Intro to QCD: Hadron Spectroscopy, Scattering, the Lattice

Wyatt A. Smith

Modern Particle Physics

Four fundamental forces:

- Electromagnetic
- Weak
- Strong
- Gravity

Modern Particle Physics

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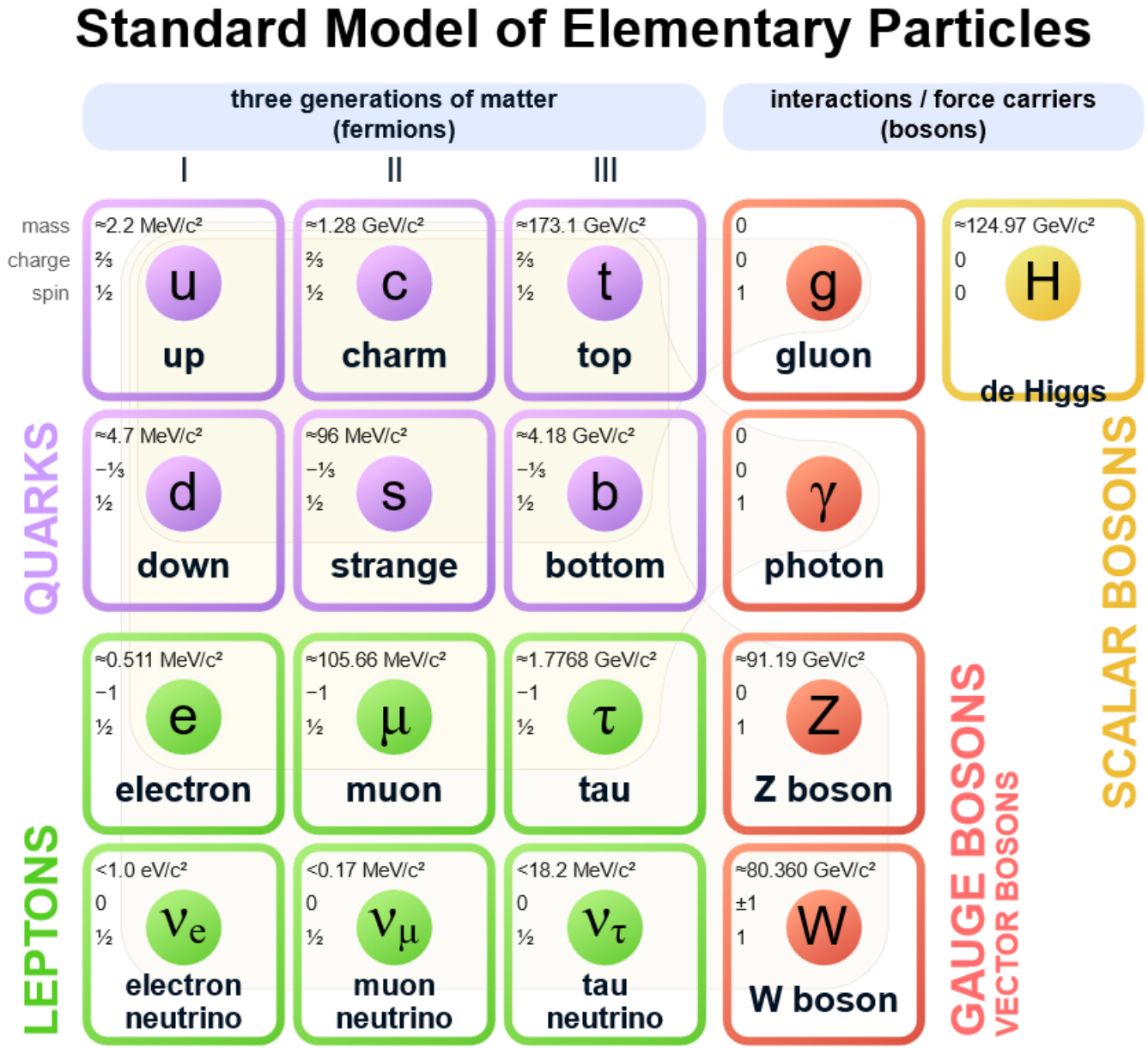
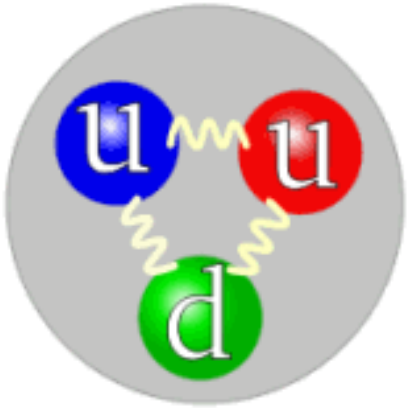
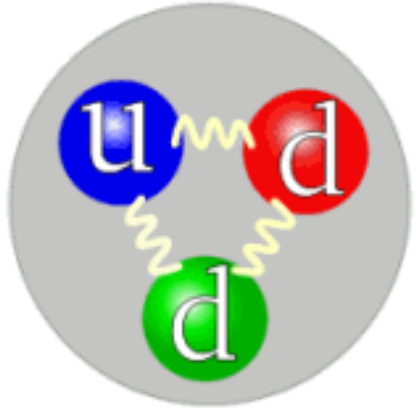


Quantum Chromodynamics:

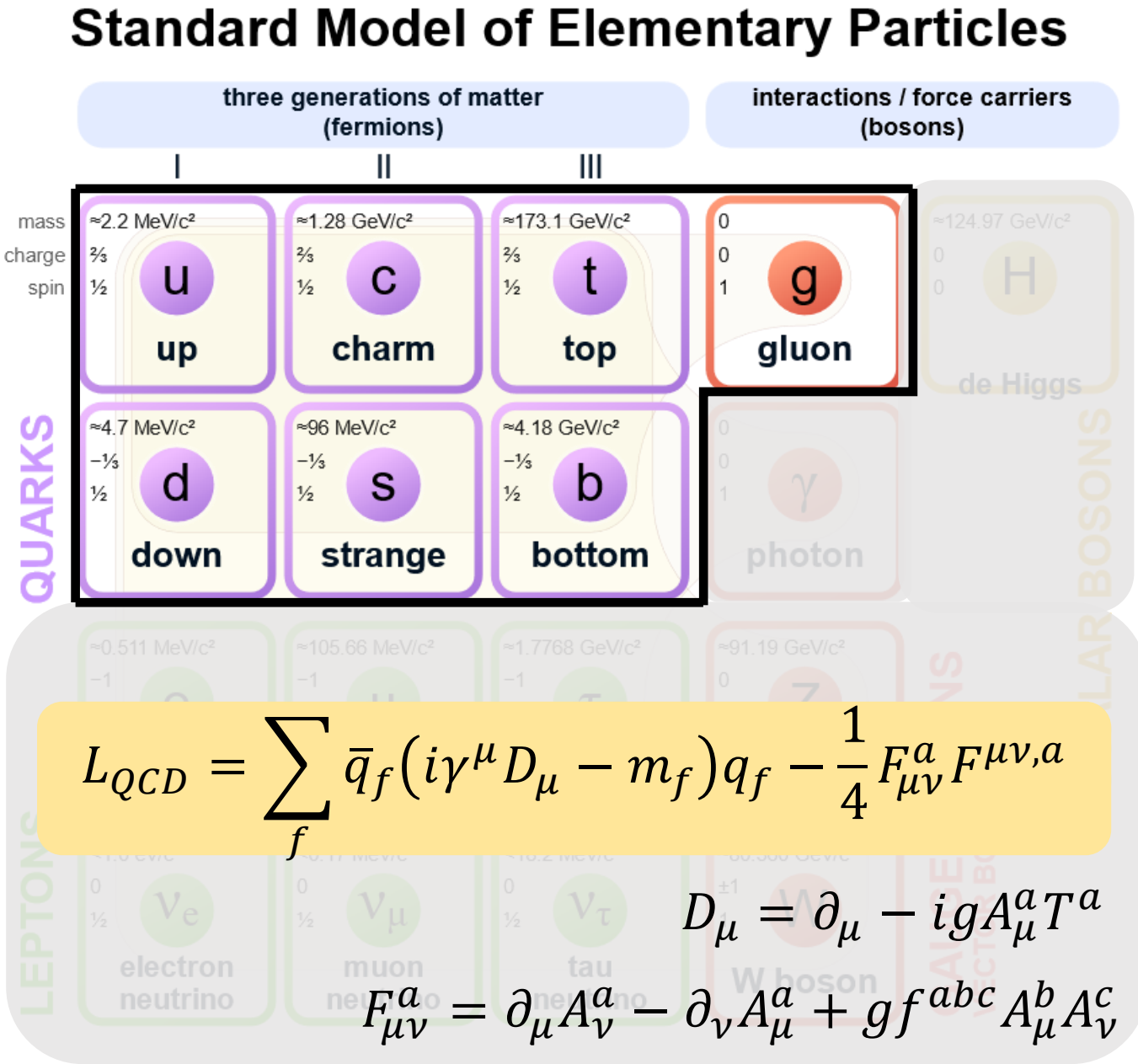
- Fundamental degrees of freedom are ‘quarks’
- Three charges (SU(3) color)
- Short range (~1fm)
- Very strong (~100x EM force)



