

Quarks, gluons and QCD at Jefferson Lab and beyond

Justin Stevens: PHYS309



Griffioen

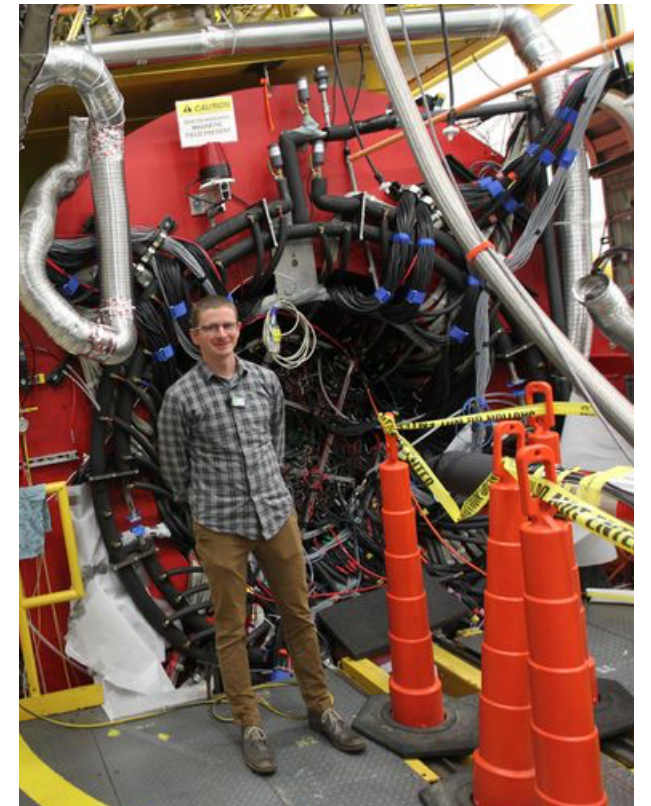
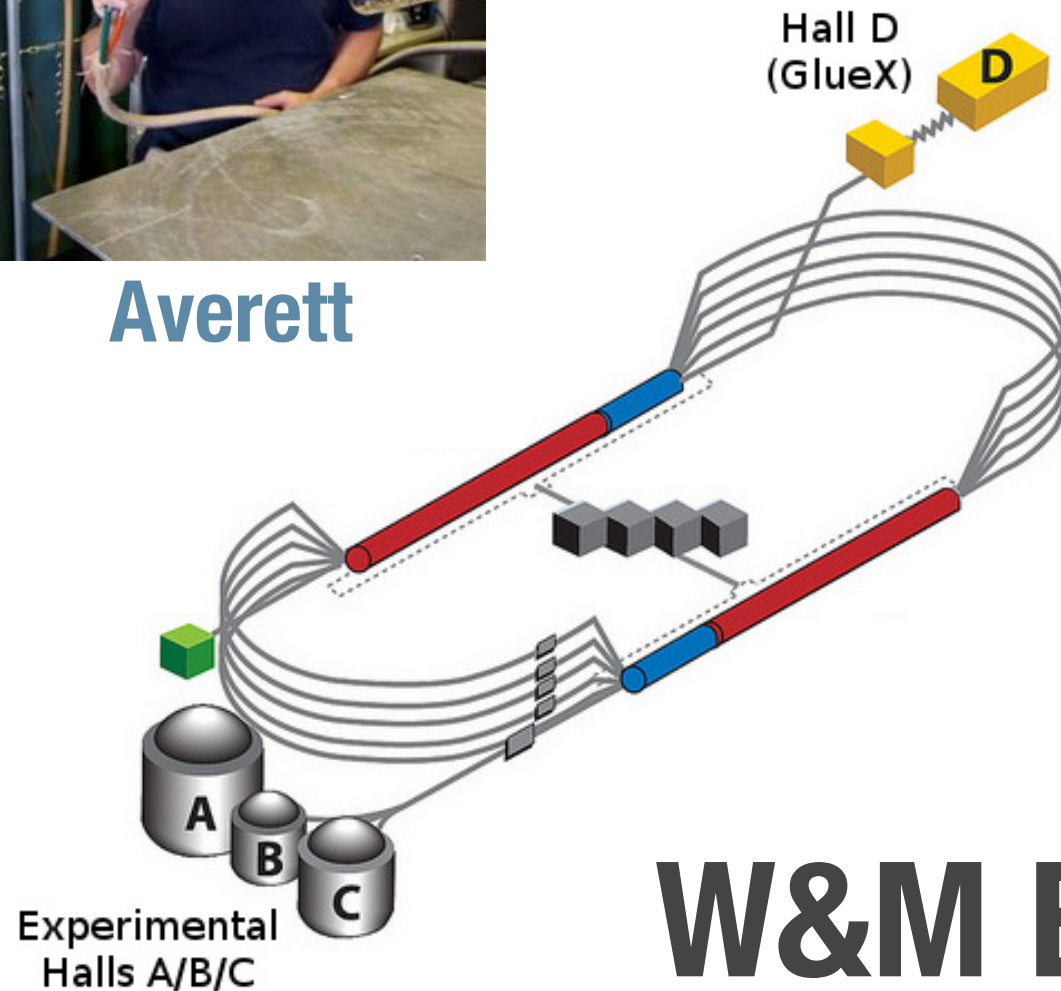


Armstrong



Averett

Jefferson Lab
Exploring the Nature of Matter



Stevens

W&M Experimental Nuclear/Hadronic Research Groups

Standard Model

Coupling Strength:

10^{-6}

$1/137$

1



Generation

1

2

3

Up u	Charm c	Top t
Down d	Strange s	Bottom b
Electron e	Muon μ	Tau τ
e-Neutrino ν_e	μ-Neutrino ν_μ	τ-Neutrino ν_τ

Quarks

Leptons

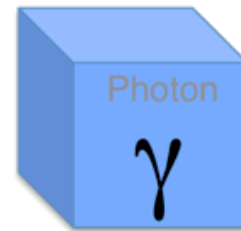
Increasing Mass

All Particles

Charged Particles

Just Quarks

Higgs Boson



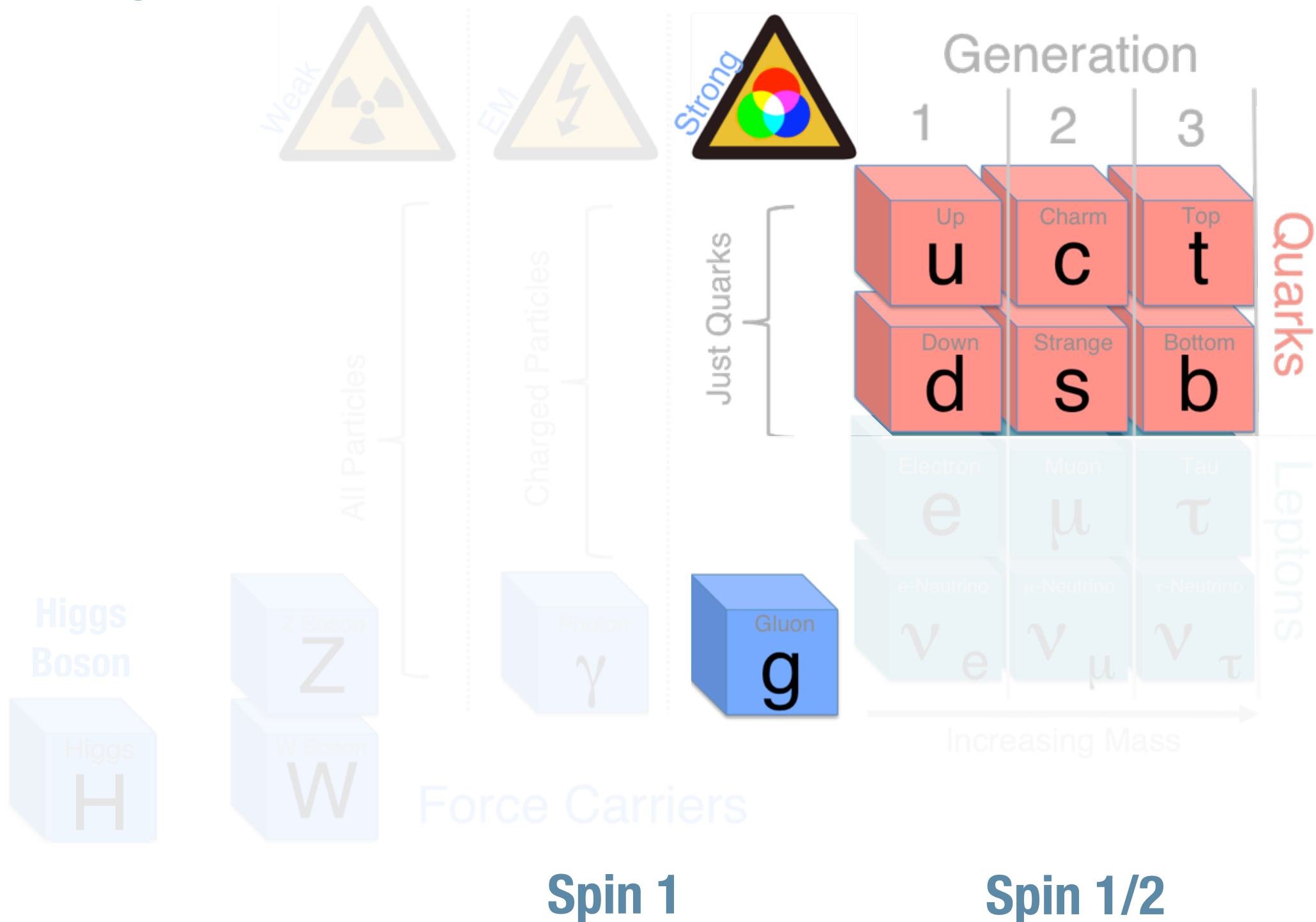
Force Carriers

Spin 1

Spin 1/2

Standard Model

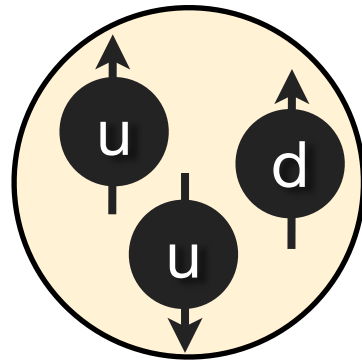
Coupling Strength:



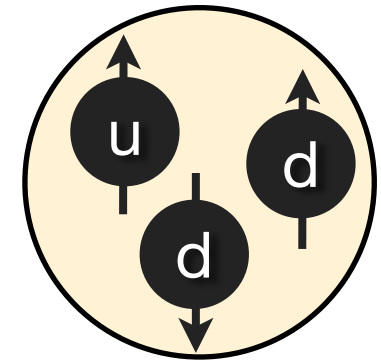
Quarks and hadrons

- * Proposed to explain proton structure and properties of other states observed at the time

$$\textit{proton} = |uud\rangle$$
$$J = 1/2$$



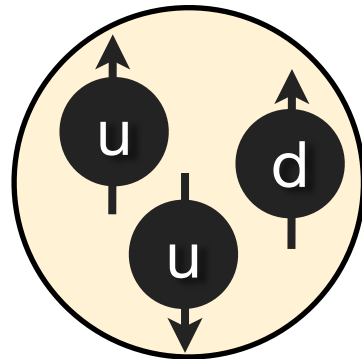
$$\textit{neutron} = |udd\rangle$$
$$J = 1/2$$



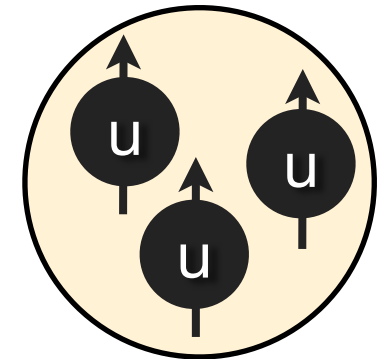
Quarks and hadrons

- * Proposed to explain proton structure and properties of other states observed at the time

$$\textit{proton} = |uud\rangle$$
$$J = 1/2$$



$$\Delta^{++} = |uuu\rangle$$
$$J = 3/2$$

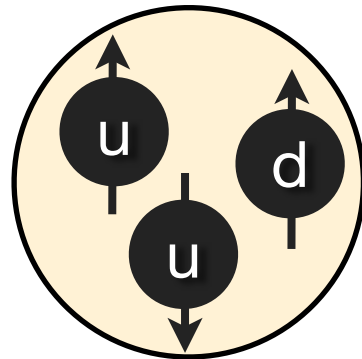


Quarks and hadrons

- * Proposed to explain proton structure and properties of other states observed at the time

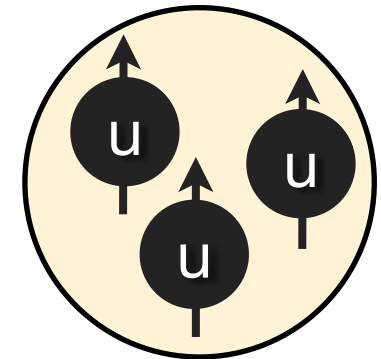
$$proton = |uud\rangle$$

$$J = 1/2$$



$$\Delta^{++} = |uuu\rangle$$

$$J = 3/2$$



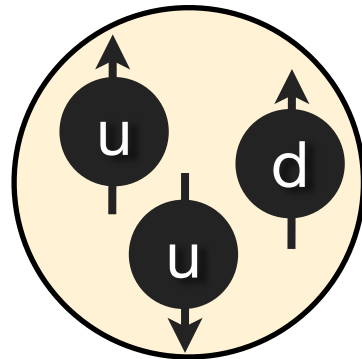
$$\psi(\Delta^{++}) = \underbrace{\psi(r)}_{\text{symmetric}} \cdot \underbrace{\psi_{\text{spin}}(J)}_{\text{symmetric}} \cdot \underbrace{\psi_{\text{flavour}}}_{\text{symmetric}}$$

Quarks and hadrons

- * Proposed to explain proton structure and properties of other states observed at the time

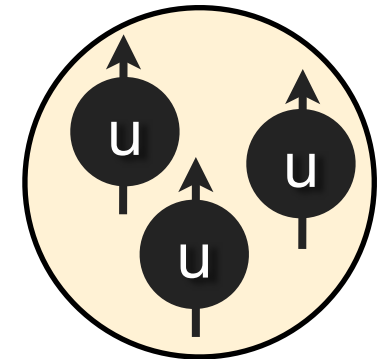
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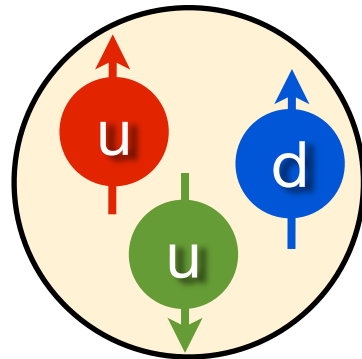
~~$$\psi(\Delta^{++}) = \underbrace{\psi(r)}_{\text{symmetric}} \cdot \underbrace{\psi_{\text{spin}}(J)}_{\text{symmetric}} \cdot \underbrace{\psi_{\text{flavour}}}_{\text{symmetric}}$$~~

$$\psi(\Delta^{++}) = \psi(r) \cdot \psi_{\text{spin}}(J) \cdot \psi_{\text{flavour}} \cdot \psi_{\text{colour}}$$

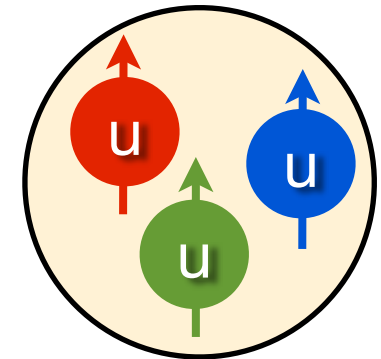
Quarks and hadrons

- * Proposed to explain proton structure and properties of other states observed at the time

$$proton = |uud\rangle$$
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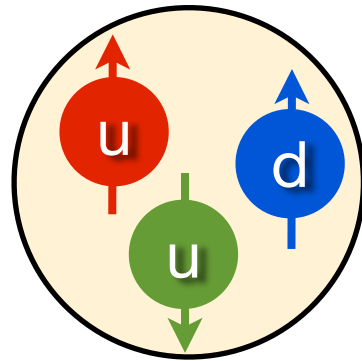
- * Color charge analogous to electric charge: atoms are electrically neutral and hadrons are color neutral (or color singlets)

Quarks and hadrons

- ✱ Proposed to explain proton structure and properties of other states observed at the time

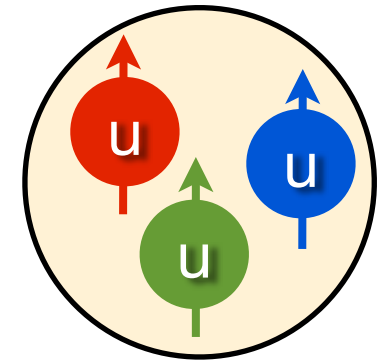
$$proton = |uud\rangle$$

$$J = 1/2$$



$$\Delta^{++} = |uuu\rangle$$

$$J = 3/2$$



- ✱ Color charge analogous to electric charge: atoms are electrically neutral and hadrons are color neutral (or color singlets)
- ✱ Another flavor of “light” quarks: **strange**

