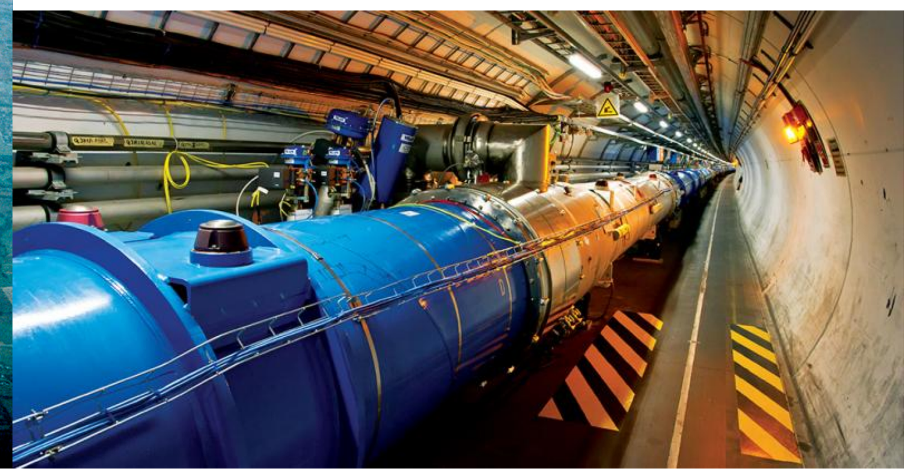
- Create "Drag" on Particles ("Molasses")
- *) Origin of Mass
  Makes some gauge bosons very heavy (W's, Z's) and therefore short-range ("Weak" interaction)
- Origin of electroweak symmetry breaking
- Pointlike, Fundamental
- Bosons (Spin 0)
- Three massless ("swallowed up" by W's, Z's); one very massive (125 GeV)
- Discovered in 2012 at CERN



The LHC at CERN

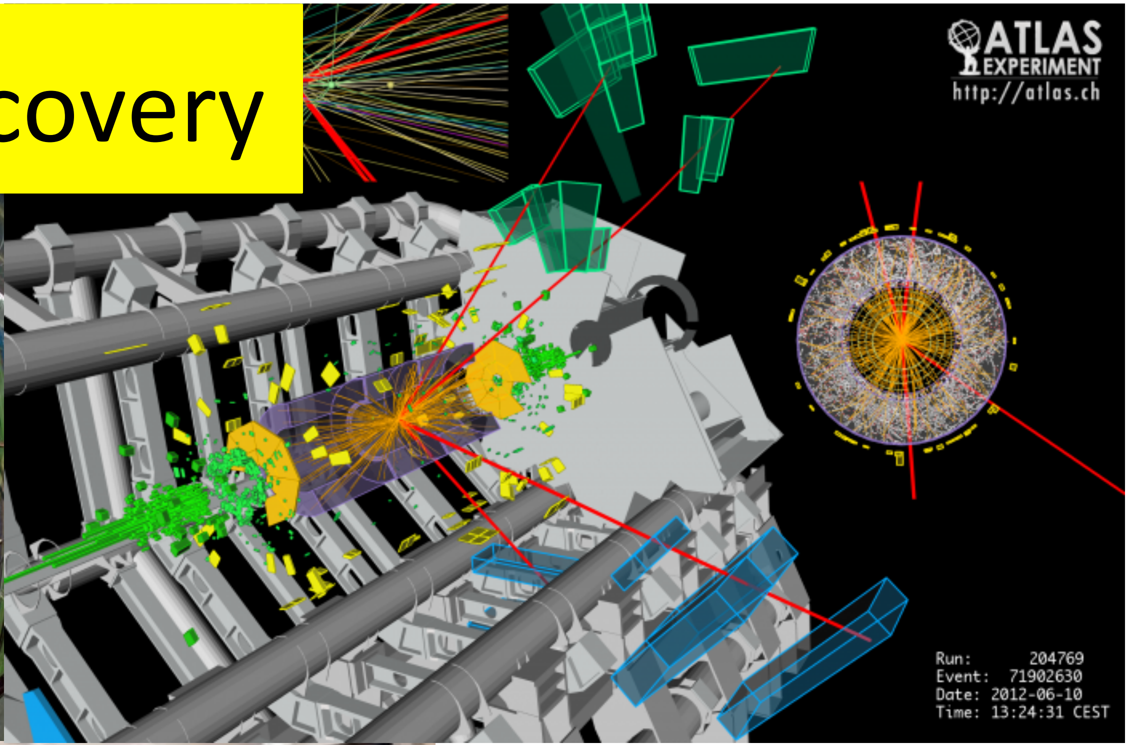


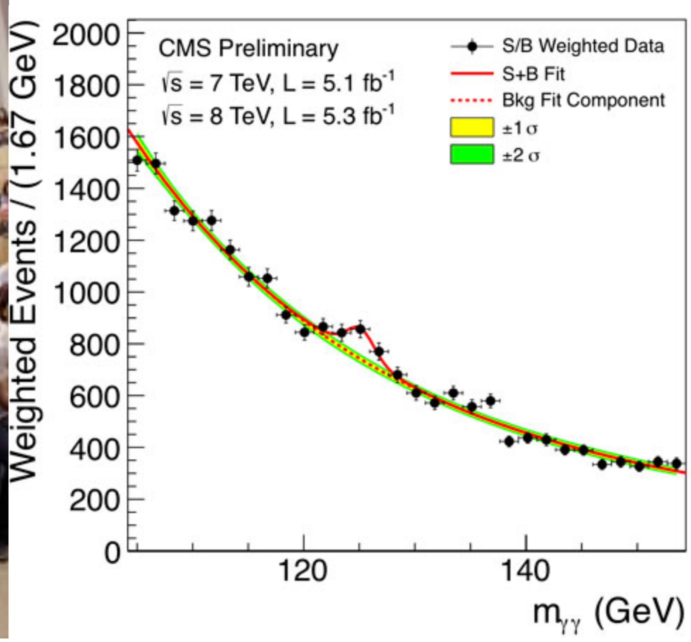




- See also the movie "Particle Fever"

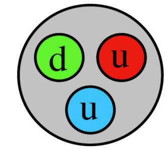
Higgs Discovery

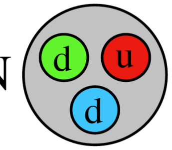




Hadronic Particle Zoo

- what can one build from quarks?

