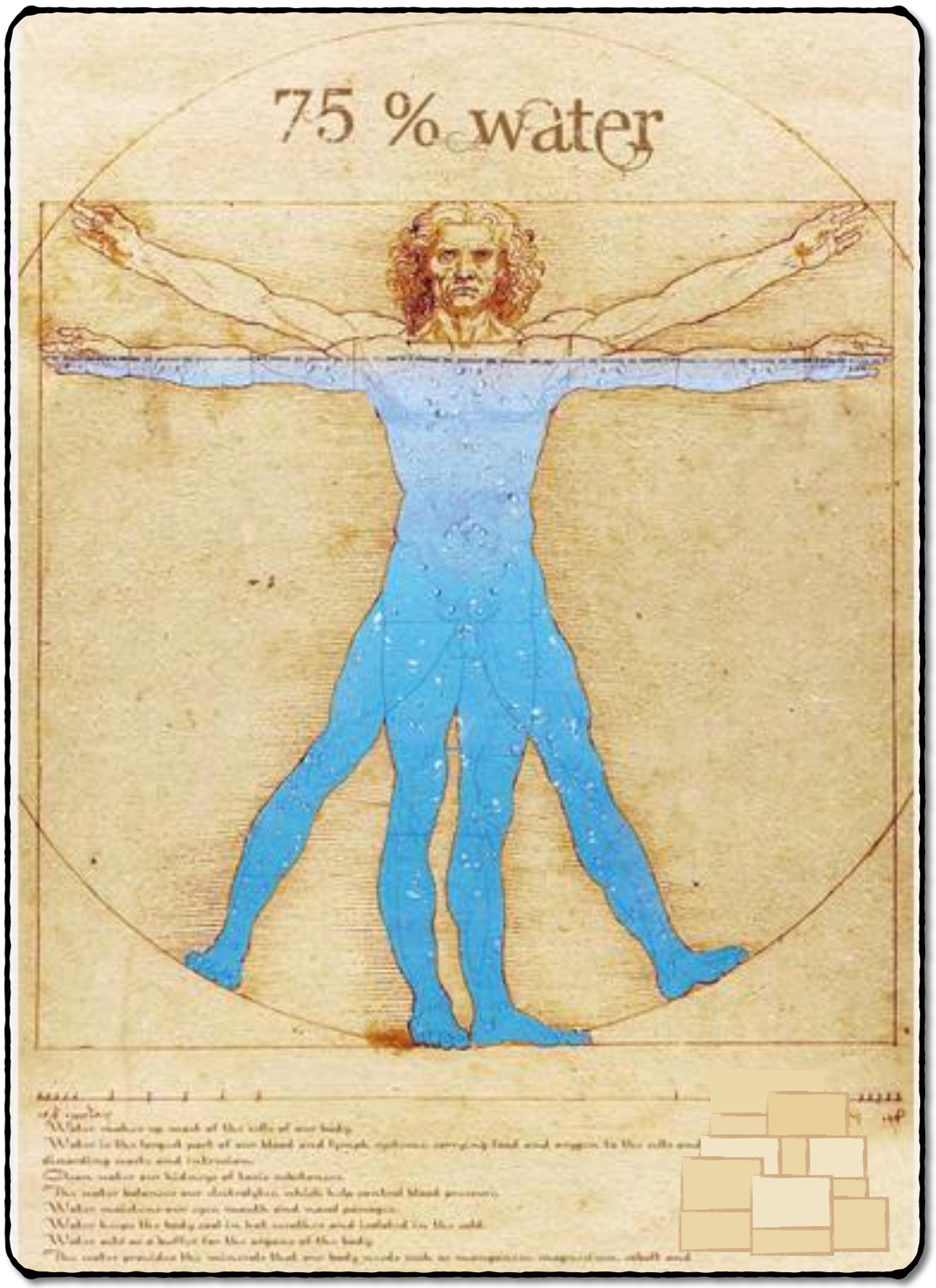
A glimpse into the exotic world of quarks and gluons

Raúl Briceño

JSA

Jefferson Lab

ODU Feb, 2017

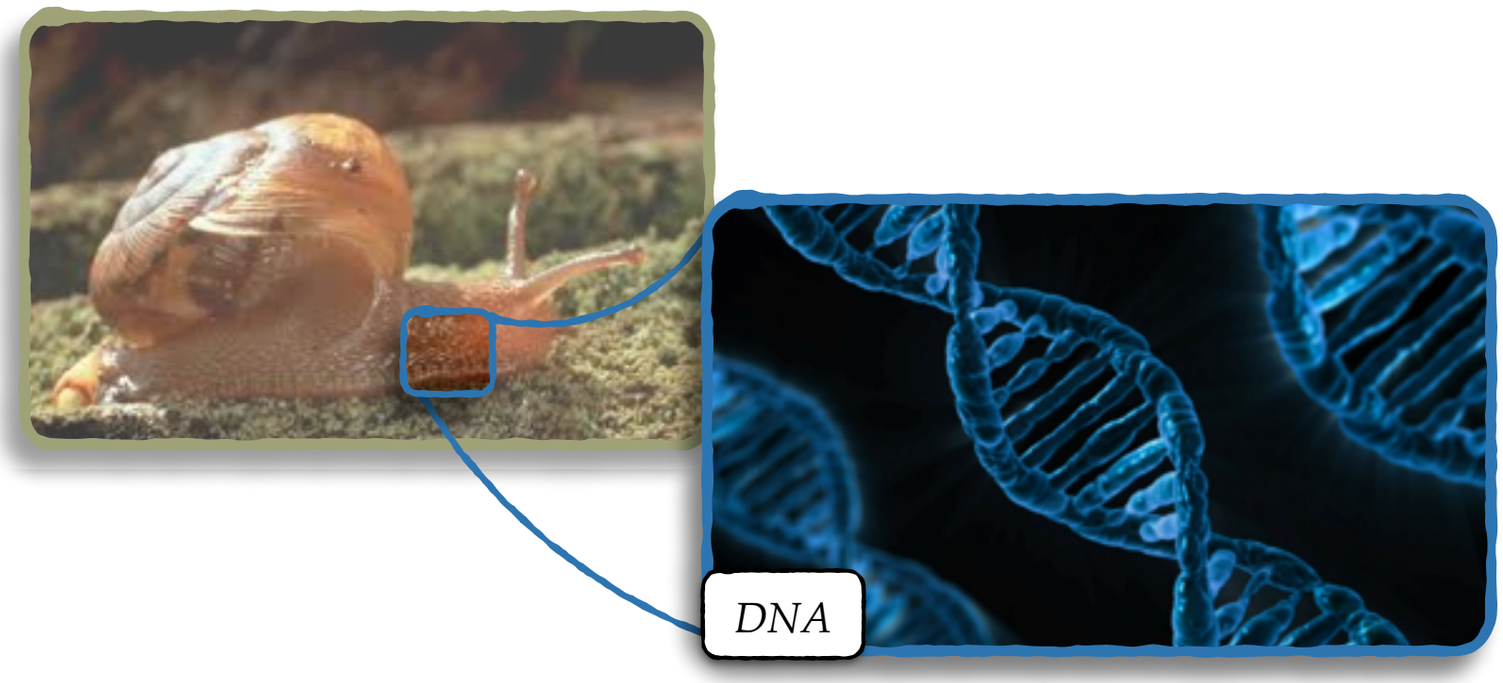

75 % water

75 % water

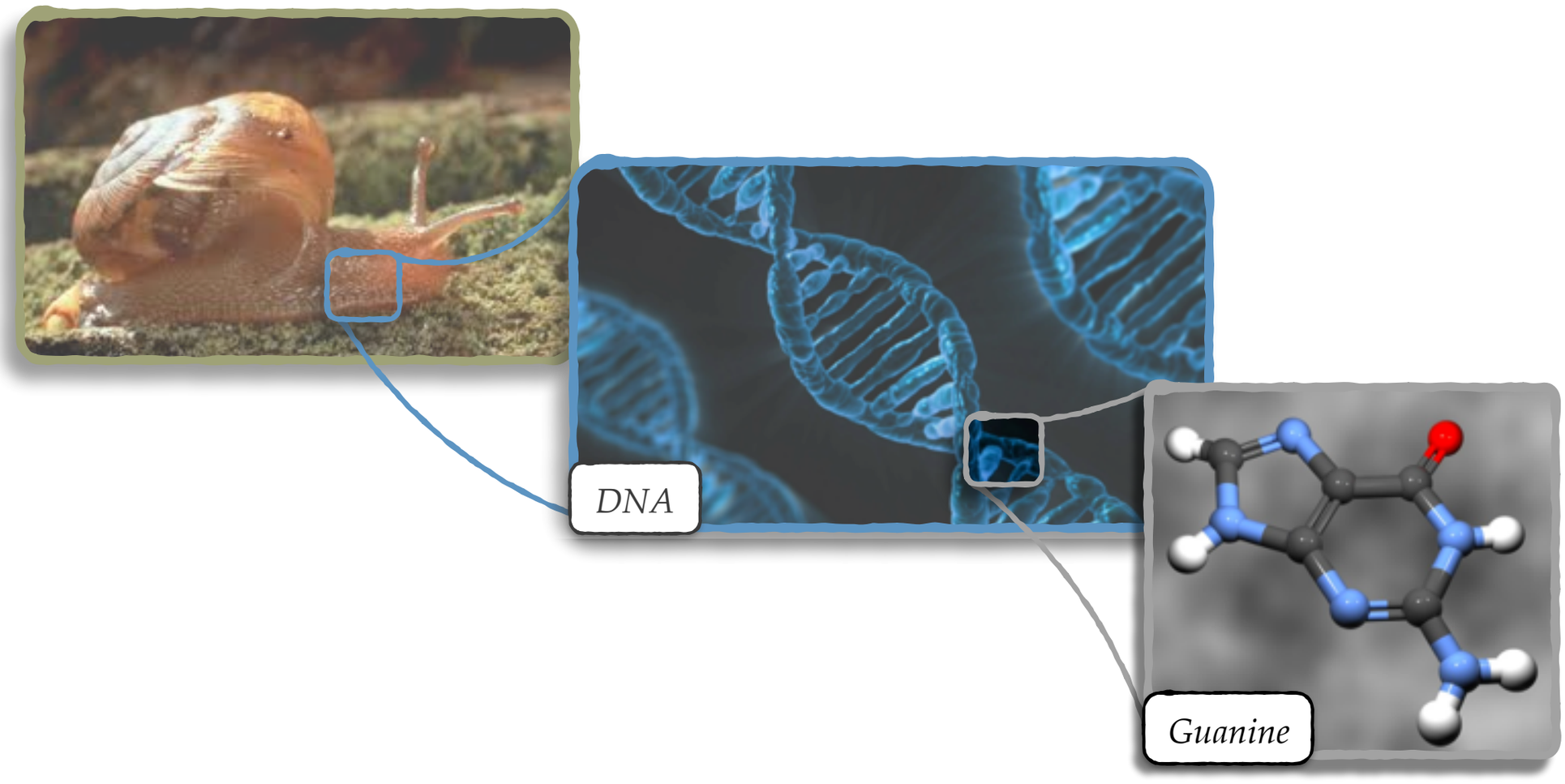
85% glue!

the big picture

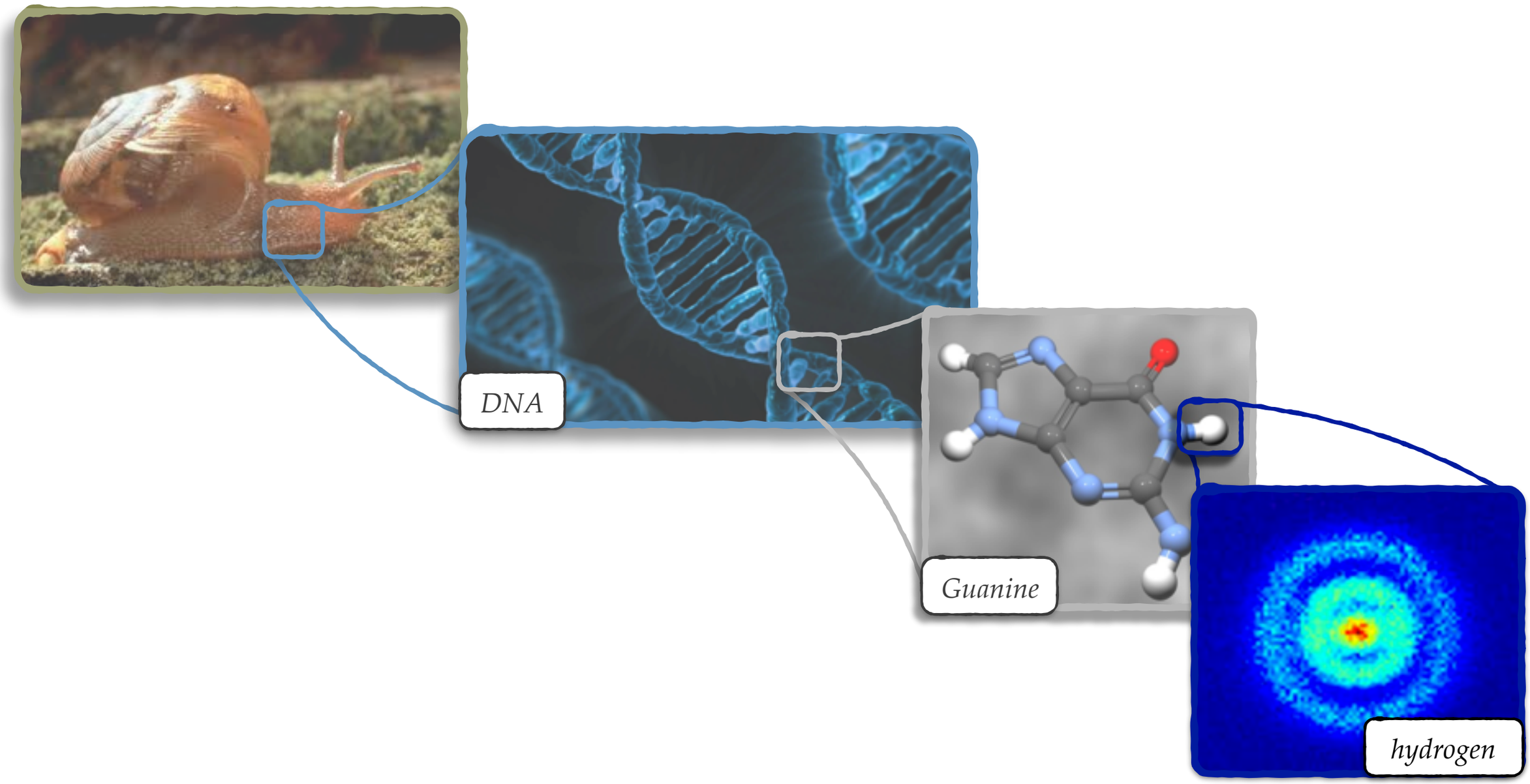
the big picture



the big picture



the big picture



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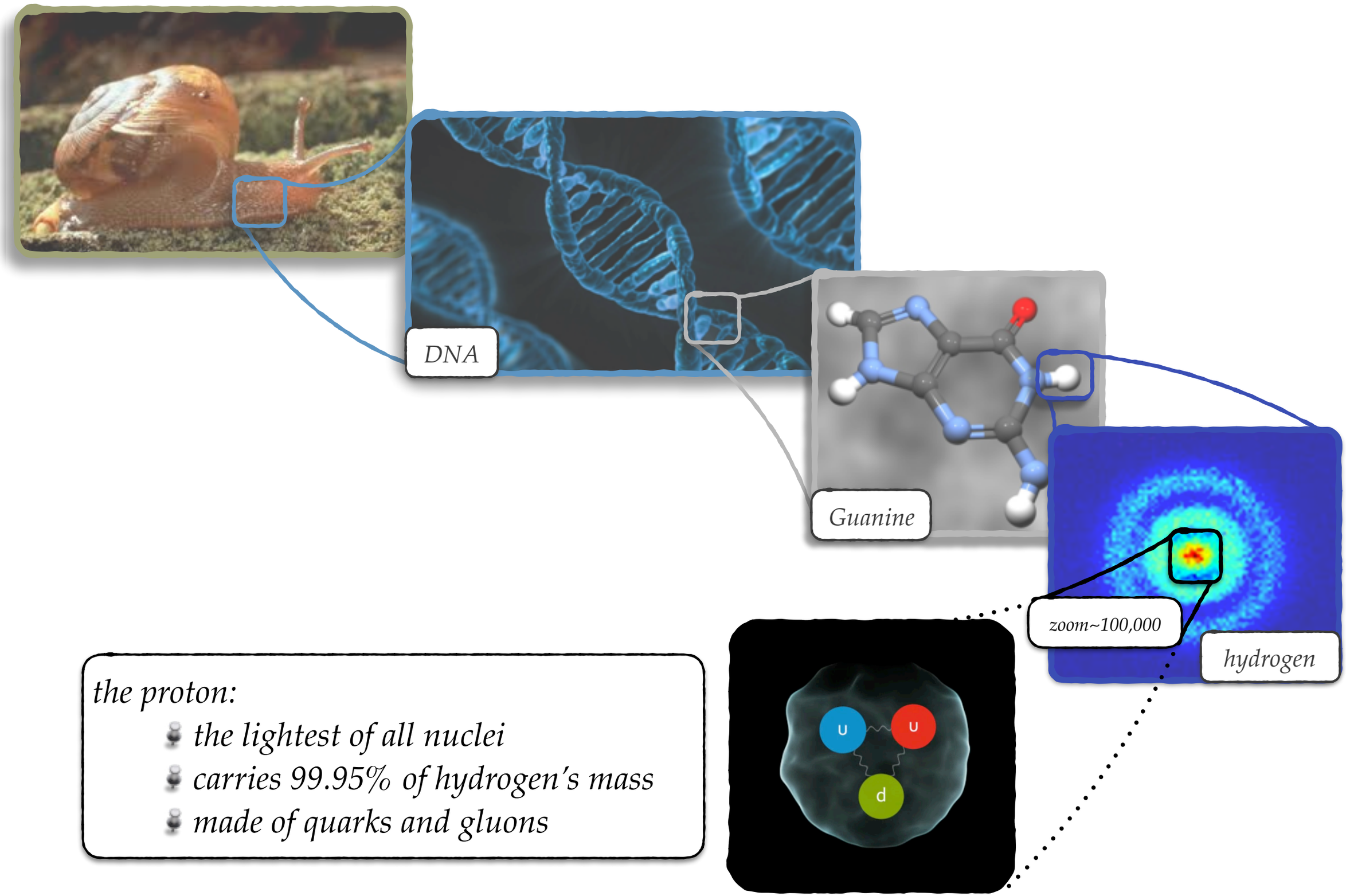


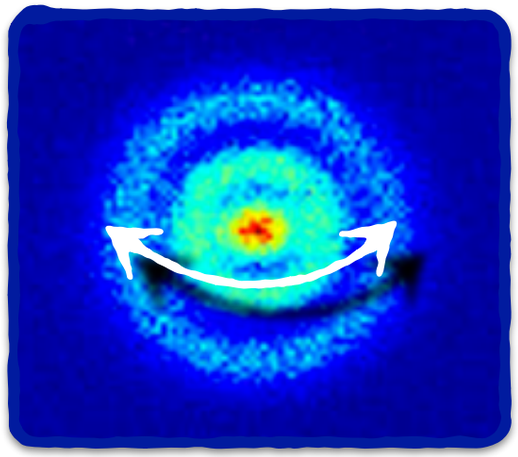
the proton:

- *the lightest of all nuclei*
- *carries 99.95% of hydrogen's mass*
- *made of quarks and gluons*

the big picture

is to

as



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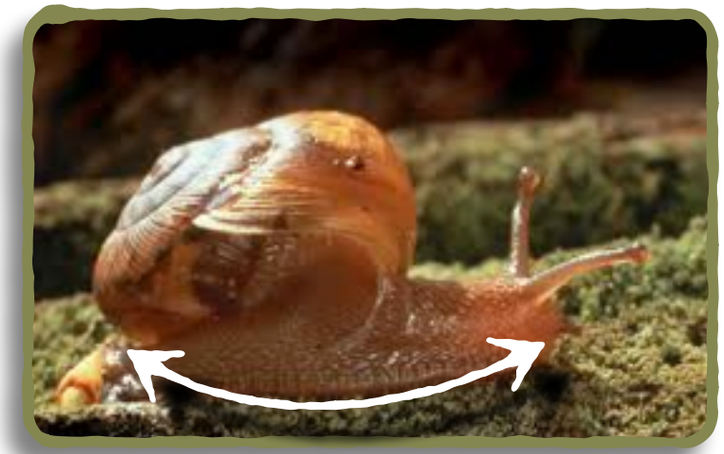

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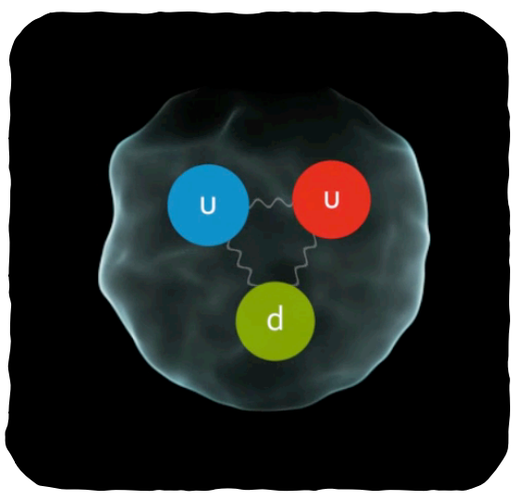
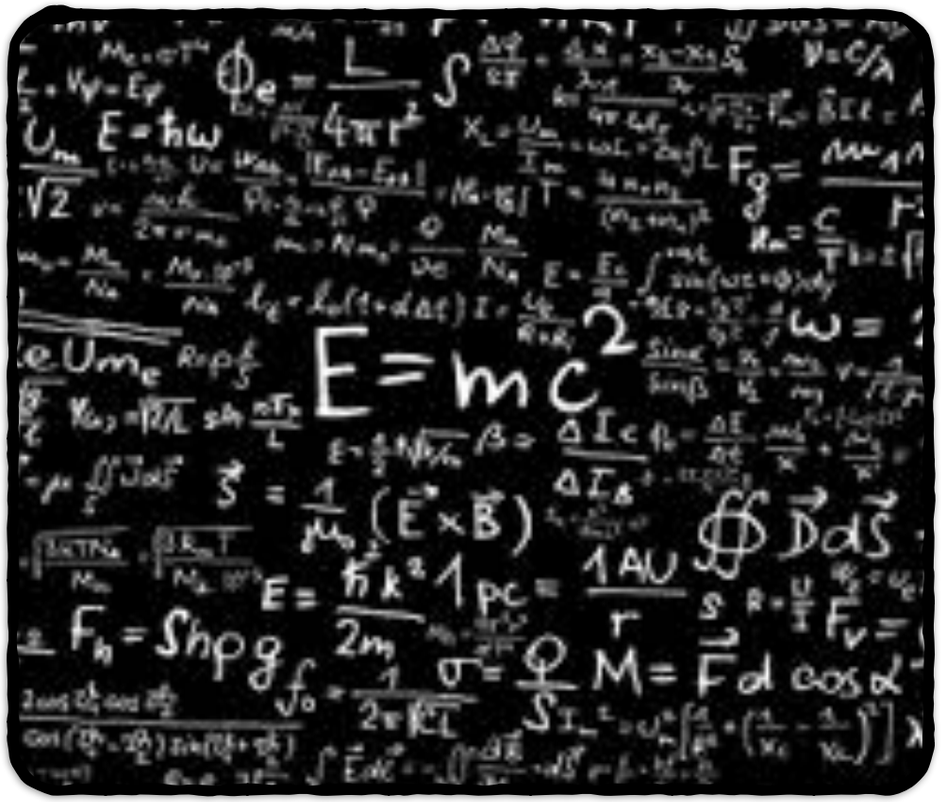


Particle accelerators

(from a theorist's perspective)

<u>Step #0:</u> write down theory / make a prediction / build accelerator



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Step #1: accelerate particles to speeds close to the speed of light!

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this can create a smattering of particles

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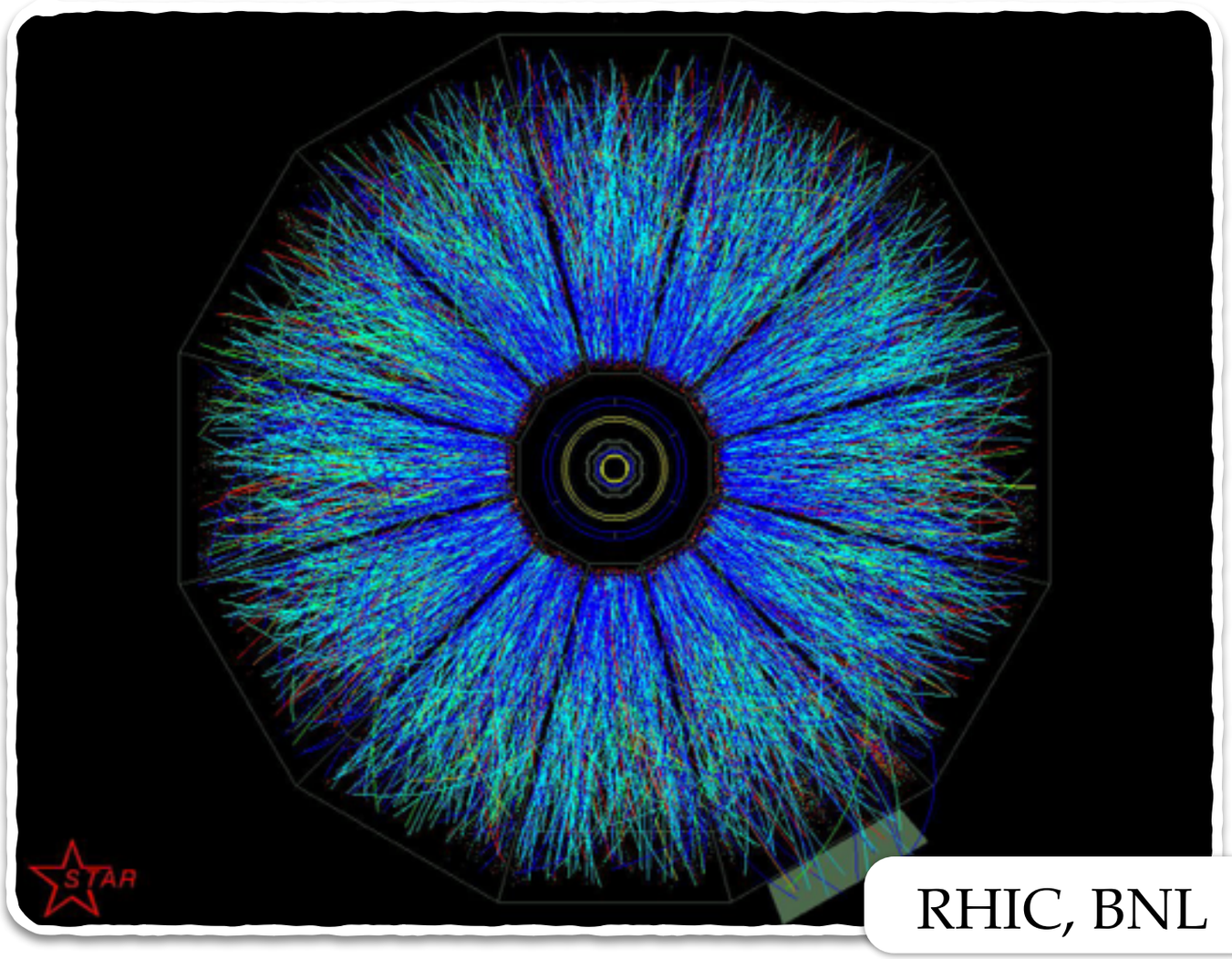
Step #3: detect the debris

isolate individual particles



RHIC, BNL

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Step #4: compare the outcome with theory

without theory, there's no meaning to experiments!
without experiments we do not know which theory is right!

