

Physics on target:

Structure of matter

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BND Graduate School

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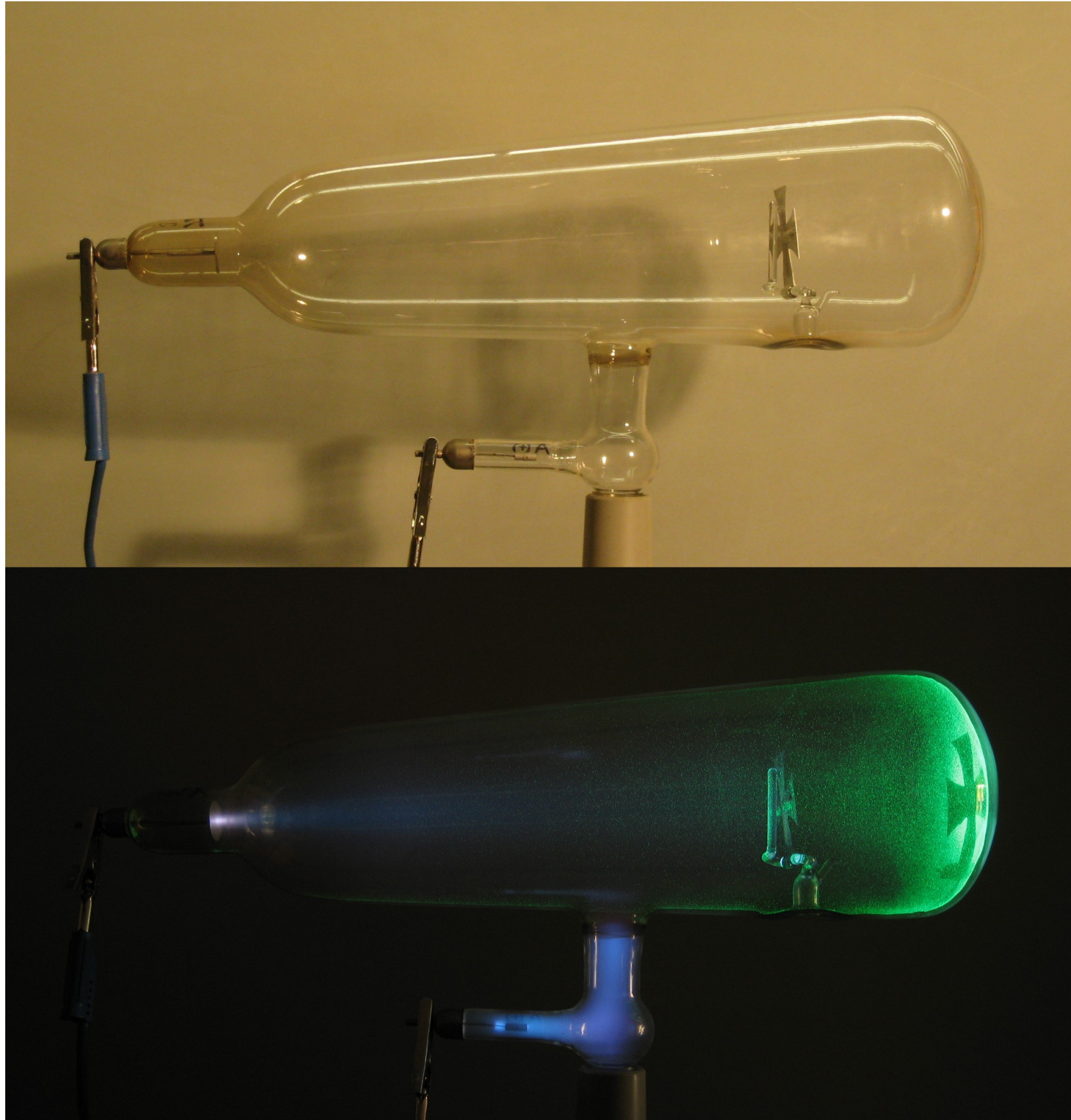
Hand mit Ringen S. 2. n. 14.



Eigenthum von Prof. Zehnder
Freiburg i/B



Mysterious rays



D-Kuru/Wikimedia Commons

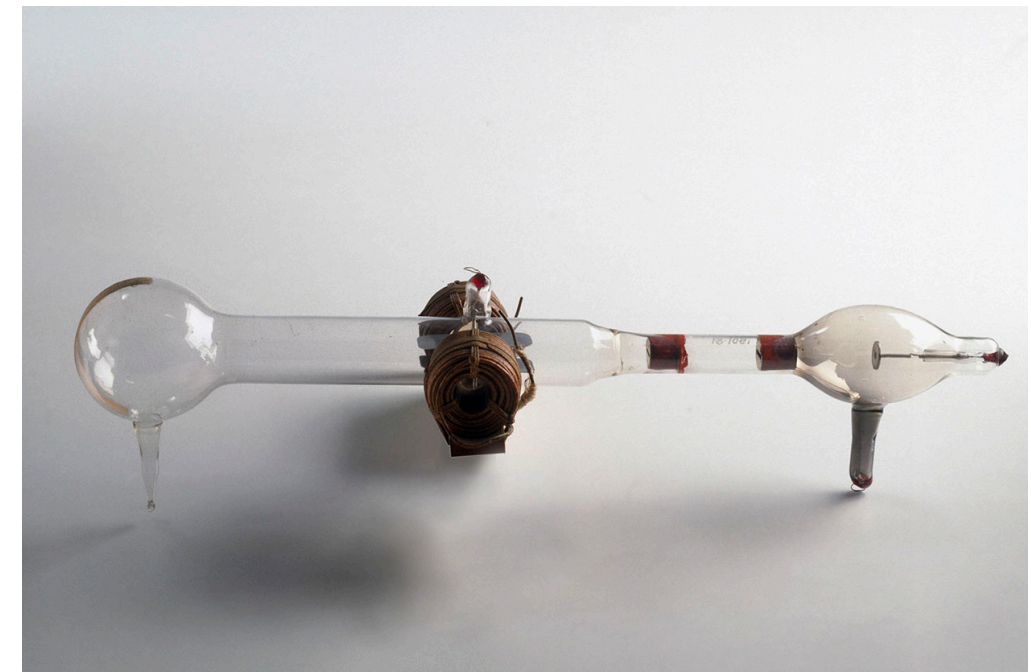
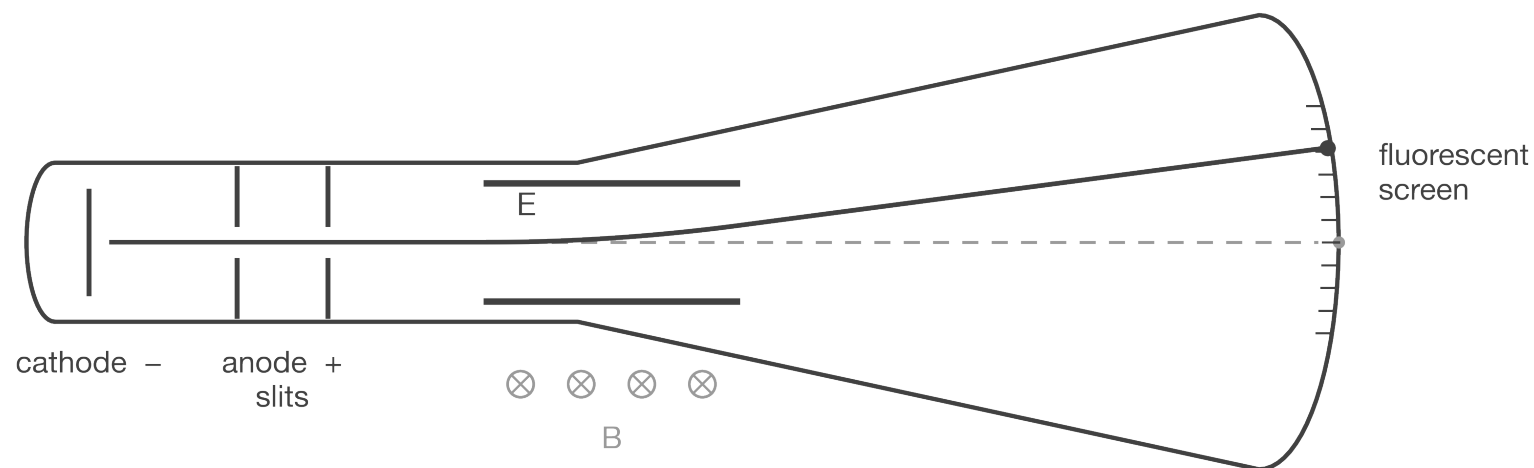
The first beam

- J. J. Thomson (1897): cathode rays bent by electric and magnetic fields → a charged particle
- By changing E and B: $e/m \approx 1800 \times$ hydrogen
- Same results for every cathode metal and gas type
- A corpuscle lighter than the lightest atom → **the electron**
- The first beam-on-target controlled collisions

THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.
—♦—
[FIFTH SERIES.]
OCTOBER 1897.

XL. Cathode Rays. By J. J. THOMSON, M.A., F.R.S.,
Cavendish Professor of Experimental Physics, Cambridge*.

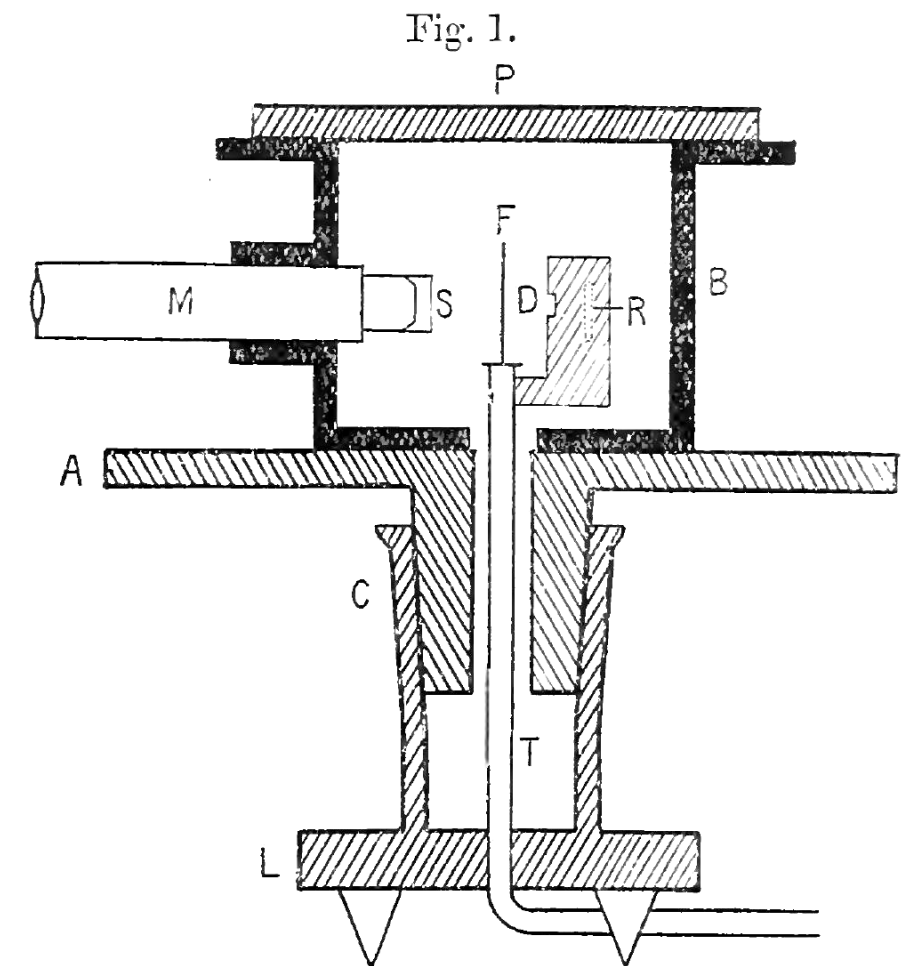
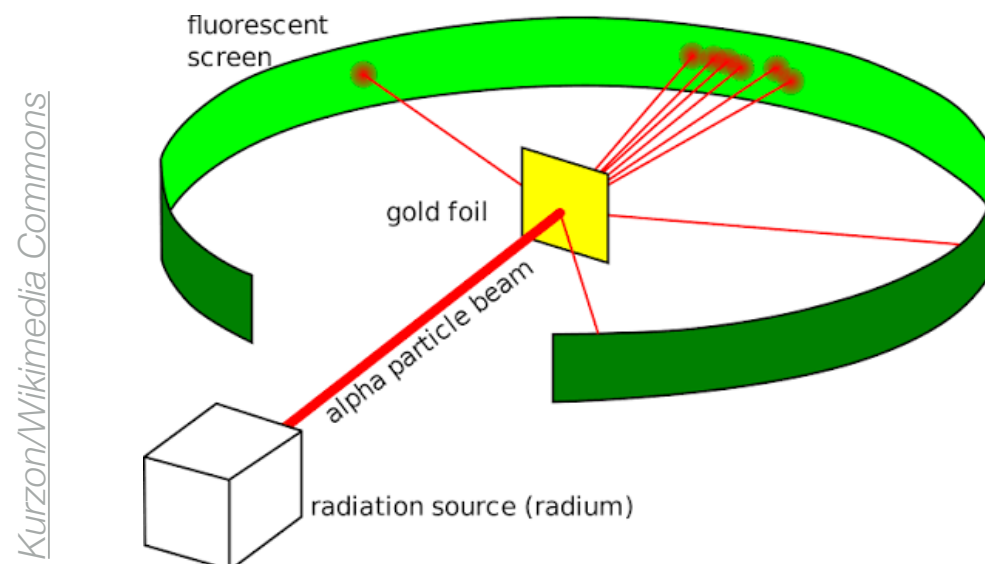
J. J. Thomson, Phil. Mag. 44 (1897) 293



Thomson tube, Science Museum London

The gold-foil experiment

- Geiger & Marsden fire α particles at gold foil to observe mild deflections
- Actual finding: ≈ 1 in 8000 particles comes straight back
- Rutherford: all charge and mass in a tiny point much smaller than atom size: the nucleus
- First fixed-target experiment to explore the **atomic structure**



Geiger & Marsden, Proc. Roy. Soc. A 82 (1909) 495

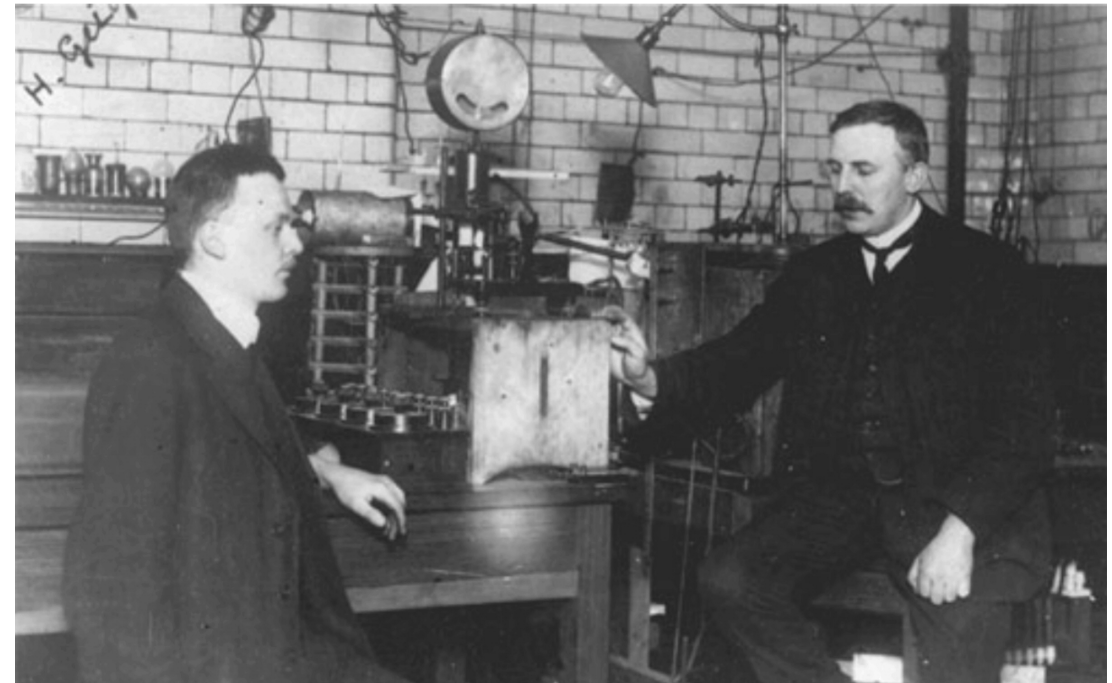
Geiger & Marsden, Phil. Mag. 25 (1913) 604

Rutherford, Phil. Mag. 21 (1911) 669

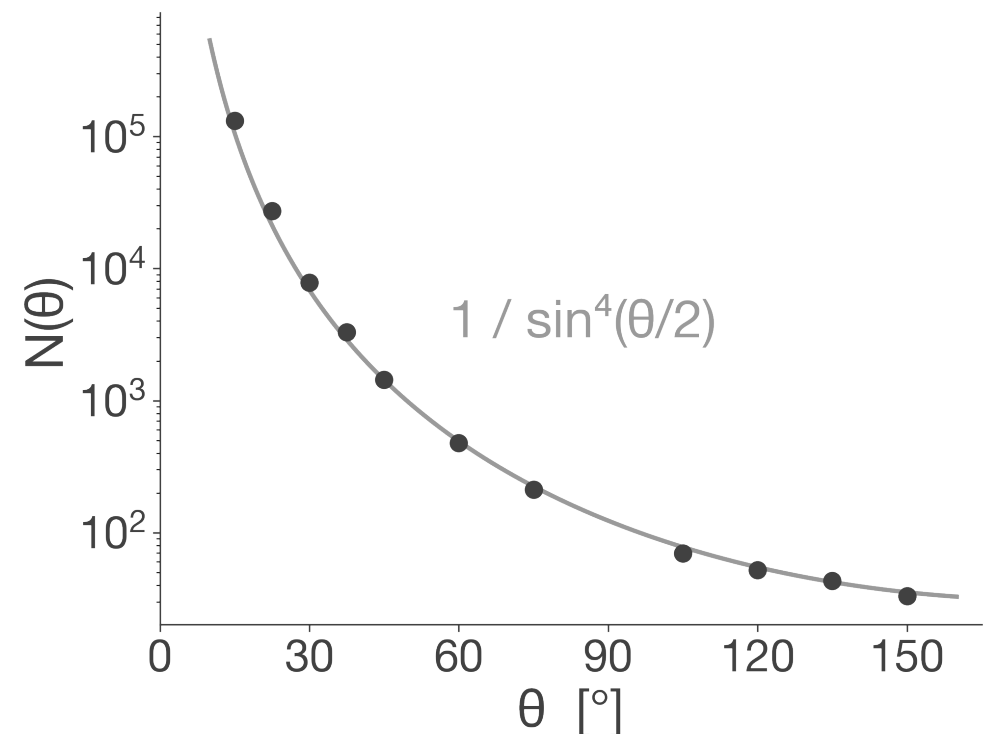
The first cross section

[Wikimedia Commons](#)

- Point-charge prediction:
$$\frac{d\sigma}{d\Omega} = \left(\frac{Z\alpha \hbar c}{4E} \right)^2 \frac{1}{\sin^4(\theta/2)}$$
- The counting rate falls as predicted - consistent with a point charge
- The first measurement of a **differential cross section**
- Distance of closest approach for a 7.7 MeV α particle on gold: $d_{\min} = \frac{2Z\alpha \hbar c}{E}$
- The nucleus is smaller than ≈ 30 fm

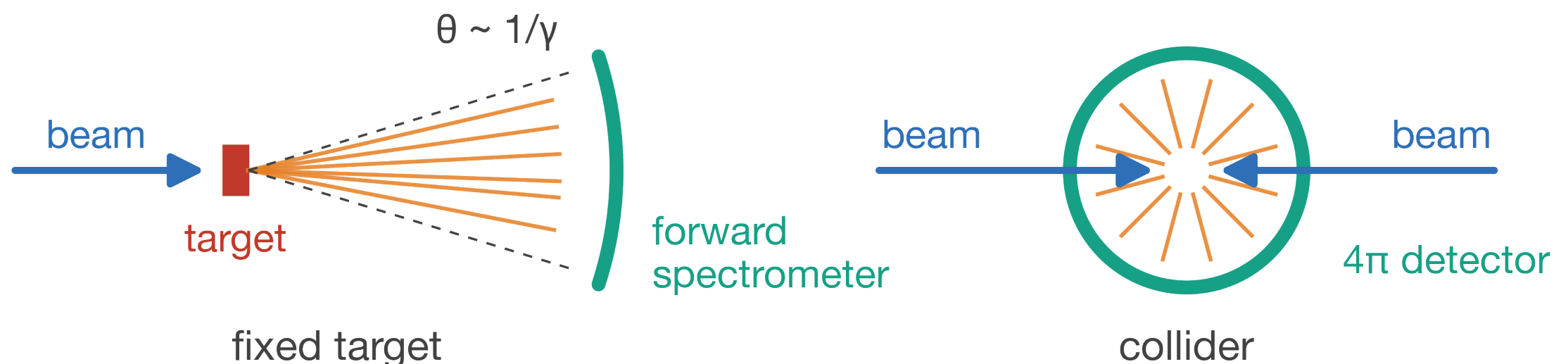


Geiger and Rutherford, Manchester, circa 1912



Fixed-target experiment

- Every fixed-target experiment is Rutherford's, but scaled up
- Head-on collisions: $\sqrt{s} = 2E_{\text{beam}}$
- Fixed target: $\sqrt{s} = \sqrt{2 E_{\text{beam}} m_{\text{target}}}$
- Center-of-mass is not at rest $\rightarrow$ collimated collisions
- Beam $\rightarrow$ Target $\rightarrow$ **Forward** detector
- A dense target $\rightarrow$ orders of magnitude more collisions, and any material: solid, gas, polarized

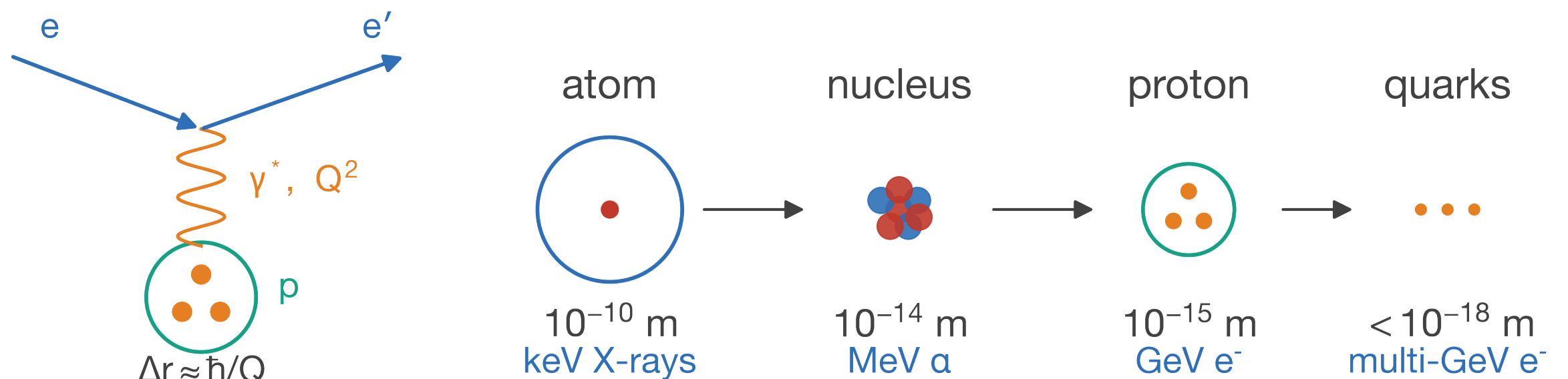


Breaking the atom

- Spatial resolution is set by the **momentum transfer** (Q^2):

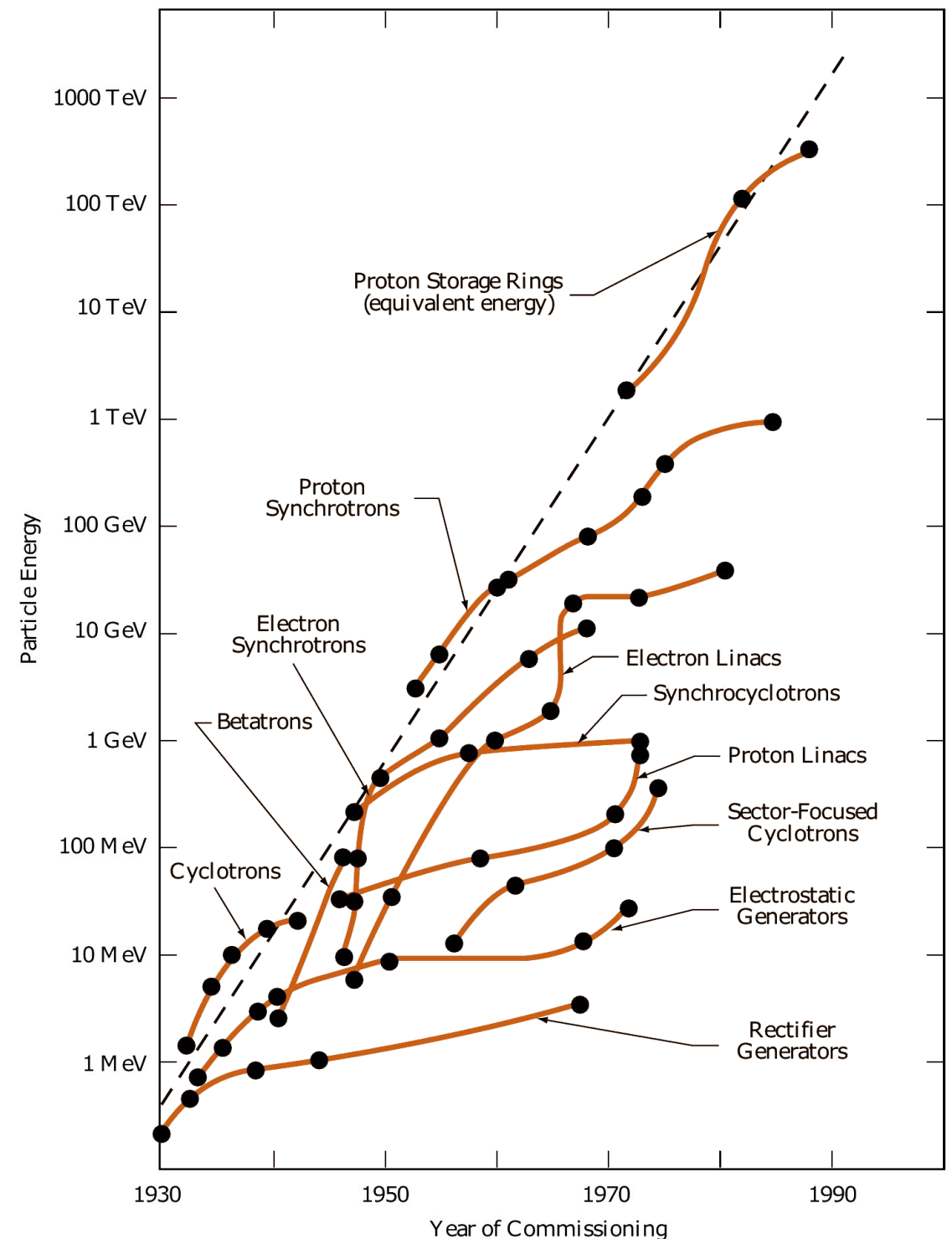
$$\Delta r \approx \frac{\hbar}{Q} \approx \frac{0.2 \text{ fm}}{Q [\text{GeV}]}$$

- Maximum transfer bounded by the beam energy: $Q^2 \lesssim 2ME \rightarrow$ with GeV beams one can study the nucleon structure
- Mott cross section decreases with Q^2 : $\frac{d\sigma}{dQ^2} \propto \frac{1}{Q^4}$
- $Q^2 \ll 1 \text{ GeV}^2$: elastic scattering $\rightarrow$ form factors
- $Q^2 \gg 1 \text{ GeV}^2$: deep inelastic scattering (DIS) $\rightarrow$ structure functions



From radium to accelerators

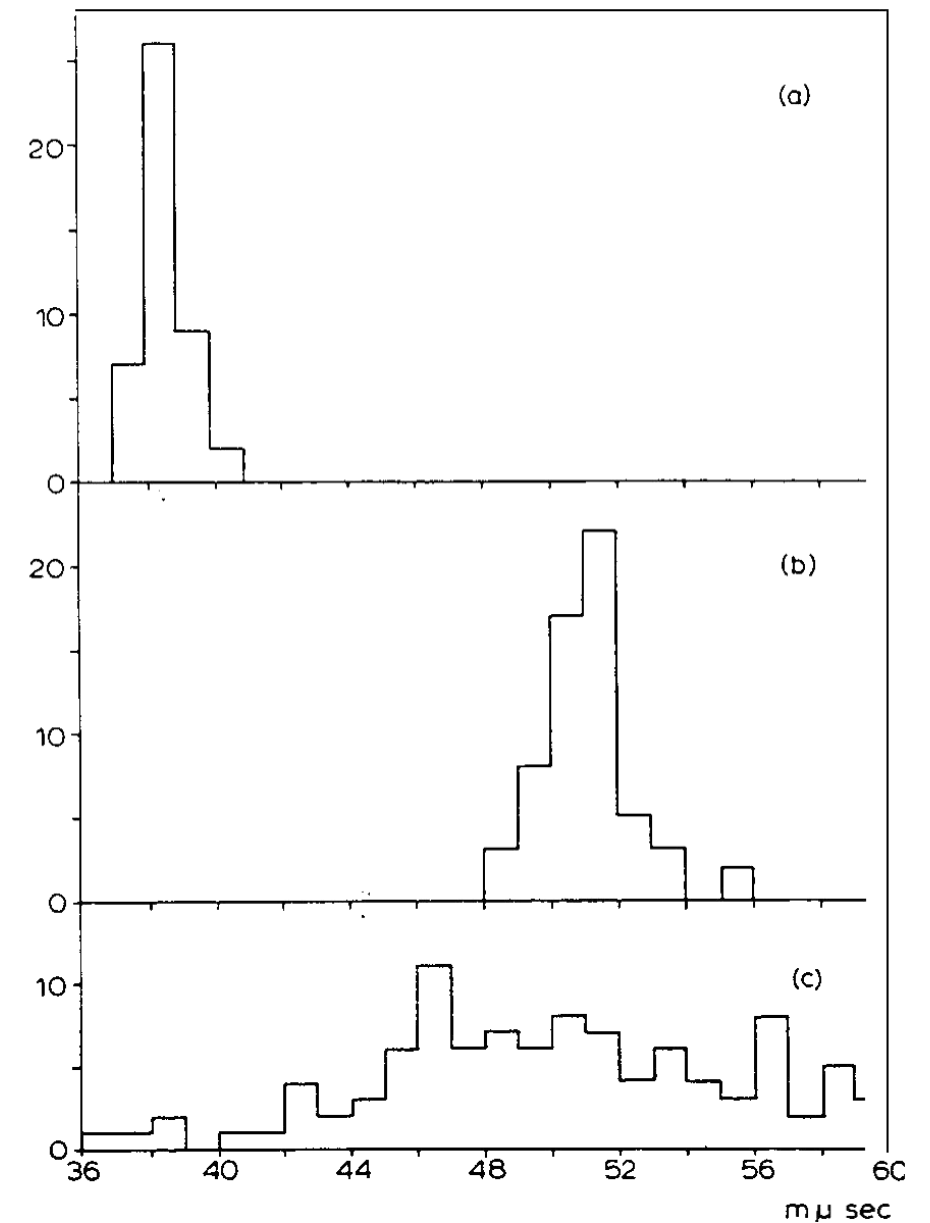
- Natural α sources with 5–8 MeV $\rightarrow$ set by the decay with no control of energy & intensity
- The first accelerator-induced nuclear reaction $p + {}^7\text{Li} \rightarrow \alpha + \alpha$ with 400 keV protons (Cockcroft & Walton, 1932)
- Cyclotrons $\rightarrow$ synchrotrons: beam energy $\times 10$ every 6–8 years over 5 decades
- Every accelerator until the 1970s was a **fixed-target machine**



The antiproton

- Discovery of antiproton required ≈ 5.6 GeV of beam energy, far beyond any machine of the 1940s
- **Bevatron** was designed for colliding ≈ 6.2 GeV protons on target
- Secondary beam dominated by pions, $\pi/\bar{p} = 3 \times 10^4$
- Time-of-flight measurement for $\bar{p}$ identification (51 ns) against pions (40 ns)

Chamberlain, Nobel lecture (1959)