P 

N 

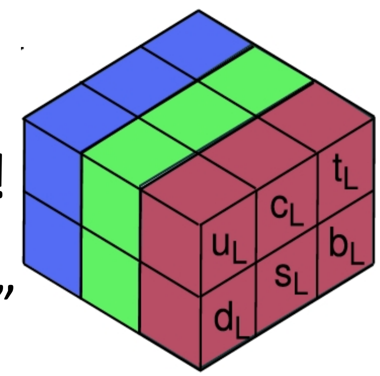
HADRONS

Family Name	Particle Name	Particle Symbol	Antiparticle Symbol	Composition	Mass	Electric Charge	Lifetime in Seconds
baryon	proton	p or p^+	$\bar{p}$	uud	1,836	+1	stable
	neutron	n or n^0	$\bar{n}$	udd	1,839	0	887
	lambda	Λ^0	$\bar{\Lambda}^0$	uds	2,183	0	2.6×10^{-10}
	lambda-c	Λ^+_c	$\bar{\Lambda}^-_c$	udc	4,471	+1	2.1×10^{-13}
	lambda-b	Λ^0_b	$\bar{\Lambda}^0_b$	udb	11,000	0	1.1×10^{-12}
	sigma	Σ^+	$\bar{\Sigma}^-$	uus	2,328	+1	0.8×10^{-10}
		Σ^0	$\bar{\Sigma}^0$	$\frac{(ud \pm du)s}{\sqrt{2}}$	2,334	0	7.4×10^{-20}
		Σ^-	$\bar{\Sigma}^+$	dds	2,343	−1	1.5×10^{-10}
	xi	Ξ^0	$\bar{\Xi}^0$	uss	2,573	0	2.9×10^{-10}
		Ξ^-	$\bar{\Xi}^+$	dss	2,585	−1	1.6×10^{-10}
	xi-c	Ξ^0_c	$\bar{\Xi}^0_c$	dsc	4,834	0	9.8×10^{-14}
		Ξ^+_c	$\bar{\Xi}^-_c$	usc	4,826	+1	3.5×10^{-13}
	omega	Ω^-	$\bar{\Omega}^+$	sss	3,272	−1	0.8×10^{-10}
	omega-c	Ω^0_c	$\bar{\Omega}^0_c$	ssc	5,292	0	6.4×10^{-14}
meson	pion	π^+	π^-	$u\bar{d}$	273	+1	2.6×10^{-8}
		π^0	π^0	$\frac{(u\bar{u} - d\bar{d})}{\sqrt{2}}$	264	0	8.4×10^{-17}
	kaon*	K^+	K^-	$u\bar{s}$	966	+1	1.2×10^{-8}
		K^0	$\bar{K}^0$	$d\bar{s}$	974	0	8.9×10^{-11} 5.2×10^{-8}
	J/psi	J or Ψ	J or Ψ	$c\bar{c}$	6,060	0	1.0×10^{-20}
	omega	ω	ω	$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$	1,532	0	6.6×10^{-23}
	eta	η	η	$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$	1,071	0	3.5×10^{-22}
	eta-c	η_c	η_c	$c\bar{c}$	5,832	0	3.1×10^{-22}
	B	B^0	$\bar{B}^0$	$d\bar{b}$	10,331	0	1.6×10^{-12}
		B^+	B^-	$u\bar{b}$	10,331	+1	1.6×10^{-12}
	B-s	B^0_s	$\bar{B}^0_s$	$s\bar{b}$	10,507	0	1.6×10^{-12}
	D	D_0	$\bar{D}_0$	$c\bar{u}$	3,649	0	4.2×10^{-13}
		D^+	D^-	$c\bar{d}$	3,658	+1	1.1×10^{-12}
	D-s	D^+_s	D^-_s	$c\bar{s}$	3,852	+1	4.7×10^{-13}
	chi	χ^0_c	χ^0_c	$c\bar{c}$	6,687	0	3.0×10^{-22}
	psi	Ψ^0_c	Ψ^0_c	$c\bar{c}$	7,213	0	1.5×10^{-20}
	upsilon	Υ	Υ	$b\bar{b}$	18,513	0	8.0×10^{-20}

*The neutral kaon is composed of two particles; the average lifetime of each particle is given.

Fundamental Problem of Nuclear and Hadronic Physics

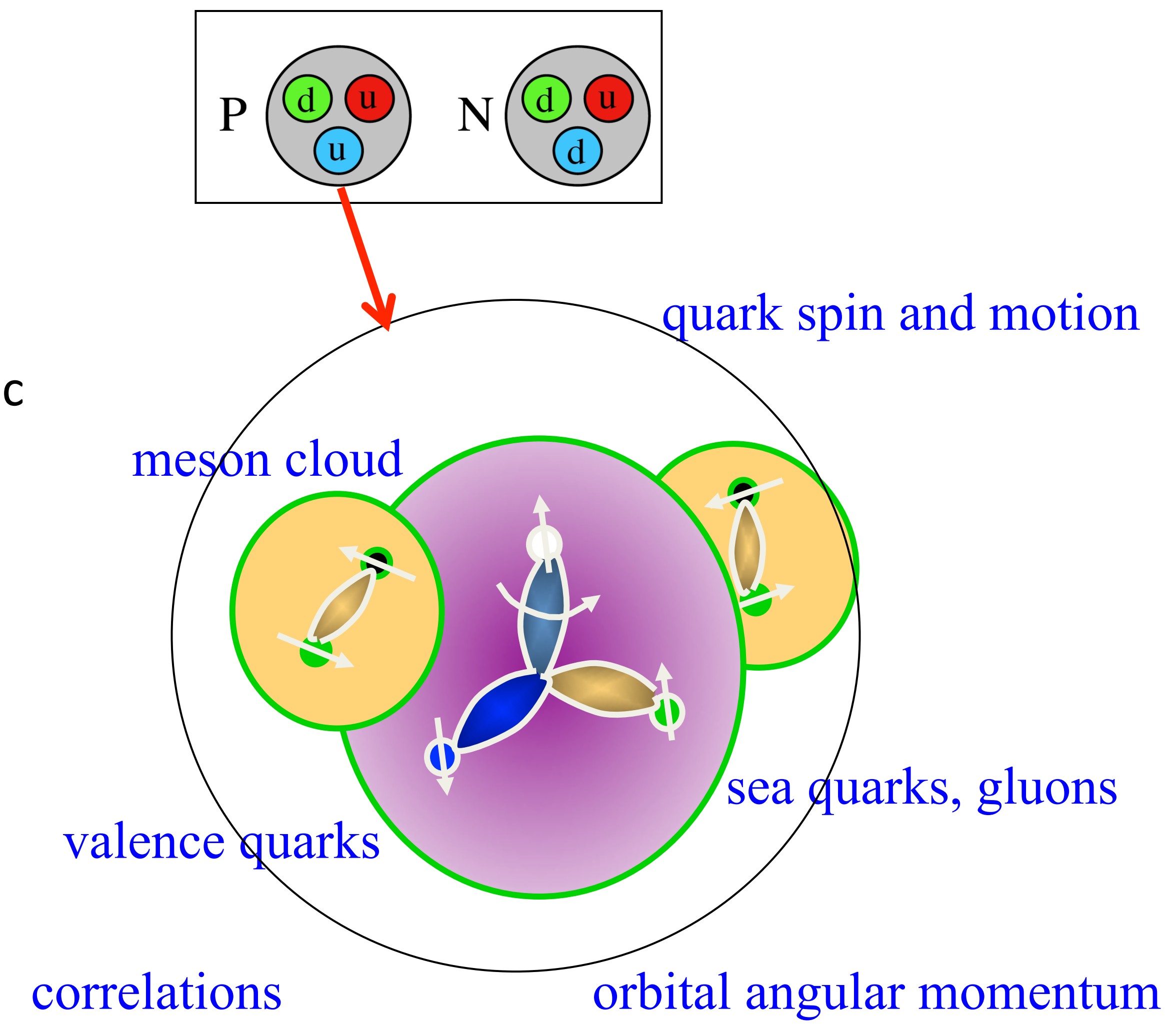
- Nearly all well-known ("visible") mass in the universe is due to hadronic (=strongly interacting) matter (protons, neutrons, pions, kaons, …)
- Fundamental theory of hadronic matter exists since the 1960-70's: Quantum Chromo Dynamics
  - "Colored" quarks (u,d,c,s,t,b) and gluons; interaction
- BUT: knowing the ingredients doesn't mean we know how to build hadrons and nuclei from them!
  - akin to the question:
    "Given bricks and mortar, how do you build a house?"