Particle accelerators

(from a theorist's perspective)

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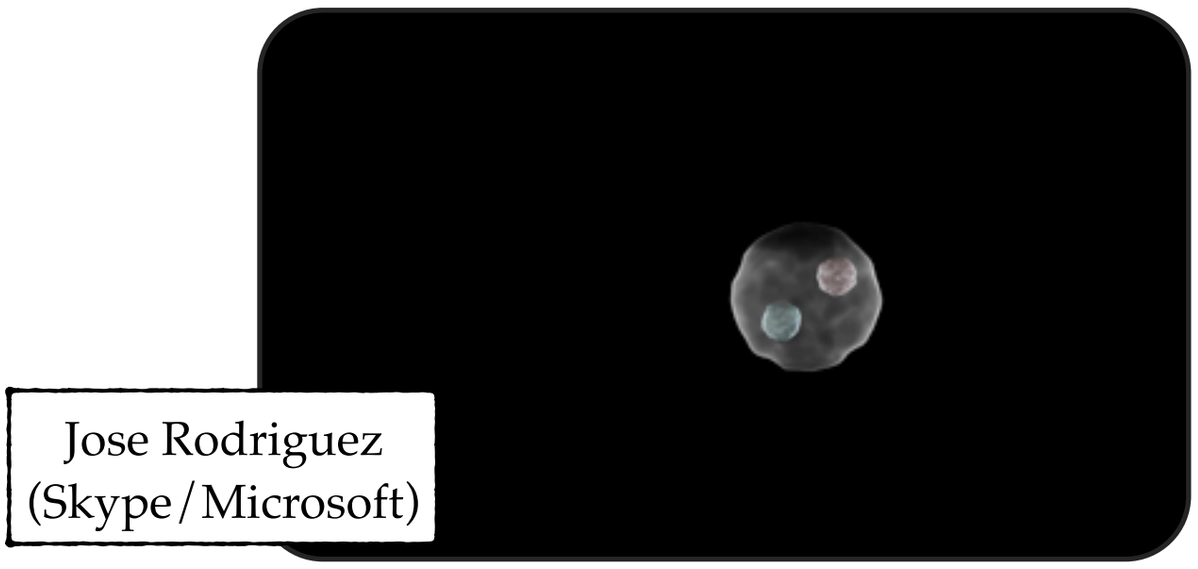

Jose Rodriguez
(Skype/Microsoft)

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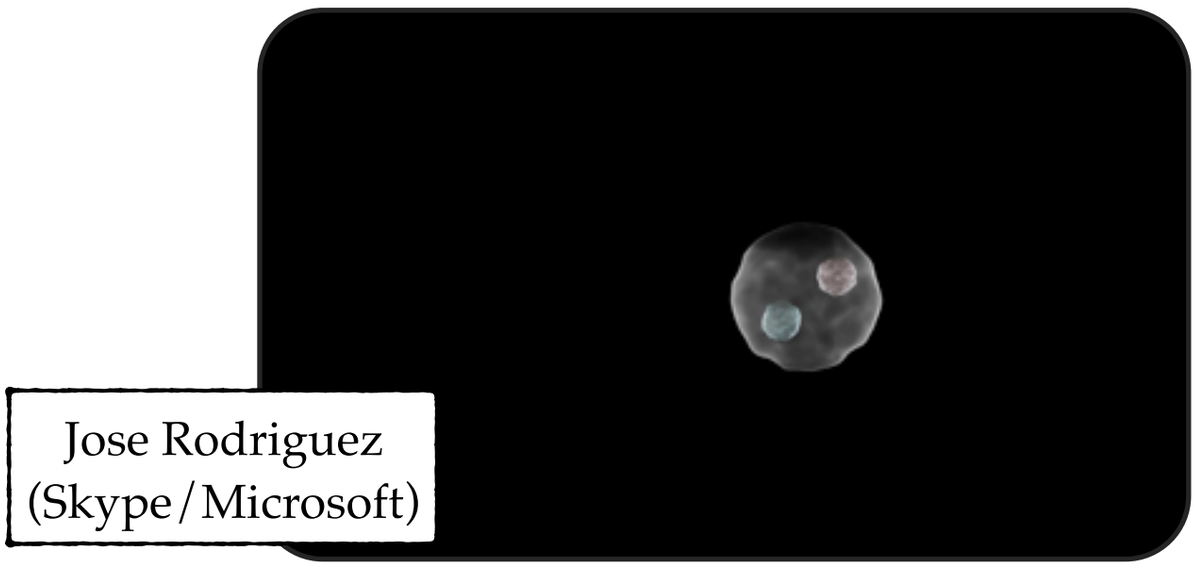


Jose Rodriguez
(Skype/Microsoft)

JLab's particle accelerator

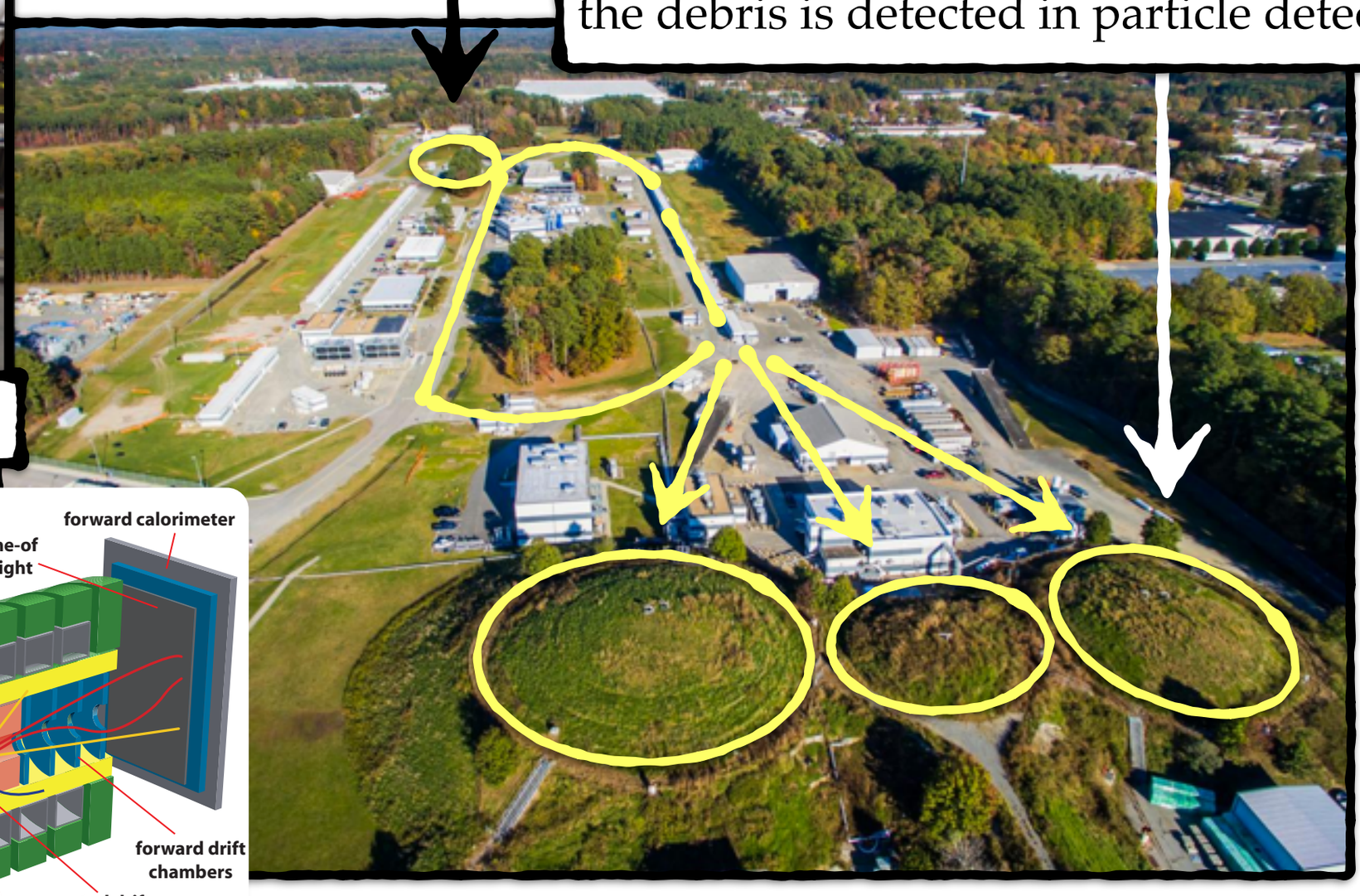
electrons are accelerate to speeds close to the speed of light

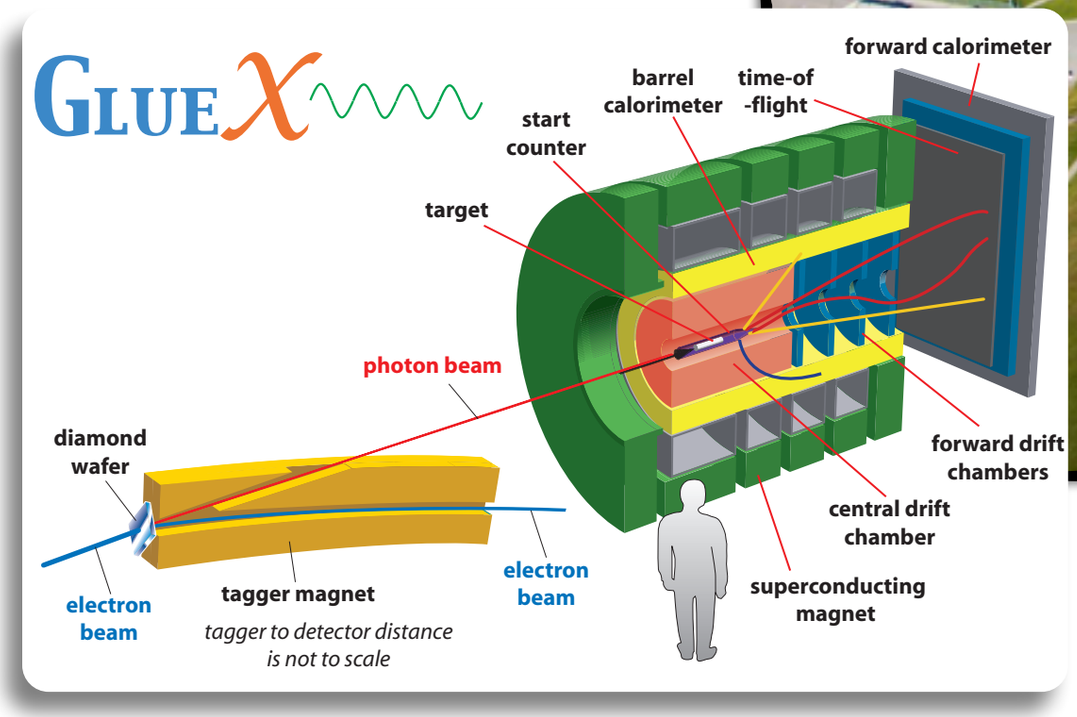
JLab's particle accelerator

David Wilson (ex-ODU postdoc)

the new GlueEx

these are smashed against a target,
the debris is detected in particle detectors

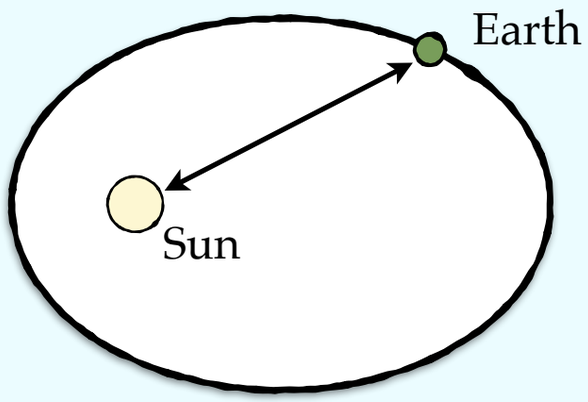




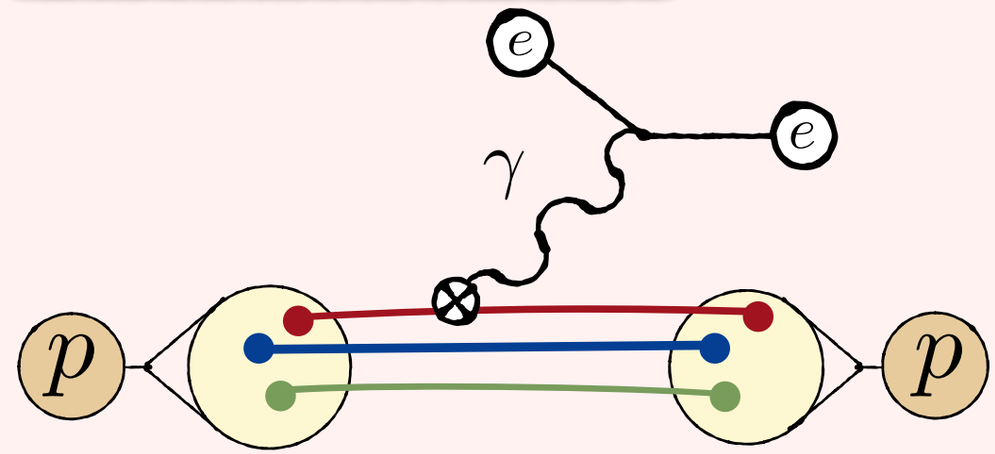
you too can visit lab and its various experiments!

The forces of nature

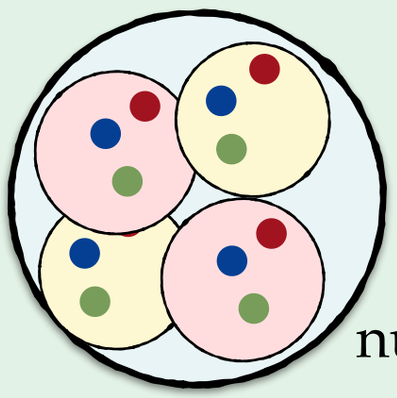
Gravitational force [GR]



Electromagnetic force [QED]

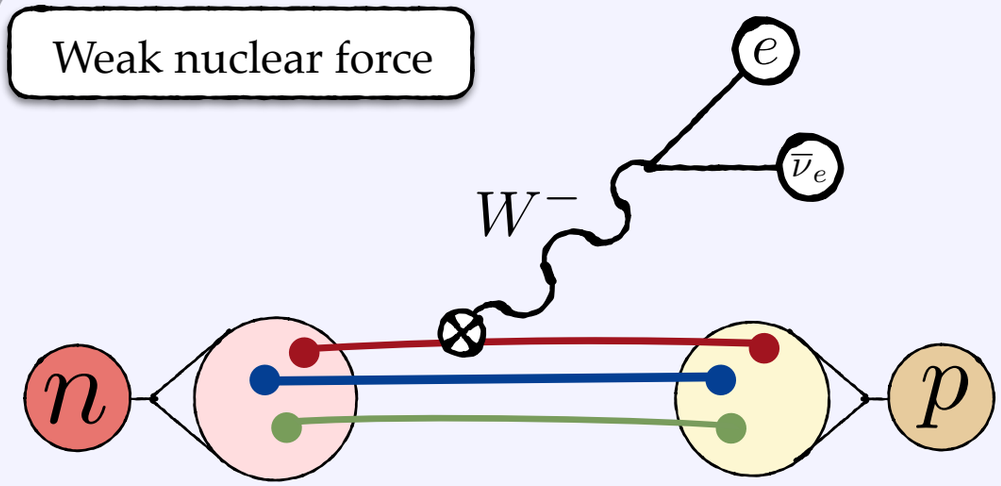


Strong nuclear force [QCD]



nuclei

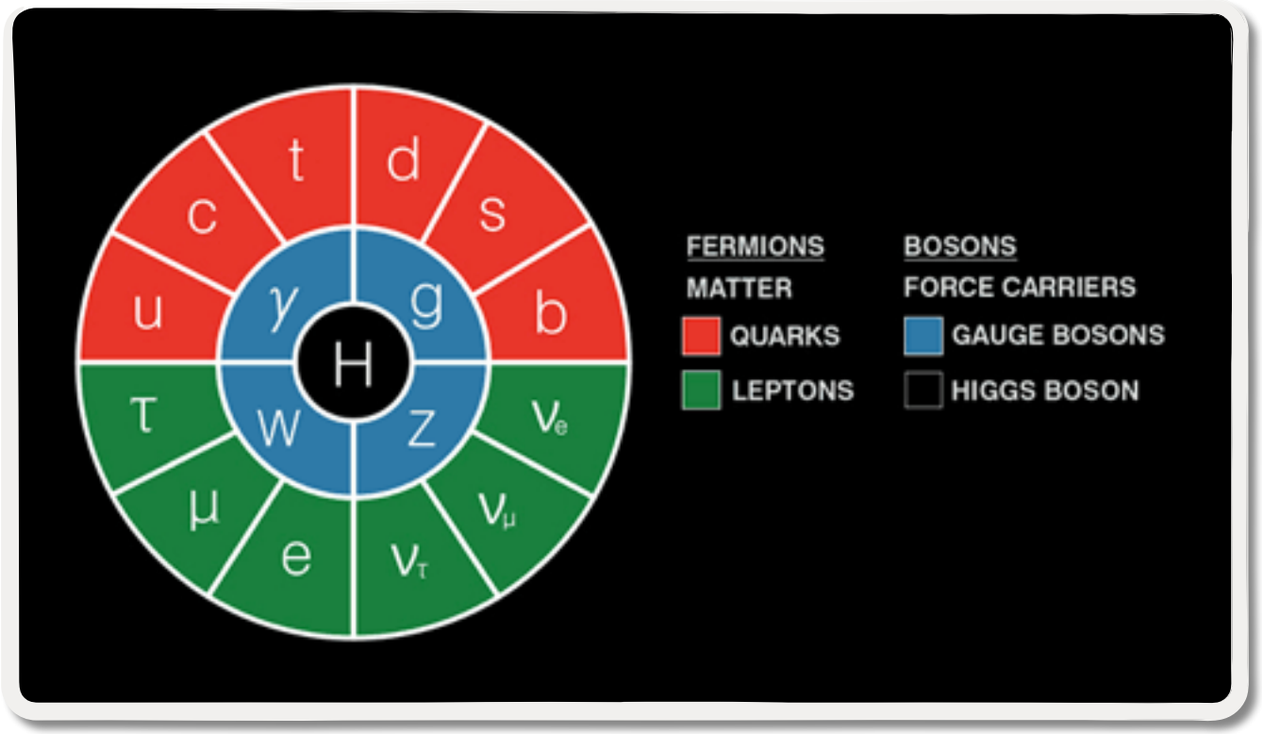
Weak nuclear force

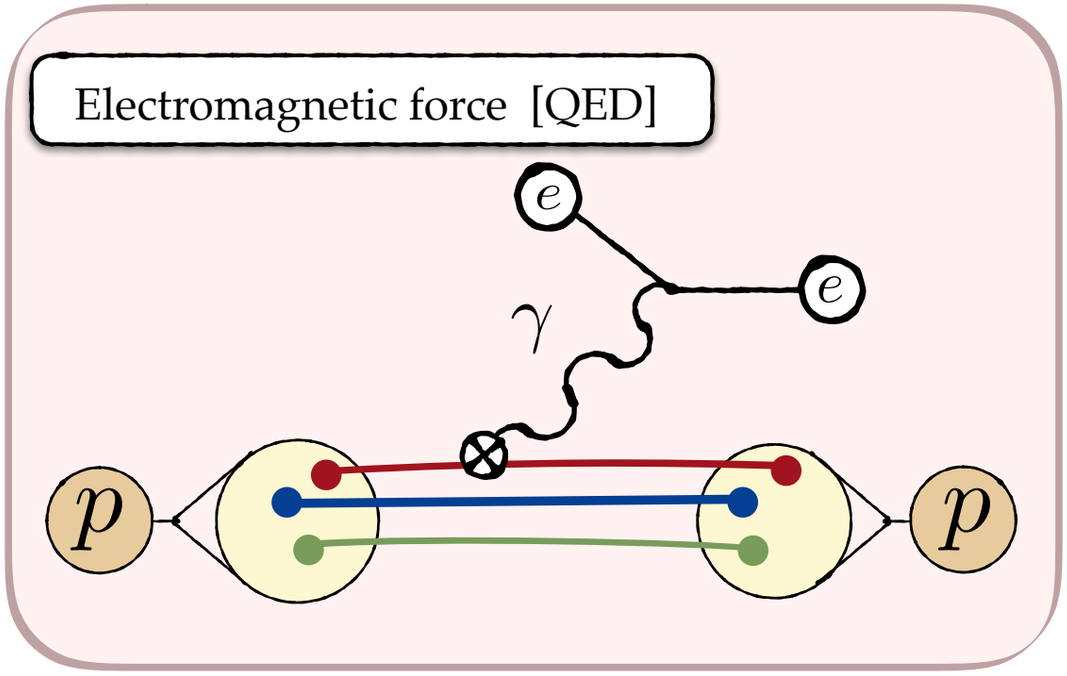


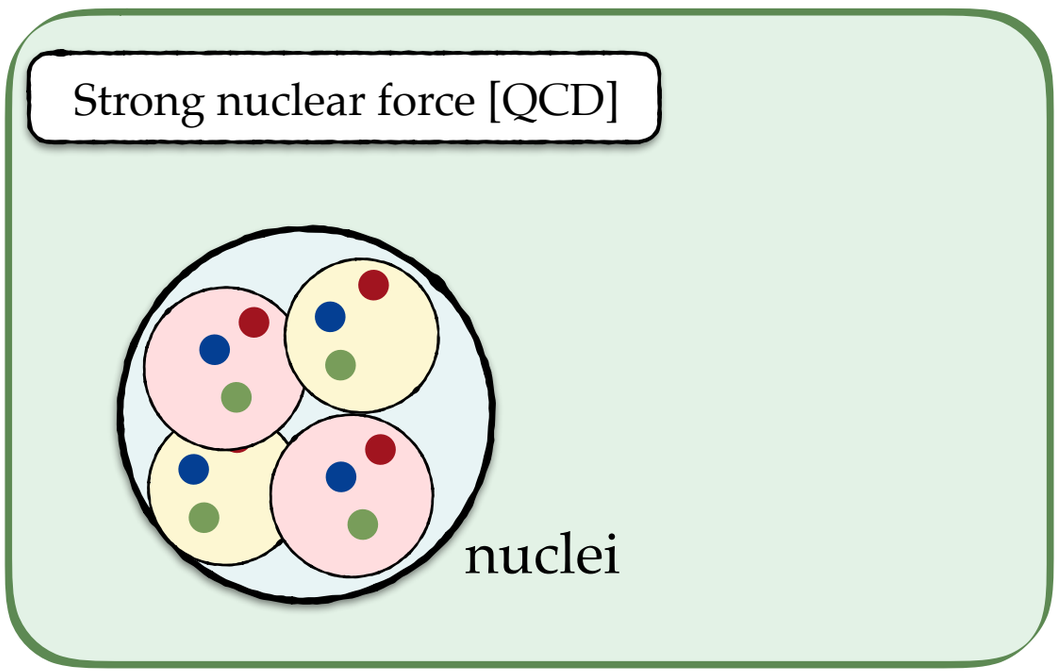
beta decay

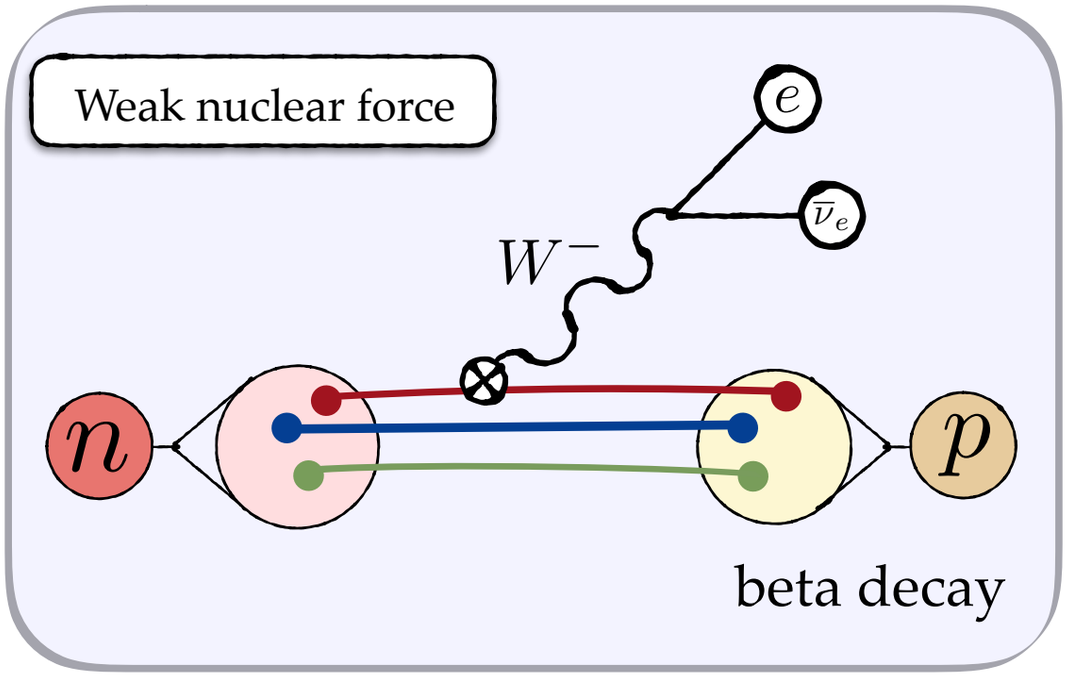
The standard model

of particle/nuclear physics



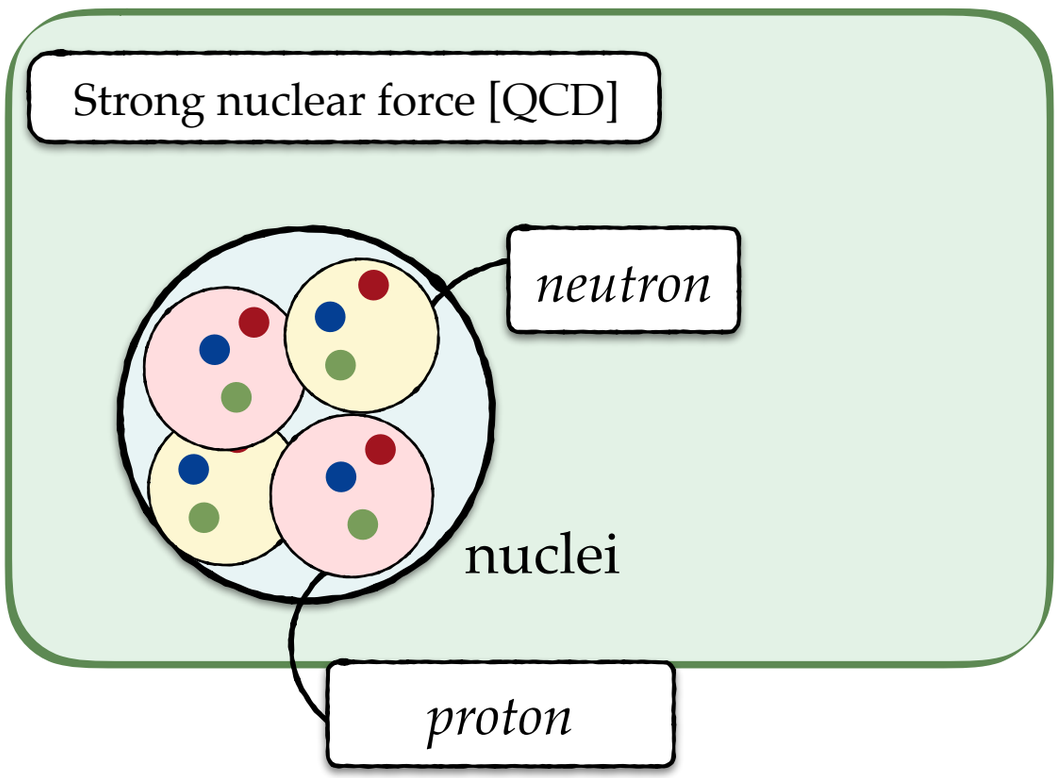






Quantum Chromodynamics

"The fundamental theory of the strong nuclear force"



atomic nuclei are composed of **protons** and **neutrons**

example: ^{12}C, the basis of life, is made of 6 protons and 6 neutrons

these interact and are bound together by the strong nuclear force

quarks and gluons, which also interact via the strong nuclear force

nuclear physics = physics of the strong nuclear force

Quantum Chromodynamics

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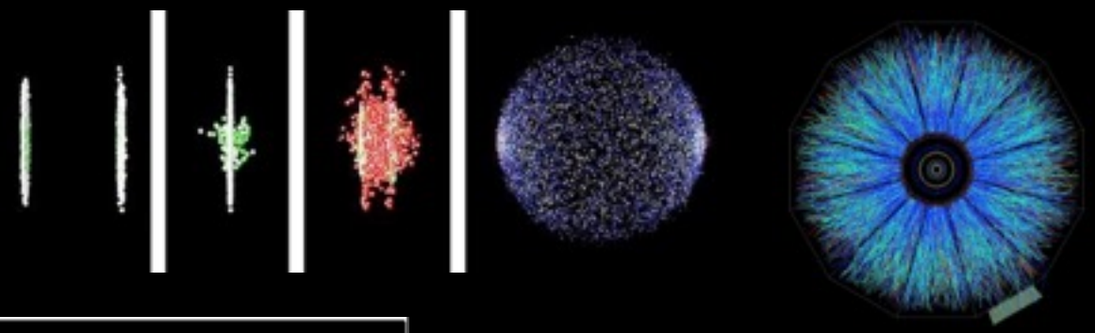
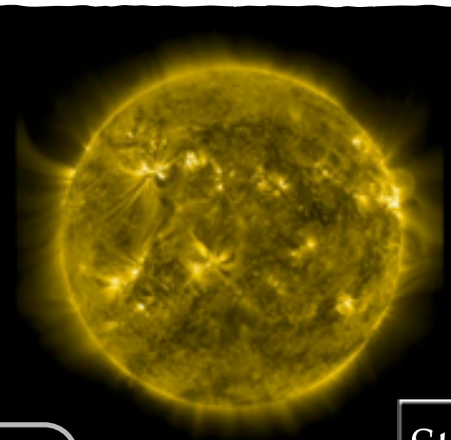


