Searching for new physics at the Large Hadron Collider

Chris Monahan
William & Mary/Jefferson Lab

Searching for new physics

What was wrong with the old physics, anyway?

Flavour physics

Where is all the new physics hiding?

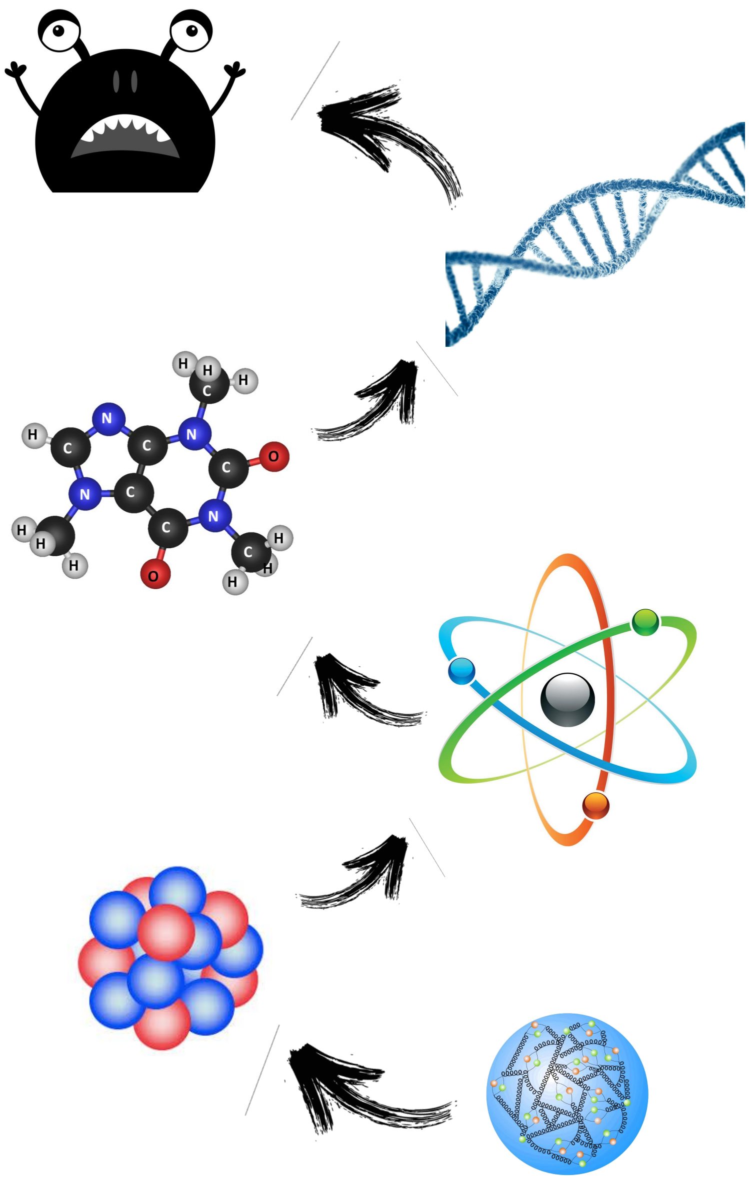
Lattice QCD

What is that and why?

Searching for new physics

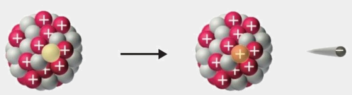
What was wrong with the old physics, anyway?

MATTER

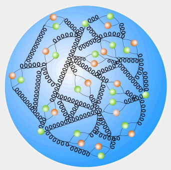


FORCES

Electromagnetism



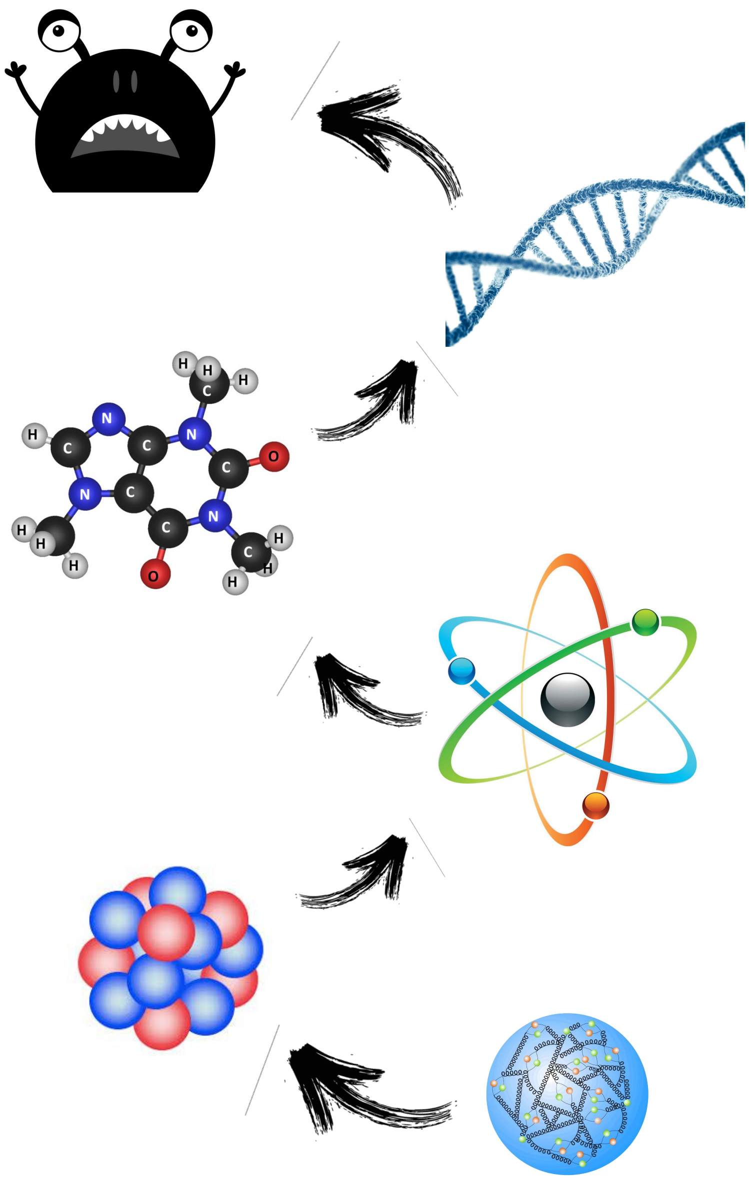
Weak force



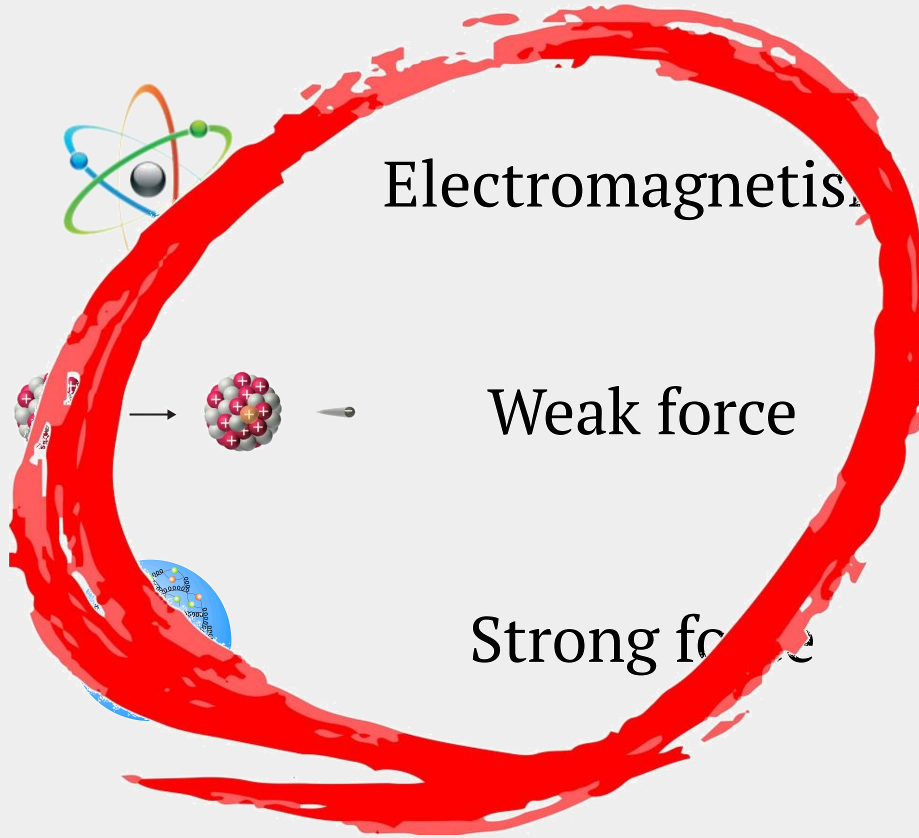
Strong force

Gravity

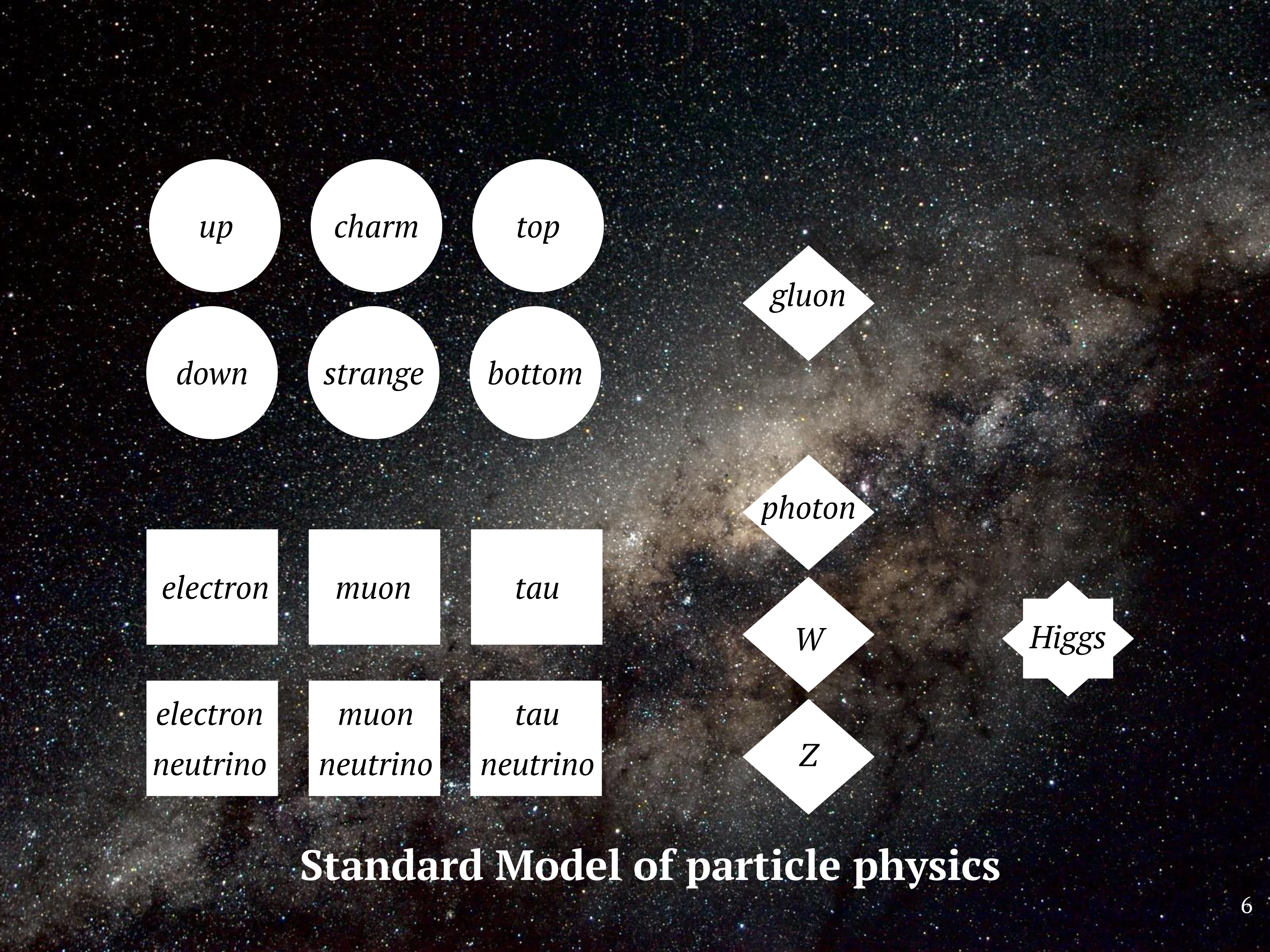
MATTER



FORCES



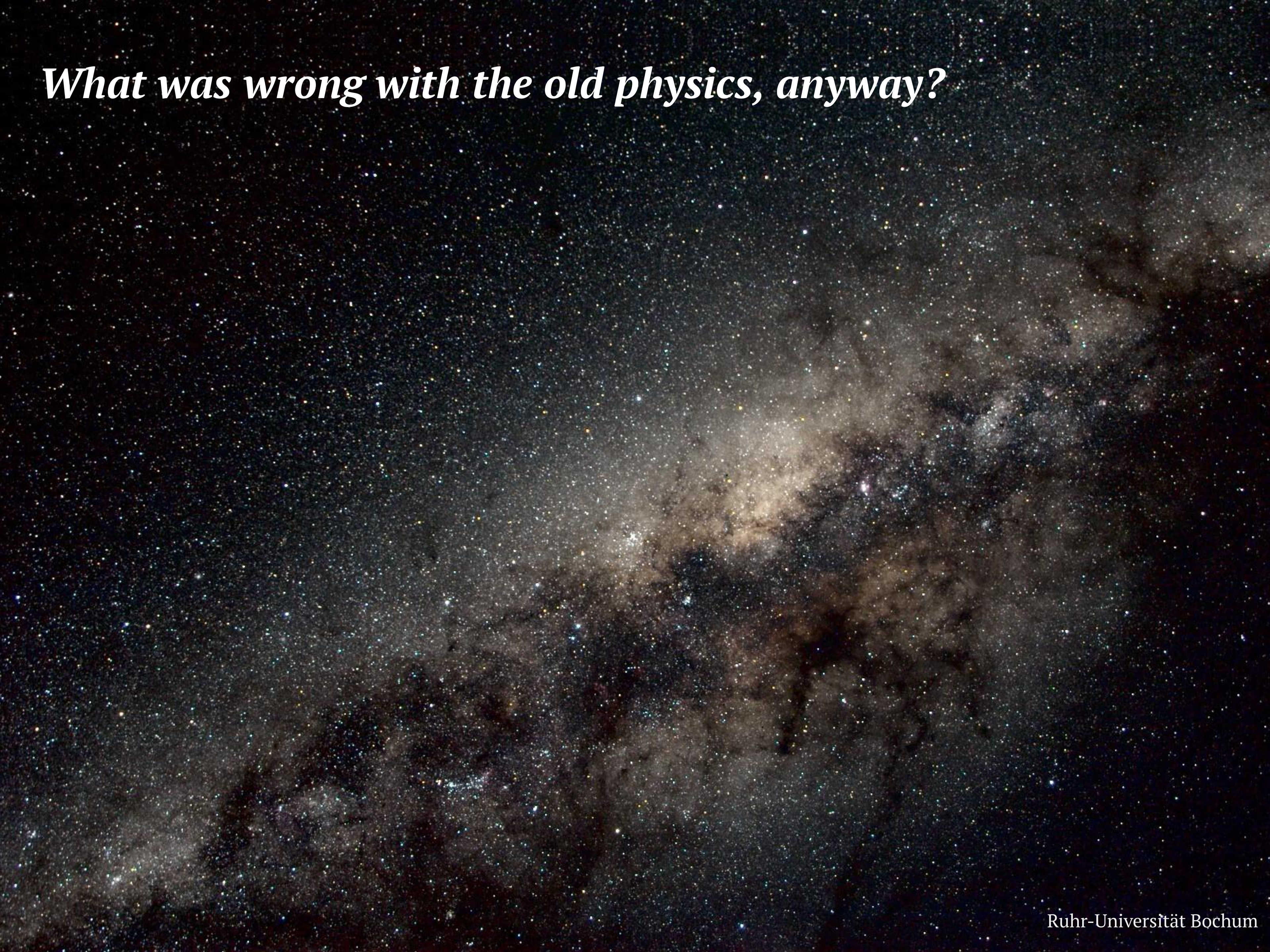
The old physics:
The Standard Model
(of particle physics)



Standard Model of particle physics

Ruhr-Universität Bochum

What was wrong with the old physics, anyway?



