From Protons to Collisions…

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Saturday Mornings of Theoretical Physics, Oxford,
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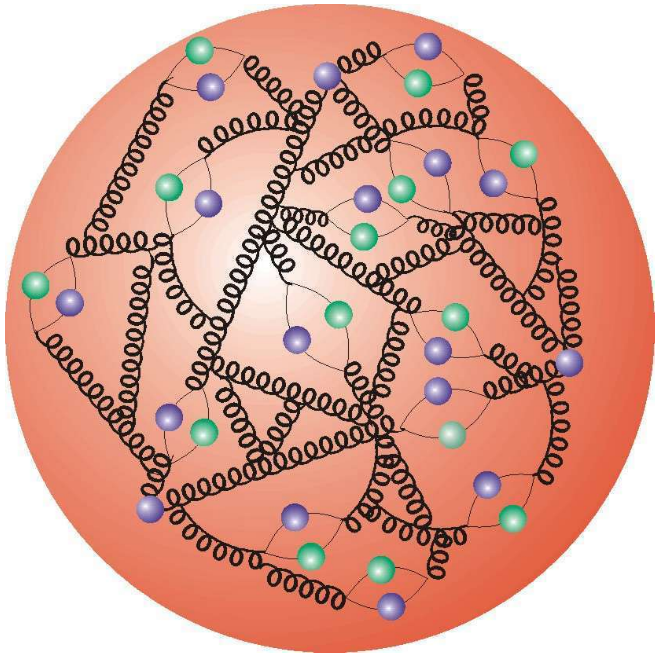
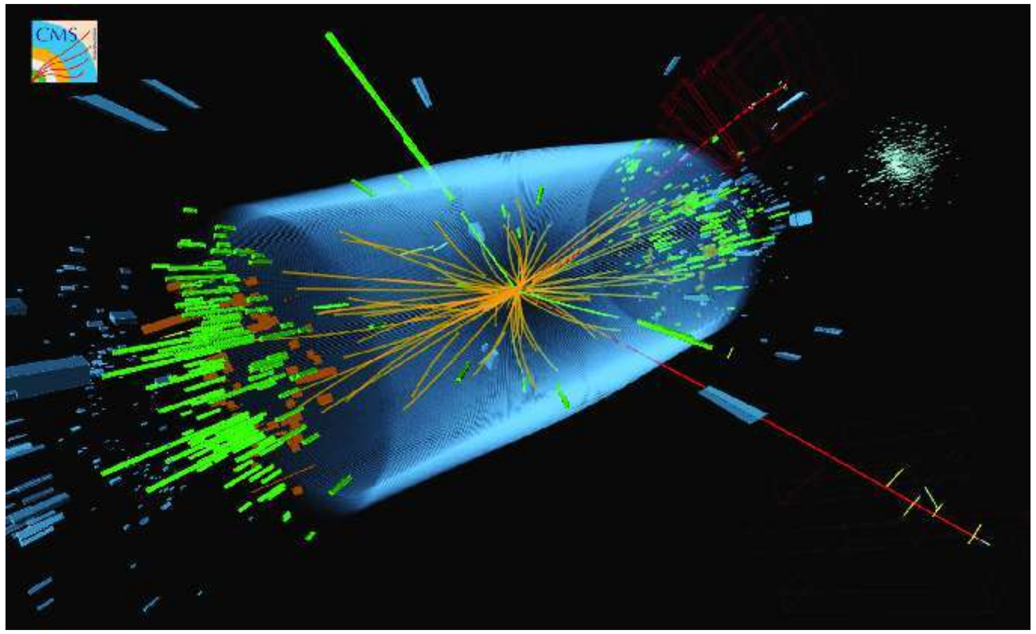
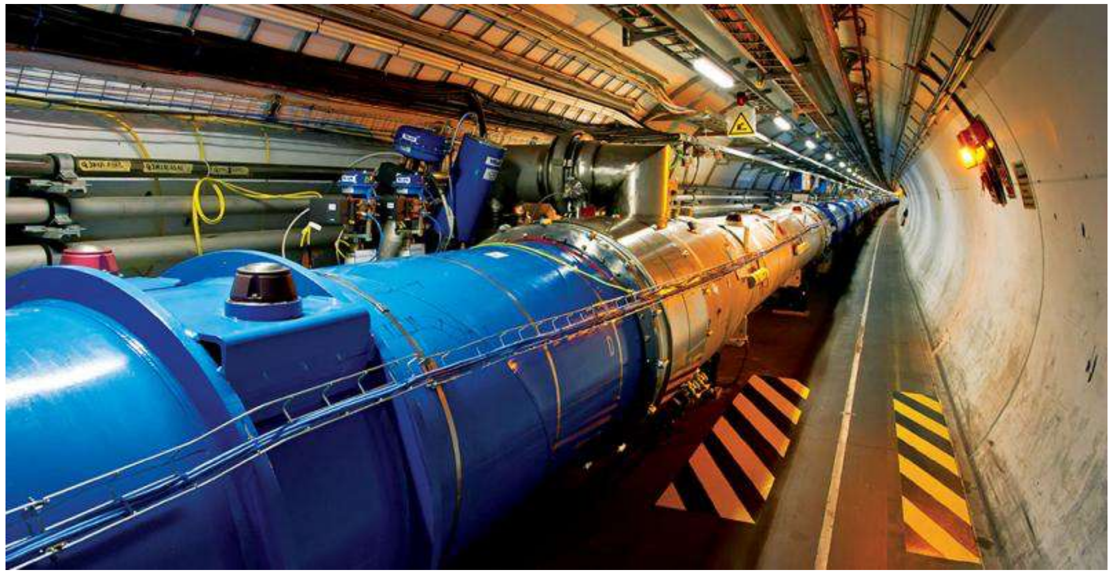
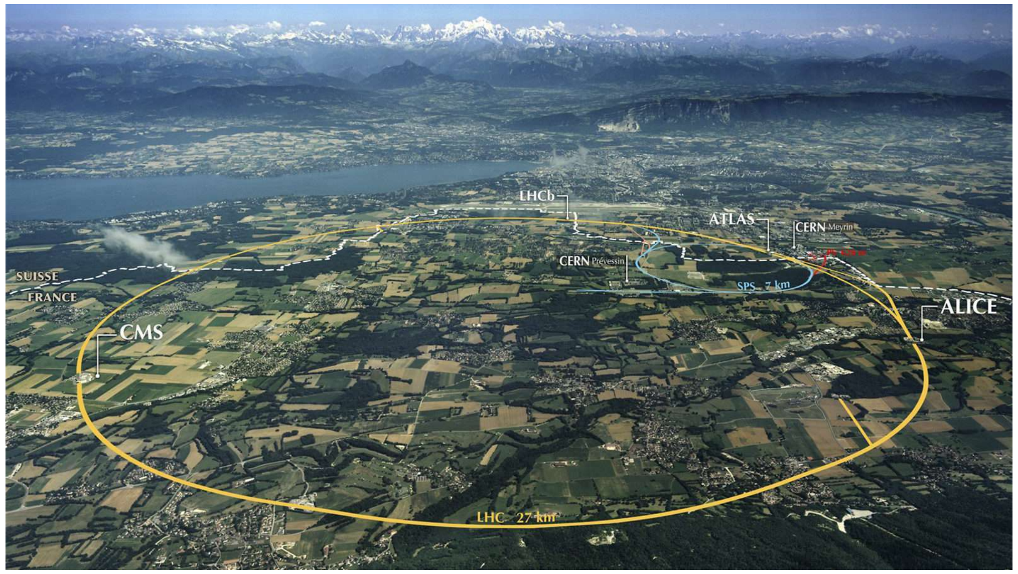




