



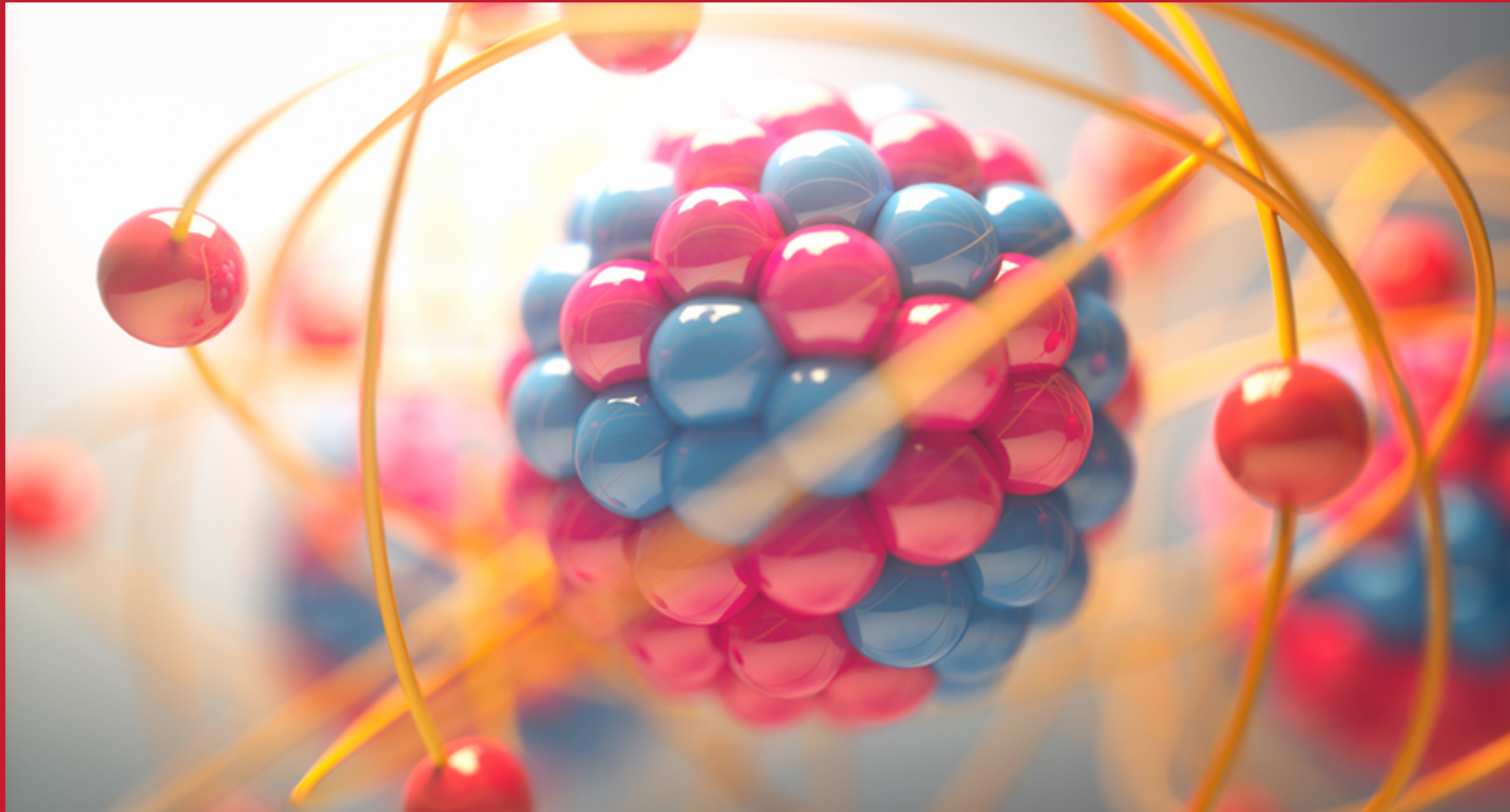
MÁRCIA QUARESMA - LIP SUMMER INTERNSHIP 2021

THE INTERNAL STRUCTURE OF THE PARTICLES

 9 July 2021

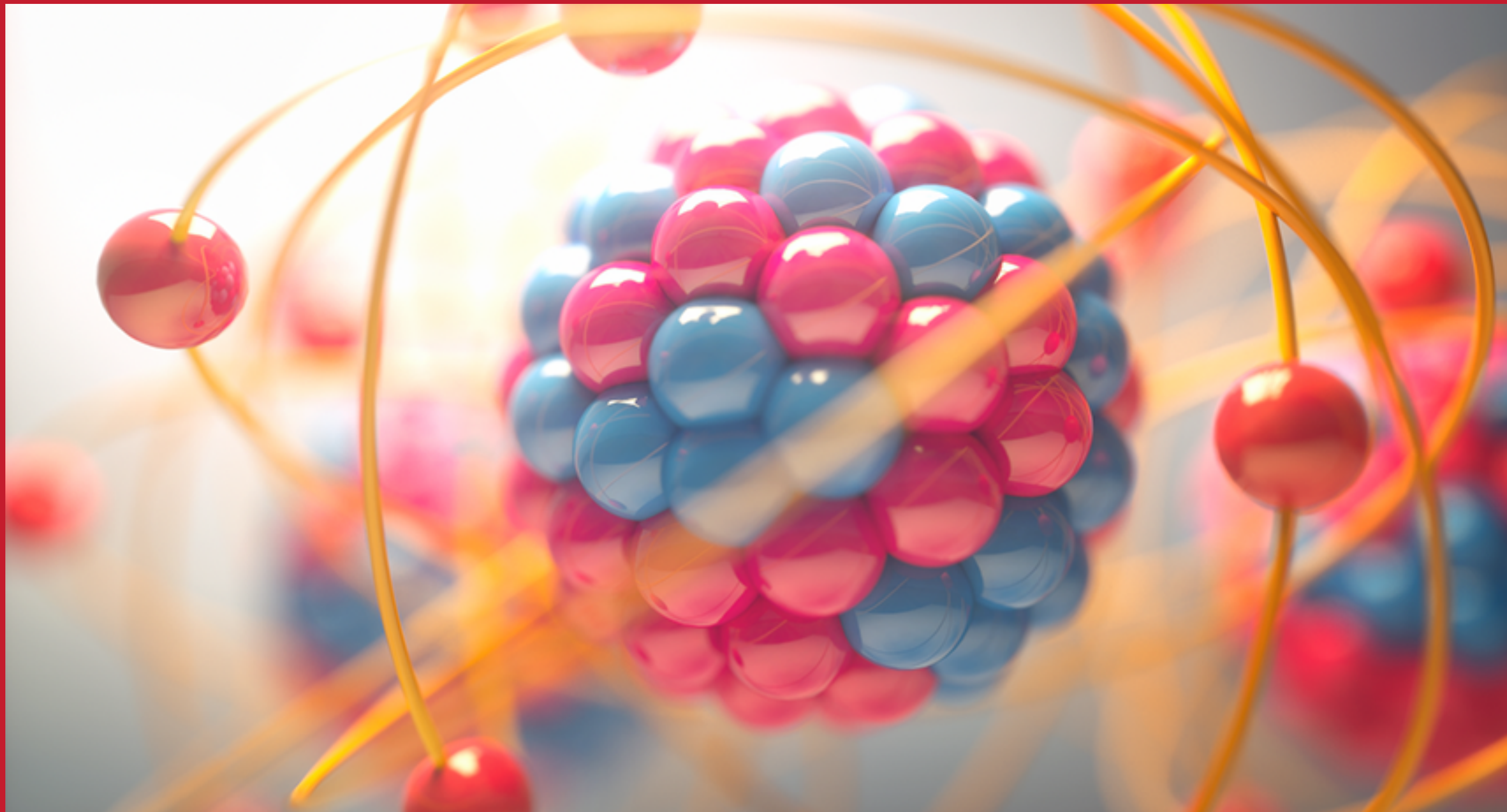
 marcia@lip.pt

DO THE PARTICLES HAVE INTERNAL STRUCTURE?



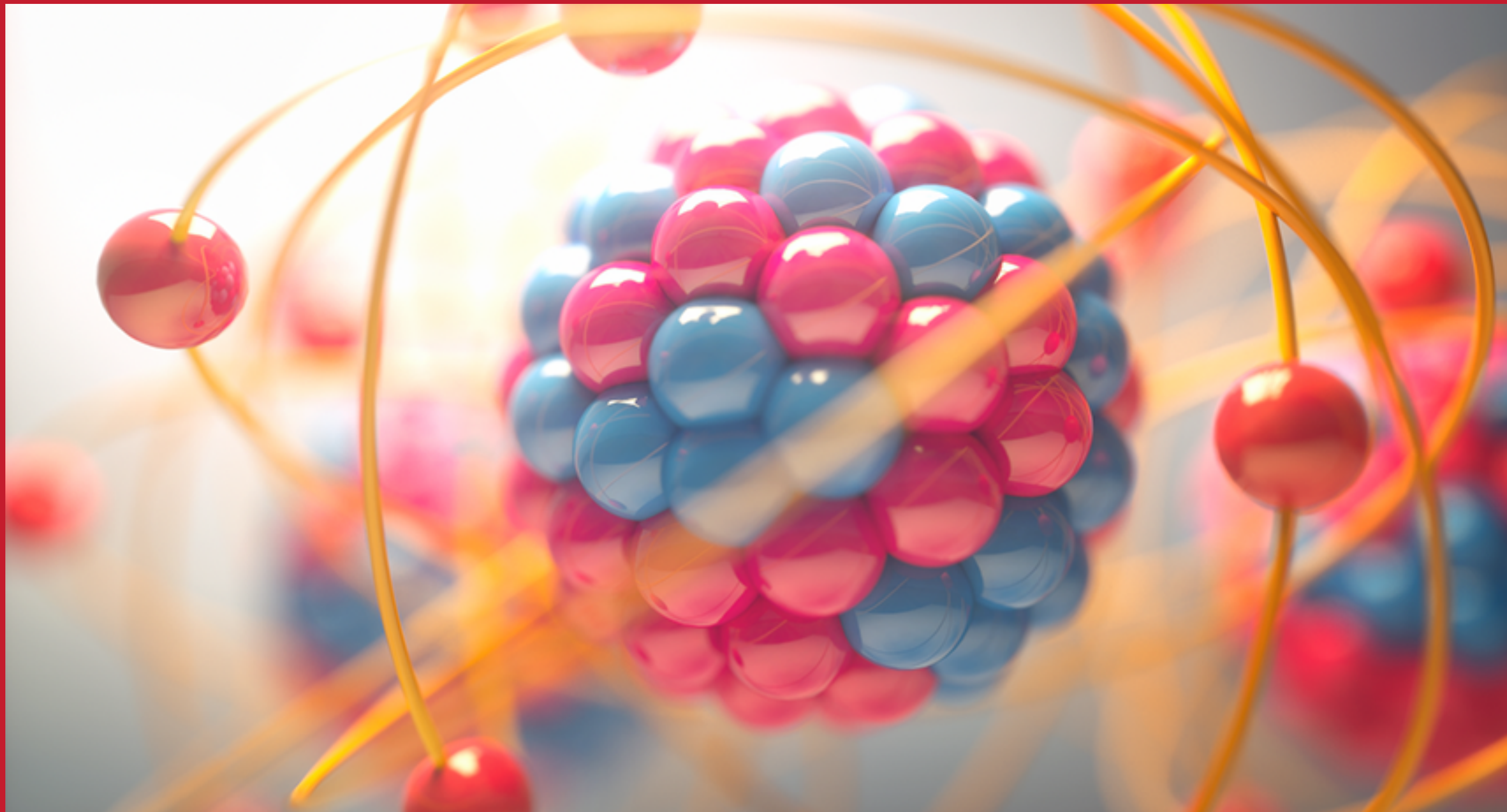
DO THE PARTICLES HAVE INTERNAL STRUCTURE?

IT DEPENDS!



DO THE PARTICLES HAVE INTERNAL STRUCTURE?

IT DEPENDS!



OUTLOOK:

1. Kinds of particles
2. What is inside the proton?
3. The birth of QCD
4. The way to access the hadrons structure
5. The mass of the hadrons
6. COMPASS experiment
7. AMBER experiment

ELEMENTARY PARTICLES

Fermions

matter particles

Quarks



Leptons



Gauge bosons

force carriers



photon



gluon



Z boson



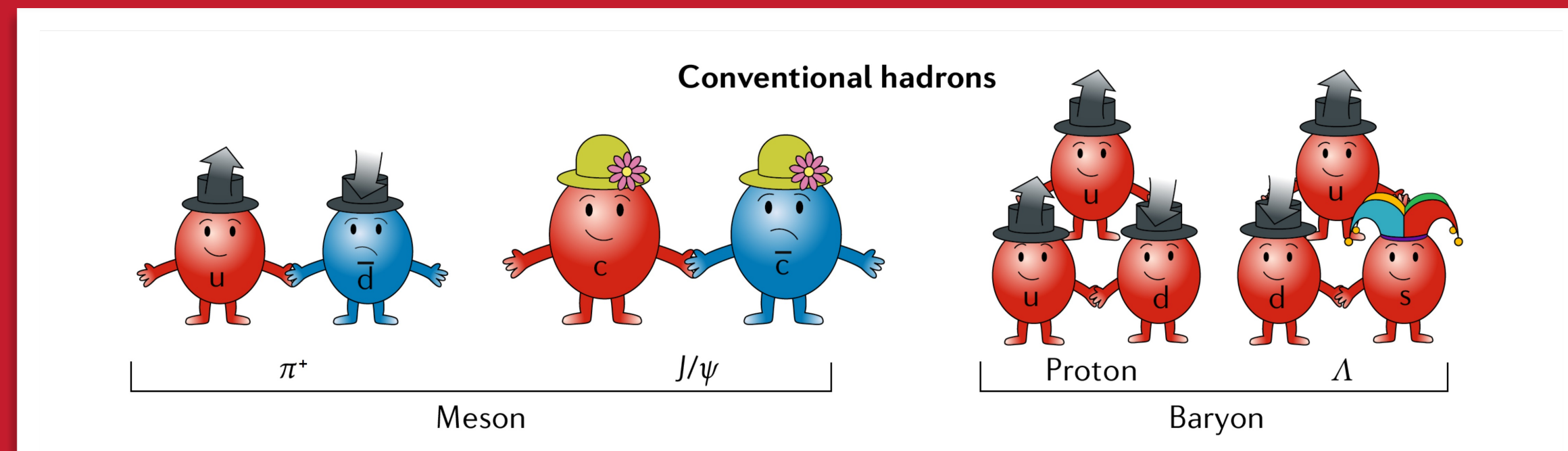
W boson

Higgs boson

origin of mass

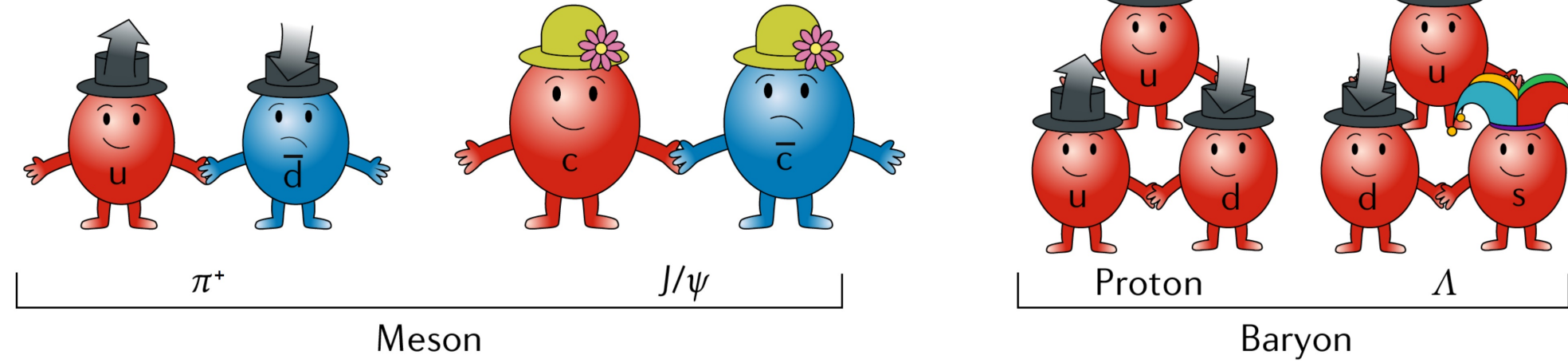


COMPOSITE PARTICLES

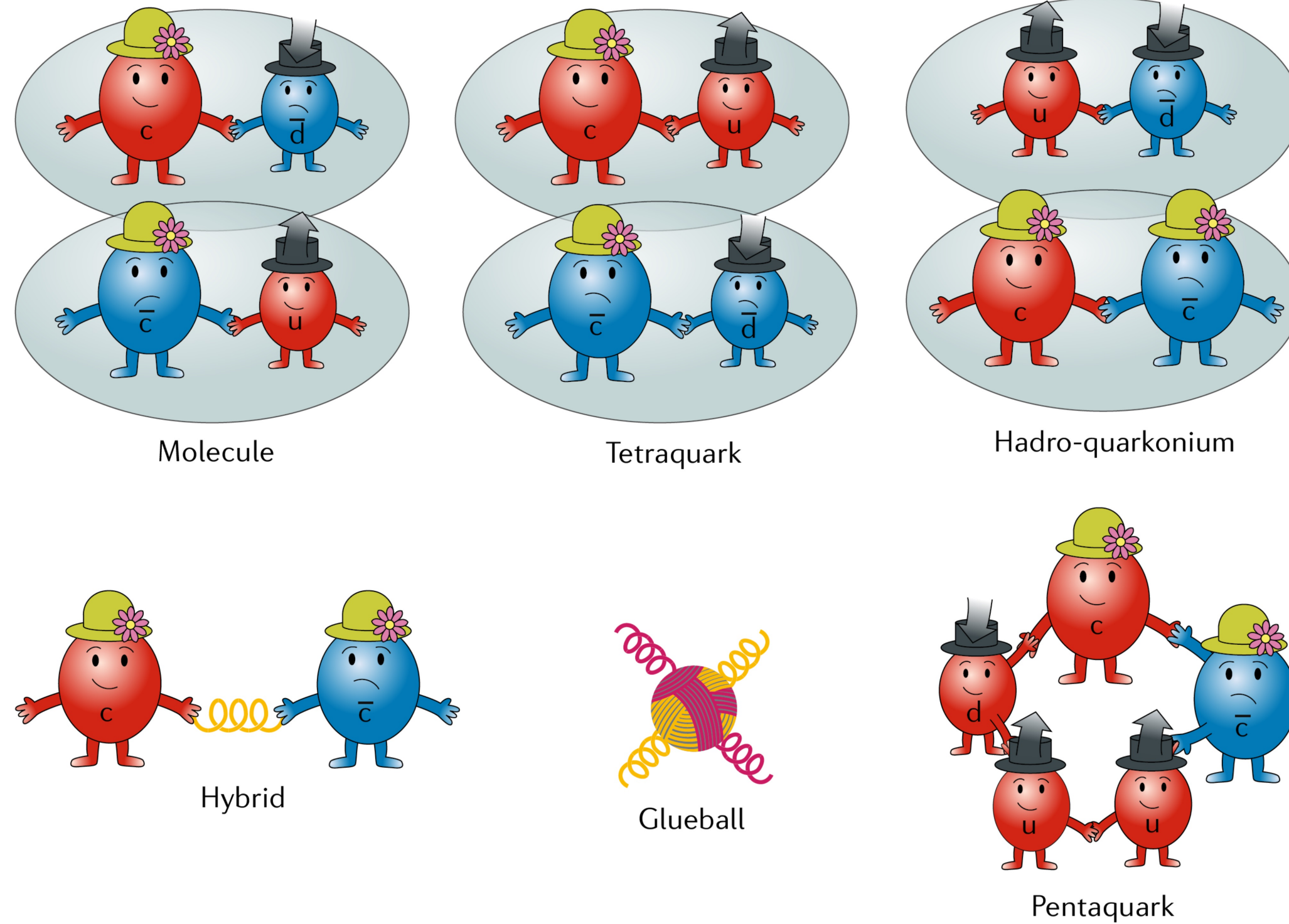


COMPOSITE PARTICLES

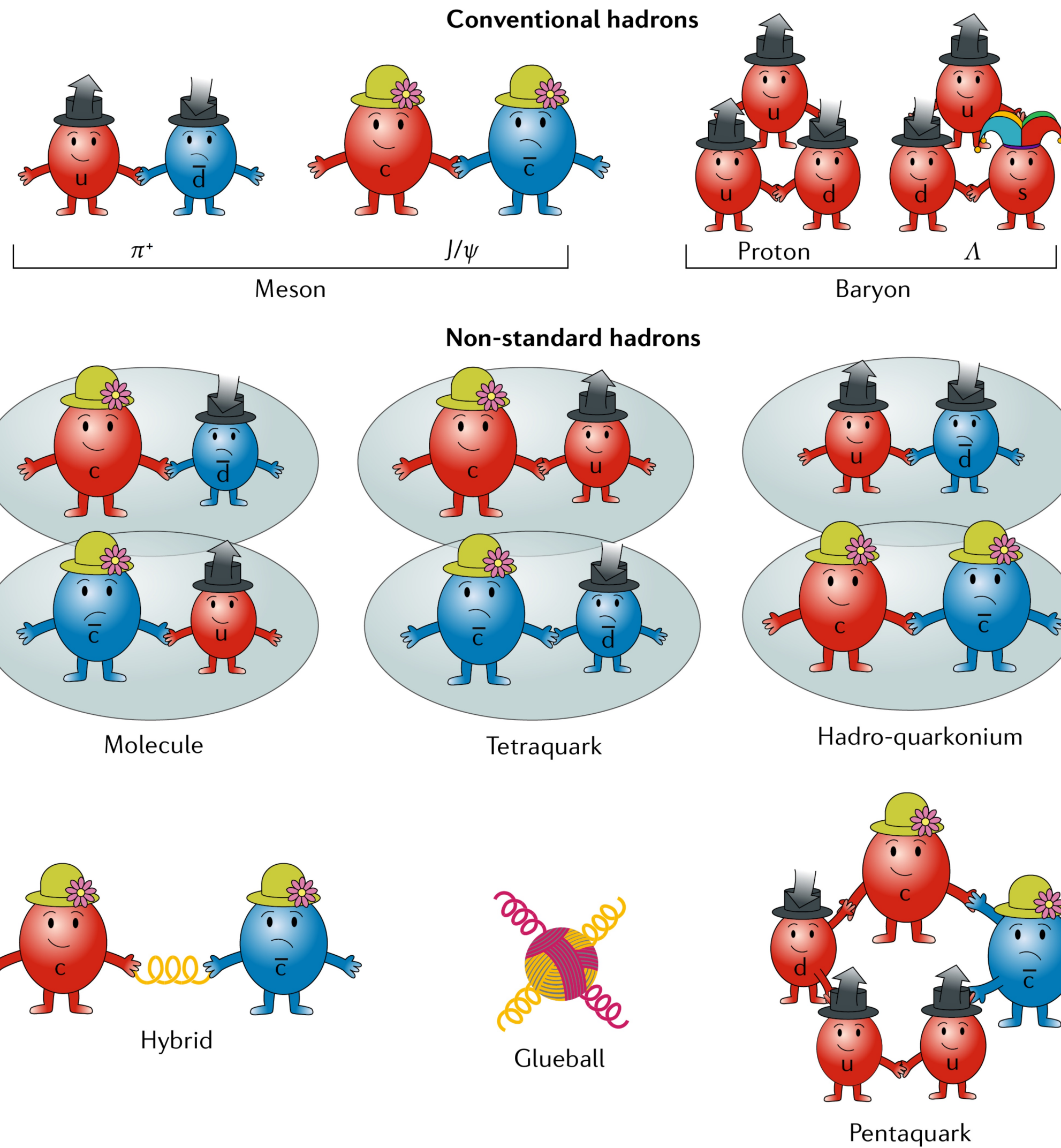
Conventional hadrons



Non-standard hadrons

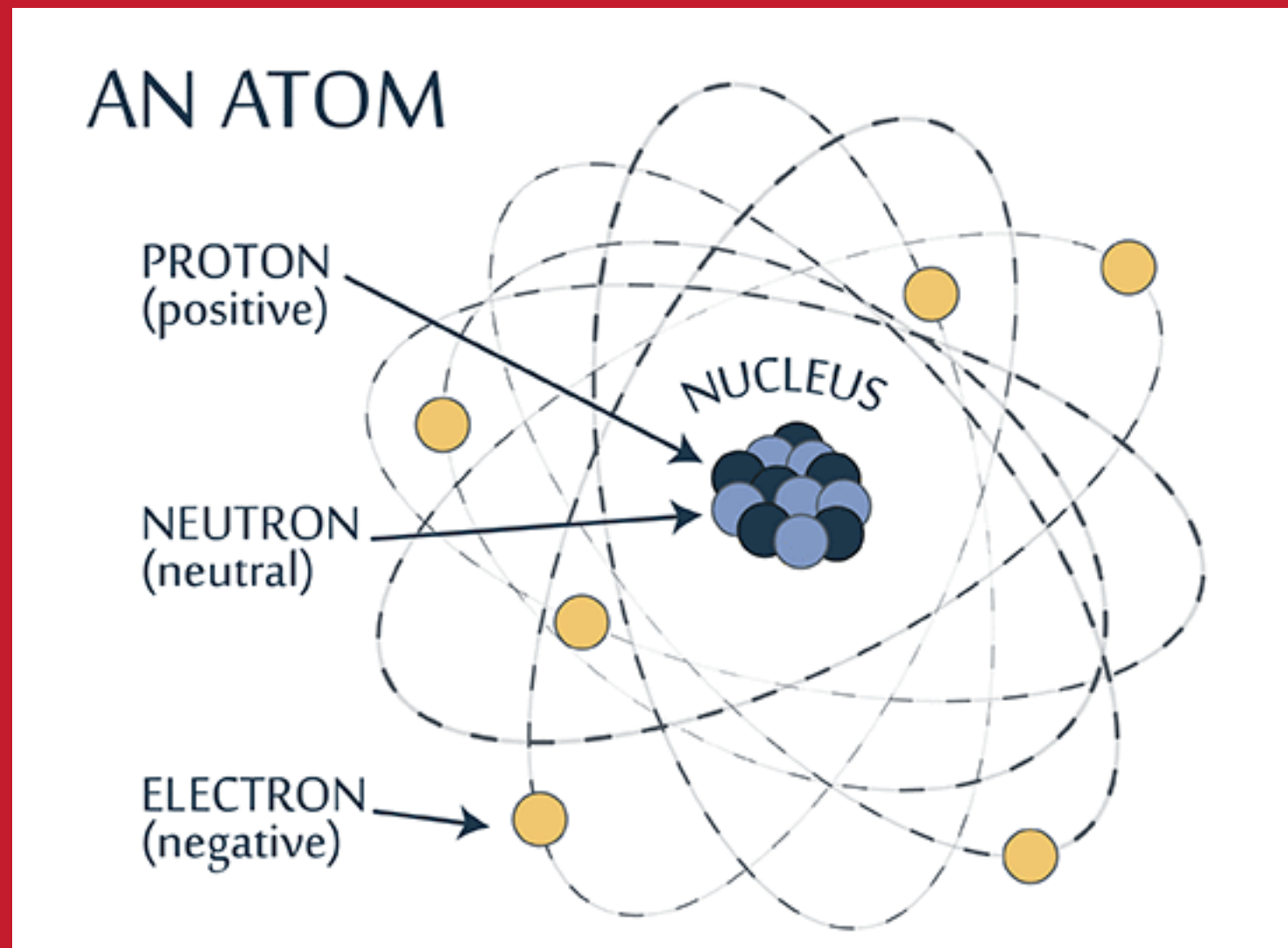


COMPOSITE PARTICLES



How did we realise that some particles
have internal structure?

THE PROTON

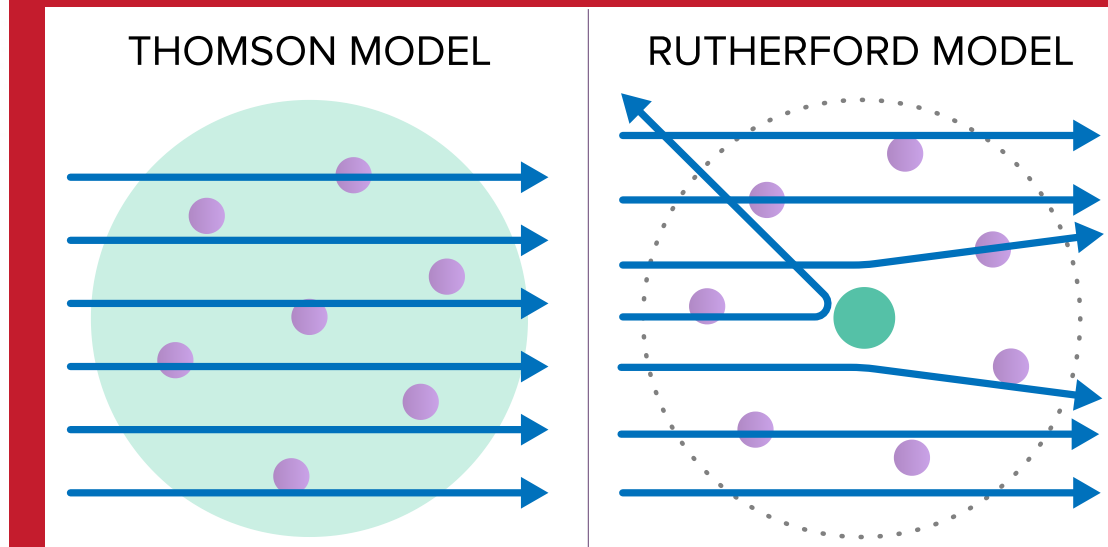
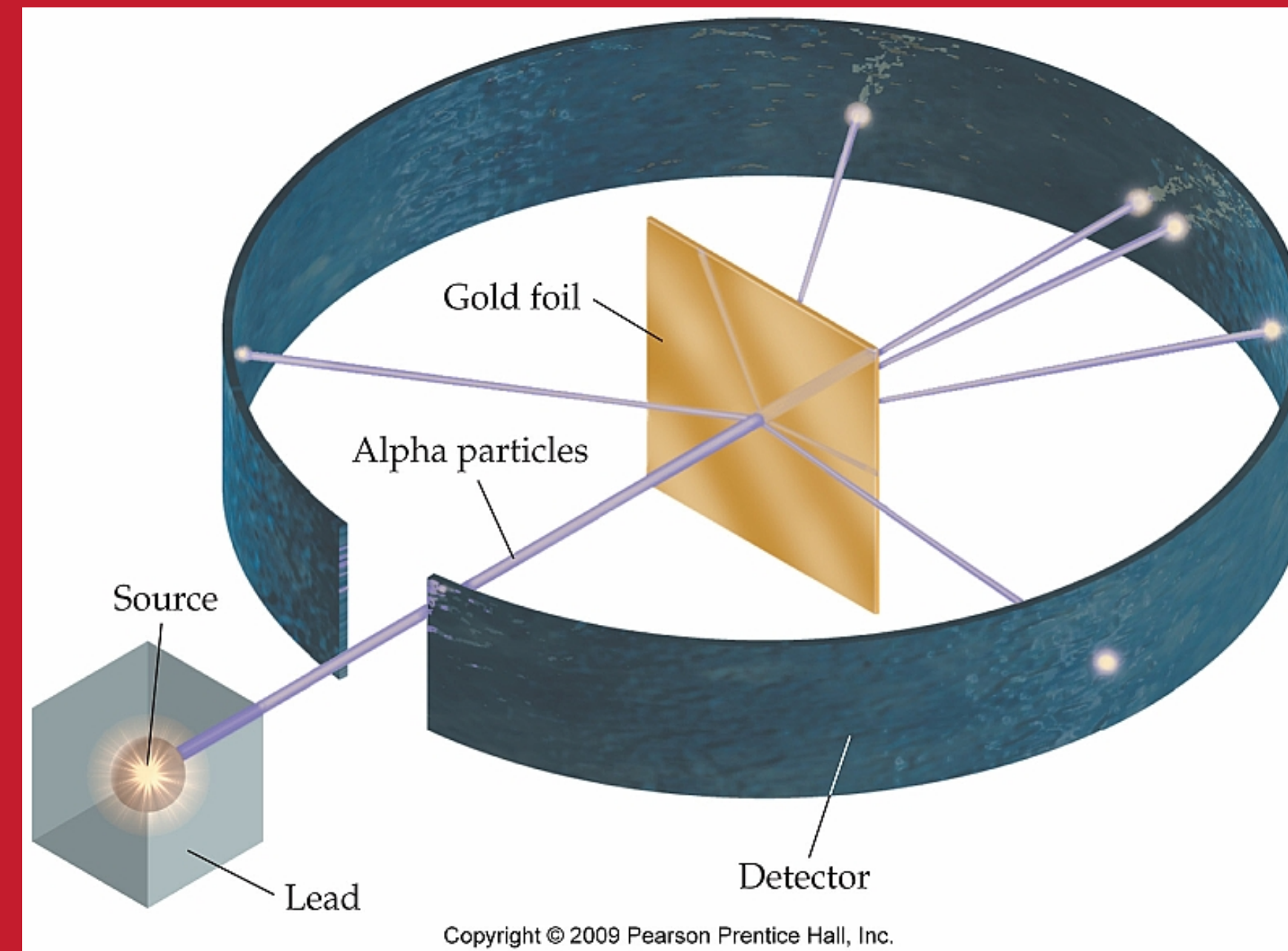
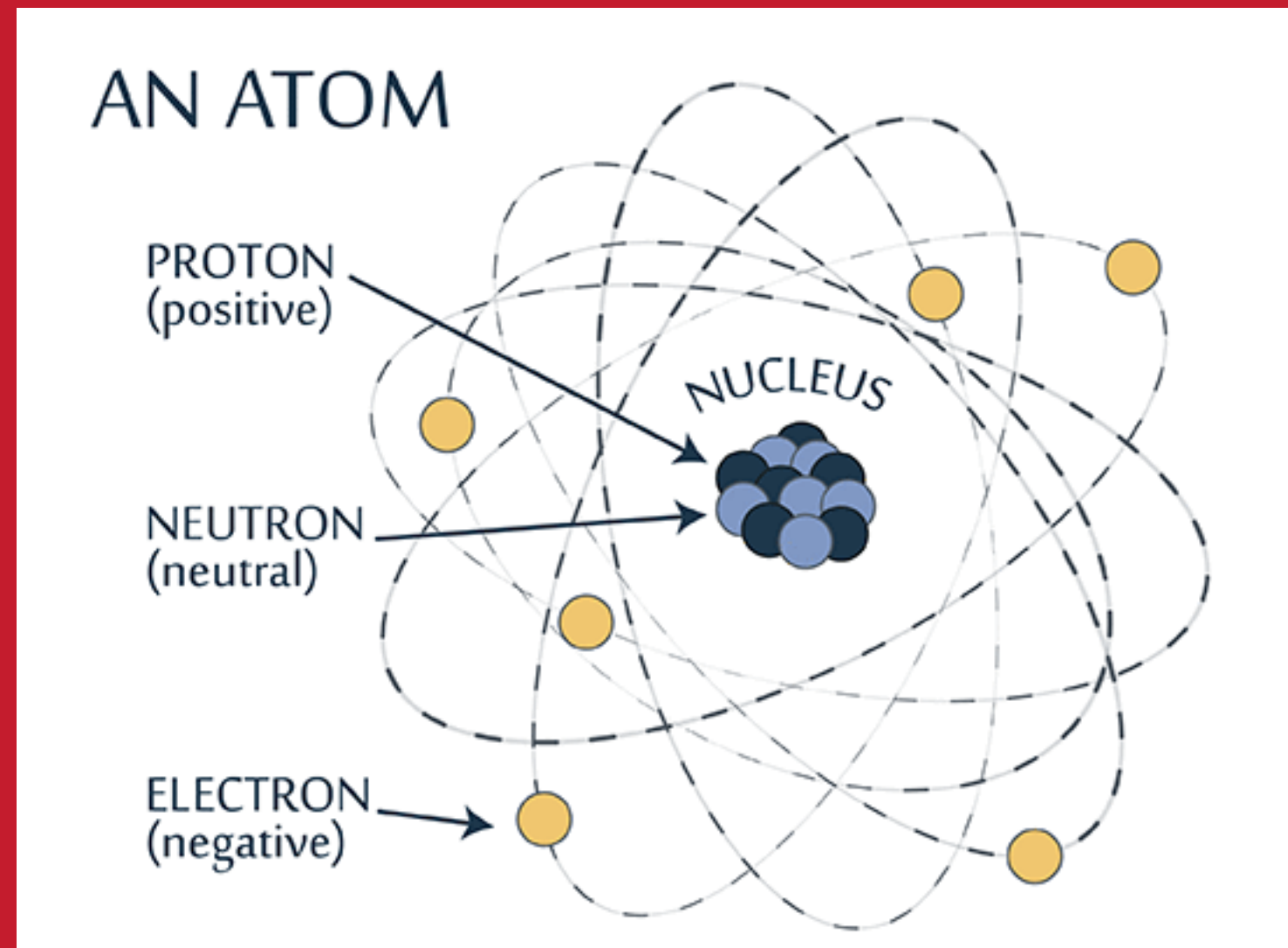


THE PROTON

Ernest Rutherford

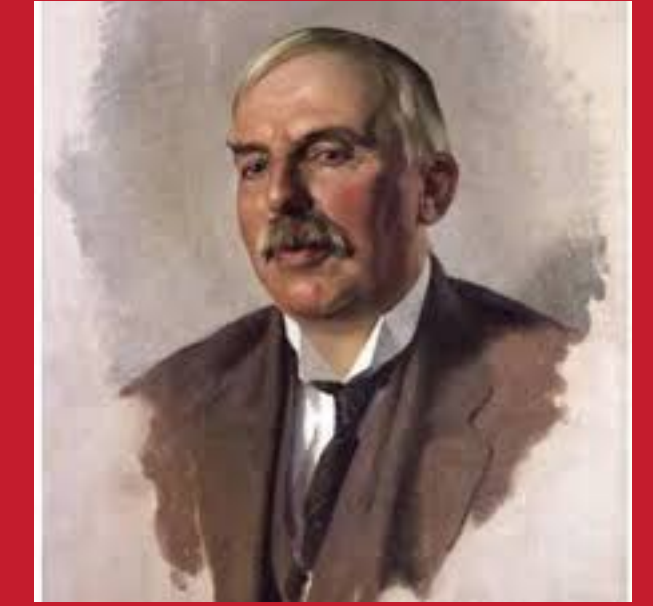


Discovery of the nucleus (1911)

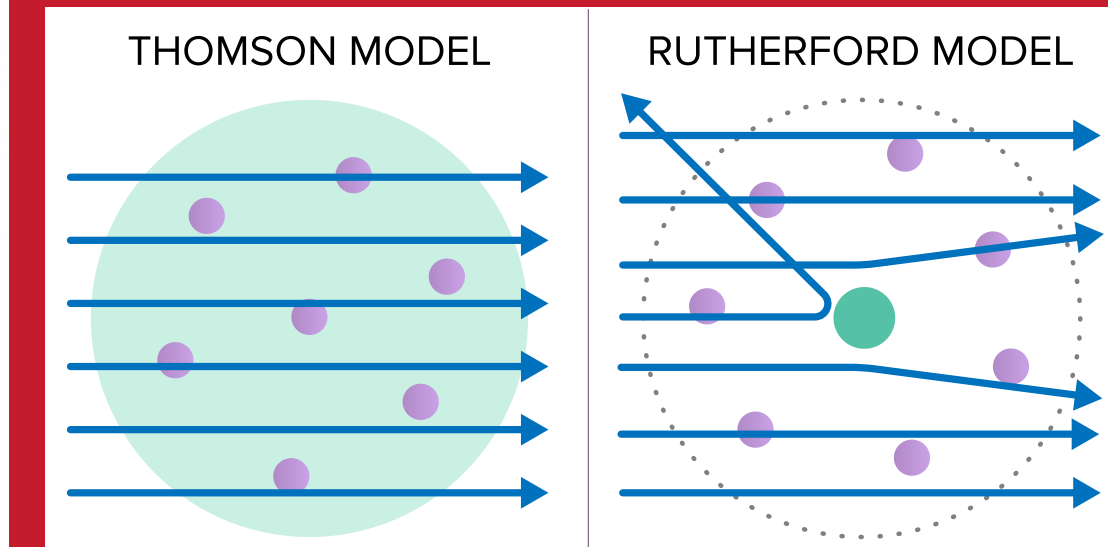
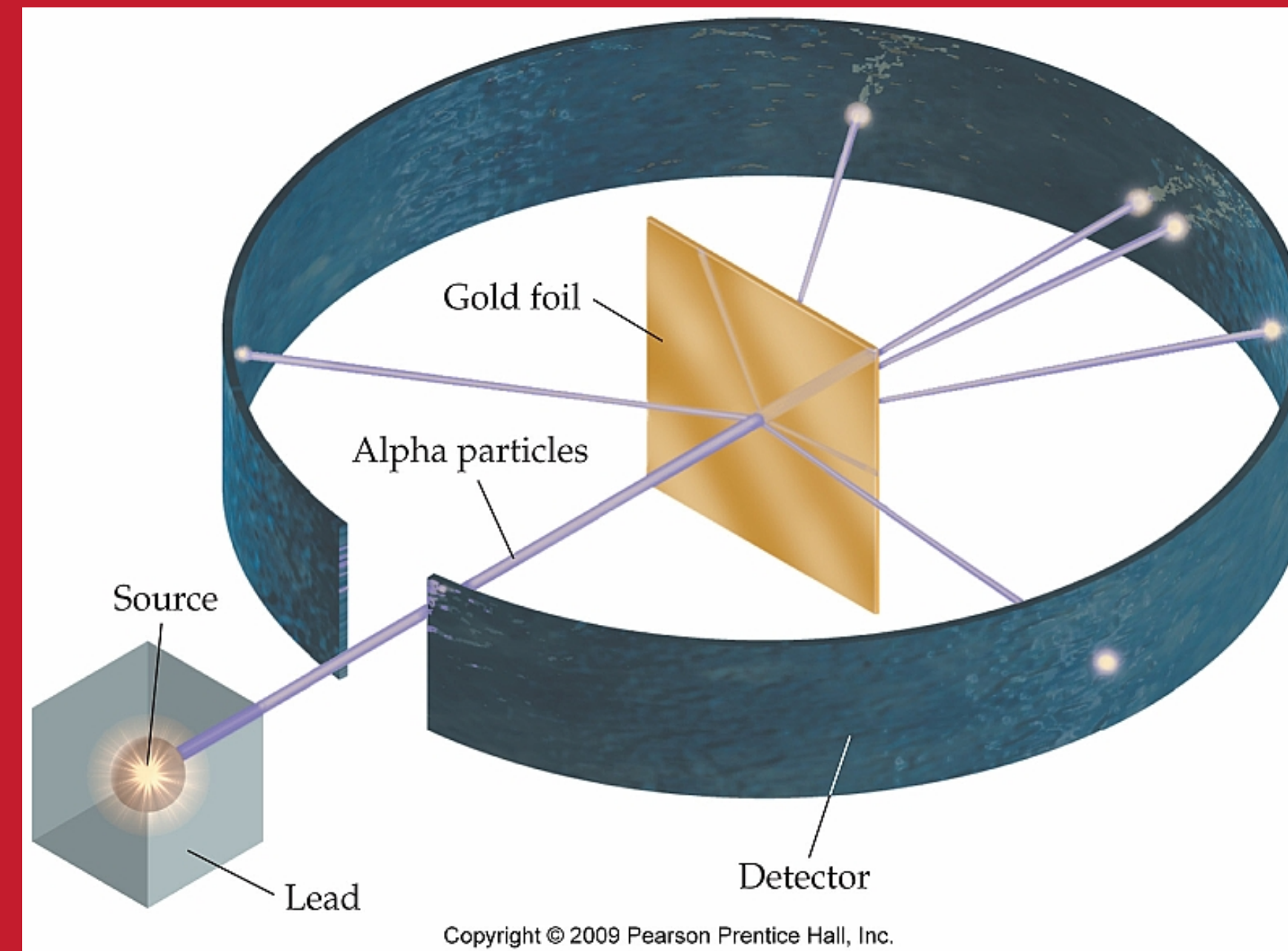
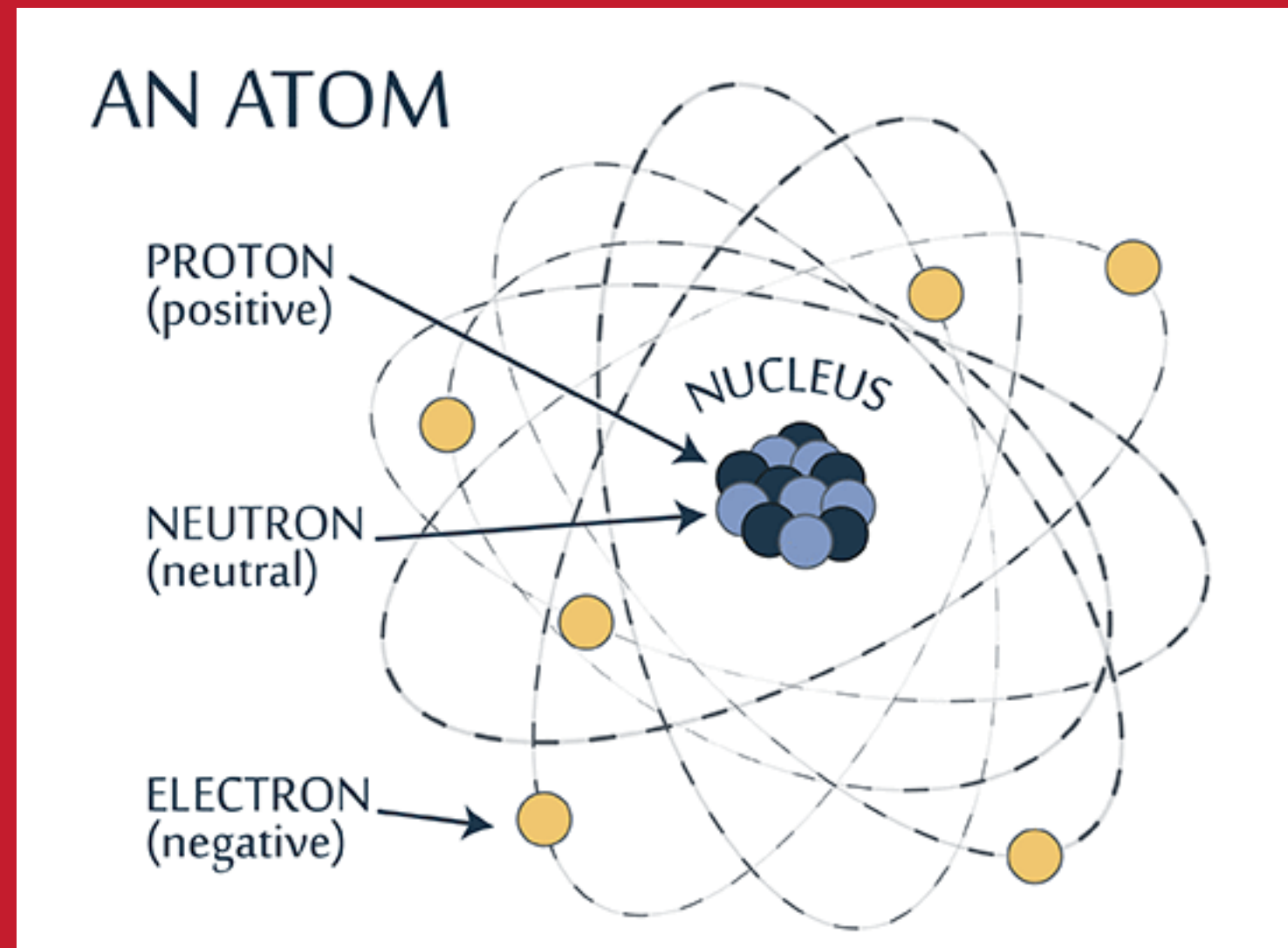