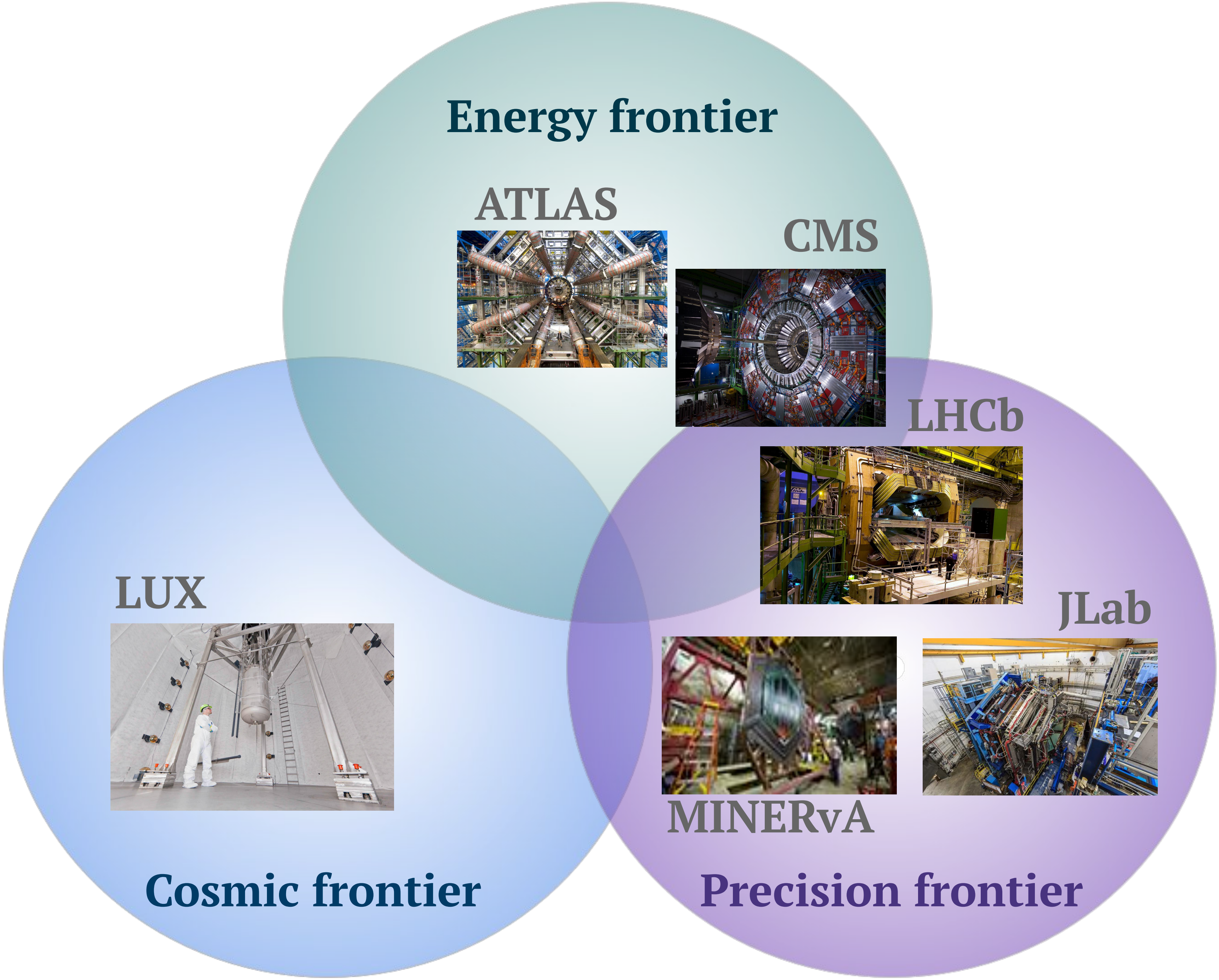
https://www.black-holes.org/

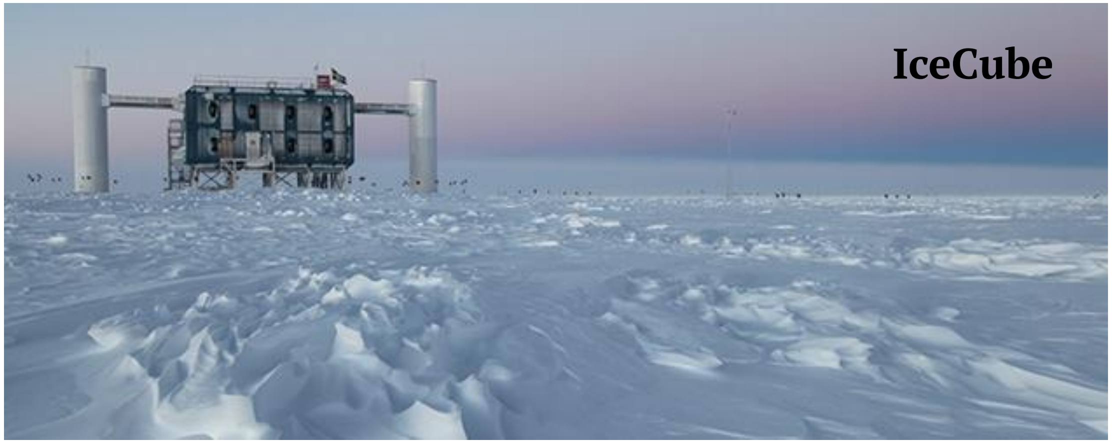
Things the Standard Model explains

All visible matter:
Electromagnetism
Nuclear forces

Things the Standard Model doesn't explain

Dark matter	Neutrino masses	Hierarchy problem
Dark energy	Origin of matter (CP asymmetry)	Strong CP problem
Gravity	Origin of Standard Model parameters	Consciousness


Energy frontier
ATLAS
CMS
LHCb
JLab
LUX
MINERvA
Cosmic frontier
Precision frontier

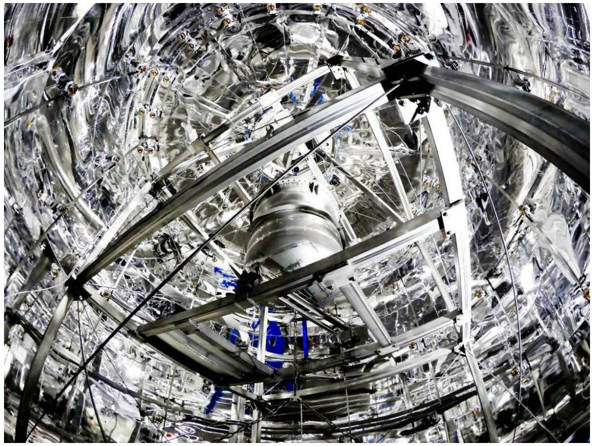


SuperCDMS
SNOLAB

LUX

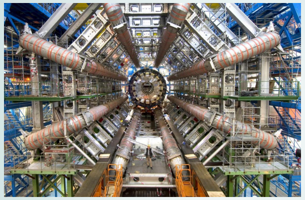
Cosmic frontier

XENON1T

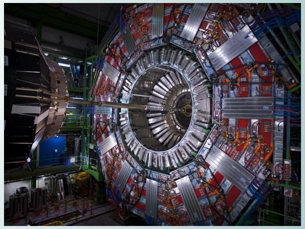


Energy frontier

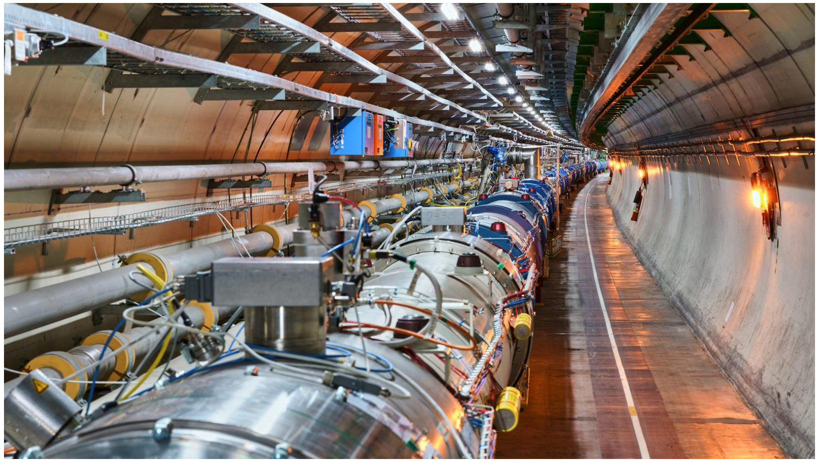
ATLAS



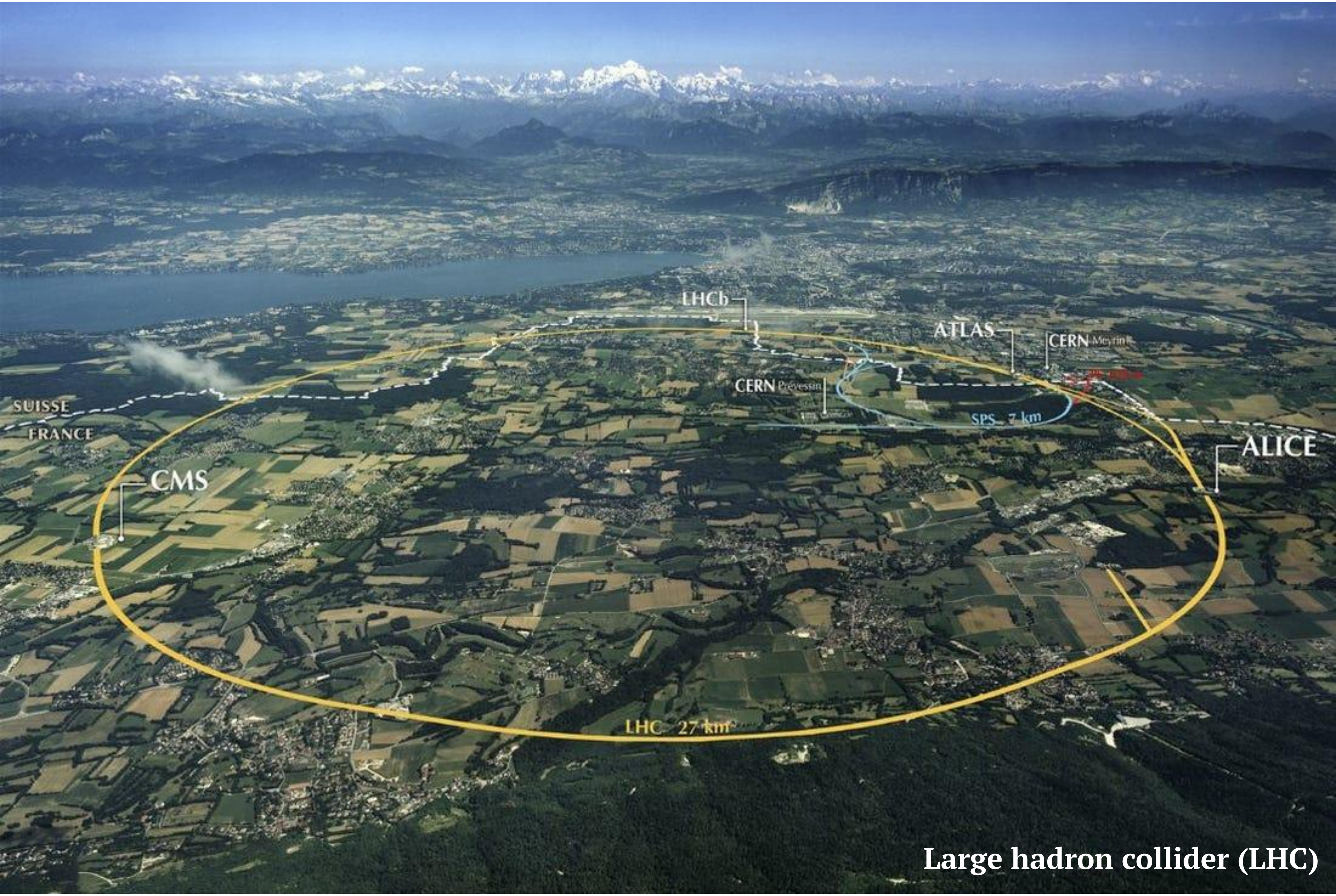
CMS



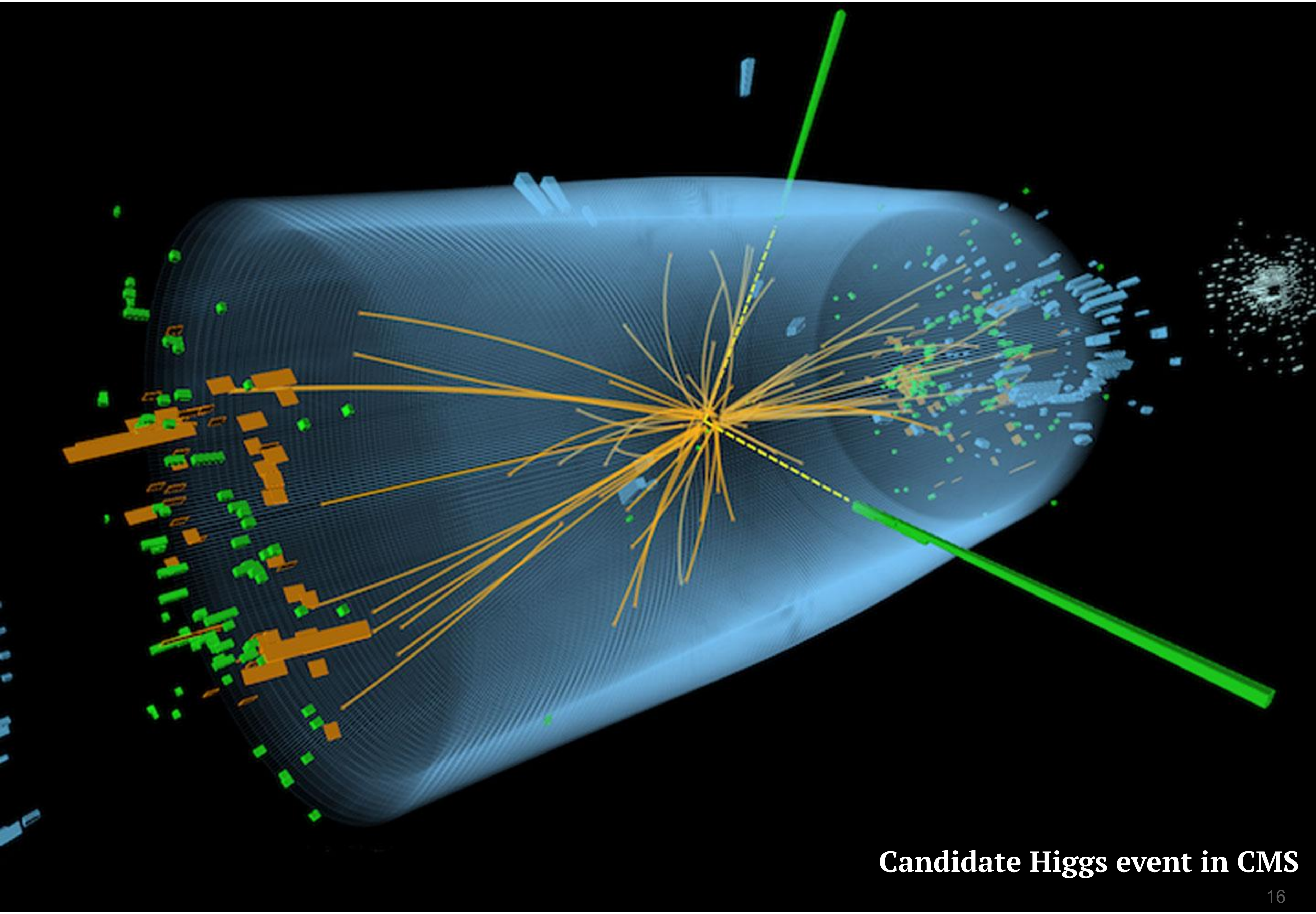
Large hadron collider (LHC)



