# Hadron Spectroscopy at GlueX and Beyond (1)

Justin Stevens

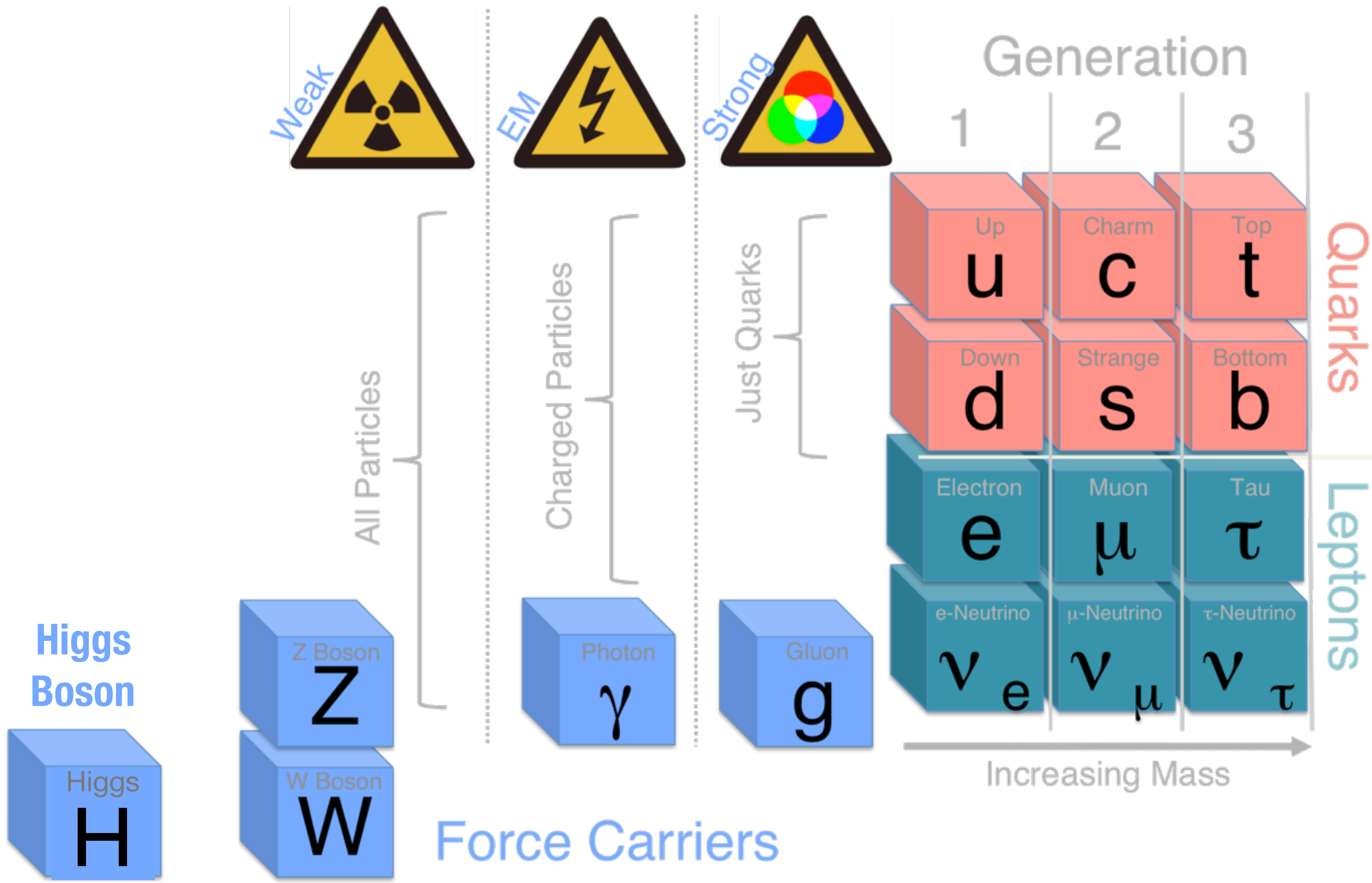
William & Mary
CHARTERED 1693

# Preliminaries

- **Goal:**
  - A self-contained introduction to hadron spectroscopy and an overview of recent excitement in the field
- **Outline:**
  - **Introduction to QCD and hadron spectroscopy**
    - Why study spectroscopy through QCD?
    - Classification of hadrons
  - Heavy quark spectroscopy: “The XYZ story”
  - Light quark spectroscopy (tomorrow and Wednesday)

# Standard Model

**Coupling Strength:** **$10^{-6}$** **1/137** **1**




**Spin 1** **Spin 1/2**

# Standard Model

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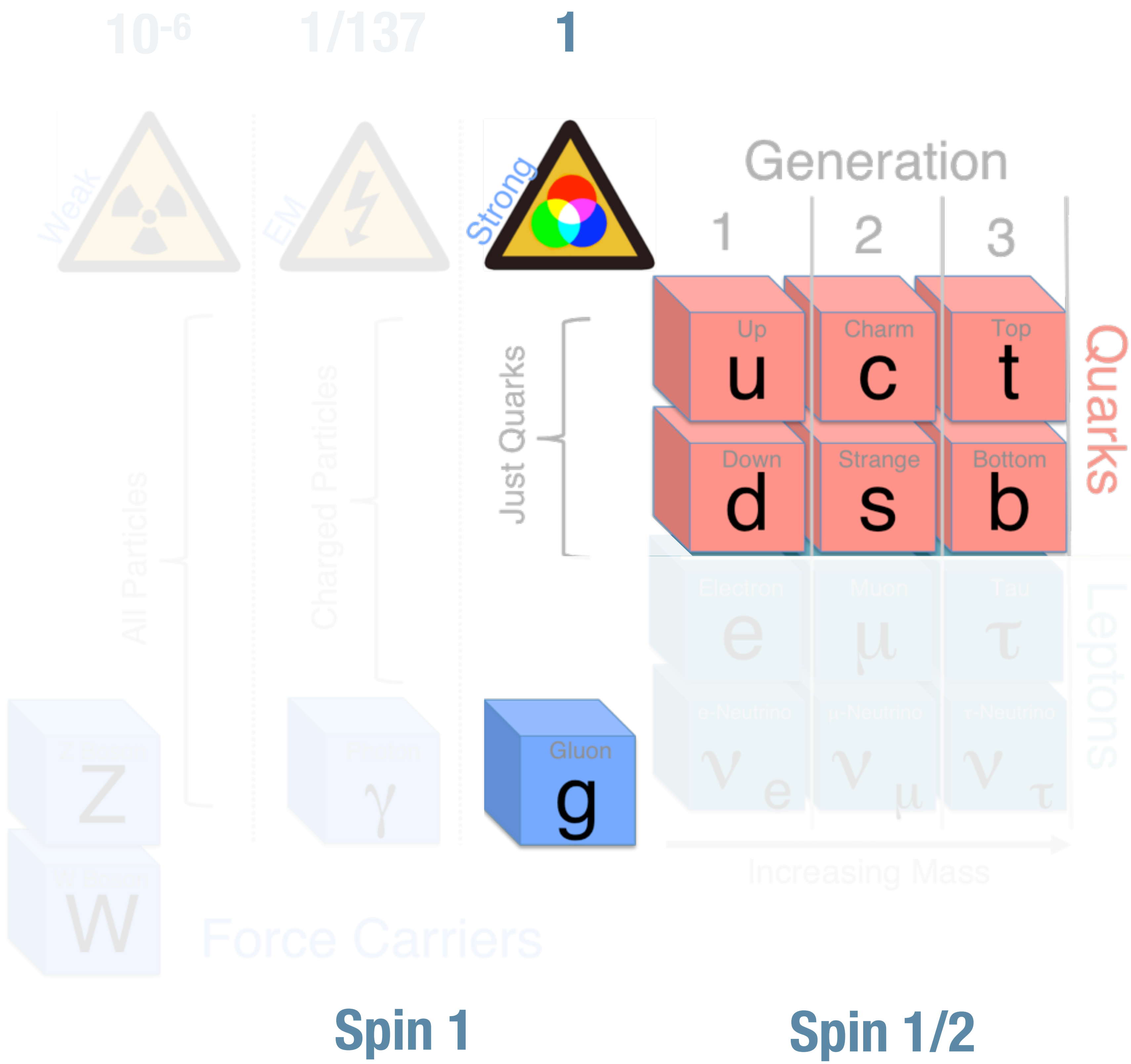
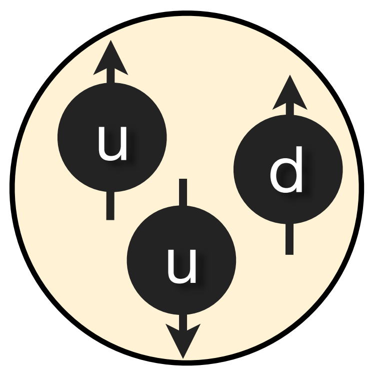


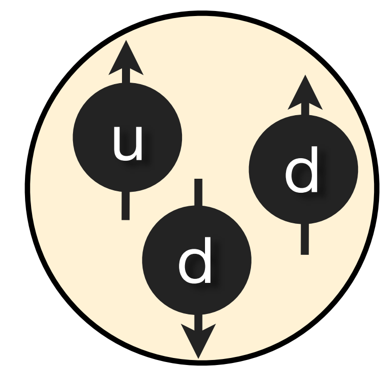
# Quarks and hadrons

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

$$proton = |uud\rangle$$
$$J = 1/2$$




$$neutron = |udd\rangle$$
$$J = 1/2$$



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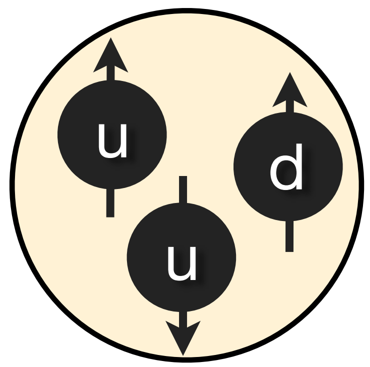
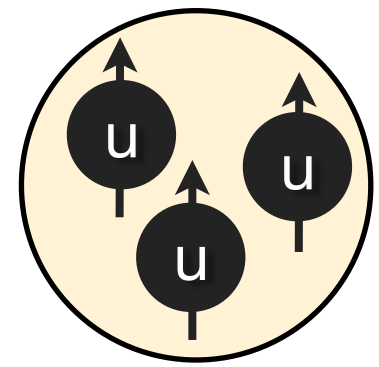



$$\Delta^{++} = |uuu\rangle$$
$$J = 3/2$$



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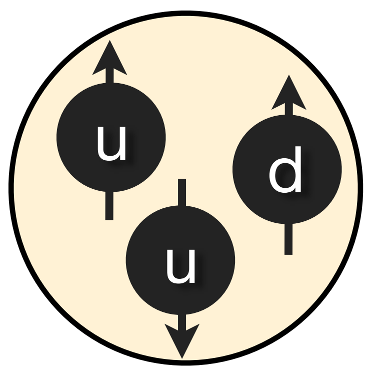


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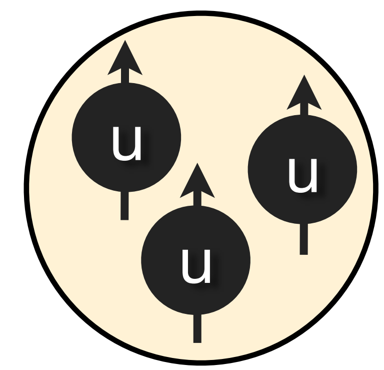


$$\Psi(\Delta^{++}) = \underbrace{\Psi(r)}_{symmetric} \cdot \underbrace{\Psi_{\text{spin}}(J)}_{symmetric} \cdot \underbrace{\Psi_{\text{flavour}}}_{symmetric}$$

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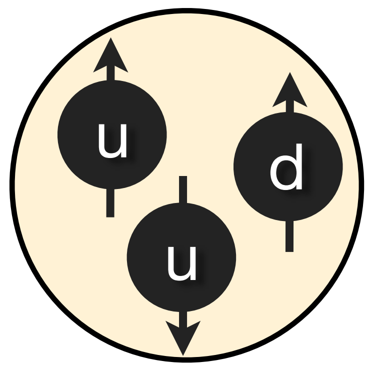


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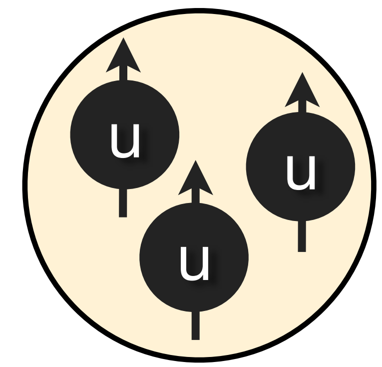


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$$\Psi(\Delta^{++}) = \Psi(r) \cdot \Psi_{\text{spin}}(J) \cdot \Psi_{\text{flavour}} \cdot \Psi_{\text{colour}}$$

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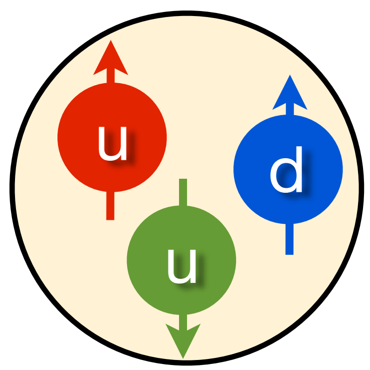


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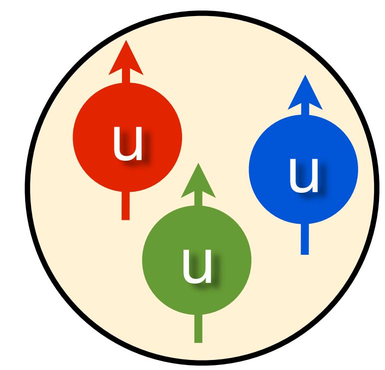


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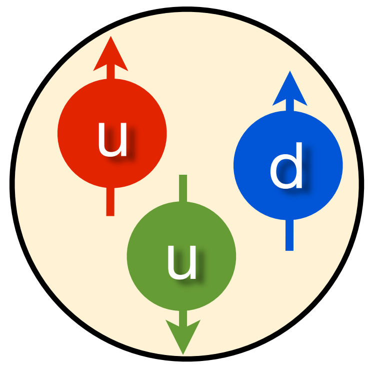