THE PROTON

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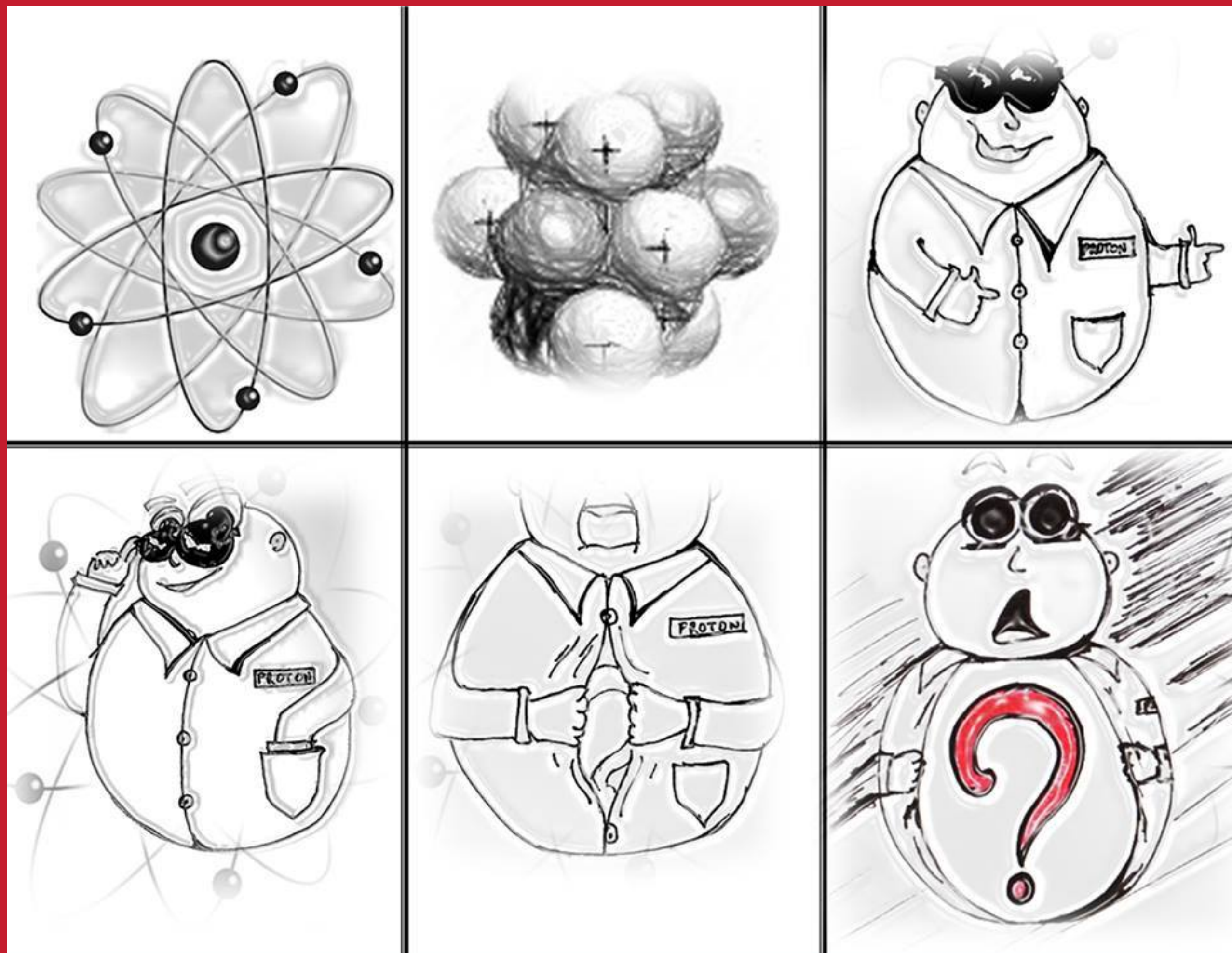


"Discovery" of the proton (1920)

Hydrogen nucleus also present in another nuclei

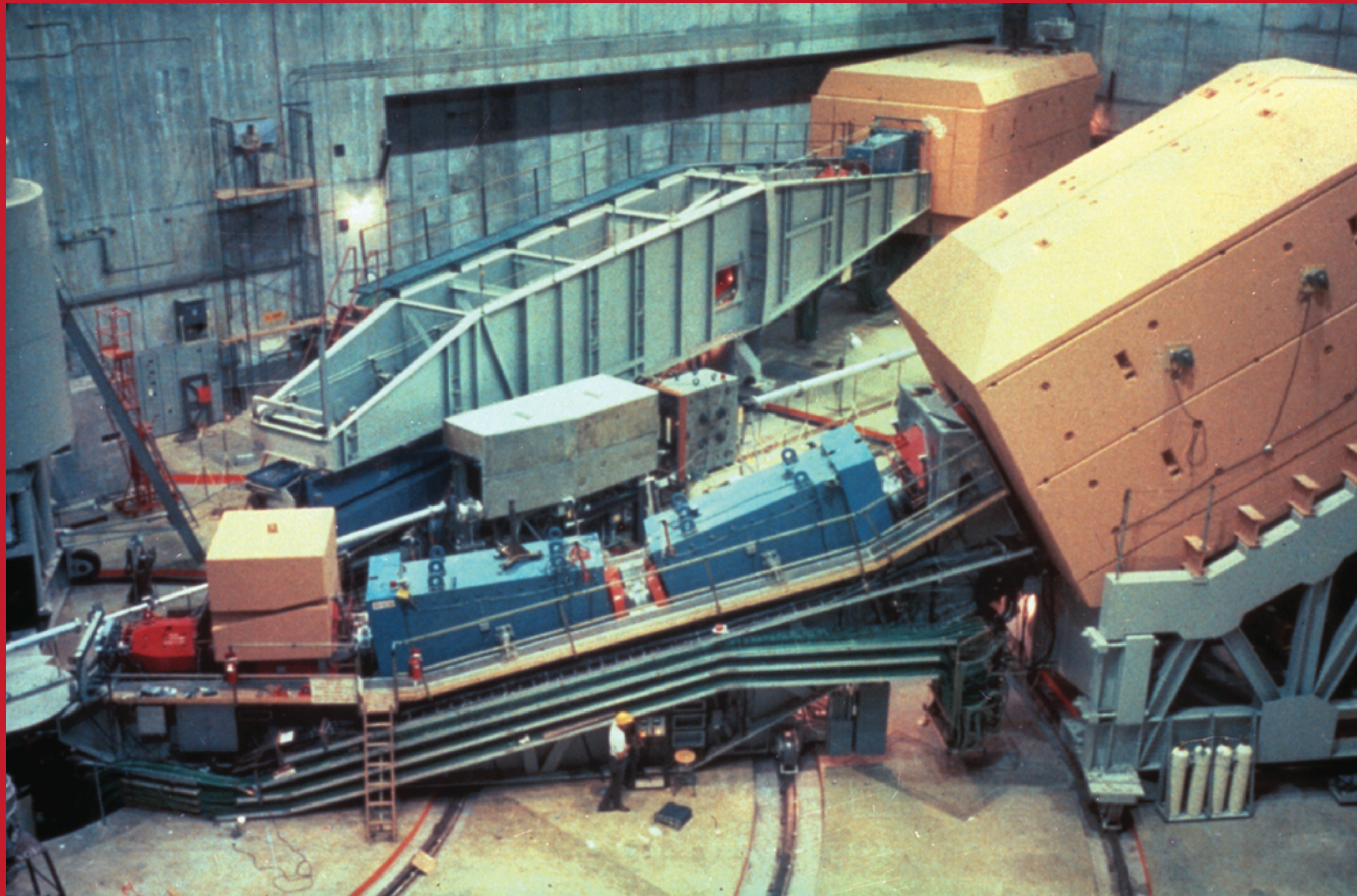
PROTON

WHAT IS INSIDE THE PROTON?



THE STRUCTURE OF THE PROTON

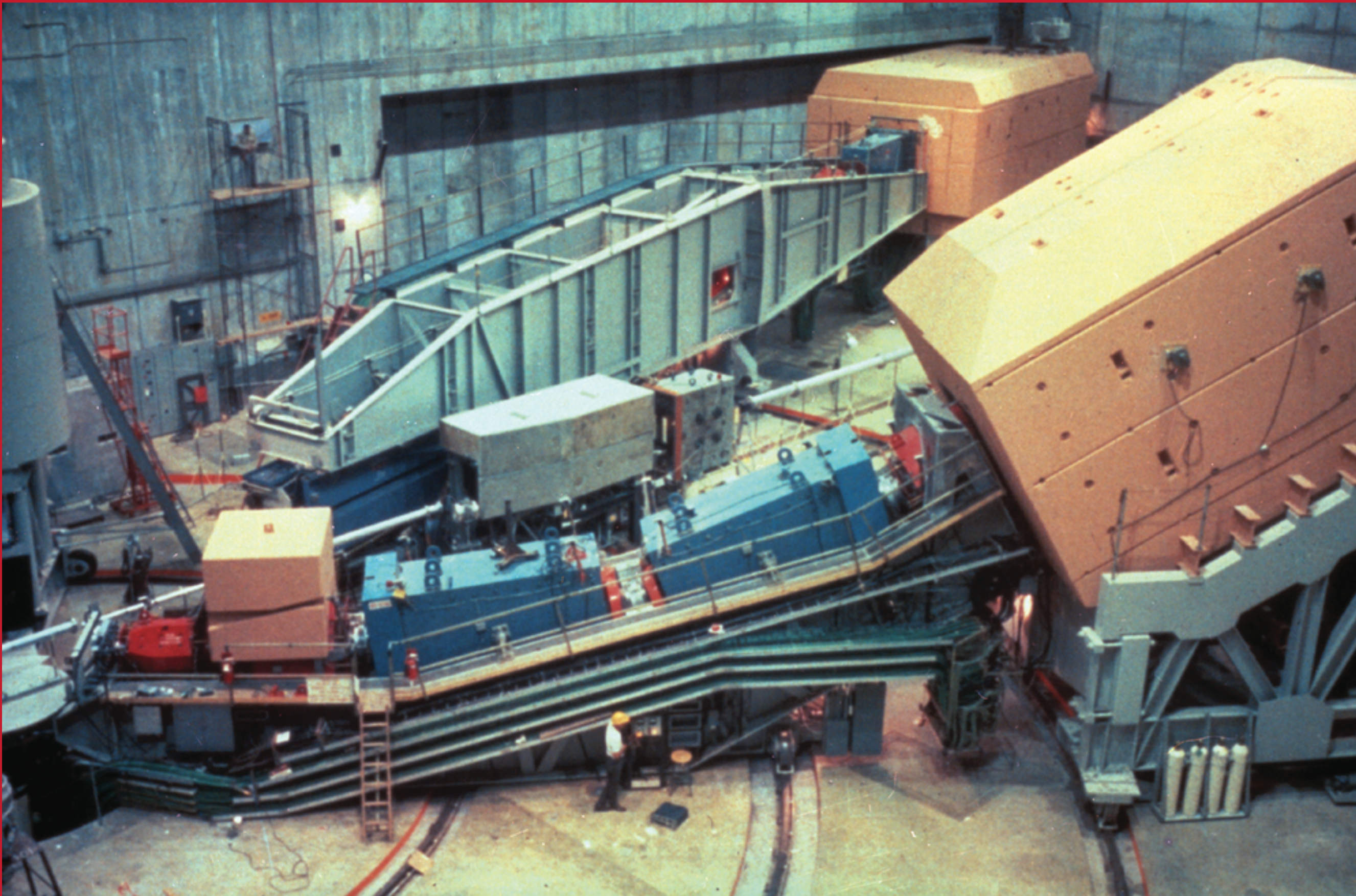
Stanford Linear Accelerator Center (SLAC) in 1968



Hydrogen targets bombarded
with high energy electron beams

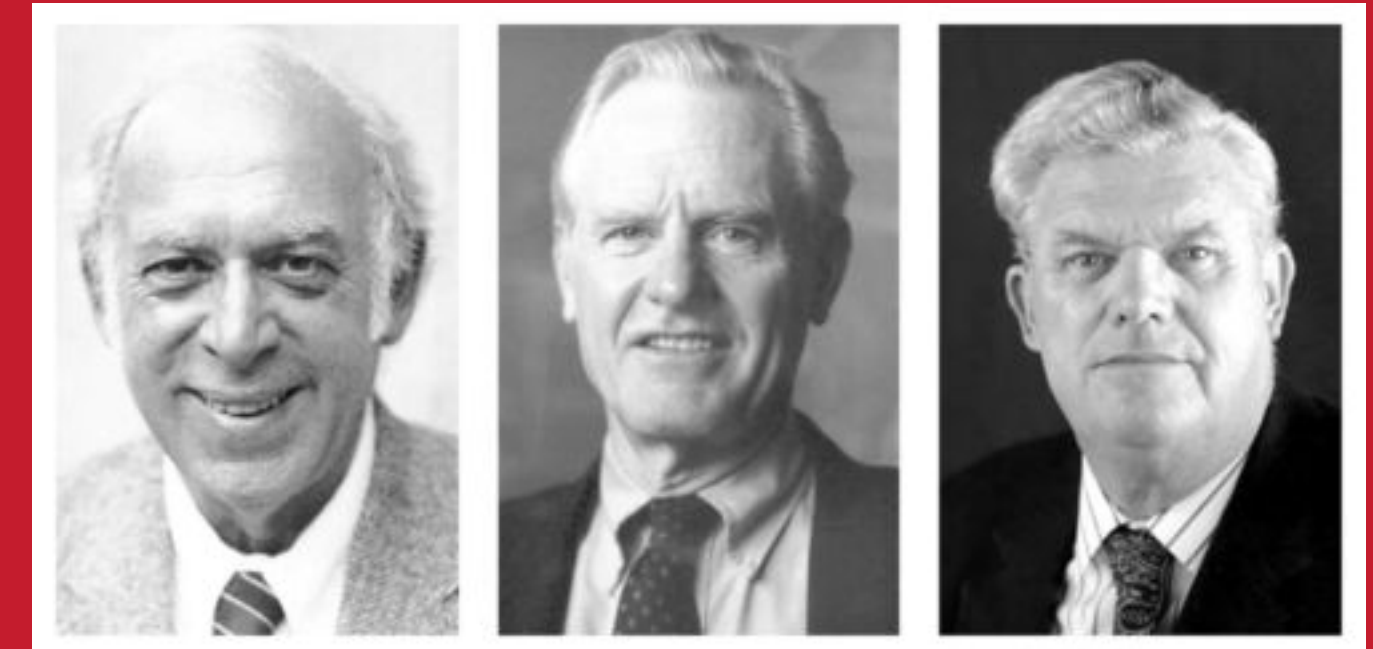
THE STRUCTURE OF THE PROTON

Stanford Linear Accelerator Center (SLAC) in 1968



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1990 Nobel Prize

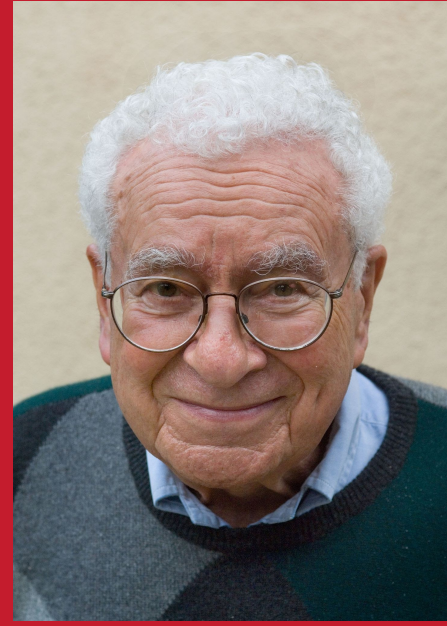


Jerome
Friedman

Henry
Kendall

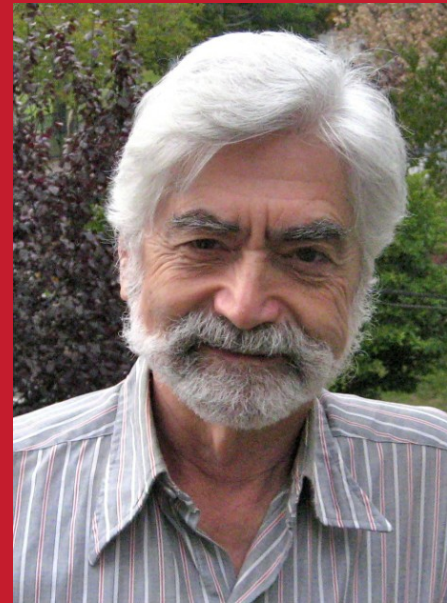
Richard
Taylor

HOW DID QUARKS COME TO PLAY?



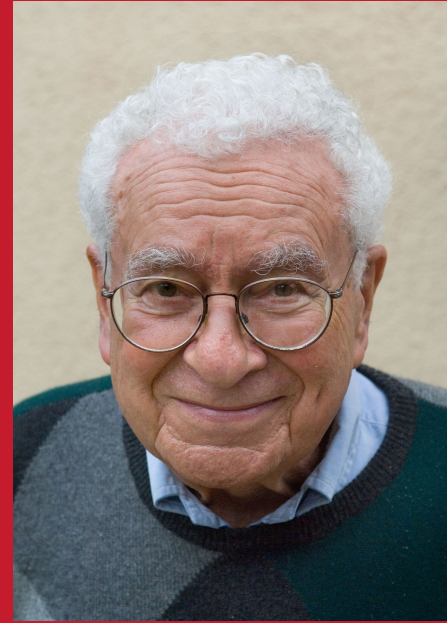
Murray Gell-Mann

Quark model (1964)

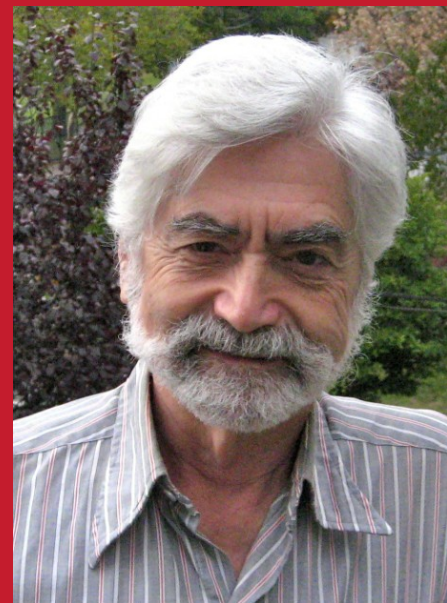


George Zweig

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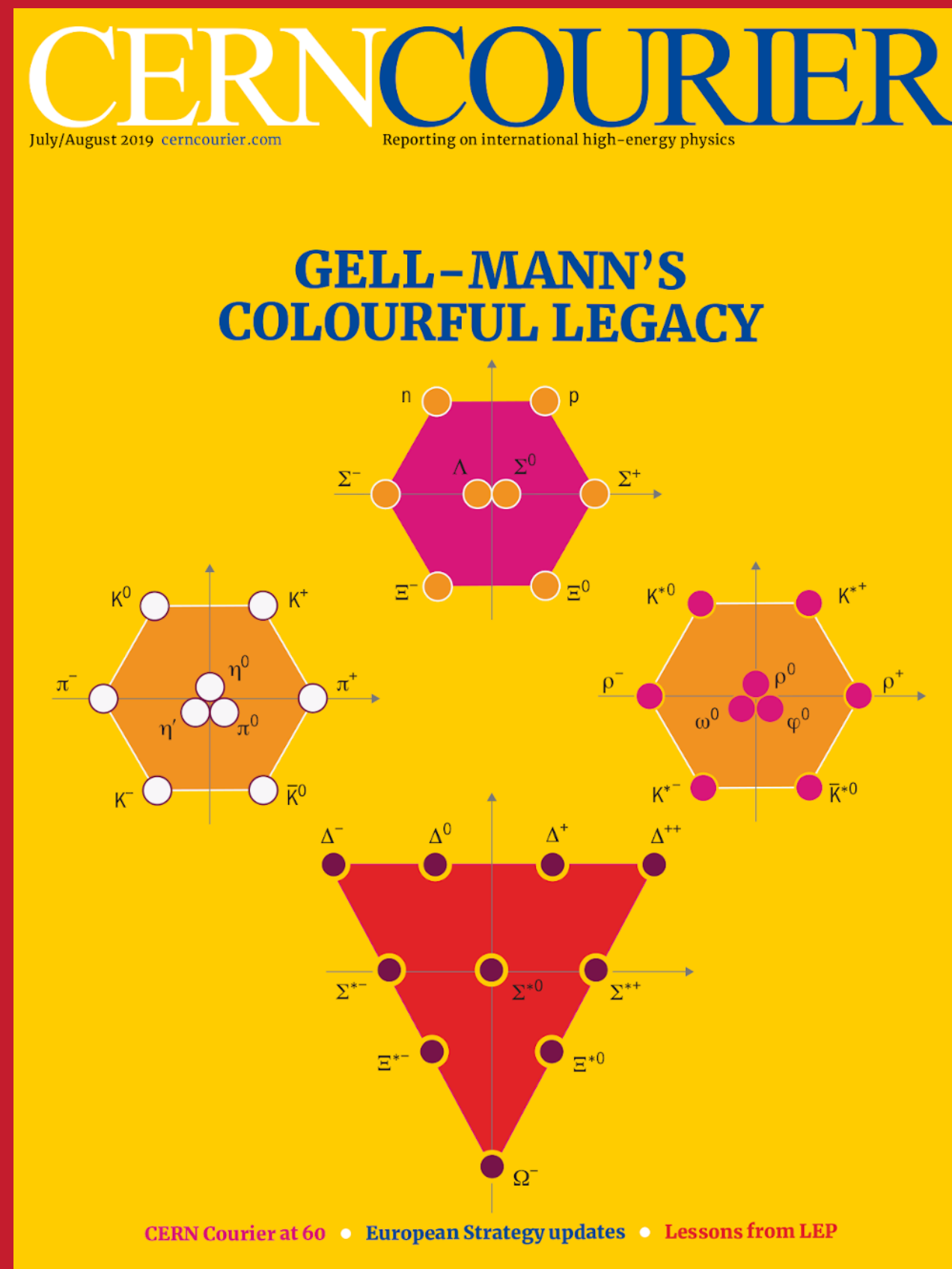


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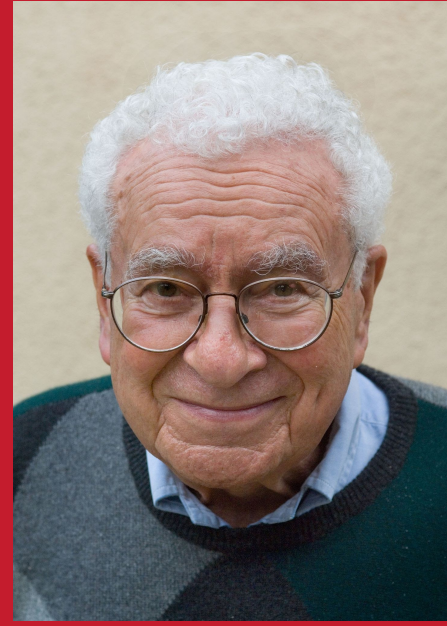


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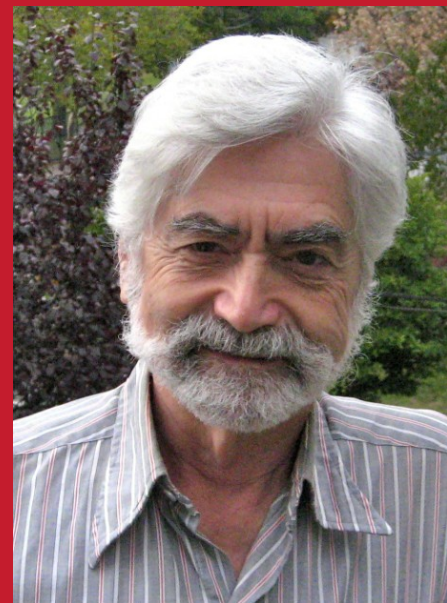
Quark model (1964)
classification system



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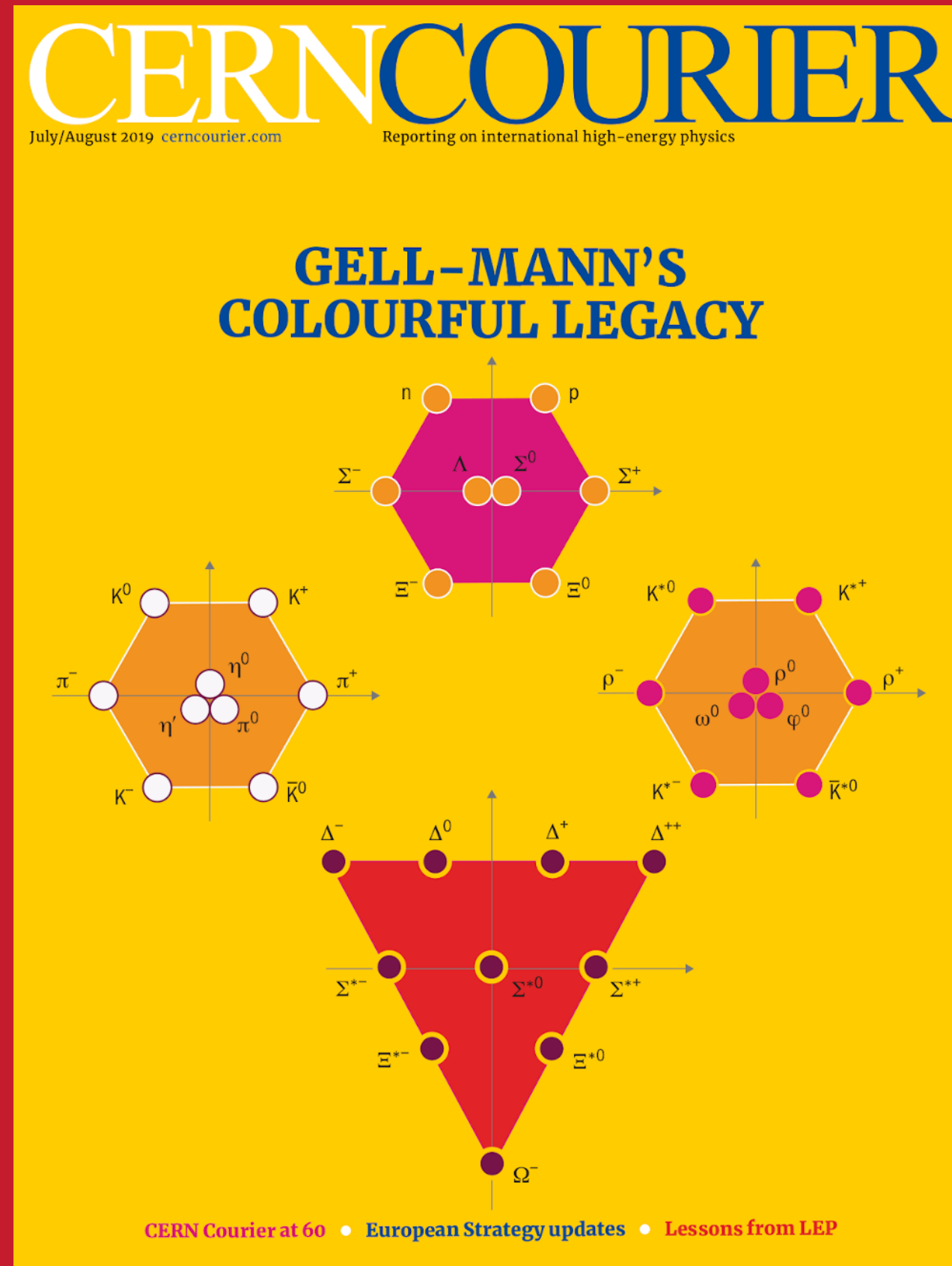


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Parton model (1969)

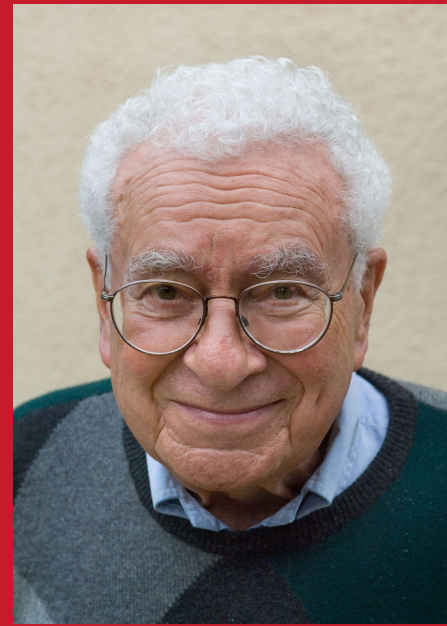


James Bjorken

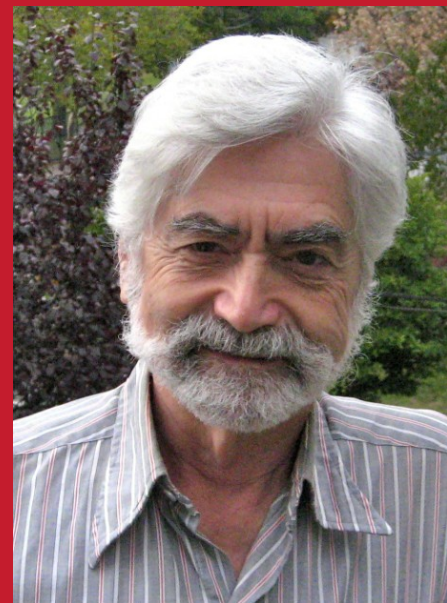


Richard Feynman

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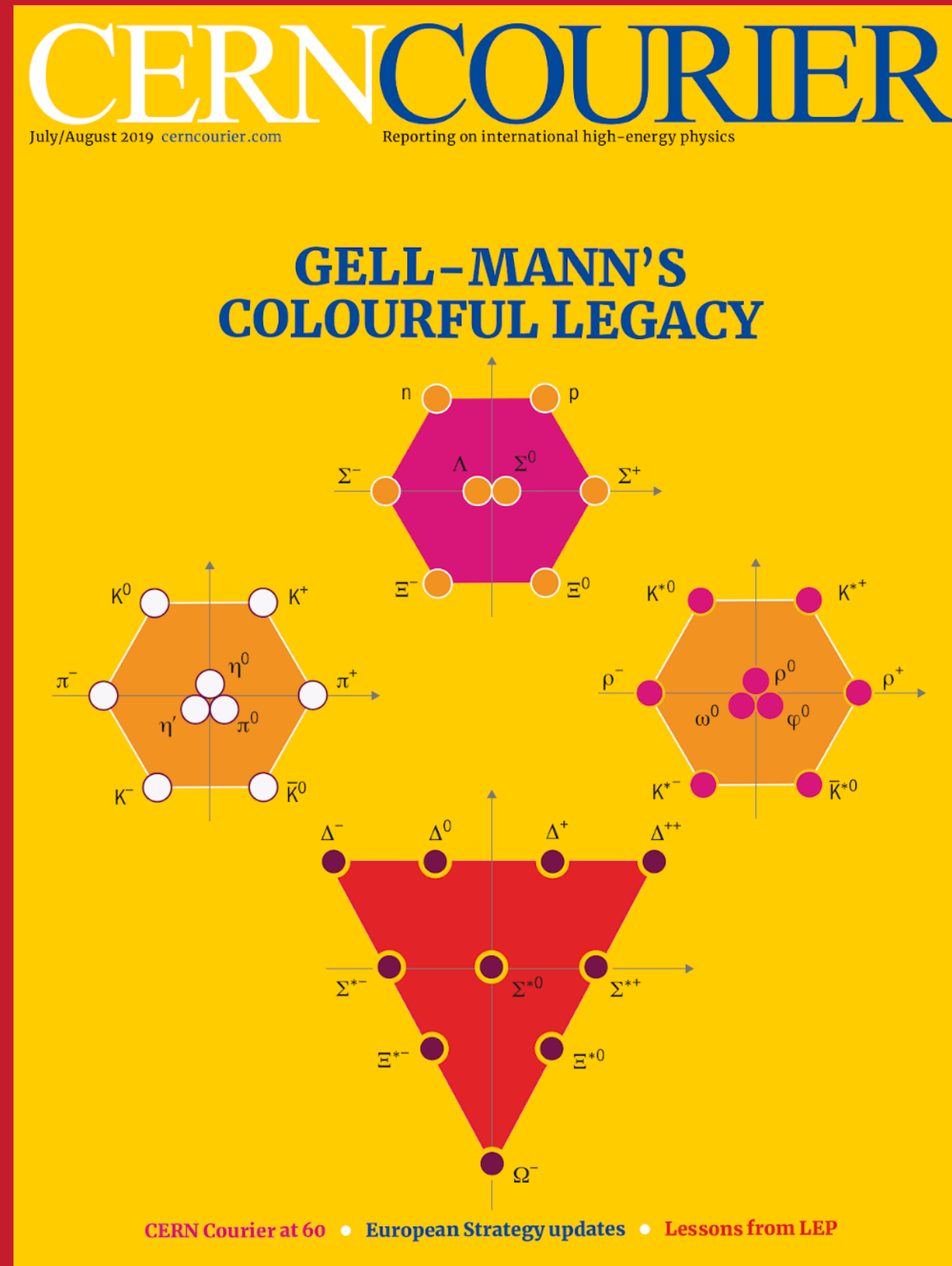


Murray Gell-Mann



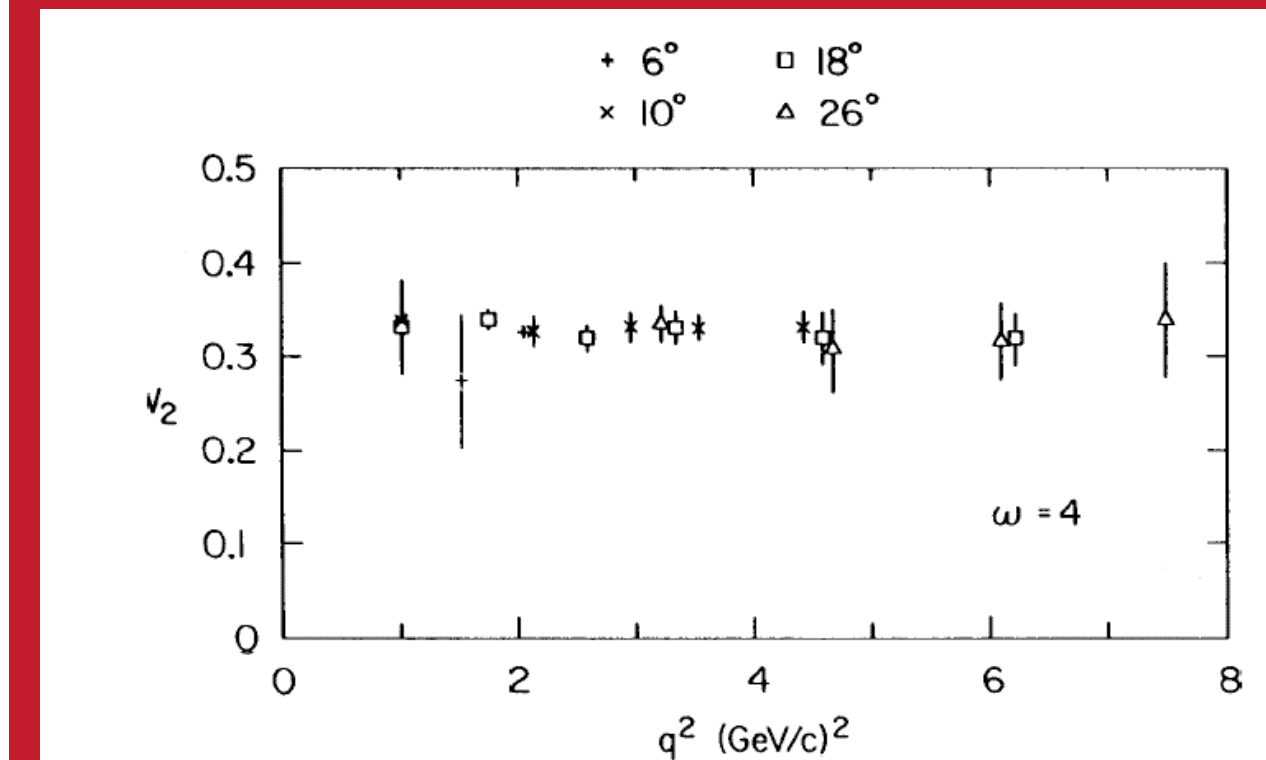
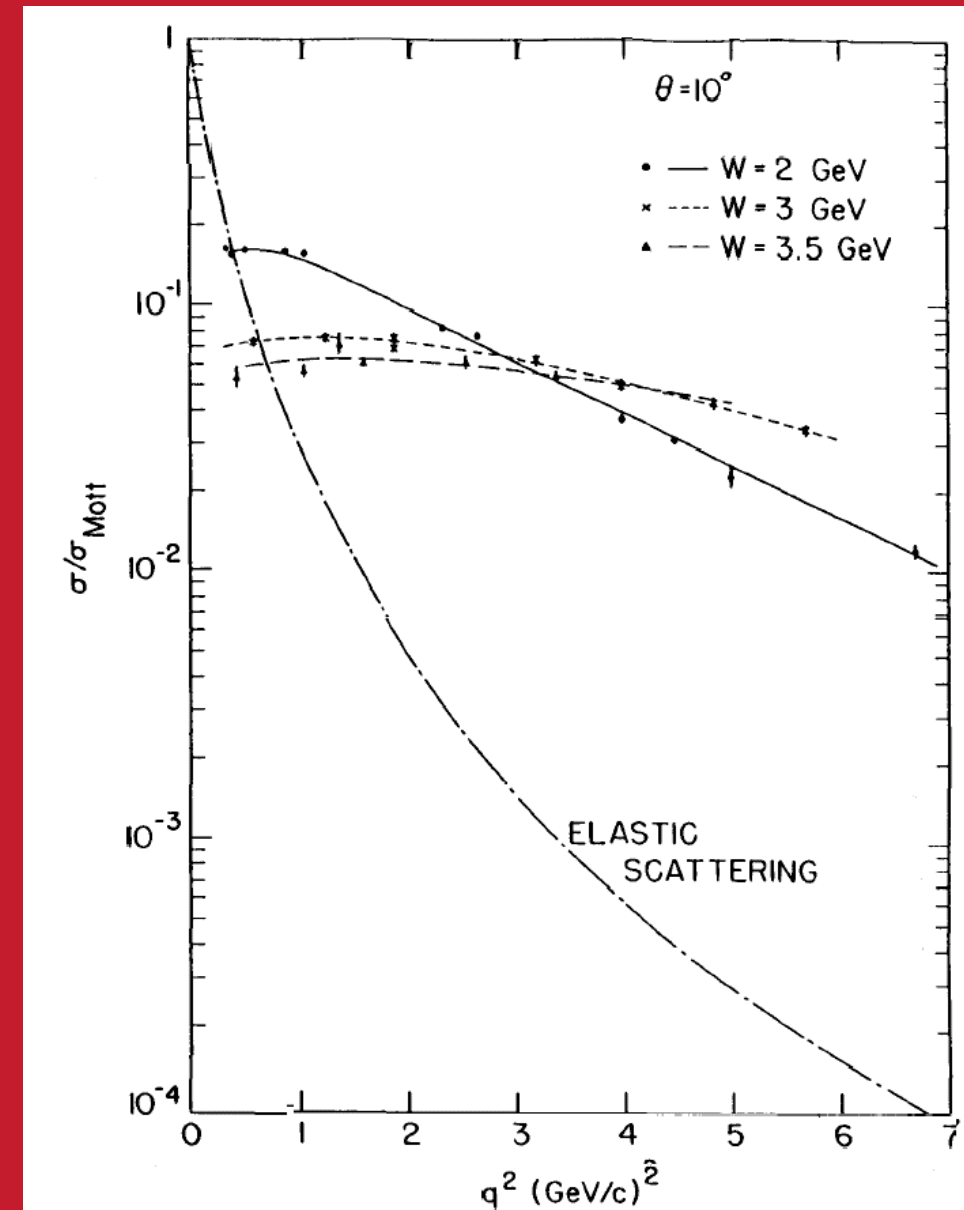
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Results from SLAC experiments

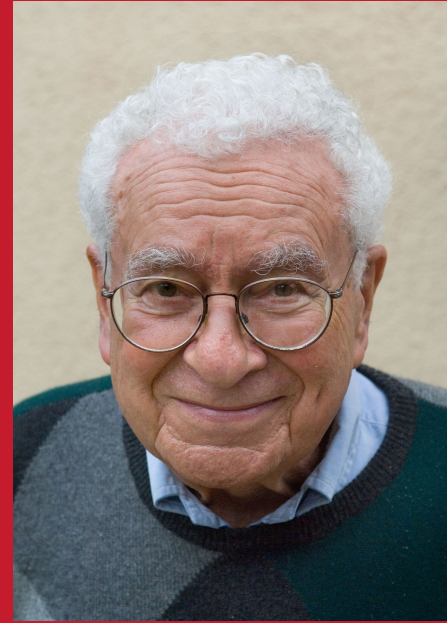


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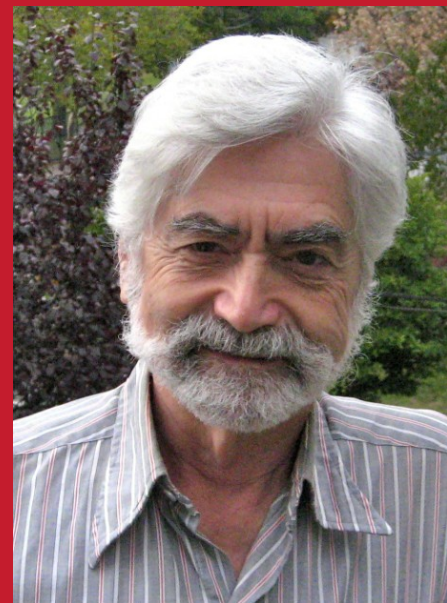


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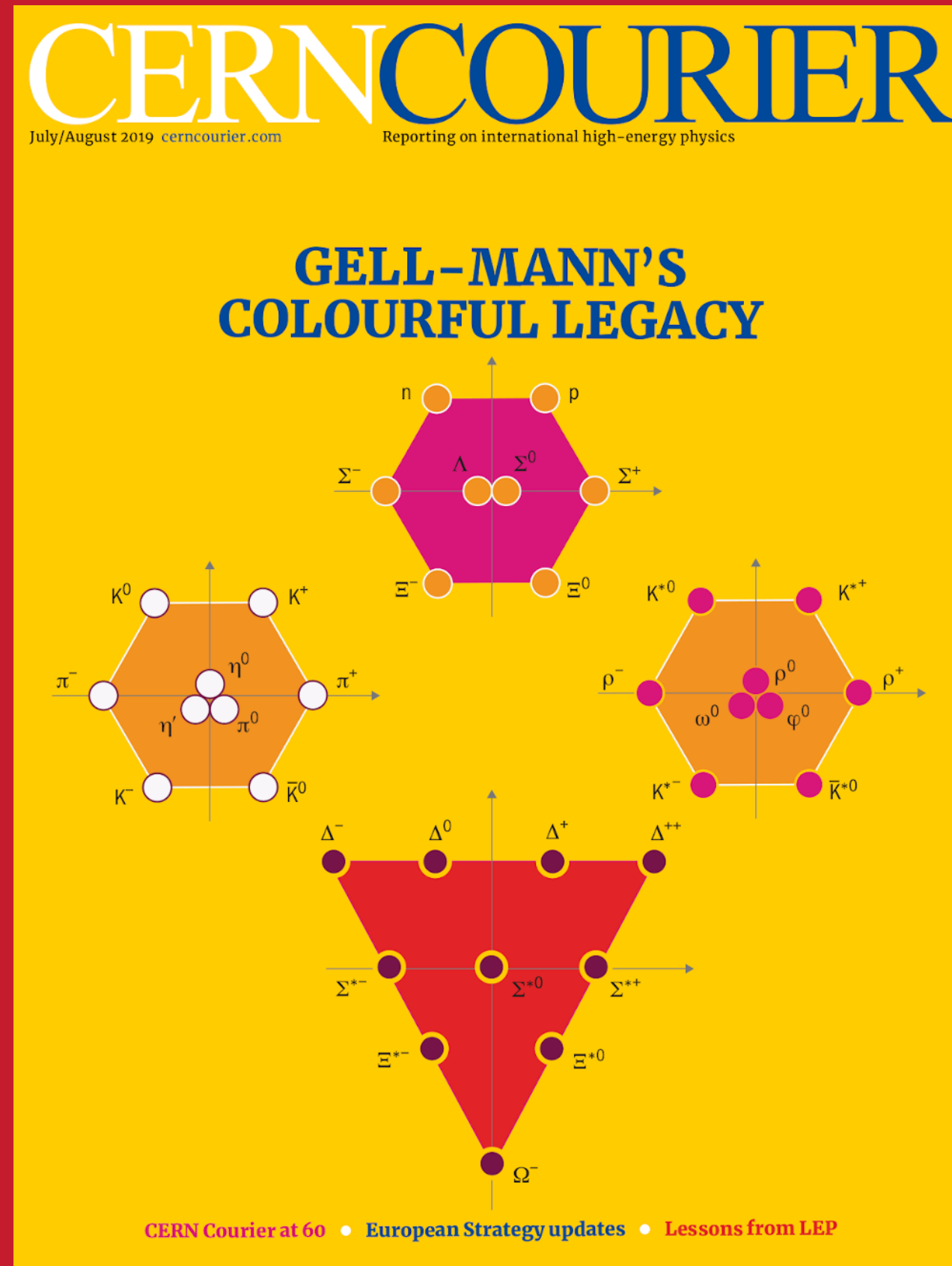