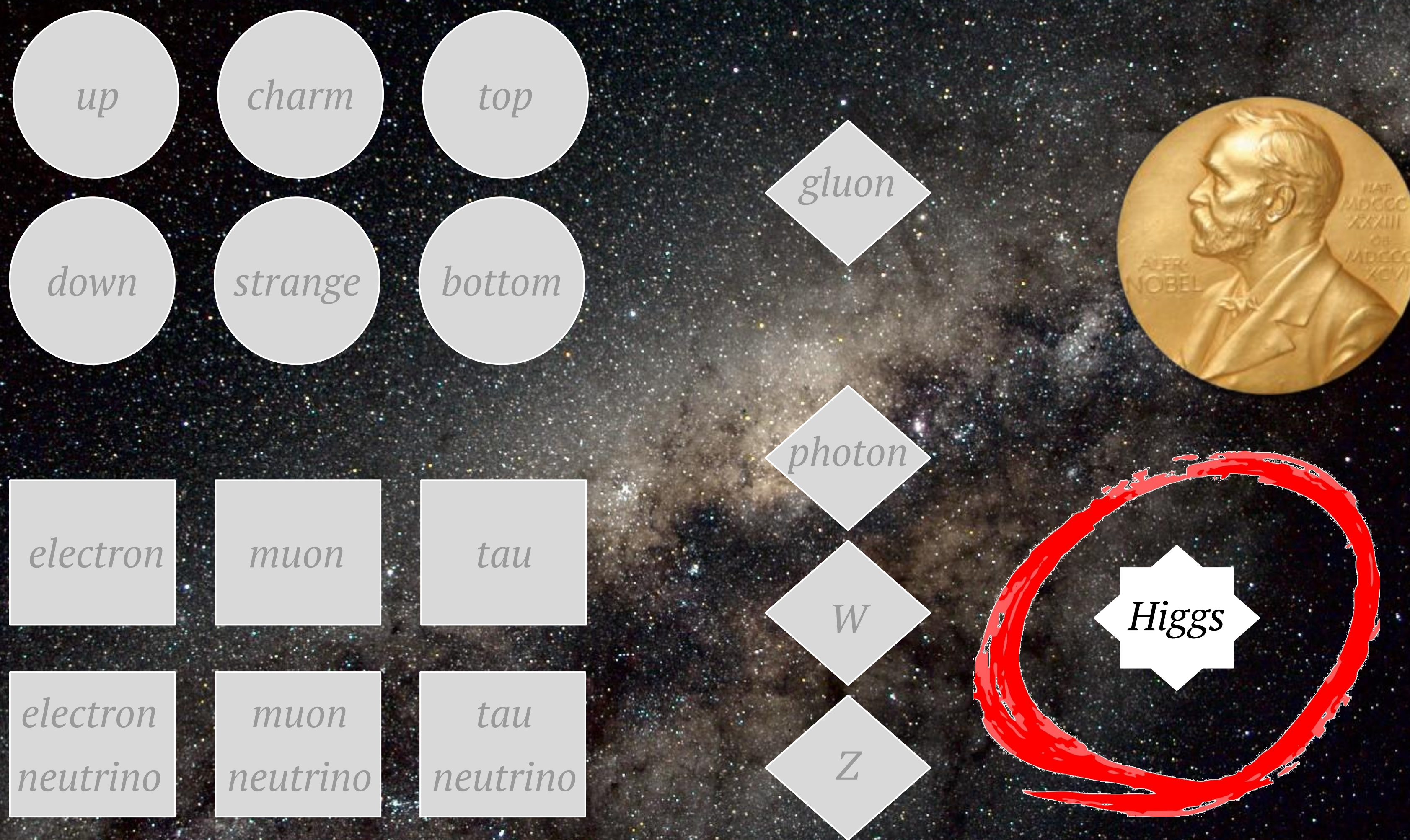
Tevatron (1983-2011)



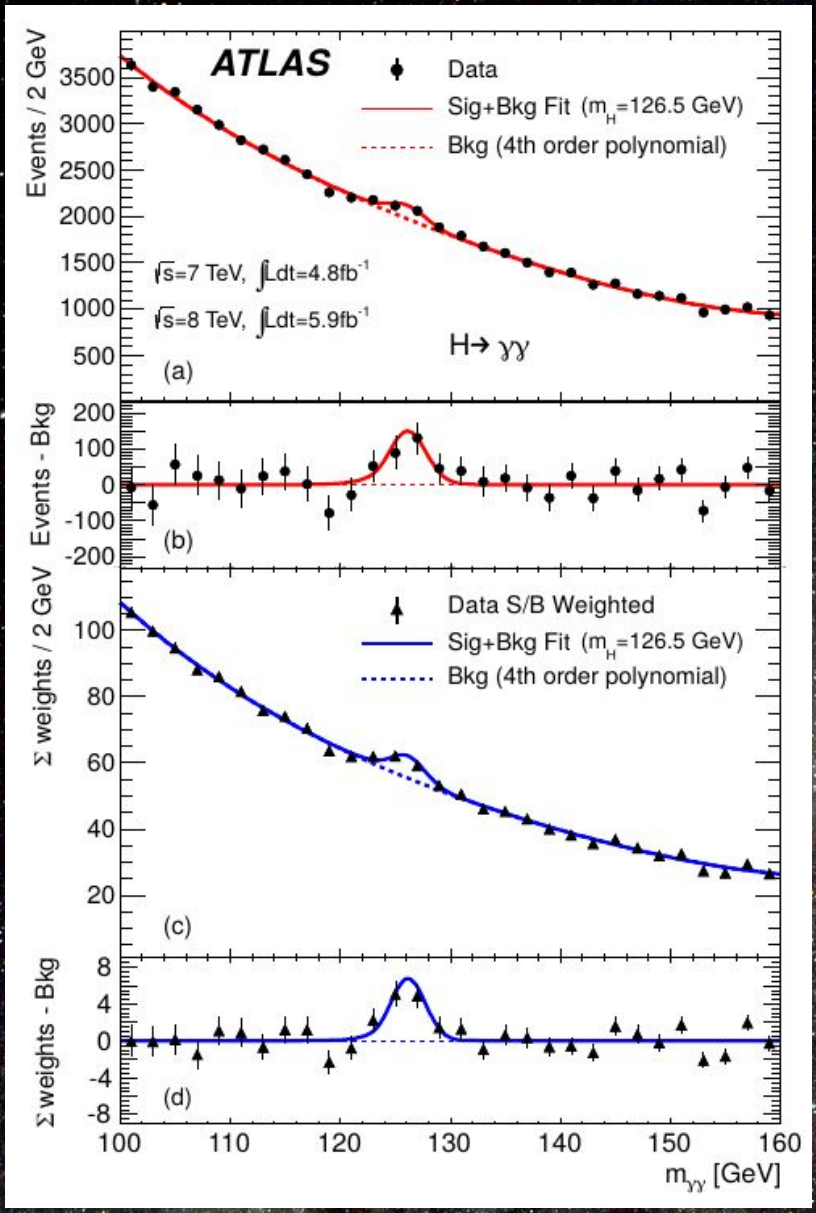
Large hadron collider (LHC)



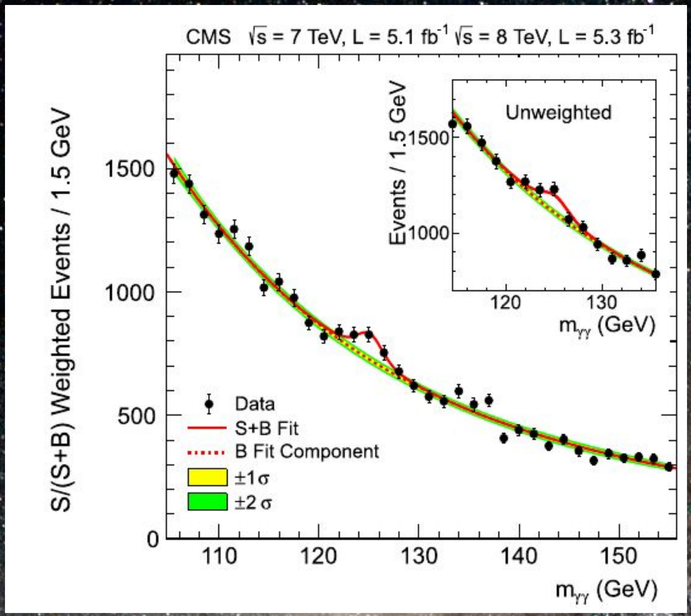
Candidate Higgs event in CMS



Standard Model of particle physics

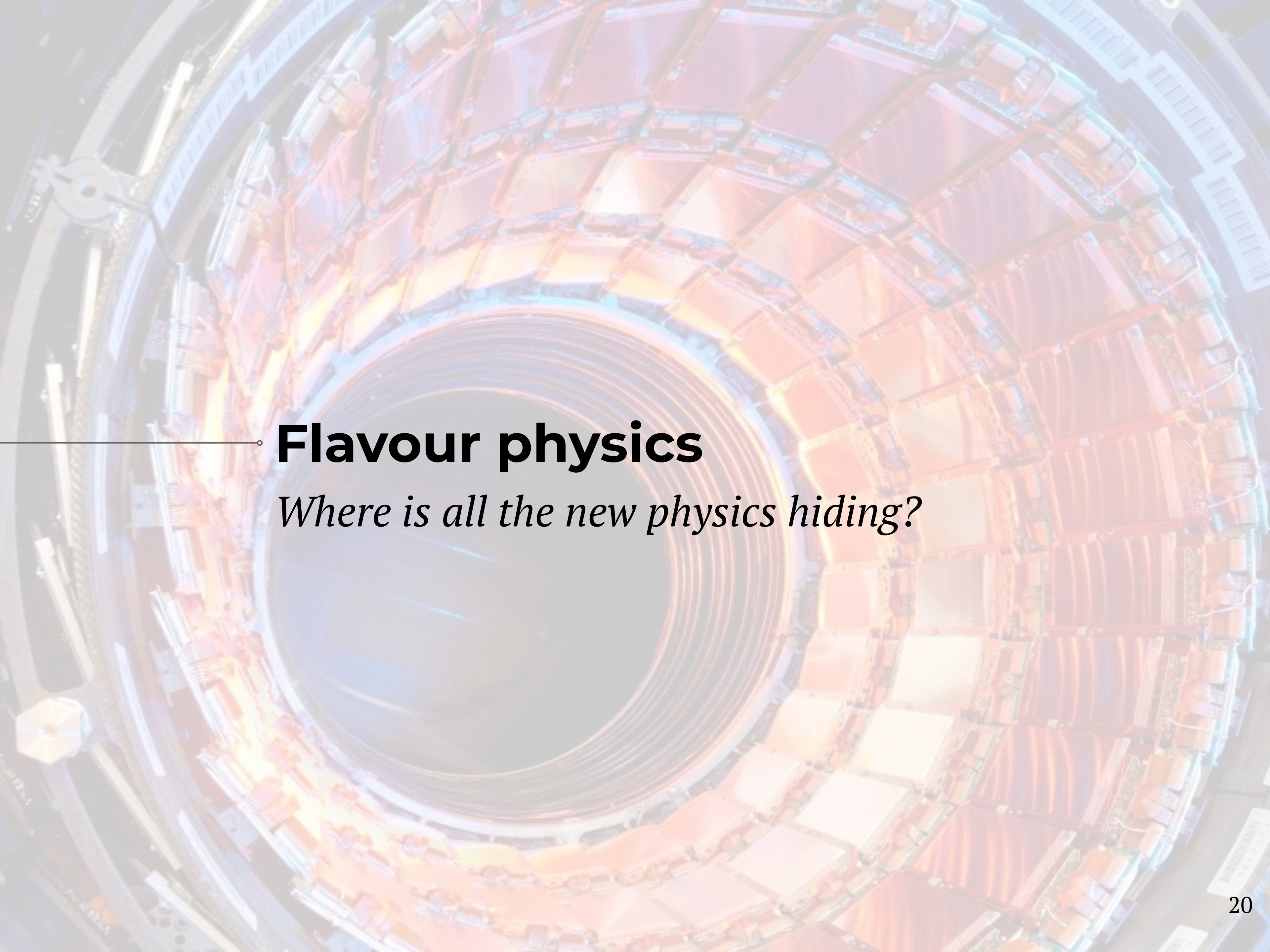


ATLAS, Phys. Lett. B 716 (2012) 1



CMS, Phys. Lett. B 716 (2012) 30


NewScientist
THE DAILY NEWSLETTER
Sign up to our daily email newsletter
News Technology Space Physics Health Environment Mind Video | Travel Live Jobs
The Higgs hunter has just turned 10.
Why is nobody celebrating?
The Economist
Fundamental physics is frustrating physicists
No GUTs, no glory
The New York Times
Ten years in, the Large Hadron Collider has failed to deliver the exciting discoveries that scientists promised.
CMS

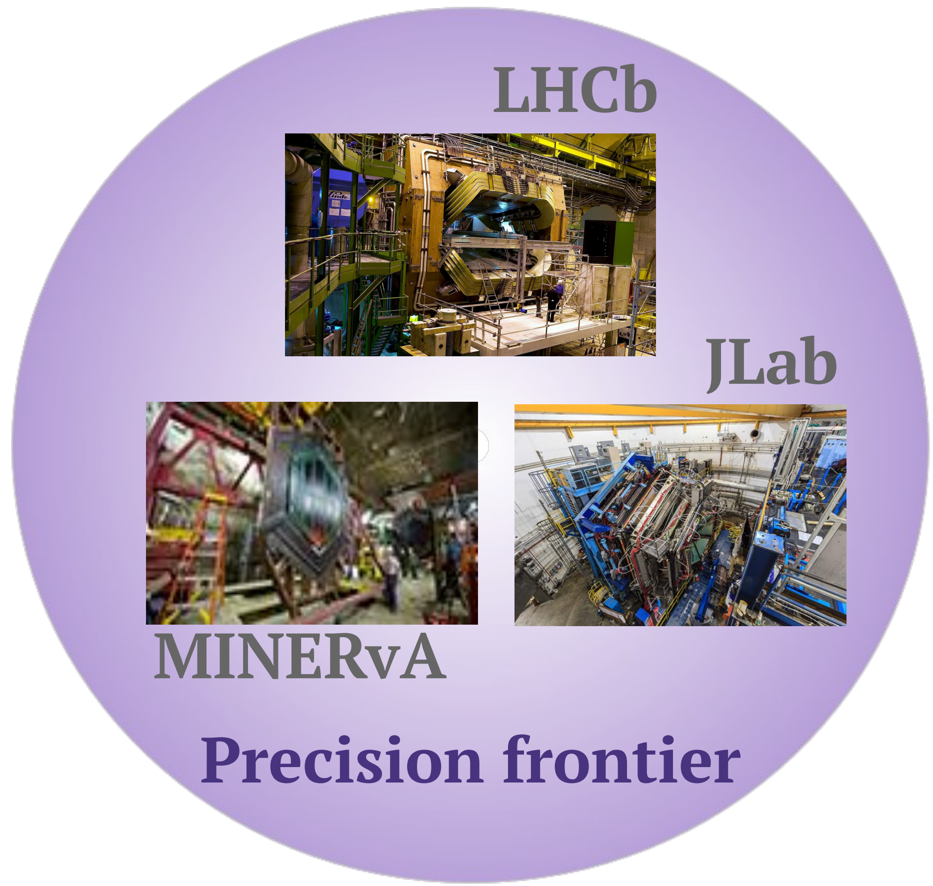


Flavour physics

Where is all the new physics hiding?

Precision frontier:

Compare detailed theoretical predictions, based on the Standard Model, to precise experimental data.