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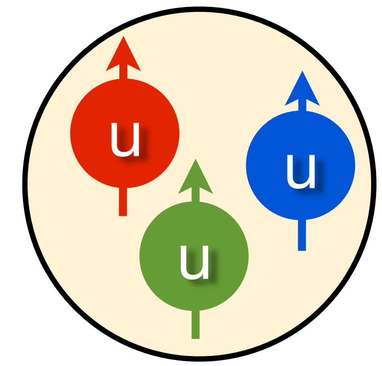
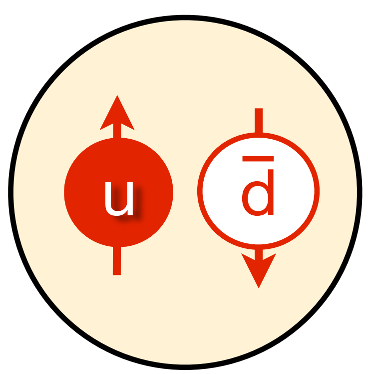
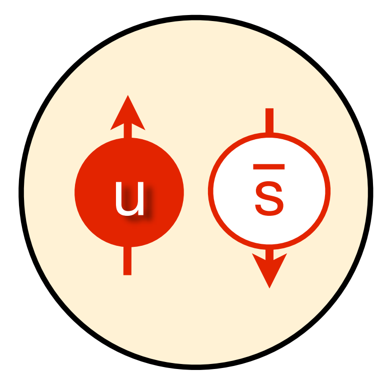



- Color charge analogous to electric charge: atoms are electrically neutral and hadrons are color neutral (or color singlets)
- Another flavor of "light" quarks: **strange**