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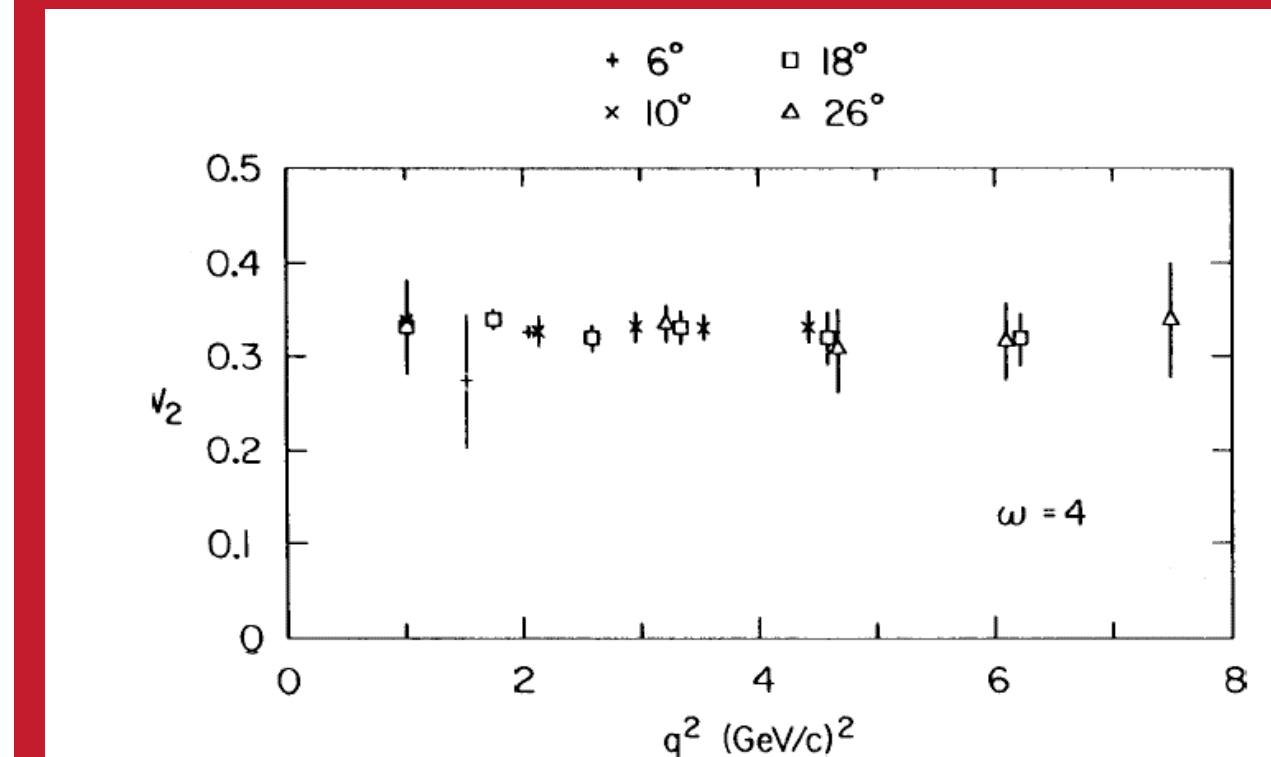
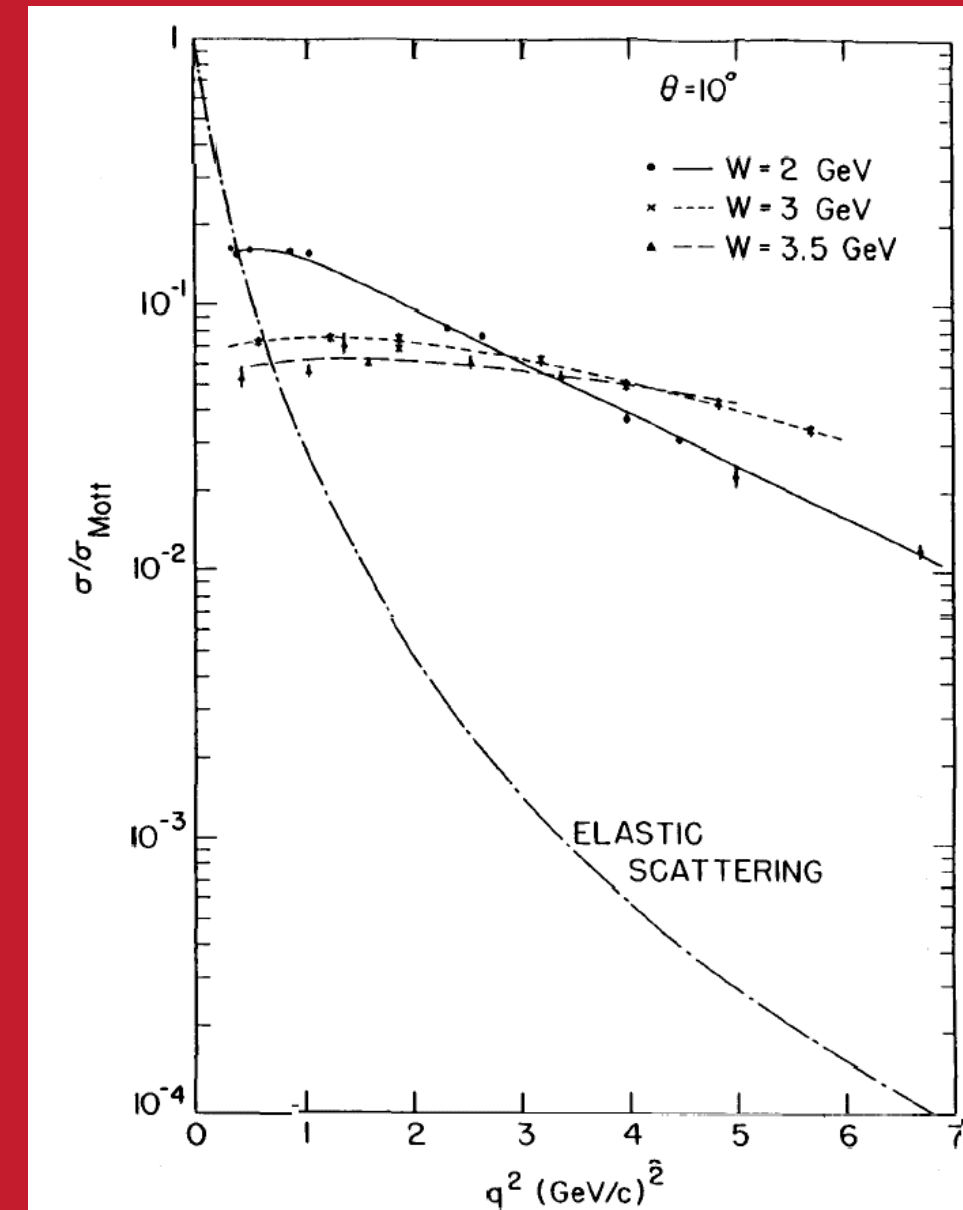
George Zweig

Quark model (1964)
classification system



Parton model (1969)

Results from SLAC experiments



James Bjorken



Richard Feynman

point-like scattering centers
inside the proton



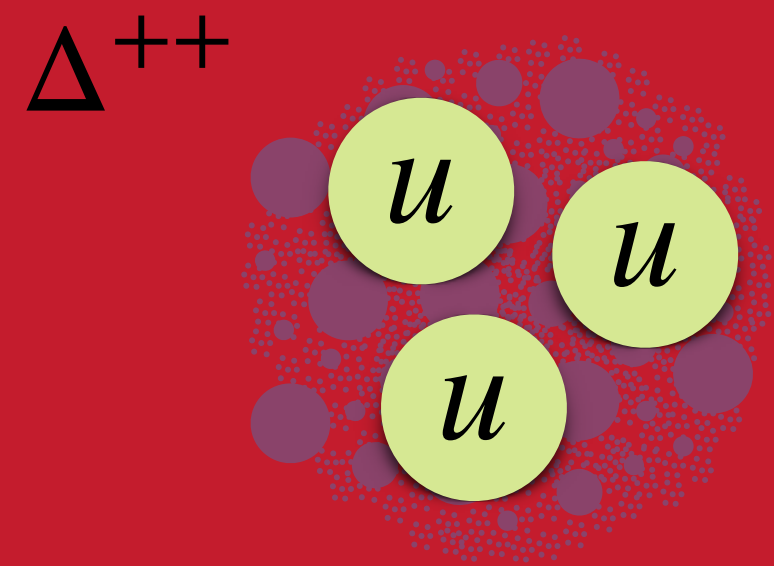
partons

THE BEGINNING OF QCD

Δ^{++} discovered experimentally in 50s

THEORETICAL OBJECTION TO QUARK MODEL (1964)

Pauli exclusion principle

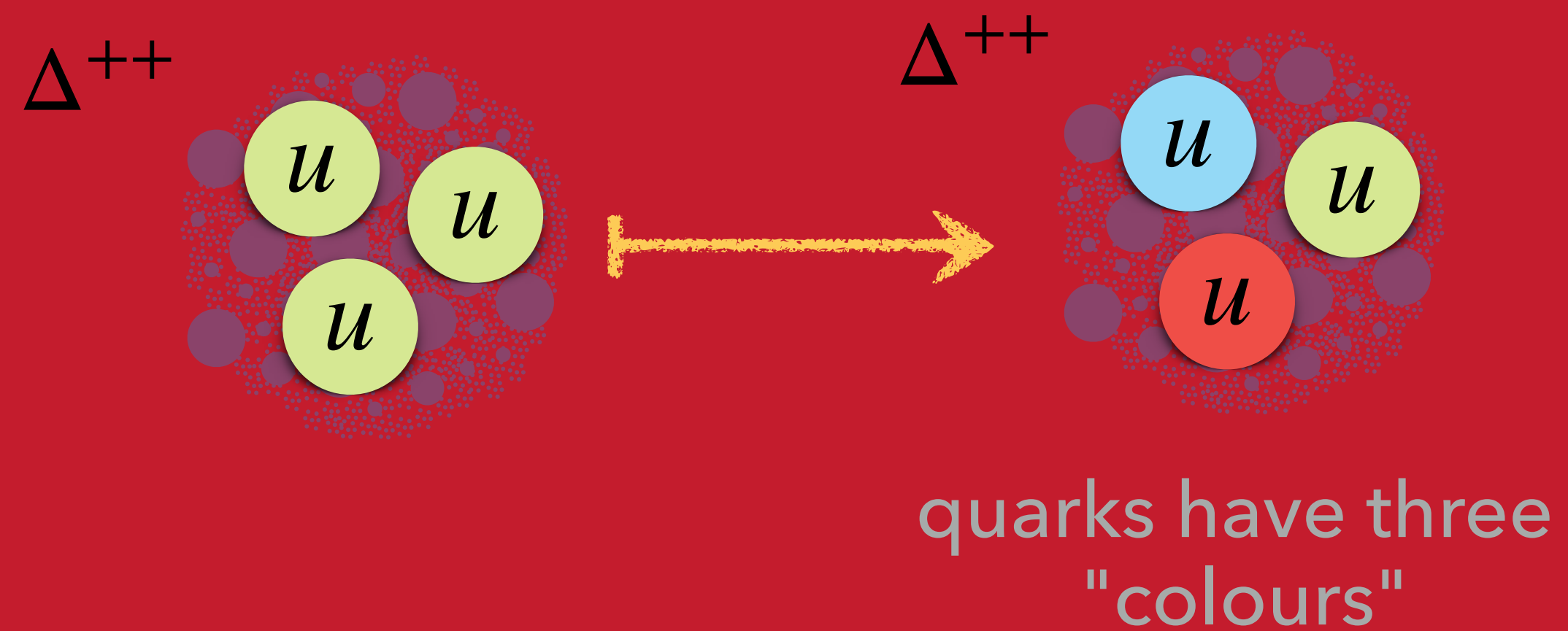


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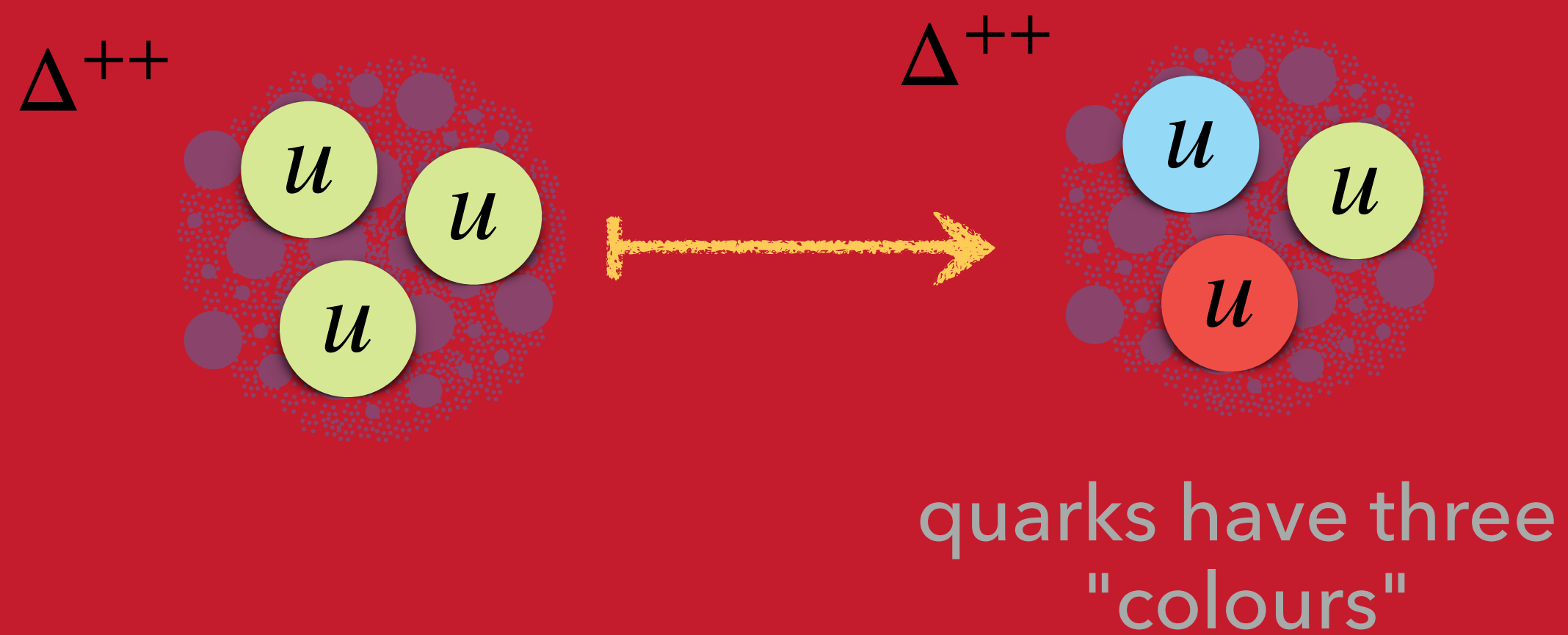


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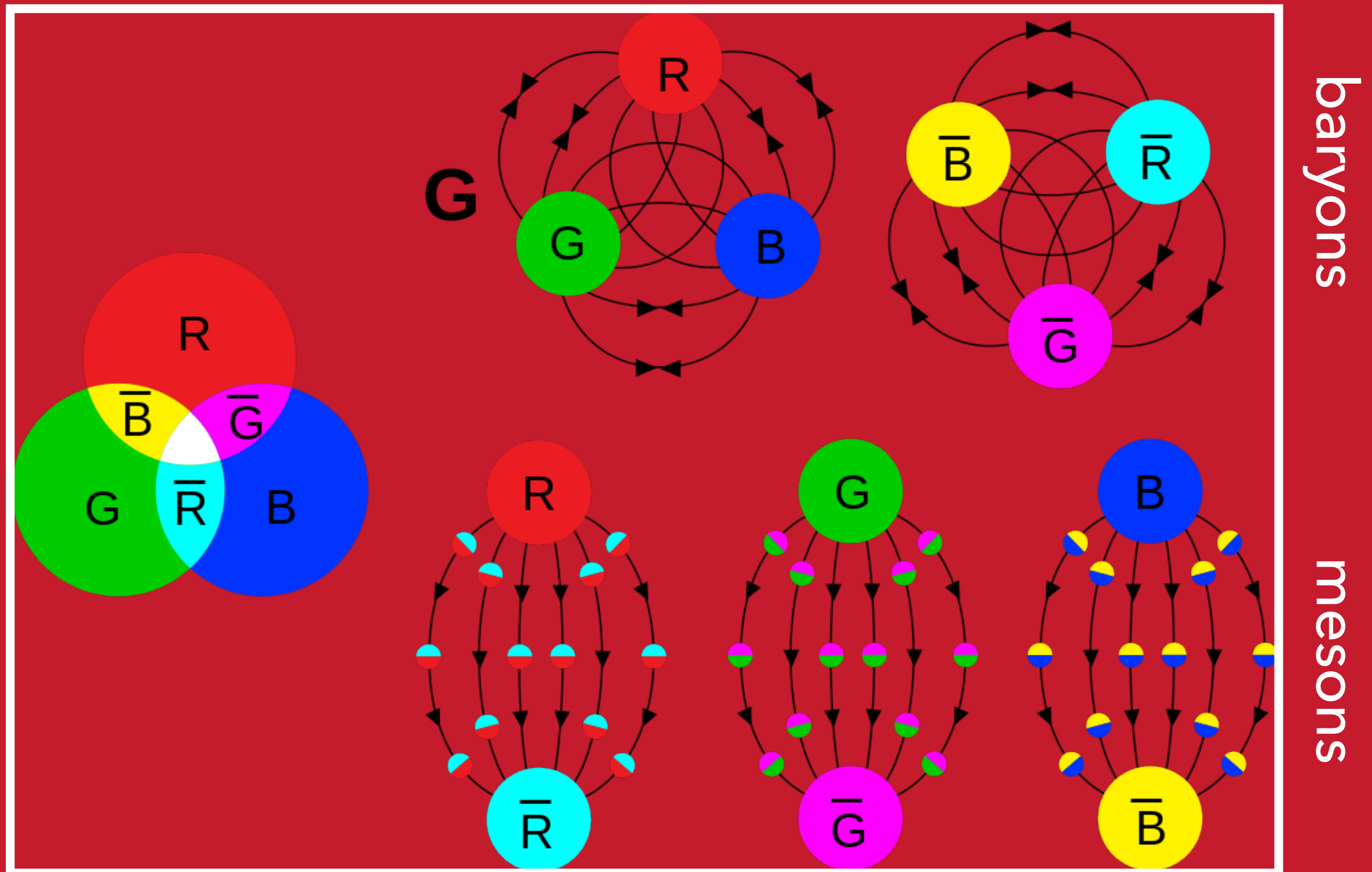
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THEORETICAL OBJECTION TO QUARK MODEL (1964)

Pauli exclusion principle



hadrons are colourless



PARTONS BECAME QUARKS

CONTRADICTION

theoretical quarks



tightly bound



observed partons



move around freely

PARTONS BECAME QUARKS

CONTRADICTION

theoretical quarks

observed partons



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SOLVED

theory of asymptotic freedom (1973)

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2004
Nobel Prize



David
Gross

David
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Frank
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tightly bound

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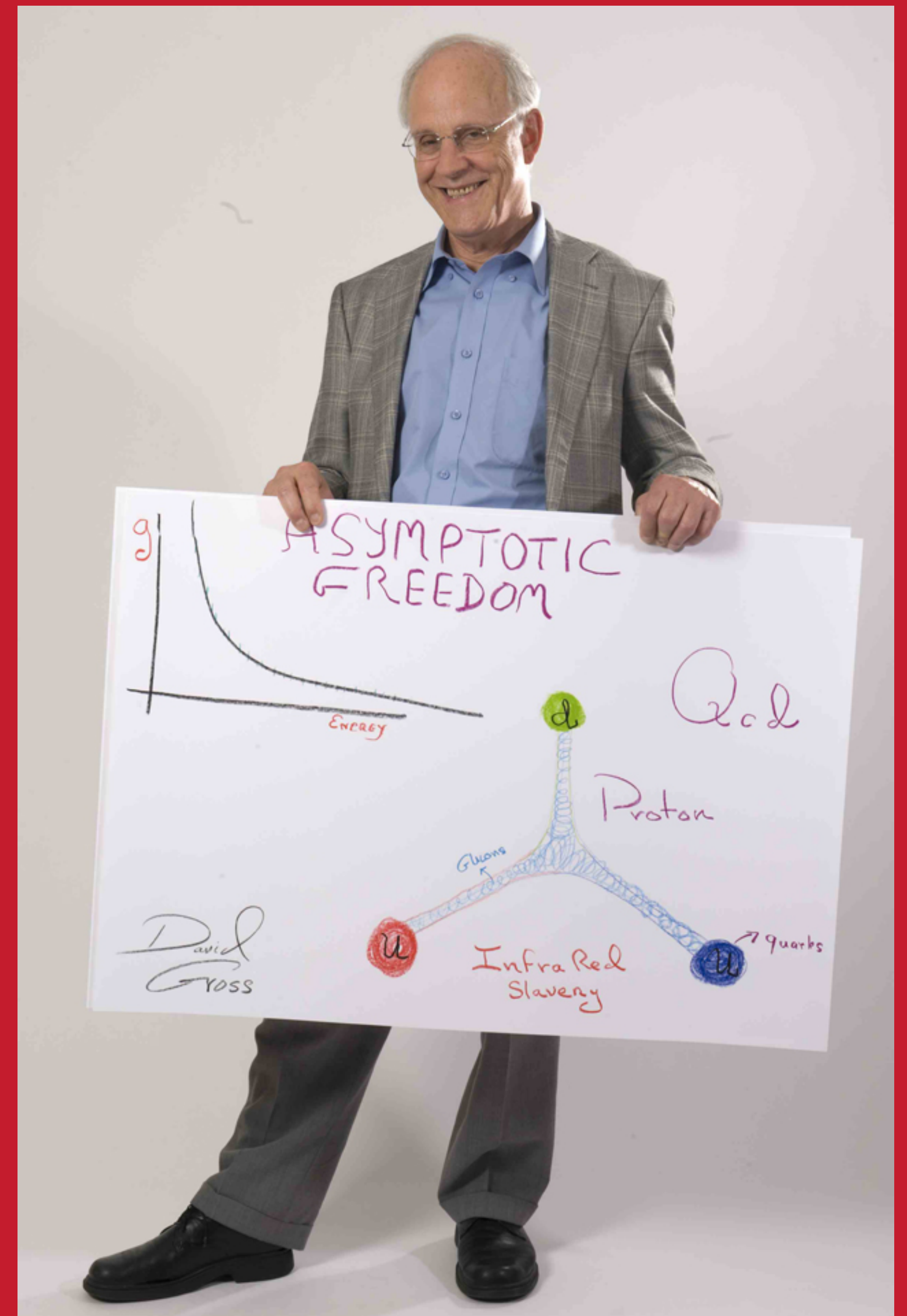
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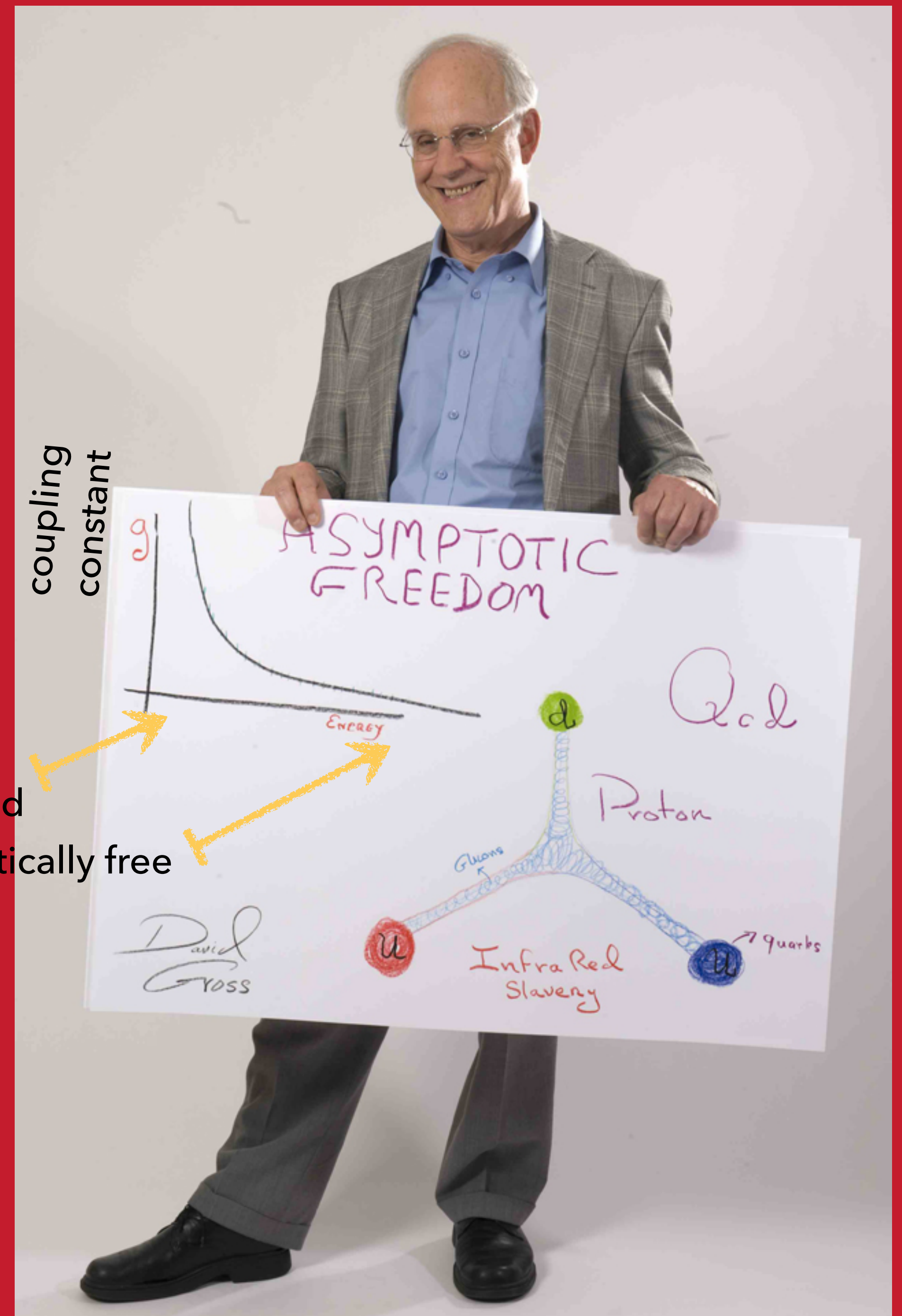


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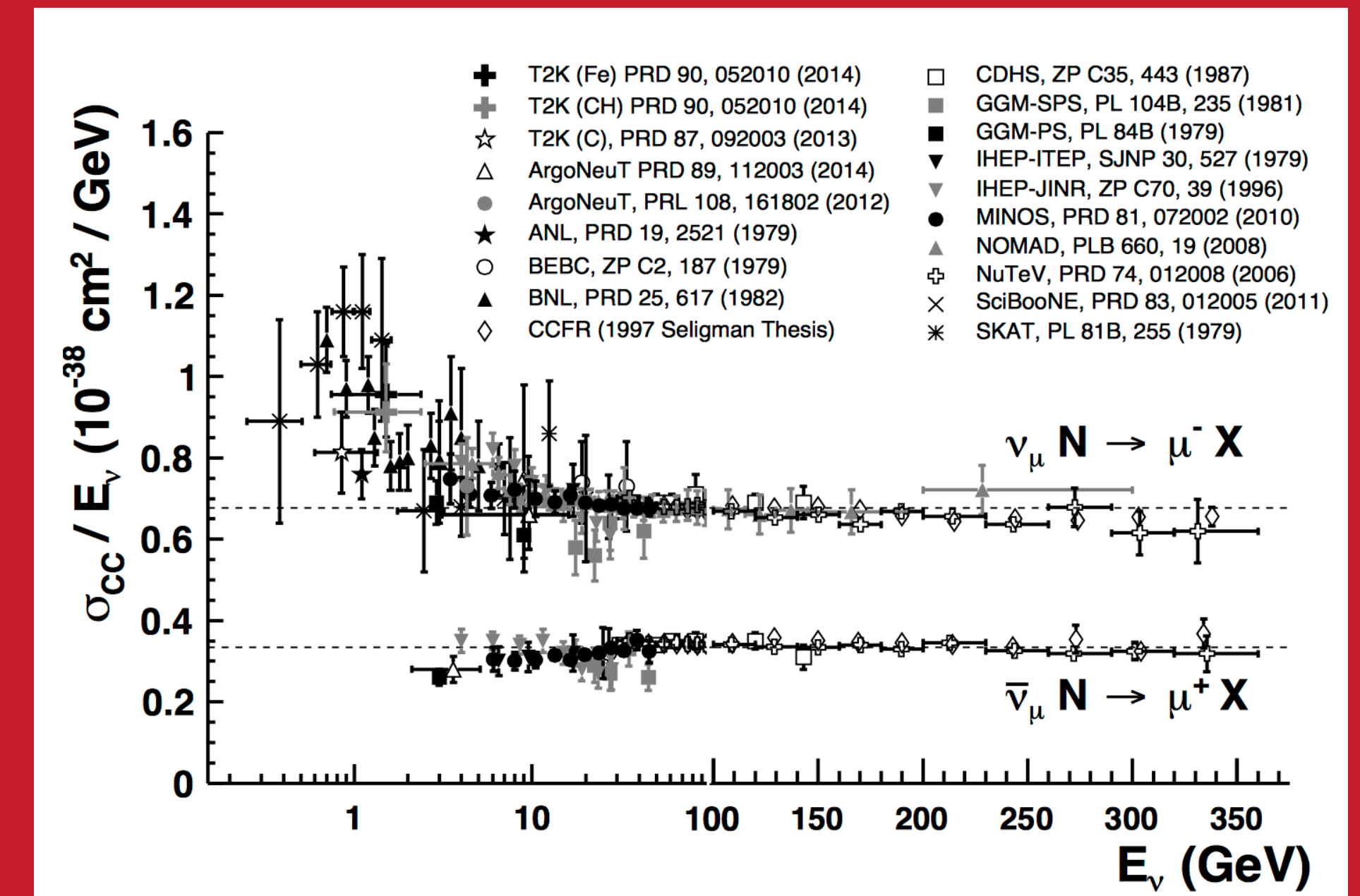
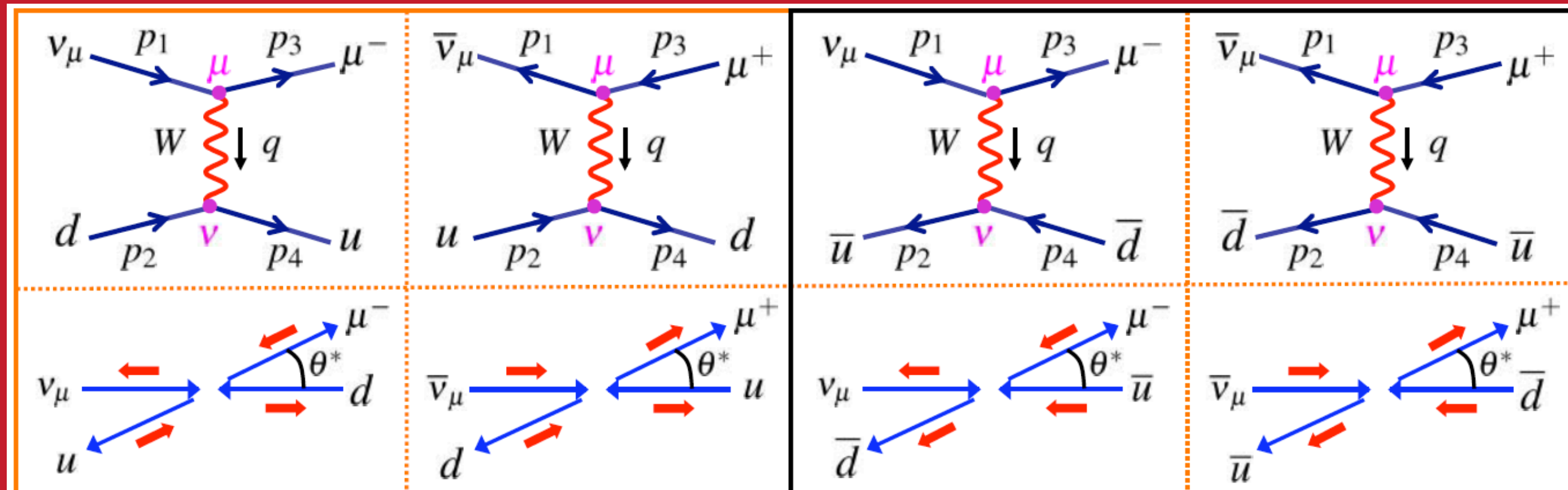
strongly confined
asymptotically free



ANTI-QUARKS AND GLUONS

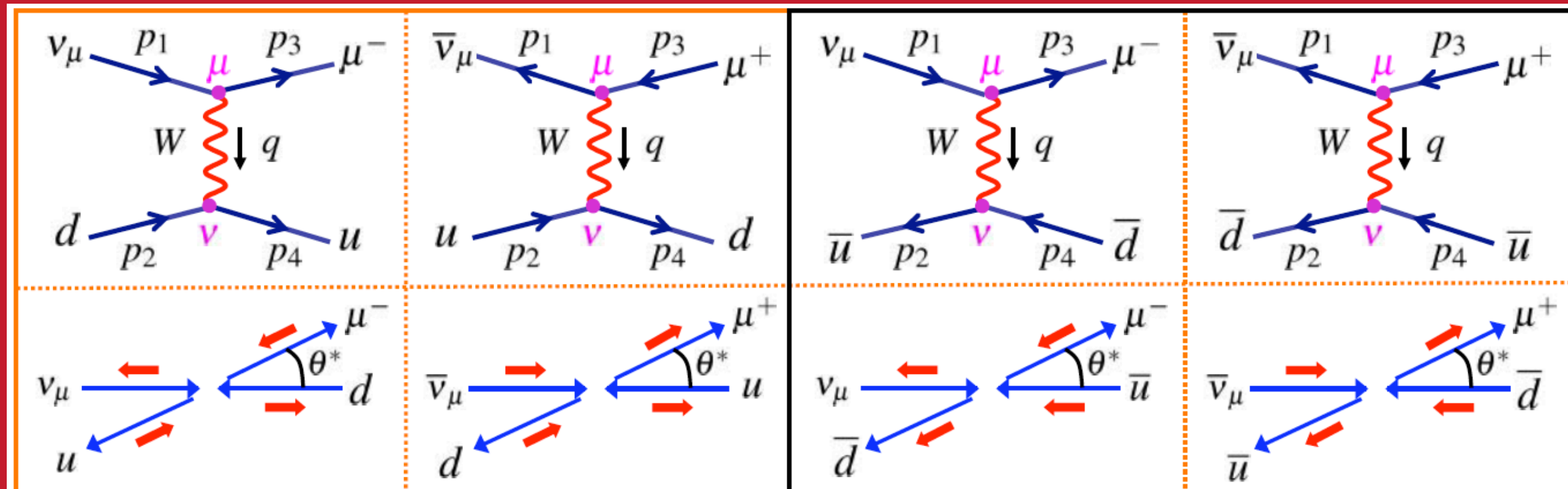
neutrino and anti-neutrino

scattering experiments (started in 70s)

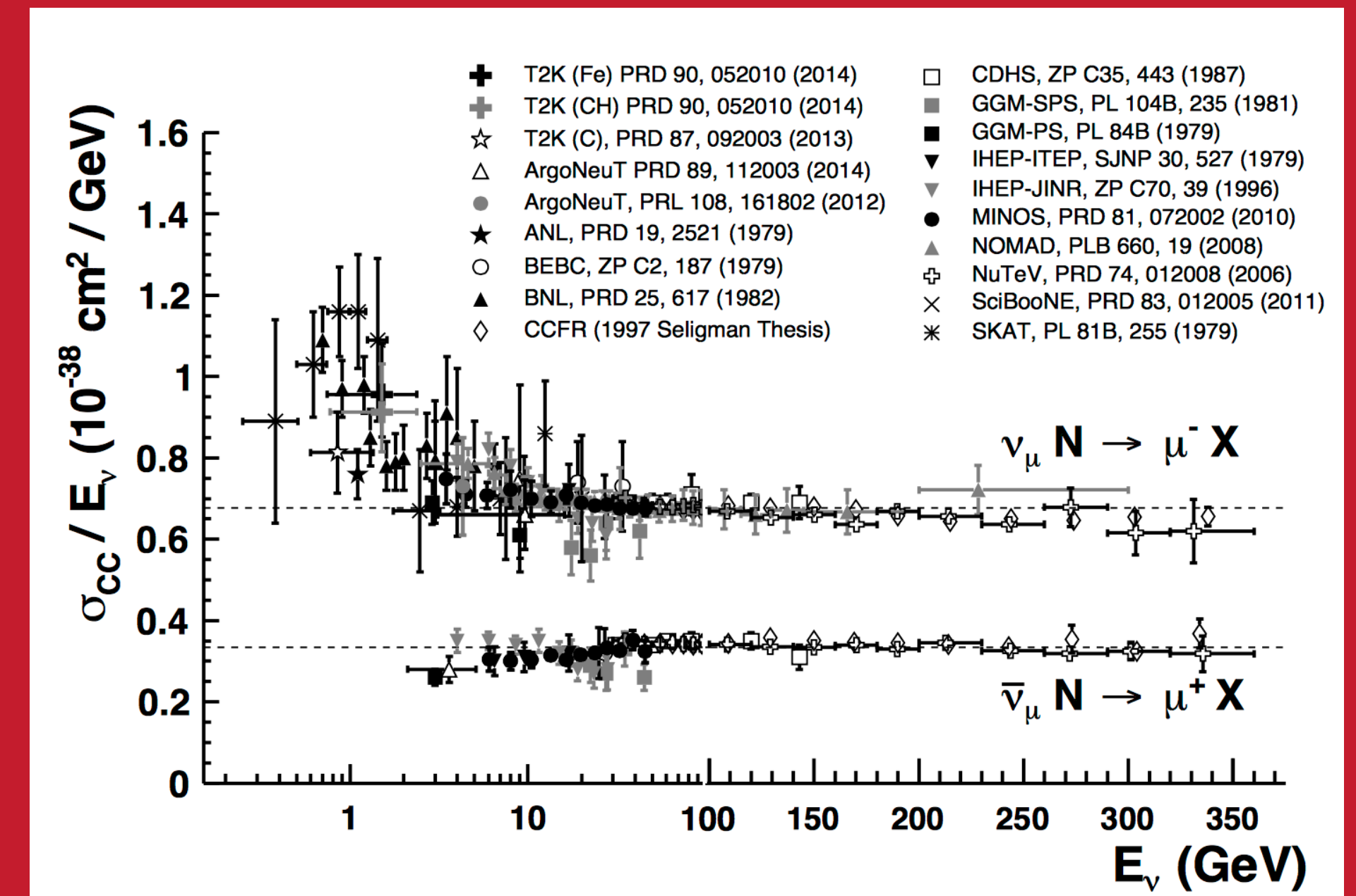


ANTI-QUARKS AND GLUONS

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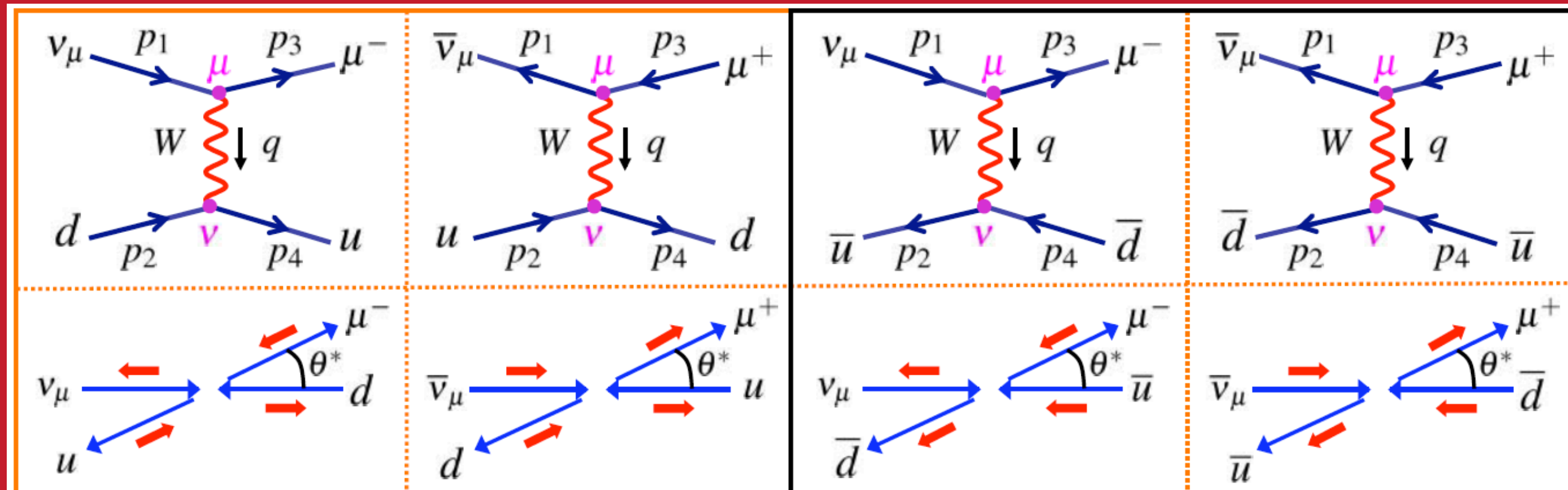


1. evidence for anti-quarks
2. quark + anti-quarks carry $\sim 50\%$ of proton energy



ANTI-QUARKS AND GLUONS

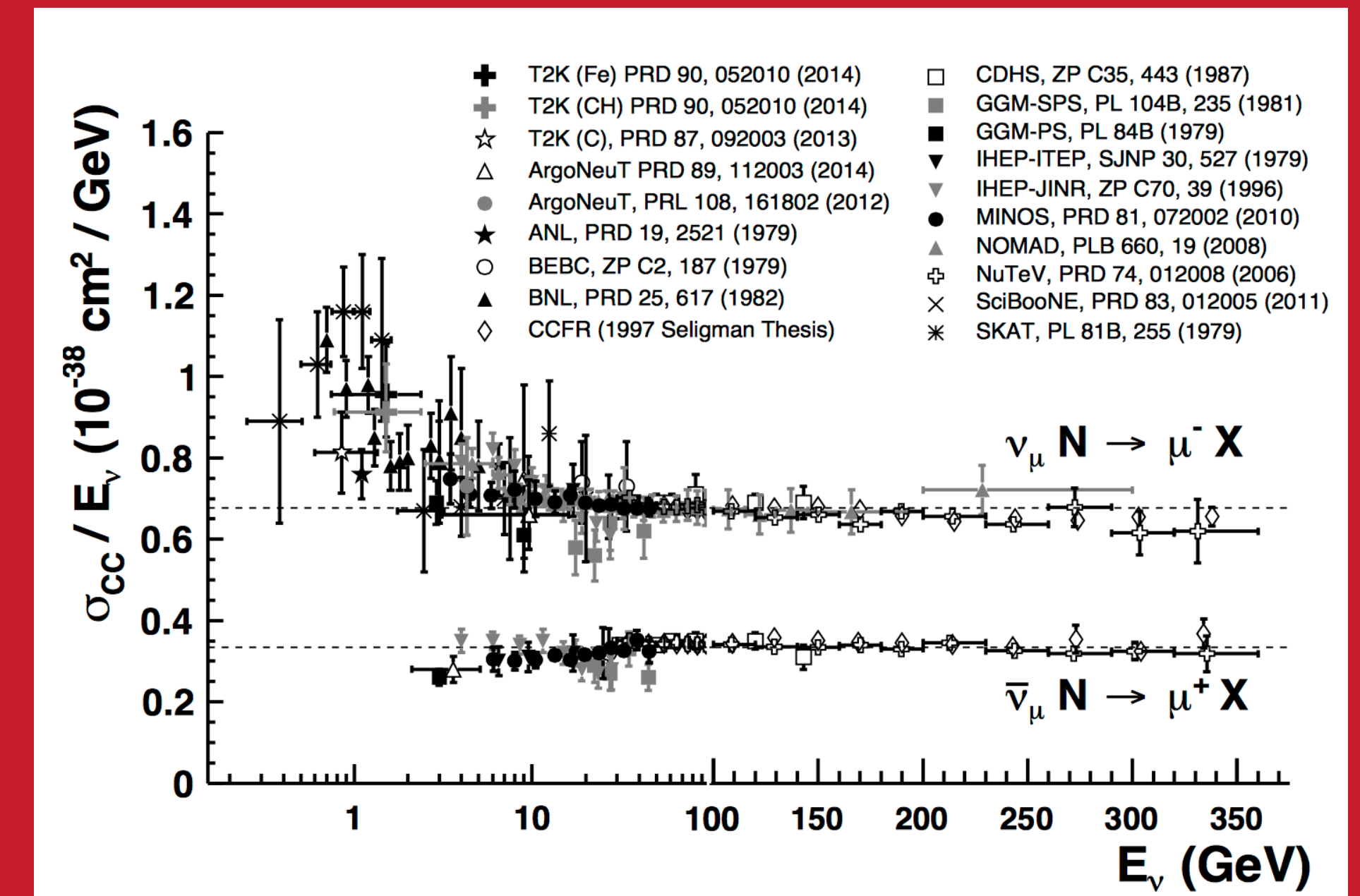
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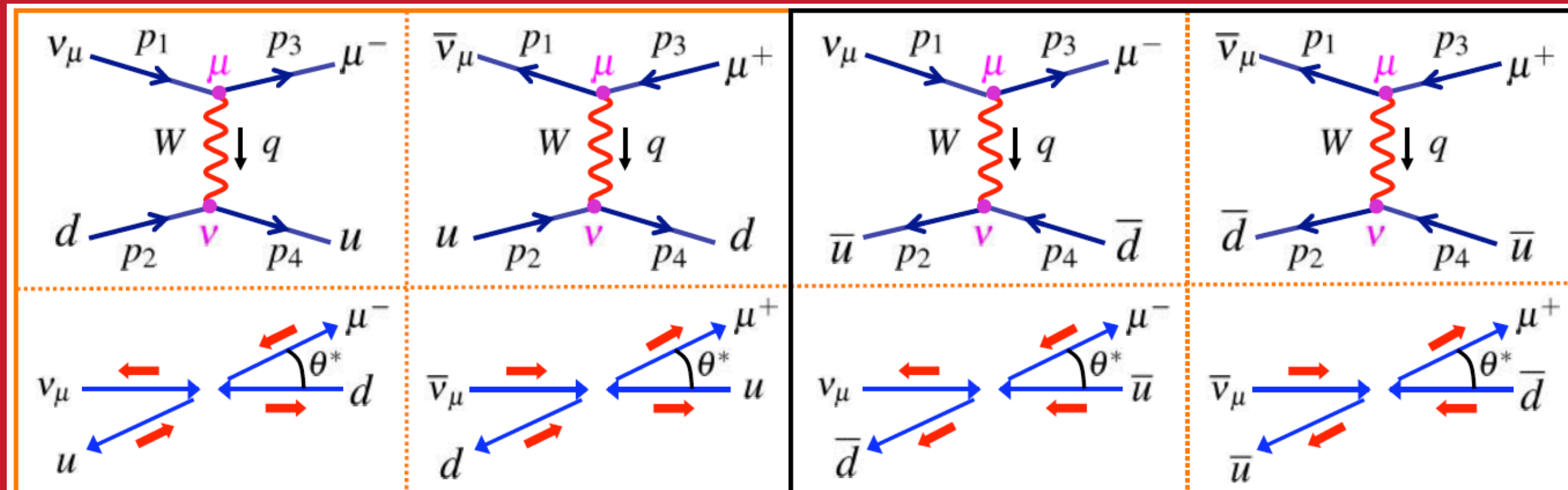


first hint of gluons



ANTI-QUARKS AND GLUONS

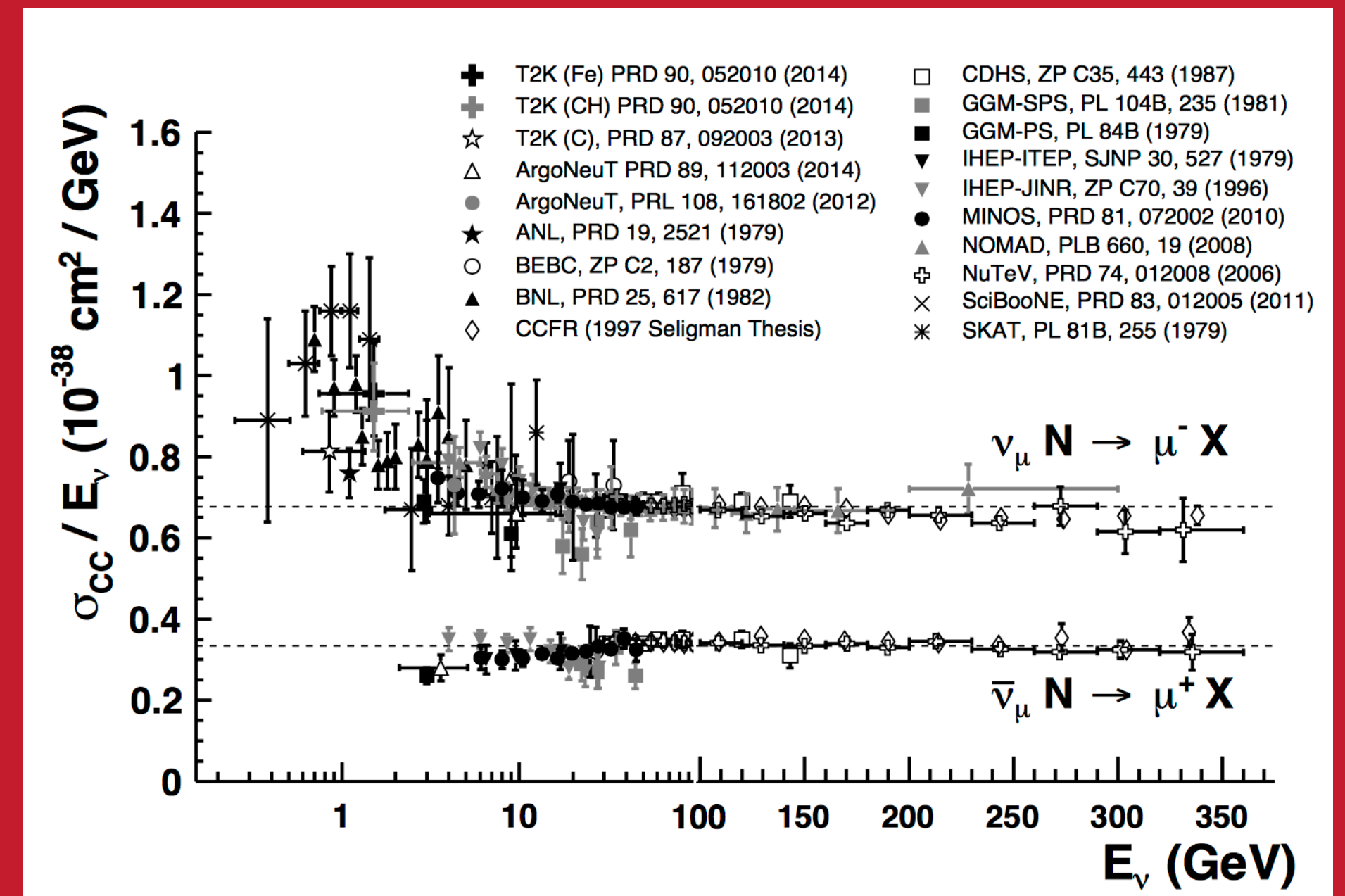
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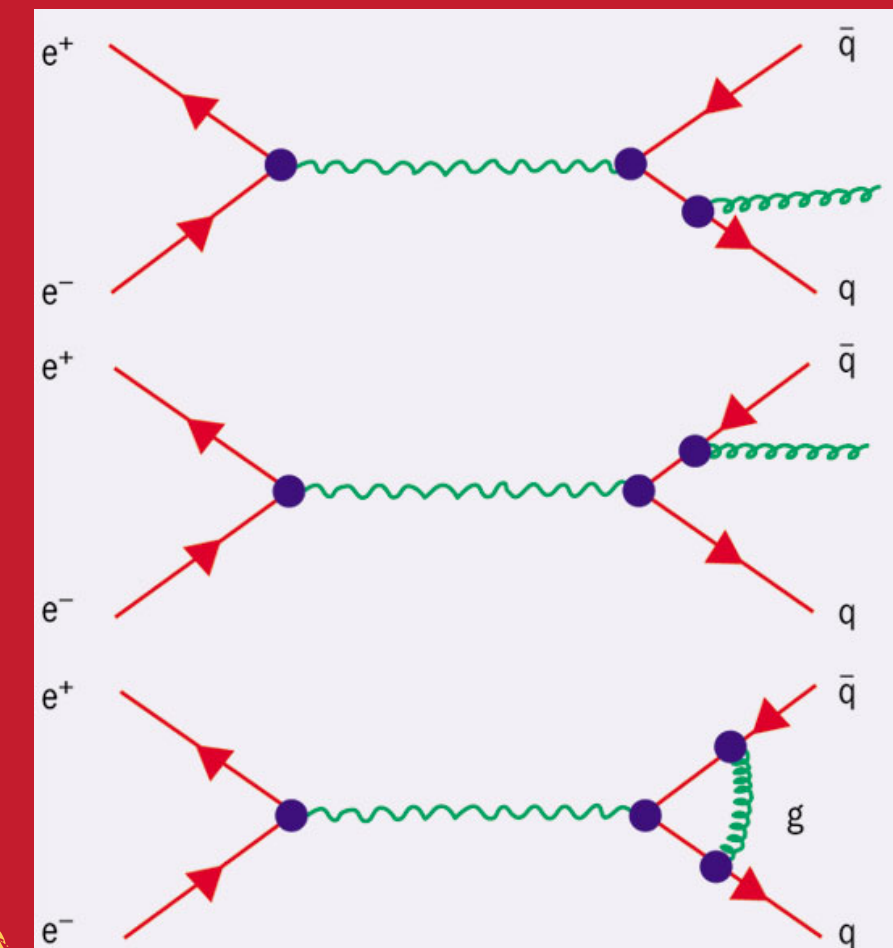
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first hint of gluons