The LHC: a proton-proton collider

- The **LHC** works by colliding proton beams head on at high energy.
- We examine the debris of these interactions for signs of the Higgs and its interactions.
- Before getting to that: we need to understand what we are colliding.
- The **proton**: What is it? What is it made of? How does it behave when given the LHC treatment?



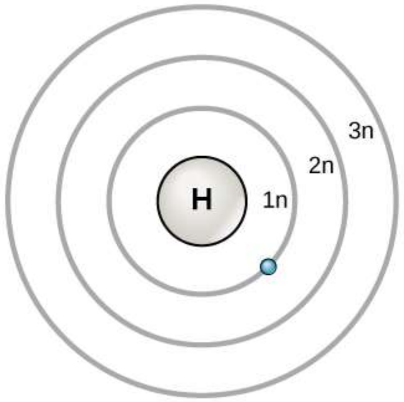


What is the Proton?

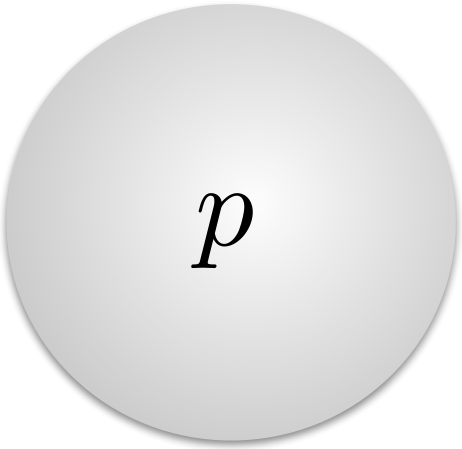
A Proton Roadmap

- In 20th century, layers of proton complexity/substructure uncovered:

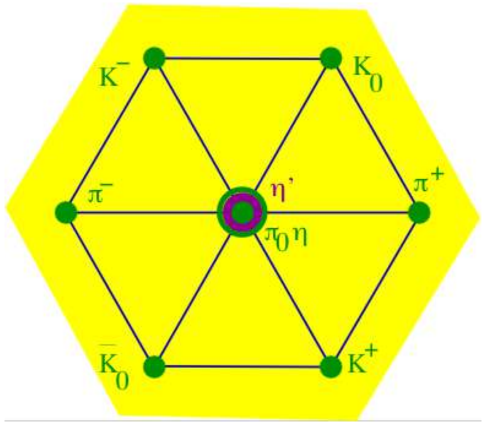
1910s: Rutherford and the compact atomic nucleus