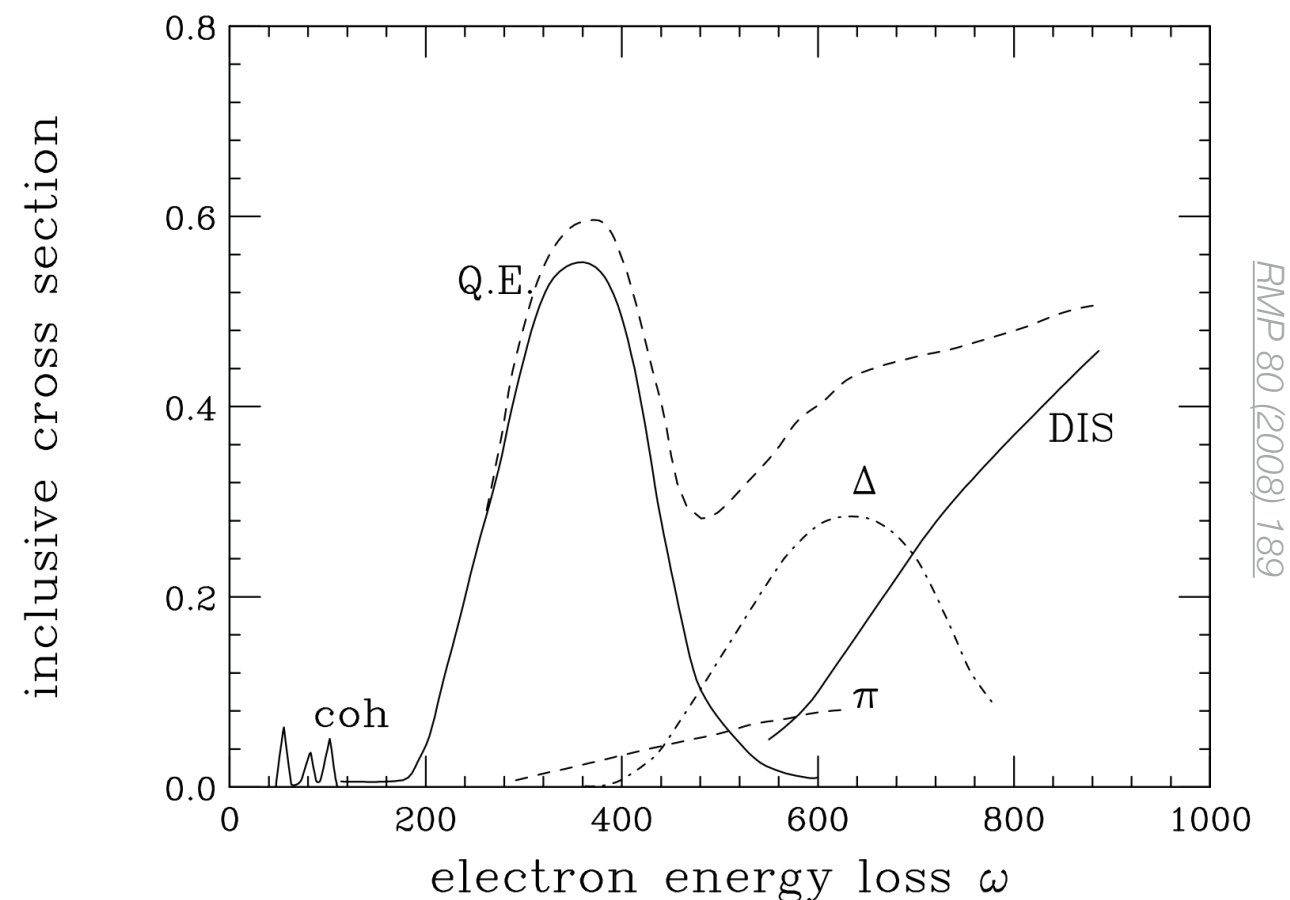
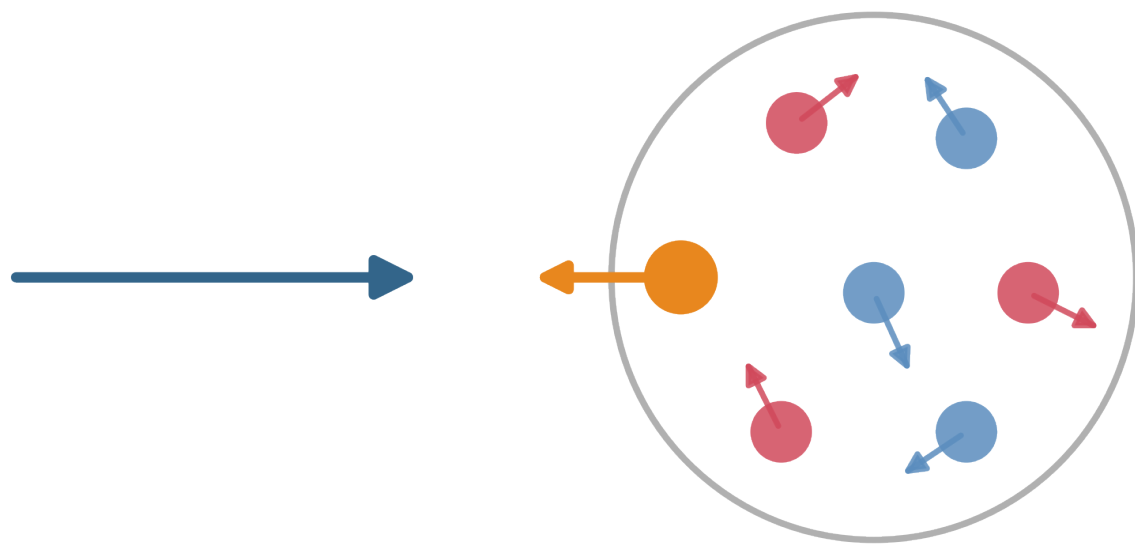
The Bevatron magnet aperture



LBL/Wikimedia Commons

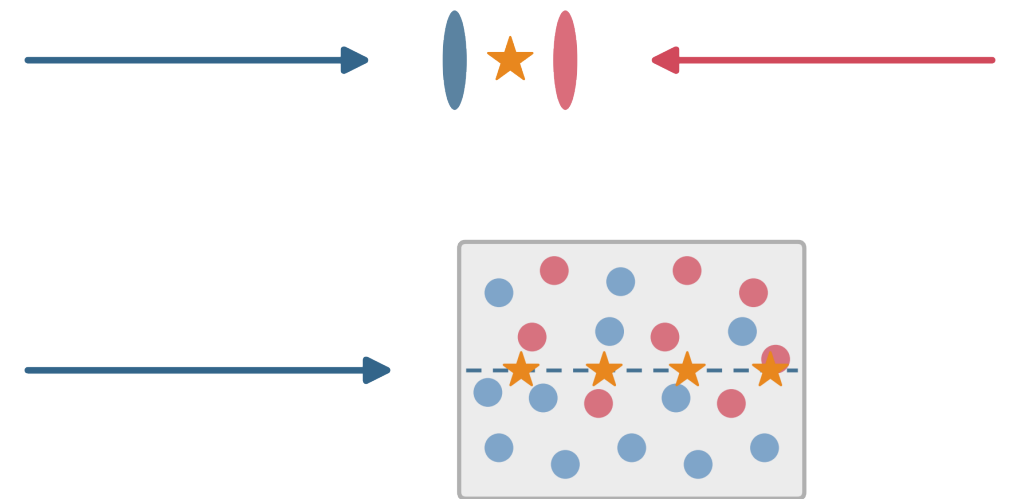
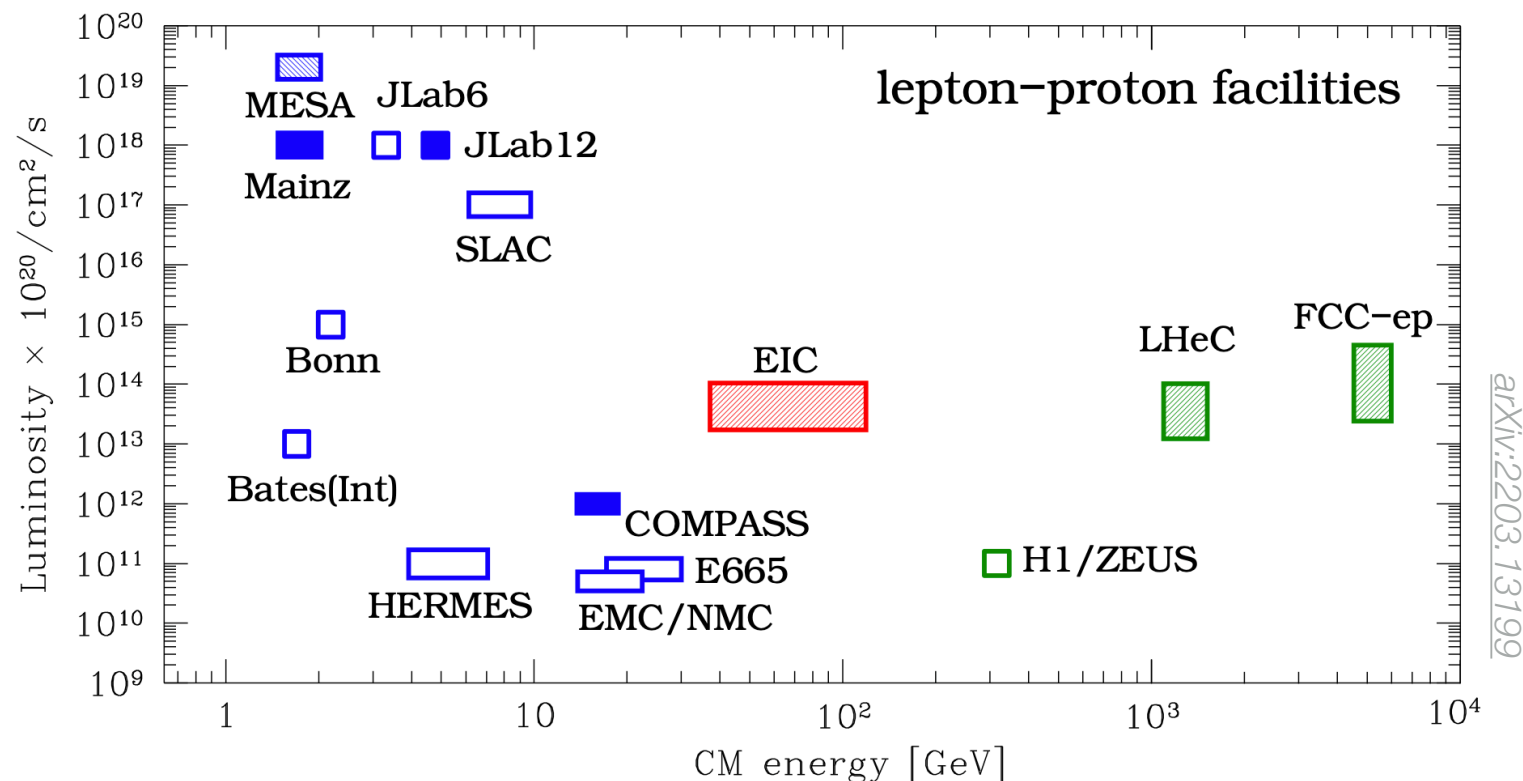
The target is never at rest

- Bound nucleons form a degenerate **Fermi gas**: $p_F = \hbar \left(\frac{3\pi^2 \rho}{2} \right)^{1/3} \approx 250 \text{ MeV}/c$
- Quasi-elastic (Q. E.) broadening of the distribution: $\Delta\omega \approx \frac{2 q p_F}{m_N}$
- A nucleon moving towards the beam $\rightarrow$ effective increase in $\sqrt{s} \rightarrow$ lower production threshold



Luminosity and rates

- For fixed target, luminosity $\mathcal{L} = \Phi_{\text{beam}} \rho \ell \frac{N_A}{A}$
- Higher rates achievable with fixed targets:
 $\mathcal{L}_{\text{FT}} \approx 10^{35} - 10^{38} \text{ cm}^{-2}\text{s}^{-1} \gg \mathcal{L}_{\text{LHC}} \approx 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Colliders own the energy frontier, fixed targets excel in collision rate
- **Many discoveries** at fixed targets: quarks are real (SLAC, 1968), the proton spin crisis (EMC, 1987), the nuclear EMC effect (1983)



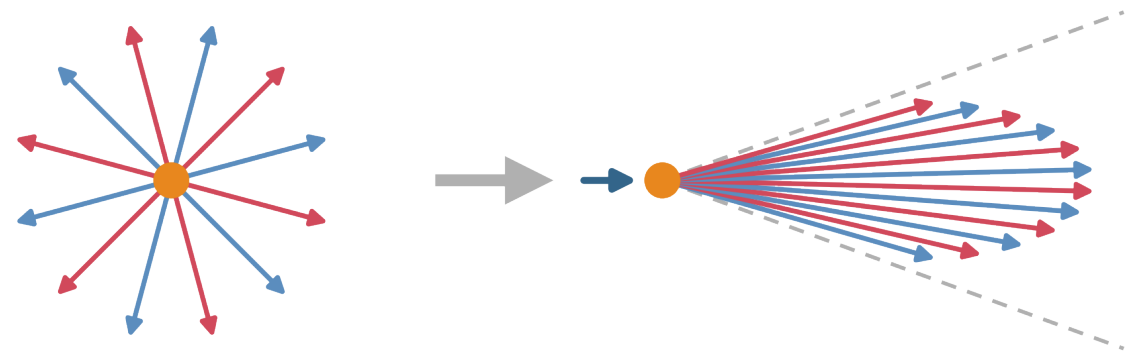
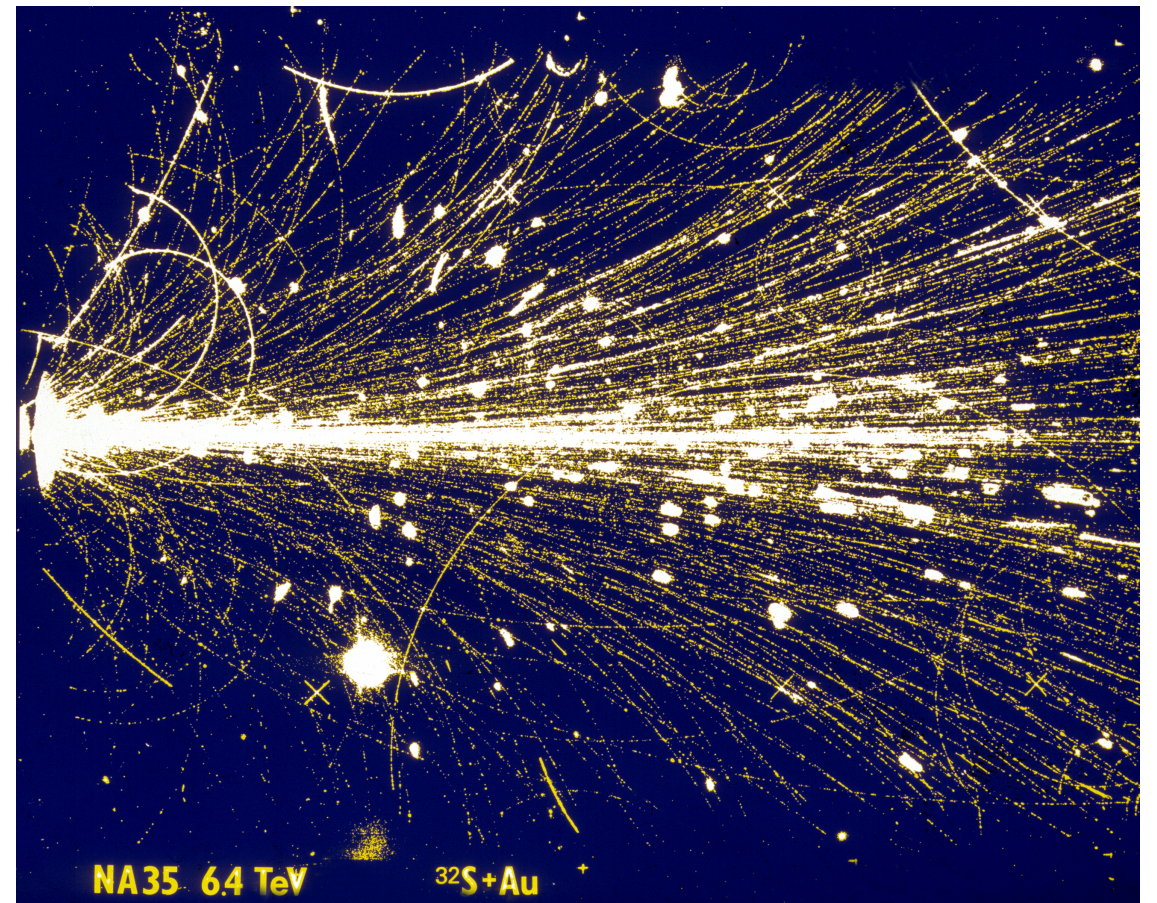
The forward boost

- Momentum boost leads to **stretched collimated tracks**
- Particle lifetimes become measurable due to time dilation
- Compact spectrometer to contain collision products:

$$\theta \approx \frac{1}{\gamma_{\text{CM}}}, \quad \gamma_{\text{CM}} = \frac{\sqrt{s}}{2m_p} \approx 15$$

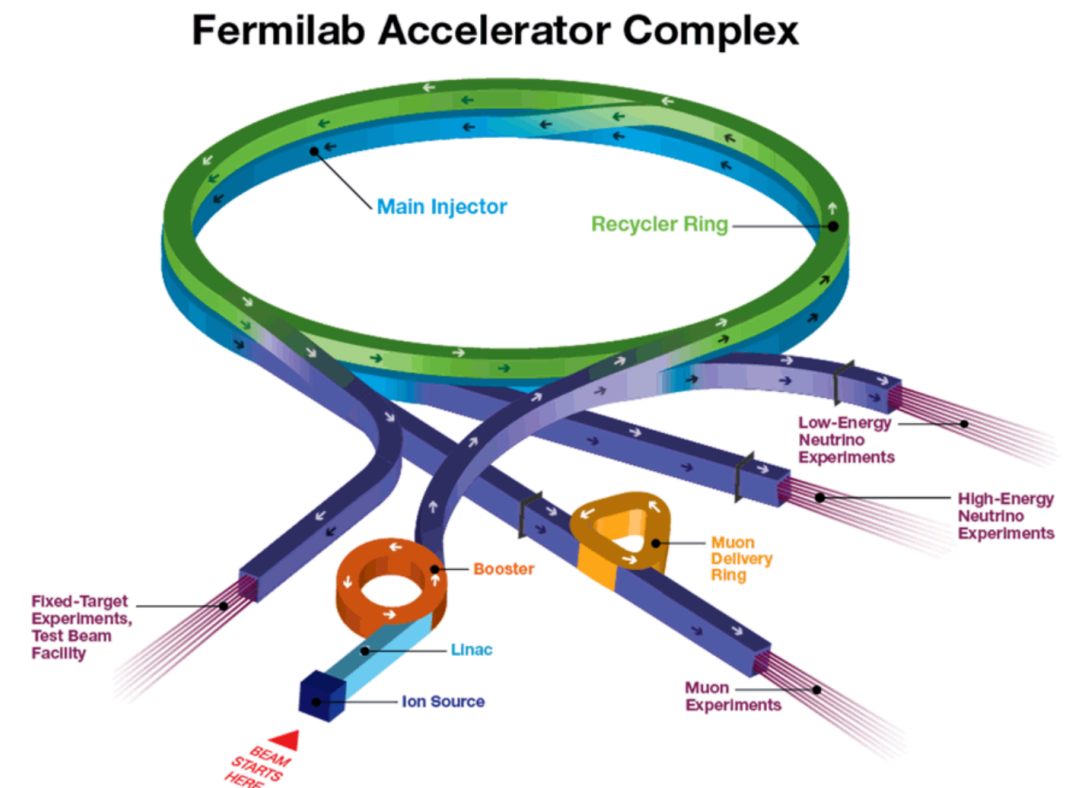
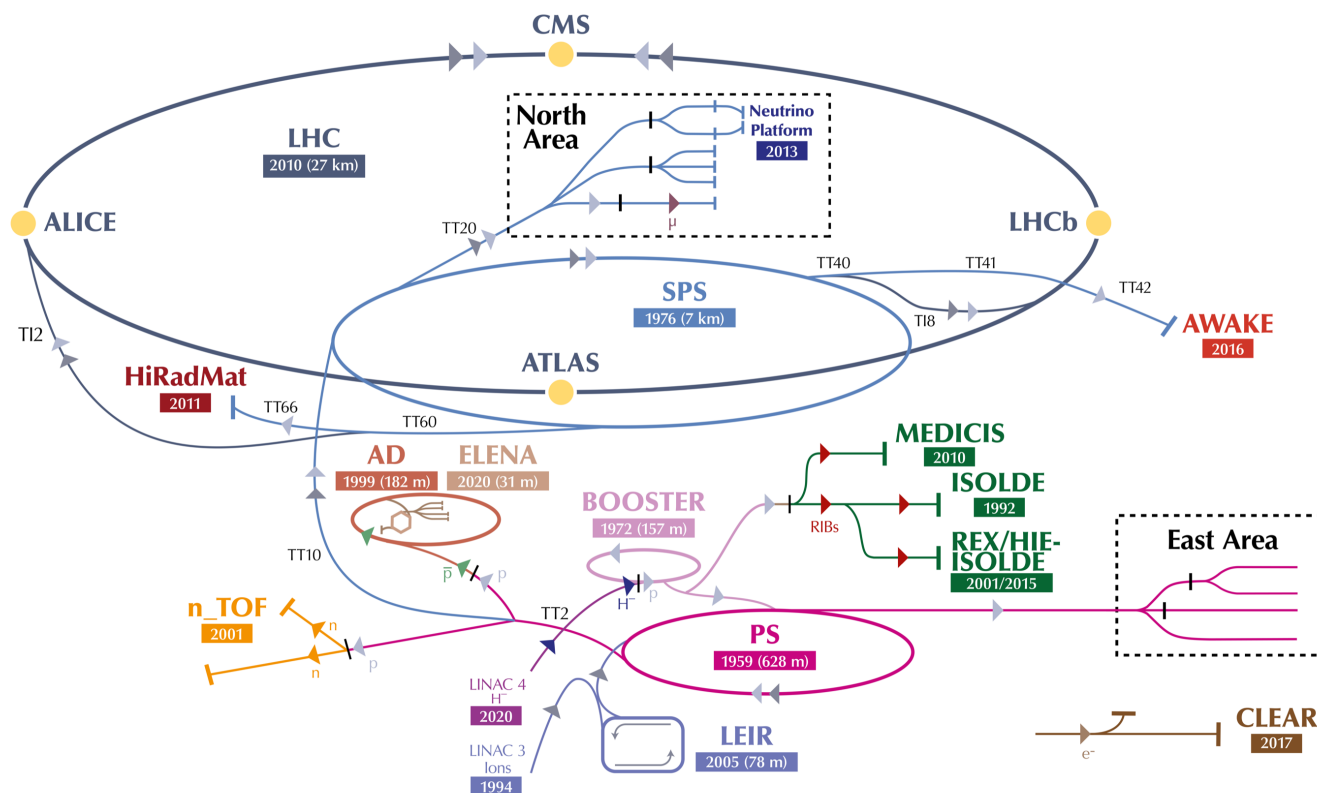
- At the extreme: light, feebly coupled particles fly 10-100 meters

NA35: sulphur-gold collision



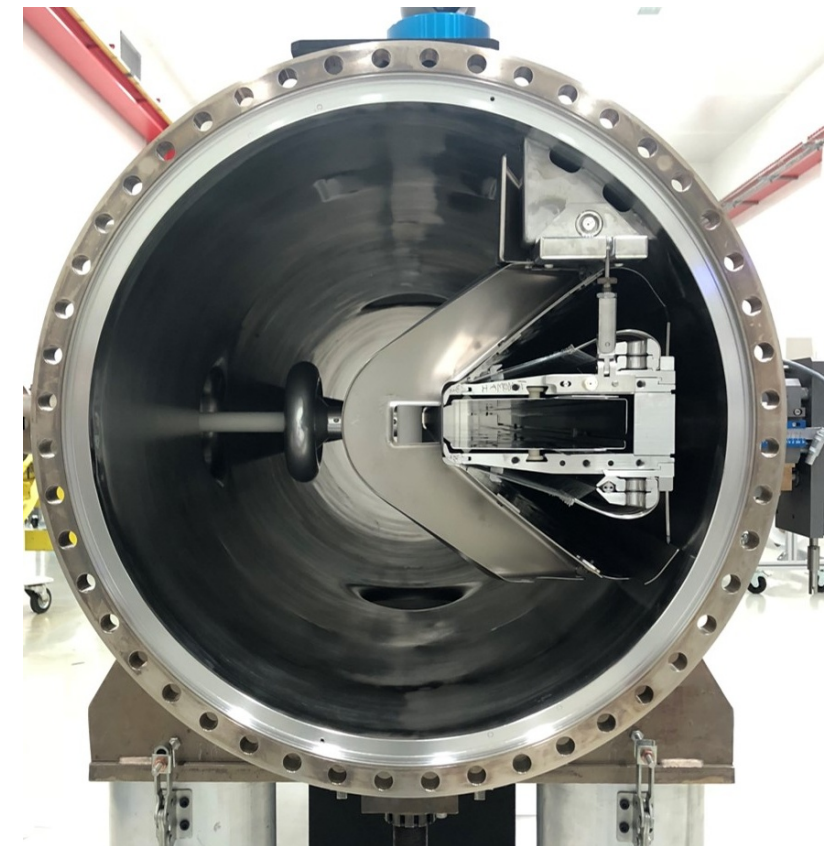
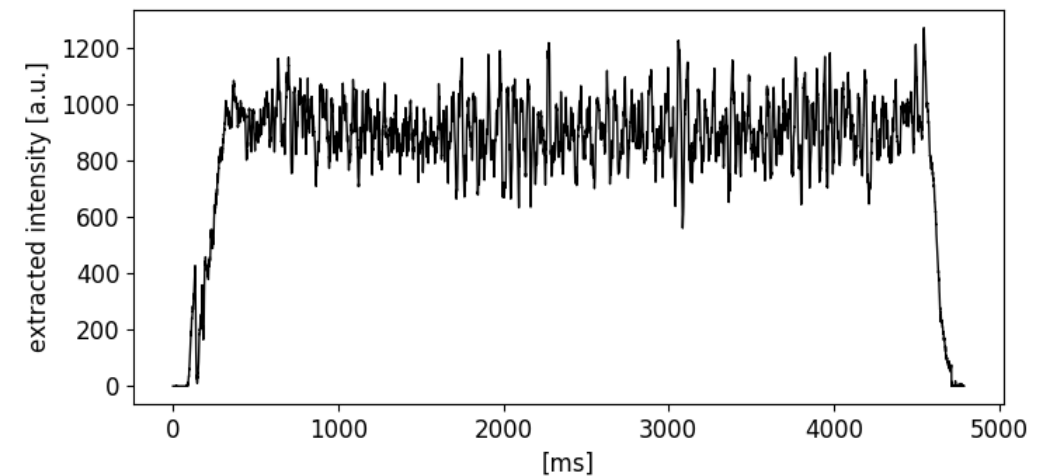
Setting up the beams

- Hydrogen bottle → Linac4 (160 MeV) → Booster (2 GeV) → PS (26 GeV) → SPS (450 GeV)
- Every acceleration stage feeds its own physics:
ISOLDE at the Booster; n_TOF, East Area and AD at the PS; the whole North Area at the SPS
- Similar chain at Fermilab: Linac → Booster (8 GeV) → Main Injector (120 GeV) — into neutrino, muon and test beams: no collider since 2011
- **Nearly every beamline ends in a target:** accelerator complexes are fixed-target ecosystems



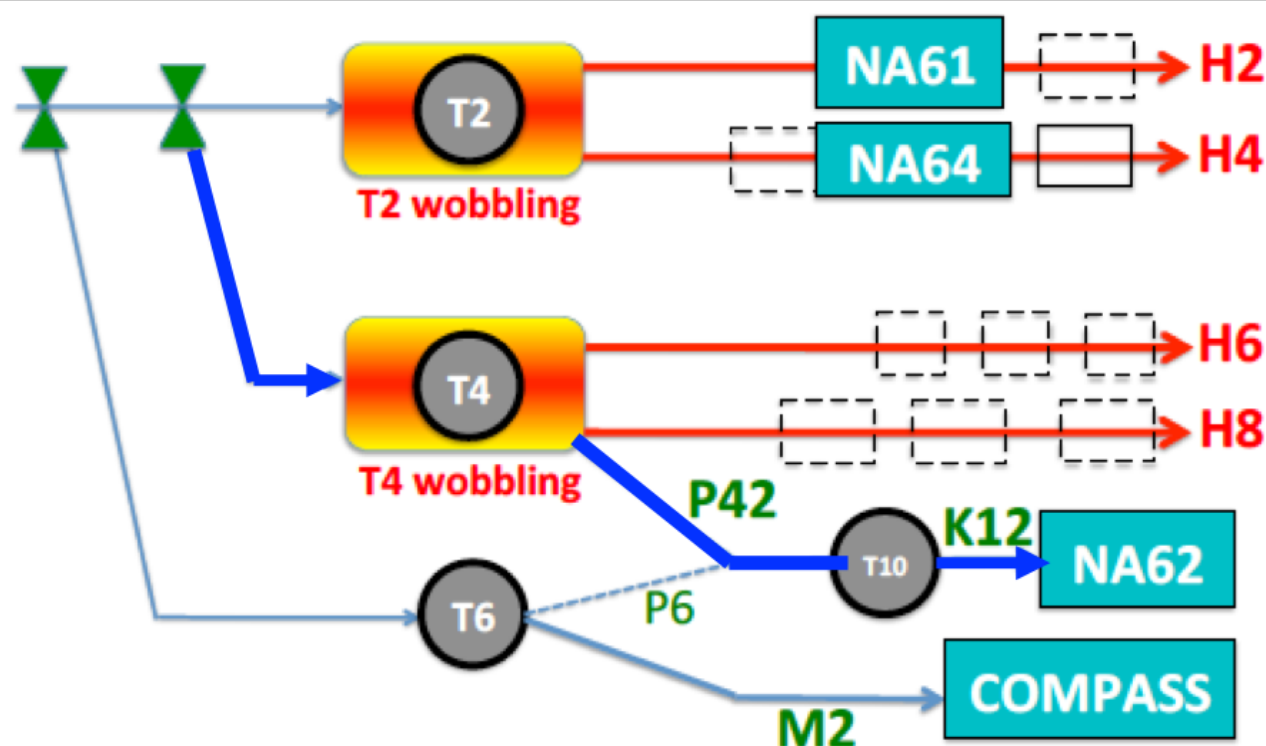
Slow extraction

- A collider stores its beam for hours, while a fixed-target program spills it
- Peel protons off over ≈ 5 s, $\approx 10^{13}$ per spill
- Flat, long spills $\rightarrow$ manageable instantaneous rates
- Fixed targets gain nothing from squeezing protons
- Colliders optimize stored energy, fixed targets optimize the **duty cycle**

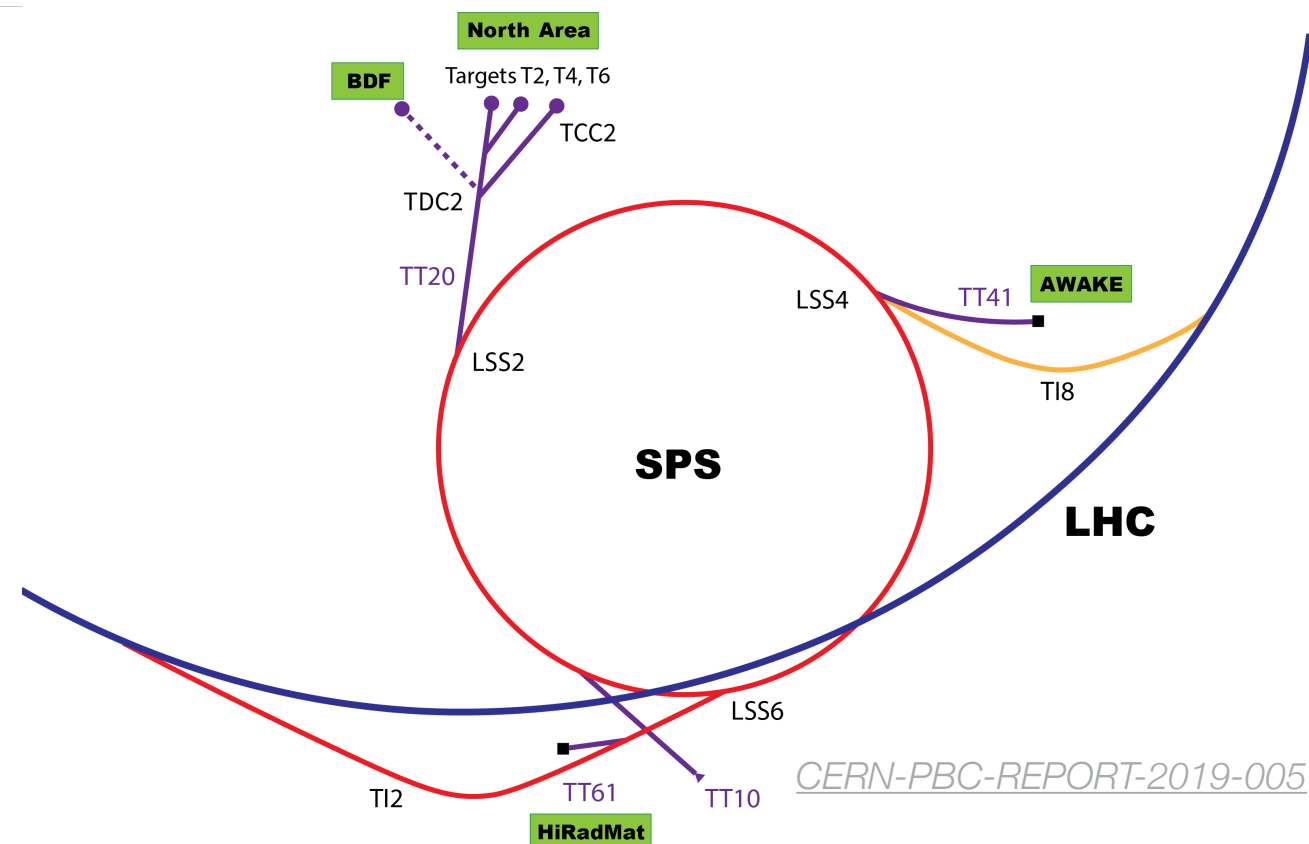


One beam for all

- The primary beam is split every cycle
- Separate targets, wobbling and splitter magnets
- EHN1, EHN2, and ENH3: COMPASS/AMBER, NA62, NA64 under one roof
- **One SPS cycle** serves the entire hall complex simultaneously



[arXiv:2110.08025](https://arxiv.org/abs/2110.08025)