DISCOVERY OF GLUONS



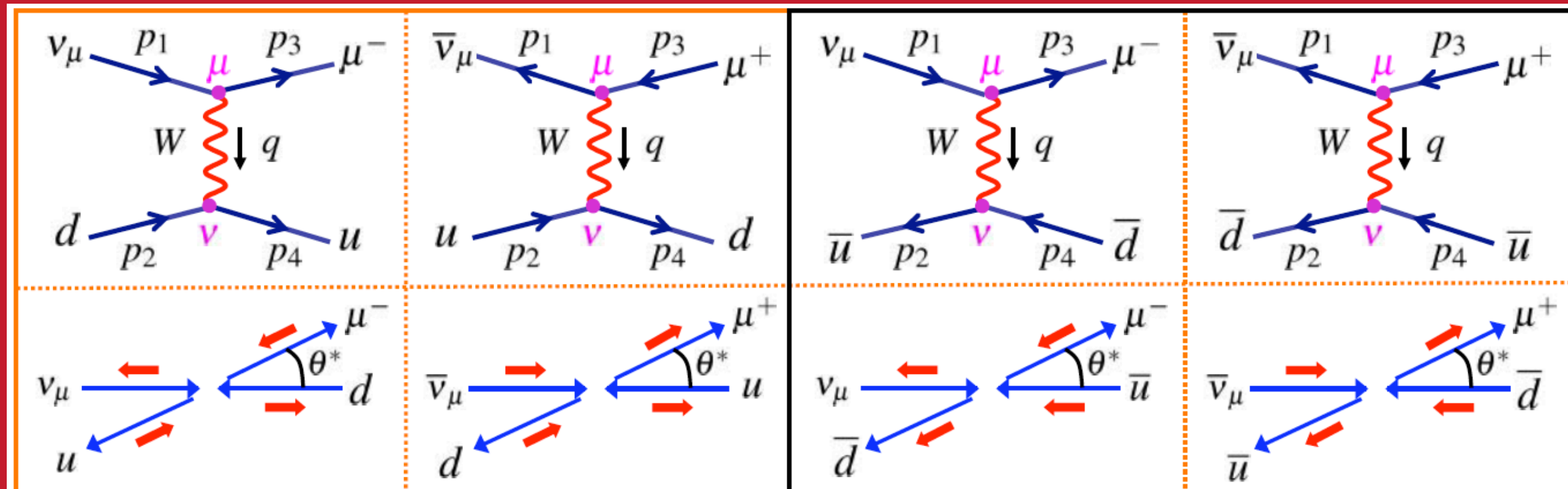
DESY's PETRA collider



three jet event at
TASSO experiment (1979)

ANTI-QUARKS AND GLUONS

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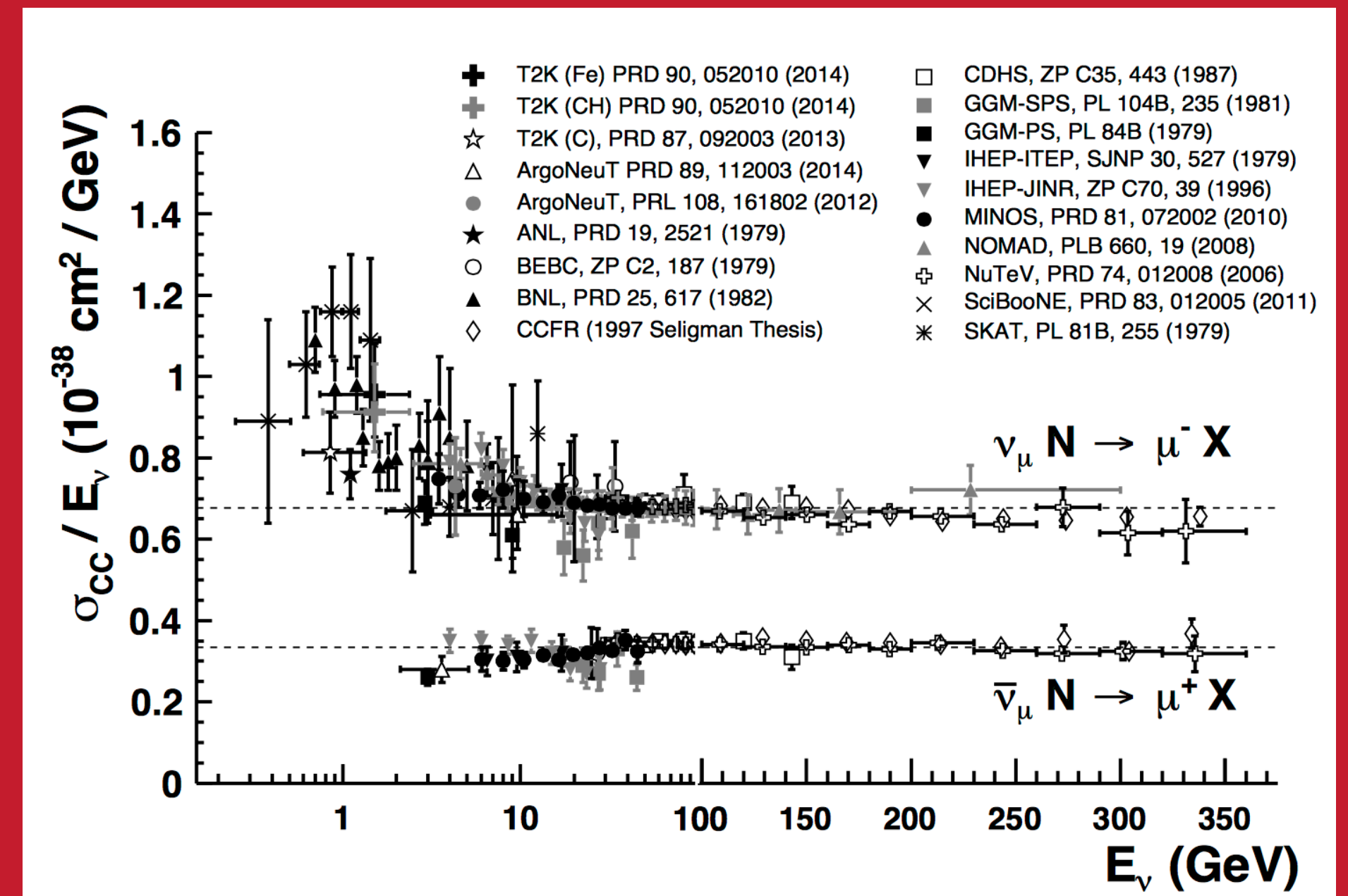


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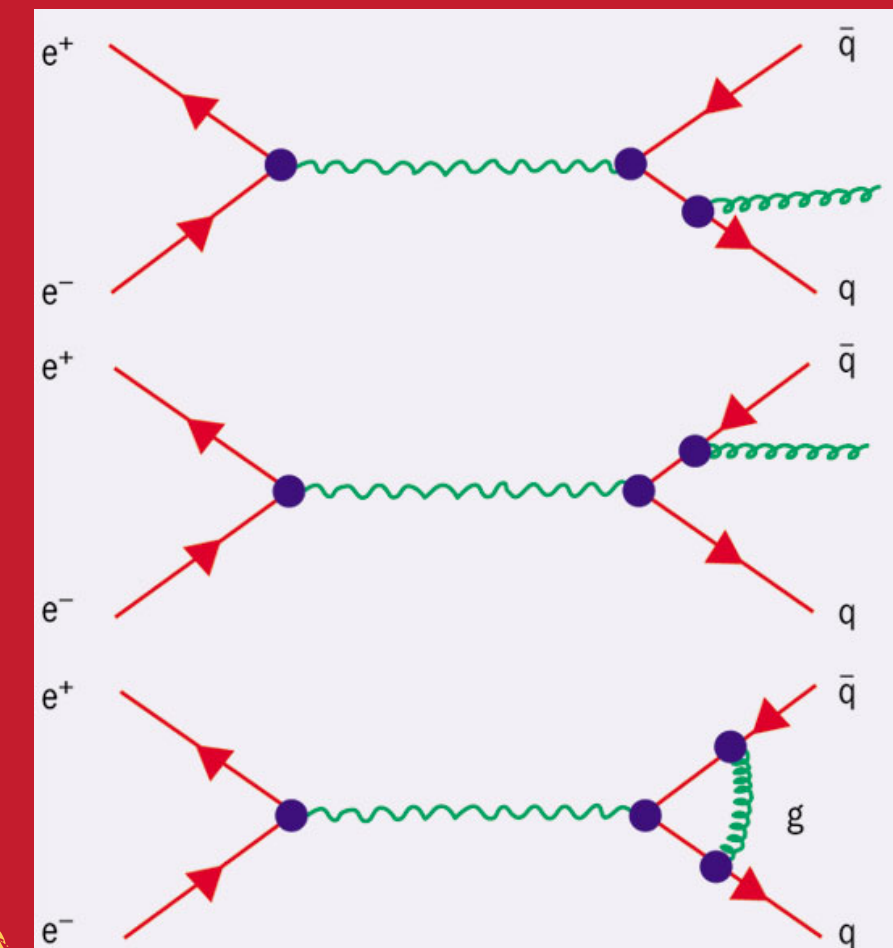


first hint of gluons

beginning of intensive tests of QCD



DISCOVERY OF GLUONS

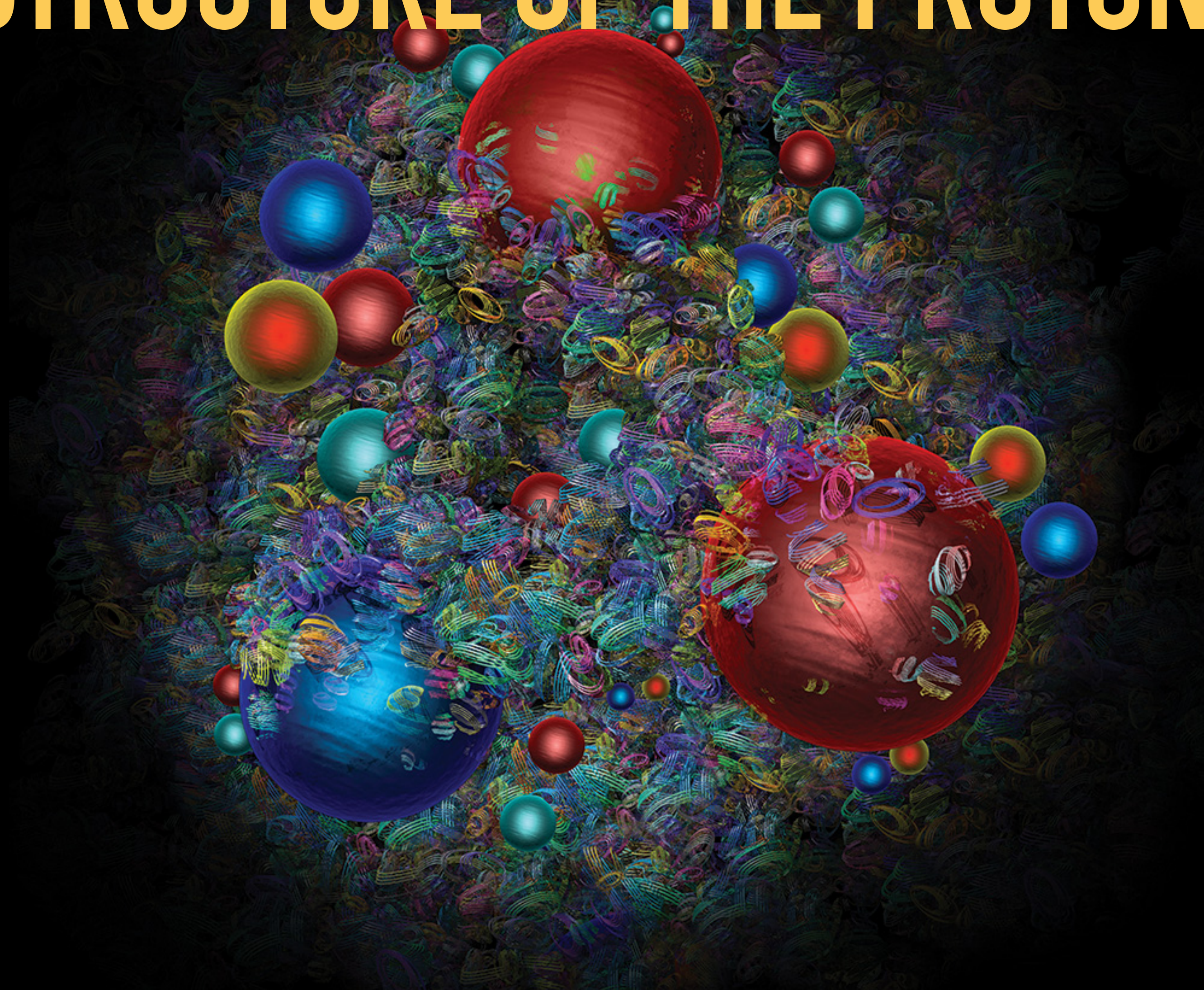


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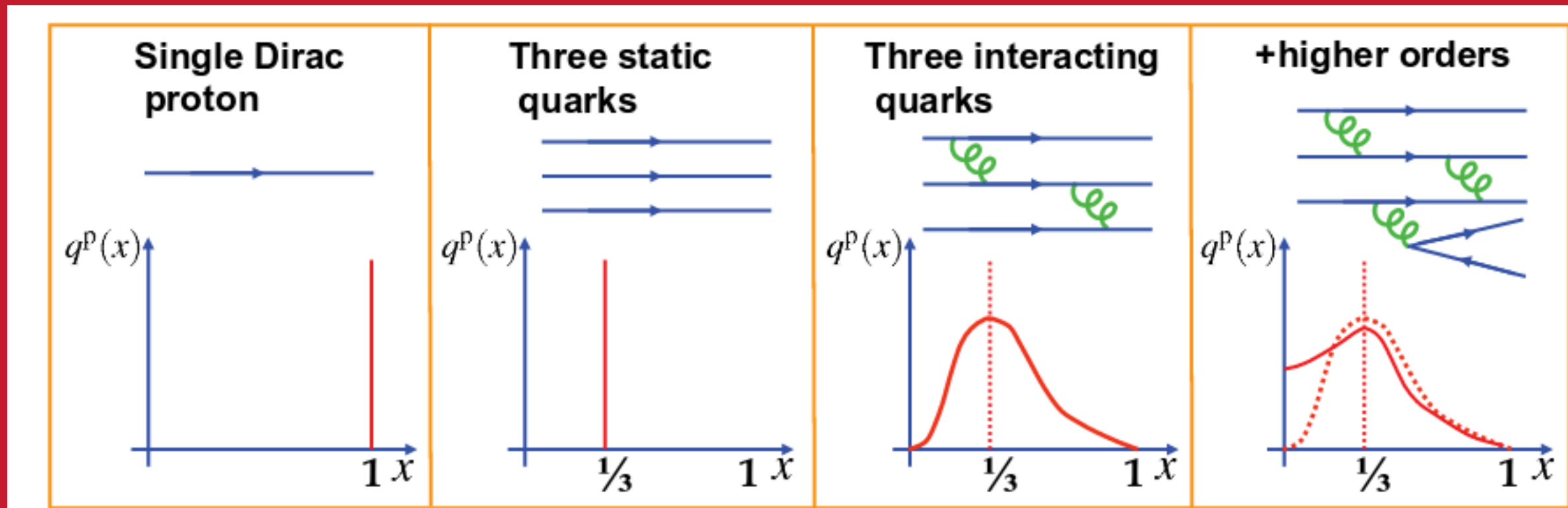


three jet event at
TASSO experiment (1979)

HOW TO UNDERSTAND THE STRUCTURE OF THE PROTON?

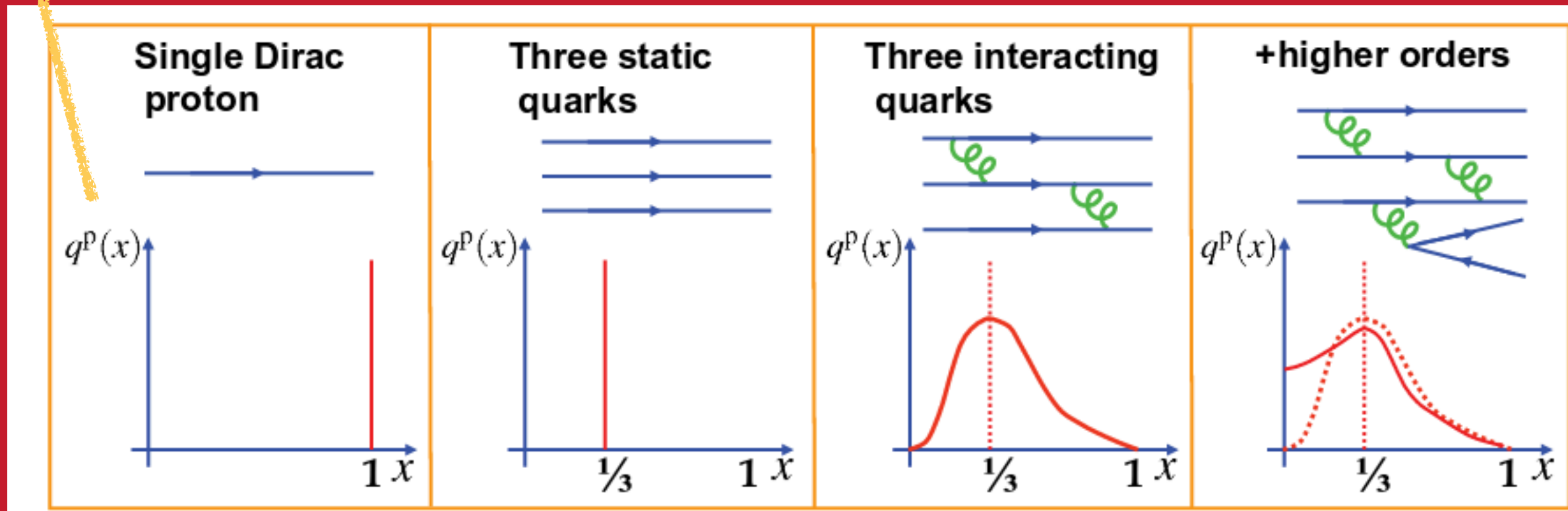


PARTON DISTRIBUTION FUNCTIONS (PDFs)



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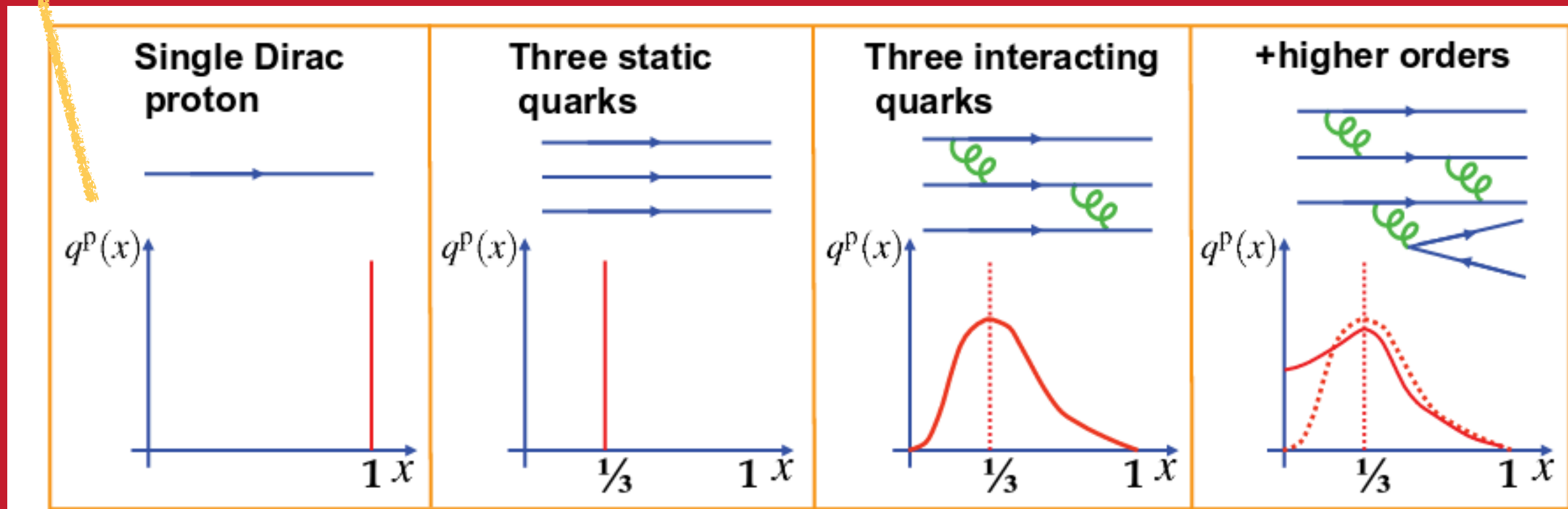
probability functions



momentum fraction

PARTON DISTRIBUTION FUNCTIONS (PDFs)

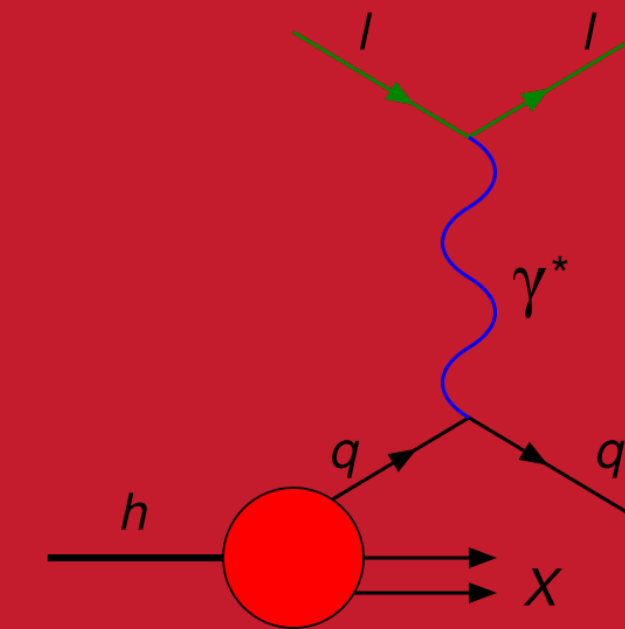
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UNIVERSALITY

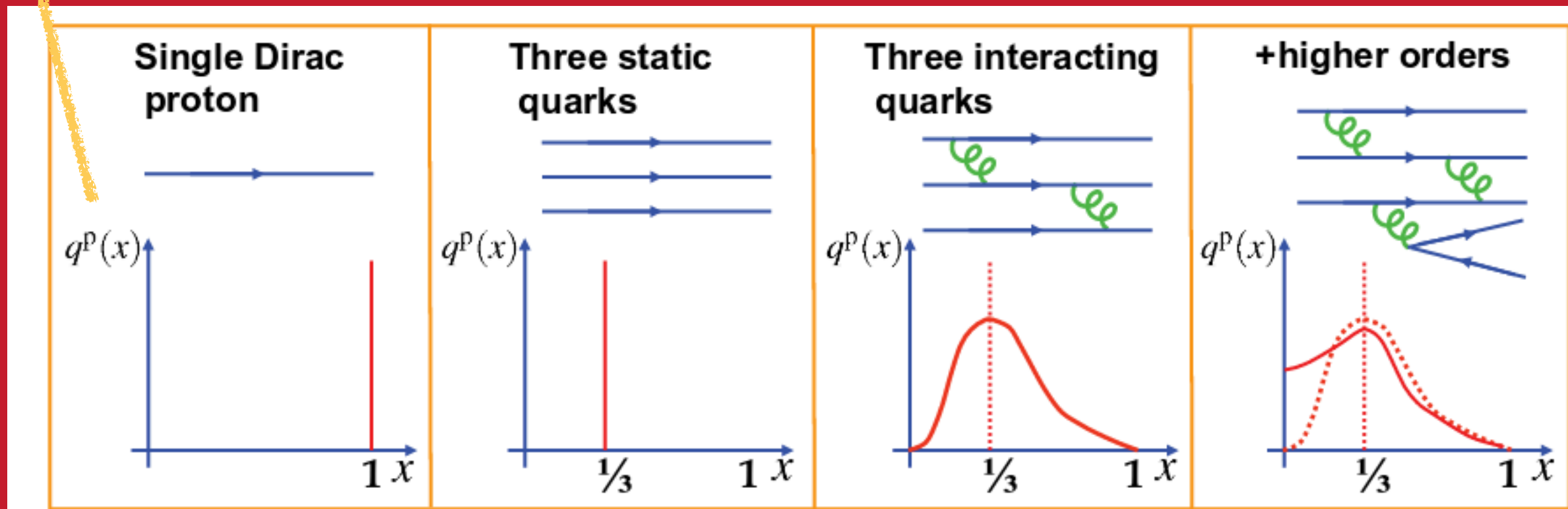
Deep Inelastic Scattering (DIS)



$$\sigma^{DIS} = \sum_j \int dx f_j(x, Q^2) \hat{\sigma}_{\gamma^*j}(x, Q^2, \dots)$$

PARTON DISTRIBUTION FUNCTIONS (PDFs)

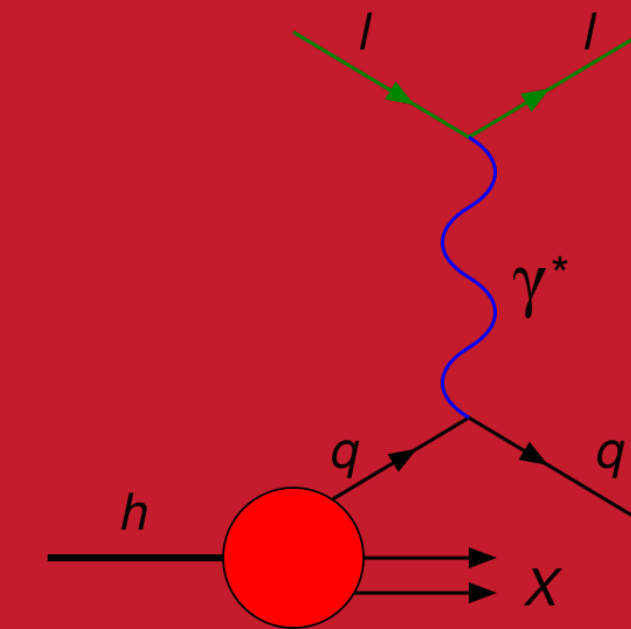
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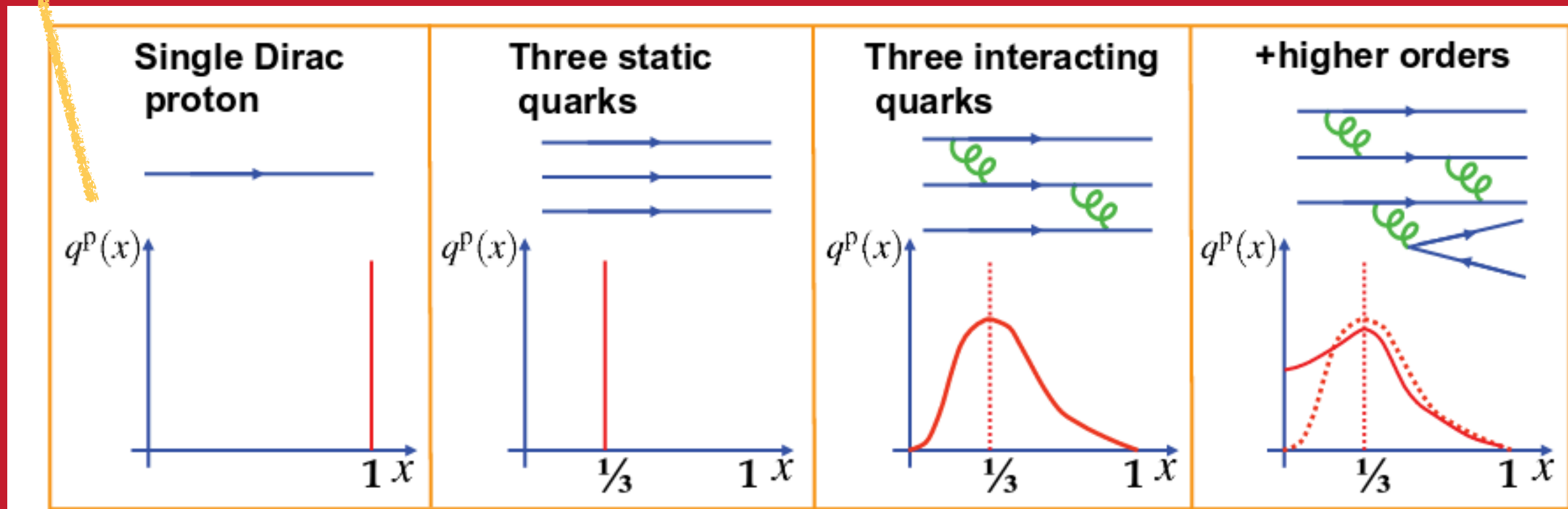
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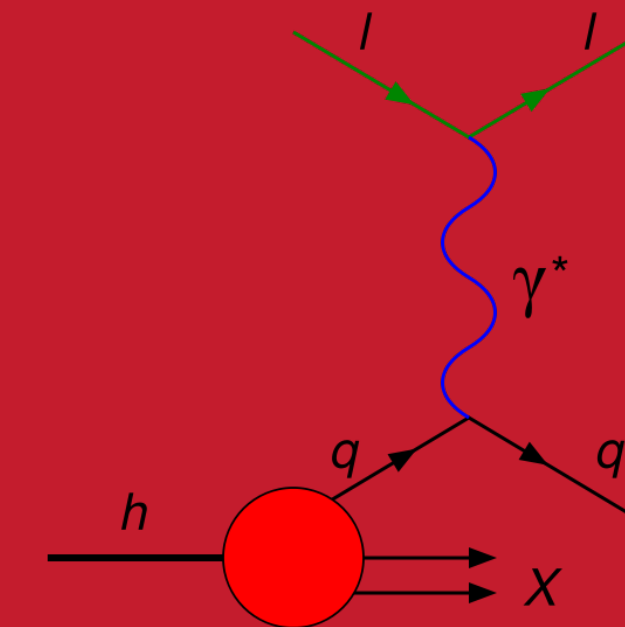
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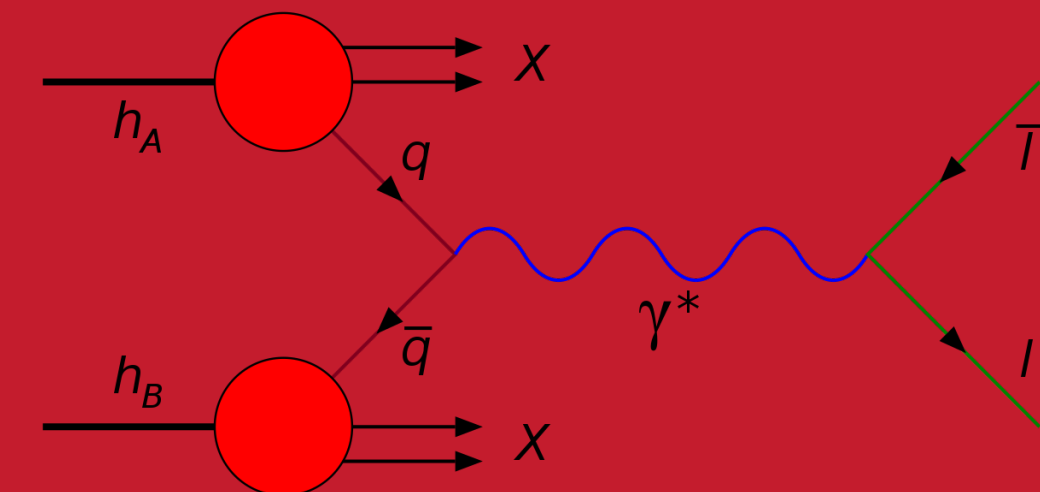
UNIVERSALITY

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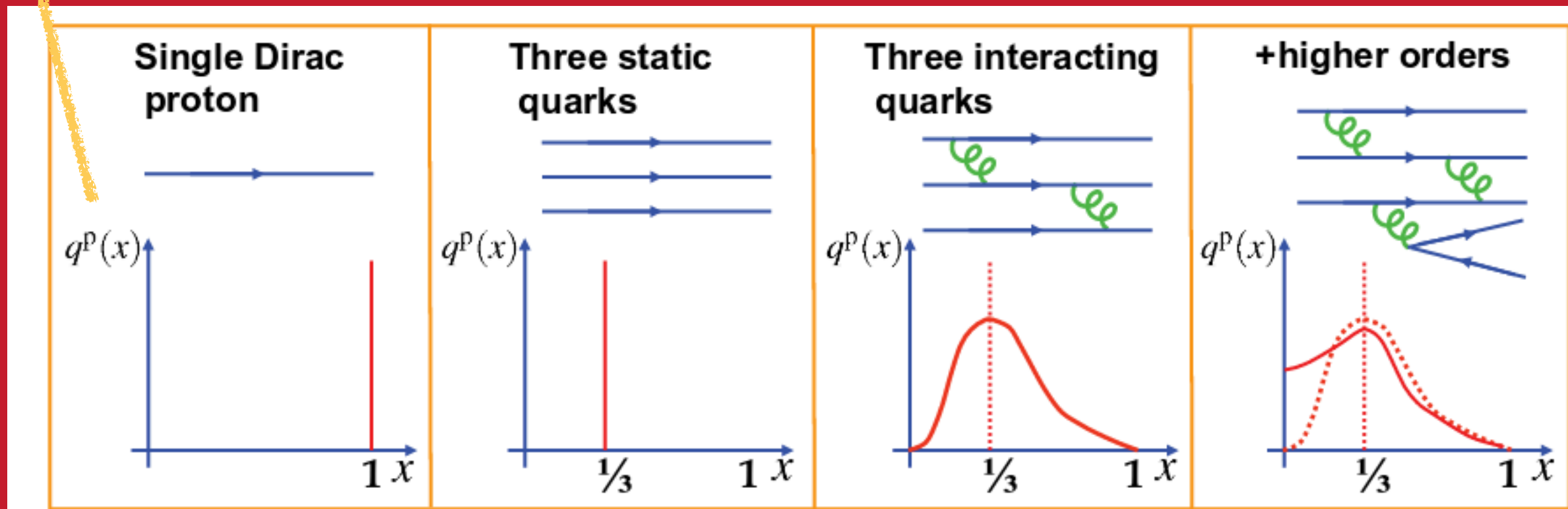
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Drell-Yan



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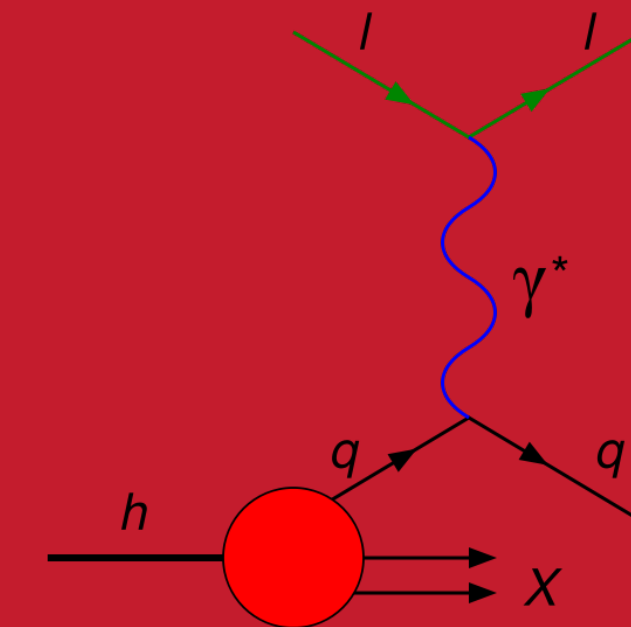
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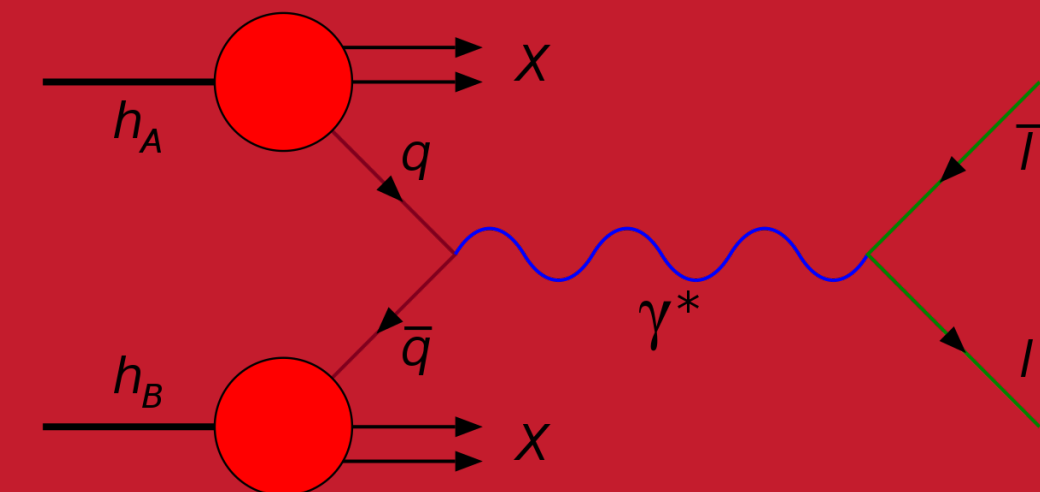
UNIVERSALITY

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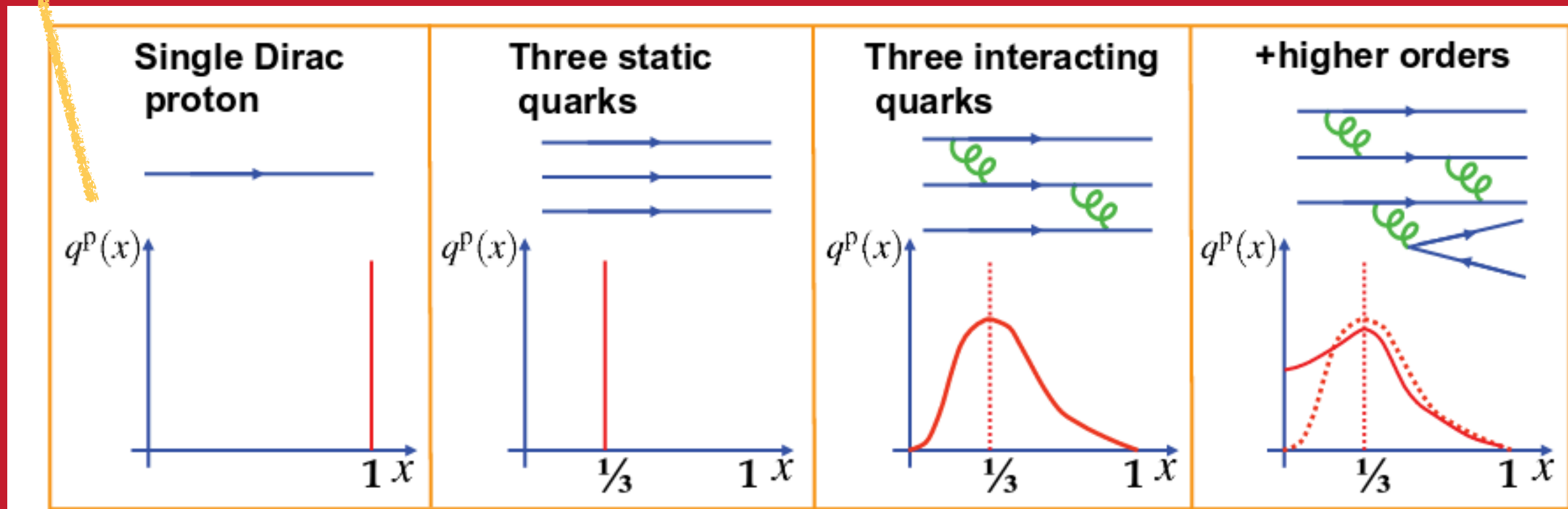
Drell-Yan



$$\sigma^{DY} = \sum_{ab} \int dx_a \int dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \hat{\sigma}_{ab \rightarrow l\bar{l}}(x_a, x_b, \dots)$$

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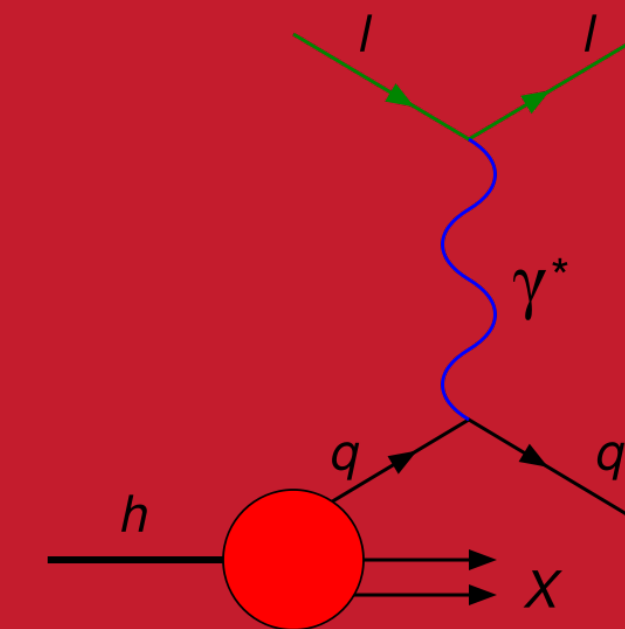
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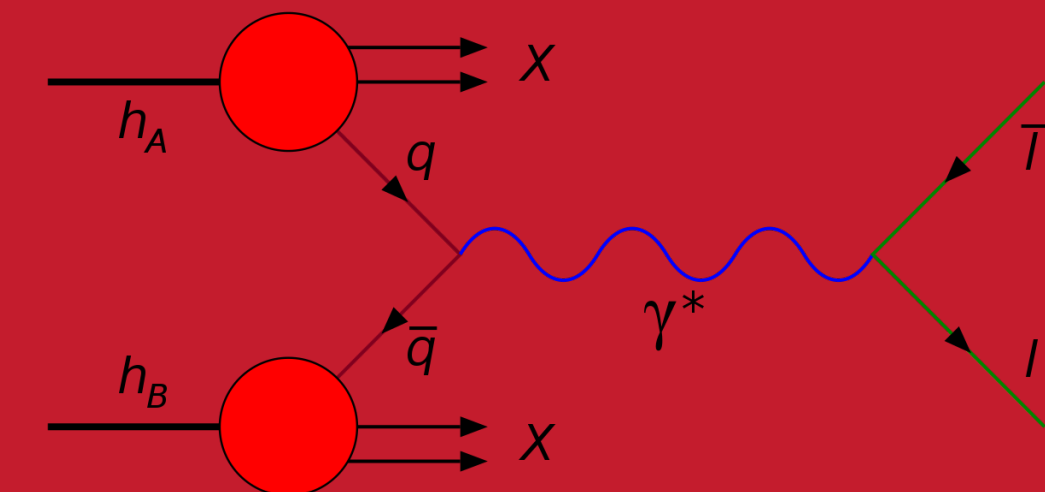
UNIVERSALITY

