

Strong Interactions in and beyond the Standard model

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22nd of November 2010
Slovak Academy of Sciences
Slovakia

FWF

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From gluons to technigluons

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**UNI
GRAZ**

Overview

Supported by 

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- The standard model

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- Strong interactions

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 - Methods to deal with strong interactions

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 - The obvious: QCD

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 - The obvious: QCD
 - The non-obvious: Higgs

Supported by **FWF**

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- The standard model
- Strong interactions
 - Methods to deal with strong interactions
 - The obvious: QCD
 - The non-obvious: Higgs
- Beyond the standard model

Supported by **FWF**

Overview

- The standard model
- Strong interactions
 - Methods to deal with strong interactions
 - The obvious: QCD
 - The non-obvious: Higgs
- Beyond the standard model
 - If, why, why now, and how
 - Technicolor, a strongly interacting Higgs alternative

Supported by 

The Standard Model

Particles

- The standard model (until now) describes the physics accessible in accelerator-based experiments

Particles

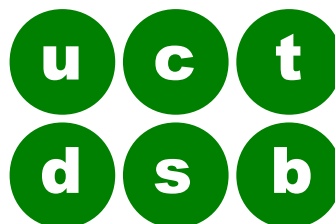
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- Contains two kinds of particles

Particles

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 - Matter

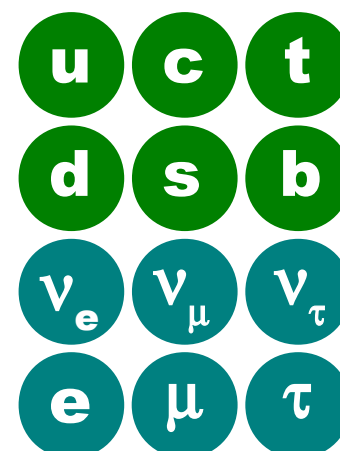
Particles

- The standard model (until now) describes the physics accessible in accelerator-based experiments
- Contains two kinds of particles
 - Matter: Quarks



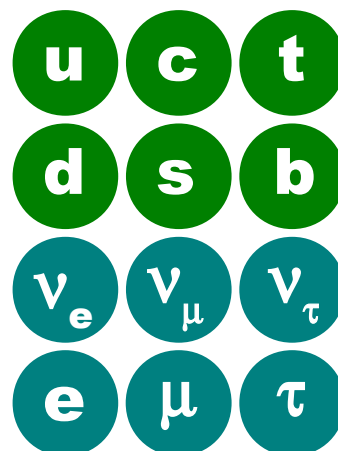
Particles

- The standard model (until now) describes the physics accessible in accelerator-based experiments
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 - Matter: Quarks, leptons



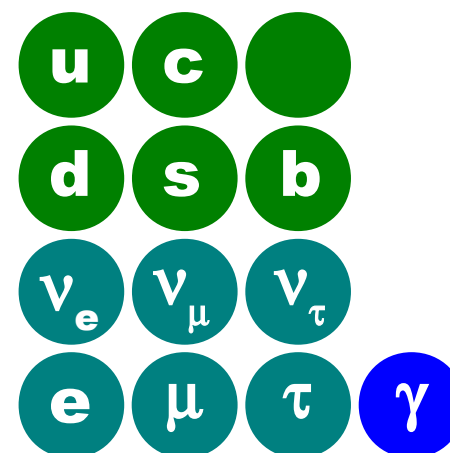
Particles

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 - Matter: Quarks, leptons
 - Force particles



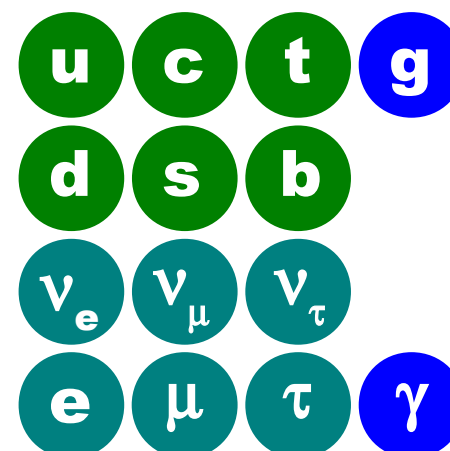
Particles

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 - Force particles: Photon



Particles

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 - Force particles: Photon, gluon



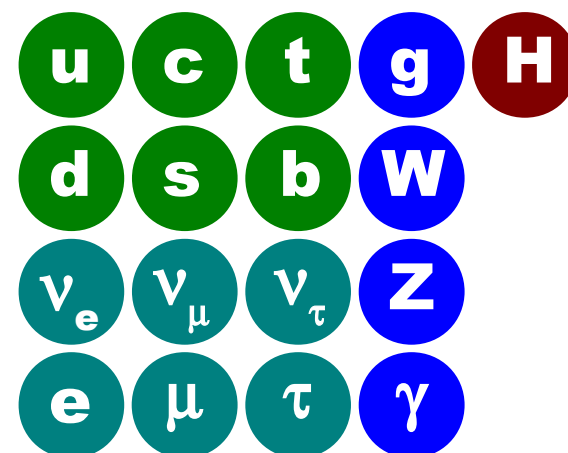
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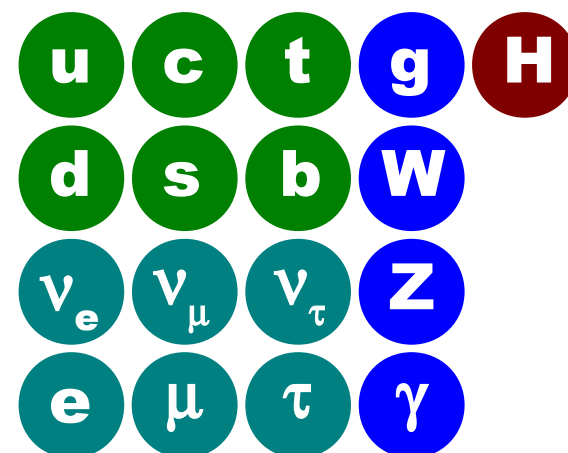
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 - Force particles: Photon, gluon, W- and Z-boson
 - The Higgs



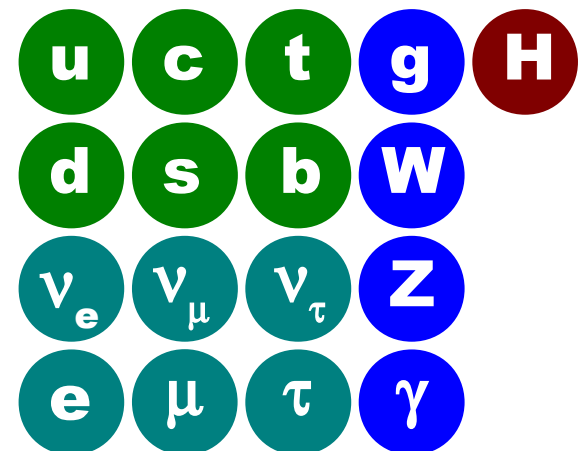
Particles

- The standard model (until now) describes the physics accessible in accelerator-based experiments
- Contains two kinds of particles
 - Matter: Quarks, leptons
 - Force particles: Photon, gluon, W- and Z-boson
 - The Higgs is a bit of both, but more like matter
 - Only not yet observed particle



The properties of the particles

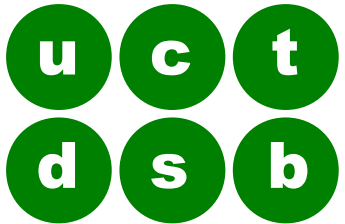
- The properties of the particles are rather different



The properties of the particles

- The properties of the particles are rather different

Quarks: Fermions



Masses:

Up: 2-3 MeV

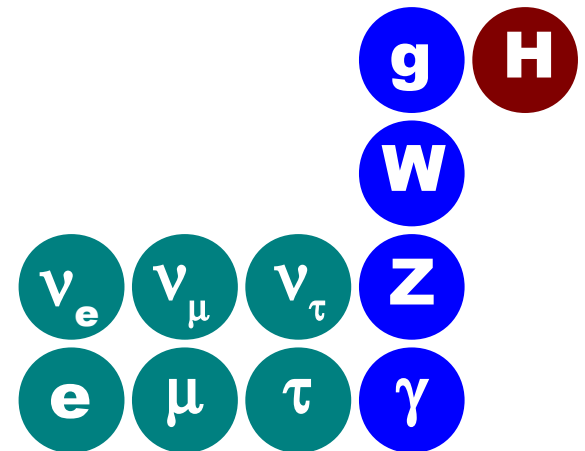
Down: 4-6 MeV

Strange: 80-130 MeV

Charm: 1270(10) MeV

Bottom: 4190(200) MeV

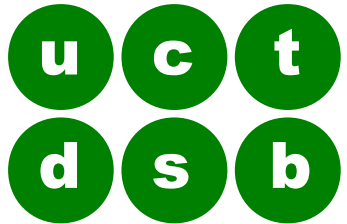
Top: 172000(1500) MeV



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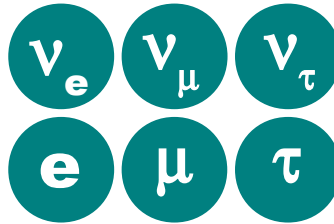
Strange: 80-130 MeV

Charm: 1270(10) MeV

Bottom: 4190(200) MeV

Top: 172000(1500) MeV

Leptons: Fermions



Masses:

Electron: 0.5 MeV

Muon: 106 MeV

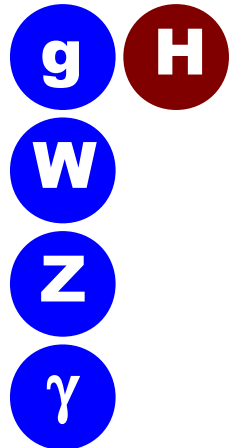
Tauon: 1777 MeV

Neutrinos:

Masses < 0.3 eV

Mass hierarchy unknown

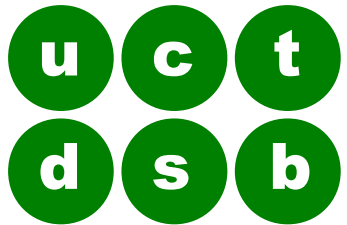
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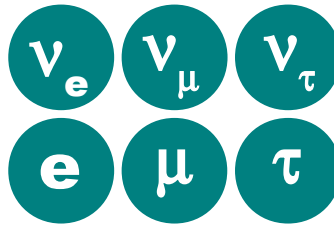
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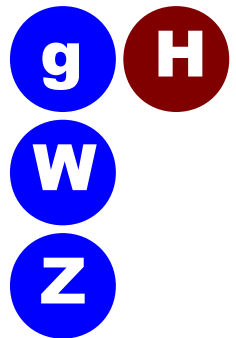
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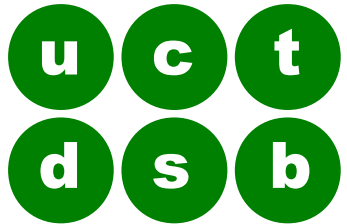


 Photon: Massless boson

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Quarks: Fermions



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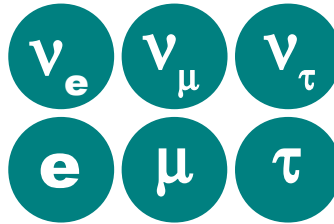
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Electron: 0.5 MeV

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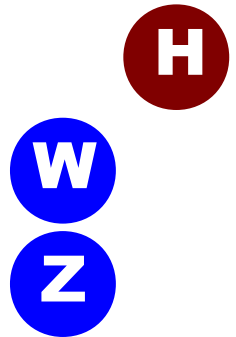
Tauon: 1777 MeV

Neutrinos:

Masses < 0.3 eV

Mass hierarchy unknown

Masses are different

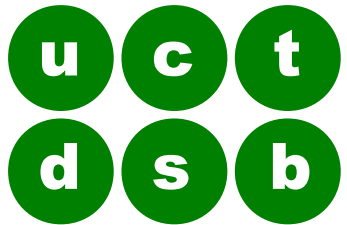


 Photon: Massless boson  Gluon: Massless boson

The properties of the particles

- The properties of the particles are rather different

Quarks: Fermions



Masses:

Up: 2-3 MeV

Down: 4-6 MeV

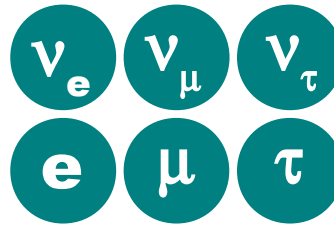
Strange: 80-130 MeV

Charm: 1270(10) MeV

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Masses:

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Tauon: 1777 MeV

Neutrinos:

Masses < 0.3 eV

Mass hierarchy unknown

Masses are different



W: 80339(23) MeV

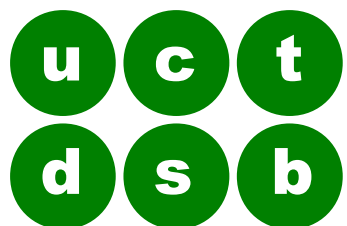
Z: 91188(2) MeV

 Photon: Massless boson  Gluon: Massless boson

The properties of the particles

- The properties of the particles are rather different

Quarks: Fermions



Masses:

Up: 2-3 MeV

Down: 4-6 MeV

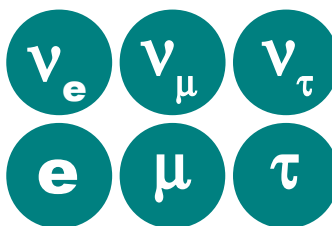
Strange: 80-130 MeV

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Bottom: 4190(200) MeV

Top: 172000(1500) MeV

Leptons: Fermions



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Tauon: 1777 MeV

Neutrinos:

Masses < 0.3 eV

Mass hierarchy unknown

Masses are different

Higgs: Boson



Mass: >115000 MeV

Weak gauge bosons

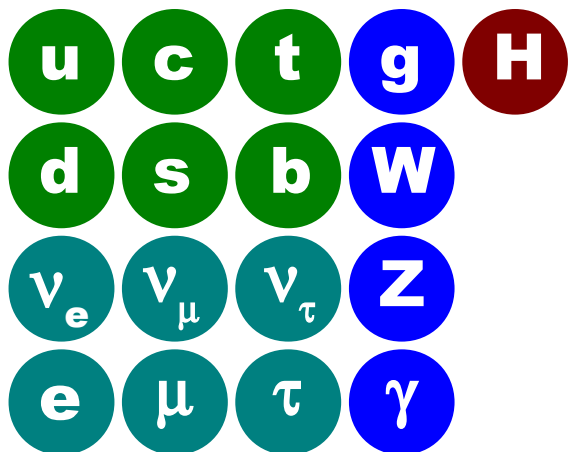


W: 80339(23) MeV

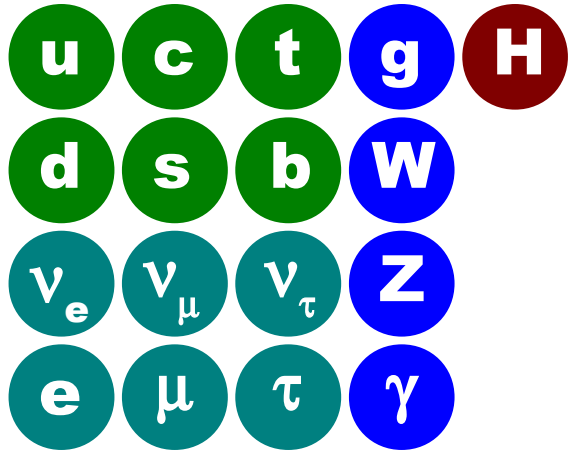
Z: 91188(2) MeV

 Photon: Massless boson  Gluon: Massless boson

Returning up

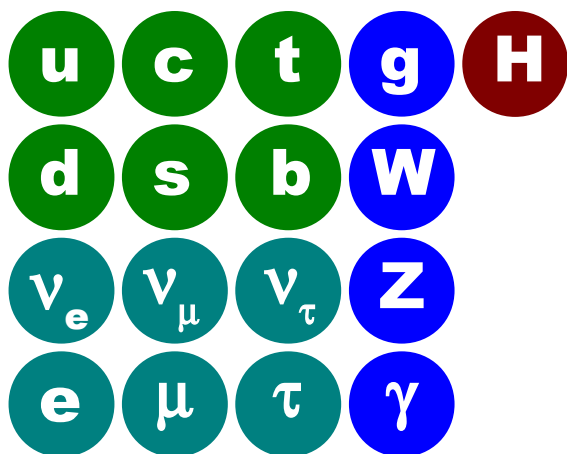


Returning up



- (Most) Elementary particles not observed directly

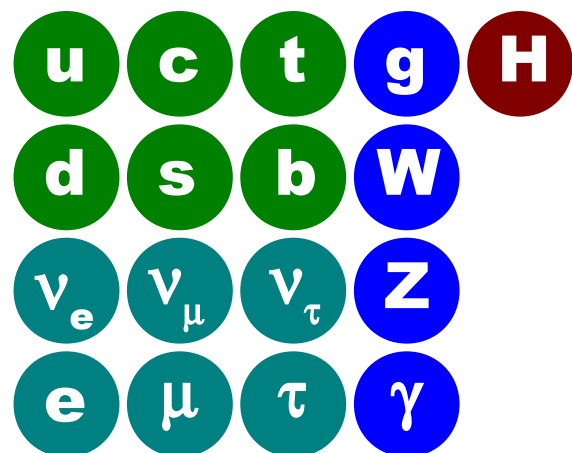
Returning up



- (Most) Elementary particles not observed directly
- Requires high resolution
 - Large energies
 - Sensitive probes

Returning up

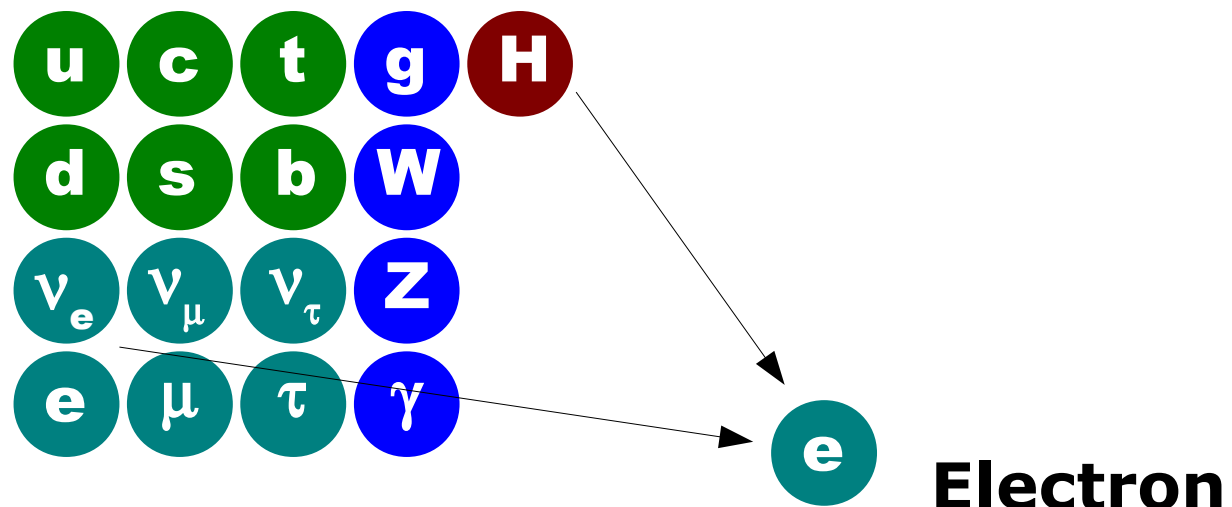
Distance 



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Returning up

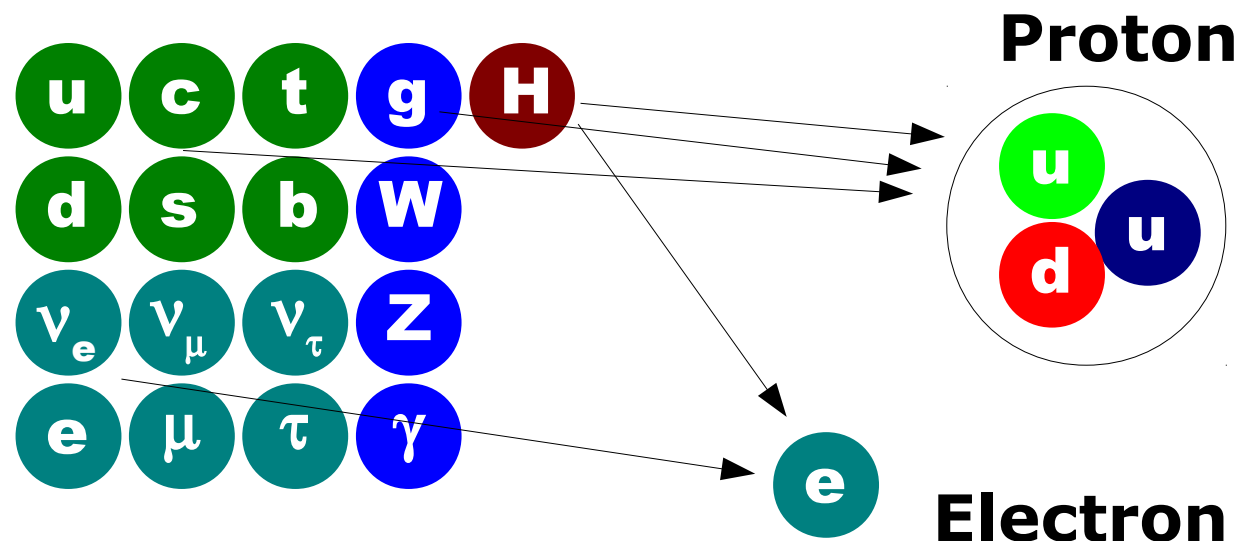
Distance 



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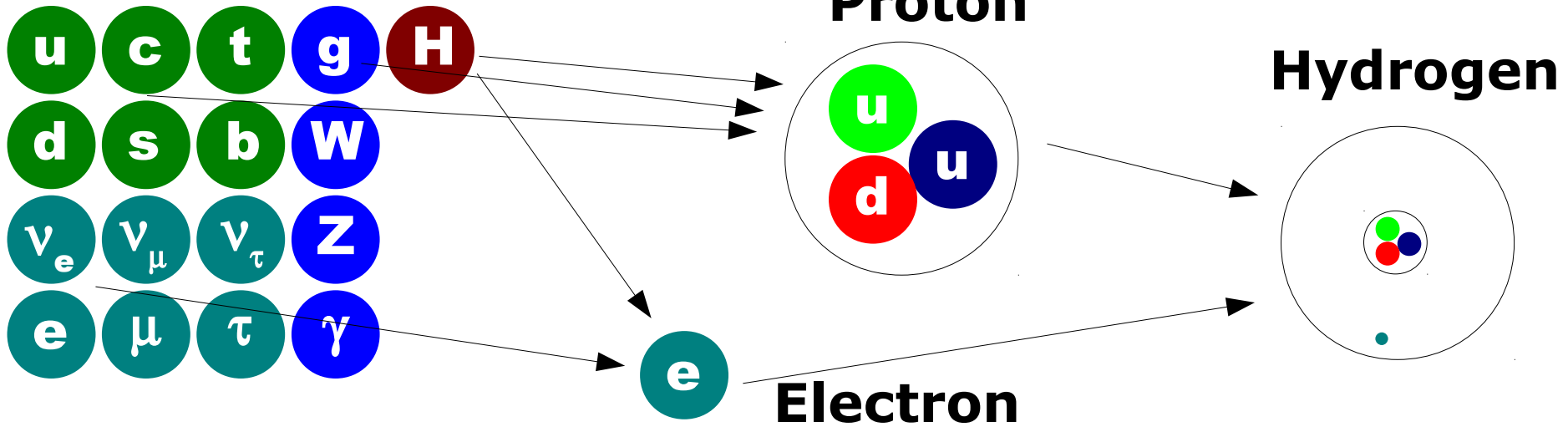
Distance \longrightarrow



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Returning up

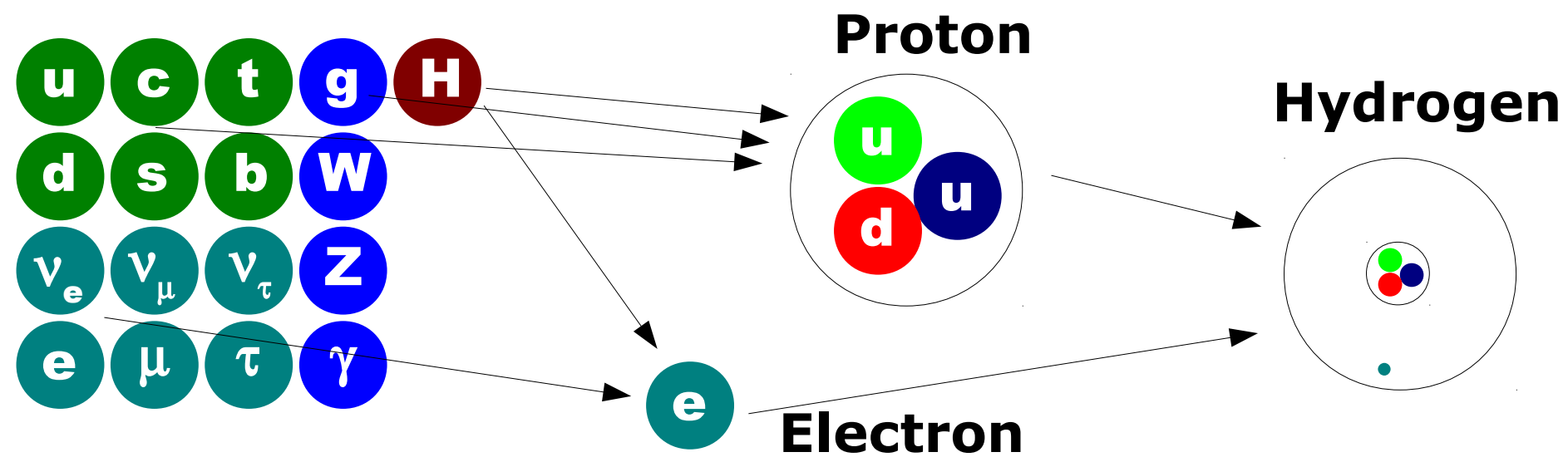
Distance 



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Returning up

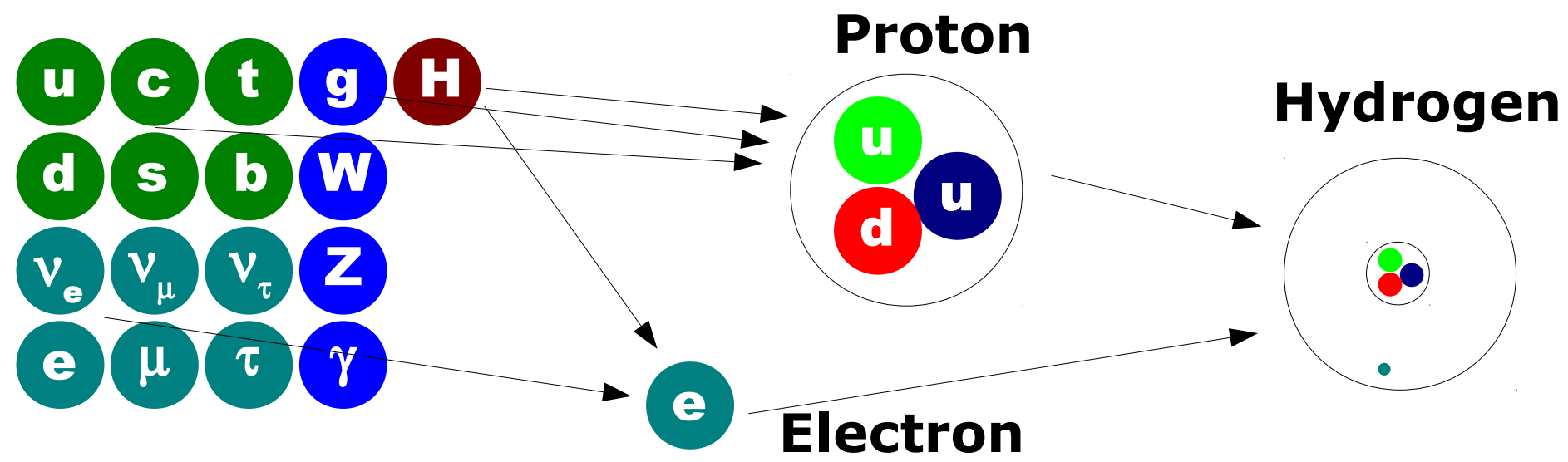
Distance ▶ Bound states



- (Most) Elementary particles not observed directly
- Requires high resolution
 - Large energies
 - Sensitive probes