- 2 related puzzles:
  - What is the "quark-gluon wave function" of known hadrons?
  - How are hadrons (nucleons) bound into nuclei?
    Does their quark-gluon wave function change inside a nucleus?

Hadron Structure

- Simple-most (constituent quark) model of nucleons (protons and neutrons)
- … becomes much more complicated once we consider the full relativistic quantum field theory called QCD



QCD = Quantum Chromo Dynamics = theory of strong interactions between quarks and gluons

⇒ Our 1D View of the Nucleon

(depends on energy ν and wave length of the virtual photon ~ $1/Q^2$)

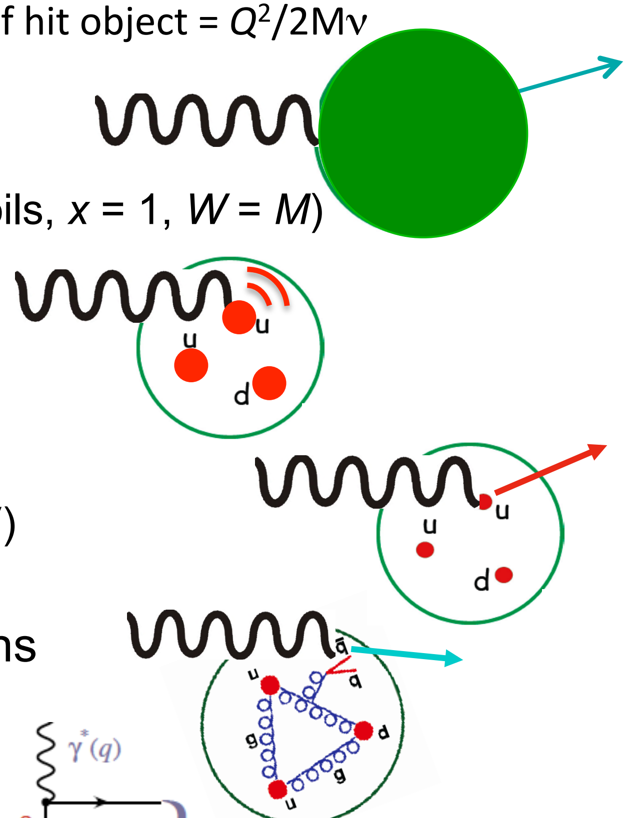
W = final state invariant mass = $\sqrt{M^2 + 2M\nu - Q^2}$

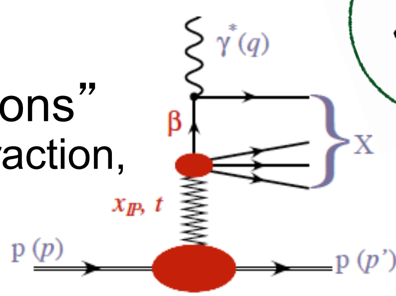
x = energy fraction of hit object = $Q^2/2M\nu$

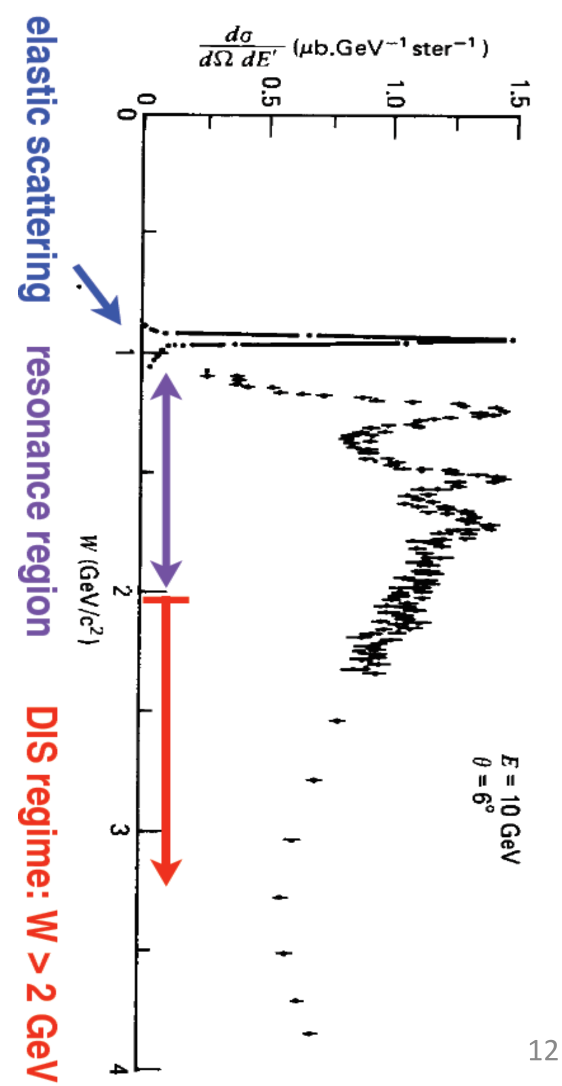
JLab

DIS

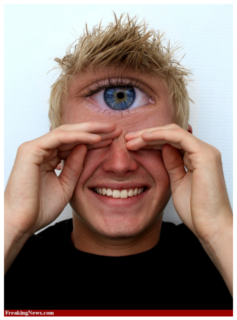
- Elastic scattering
  (Whole system recoils, $x = 1$, $W = M$)
- Resonances
  ($x < 1$, $W < 2$ GeV)
- Valence quarks
  ($x \geq 0.3$, $W > 2$ GeV)
- Sea quarks, gluons
  ($x < 0.3$)
- "Wee Partons"
  ($x \to 0$, Diffraction, Pomerons)