Proton



Neutron

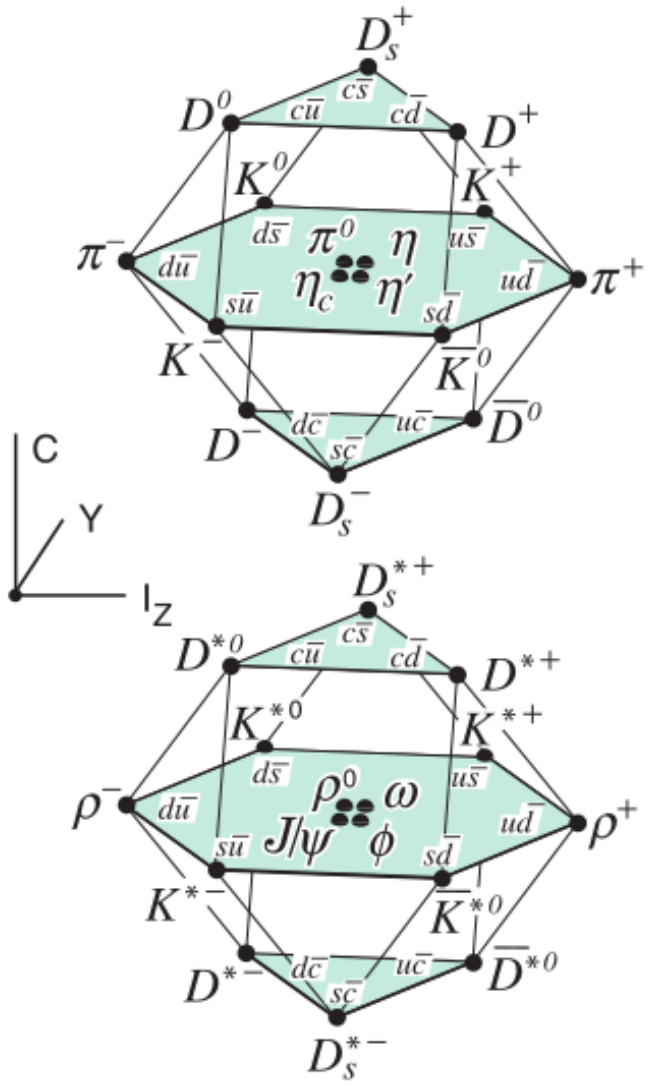


$$L_{QCD} = \sum_f \bar{q}_f \left(i\gamma^\mu D_\mu - m_f\right) q_f - \frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a}$$

$$D_\mu = \partial_\mu - igA^a_\mu T^a$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

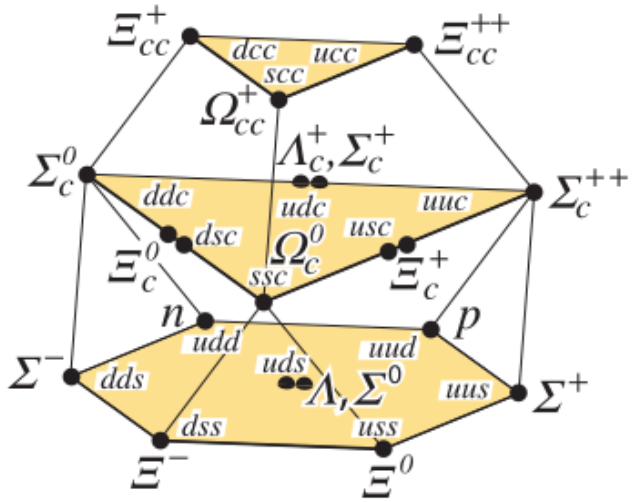
Quark model

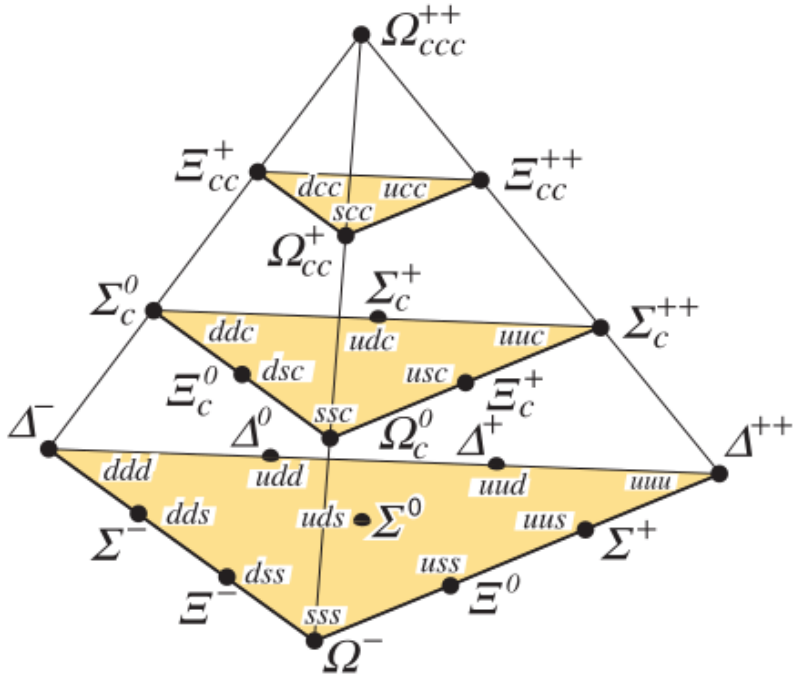


‘Hadrons’ are quark bound states:

a) Mesons = $q\bar{q}$

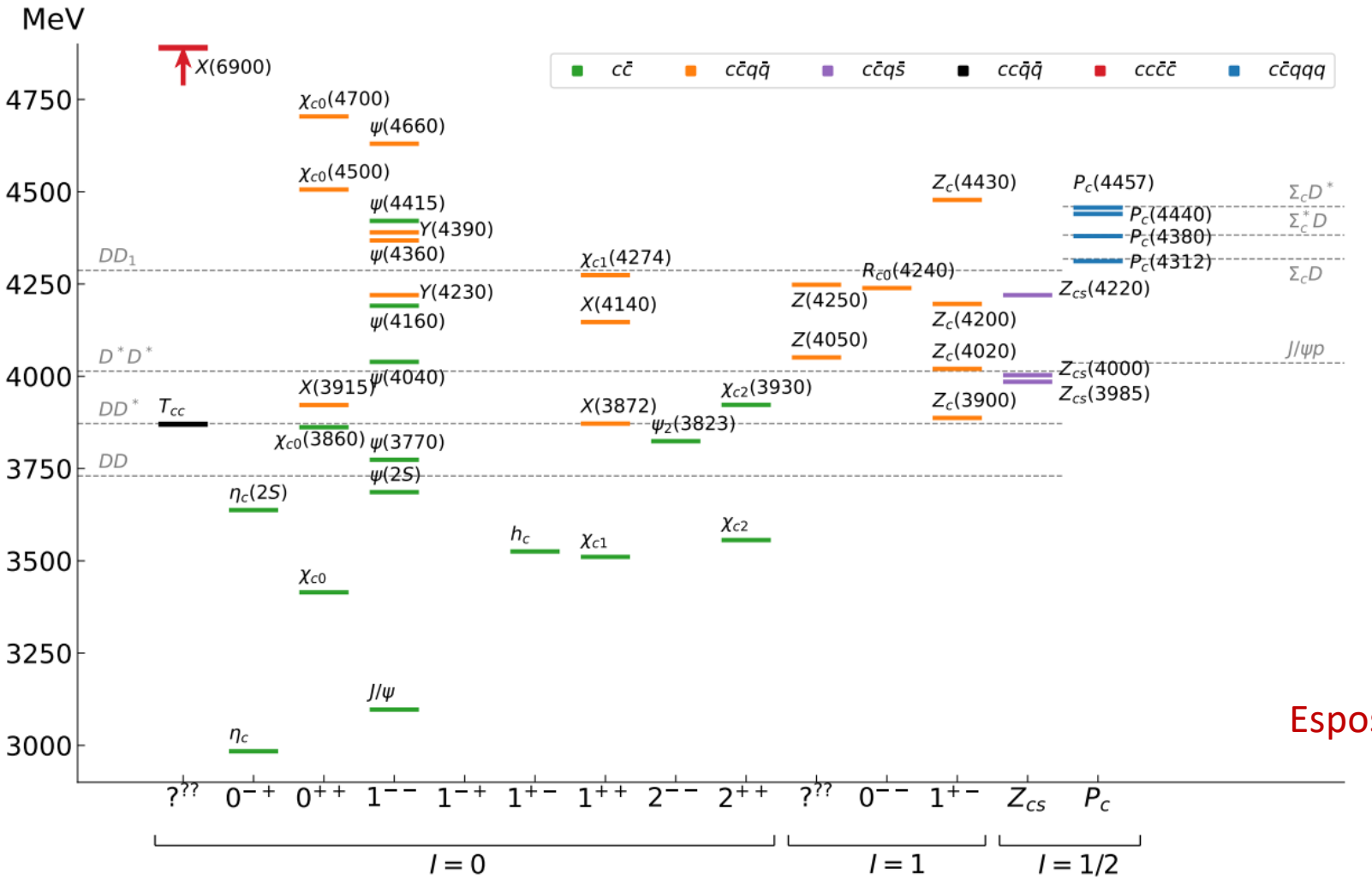
b) Baryons = qqq





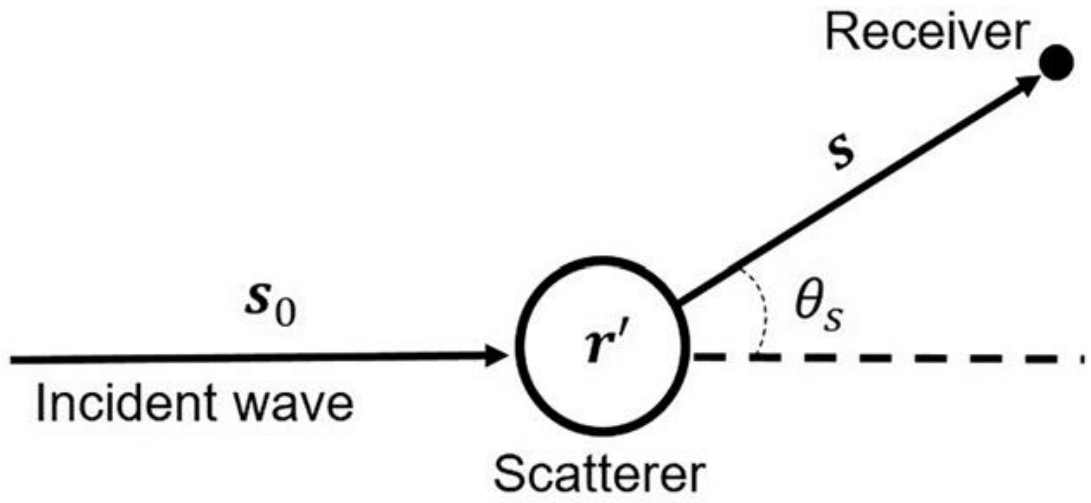
Exotics in $c\bar{c}$

Lots of new particles which are incompatible with usual $q\bar{q}/qqq$ description (J^{PC})