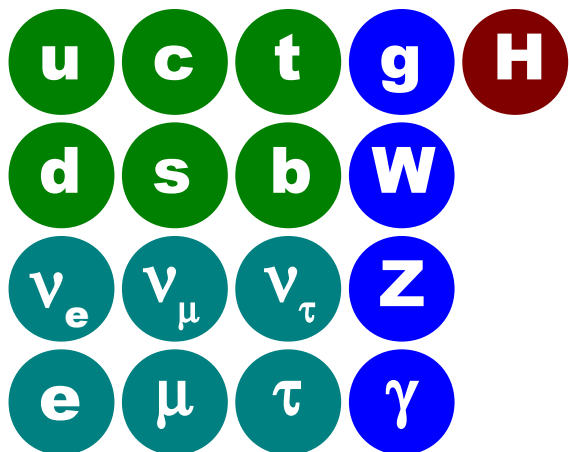
Returning up

Distance → Bound states



- (Most) Elementary particles not observed directly
- Requires high resolution
 - Large energies
 - Sensitive probes
- Hierachy of effective degrees of freedom

Sectors



Sectors



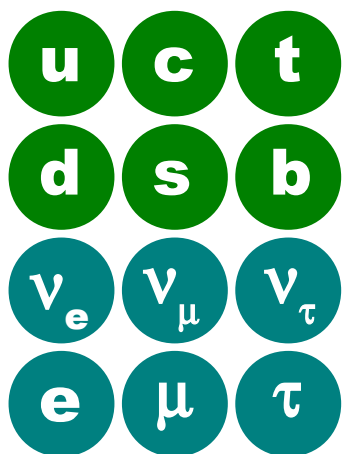
- The force particles mediate the forces between the matter particles

Sectors



- The force particles mediate the forces between the matter particles
- Each force particle can be associated with a particular force or sector of the standard model

Sectors

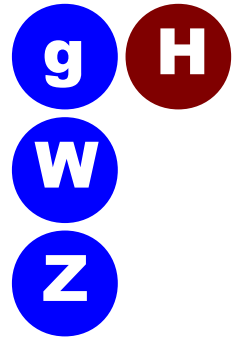
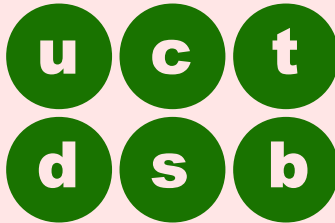


- Particles can be grouped according to the forces

Sectors

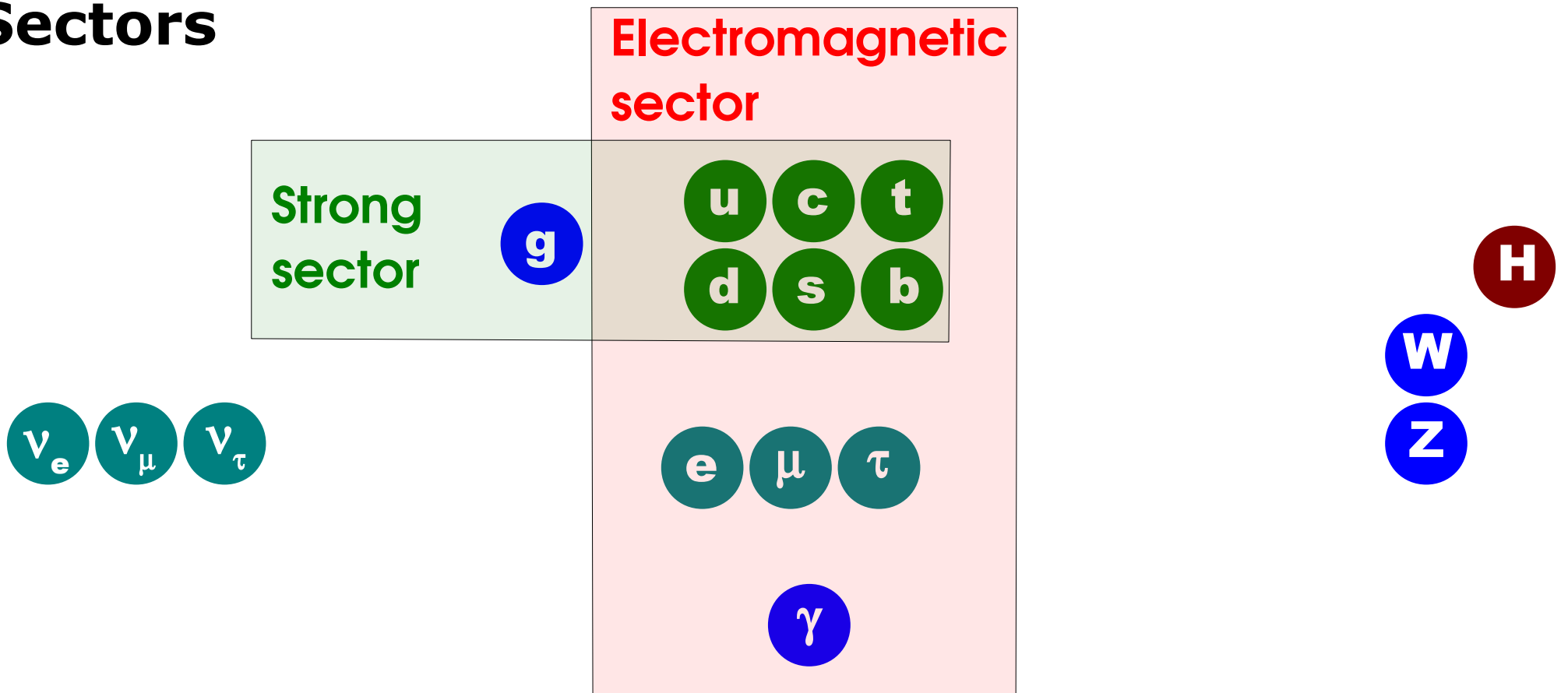


Electromagnetic sector



- Particles can be grouped according to the forces
 - Electromagnetic sector

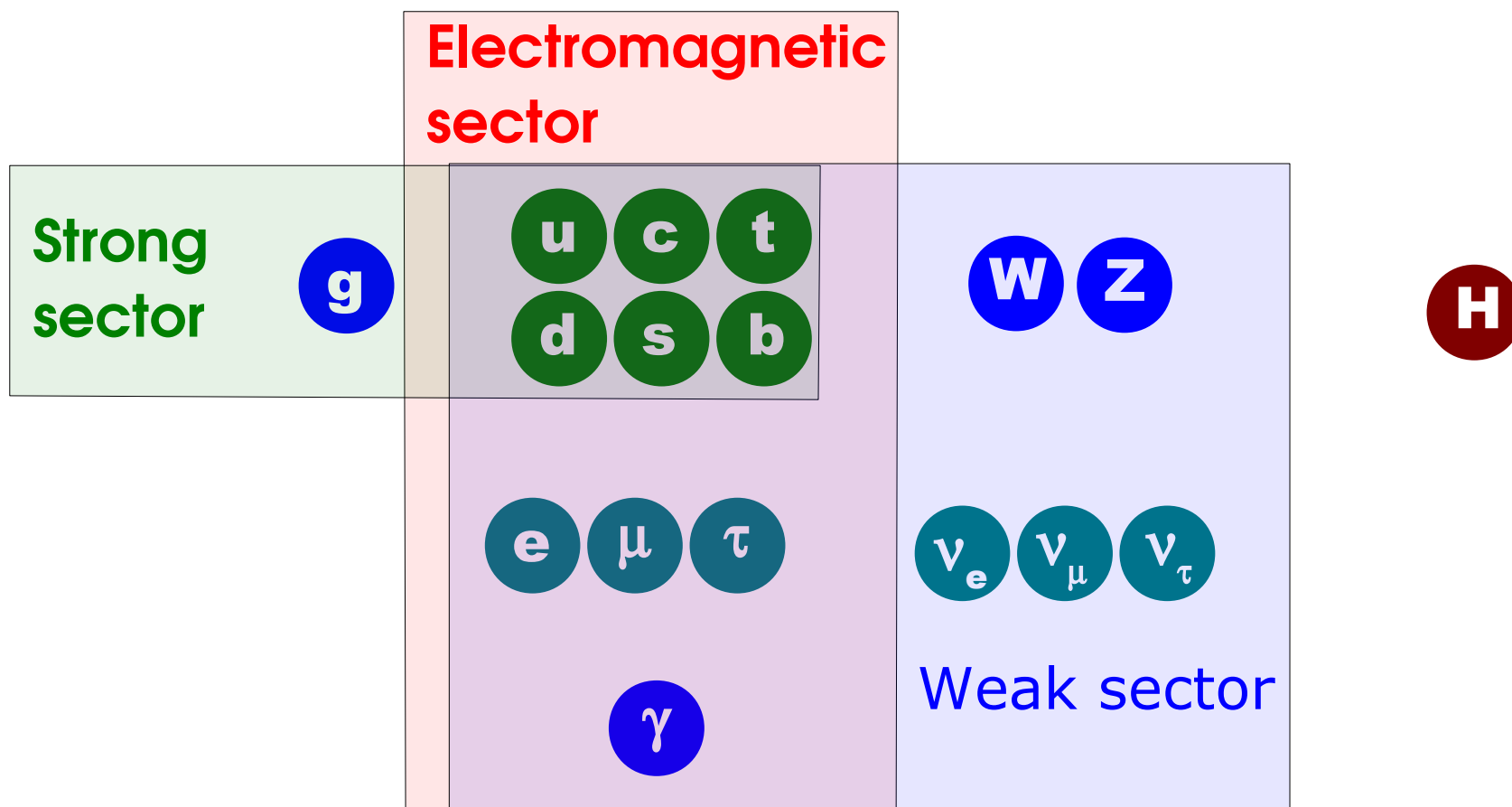
Sectors



- Particles can be grouped according to the forces
 - Electromagnetic sector
 - The strong sector

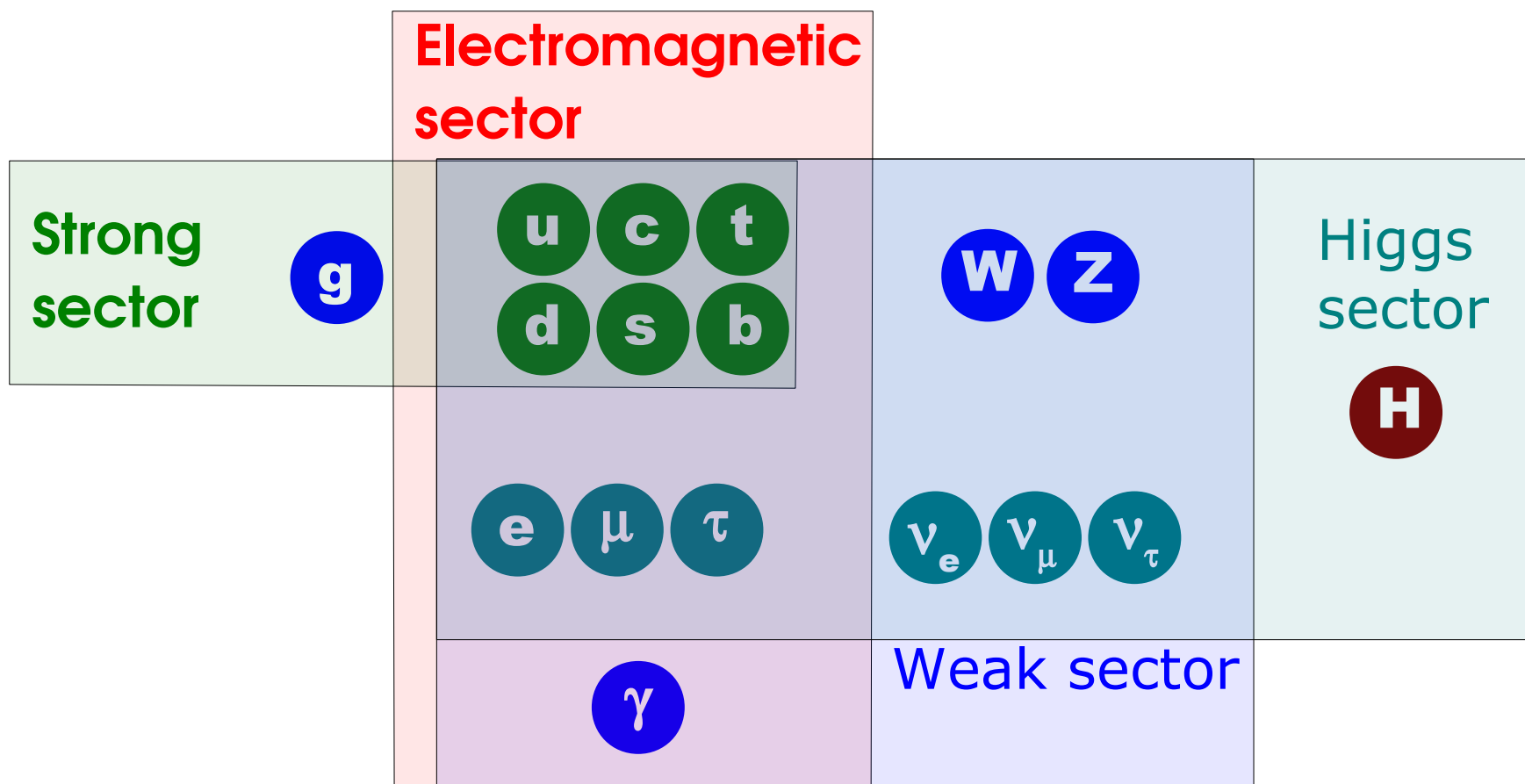


Sectors



- Particles can be grouped according to the forces
 - Electromagnetic sector
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Sectors

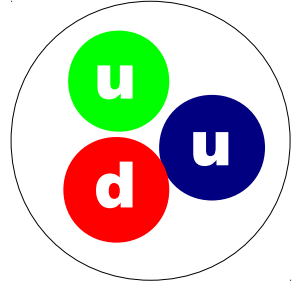


- Particles can be grouped according to the forces
 - Electromagnetic sector
 - The strong sector
 - The weak sector
 - The Higgs sector

Strong interactions in the standard model

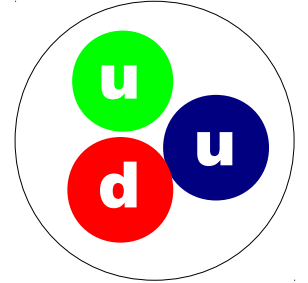
Strong interactions in the standard model

- Bound states – hadrons, nucleons, and nuclei



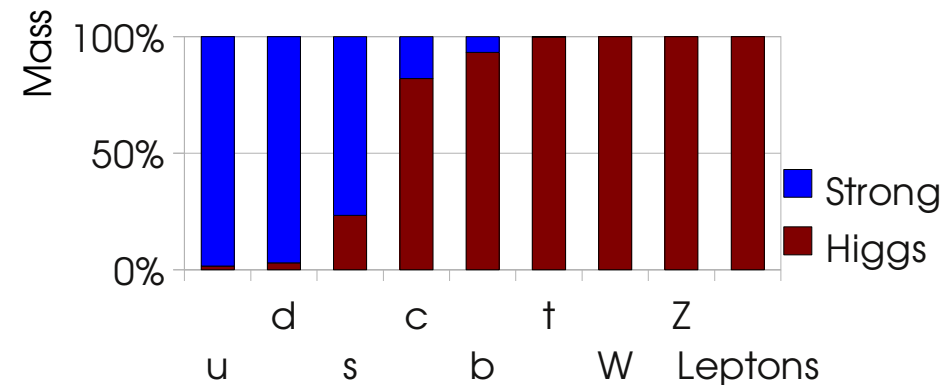
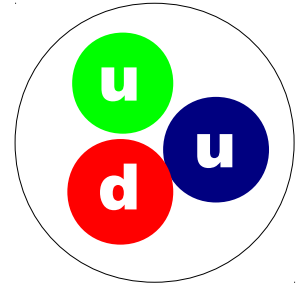
Strong interactions in the standard model

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- Confinement
 - There are no free quarks and gluons



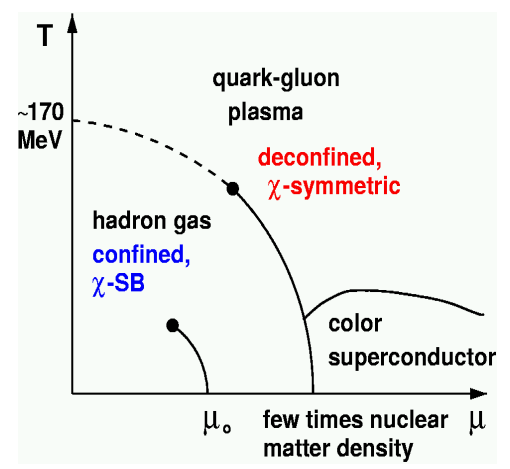
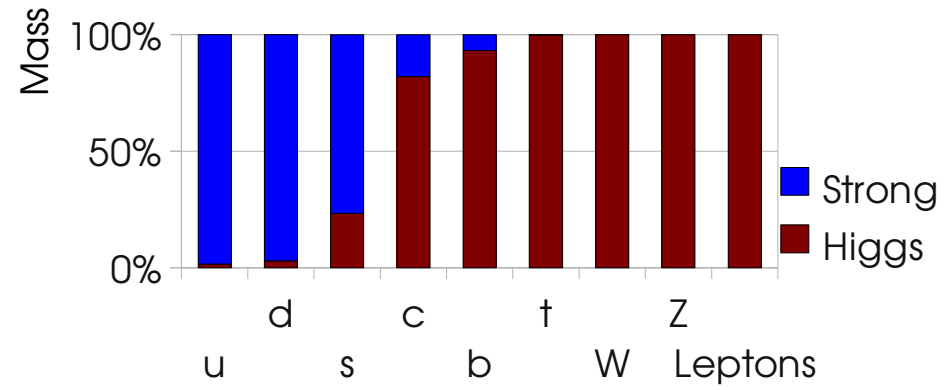
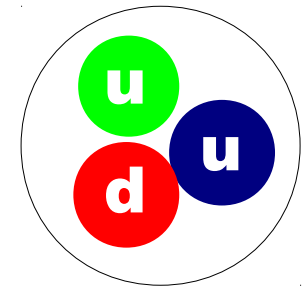
Strong interactions in the standard model

- Bound states – hadrons, nucleons, and nuclei
- Confinement
 - There are no free quarks and gluons
- Dynamical mass generation
 - Chiral symmetry breaking
 - Formation of the Higgs condensate



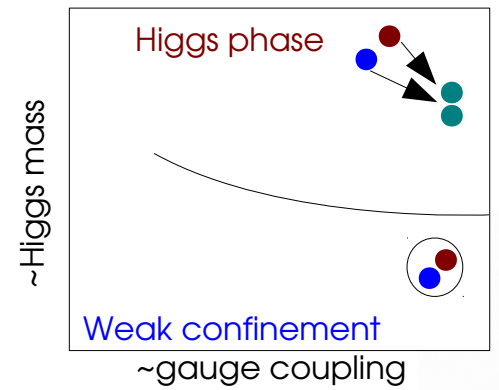
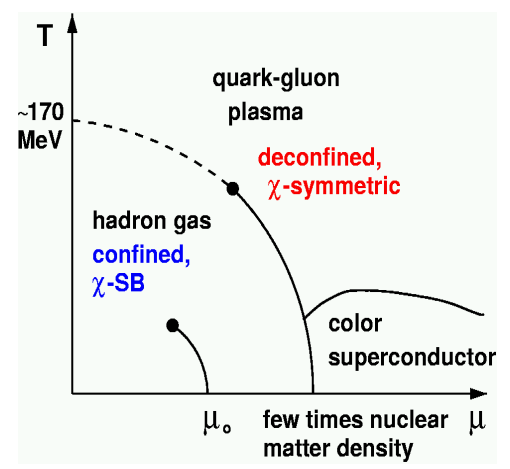
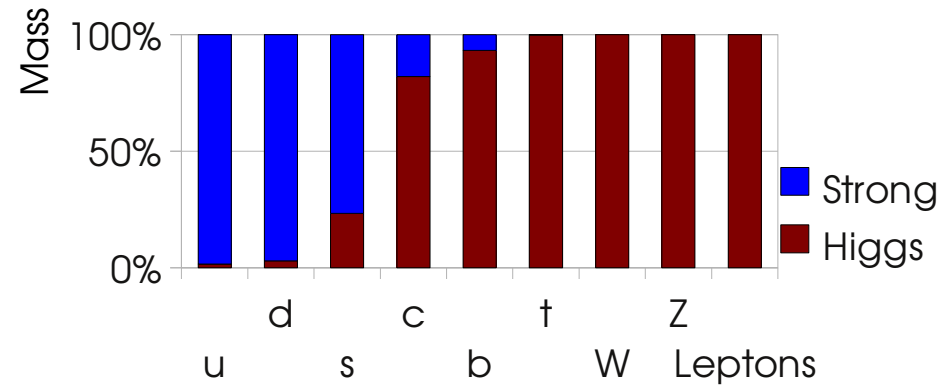
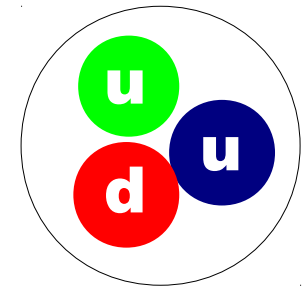
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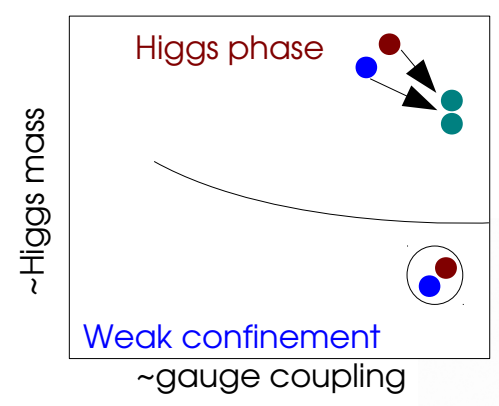
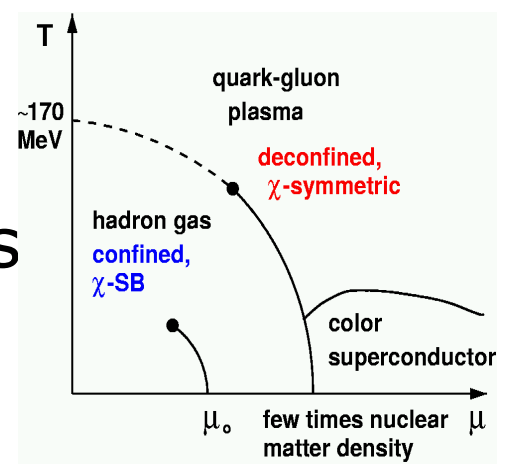
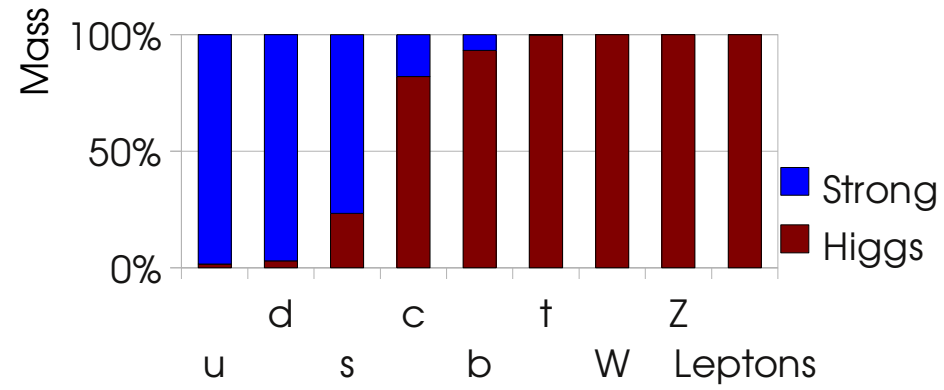
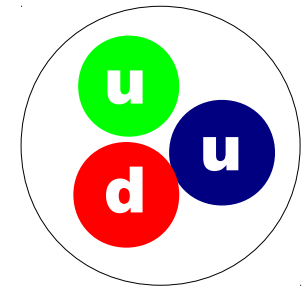
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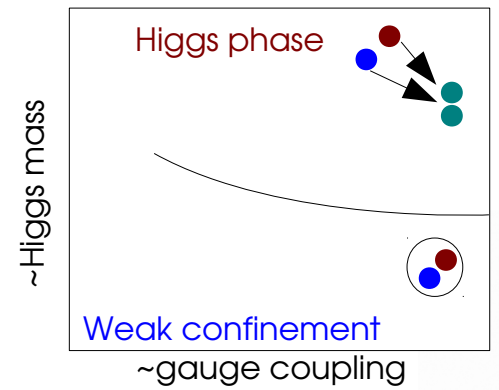
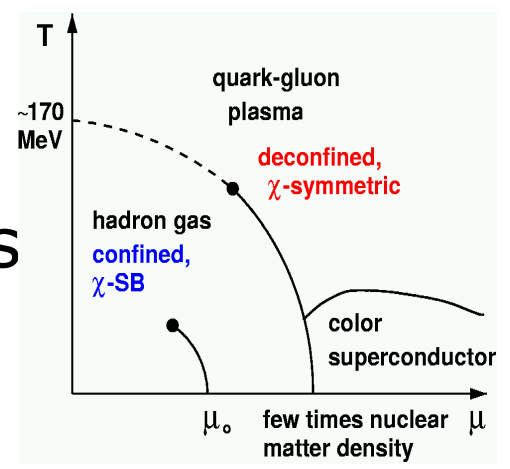
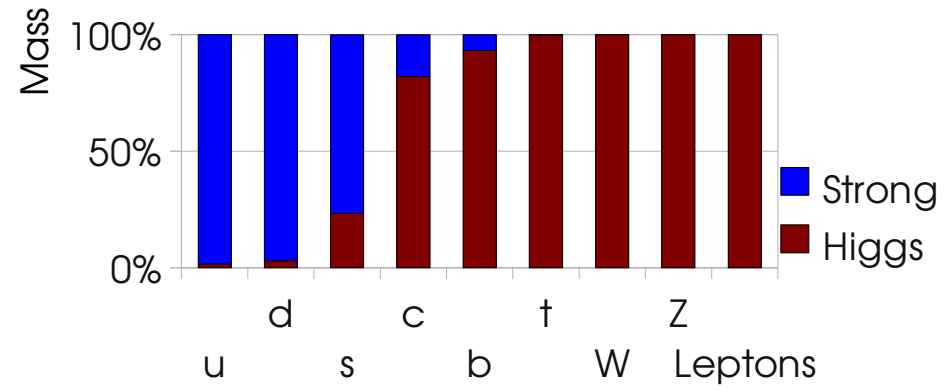
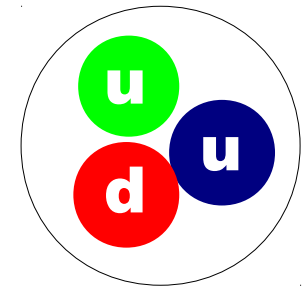
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- Bound states – hadrons, nucleons, and nuclei
- Confinement
 - There are no free quarks and gluons
- Dynamical mass generation
 - Chiral symmetry breaking
 - Formation of the Higgs condensate
- Phase transitions
- Strong initial and final state interactions



Strong interactions in the standard model

- Bound states – hadrons, nucleons, and nuclei
- Confinement
 - There are no free quarks and gluons
- Dynamical mass generation
 - Chiral symmetry breaking
 - Formation of the Higgs condensate
- Phase transitions
- Strong initial and final state interactions
- Require non-perturbative methods



Methods

Correlation functions [Alkofer & von Smekal 2000]

- Correlation functions, describe a theory completely

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 - Build from the elementary particles
 - E.g. photon 2-point correlator: $\langle \gamma(x) \gamma(y) \rangle$