A circular diagram representing a pi+ meson. It contains two quarks: a red circle labeled 'u' and a red circle labeled 'd' with a bar over it. The red 'u' has an upward-pointing red arrow. The red 'd' with a bar has a downward-pointing red arrow.

$$\pi^+ = |u\bar{d}\rangle$$

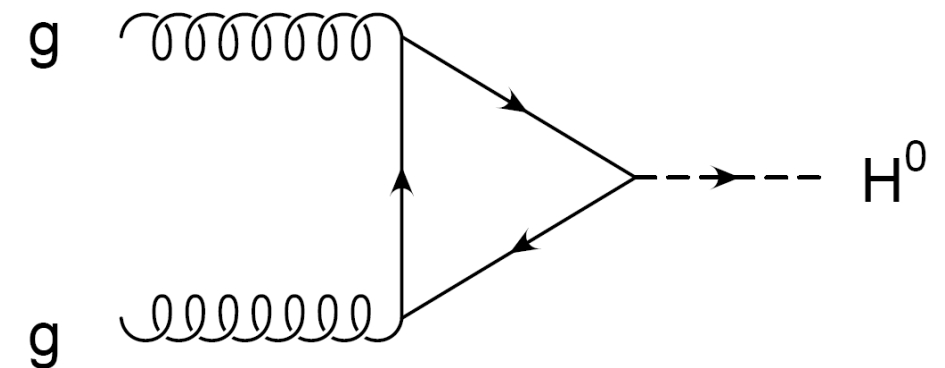
A circular diagram representing a K+ meson. It contains two quarks: a red circle labeled 'u' and a red circle labeled 's' with a bar over it. The red 'u' has an upward-pointing red arrow. The red 's' with a bar has a downward-pointing red arrow.

$$K^+ = |u\bar{s}\rangle$$

Color interactions in QCD

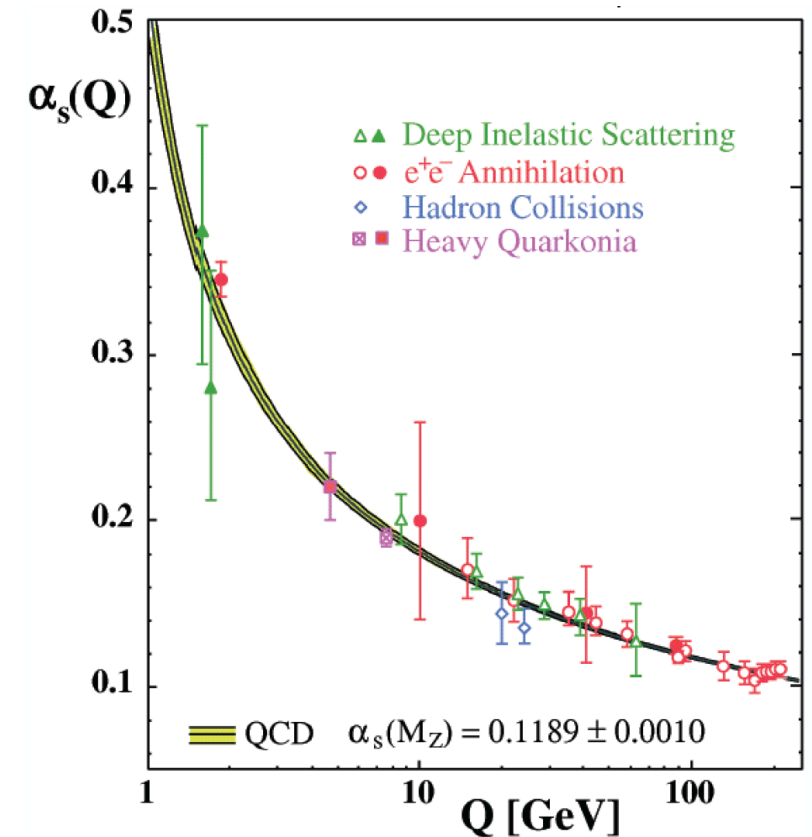
* High energy (short distance) limit

- * Interactions are weak: quarks are “asymptotically free”
- * QCD is calculable using perturbation theory, e.g. Higgs production at LHC

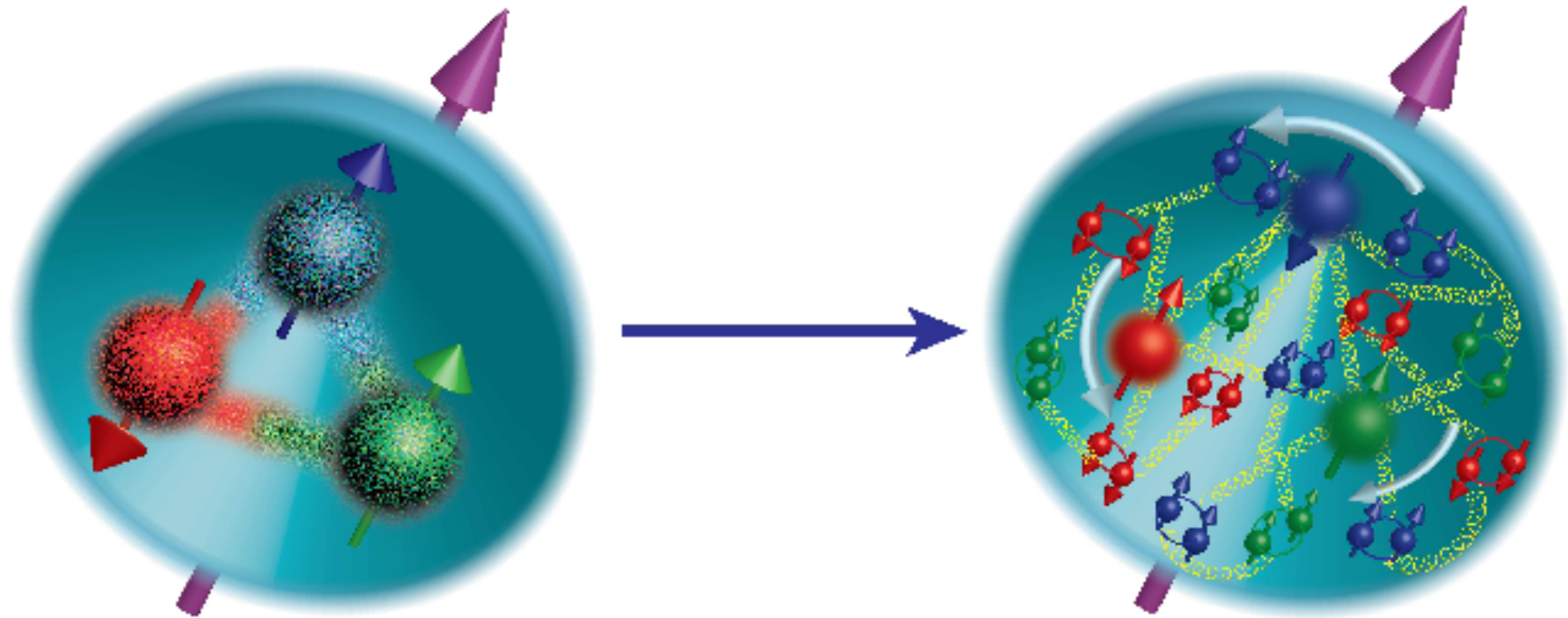


* Low energy (long distance) limit

- * Interactions are strong and increase with distance, so quarks are **confined**
- * QCD is **not** calculable perturbatively, but recent, dramatic progress in lattice QCD
- * Opportunity to study QCD in strongly coupled bound states, *i.e.* hadrons



Aside: what about nucleon structure?

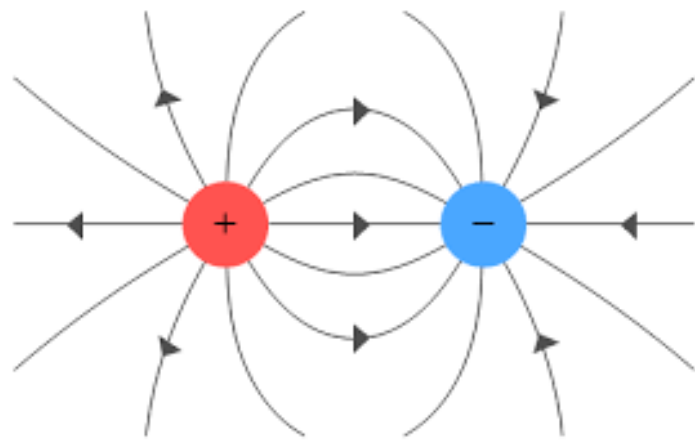


Griffioen



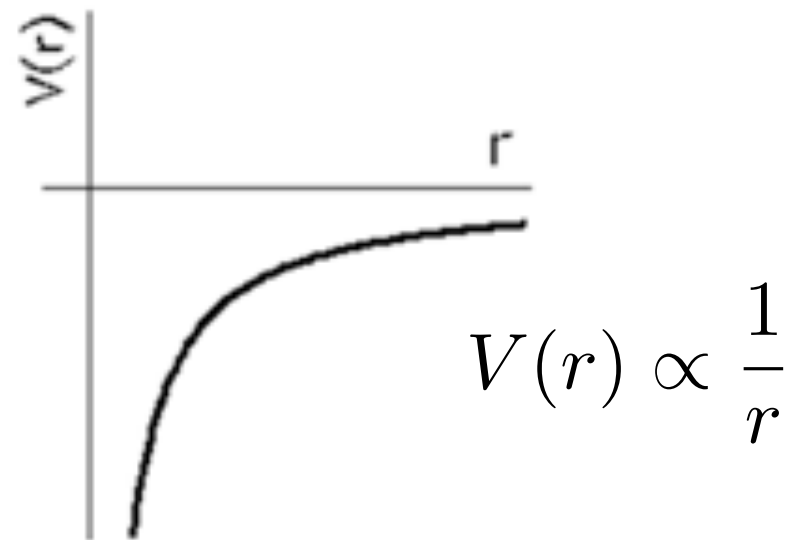
Averett

E&M

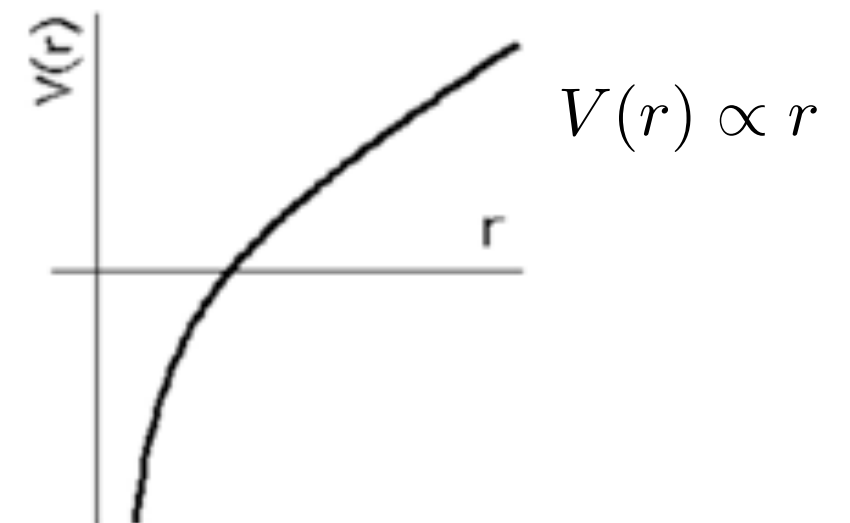
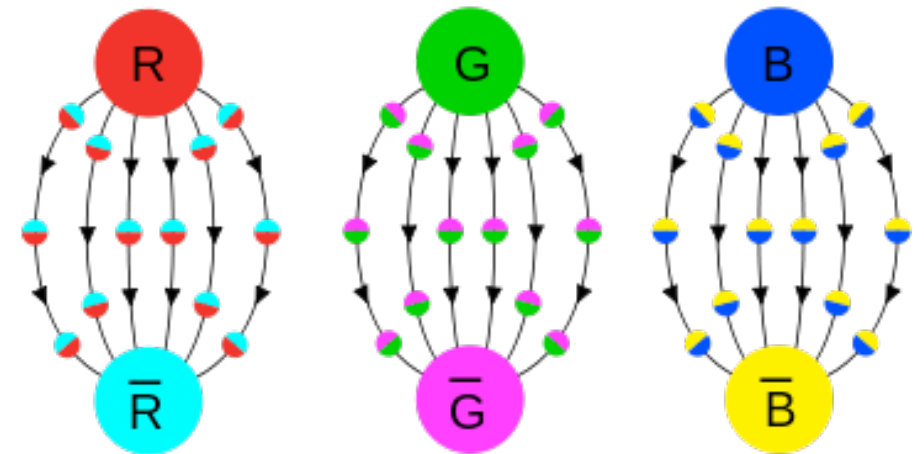


Photons (gluons) mediate forces between electric (color) charges

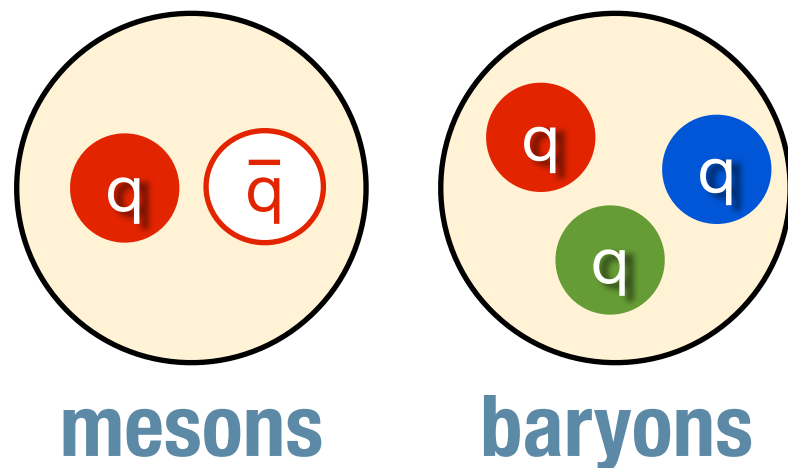
Gluon self-interaction produces a potential that grows ~linearly with distance, not possible for photons