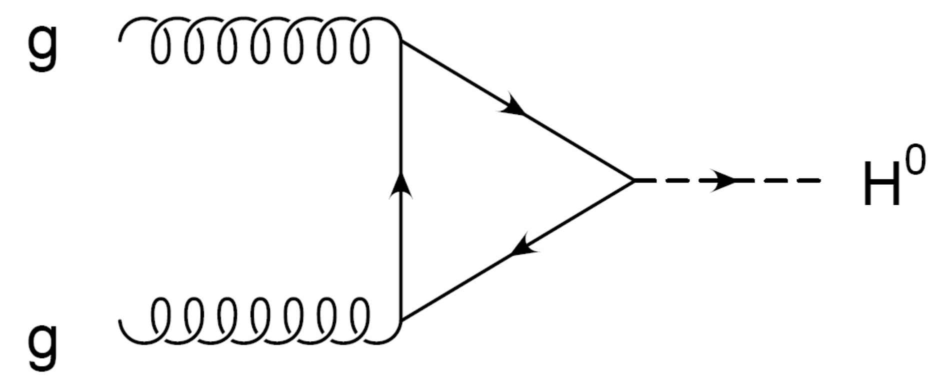

$$\pi^{+} = |u\bar{d}\rangle$$

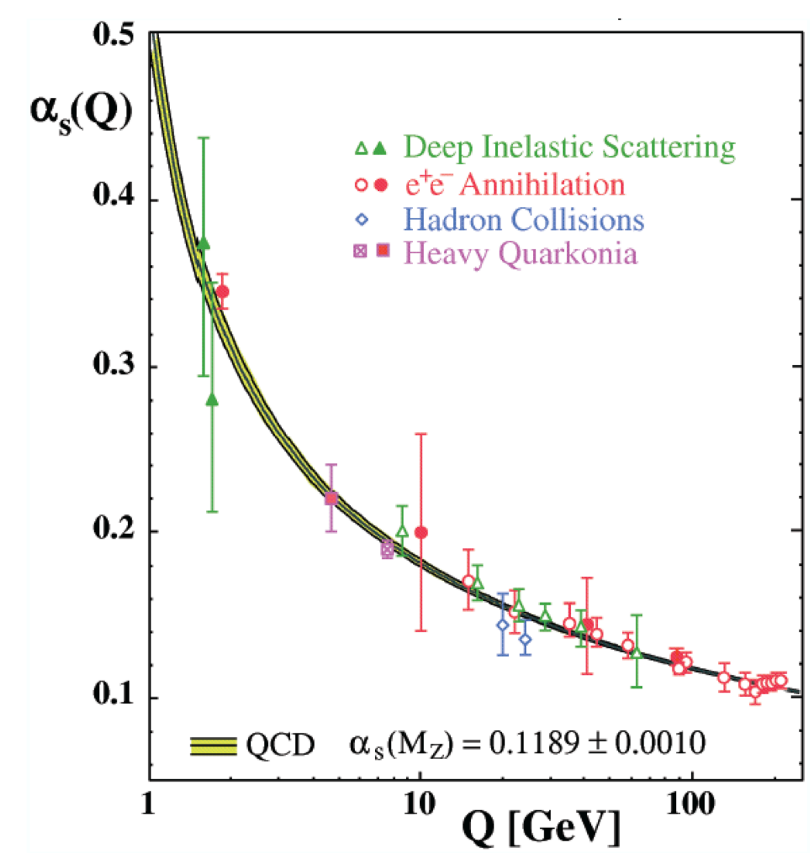



$$K^{+} = |u\bar{s}\rangle$$

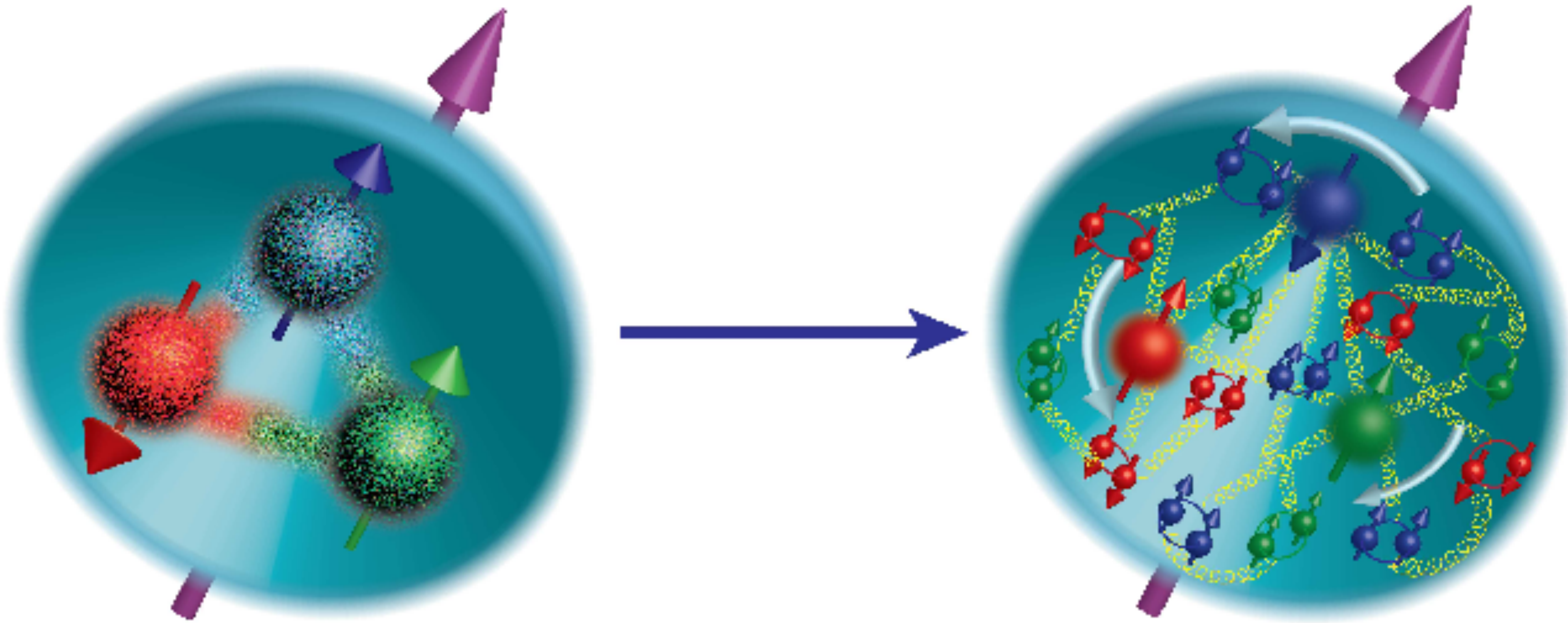
# Color interactions in QCD

- **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



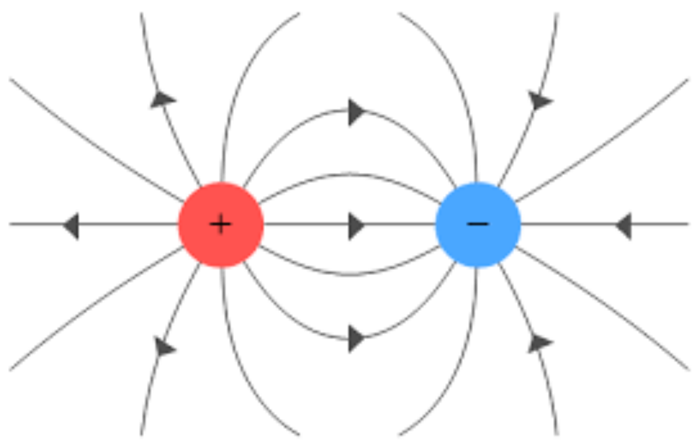



# Aside: what about nucleon structure?

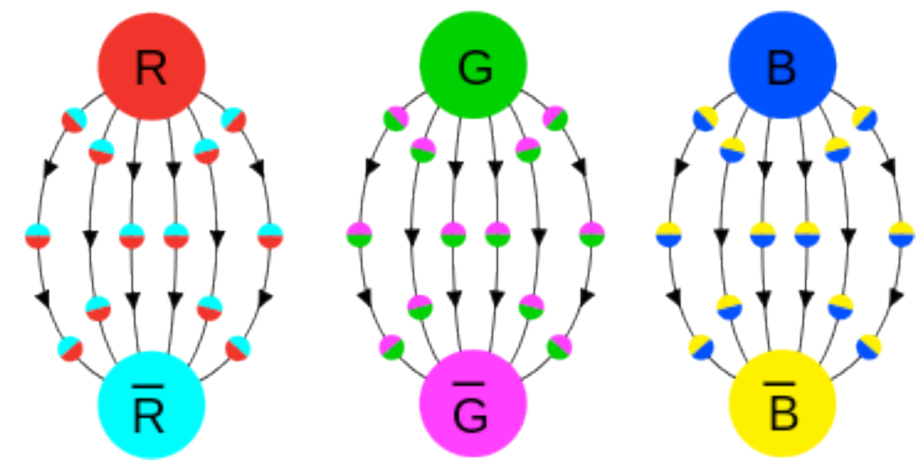


# Comparing E&M and QCD

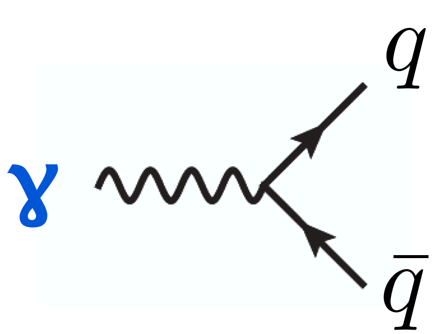
## E&M

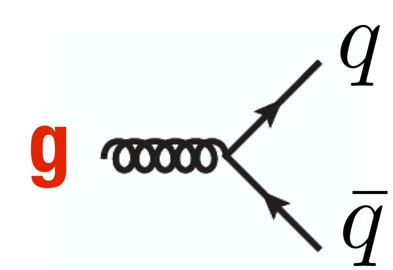


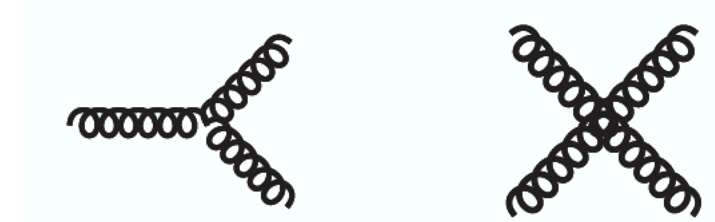

## QCD



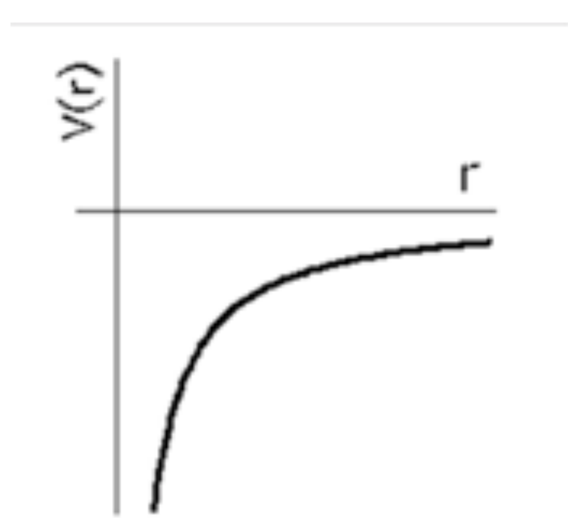

Photons (gluons) mediate forces between electric (color) charges

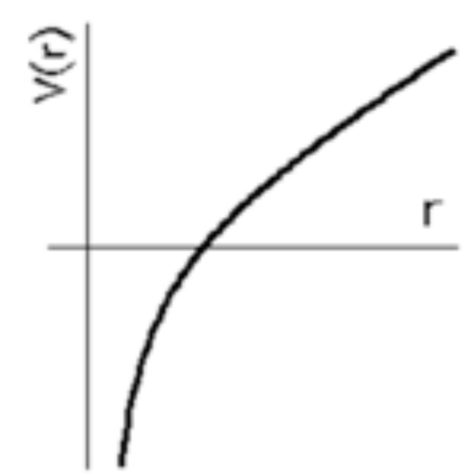


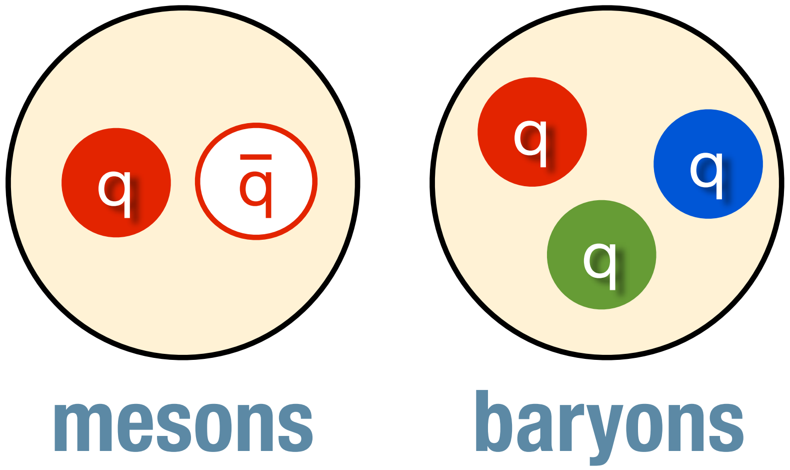



Gluon self-interaction produces a potential that grows ~linearly with distance

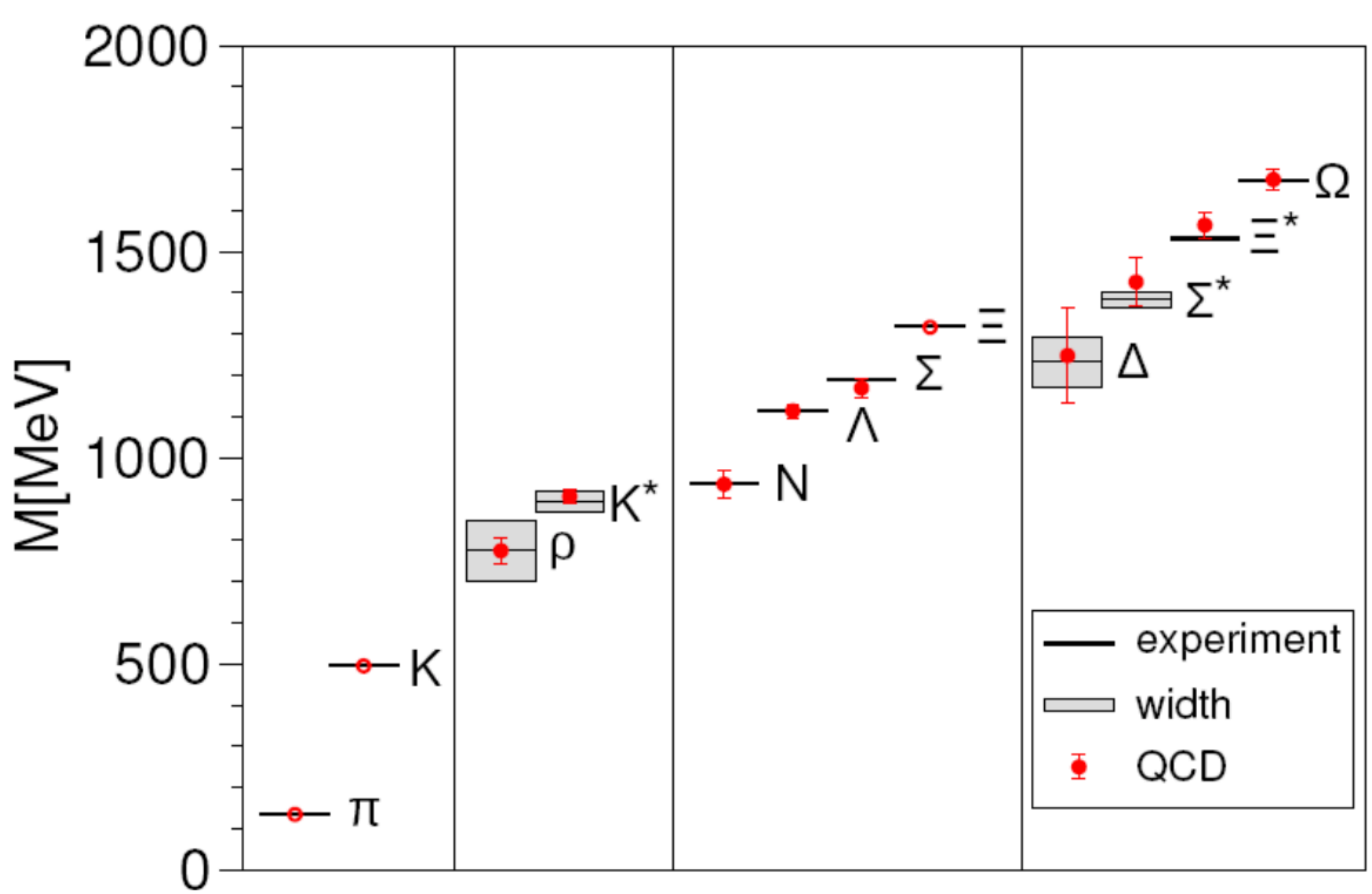


# Confined states of quarks and gluons

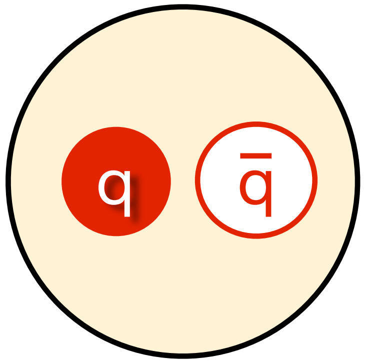



**Observed mesons and baryons well described by 1st principles QCD**

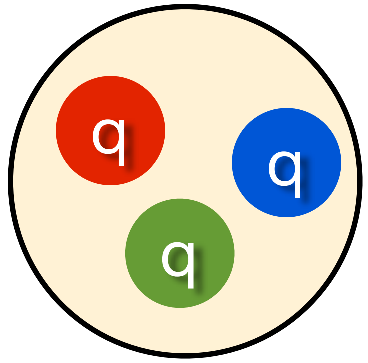



**Lattice QCD: Science (2008)**

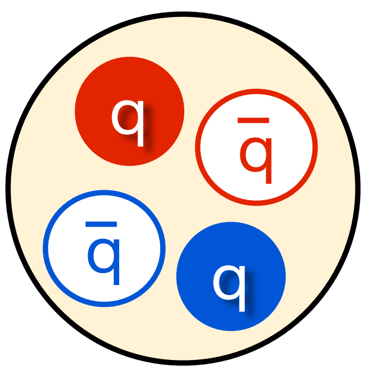
# Confined states of quarks and gluons



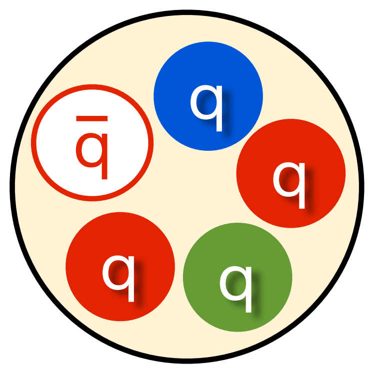

**mesons**




**baryons**




**tetraquark**




**pentaquark**

**Observed mesons and baryons well described by 1st principles QCD**

**But these aren't the only states permitted by QCD**

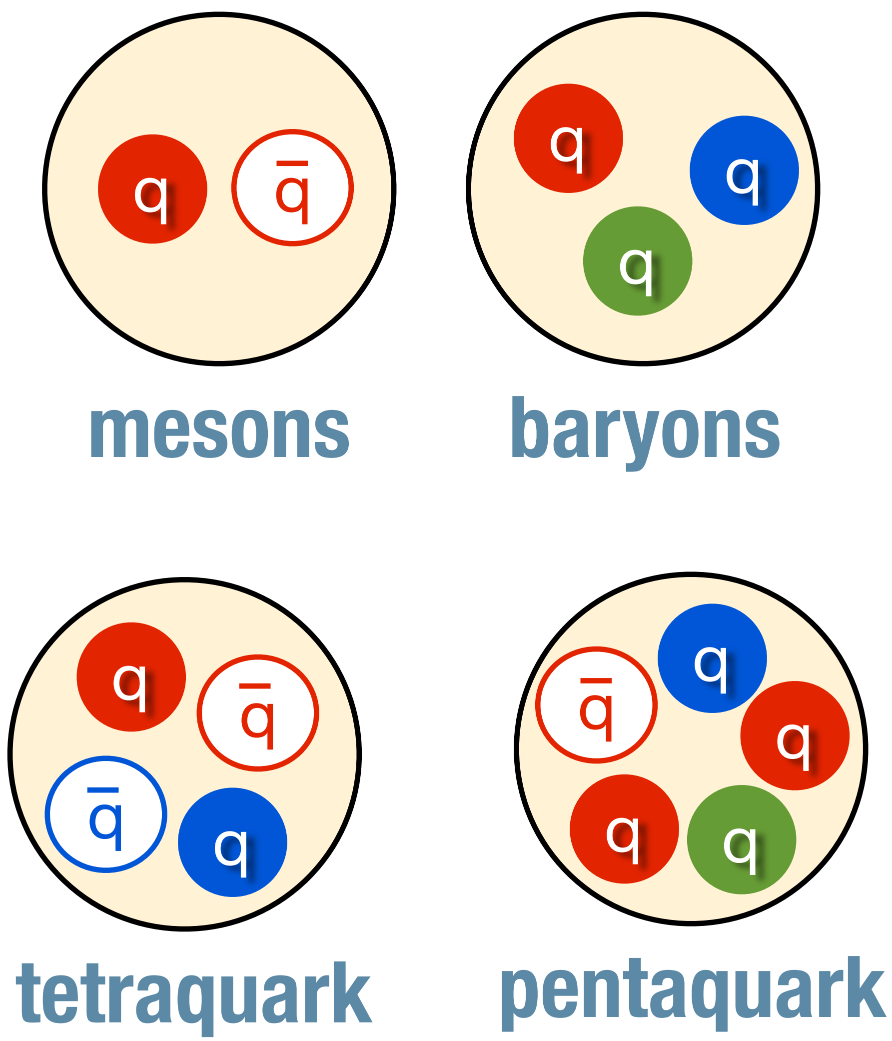
A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

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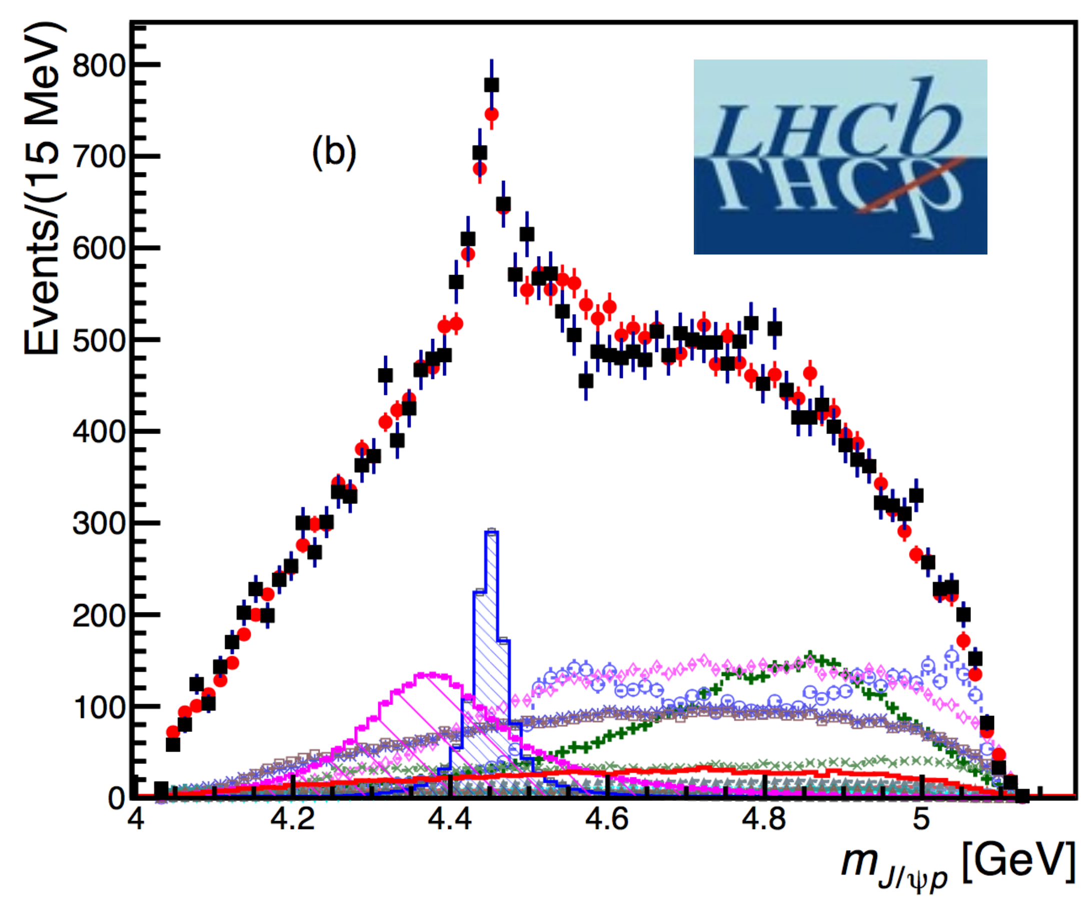
$$\Lambda_b \to J/\psi p K^-$$



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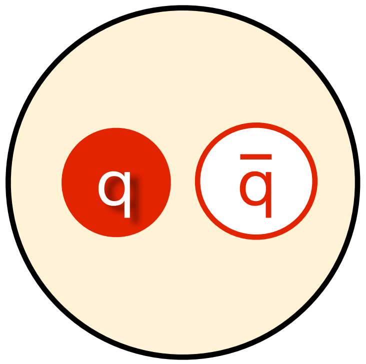


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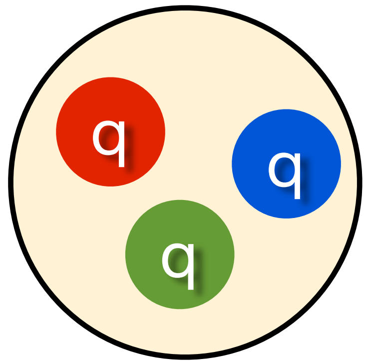


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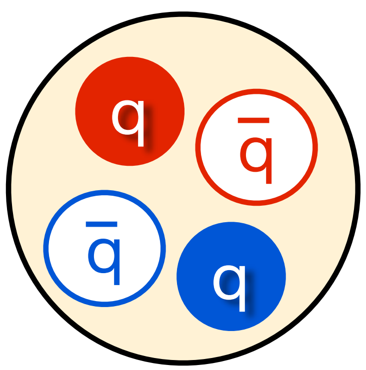