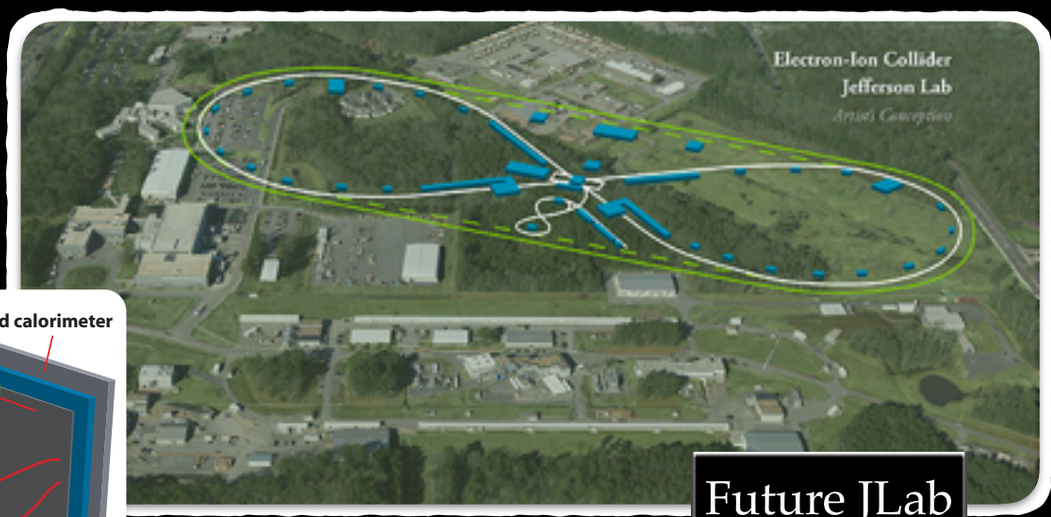
Heavy ion collisions

$$\mathcal{L}_{\mathbf{QCD}} = \bar{\psi}_{\mathbf{f}} \left(\mathbf{i} \not{\mathbf{D}} - \mathrm{m}_{\mathrm{f}} \right) \psi_{\mathbf{f}} - \frac{\mathbf{1}}{\mathbf{4}} \mathrm{tr} \left(\mathrm{GG} \right)$$

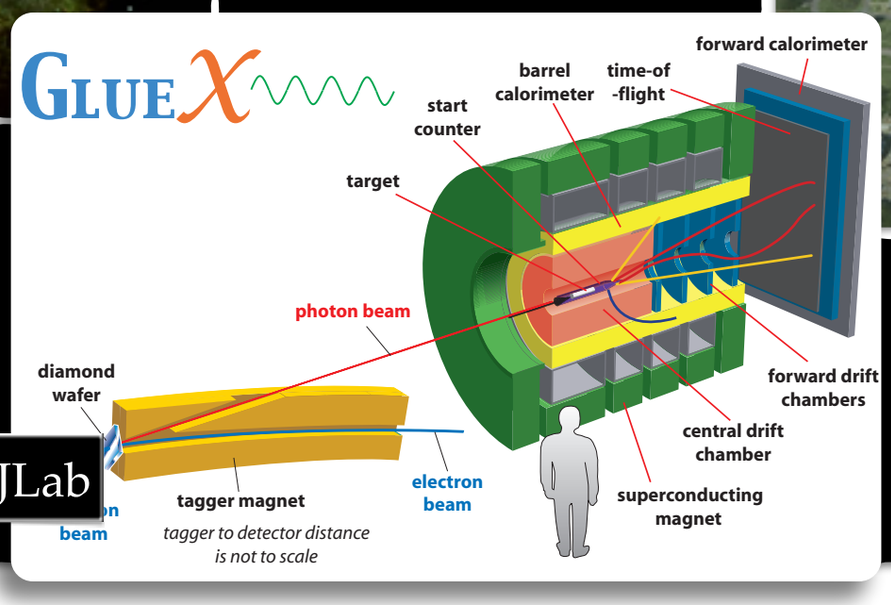


Stellar evolution

Supernova



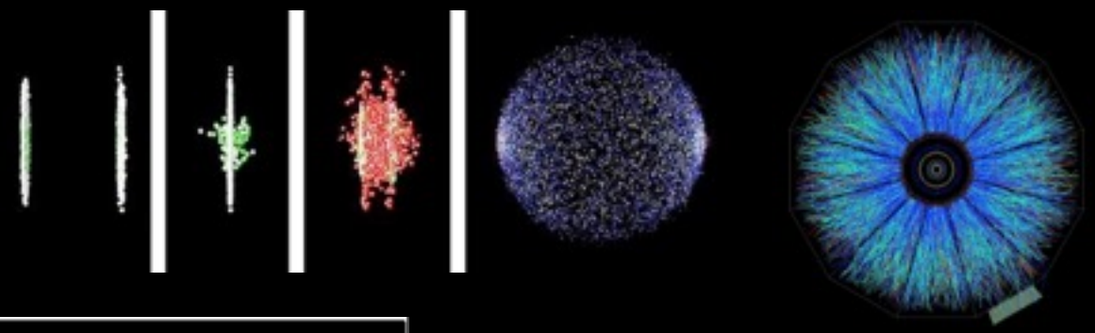
Future JLab



Present JLab

Quantum Chromodynamics

"The fundamental theory of the strong nuclear force"



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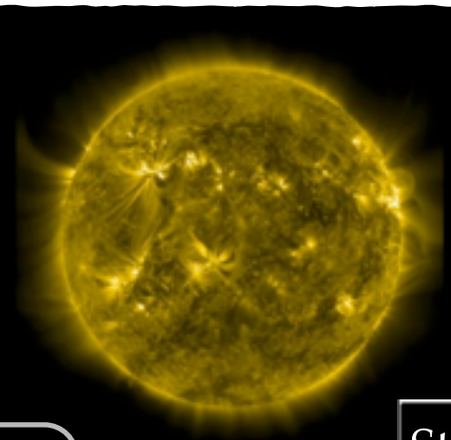

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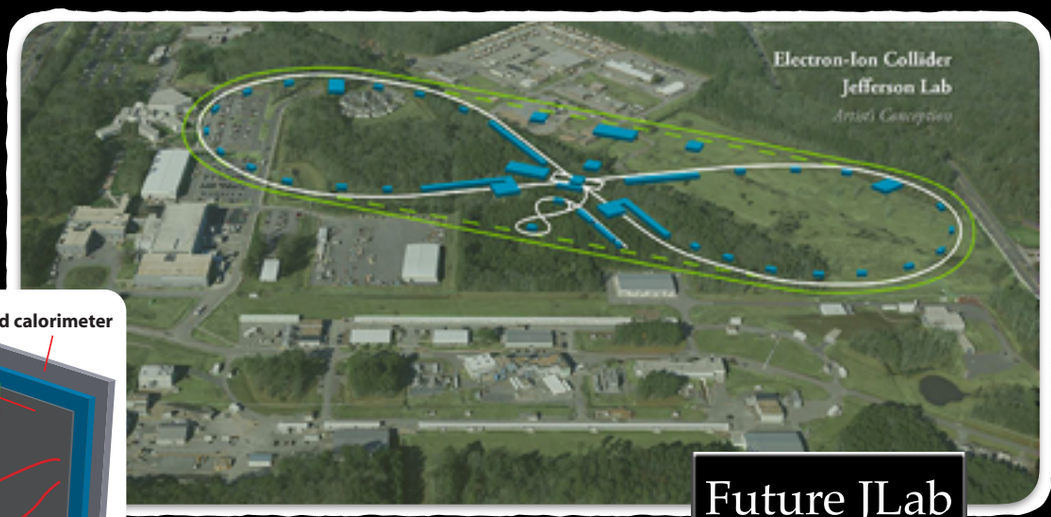

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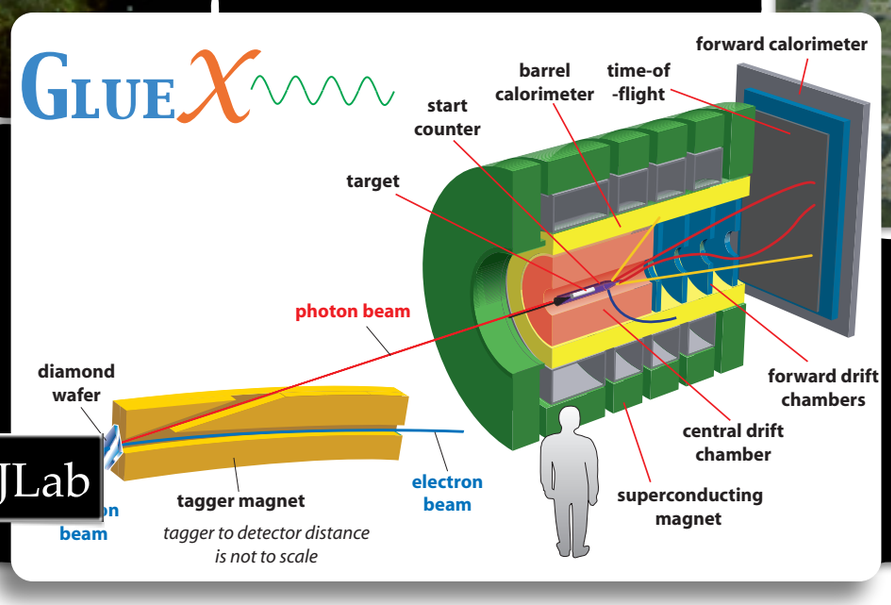


Present JLab

Quantum Chromodynamics

- ***quarks & gluons*** carry "***color***"
- ***quarks*** come in six different "***flavors***"

$$\mathcal{L}_{\mathbf{QCD}} = \bar{\psi}_{\mathrm{f}} \left(\mathbf{i} \not{\mathbf{D}} - \mathrm{m}_{\mathrm{f}} \right) \psi_{\mathbf{f}} - \frac{\mathbf{1}}{\mathbf{4}} \mathrm{tr} \left(\mathrm{GG} \right)$$

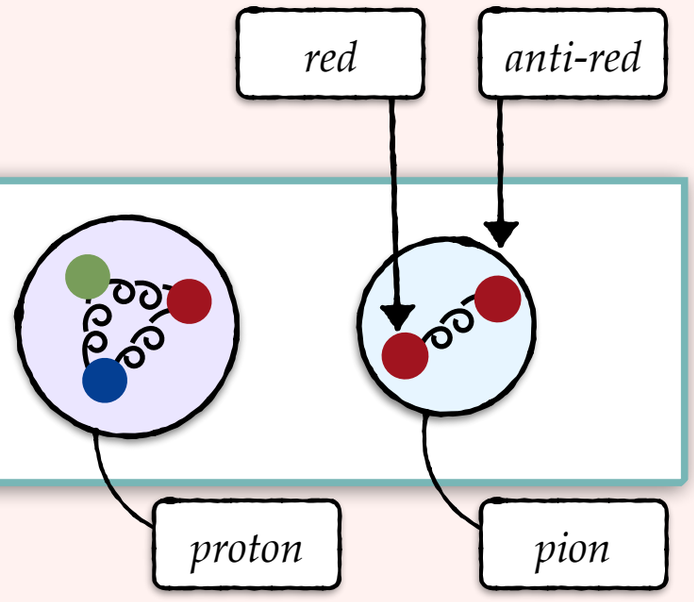
WARNING!

Different flavors have wildly different caloric content!

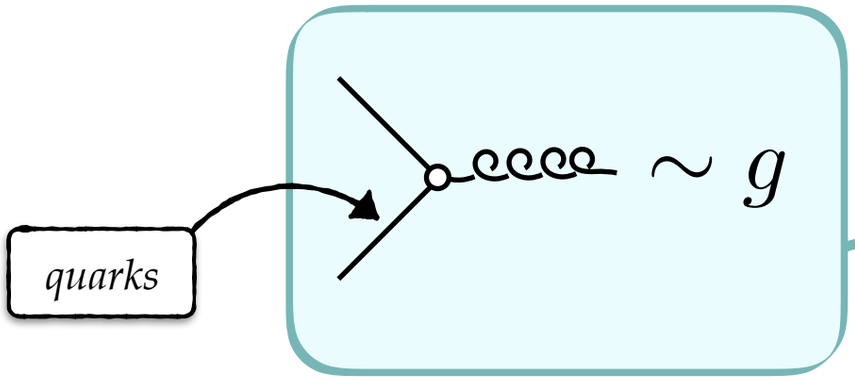
"confinement"

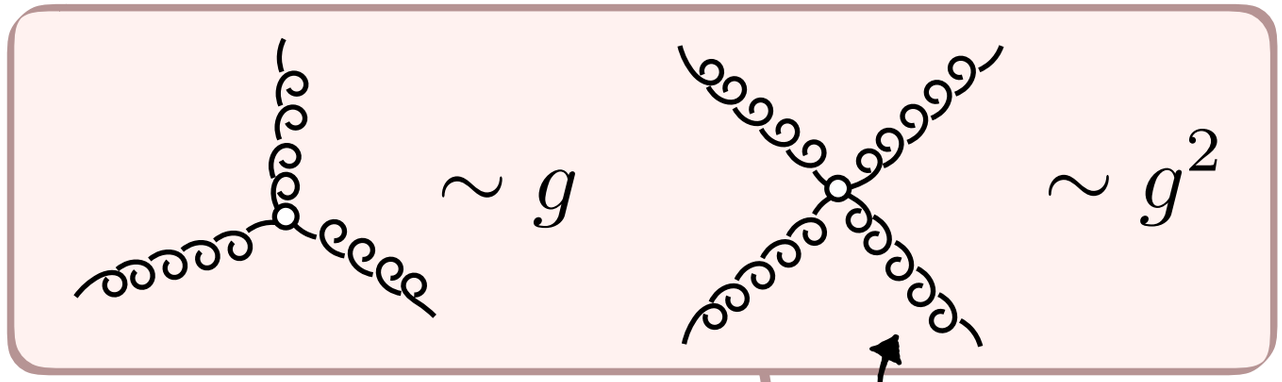
confined to color neutral bound states:

- red+blue+green
- red+anti-red



Quantum Chromodynamics





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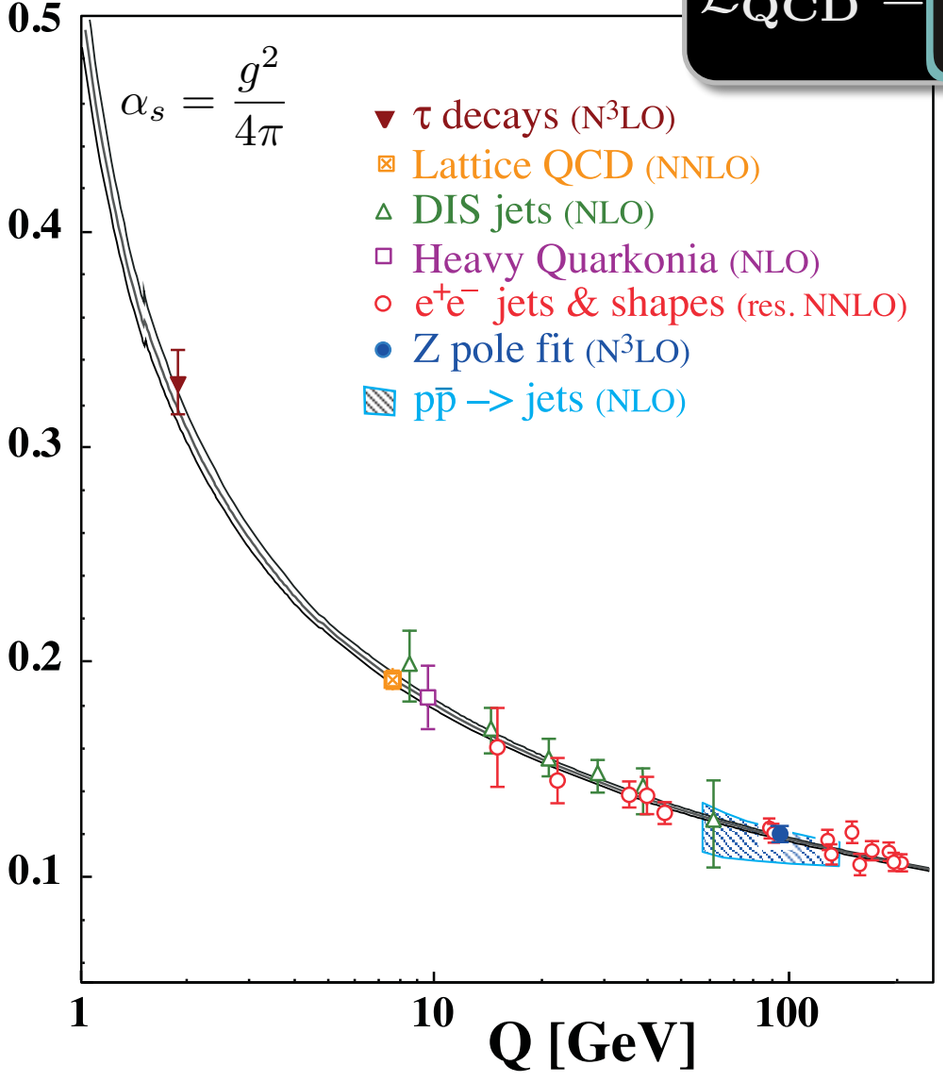
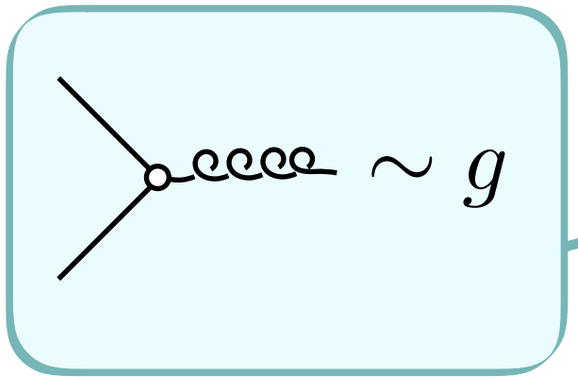
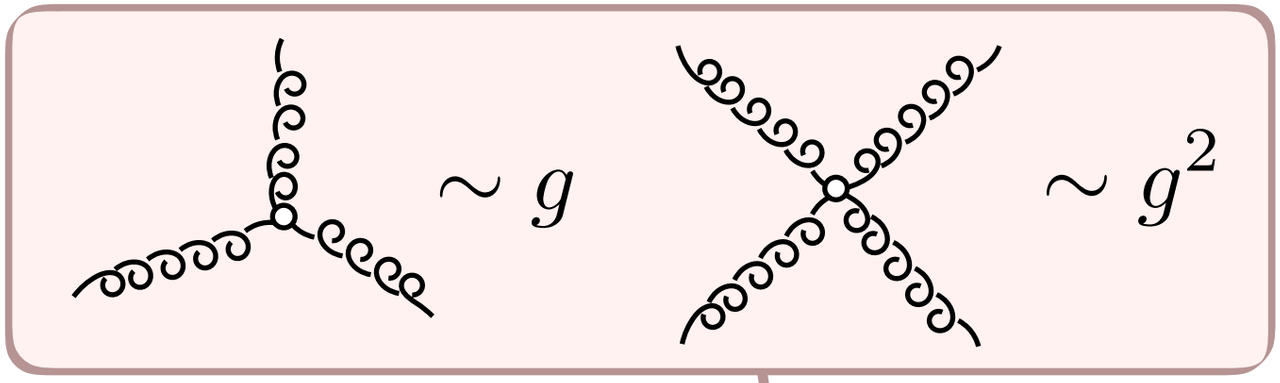
gluons



Quantum Chromodynamics





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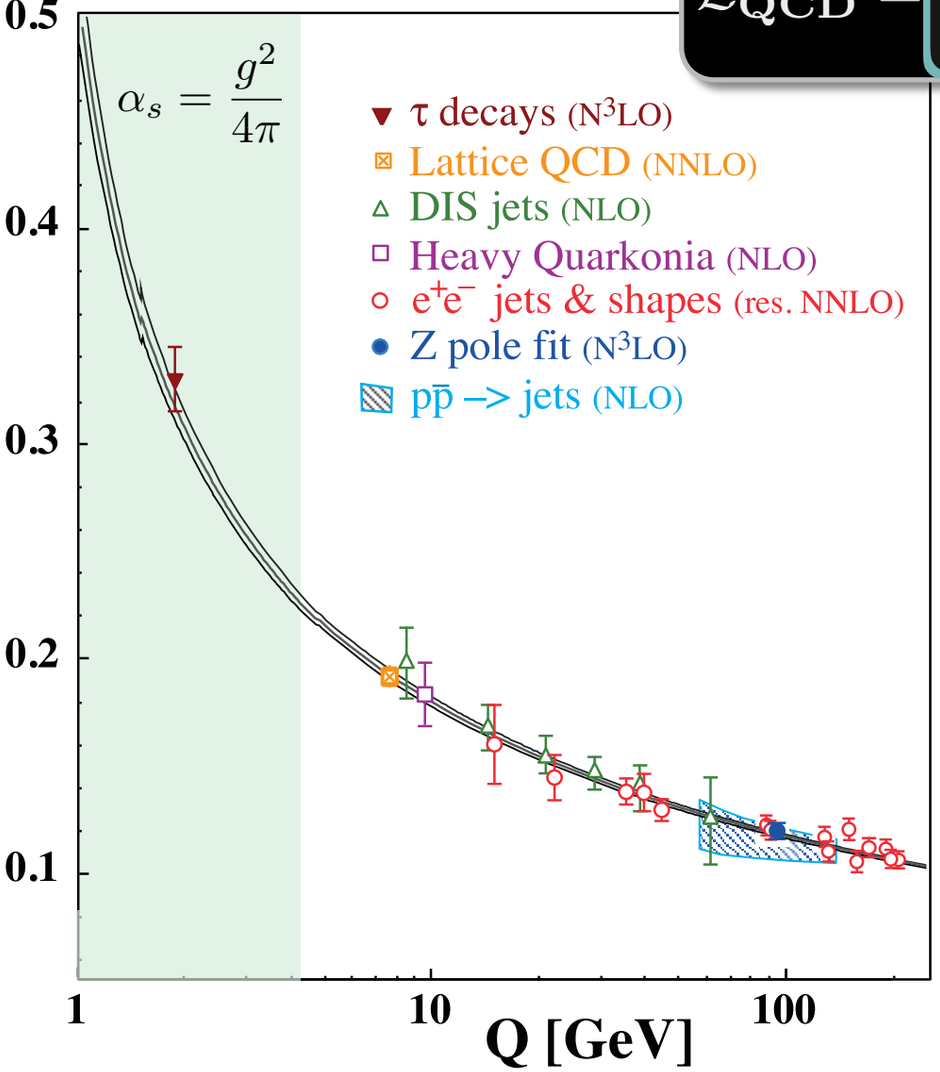
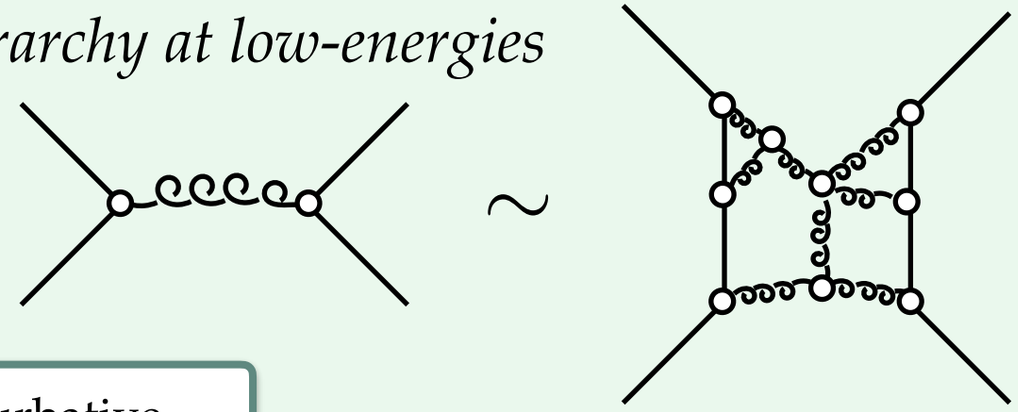


No hierarchy at low-energies



non-perturbative….

- *confinement?*
- *origin of mass?*
- *formation of matter*
- …

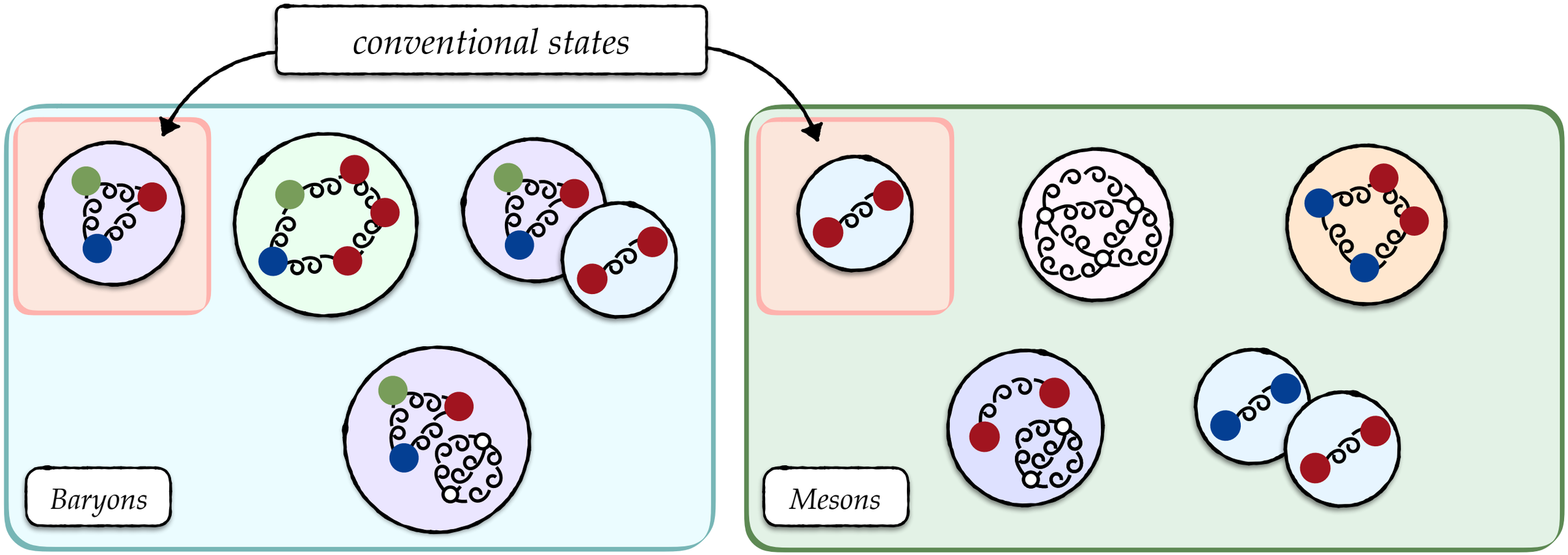
Desperate for a Nobel Prize?