Esposito, AP, Polosa, Phys.Rept. 668
JPAC, arXiv:2112.13436

We match theory and expt. by calculating/measuring the ‘Scattering Amplitude’



$$\frac{d\sigma}{d\Omega}(\theta,\phi) = |f(\theta,\phi)|^2$$

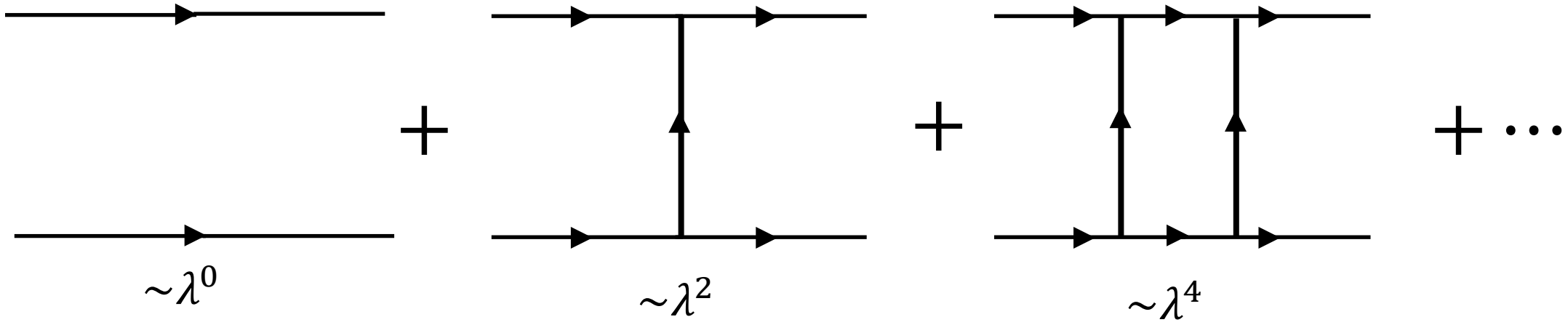
Differential cross section
(what expt. measures!)

Scattering amplitude
(Probability amplitude of
particle going in a direction)

Feynman Diagrams

$$L = \frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi - \frac{1}{2}m\phi^2 - \frac{1}{3!}\lambda\phi^3$$

"phi-cubed theory"

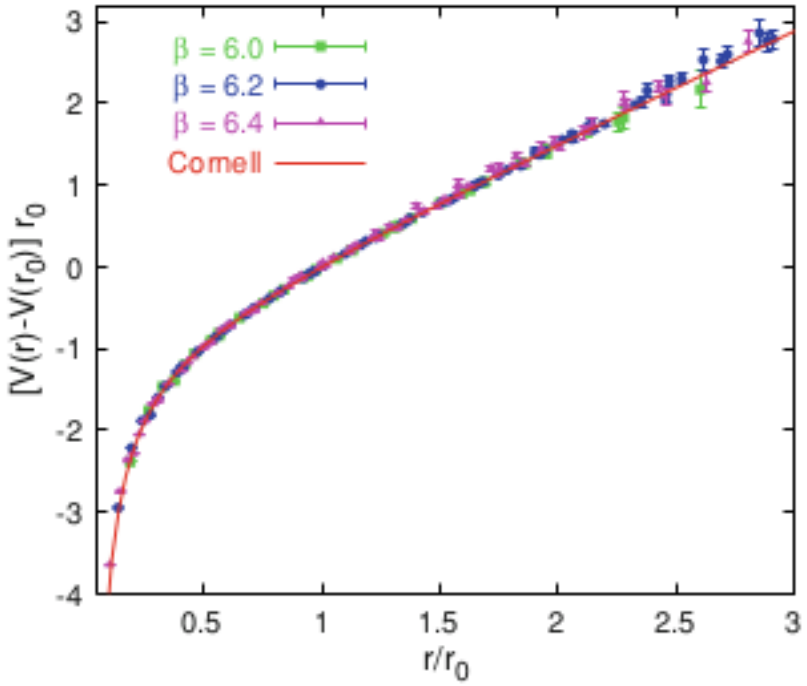
$|f(\theta,\phi)|^2 =$ 

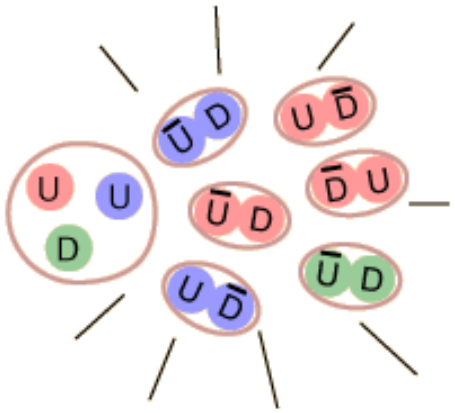
- Lines correspond to particle
- Vertices correspond to interactions of particles
- Perturbation Theory: Everything is a Taylor series!

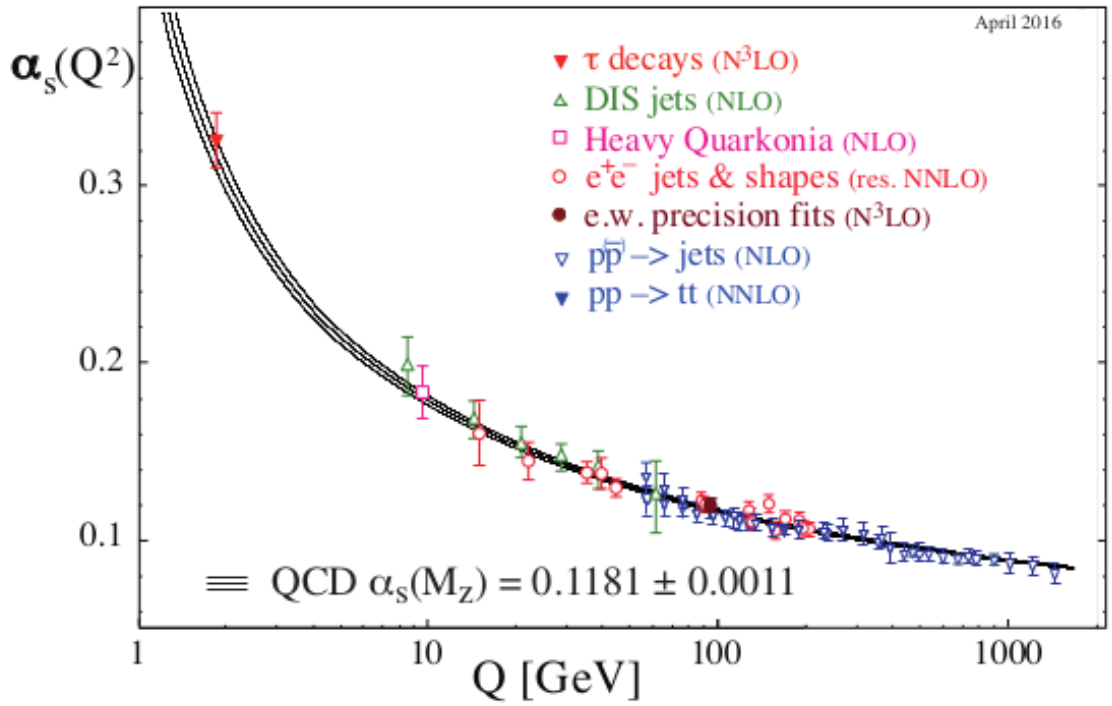
Problem: We can't solve QCD!

- QCD is non-abelian
- QCD is non-perturbative
- Confinement

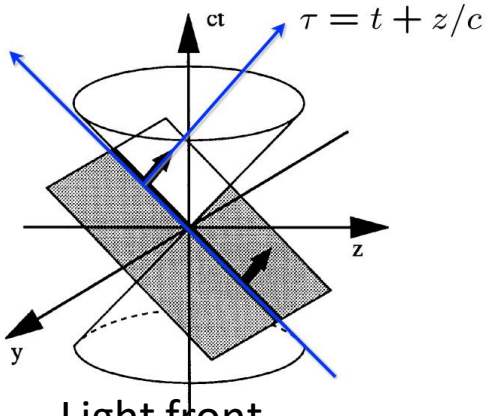
$$L_{QCD} = \sum_f \bar{q}_f \left(i\gamma^\mu D_\mu - m_f \right) q_f - \frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a}$$



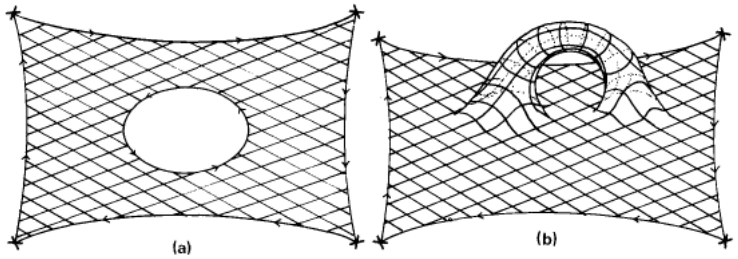




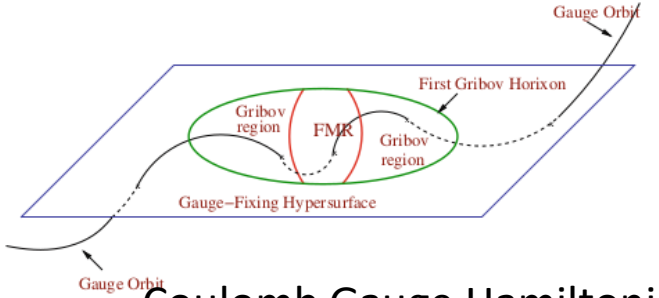
How do we study a theory we can't solve?