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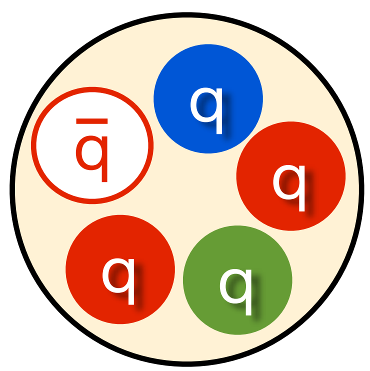
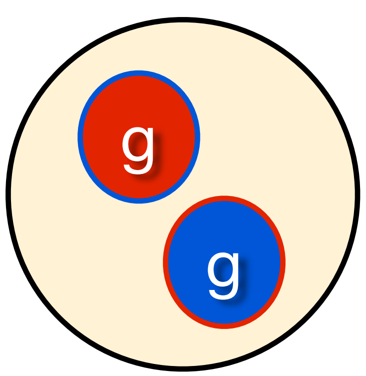
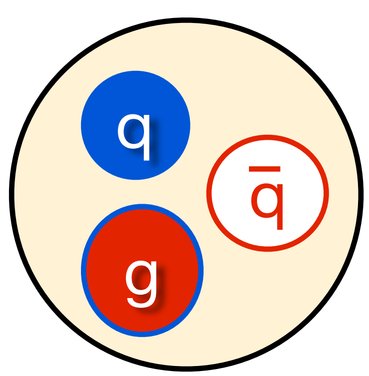



pentaquark



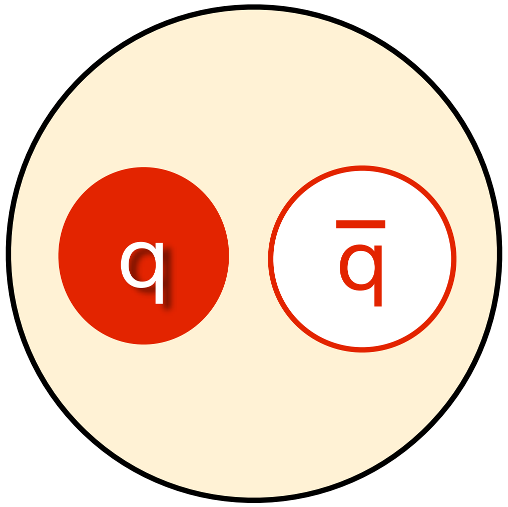

glueball




hybrid meson

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

# Classifying mesons




- General properties: mass, electric charge, quark flavor
- Grouped by quantum numbers: $J^{PC}$
  - Angular momentum: $\vec{J} = \vec{L} + \vec{S}$
  - Parity: Invert spatial coordinates

$$P = (-1)^{L+1}$$

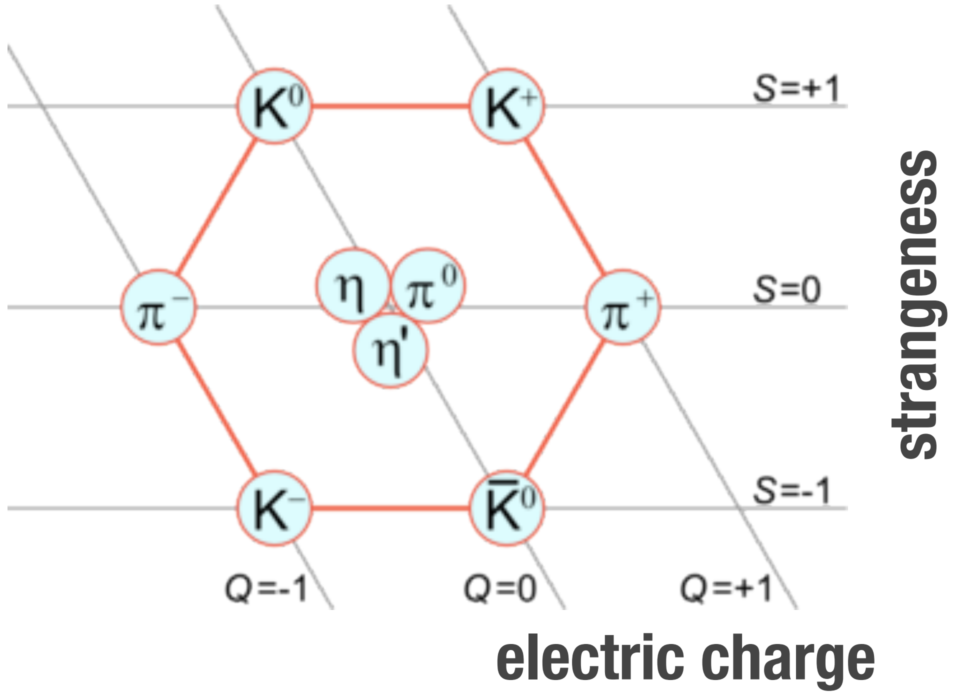
  - Charge conj.: particle ↔ antiparticle

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

- Allowed **J^PC** for $q\bar{q}$ mesons:

$$J^{PC} = 0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 2^{++} ...$$

**Spin 0**



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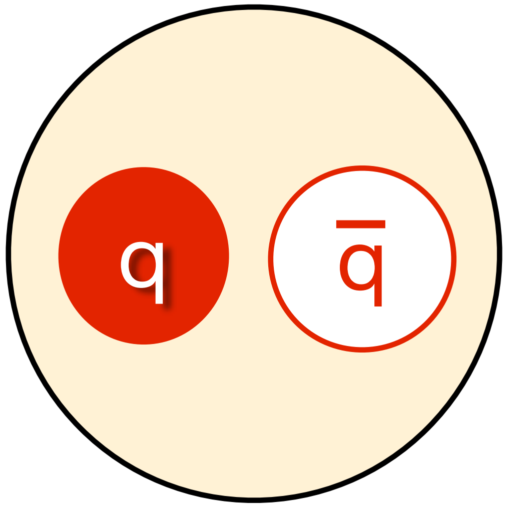
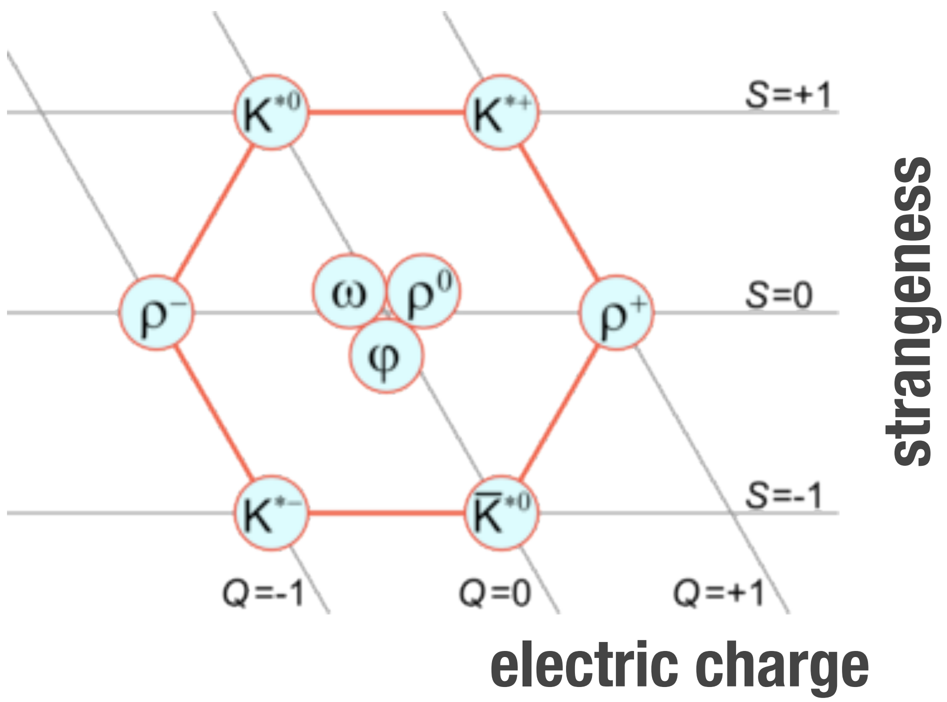
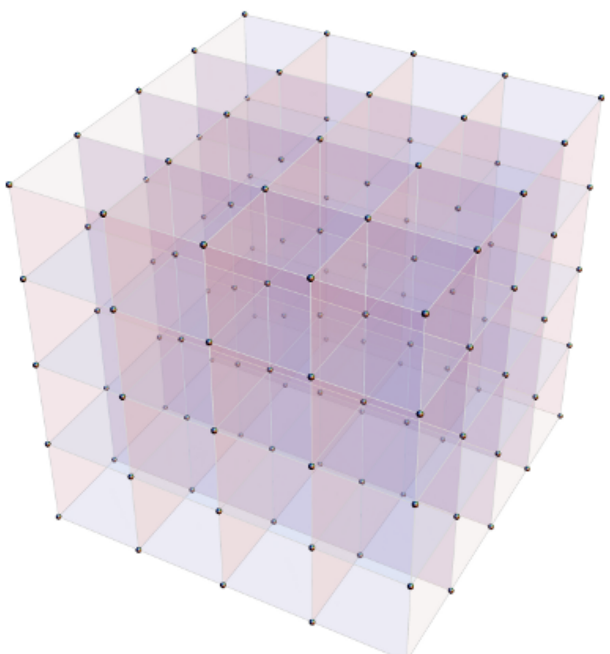