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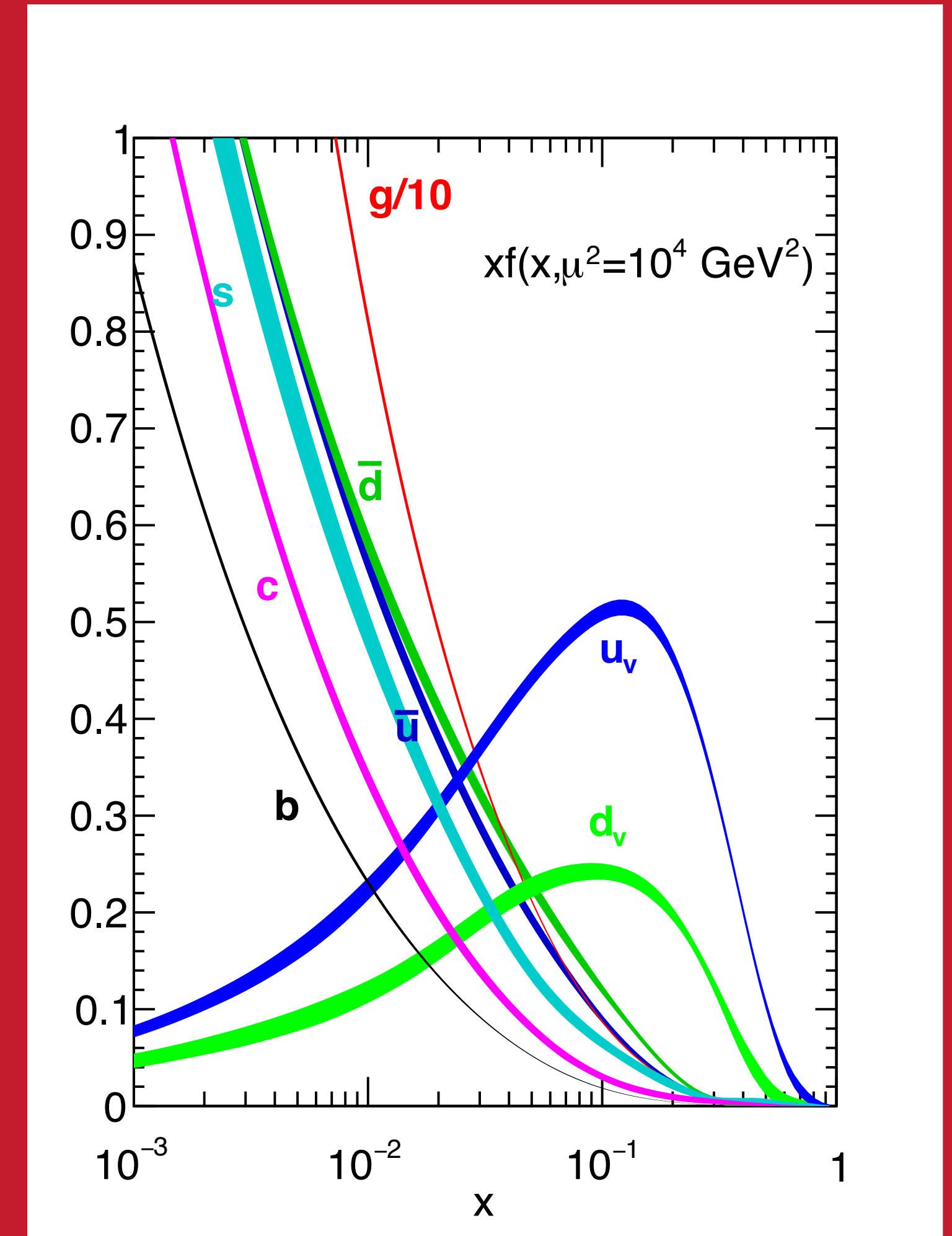
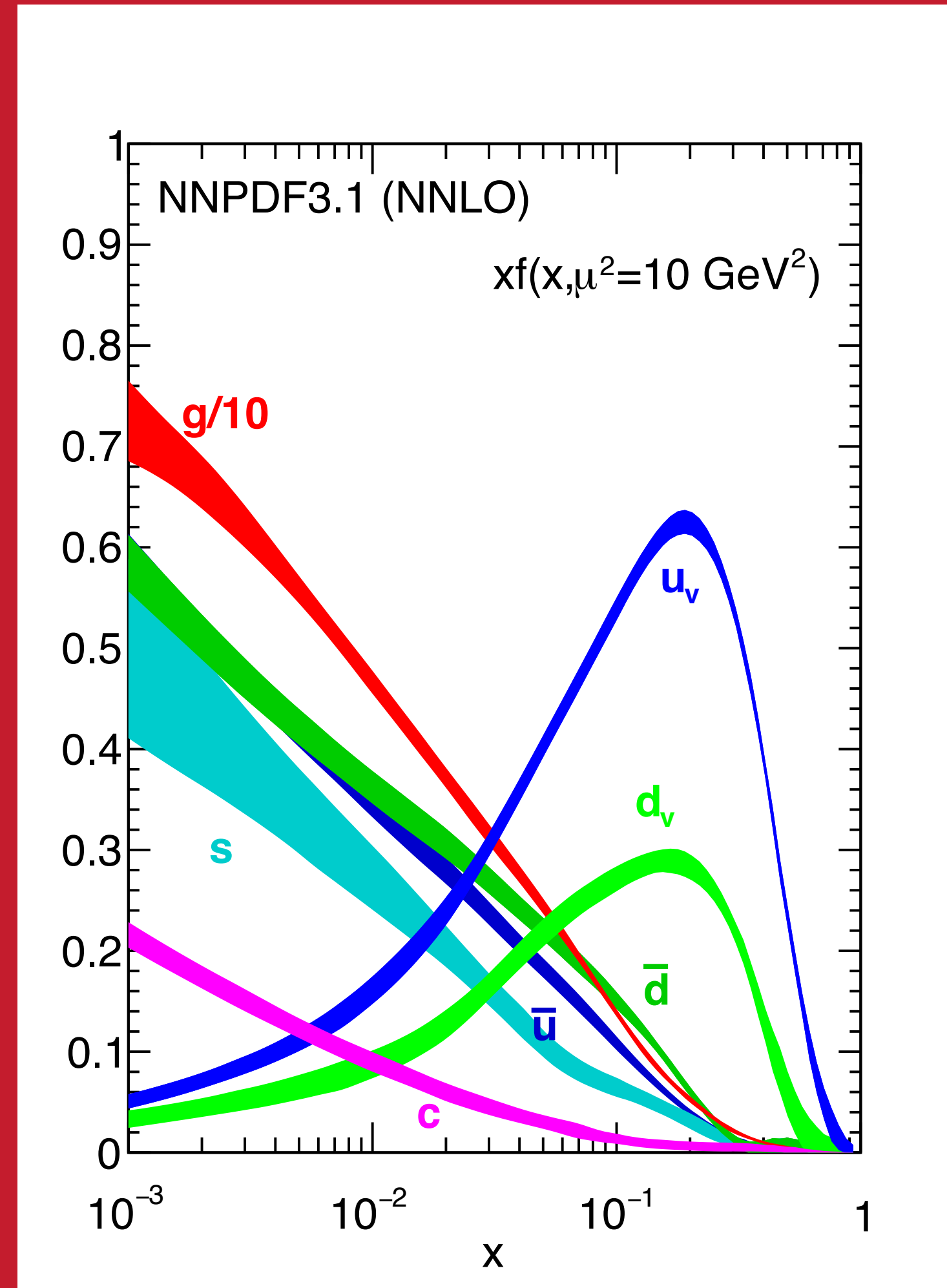
$$\sigma^{DIS} = \sum_j \int dx \text{ PDF } f_j(x, Q^2) \hat{\sigma}_{\gamma^* j}(x, Q^2, \dots)$$

Drell-Yan



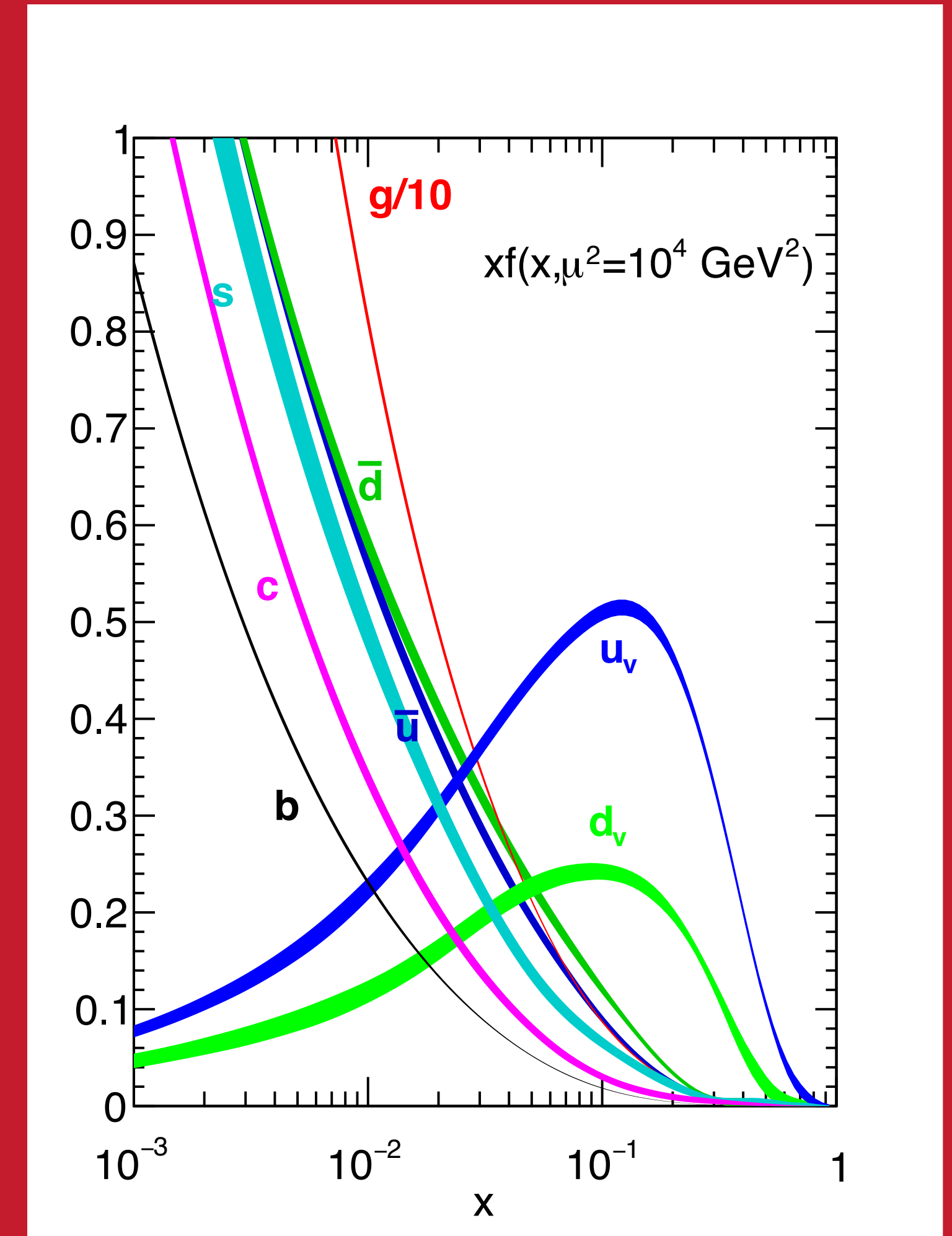
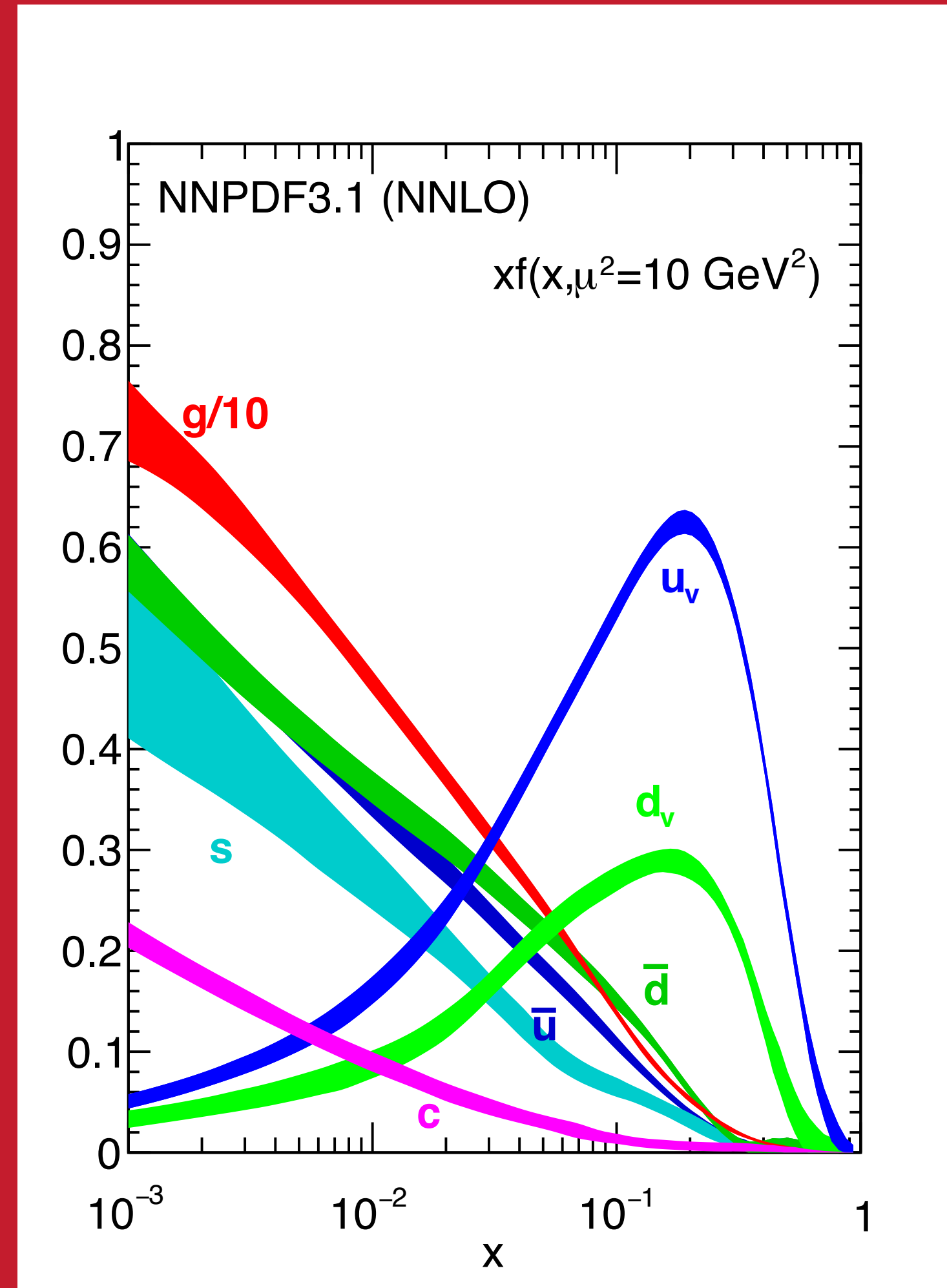
$$\sigma^{DY} = \sum_{ab} \int dx_a \int dx_b \text{ PDF } f_a(x_a, Q^2) \text{ PDF } f_b(x_b, Q^2) \hat{\sigma}_{ab \rightarrow l\bar{l}}(x_a, x_b, \dots)$$

PROTON PDFs



PROTON PDFs

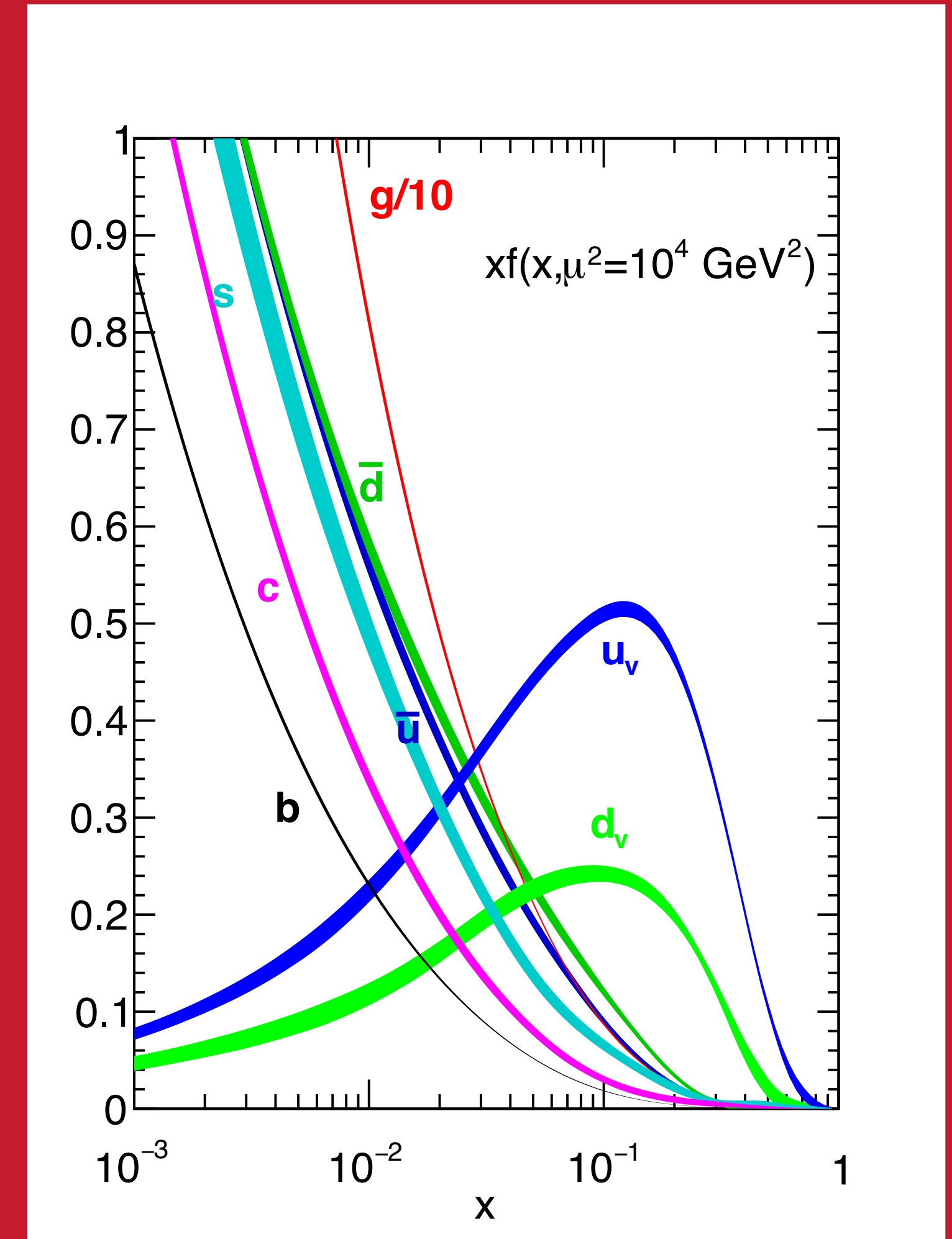
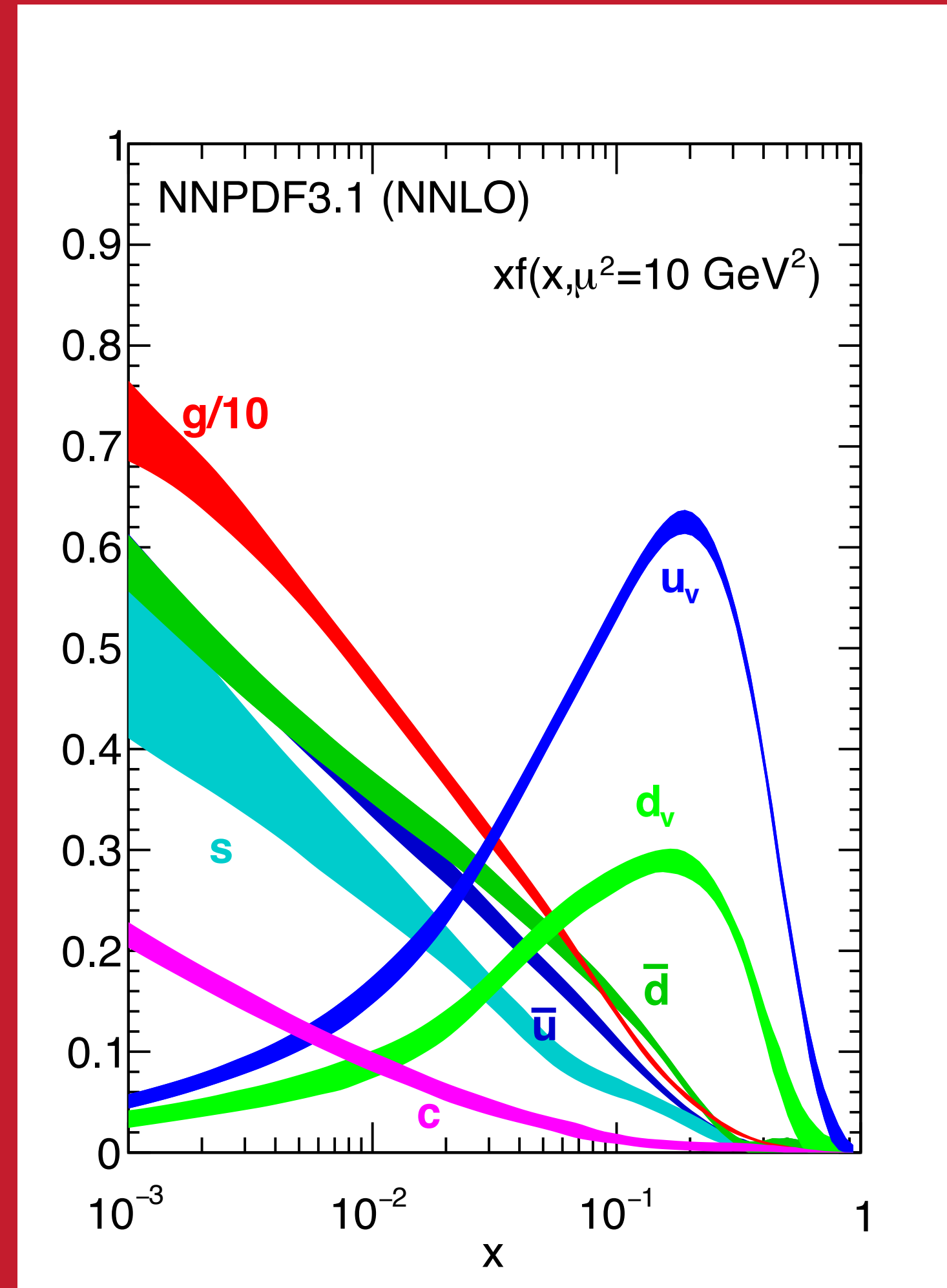
good level of precision



PROTON PDFs

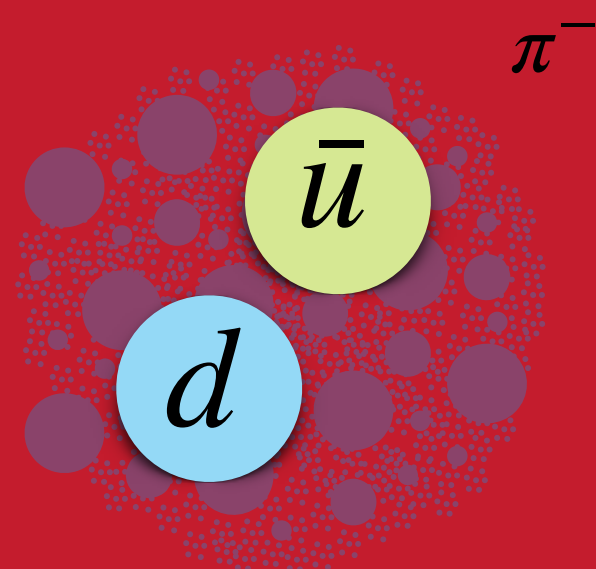
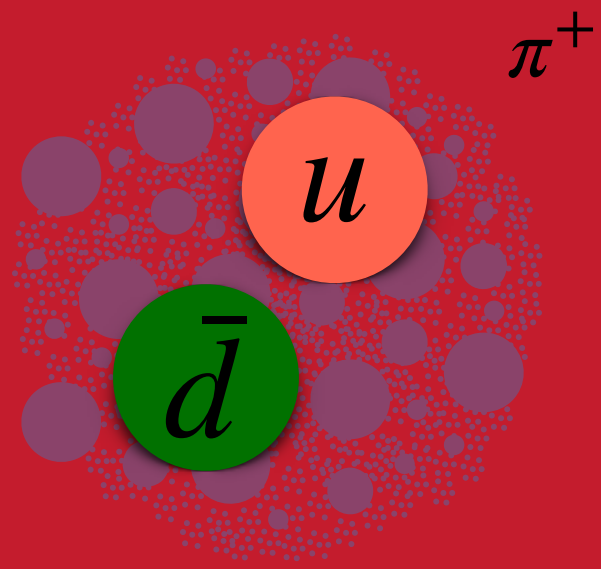
good level of precision

still not enough for
new physics predictions
for LHC precision era



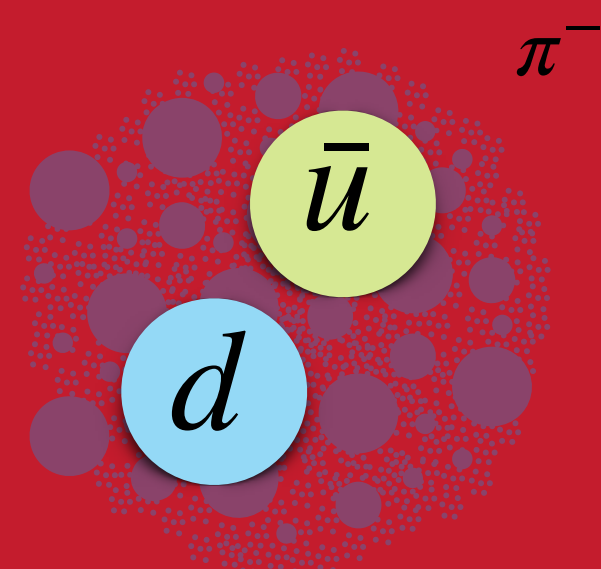
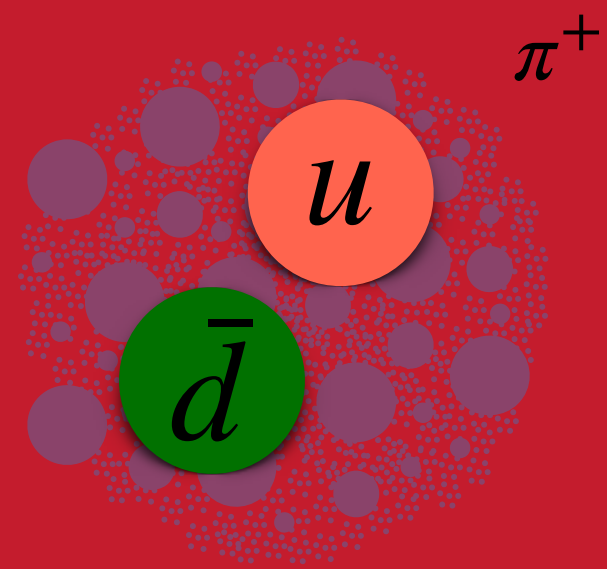
WHAT ABOUT OTHER HADRONS?

simplest $q\bar{q}$ state

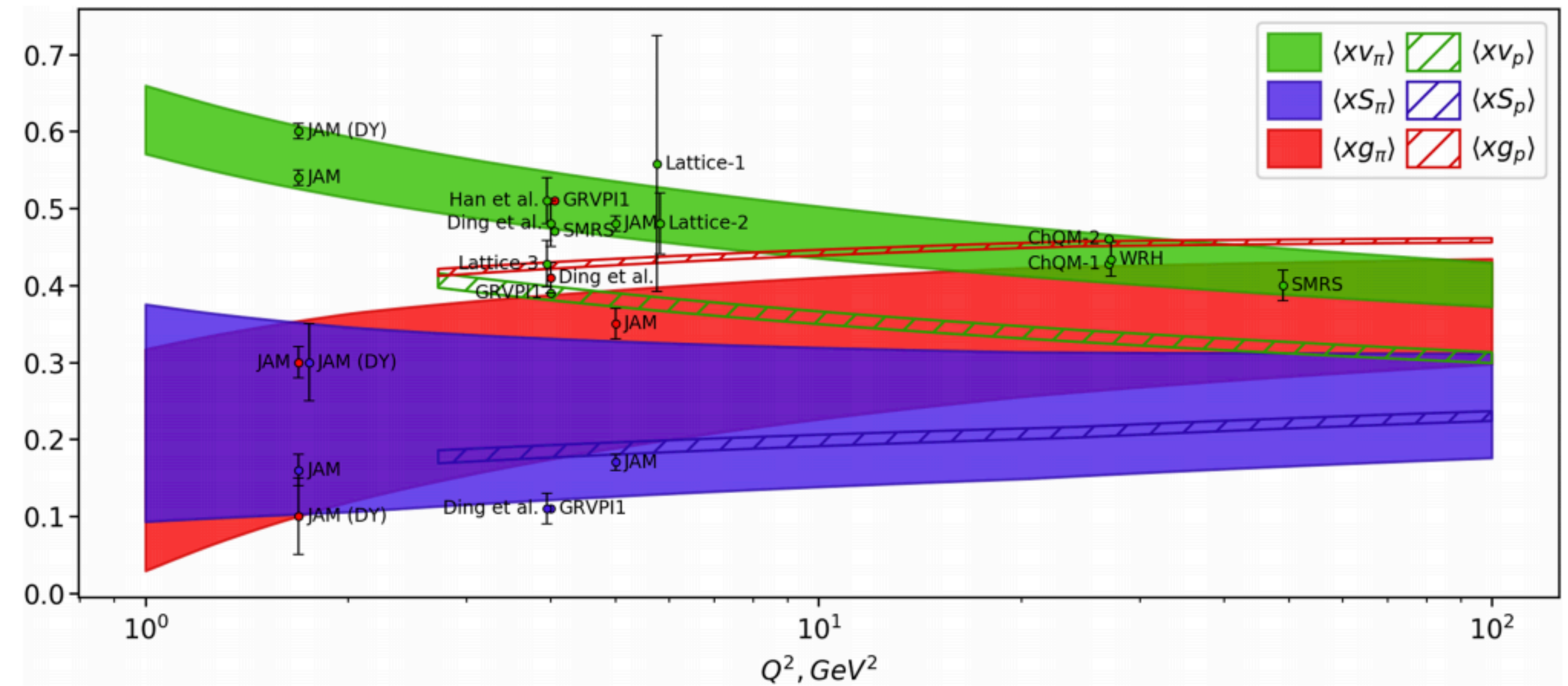


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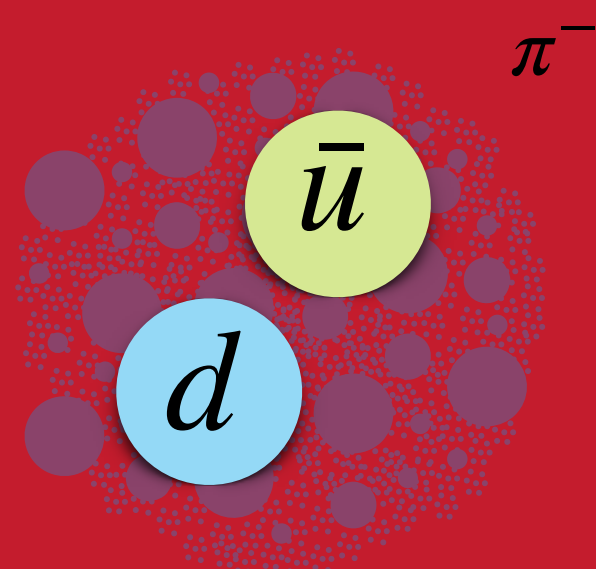
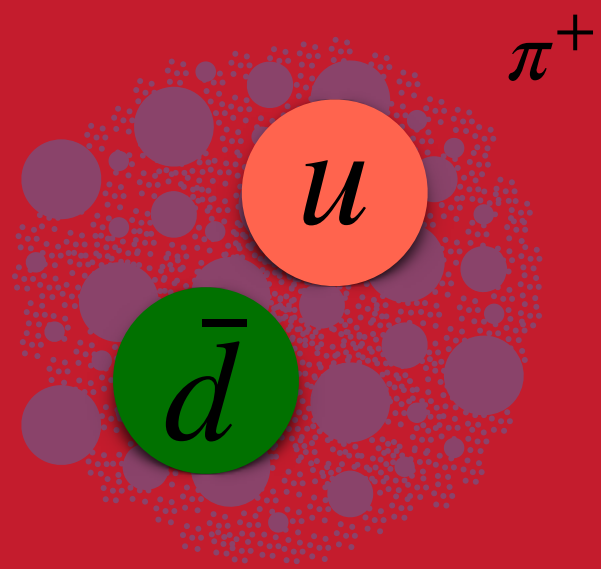


PION VERSUS PROTON



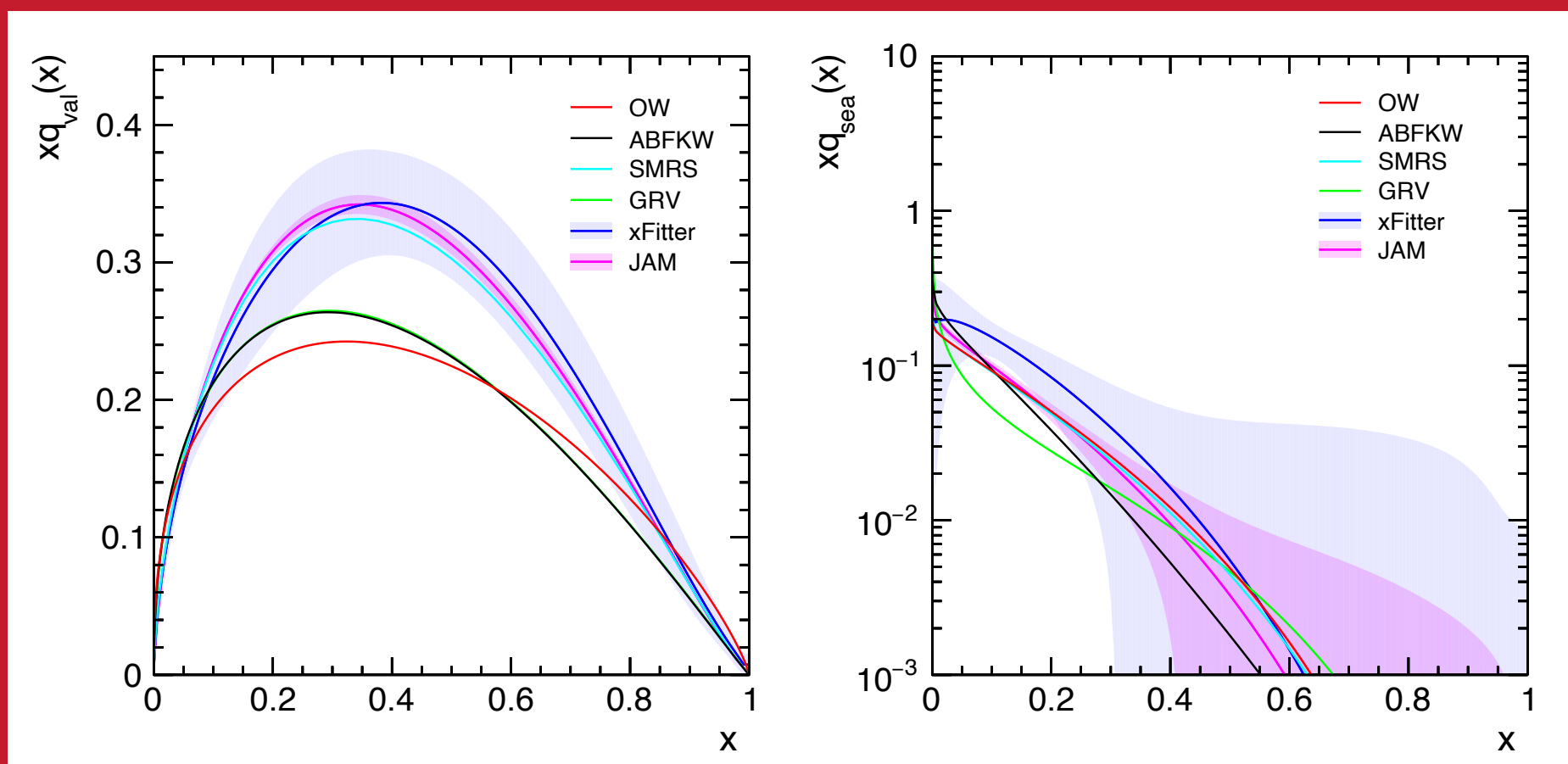
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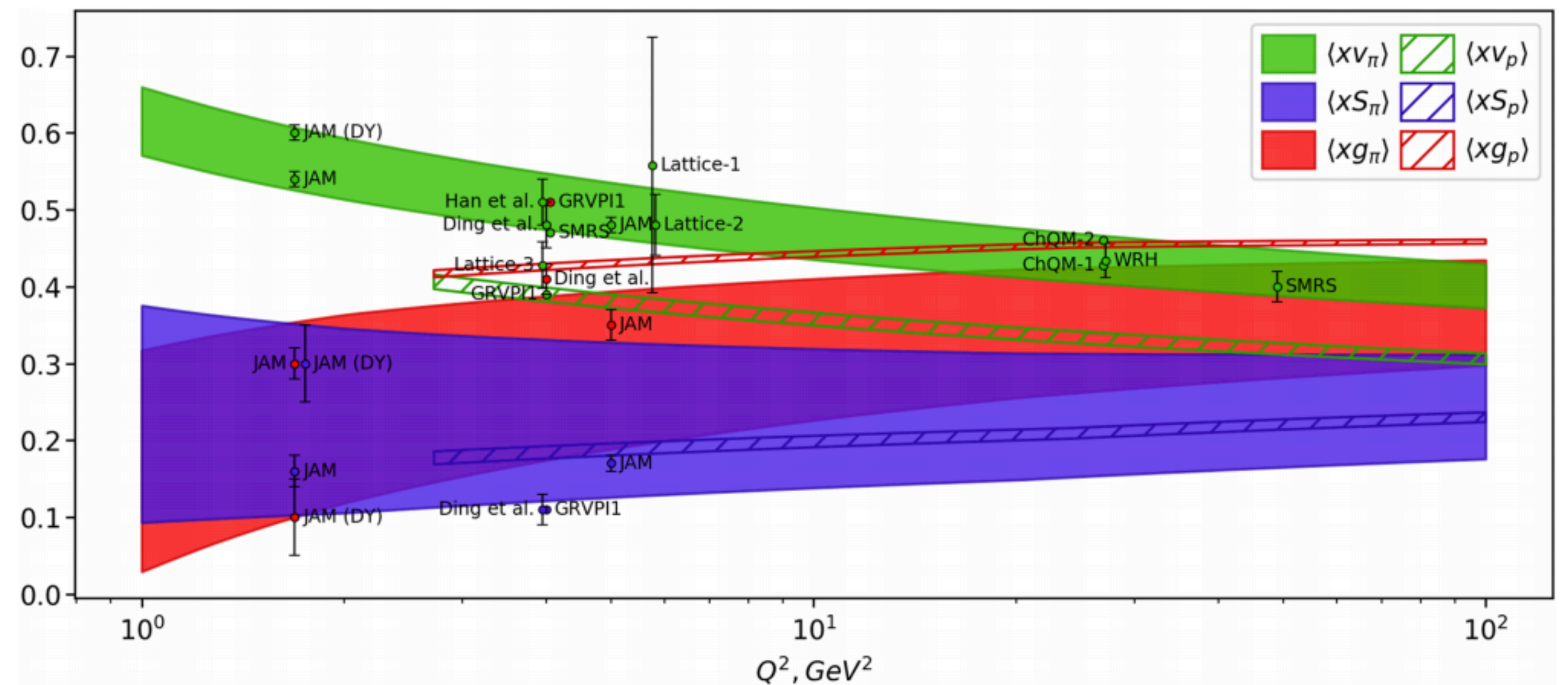