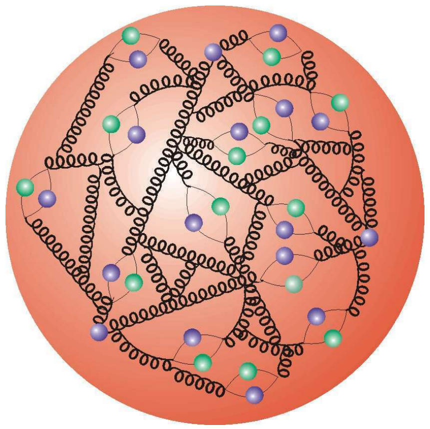
1950s: Measurement of proton radius



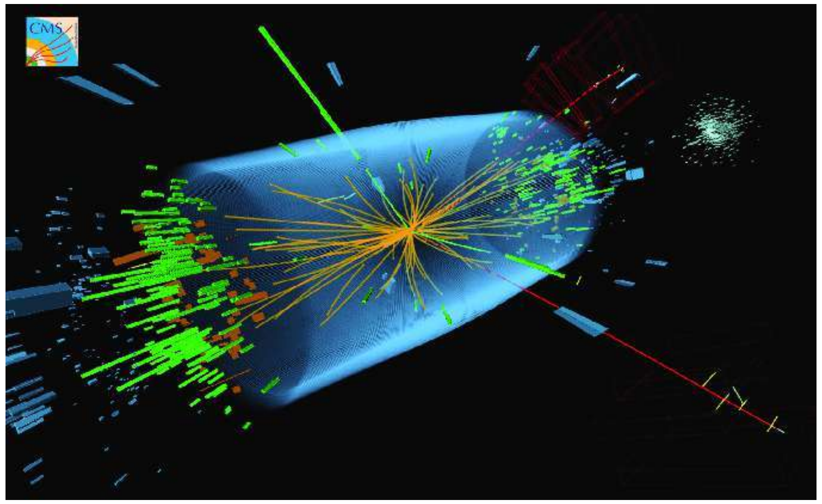
1960s: The Quark Model



1970s: QCD and the proton.

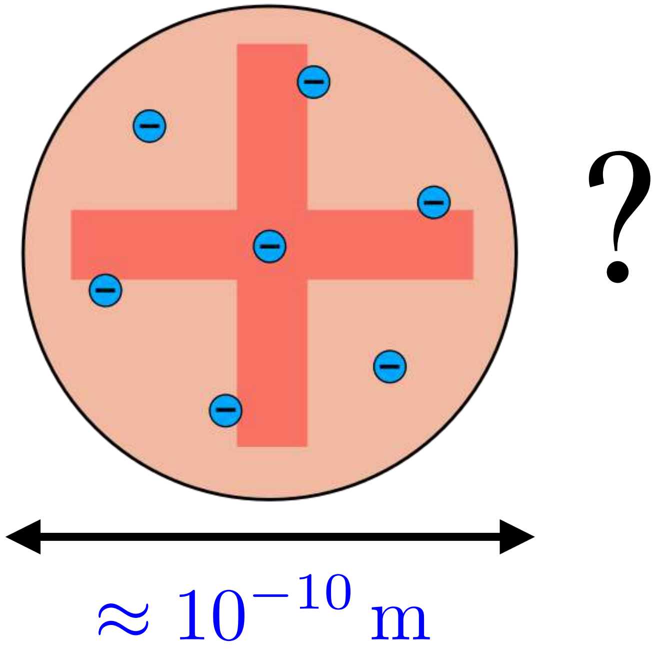


2019: proton collisions, the LHC discovery tool!



Observing Nuclear Structure

- Start of 20th century: no clear picture of structure of atom
- Need to 'look' **inside atom**. Idea: fire beam of particles at target of interest, and measure the corresponds scattering in detector.