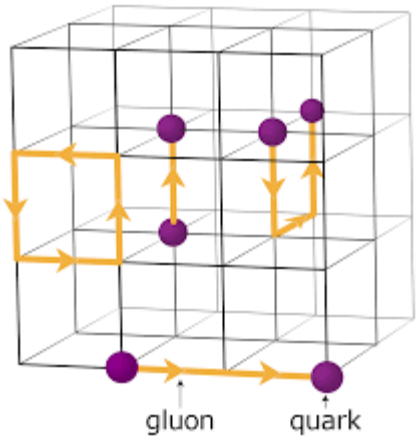
Light front



Large N Limit

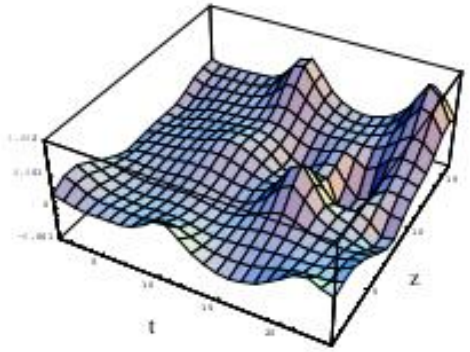


Coulomb Gauge Hamiltonian

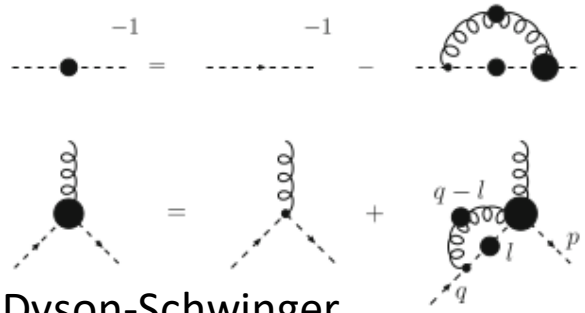


Lattice QCD

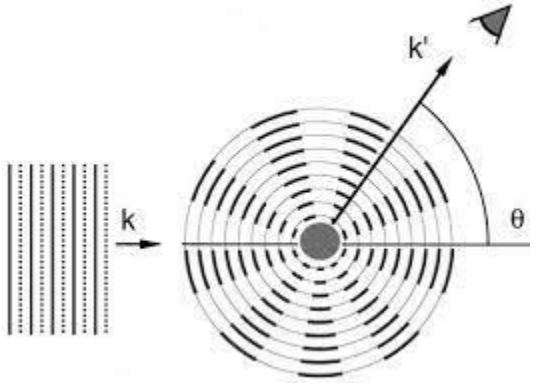
Confinement
QCD Spectrum



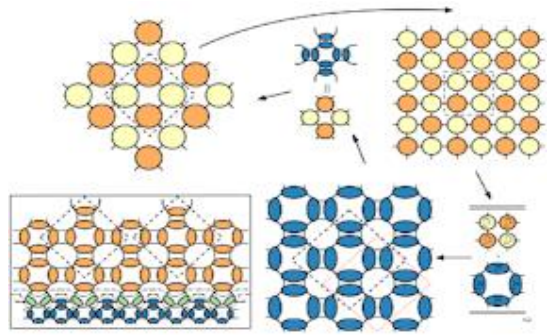
Solitons and Instantons



Dyson-Schwinger

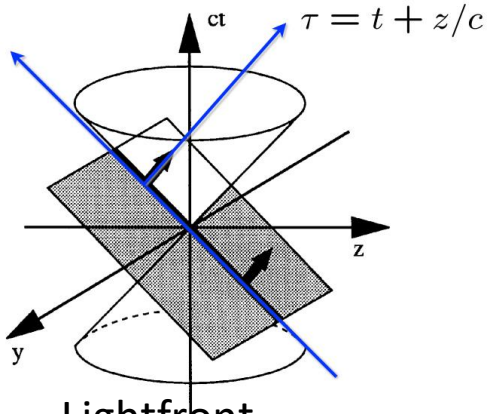


Scattering Theory



Tensor Networks

How do we study a theory we can't solve?



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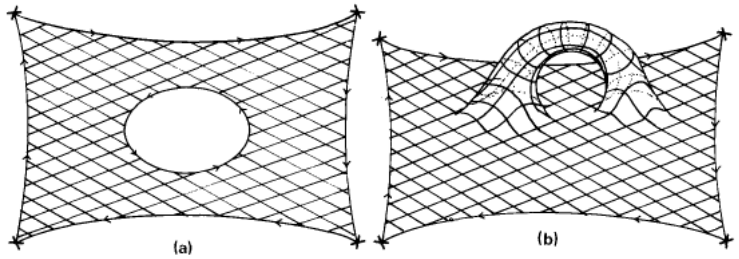

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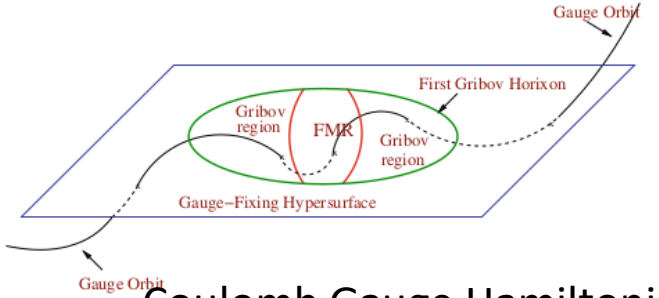

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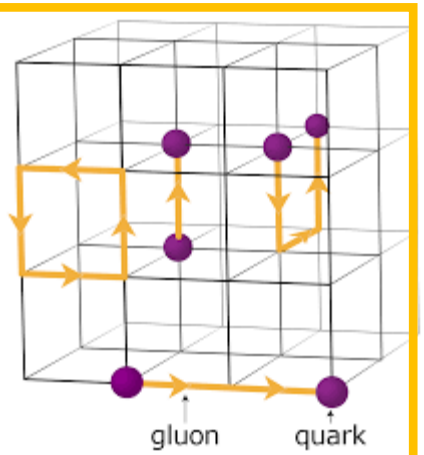
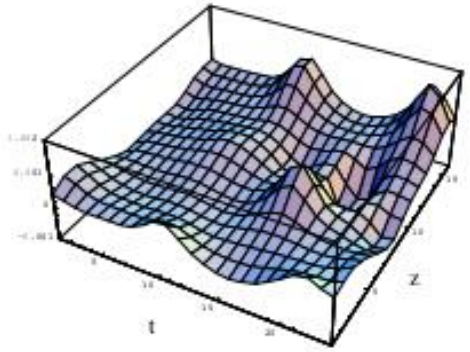
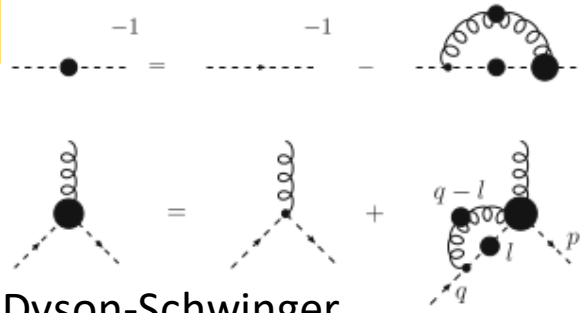


Lattice QCD

Confinement
QCD Spectrum



Solitons and Instantons



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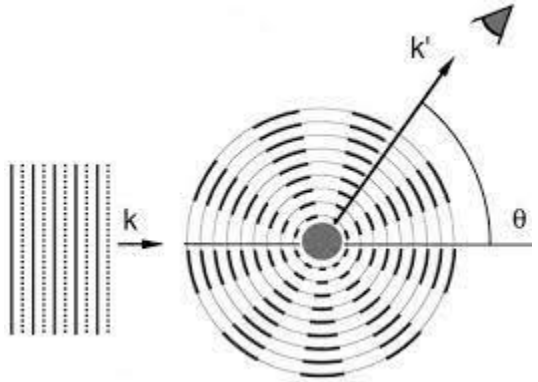
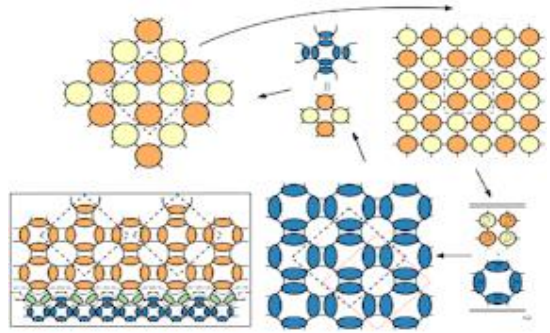
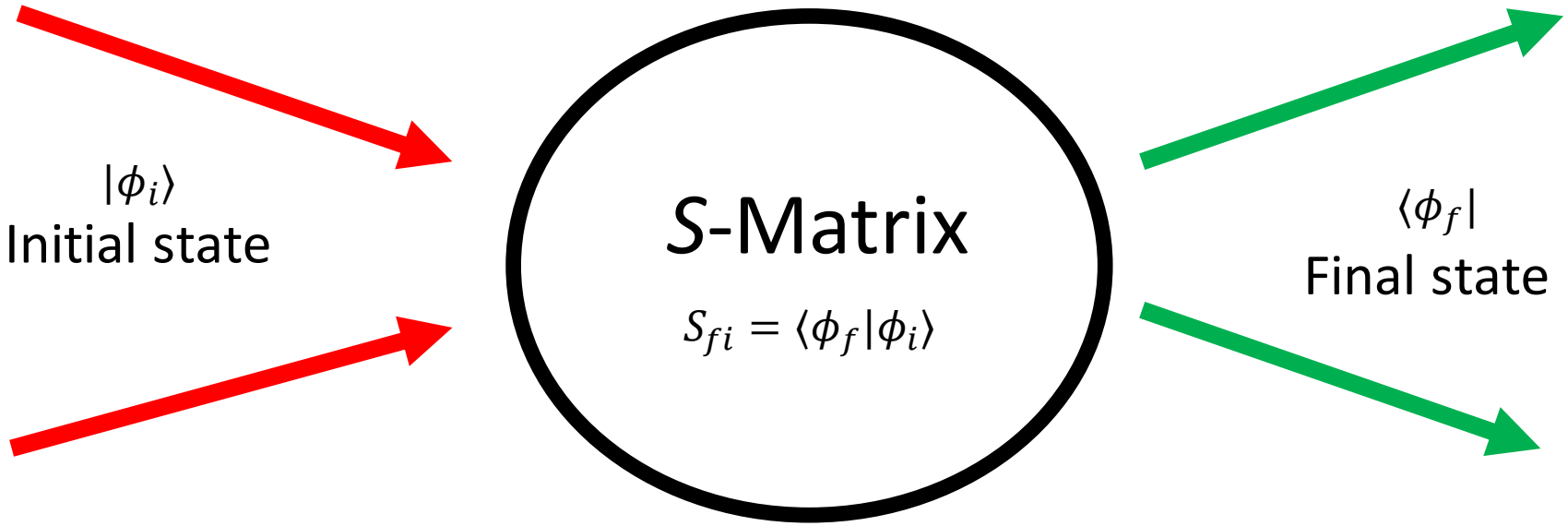