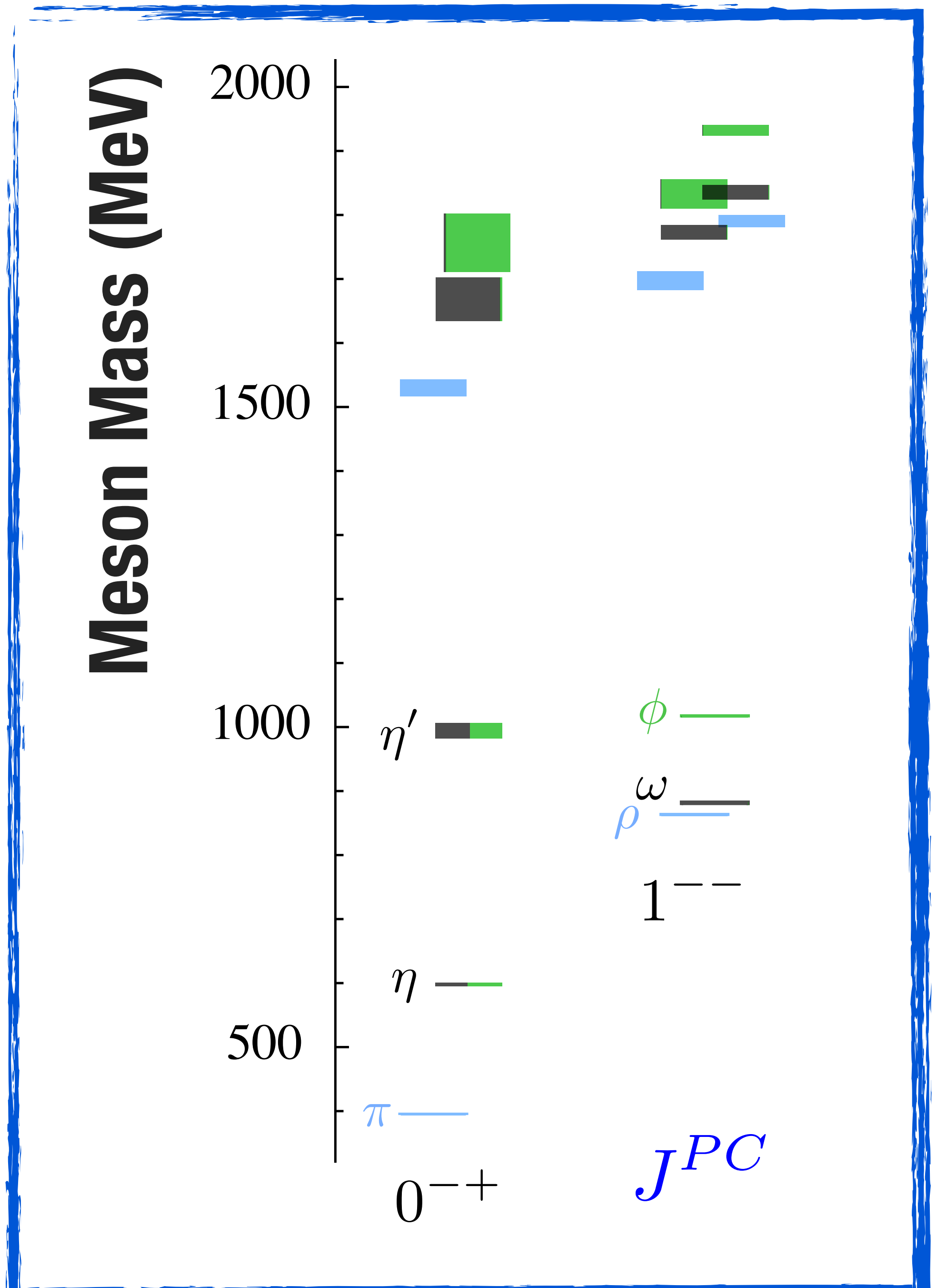

**Spin 1**



# Lattice QCD spectrum

Dudek et al. PRD 88 (2013) 094505






$u\bar{u} + d\bar{d}$

$s\bar{s}$

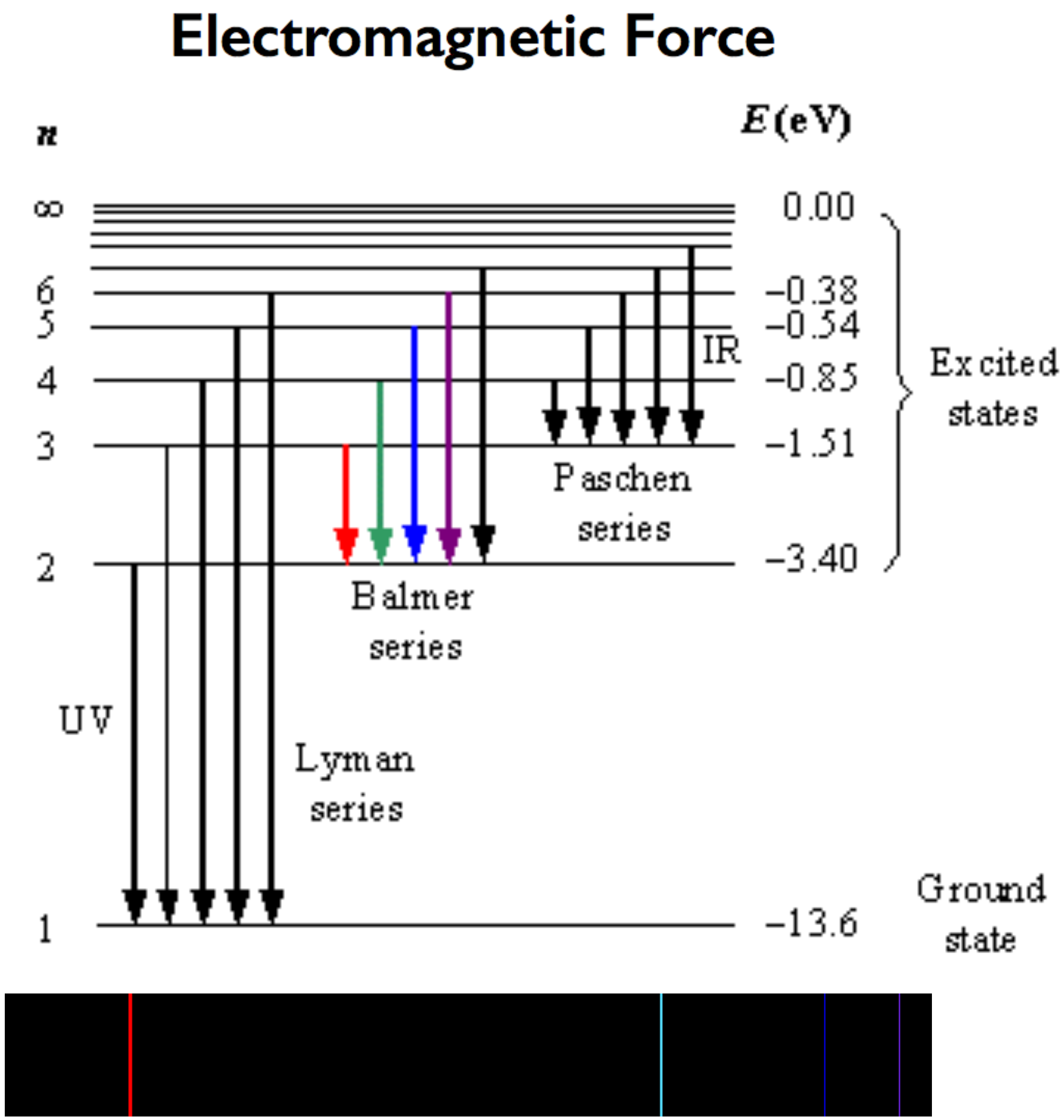
$\pi^0 = |u\bar{u} - d\bar{d}\rangle$

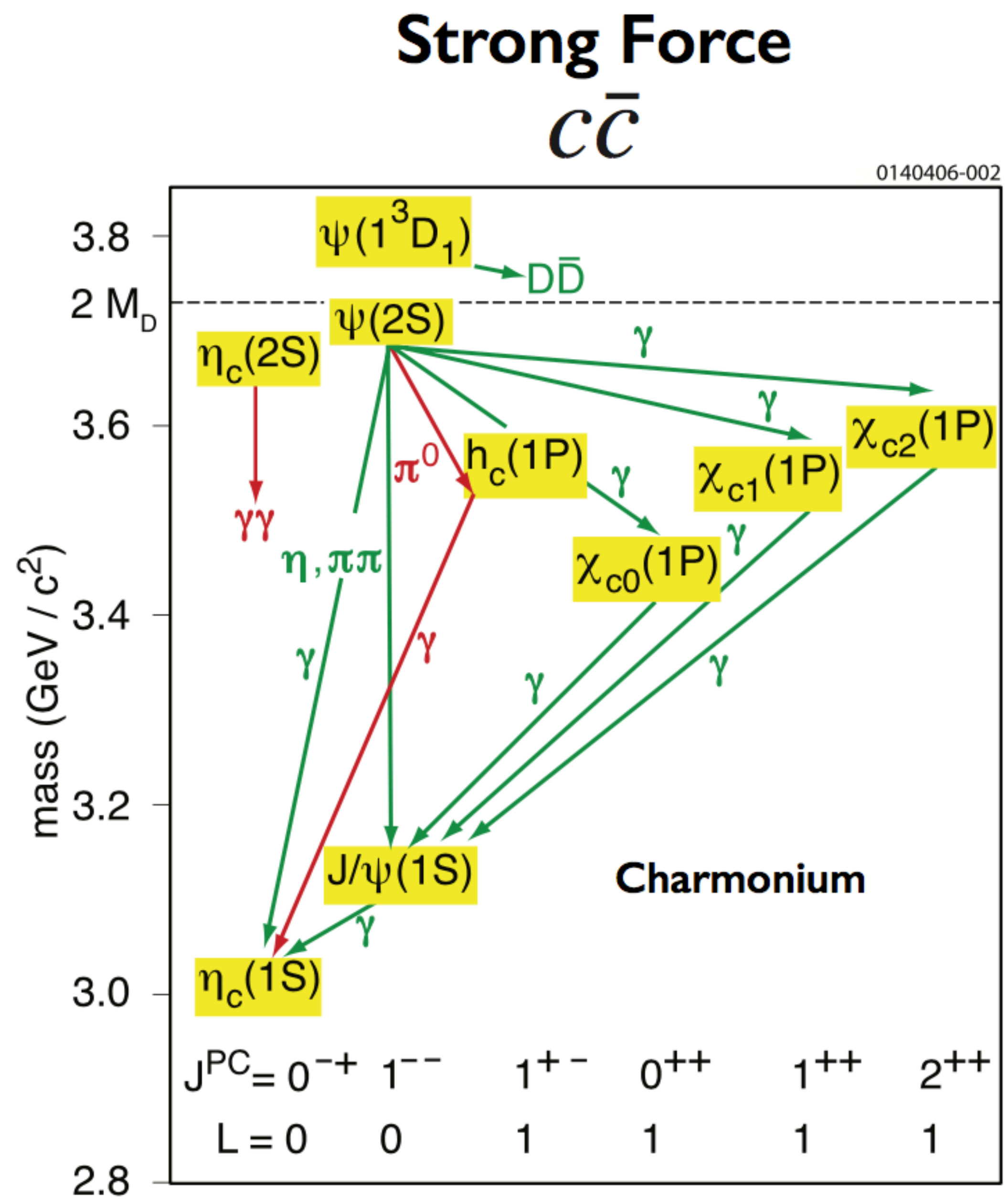
$\phi = |s\bar{s}\rangle$

$\omega = |u\bar{u} + d\bar{d}\rangle$

**Note:** $m_\pi = 392\,\mathrm{MeV}$

# "Conventional" charmonium



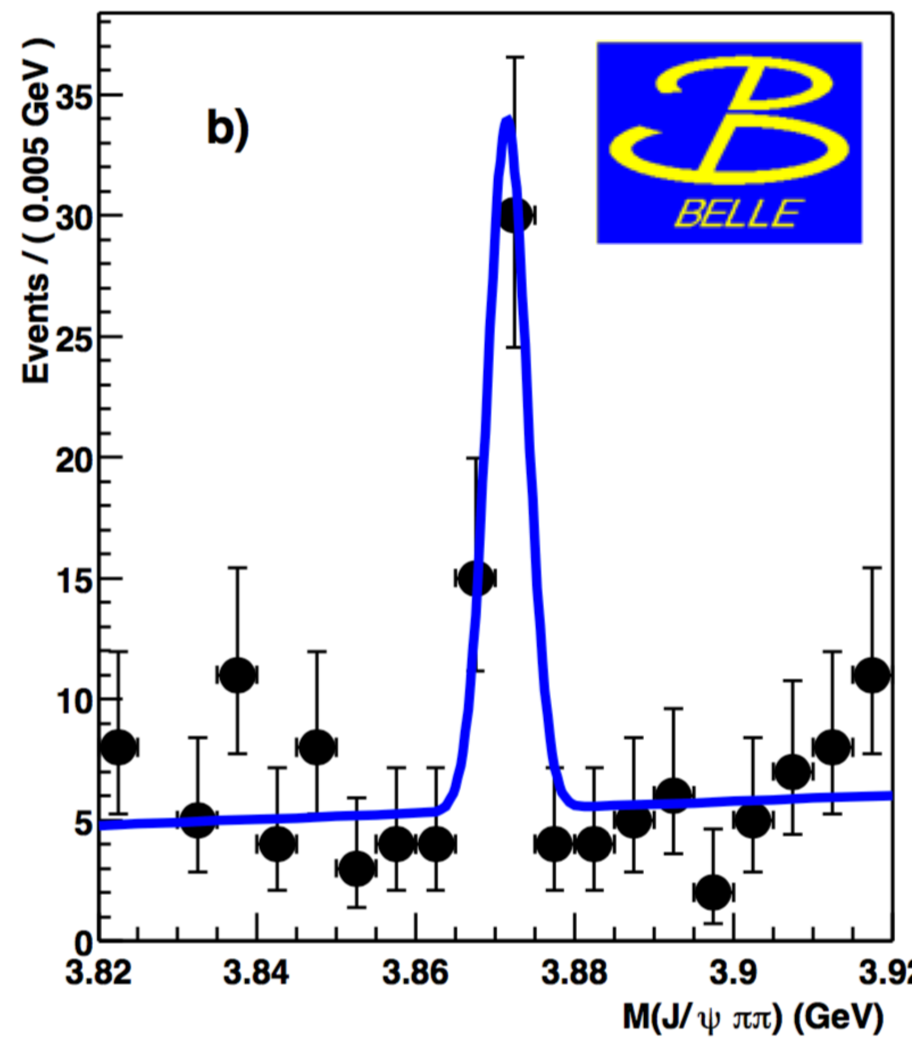




**"Simple" $c\bar{c}$ spectrum well described by quark model expectation with expected electromagnetic transitions**

# Experimental strategy

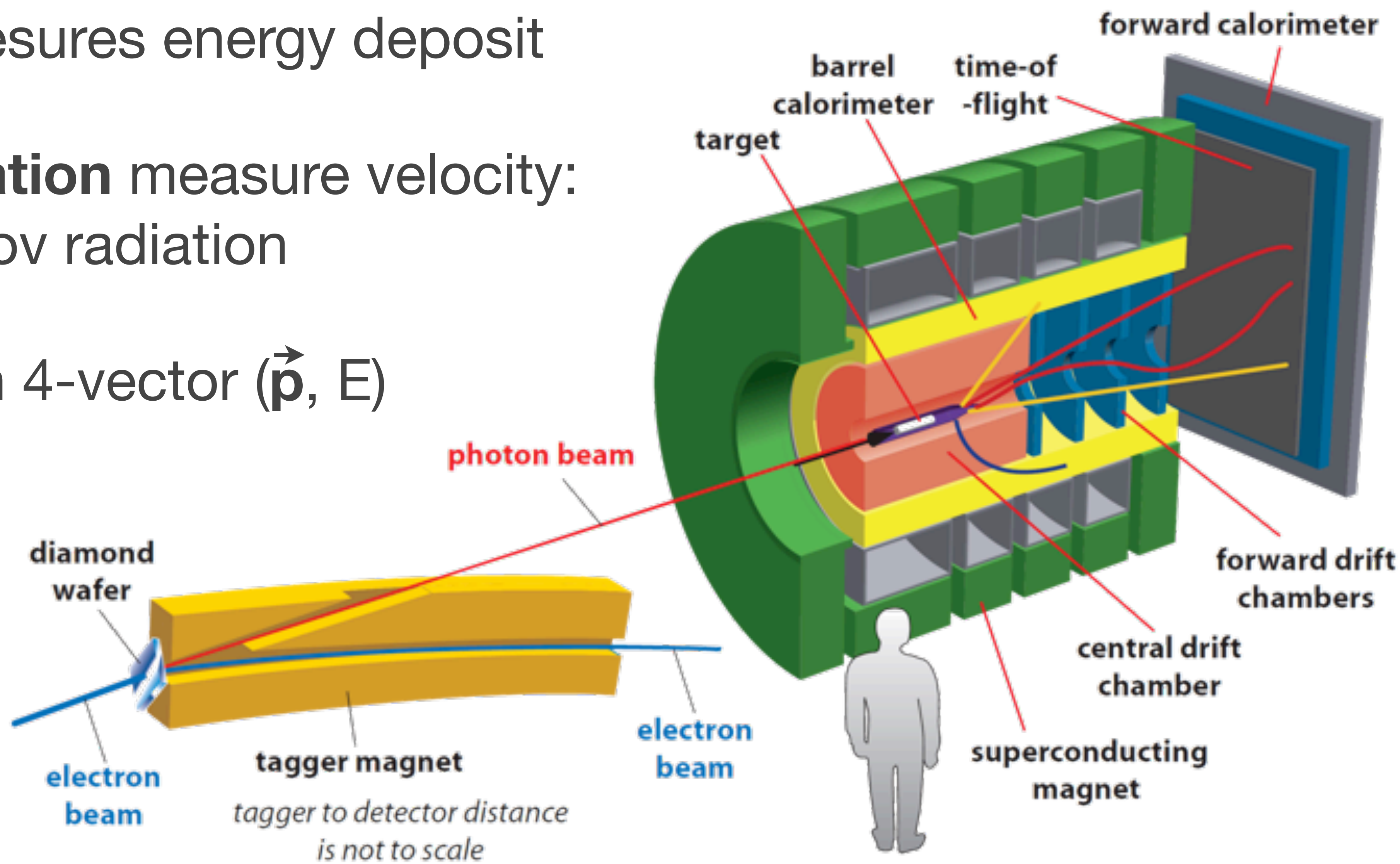
- **Search for new particles**
  - Bumps in mass spectra
  - Unique decay distributions
- **Next measure:**
  - mass and width
  - decay modes
  - quantum numbers: $J^{PC}$
- Identify **patterns** and compare with QCD and models