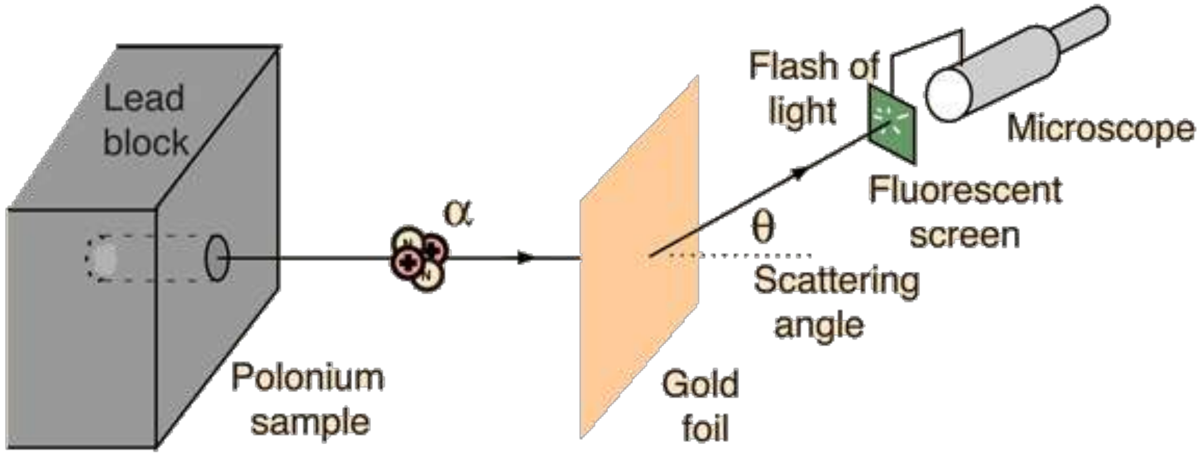


Beam: alpha particles from radioactive source

Target: Gold Foil

Detector: Geiger and Marsden sitting in basement

Rutherford in 1909:



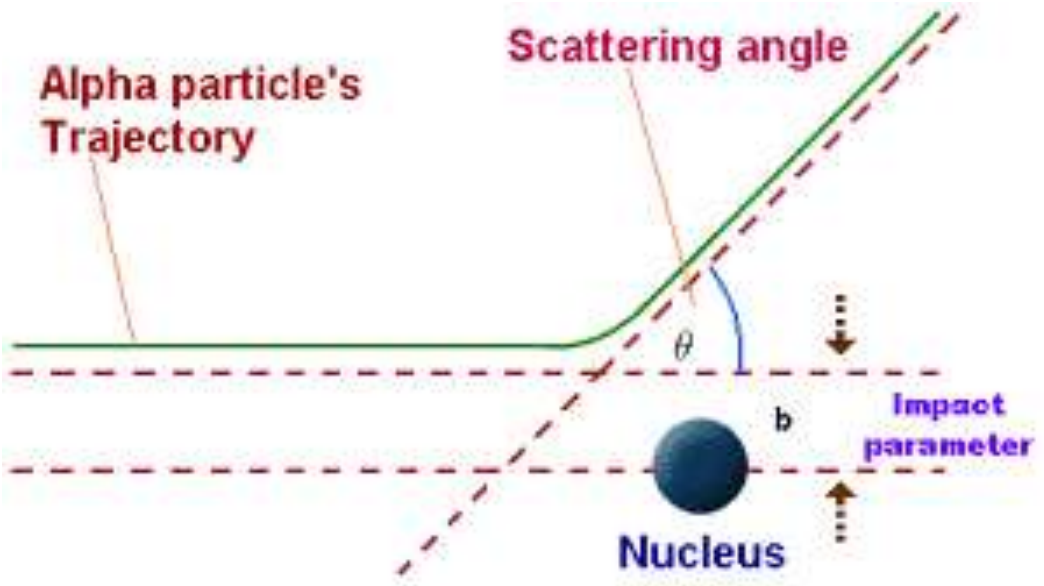
- This basic idea is fundamentally unchanged today: forms the **basis of all particle physics.**

Rutherford Scattering

- α particles observed to occasionally deflect at **very large angles.** Could only be explained by compact, ~ point-like nucleus!

- Data well described by scattering due to electrostatic repulsion by positive '**point-like**' charge:

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} \propto \frac{Z^2\alpha^2}{\sin^4\left(\frac{\theta}{2}\right)}$$



- In what sense was nucleus point-like? Only within **resolution of experiment**.

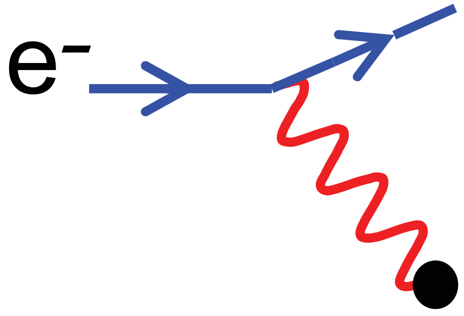
- Here 'point-like' scattering observed up to closest permitted approach of alpha particles ~ **30 fm** (~ 1/10000th of atomic radius).

$1\,\mathrm{fm} = 10^{-15}\,\mathrm{m}$

Looking Into the Proton

- By 1950s still no idea of internal structure of proton/neutrons. How to probe this? Use cleaner electron beam.

  - Electron interacts with proton via photon exchange. **Resolution** $\leftrightarrow$ **photon wavelength**:



$$E = hf \Rightarrow \lambda = \frac{hc}{E}$$

- Thus **higher energies** $\Rightarrow$ see **further inside** proton! Plugging in some (rough!) numbers…

~ Proton size

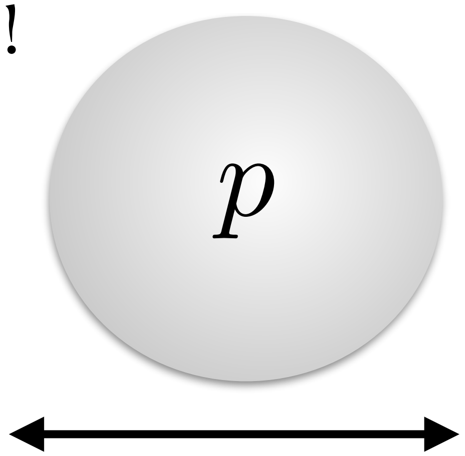
Energy unit (LHC beam = 7000 GeV)

$$\lambda \sim 1\,\mathrm{fm} \Rightarrow E = 1\,\mathrm{GeV}$$

- Much less than LHC energies but at time required cutting edge technology to accelerate electrons.