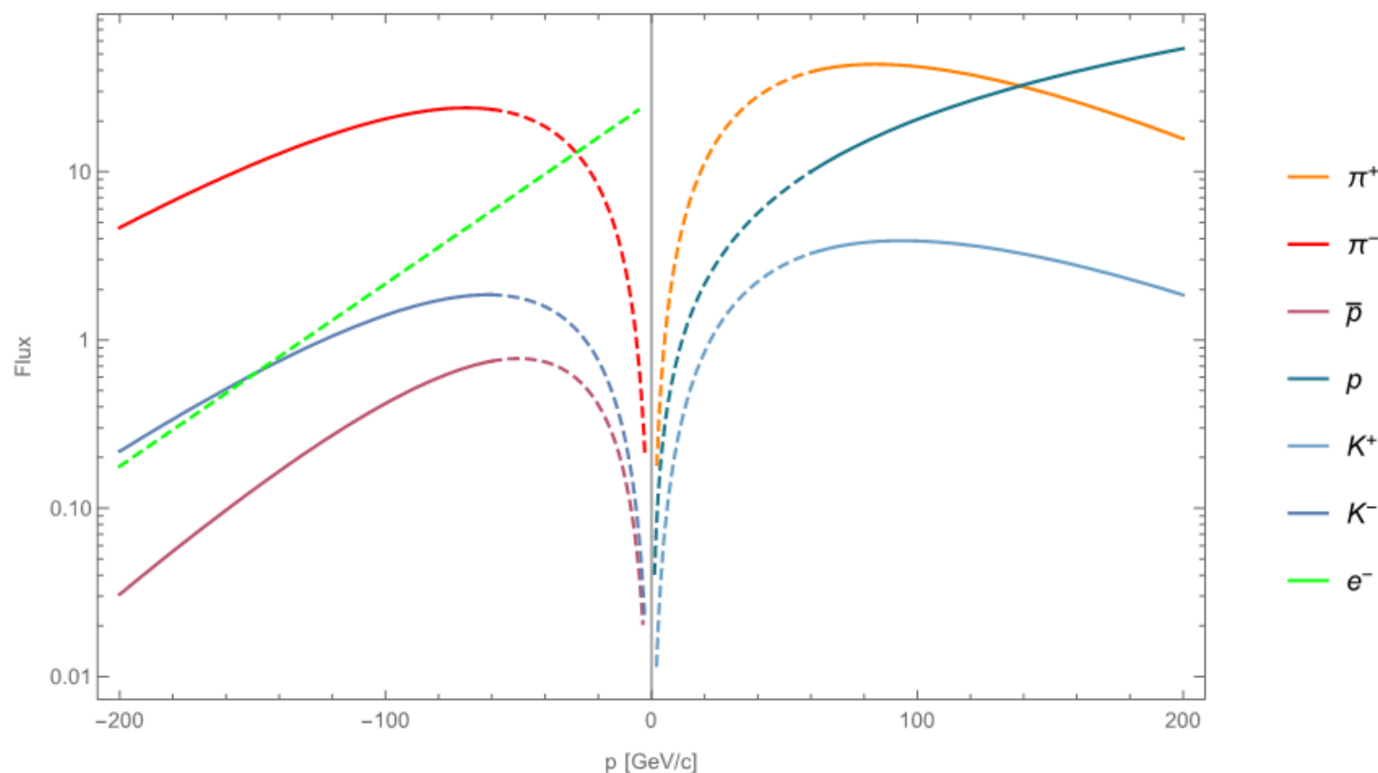


CERN-PBC-REPORT-2019-005

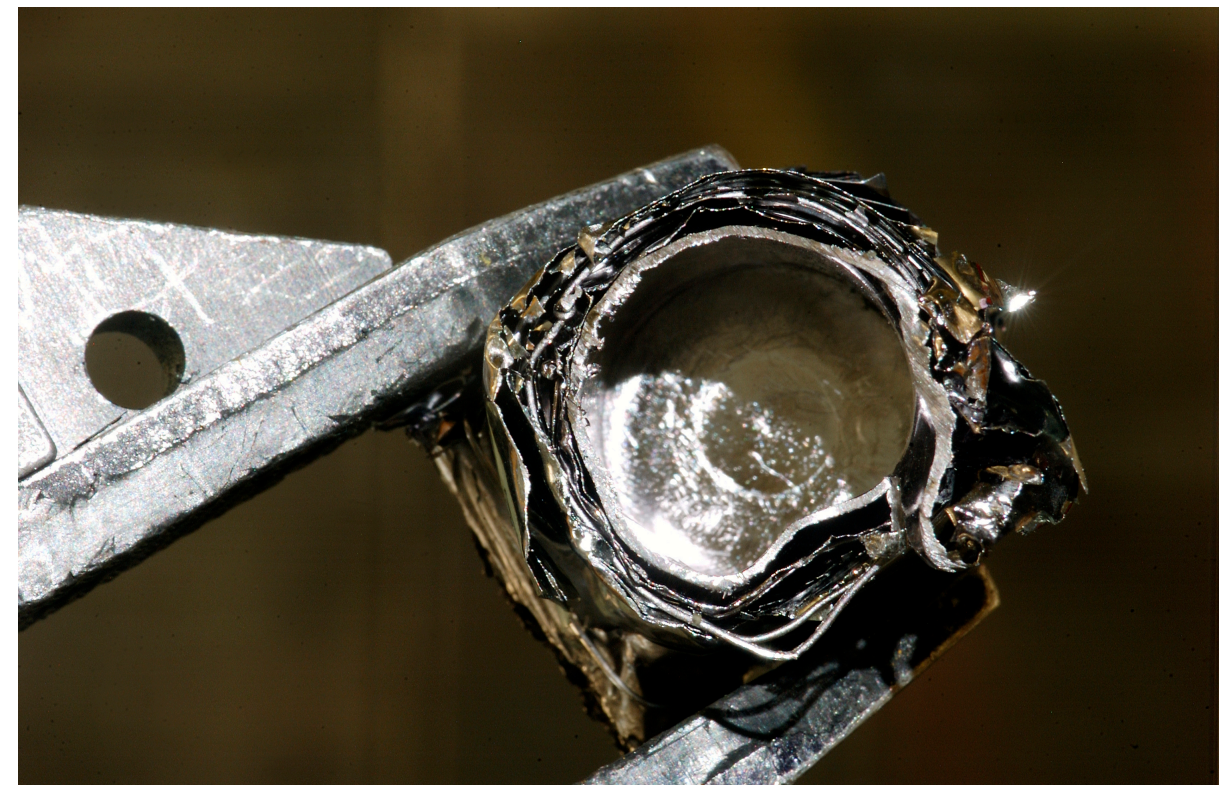
Production targets

- **Convert** incoming protons into secondary particles
- Low-Z, density material with high melting temperature, e.g. thin beryllium plates
- Optimize target length for hadron/EM secondary composition
- Atherton parametrization describes the secondary yield: pions dominate

Production rates / CERN beamline for fixed-target experiments



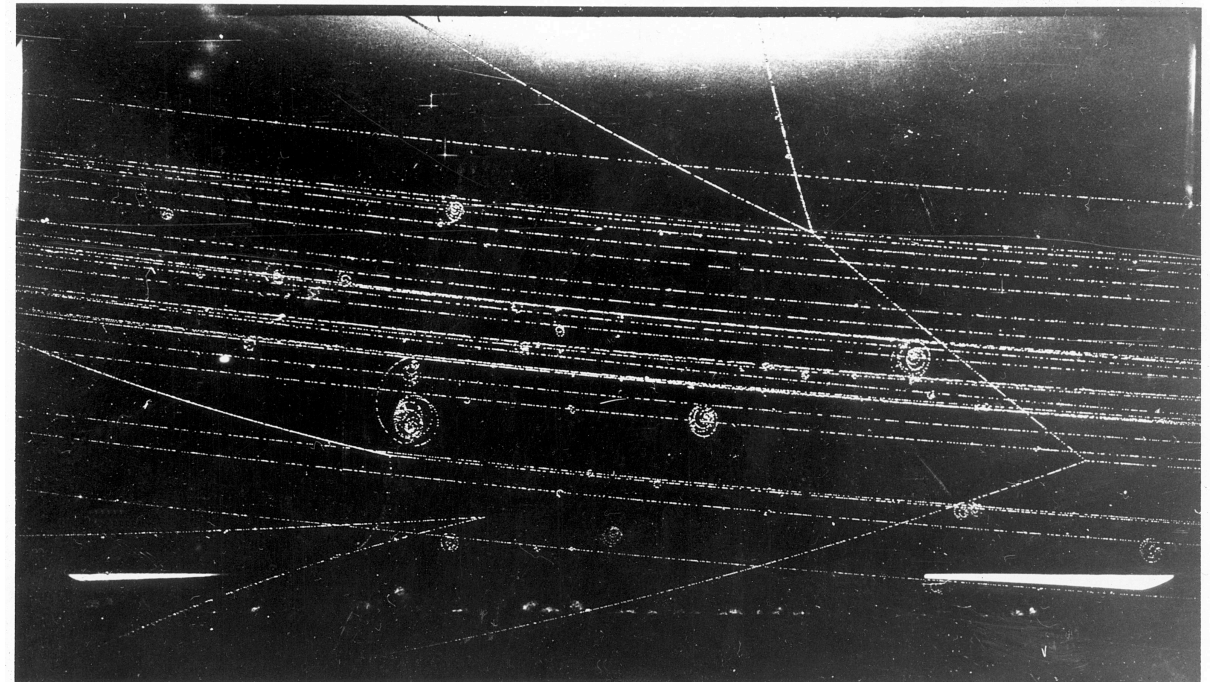
Irradiated ISOLDE tantalum target



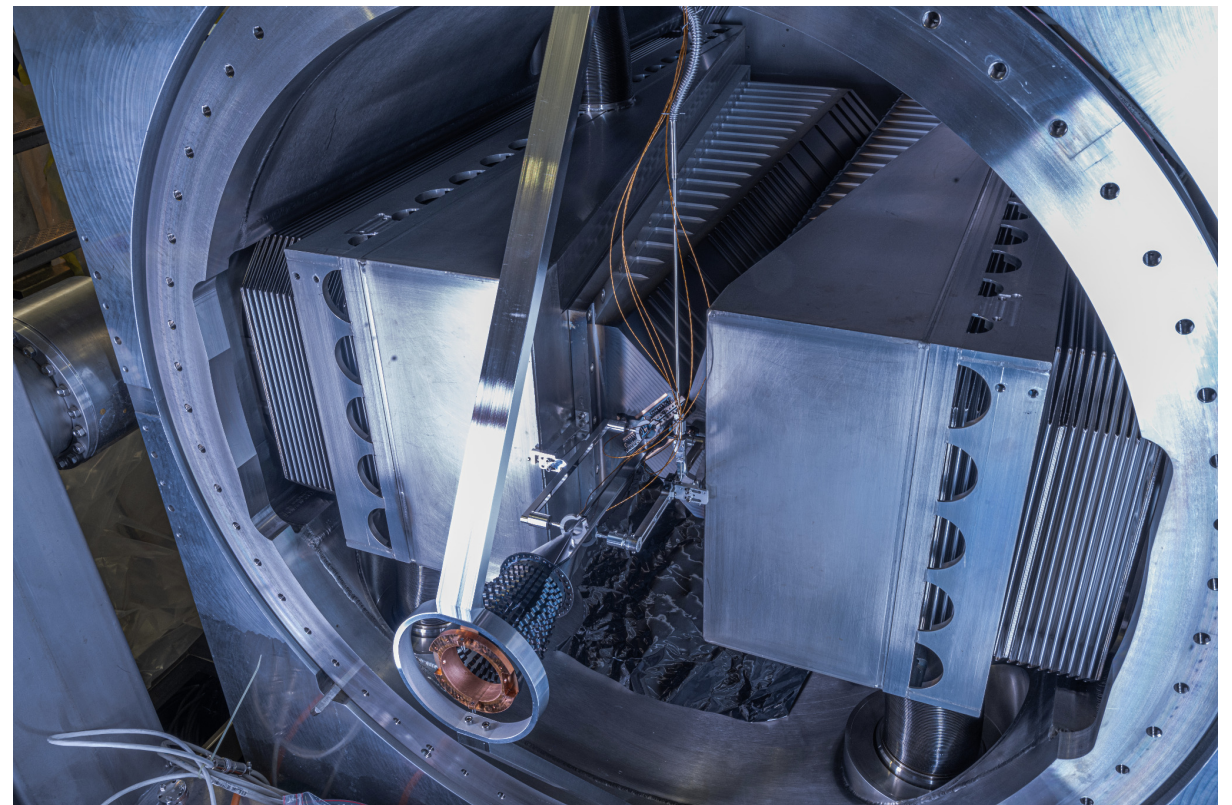
CERN-EX-0302006

Physics targets

- Choosing the target is **choosing the physics** question
- Hydrogen is the only pure single-nucleon target
- No free-neutron target: use deuterium, apply nuclear corrections
- Polarized target $\rightarrow$ spin asymmetries
- Nuclear target $\rightarrow$ quark distributions are modified inside nuclei (« EMC effect »)
- Target can also be a detector: displaced decay vertices of a few μm become visible



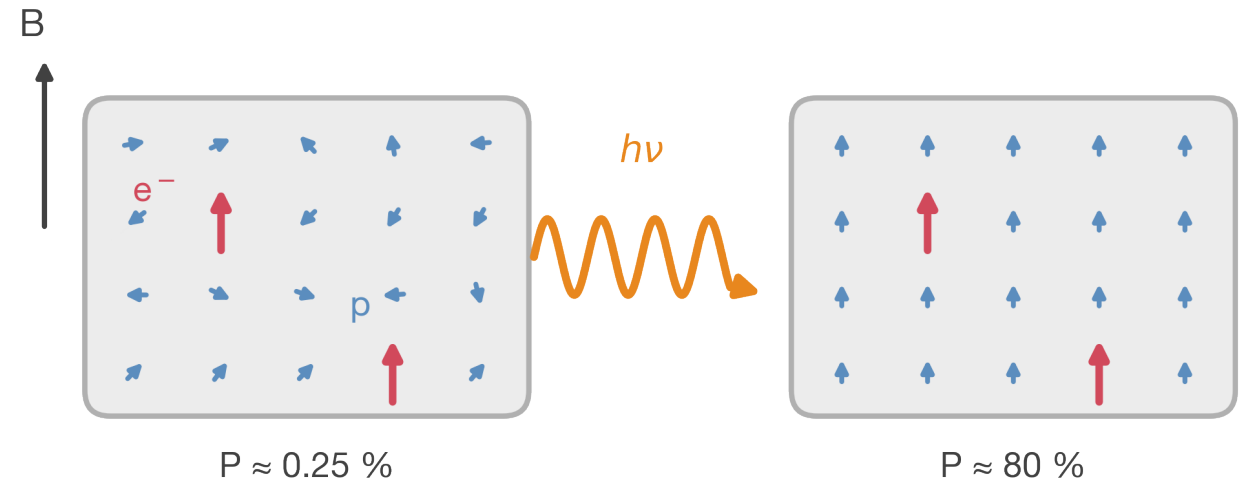
Liquid hydrogen bubble chamber hit by 2.85 GeV protons



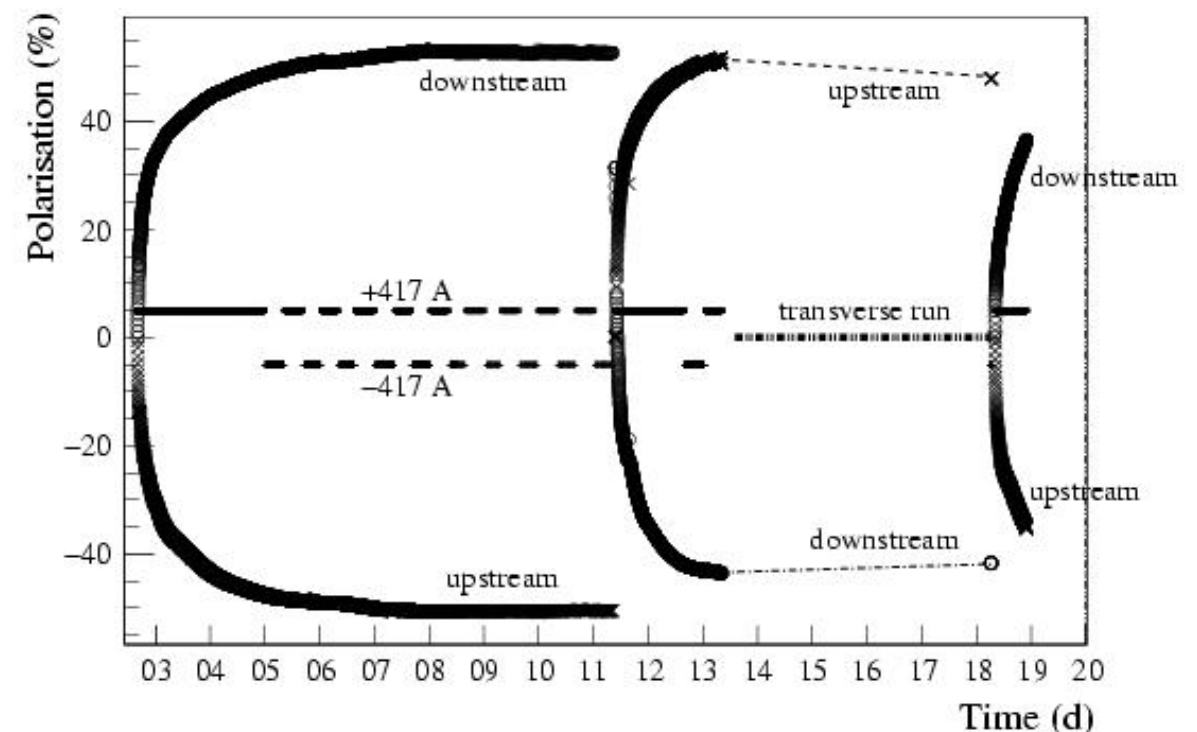
SMOG2 storage cell in the LHCb VELO

Polarizing the target

- Unpolarized scattering averages spin away
- **Polarize beam and target:** parallel vs antiparallel
- Protons barely polarize (0.25%), electrons almost fully (93%)
- Microwaves transfer the electron alignment to the nuclei (80-90%)
- Frozen spin for weeks with 50 mK dilution refrigerator
- Two cells, opposite spins in one field (two microwave frequencies) → swap them to cancel systematics



NIMA 577 (2007) 455

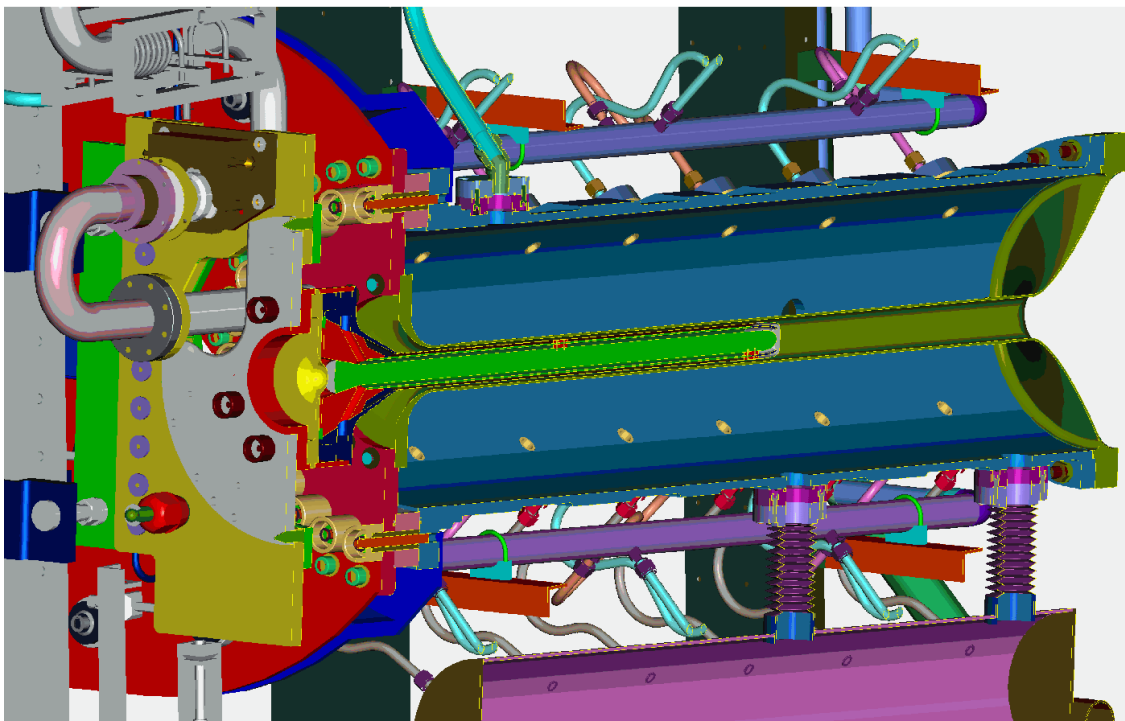


COMPASS target polarization over 20 days, 2004

High-power targets

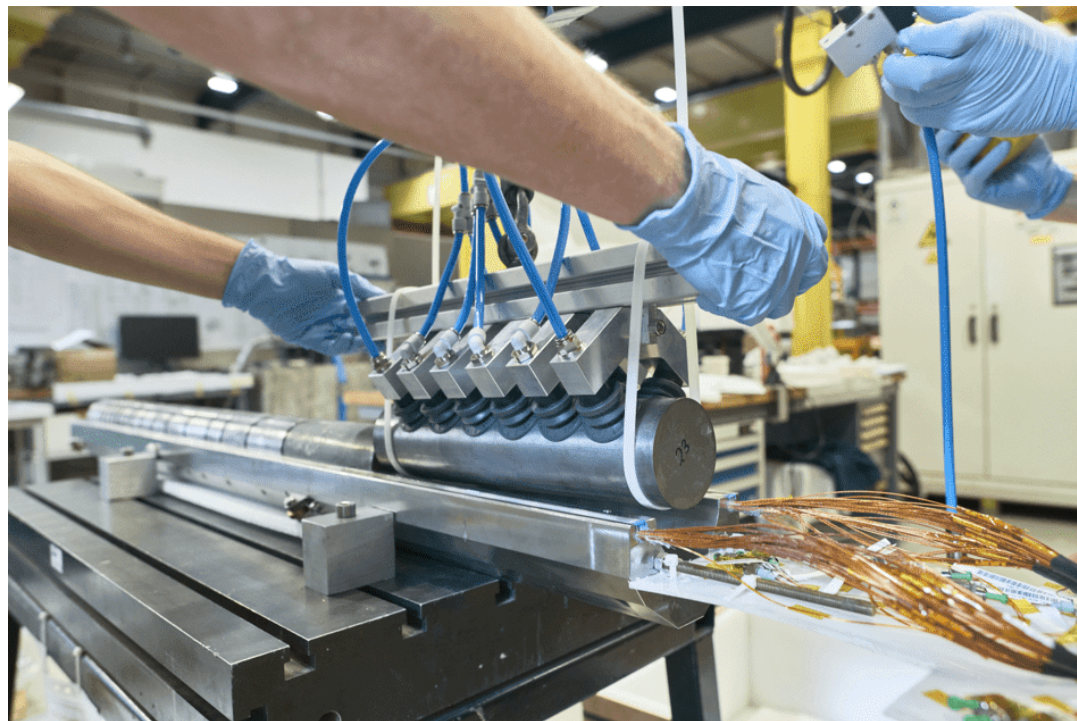
- The beam **heats the target** faster than it can expand
- The target material is continuously destroyed by the beam
- Neutrino targets stay thin - a meter-long graphite rod, gas-cooled, and still glowing at 700°C
- Beam-dump experiments do the reverse: absorb the whole beam in dense metal and look for the rare particles that still come out

NIM A 659 (2011) 106

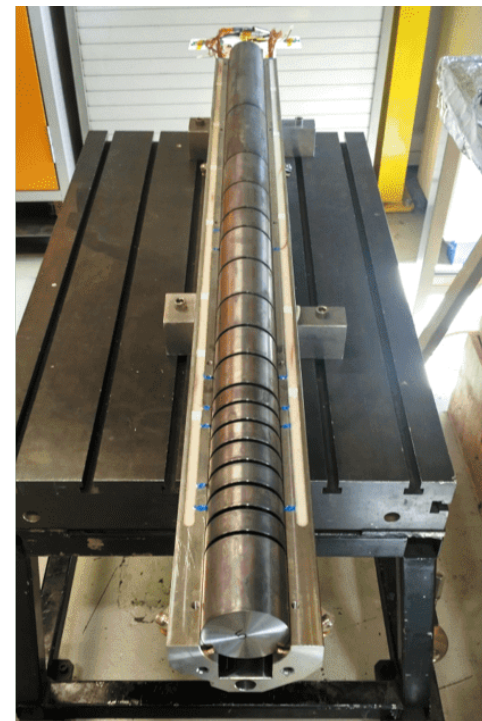


Cross section of the first horn and target at T2K

arXiv:1912.06356

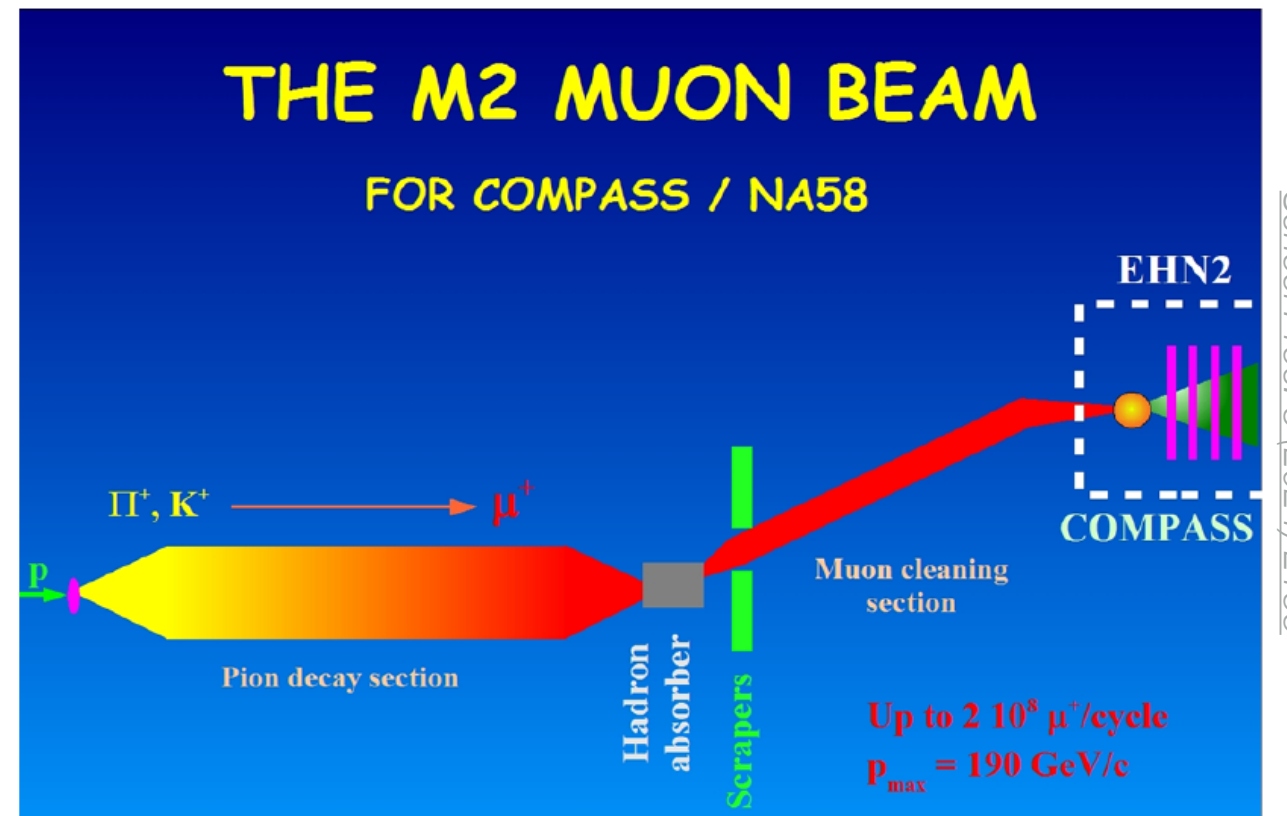
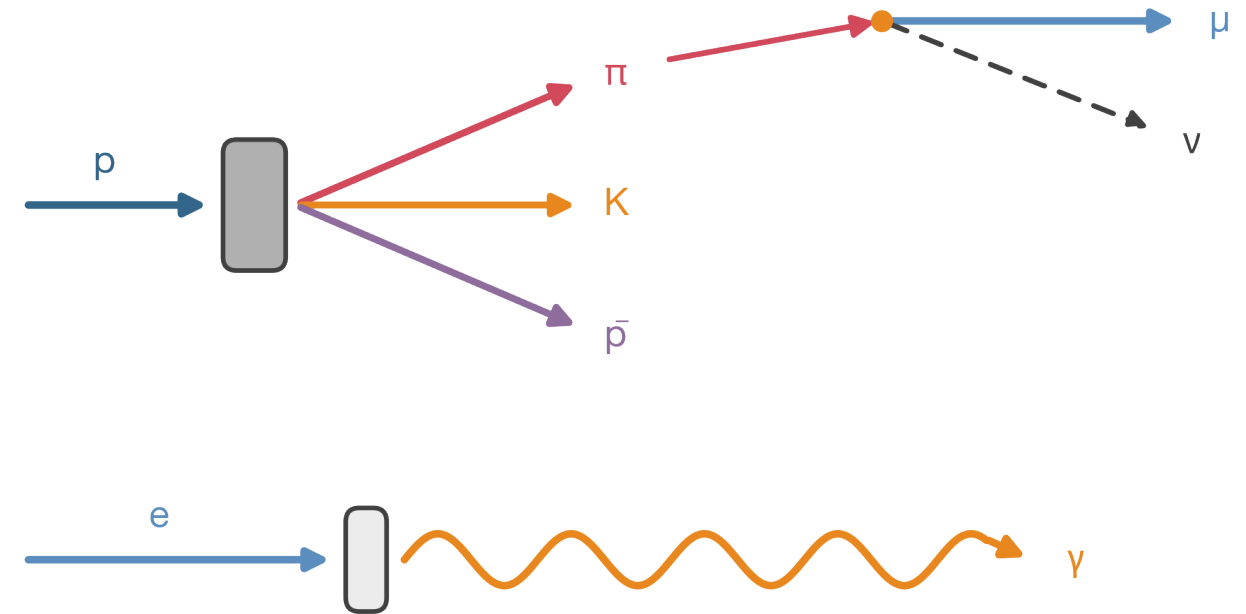


SHiP/BDF prototype tungsten target



Secondary beams

- Produce particles that **can not be stored** at colliders
- Primary protons on production target $\rightarrow \pi, K, \bar{p}$ selected by magnets
- $\pi \rightarrow \mu\nu \rightarrow$ muon beams
- π/K decays in flight $\rightarrow$ neutrino beams
- $e^- \rightarrow$ bremsstrahlung / Compton $\rightarrow$ photon beams



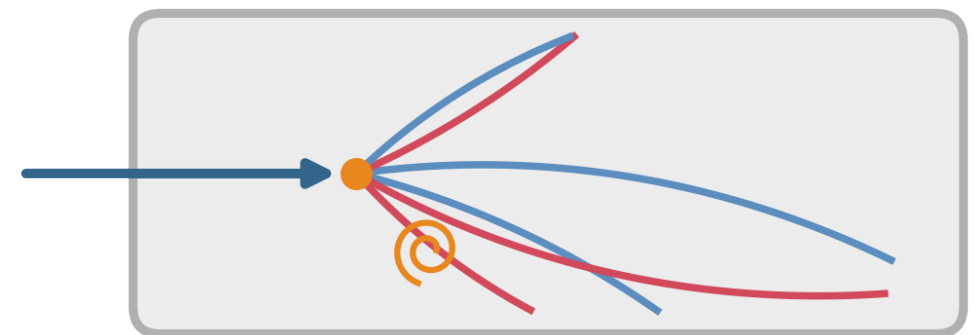
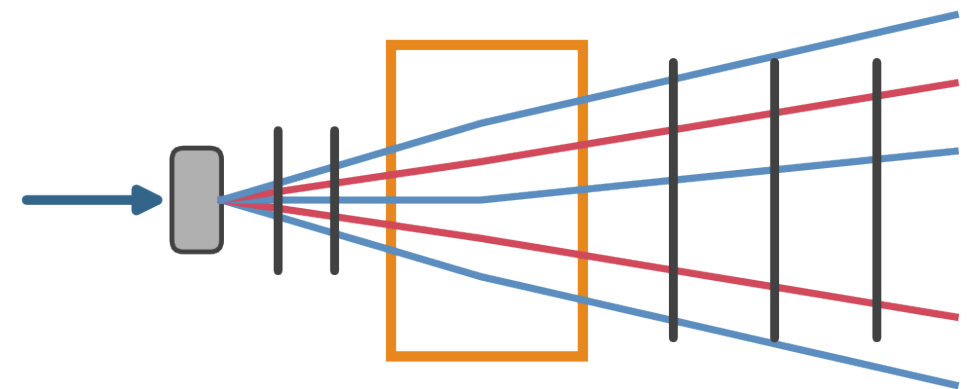
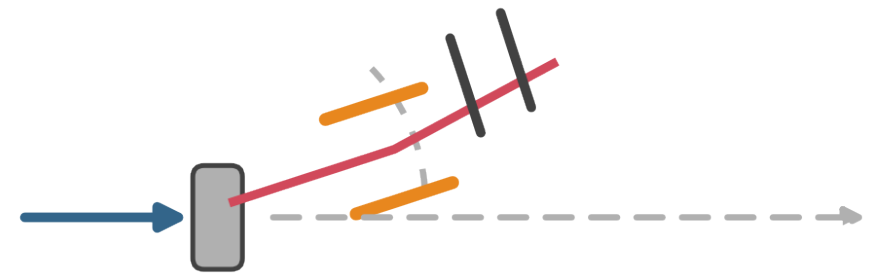
Facilities

- A **worldwide** running ecosystem
- Fermilab: 120 GeV protons, neutrino beams
- JLab CEBAF: 12 GeV electrons, high rate
- PSI: 1.4 MW protons, intense muon source
- J-PARC: $\approx$ 1MW protons, kaons and neutrinos
- TRIUMF, GSI/FAIR, SNS, CERN ..