Quantum Chromodynamics

Jose Rodriguez (Skype/Microsoft)

Hadrons

QCD's rich spectrum



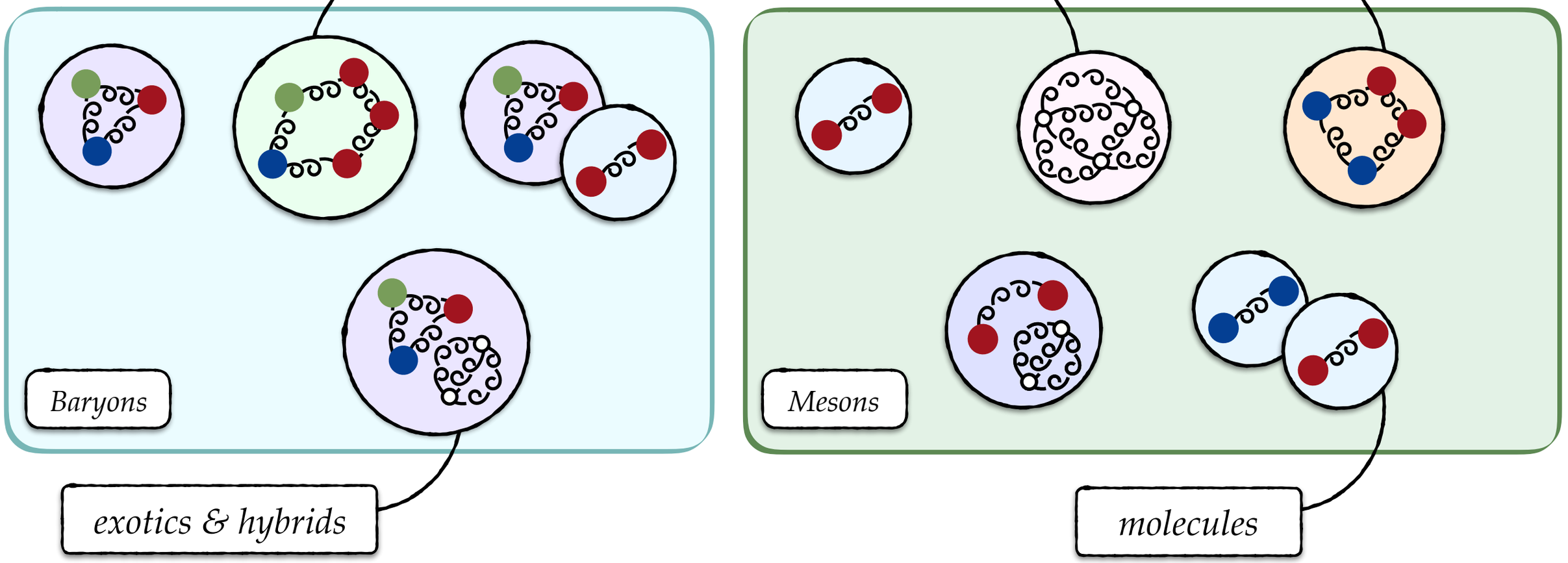
Hadrons

QCD's rich spectrum

pentaquarks - LHCb (2015)

glueballs

tetraquarks - Belle (2003)



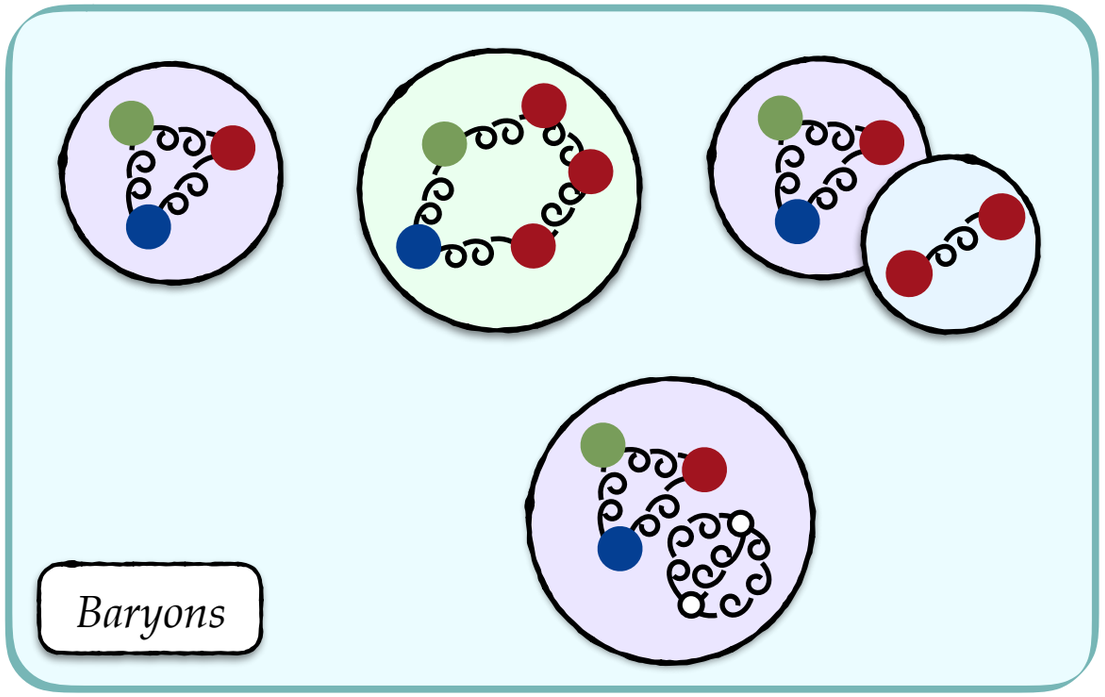
exotics & hybrids

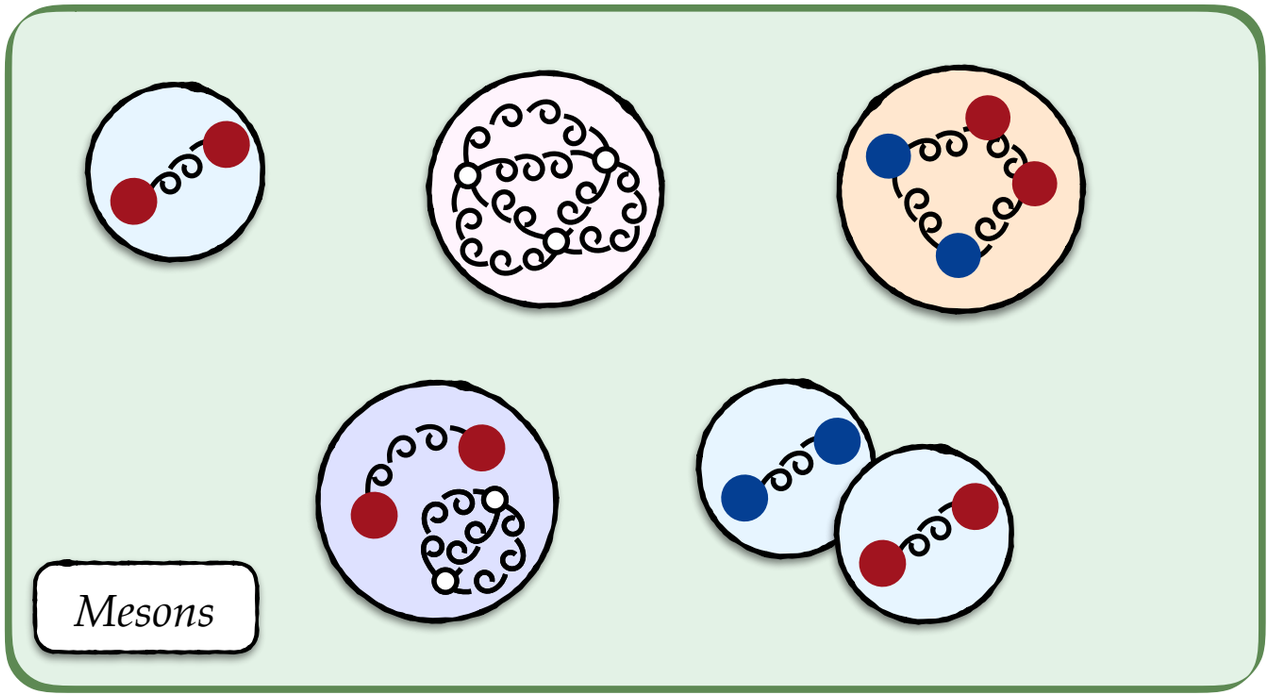
molecules

JLab searches:

Hadrons

QCD's rich spectrum





$$|n\rangle_{\mathrm{QCD}} = c_0 + c_1 + c_2 + c_3 + \cdots$$

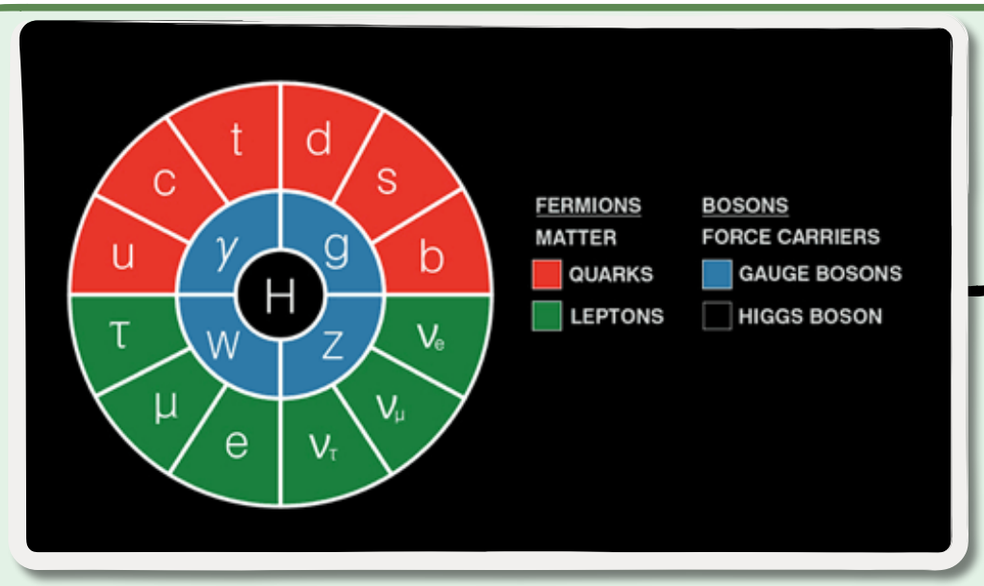
…but perhaps there is a hierarchy [.e.g. $c_0 > c_1 > c_2 > c_3$*]*

Questions?

Lattice QCD

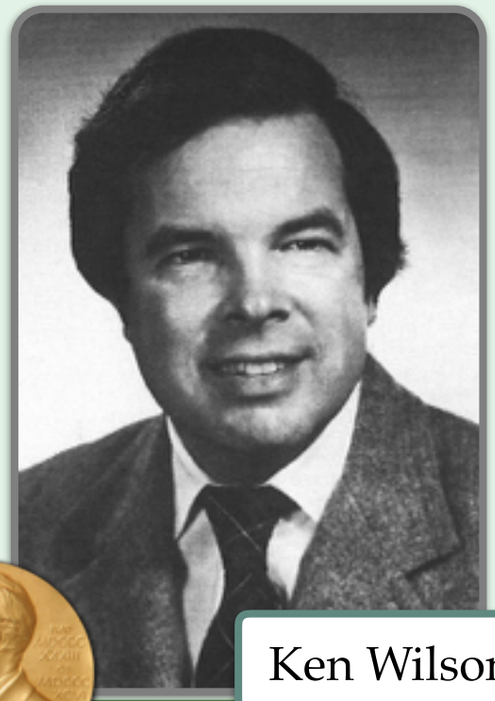
In summary:

- QCD is non-perturbative
- Solution: *be smart* and *let computers do the hard work!*

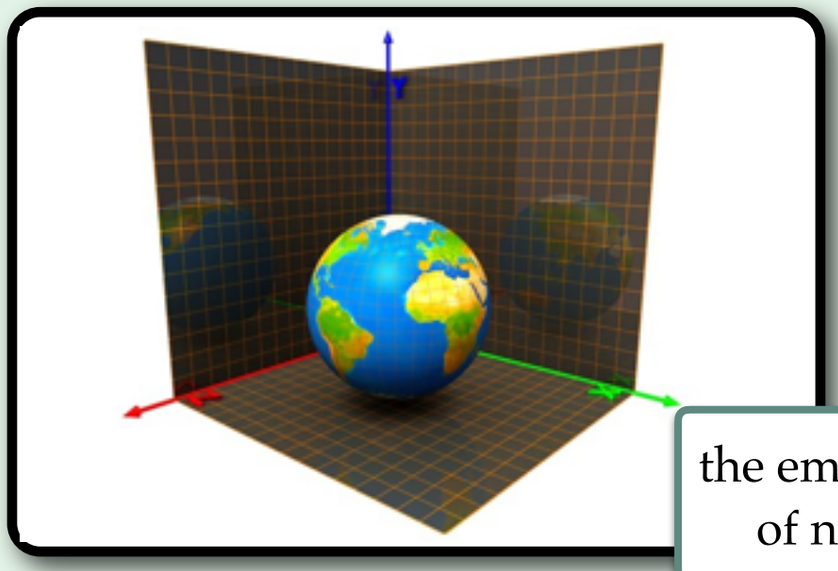


Virginia's biggest and fastest supercomputer

Richard Feynman



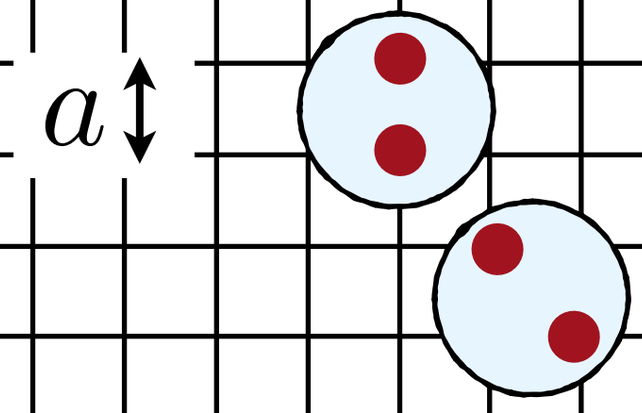
Ken Wilson

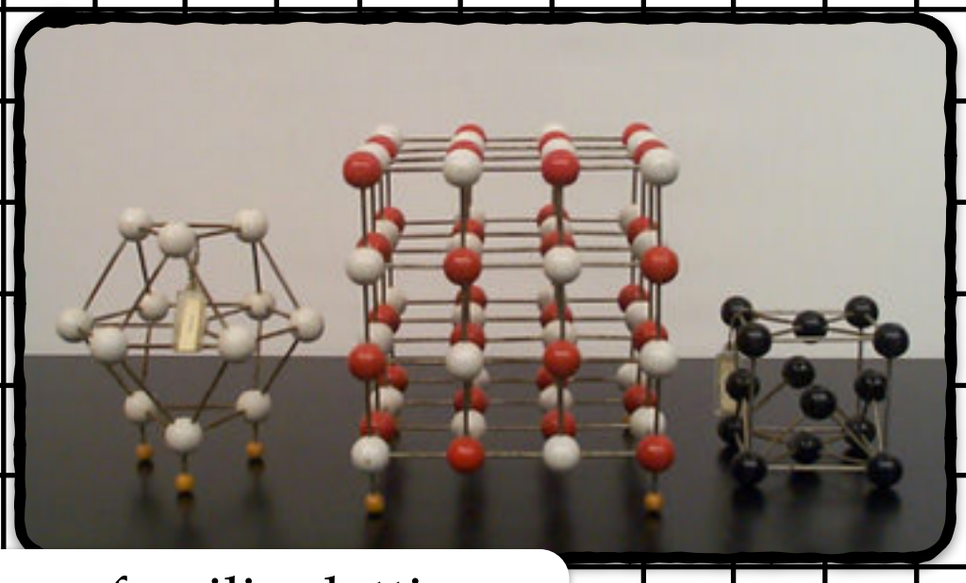


the emergence of nature

Lattice QCD

- lattice spacing: $a \sim 0.03 - 0.15$ fm

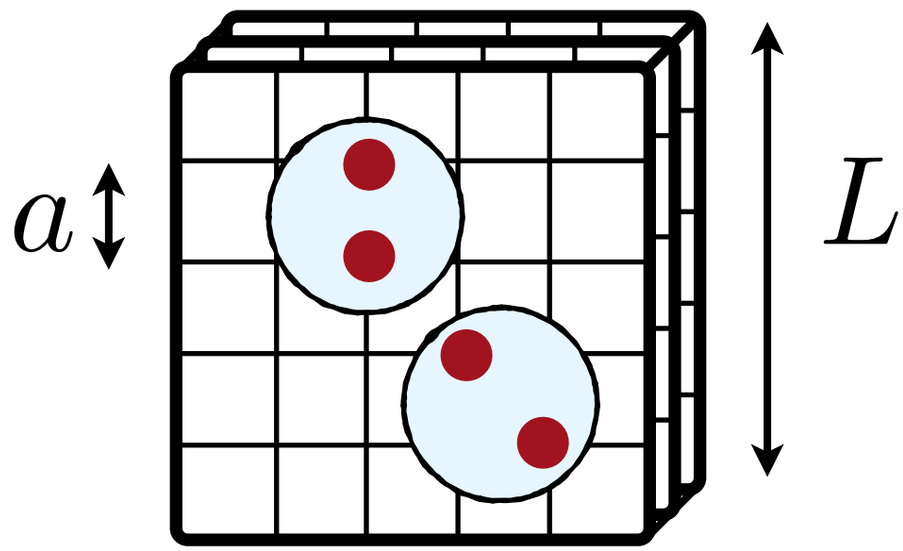




more familiar lattices

Lattice QCD

- lattice spacing: $a \sim 0.03 - 0.15$ fm
- finite volume: $L \sim 4 - 10$ fm

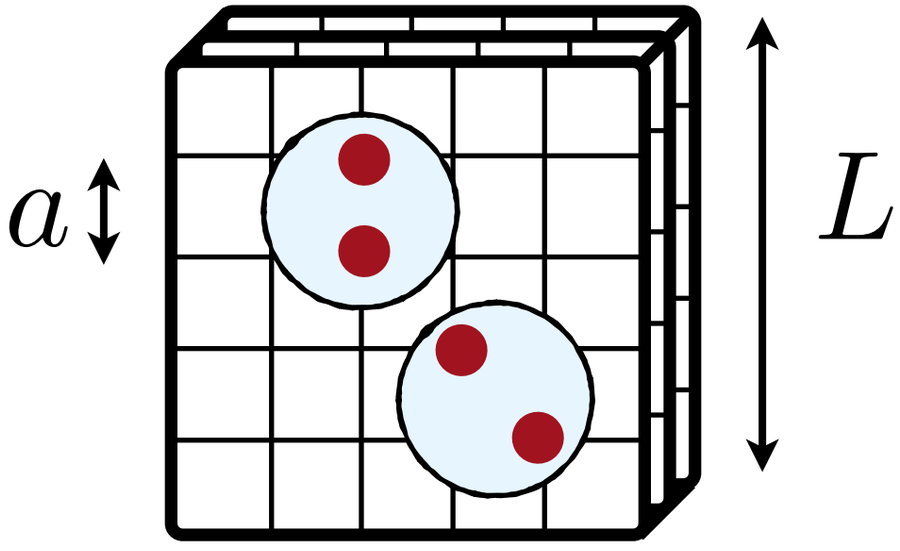


Never free!

No reactions!

Lattice QCD

- lattice spacing: $a \sim 0.03 - 0.15$ fm
- finite volume: $L \sim 4 - 10$ fm
- quark masses

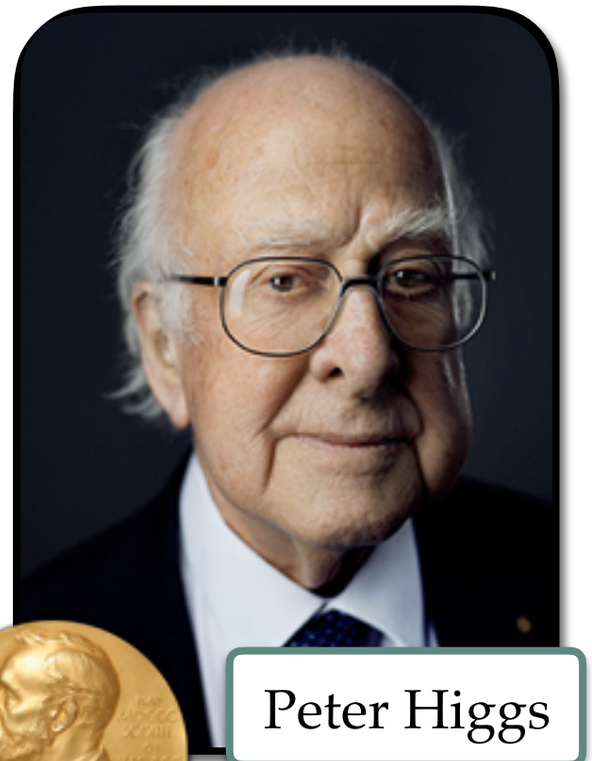


Advantage over experiment!

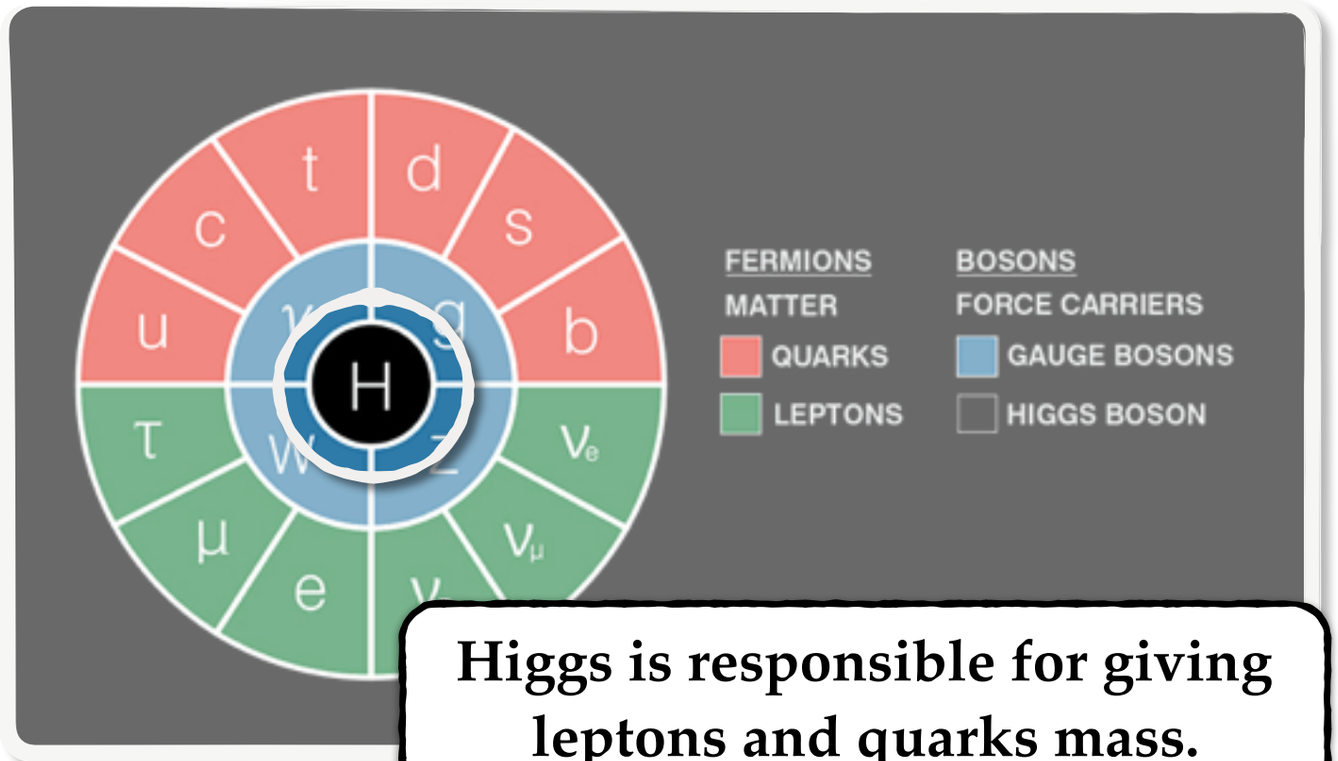
the origin of mass

2012, LHC @ CERN

Francois Englert

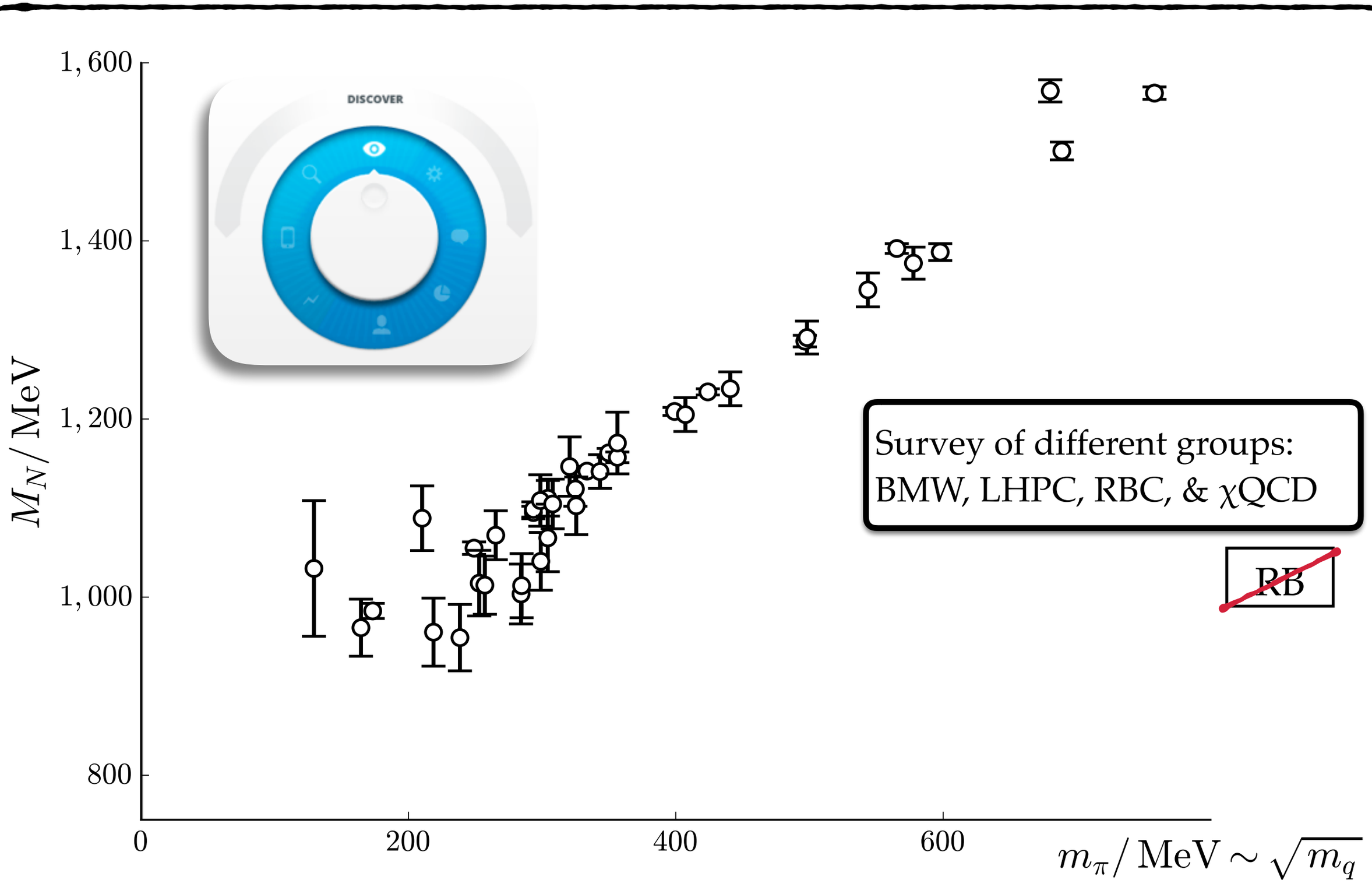


Peter Higgs



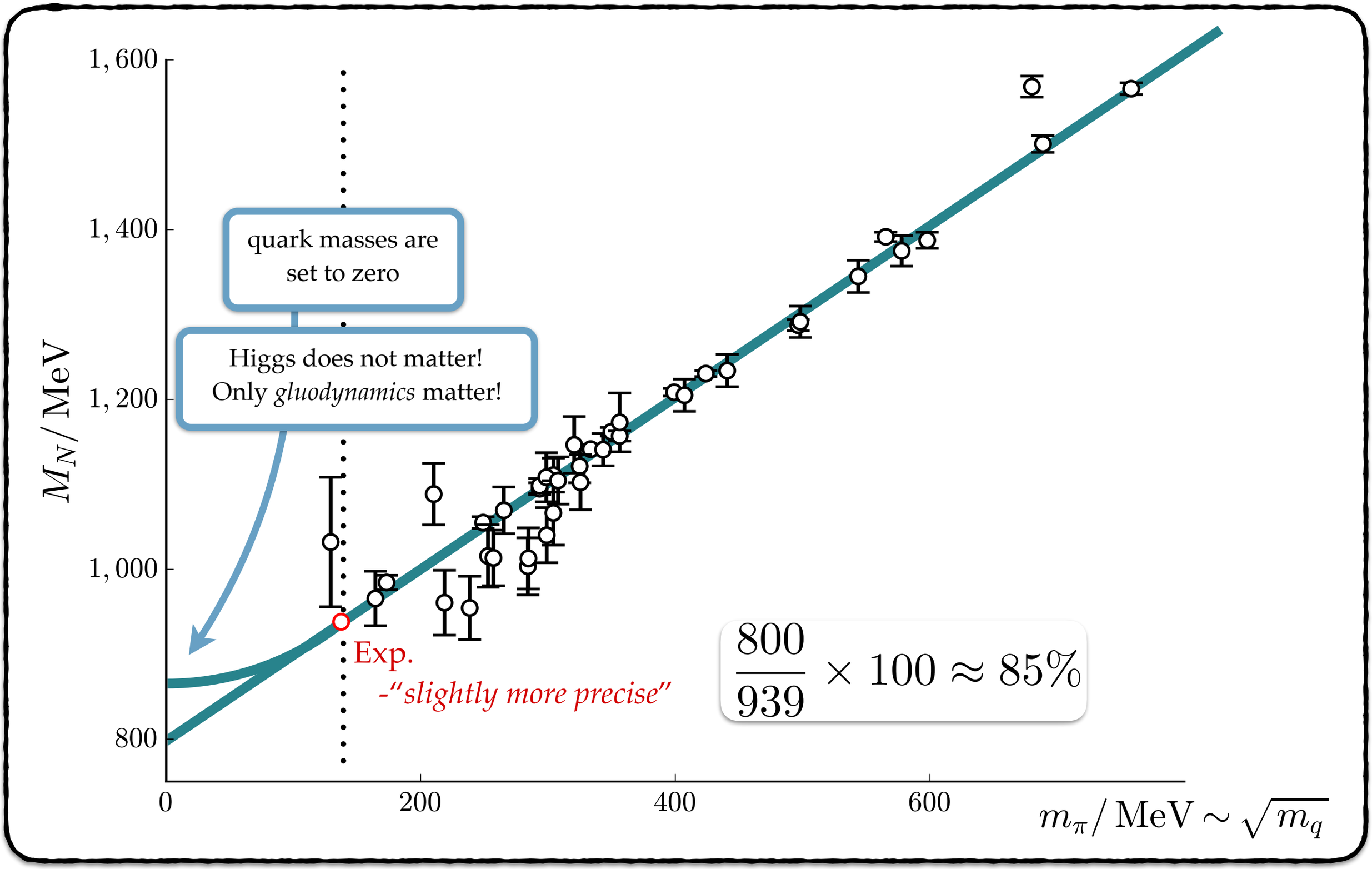
Higgs is responsible for giving leptons and quarks mass.

the origin of mass



the origin of mass

the origin of mass



the origin of mass

>

M_N/ MeV

1, 600

1, 400

1, 200

1, 000

800

Exp.