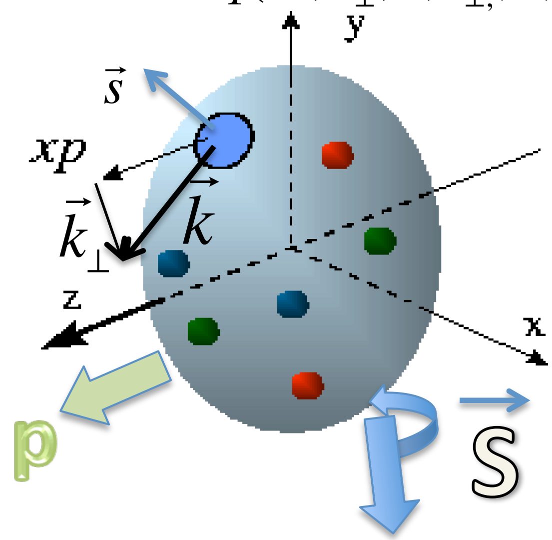
The Future: 3D Partonic Structure (Holography)

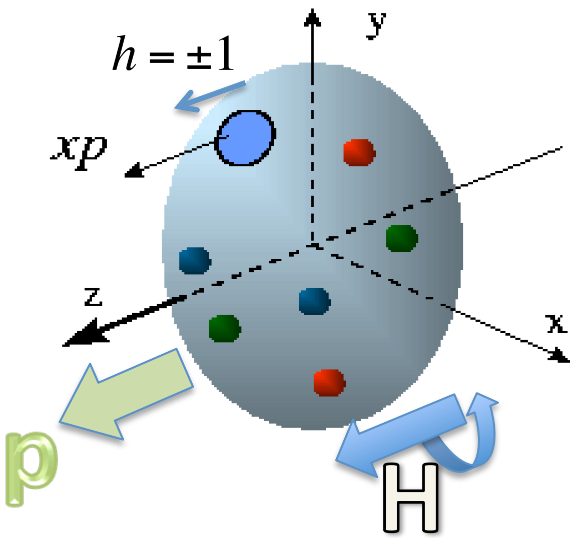


- From 1-D to 3-D:

3-D Picture of parton flavor, spin and momentum (TMDs)

$$q(H,\vec{S}_\perp,x,\vec{k}_{\perp},h,\vec{s}_\perp;Q^2)$$



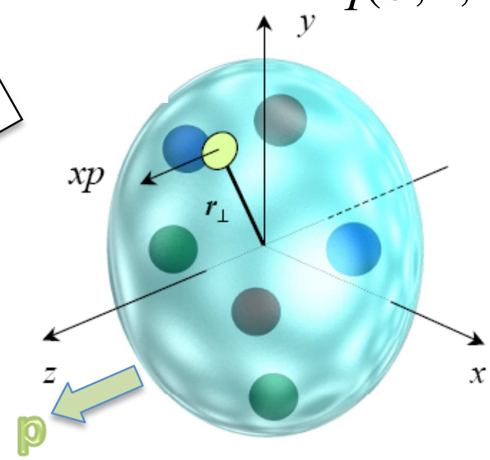


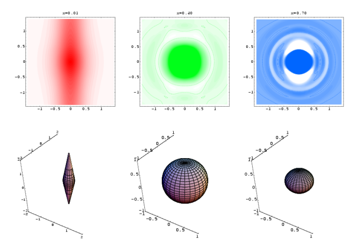
$$q(x;Q^2),\langle h\cdot H\rangle q(x;Q^2)$$

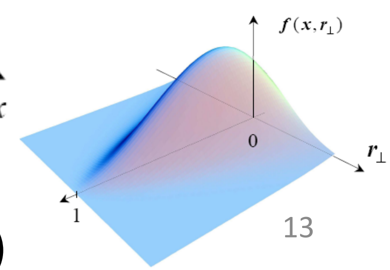
Traditional "1-D" Parton Distributions (PDFs)

(inclusive, integrated over many variables)

$$q(\vec{S},x,\vec{r}_{\perp},\vec{s};Q^2)$$



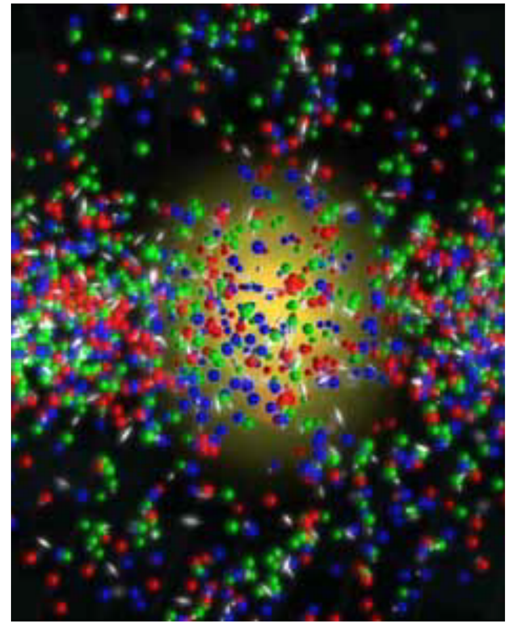


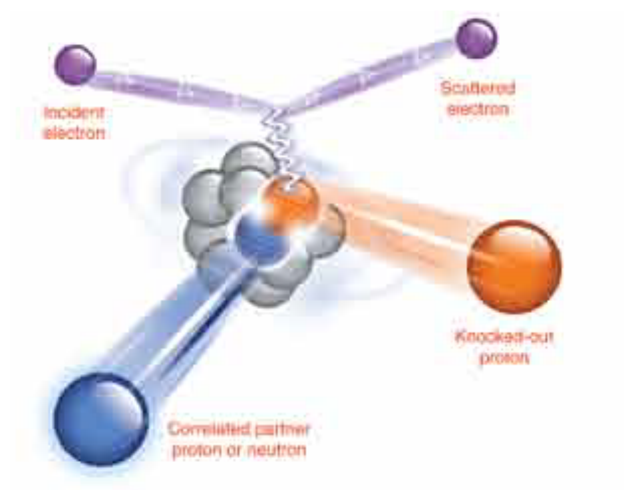


3-D parton orbits (GPDs)

Nuclear Structure

- Even more complicated!
- Nuclei effectively look like a bunch of nucleons, mesons, nucleon resonances… bound together by the strong interaction
- Ultimately, must be explained in terms of quarks and gluons, as well!
- Quark structure might be modified (EMC effect) and in turn affects nuclear binding