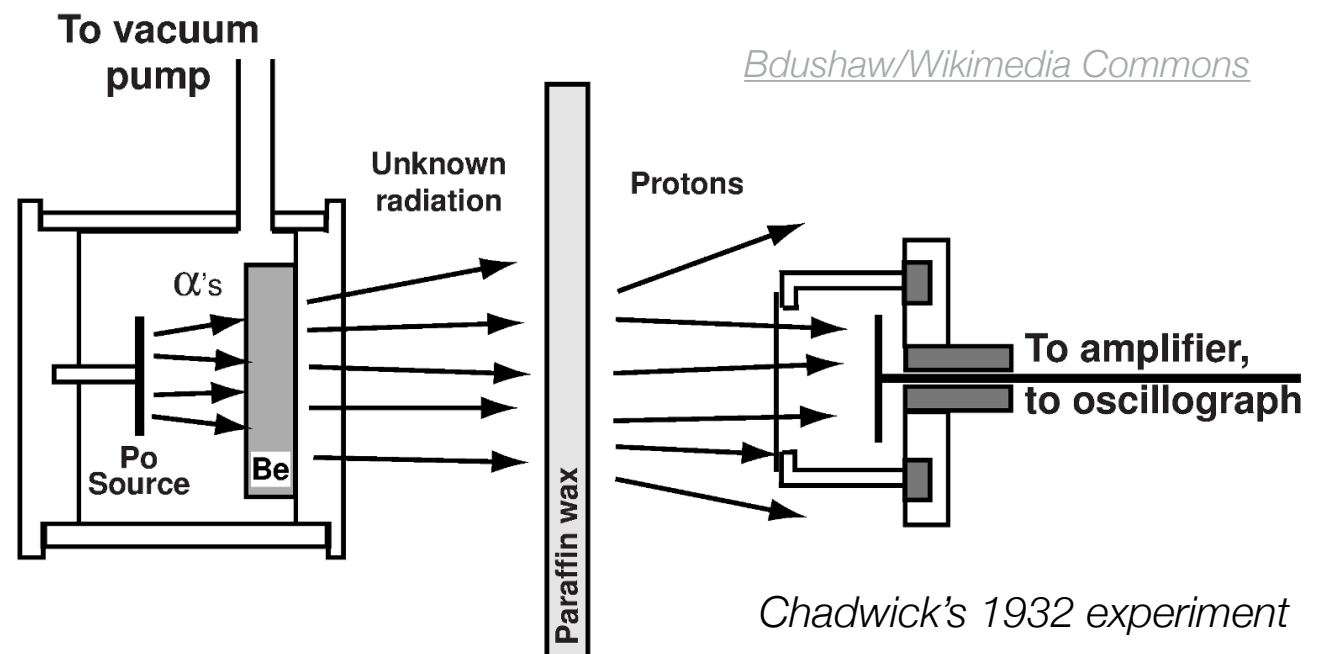
Detector archetypes

- Single-arm magnetic spectrometer (SLAC End Station A)
- Open forward spectrometer (COMPASS, LHCb-like geometry)
- Target is a detector (Gargamelle, emulsions)



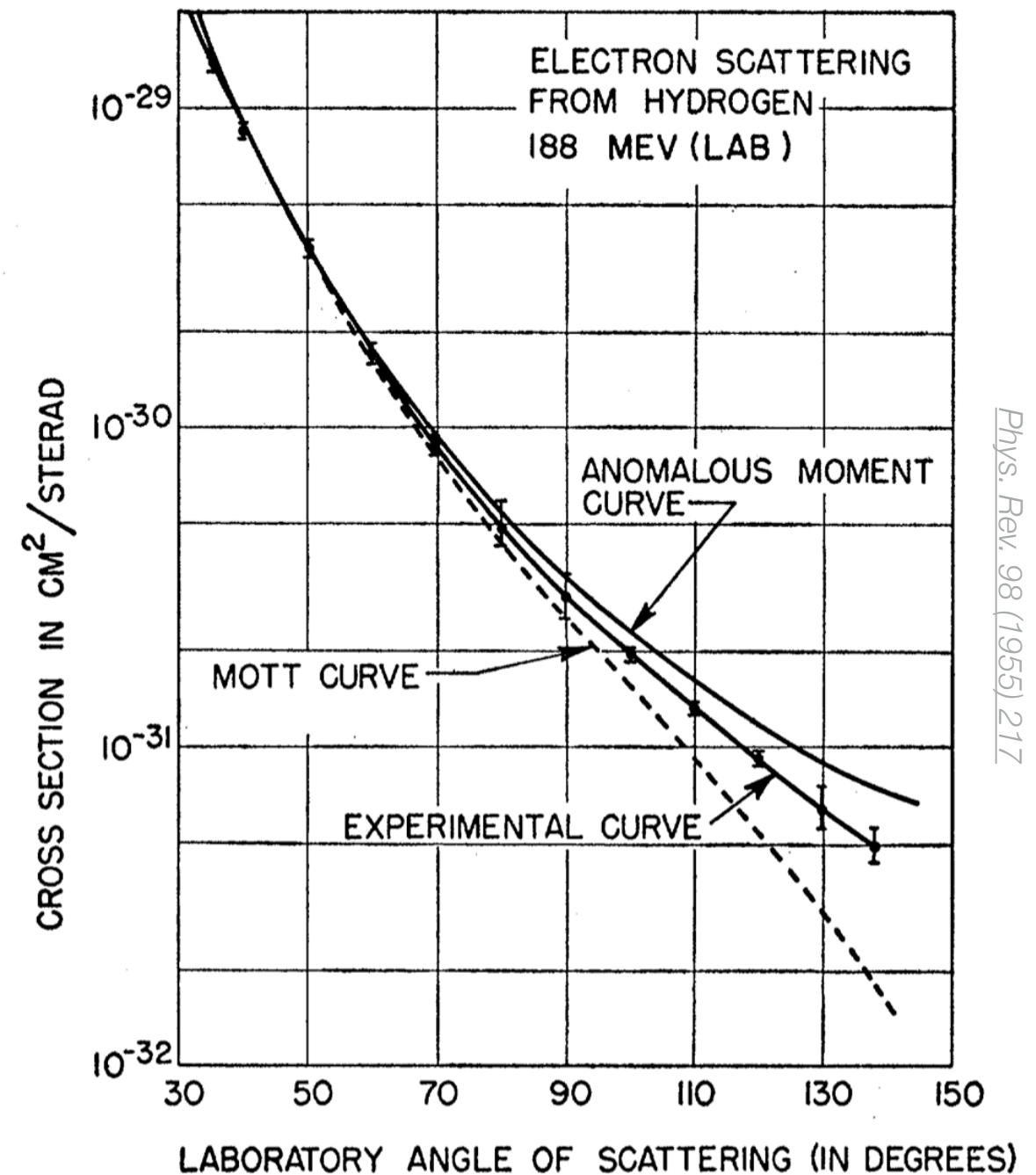
The neutron

- Source → beryllium → unknown radiation → paraffin → counter
- **Single-arm fixed-target setup:** one particle counter, narrow acceptance, energy measured by range
- Alpha-particle on beryllium gives a neutral, penetrating radiation
- This radiation is not γ rays: it knocks 5 MeV protons out of paraffin
- The ratio of recoils on H and N gives $m_n \simeq m_p$
- The nucleus is a composite object
- Do the parts have parts?



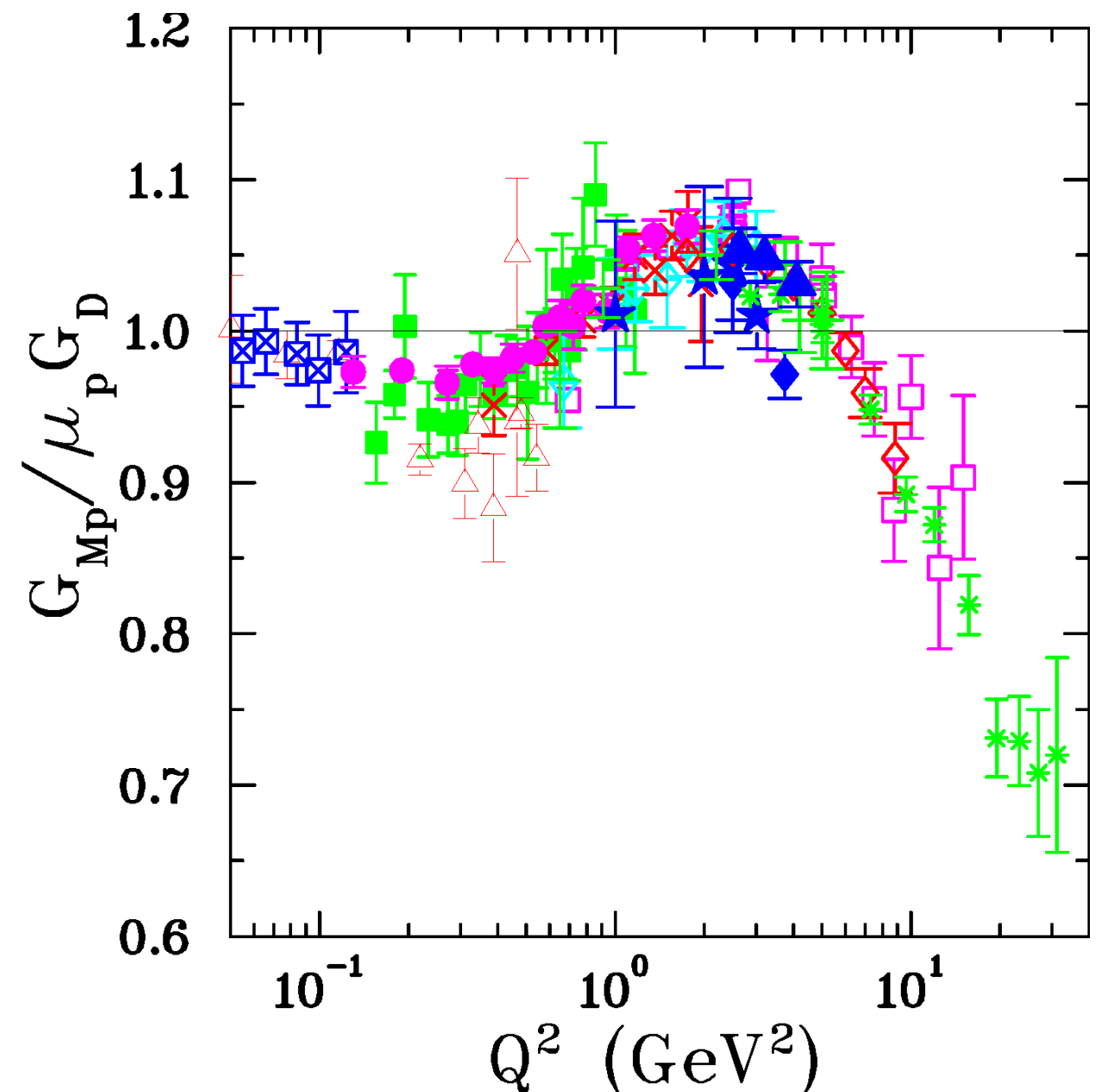
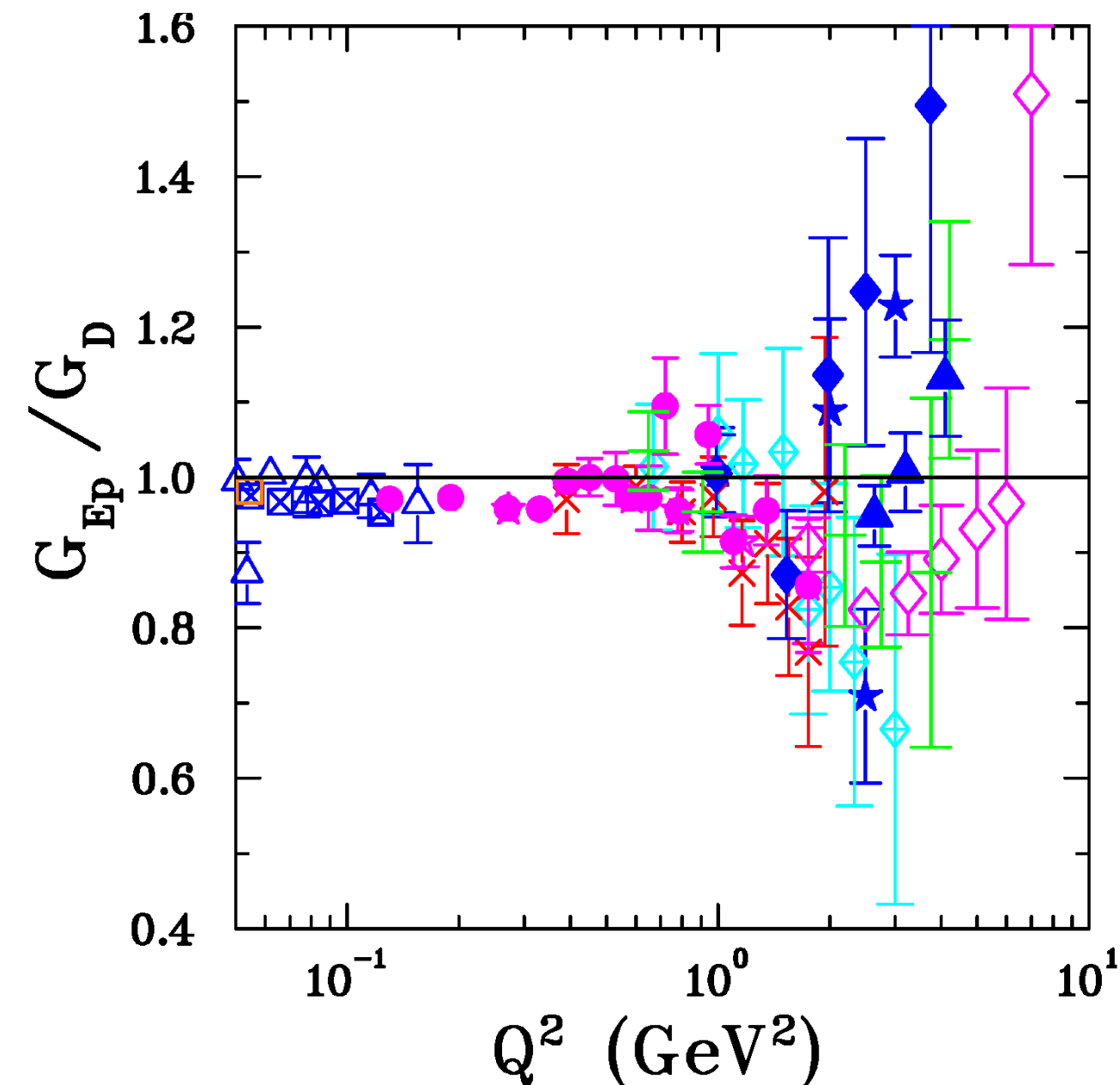
Inside the proton

- Rutherford's method to study the internal structure of the proton itself
- Shoot 188 MeV electrons on hydrogen (Hofstadter)
- **Single-arm spectrometer**, now with a magnet: Stanford's Mark III linac, the arm on rails
- Electron beam, point-like scattering
- Deviation from Mott cross section → presence of internal structure
- Proton's RMS charge radius 0.8 fm (Nobel prize)



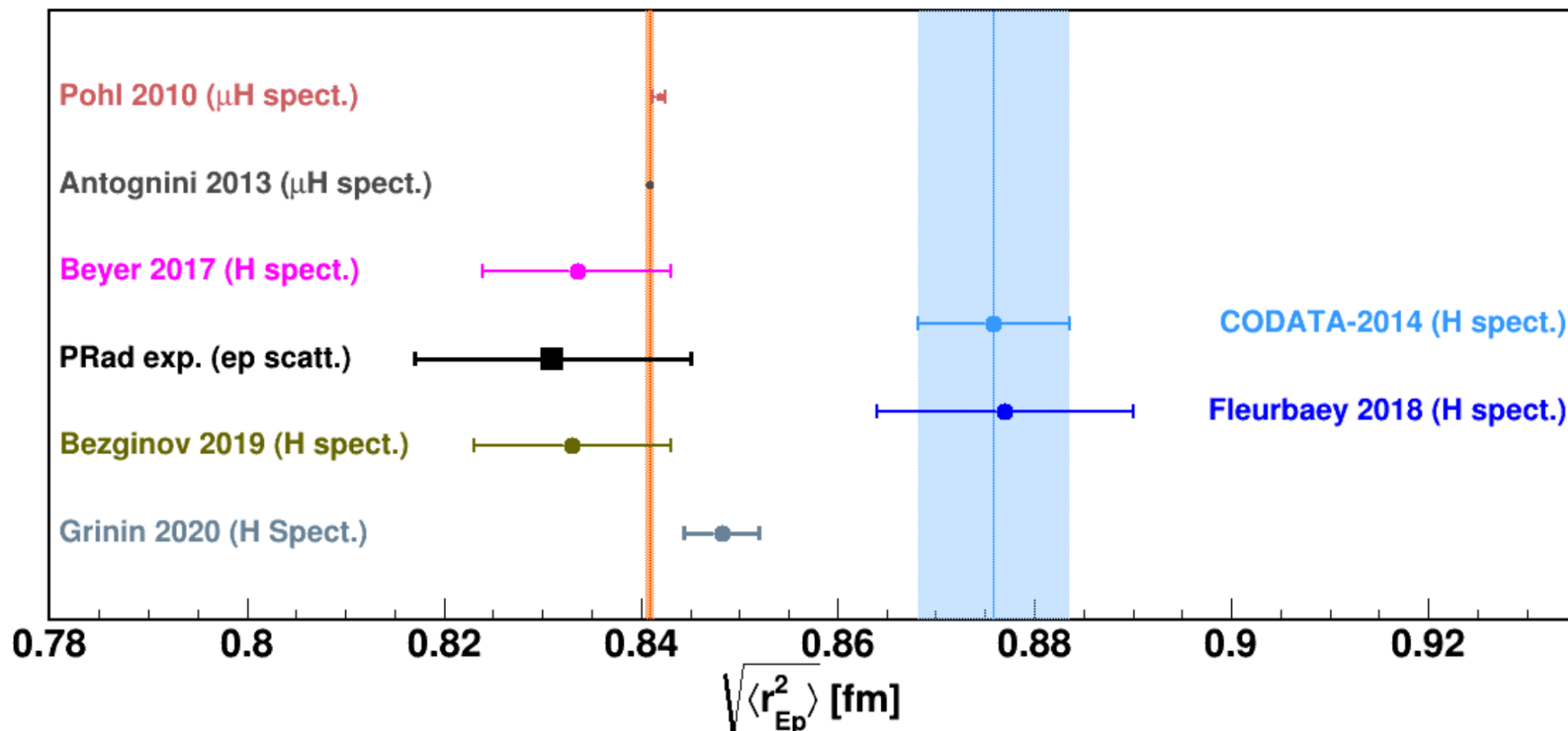
Form factors

- Charge $G_E(Q^2)$ and magnetic moment $G_M(Q^2)$ distributions
- No dependence on Q^2 for a point-like proton
- Dipole form $G_D(Q^2) = (1 + Q^2/0.71 \text{ GeV}^2)^{-2}$



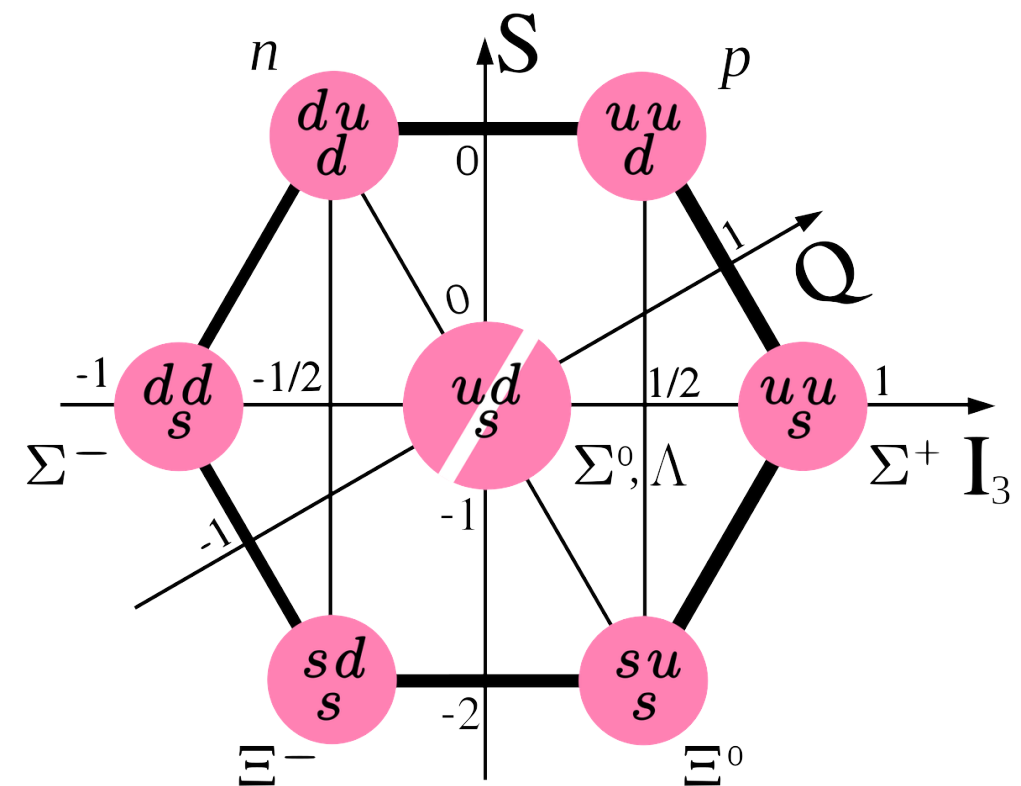
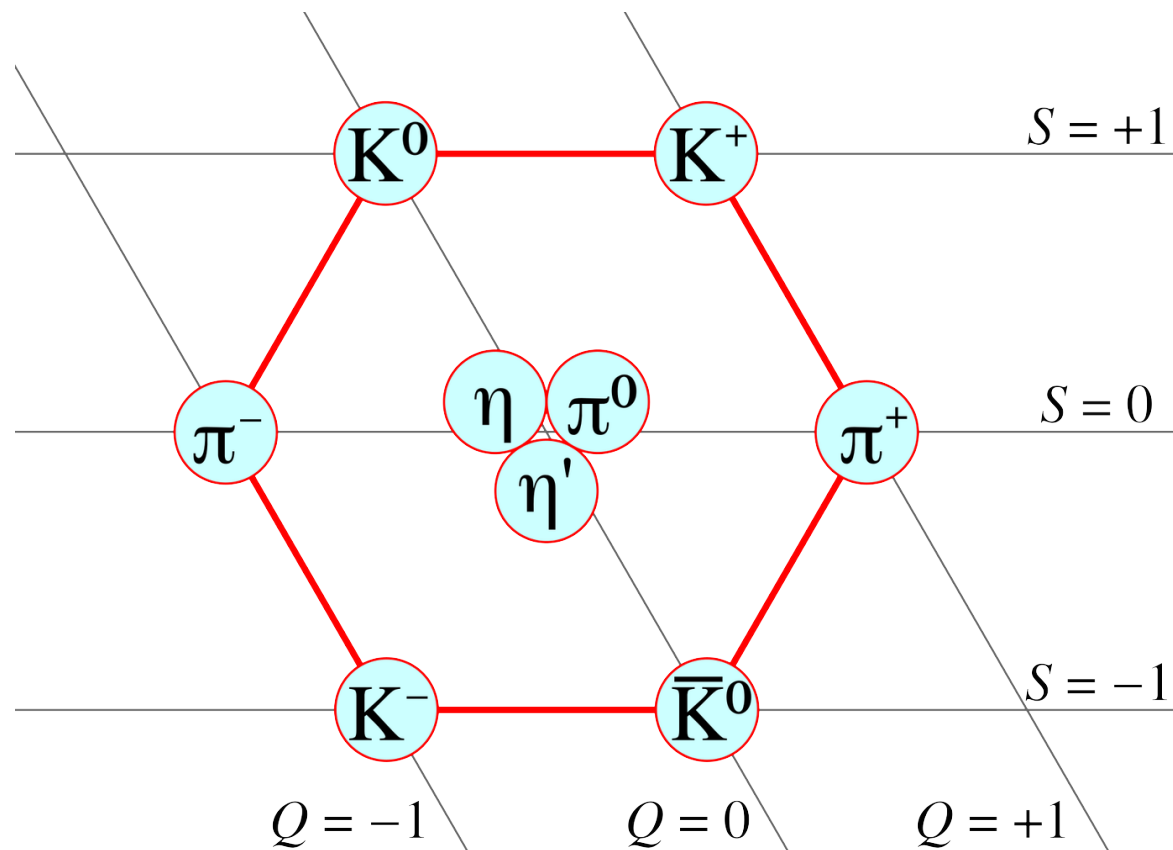
The proton radius puzzle

- **Measure radius** from the slope of G_E at $Q^2 \rightarrow 0$ (electron scattering) and S-state energy shift (atomic spectroscopy), $r_p \approx 0.88$ fm
- Muonic hydrogen (2010): $r_p \approx 0.84$ fm - largely validated by many experiments
- A few outliers still exist



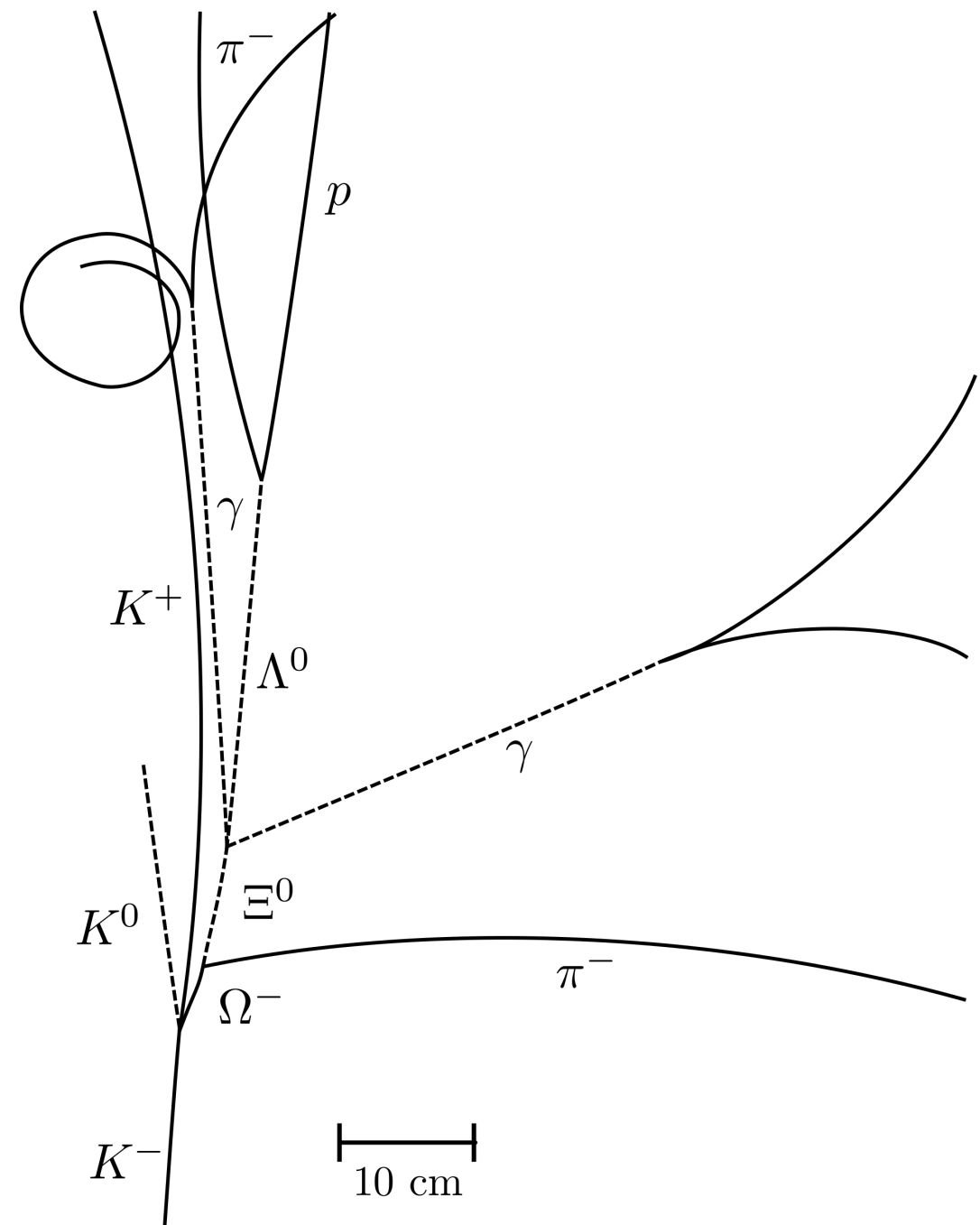
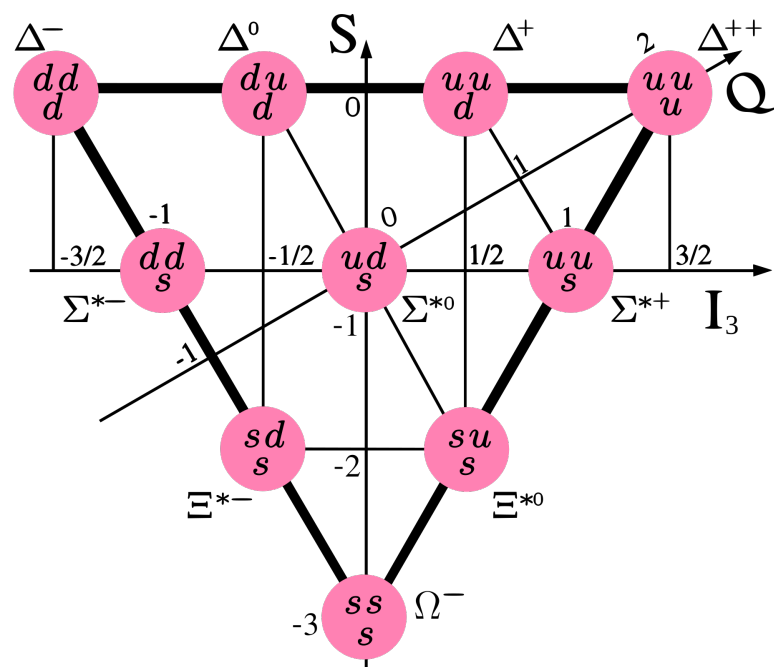
Quarks on paper

- 1964, Gell-Mann and Zweig: the **hadron zoo** is built from three constituents, u, d, and s
- Every search for a free quark with a fractional charge came back null
- Quarks are purely mathematical entities?



The Ω^-

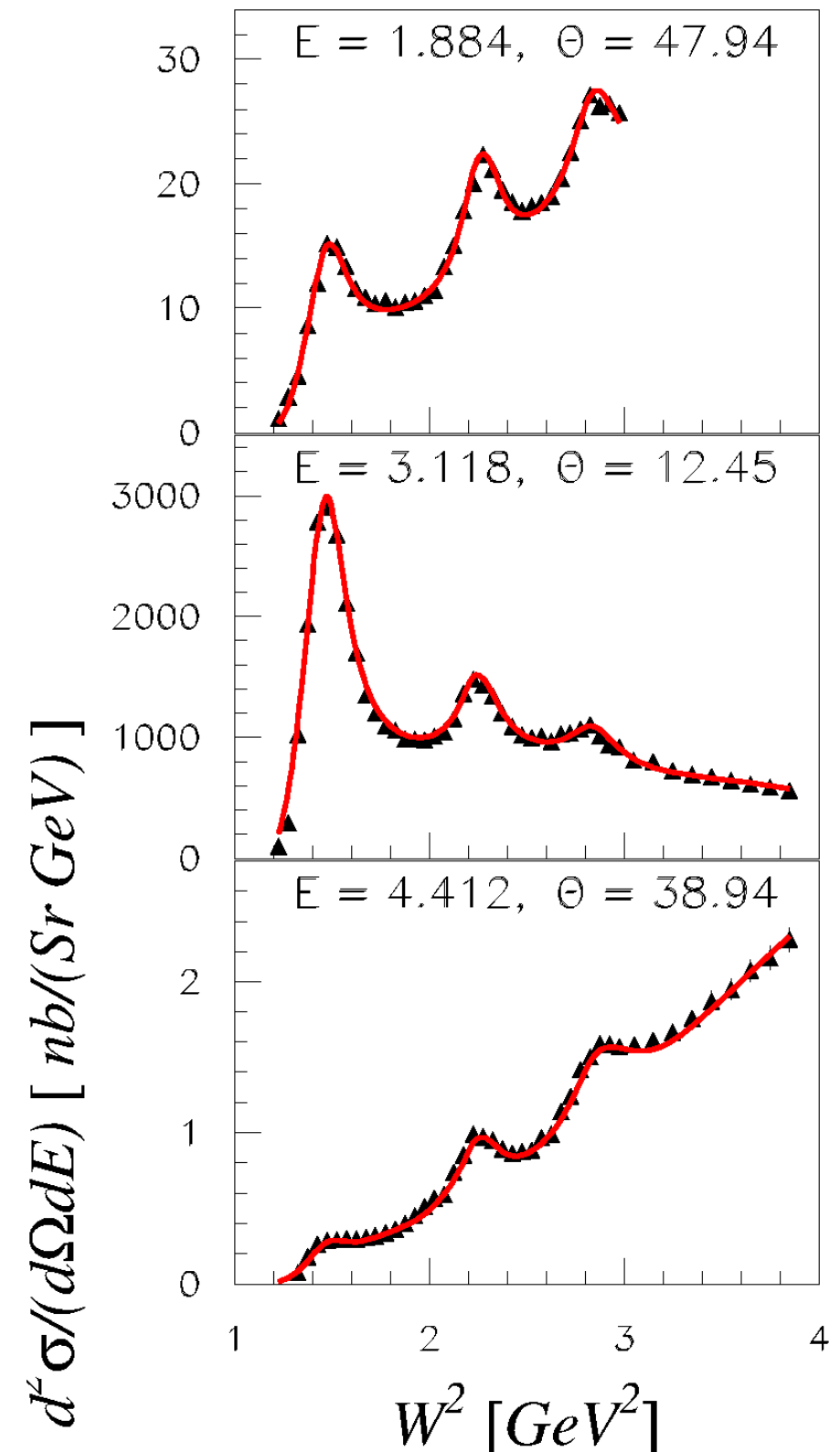
- Symmetric flavor states belong to a decuplet
- **Predicted** the state with $S = -3$, $Q = -1$, $m \approx 1680$ MeV
- Ω^- is the lightest $S = -3$ state with a weak decay and measurable displacement
- 1964, 5 GeV/c K^- into the BNL 80-inch bubble chamber to observe the full decay chain



PRL 12 (1964) 204

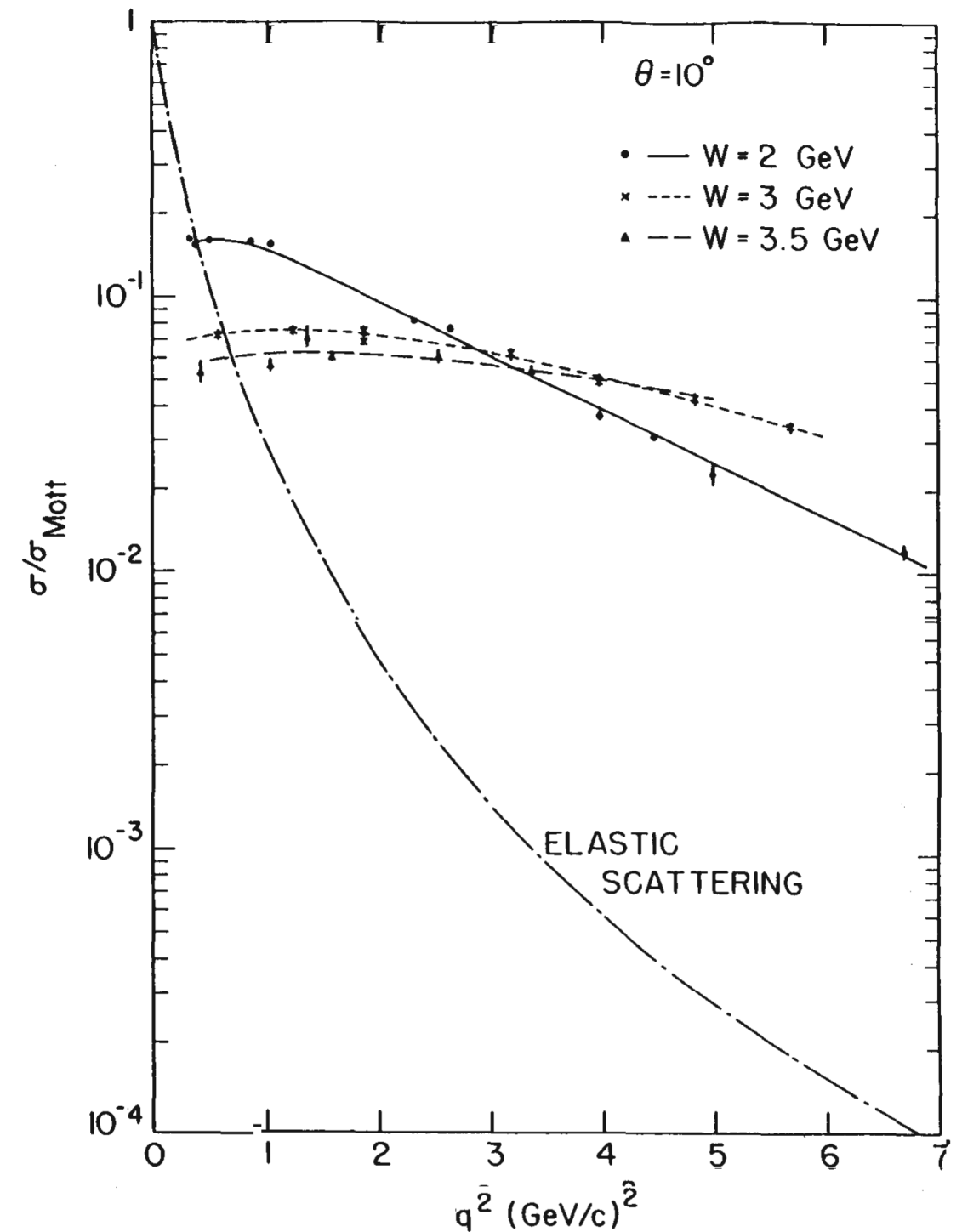
From elastic to deep inelastic

- SLAC End Station A, 1967: electrons on liquid hydrogen, single-arm spectrometer at a fixed angle
- Scan the scattered electron energy: $W^2 = M^2 + 2M\nu - Q^2$ is the mass of what the proton became
- $W = M$: the elastic peak - the proton survives
- Just above: $\Delta(1232)$, $N(1520)$, $N(1680)$ - the nucleon excited states
- A smooth continuum above $W \approx 2$ GeV - the proton shattered into many hadrons $\rightarrow$ nucleon **substructure**!