-"slightly more precise"

$$\frac{800}{939} \times 100 \approx 85\%$$

0

200

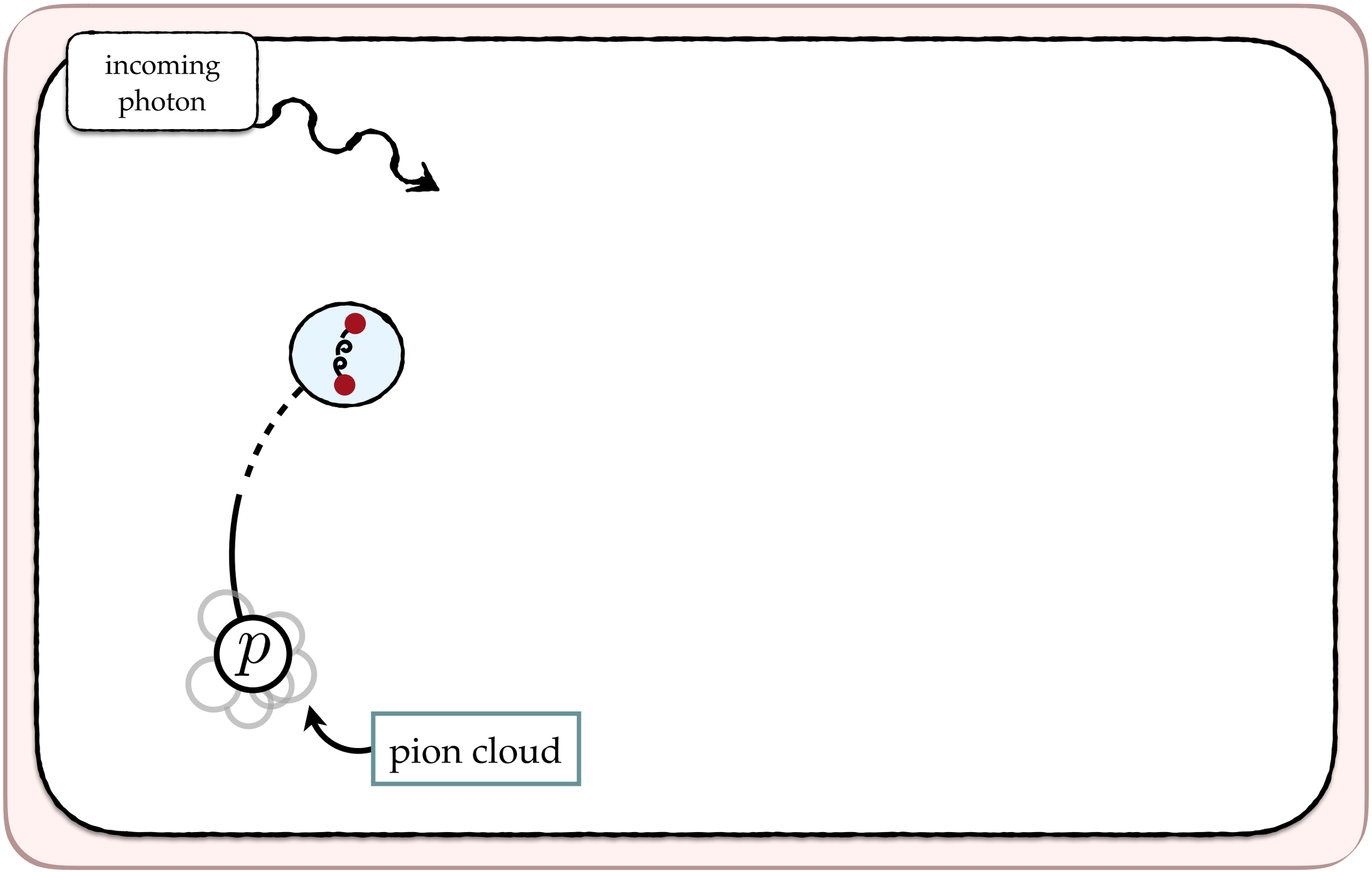
400

600

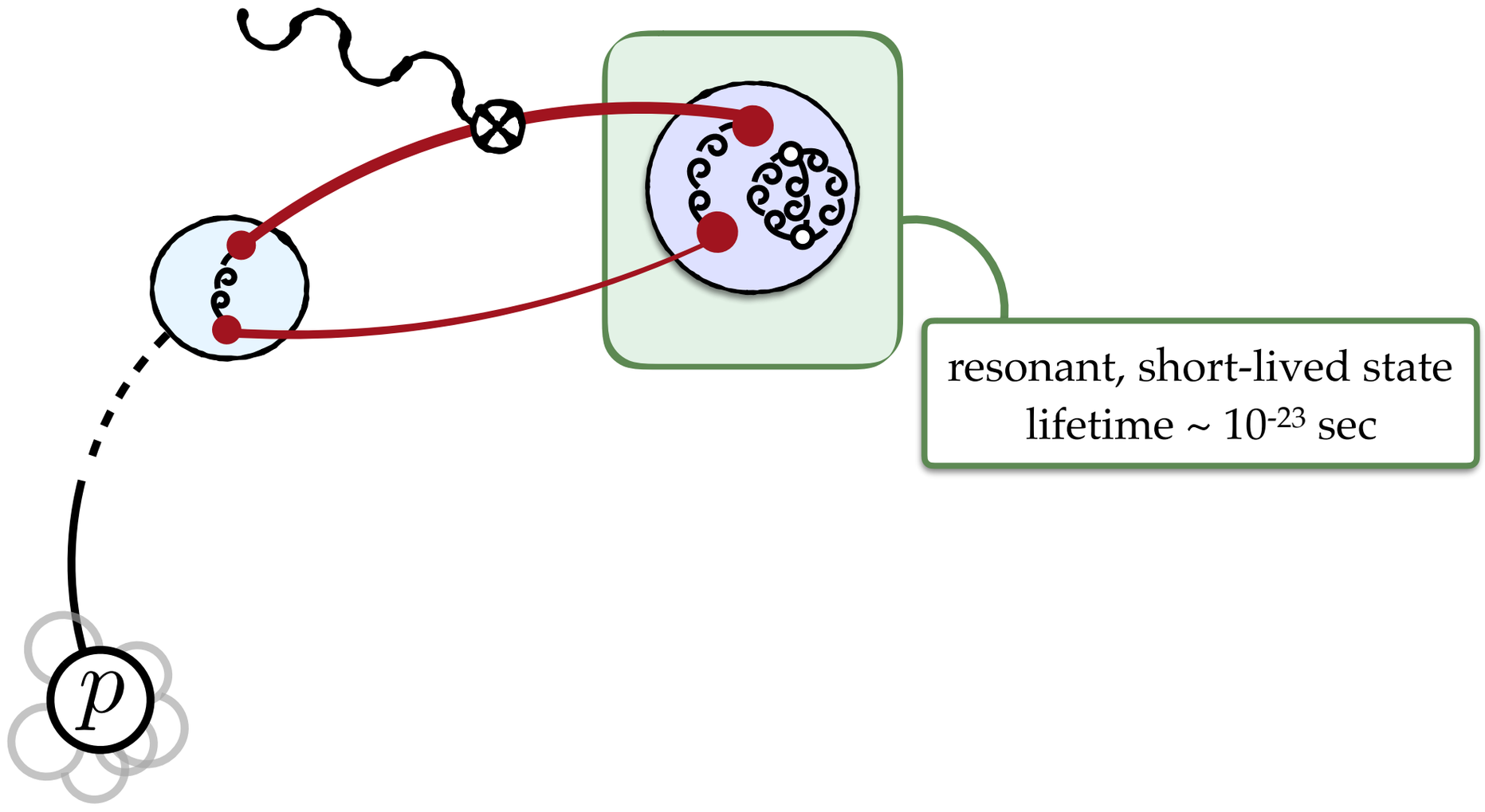
m_π/ MeV $\sim \sqrt{m_q}$

Searches for glue at JLab

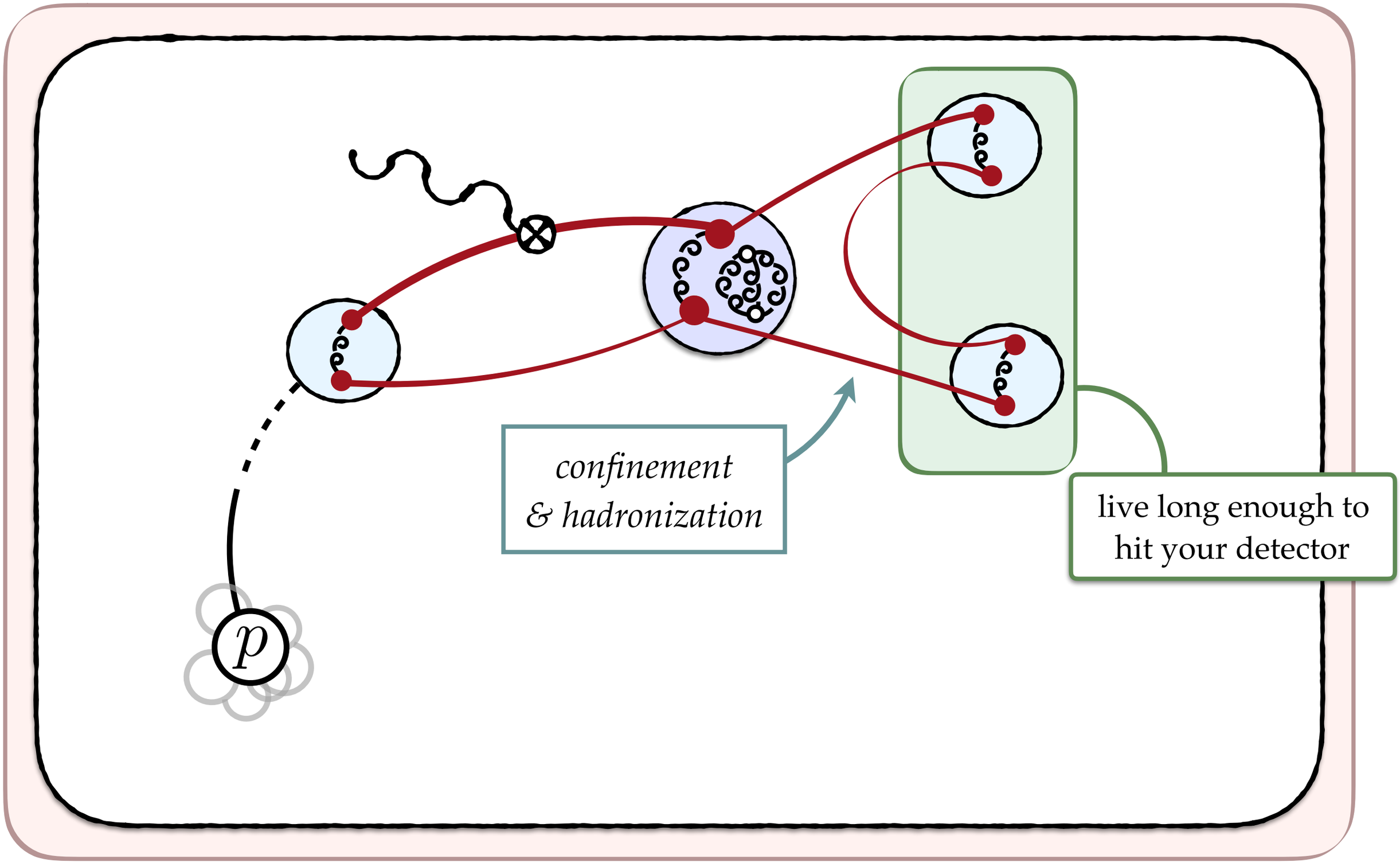
Searches for glue at JLab



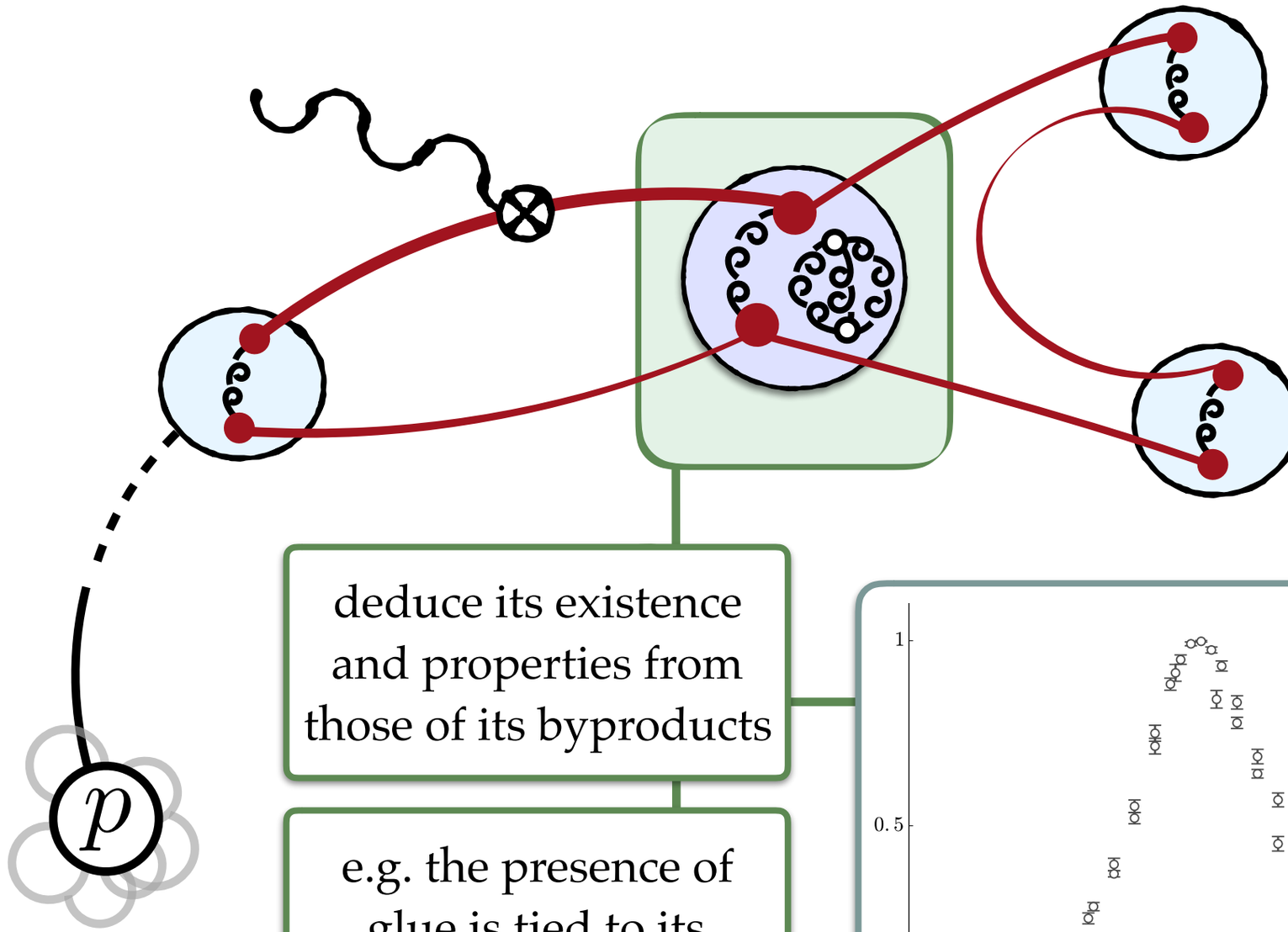
Searches for glue at JLab



Searches for glue at JLab

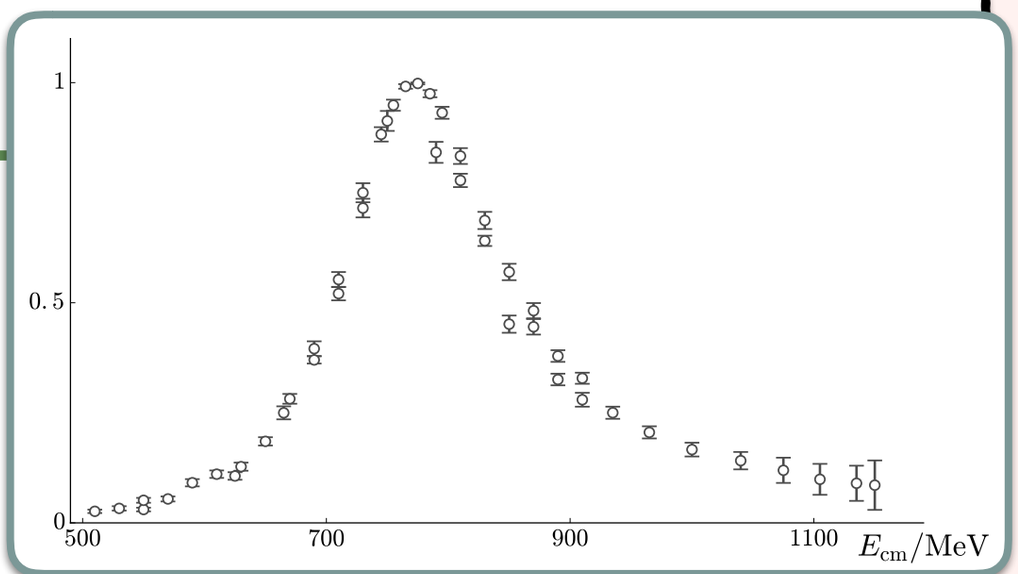


Searches for glue at JLab



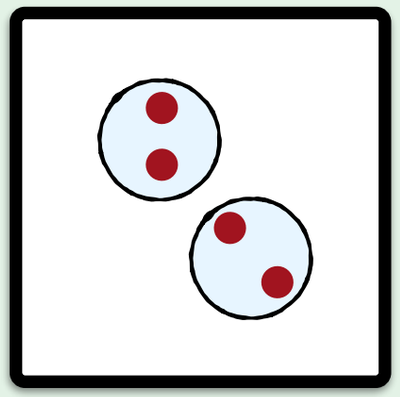
deduce its existence and properties from those of its byproducts

e.g. the presence of glue is tied to its quantum numbers



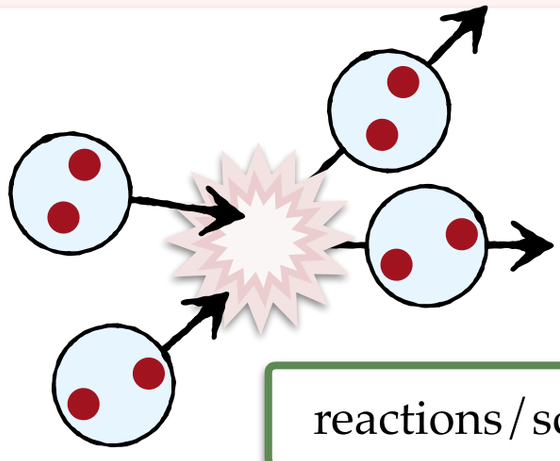
Reactions from QCD

- Puzzle:
  - Need to use LQCD
  - Particles cannot be separated
  - No scattering or reactions in a finite-volume!



- Observation #1:

$\langle \hat{V} \rangle$ ⟷



interacting potential

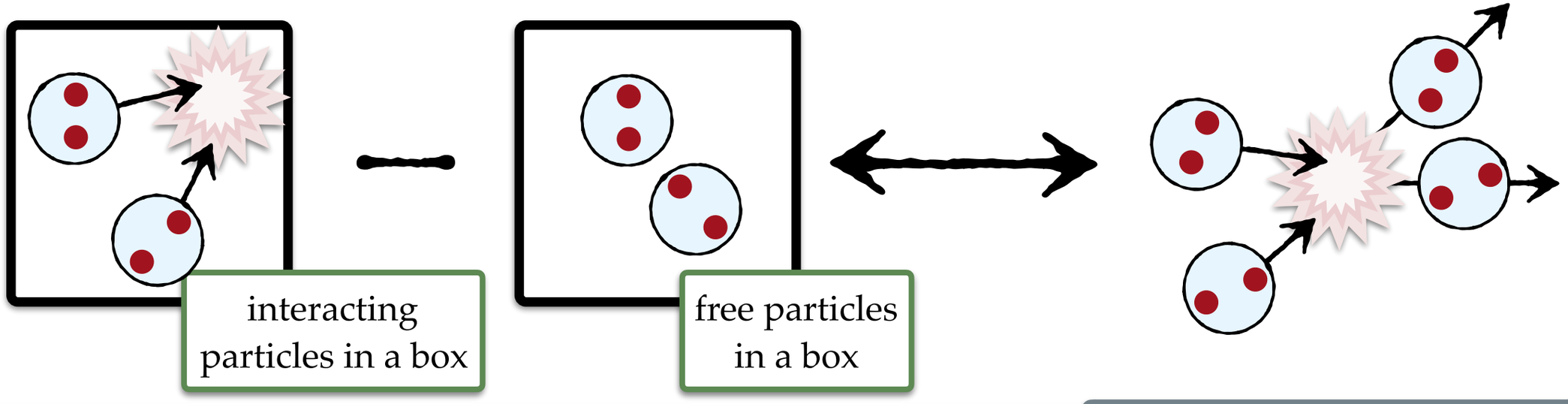
reactions / scattering

- Observation #2:
  - Energies are "easily" determined in LQCD

$$\Delta E_n = \langle n | \hat{V} | n \rangle$$

Reactions from QCD

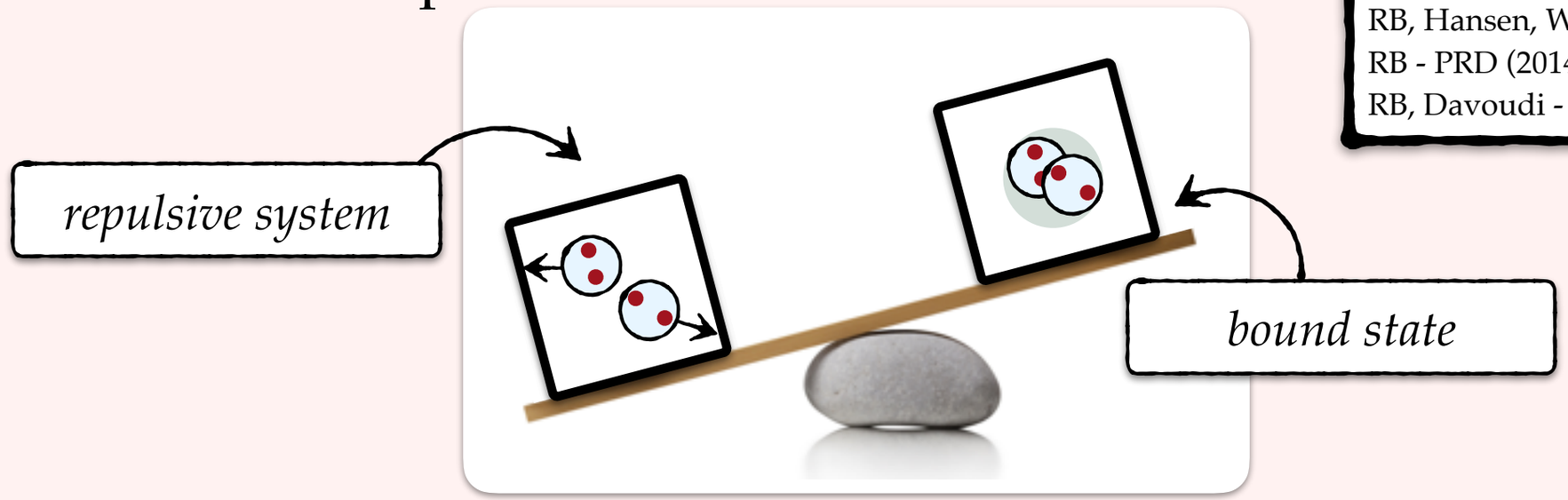
- Conclusion:



the devil is in the details…

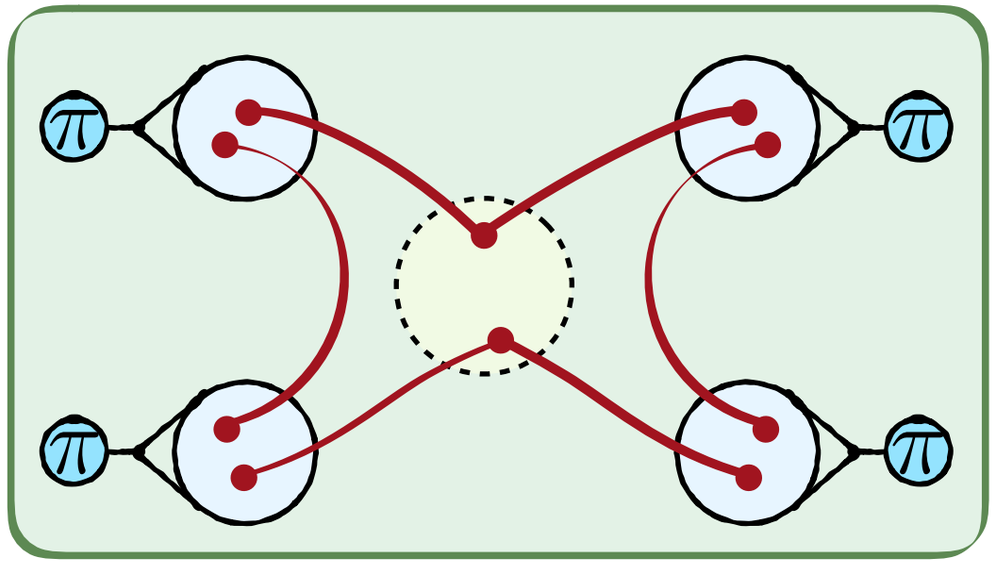
RB, Hansen, Sharpe - (2016)
RB, Hansen - PRD (2016)
RB, Hansen - PRD (2015)
RB, Hansen, Walker-Loud - PRD (2015)
RB - PRD (2014)
RB, Davoudi - PRD (2013)

- Intuitive example:



Questions?