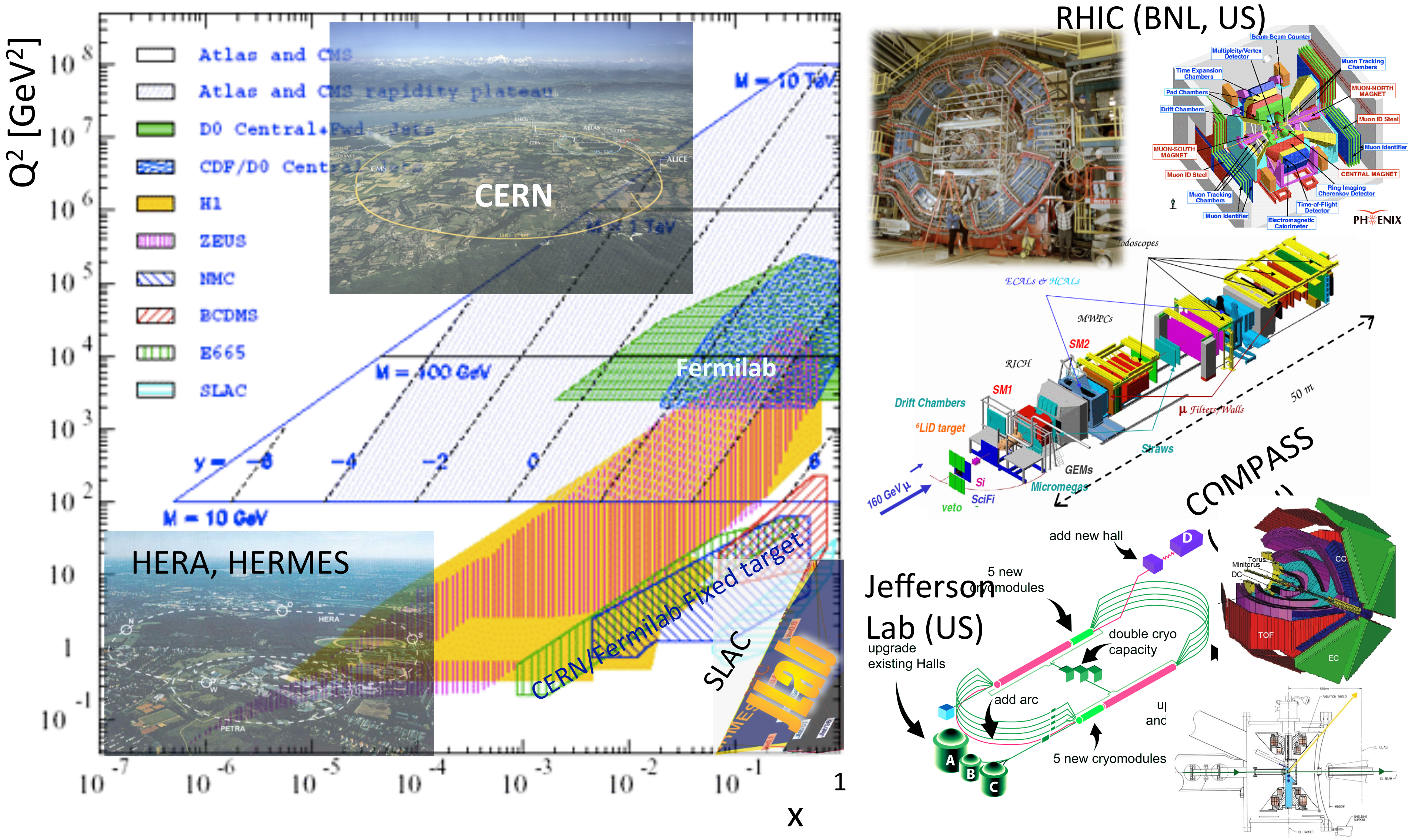




How Do We Study Hadron/Nuclear Structure?

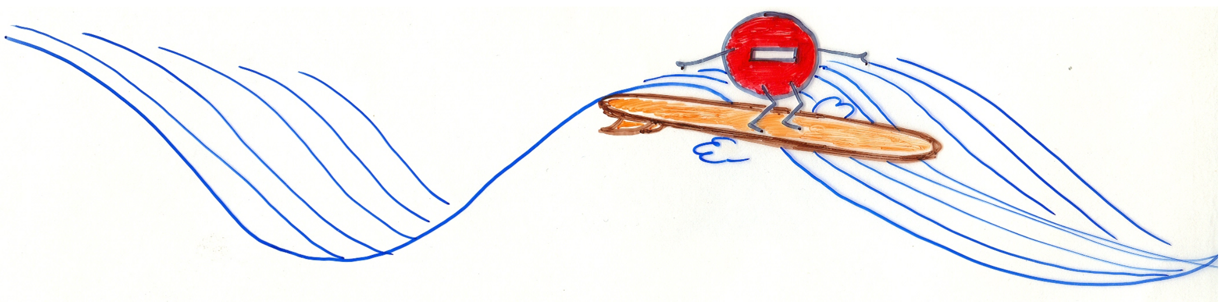
- Energy levels: Nuclear and particle (baryon, meson) masses, excitation spectra, excited state decays -> Spectroscopy
  (What states exist?)
- Elastic and inelastic scattering, particle production, Reactions
  (*How do they interact?*)
- Probing the internal structure directly
  Imaging, "Tomography" and "Holography"
  (*Shape and Content?*)

Experimental Facilities



Example: Jefferson Lab

Electrons get accelerated to 99.9999999% of the speed of light (12 GeV)…



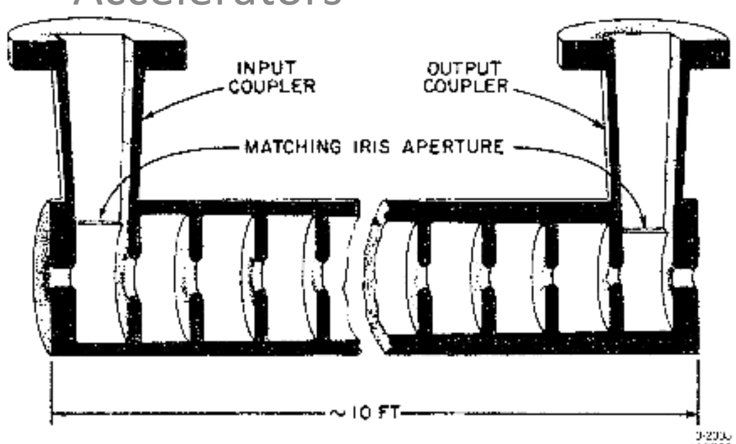
Surf the microwaves!