$$B \to K X$$
$$X \to \pi^+ \pi^- J/\psi$$

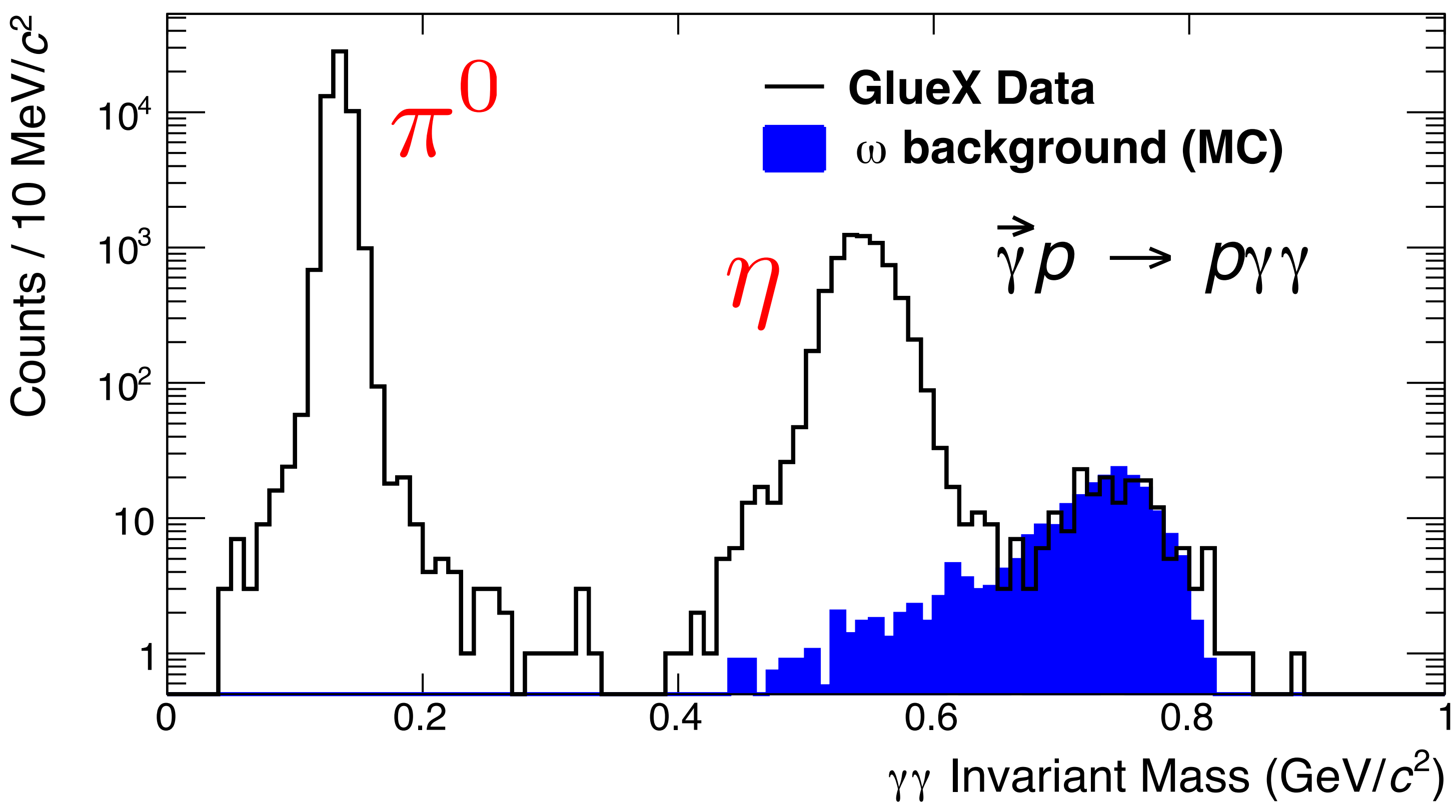


# Detection strategy

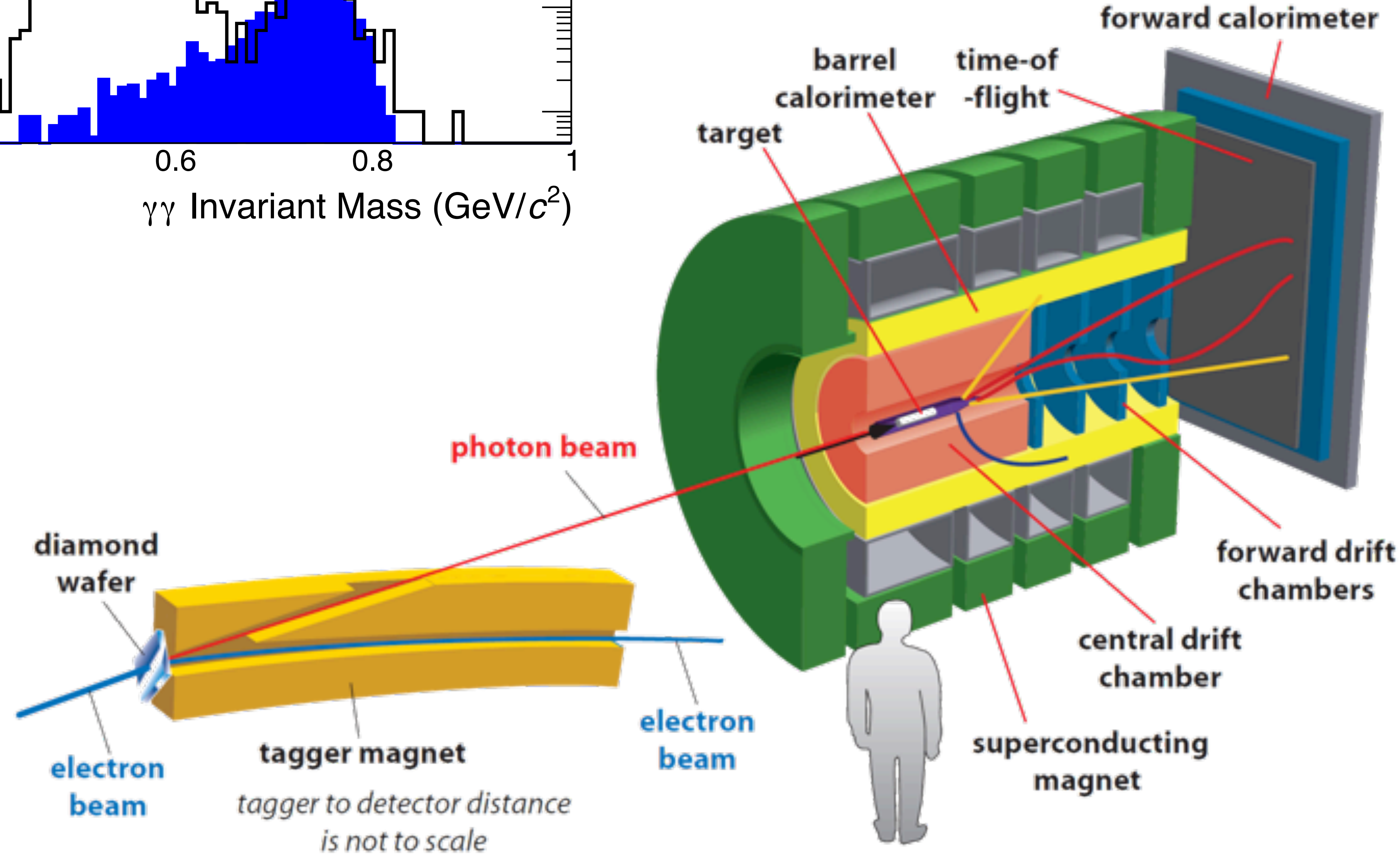
- **Charged particles ($\pi^{\pm}$, $K^{\pm}$, p)**
  - Momentum of "track" through ionization
- **Neutral particles ($\gamma$, n, $K_L$)**
  - Calorimeter mesures energy deposit
- **Particle identification** measure velocity: timing or Cherenkov radiation
- Combine to obtain 4-vector ($\vec{p}$, E)



# Detection strategy



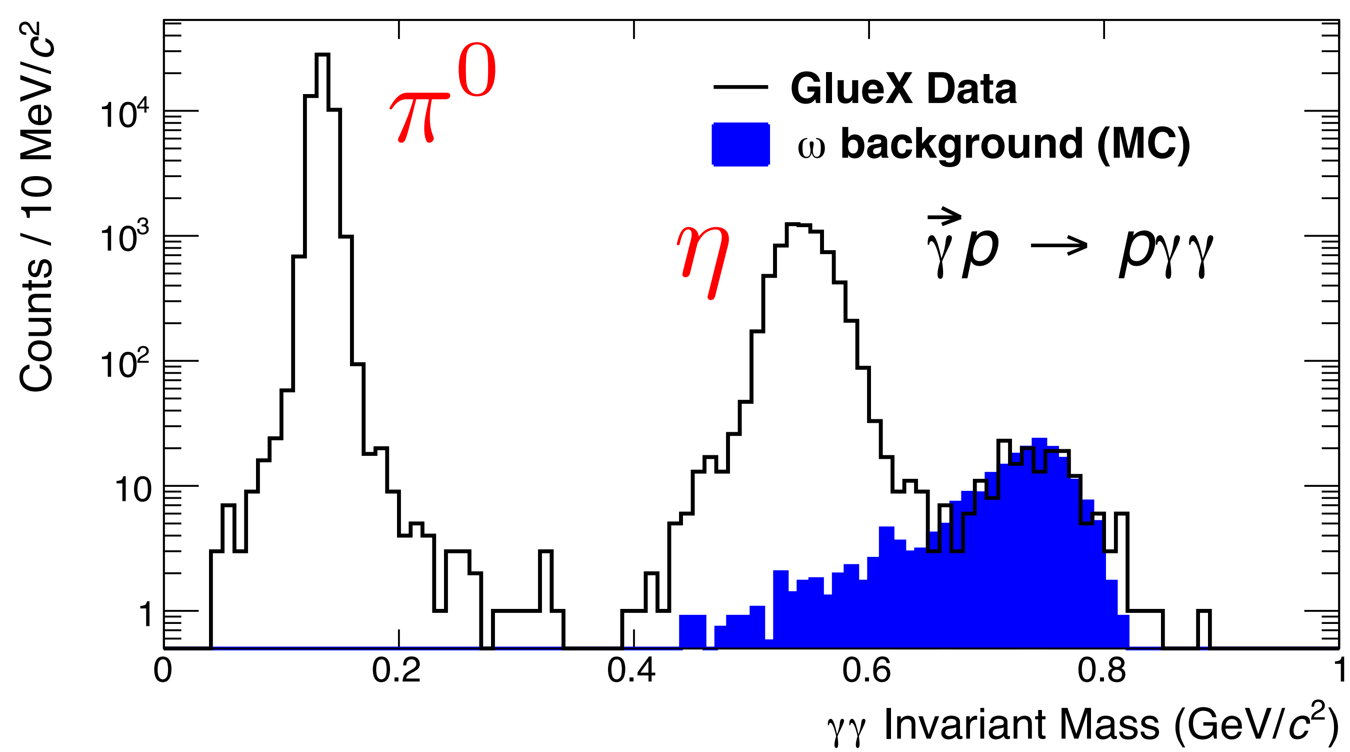

$$\gamma p \longrightarrow p\gamma\gamma$$



# Decays: Width and Branching Ratios

- Decay width: $\Gamma_{tot} = \Sigma \Gamma_i$
  - Related to lifetime of particle: $\Gamma_{tot} = h/\tau$
- What can we measure?
  - Breit-Wigner resonance width, however difficult to separate from experimental resolution

$$\Gamma_{\pi^0} \sim 8 \text{ eV}$$



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  - Breit-Wigner resonance width
  - Branching ratios: $B_i = \Gamma_i/\Gamma_{tot}$

**$f_2(1270)$ DECAY MODES**

| | Mode | Fraction ($\Gamma_i/\Gamma$) | Scale factor/ Confidence level |
|---|---|---|---|
| $\Gamma_1$ | $\pi\pi$ | $(84.2 {}^{+2.9}_{-0.9})$ % | S=1.1 |
| $\Gamma_2$ | $\pi^+\pi^-2\pi^0$ | $(7.7 {}^{+1.1}_{-3.2})$ % | S=1.2 |
| $\Gamma_3$ | $K\overline{K}$ | $(4.6 {}^{+0.5}_{-0.4})$ % | S=2.7 |

# Spectroscopy: a global endeavor

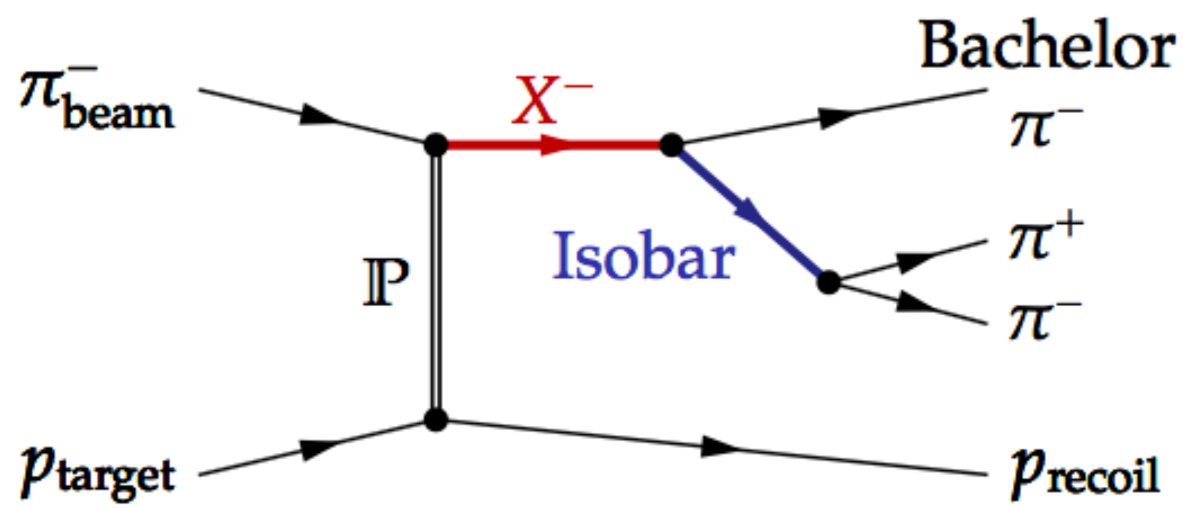
| | Heavy quarks | Light quarks |
|---|---|---|
| Electromagnetic probes | $e^+e^-$<br>BaBar, BESIII<br>BELLE, Belle II | $\gamma p$<br>CLAS12, GlueX<br>clas (CEBAF Large Acceptance Spectrometer) |
| Hadronic probes | $\bar{p}p$: DØ, CDF II<br>$pp$: CMS, ATLAS, LHCb | $\bar{p}p$: panda<br>$\pi p$: COMPASS |