Isovector $\pi\pi$ cross section

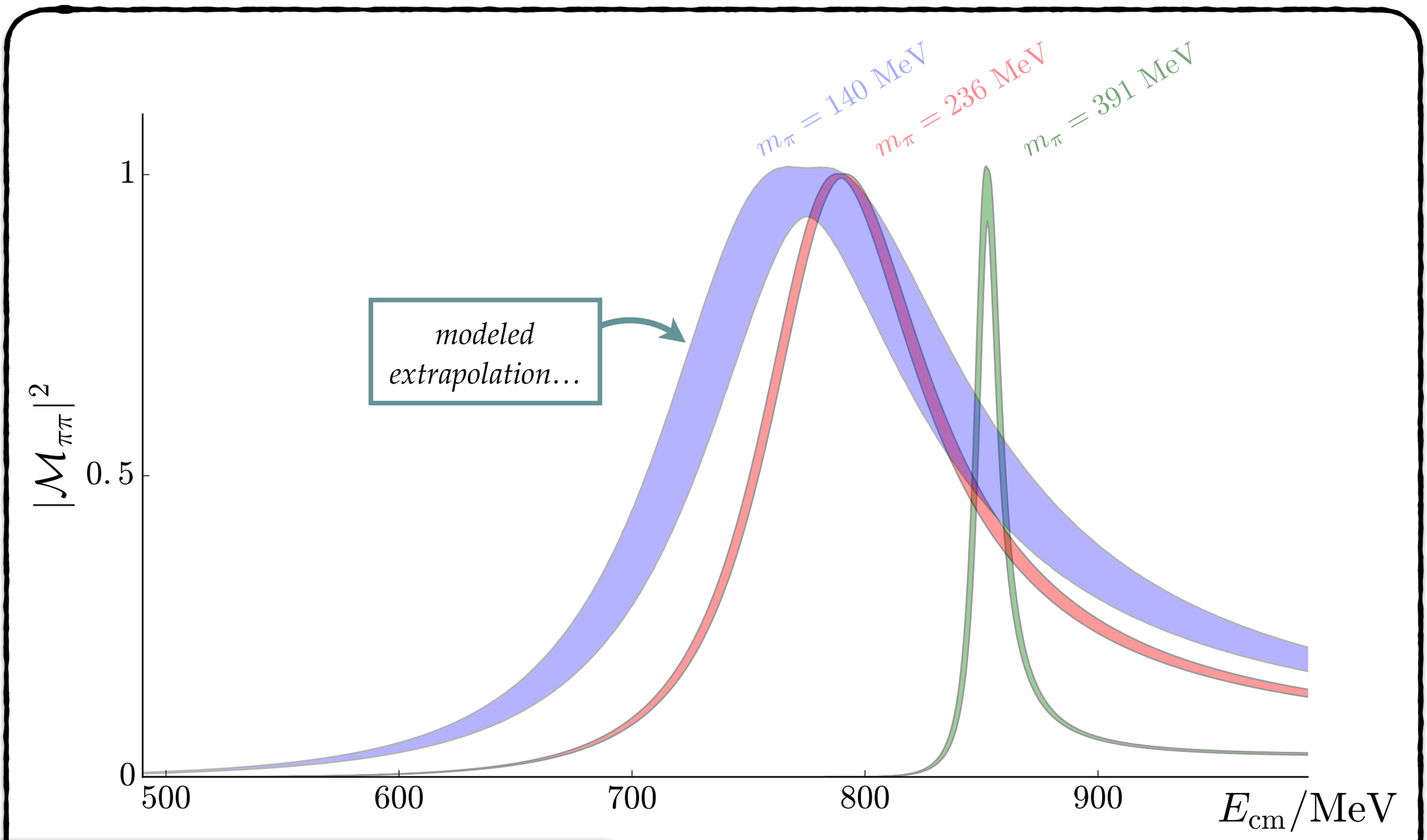


Dudek

Wilson

Dudek, Edwards & Thomas (2012)
Wilson, RB, Dudek, Edwards & Thomas (2015)
Bolton, RB & Wilson (2015)

Isovector $\pi\pi$ cross section



Dudek, Edwards & Thomas (2012)
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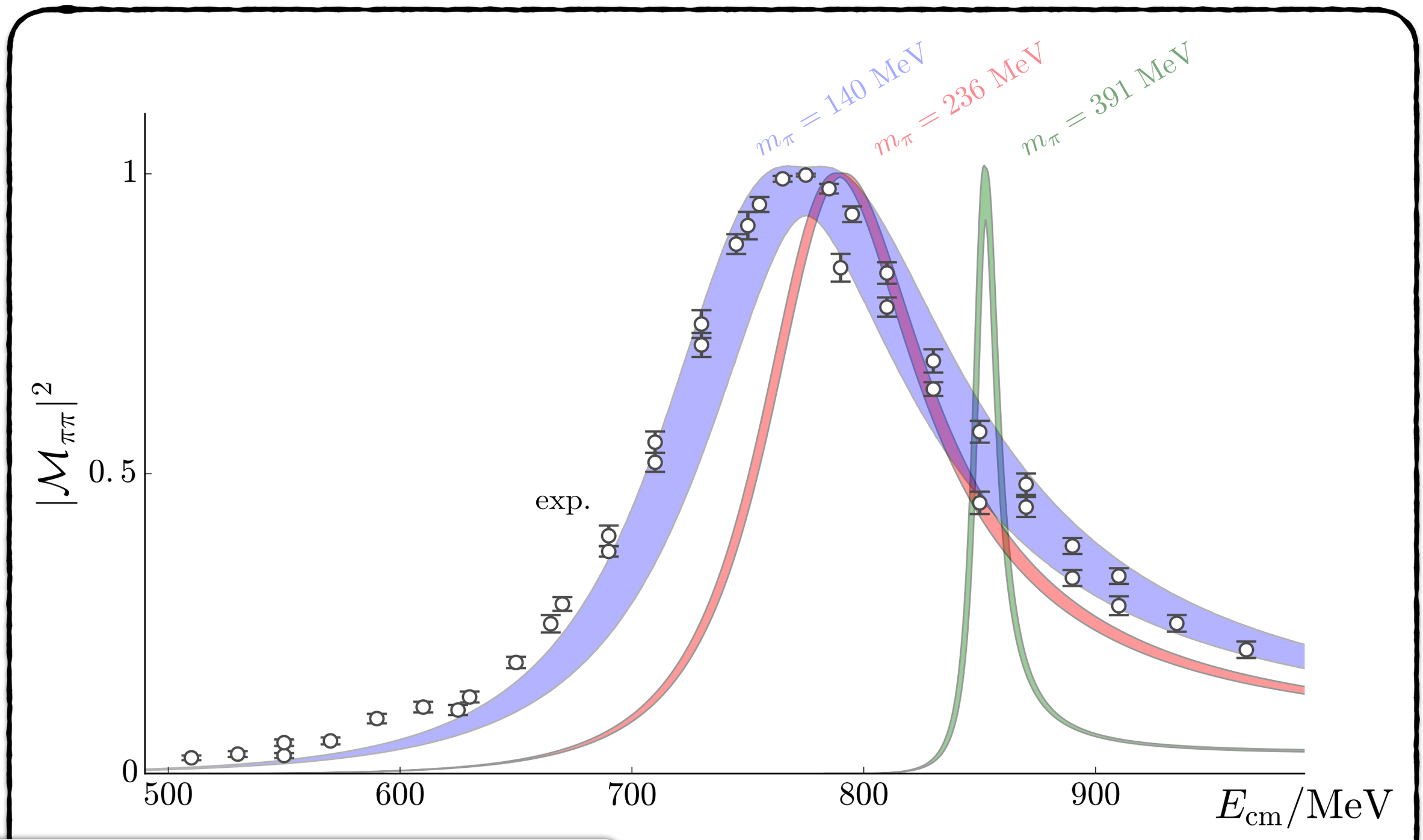
Isovector $\pi\pi$ cross section



Dudek, Edwards & Thomas (2012)
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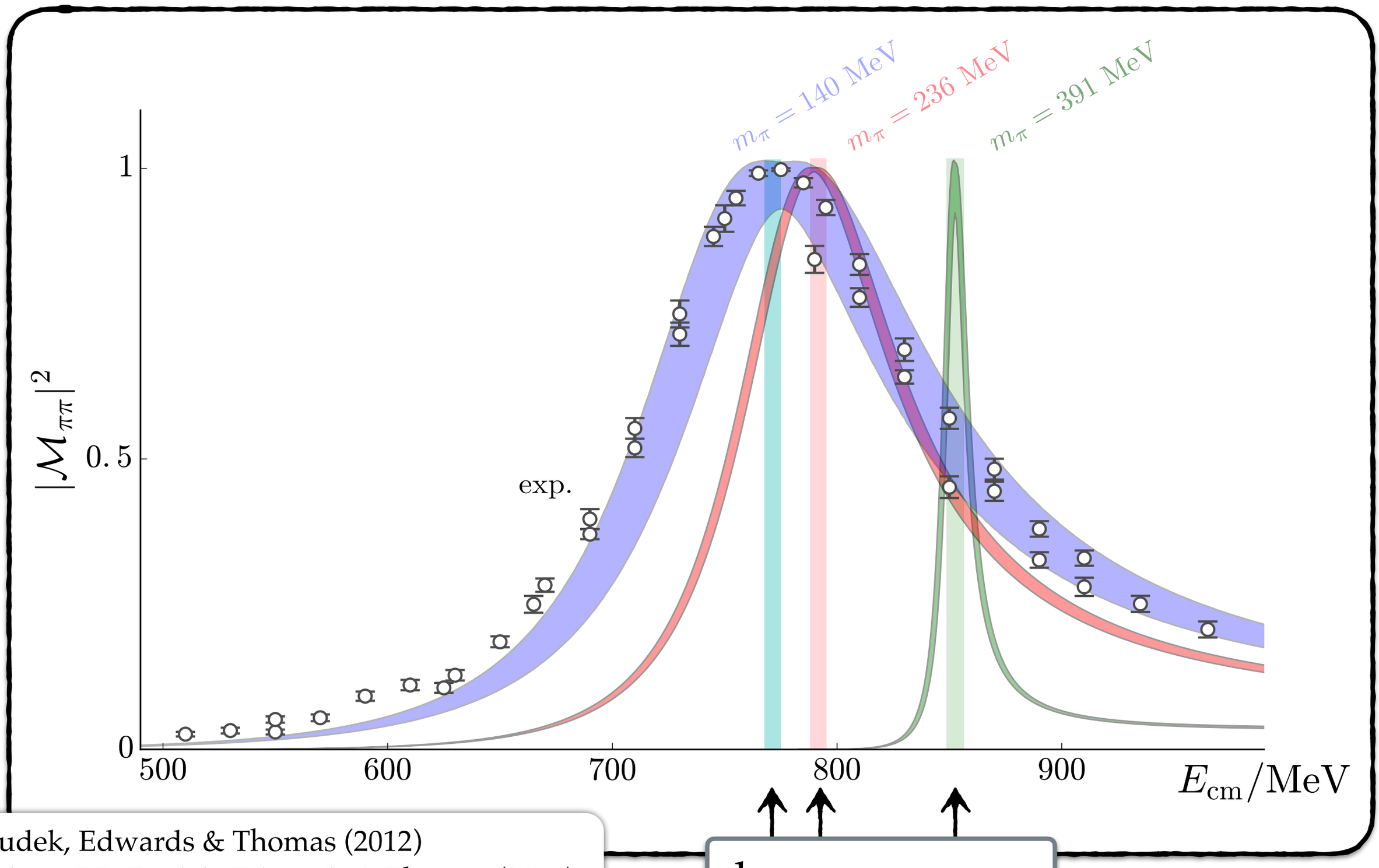
Bolton, RB & Wilson (2015)

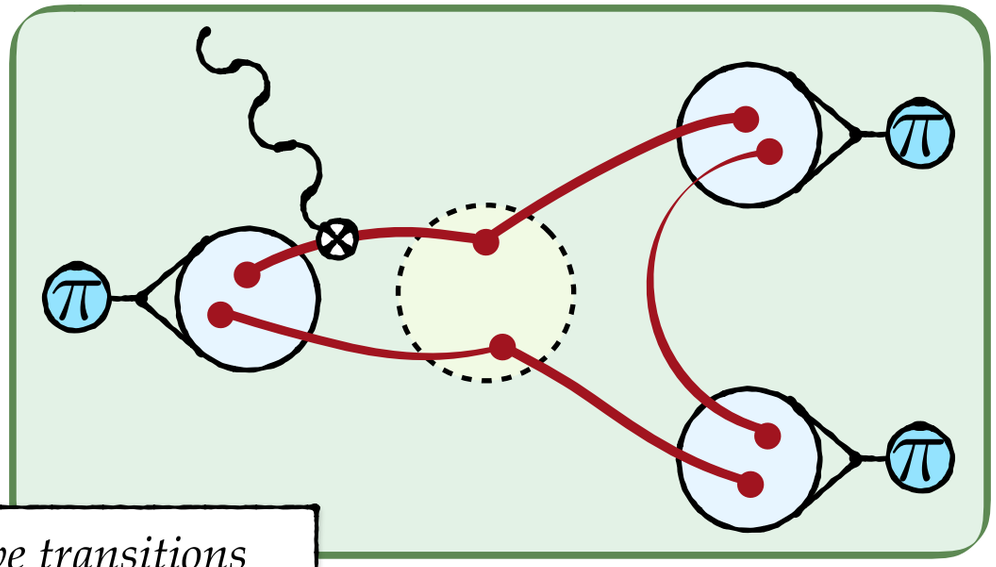
Isovector $\pi\pi$ cross section



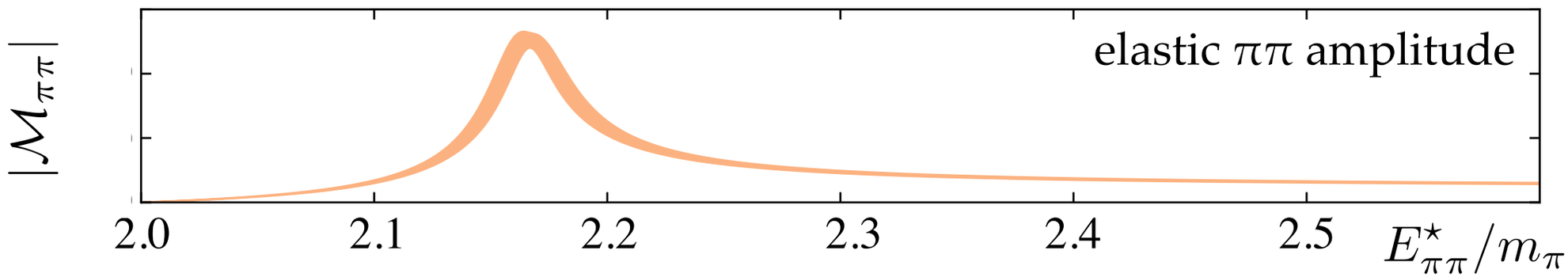
Dudek, Edwards & Thomas (2012)
Wilson, RB, Dudek, Edwards & Thomas (2015)
Bolton, RB & Wilson (2015)

the ϱ resonance

Electromagnetic reactions



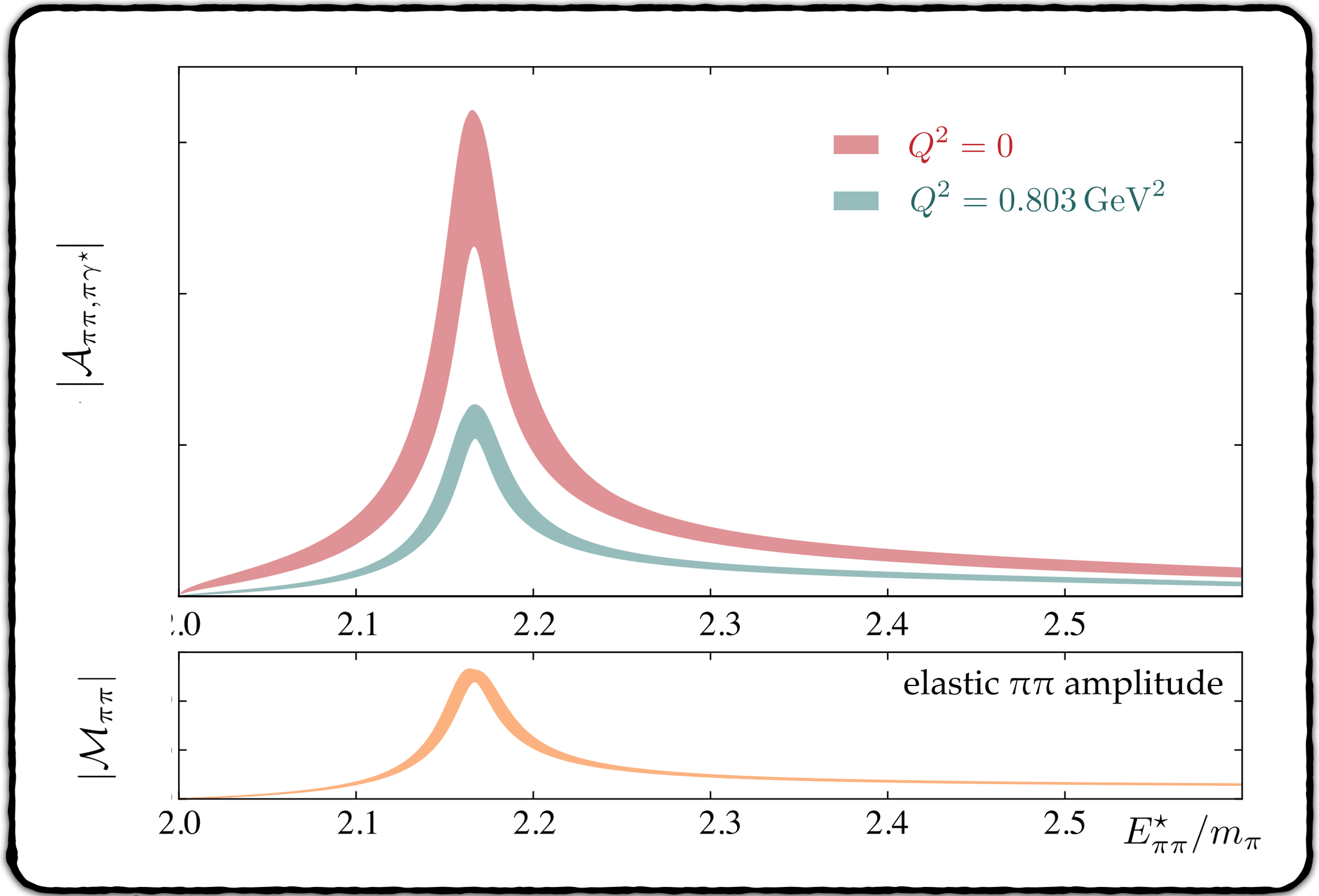
radiative transitions



m_{π}=391 MeV

RB, Dudek, Edwards, Thomas, Shultz, Wilson - PRL (2015)

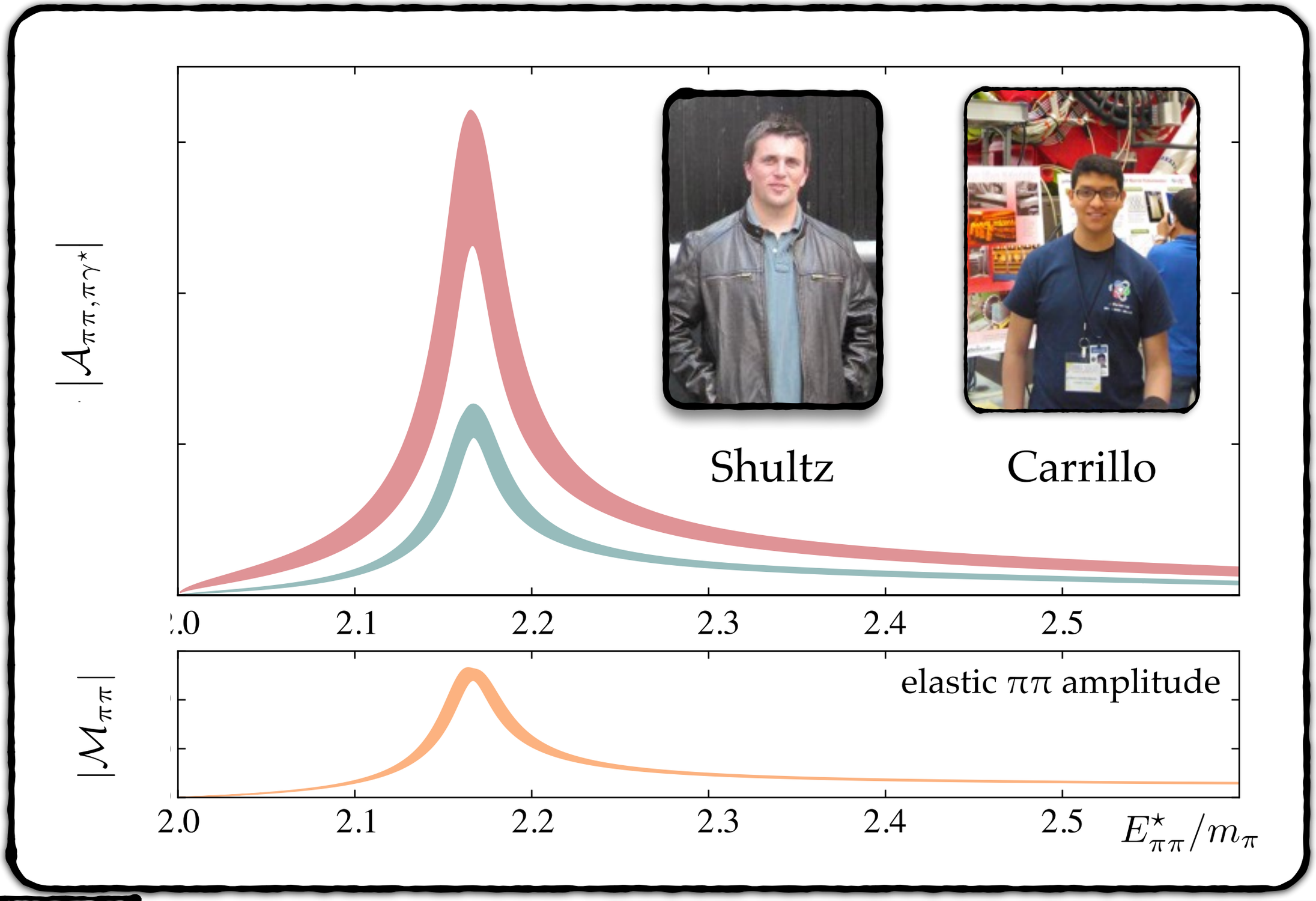
Electromagnetic reactions



m_π=391 MeV

RB, Dudek, Edwards, Thomas, Shultz, Wilson - PRL (2015)

Electromagnetic reactions

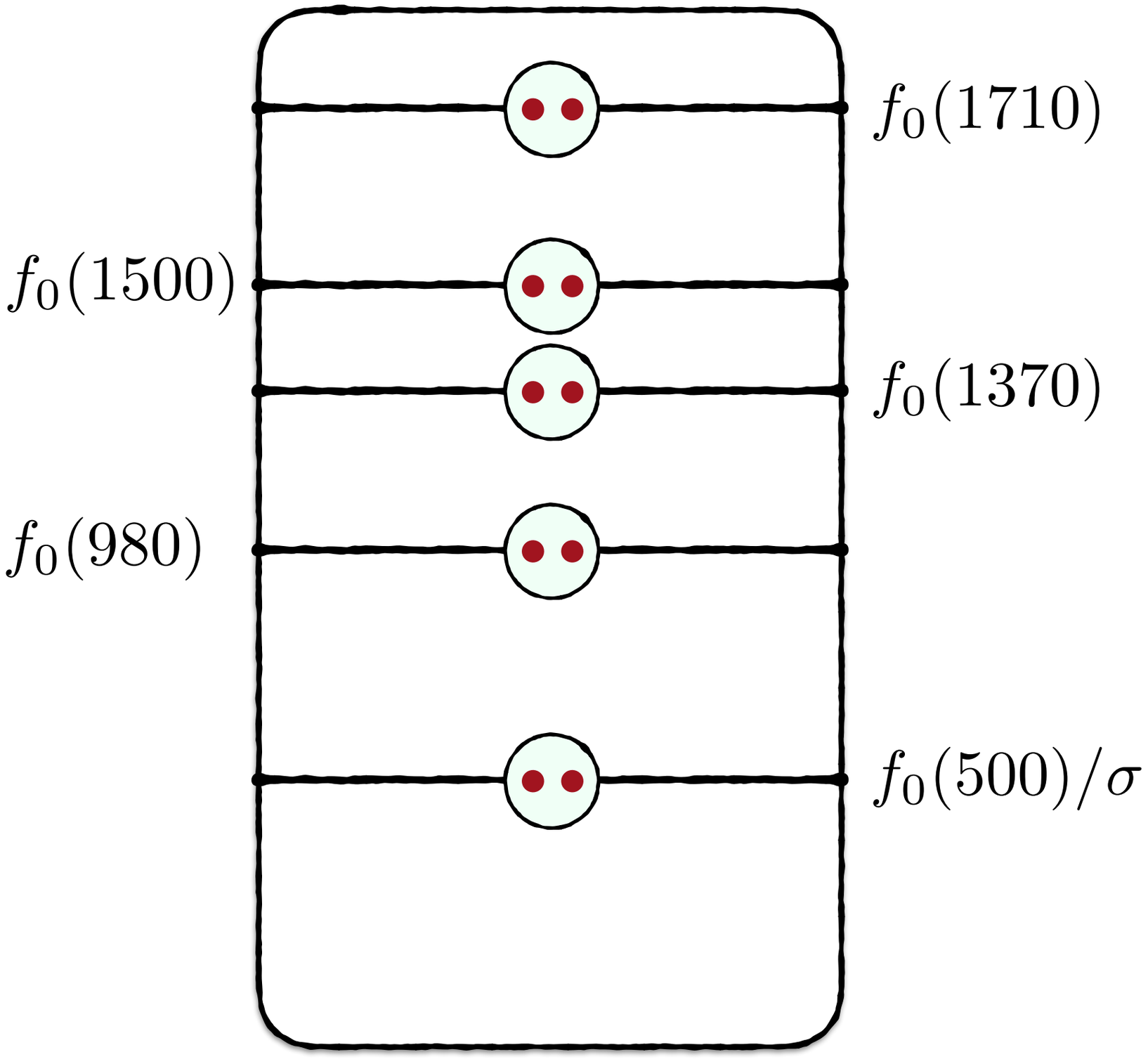


m_π=391 MeV

RB, Dudek, Edwards, Thomas, Shultz, Wilson - PRL (2015)

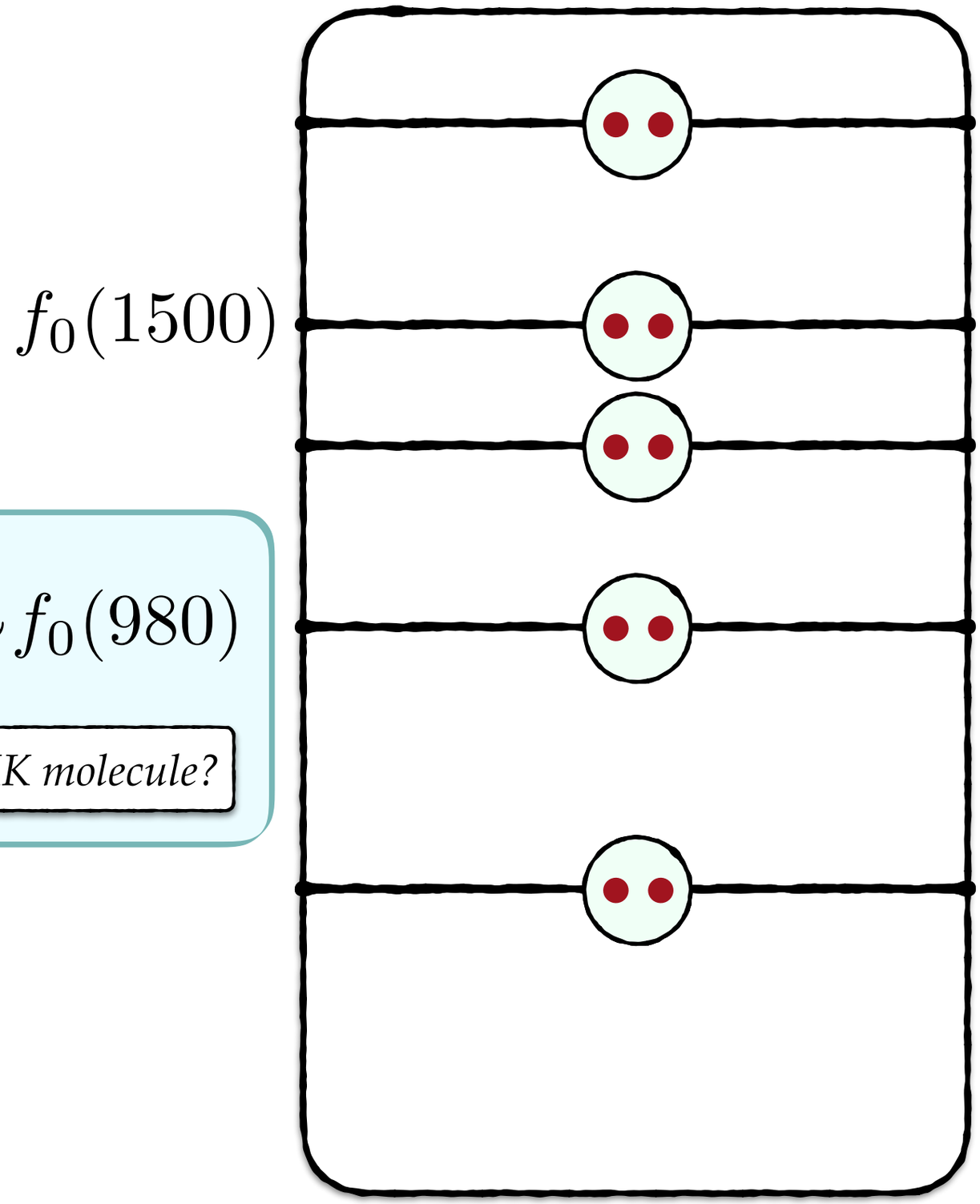
The isoscalar, scalar sector

[i.e., the quantum numbers of the vacuum]

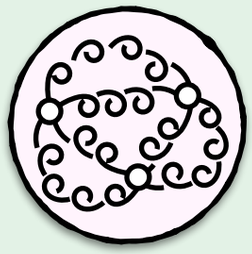


The isoscalar, scalar sector

[i.e., the quantum numbers of the vacuum]



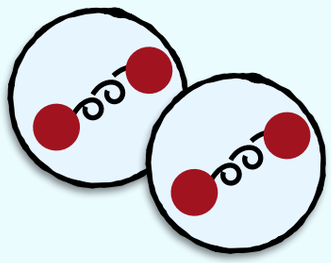
$f_0(1710) \sim$



glueball?