VALENCE

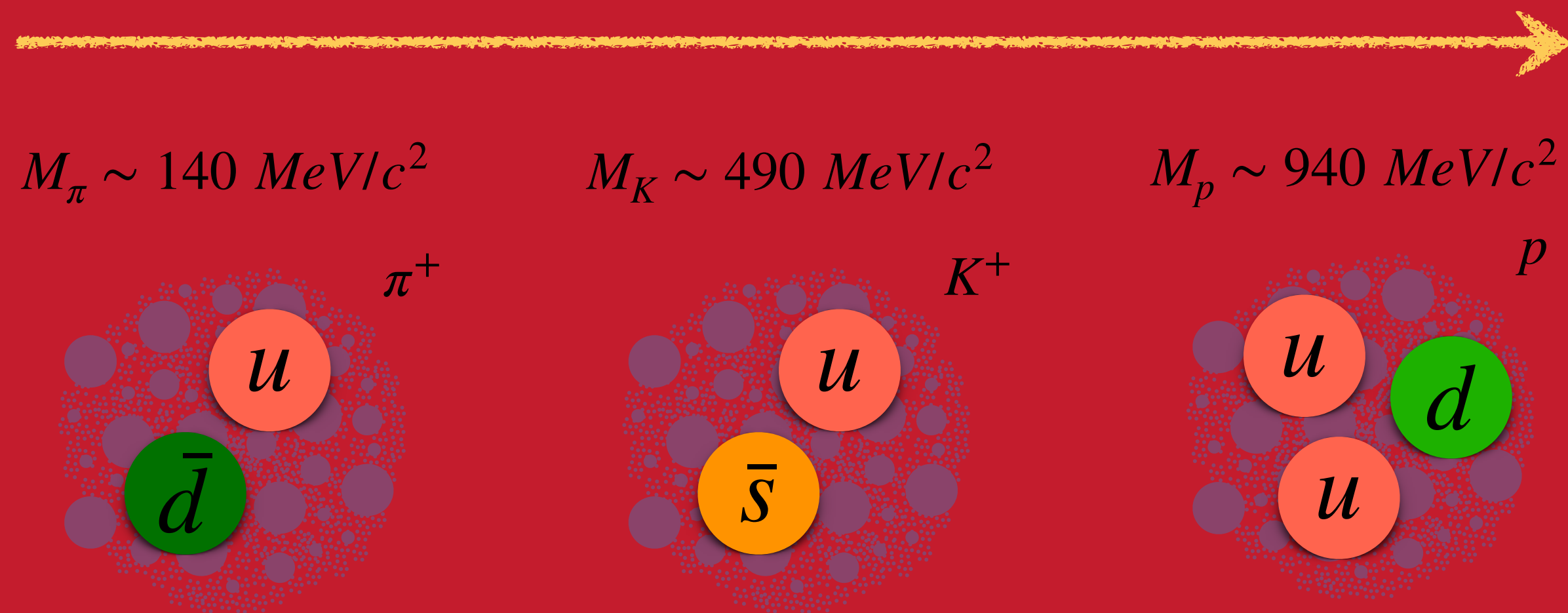
SEA



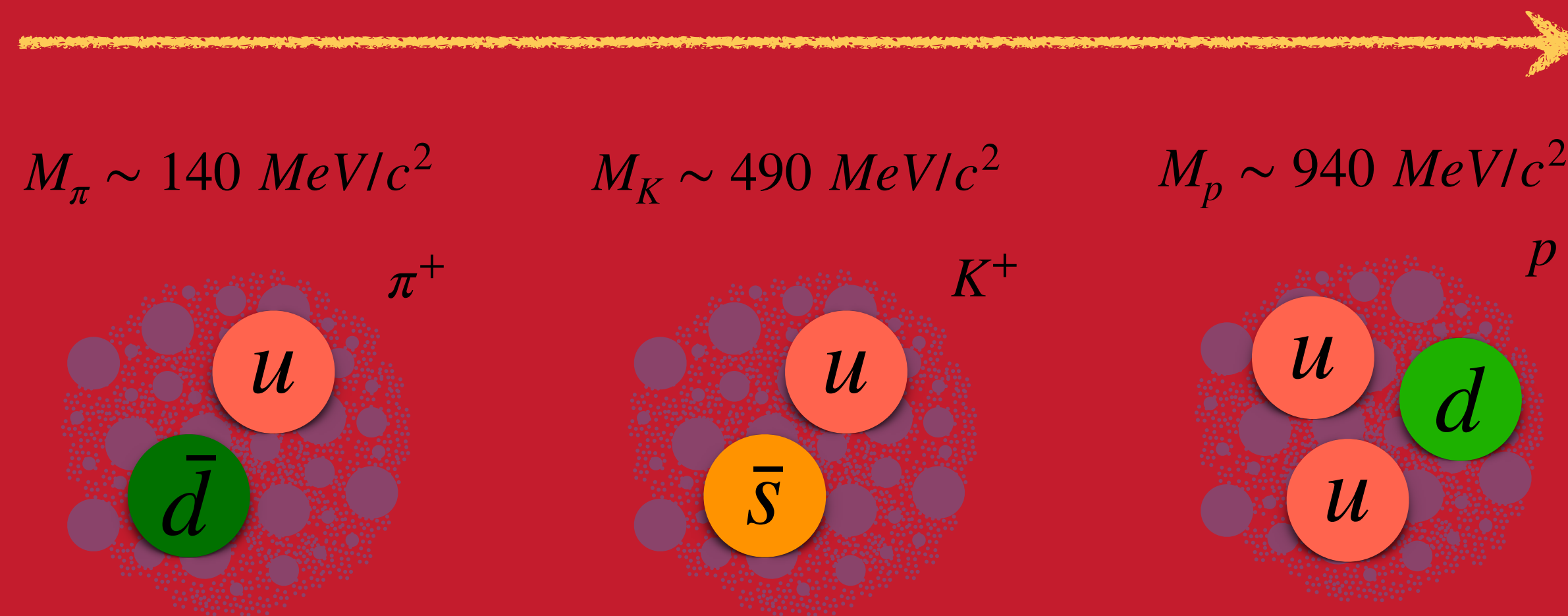
PION VERSUS PROTON



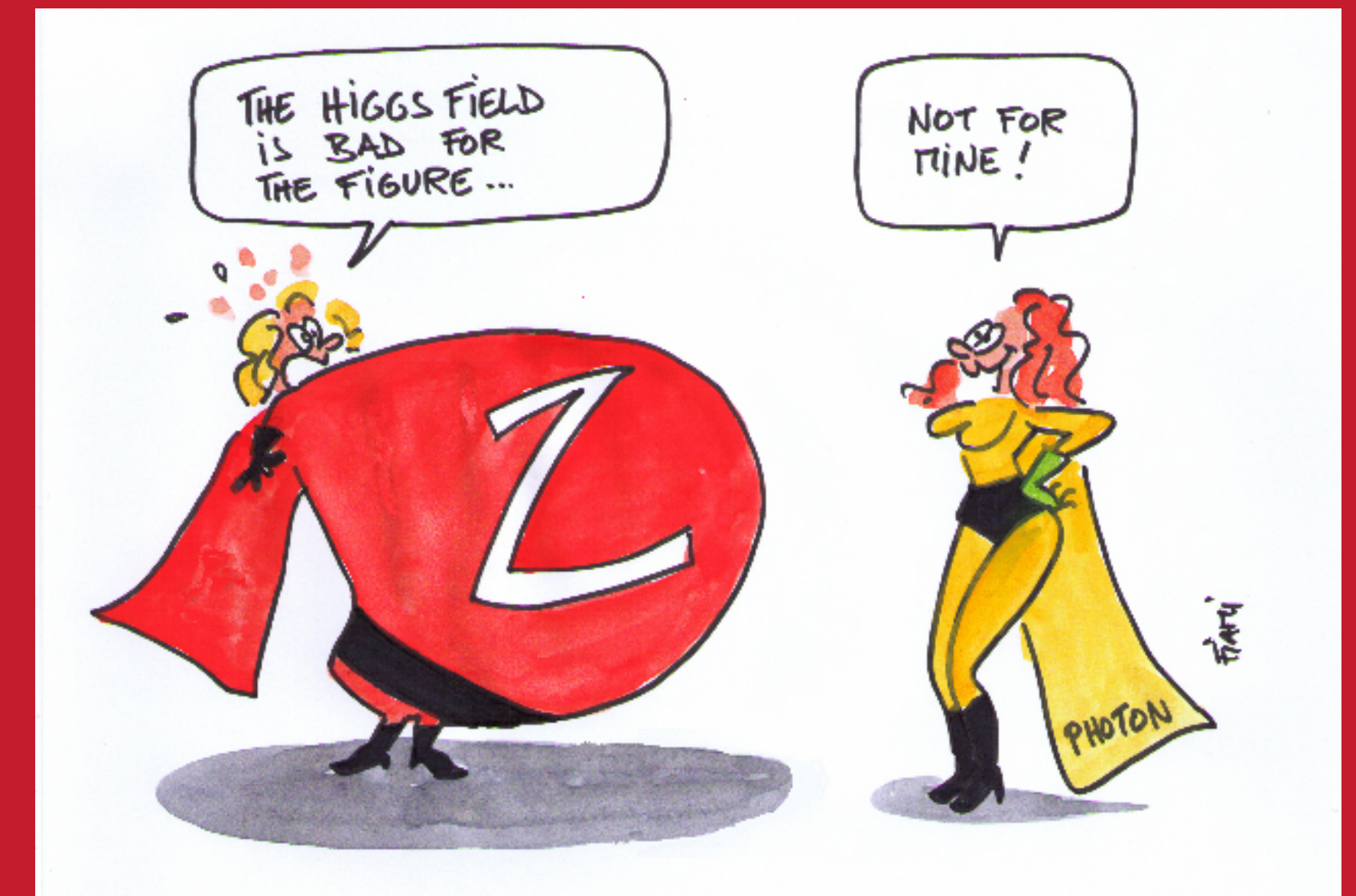
MASS HIERARCHY PUZZLE



MASS HIERARCHY PUZZLE

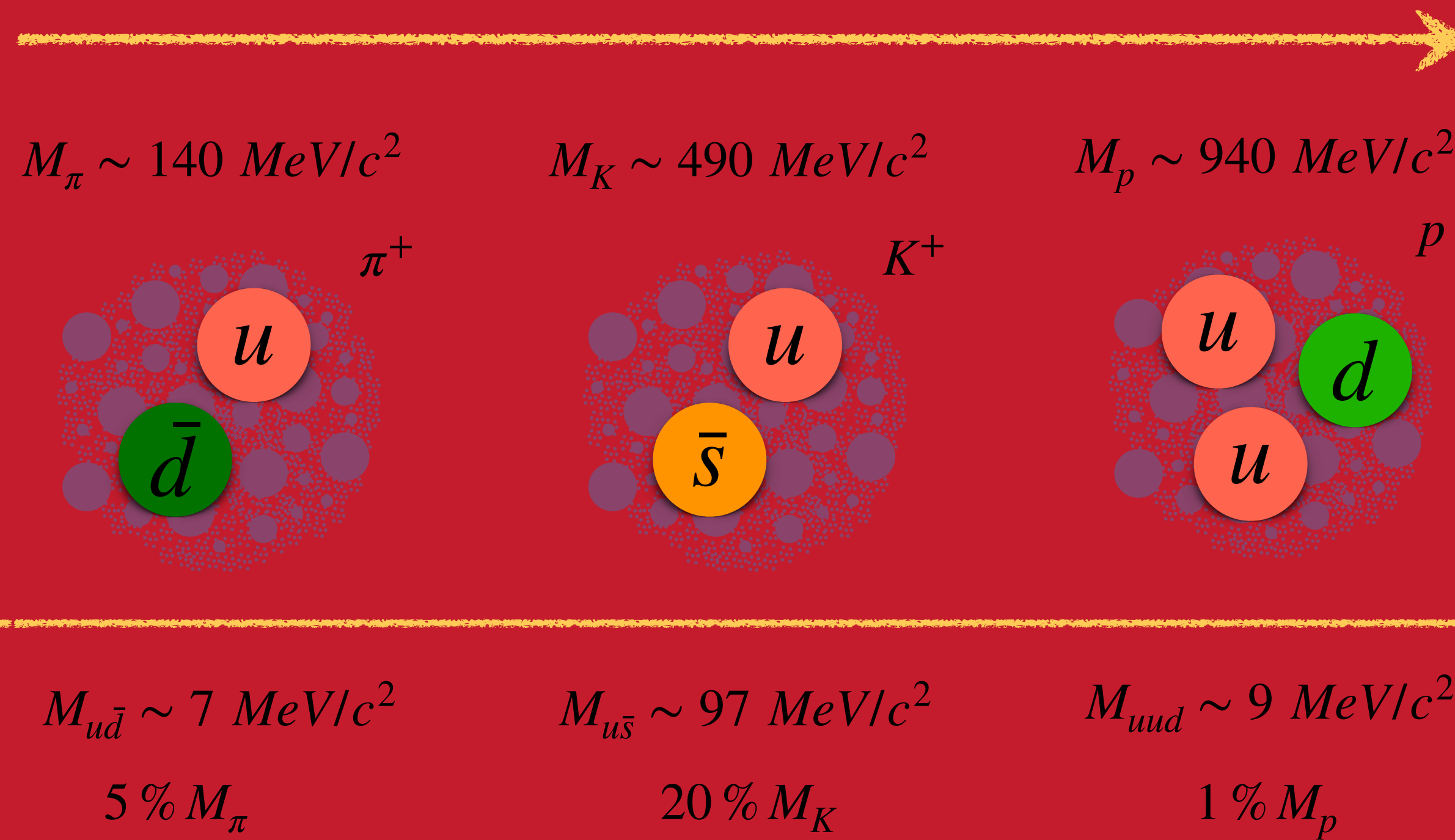


HIGGS MECHANISM

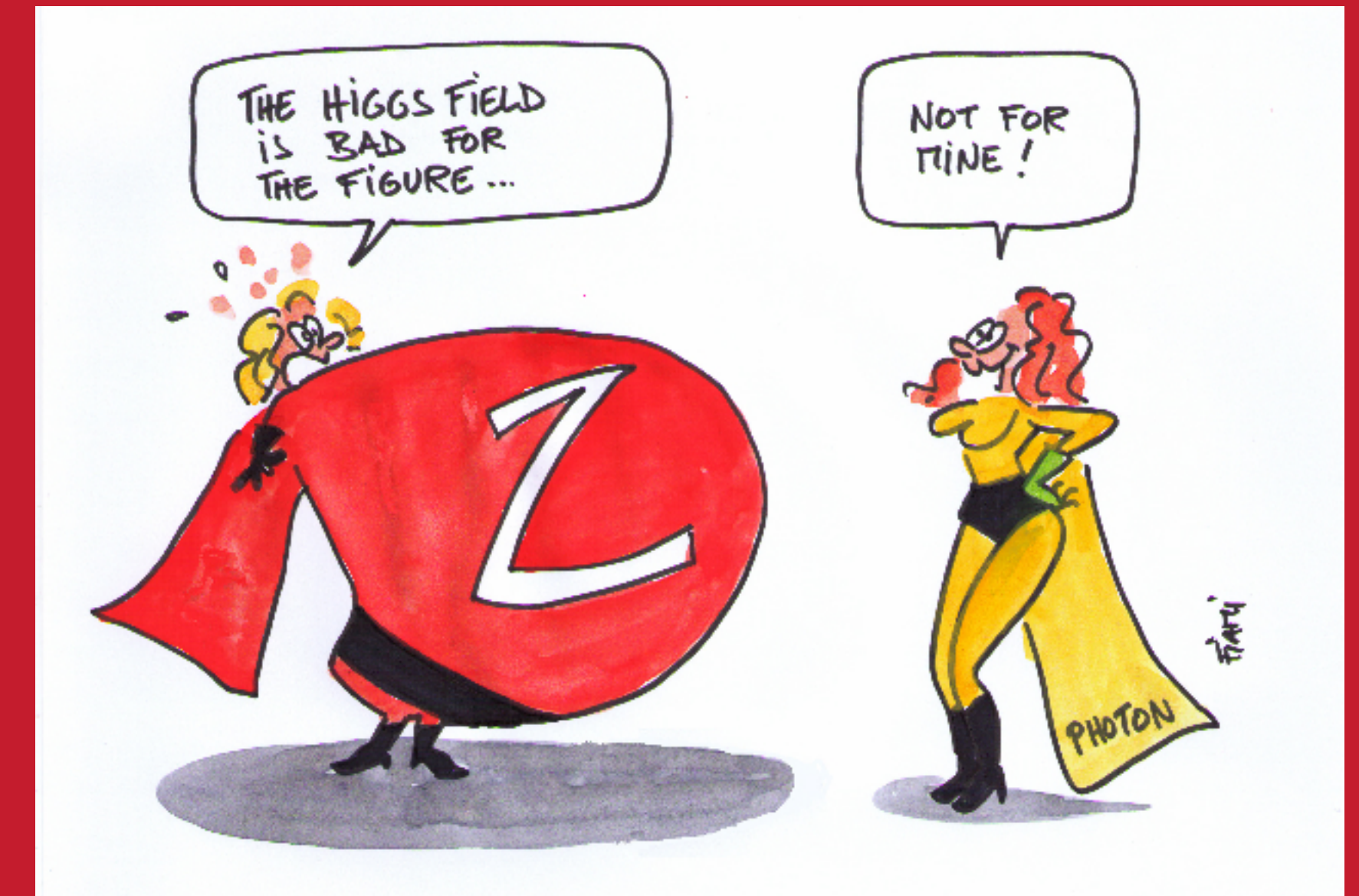


MASS HIERARCHY PUZZLE

HIGGS MECHANISM

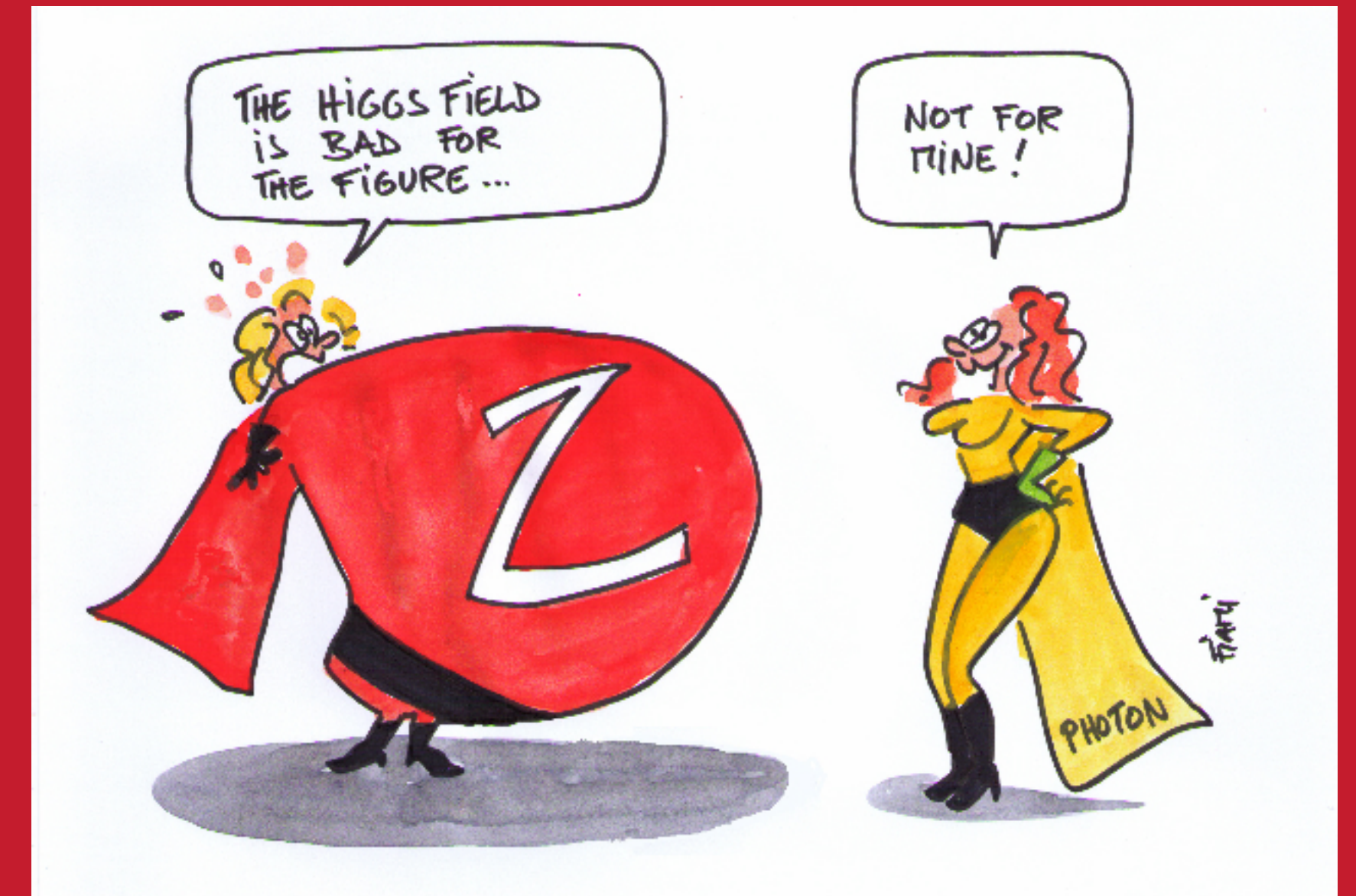
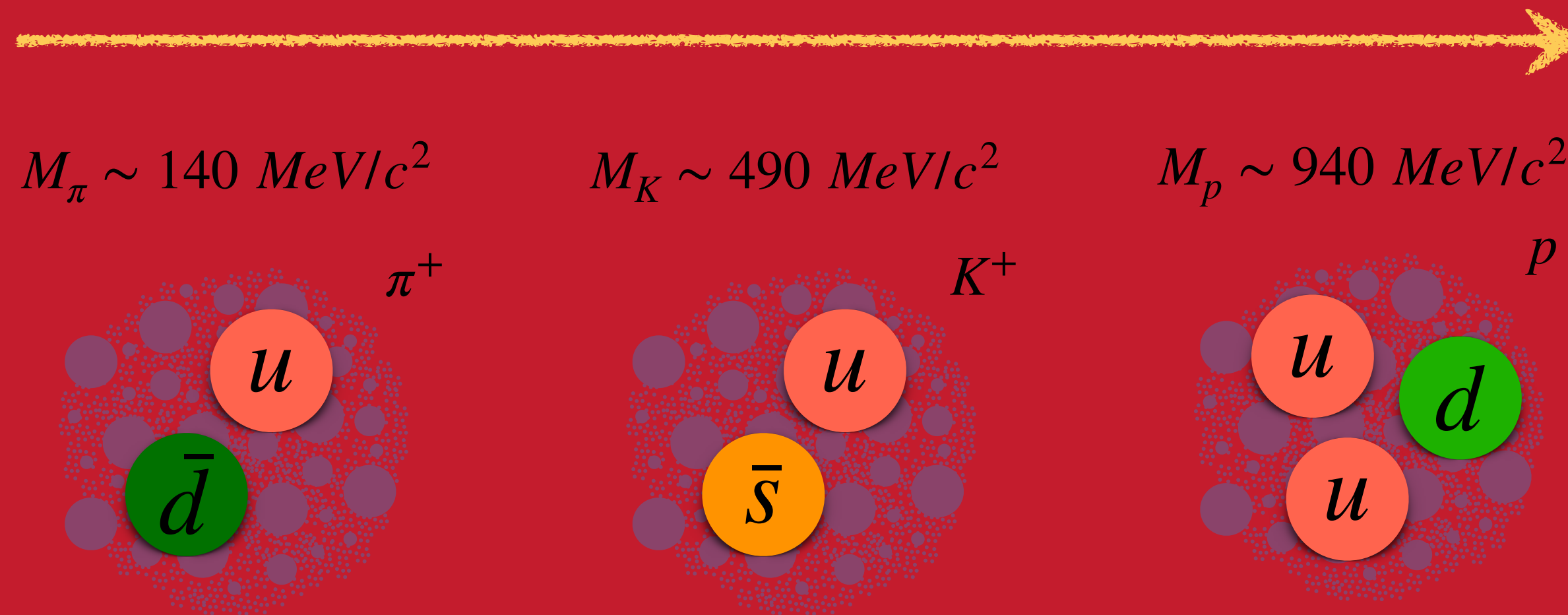


HIGGS MECHANISM



MASS HIERARCHY PUZZLE

HIGGS MECHANISM



$$M_{u\bar{d}} \sim 7 \text{ MeV}/c^2$$

$$5 \% M_\pi$$

$$M_{u\bar{s}} \sim 97 \text{ MeV}/c^2$$

$$20 \% M_K$$

$$M_{uud} \sim 9 \text{ MeV}/c^2$$

$$1 \% M_p$$

HIGGS MECHANISM

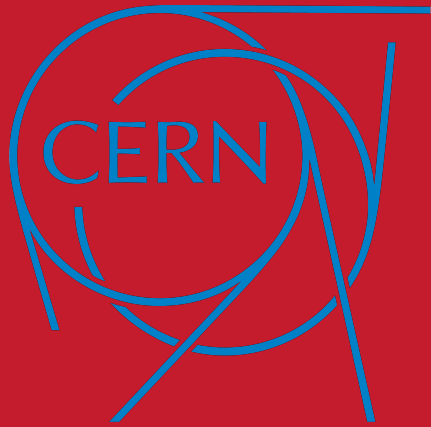
$$95 \% M_\pi$$

$$80 \% M_K$$

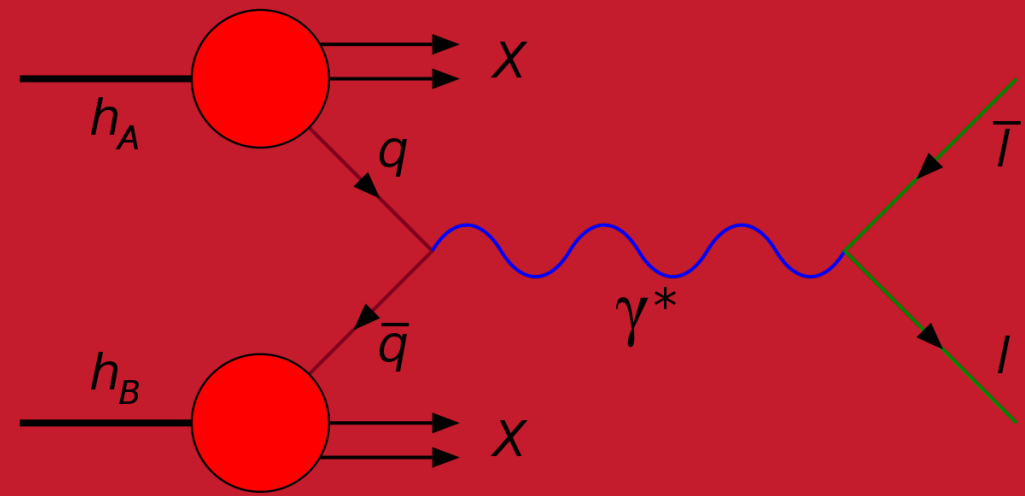
$$99 \% M_p$$

DYNAMICS OF GLUONS

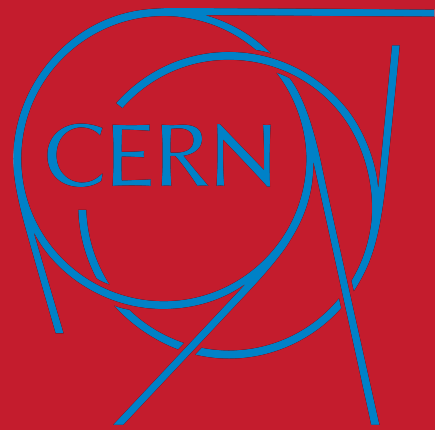
CERN LEGACY ON PION STRUCTURE



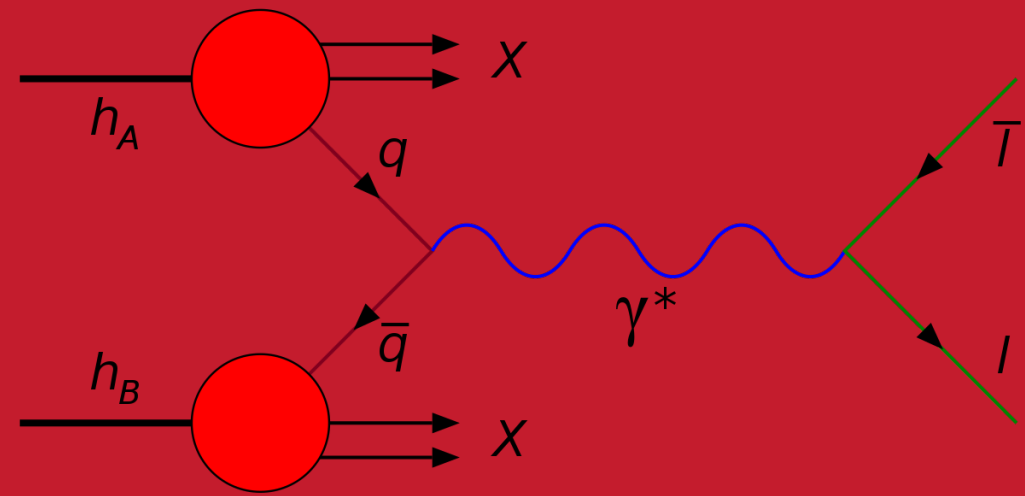
π induced Drell-Yan



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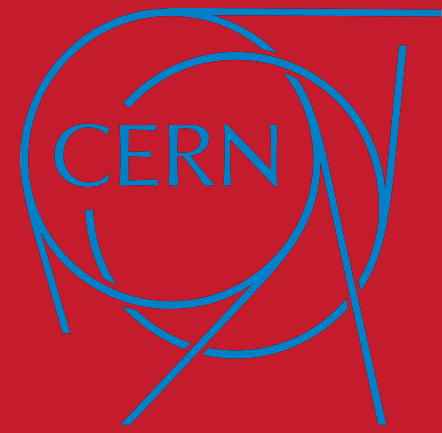
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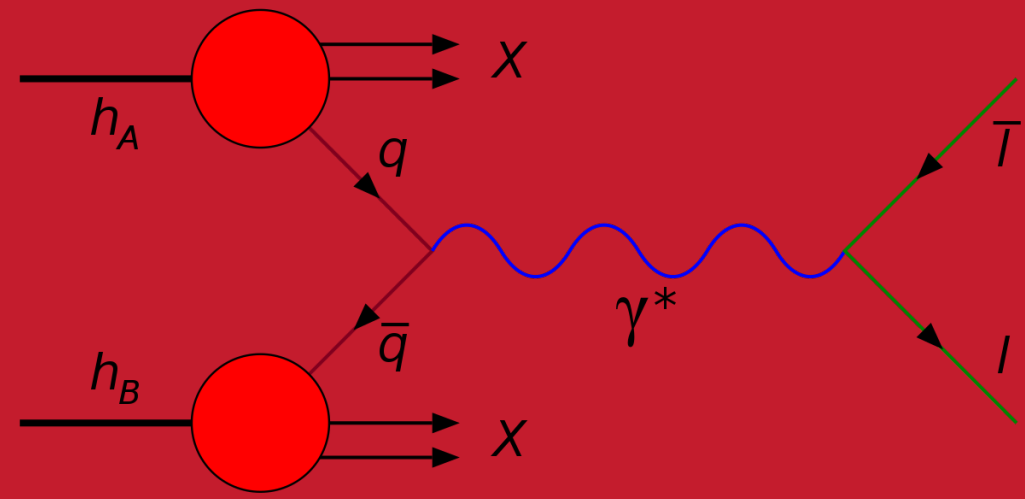
Fixed target experiments:

1. NA3 (1979)
2. NA10 (1984)
3. NA58/COMPASS (2015/2018)
4. NA66/AMBER (>2024)

CERN LEGACY ON PION STRUCTURE



π induced Drell-Yan



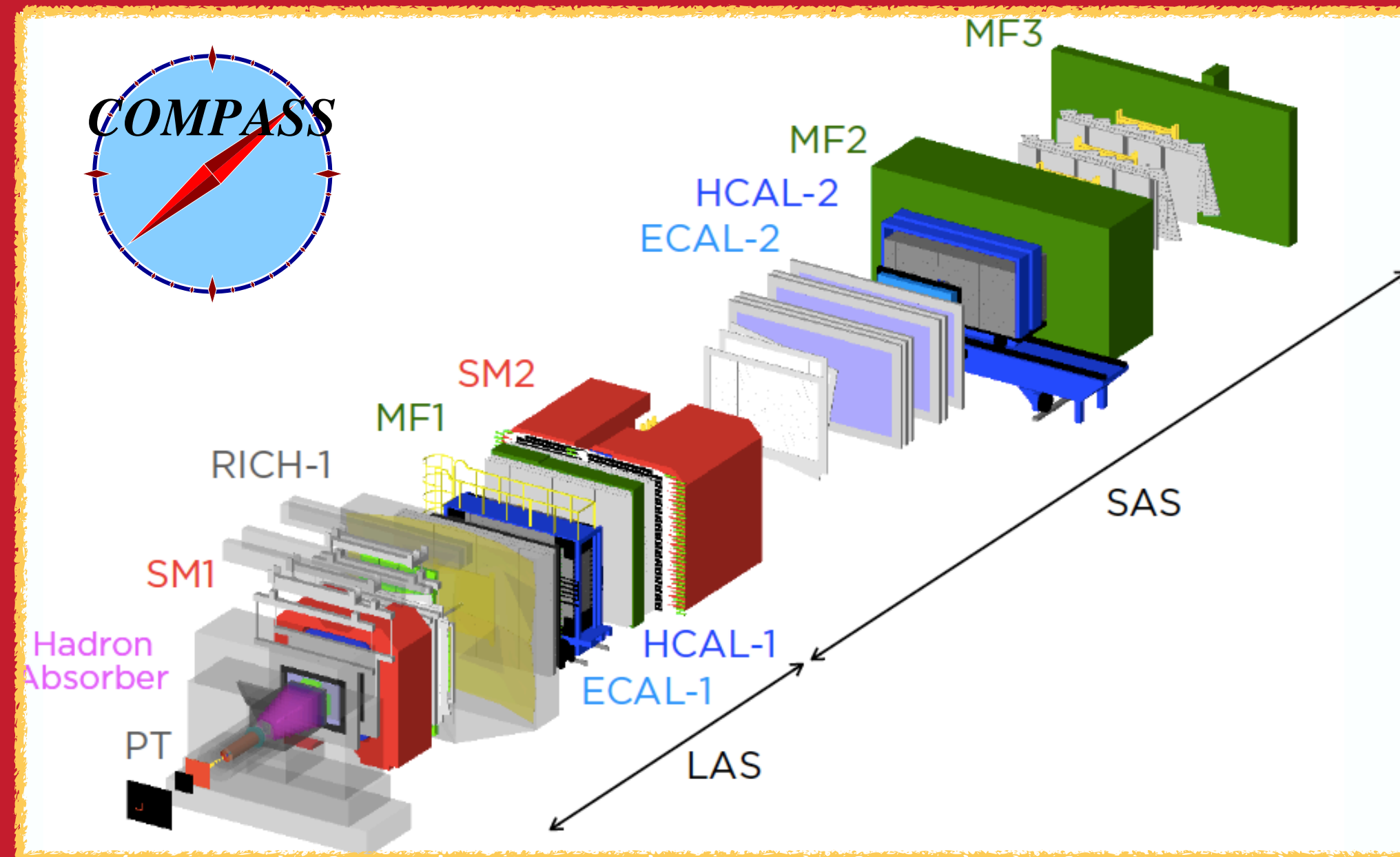
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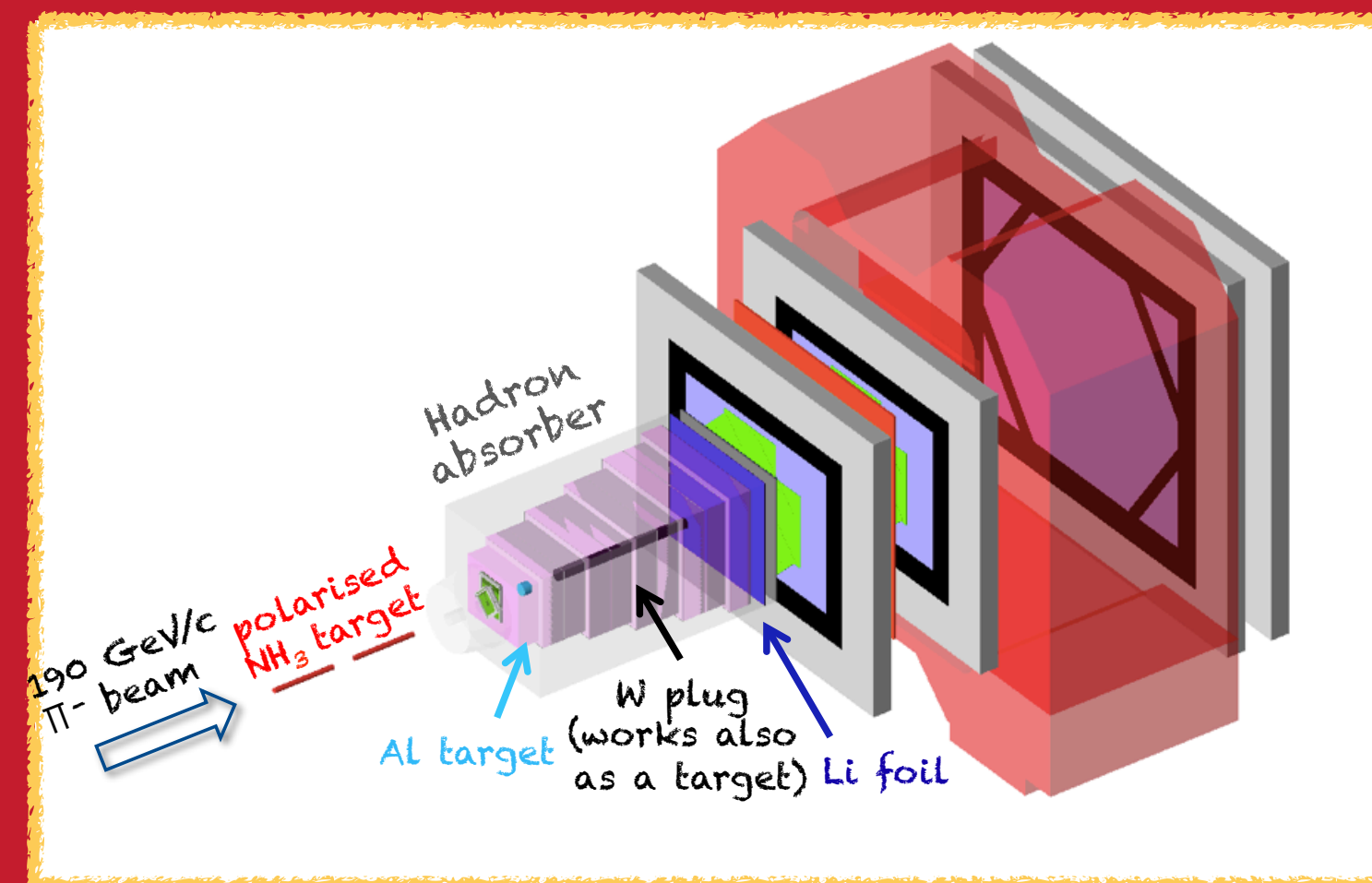
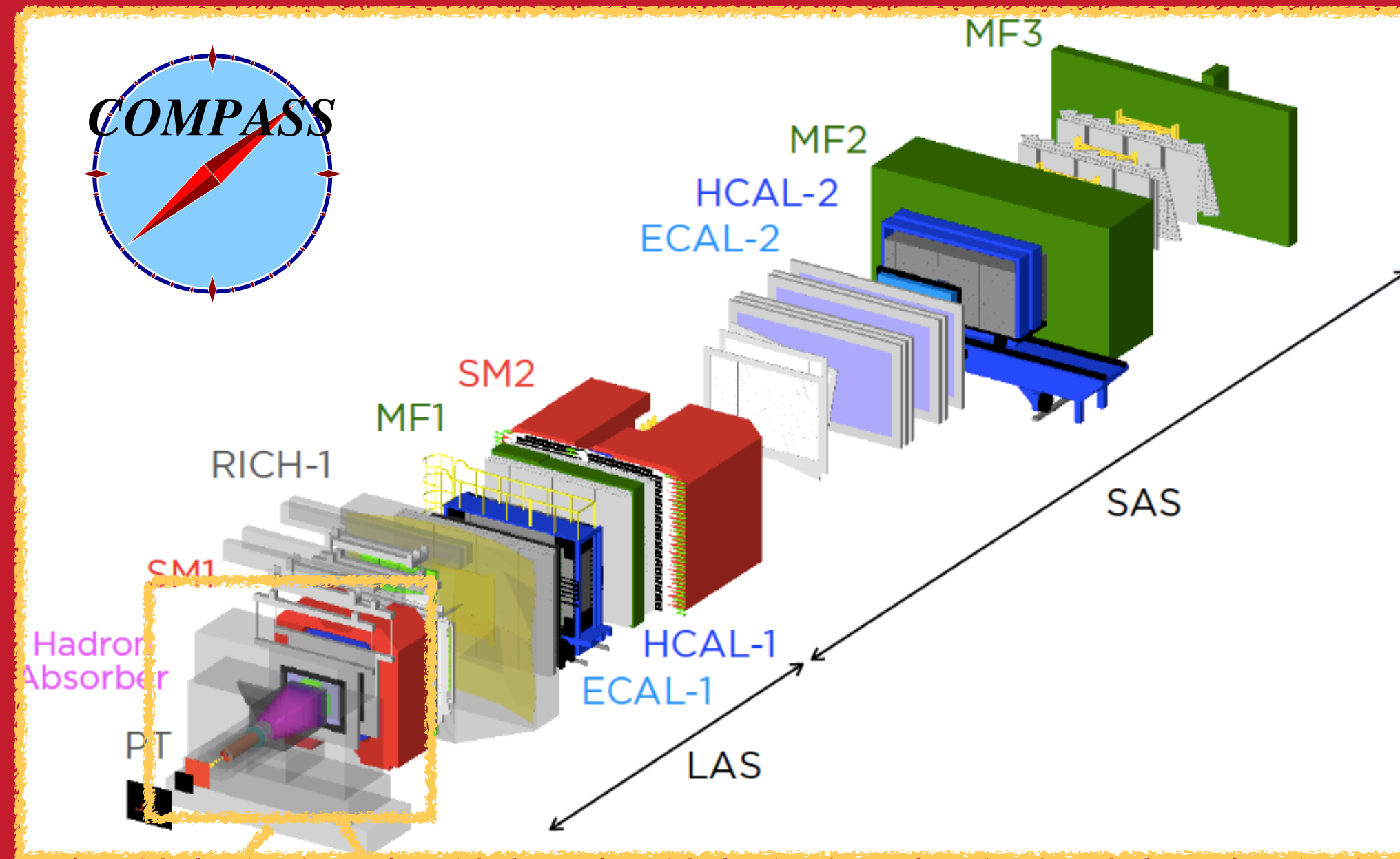
COMPASS EXPERIMENT (2002-2022)

Common Muon Proton Apparatus for Structure and Spectroscopy



COMPASS EXPERIMENT (2002-2022)

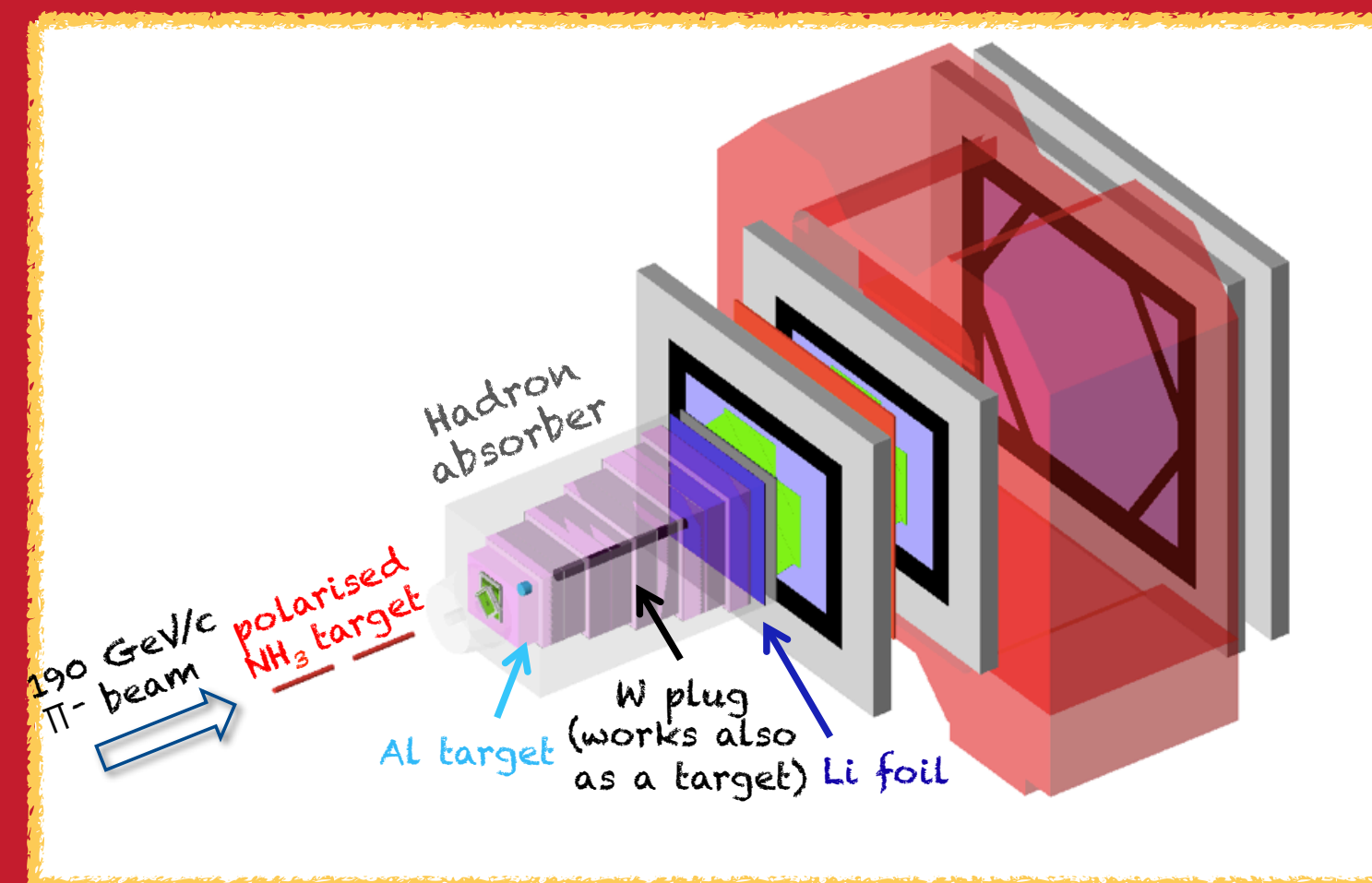
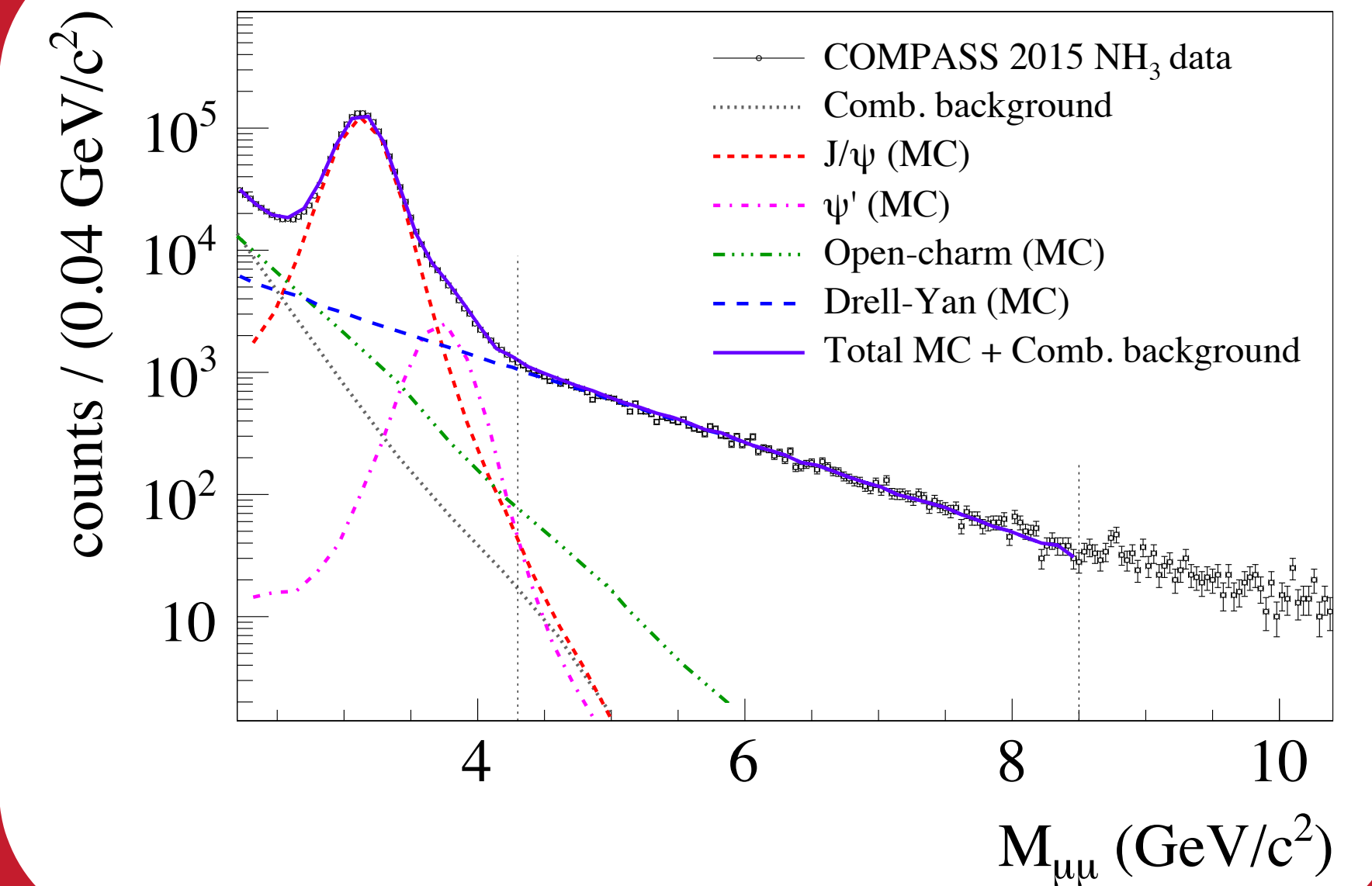
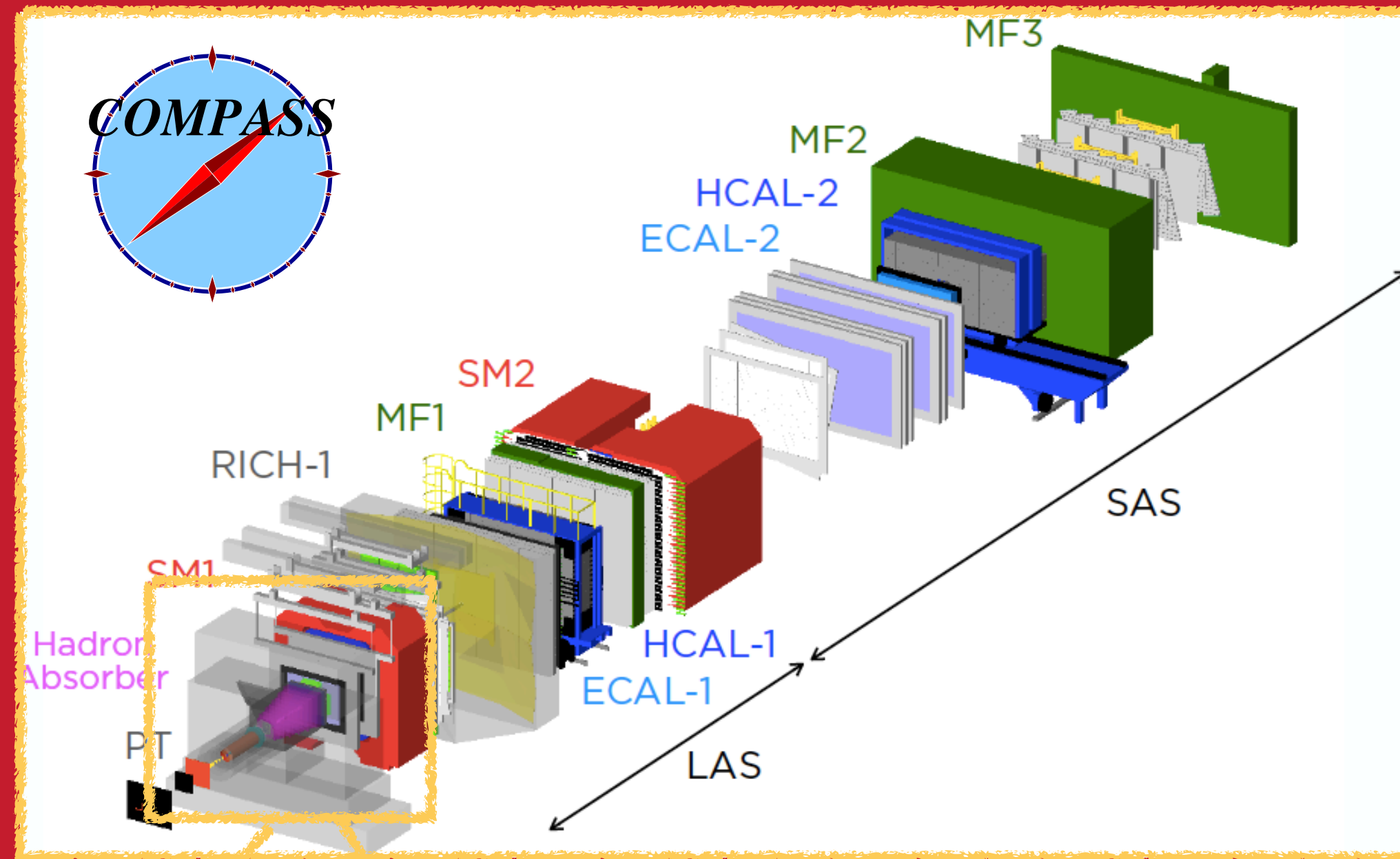
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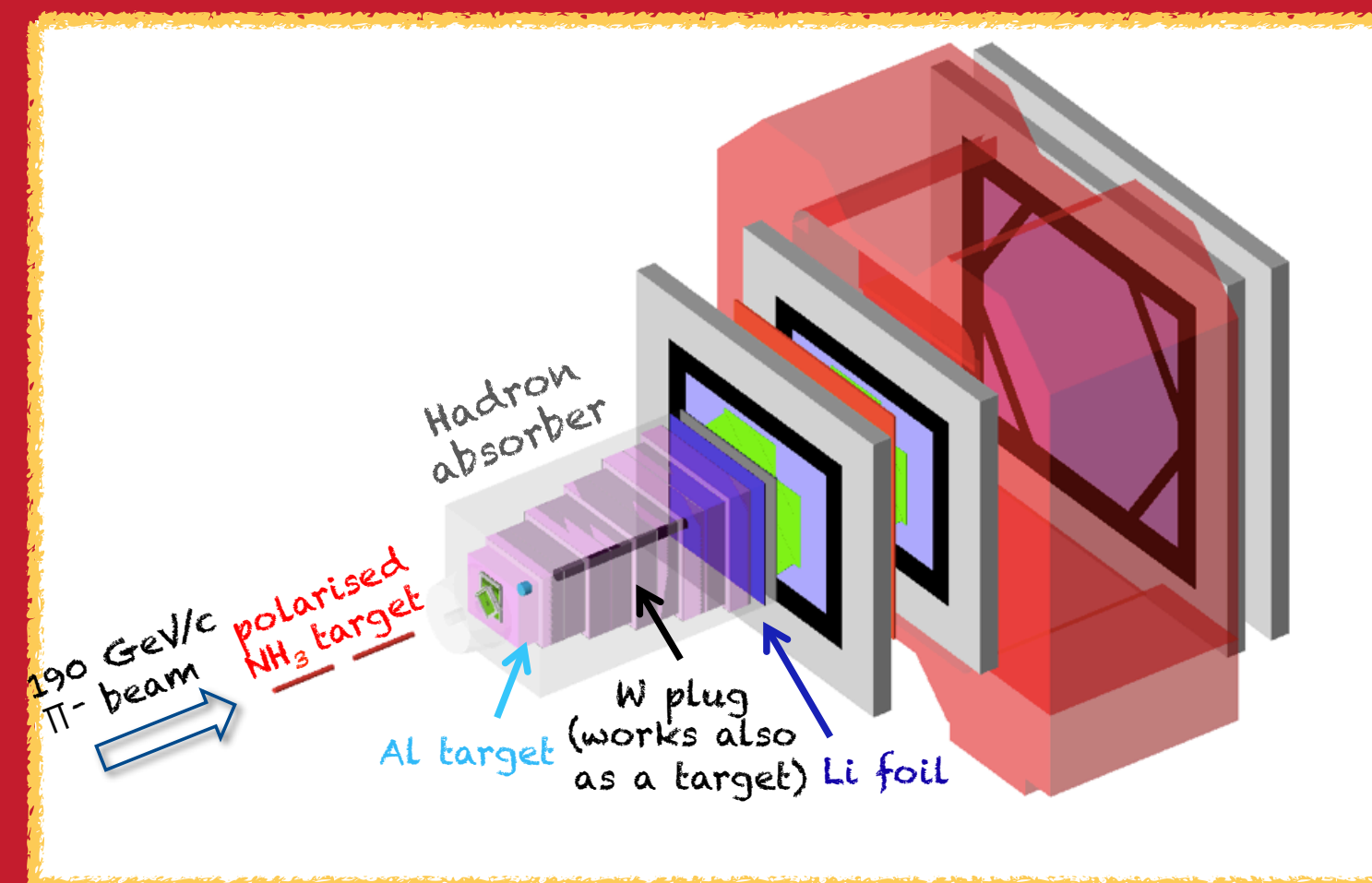
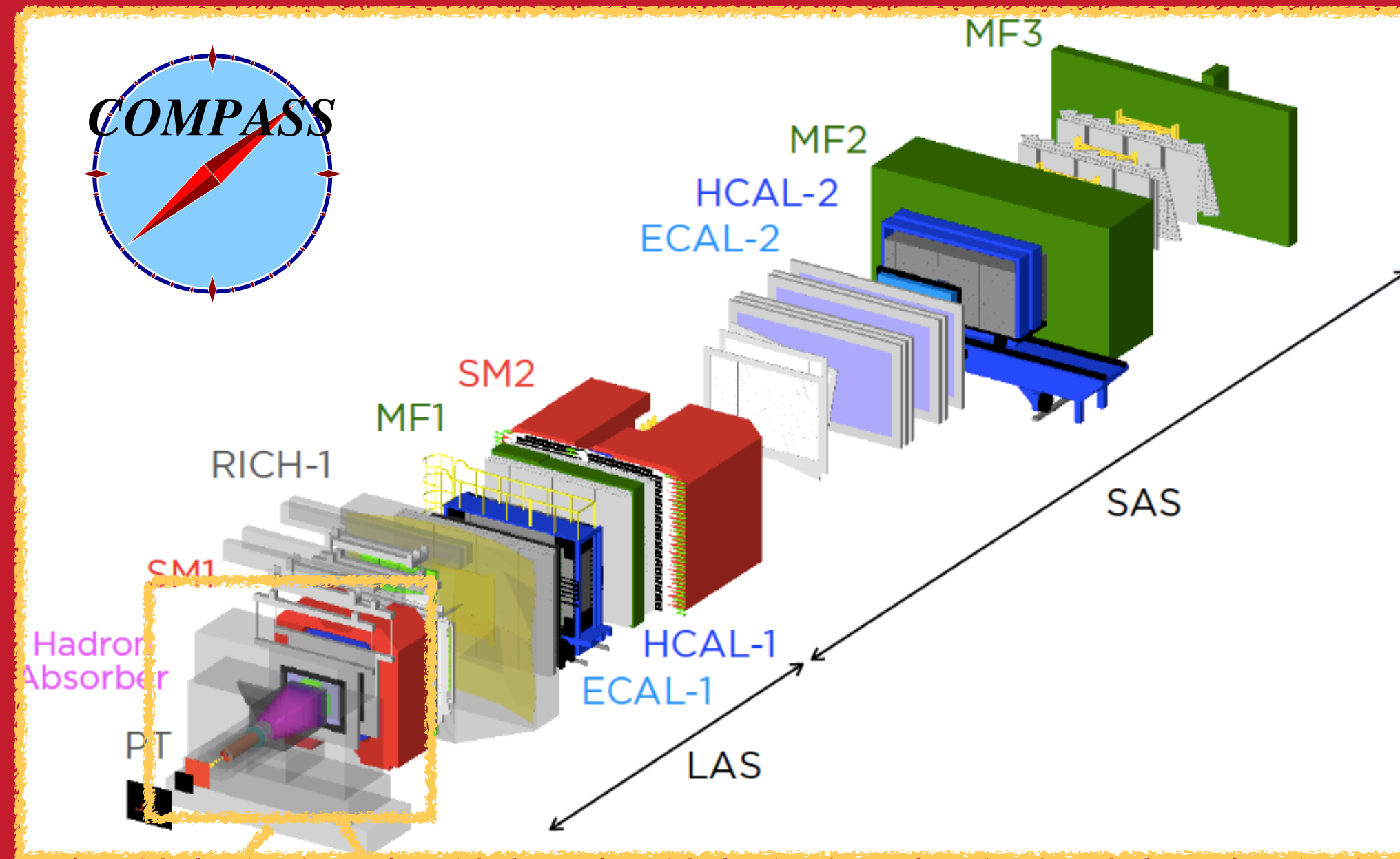
Common Muon Proton Apparatus for Structure and Spectroscopy