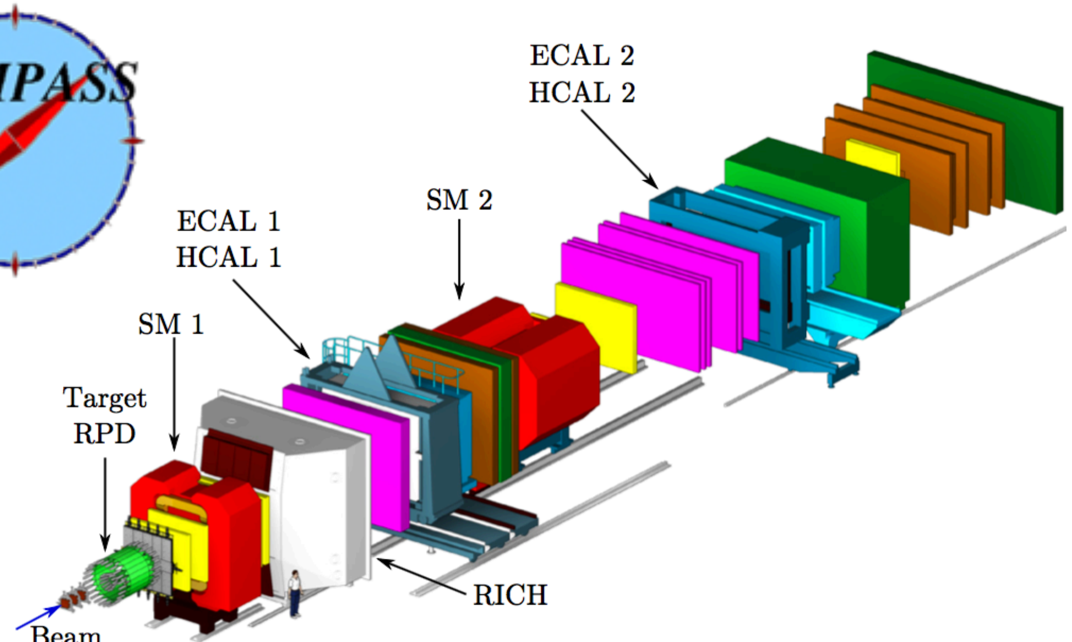
# Light quark experiments

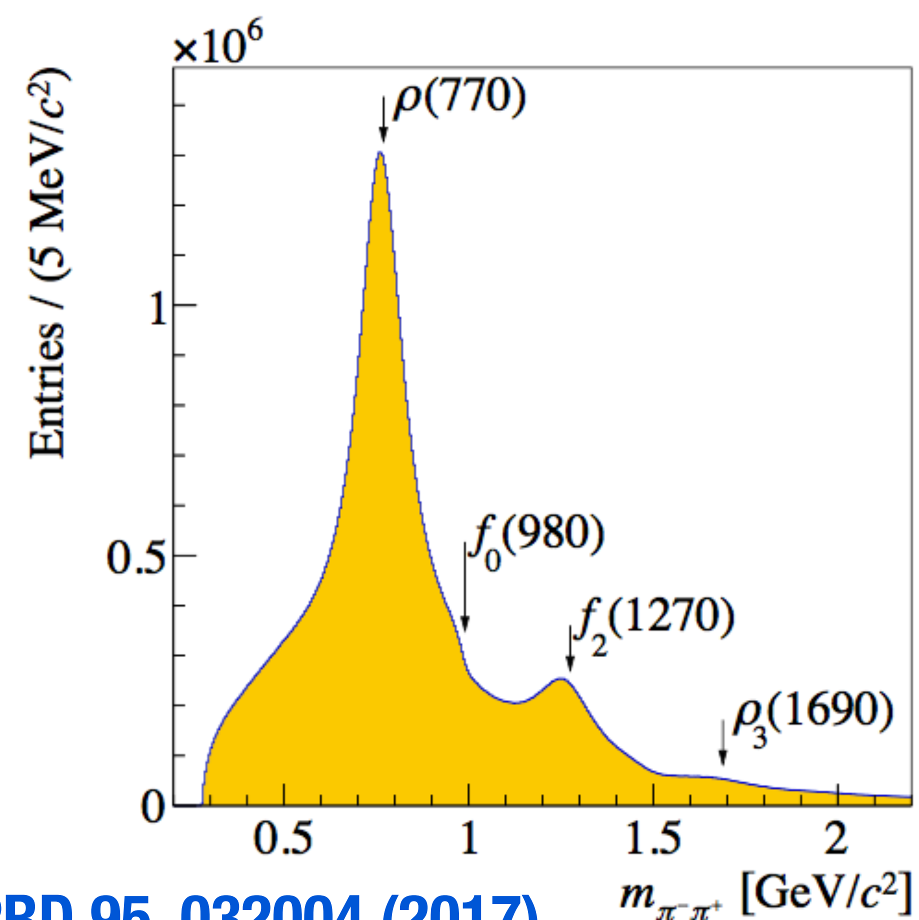
| | Heavy quarks | **Light quarks** |
|---|---|---|
| Electromagnetic probes | $e^+e^-$<br>BaBar, BESIII, BELLE, Belle II | $\gamma p$<br>CLAS12, GlueX, clas (CEBAF Large Acceptance Spectrometer) |
| Hadronic probes | $\bar{p}p$: DØ, CDF II<br>$pp$: CMS, ATLAS, LHCb | $\bar{p}p$: panda<br>$\pi p$: COMPASS |

# Compass: Diffractive πp scattering

- Long history of hadron spectroscopy in pion production experiments
- Rich structure in $\pi^-\pi^+\pi^-$ spectrum, modeled as intermediate resonances ***X*⁻** and $\pi^+\pi^-$ **Isobars**



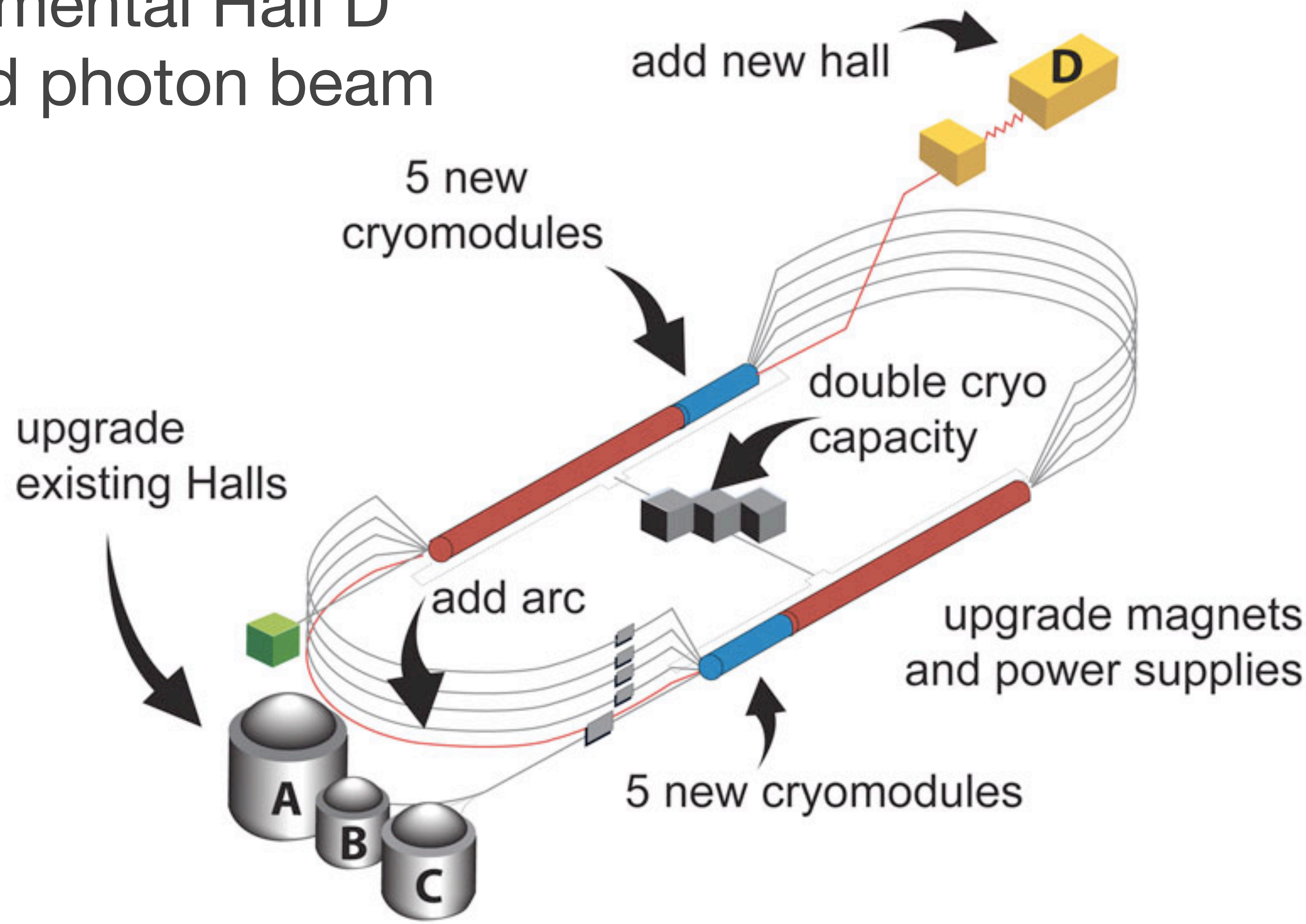




Compass: PRD 95, 032004 (2017)

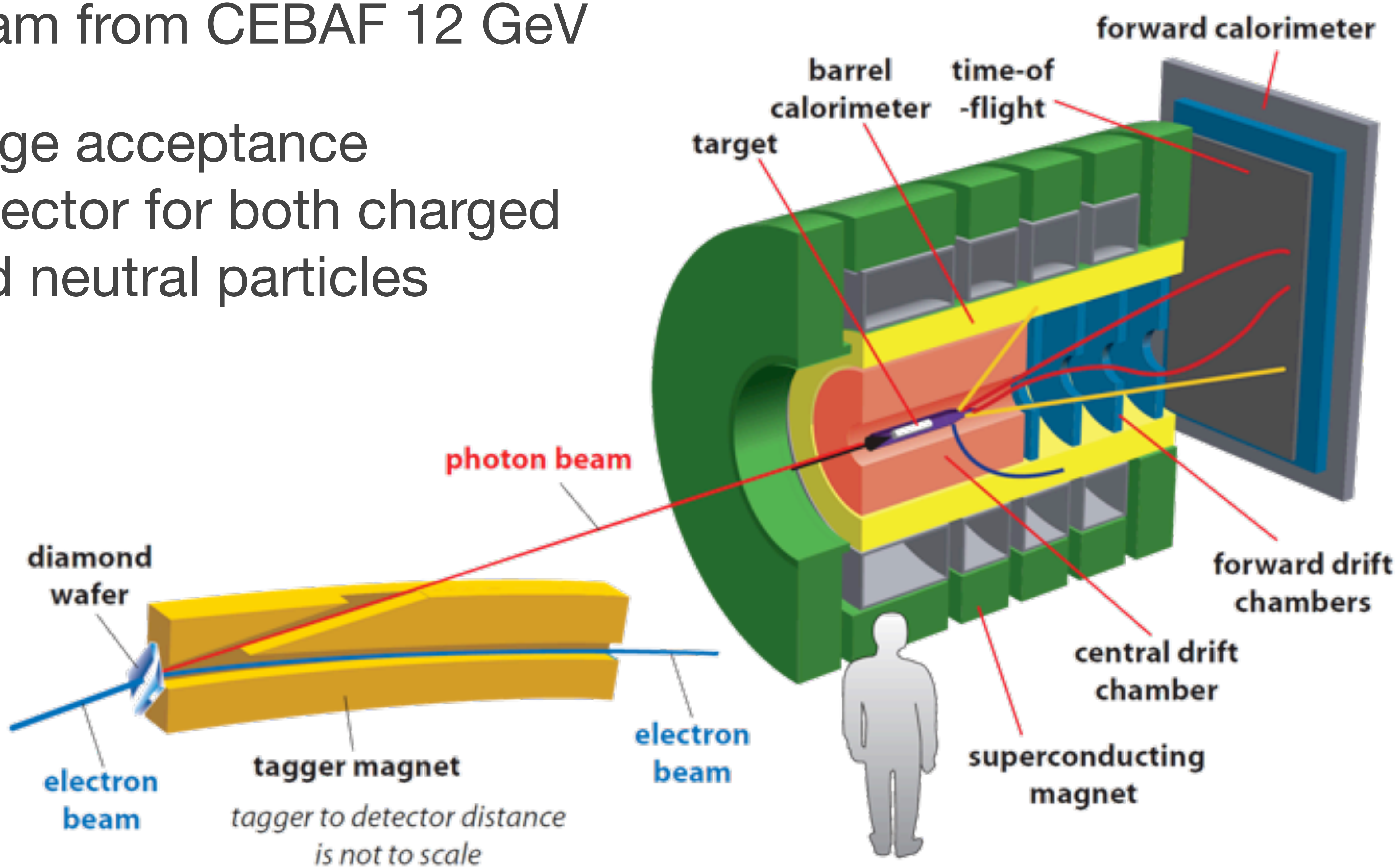
# Jefferson Lab 12 GeV Upgrade

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



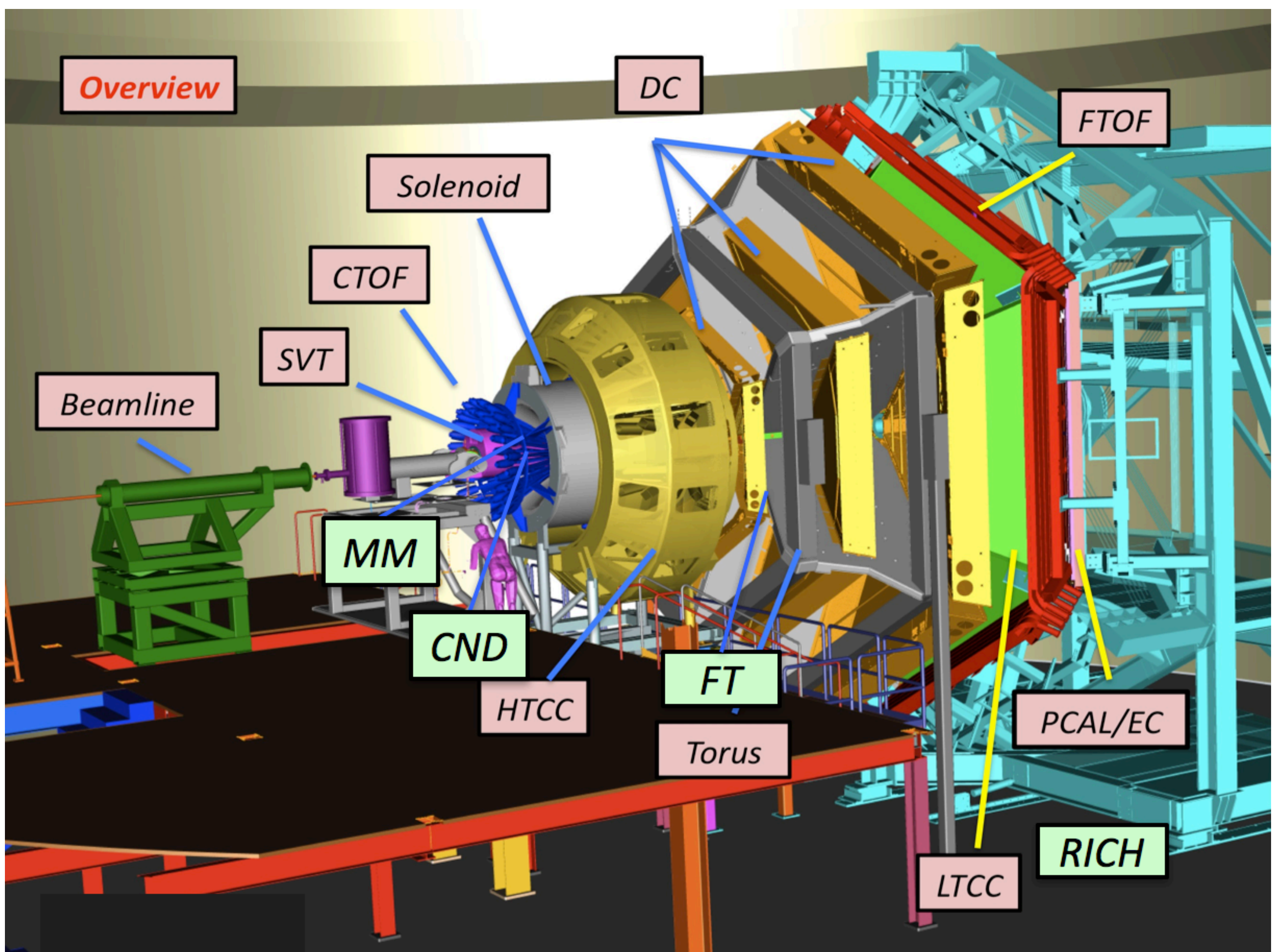
# GlueX in Hall D

- Linearly polarized photon beam from CEBAF 12 GeV
- Large acceptance detector for both charged and neutral particles