For example:

Neutron electric dipole moment

Neutrinoless double beta decay

Violation of fundamental symmetries

Quark flavour physics

…

Cabibbo-Kobayashi-Maskawa (CKM) matrix:

$$\mathcal{L}_{\mathrm{SM}} \supset -\frac{g}{2}\left(\overline{u_{\mathrm{L}}},\ \overline{c_{\mathrm{L}}},\ \overline{t_{\mathrm{L}}}\right)\gamma^{\mu}\,W_{\mu}\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d_{\mathrm{L}} \\ s_{\mathrm{L}} \\ b_{\mathrm{L}} \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) matrix:

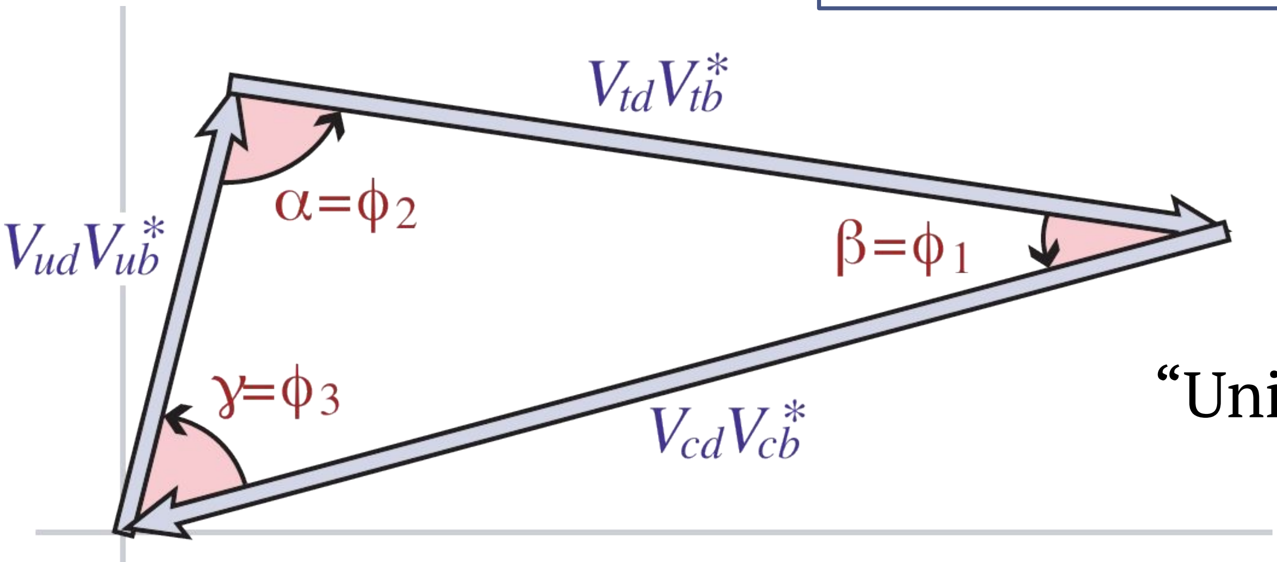
$$\mathcal{L}_{\mathrm{SM}} \supset -\frac{g}{2}\left(\overline{u_{\mathrm{L}}},\ \overline{c_{\mathrm{L}}},\ \overline{t_{\mathrm{L}}}\right)\gamma^{\mu}W_{\mu}\begin{pmatrix} \boxed{\begin{matrix} V_{ud} \\ V_{cd} \\ V_{td} \end{matrix}} & \begin{matrix} V_{us} \\ V_{cs} \\ V_{ts} \end{matrix} & \boxed{\begin{matrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{matrix}} \end{pmatrix}\begin{pmatrix} d_{\mathrm{L}} \\ s_{\mathrm{L}} \\ b_{\mathrm{L}} \end{pmatrix}$$

$$\boxed{V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0}$$

Cabibbo-Kobayashi-Maskawa (CKM) matrix:

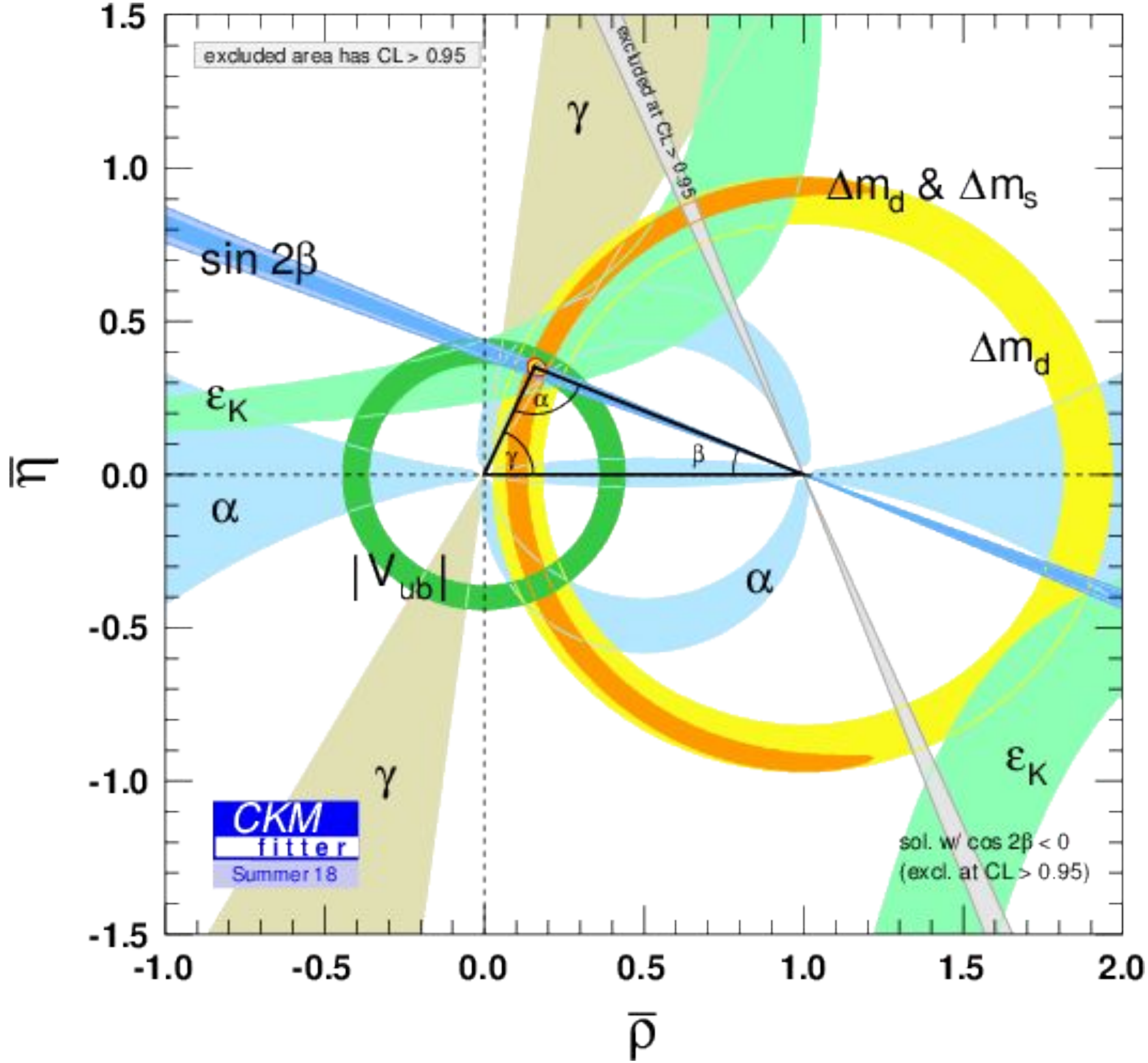
$$\mathcal{L}_{\rm SM} \supset -\frac{g}{2}\left(\overline{u_{\rm L}},\ \overline{c_{\rm L}},\ \overline{t_{\rm L}}\right)\gamma^\mu W_\mu \begin{pmatrix} \boxed{\begin{matrix} V_{ud} \\ V_{cd} \\ V_{td} \end{matrix}} & \begin{matrix} V_{us} \\ V_{cs} \\ V_{ts} \end{matrix} & \boxed{\begin{matrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{matrix}} \end{pmatrix} \begin{pmatrix} d_{\rm L} \\ s_{\rm L} \\ b_{\rm L} \end{pmatrix}$$

$$\boxed{V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0}$$



"Unitarity triangle(s)"

PDG, PRD 98 (2018) 030001


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
|V_ub|
α
γ
ε_K
CKM
fitter
Summer 18
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \beta\,\text{decay} & K\to\pi\ell\nu & B\to\tau\nu \\ & & B\to\pi\ell\nu \\ & & B_s\to K\ell\nu \\ V_{cd} & V_{cs} & V_{cb} \\ D\to\pi\ell\nu & D_s\to\ell\nu & B\to D^{(*)}\ell\nu \\ & D\to K\ell\nu & B_s\to D_s^{(*)}\ell\nu \\ V_{td} & V_{ts} & V_{tb} \\ & B_s\to\mu^+\mu^- & B_s\to\mu^+\mu^- \\ & B\to K\ell^+\ell^- & B\to K\ell^+\ell^- \\ B_{(s)}\,\text{mixing} & B_{(s)}\,\text{mixing} & \end{pmatrix}$$

CJM et al., PRD 87 (2013) 034017
CJM et al., PRD 90 (2014) 054015

V_{ud} V_{us} V_{ub}

Dowdall et al., PRL 110 (2013) 222003
Bouchard et al., PRD 90 (2014) 054506
Davies, Hughes & CJM, PRD 97 (2018) 054509