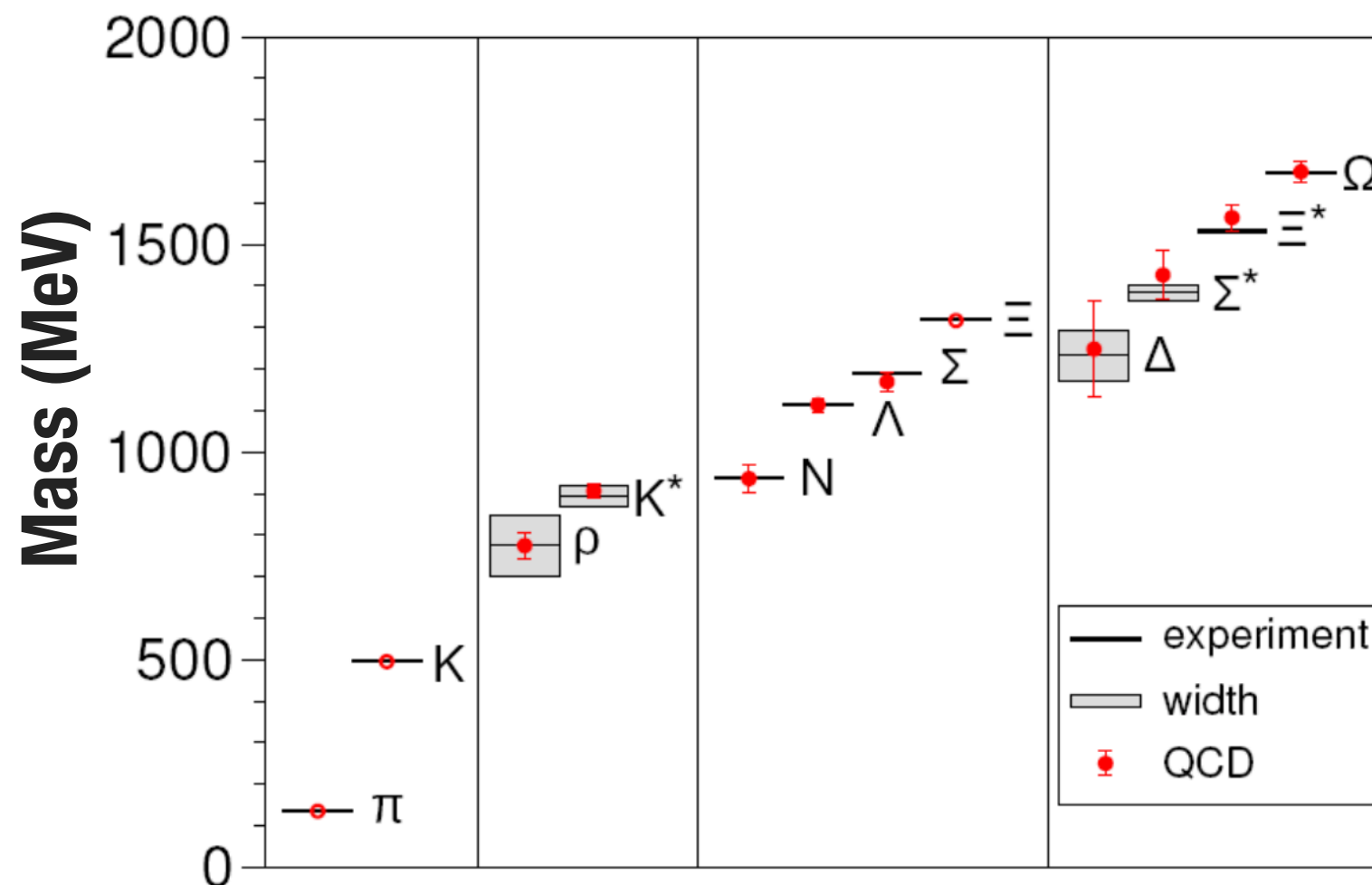
Strong nuclear force: QCD



Confined states of quarks and gluons



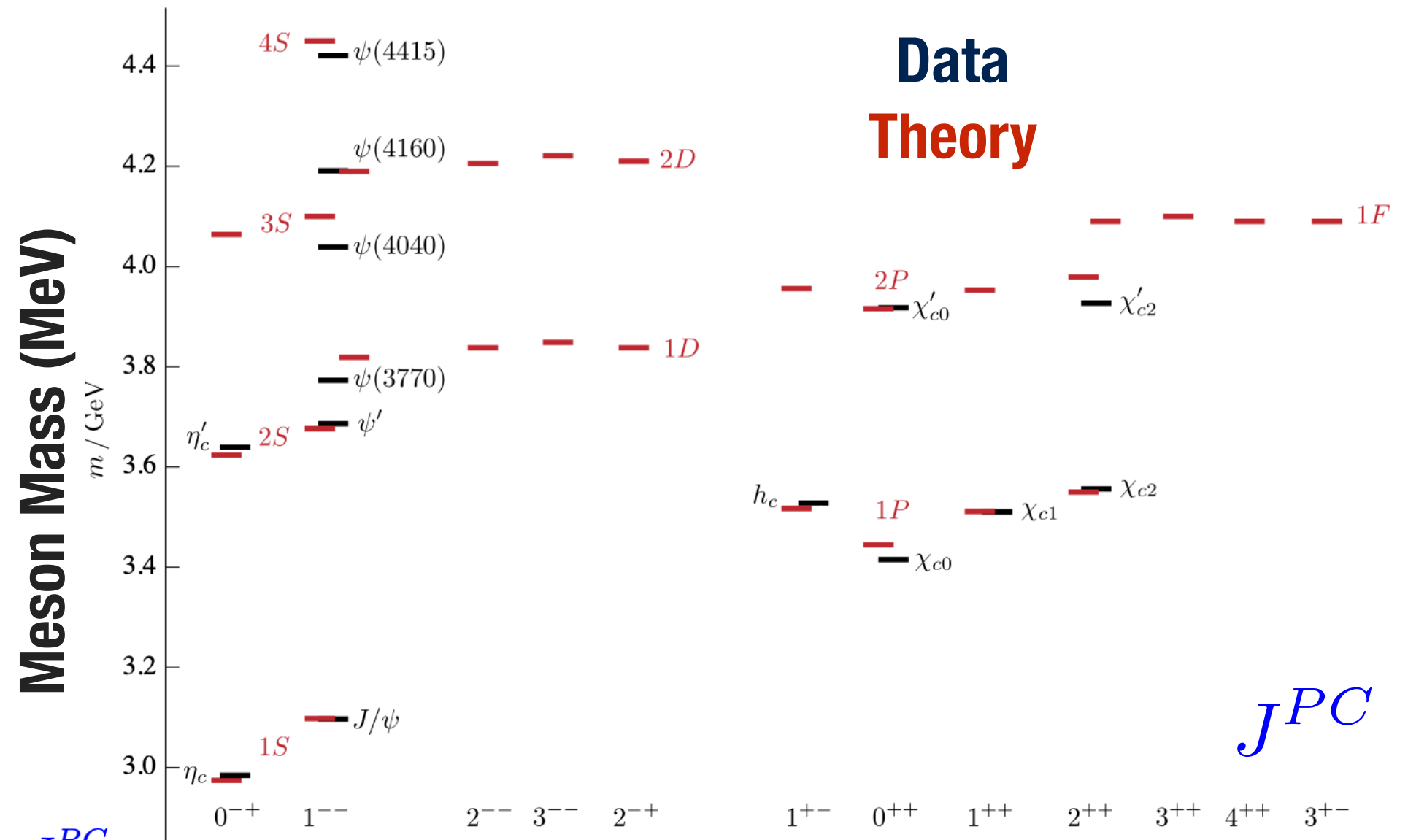
Observed mesons and baryons well described by 1st principles QCD



Lattice QCD: Science (2008)

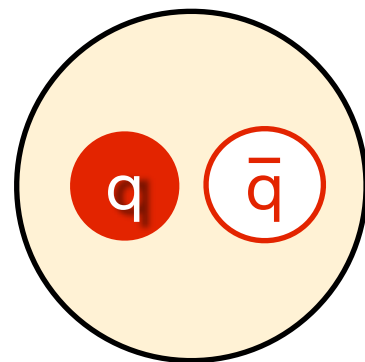
A diagram of a meson, consisting of a large light-yellow circle containing two smaller circles: a red one with a white 'q' and a white one with a red 'q' and a bar over it.

mesons

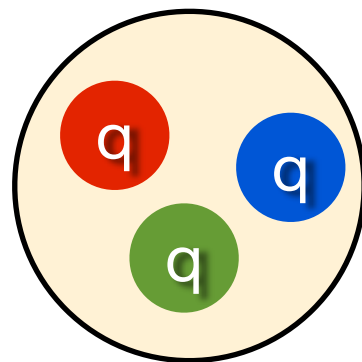

$$C = (-1)^{L+S}$$

Nature Review: 1802.08131

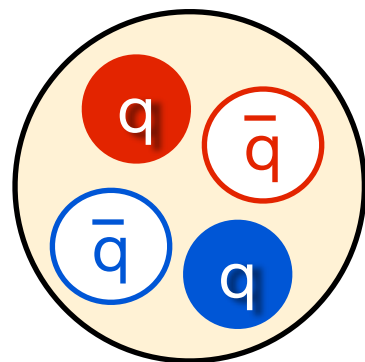
Confined states of quarks and gluons



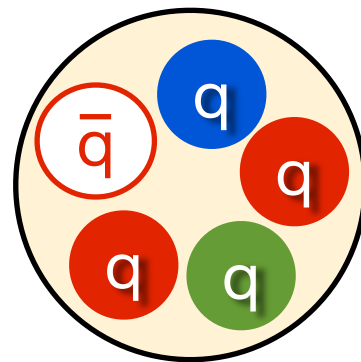
mesons



baryons



tetraquark



pentaquark

Observed mesons and baryons well described by 1st principles QCD

But these aren't the only states permitted by QCD

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

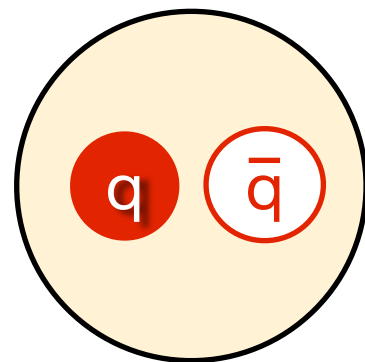
California Institute of Technology, Pasadena, California

... Baryons can now be constructed from quarks by using the combinations (qqq) , $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. ...

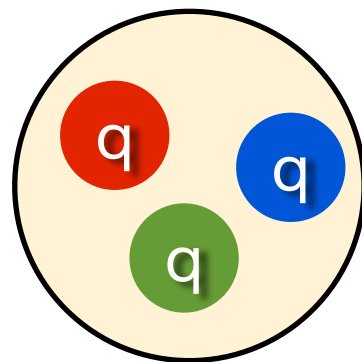
Phys. Lett. 8 (1964) 214



Confined states of quarks and gluons



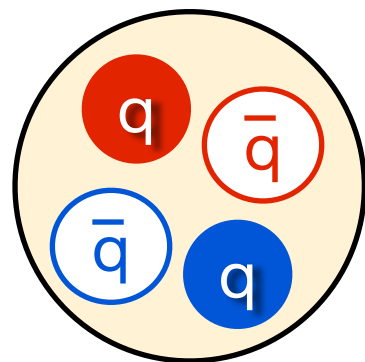
mesons



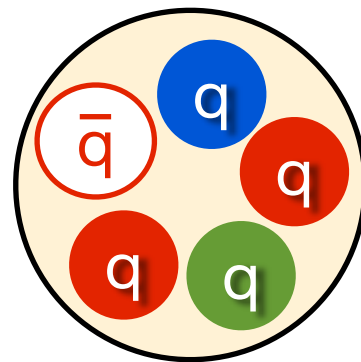
baryons

Observed mesons and baryons well described by 1st principles QCD

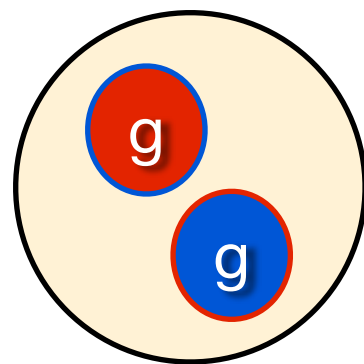
But these aren't the only states permitted by QCD



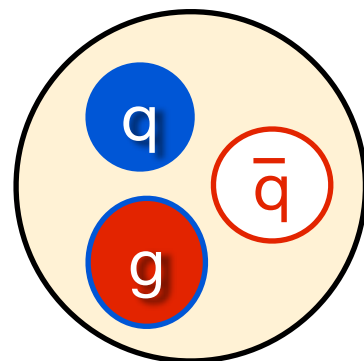
tetraquark



pentaquark



glueball

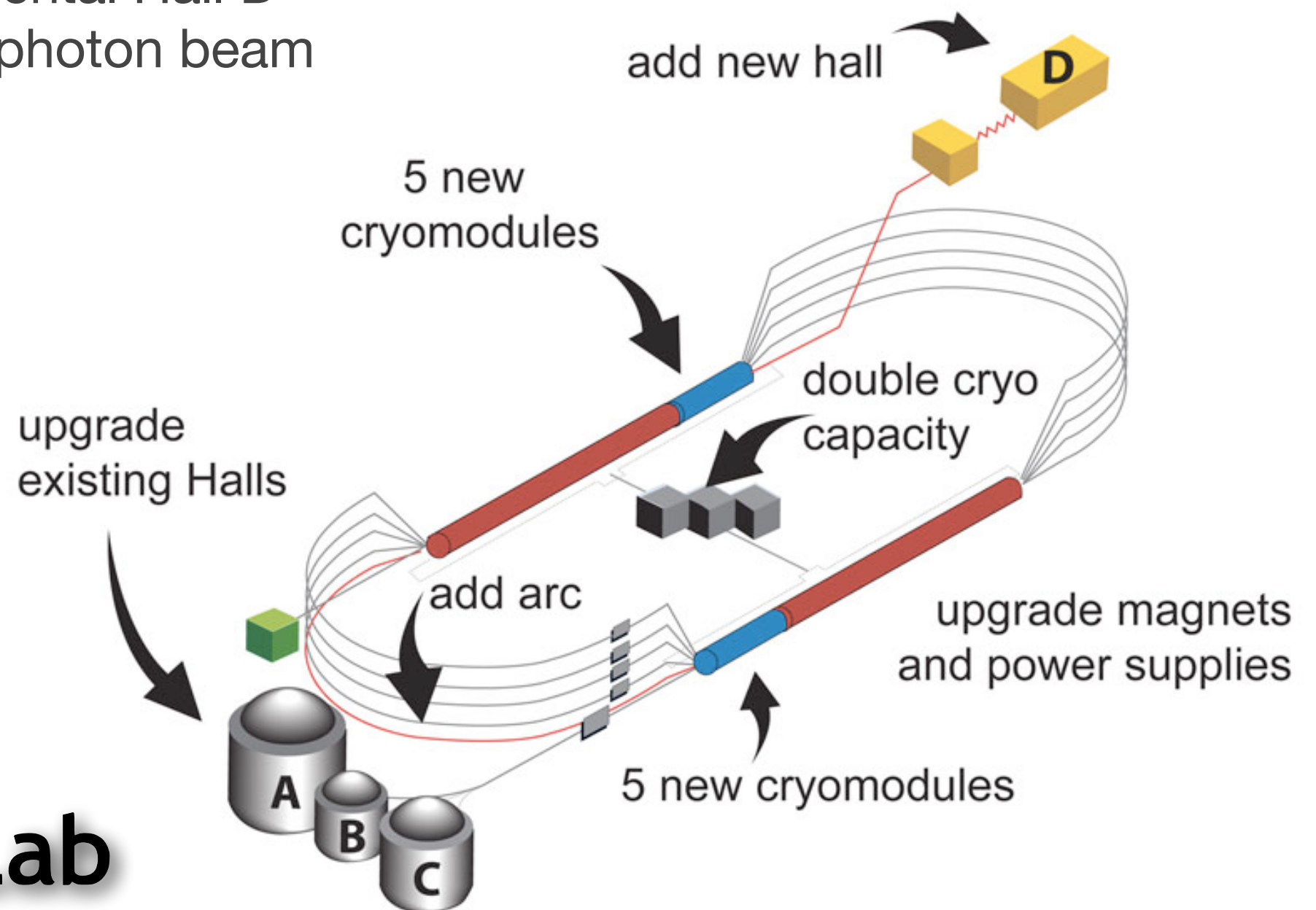


hybrid meson

Do gluonic degrees of freedom manifest themselves in the bound states we observe in nature?

Jefferson Lab

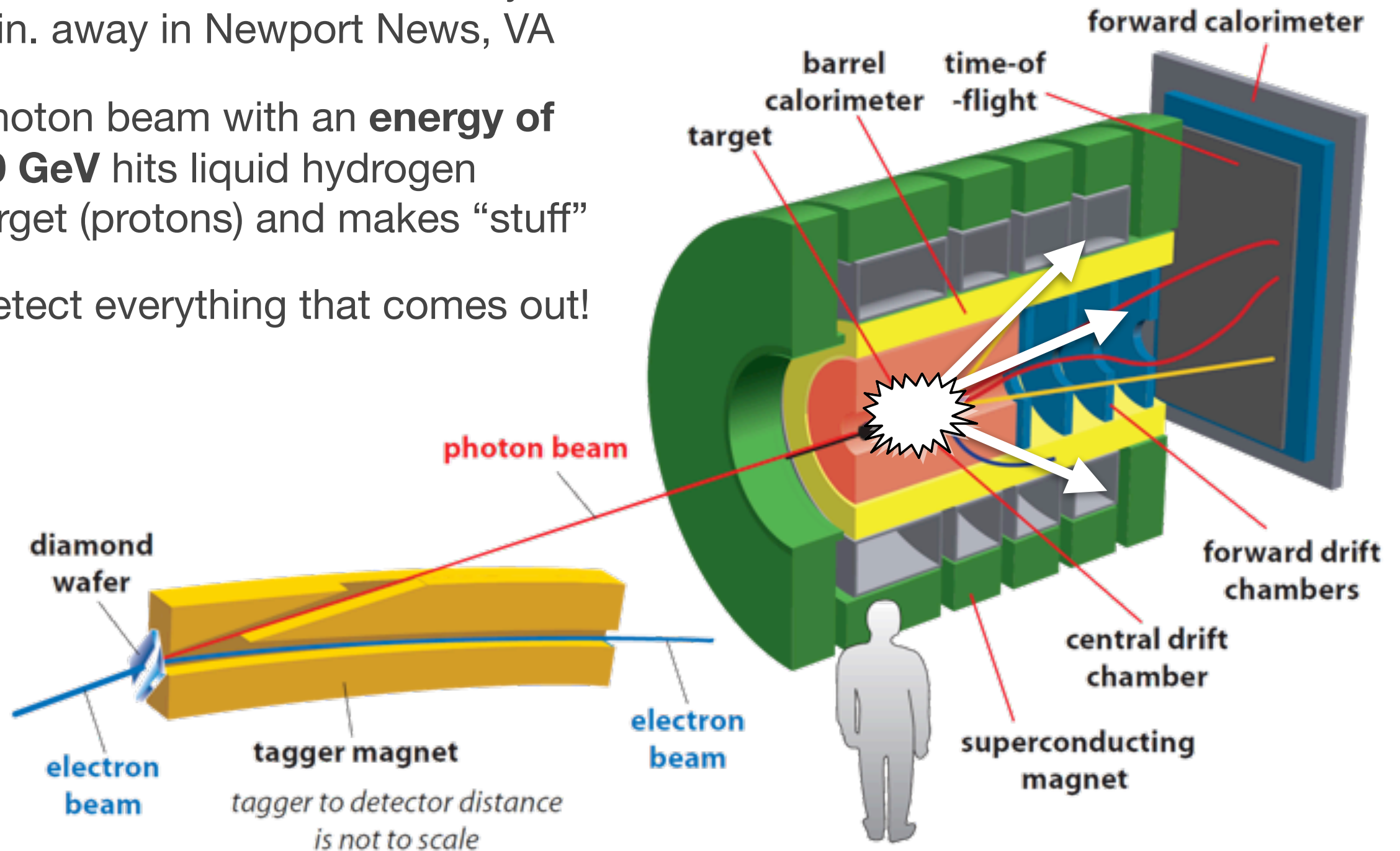
- * Upgrade maximum electron beam energy from 6 to 12 GeV
- * Add new experimental Hall D with a dedicated photon beam



Jefferson Lab

GLUEX Experiment

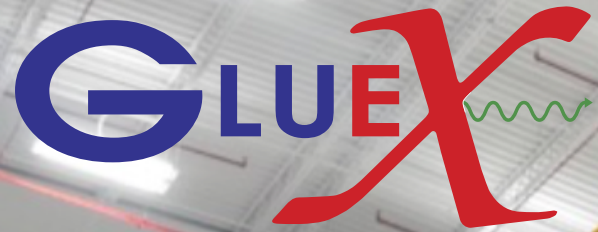
- * Located at Jefferson Lab, only 30 min. away in Newport News, VA
- * Photon beam with an **energy of 10 GeV** hits liquid hydrogen target (protons) and makes “stuff”
- * Detect everything that comes out!