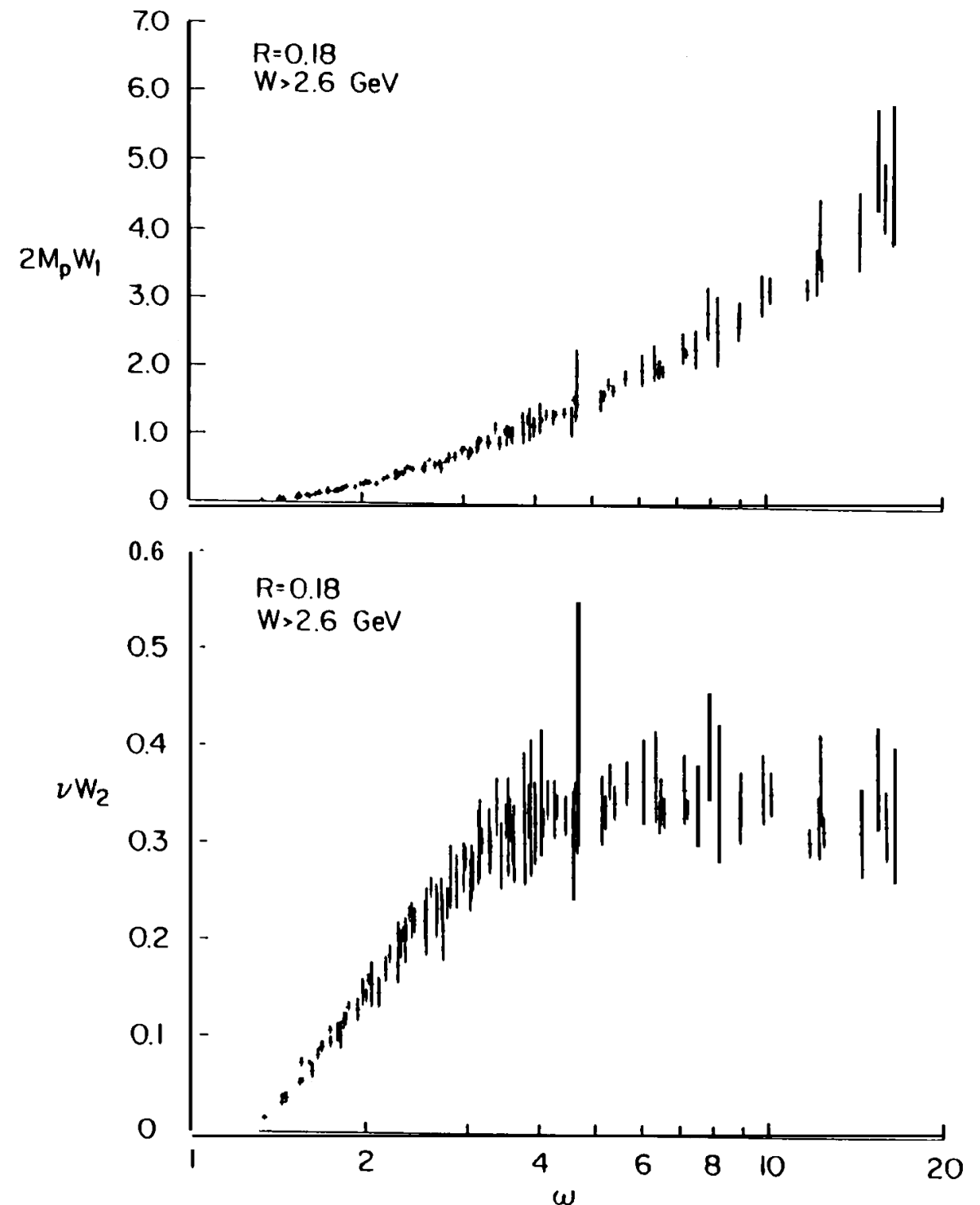
The surprise

- SLAC-MIT, 1968-69: inclusive $ep \rightarrow eX$, beam up to 20 GeV
- Probe target's response by normalizing to Mott's cross section
- **Nearly independent** of $Q^2 \rightarrow$ scattering on point-charge centers inside the proton



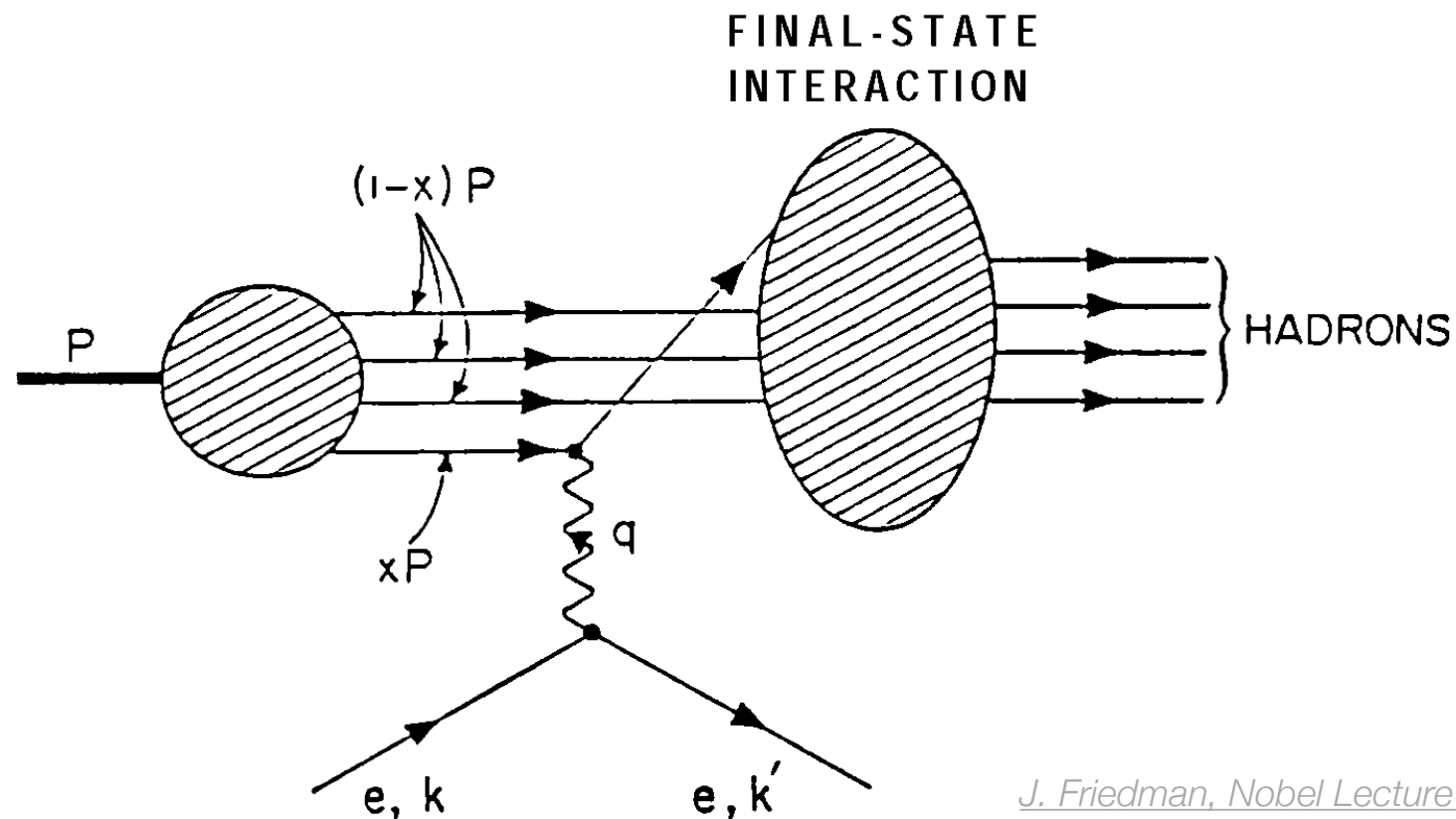
Bjorken scaling

- $W_1(Q^2, \nu)$ and $W_2(Q^2, \nu)$: two functions hold the target's structure
- At high Q^2 and ν **only**
 $\omega = 2M\nu/Q^2 = 1/x$ **matters**
 (Bjorken, 1969): $\nu W_2 \rightarrow F_2(\omega)$,
 $MW_1 \rightarrow F_1(\omega)$
- SLAC-MIT: every $Q^2 = 1 - 20 \text{ GeV}^2$ gives the same curve
- Probing harder reveals no structure



The parton model

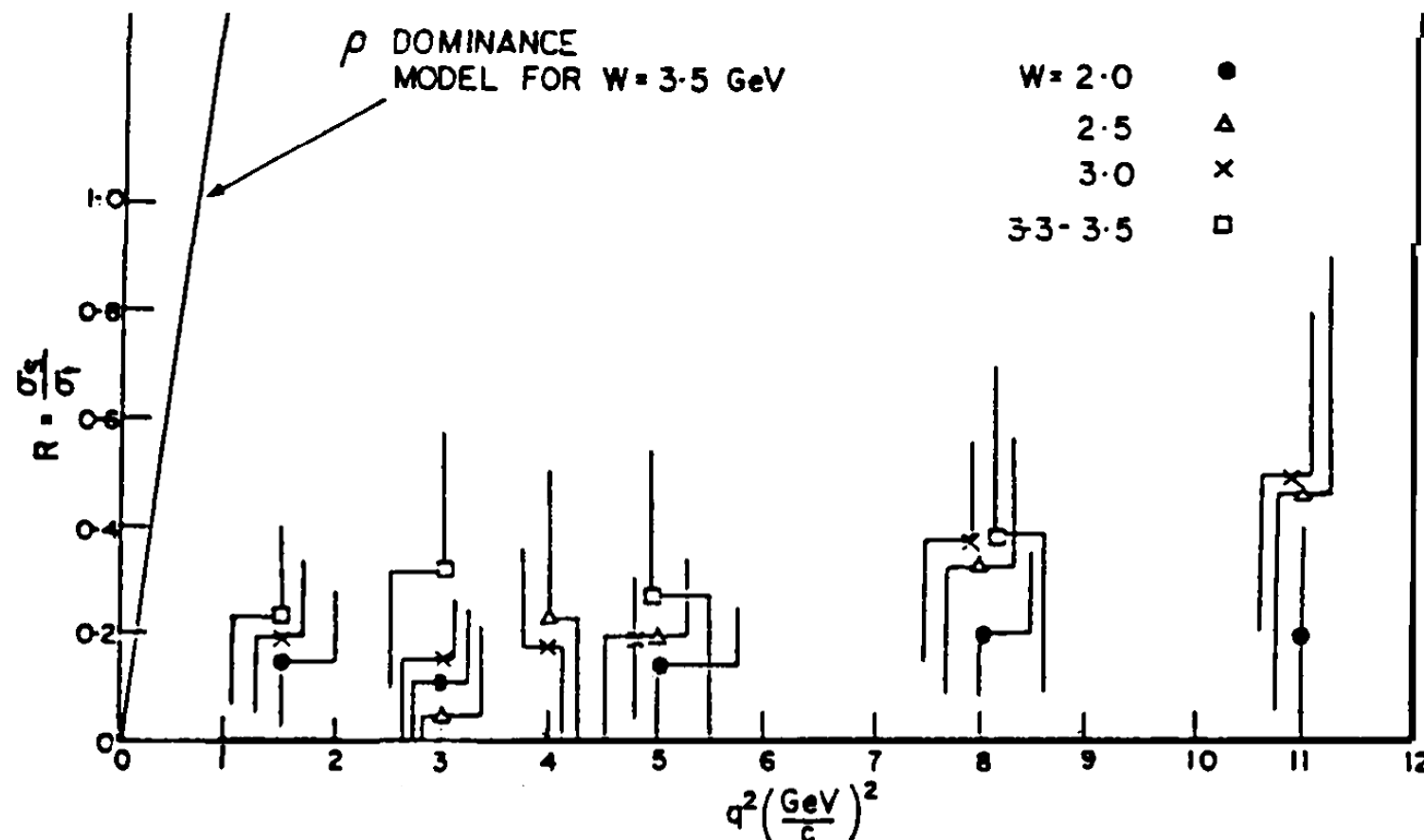
- Feynman, 1969: in a fast-moving frame the proton is a set of **quasi-free partons** - the collision is too brief for them to interact
- Elastic scattering off a free parton of momentum fraction $x = Q^2/2M\nu = 1/\omega$
- (Probability of a parton at x) $\times$ (point-charge elastic) $\rightarrow F_2(x) = \sum e_q^2 x q(x)$
- Partons identified either with bare nucleons and pions (Drell-Levy-Yan) or with quarks (Bjorken-Paschos)



J. Friedman, Nobel Lecture (1990)

Callan-Gross relation

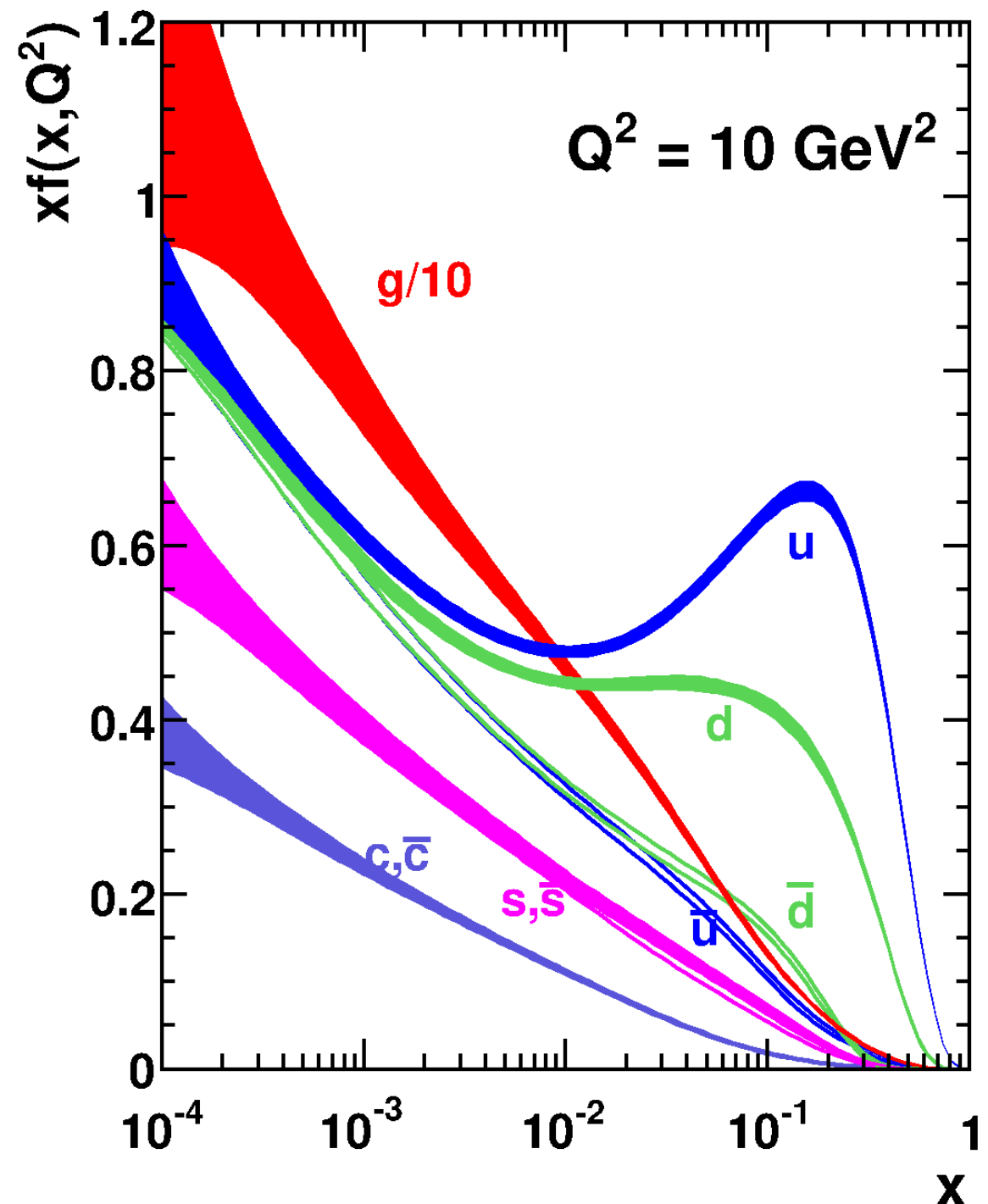
- $R = \sigma_L/\sigma_T$: helicity conservation forbids a massless spin-1/2 parton from absorbing a longitudinal photon
- Spin 1/2 $\Rightarrow R \rightarrow 0$, i.e. $2xF_1 = F_2$ (Callan-Gross, 1969)
- Spin 0 $\Rightarrow \sigma_T \rightarrow 0$, $R \rightarrow \infty$
- SLAC-MIT: $R \simeq 0.1 - 0.2$, no rise with $Q^2 \Rightarrow$ the constituents carry spin-1/2
- Same data exclude ρ dominance, which predicts R growing as Q^2/m_ρ^2



J. Friedman, Nobel Lecture (1990)

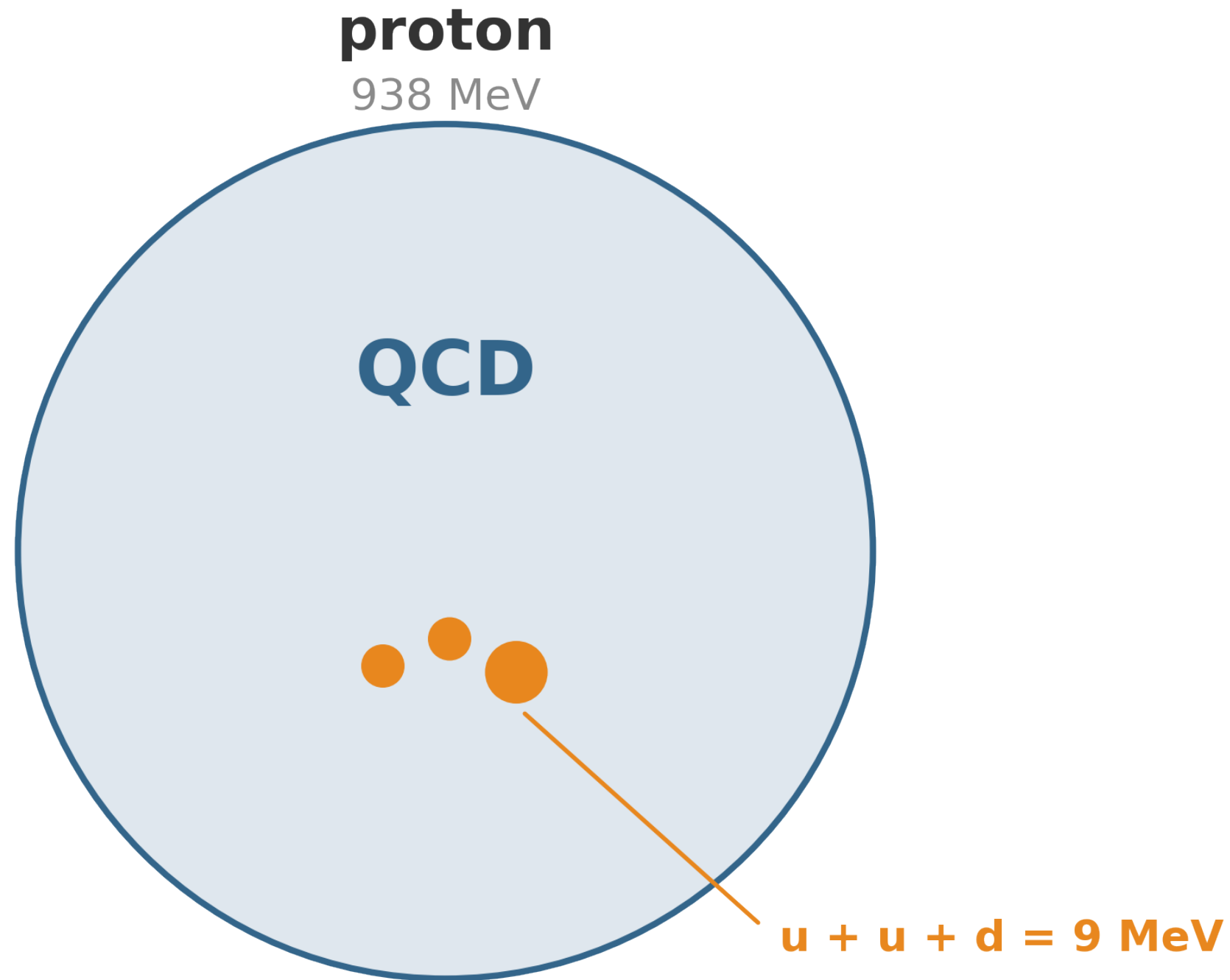
Parton distribution functions

- $q(x)$ are the proton's **parton distribution functions** (PDFs)
- $q(x)dx \rightarrow$ number of constituents of type q within momentum fraction in $[x, x + dx]$
- $F_2(x) = \sum_q e_q^2 x q(x)$
- $\int (u - \bar{u})dx = 2, \int (d - \bar{d})dx = 1$
- Charged constituents carry only ≈ 0.54 of the momentum - half the proton is invisible to the photon



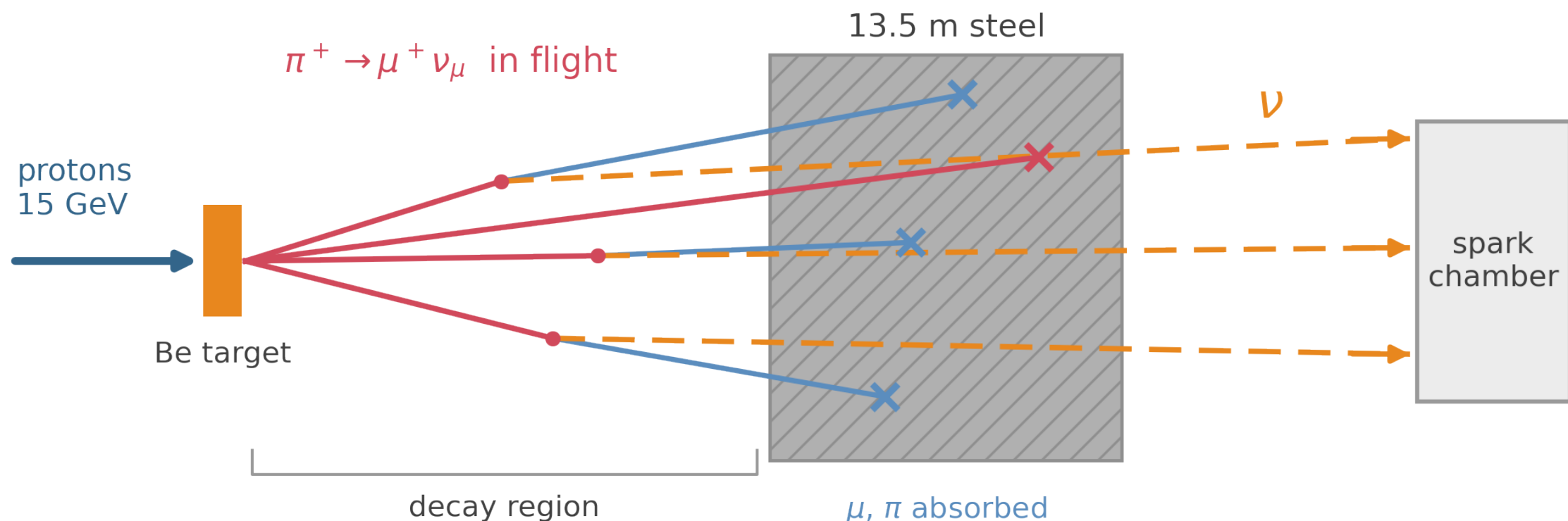
Eur. Phys. J. C 63 (2009) 189

The Higgs gives 1%



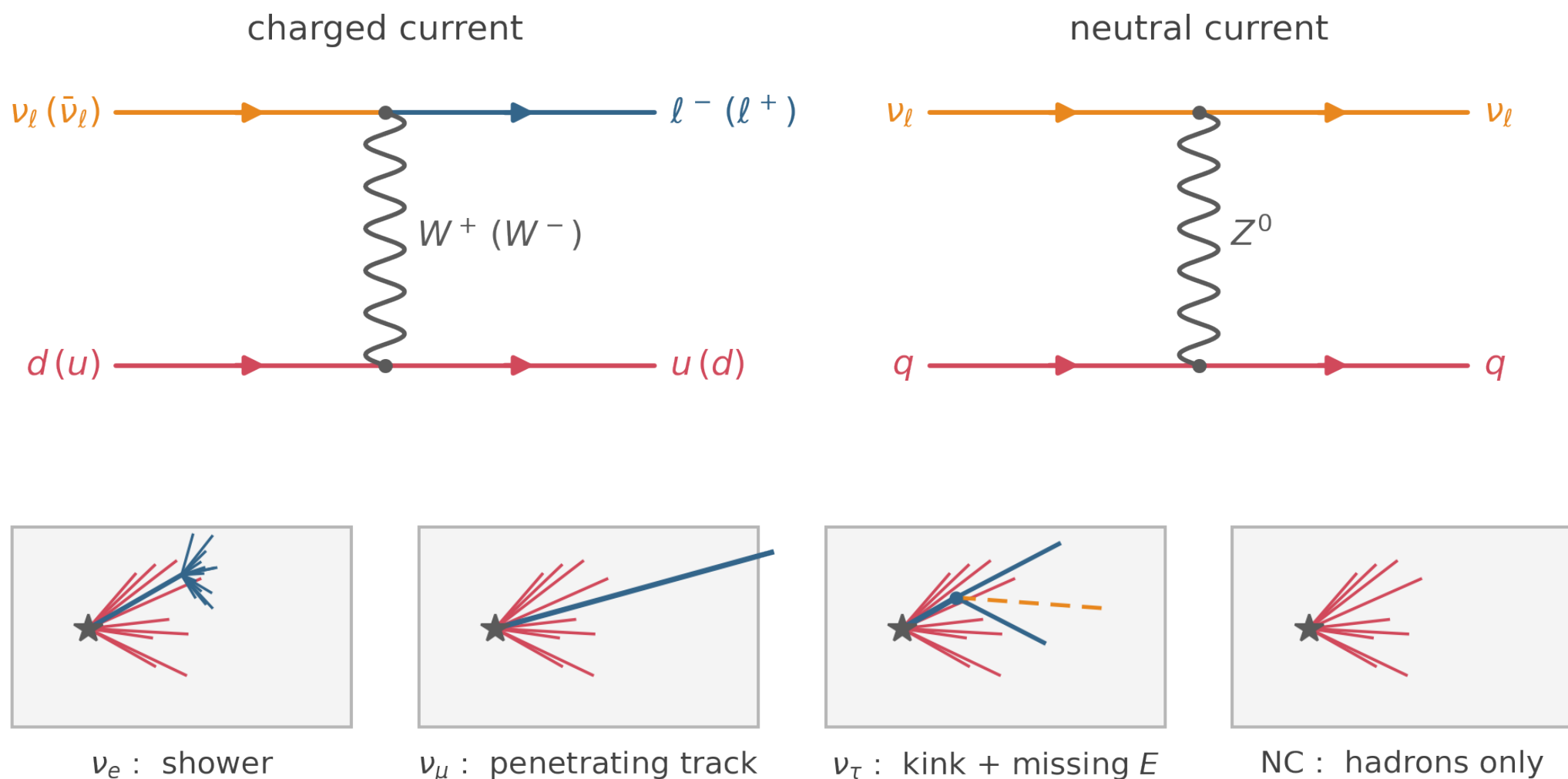
Inventing the neutrino beam

- Neutrinos are the only purely weak probe
- BNL AGS, 1962: 15 GeV protons on beryllium; pions decay in flight → a neutrino beam
- Use deck plates of a dismantled cruiser (13.5 m of steel) as absorber
- Recorded 29 muon events, 6 shower candidates
- Neutrino beams as an **instrument** (Lederman, Schwartz, Steinberger - Nobel 1988)



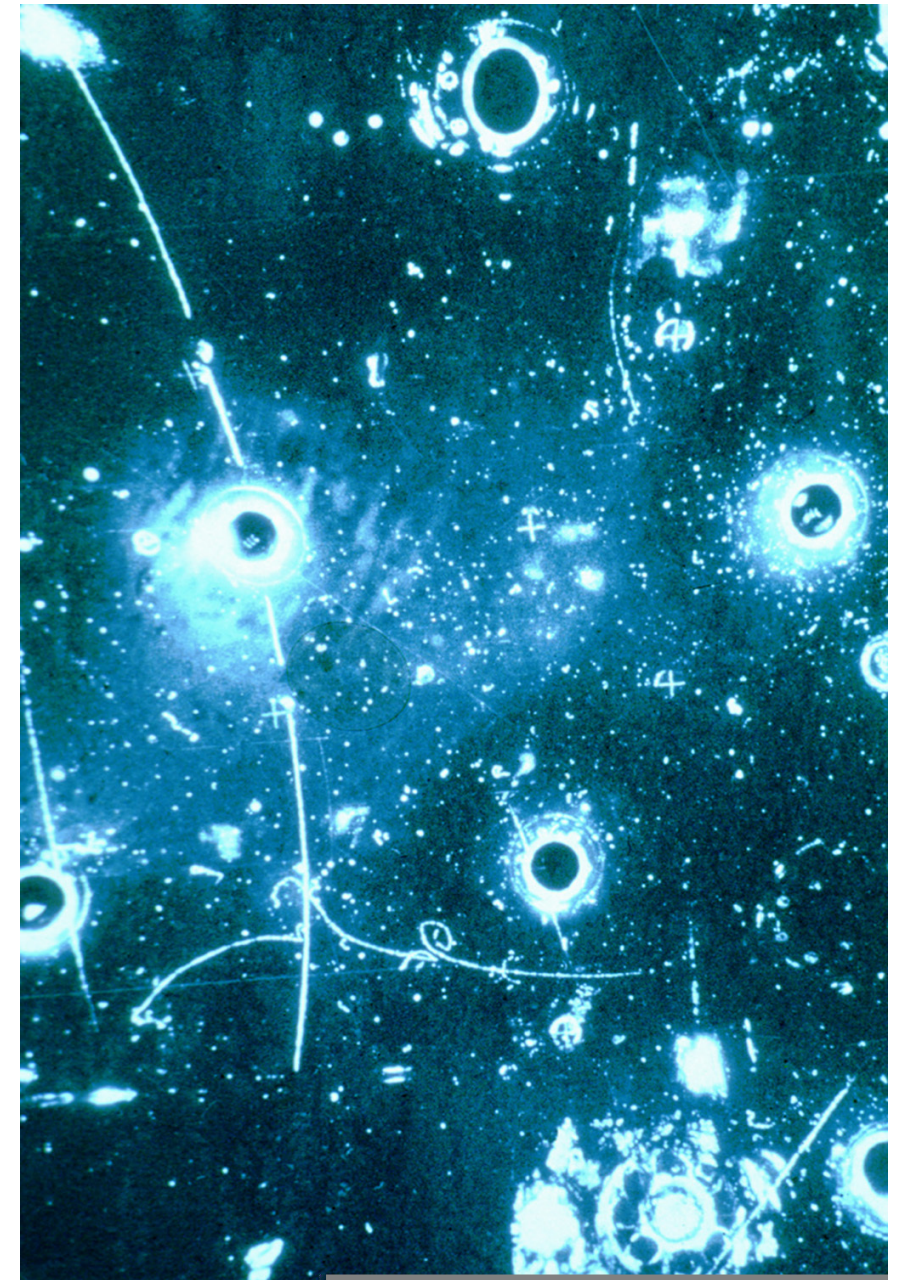
Neutrino DIS

- Charged current ($W^\pm$): the struck quark changes flavor
- Neutral current (Z^0): hadronic final state and escaping neutrino
- The outgoing lepton identifies the neutrino: electromagnetic showers, muon track, displaced tau decay vertex
- Differentiates quark flavors and quarks from antiquarks