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 - Build from the elementary particles
 - E.g. photon 2-point correlator: $\langle \gamma(x) \gamma(y) \rangle$
- Full correlation functions contain all information
- There are an infinite number of them
 - Polynomials with any number of fields

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- Scattering of bound states: min. 8-point correlator
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Information from correlation functions

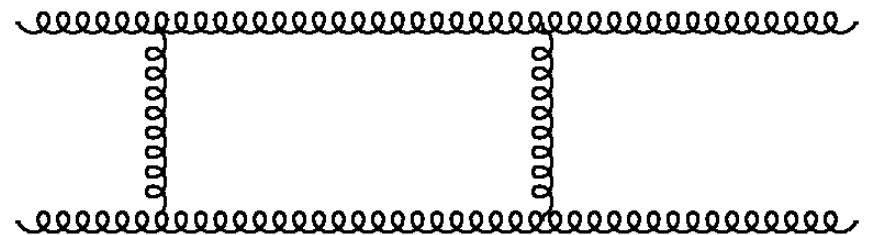
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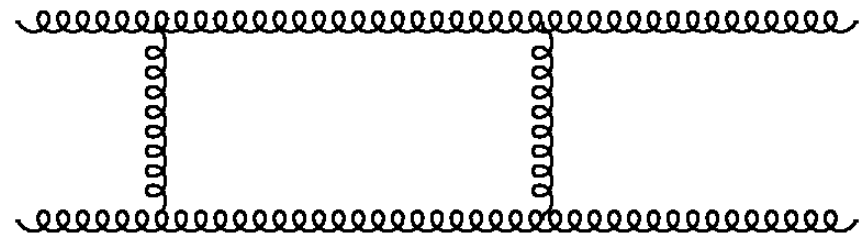
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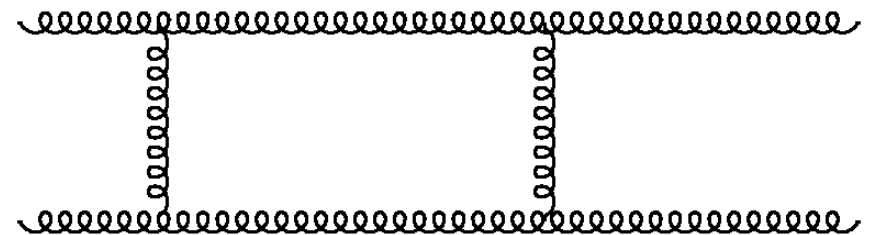
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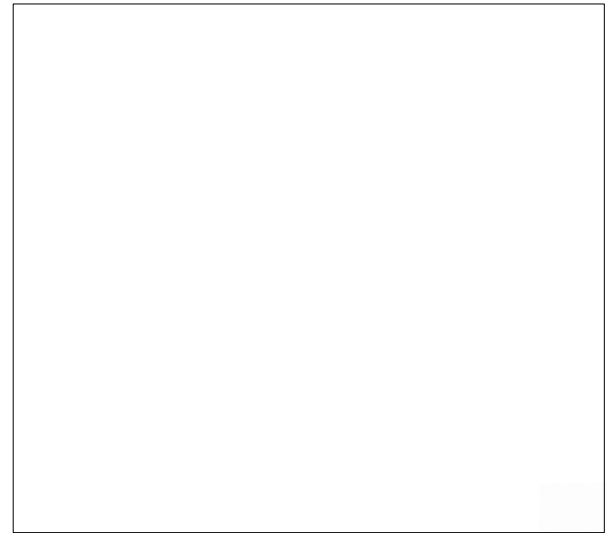
- Correlation functions can depend on the gauge
- Physical quantities (hadron masses, scattering cross sections) are gauge-invariant
- Gauge-dependent result shown are in Landau gauge

Methods to calculate correlation functions

- Lattice

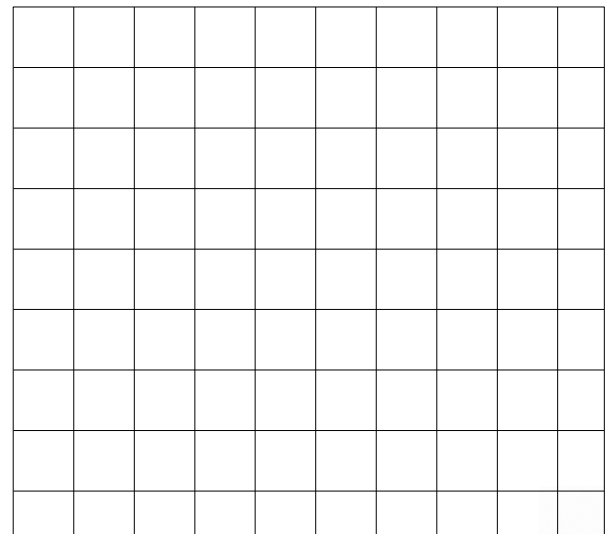
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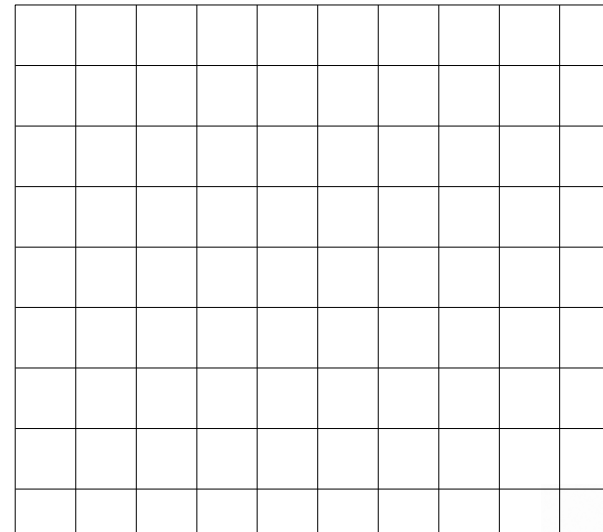
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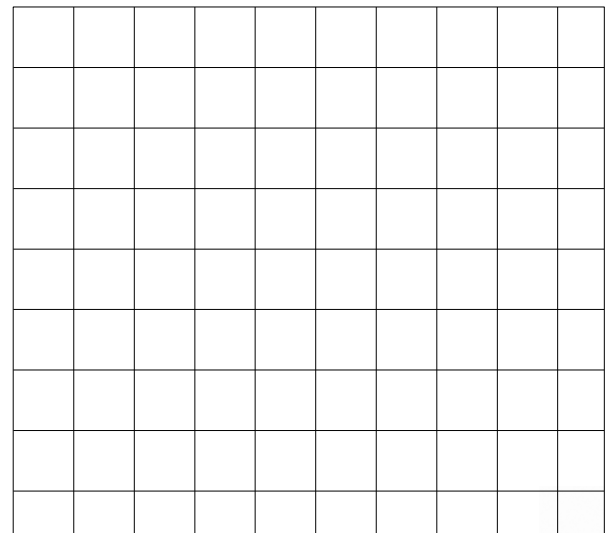
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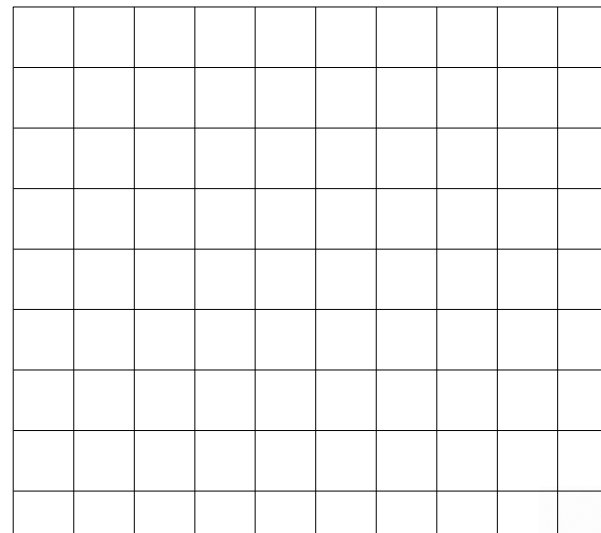
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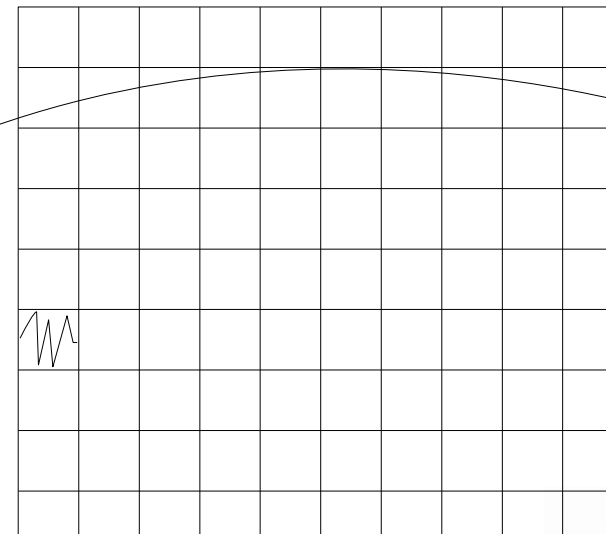
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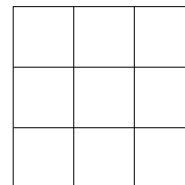
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Methods

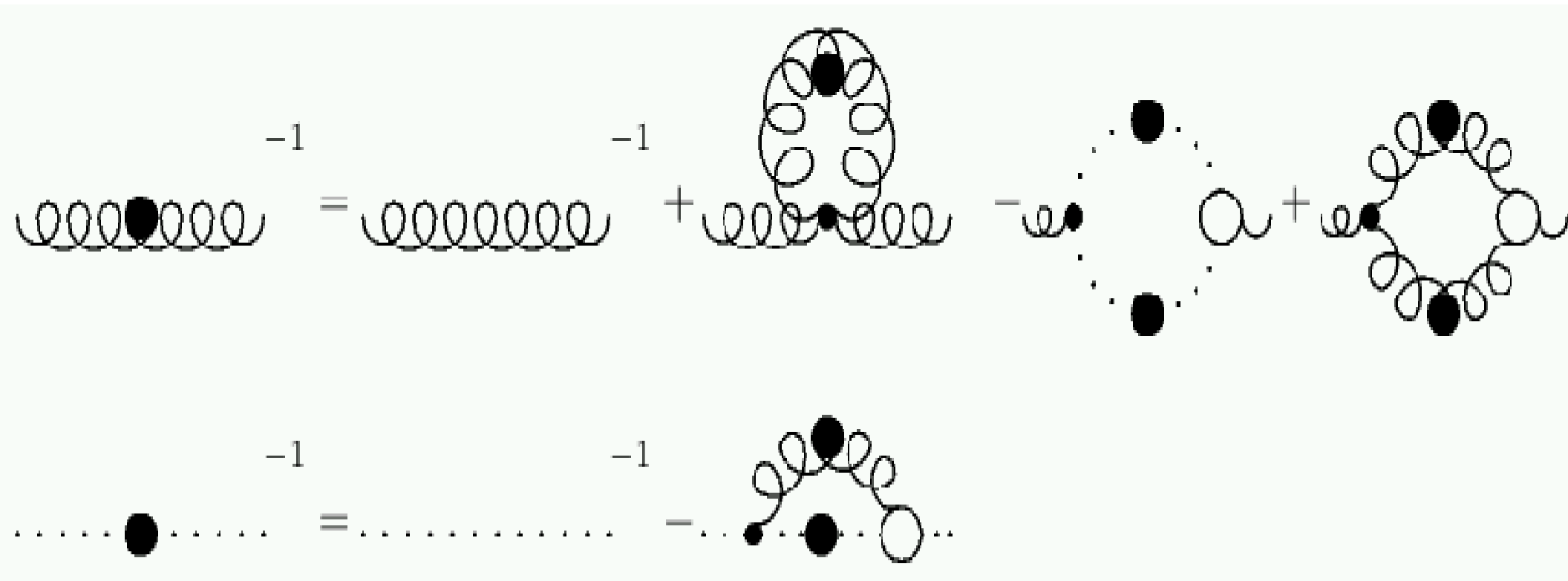
- **Lattice**
 - Discretize space-time in a box and calculate the path-integral and expectation values explicitly
 - Full non-perturbative dynamics correctly implemented
 - Finite volume artifacts, disparate scales most severe obstacles
- **Functional methods** (DSE, RGE...)



(Truncated) Dyson-Schwinger Equations (DSEs)

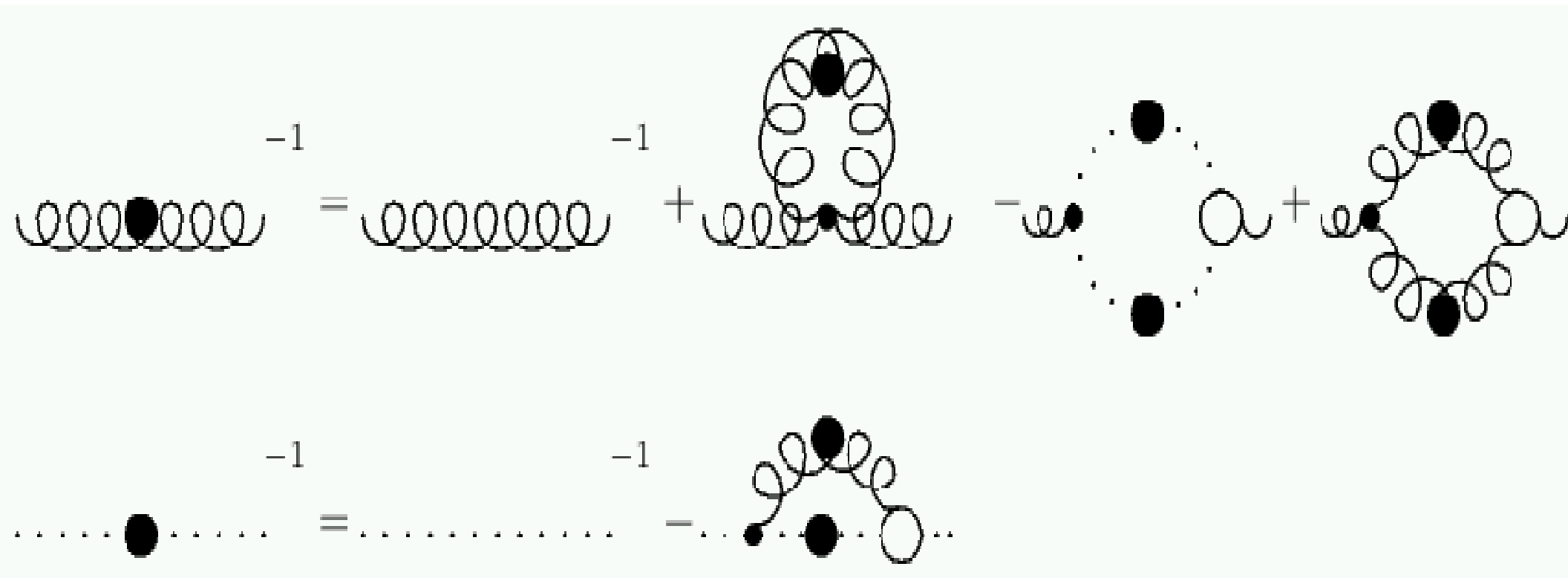
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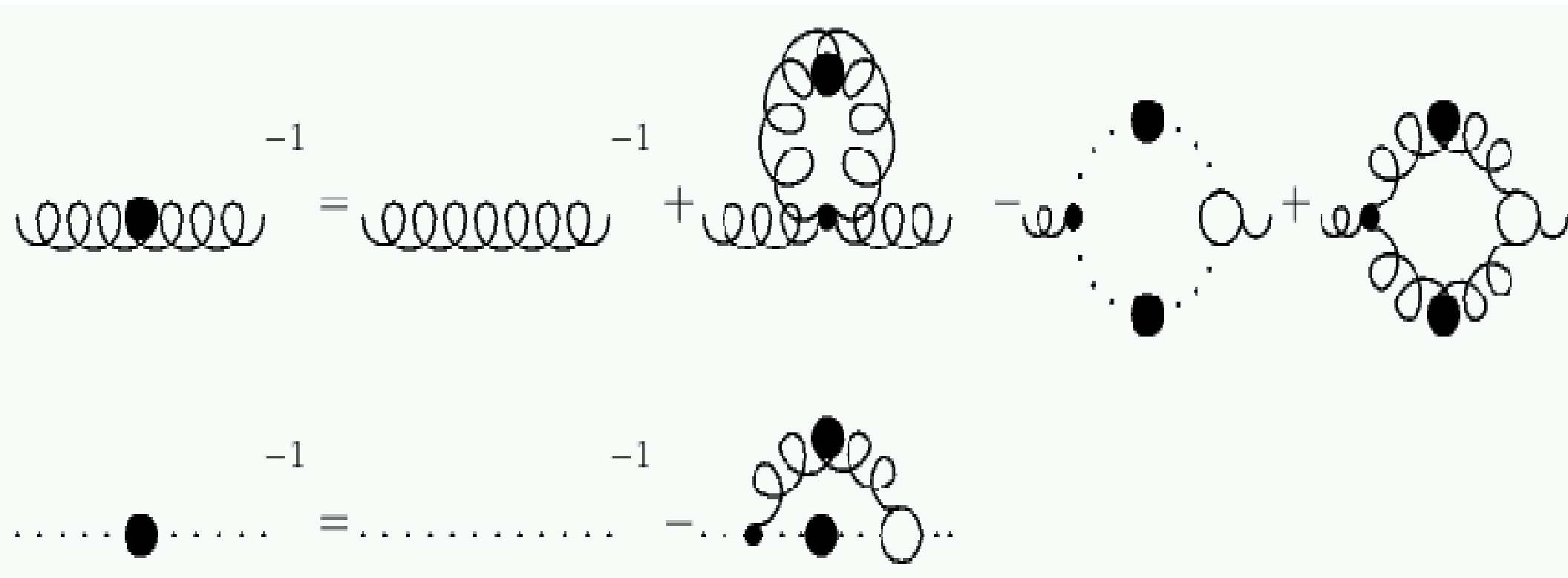
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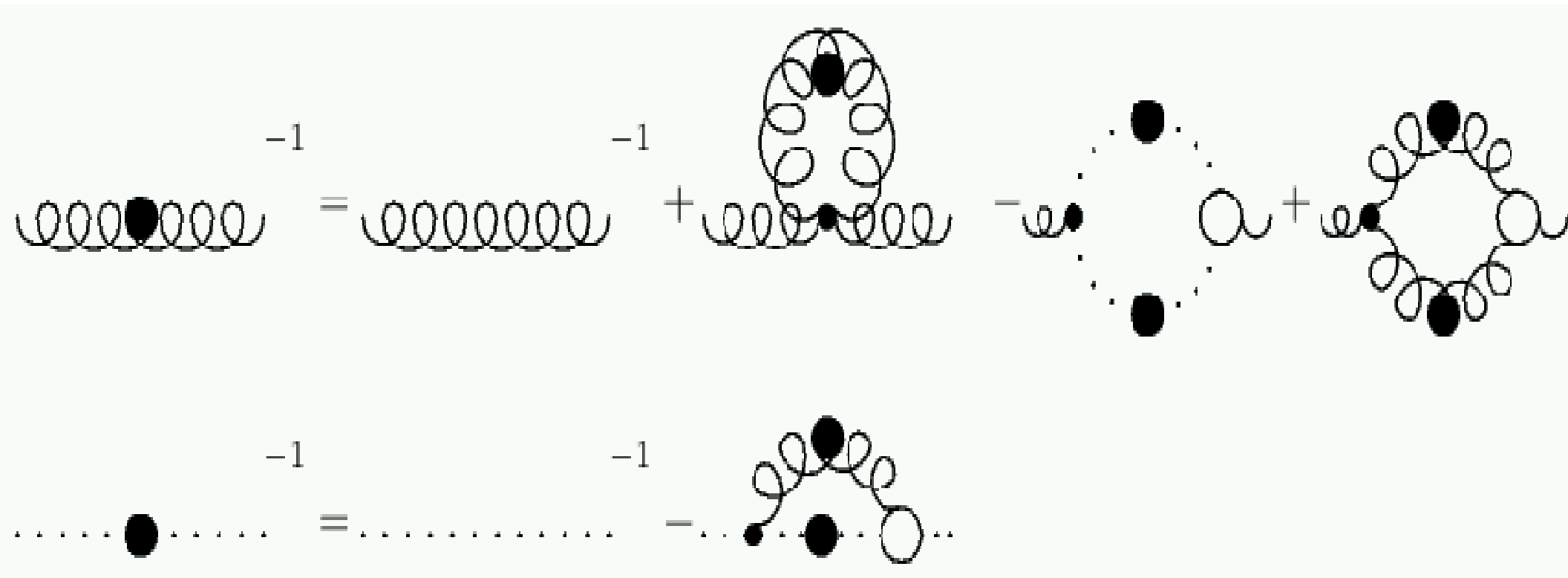
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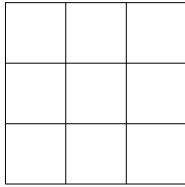
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- Similar: Renormalization group equations

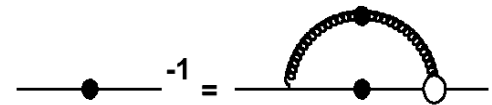
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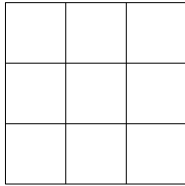
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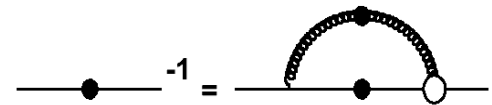
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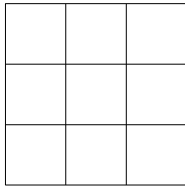


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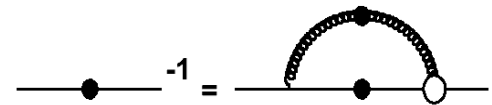
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The obvious: QCD

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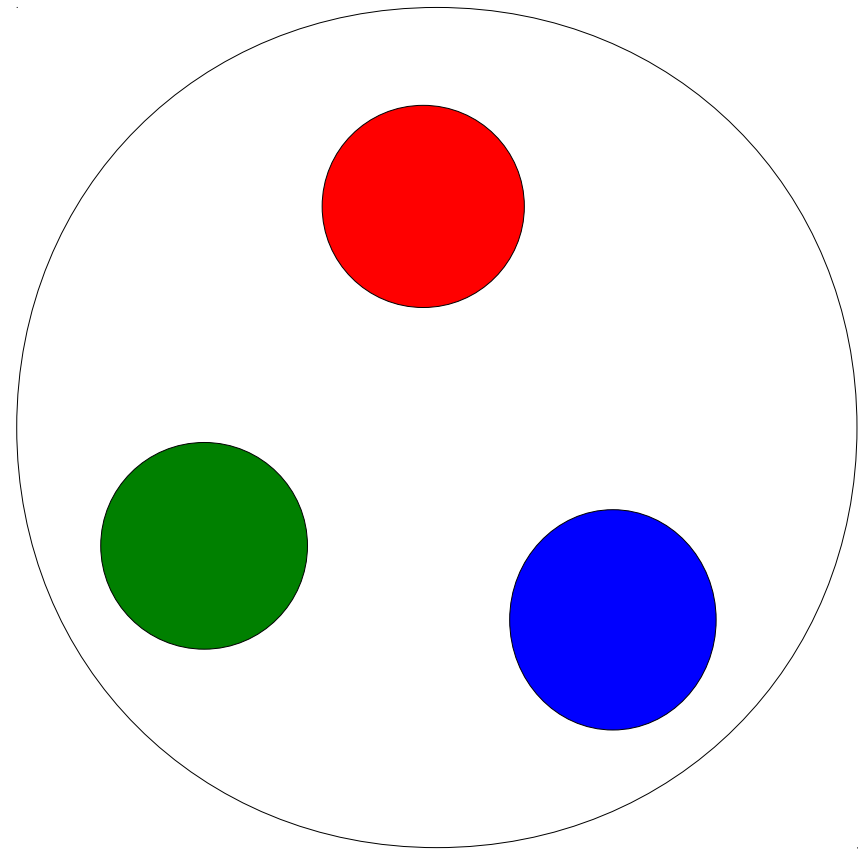
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QCD degrees of freedom

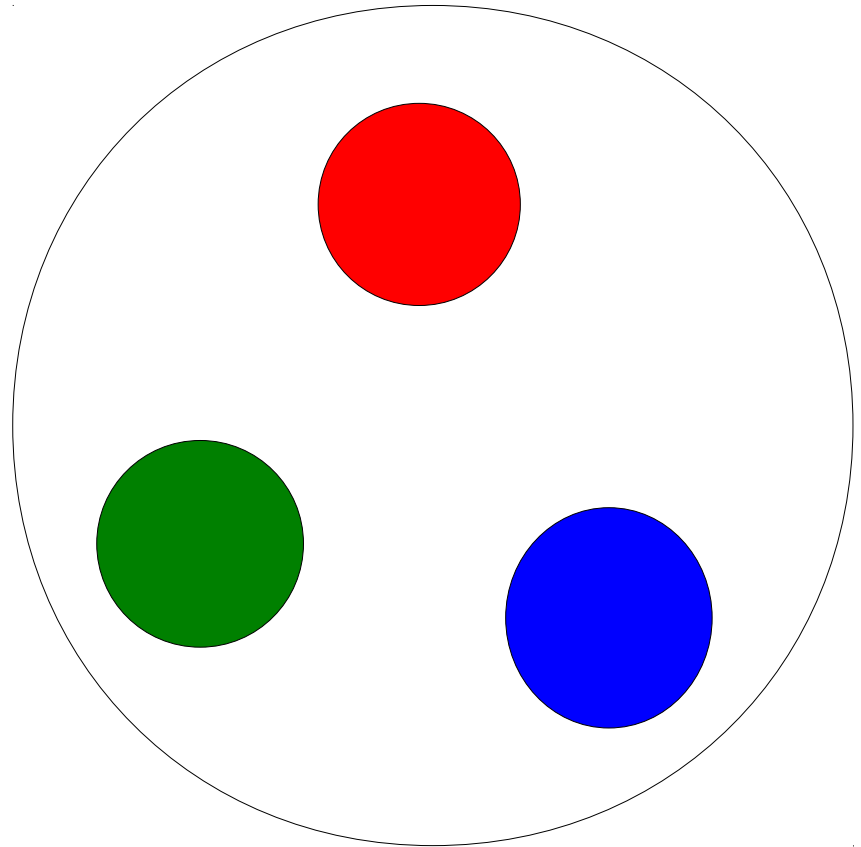
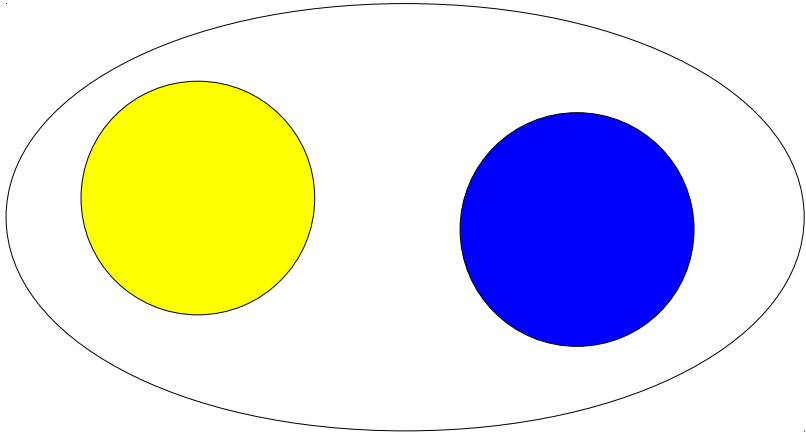
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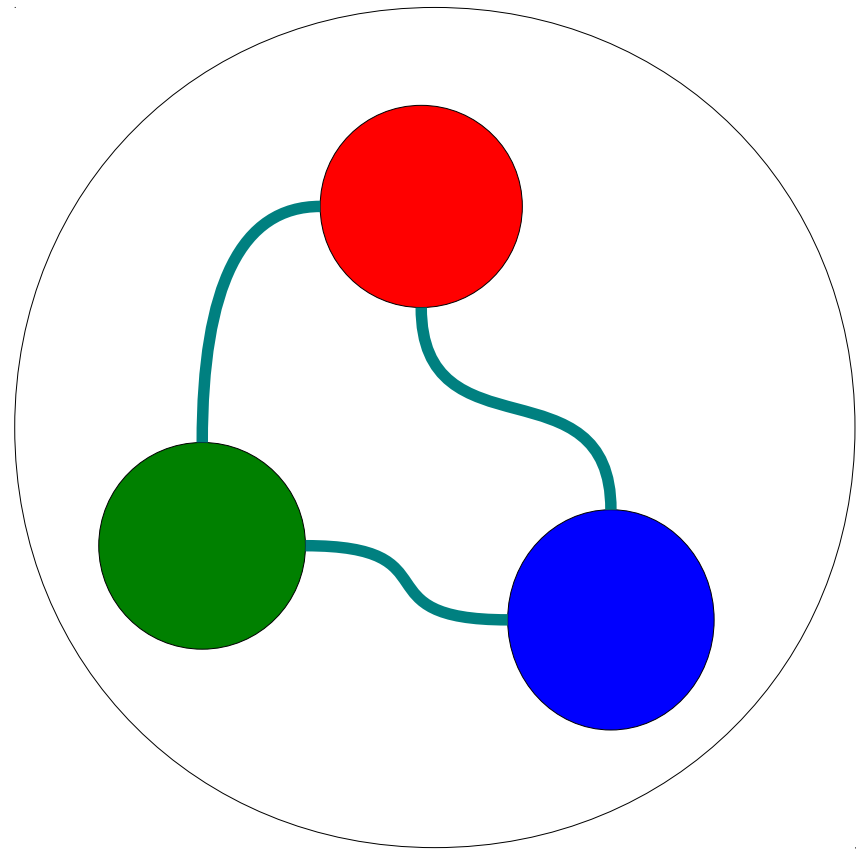
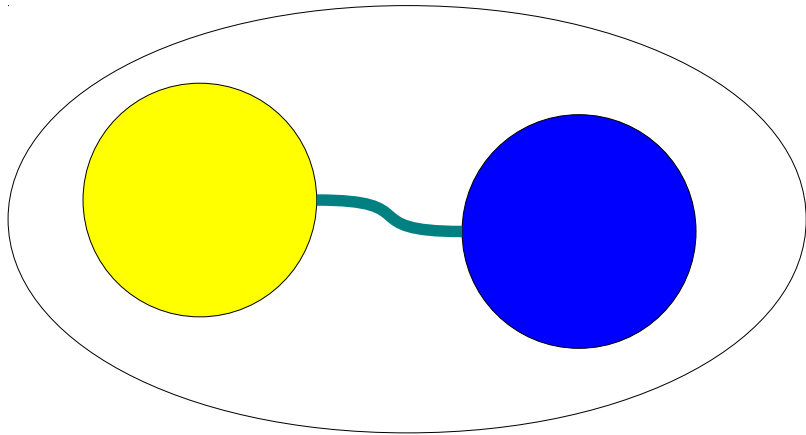