- 1950s experiments of **Hofstadter**: collisions of electron beam (up to ~ 0.5 GeV) with protons.

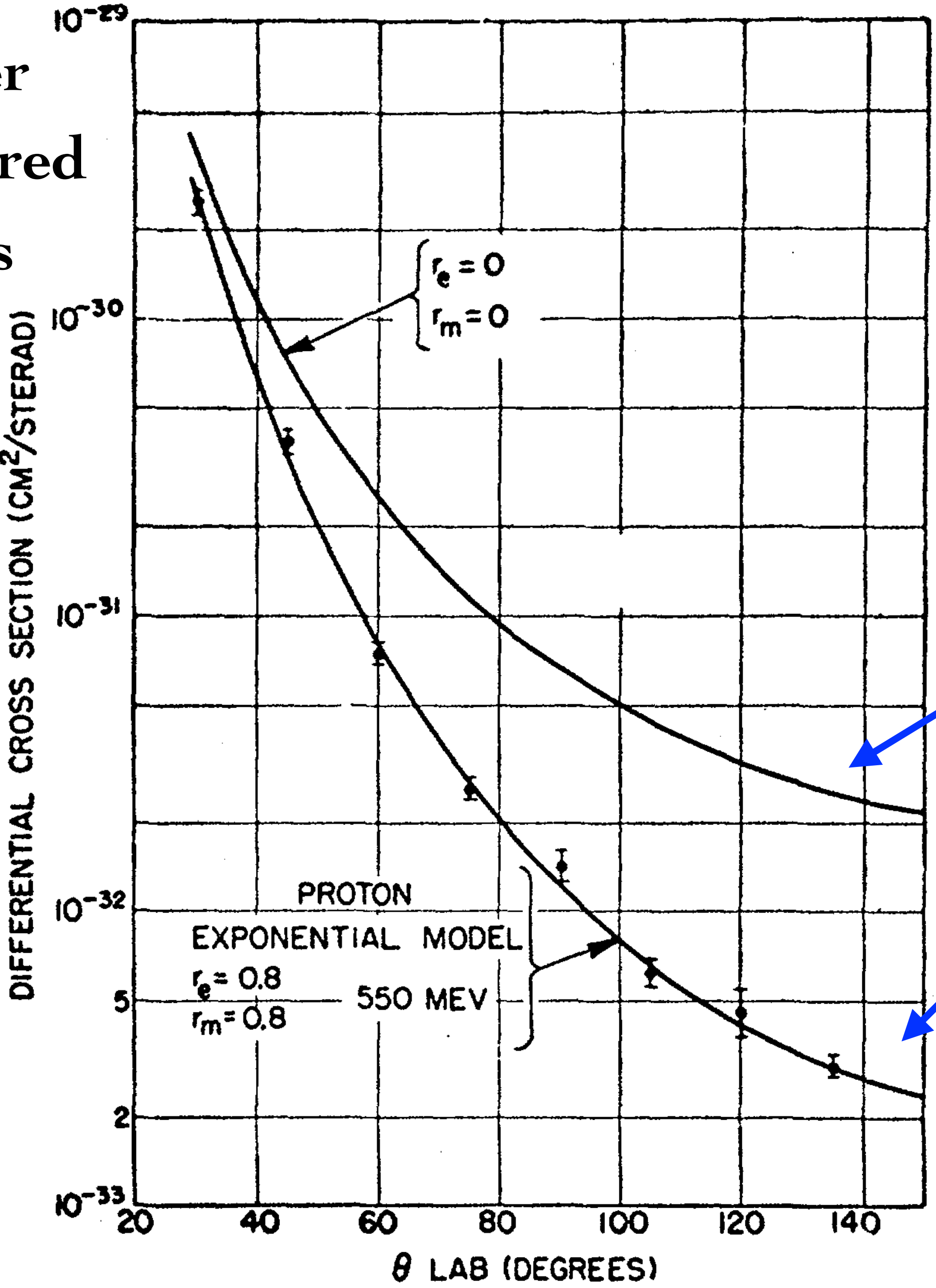
- **Clear deviation** from point-like behaviour seen ⇒ **proton has size**!



≈ 1 fm

- What is the nature of this extended object? Continuous extent of charged 'stuff', or formed of something **more fundamental**?