$B \to \tau\nu$

$B \to \pi\ell\nu$

Na et al., PRD 86 (2012) 034506
CJM et al., PRD 98 (2018) 114509

$B_s \to K\ell\nu$

V_{cd} V_{cs} V_{cb}

Na et al., PRD 92 (2015) 054510

$B \to D^{(*)}\ell\nu$

CJM et al., PRD 95 (2017) 114506
CJM et al., PRD 98 (2018) 114509

$B_s \to D_s^{(*)}\ell\nu$

V_{td} V_{ts} V_{tb}

$B_s \to \mu^+\mu^-$ $B_s \to \mu^+\mu^-$

$B \to K\ell^+\ell^-$ $B \to K\ell^+\ell^-$

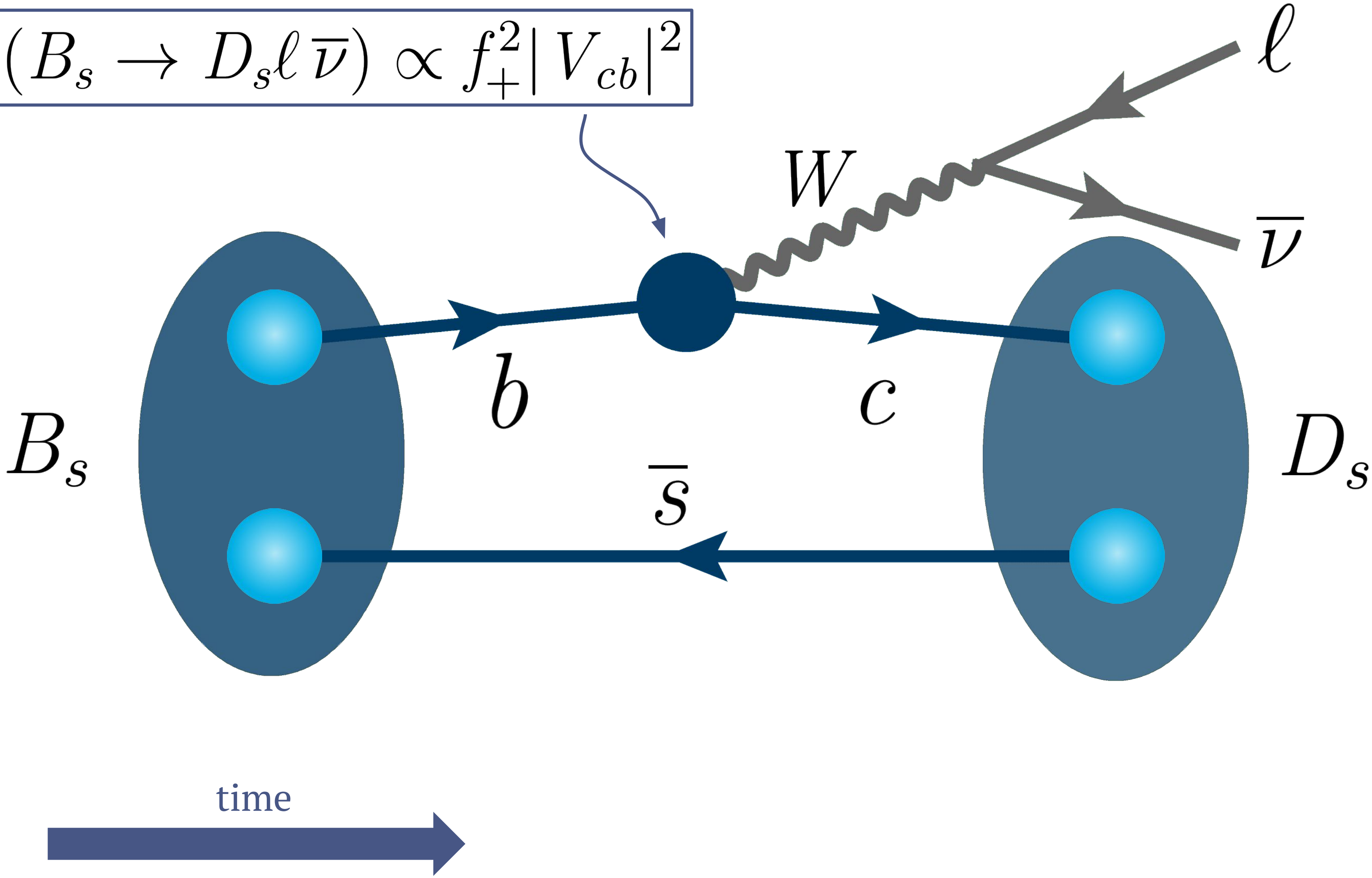
Bouchard et al.,
PRL 111 (2013) 162002

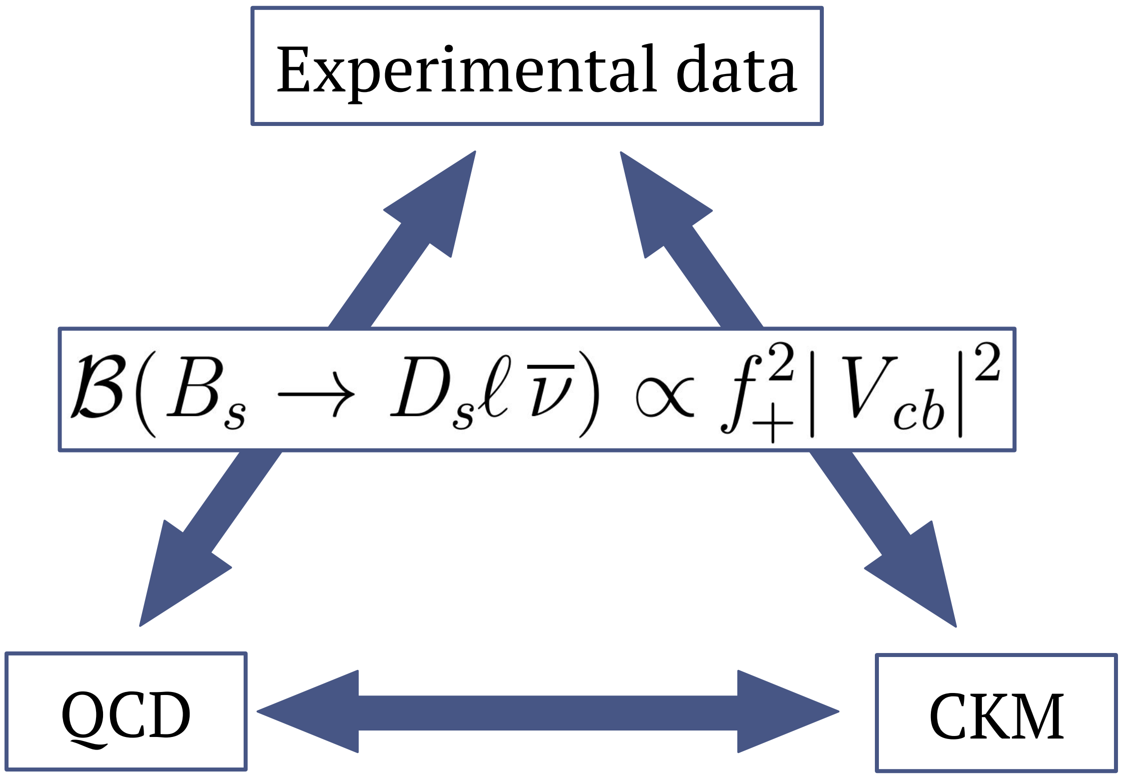
$B_{(s)}$ mixing $B_{(s)}$ mixing

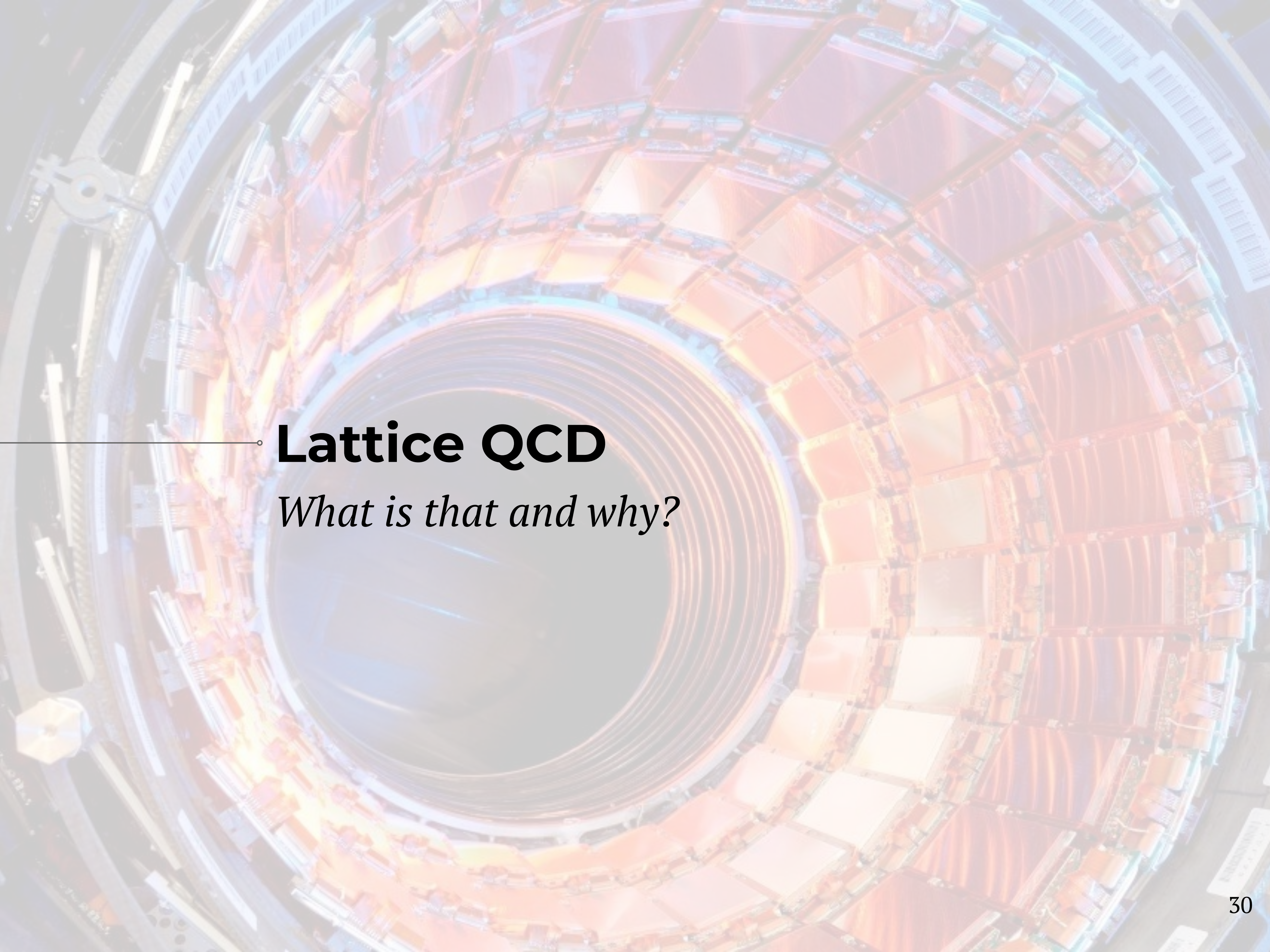
Dowdall et al., LATT(2014), Davies et al., LATT(2018)

CJM et al., PRD 95 (2017) 114506
CJM et al., PRD 98 (2018) 114509

$$\boxed{\mathcal{B}(B_s \to D_s \ell \,\overline{\nu}) \propto f_+^2 |V_{cb}|^2}$$




Experimental data
$\mathcal{B}(B_s \to D_s \ell \overline{\nu}) \propto f_+^2 |V_{cb}|^2$
QCD
CKM

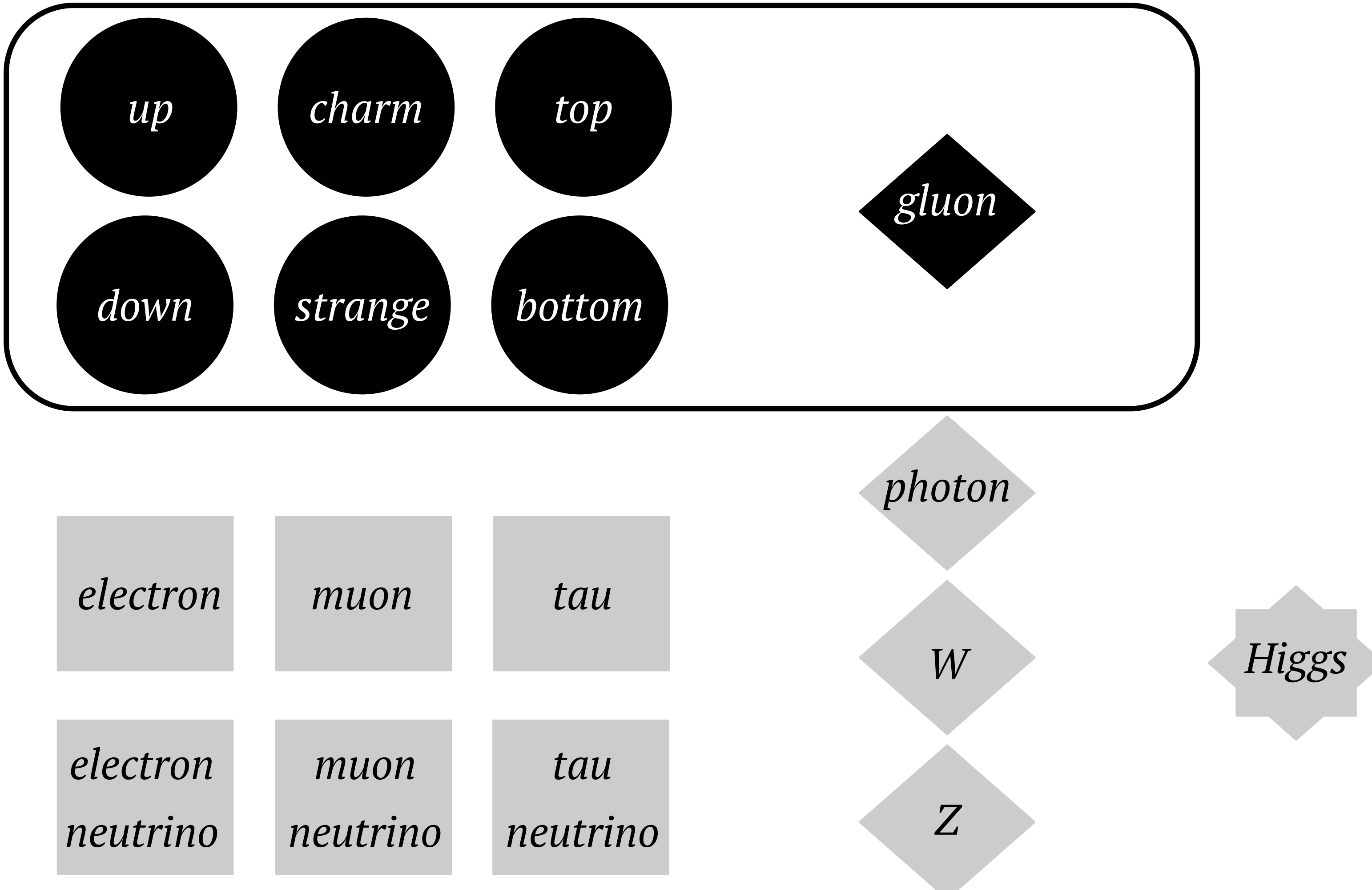


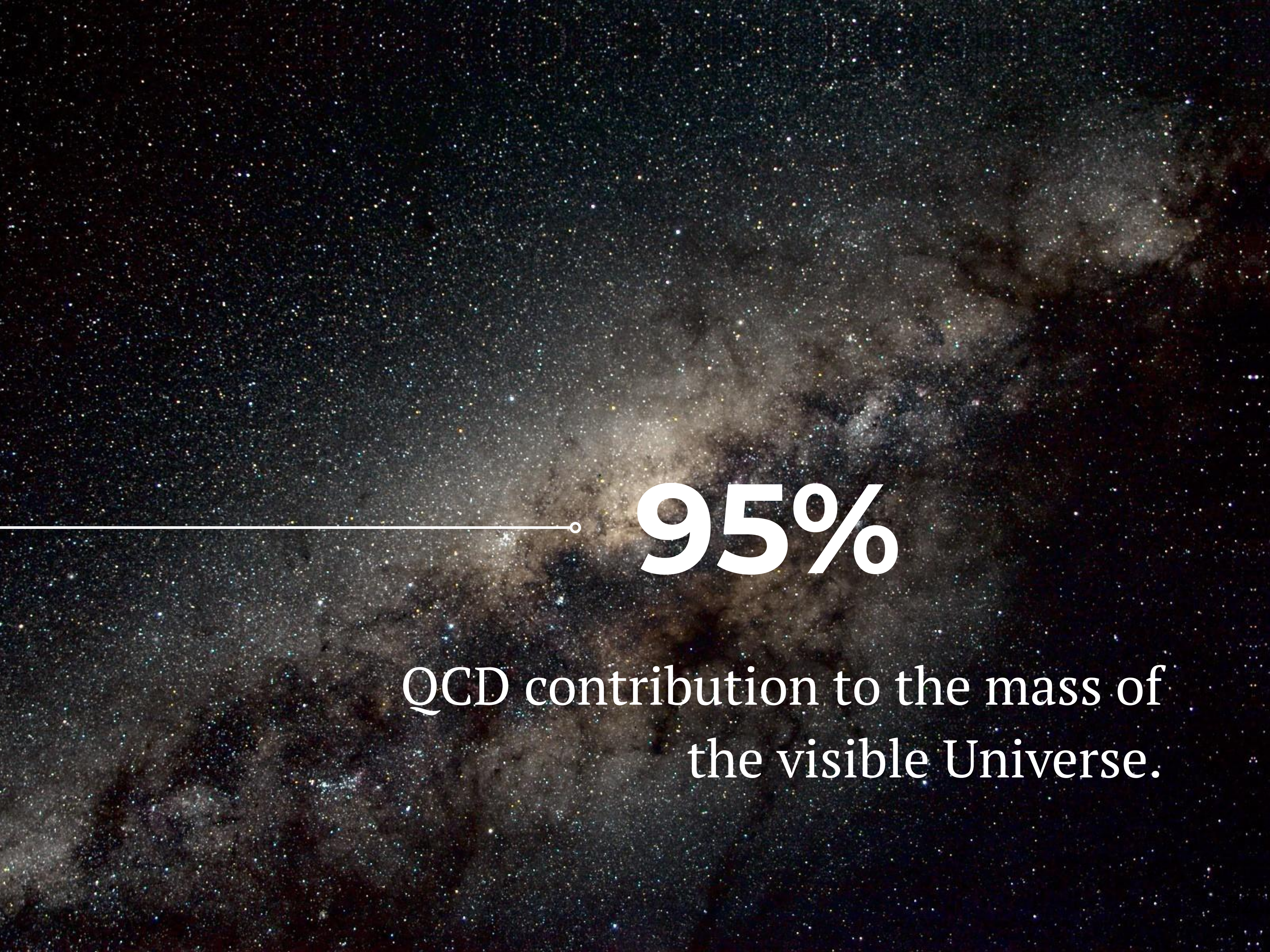
Lattice QCD

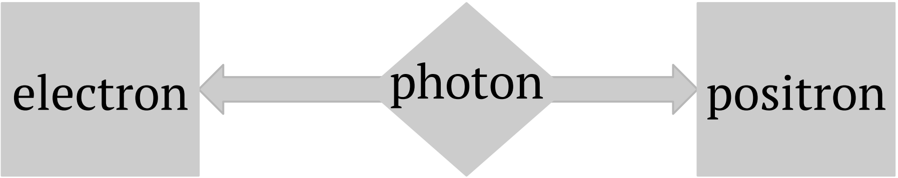
What is that and why?

QUANTUM CHROMODYNAMICS (QCD):

mathematical description of the strong force



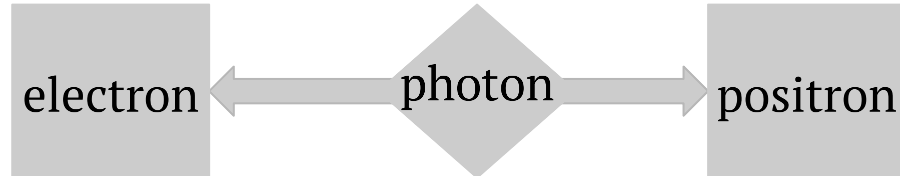

95%
QCD contribution to the mass of the visible Universe.



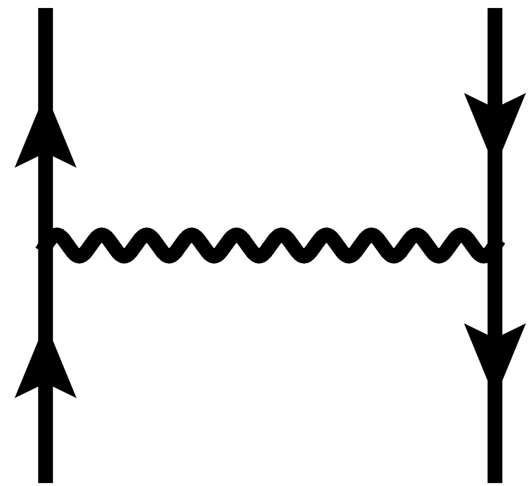
Charged particles interact by exchanging photons.

Quantum field theory description of electromagnetism.

Charged particles interact by exchanging photons.

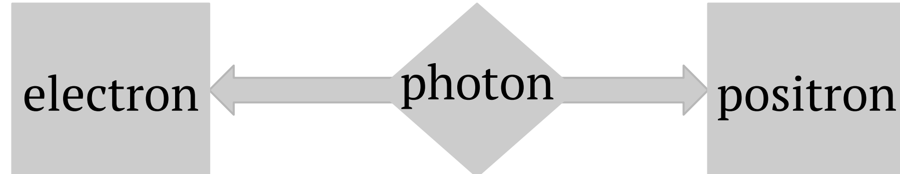


Quantum field theory description of electromagnetism.



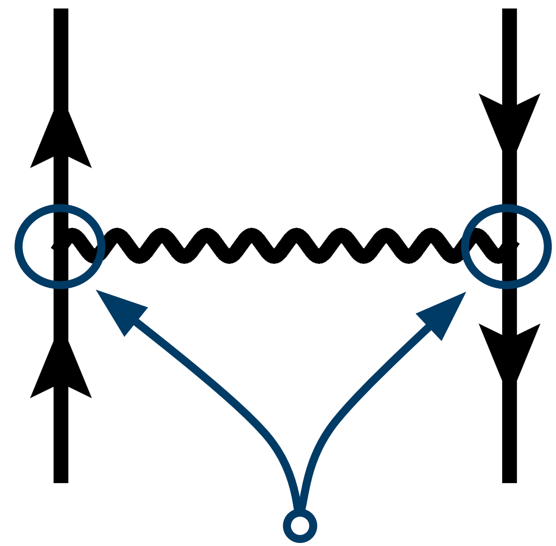
Represent process via Feynman diagrams.