Gargamelle

- Heavy-liquid bubble chamber in the CERN PS neutrino beam: 18 t of freon, target and detector in one
- Dense liquid for higher rate
- A whole event is visible in one photograph
- The instrument behind the first studies of **neutrino structure functions**: valence, momentum, quark charges
- The first thing it found: hadrons with no muon - the neutral current, 1973

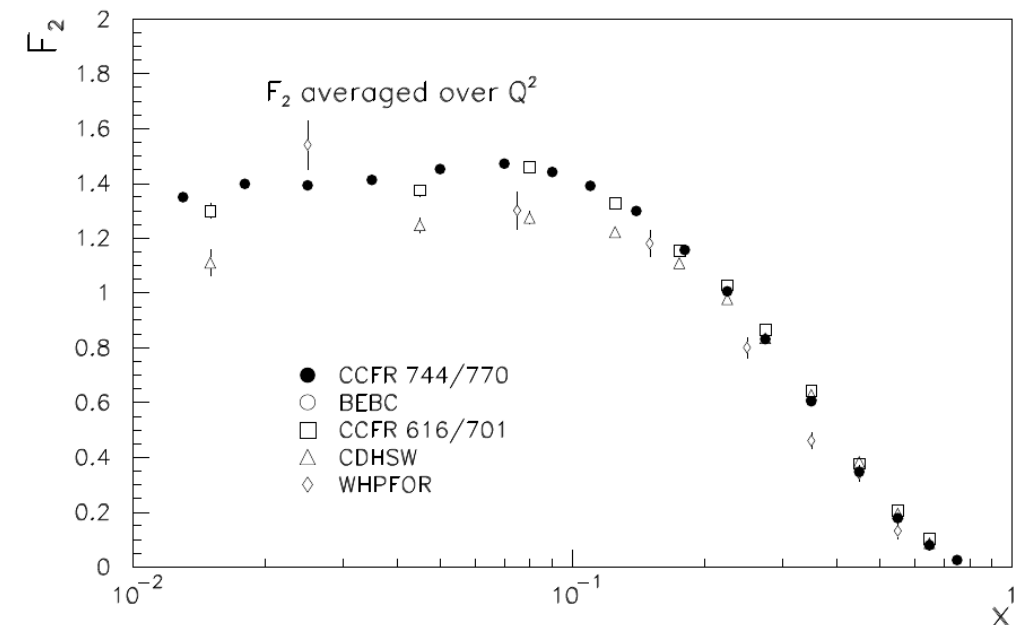
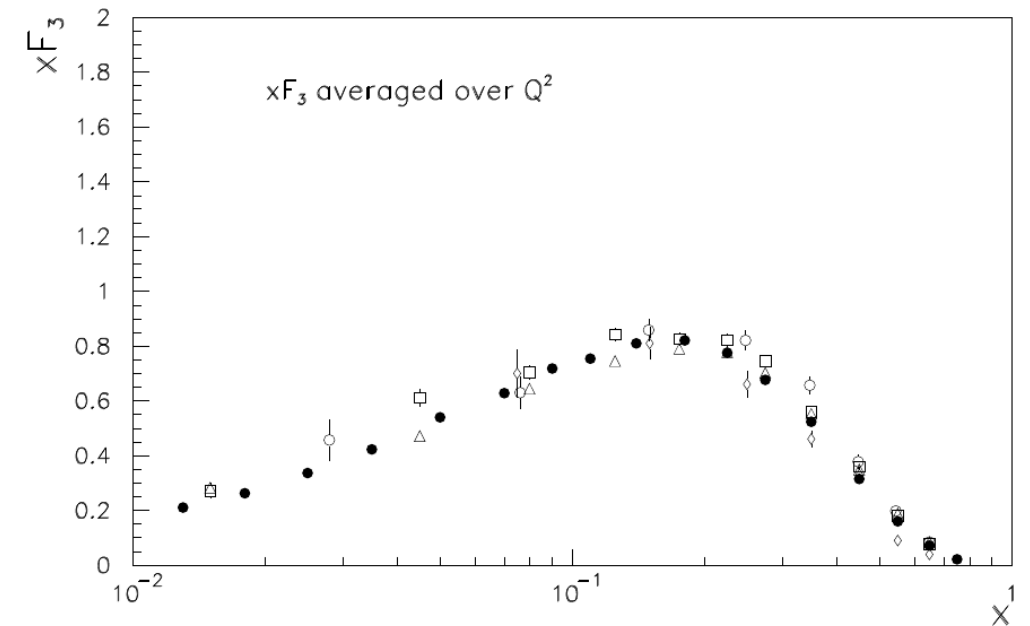


Gargamelle, 1973

Structure functions

- How many depends on the interaction:
 $\gamma \rightarrow F_1, F_2$; $\gamma/Z \rightarrow F_3$ as well; $W^\pm \rightarrow$ five functions
- F_1, F_2 : transverse and longitudinal response -
 $2xF_1 = F_2$ for point-like spin-1/2 constituents
- F_3 needs parity violation - a neutrino beam has it: probe F_3 with $\nu/\bar{\nu}$
- Sea quark contributions cancel in
 $xF_3 \propto x(q - \bar{q})$
- F_4 and F_5 always carry m_ℓ^2 - invisible except for ν_τ ; $F_4 = 0$, $2xF_5 = F_2$ at leading order

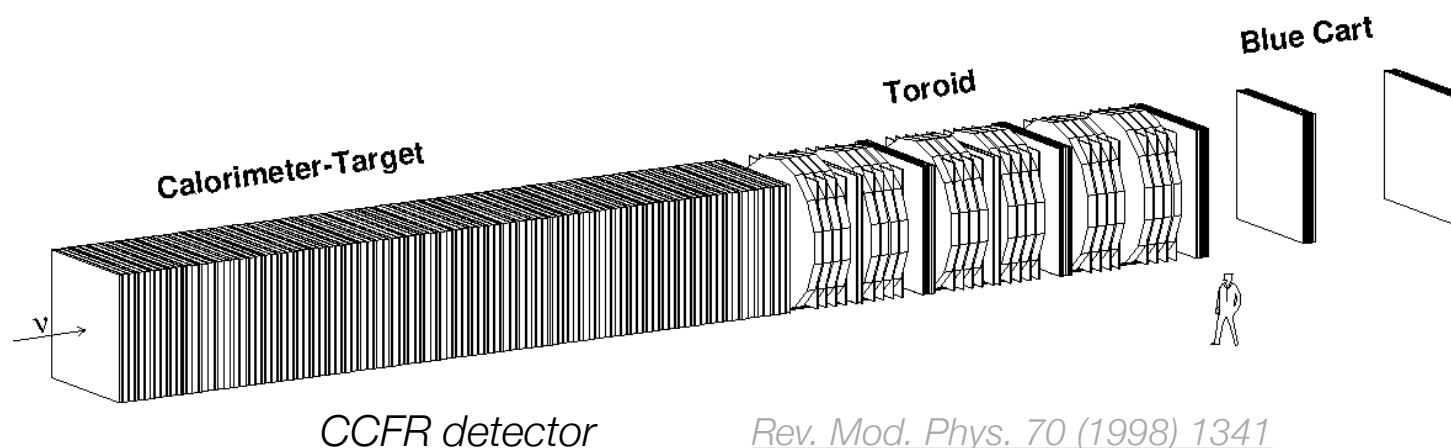
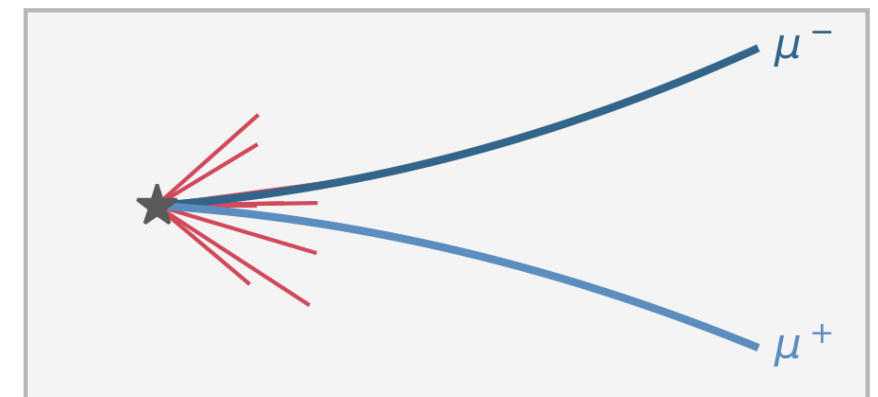
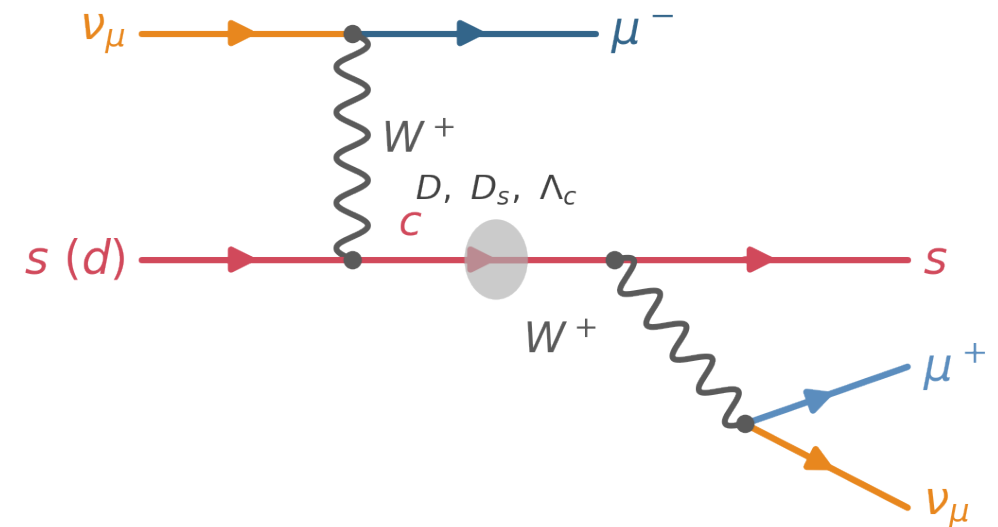
Rev. Mod. Phys. 70 (1998) 1341



$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi (1 + Q^2/M_W^2)^2} \left\{ \left(xy^2 + \frac{m_\ell^2 y}{2ME_\nu} \right) F_1 + \left(1 - y - \frac{Mxy}{2E_\nu} - \frac{m_\ell^2}{4E_\nu^2} \right) F_2 \pm \left(xy \left(1 - \frac{y}{2} \right) - \frac{m_\ell^2 y}{4ME_\nu} \right) F_3 + \frac{m_\ell^2 (m_\ell^2 + Q^2)}{4M^2 E_\nu^2 x} F_4 - \frac{m_\ell^2}{ME_\nu} F_5 \right\}$$

Weighing the strange sea

- Strangeness has no valence component — the strange sea is **made entirely by gluons**
- CDHS, CCFR, NuTeV: magnetized iron
- Opposite-sign dimuons tag charm
- Contribution from strange quarks is suppressed by $m_s \approx 93 \text{ MeV}$
- Measured NC/CC ratio gives $\sin^2\theta_W = 0.2277 \pm 0.0016$ (NuTeV) — 3σ above every other measurement



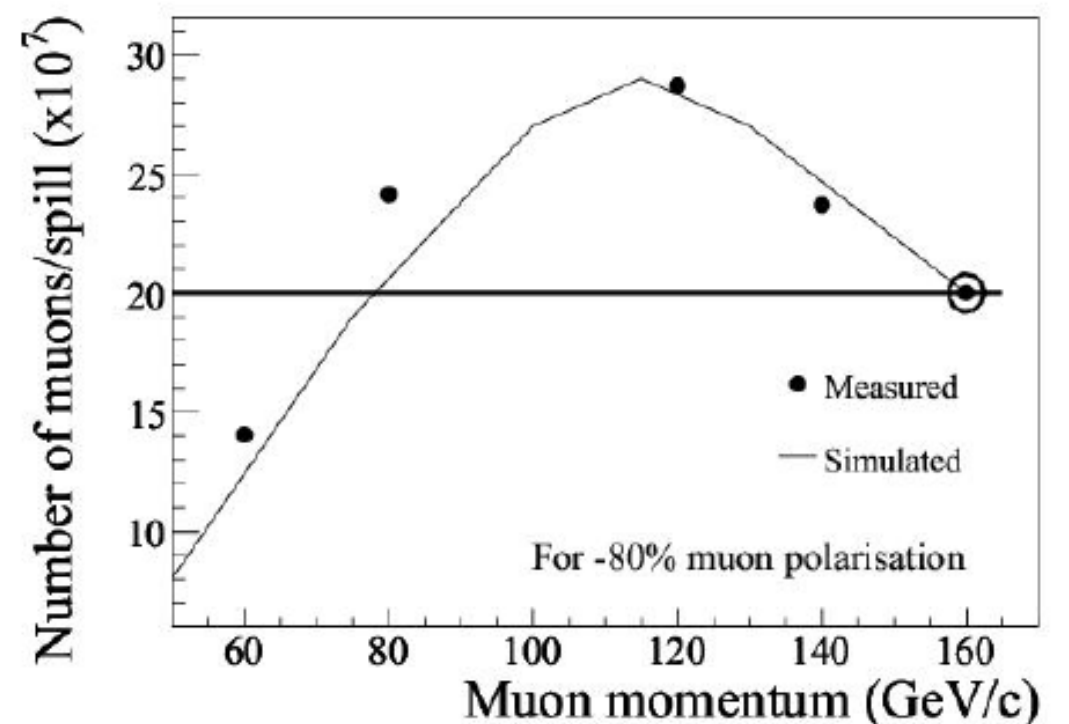
Rev. Mod. Phys. 70 (1998) 1341

Muon DIS

- Unlike neutrinos: **huge rates**
- Can use lightweight thin targets, e.g. Hydrogen
- Tertiary μ beams from π/K decays: 100-280 GeV at CERN SPS
- EMC $\rightarrow$ BCDMS $\rightarrow$ NMC at CERN, E665 at Fermilab: ratio for F_2 on p and d at the sub-percent level

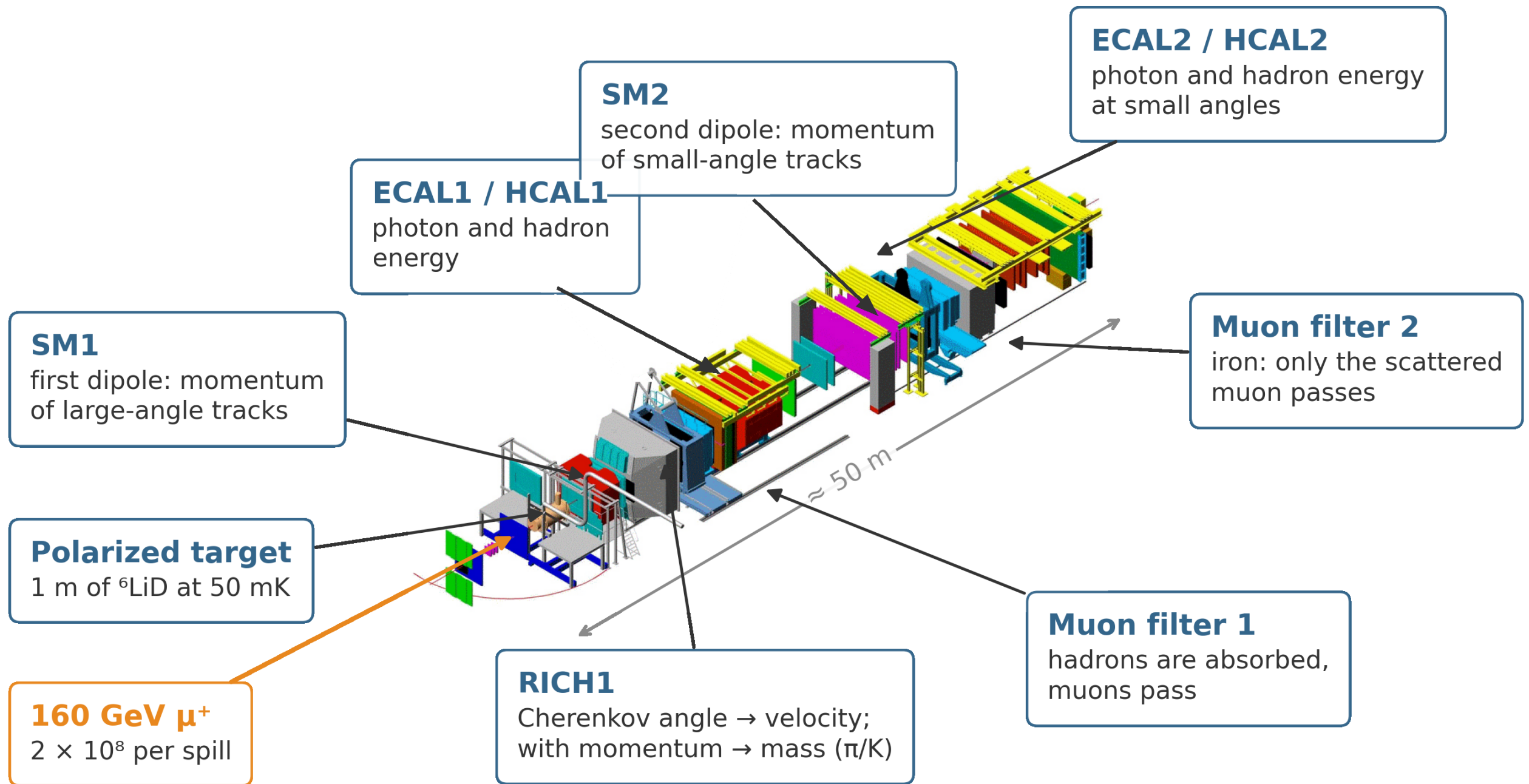


EMC apparatus in EHN2, 1977



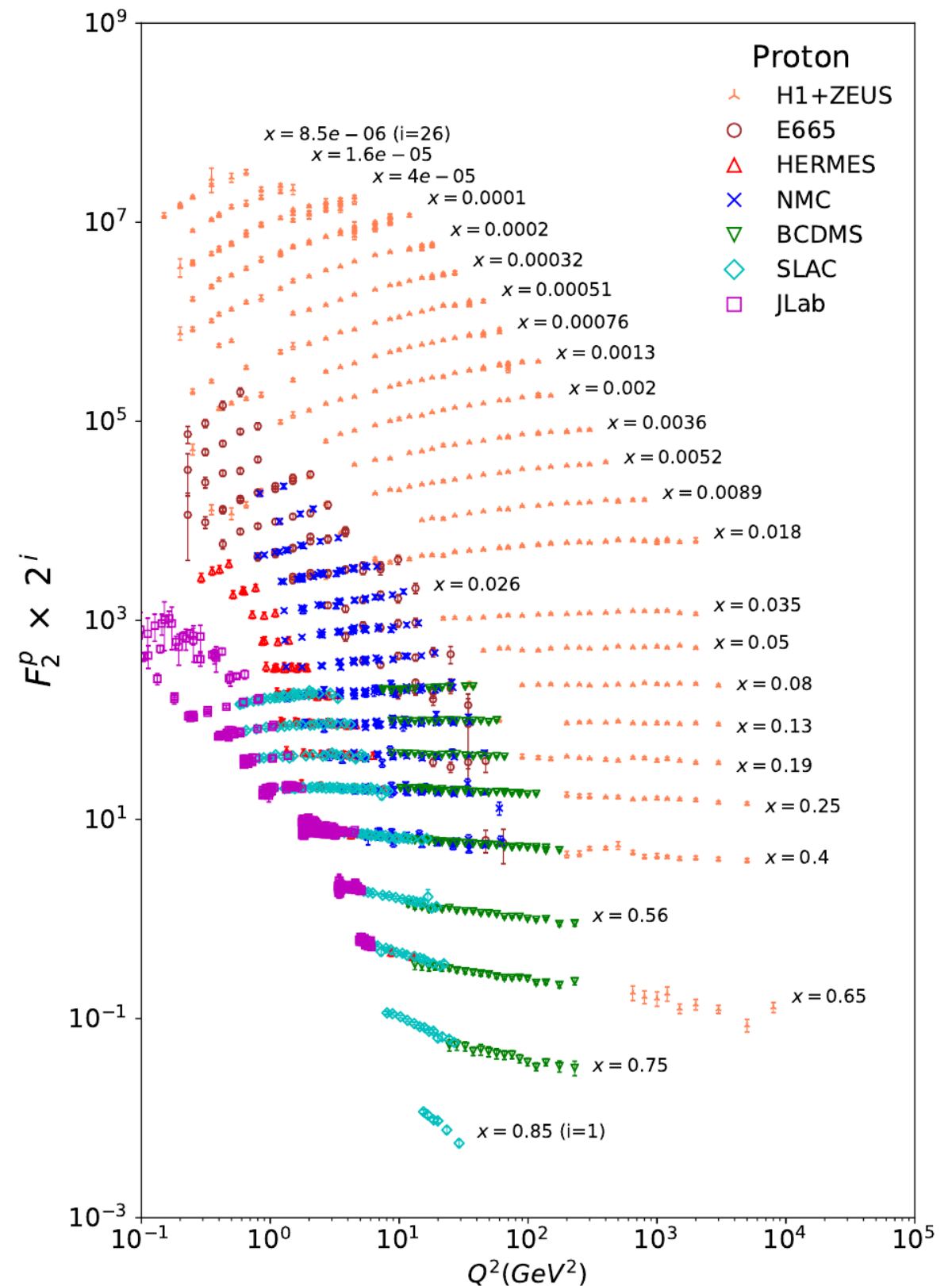
COMPASS at M2 beam line

Anatomy of a measurement



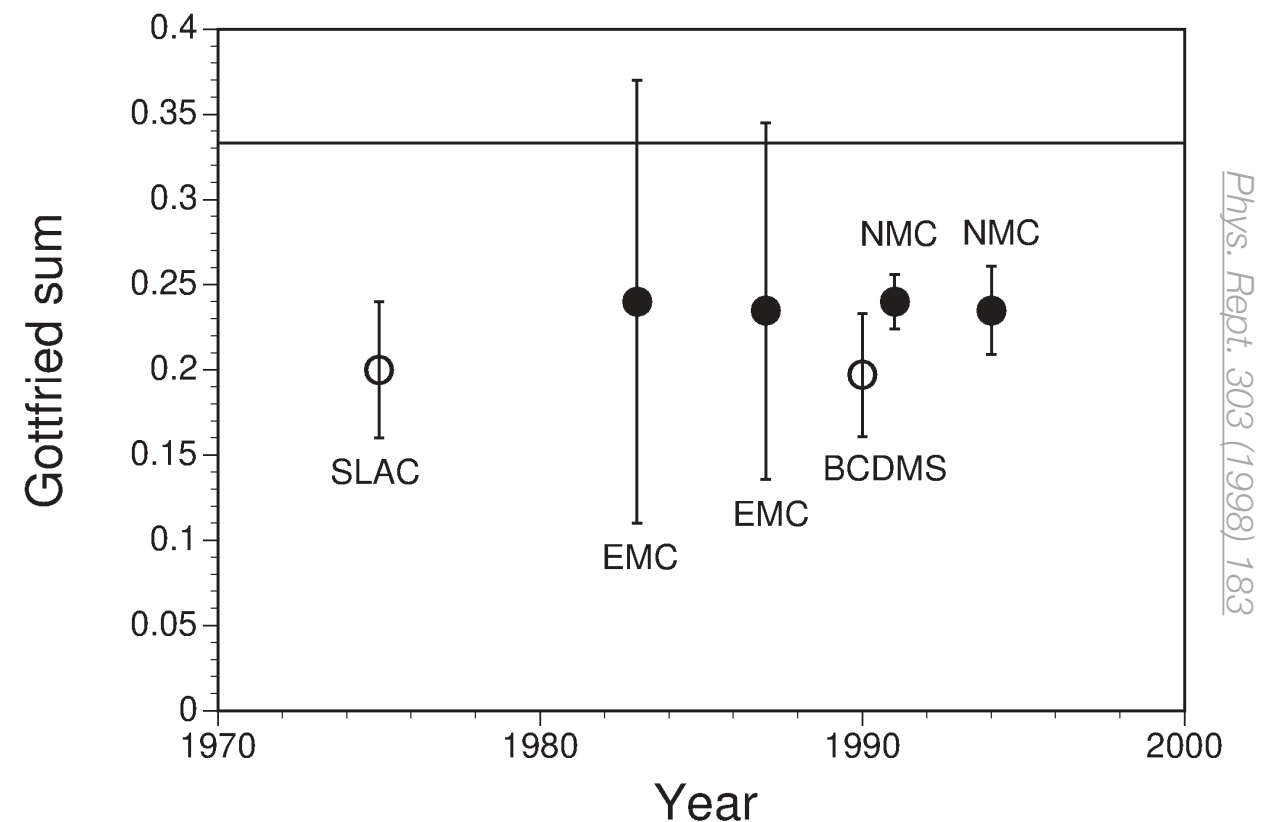
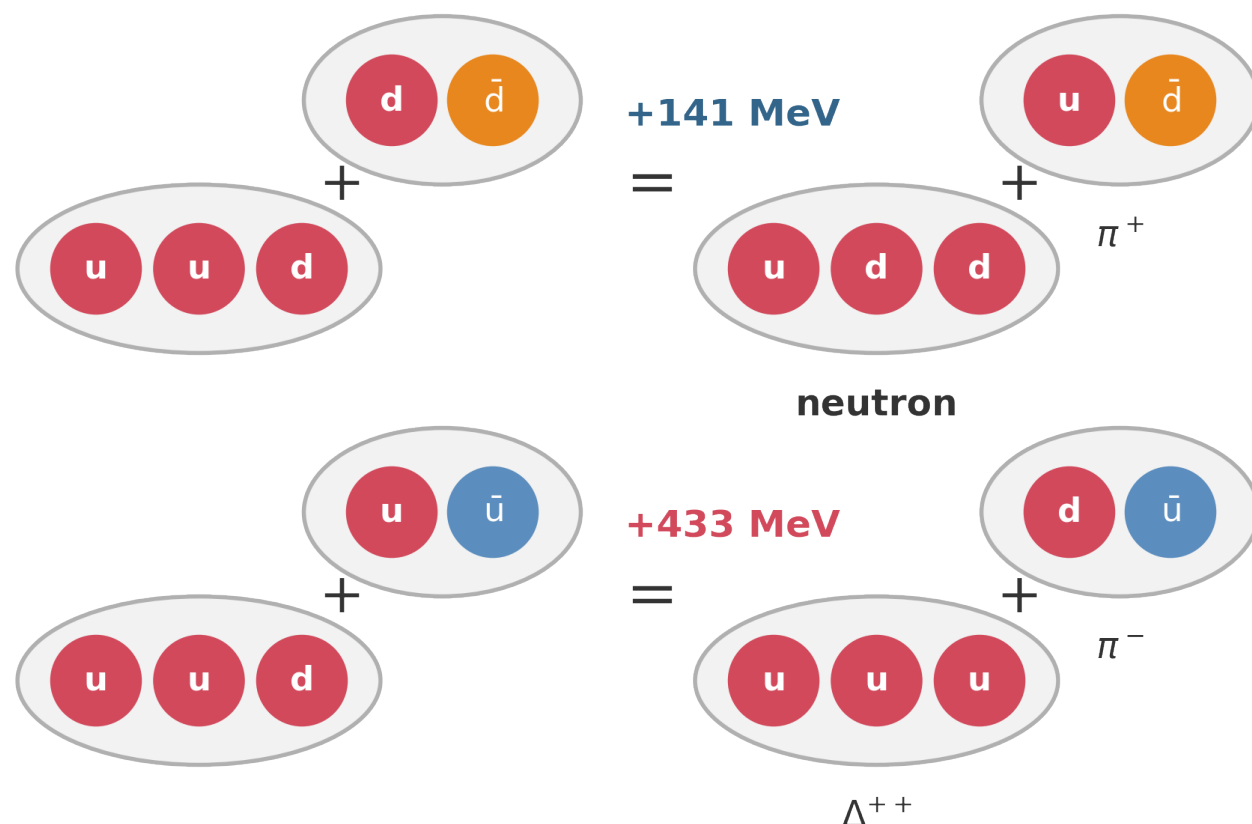
Scaling violations

- If quarks were free, F_2 would not depend on Q^2
- Quarks radiate gluons $\rightarrow F_2$ drifts with Q^2 : this is DGLAP evolution
- Goes down at large x and up at small x
- Logarithmic dependence, not a power law $\rightarrow$ quarks are still point-like
- Extract α_s from the slope
- Fixed targets hold large x , HERA reaches $x \approx 10^{-5}$



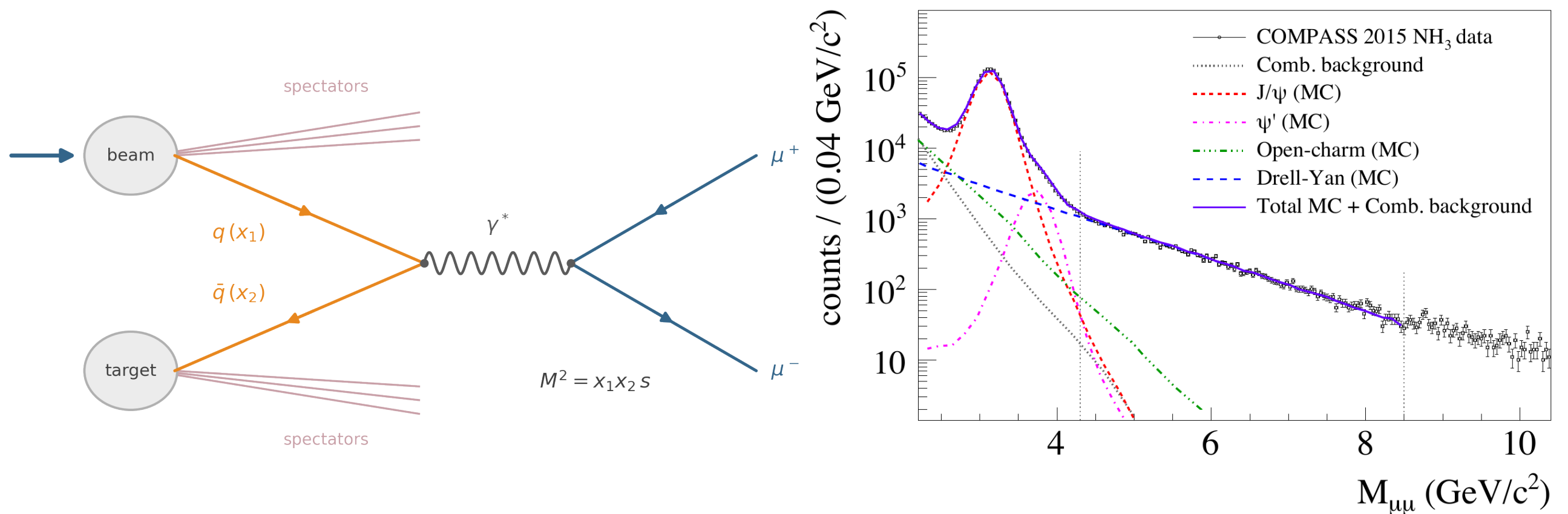
Sea flavor asymmetry

- Gottfried: $\int_0^1 \left(F_2^p - F_2^n \right) \frac{dx}{x} = \frac{1}{3}$ if the sea is flavor-blind
- NMC measured 0.235 ± 0.026 suggesting violation of the sum rule
- The deficit is the sea itself: the proton holds more $\bar{d}$ than $\bar{u}$
- Gluon splitting cannot do it: gluons are flavor blind and $m_u \simeq m_d$
- A pion cloud can: $d \bar{d}$ regroups into $n + \pi^+$, but $u \bar{u}$ would need a Δ^{++}