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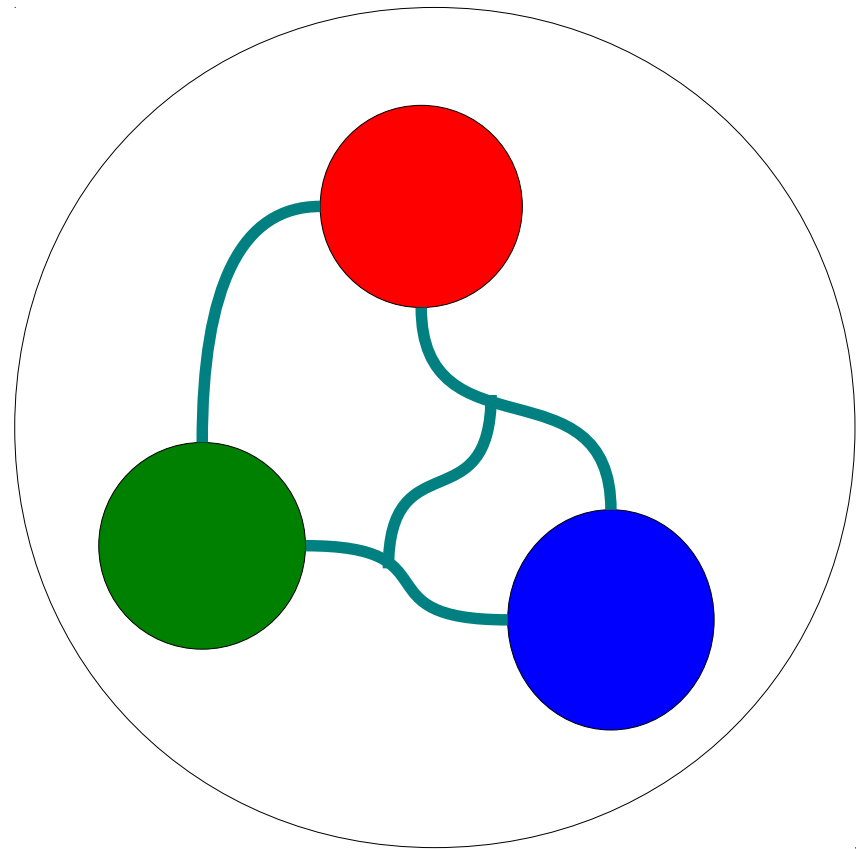
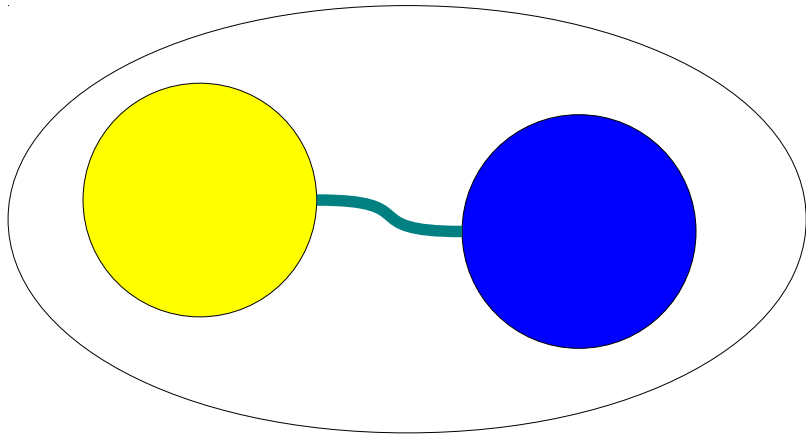
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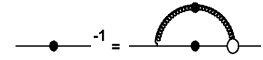
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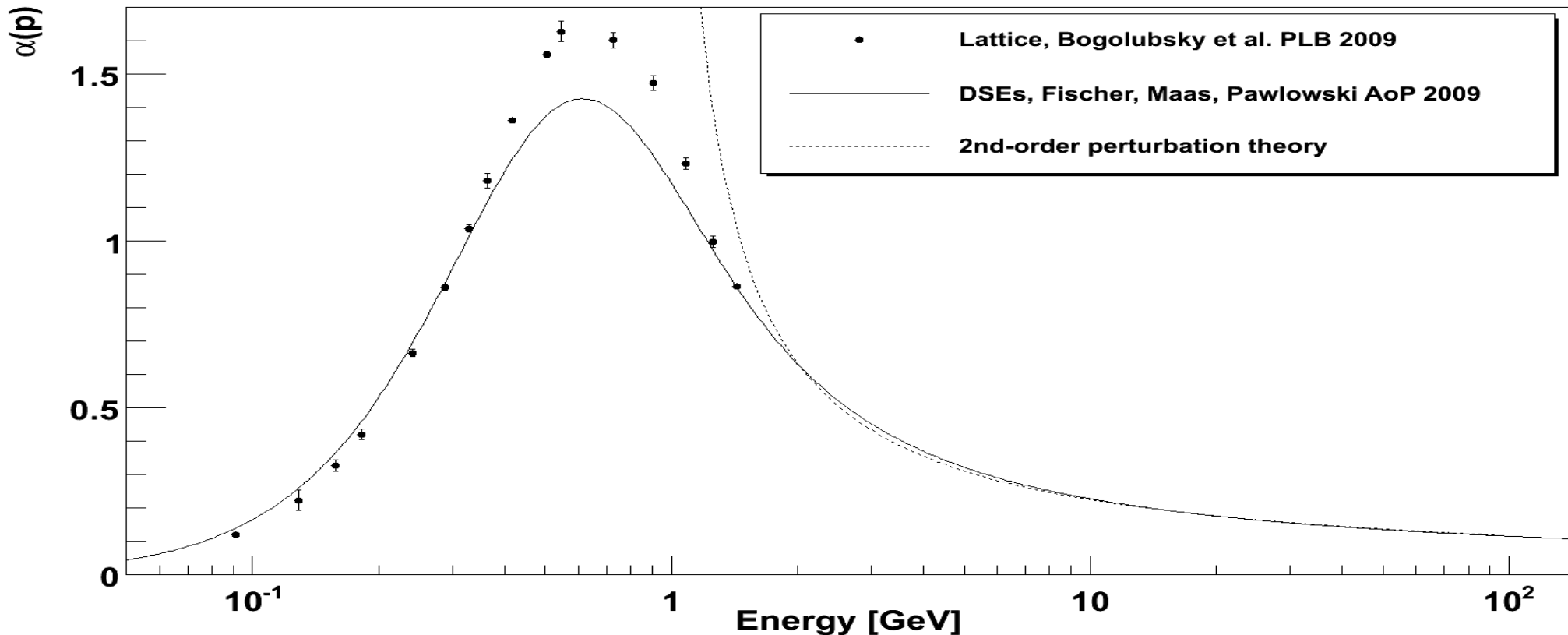
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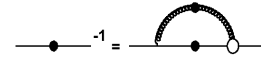


Running coupling

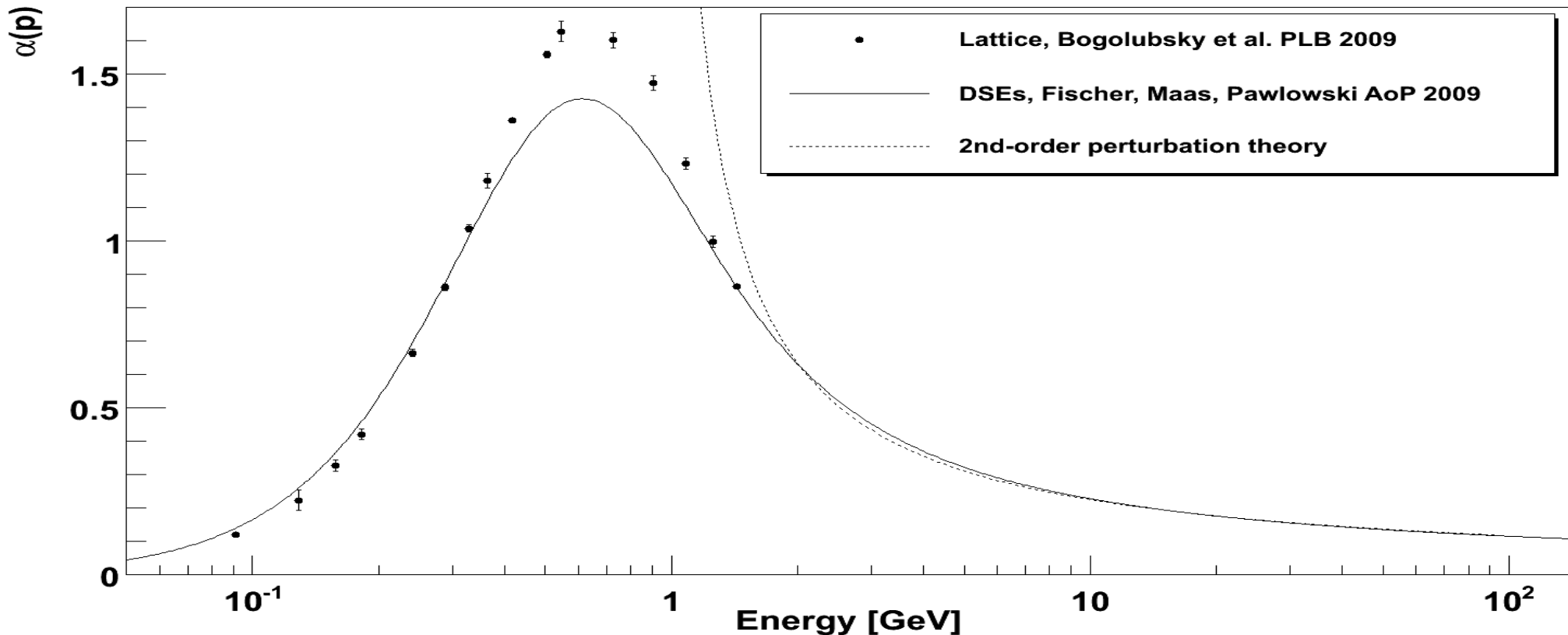


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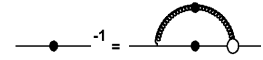


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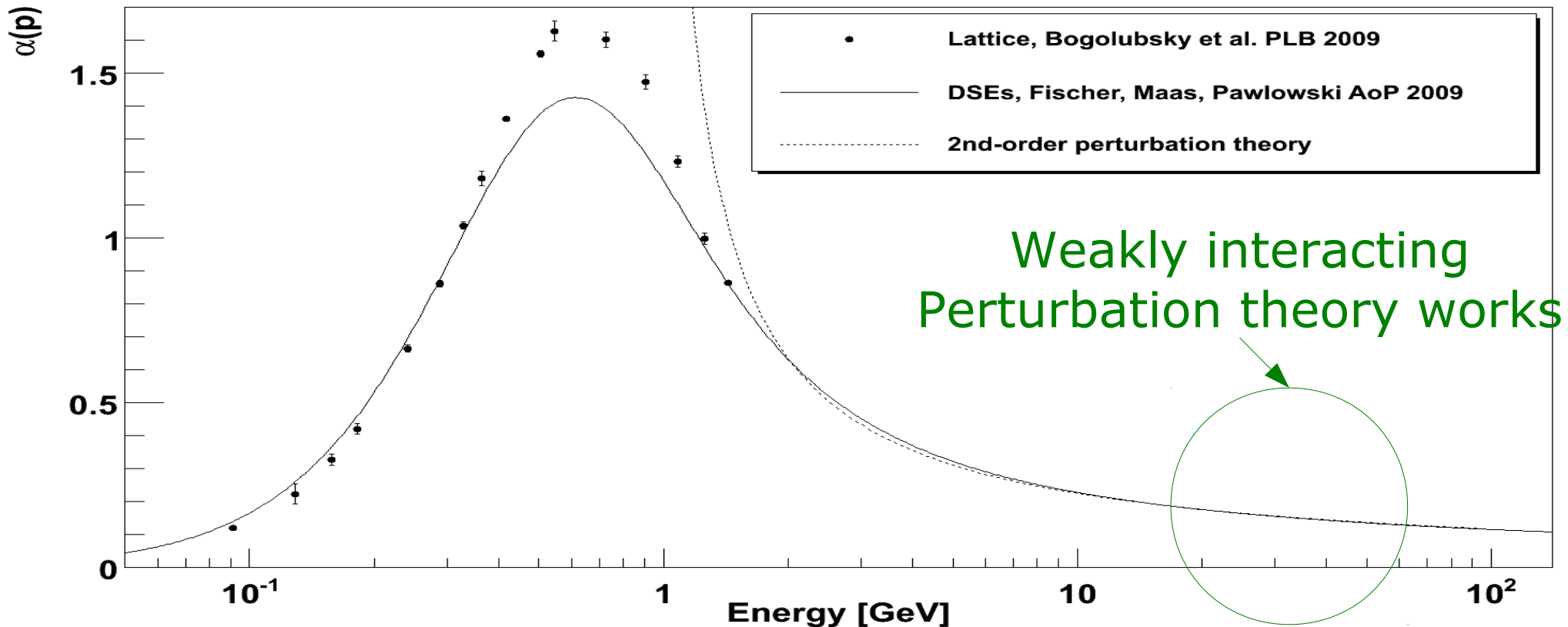


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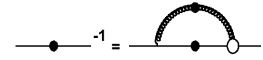


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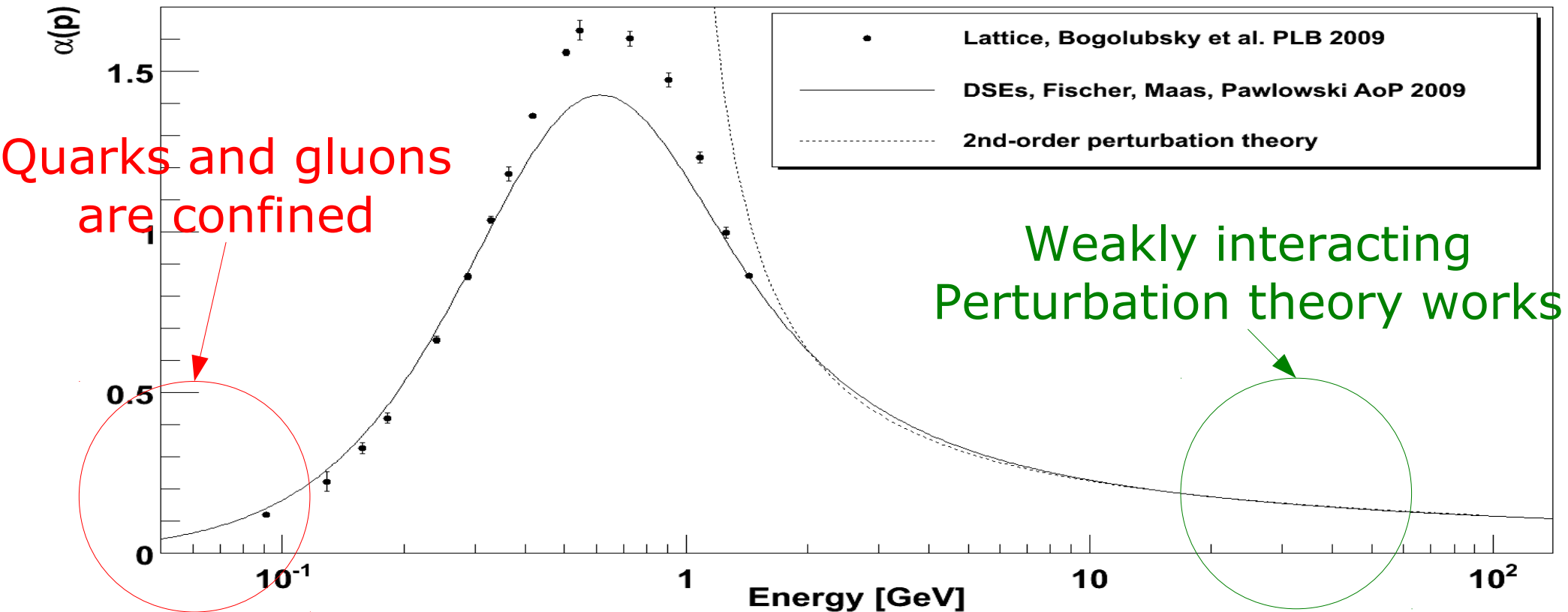


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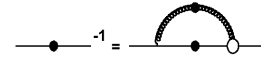


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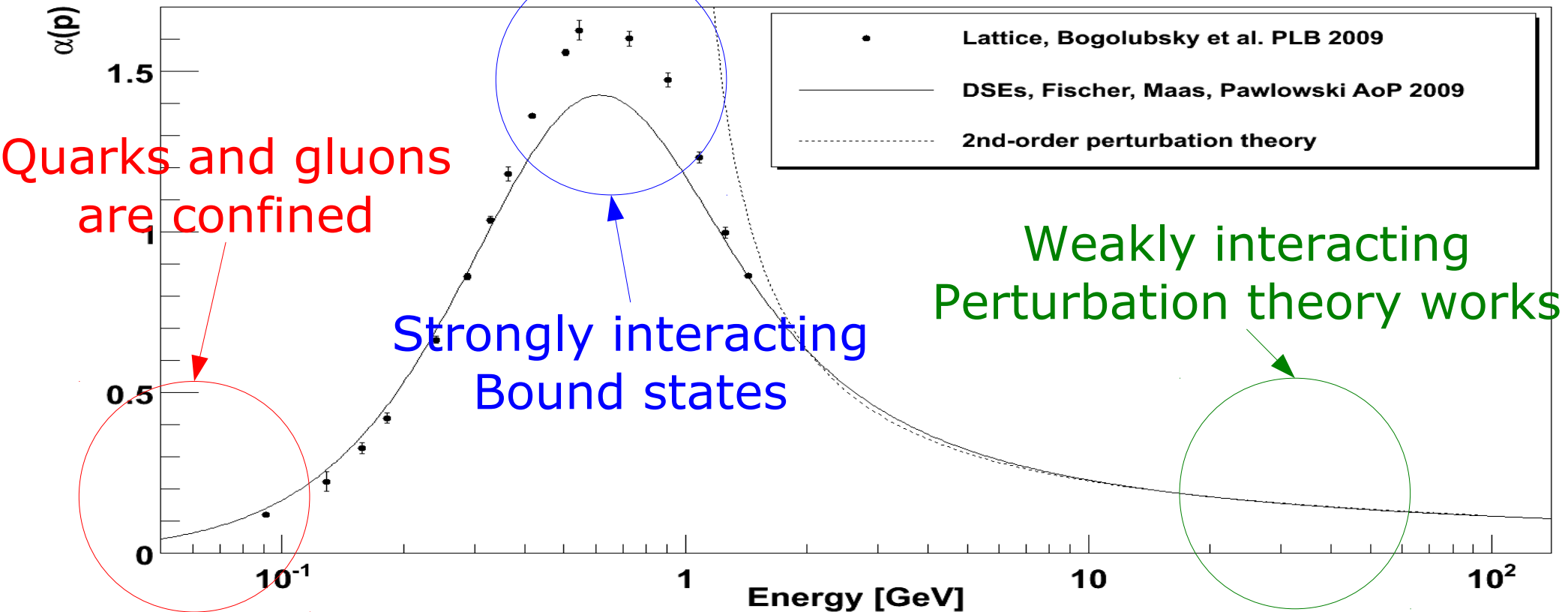


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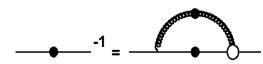


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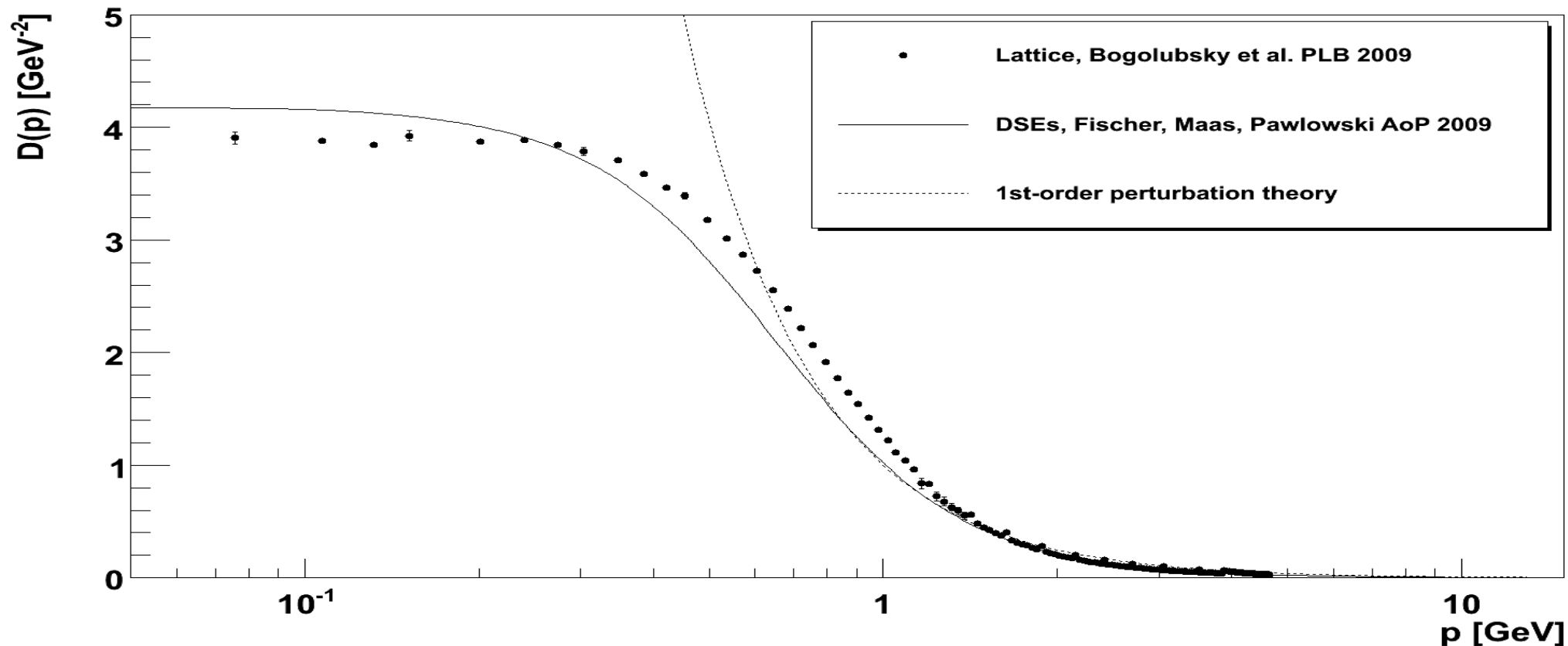
Gluon correlation function

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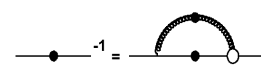


Gluon 2-point correlation function

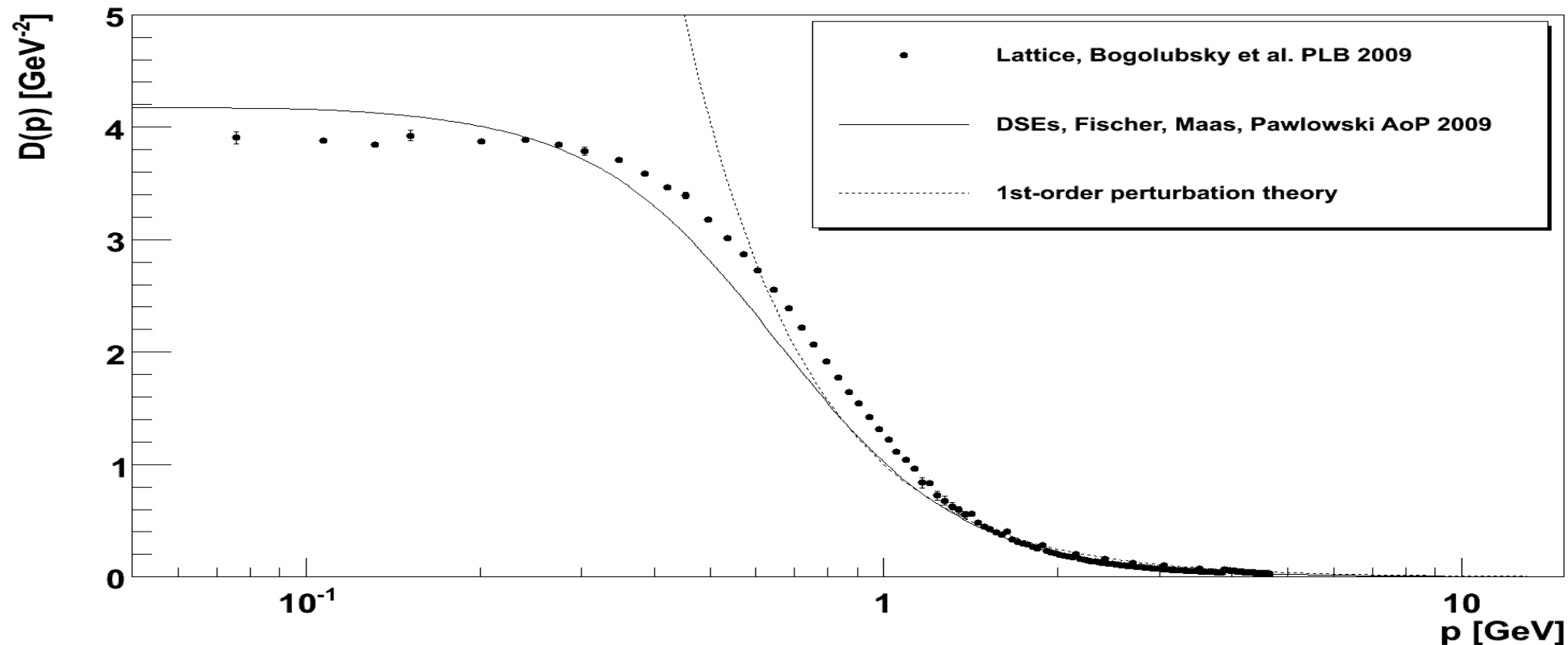


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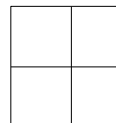
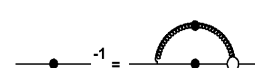