Charged particles interact by exchanging photons.



Quantum field theory description of electromagnetism.

Represent process via Feynman diagrams.

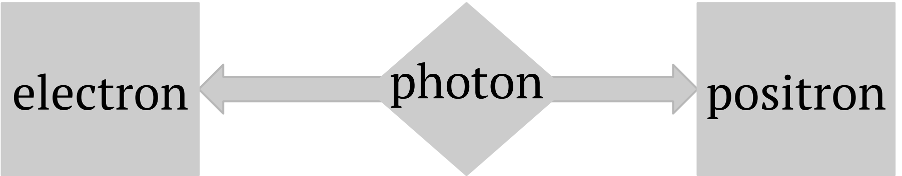


$$\sqrt{\alpha} \simeq \frac{1}{\sqrt{137}}$$

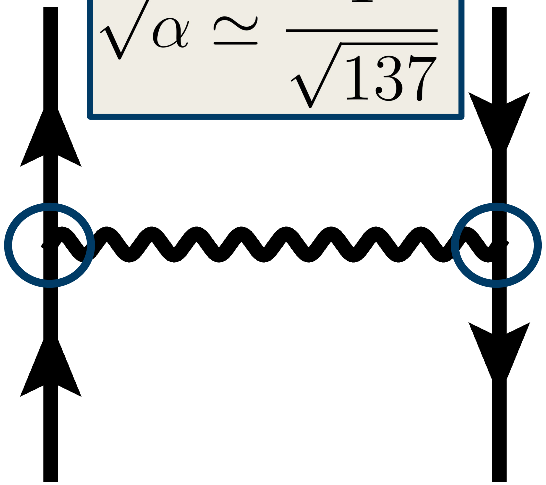
Every interaction proportional to the coupling

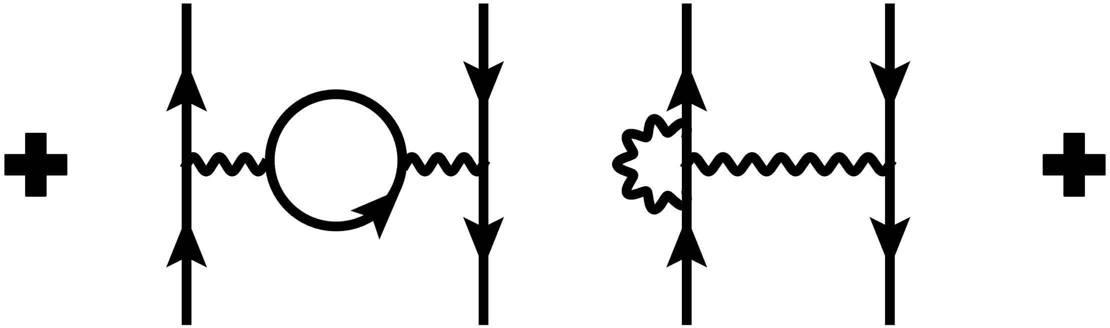
QUANTUM ELECTRODYNAMICS

Charged particles interact by exchanging photons.



$$\sqrt{\alpha} \simeq \frac{1}{\sqrt{137}}$$



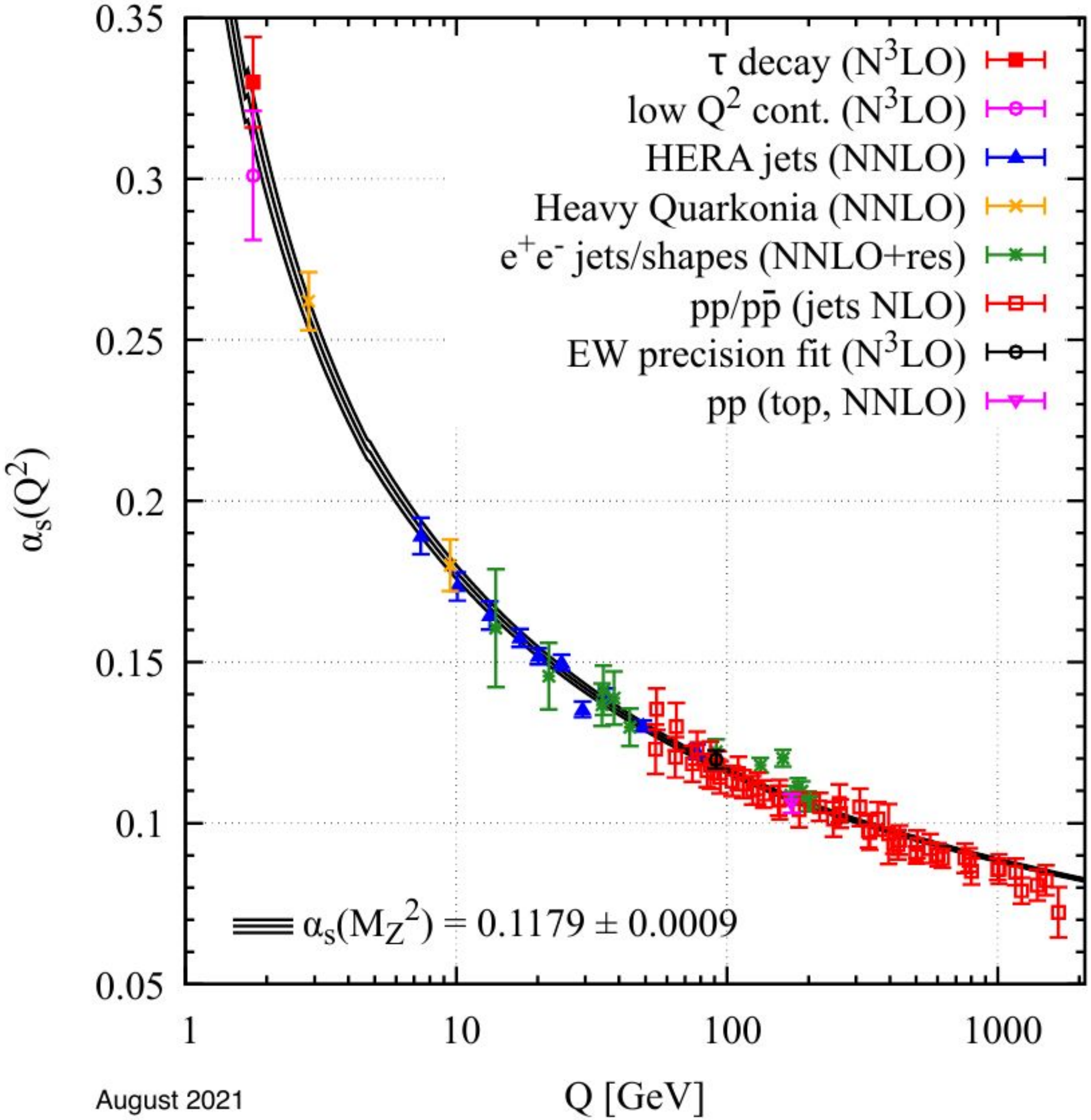


$$\alpha$$

$$\alpha^2$$

Perturbative series well-behaved

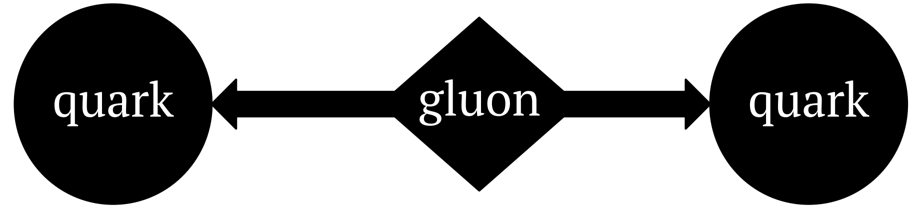
$$\frac{a_1}{137} + \frac{a_2}{137^2} + \ldots$$



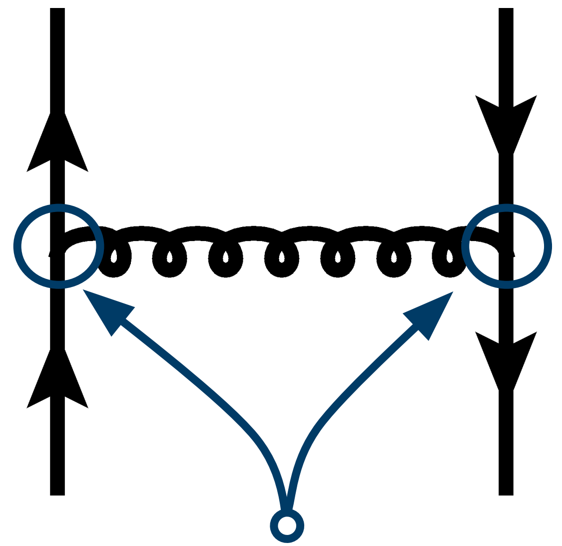
PDG, PTEP 0803C01 (2020)

QUANTUM CHROMODYNAMICS

Coloured particles interact by exchanging gluons.



Quantum field theory description of the strong force.



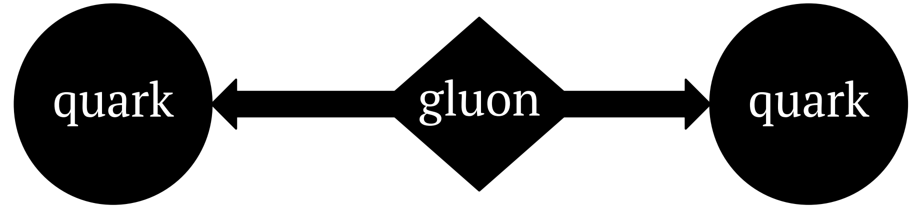
$$\boxed{\sqrt{\alpha_S(Q^2)} \simeq 0.1 - 1}$$

Represent process via Feynman diagrams.

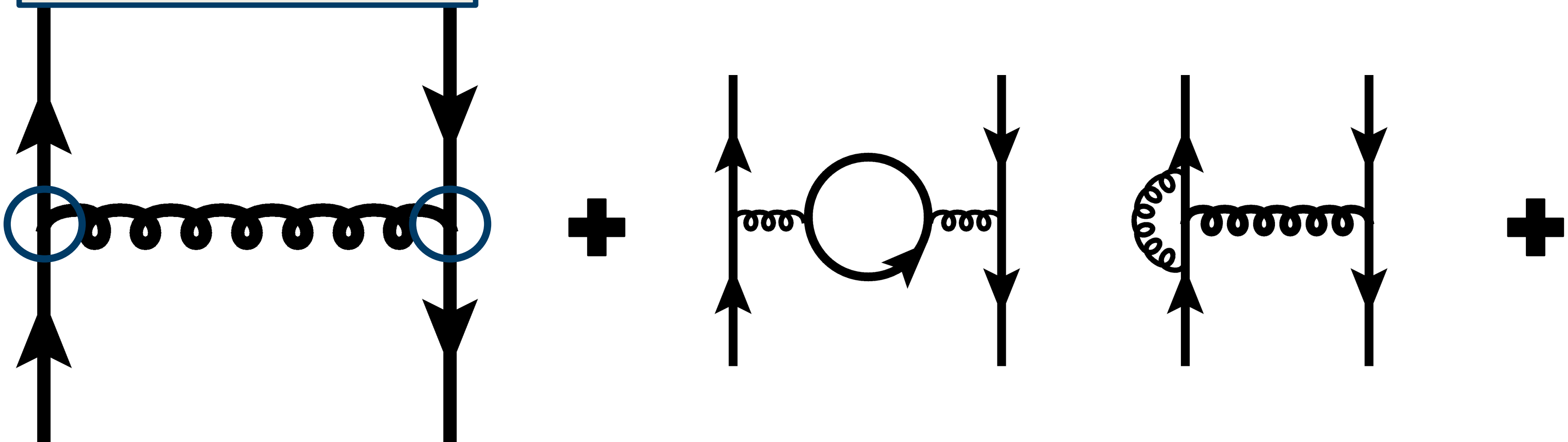
Every interaction proportional to the coupling

QUANTUM CHROMODYNAMICS

Coloured particles interact by exchanging gluons.



$$\sqrt{\alpha_S(Q^2)} \simeq 0.1 - 1$$

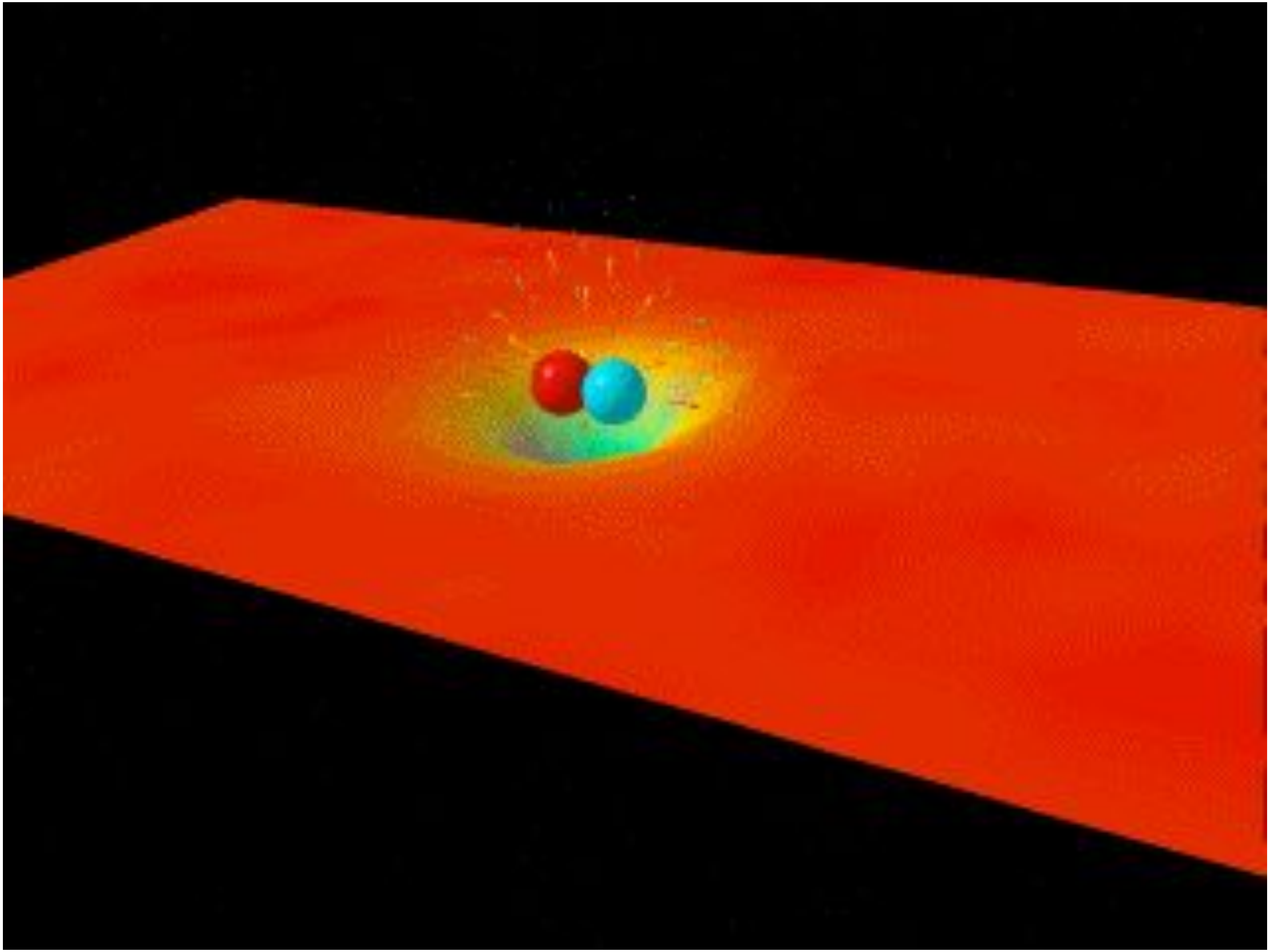


$$\alpha_S(Q^2)$$

$$\alpha_S^2(Q^2)$$

Perturbative series badly behaved

$$b_1 \times 1 + b_2 \times 1 + \ldots$$



http://www.physics.adelaide.edu.au/cssm/lattice/

1. There are three types of M&M: red, green and blue.
2. M&Ms arrange themselves so that they minimise some function, *S[r,g,b]*, that depends strongly on the position and colour of the M&Ms near them.