~Number of scattered electrons



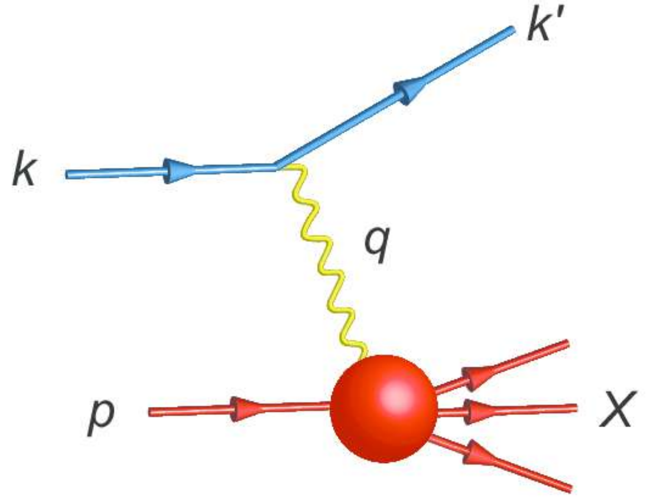
$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} \propto \frac{Z^2\alpha^2}{\sin^4\left(\frac{\theta}{2}\right)}$$

Point-like theory

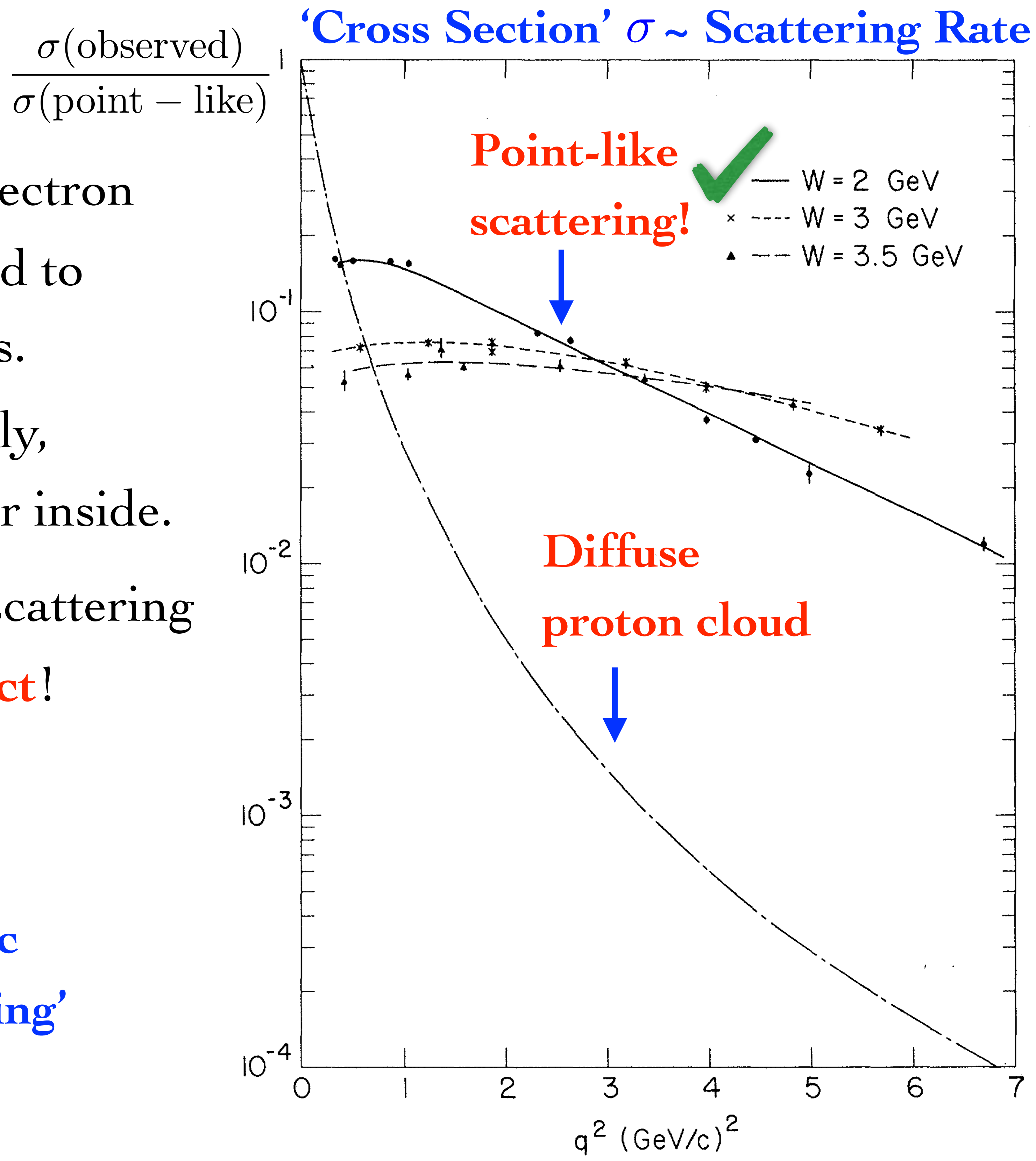
Data

Looking Deeper

- **1976**: The Stanford Linear Electron Collider (**SLAC**) collider pushed to unprecedented electron energies.
- Electrons scattered inelastically, destroying proton, seeing deeper inside.
- Something **completely new**: scattering of electron with **point-like object**!