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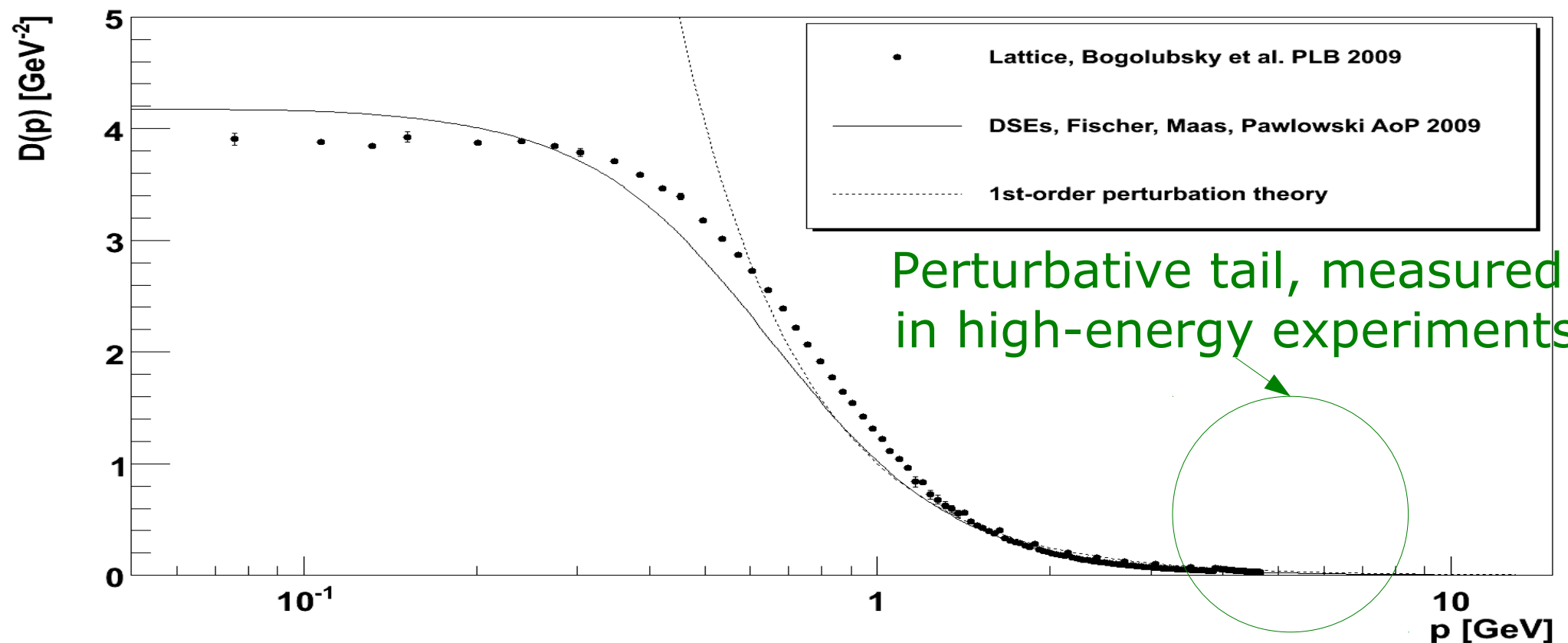


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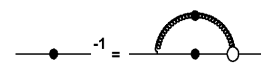


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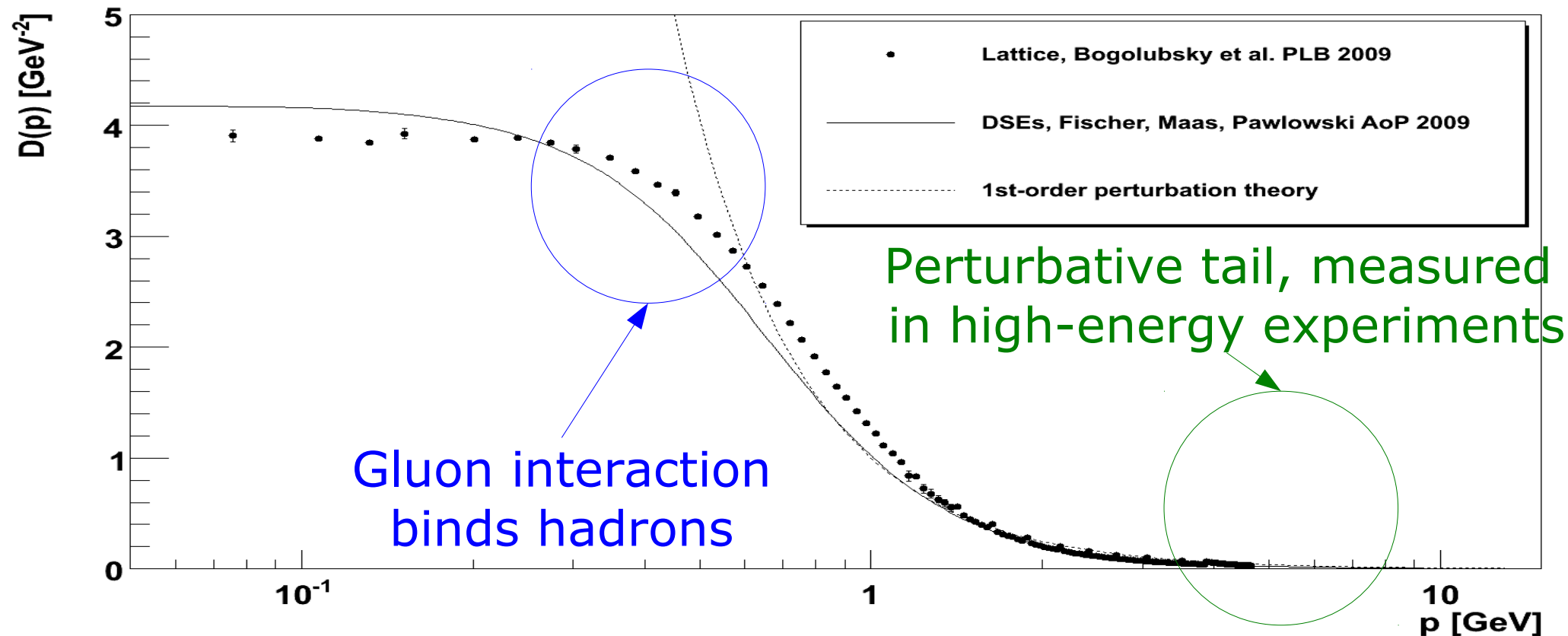


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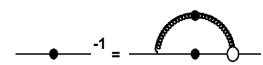


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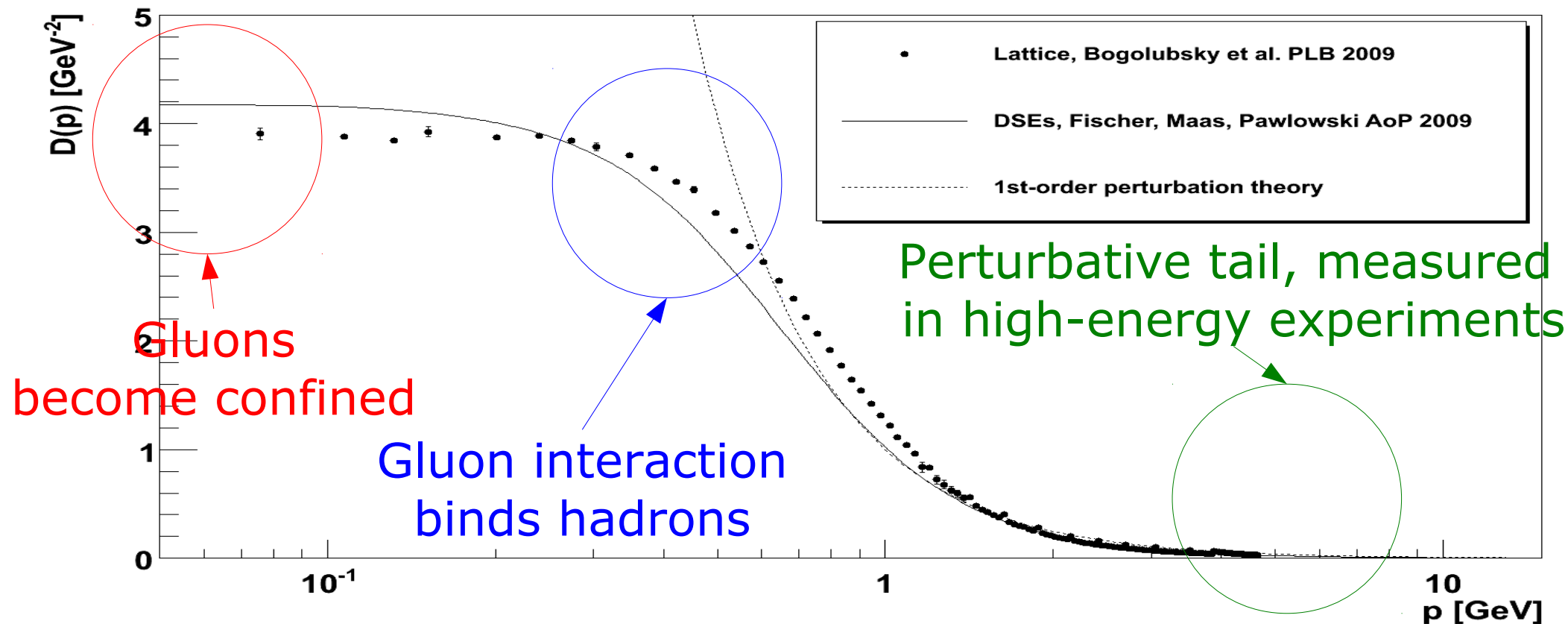


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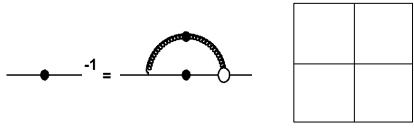


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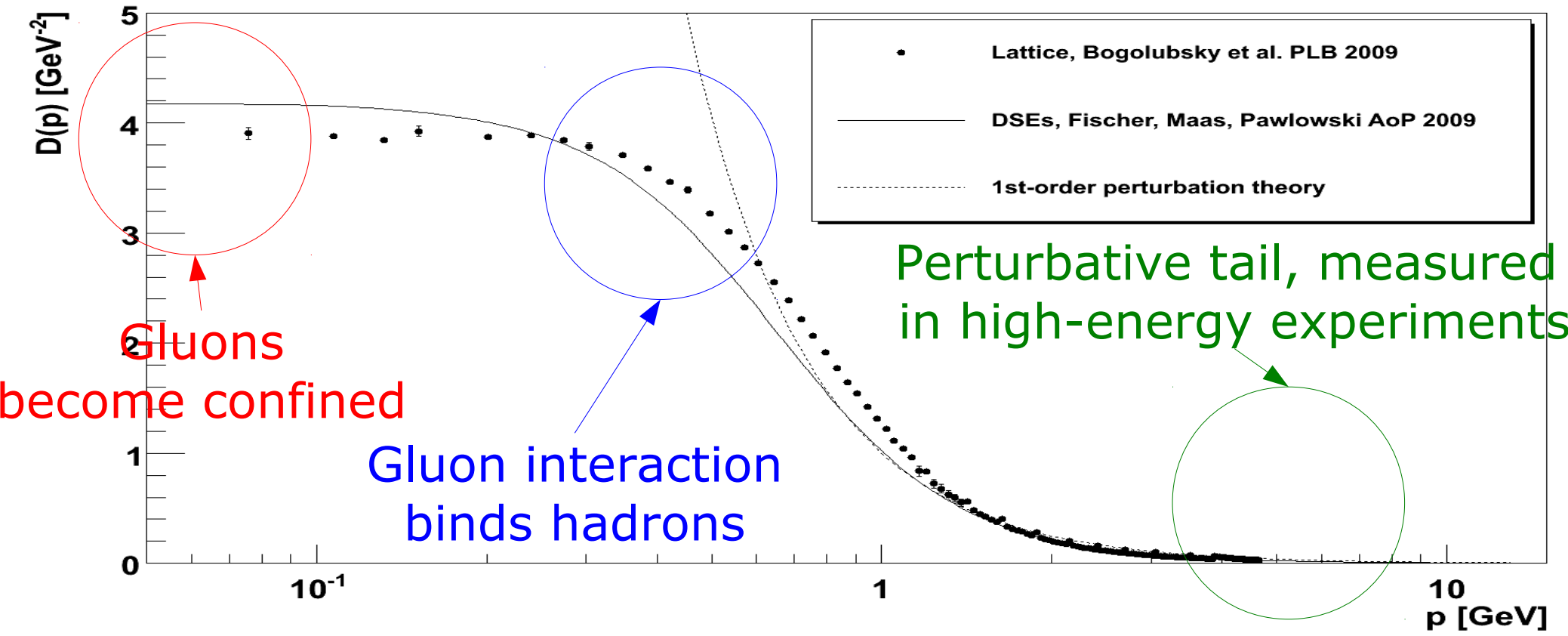


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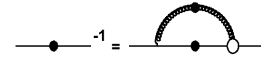
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- Similar for three-point functions

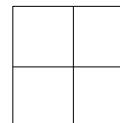
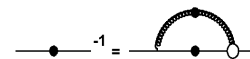


Bound states



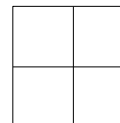
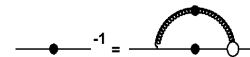
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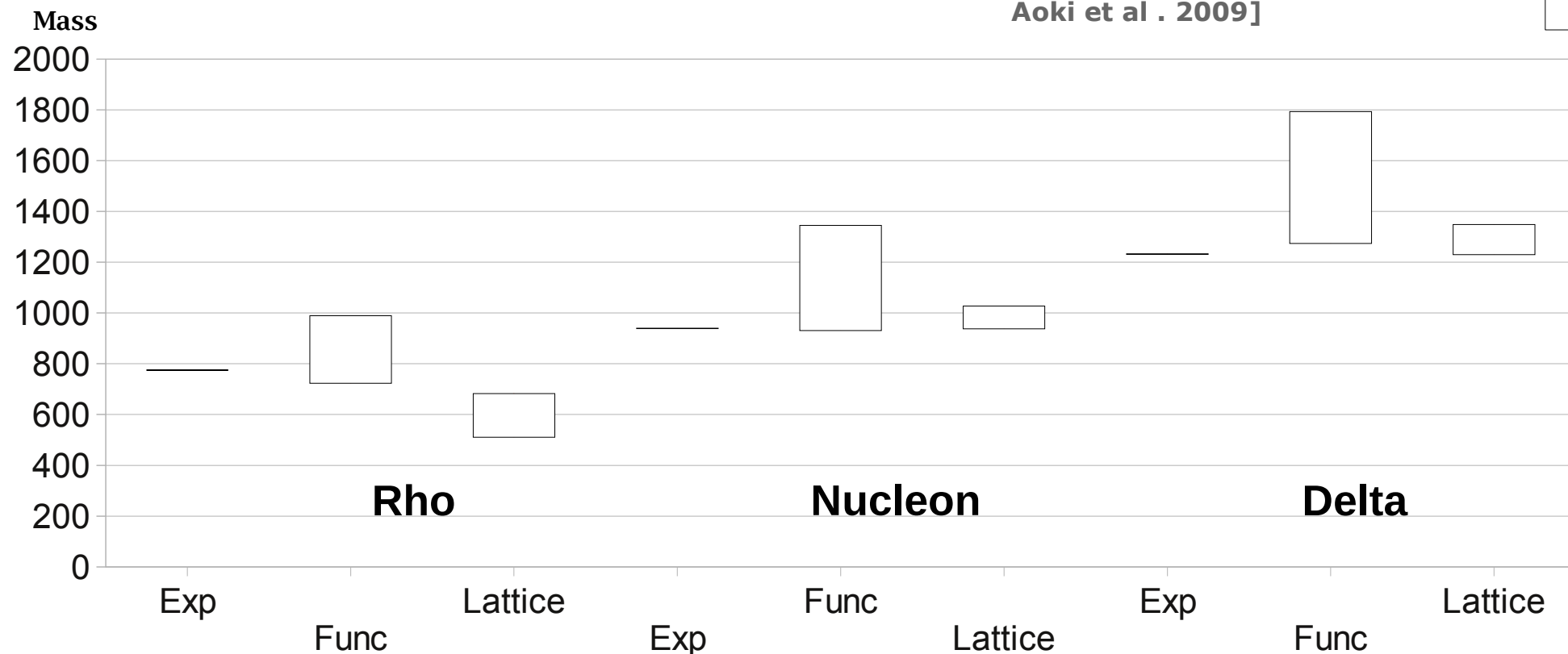
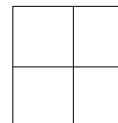
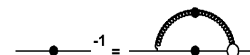
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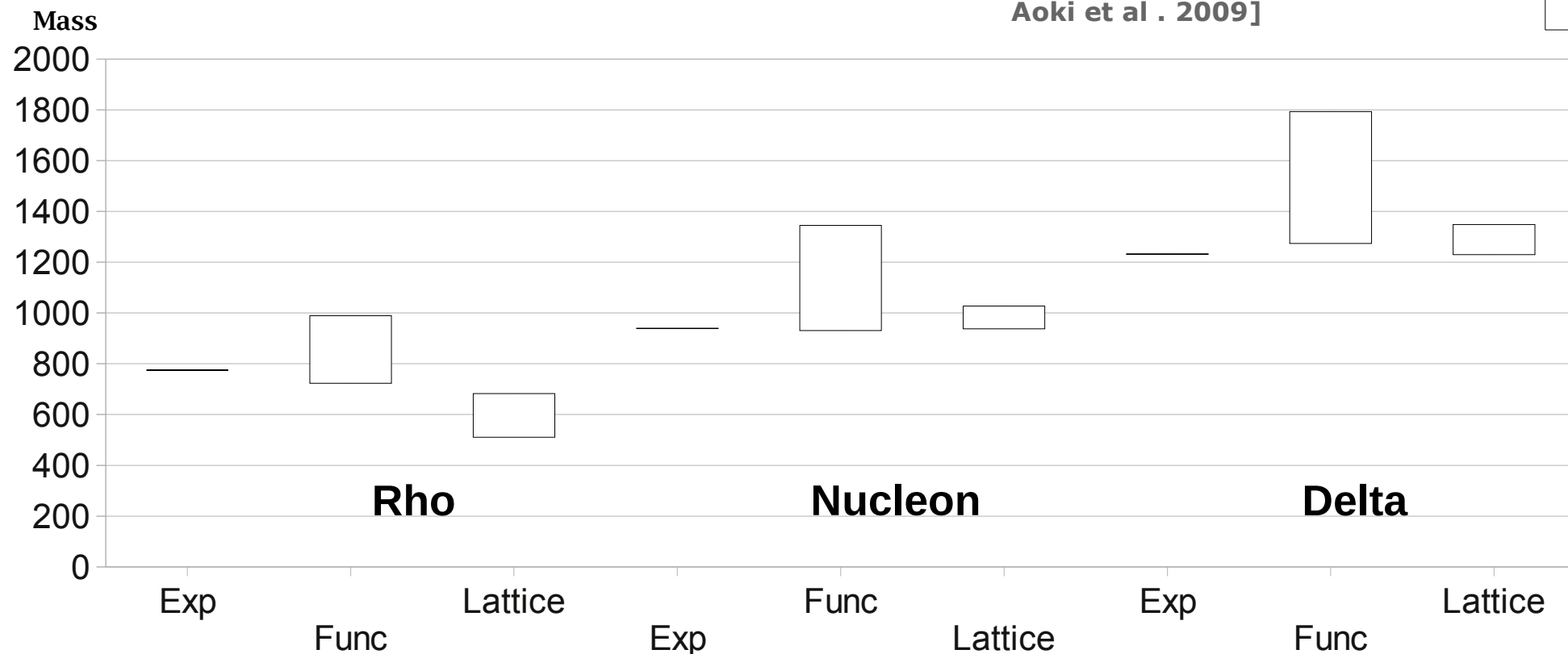
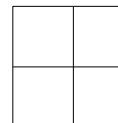
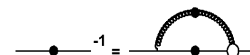
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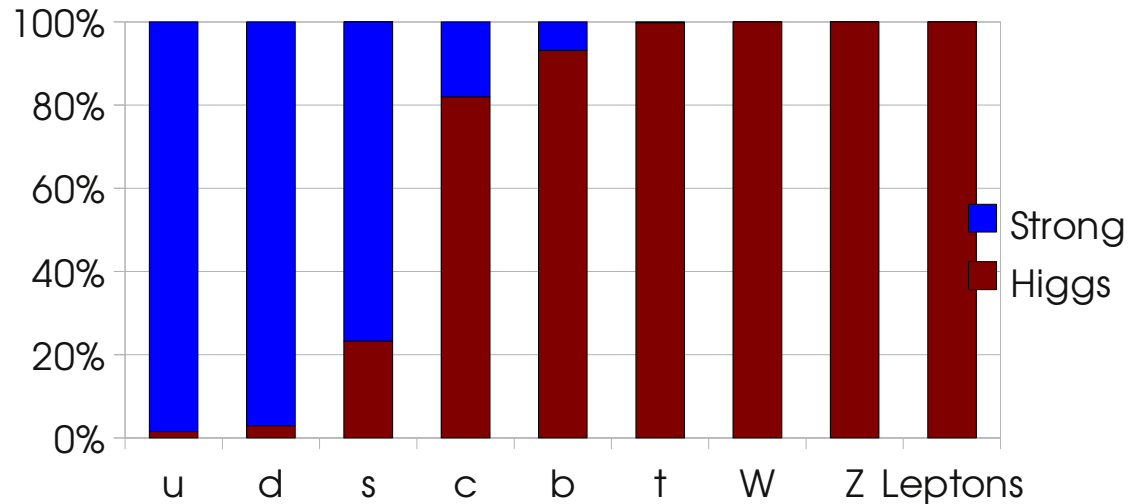
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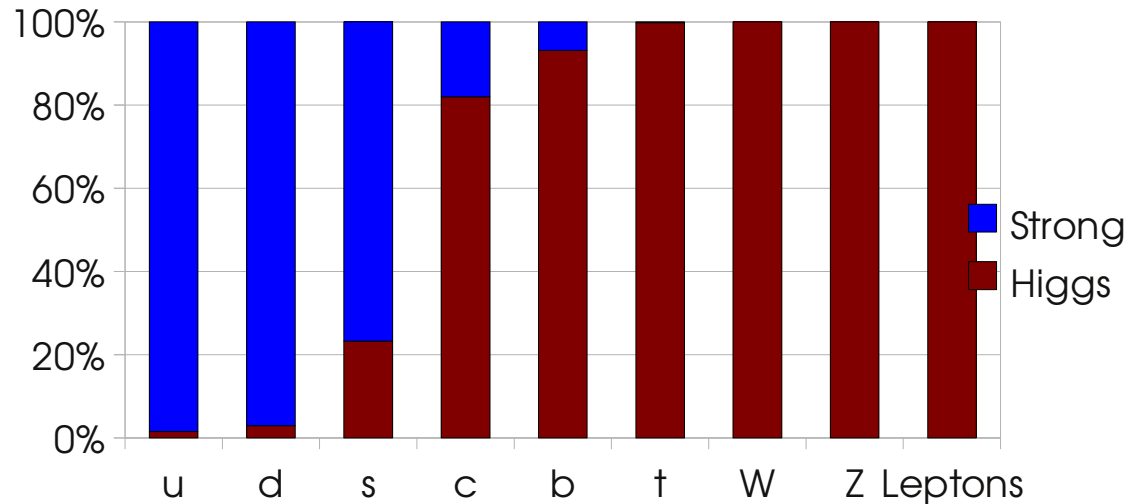
The non-obvious: Higgs