1. There are three types of M&M: red, green and blue.
2. M&Ms arrange themselves so that they minimise some function, *S[r,g,b],* that depends strongly on the position and colour of the M&Ms near them.

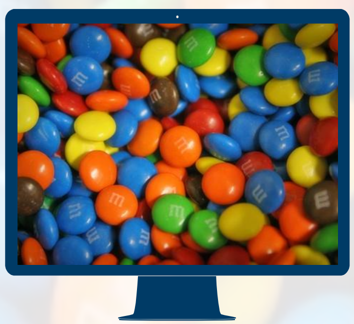
How are M&Ms distributed?

Given a green M&M at some random point, what is the chance that we find a second green M&M at a distance r away?

We will call this G(r).

We can solve this problem with lattice M&M theory.

Step 1. Take a small box of M&Ms.

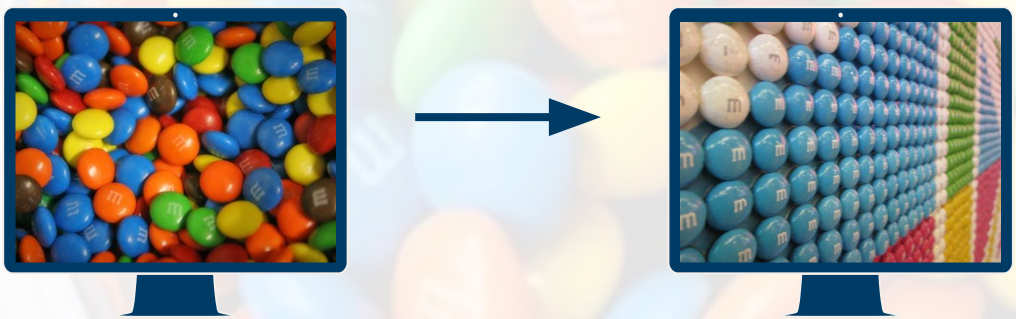


Given a green M&M at some random point, what is the chance that we find a second green M&M at a distance r away?

We will call this G(r).

We can solve this problem with
lattice M&M theory.

2. Discretise the small box.



Given a green M&M at some random point, what is the chance that we find a second green M&M at a distance r away?

We will call this G(r).

We can solve this problem with lattice M&M theory.

3. Distribute M&Ms in the box.

Markov chain Monte Carlo:

a) Distribute randomly

b) Choose one to change

c) Calculate change in *S[r,g,b]*

d) Accept change if *S* decreases

e) Return to b)

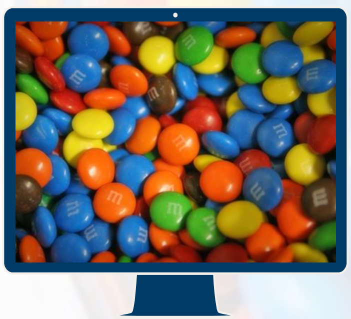
Given a green M&M at some random point, what is the chance that we find a second green M&M at a distance r away?

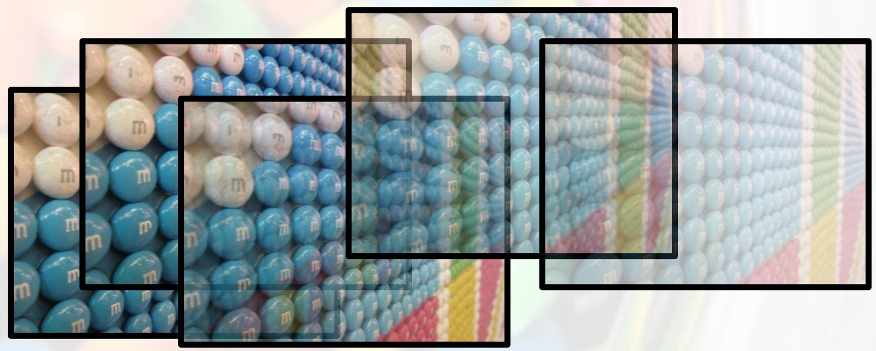
We will call this G(r).

We can solve this problem with lattice M&M theory.

Each of these copies is an example of the “M&M vacuum”.

4. Generate many “copies”.



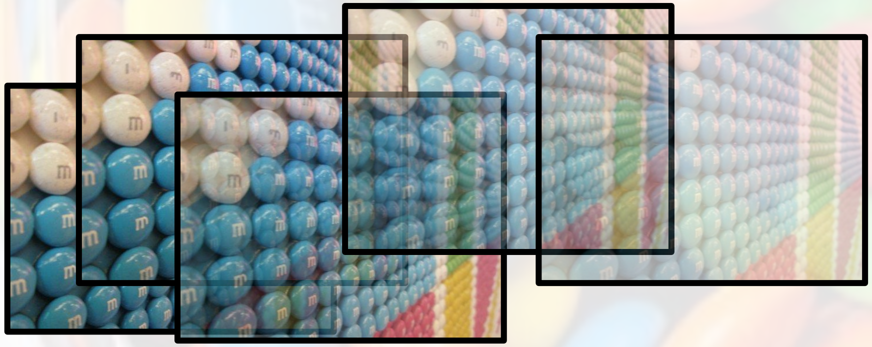


Given a green M&M at some random point, what is the chance that we find a second green M&M at a distance r away?

We will call this G(r).

We can solve this problem with lattice M&M theory.

5. On each copy, “measure” *G(r)*.

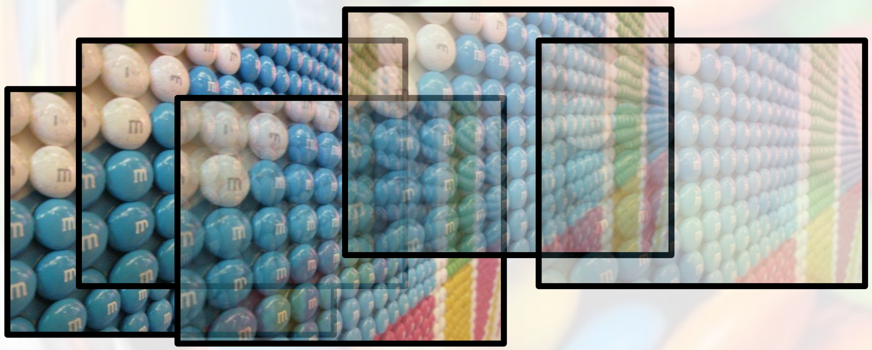


Given a green M&M at some random point, what is the chance that we find a second green M&M at a distance r away?

We will call this G(r).

We can solve this problem with lattice M&M theory.

5. On each copy, “measure” *G(r)*.



a) Find a green M&M

b) Look at point at distance *r*

c) Record whether there is a second green M&M there

d) Return to b)

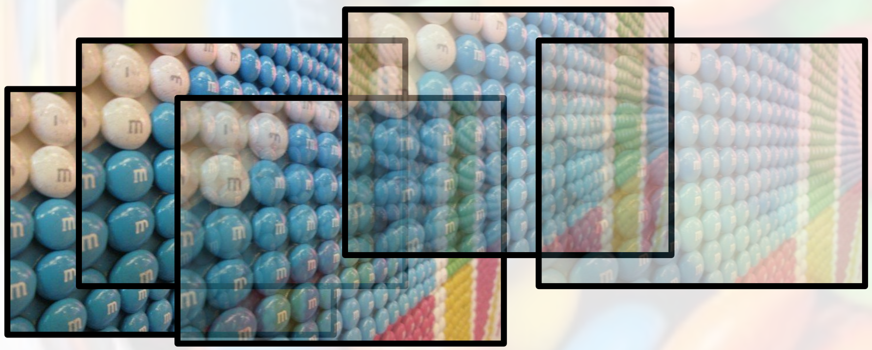
e) Repeat with different *r*

Given a green M&M at some random point, what is the chance that we find a second green M&M at a distance r away?

We will call this G(r).

We can solve this problem with lattice M&M theory.

6. Mean value <*G(r)*> is our result.



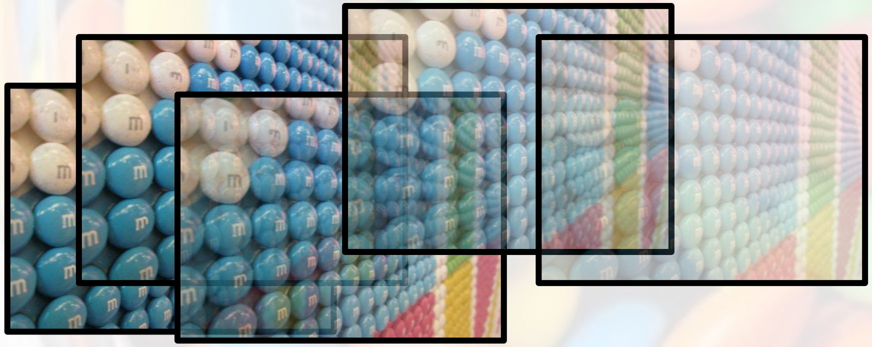
Given a green M&M at some random point, what is the chance that we find a second green M&M at a distance r away?

We will call this G(r).

We can solve this problem with lattice M&M theory.

$\langle G(r) \rangle$ is a Monte Carlo estimate of the true correlation function *G(r)*.

6. Mean value $\langle G(r) \rangle$ is our result.



Given a green M&M at some random point, what is the chance that we find a second green M&M at a distance r away?

We will call this G(r).

We can solve this problem with lattice M&M theory.

7. Repeat with smaller grid size.
8. Take limit of zero node spacing.
   Gives our final result: the continuum value of <*G(r)*>.

Given a green M&M at some random point, what is the chance that we find a second green M&M at a distance r away?

We will call this G(r).

1. Take a small box of M&Ms.
2. Discretise the small box.
3. Distribute M&Ms in the box.
4. Generate many “copies” of the “M&M vacuum”.
5. On each copy, “measure” *G(r)*.
6. Mean value <*G(r)*> is result.
7. Repeat with smaller grid size.
8. Take limit of zero node spacing.
   Gives our final result: the
   continuum value of <*G(r)*>.

1. Take a small box of M&Ms.
2. Discretise the small box.
3. Distribute M&Ms in the box.
4. Generate many "copies".
5. On each copy, "measure" $G(r)$.
6. Mean value $\langle G(r) \rangle$ is result.
7. Repeat with smaller grid size.
8. Take limit of zero node spacing.
   Gives our final result: the continuum value of $\langle G(r) \rangle$.

Finite volume effects

M&Ms near the edge experience different interactions.

1. Take a small box of M&Ms.
2. **Discretise the small box.**
3. Distribute M&Ms in the box.
4. Generate many “copies”.
5. On each copy, “measure” *G(r)*.
6. Mean value <*G(r)*> is result.
7. Repeat with smaller grid size.
8. Take limit of zero node spacing.
   Gives our final result: the continuum value of <*G(r)*>.

Finite volume effects

Discretisation effects

M&Ms can only live at the nodes of the lattice.

1. Take a small box of M&Ms.
2. Discretise the small box.
3. Distribute M&Ms in the box.
4. Generate many “copies”.
5. On each copy, “measure” *G(r)*.
6. Mean value <*G(r)*> is result.
7. Repeat with smaller grid size.
8. Take limit of zero node spacing.
   Gives our final result: the continuum value of <*G(r)*>.

Finite volume effects

Discretisation effects

Statistics

The standard error of the mean decreases with the number of copies.

1. Take a small box of M&Ms.
2. Discretise the small box.
3. Distribute M&Ms in the box.
4. Generate many “copies”.
5. On each copy, “measure” $G(r)$.
6. Mean value $<G(r)>$ is result.
7. Repeat with smaller grid size.
8. Take limit of zero node spacing.
   Gives our final result: the continuum value of $<G(r)>$.

Finite volume effects

Discretisation effects

Statistics

Continuum limit

Extrapolation error with only a couple of values of the node spacing.

1. Take a small box of ~~M&Ms~~ (Euclidean) spacetime.
2. Discretise the small box.
3. Distribute ~~M&Ms~~ quarks and gluons in the box.
4. Generate many "copies" of the ~~M&M~~ QCD vacuum.
5. On each copy, "measure" *G(r)*.
6. Mean value <*G(r)*> is result.
7. Repeat with smaller grid size.
8. Take limit of zero node spacing. Gives our final result: the continuum value of <*G(r)*>.

Finite volume effects

1. Take a small box of ~~M&Ms~~ (Euclidean) spacetime.

Discretisation effects

2. Discretise the small box.
3. Distribute ~~M&Ms~~ quarks and gluons in the box.
4. Generate many “copies” of the ~~M&M~~ QCD vacuum.
5. On each copy, “measure” *G(r)*.

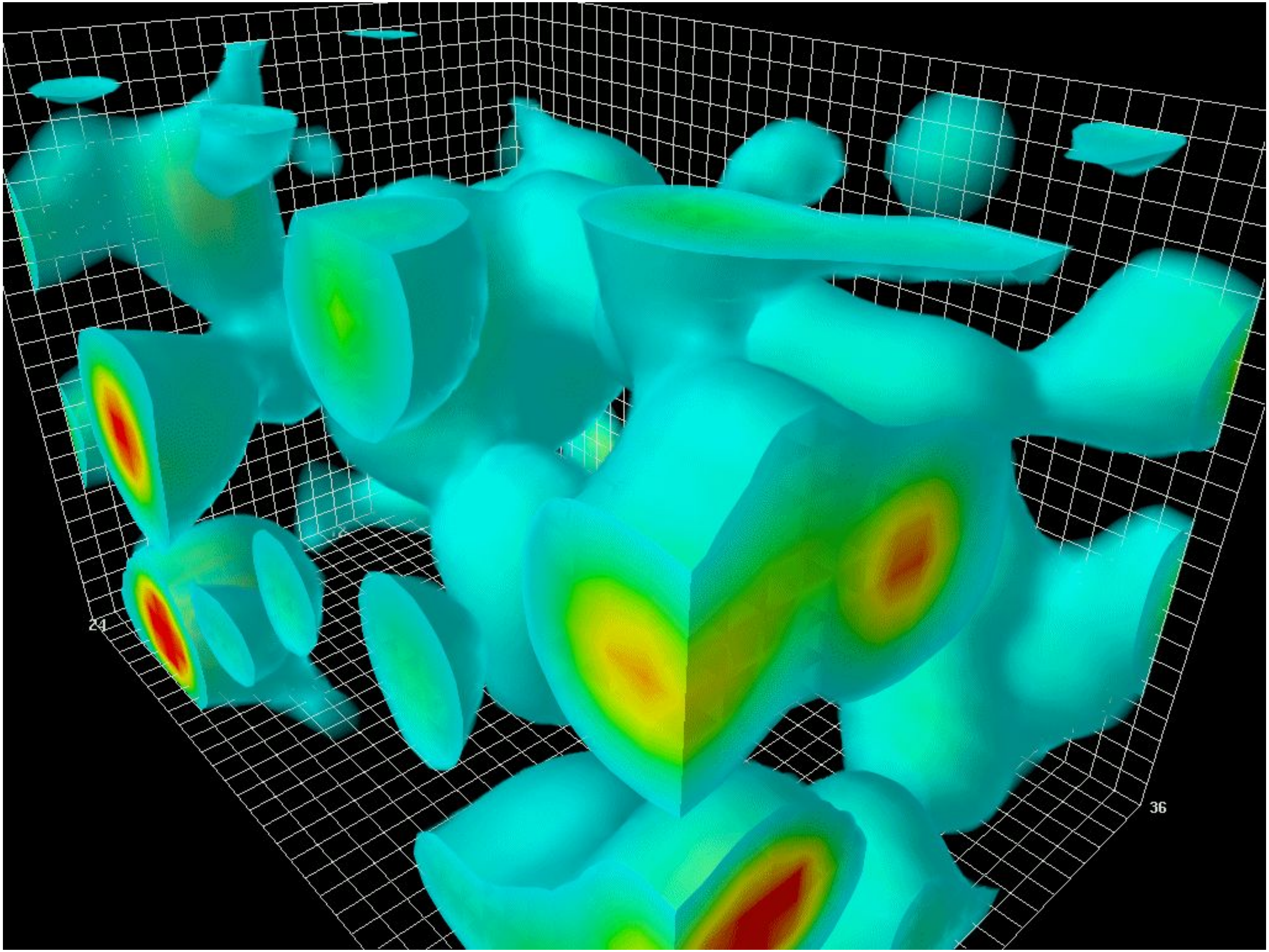
Statistics

6. Mean value <*G(r)*> is result.
7. Repeat with smaller grid size.
8. Take limit of zero node spacing. Gives our final result: the continuum value of <*G(r)*>.