GLUEX Collaboration



112 collaborators
25 institutions
9 countries



GlueX Detector with
Prof. Curtis Meyer
GlueX Spokesperson
October 2014

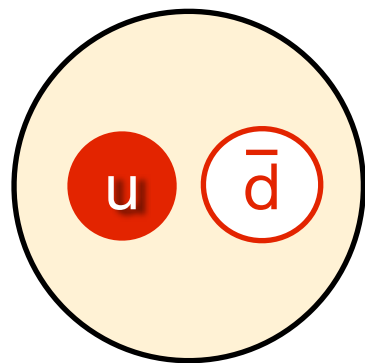


Construction (~5 years)



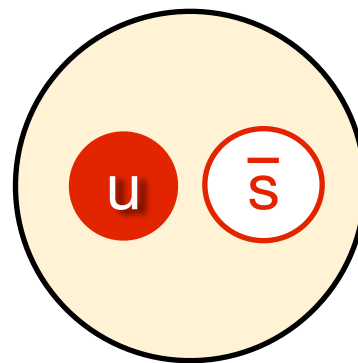
Identifying particles

- * **How do you know which particle you detected?**
- * Measure electric charge
- * Interaction with different kinds of materials
- * Measure particle mass



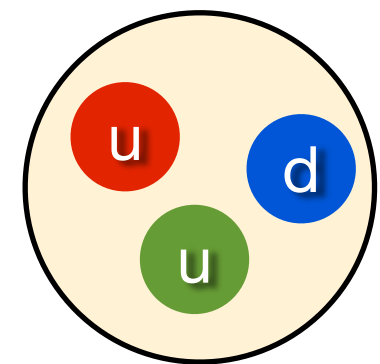
$$\pi^+ = |u\bar{d}\rangle$$

$$M_\pi \sim 140 \text{ MeV}$$



$$K^+ = |u\bar{s}\rangle$$

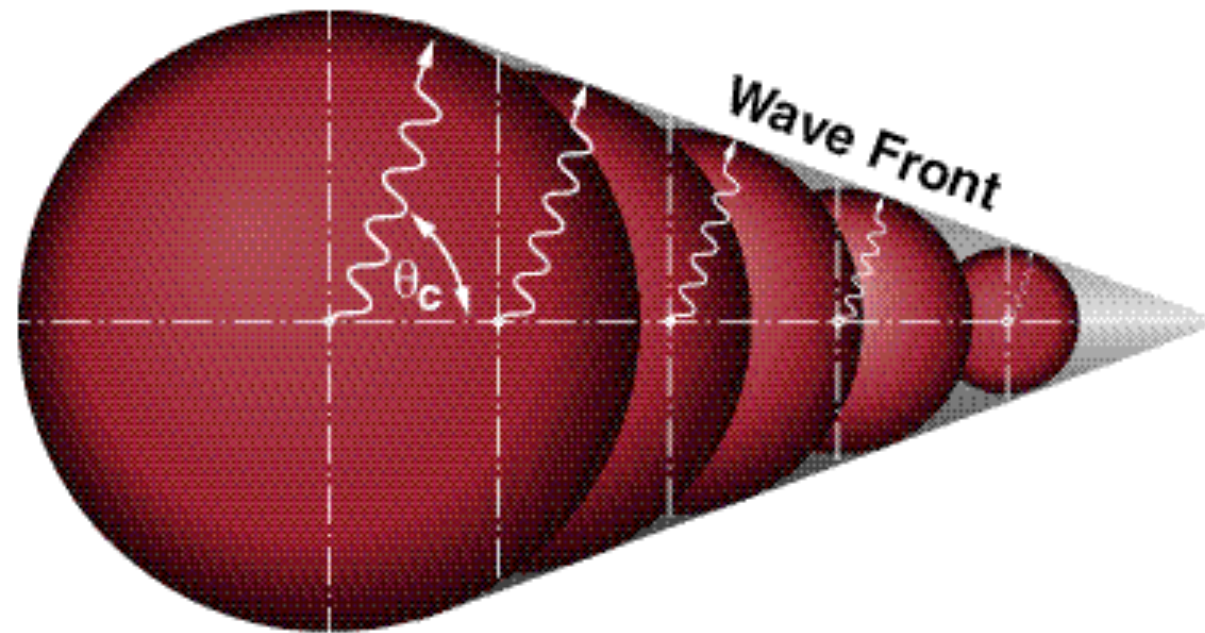
$$M_K \sim 490 \text{ MeV}$$



$$\textit{proton} = |uud\rangle$$

$$M_p \sim 940 \text{ MeV}$$

Cherenkov radiation



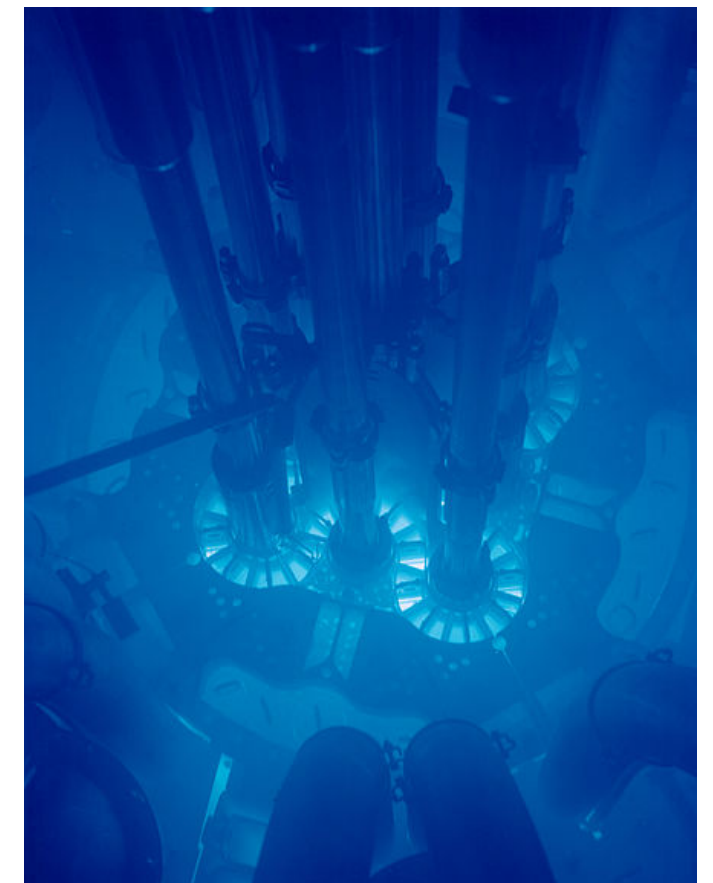
Nuclear Reactor

- * Charged particles traveling faster than the speed of light in a medium emit Cherenkov light

- * Wavelength dependence:
$$N_\gamma \sim \frac{1}{\lambda^2}$$

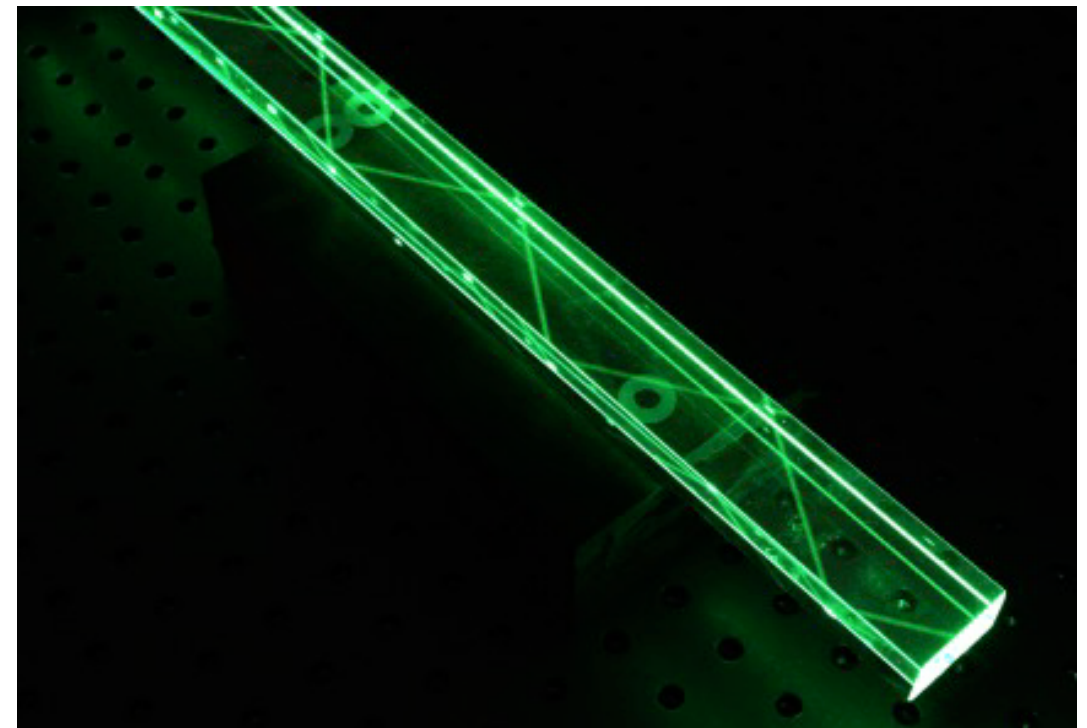
- * Cherenkov angle:
$$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$

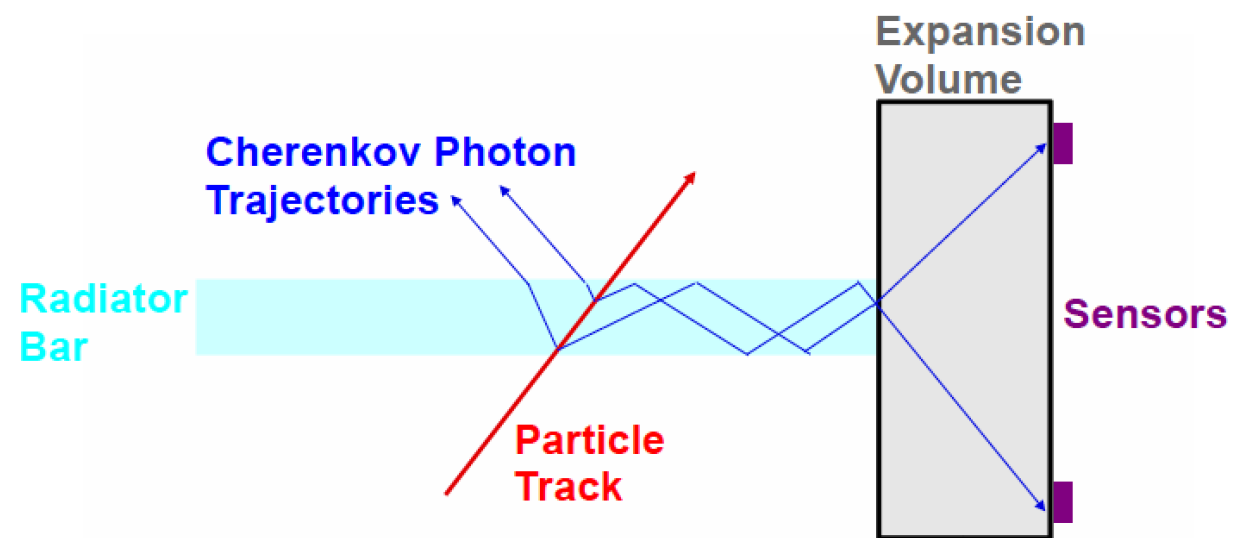
- * Determine $\beta = v/c$ with known index of refraction n , separate particles by difference in masses



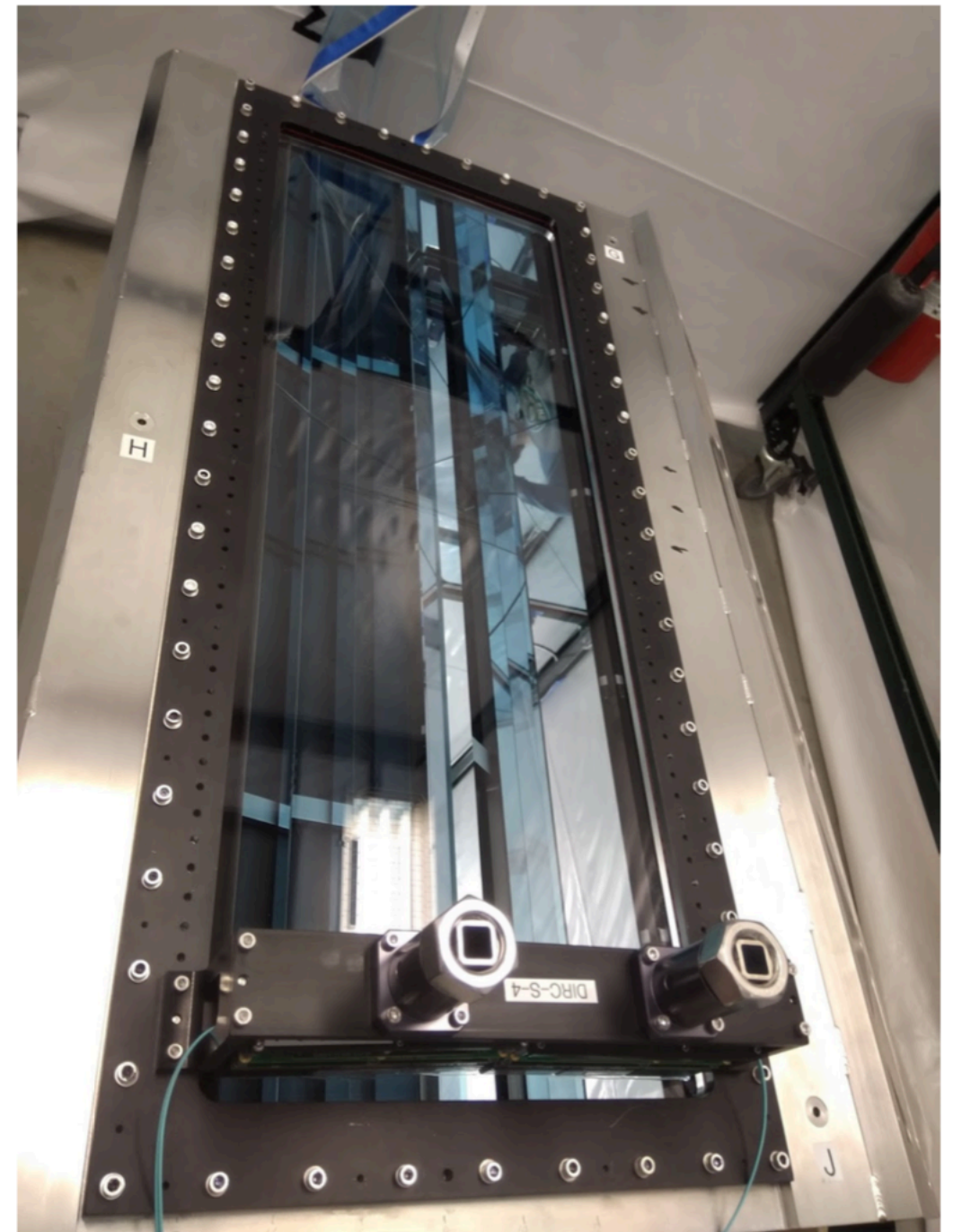
Cherenkov radiation: imaging

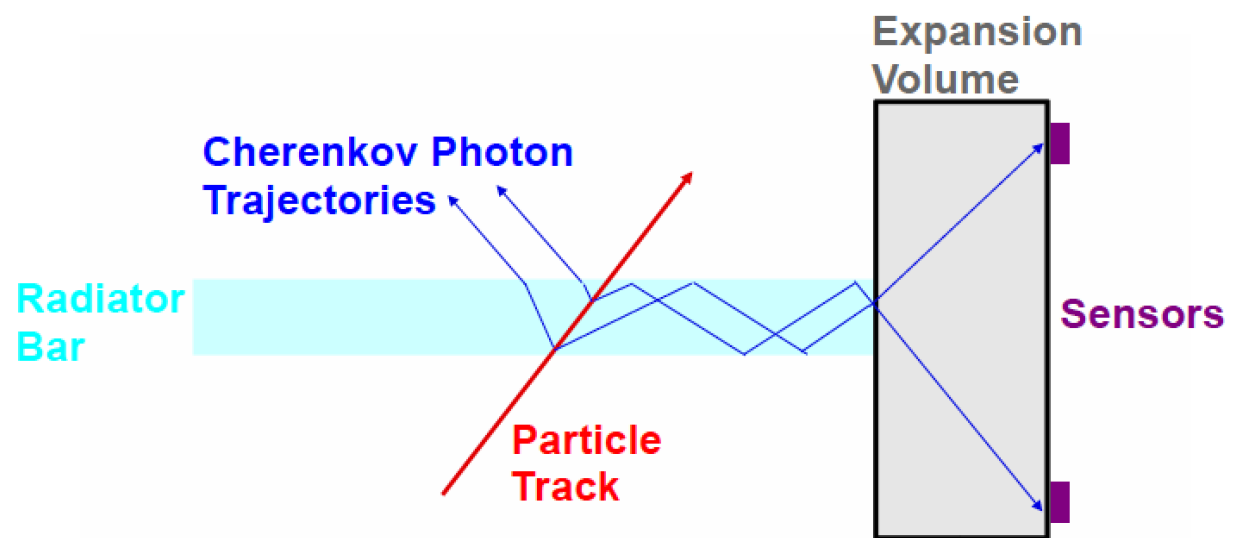
- ✱ **DIRC**: Detection of Internally Reflected Cherenkov Light
- ✱ Image single photons to measure Cherenkov angle
- ✱ Need large array (~12,000) of photomultiplier tubes (PMTs)