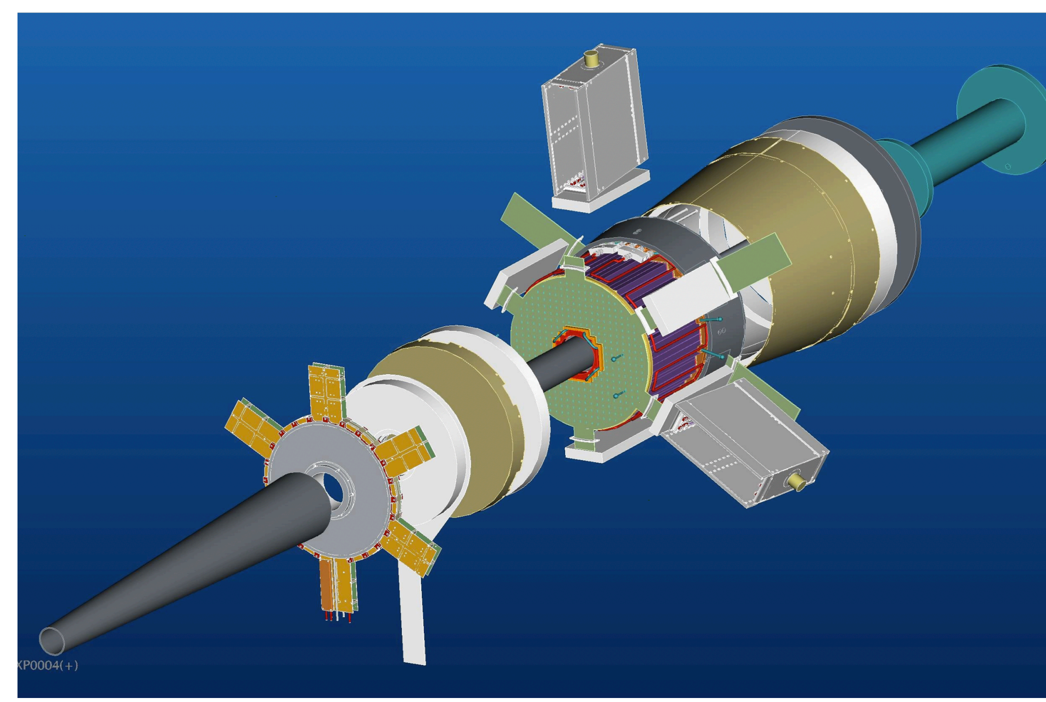


# CLAS12 in Hall B

- CEBAF delivers 11 GeV electron beam to Hall B
  - Linearly polarized photons through quasi-real photoproduction
  - Electron scattering provides access to hybrid baryons




**Forward Tagger (FT)**

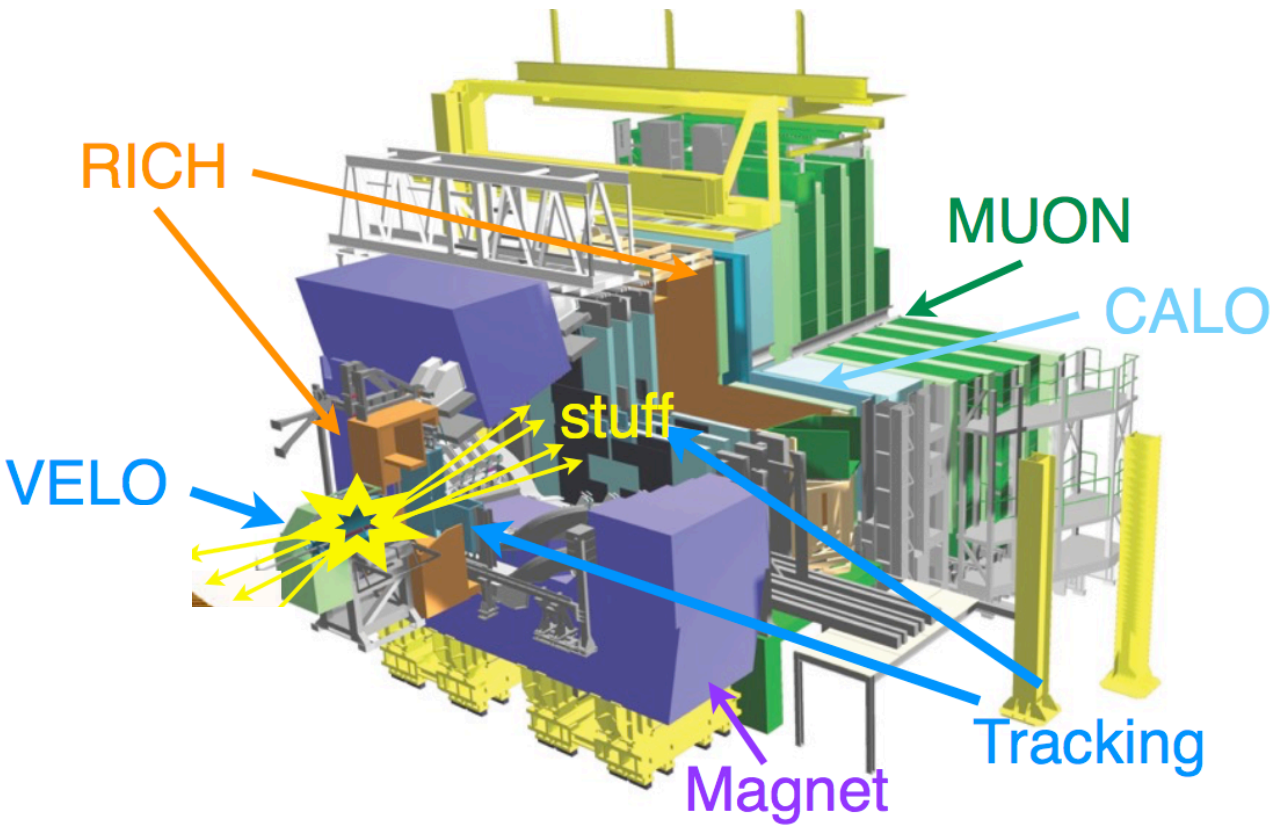


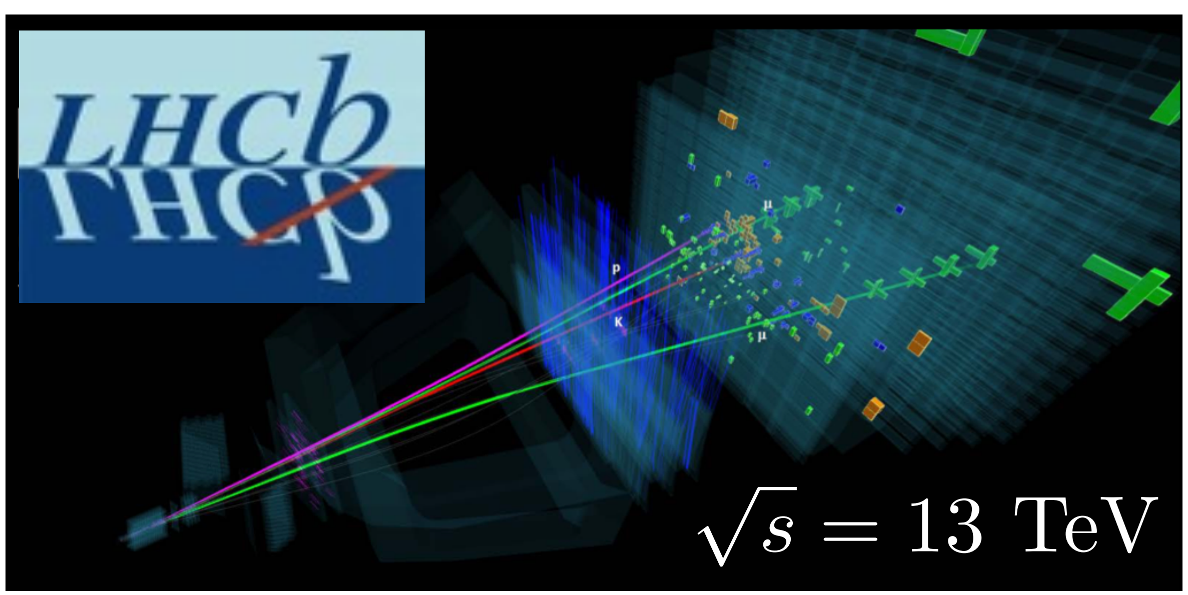
# Heavy quark experiments

| | Heavy quarks | Light quarks |
|---|---|---|
| Electromagnetic probes | $e^+e^-$: BABAR, BESIII, BELLE, Belle II | $\gamma p$: CLAS12, GlueX, clas (CEBAF Large Acceptance Spectrometer) |
| Hadronic probes | $\bar{p}p$: DØ, CDF II; $pp$: CMS, ATLAS, LHCb | $\bar{p}p$: $\bar{\text{p}}$anda; $\pi p$: COMPASS |

# Heavy quark production and detection

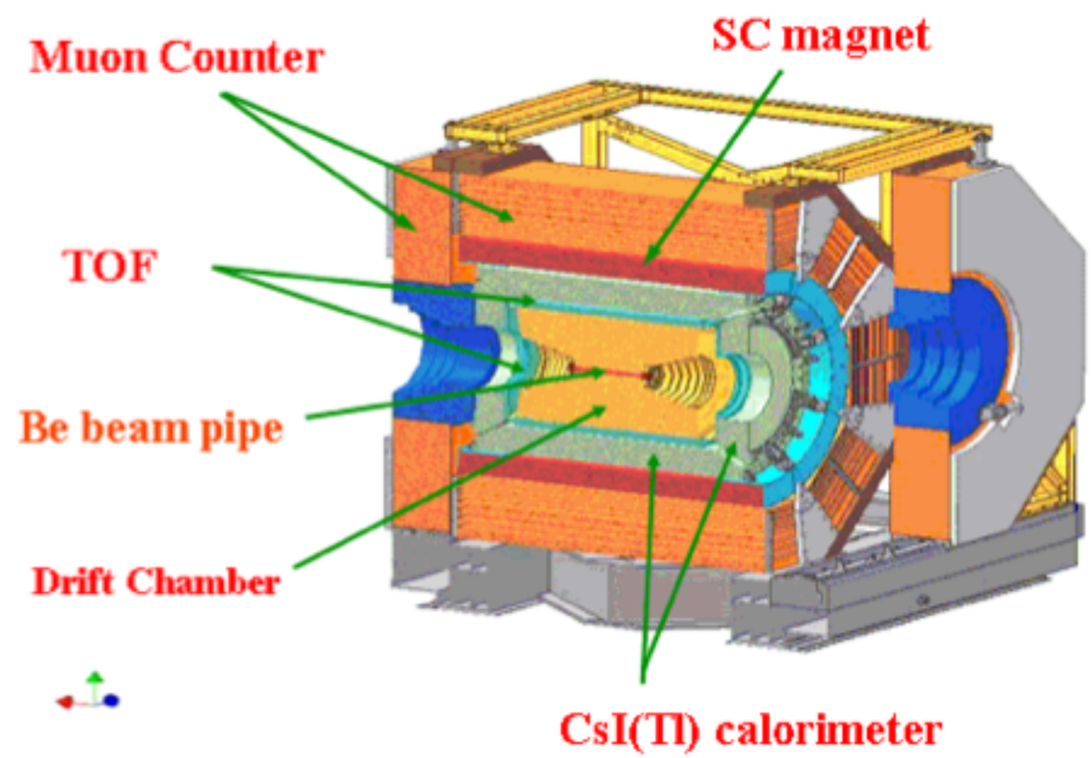
Inclusive: $pp \to BX$ or $\Lambda_B X$



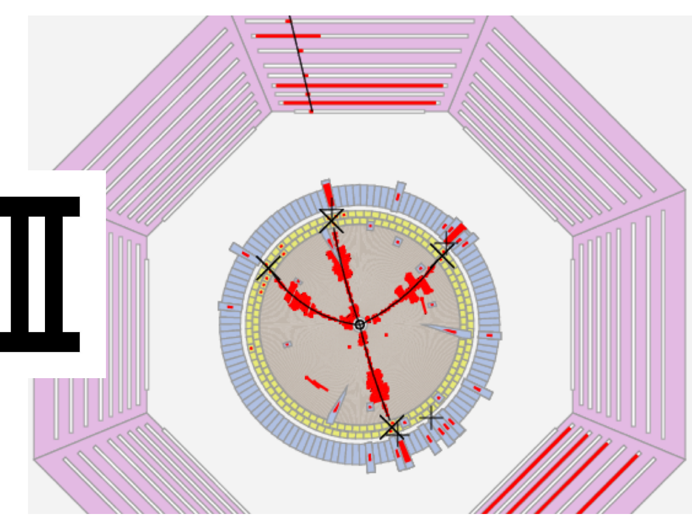

**Pro: high rate** **Con: messy**

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




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

BESIII



**Pro: controlled** **Con: statistics**

# Experimental strategy

$$B \to KX$$
$$X \to \pi^+\pi^- J/\psi$$

- **Search for new particles**
  - Bumps in mass spectra
  - Unique decay distributions
- **Next measure:**
  - mass and width
  - decay modes
  - quantum numbers: $J^{PC}$
- Identify **patterns** and compare with QCD and models