Scattering Theory



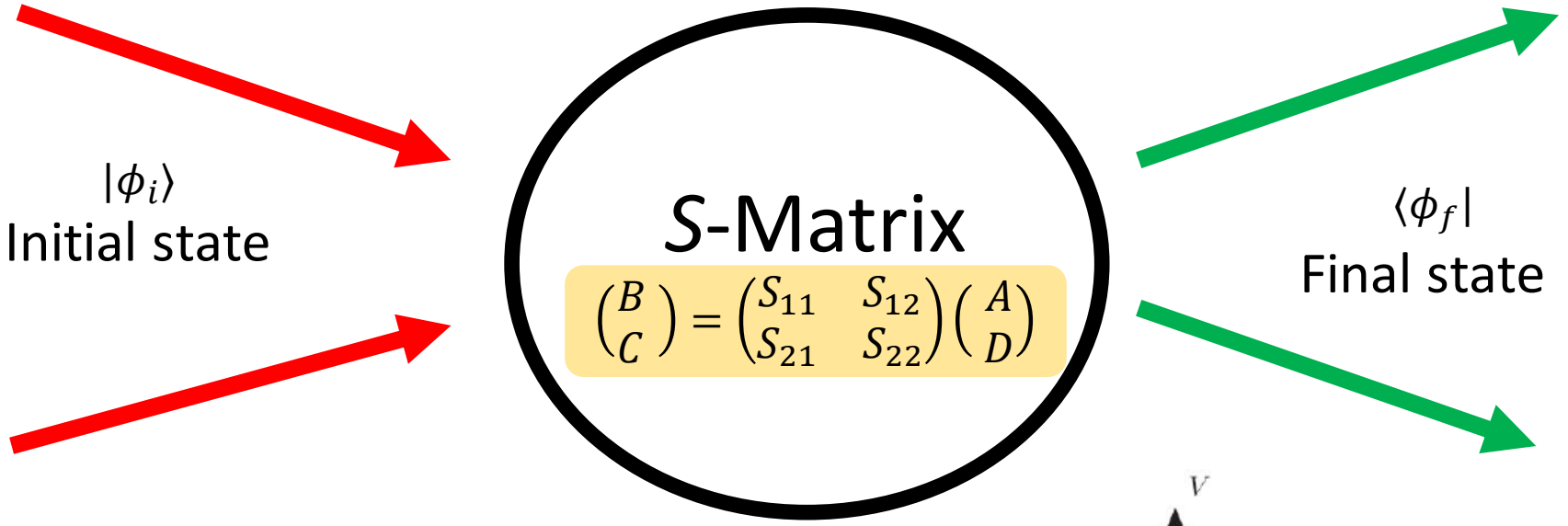
Tensor Networks

Scattering Theory: The S-Matrix

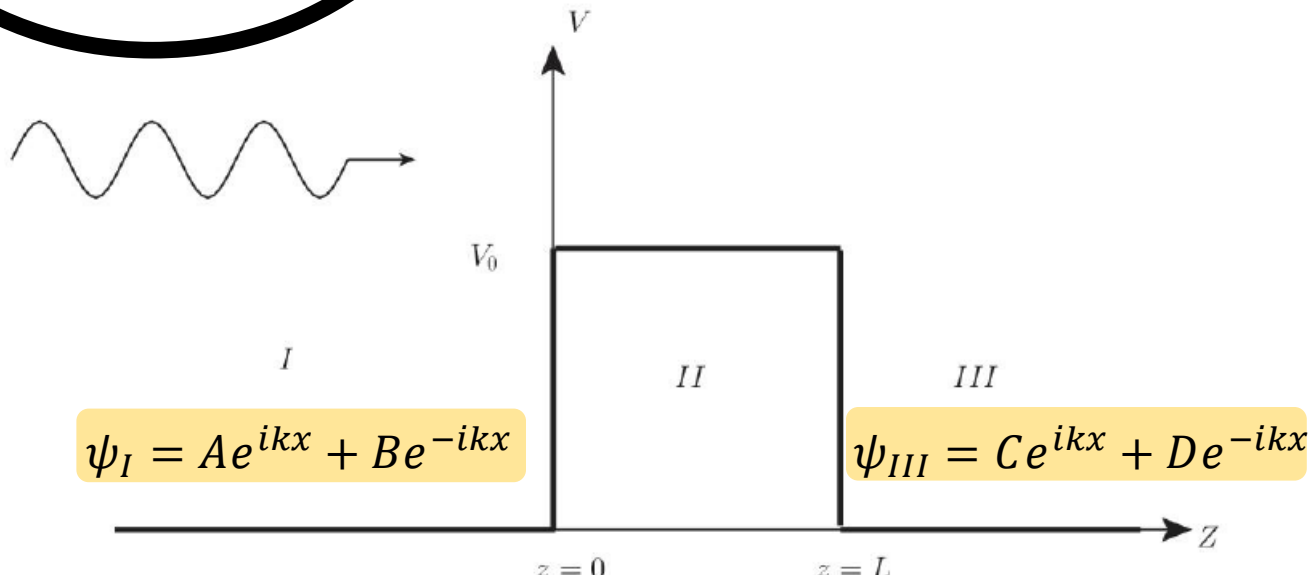


- Asymptotic states
- Interaction radius (~1fm for QCD)

Scattering Theory: The S-Matrix



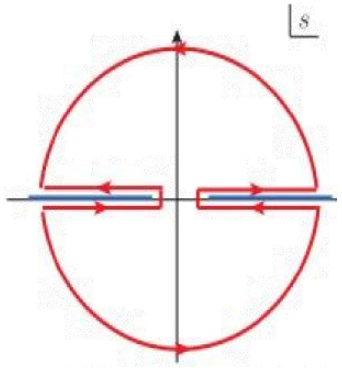
You've (probably) seen this before!



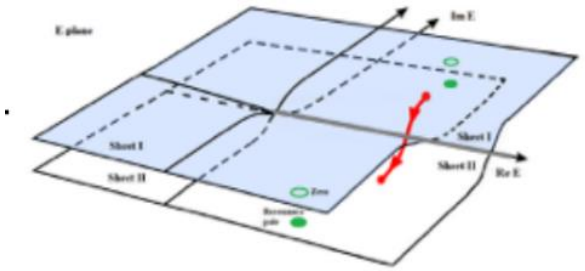
The *S*-Matrix principles

- Future cannot change the past (analyticity)
- 100%, something will happen (unitarity)
- The anti-particle is an anti-particle
  and not just a different particle (crossing symmetry)