The Higgs effect



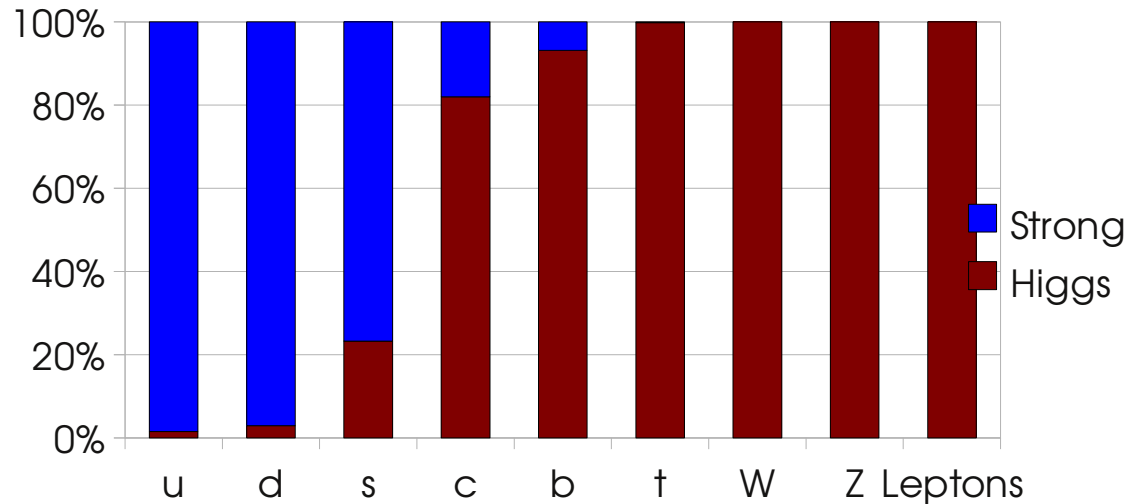
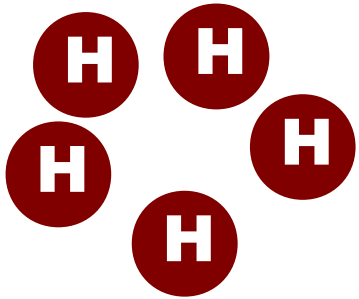
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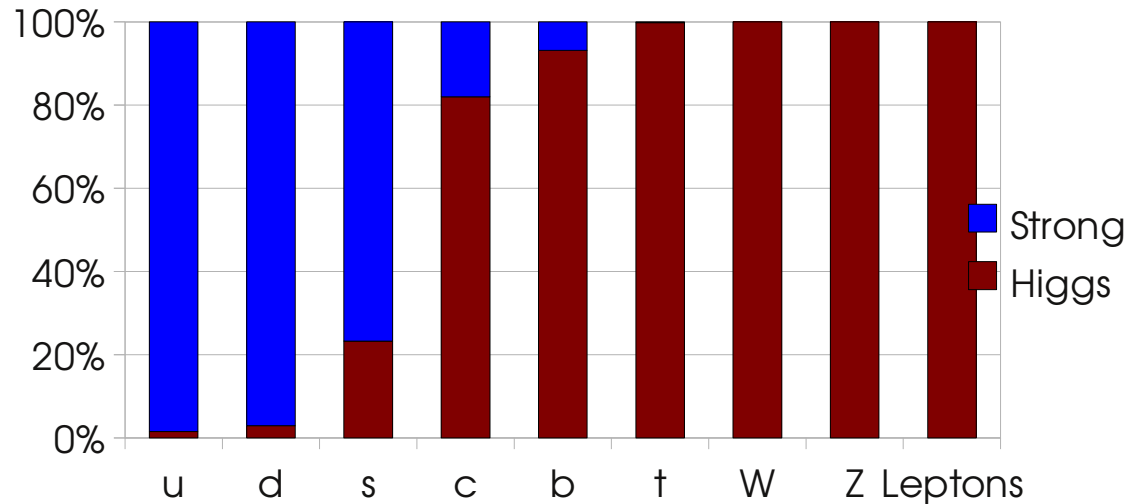
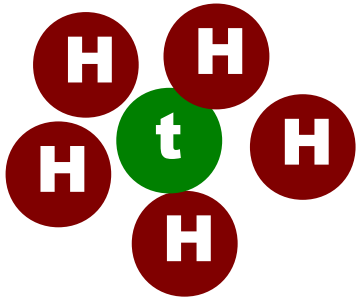
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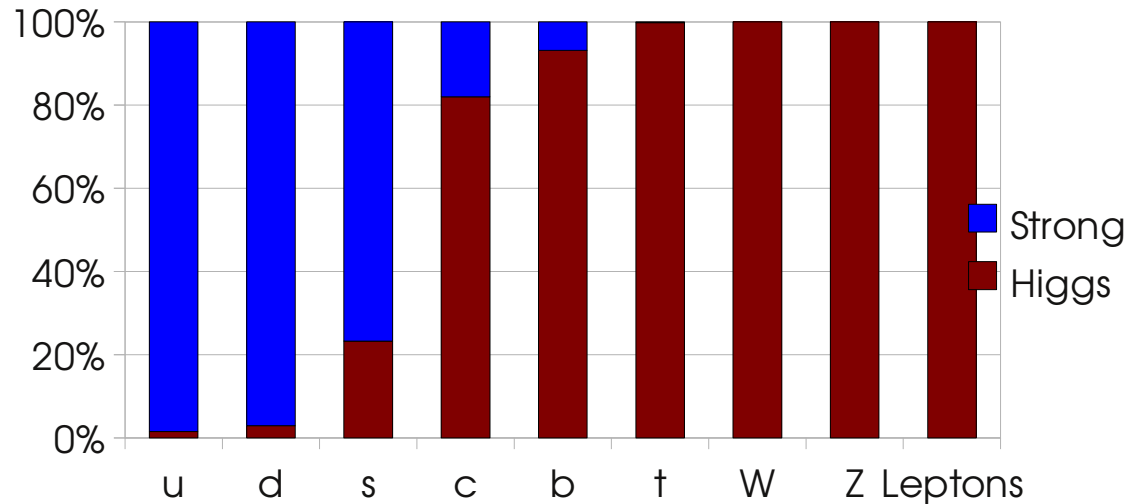
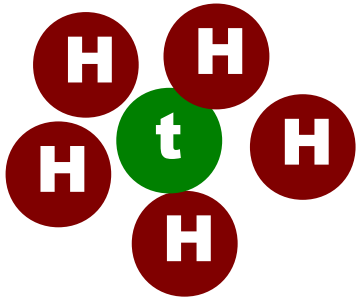
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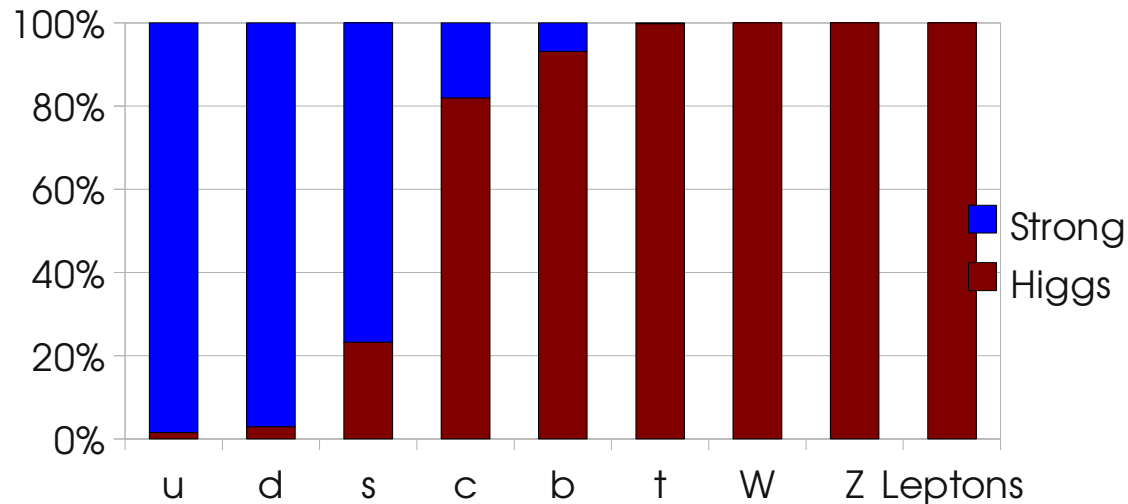
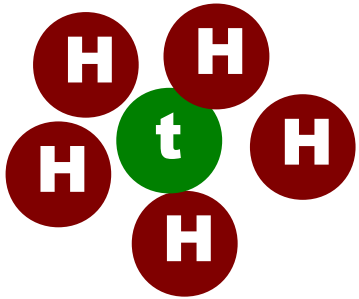
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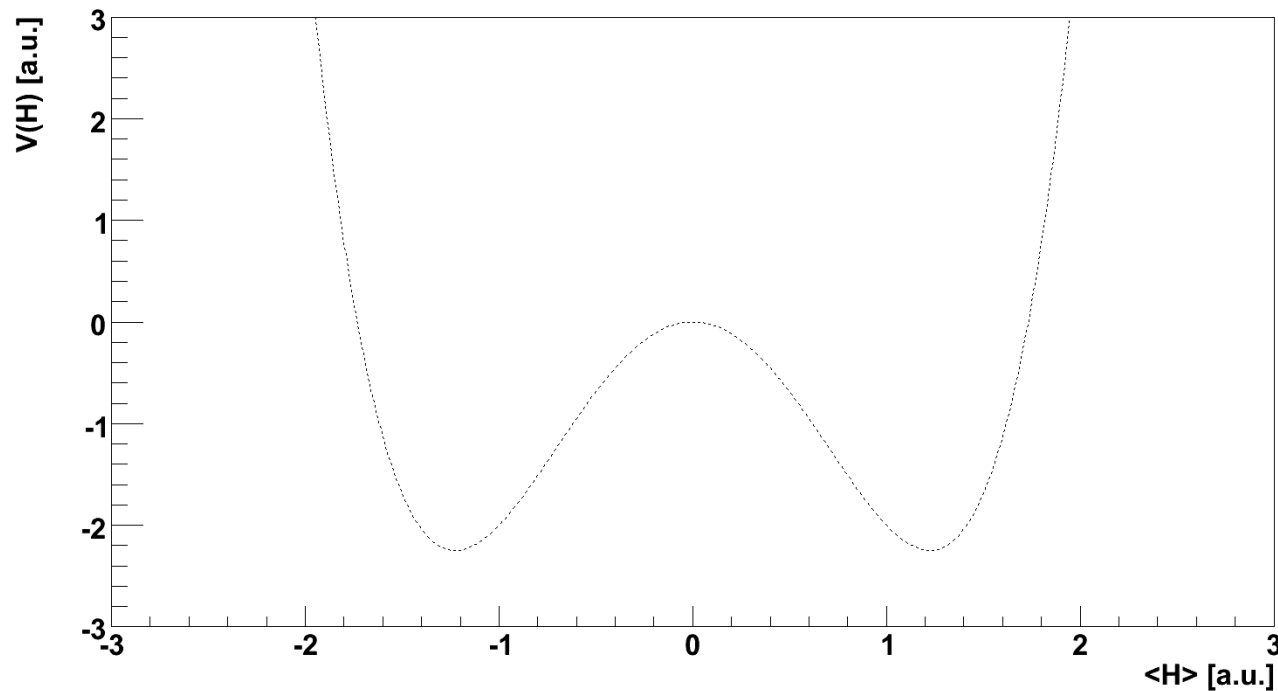
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 - Assume that it exists
 - Only particle which has a static mass

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- **Semi-classically** a spontaneous breaking of the gauge symmetry

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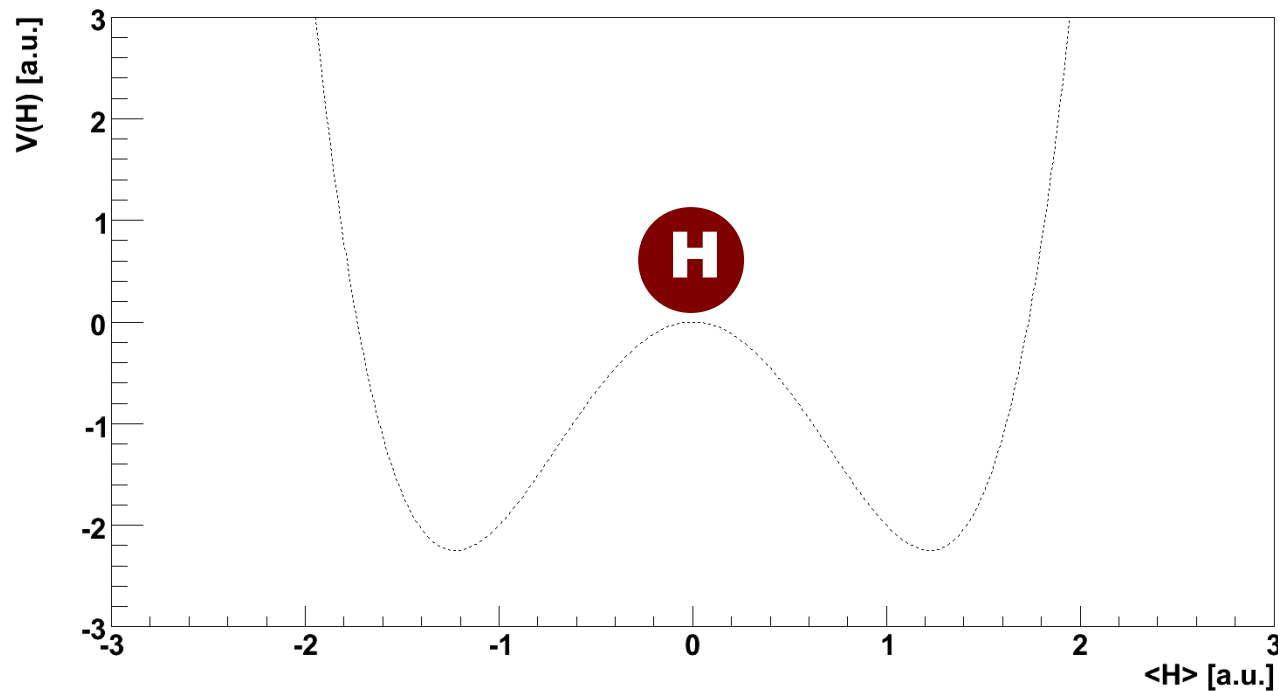
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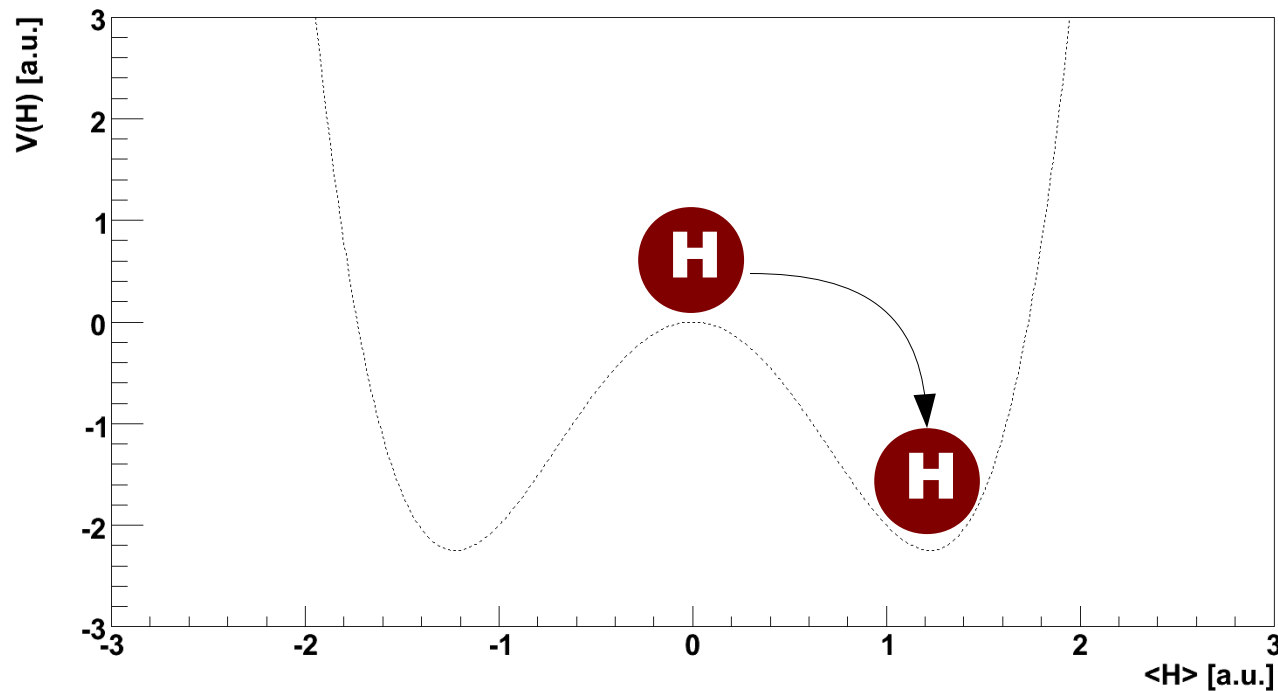
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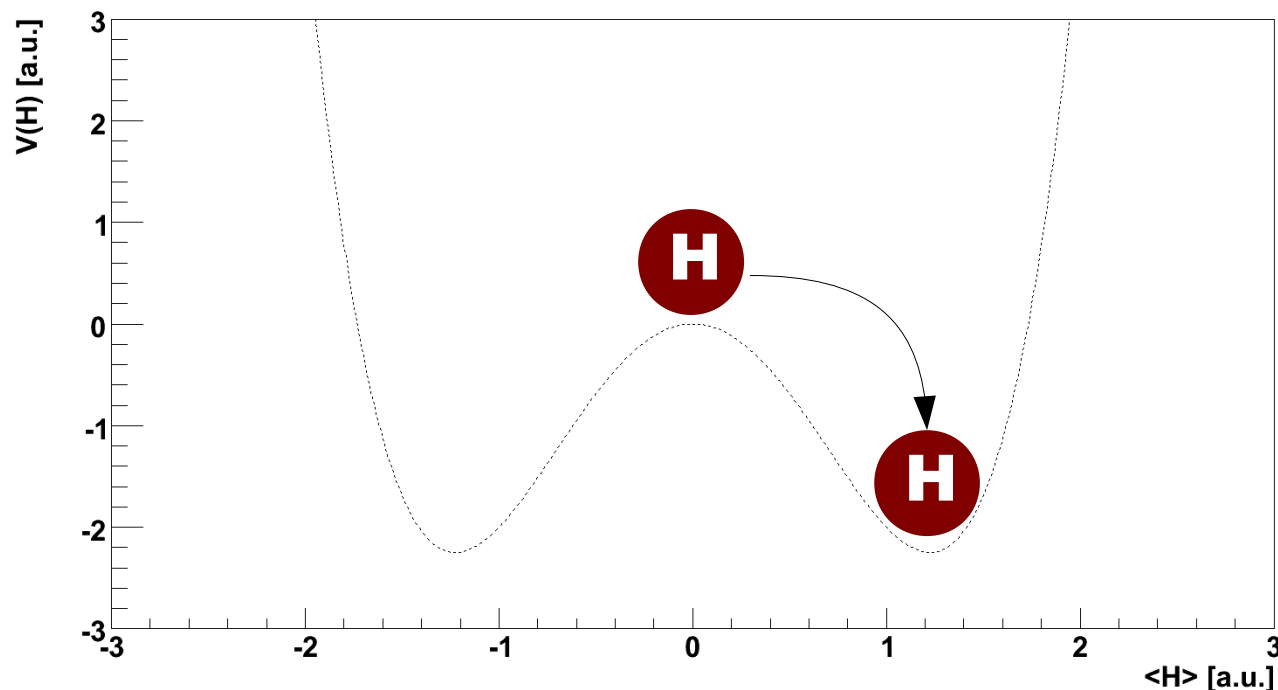
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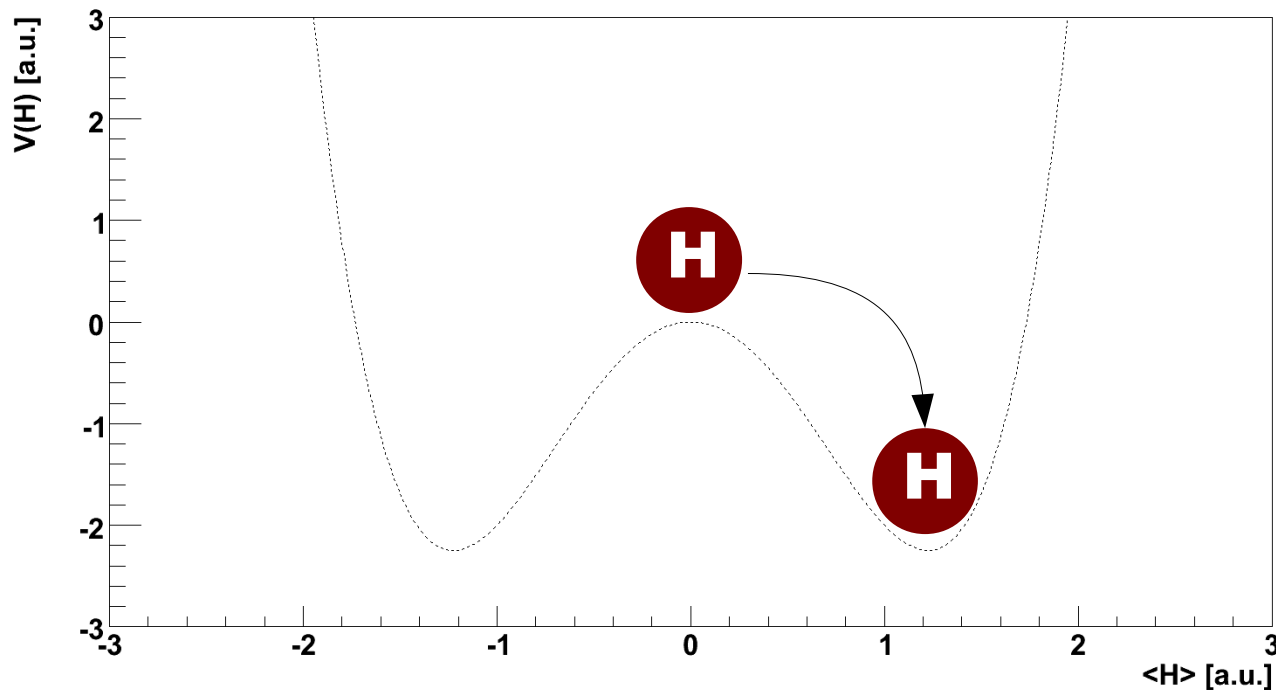
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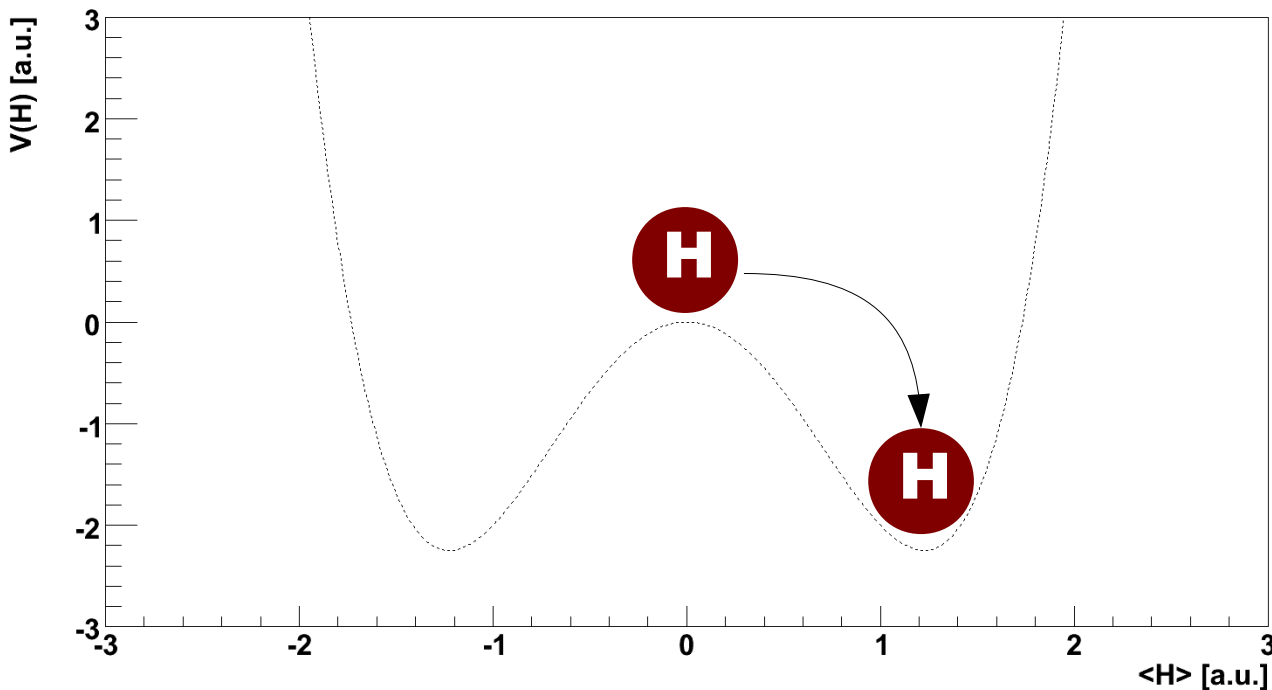
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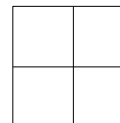
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The W-Boson