'Deep Inelastic Scattering'



'Cross Section' σ ~ Scattering Rate

$$\frac{\sigma(\text{observed})}{\sigma(\text{point}-\text{like})}$$

Point-like scattering! ✓

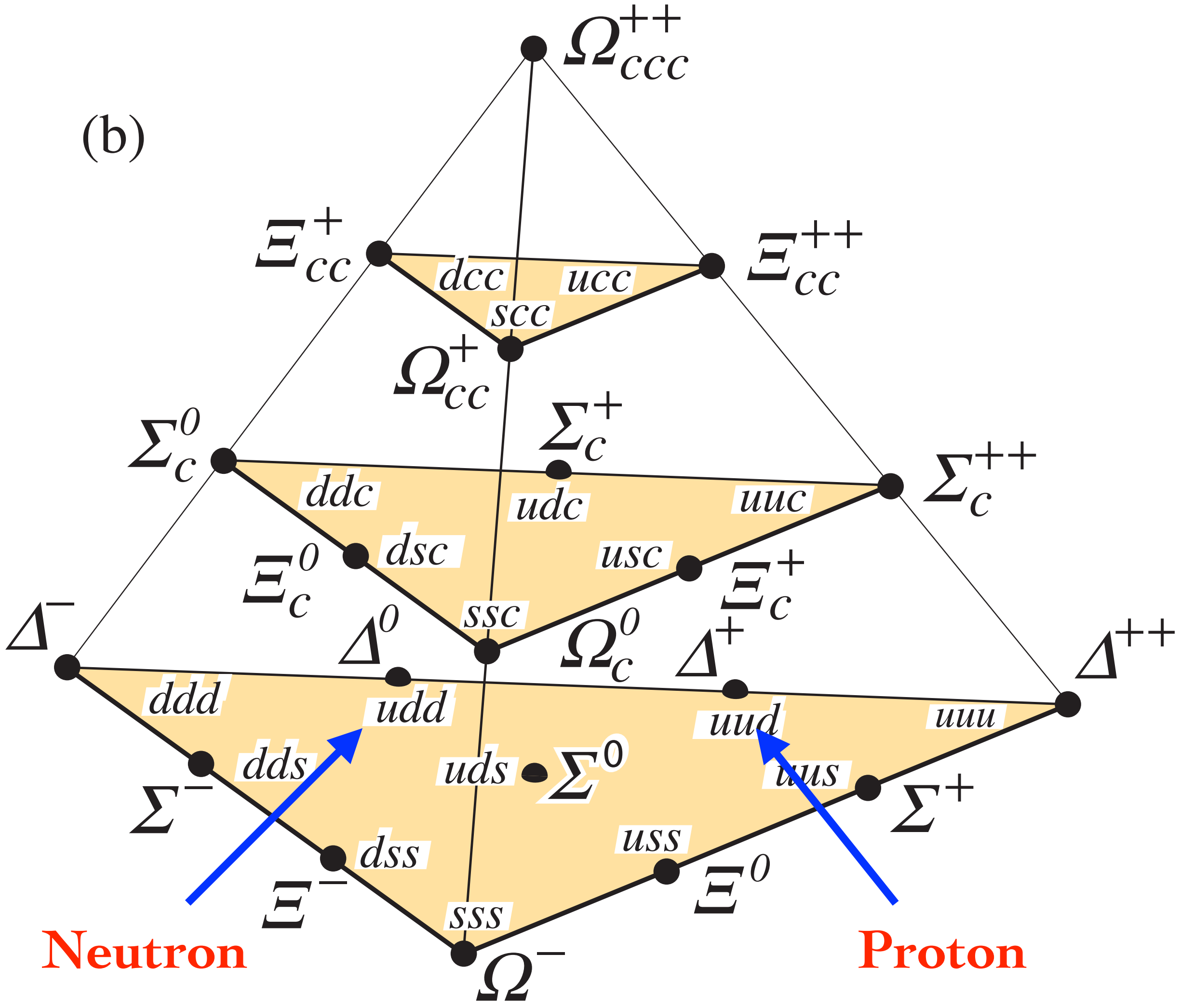
Diffuse proton cloud

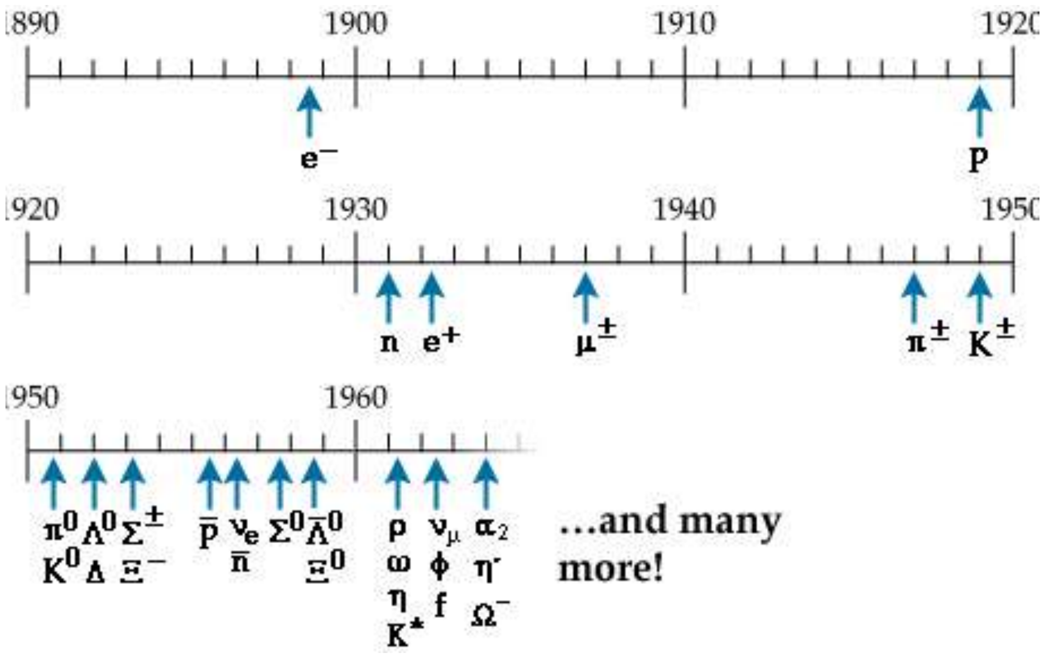
~ scattering angle

Quarks

- These objects, first given the agnostic label of ‘**partons**’ by Feynman, but soon identified with the ‘**quarks**’ needed to explain the ‘**hadron zoo**’.

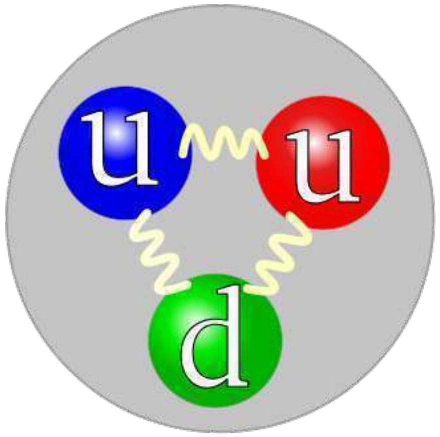
- Initially required 3 distinct types (**up, down, strange**). Since then 3 more discovered (**charm, bottom, top**).