$f_0(1500)$

$f_0(1370)$



$\sim f_0(980)$

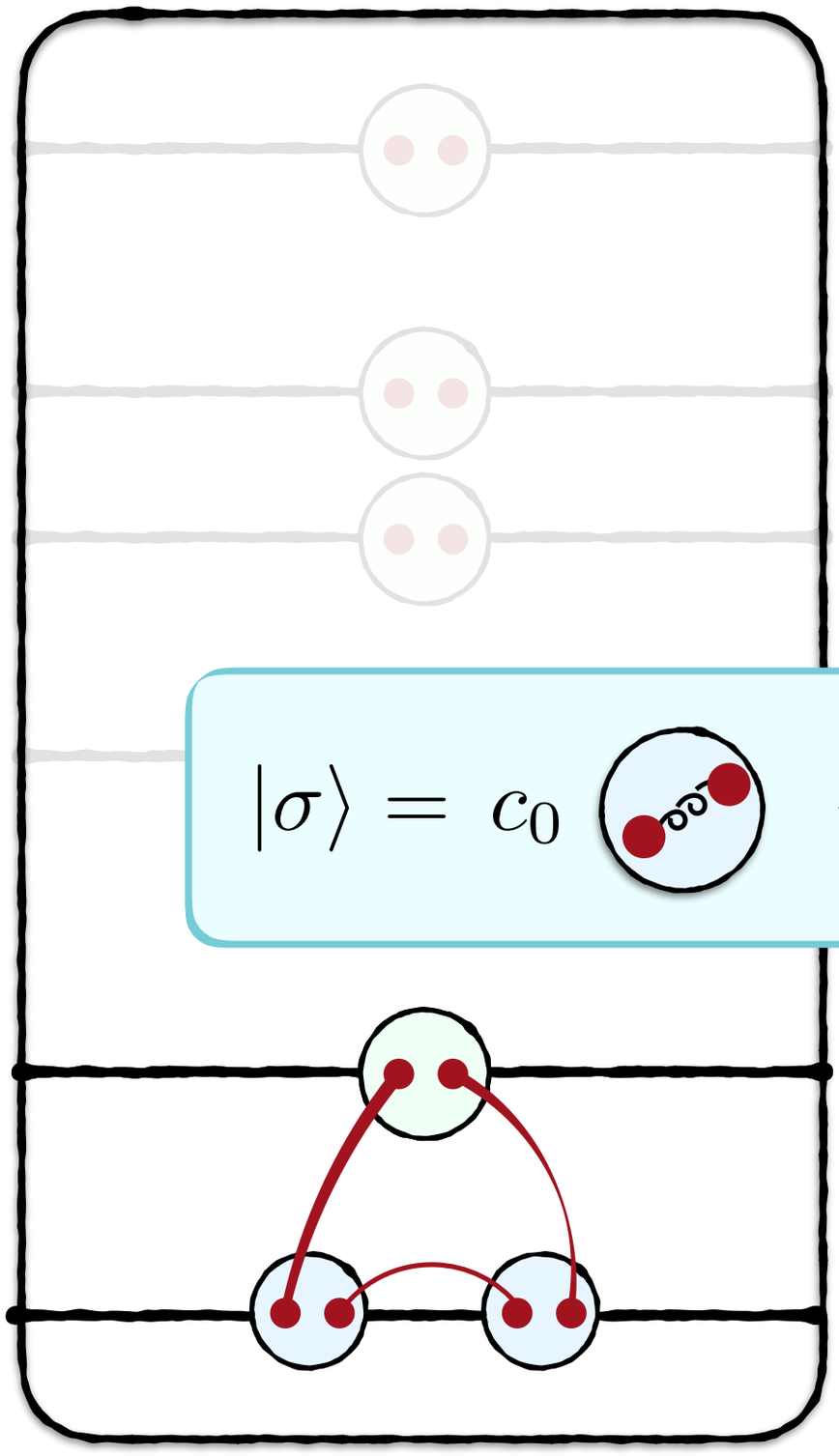
KK molecule?

$f_0(500)/\sigma$

is it real?

The isoscalar, scalar sector

[i.e., the quantum numbers of the vacuum]



$f_0(1710) \sim$

glueball?

$f_0(1500)$

$f_0(1370)$

$\sim f_0(980)$

KK molecule?

$$|\sigma\rangle = c_0 \quad + c_1$$

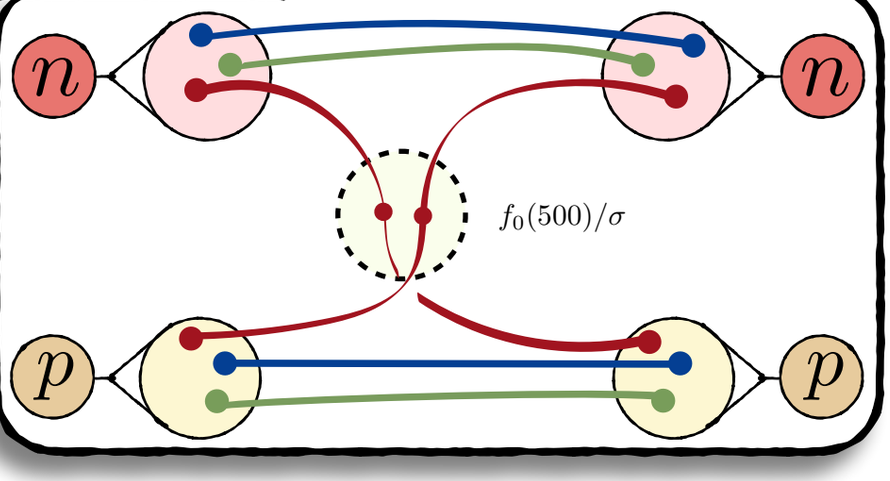
$f_0(500)/\sigma$

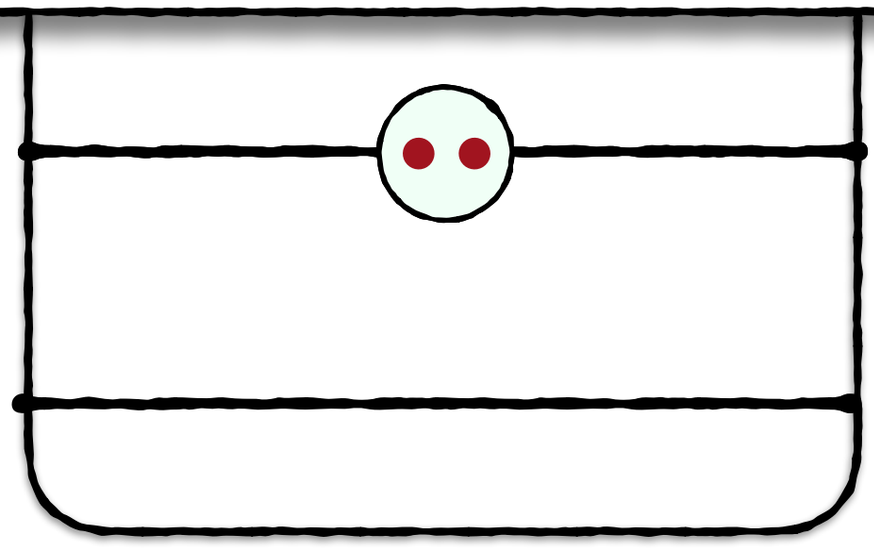
is it real?

The isoscalar, scalar sector

[i.e., the quantum numbers of the vacuum]

nuclear forces



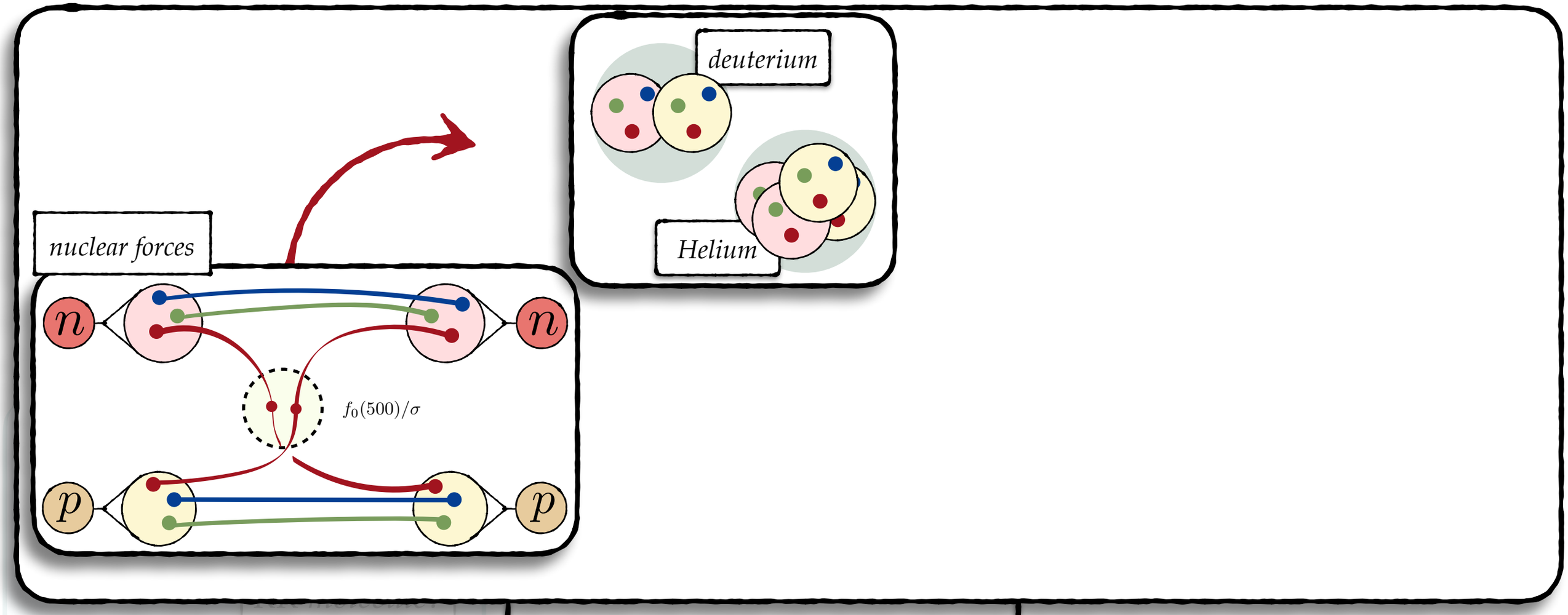


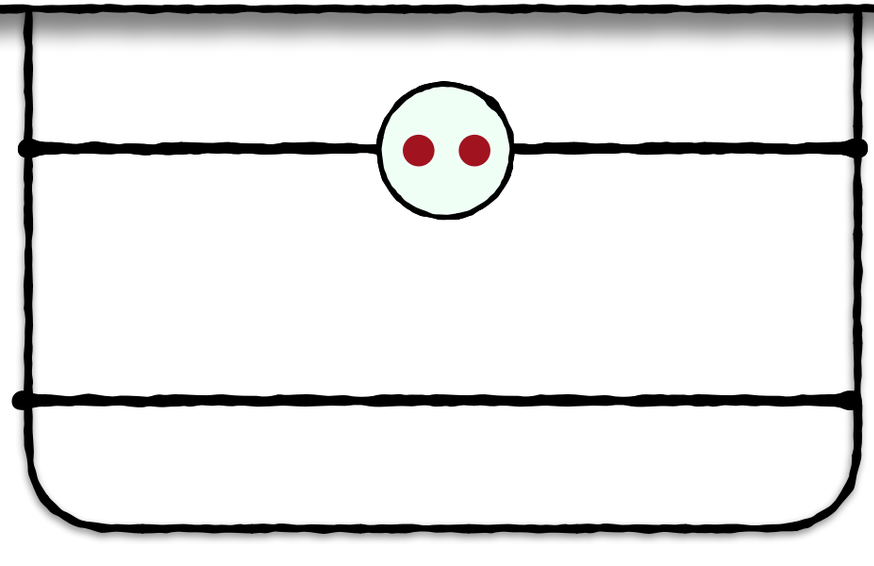
$f_0(500)/\sigma$

is it real?

The isoscalar, scalar sector

[i.e., the quantum numbers of the vacuum]



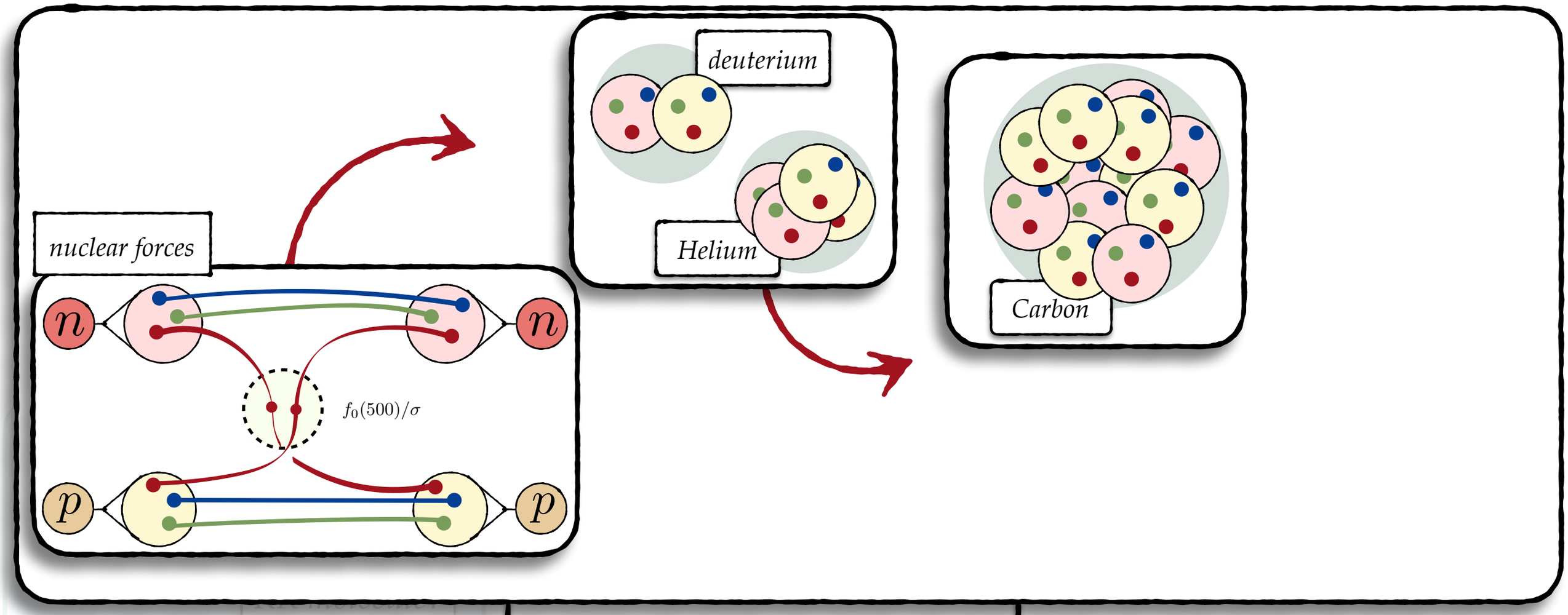


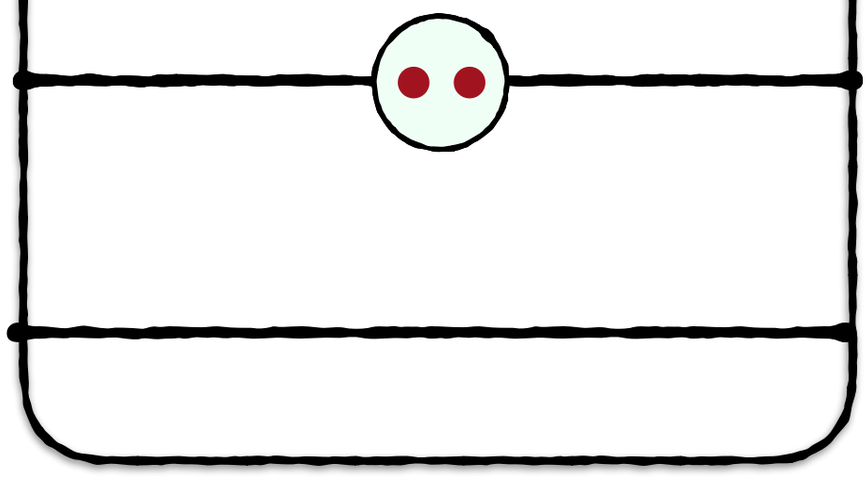
$f_0(500)/\sigma$

is it real?

The isoscalar, scalar sector

[i.e., the quantum numbers of the vacuum]





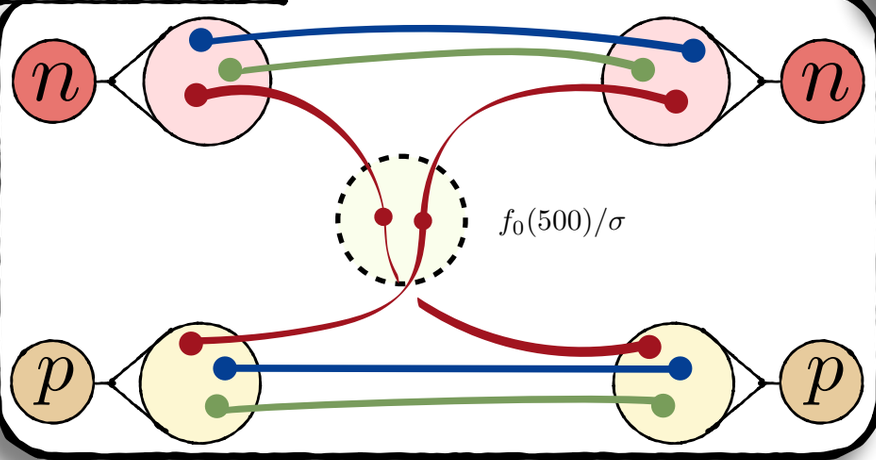
$f_0(500)/\sigma$

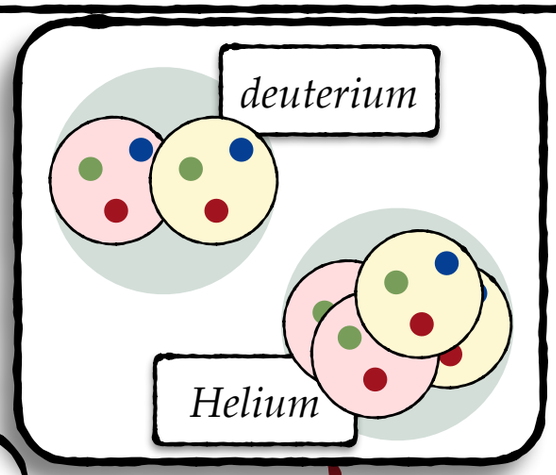
is it real?

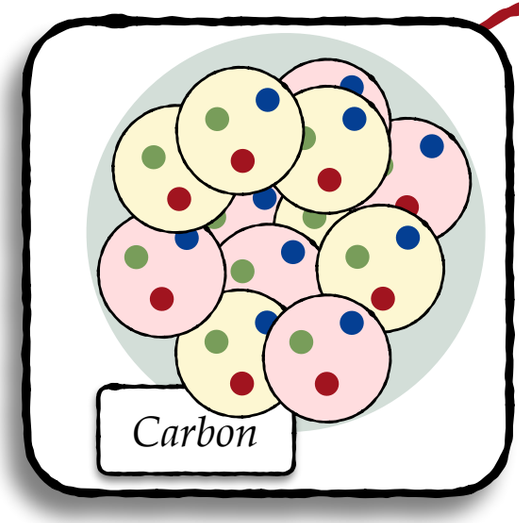
The isoscalar, scalar sector

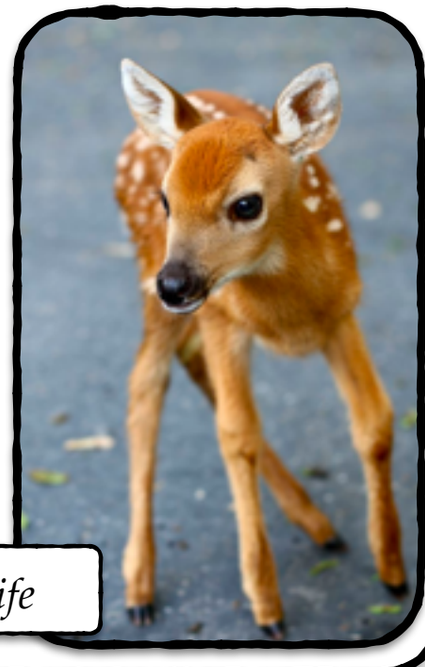
[i.e., the quantum numbers of the vacuum]

nuclear forces

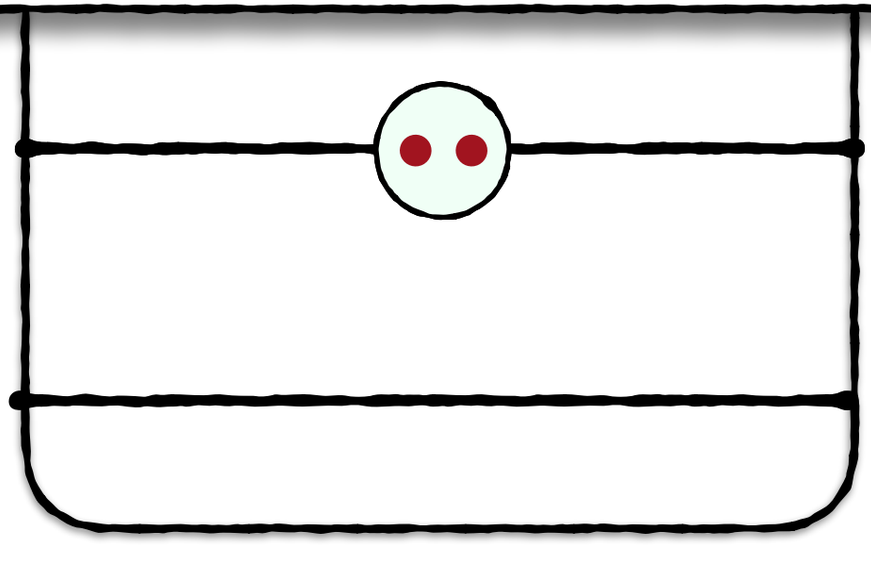








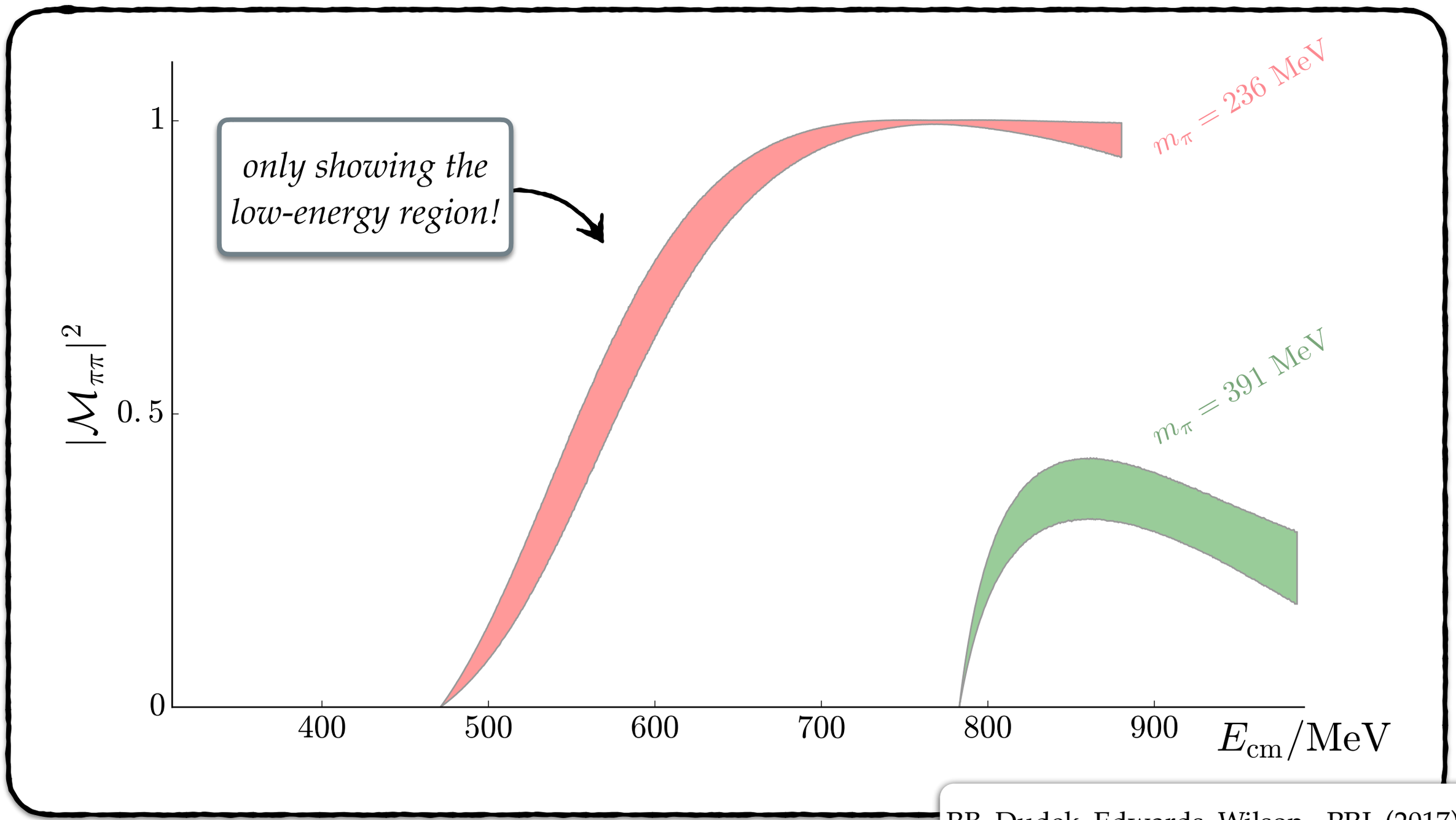
Life



$f_0(500)/\sigma$

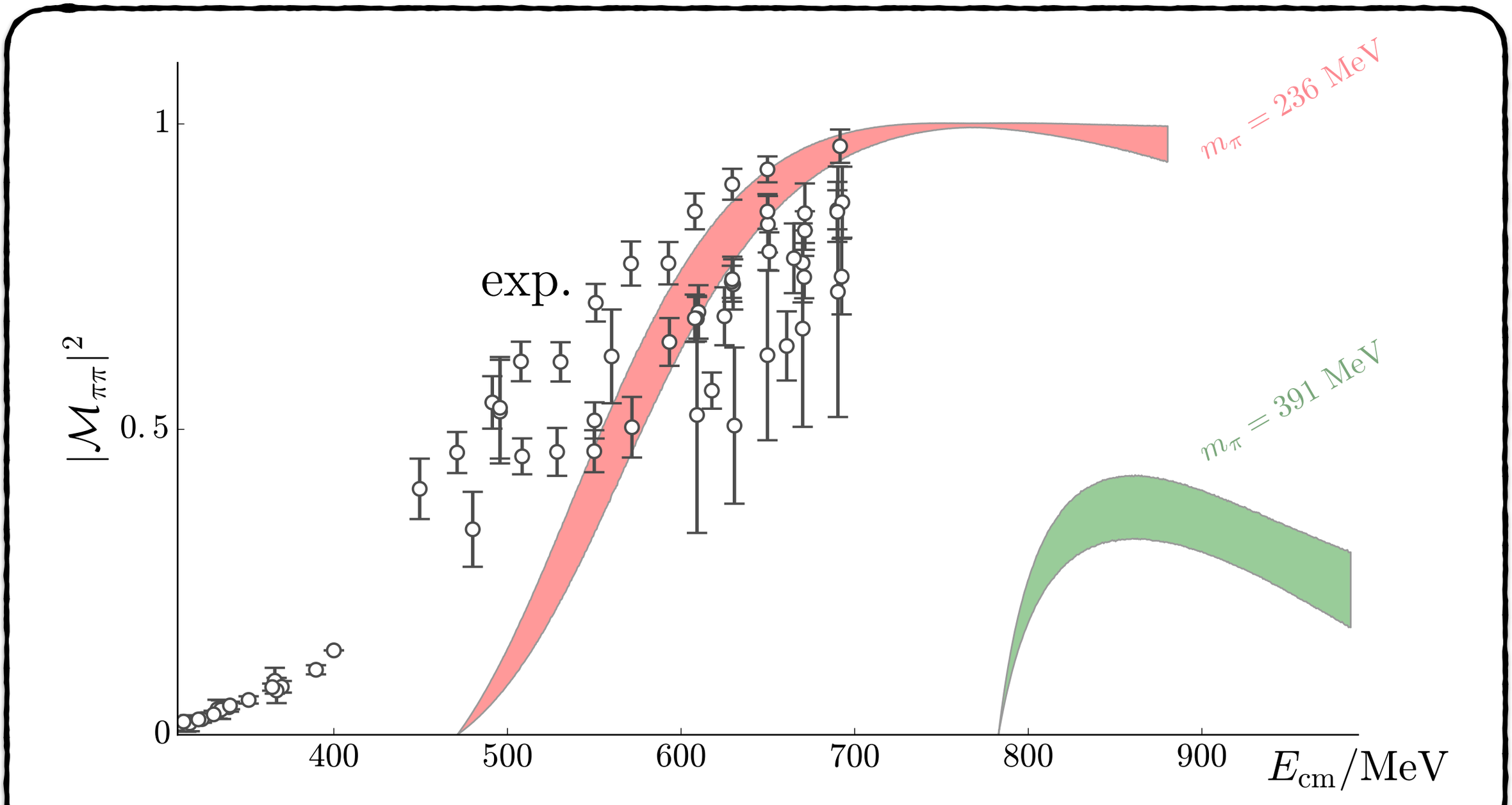
is it real?