- Example: The W-boson

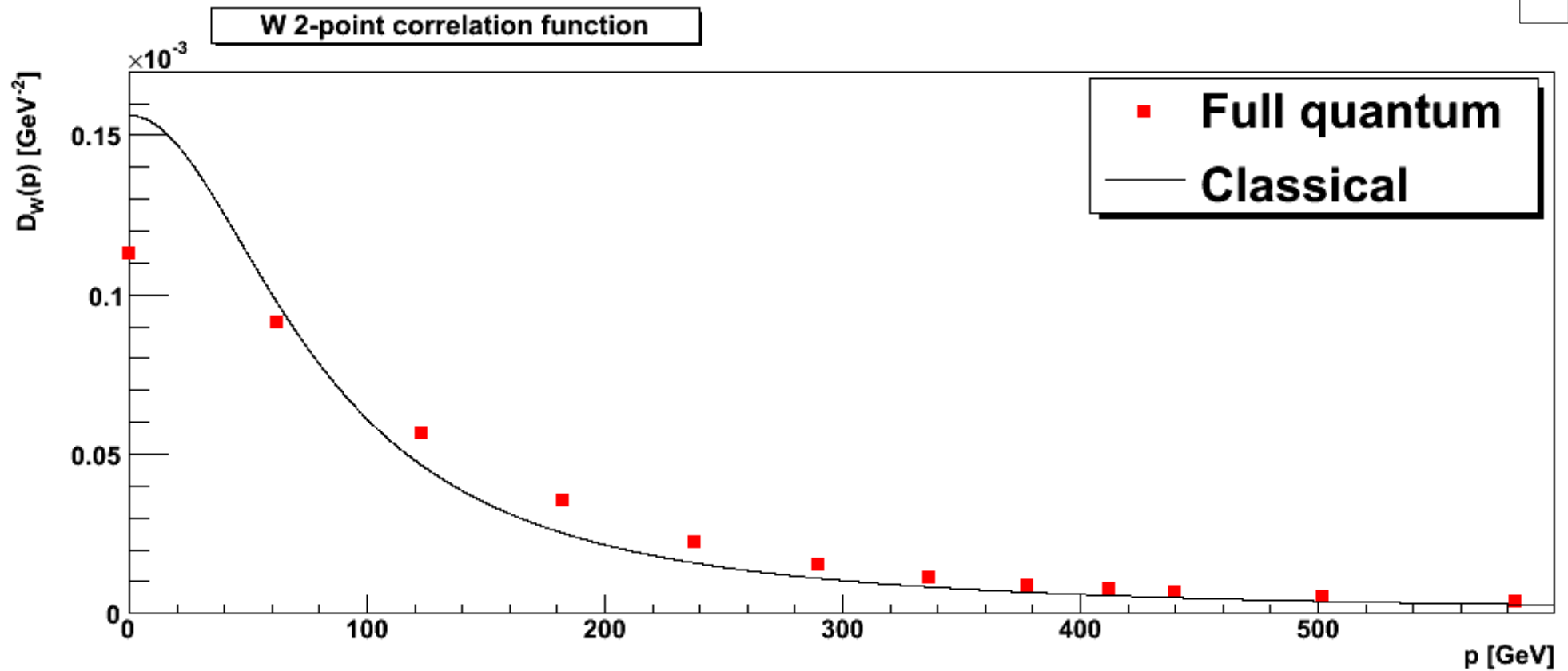
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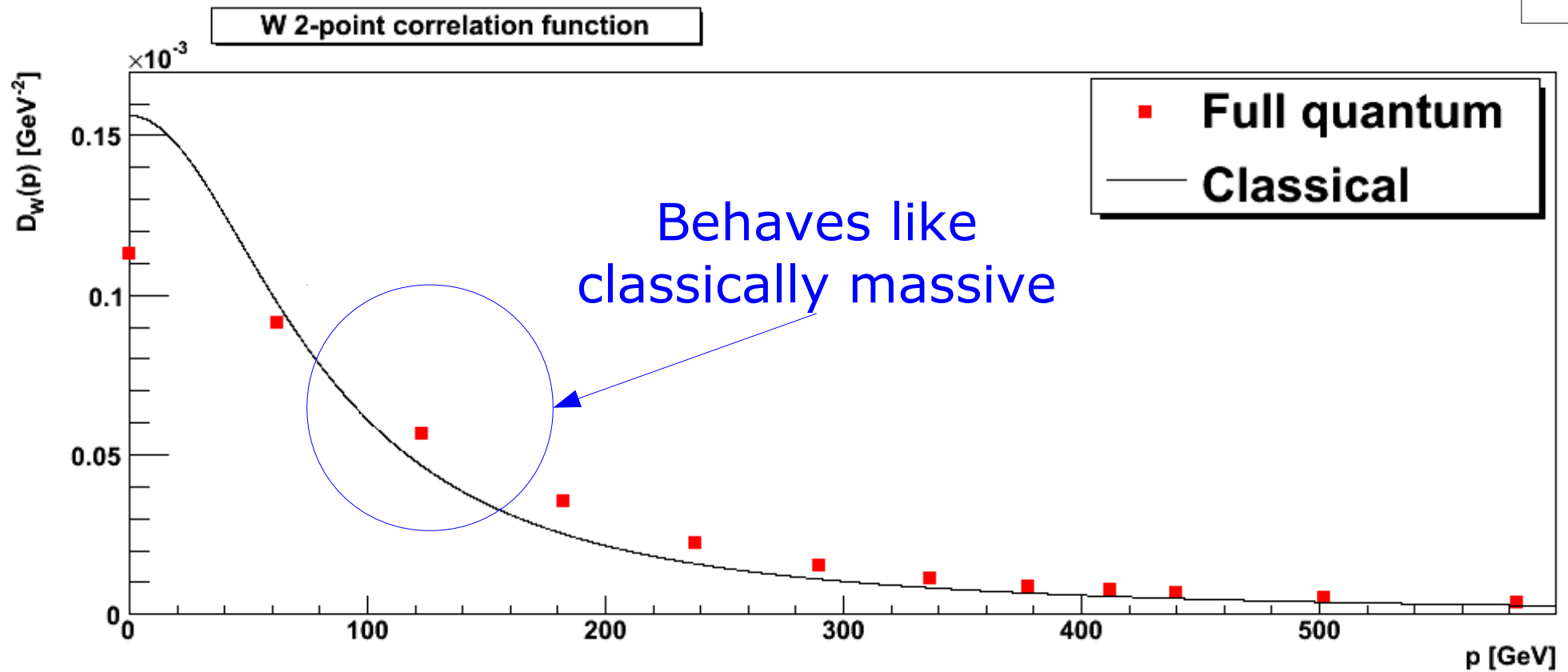
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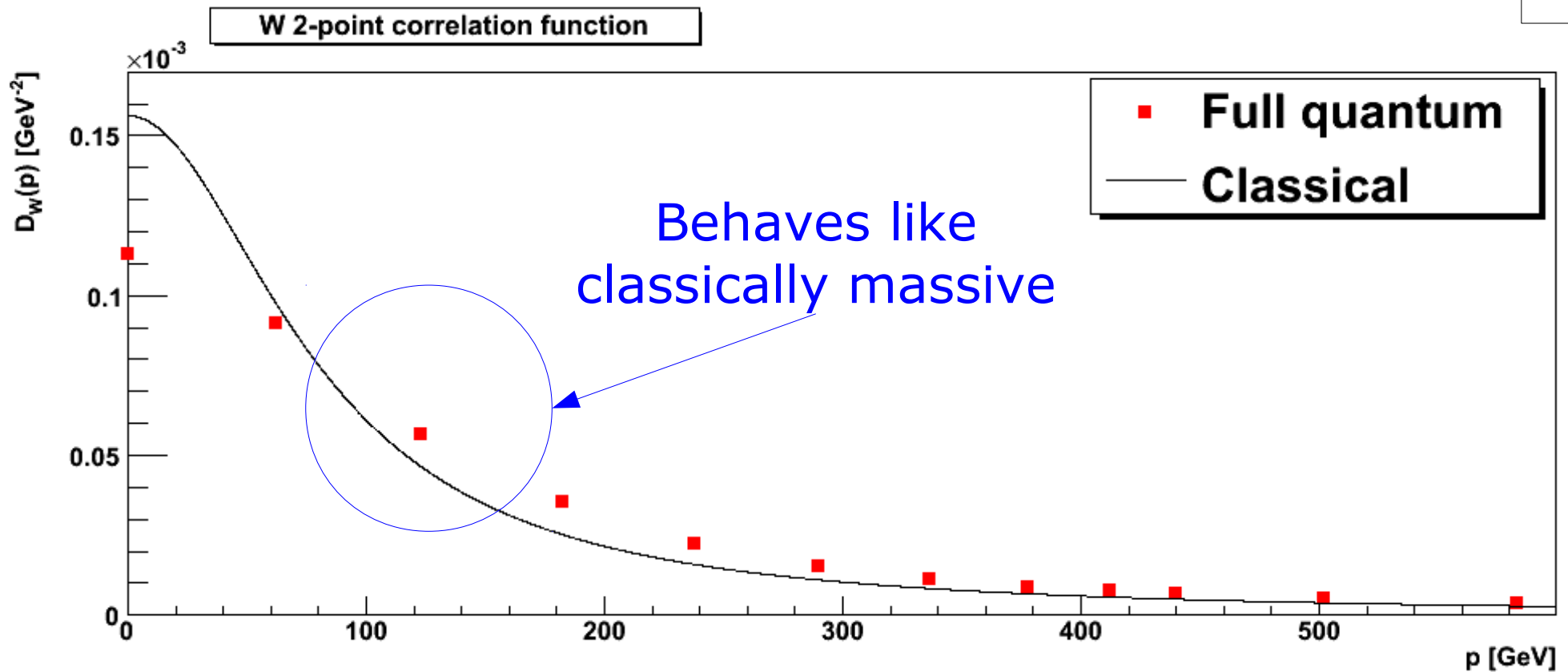
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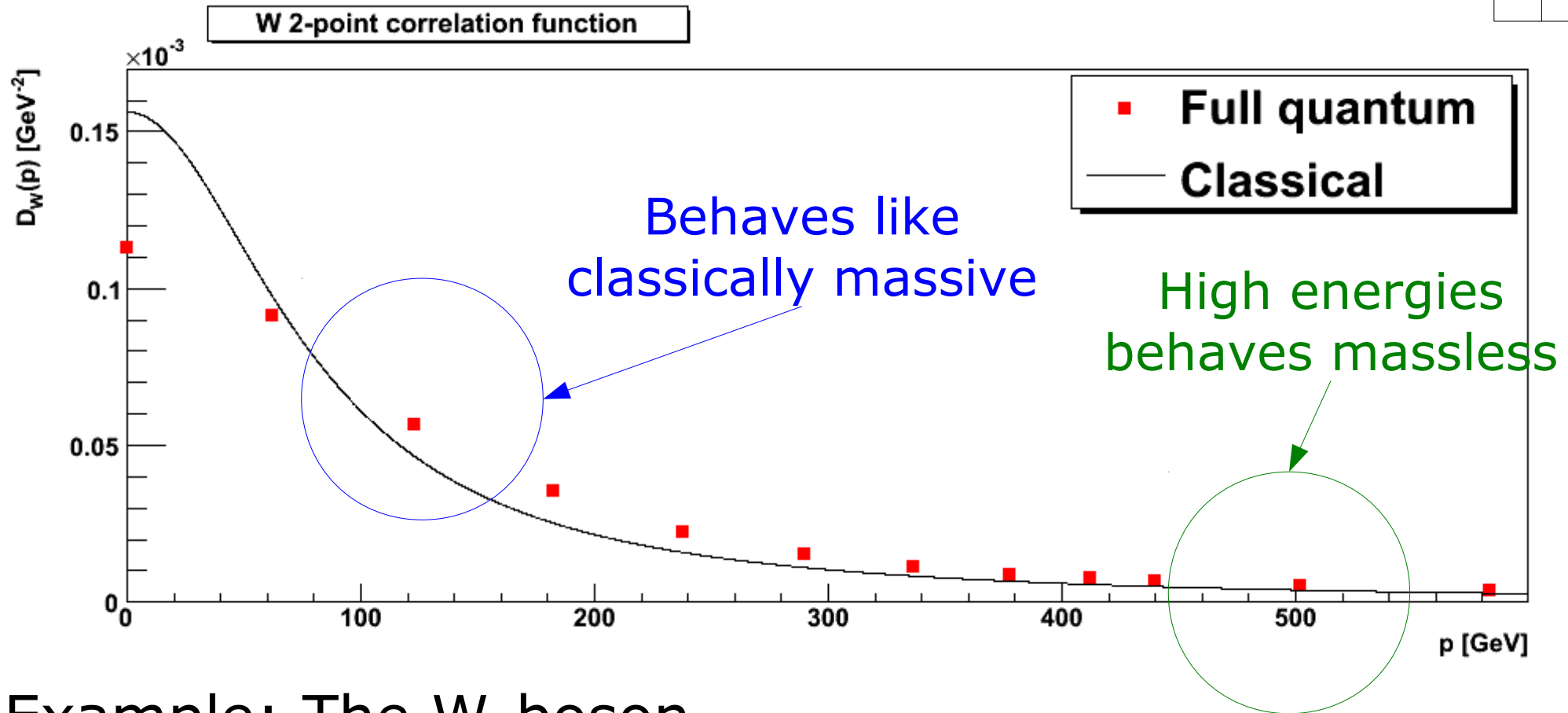
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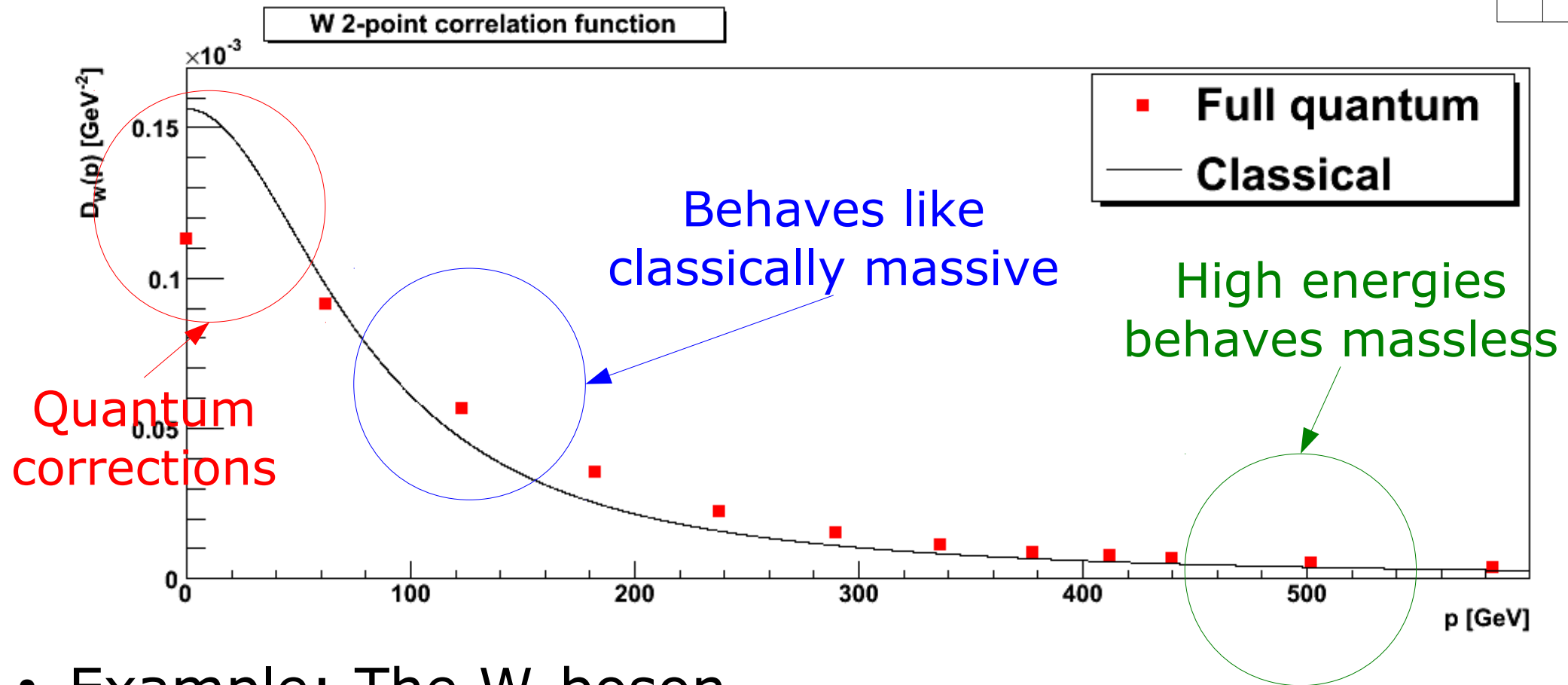
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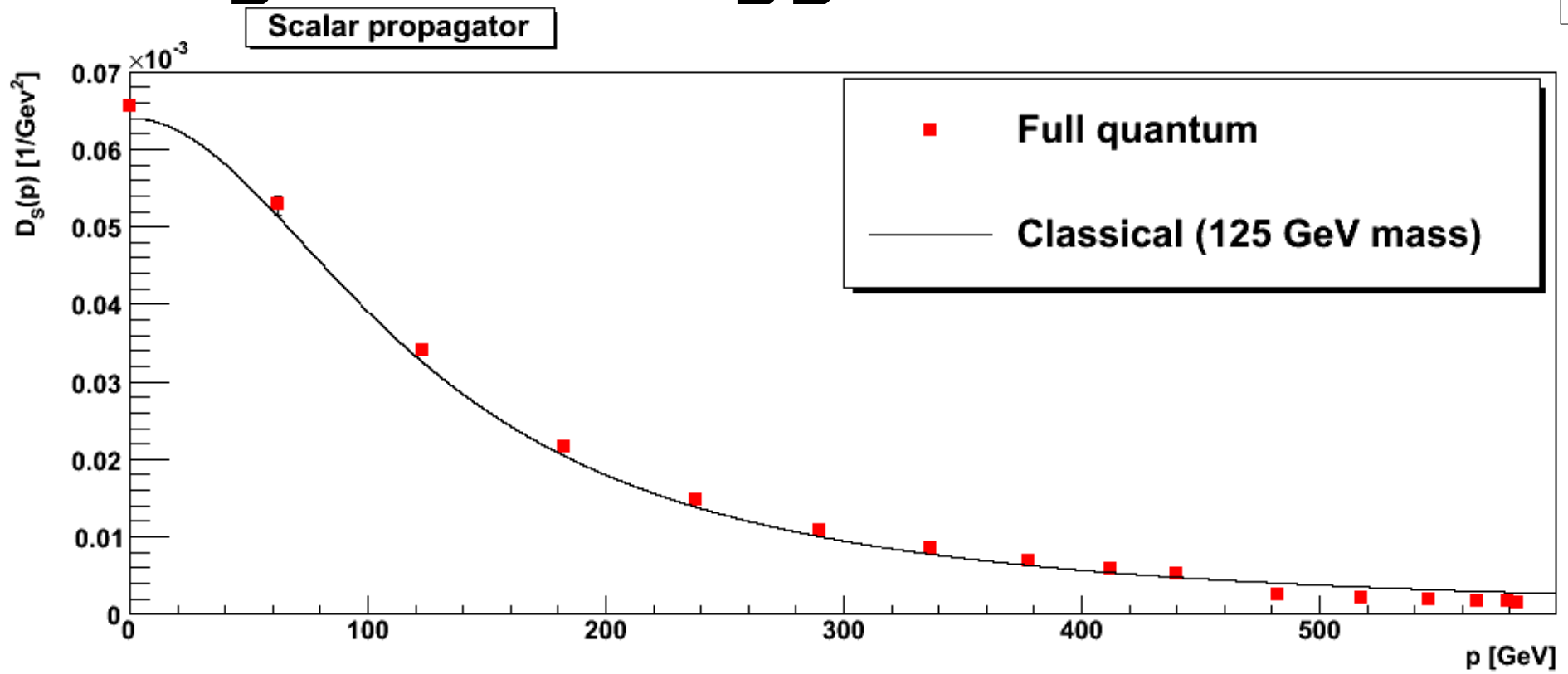
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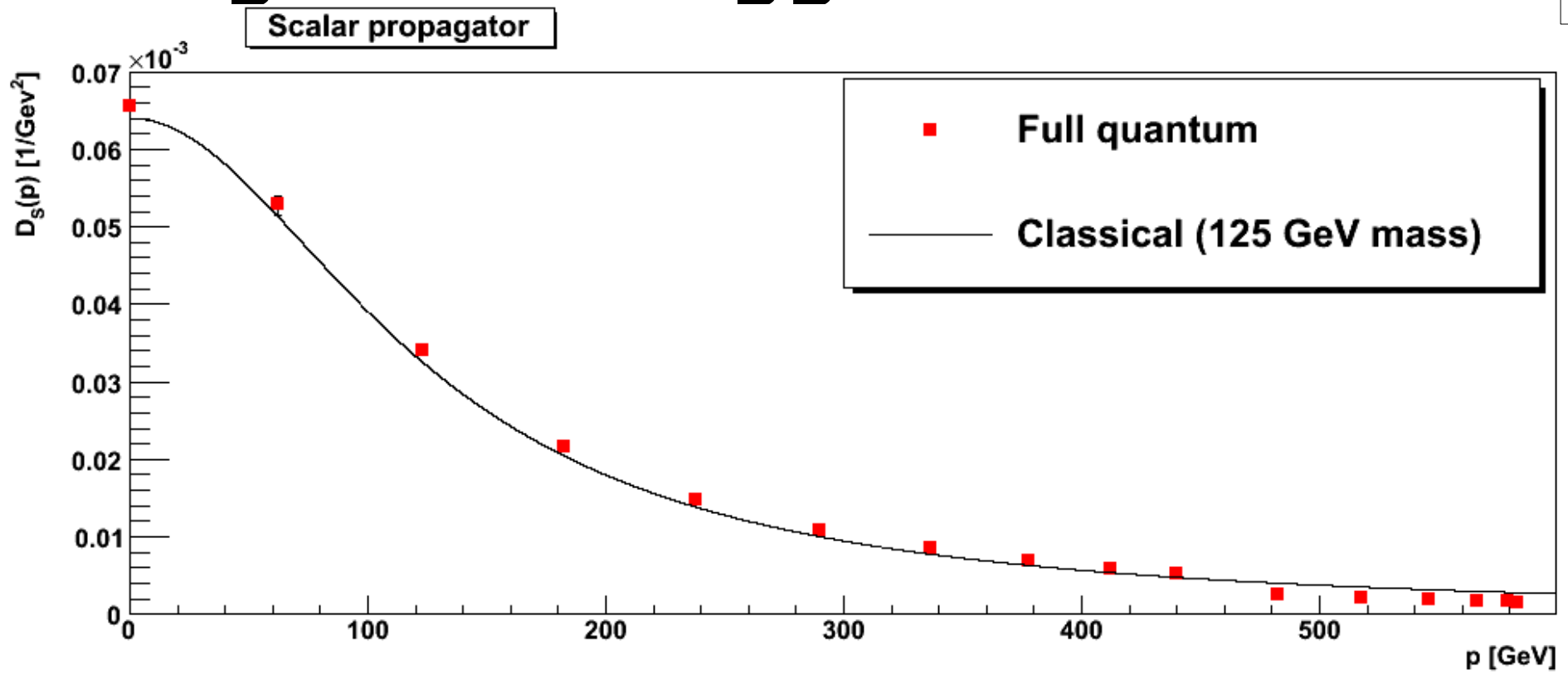
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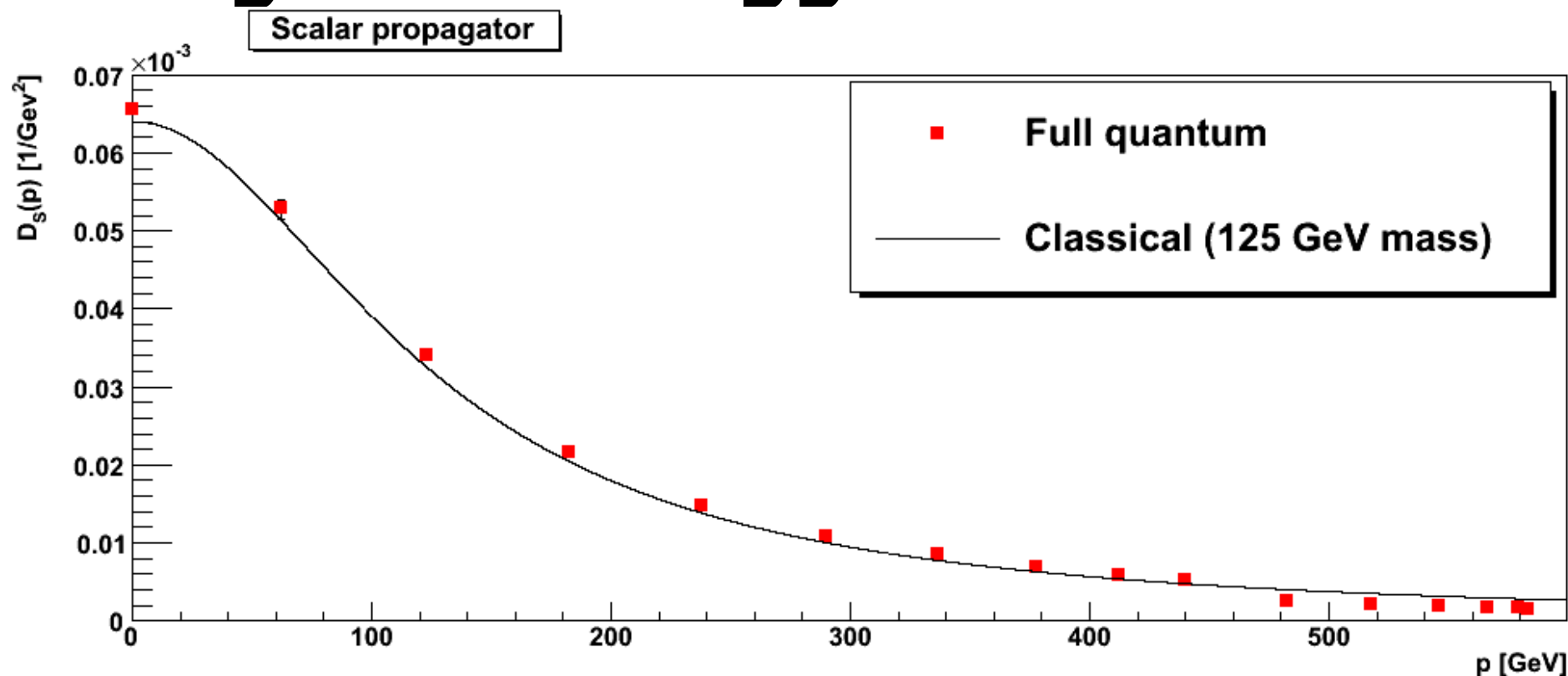
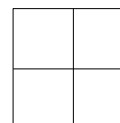
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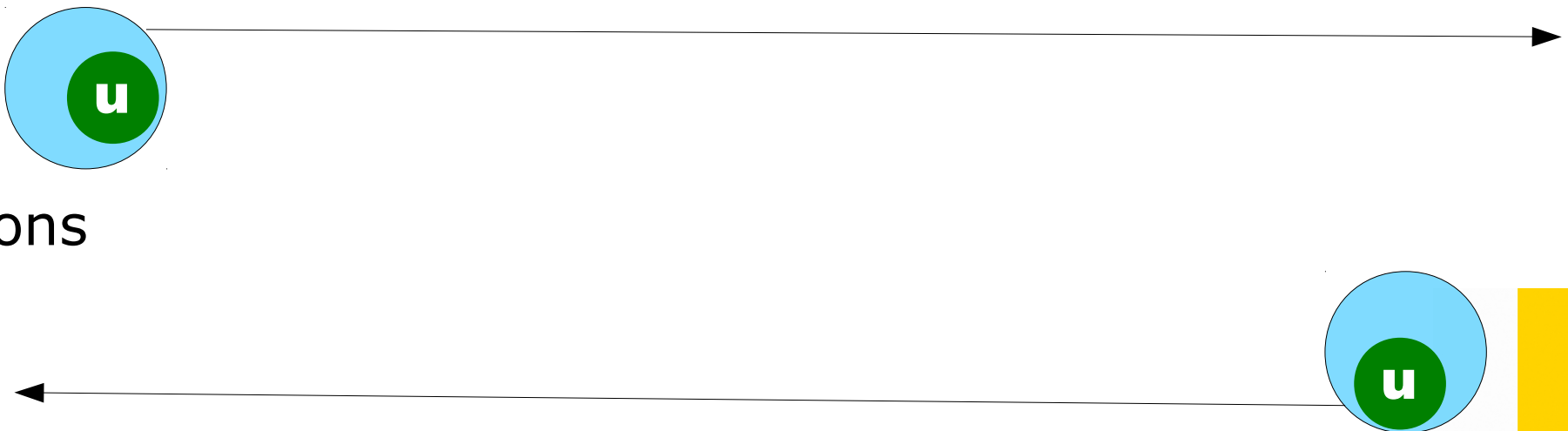
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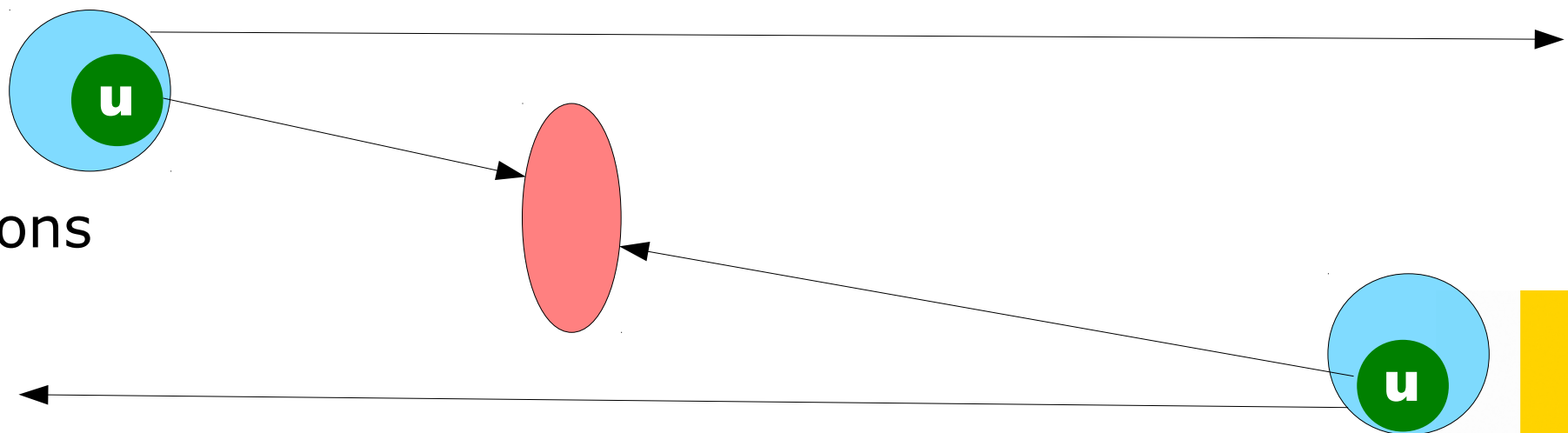
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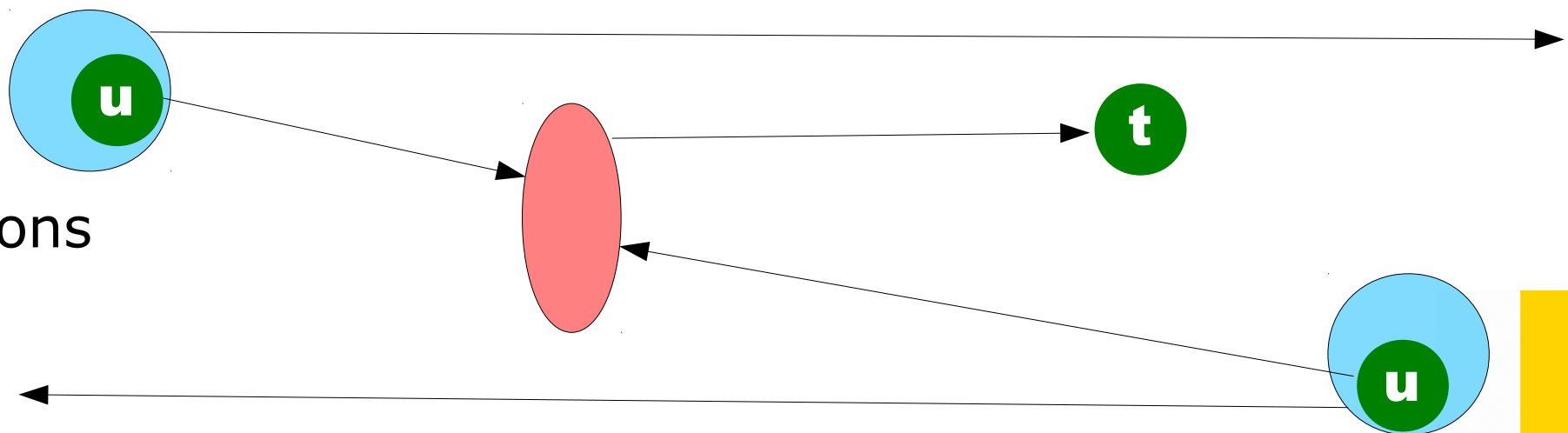
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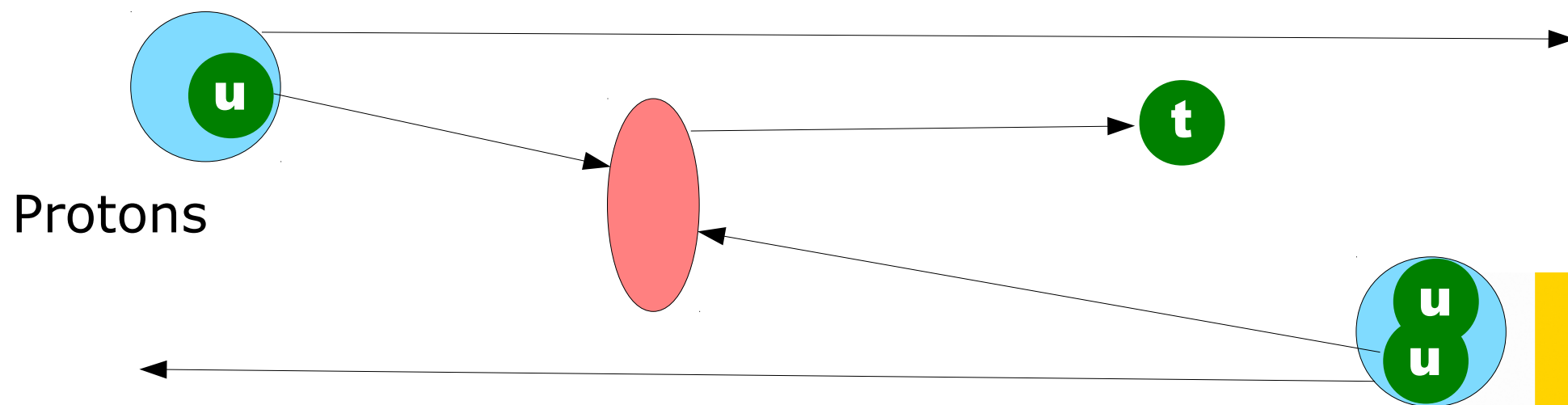
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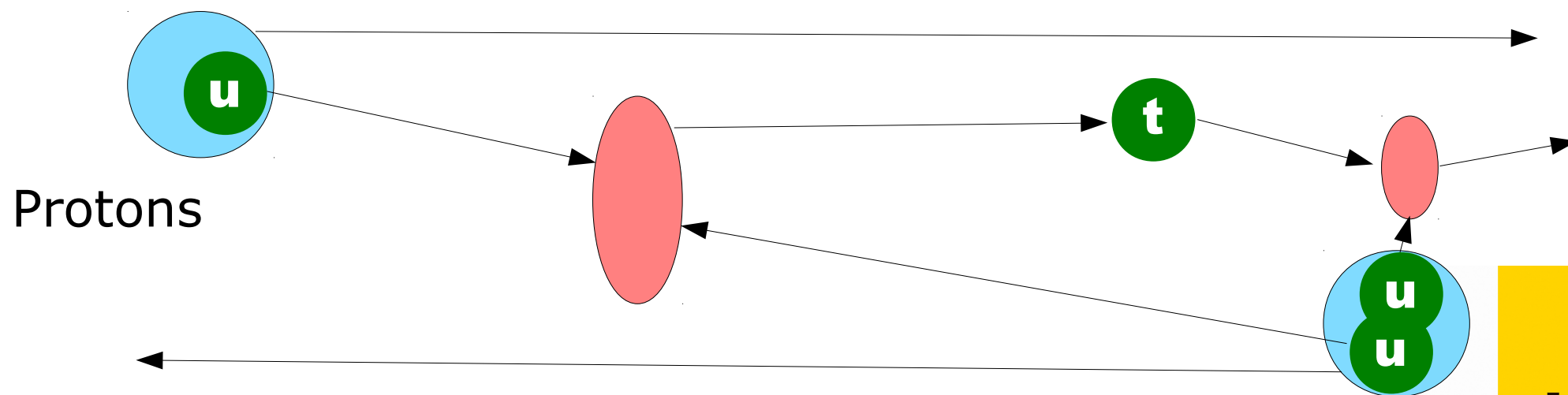
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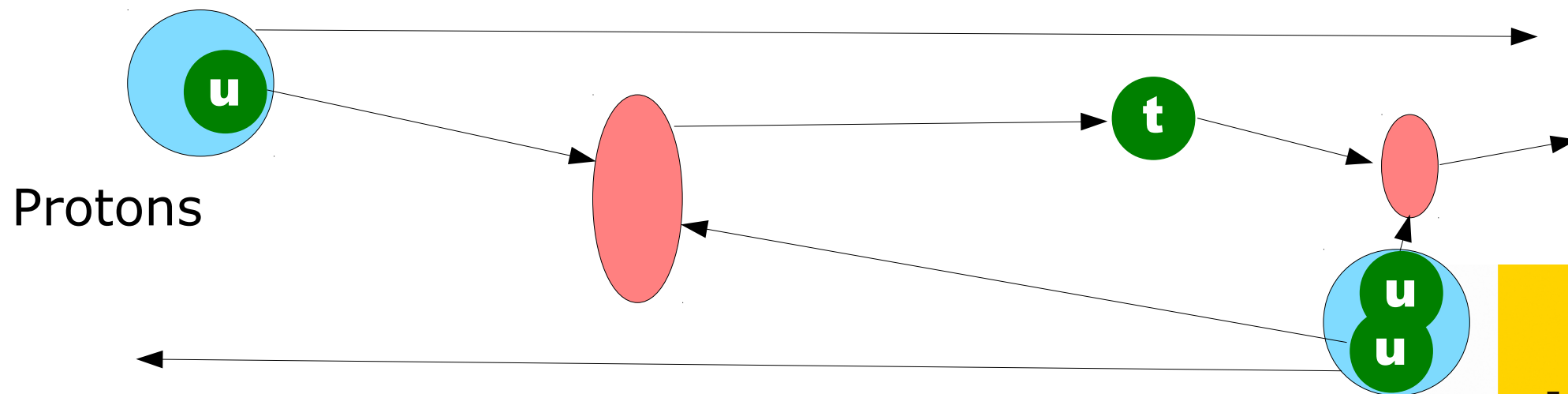
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Beyond the standard model