2015 data

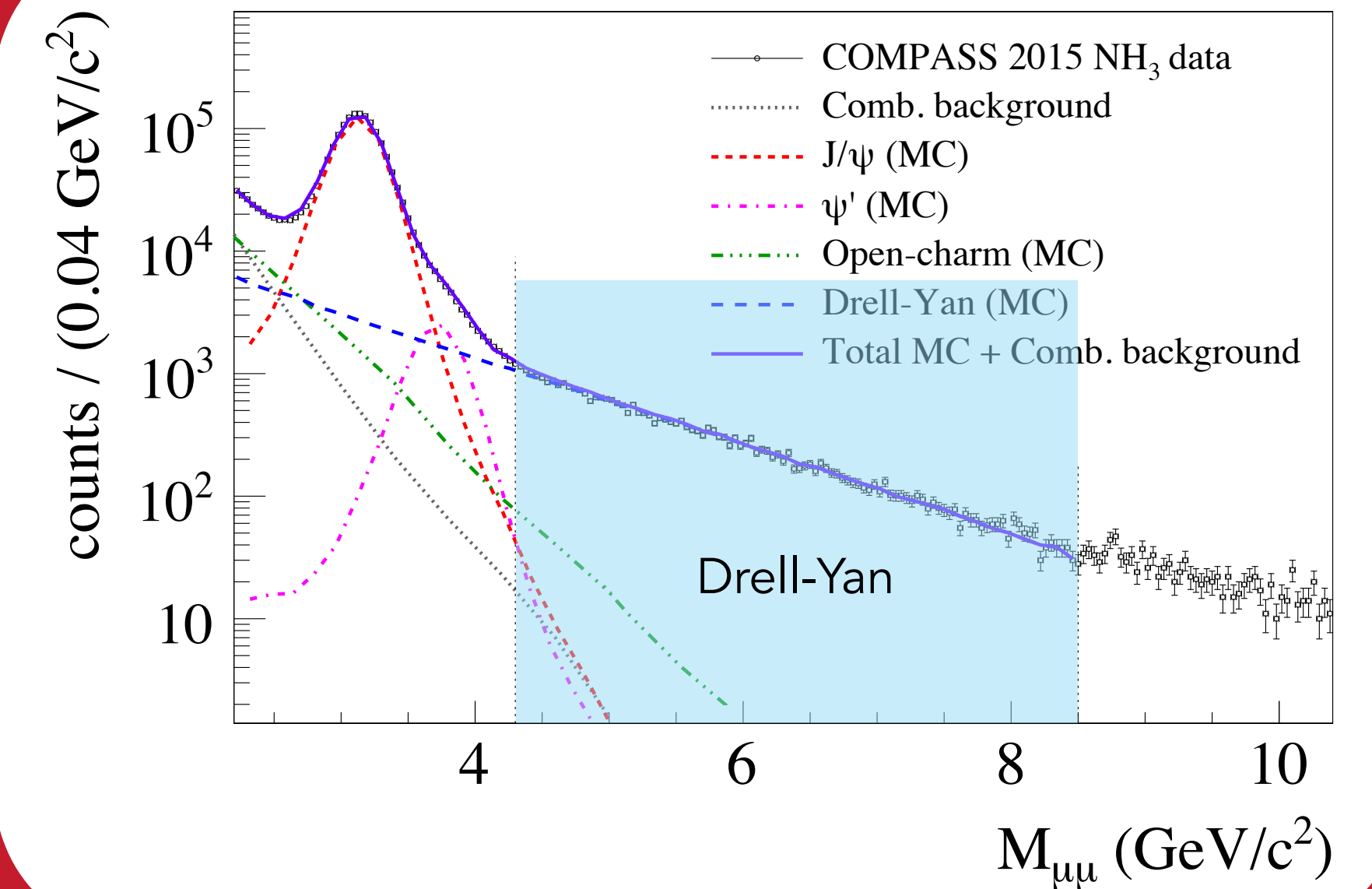


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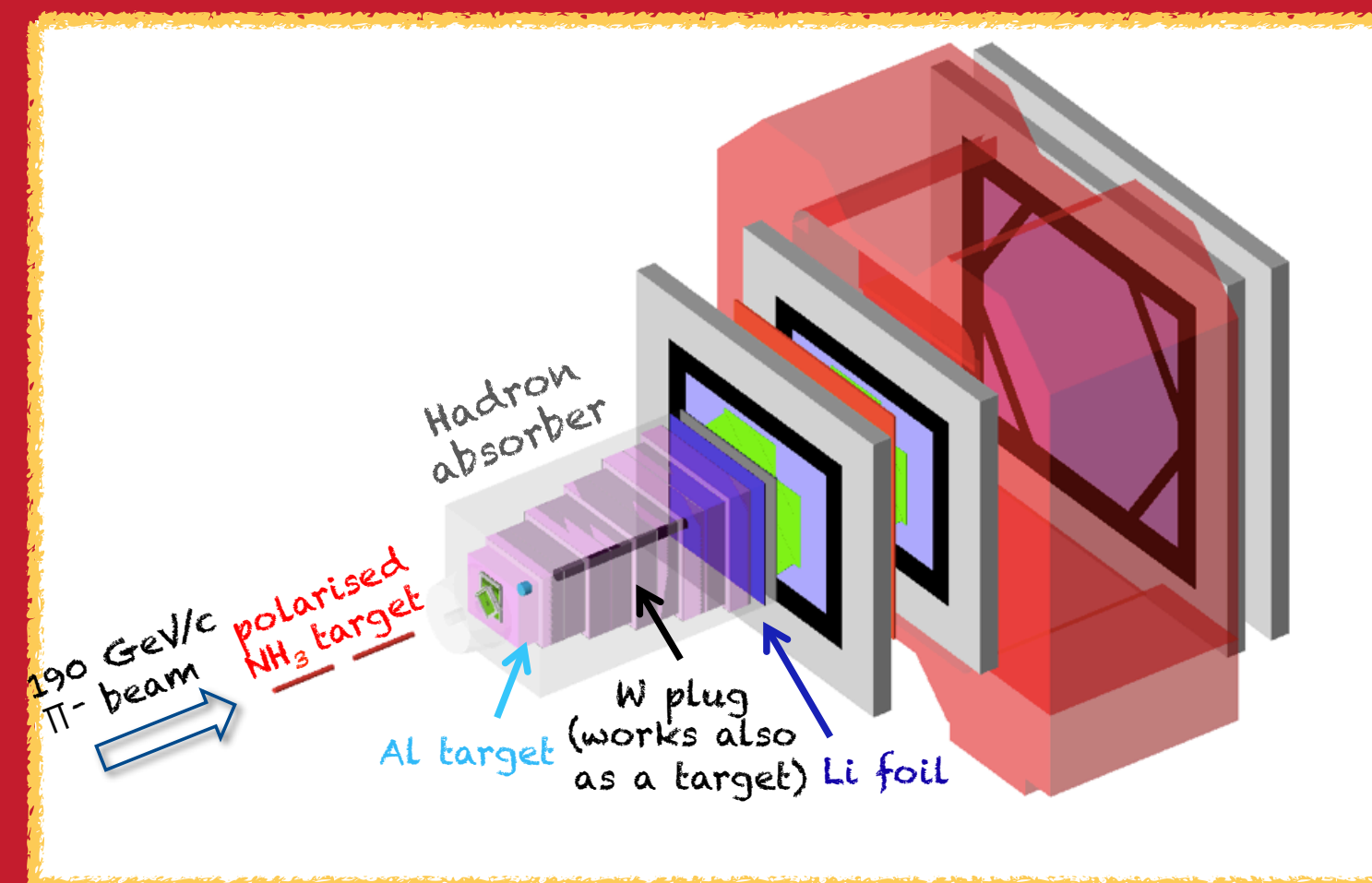
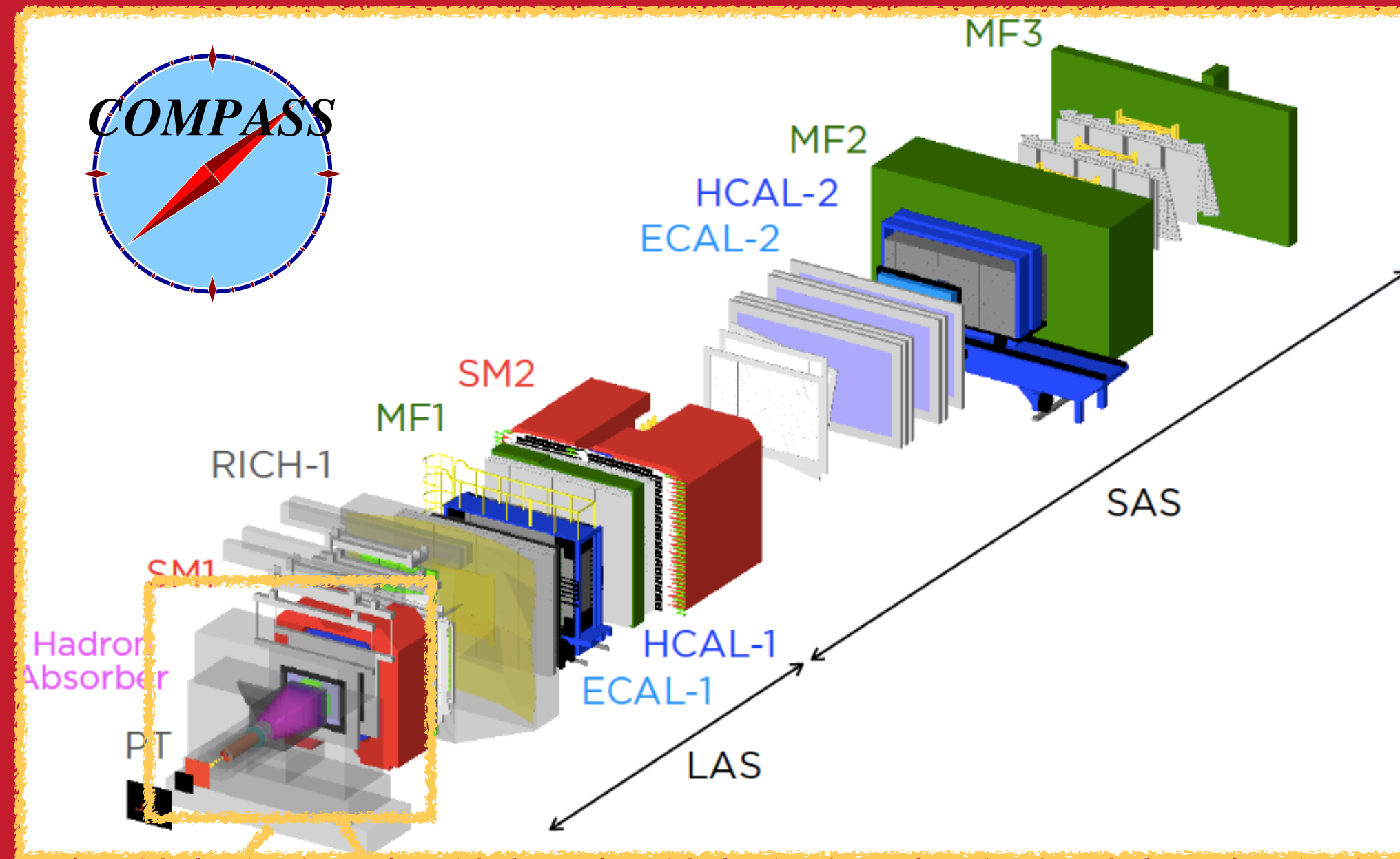


2015 data

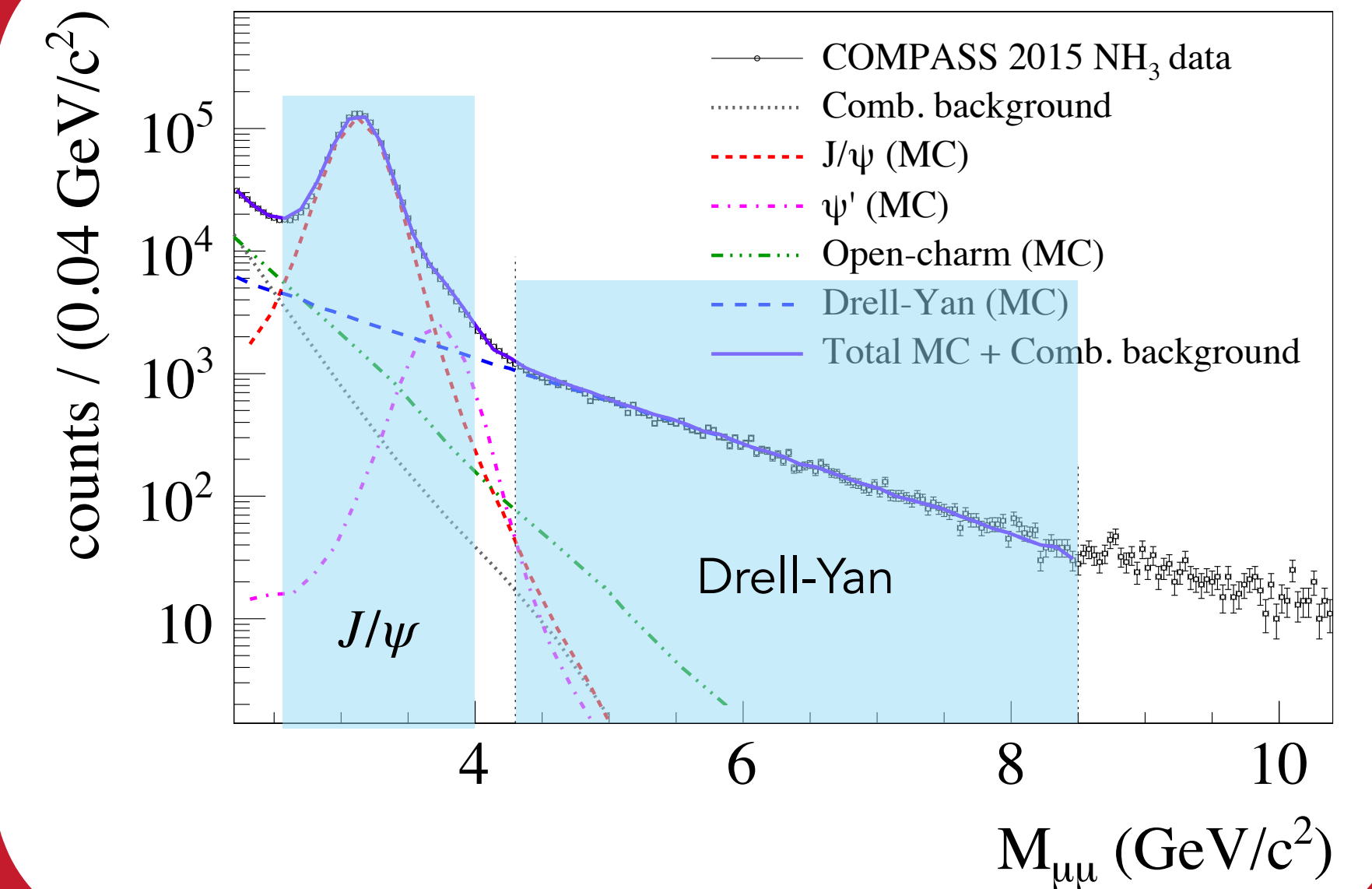


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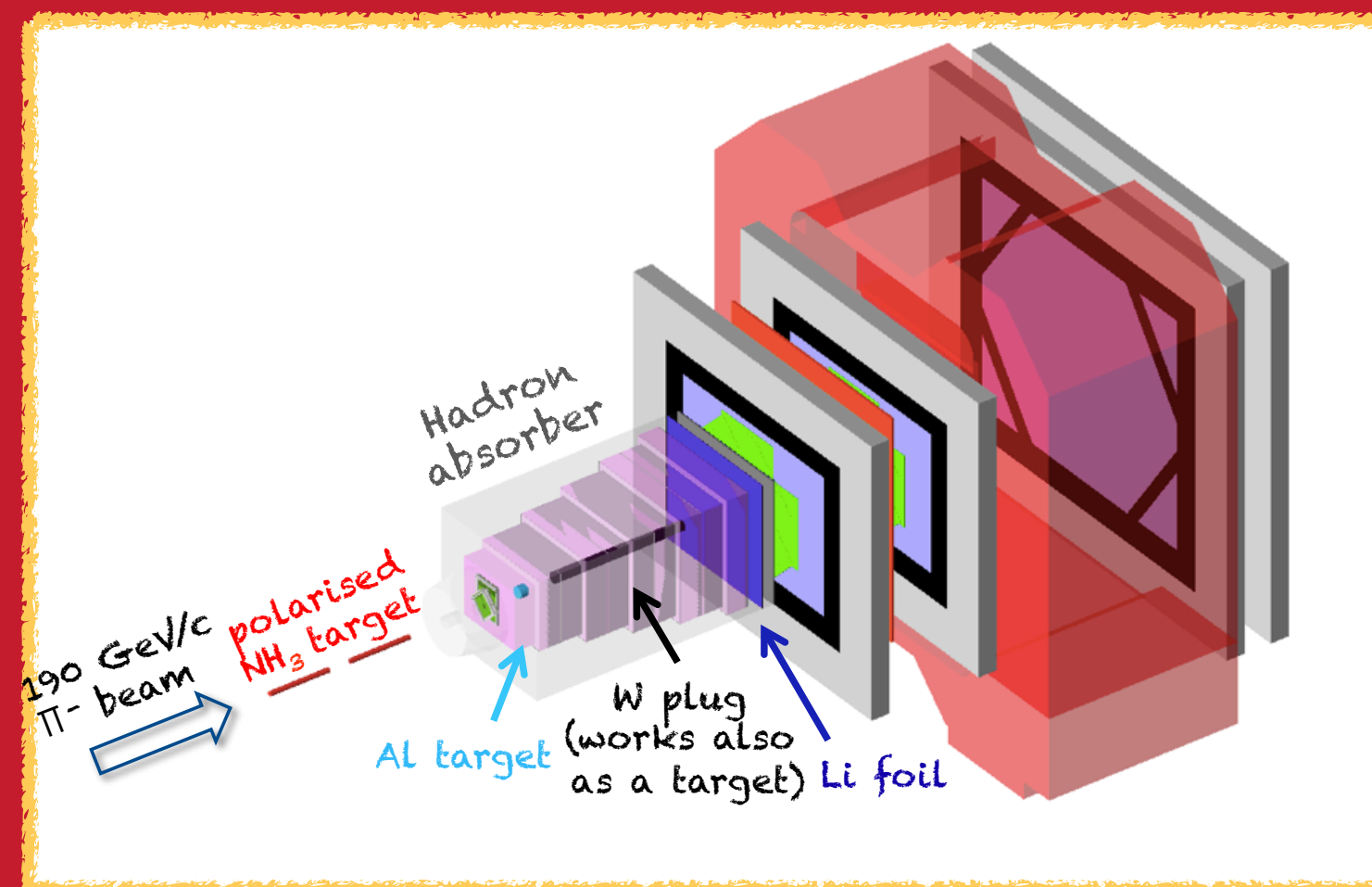
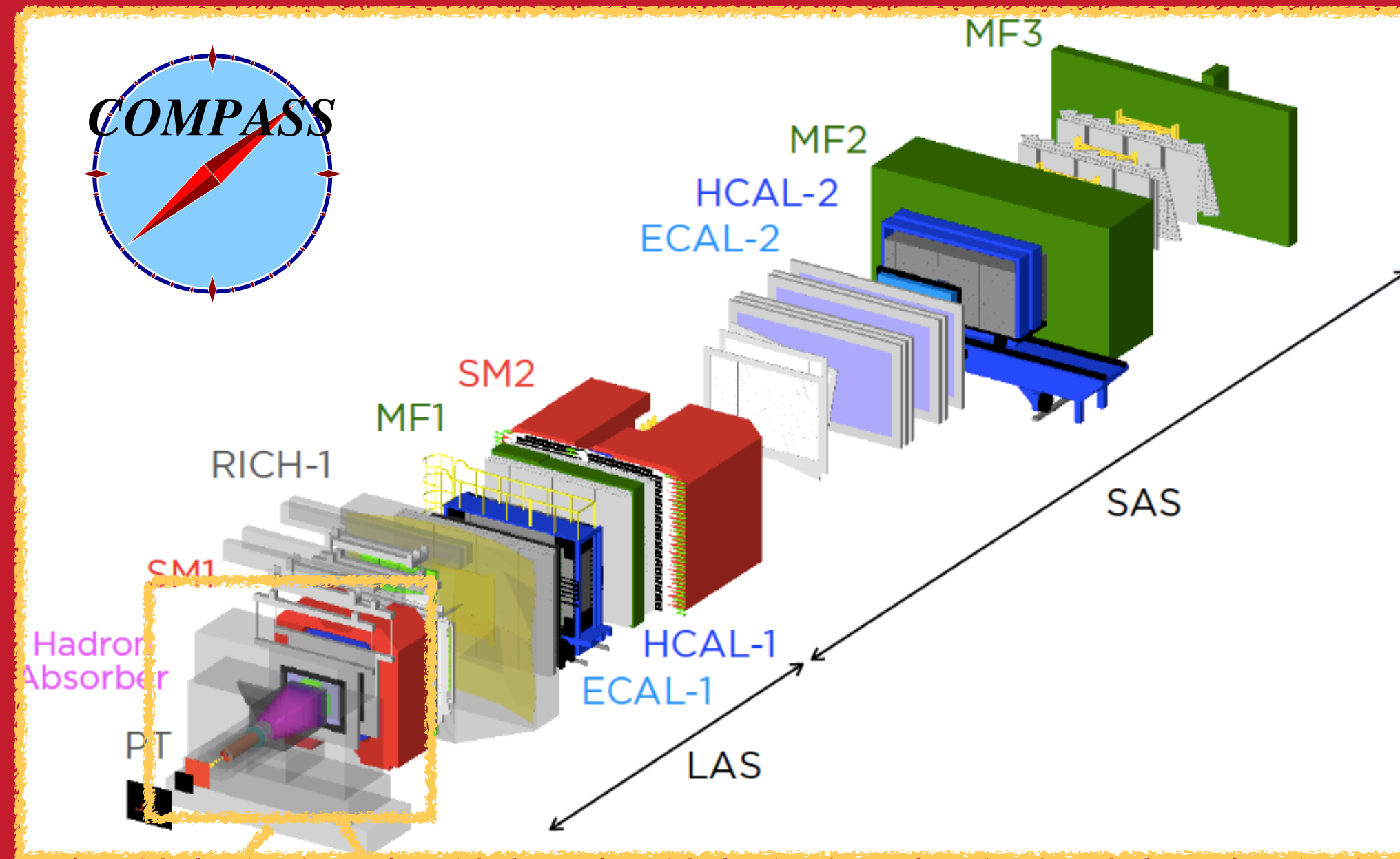


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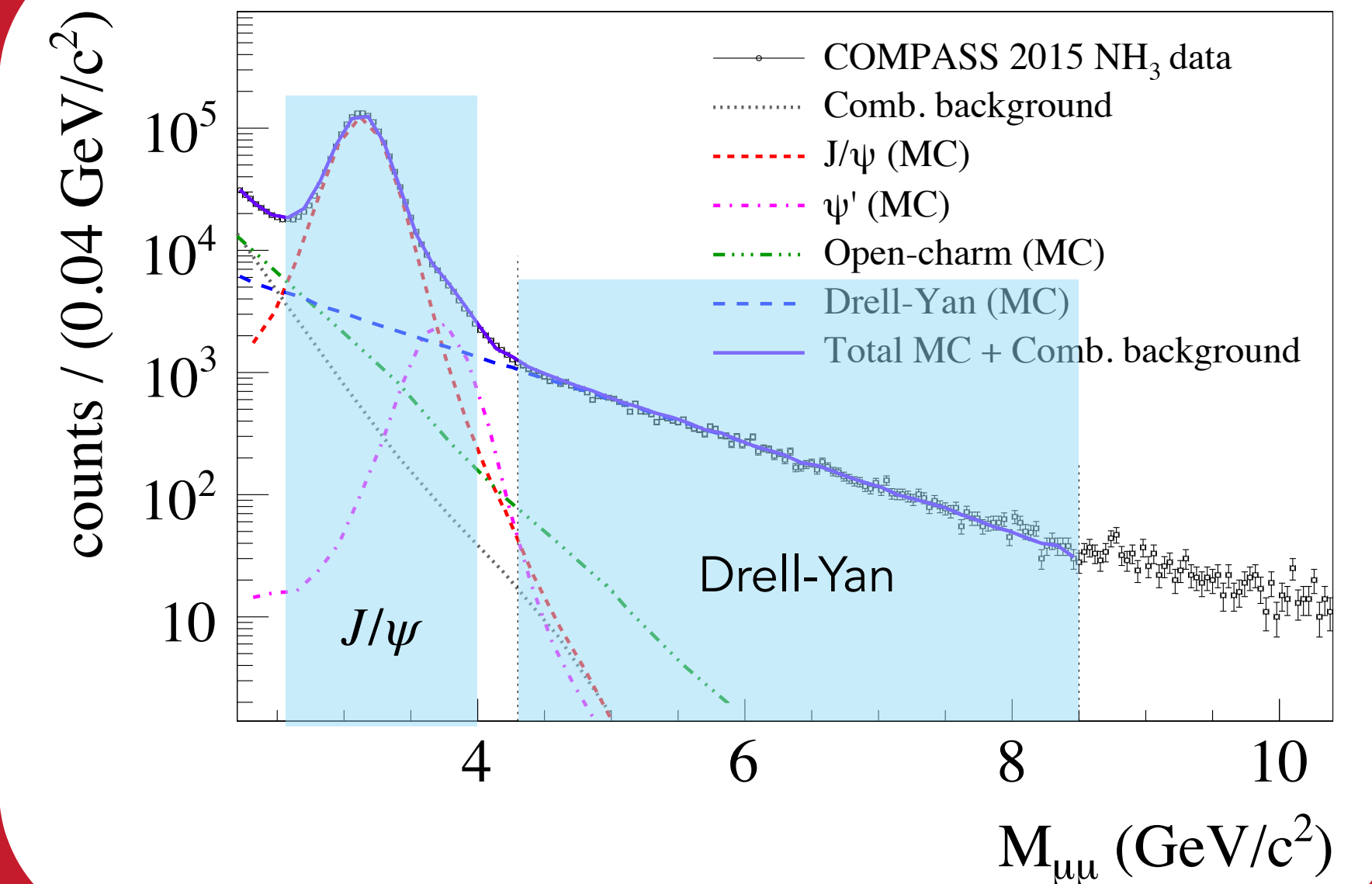


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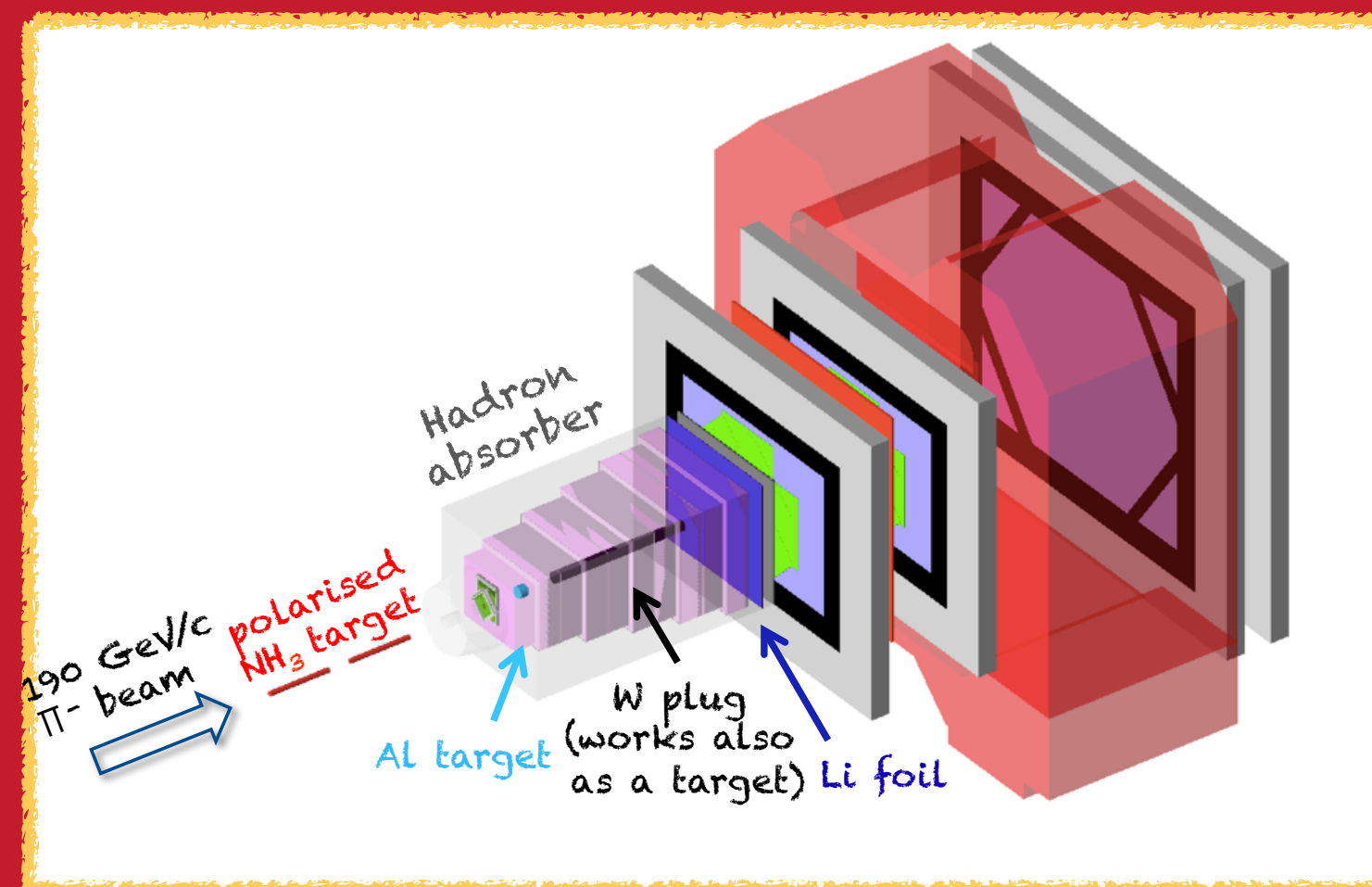
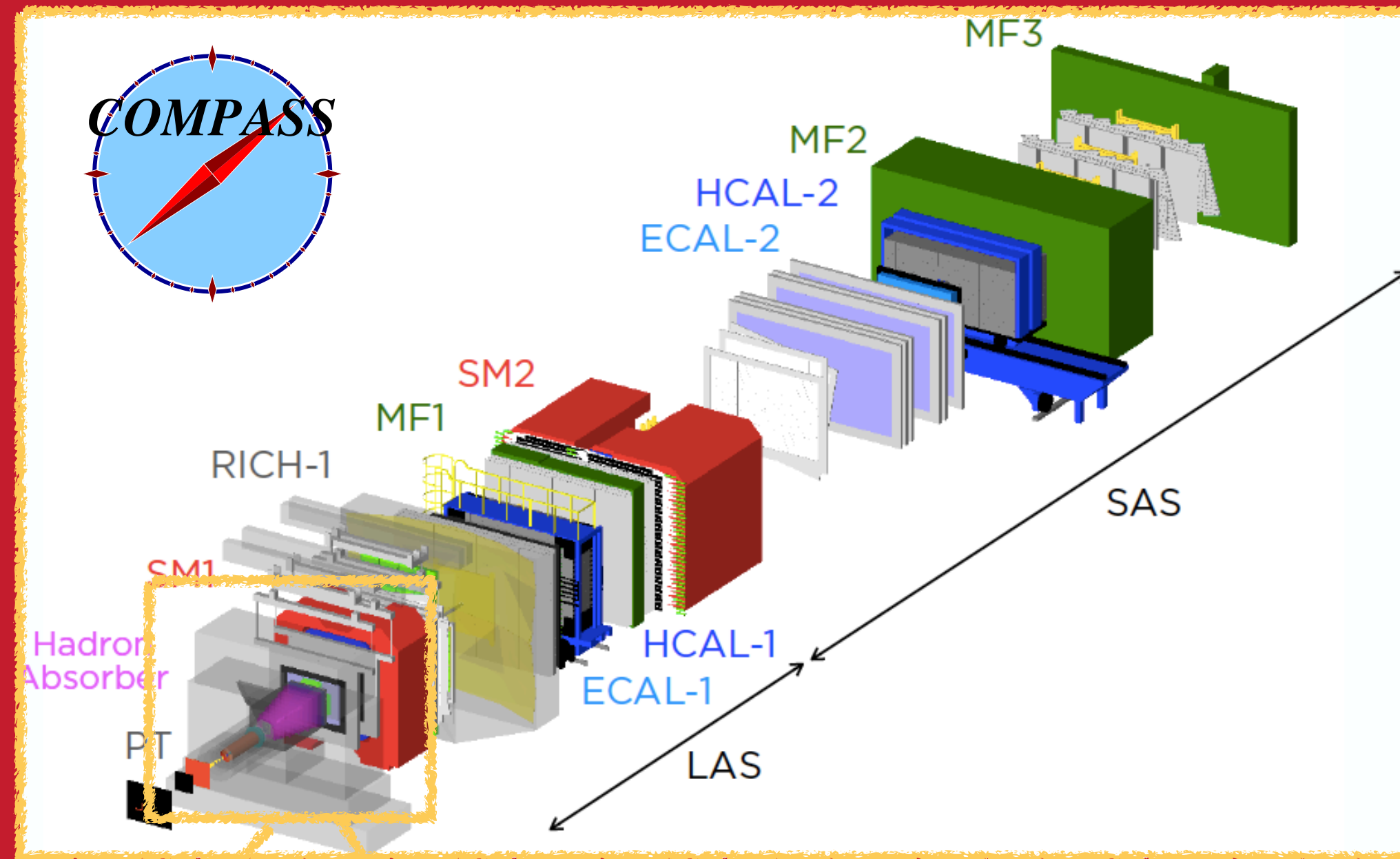
2015 data



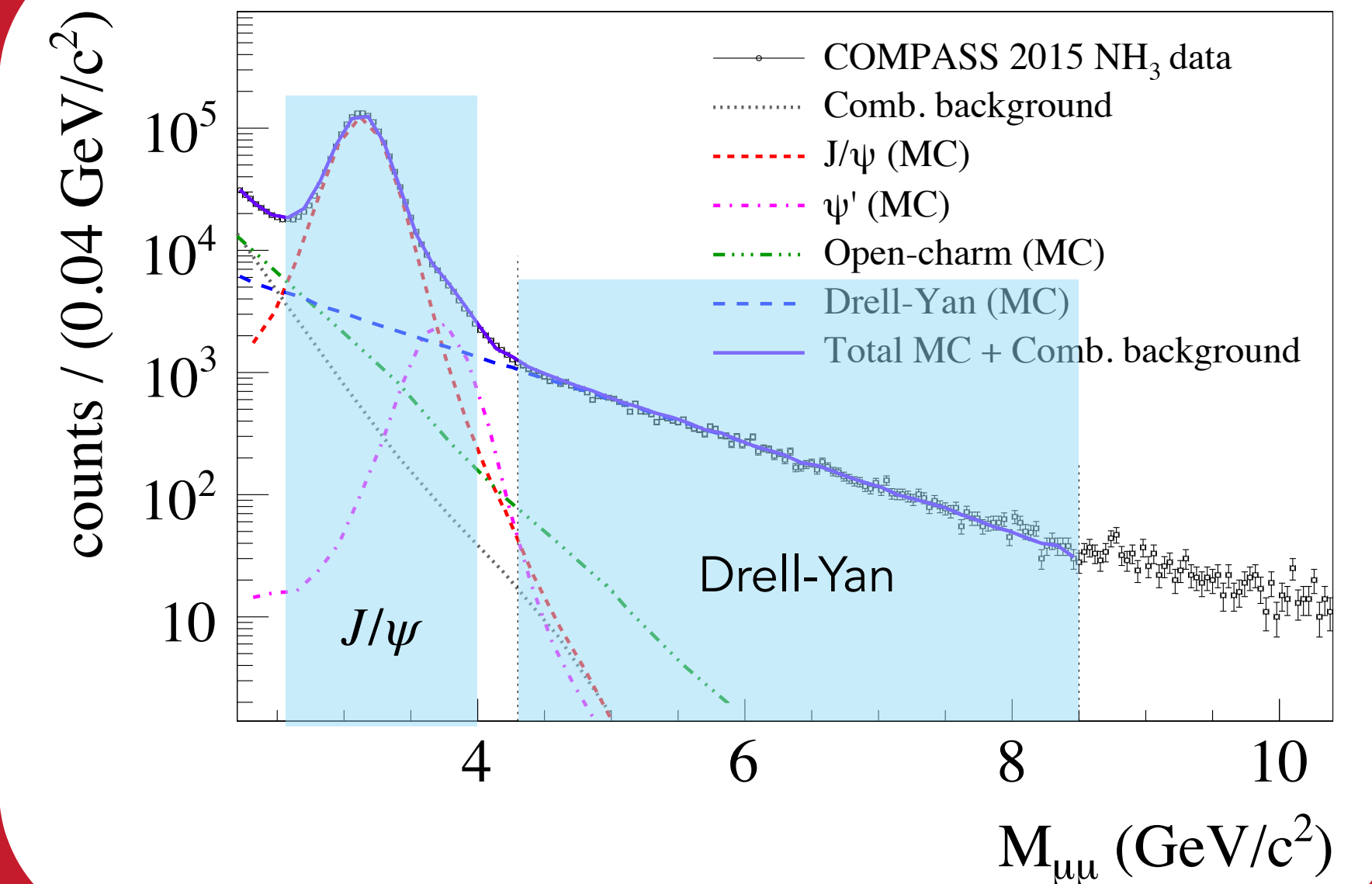
$$\sigma [cm^2] = \frac{\#events}{eff \times \mathcal{L} [cm^{-2}]}$$

COMPASS EXPERIMENT (2002-2022)