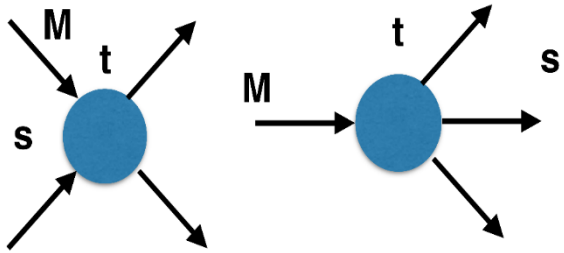
Sherlock Holmes, QFT



Analyticity



Unitarity

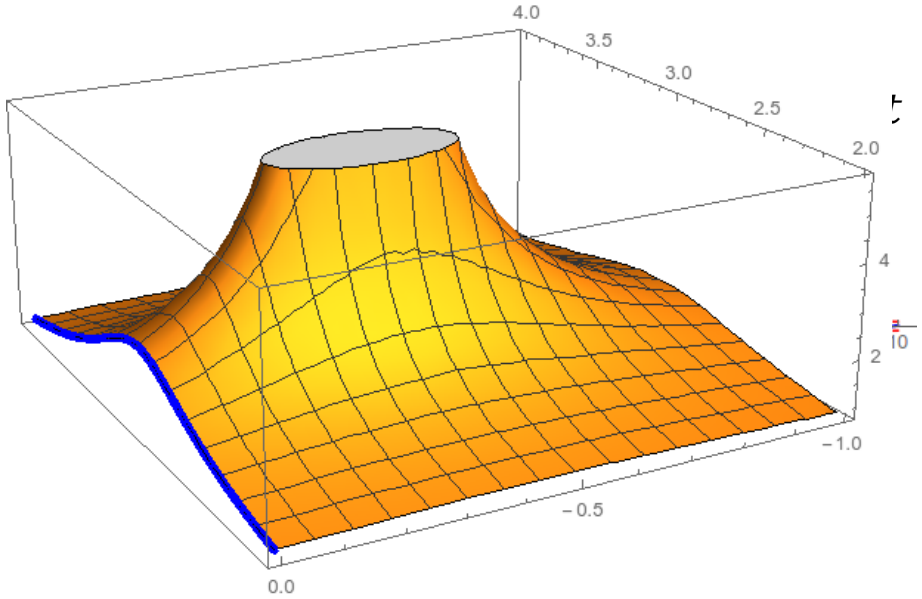


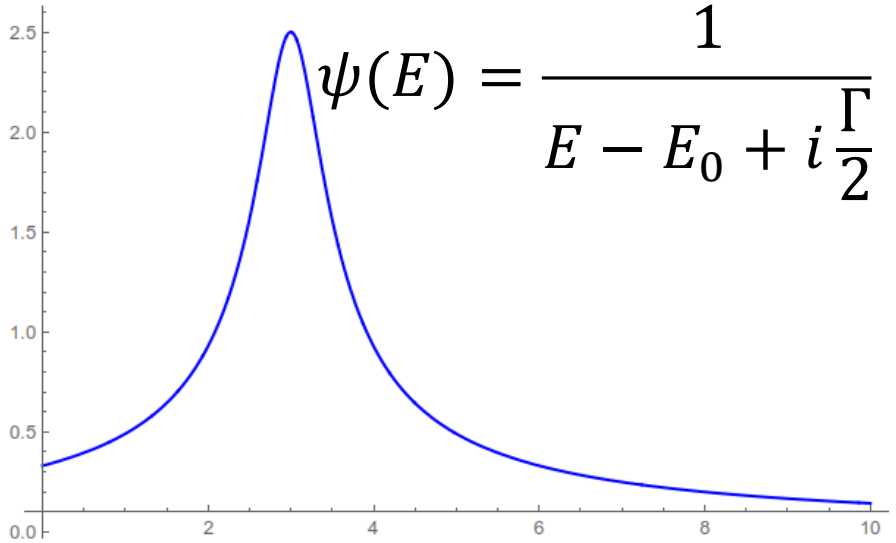
Crossing

Parameterize your ignorance. Build a model. Fit data. Have fun.

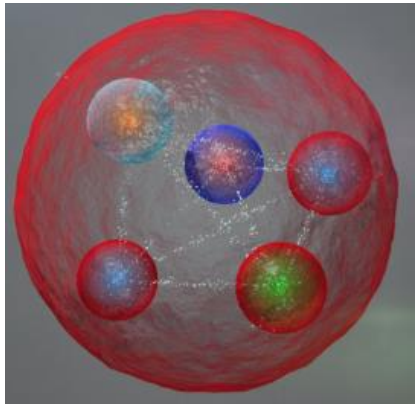
Slide from A. Pilloni

Resonances = Unstable states





$$\psi(E) = \frac{1}{E - E_0 + i\frac{\Gamma}{2}}$$



The function explodes for value of energy $E = E_0 - i\frac{\Gamma}{2}$

Excited states are unstable

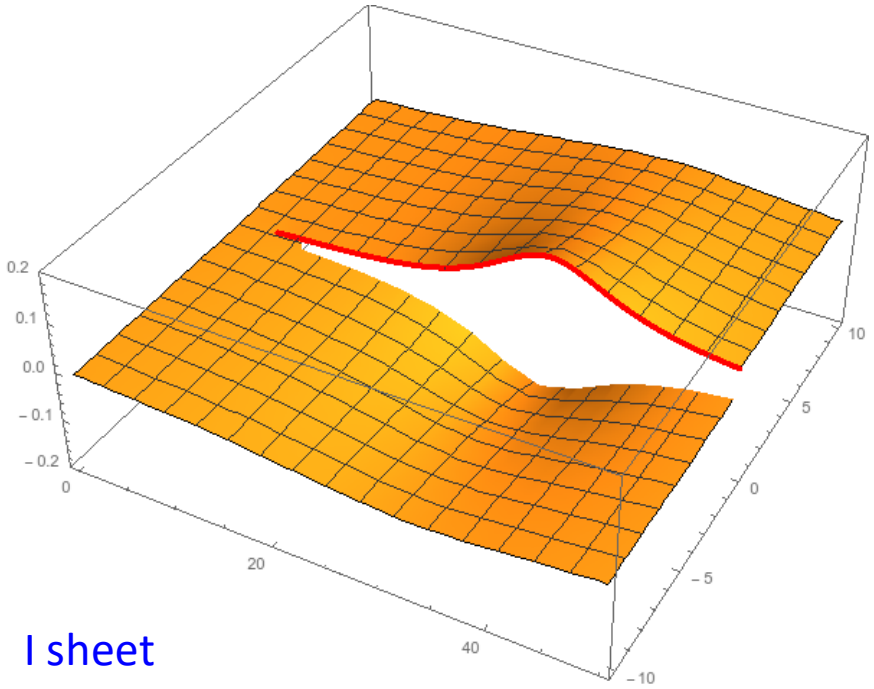
They manifest as resonant peaks

Resonances are poles in the complex energy plane

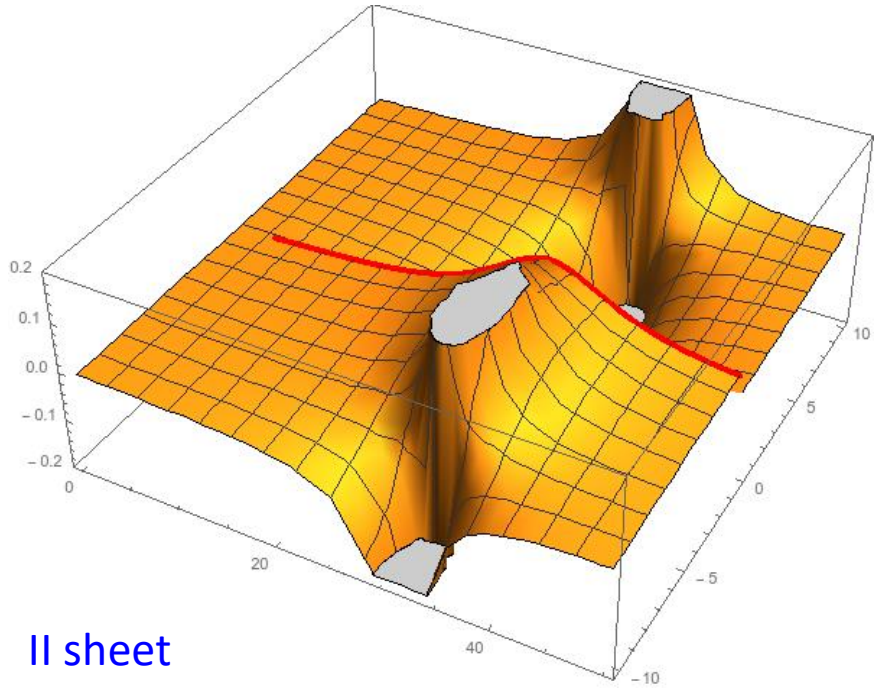
Slide from A. Pilloni

Unitarity & Pole hunting

Unitarity creates a branch cut on the real axis,
two sheets continuosly connected



I sheet



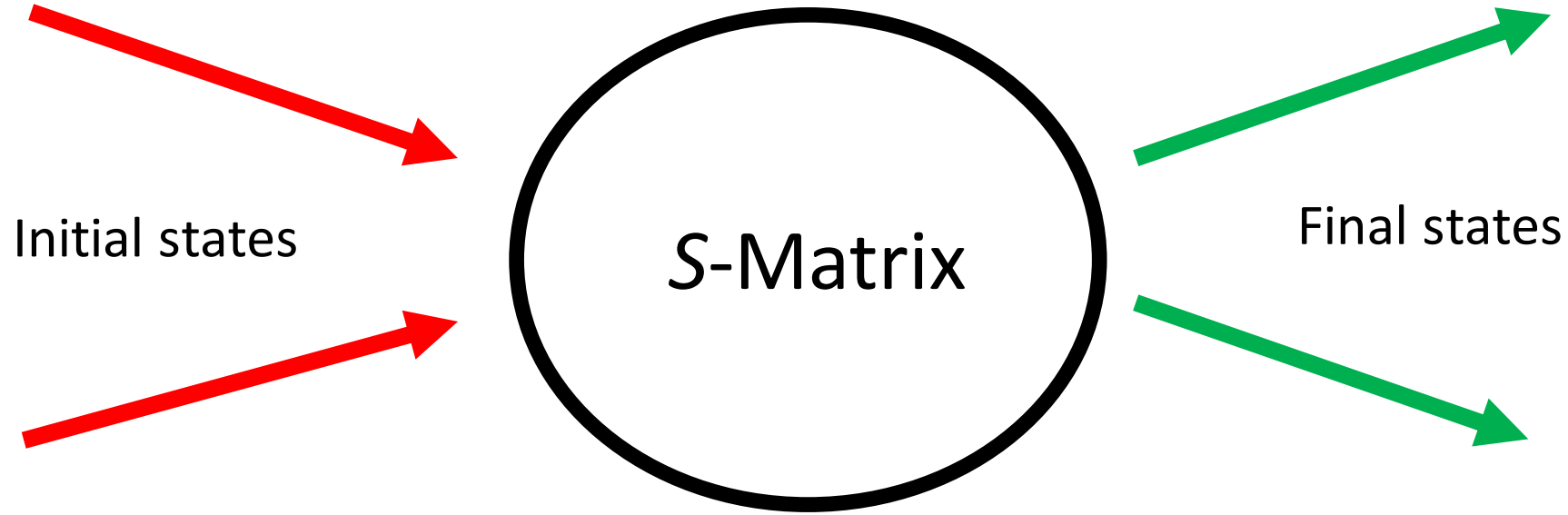
II sheet

Finding resonances means writing analytic amplitude,
and hunting for poles in the complex plane