Accelerating cavity: disk loaded cylindrical wave guide

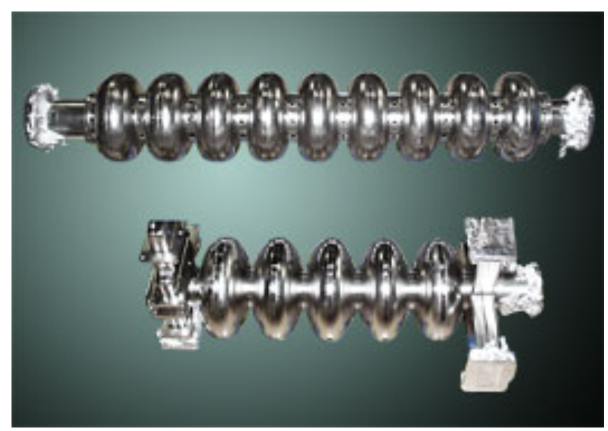
use TM_{01} mode to get a longitudinal electric field

match phase and velocity

Accelerators



DESY



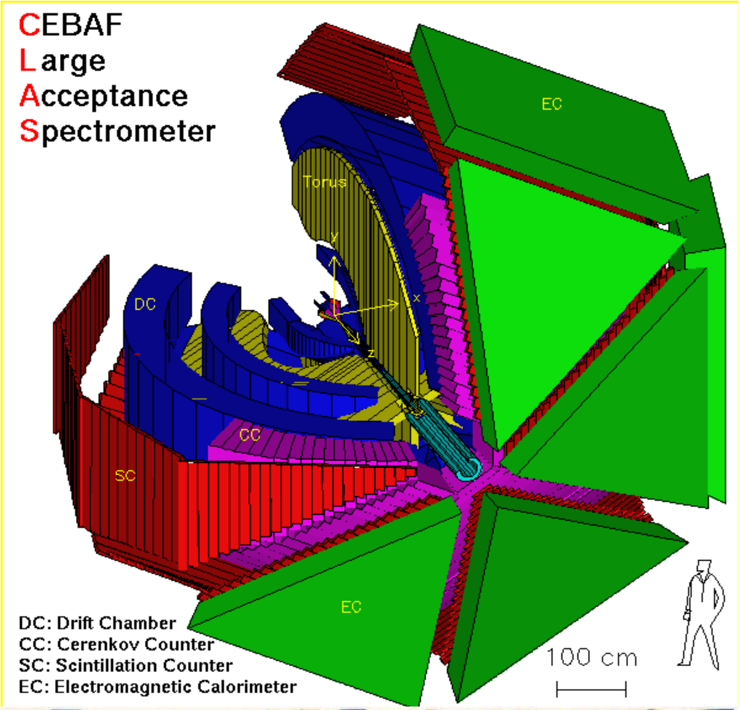
new

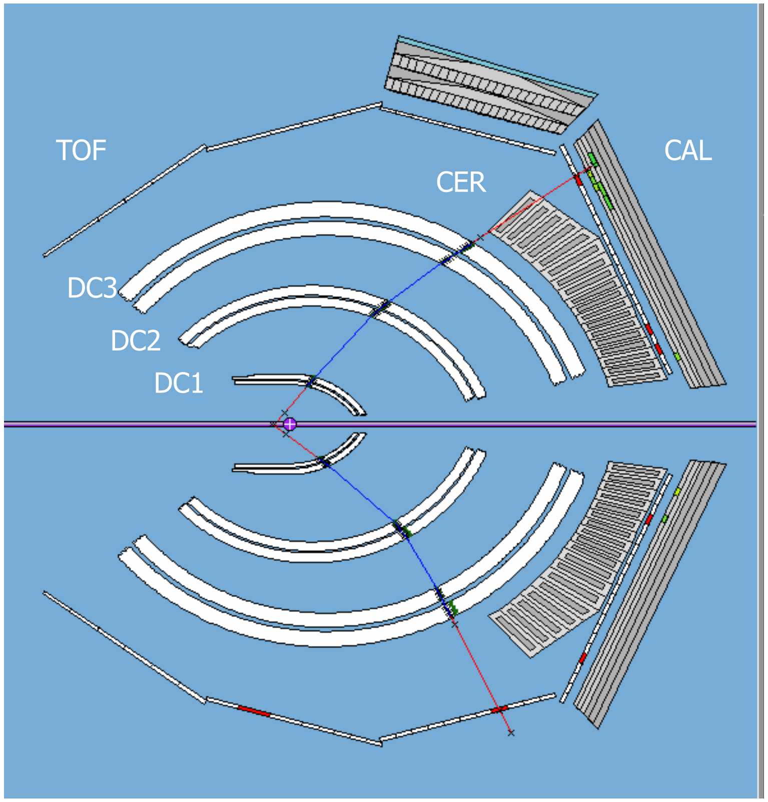
old

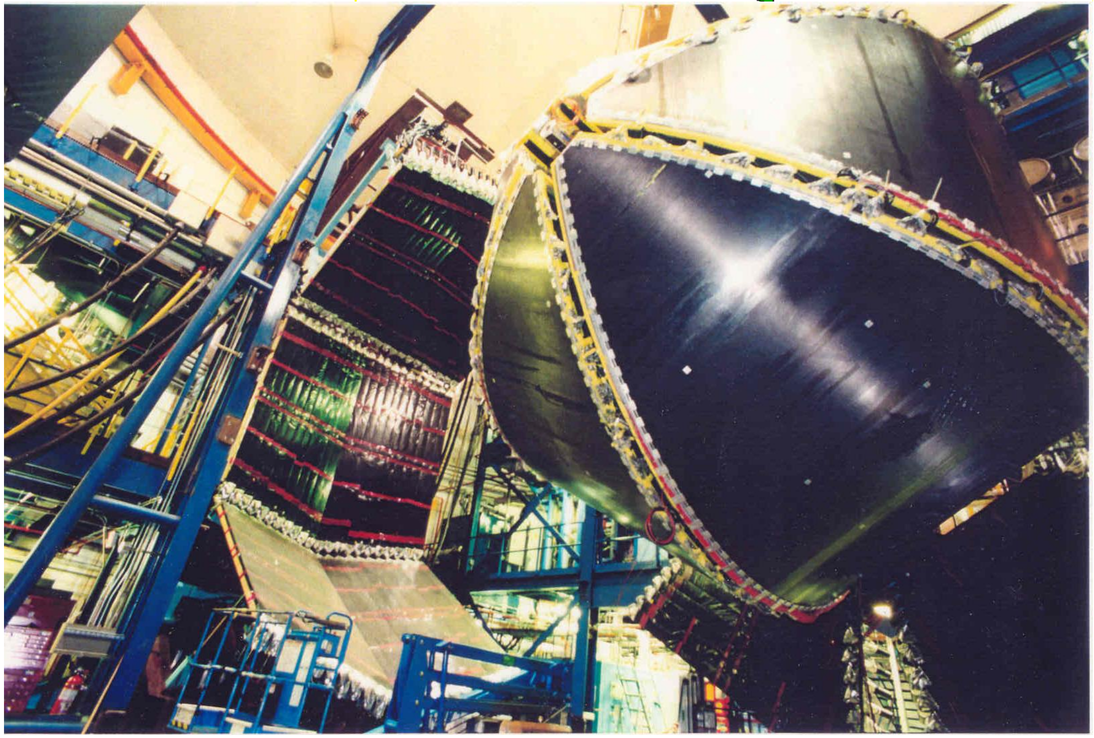
Jefferson Lab

Example: Jefferson Lab

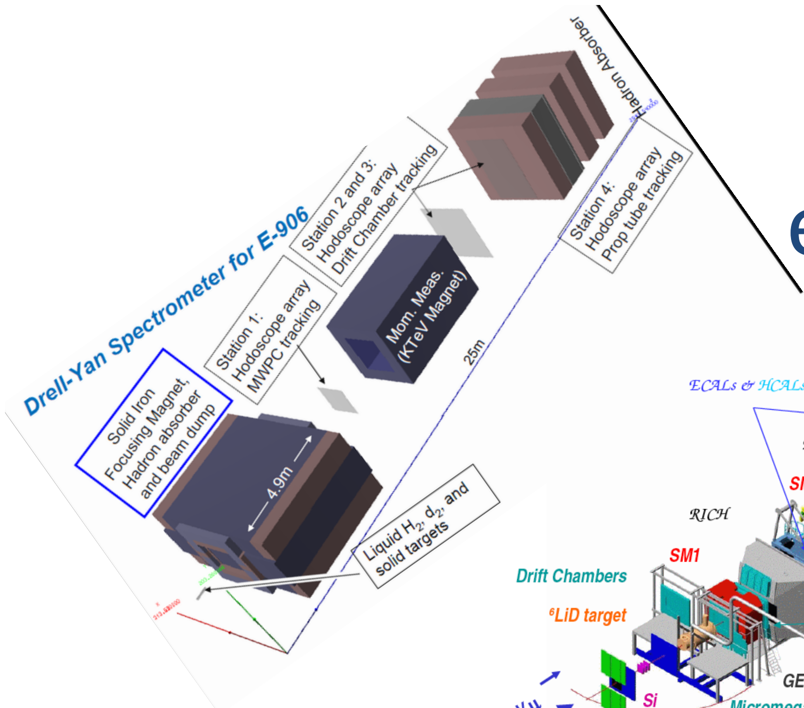
…and smashed into a "target".
The debris is detected and measured.