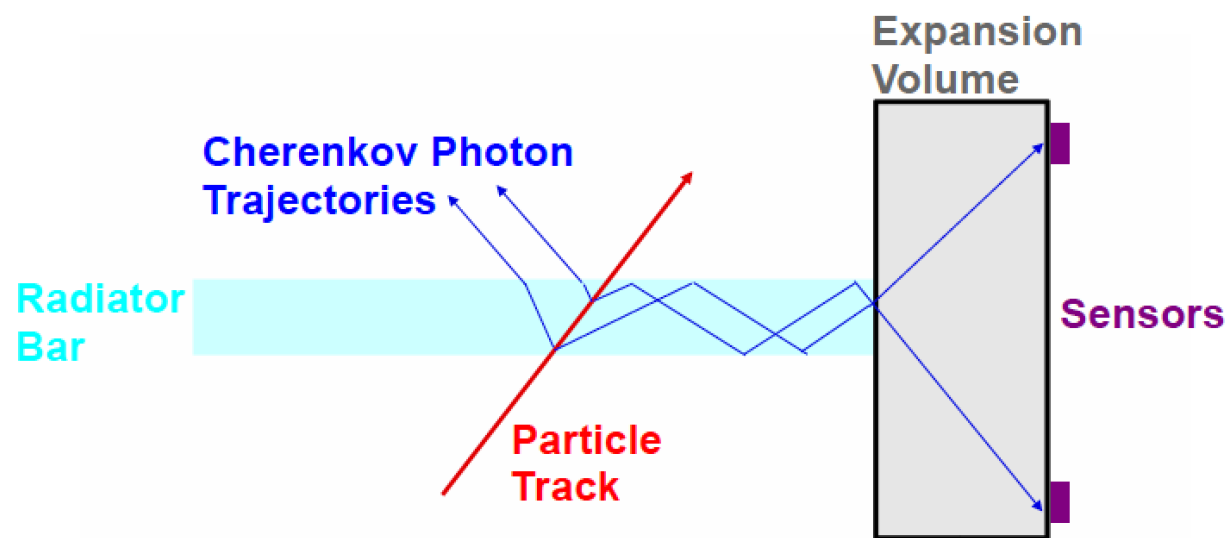
- * Sensor array constructed by team from W&M and MIT
- * Data analysis ongoing now at by W&M group!



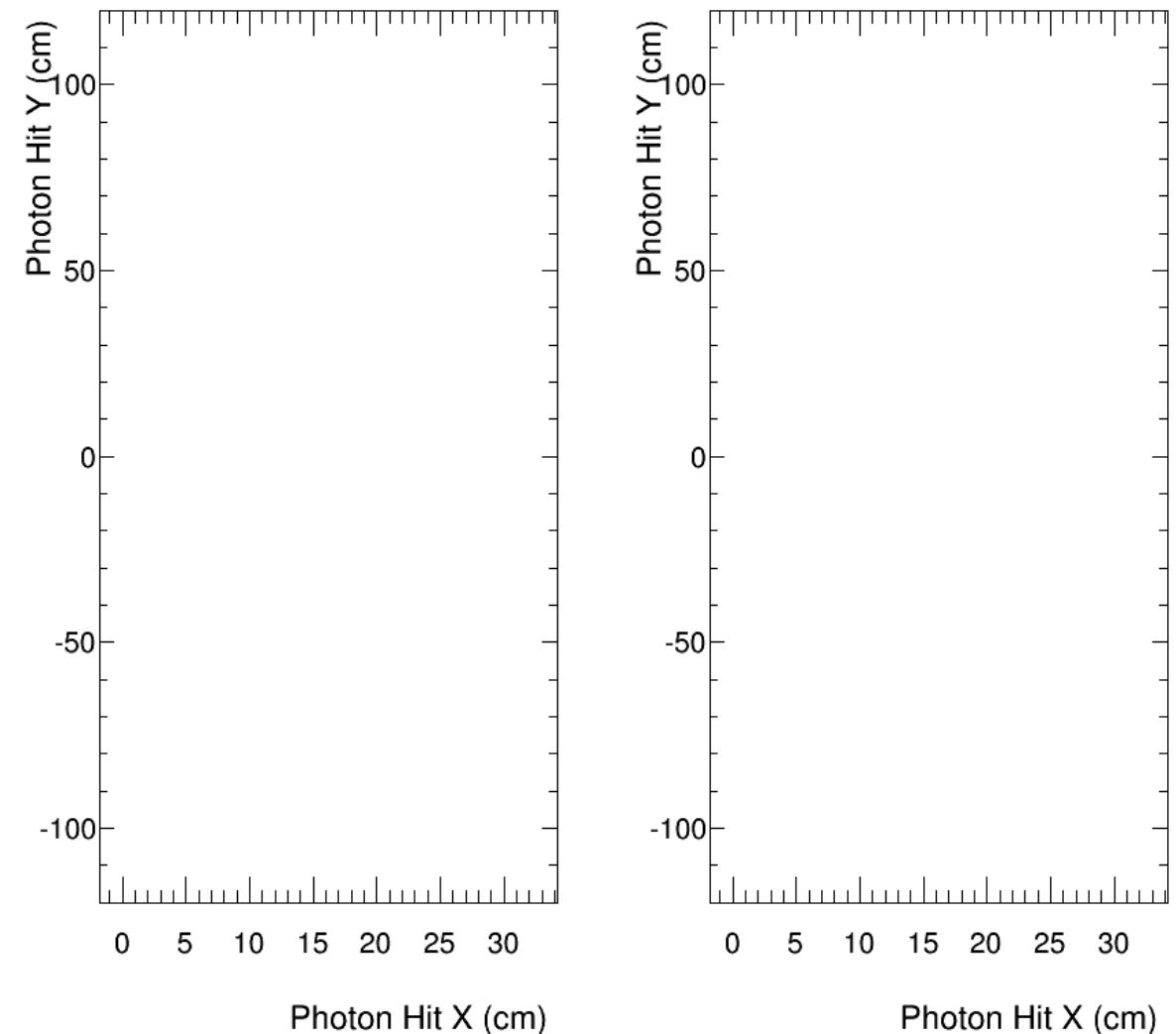


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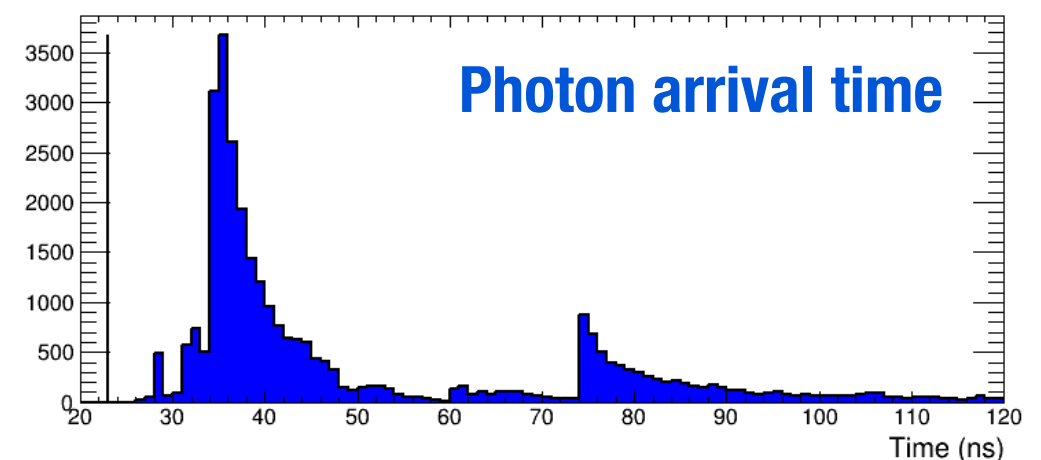




Cherenkov Photon “Ring”

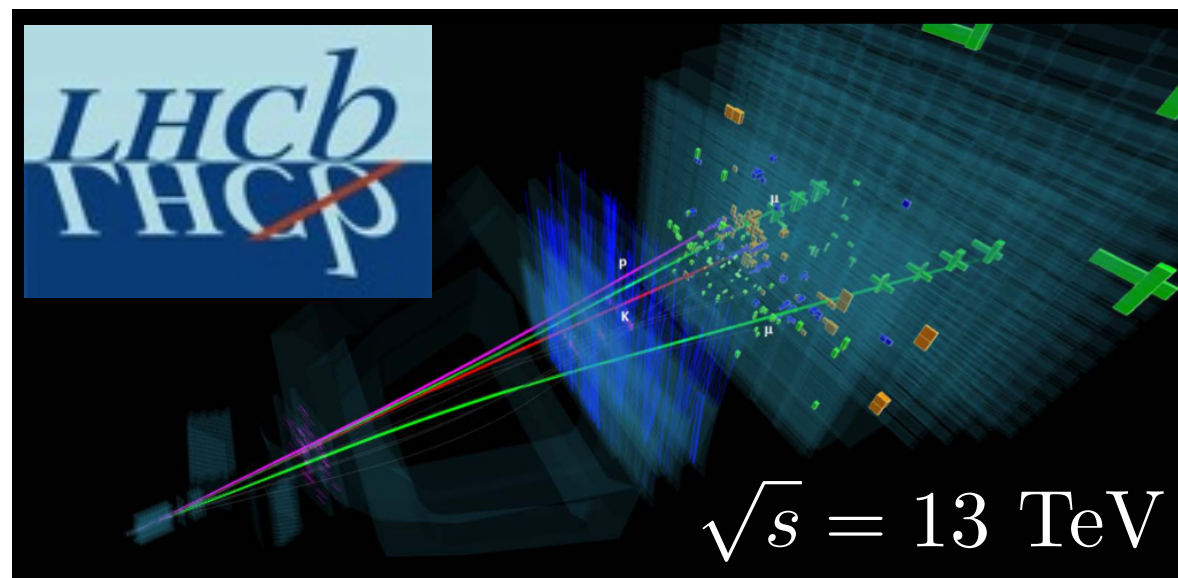
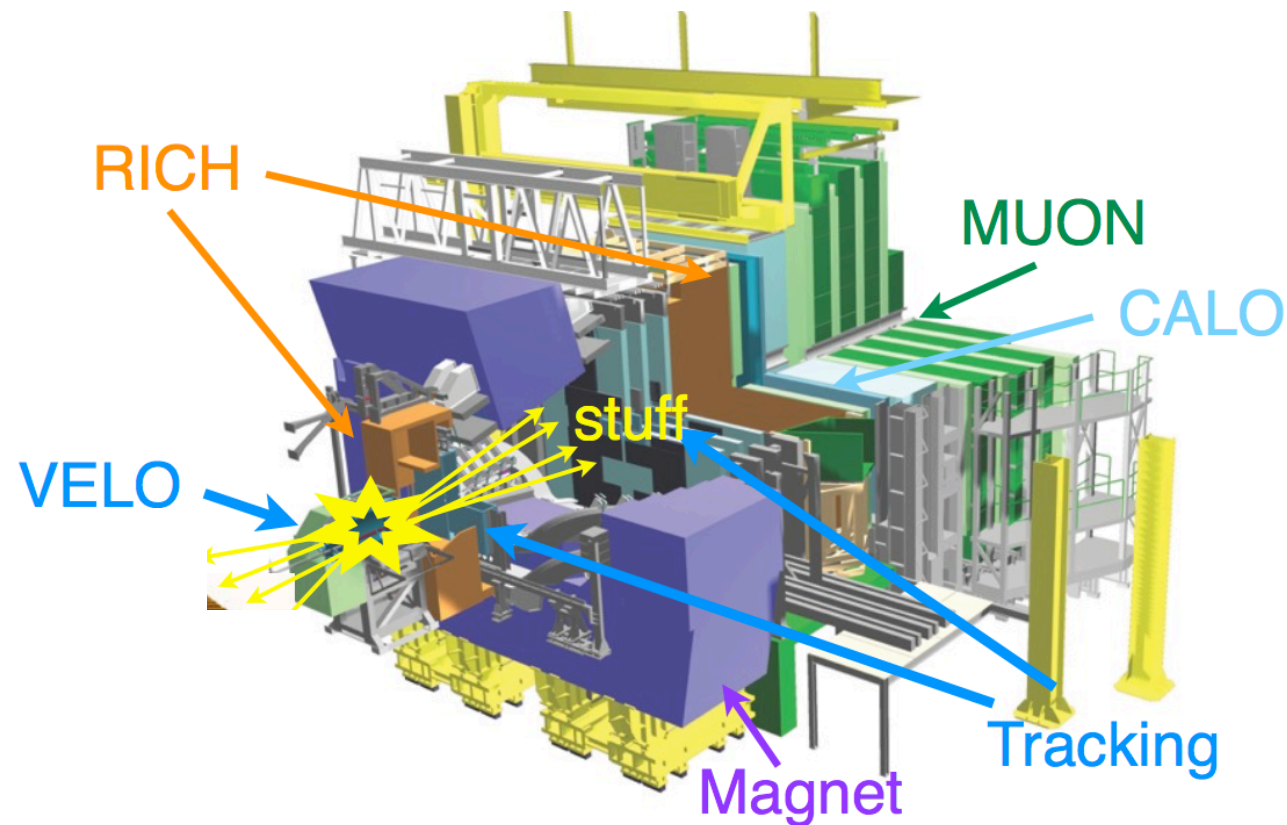


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Heavy quark production and detection

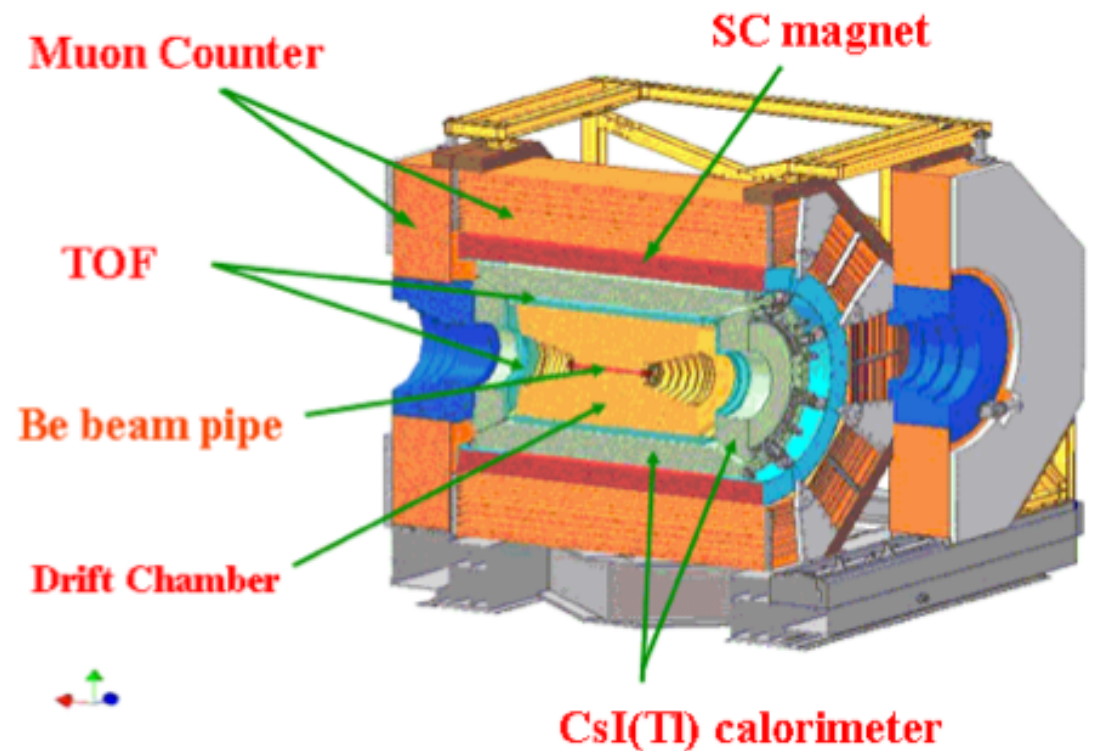
Inclusive: $pp \rightarrow BX$ or $\Lambda_B X$