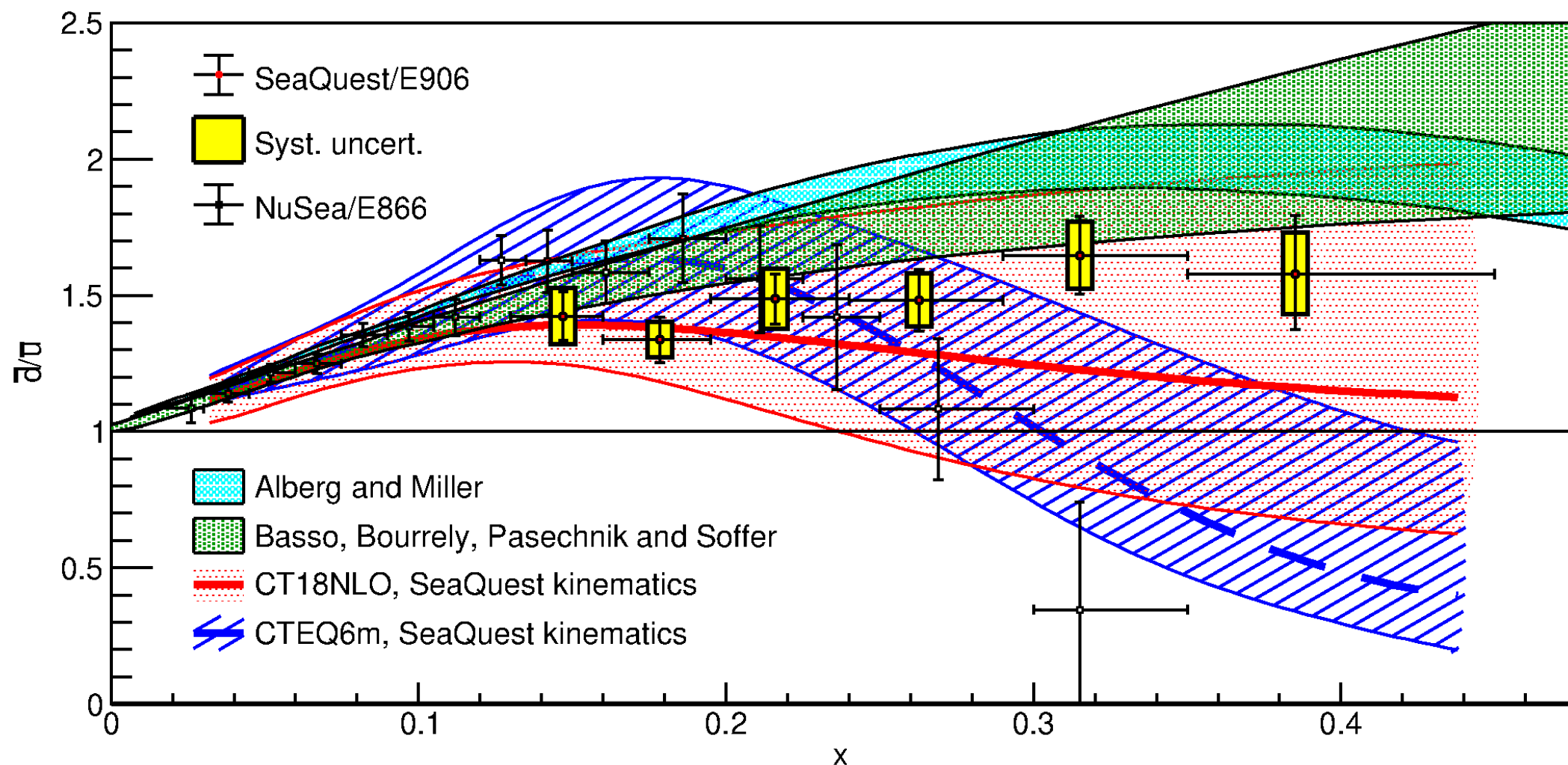
Drell-Yan

- A quark and an antiquark annihilate into a muon pair
- Involves both momentum fractions: $M^2 = x_1 x_2 s$
- At small x the proton's quarks are mostly sea, and here it enters at the same order as valence
- Proton beam, H_2 vs $D_2 \rightarrow$ the nucleon sea, and $\bar{d}$ against $\bar{u}$ (E866)
- Pion beam on a nucleon $\rightarrow$ the pion's own structure (COMPASS, AMBER)



Quest for antimatter asymmetry

- A larger contribution from $\bar{d}$ than from $\bar{u}$ at every measured x
- The perturbative sea is flavor-symmetric at small x
- Probing **pion cloud mechanism** inside the proton
- The antiquark flavor as a fingerprint of chiral symmetry breaking

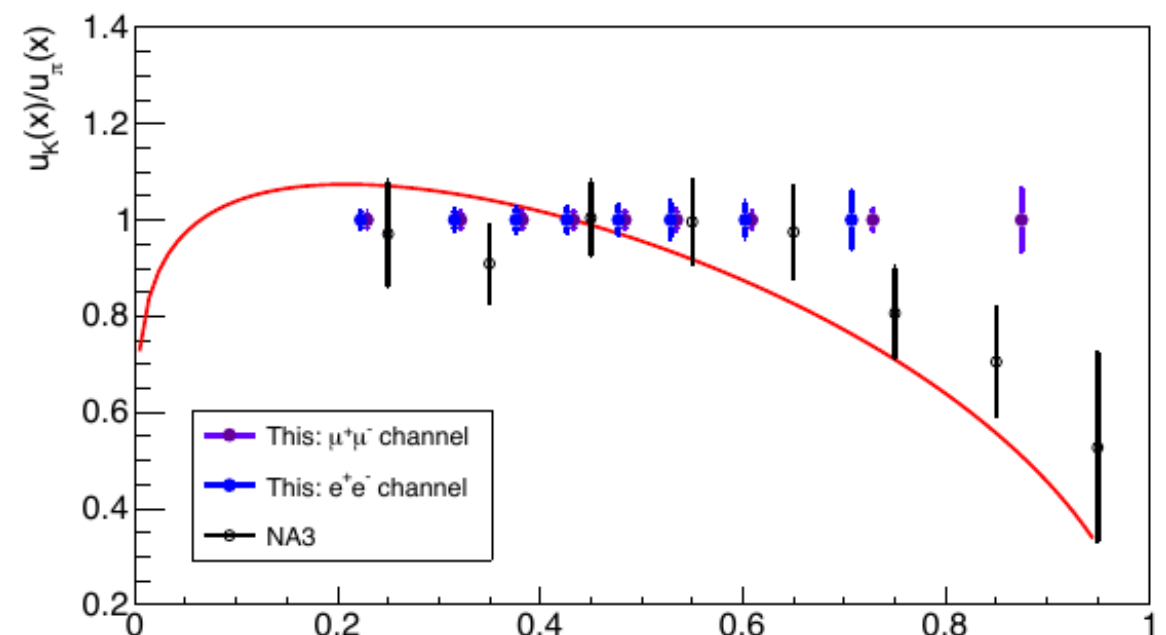
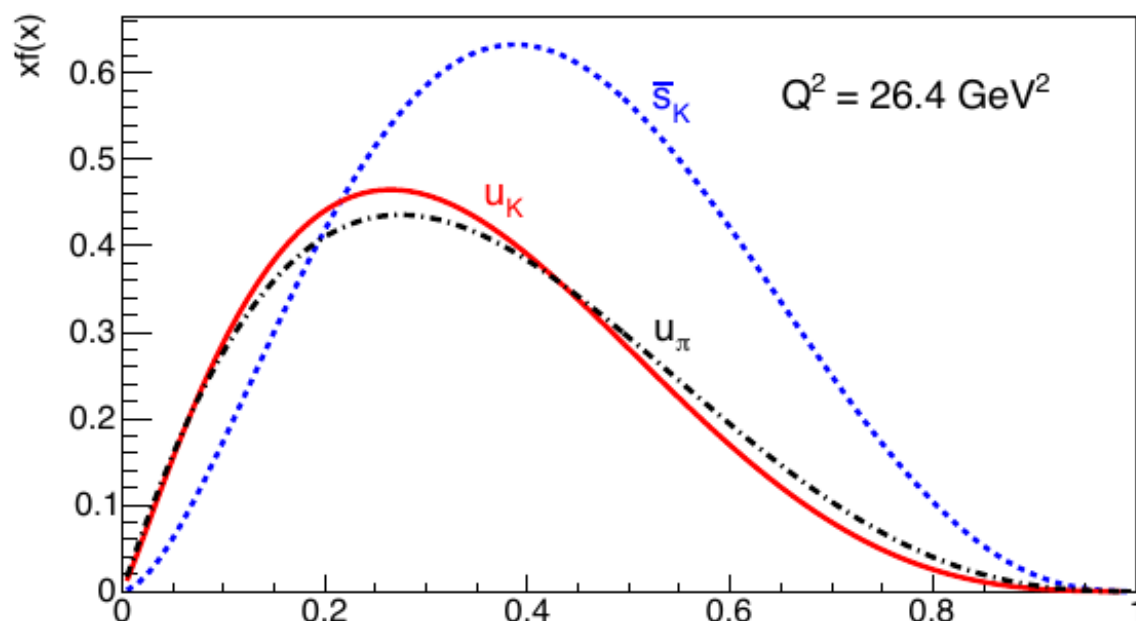


Nature 590 (2021) 561

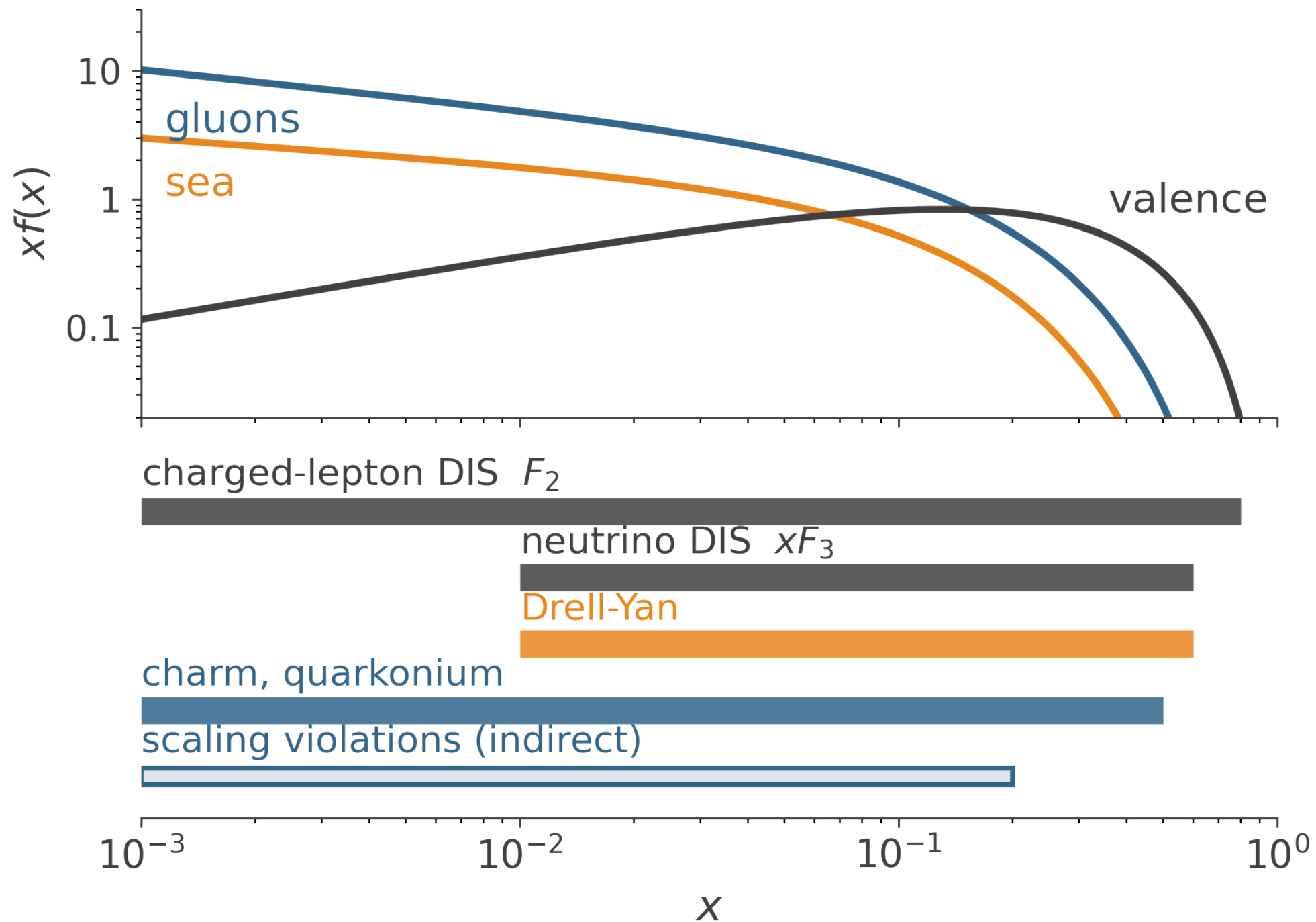
Pion and kaon structure

- **Only two valence partons:** the simplest QCD bound state
- Valence fall-off as $x \rightarrow 1$: data $(1 - x)^1$ vs theory $(1 - x)^2$
- Resolved by resumming soft gluons in theory
- The kaon is the same Goldstone boson with one heavy quark: Higgs mass against QCD mass
- The $\bar{s}$ sits at higher x while the u barely moves: dressed masses differ by ~ 1.4 , not 20
- Almost no data on kaon structure for $x > 0.6$

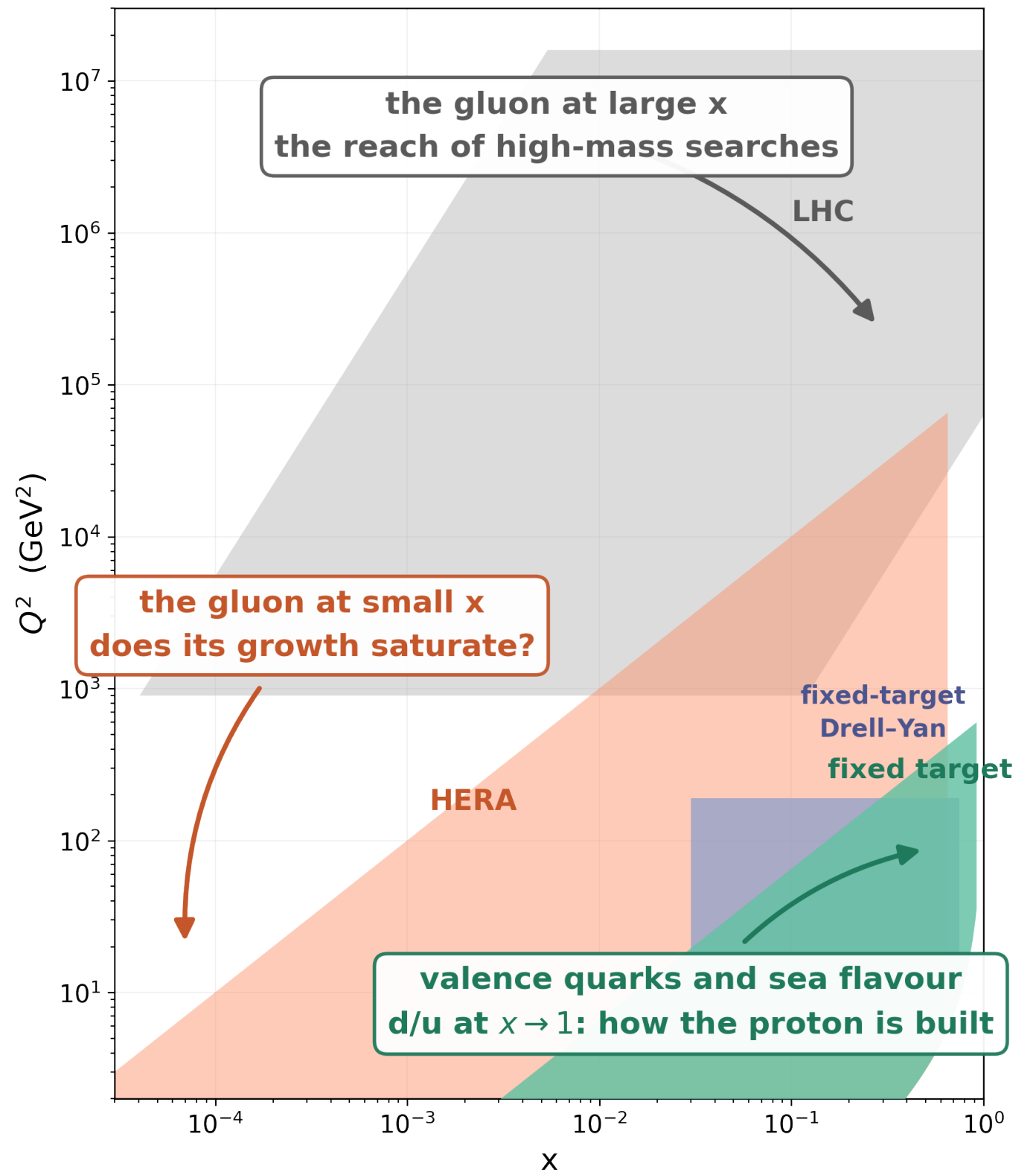
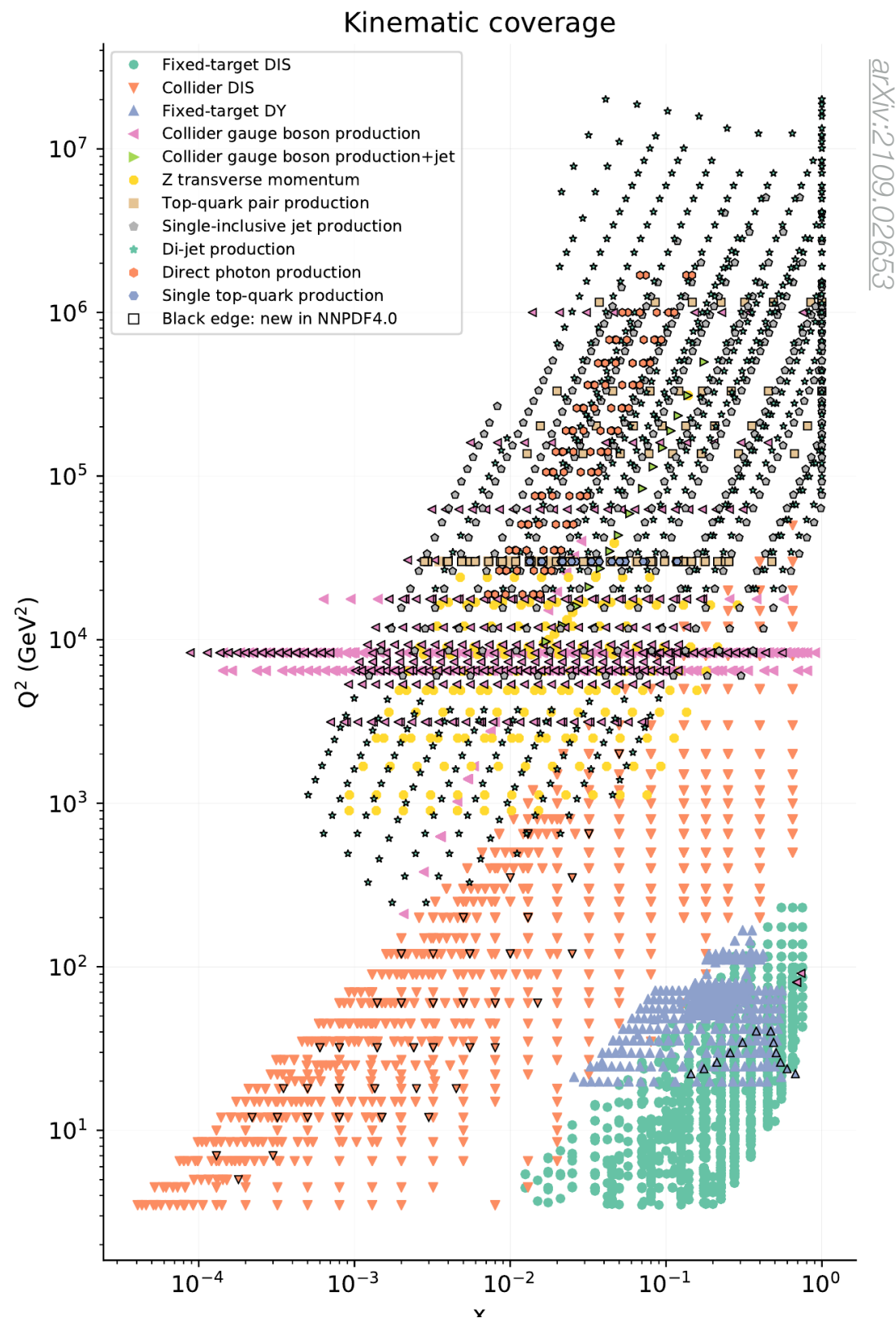
[arXiv:1808.00848](https://arxiv.org/abs/1808.00848)



Probes and partons



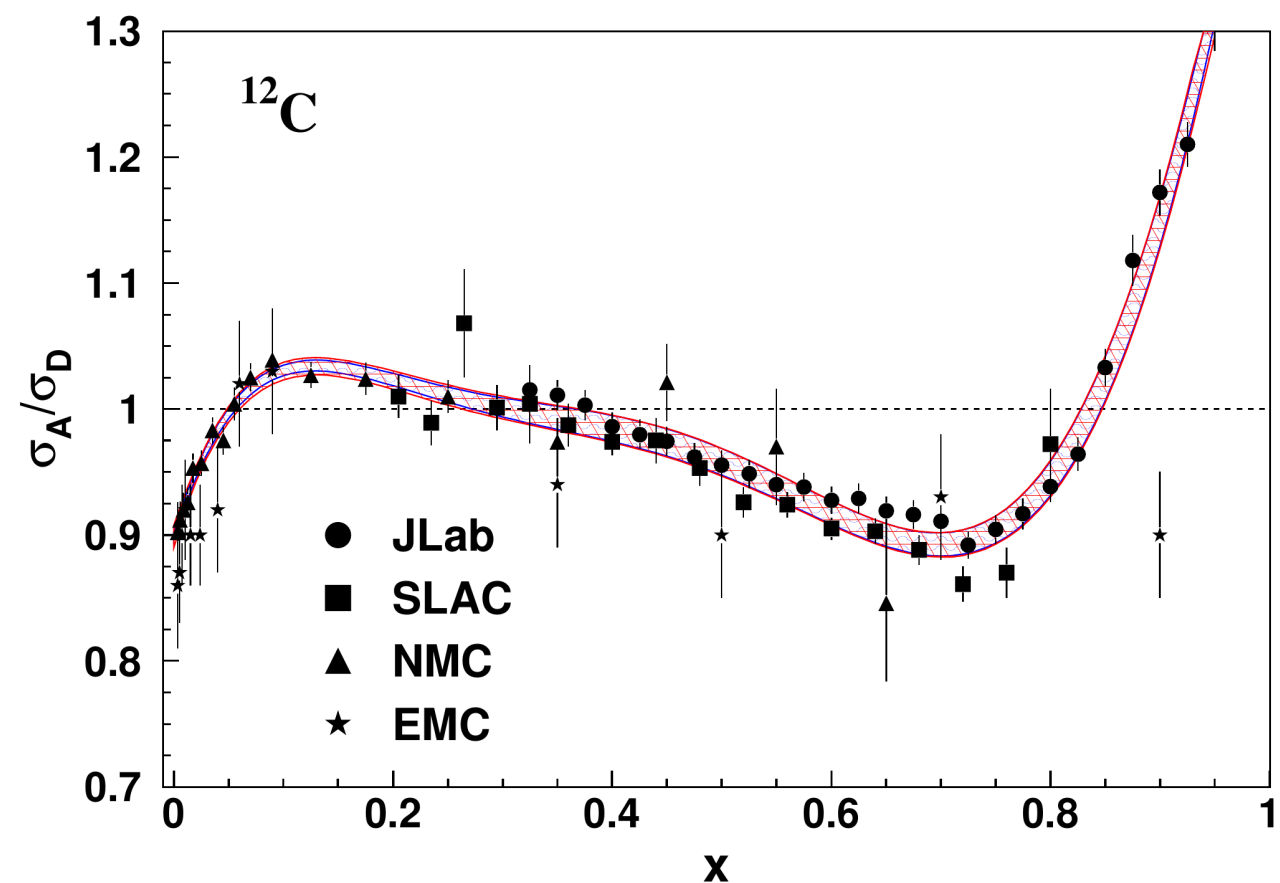
Global PDF fits



The EMC effect

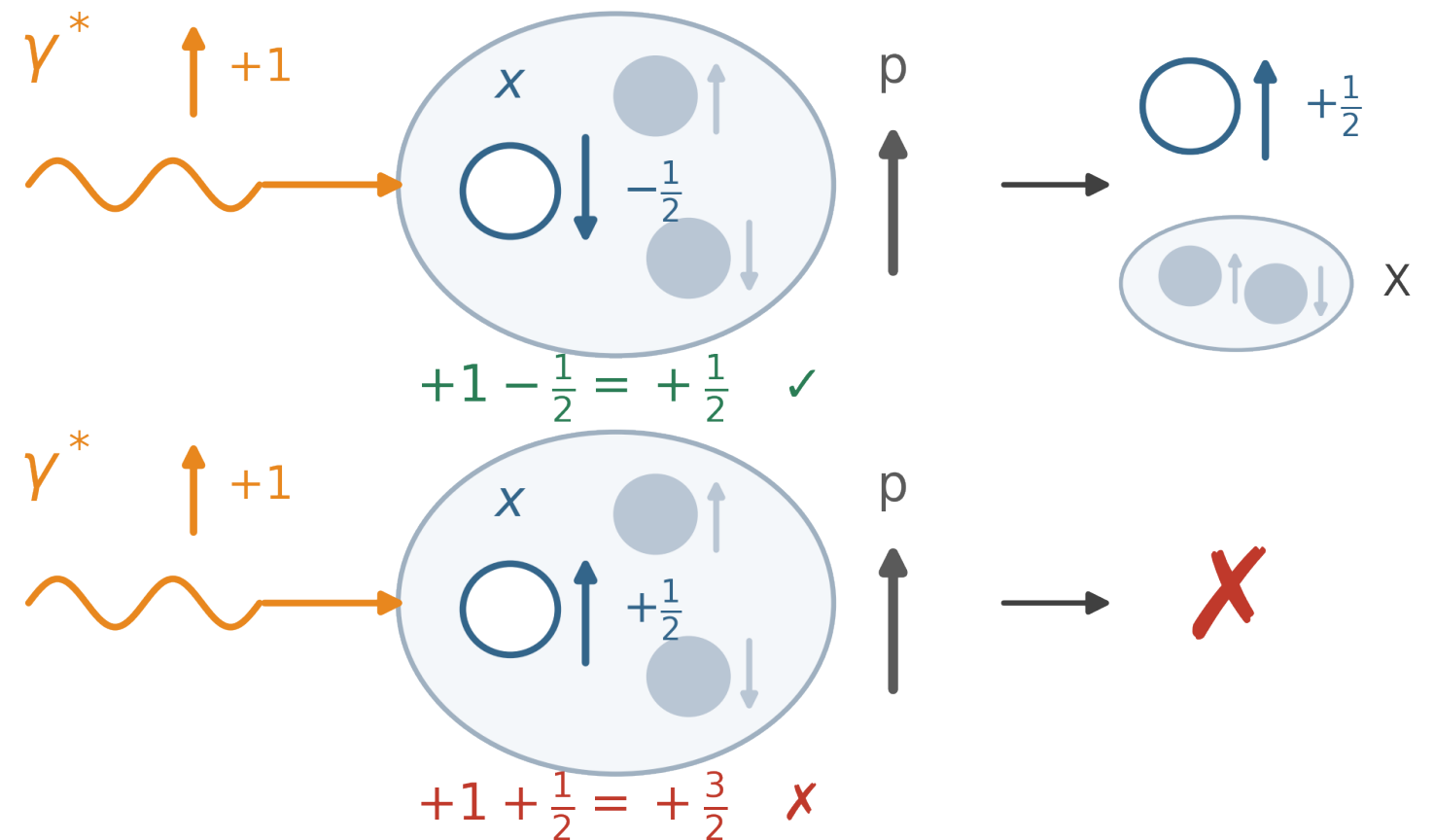
- Quarks in a bound nucleon are not distributed like quarks in a free one
- EMC found it by accident in 1983: iron over deuterium
- Nobody expected it — a nucleus is bound by MeV, and the experiment probes already at GeV
- Forty years on - **still no agreed explanation**
- Largest where nucleons come closest together
- Every experiment on a nuclear target carries this as an uncertainty

Int. J. Mod. Phys. E 23 (2014) 1430013



Polarized DIS

- Quark model: the proton gets spin-1/2 from its three quarks
- Unpolarized DIS: count quarks regardless of their spin
- **Polarize beam and target** to probe the spin
- Measure $g_1(x)$: how much quark spin points along the proton
- Summed over all x : $\Delta\Sigma$, the quark-spin share

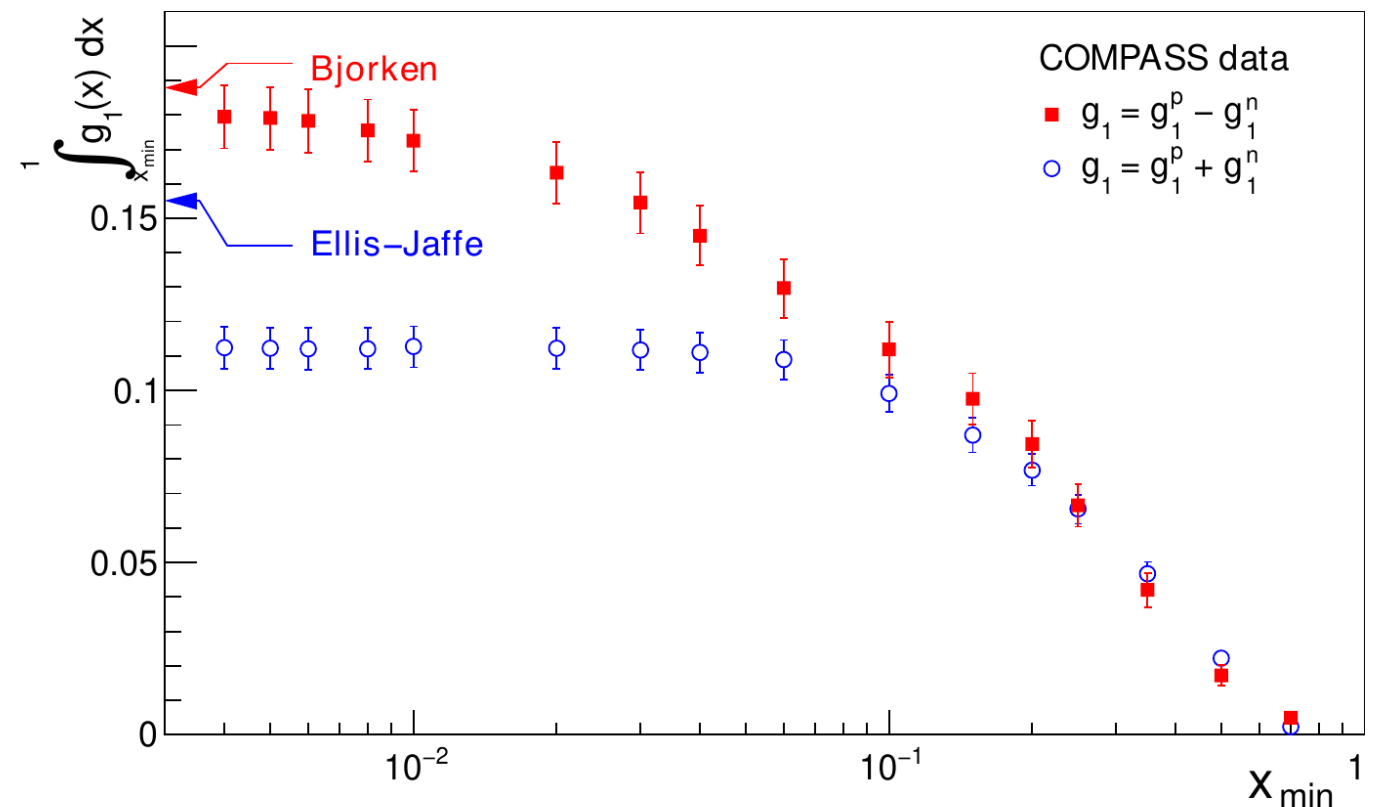
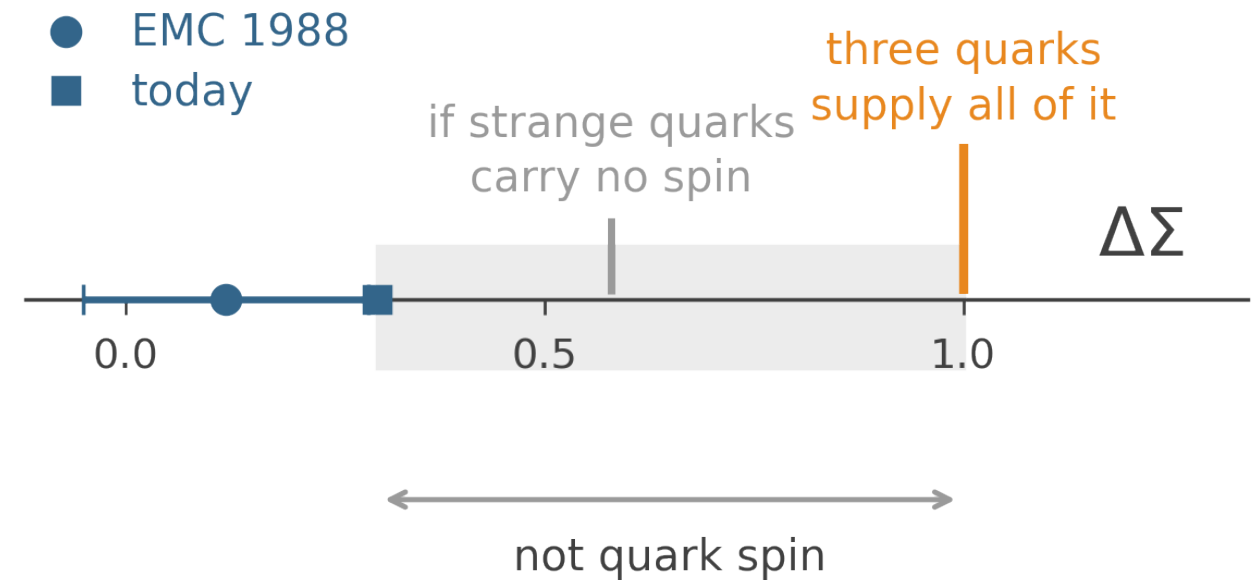


flip the target spin, count: $A = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} \rightarrow g_1(x)$

arrows: beam spin, target spin

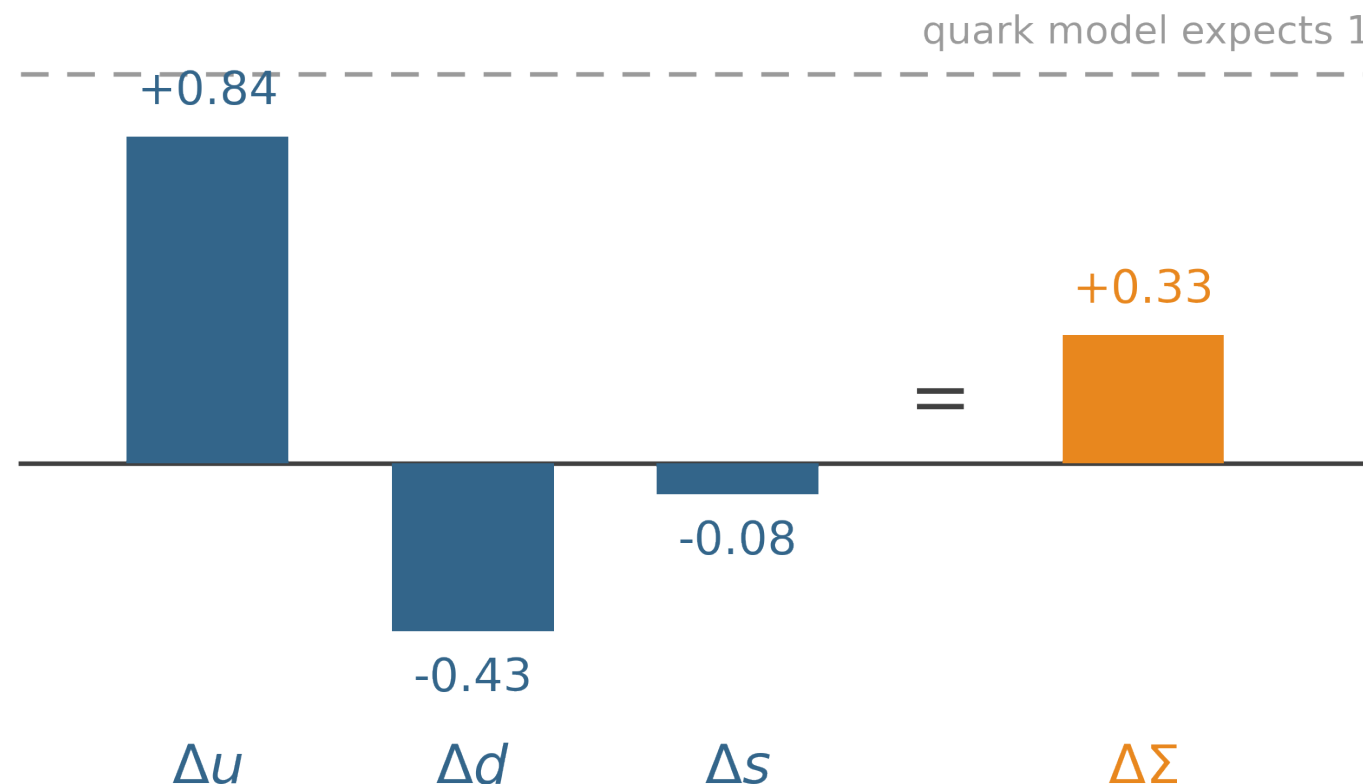
Spin crisis

- EMC 1988: $\Delta\Sigma = 0.12 \pm 0.17$, consistent with zero!
- The three-quark picture is wrong?
- Two predictions: Bjorken from QCD alone, Ellis-Jaffe assuming strange quarks carry no spin
- Today's measurement is $\Delta\Sigma \approx 0.3$ - **most of the proton's spin is elsewhere**
- Mass, momentum, spin: none add up from the quarks alone