Slide from A. Pilloni

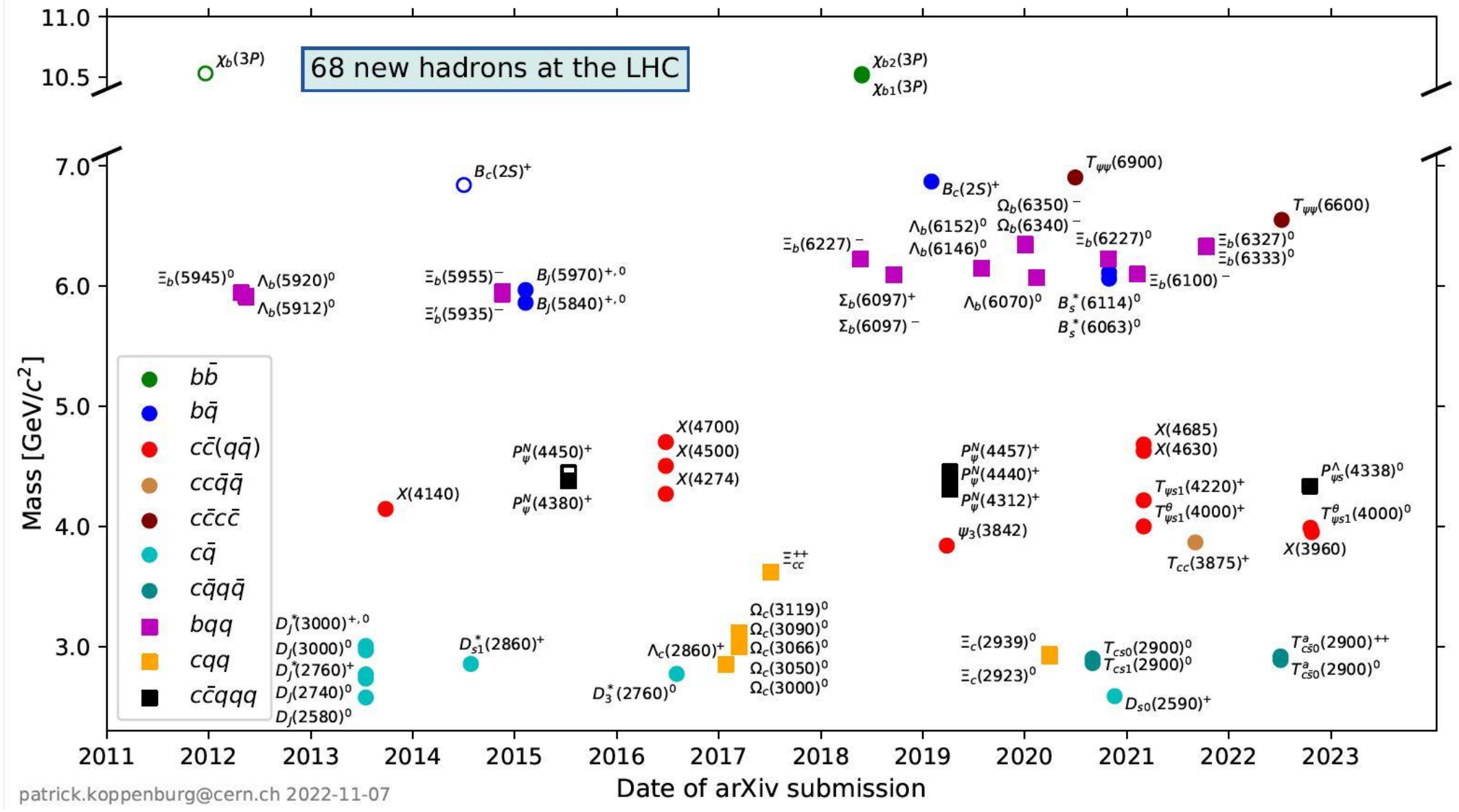
So what?

If we know the location of every pole, every resonance/bound state of particles in the S-matrix, we've effectively solved QCD



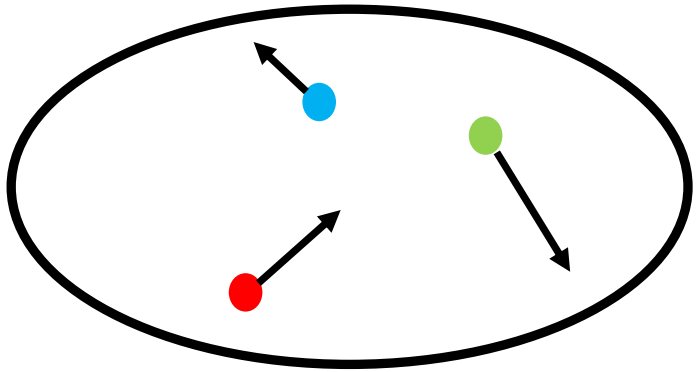
Just one problem…

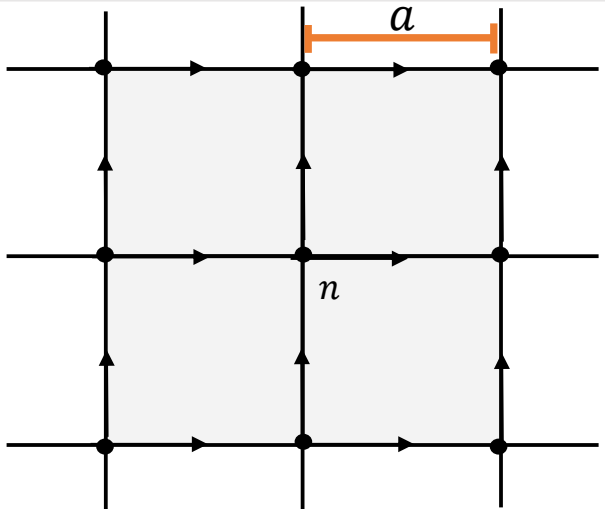
Experimentalists keep finding more!



Lattice QCD

Basic Idea: Discretize spacetime, write QCD on a lattice, use a computer to calculate everything we want





$$U_\mu(n) = e^{iaA_\mu(n)}.$$

$$L_{QCD} = \sum_f \bar{\psi}_f \left(i\gamma^\mu D_\mu - m_f\right)\psi_f - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu,a}$$

$$S_{Lat} = \frac{\beta}{3}\sum_n \sum_{\mu<\nu} \mathrm{Re\,Tr}\left[1 - U_{\mu\nu}(n)\right]$$

- No approximations required!
- Systematically improvable
- Gives access to quark operators
- More ‘experimental’ data to use to check models

- Very computationally expensive (fermions = pain)
- Need to write observables in terms of ‘links’