Pro: high rate

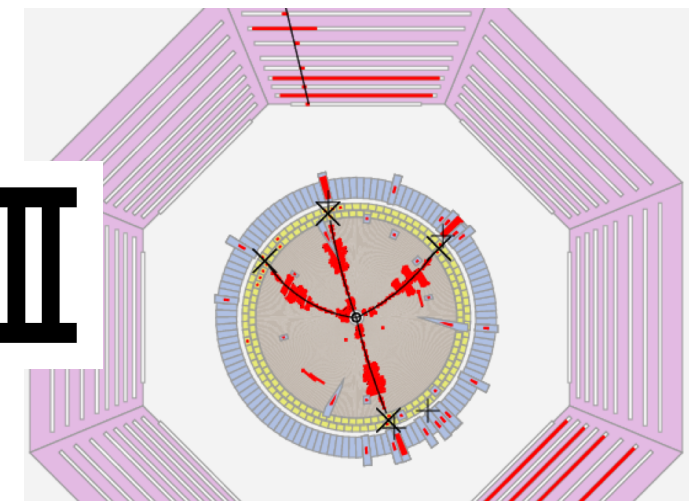
Con: messy

Exclusive: $e^+e^- \rightarrow c\bar{c}$



$\sqrt{s} = 2 - 4.6 \text{ GeV}$

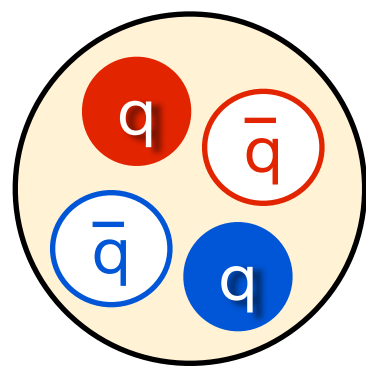
BESIII



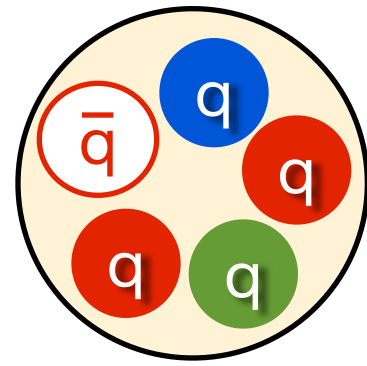
Pro: controlled

Con: statistics

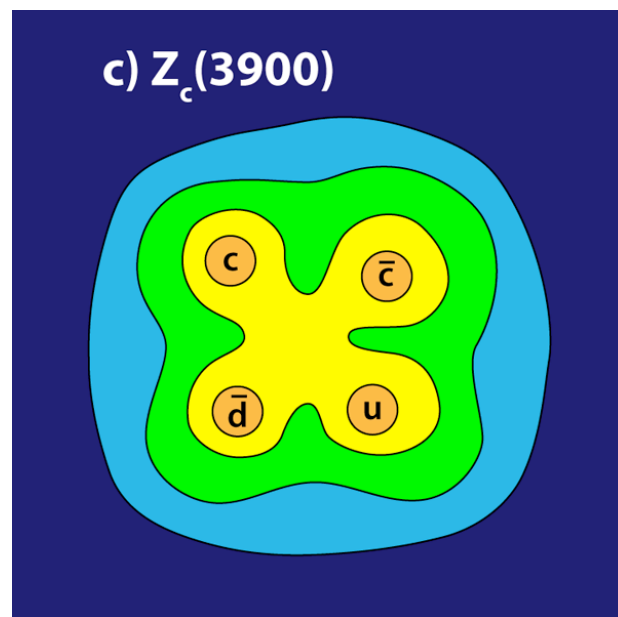
Exotic candidates



tetraquark



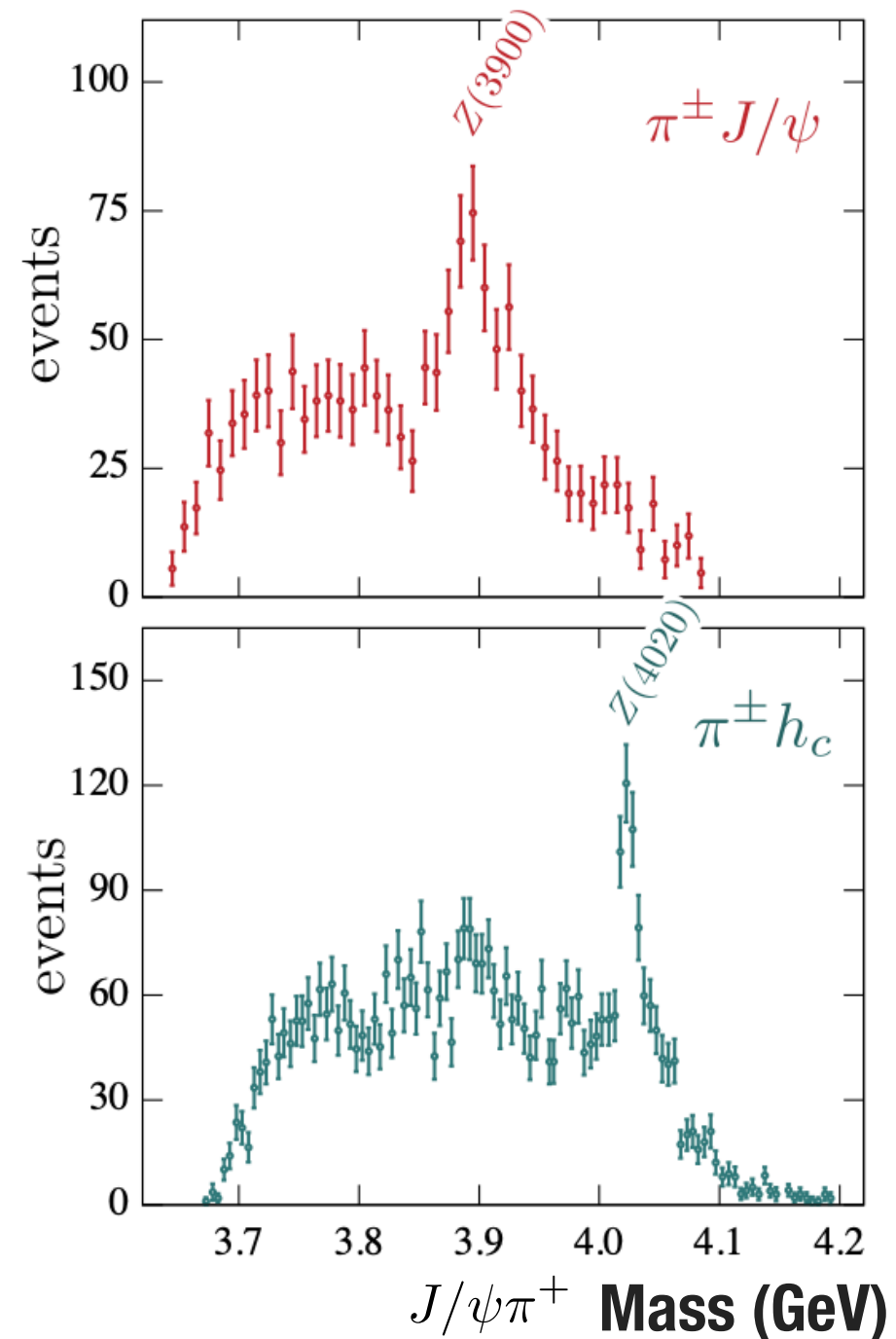
pentaquark



Physics Viewpoint 6, 69 (2013)

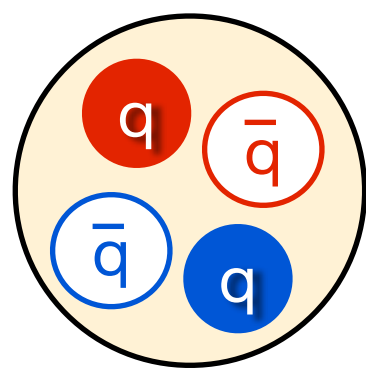
$$e^+ e^- \rightarrow Z_c^+ \pi^-$$

$$Z_c^+ \rightarrow J/\psi \pi^+$$

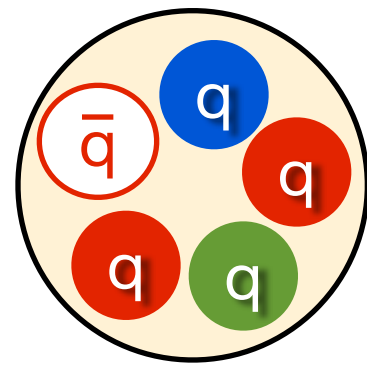


Nature Review: 1802.08131

Exotic candidates

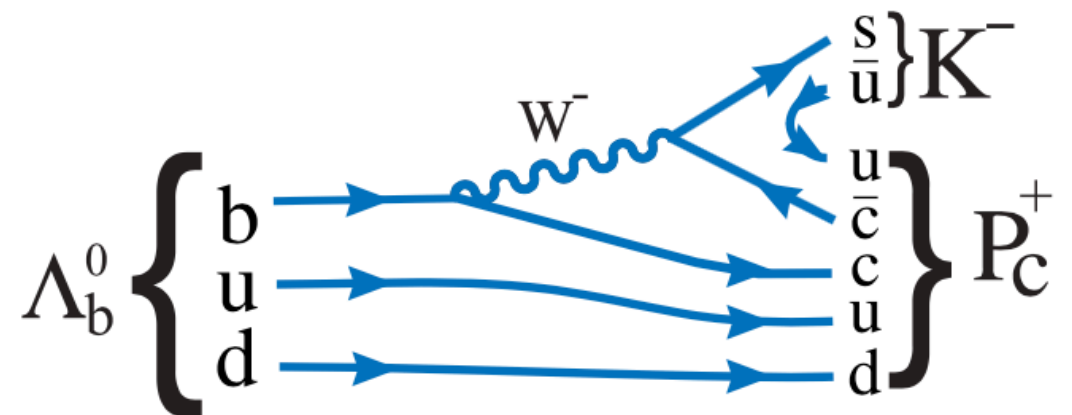
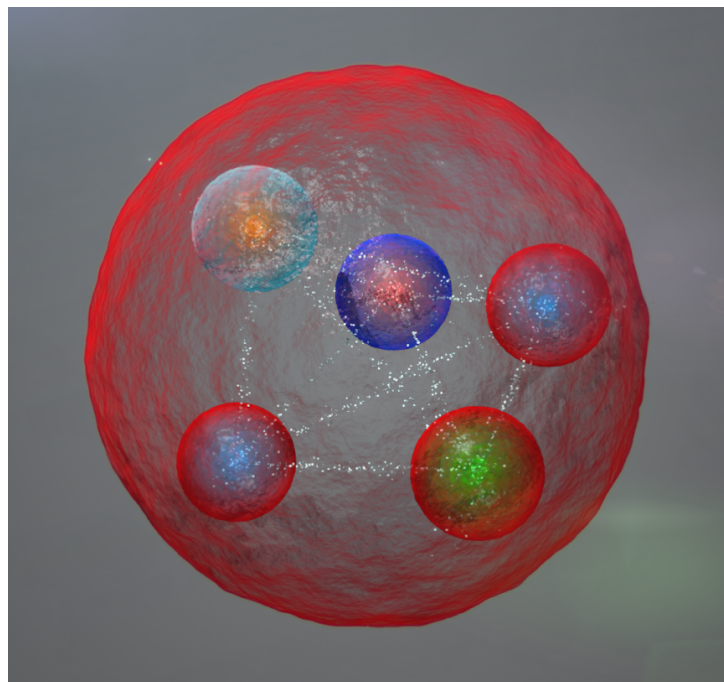