Common Muon Proton Apparatus for Structure and Spectroscopy



2015 data



$$\sigma [cm^2] = \frac{\#events}{eff \times \mathcal{L} [cm^{-2}]}$$

webpage for more details

<https://wwwcompass.cern.ch/>

AMBER EXPERIMENT

Apparatus for Meson and Baryon Experimental Research

Approved by the CERN research board in December 2020

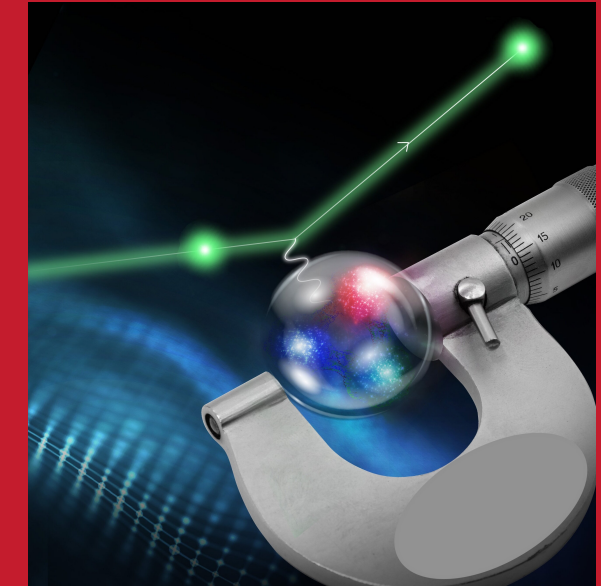
AMBER EXPERIMENT

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to start data taking in 2022

proton-radius measurement
using elastic μ -p scattering



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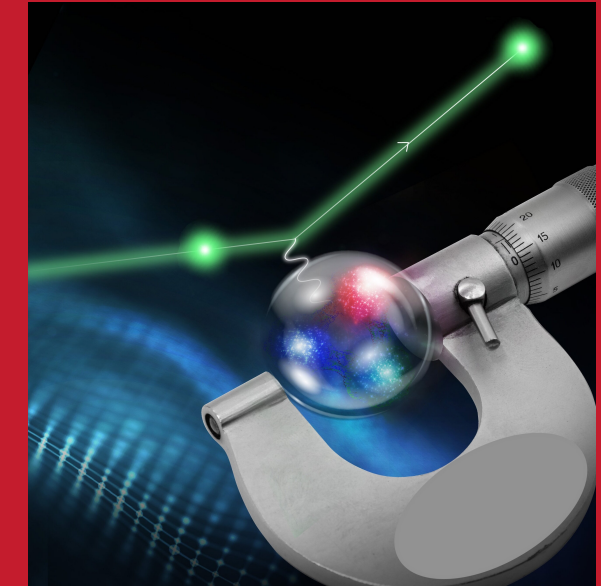
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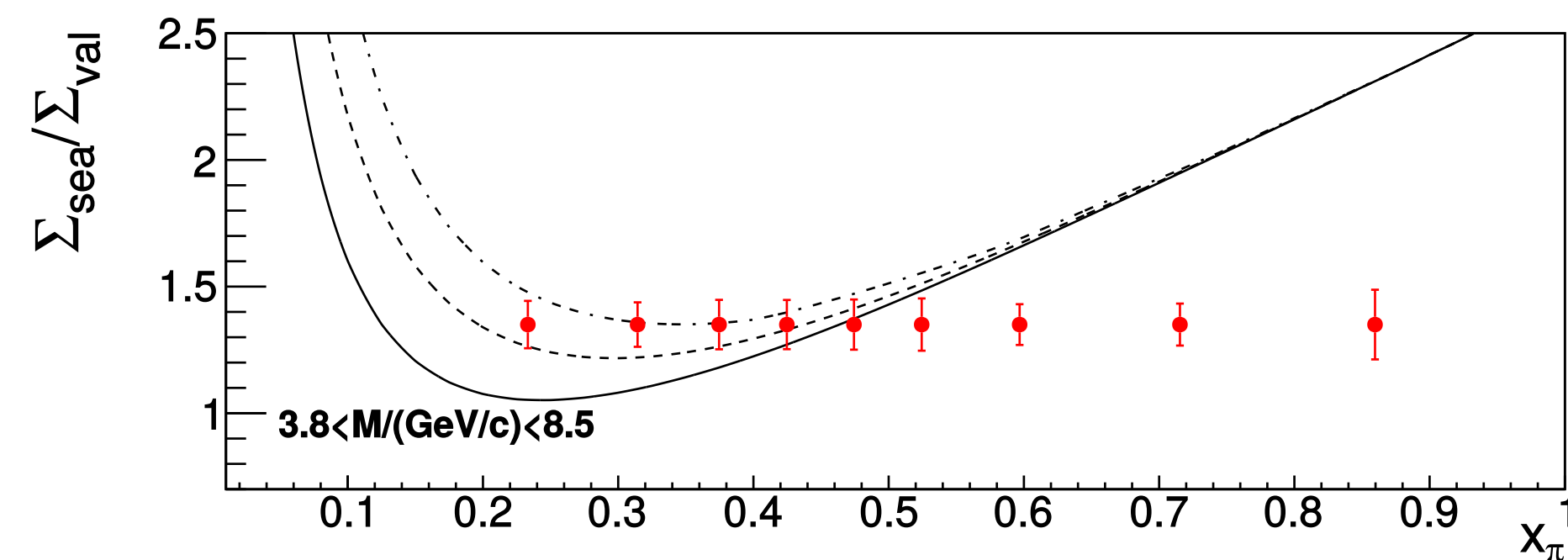
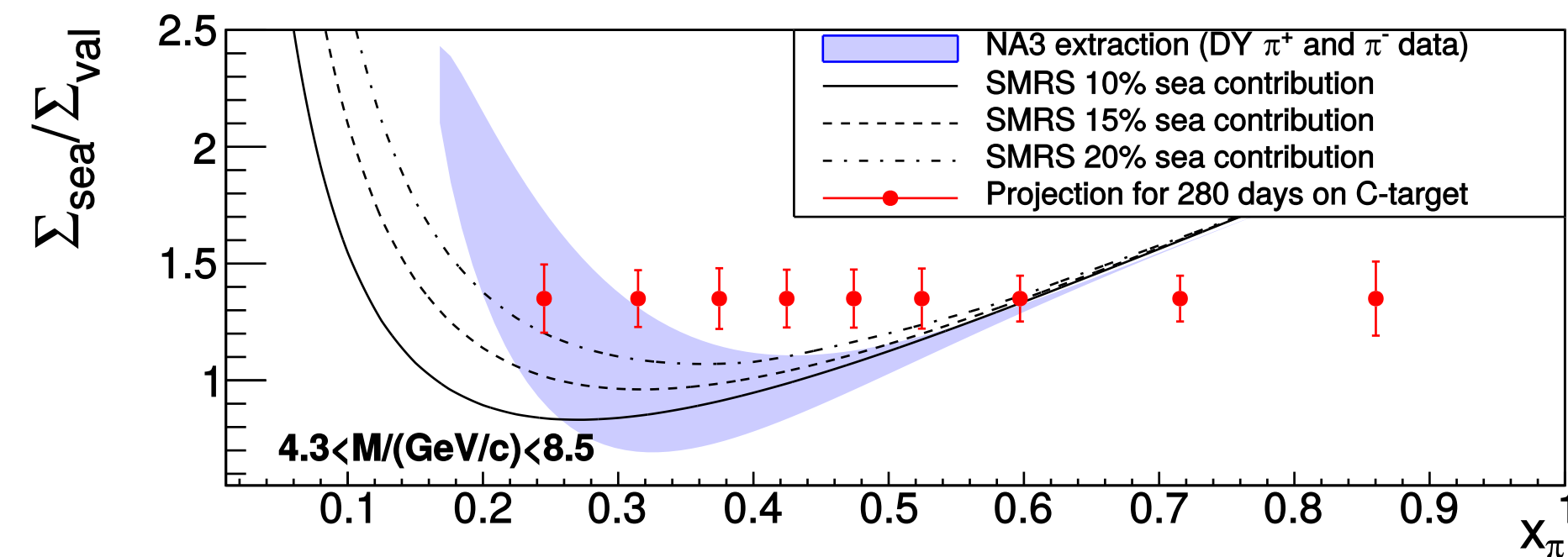
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$$\frac{\Sigma_{sea}}{\Sigma_{valence}} = \frac{4\sigma^{\pi^+C} - \sigma^{\pi^-C}}{-\sigma^{\pi^+C} + \sigma^{\pi^-C}}$$



AMBER EXPERIMENT

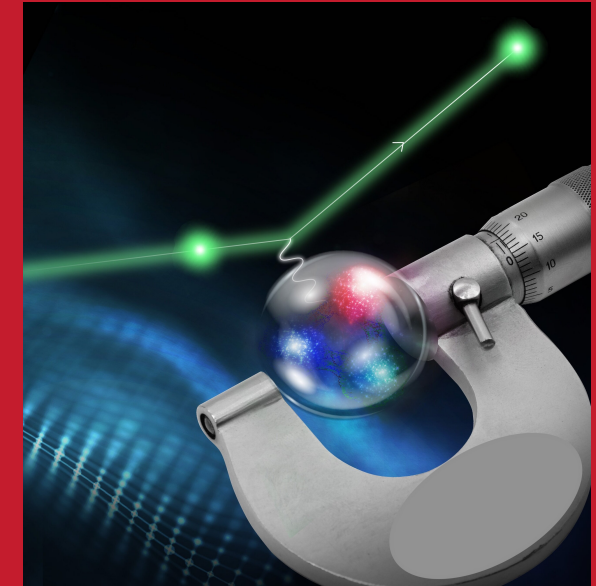
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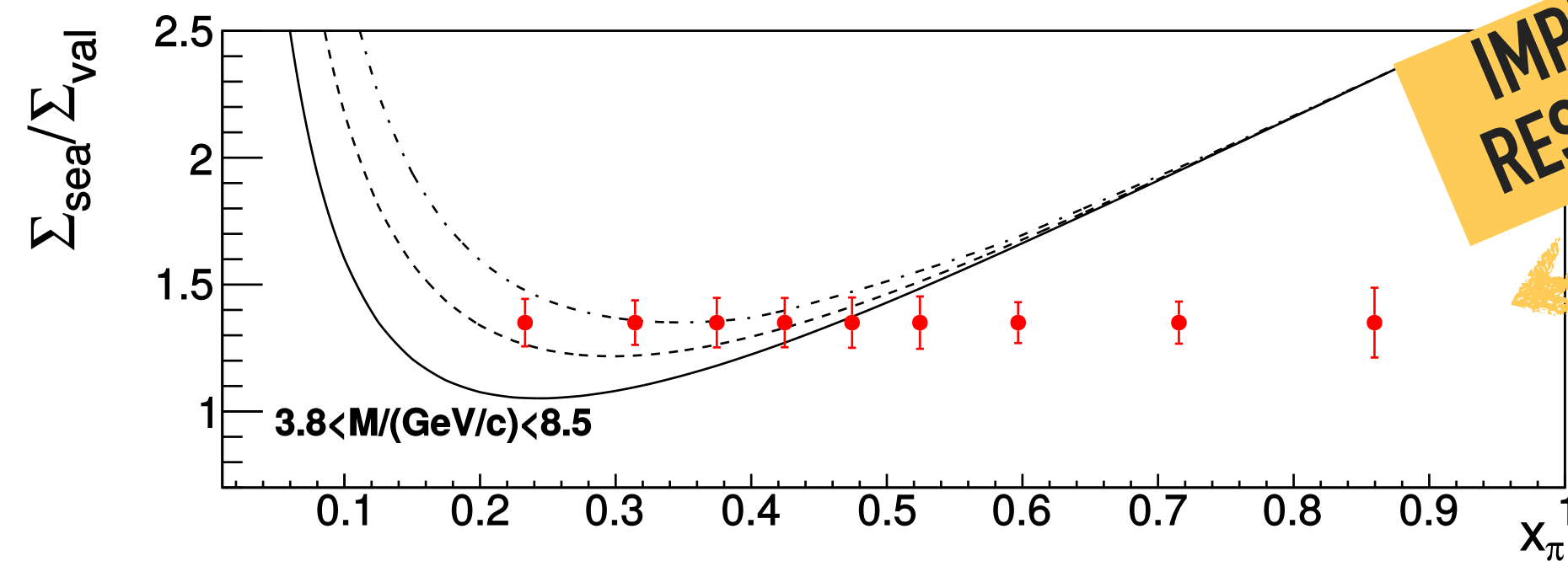
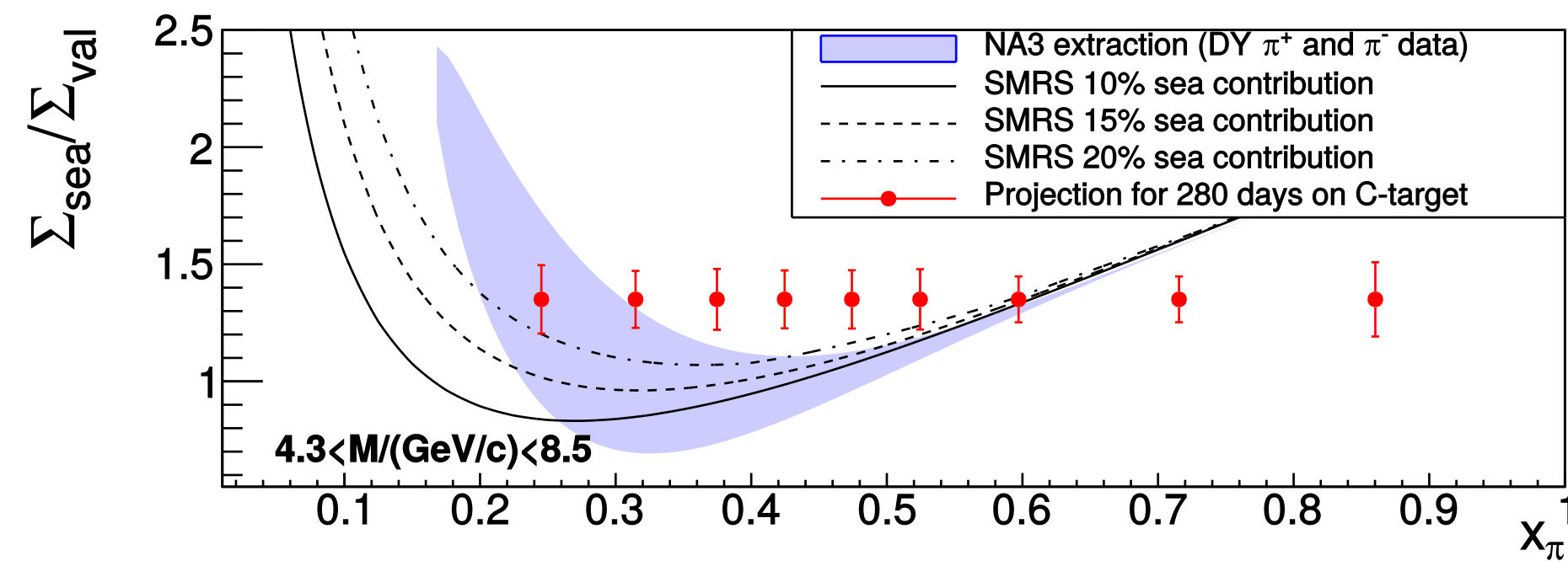
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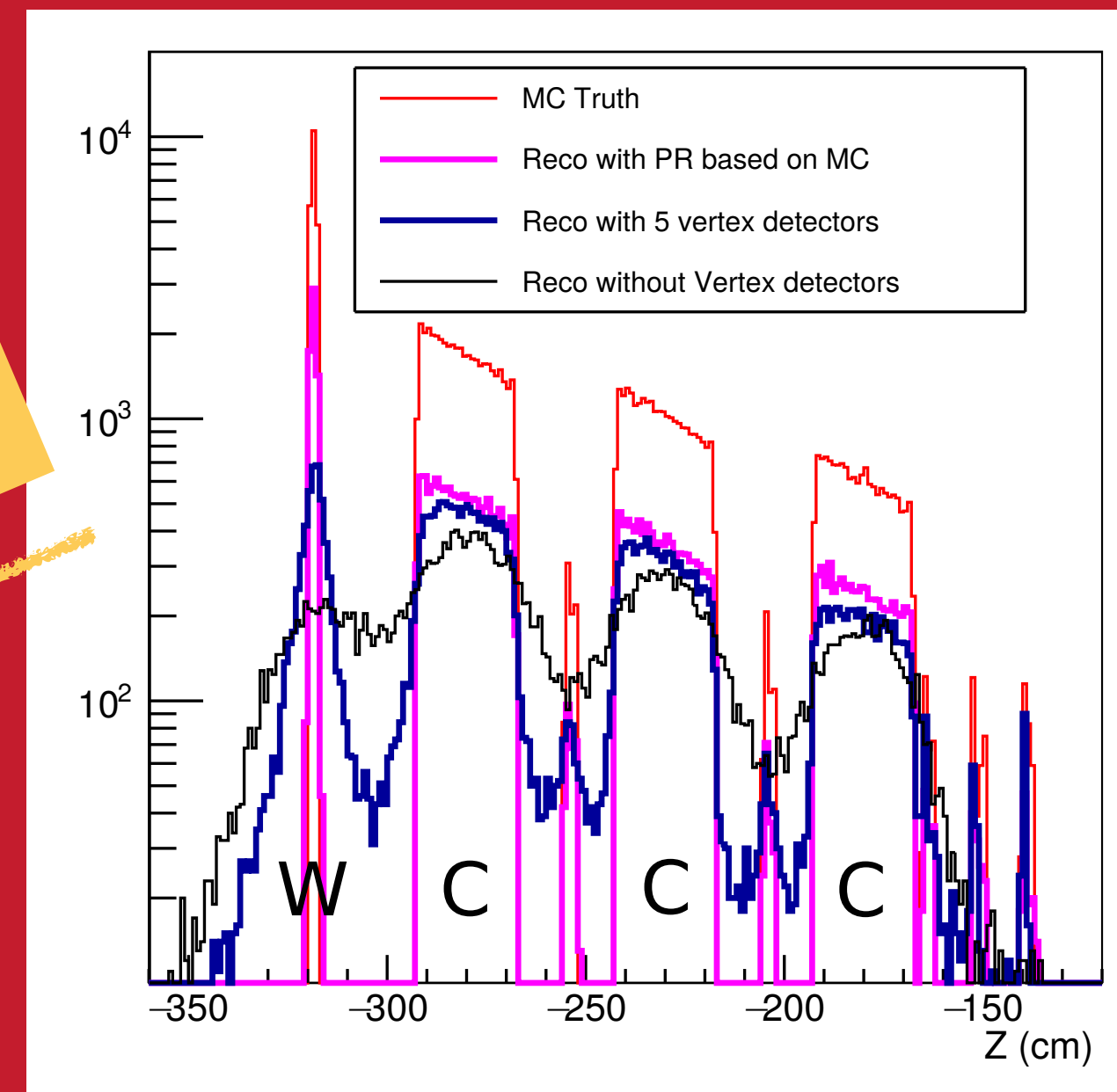
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IMPROVED
RESOLUTION



AMBER EXPERIMENT

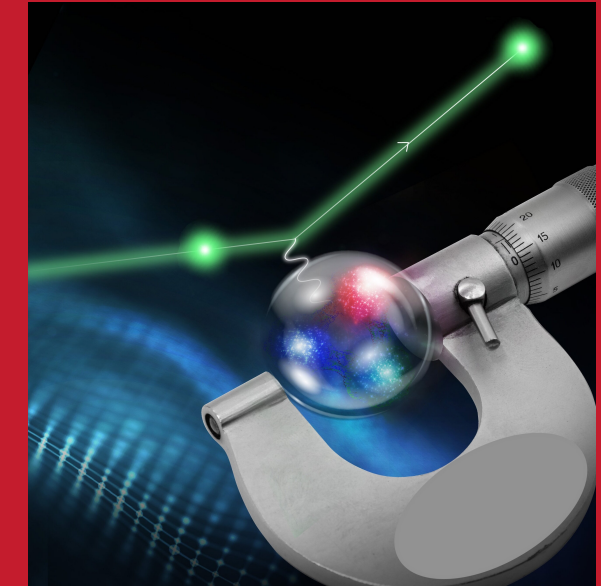
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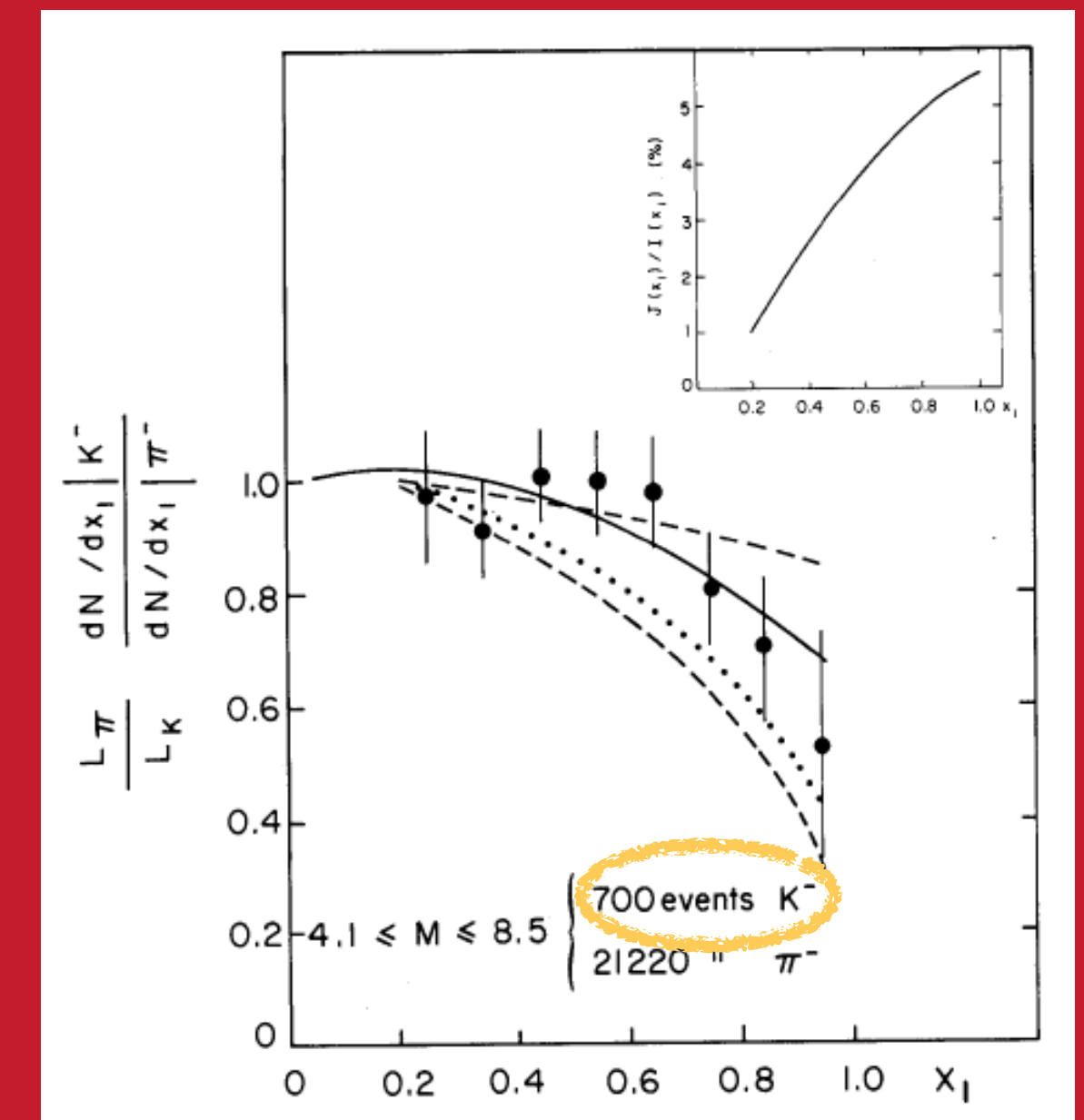
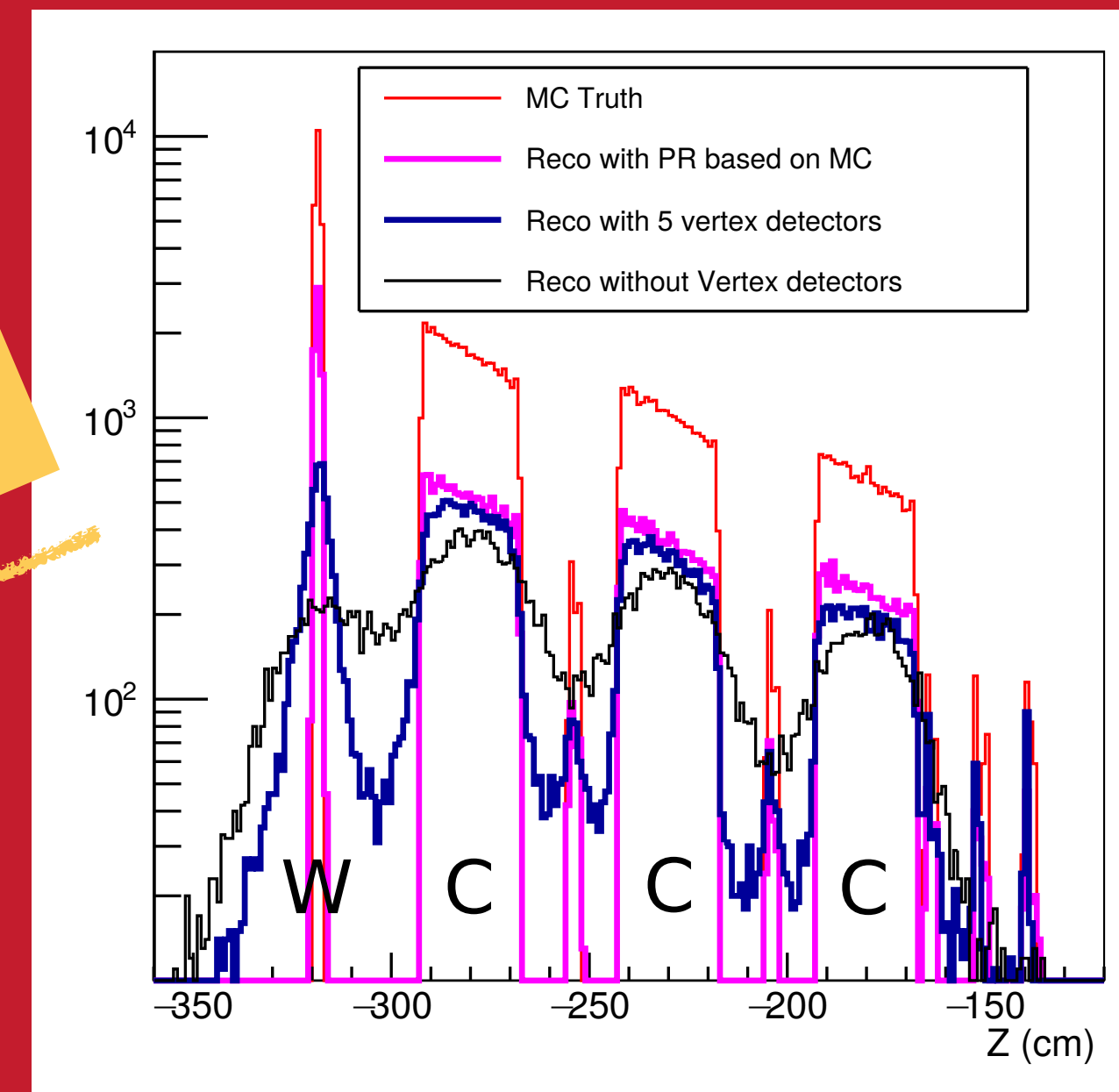
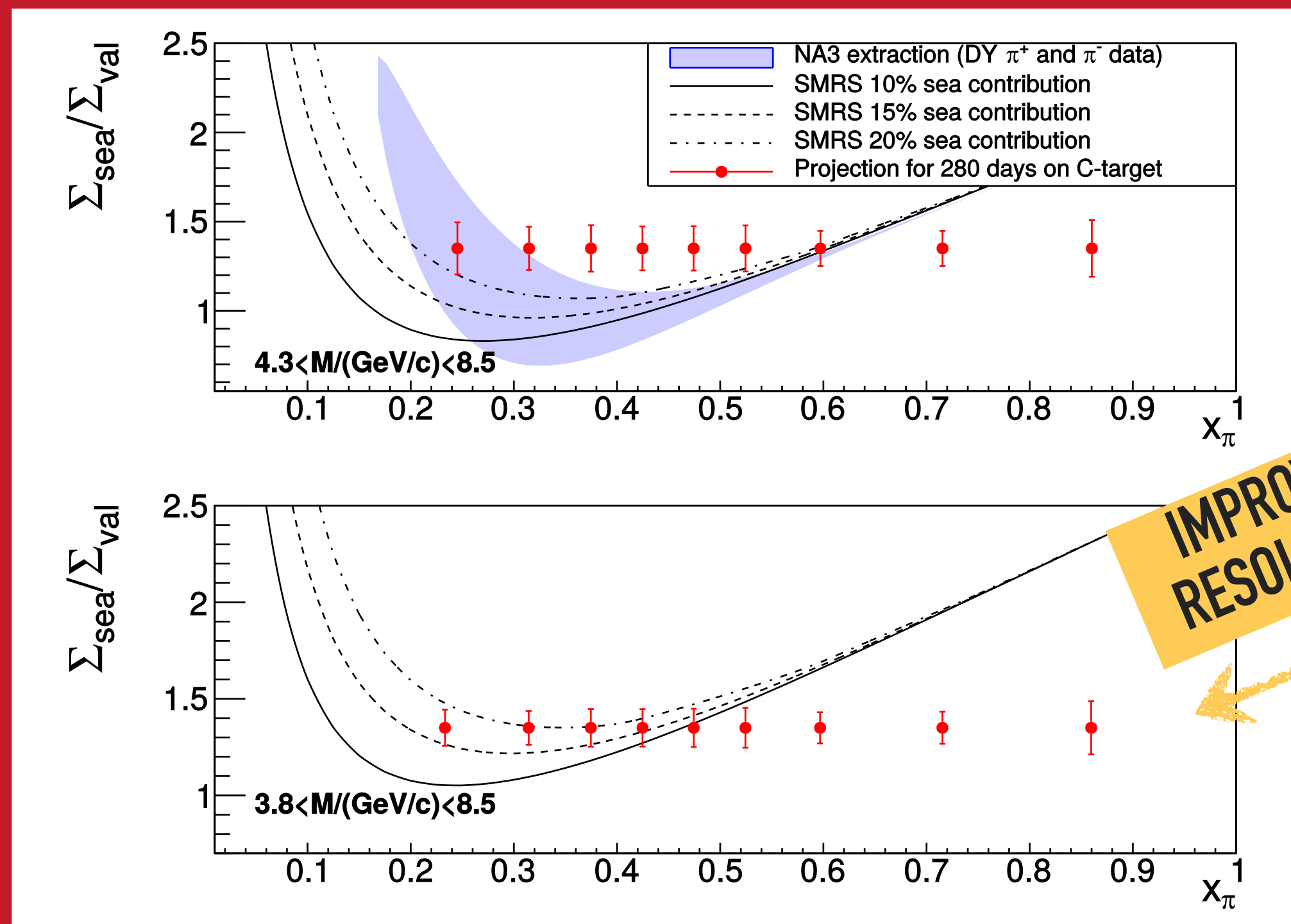
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future: kaon induced Drell-Yan



AMBER EXPERIMENT

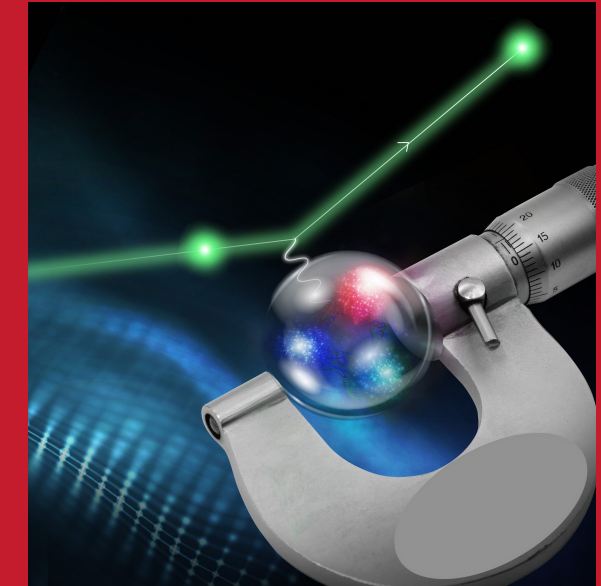
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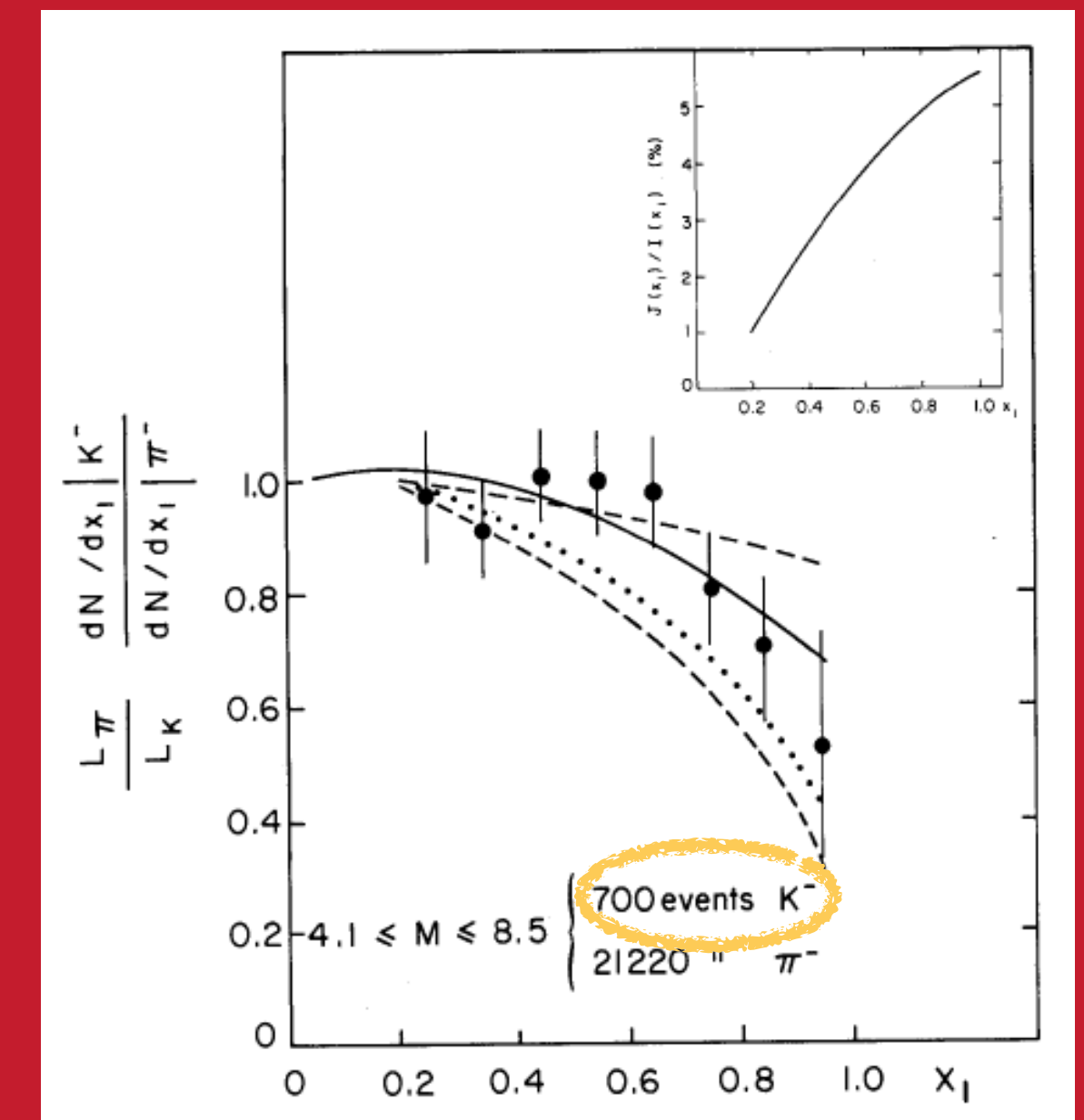
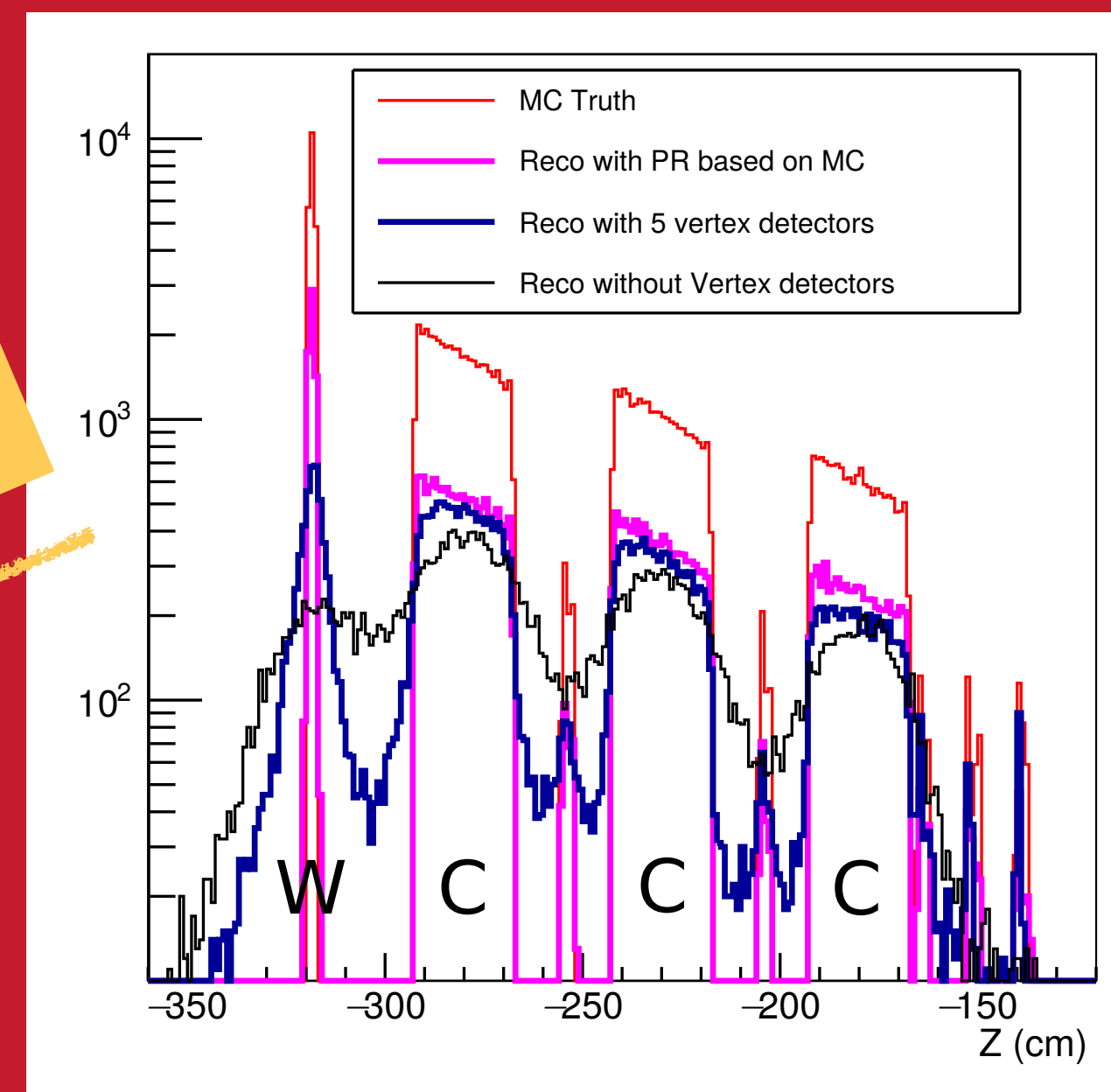
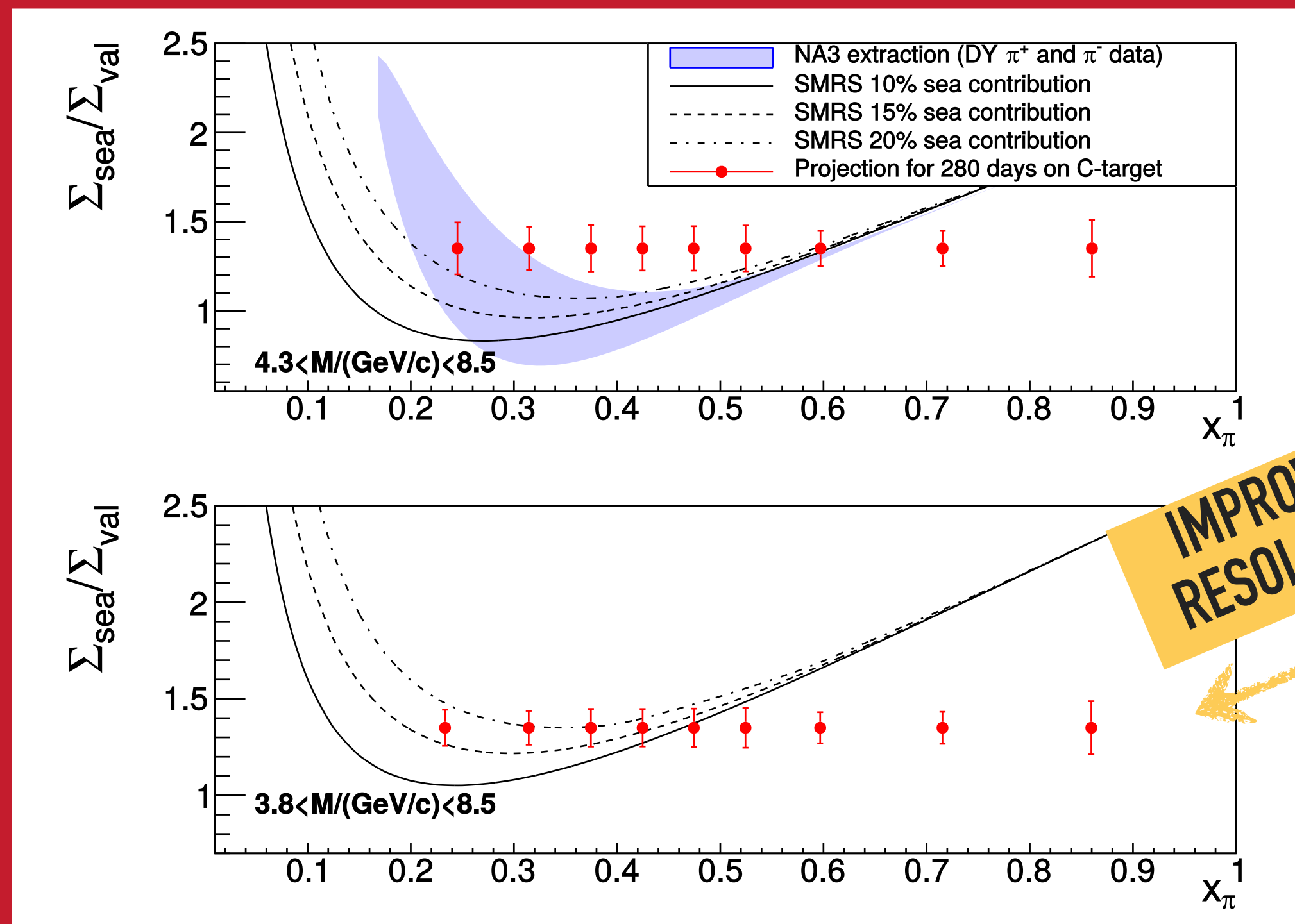
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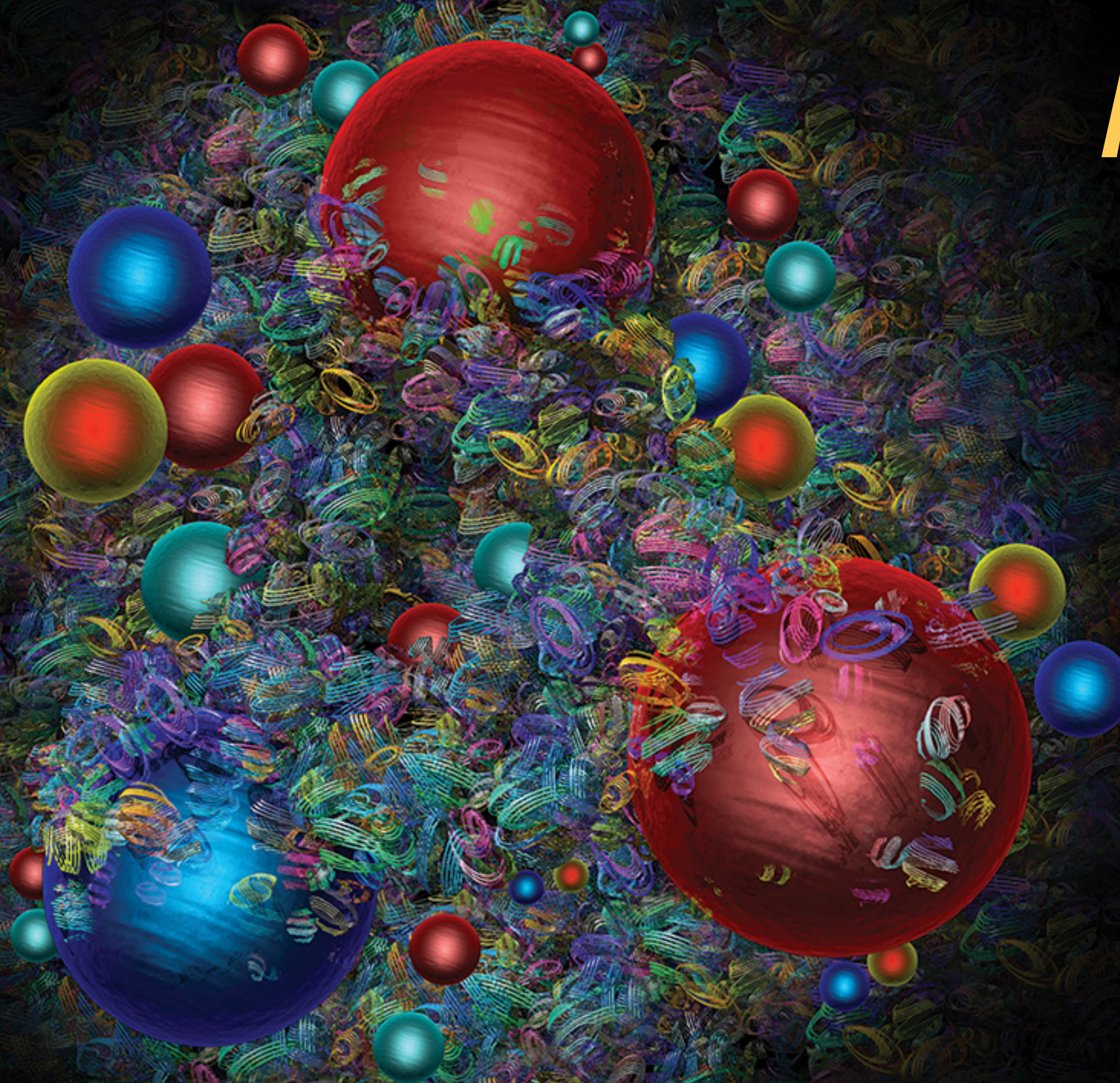
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webpage for more details
<https://nqf-m2.web.cern.ch/>

**QCD IS A GOOD
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THE UNDERSTANDING OF THE HADRONS STRUCTURE HAS JUST BEGUN

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THANK YOU!

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