Four decades of Lattice QCD

1975 1980 1985 1990 1995 2000 2005 2010 2020

1973 QCD

1974 lattice QCD

Physics

1st spec calculation 1981
Hamber-Parisi
Weingarten

Lattice size L

0.8fm 4^3x8

1.6fm 16^3x32

3.0fm 64^3x118

2.4fm 24^3x48

6.0fm 64^3x128

Algorithms

Nf=0 quenched

Nf=2 u,d

Nf=2+1 u,d,s

Nf =#sea quarks

Machines

1st generation 1Gflops

APE1

QCDPAX

2nd generation 10Gflops

APE100

CP-PACS

3rd generation 1Tfops

QCDSP

4th generation 10Tfops

QCDOC

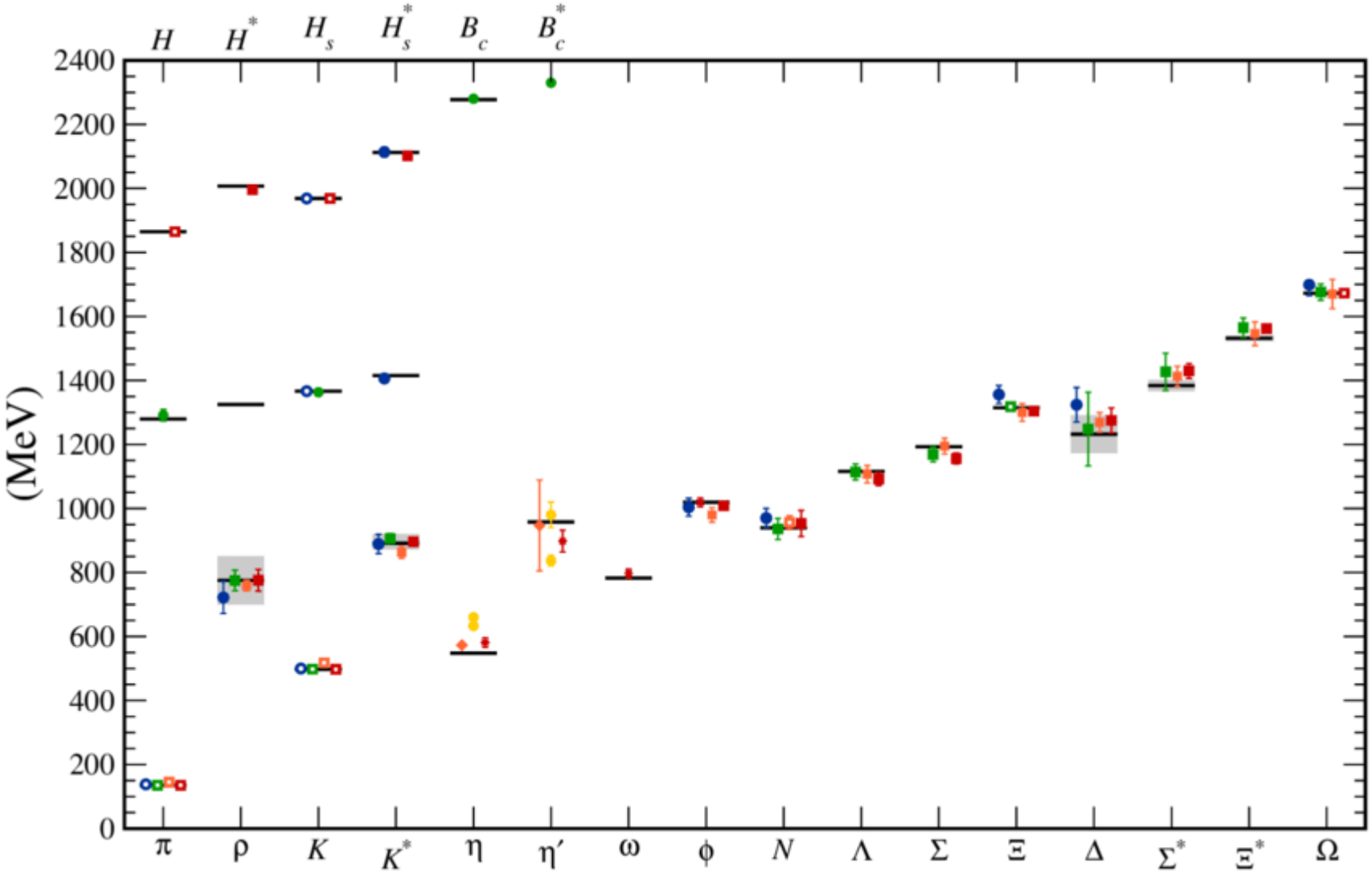
PACS-CS

5th generation 10Pfops

K comouter

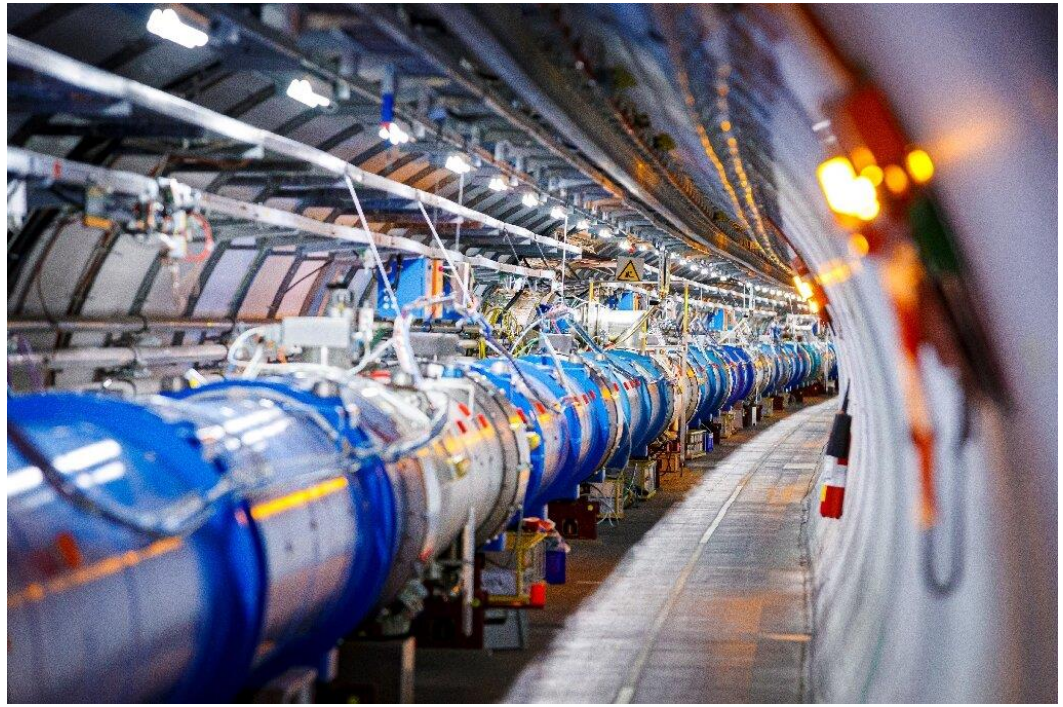
BlueGene/Q

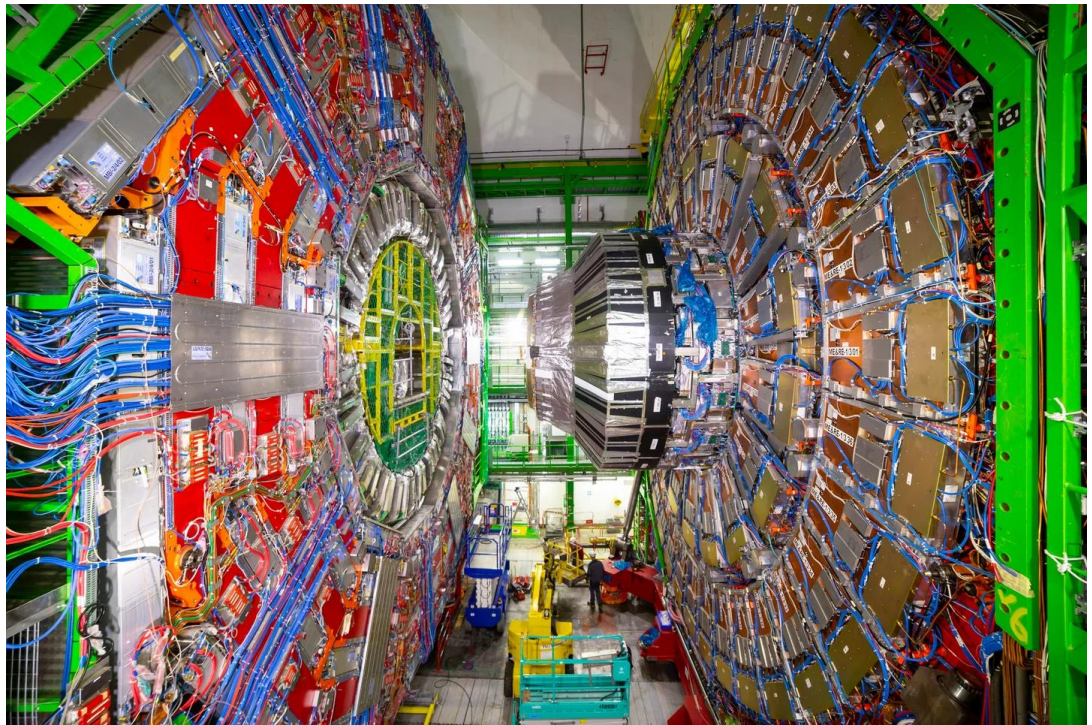
Hadrons from LQCD



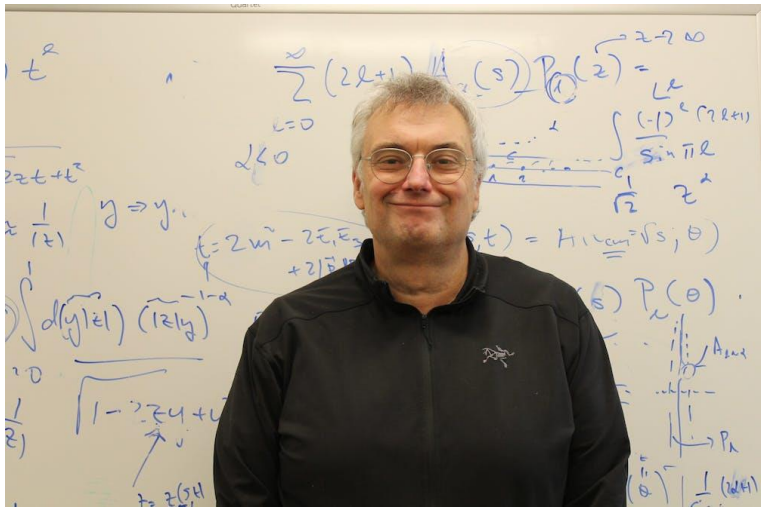
Summary

- QCD is difficult to deal with but not impossible
- S-matrix principles constrain the physics
- Theory, Lattice and Expt. work together to make sense of the hadron spectrum

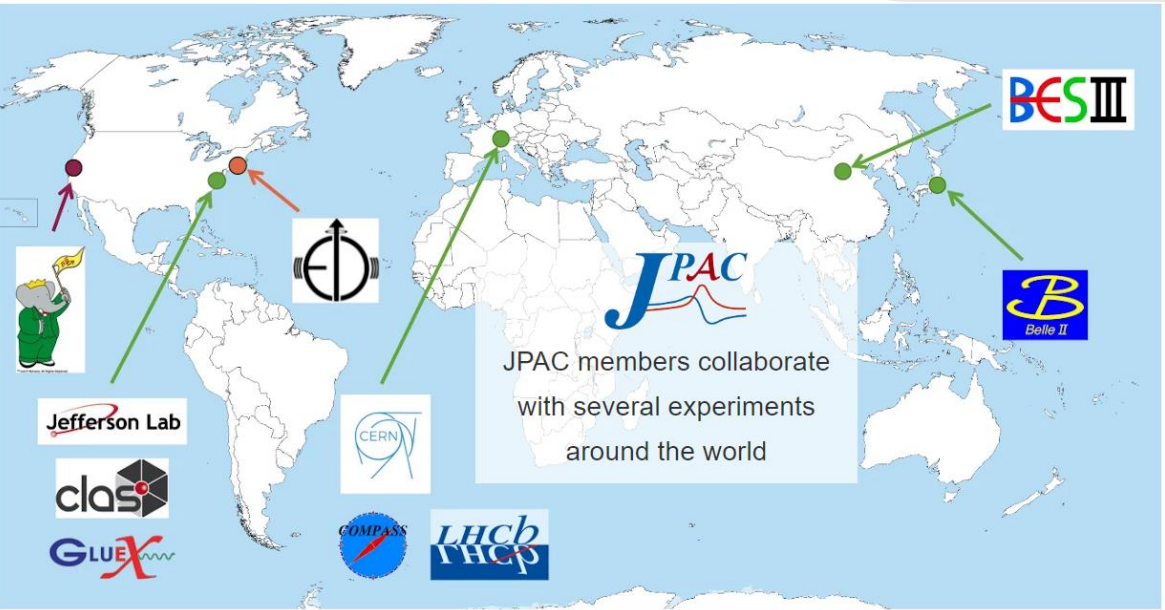




Bonus: Grad School at IU



- Choose a school based on prospective advisors!
- Are the students happy?
- Travel = ☺
- $$$ = ☺
- Grad Worker Union = $$$



IGWC-UE
EST. 2017