tetraquark

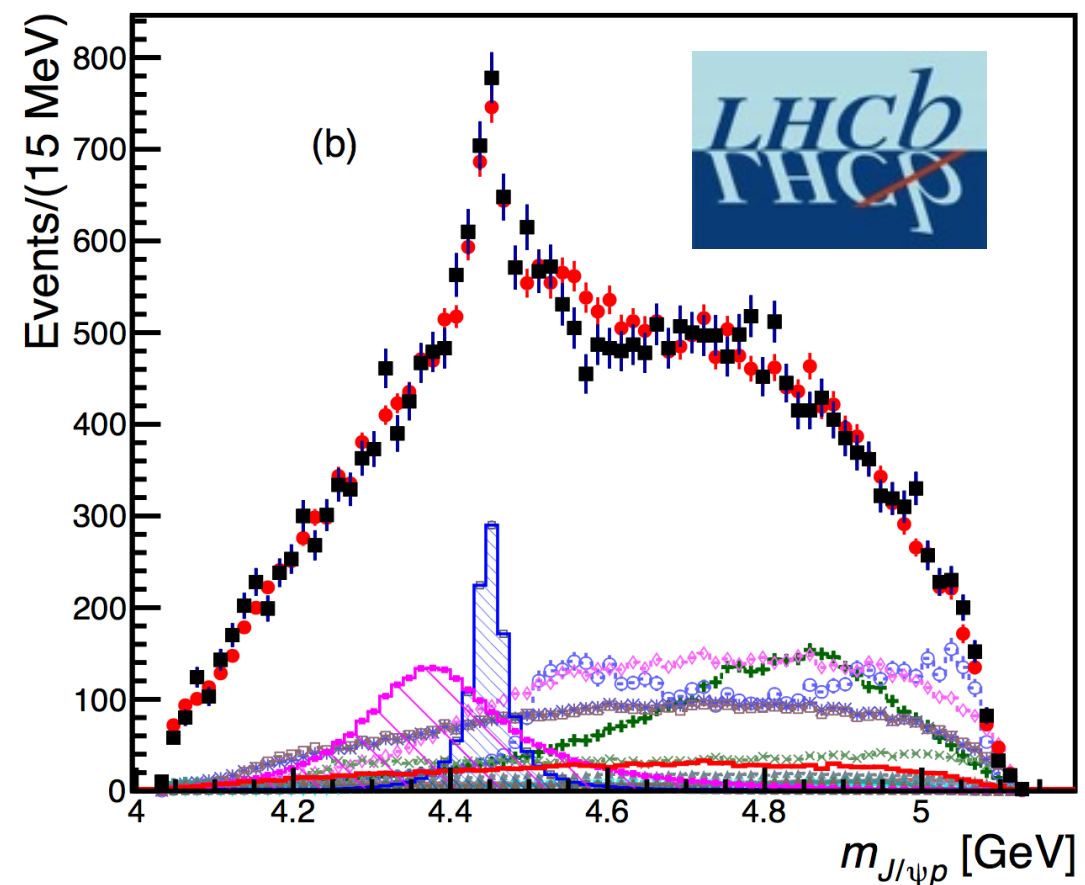


pentaquark

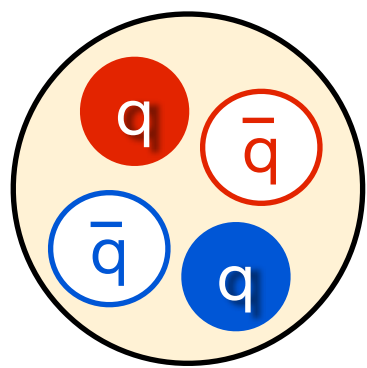
$$pp \rightarrow \Lambda_B + stuf f$$



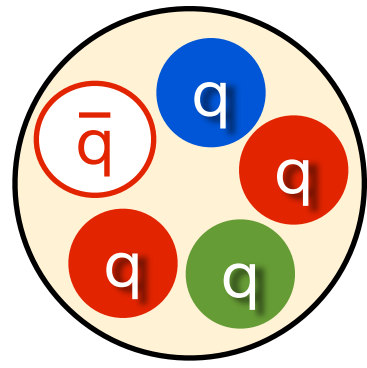
$$\Lambda_b \rightarrow J/\psi p K^-$$



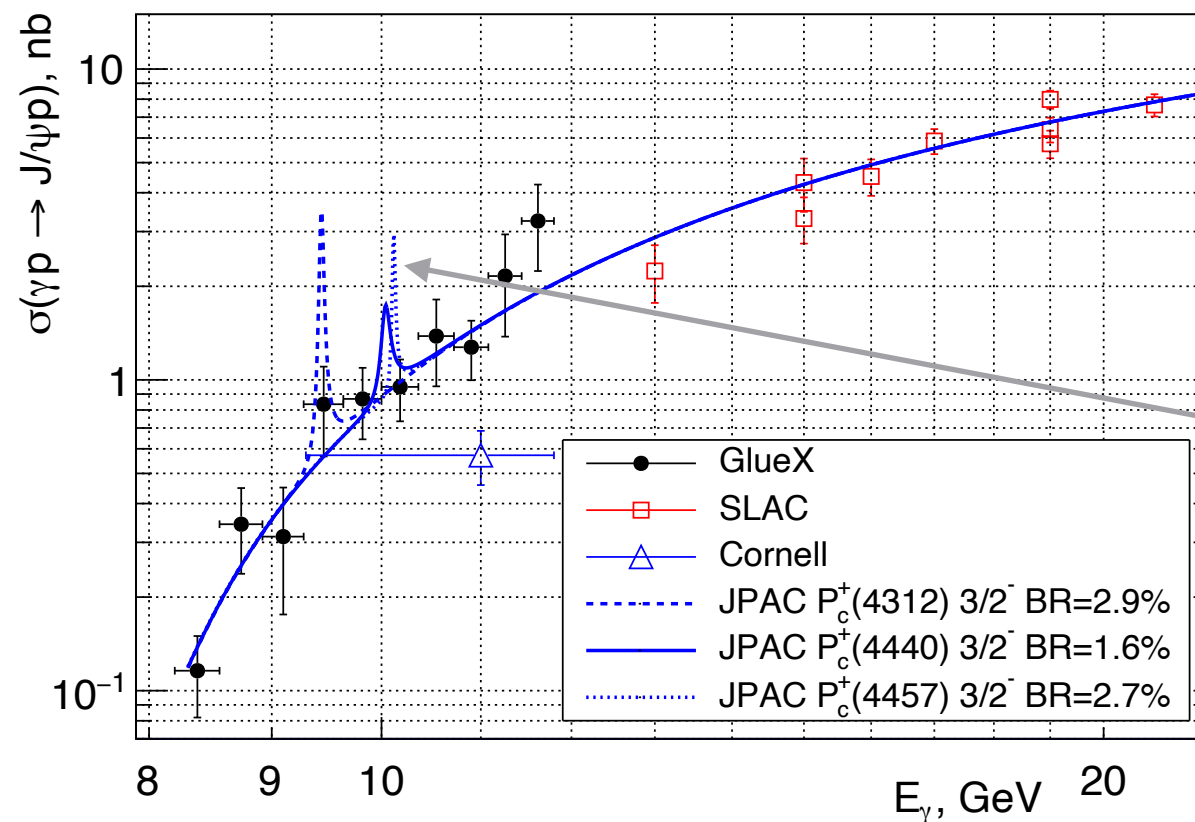
Exotic candidates



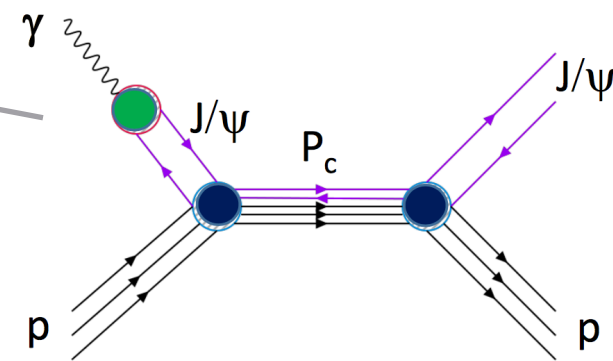
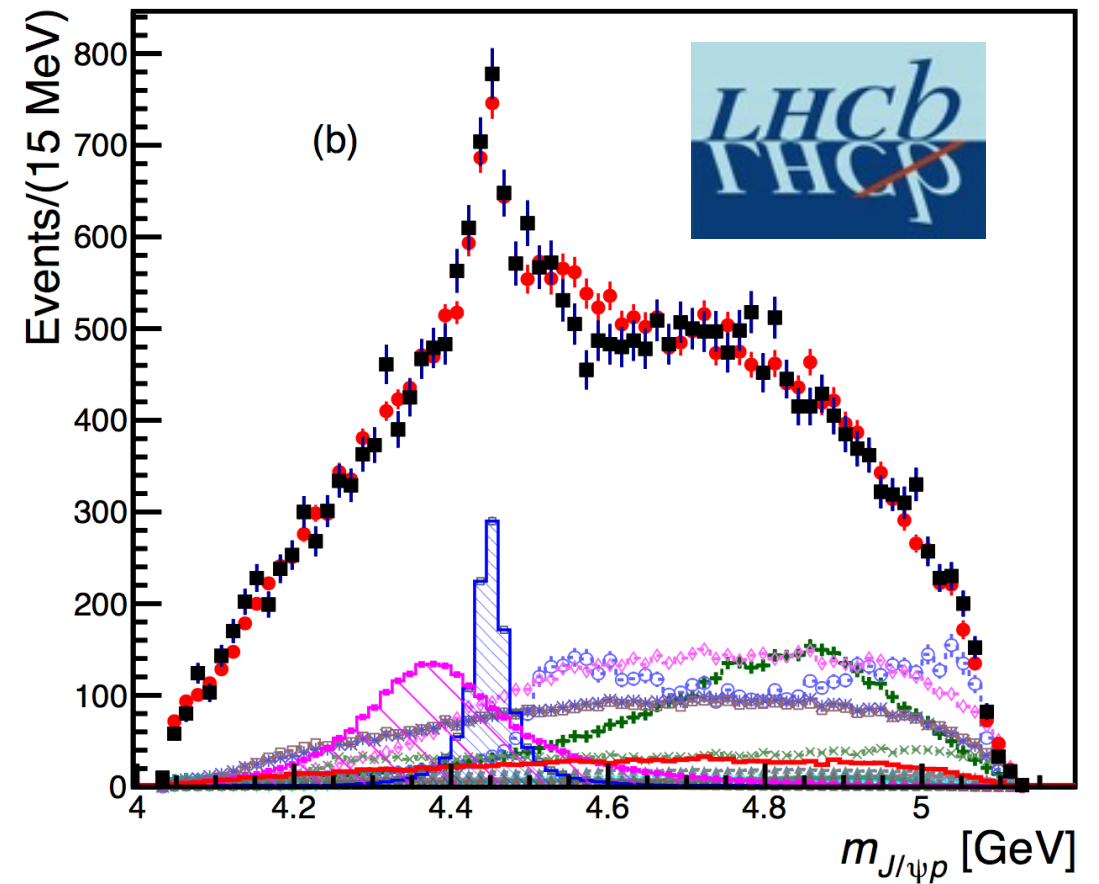
tetraquark



pentaquark

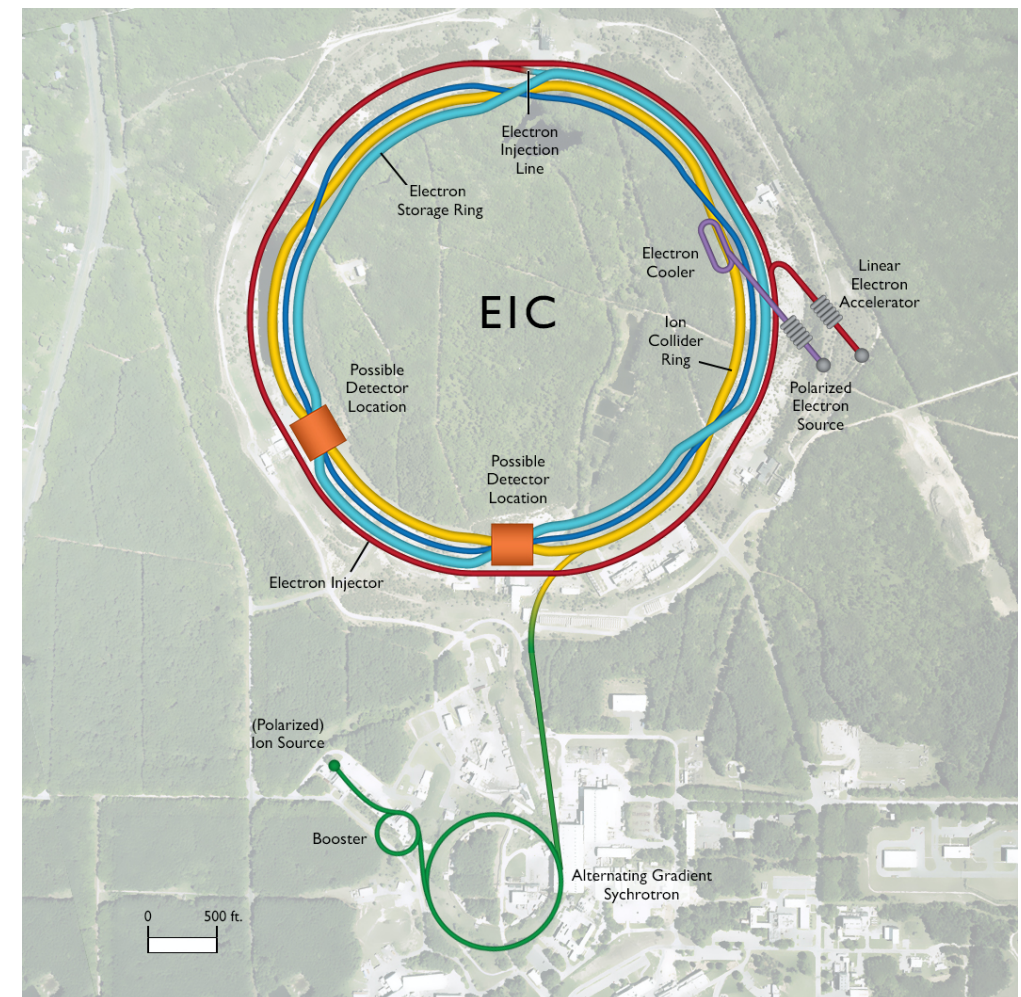
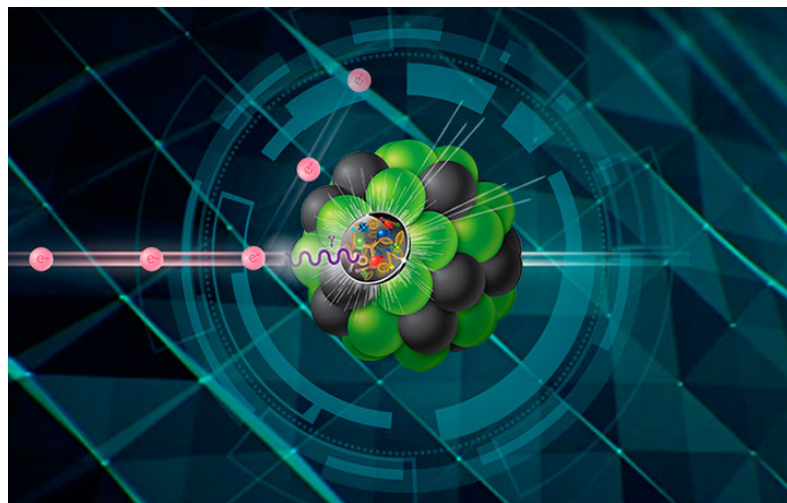


$$\Lambda_b \rightarrow J/\psi p K^-$$



- * **GLUEX**: use a real photon beam to produce exotic hadrons
- * **Recent**: limits on “pentaquark” seen at LHC

The Future: **Electron Ion Collider**

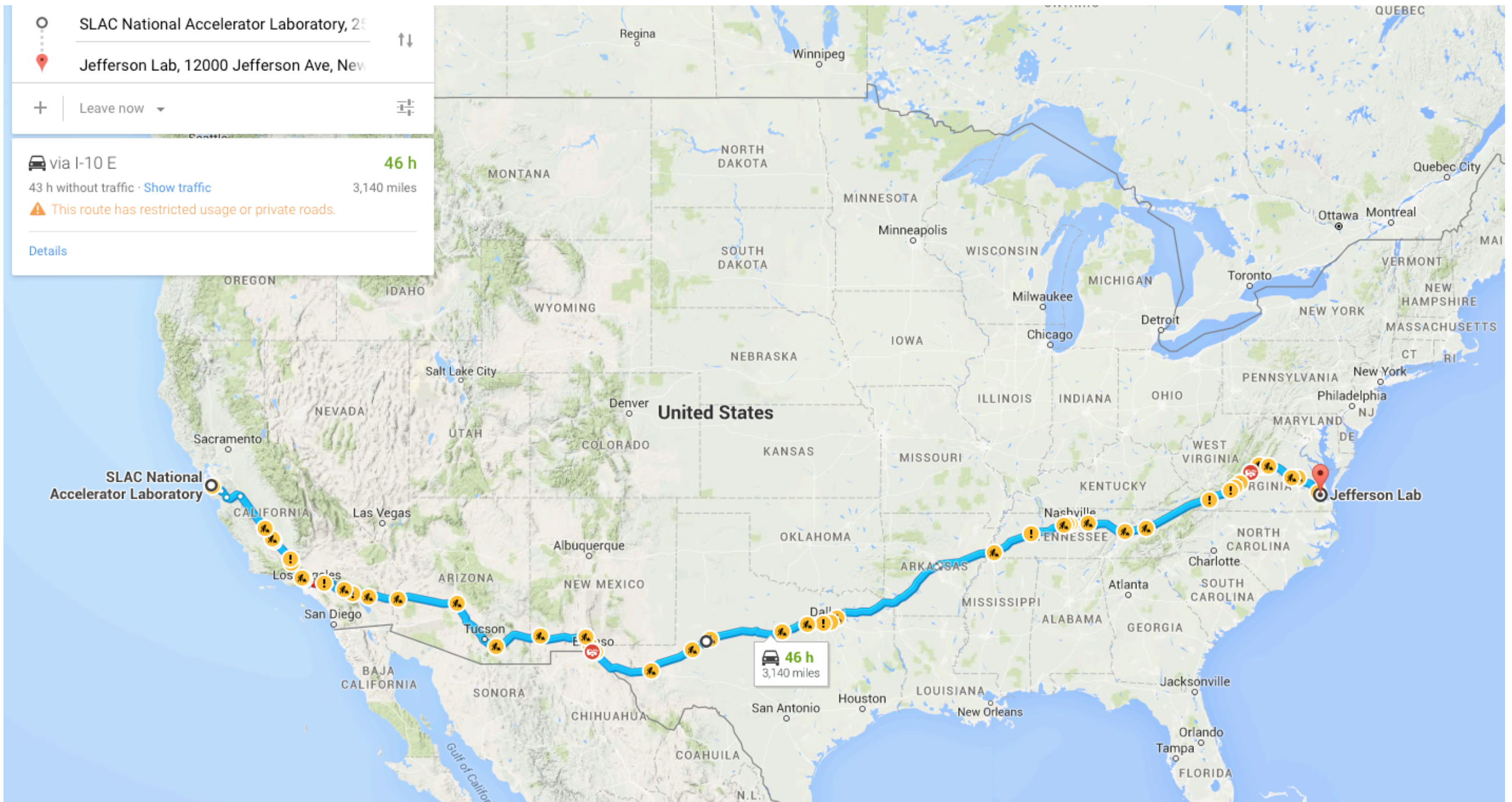


<https://www.bnl.gov/newsroom/news.php?a=116998>

- ✱ Versatile high luminosity, polarized $e+p$ and $e+A$ collider to explore:
 - ✱ Nucleon spin and 3D structure
 - ✱ High gluon density and saturation
- ✱ Construction could start in ~5 years with data in ~2030(?)

Backup

Road trip!