Isoscalar $\pi\pi$ cross section



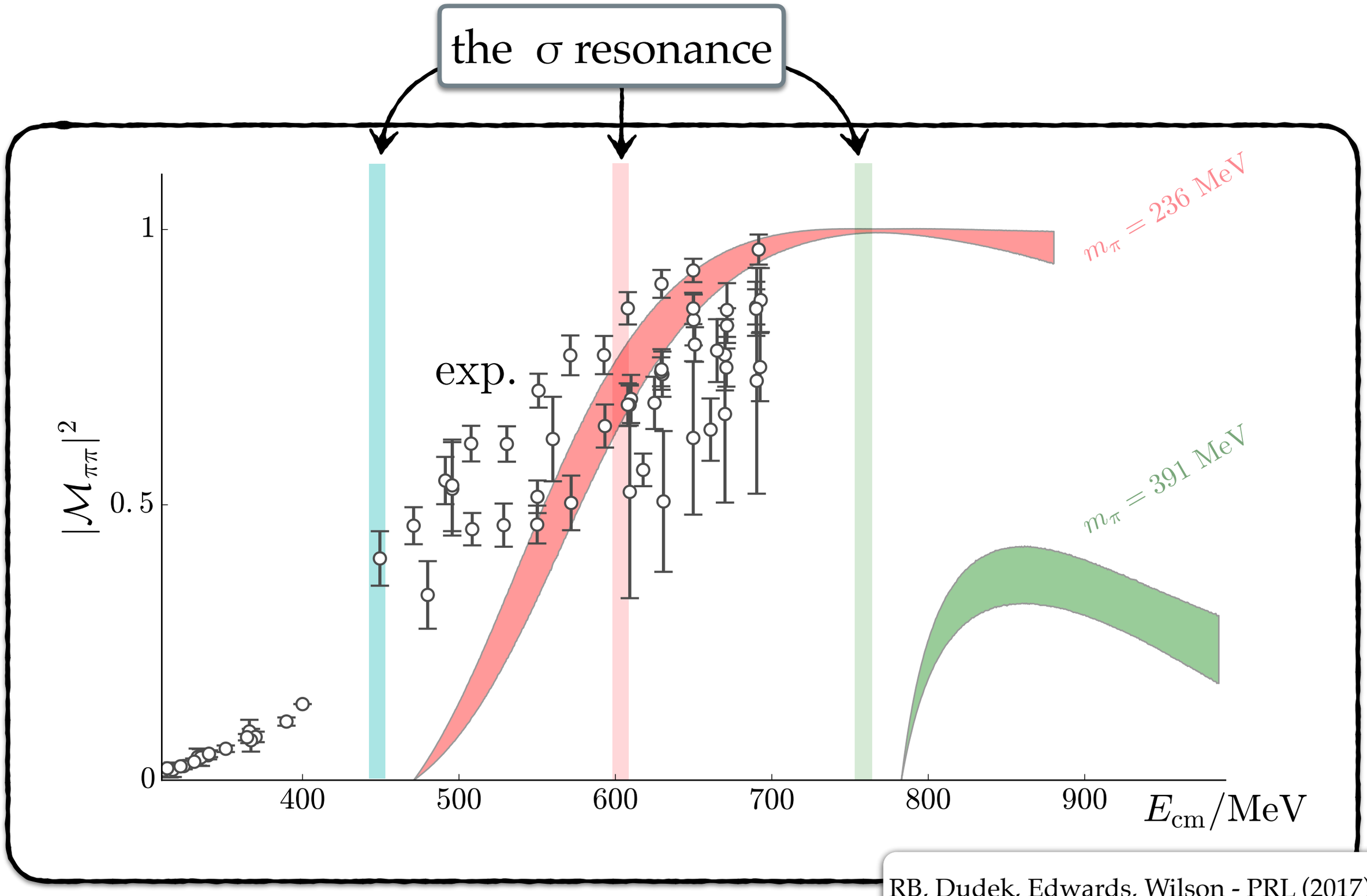
RB, Dudek, Edwards, Wilson - PRL (2017)

Isoscalar $\pi\pi$ cross section



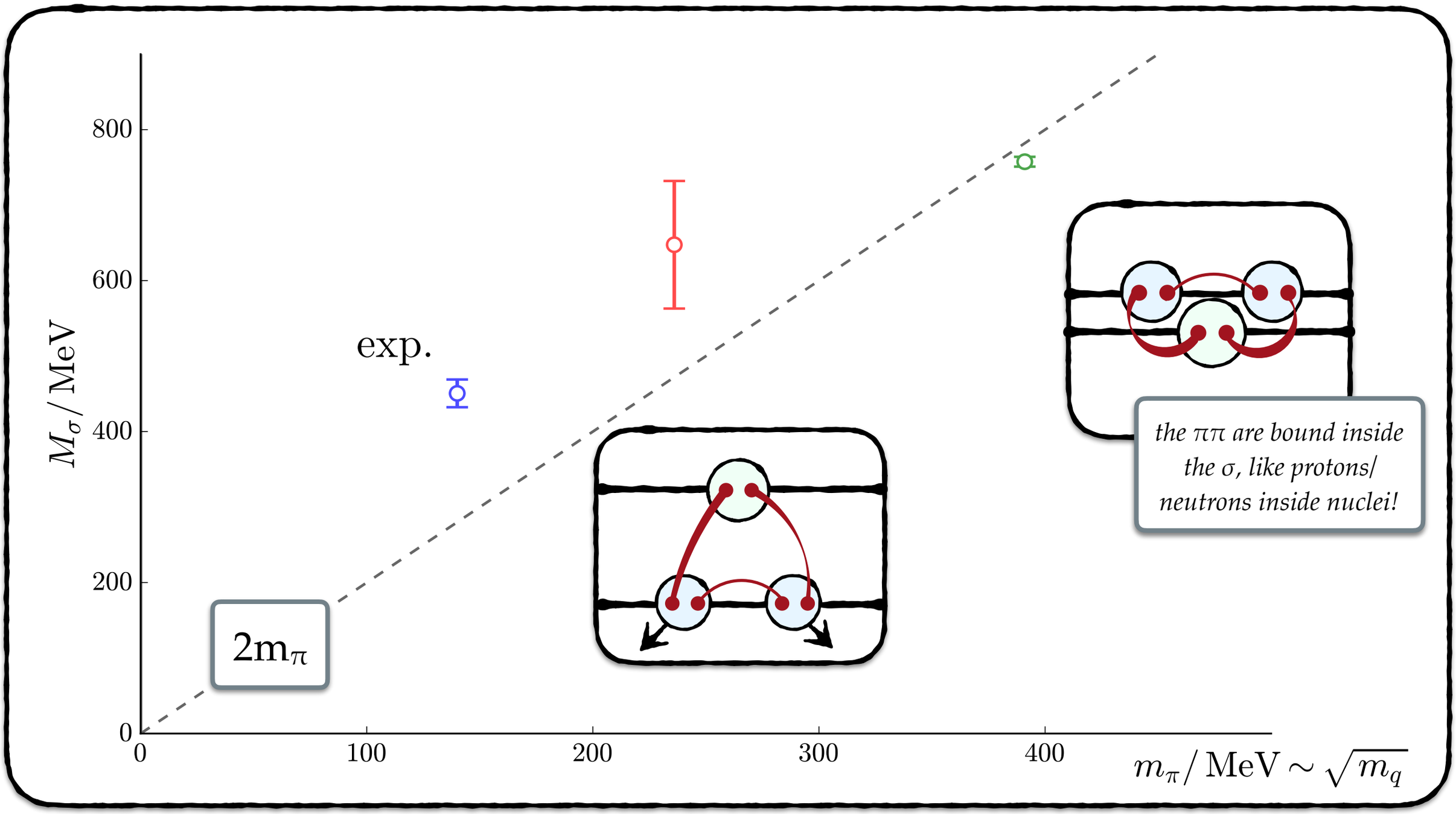
RB, Dudek, Edwards, Wilson - PRL (2017)

Isoscalar $\pi\pi$ cross section



RB, Dudek, Edwards, Wilson - PRL (2017)

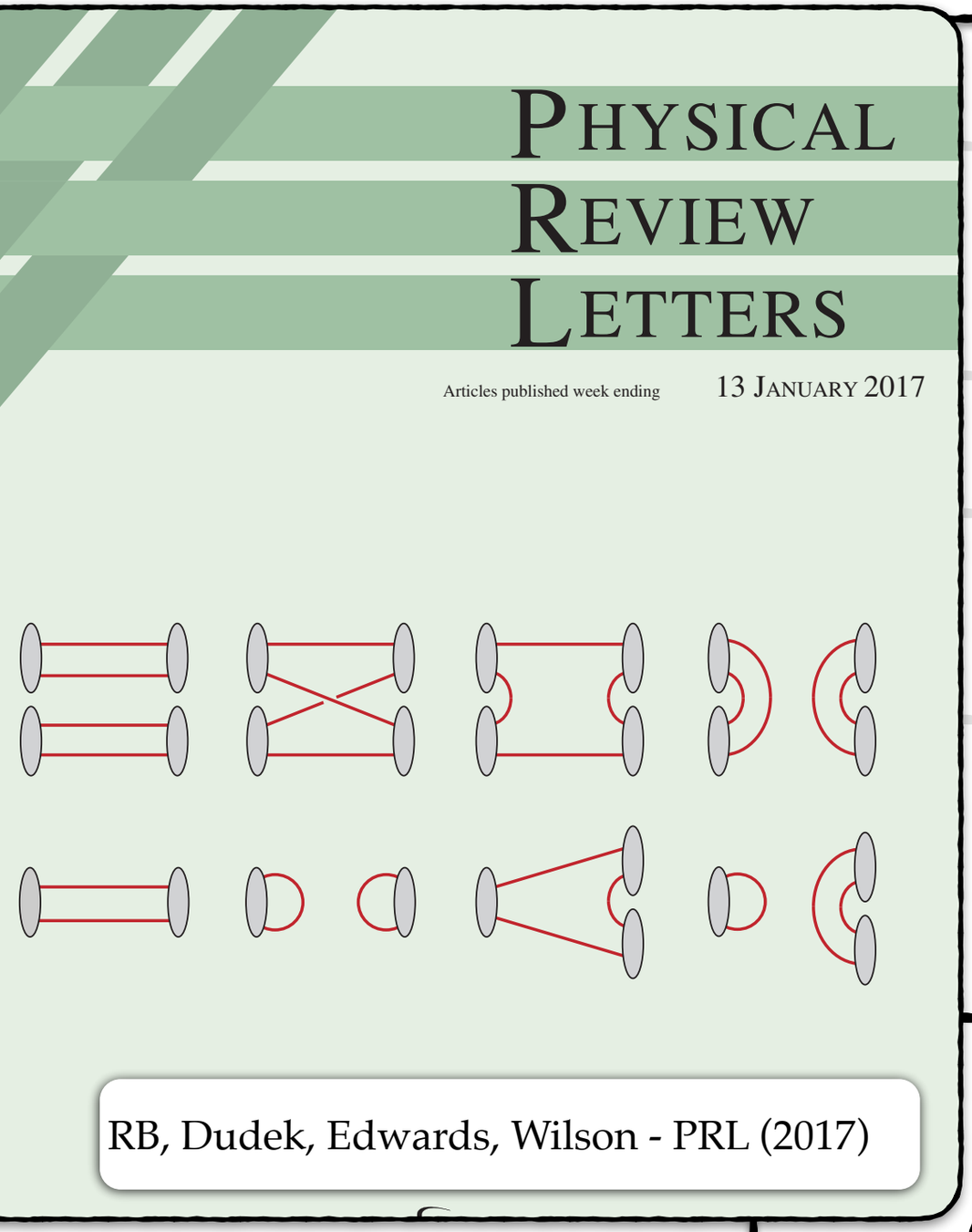
The σ resonance



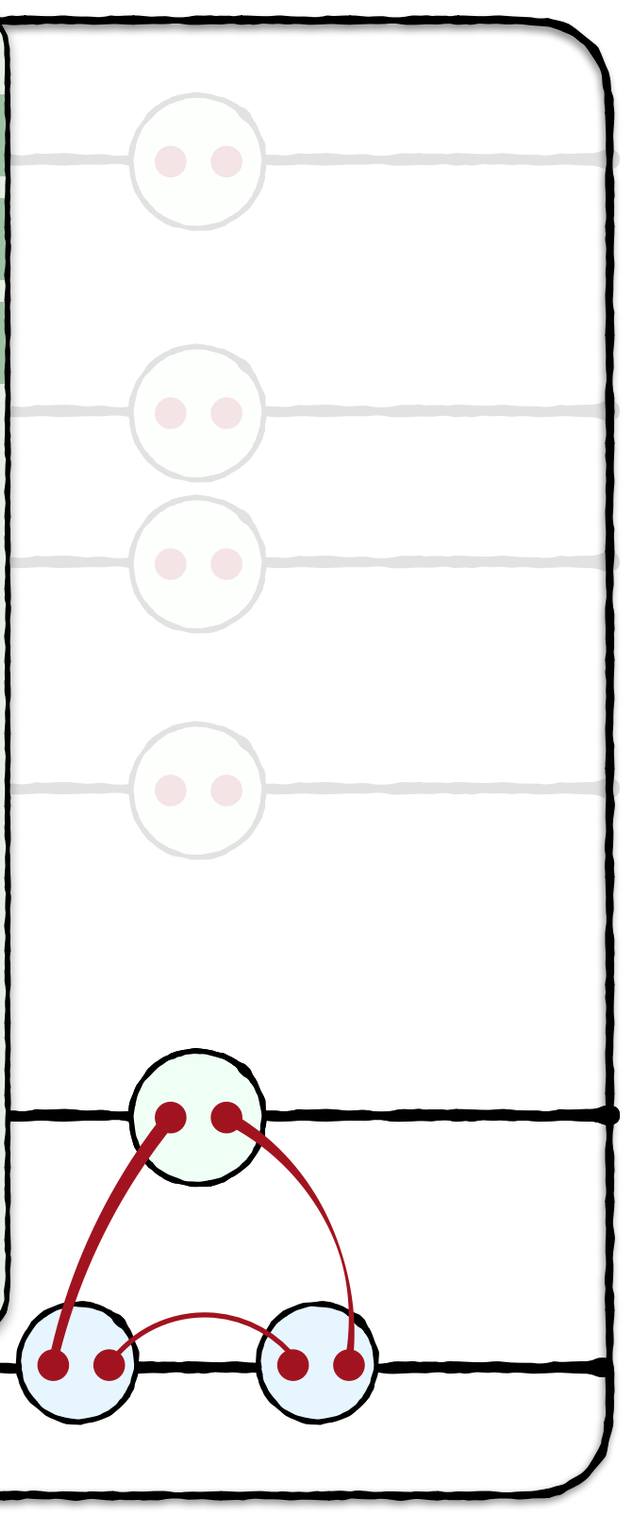
RB, Dudek, Edwards, Wilson - PRL (2017)

The isoscalar, scalar sector

[i.e., the quantum numbers of the vacuum]



RB, Dudek, Edwards, Wilson - PRL (2017)



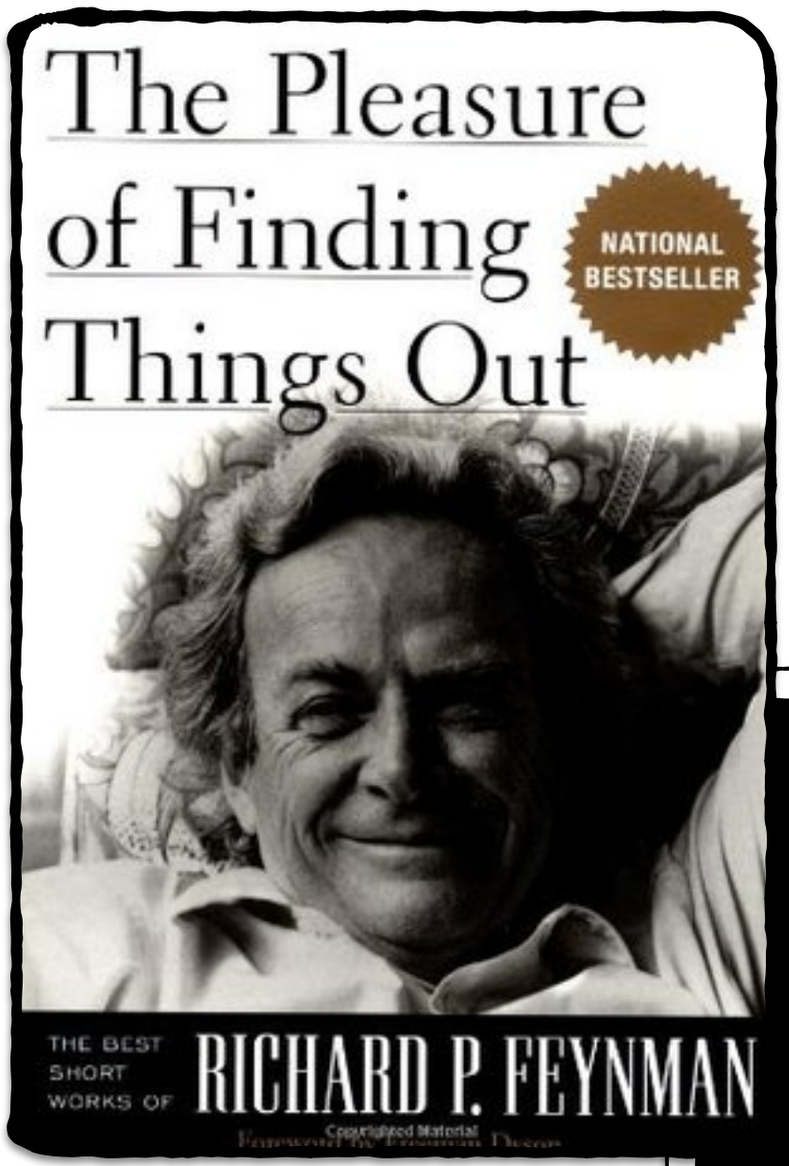
$f_0(1710) \sim$

glueball?

$f_0(1370)$

$f_0(500)/\sigma$

is it real?



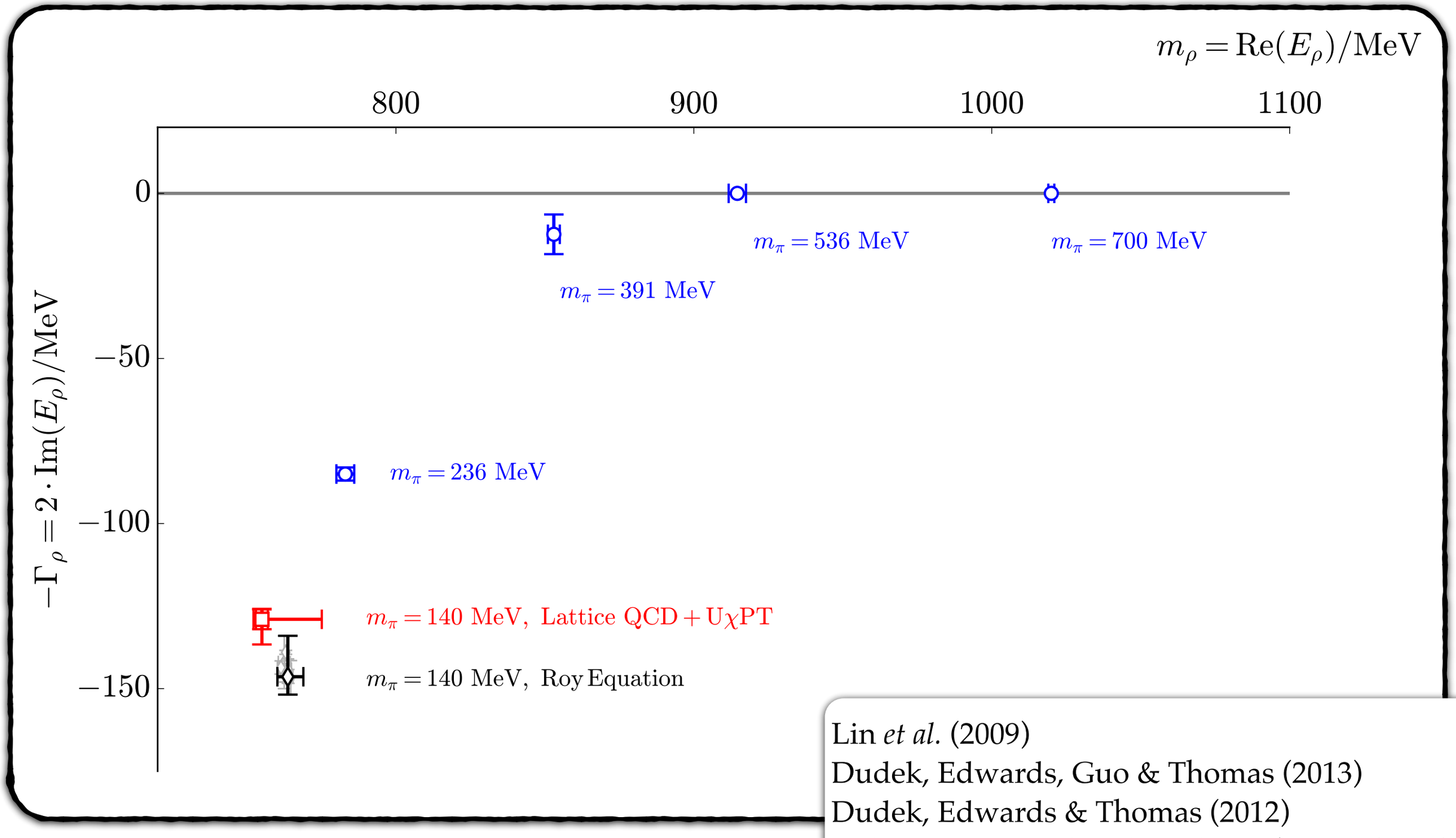
On QCD:

"…what we have to do is to calculate the consequences of the theory…The mathematics needed to figures what the consequences of this theory are have turned out to be, at the present time, insuperably difficult…my problem is to try to develop a way of getting numbers out of this theory, to test it really carefully…I can't stand it, I have to figure it out. Someday, maybe."

-Richard Feynman (1981)

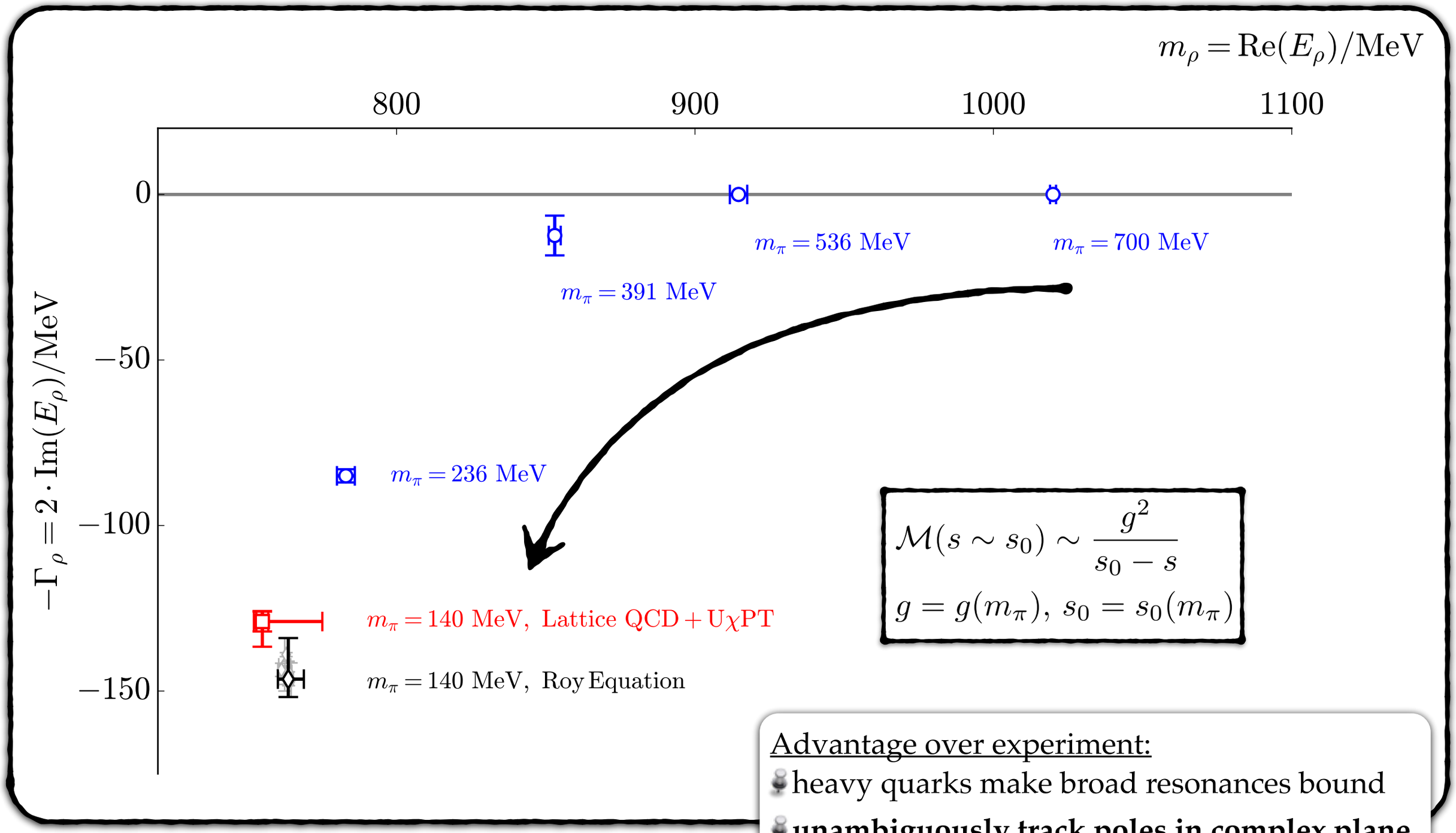
Jose Rodriguez (Skype/Microsoft)

The ϱ vs m_π



Lin *et al.* (2009)
Dudek, Edwards, Guo & Thomas (2013)
Dudek, Edwards & Thomas (2012)
Wilson, RB, Dudek, Edwards & Thomas (2015)
Bolton, RB & Wilson (2015)

The ϱ vs m_π

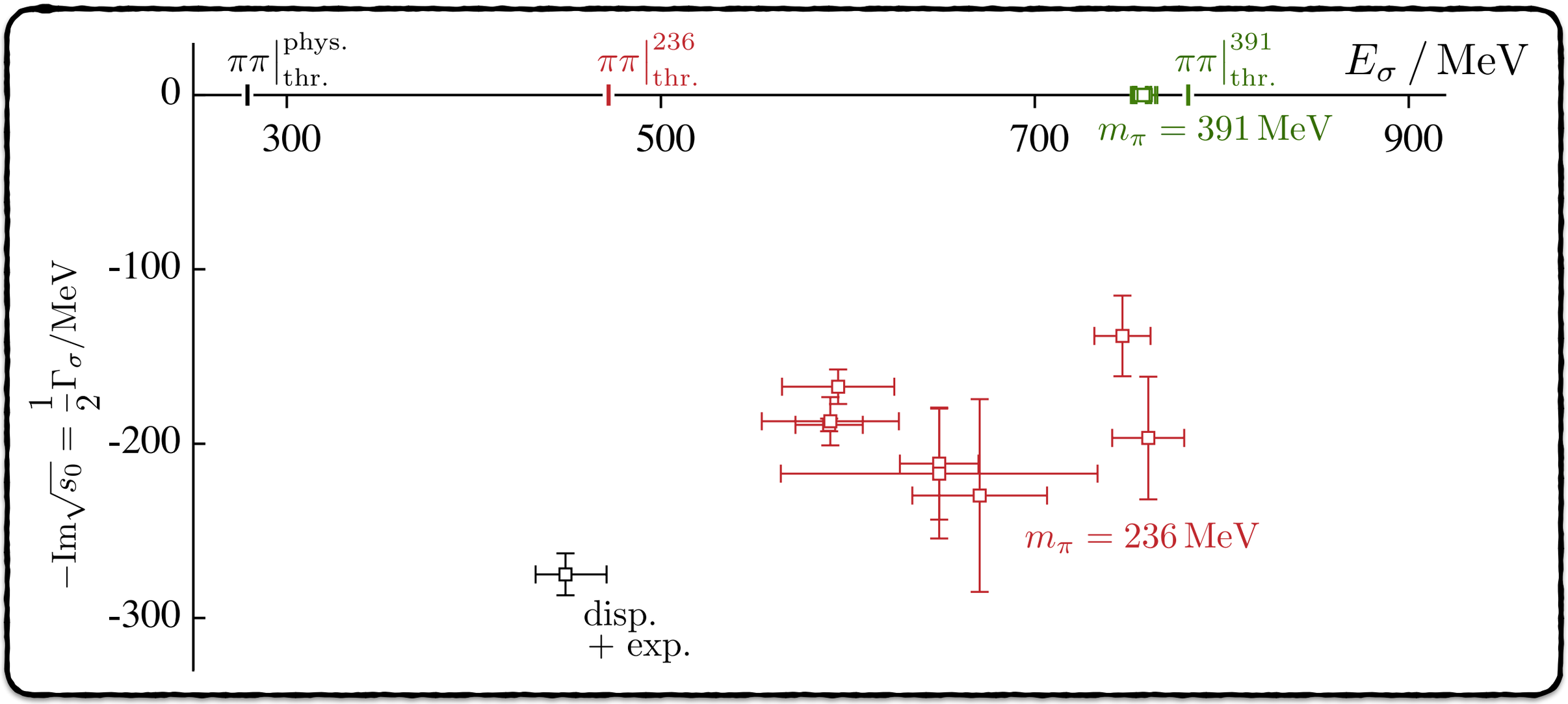


$$\mathcal{M}(s \sim s_0) \sim \frac{g^2}{s_0 - s}$$
$$g = g(m_\pi),\ s_0 = s_0(m_\pi)$$

Advantage over experiment:

- heavy quarks make broad resonances bound
- **unambiguously track poles in complex plane**

The σ / $f_0(500)$ vs m_π



RB, Dudek, Edwards, Wilson - PRL (2017)