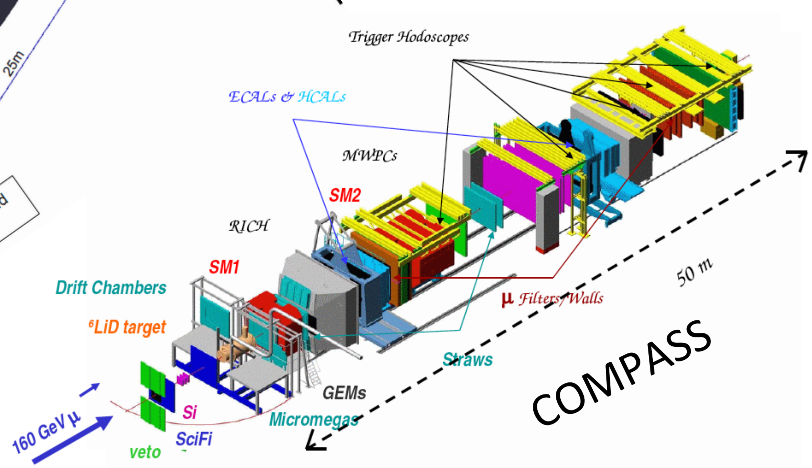




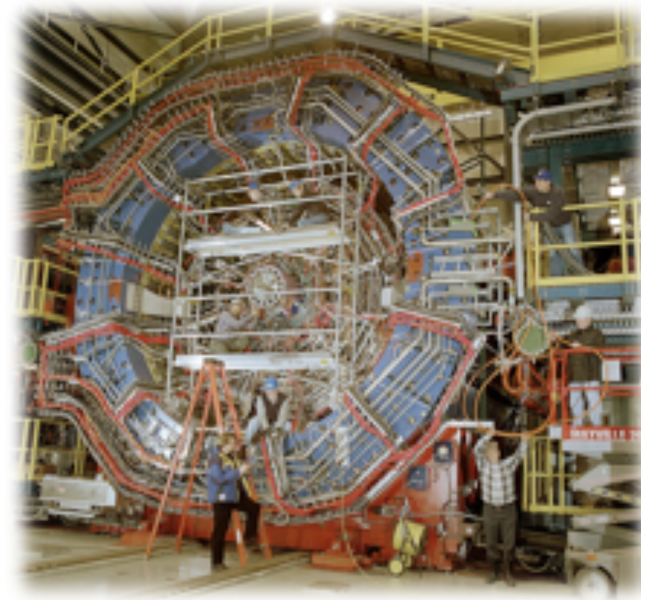


Other experiments

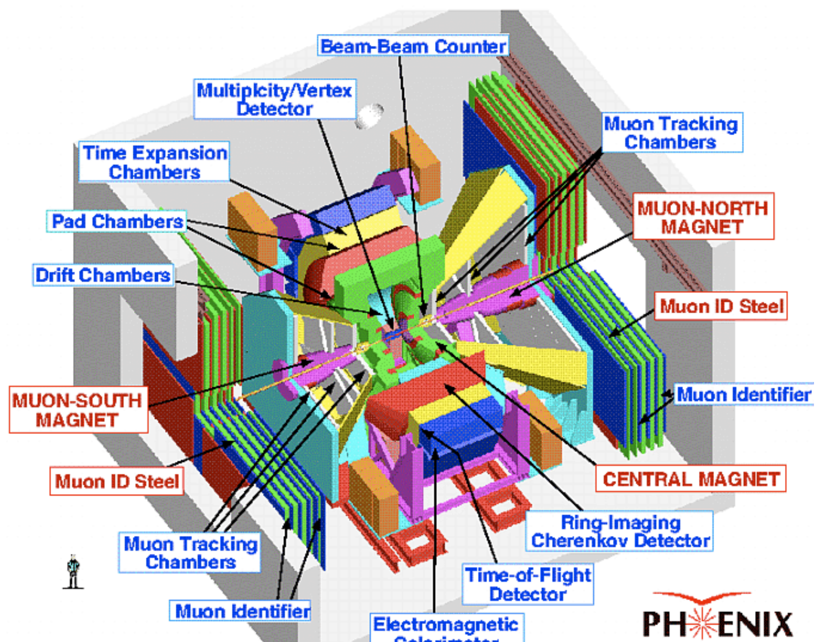


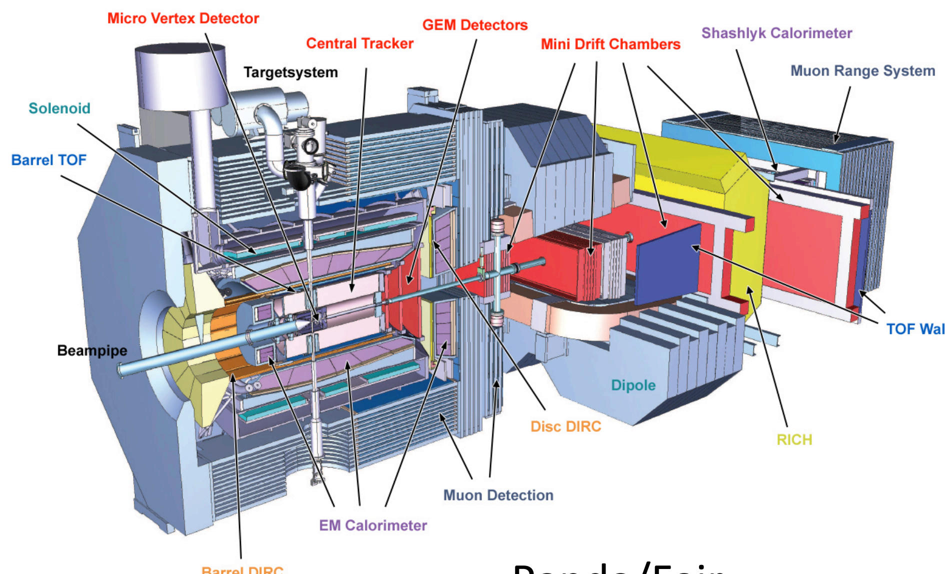


COMPASS

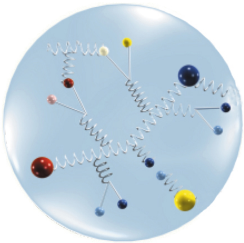


STAR

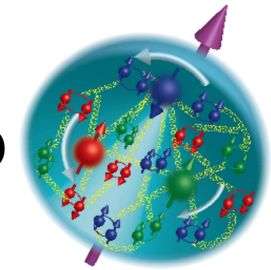




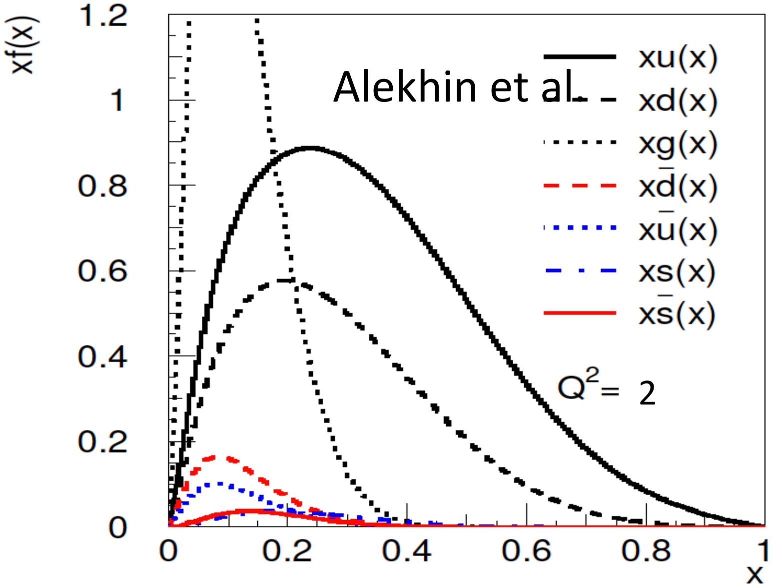
Panda/Fair



…and what have we learned?

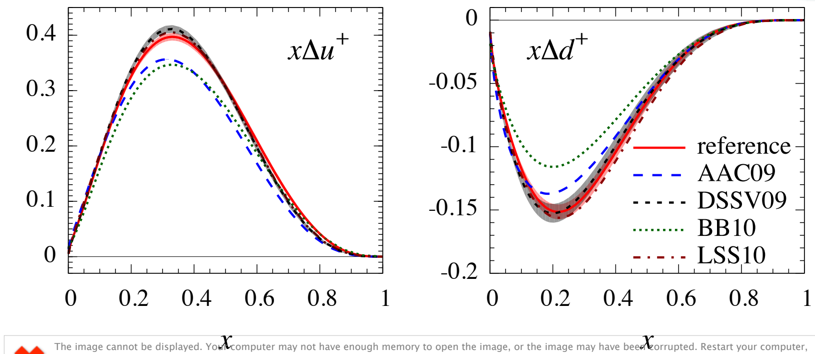


How many of those partons are there?



Fraction of p mass carried by partons

…times spin



- Begun to map the 1D and even 3D motion of quarks and gluons inside nucleons
- Developed an approximate solution of QCD (Lattice QCD) that can predict masses, excited states etc.
- “Sorta” understand the size, magnetic moment and other properties of nucleons
- Begun to get a QCD-based picture of nuclei
- BUT: Much left to do – will you join us?

The future landscape of Nuclear Physics