Where $\Delta\Sigma$ comes from

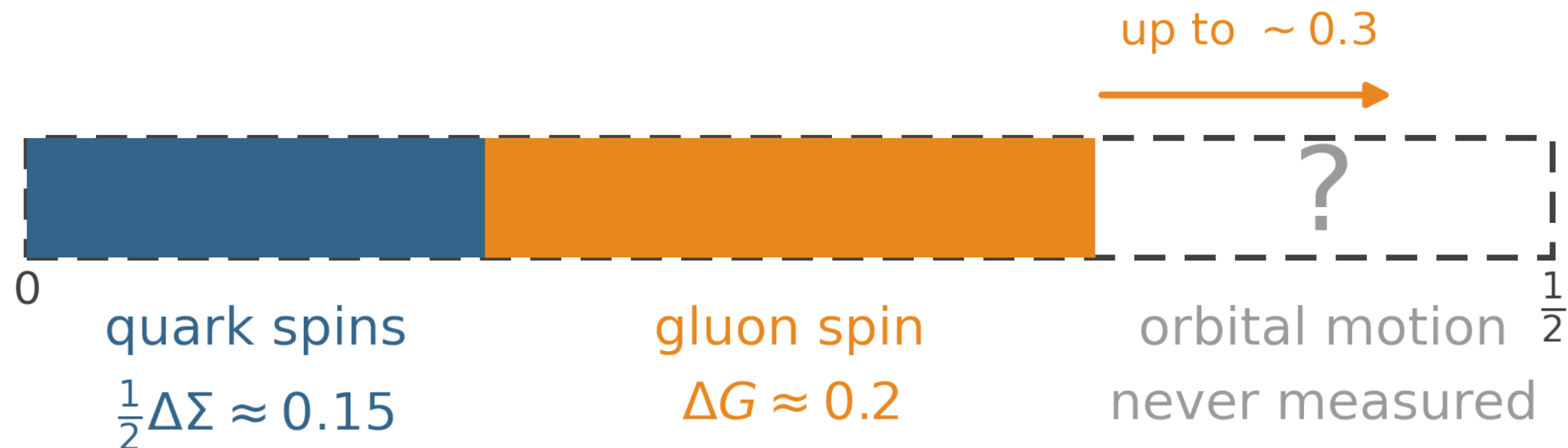
- $\Delta\Sigma$ is **derived from several measurements**:
 - Polarized muons on a polarized target: $4\Delta u + \Delta d + \Delta s = 2.58$
 - A neutron decay: $\Delta u - \Delta d = 1.27$
 - Decays of Λ and Σ baryons: $\Delta u + \Delta d - 2\Delta s = 0.58$
- Solving the system of equations: $\Delta u = 0.84$, $\Delta d = -0.43$, $\Delta s = -0.08 \Rightarrow \Delta\Sigma = 0.33$



The spin budget

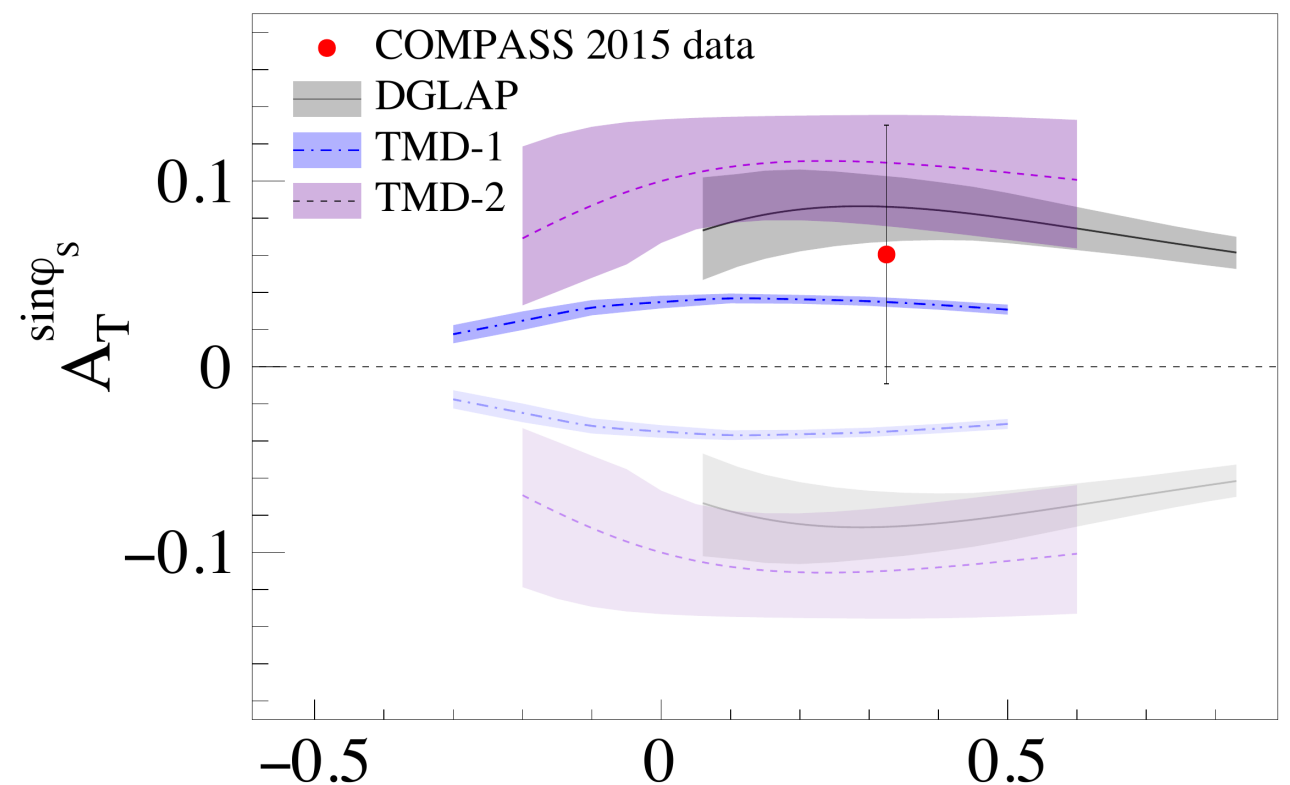
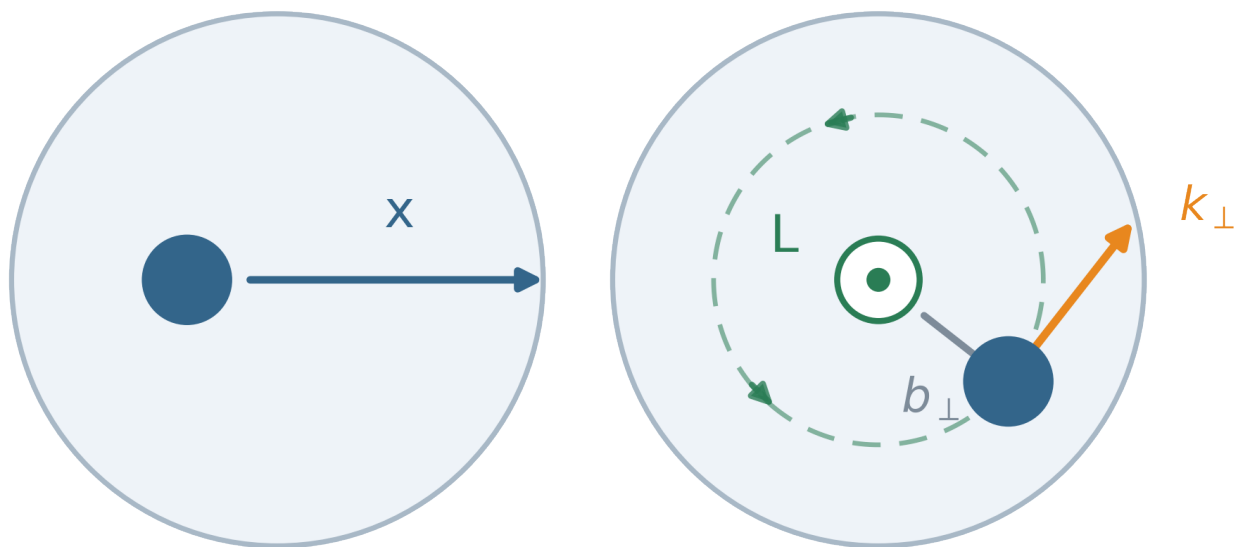
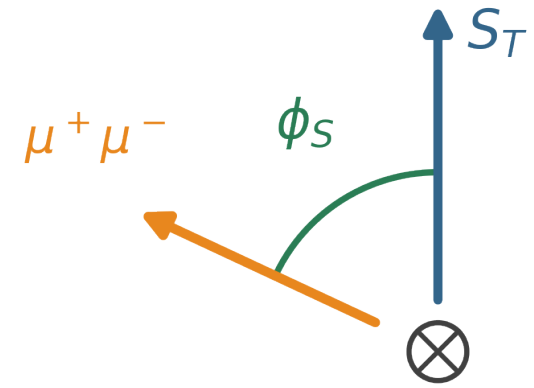
- Quarks supply $\Delta\Sigma = 0.33$ - nonzero, but still **only a third** of the quark model
- Gluon spin non-zero at RHIC and COMPASS, but too small on its own
- Orbital motion never measured

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



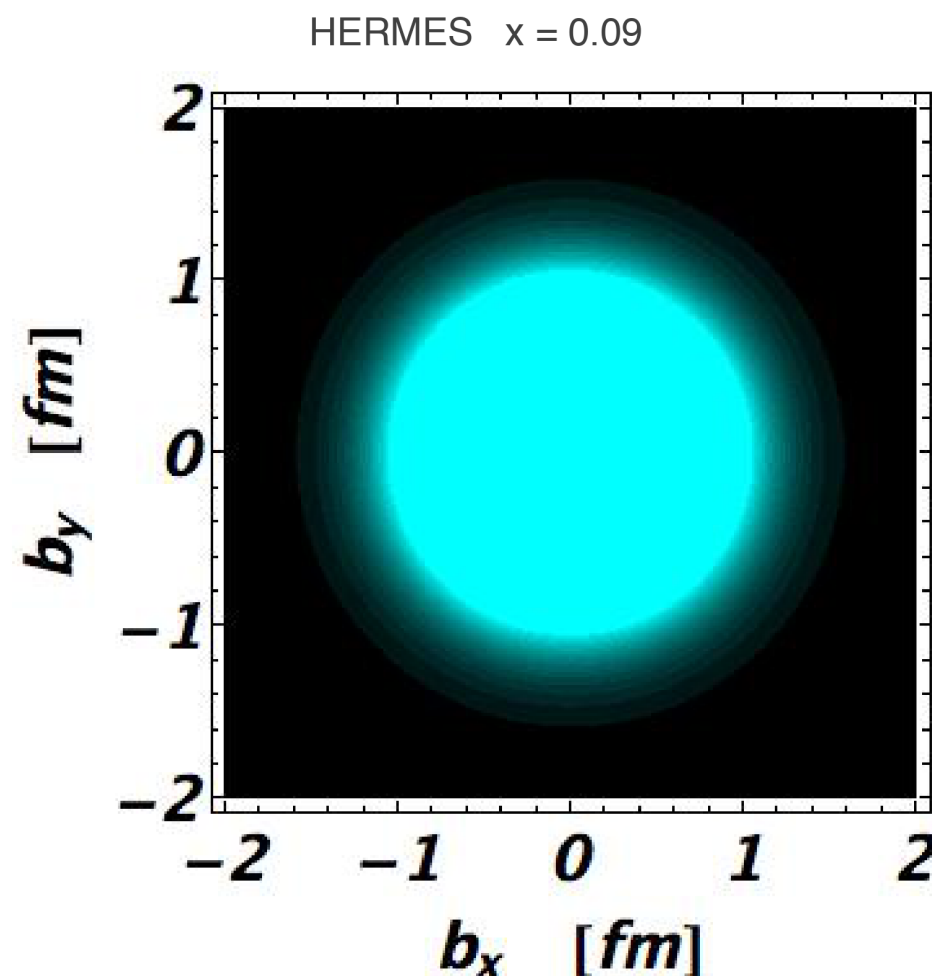
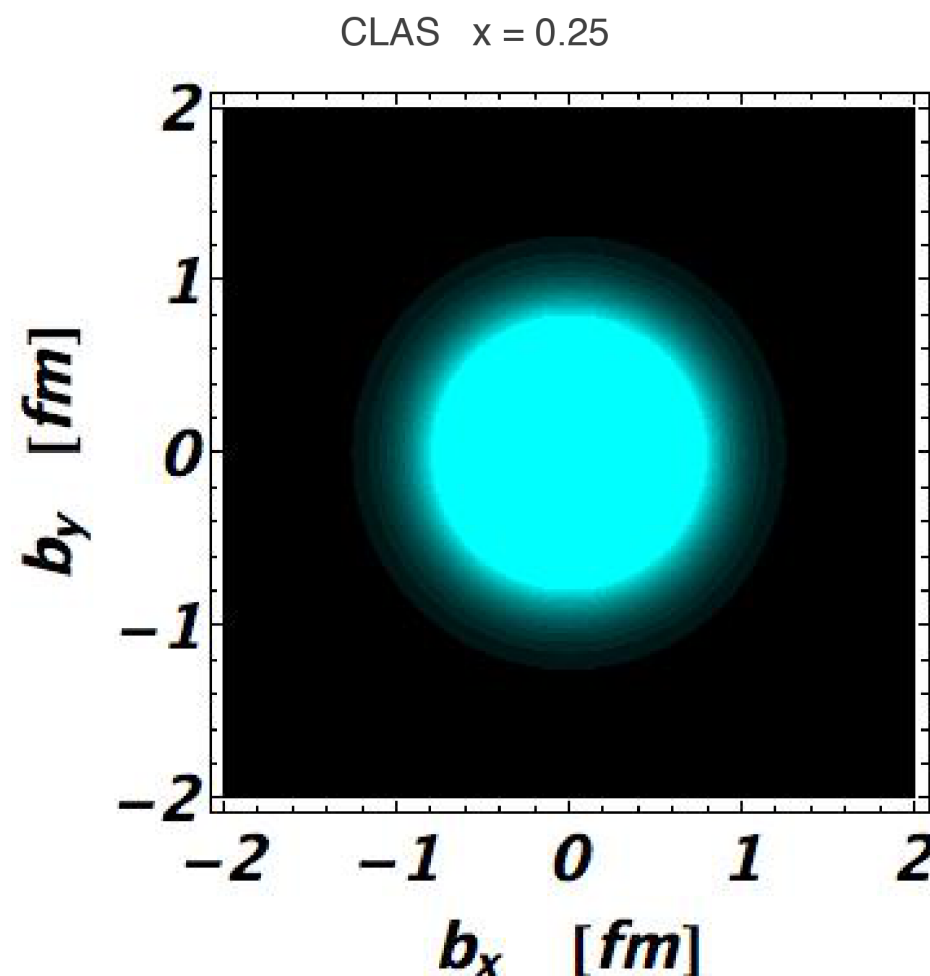
Proton tomography

- Visualize a proton in **multiple dimensions**:
 - $q(x)$ - momentum carried by the quark
 - $b_{\perp}$ - location in the transverse plane (GPDs)
 - $k_{\perp}$ - momentum in the transverse plane (TMDs)
- Get total angular momentum from one of the moments
- Probe GPDs in $ep \rightarrow e'p'\gamma$, polarize the target sideways (S_T) to study TMDs



Imaging at JLab

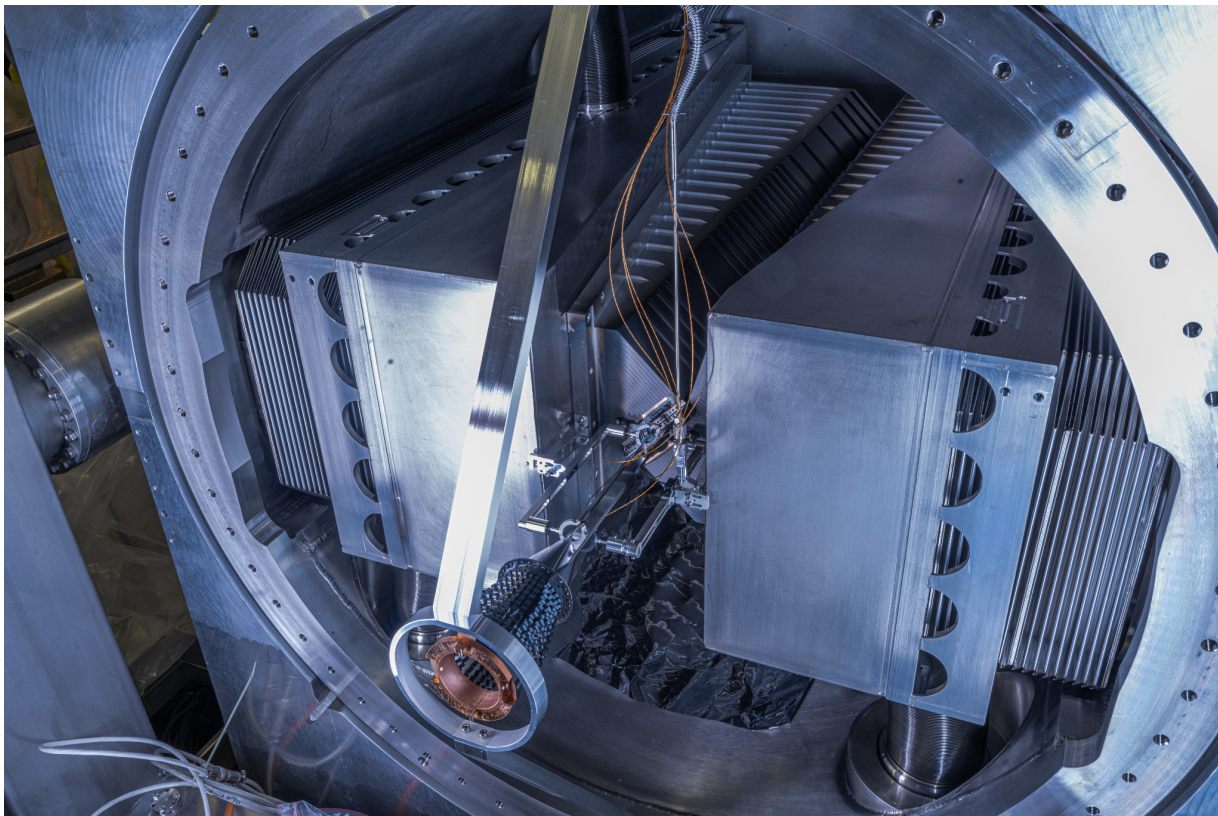
- **Exclusive scattering** - proton intact
- Continuous beam instead of intense spills to minimize pileup
- How hard the proton recoils - where the quark sits
- The proton looks smaller when the quark carries more momentum
- Reaches large x , small x - the sea and the gluon - needs a collider



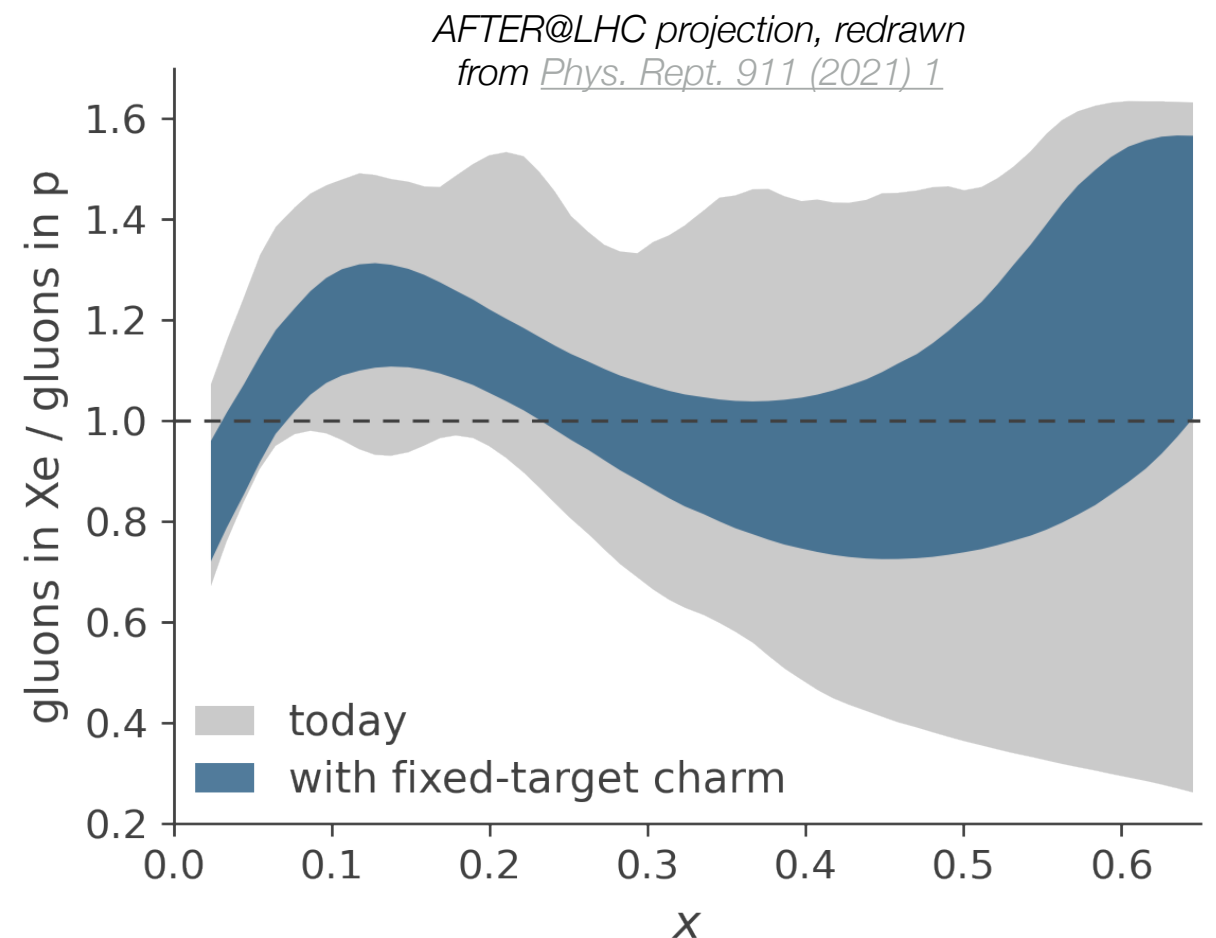
Rept. Prog. Phys. 76 (2013) 066202

Fixed target at the LHC

- A gas cell in the LHC beam pipe, in front of LHCb (SMOG2)
- 7 TeV proton on gas at rest - $\sqrt{s} = 115$ GeV, **the highest fixed-target energy**
- Any gas: H₂, D₂, He, Ne, Ar, Kr, Xe
- LHCb points forward: charm from the target at large x

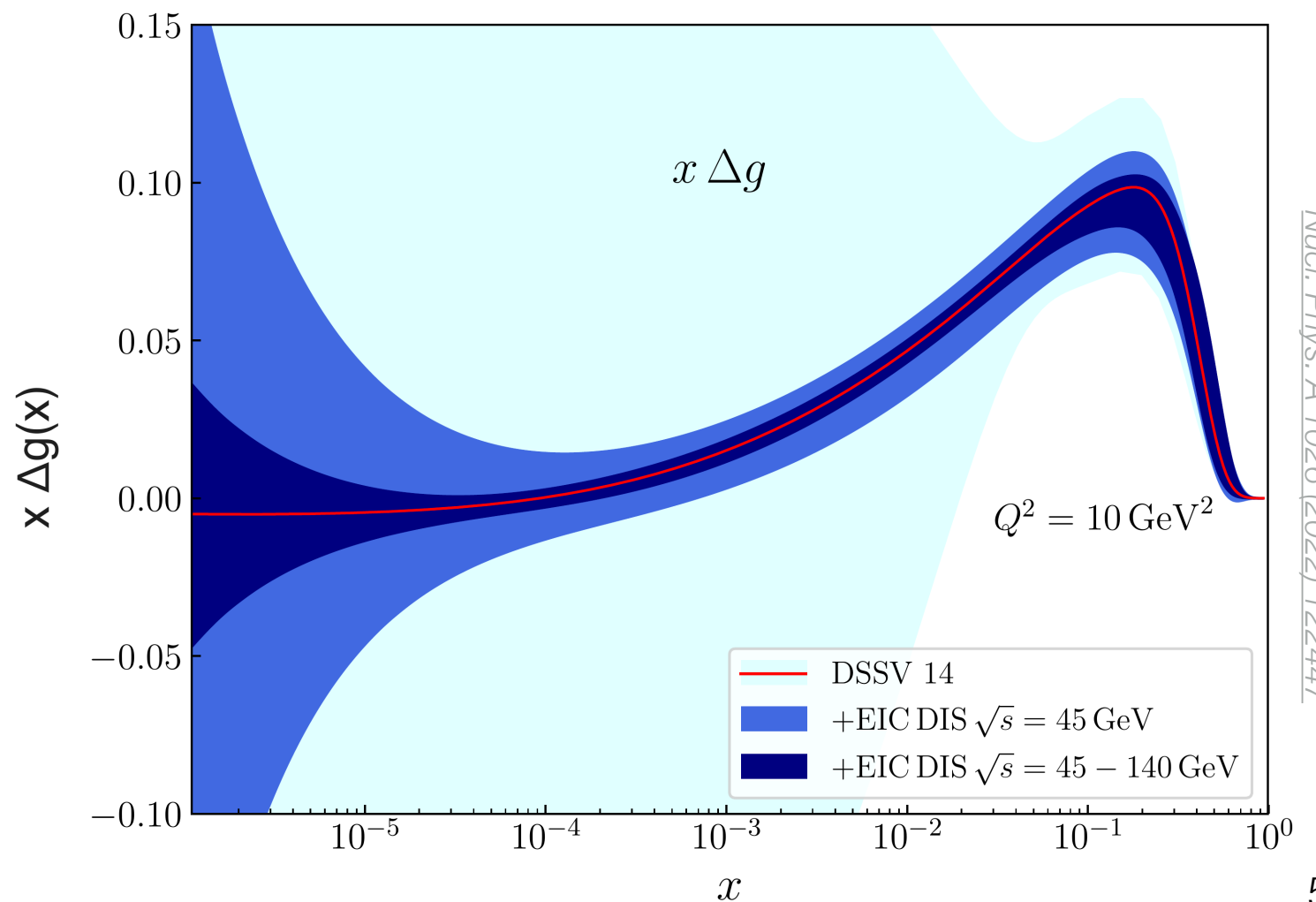
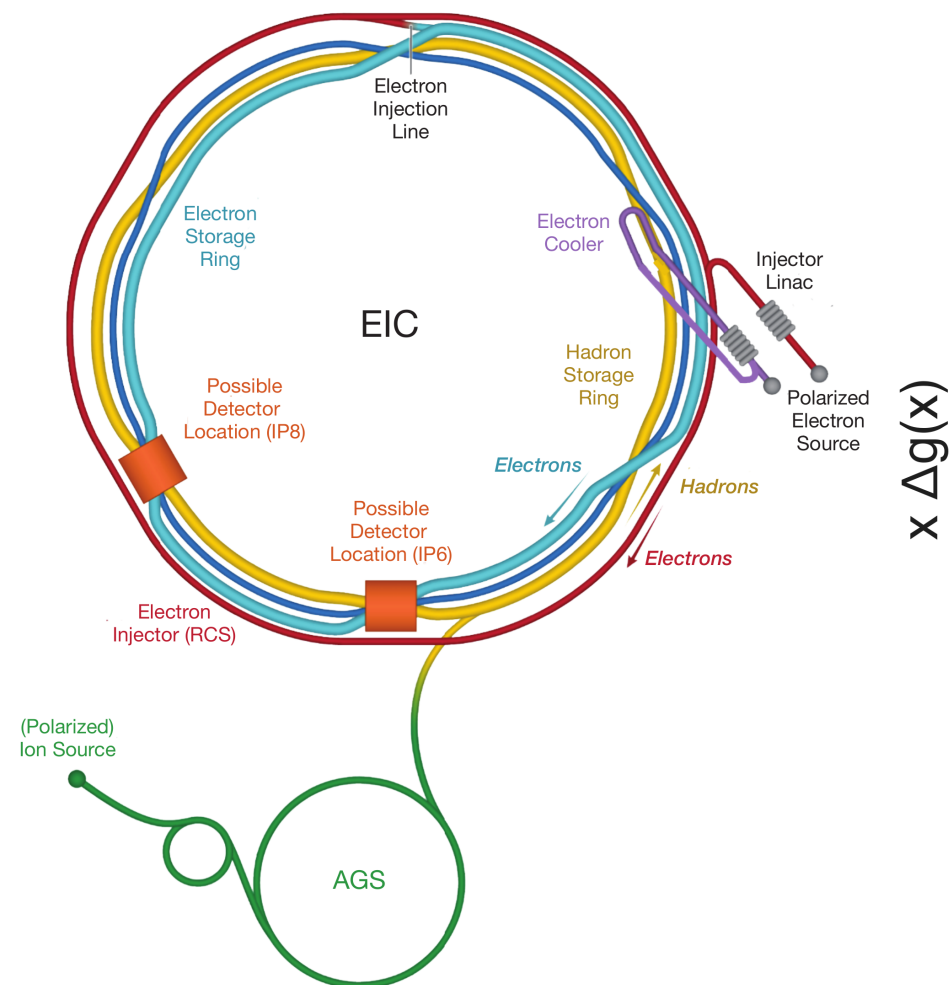


The gas cell, inside the LHCb vertex detector



Electron-ion collider

- **Electrons colliding with protons and nuclei** (EIC), at Brookhaven in the 2030s
- $\sqrt{s} = 20\text{-}140$ GeV, and a thousand times HERA's luminosity
- Both beams polarized: the gluon spin and the missing orbital motion
- Nuclei up to uranium: the EMC effect at the gluon level
- Same kinematics as at HERA, but with polarized beams, higher luminosity and nuclei: probe a broad range of x



Not in this lecture

- **Fixed-target hadron physics is much bigger than this lecture**
- Heavy ions on fixed targets: NA61/SHINE at CERN, CBM at FAIR
- Hadron spectroscopy with antiprotons: PANDA at FAIR
- Hyperon beams
- Applications: spallation sources, medical isotopes, test beams
- Neutrino beams and oscillations

Summary

- **What we knew:** a proton with a size, and point-like quarks inside it
- **Where we are:** u , d , $\bar{u}$, $\bar{d}$, s mapped to a few per cent - the gluon is not
- **What is next:** the gluon's spin, the gluon in a nucleus, the proton in 3-D