Continuum limit

1. Take a small box of ~~M&Ms~~ (Euclidean) spacetime.
2. Discretise the small box.
3. Distribute ~~M&Ms~~ quarks and glu
4. Generate many “copies” of the
5. On each copy, “measure” *G(r)*.
6. Mean value <*G(r)*> is result.
7. Repeat with smaller grid size.
8. Take limit of zero node spa ur final

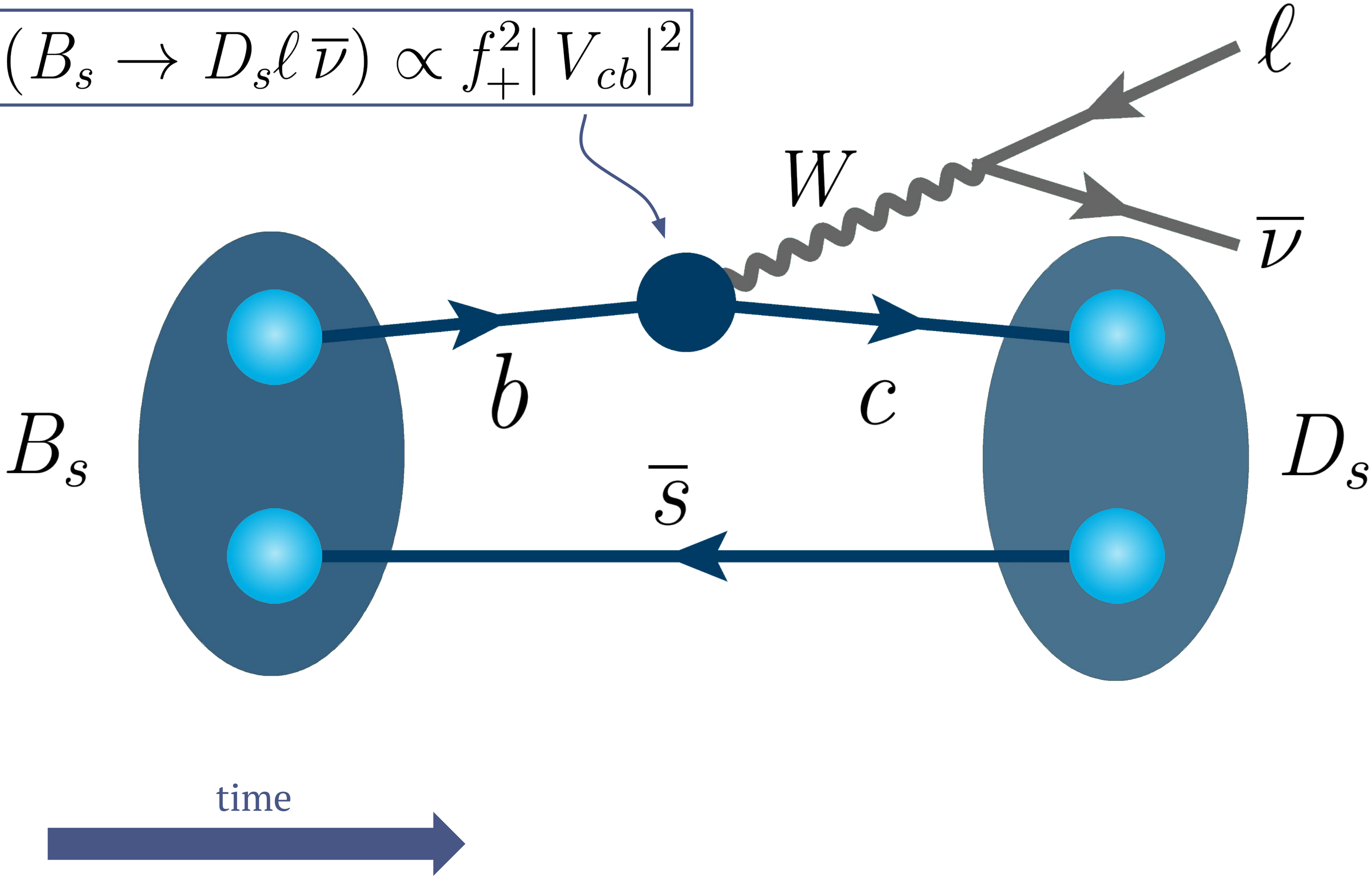
   result: the continuum



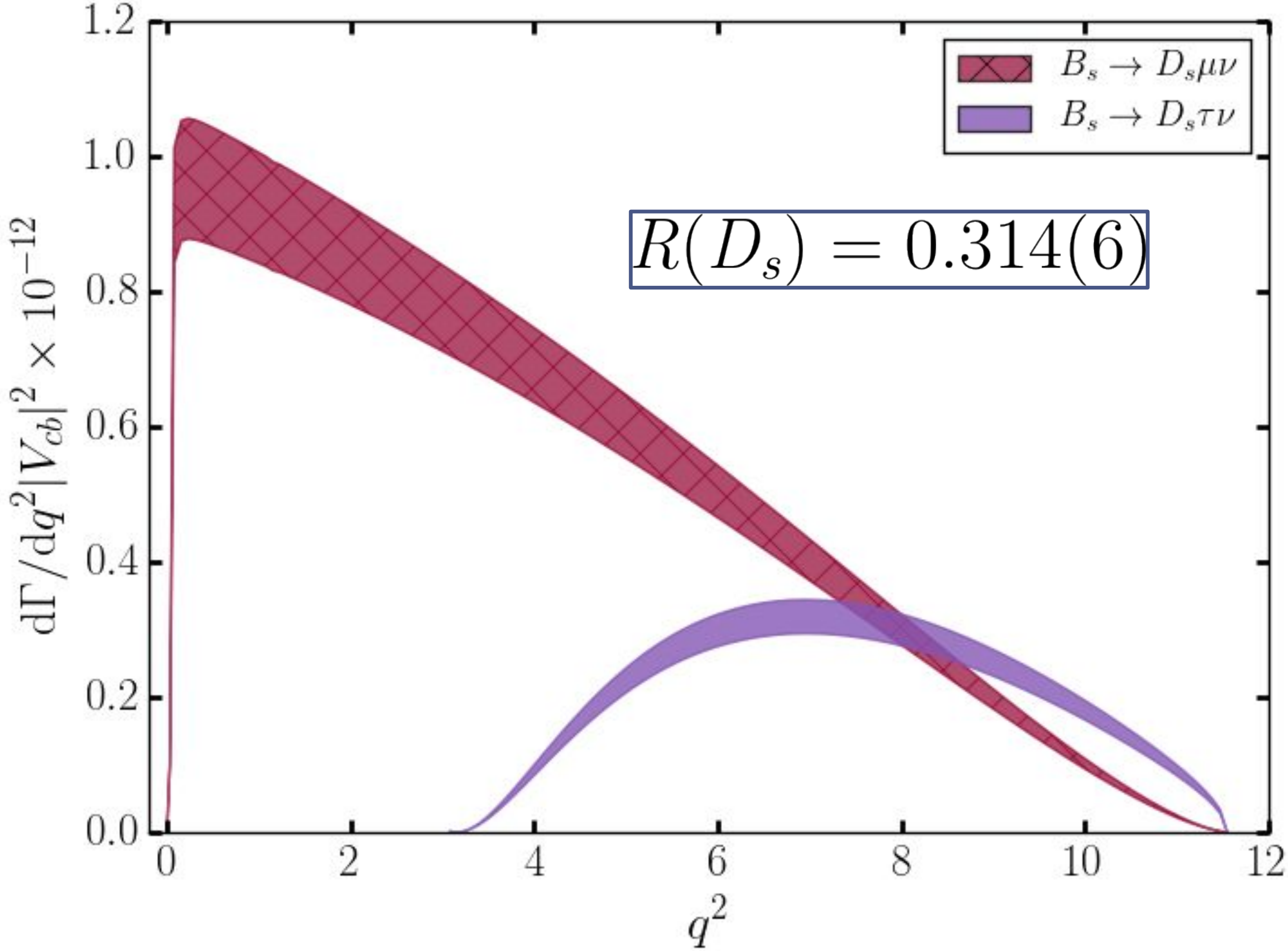
http://www.physics.adelaide.edu.au/cssm/lattice/

CJM et al., PRD 95 (2017) 114506
CJM et al., PRD 98 (2018) 114509

$$\mathcal{B}(B_s \to D_s \ell \, \overline{\nu}) \propto f_+^2 |\, V_{cb}|^2$$



$$R(D_s) = \frac{\mathcal{B}(B_s \to D_s \tau \overline{\nu}_\tau)}{\mathcal{B}(B_s \to D_s \ell \overline{\nu}_\ell)}$$



$$R(D) = 0.299(3)$$

CJM et al., PRD 95 (2017) 114506

CKM MATRIX

$$\begin{pmatrix}
\begin{array}{c} V_{ud} \\ \beta\,\text{decay} \end{array} & \begin{array}{c} V_{us} \\ K \to \pi \ell \nu \end{array} & \begin{array}{c} V_{ub} \\ B \to \tau \nu \\ B \to \pi \ell \nu \\ B_s \to K \ell \nu \end{array} \\
\begin{array}{c} V_{cd} \\ D \to \pi \ell \nu \end{array} & \begin{array}{c} V_{cs} \\ D_s \to \ell \nu \\ D \to K \ell \nu \end{array} & \begin{array}{c} V_{cb} \\ B \to D^{(*)} \ell \nu \\ B_s \to D_s^{(*)} \ell \nu \end{array} \\
\begin{array}{c} V_{td} \\ \\ \\ B_{(s)}\ \text{mixing} \end{array} & \begin{array}{c} V_{ts} \\ B_s \to \mu^+ \mu^- \\ B \to K \ell^+ \ell^- \\ B_{(s)}\ \text{mixing} \end{array} & \begin{array}{c} V_{tb} \\ B_s \to \mu^+ \mu^- \\ B \to K \ell^+ \ell^- \\ \\ \end{array}
\end{pmatrix}$$

Searching for new physics

What was wrong with the old physics, anyway?

Flavour physics

Where is all the new physics hiding?

Lattice QCD

What is that and why?

(more) questions?

Chris Monahan
cjmonahan@wm.edu

1. Take a small hypercube of Euclidean spacetime.
2. Discretise that small hypercube - the “lattice”.
3. Generate copies of the QCD vacuum with probability $e^{-S_{\rm QCD}}$.
4. On each copy, calculate desired correlation function.
5. The mean value is a statistical estimate of the correlation function at finite lattice spacing and volume.

$$\langle \mathcal{O} \rangle = \int D[\overline{\psi}, \psi, A]\, \mathcal{O}\, e^{-S_{\rm QCD}} \qquad \frac{1}{N}\sum \mathcal{O}\, e^{-S_{\rm QCD}} = \langle \mathcal{O} \rangle + O(1/\sqrt{N})$$

6. Repeat at different lattice spacings and volumes.
7. Take the continuum and infinite volume limits.
8. Repeat at different momentum transfers.

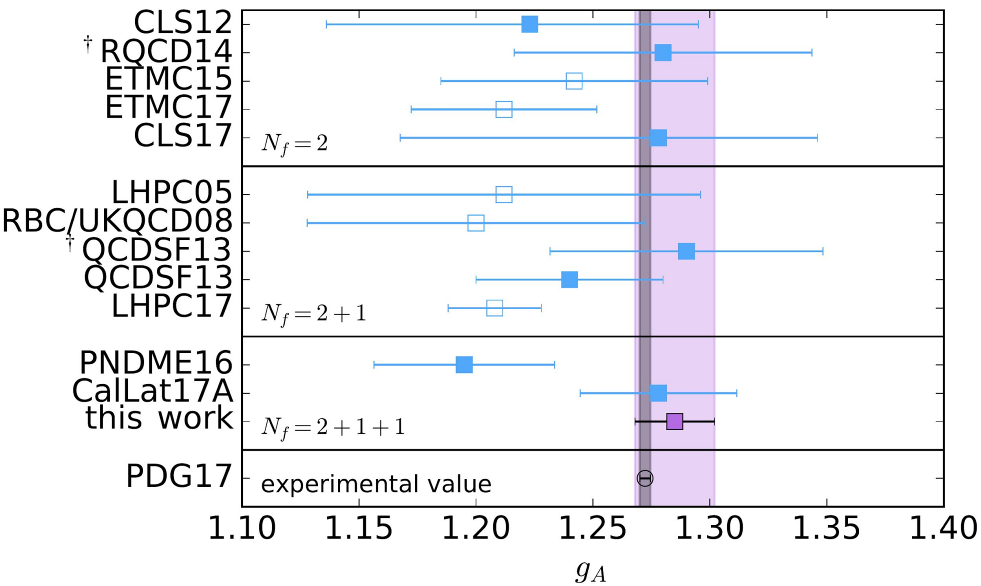
gA AND THE NEUTRON LIFETIME

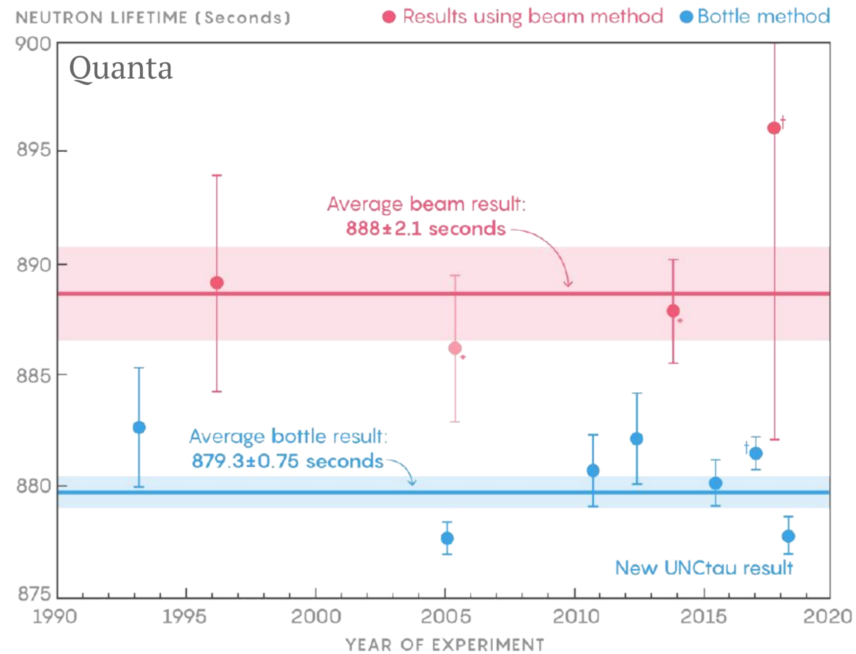
CalLat collaboration and friends: first calculation at 1% precision

$$g_A^{\text{CalLat}} = 1.2711(126) \qquad g_A^{\text{exp}} = 1.2723(23)$$

Nature 558 (2018) 91

Achieved through improved computational strategy to control systematics





Precision will improve with new data

$$|V_{ud}|^2 \tau_n (1 + 3 g_A^2) = 4908.6(1.9)\ \text{s}$$

Czarnecki et al., PRL 120 (2018) 202002

Results being generalised to nonzero momentum transfer

Experimental limits on neutron electric dipole moment

$$d_n^{\mathrm{exp}} < 3 \times 10^{-26}\,\mathrm{e \cdot cm}$$

Standard Model expectations

$$d_n^{\mathrm{EW}} < 10^{-32}\,\mathrm{e \cdot cm} \qquad d_n^{\mathrm{QCD}} < \theta \times 10^{-16}\,\mathrm{e \cdot cm}$$

First principles' calculations of contributions from
- QCD
- higher order operators

Higher dimensional operators have power-divergent mixing
- Use the gradient flow

Perturbation theory to guide numerical extraction of power divergences

Rizik, CJM & Shindler, PoS(LATTICE2018)