1. Study how nucleons are made up from quarks ("flavor", **p**, **L**, **S** -> 3D tomography)
2. Study how hadronic quark structure is influenced by the nuclear environment
3. Understand nuclear structure and dynamics in terms of quark degrees of freedom
4. Study extreme forms of nuclear matter: high energy (Quark-Gluon plasma), high density (short range correlations, n stars, "color glass condensates",…), non-zero strangeness (hypernuclei, strangelets, …), large n/p imbalance (radioactive beams)…
5. Study fundamental symmetries, neutrinos, nuclei in the universe
6. Develop new applications in medicine, energy, materials, homeland security, …

Hadron Machines

FAIR

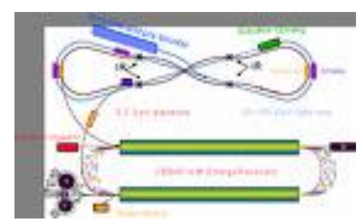
J-PARC

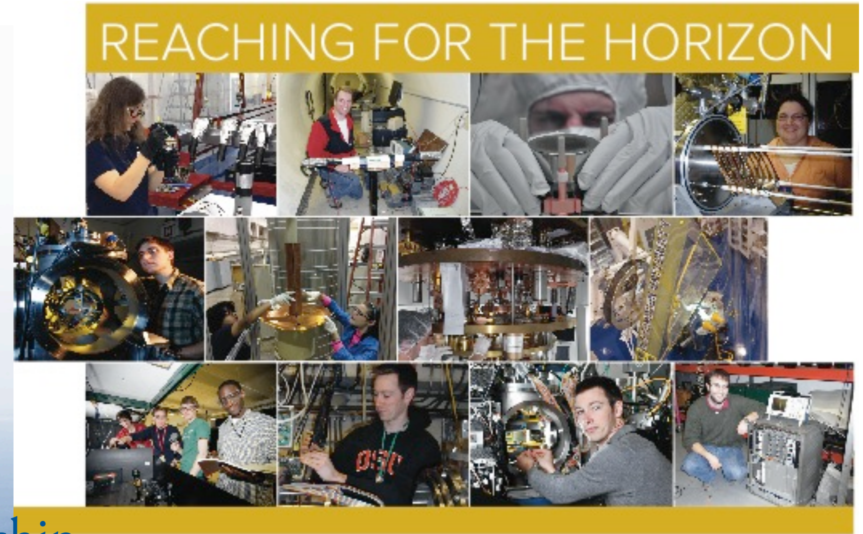
LHC

Electron machines

Jlab

Electron-Ion-Collider (2025?)





A.2 The Long Range Plan Working Group Membership