GLUEX DIRC upgrade

Loading of 1st BaBar bar box at SLAC

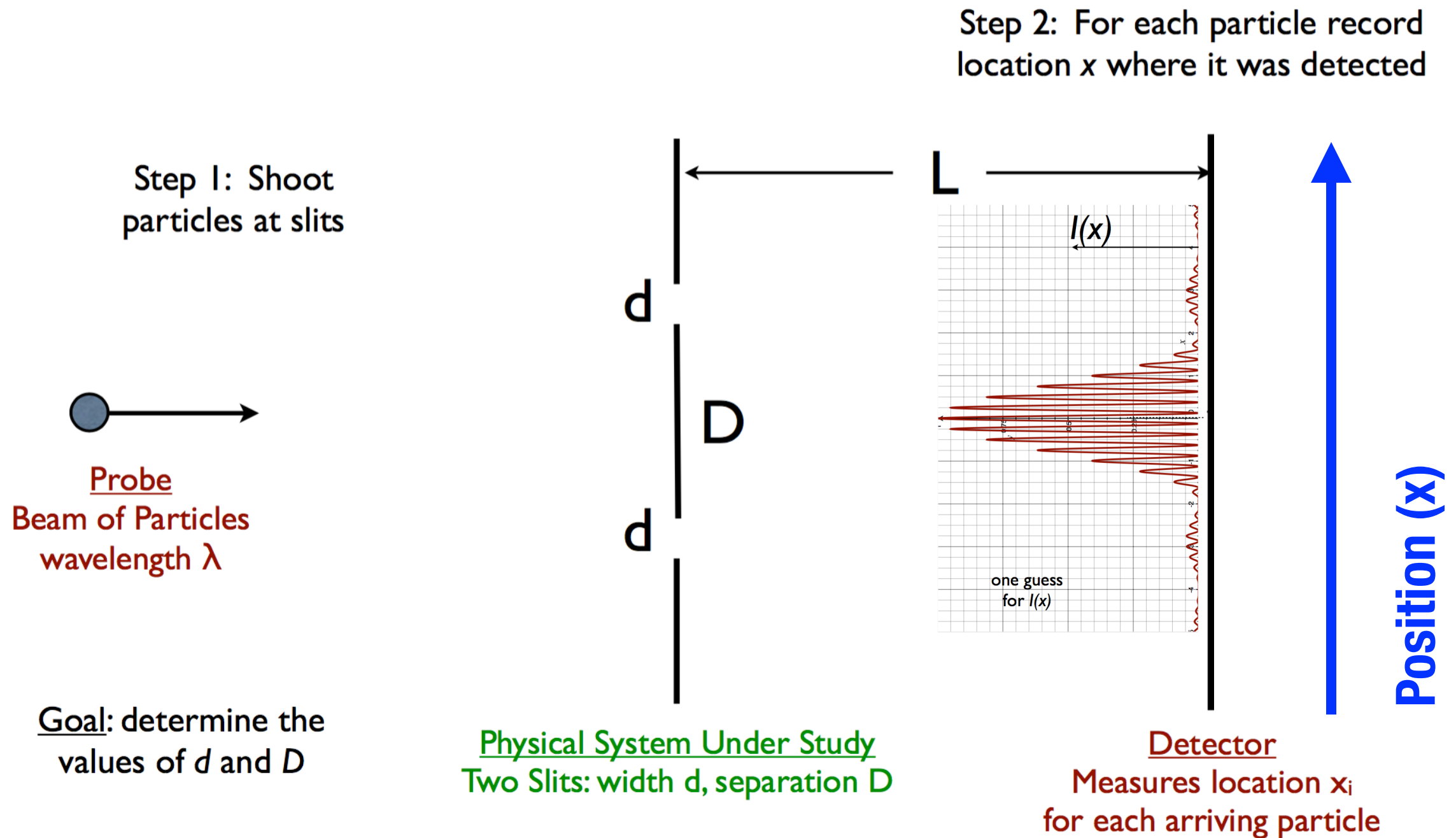


Delivered safely to JLab in November 2017



@GlueX_DIRC

Double Slit Experiment



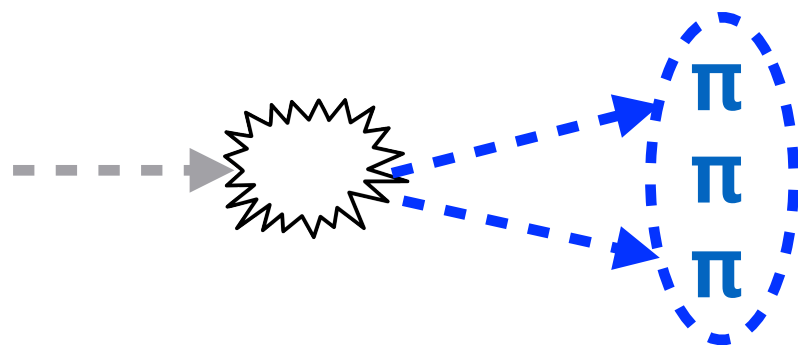
Physical Model:

$$I(x) = I_0 \left(\frac{\sin(d\pi x / \lambda L)}{d\pi x / \lambda L} \right)^2 \cos^2(2D\pi x / \lambda L)$$

Particle physics “many slits”

Step 1: Create 3 pions in some collision

Probe: 3 pions which can form heavier particles X, Y or Z



Physical Model:

$$I(M) = \left| \sum_{i=X,Y,Z} V_i A_i(M) \right|^2$$

Goal: determine properties of X, Y, and Z

**Intermediate
Particles**

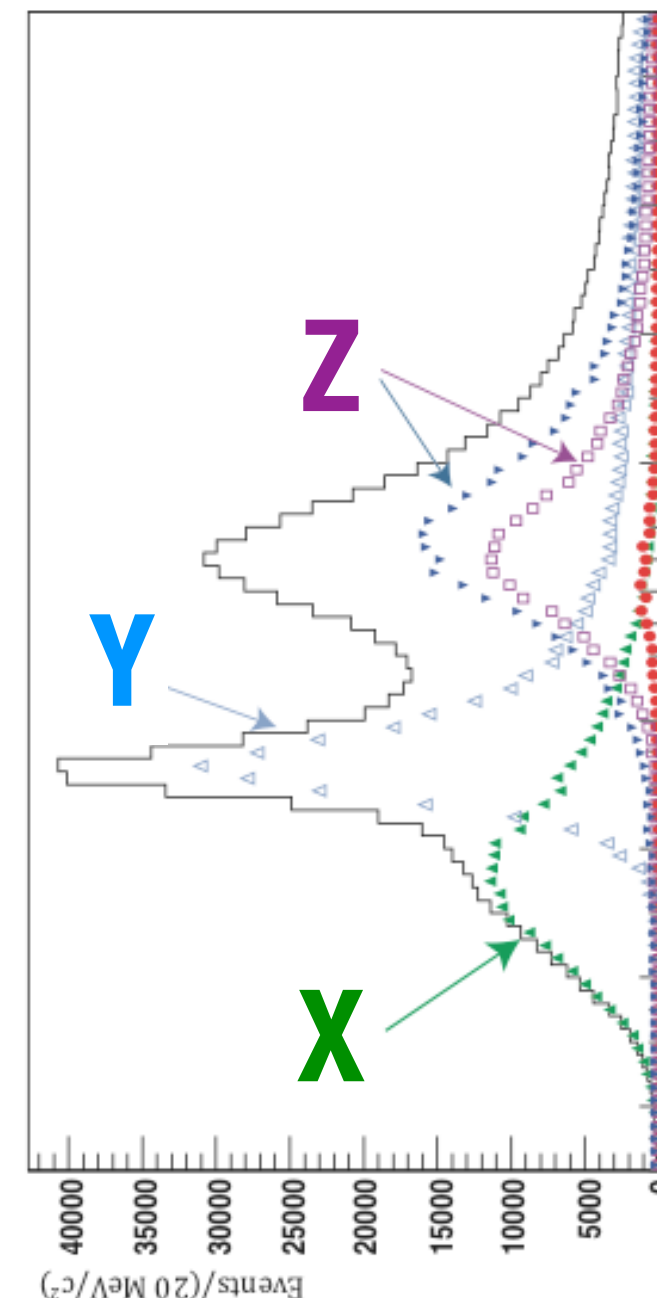
Z

Y

X

Physical System Under Study:
intermediate particles X, Y, and Z

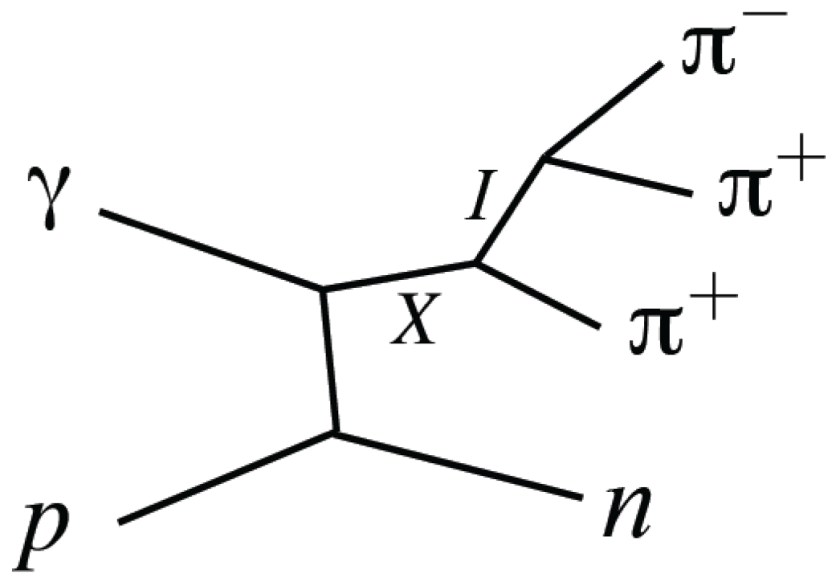
Step 2: For each collision record the **mass of the 3π system**



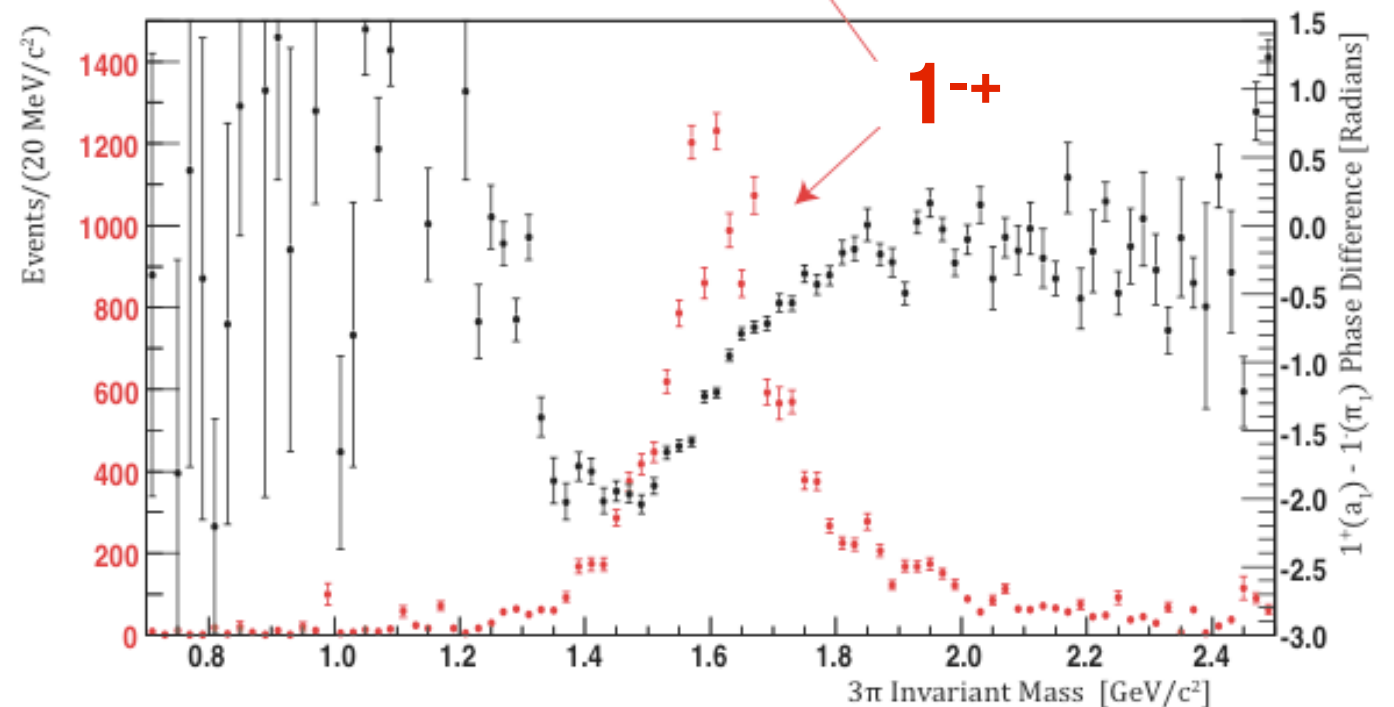
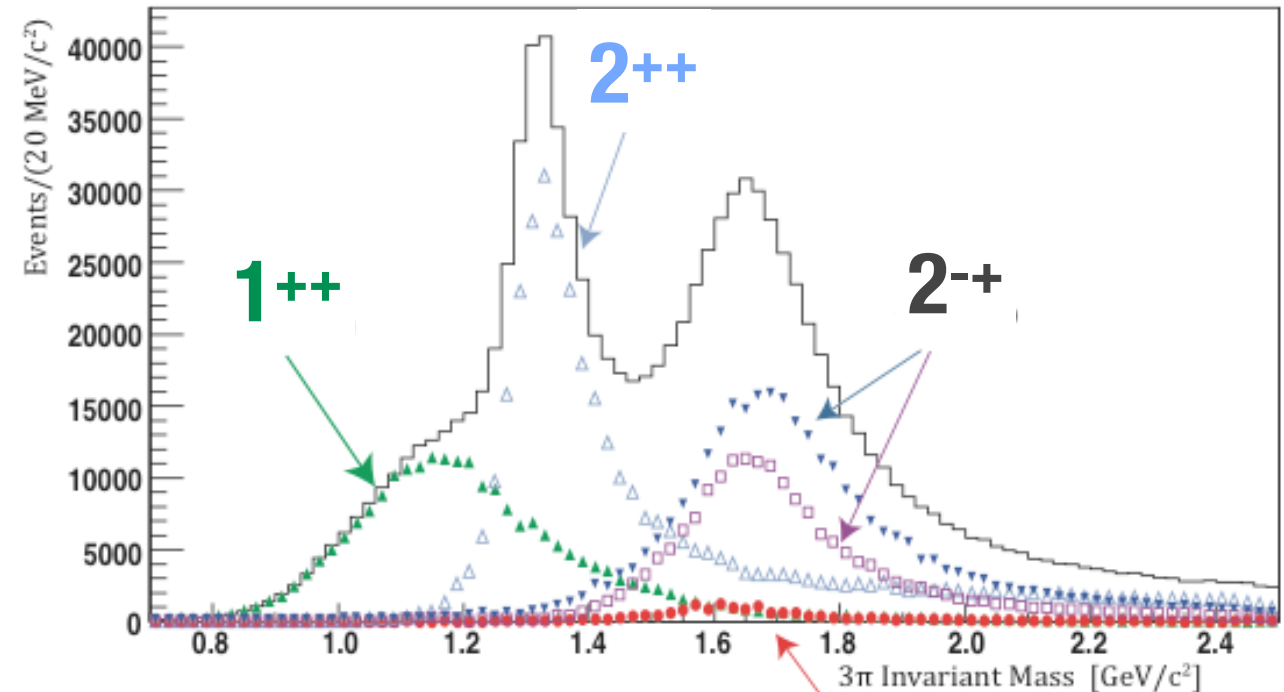
Detector: Measure mass of 3π system for each collision

Amplitude Analysis

GLUEX Simulation



$$I(\vec{x}) = \frac{dN}{d\vec{x}} = \left| \sum_{\alpha}^{N_{\text{amps}}} V_{\alpha} A_{\alpha}(\vec{x}) \right|^2$$



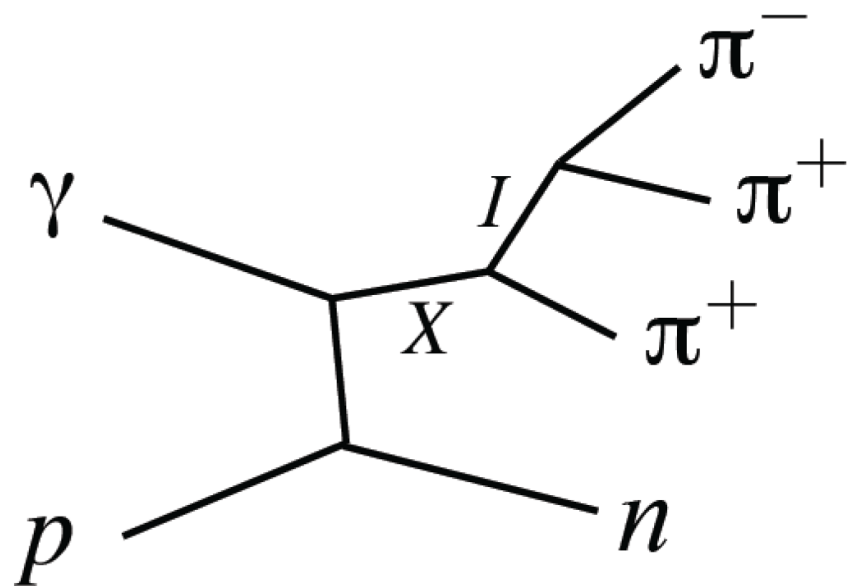
Amplitude Analysis

✱ **Goal:** Identify J^{PC} of $X \rightarrow \pi^+\pi^-\pi^+$

✱ Model the intensity of events at the level of QM amplitudes (allow for interference)

$$I(\vec{x}) = \frac{dN}{d\vec{x}} = \left| \sum_{\alpha}^{N_{\text{amps}}} V_{\alpha} A_{\alpha}(\vec{x}) \right|^2$$

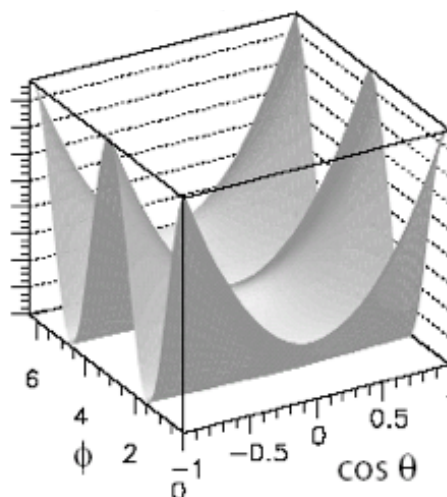
✱ 5-dimensional problem: two new angles at each decay step (X and I)



Example Intensity:

$$X(1^{++}) \rightarrow \rho\pi^+ \text{ (S wave)}$$

$$X \rightarrow \rho\pi^+$$



$$\rho \rightarrow \pi^+\pi^-$$