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 - Learn the systematics of the theories to identify promising candidates

Technicolor – The search

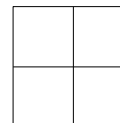
- Which technicolor theories have these properties?
 - **Current search**: Number and charges of Techniquarks
 - Check each theory whether it is viable
 - Learn the systematics of the theories to identify promising candidates
 - Compare predictions to experiments
 - Very hard
 - **Most results yet very approximative**

Technigluon properties

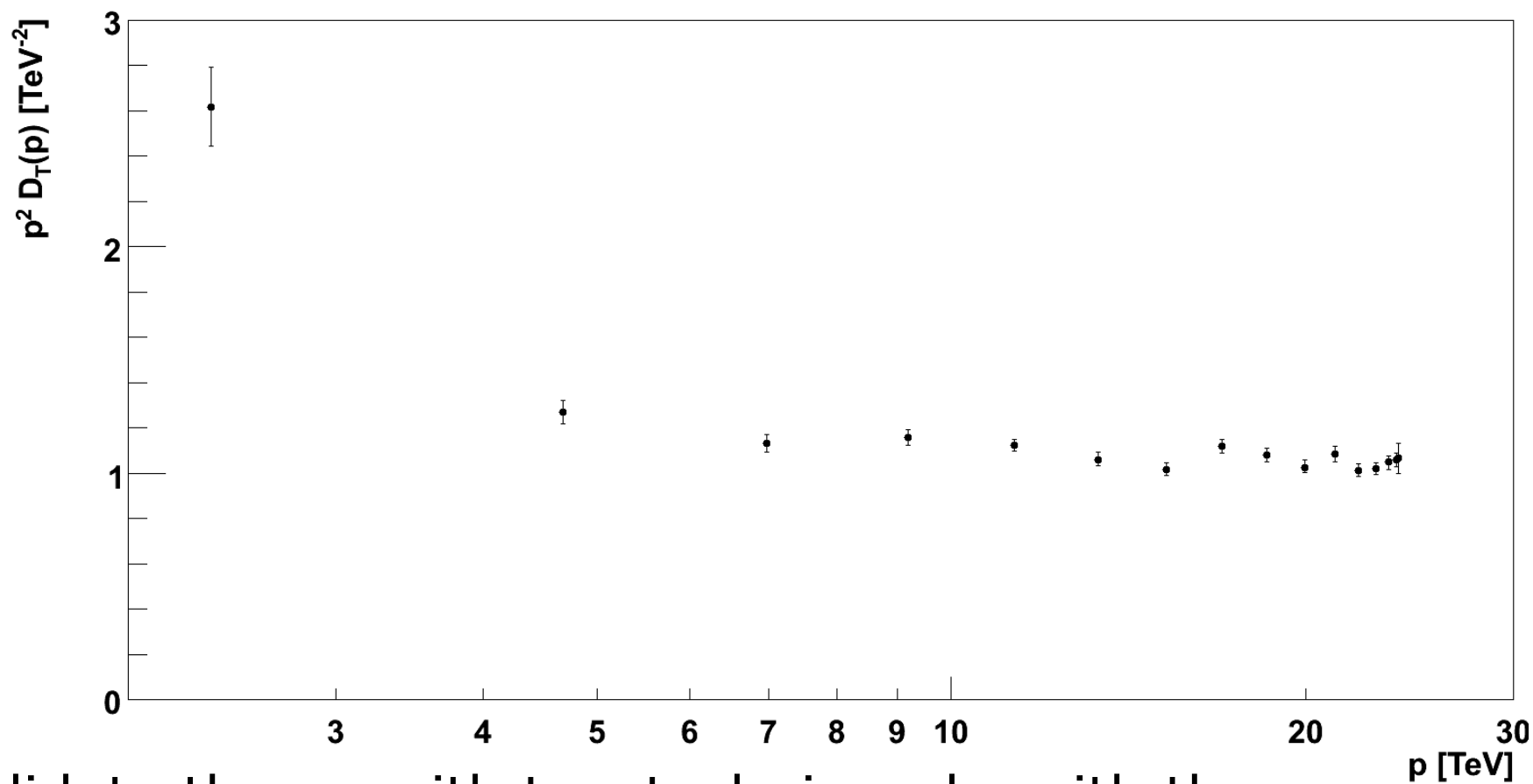
- Candidate theory with two techniquarks with the same charge as the technigluons

Technigluon properties

[Maas, unpublished]



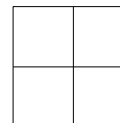
Technigluon 2-point function



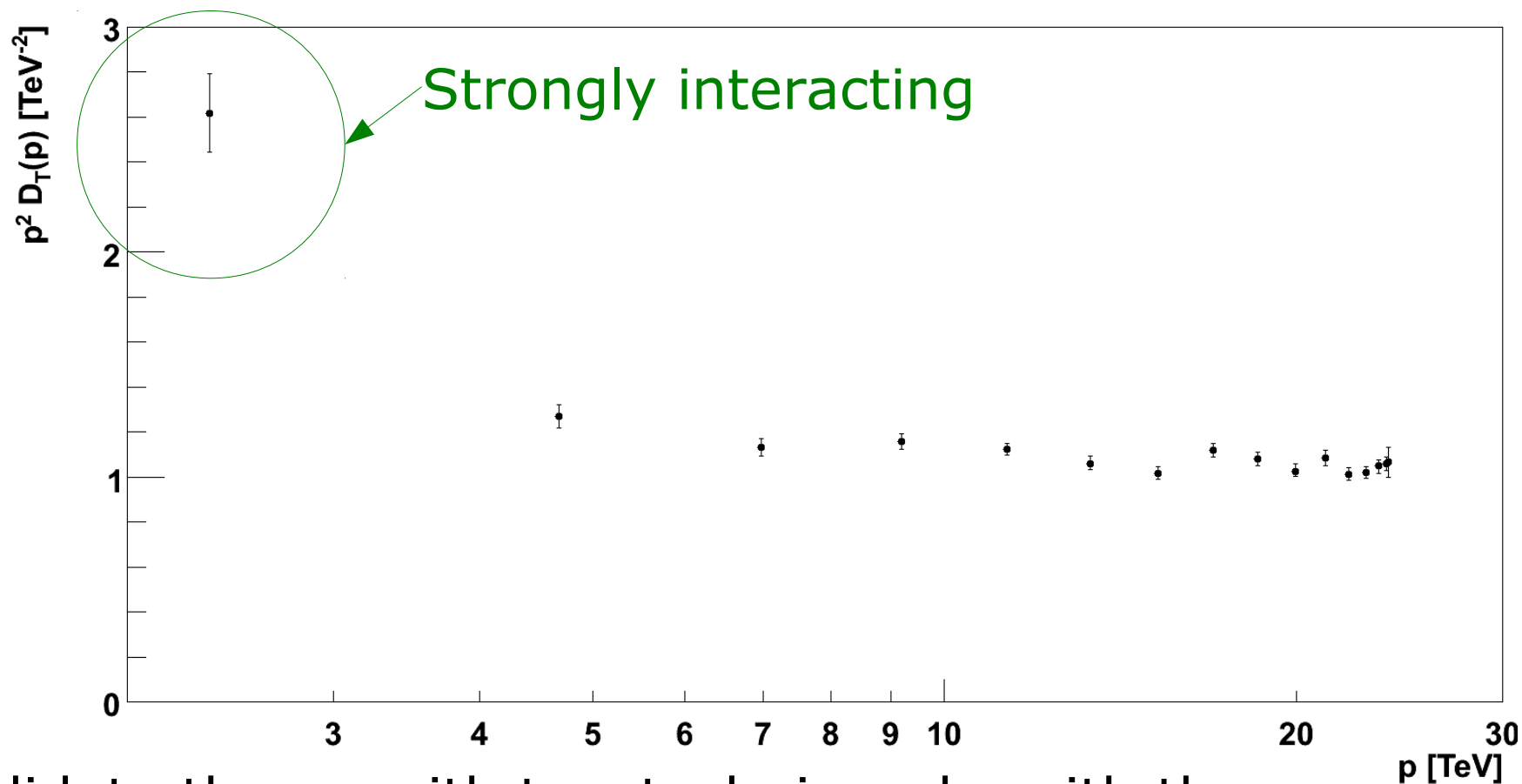
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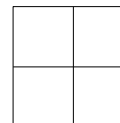
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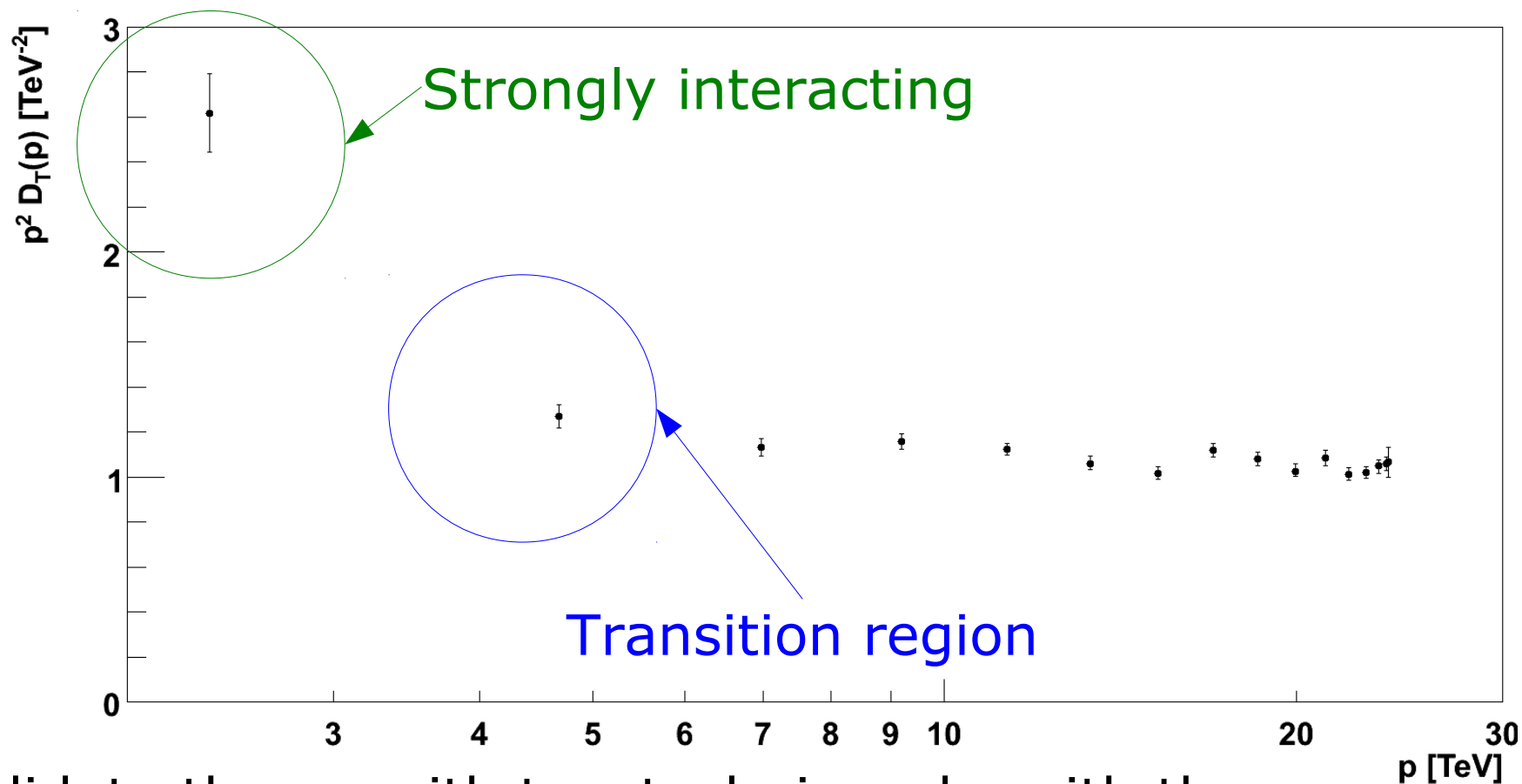
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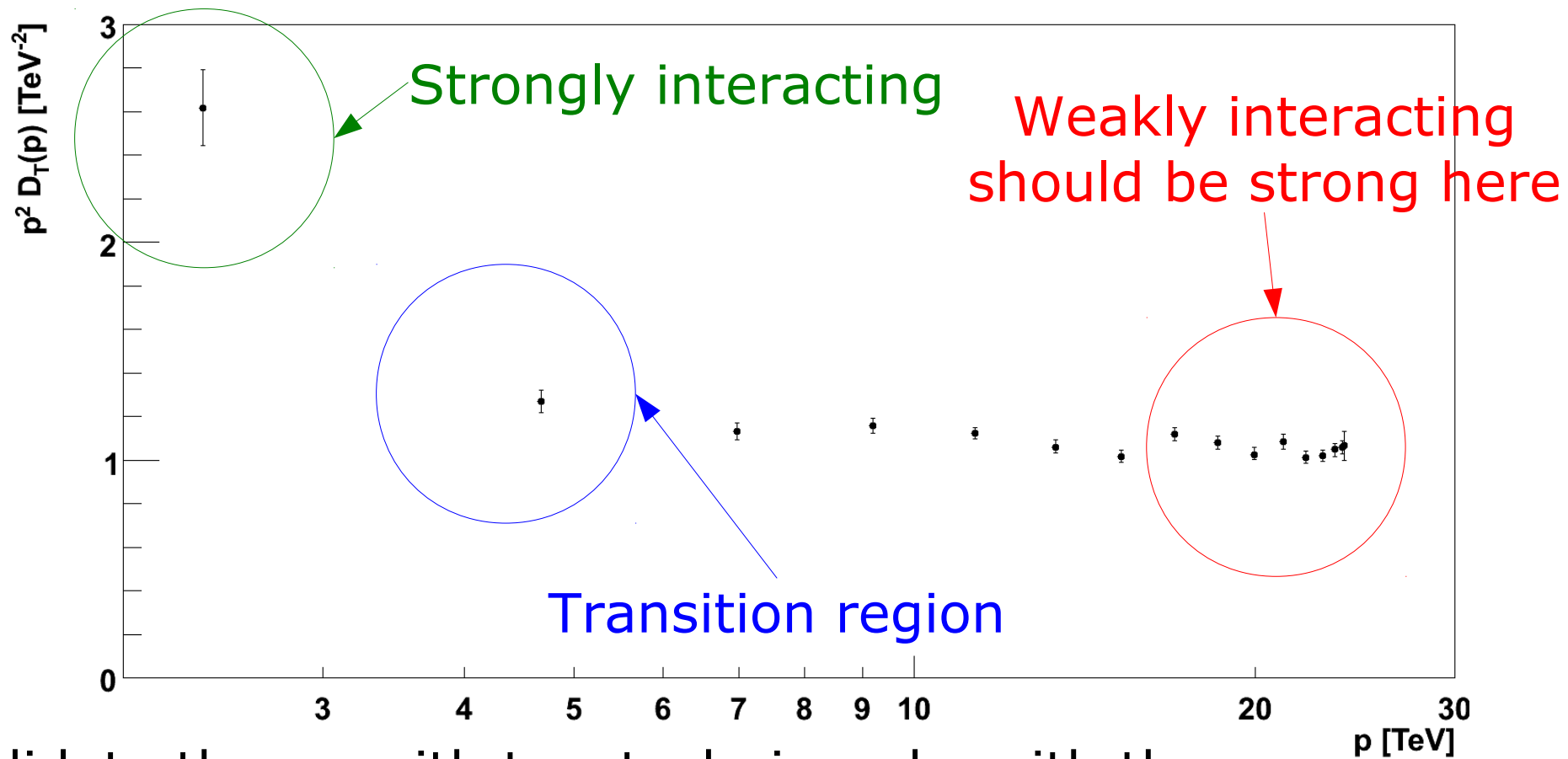
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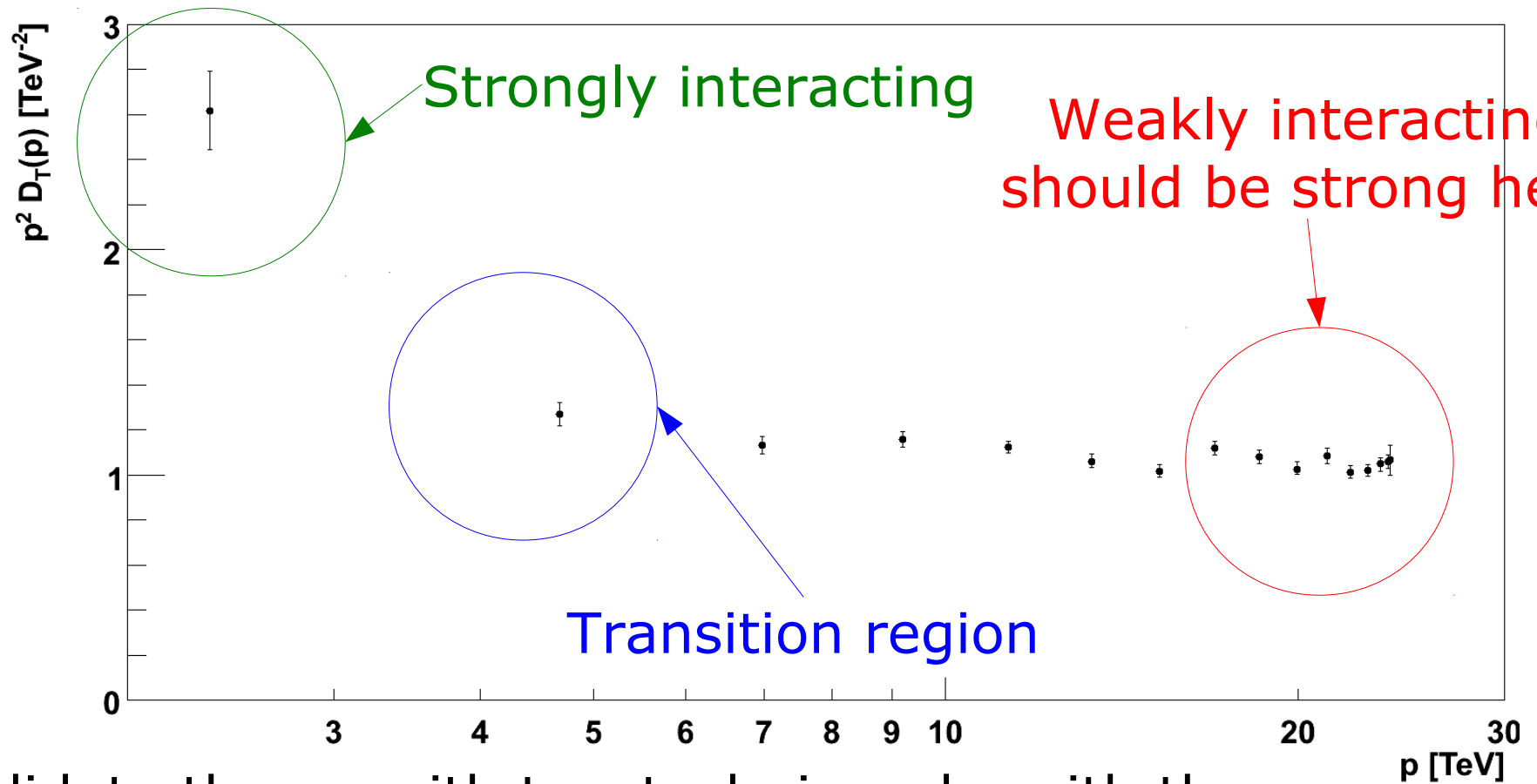
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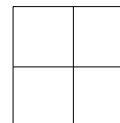
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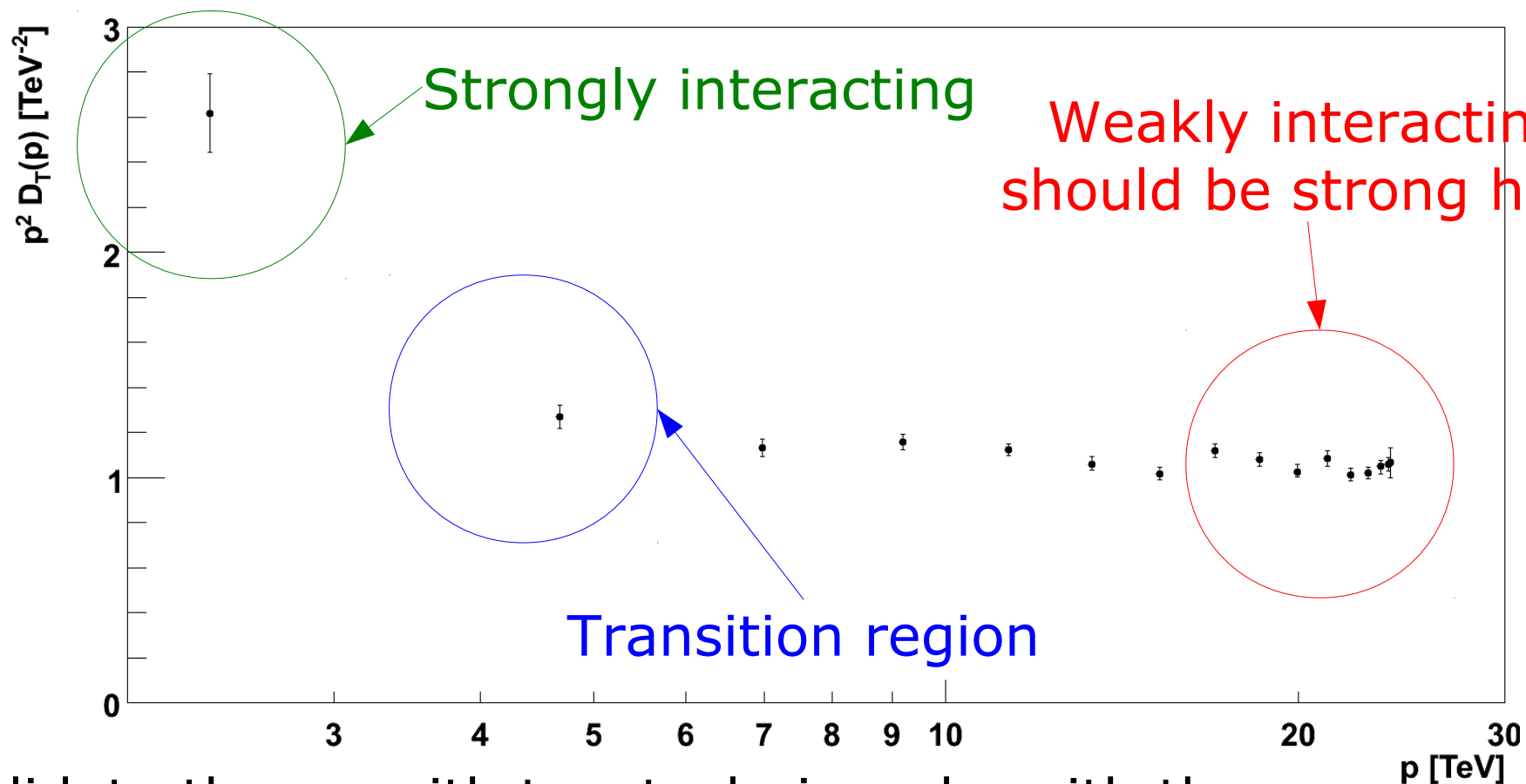
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- Not yet large enough strong interaction domain

Technigluon properties

[Maas, unpublished]



Technigluon 2-point function



- Candidate theory with two techniquarks with the same charge as the technigluons
- Not yet large enough strong interaction domain
- But has other peculiar features (almost scale-invariant)

Summary

- Strong interactions are abundant in the standard model and in its extensions
 - Can be present directly or indirectly

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 - Can be present directly or indirectly
- Require adequate non-perturbative methods
 - Combination of numerical and analytical methods most successful
 - Many subtleties
 - Gauge theories are more complicated than anticipated
- Control over strong interactions is slowly but steadily developed