The Proton

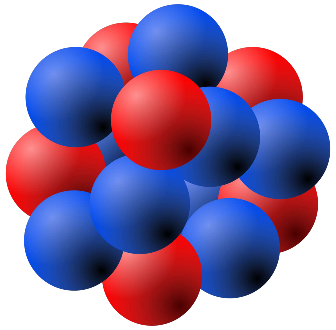
- **Proton** naturally described in quark model: one part of a larger family of 'baryons' - **bound state of 3 quarks**.
- Proton: two 'up' quarks and one 'down'.
- Quarks carry fractional electric charge:



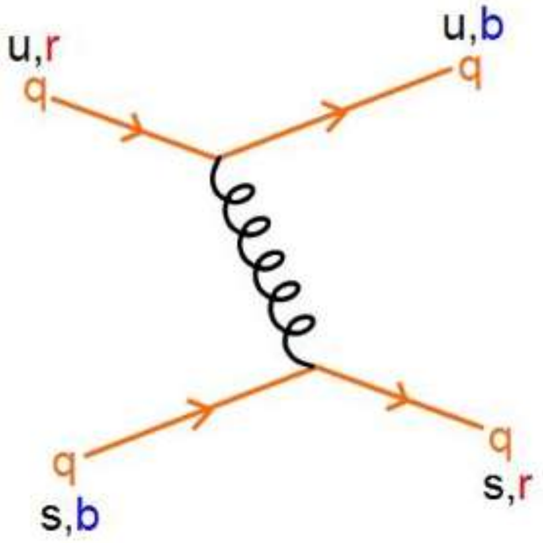
Up quark: +2/3 **Down quark: -1/3** **Proton:** $2 \times \frac{2}{3} - \frac{1}{3} = +1$ ✓

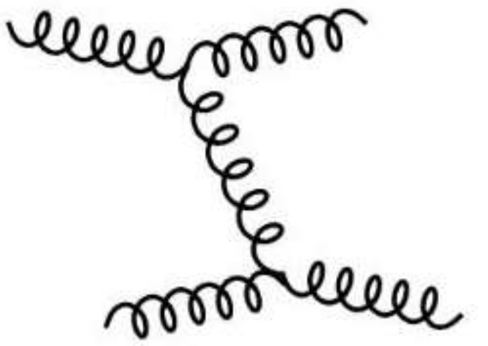
- This is the basic idea, and it still holds true today. But more fundamental questions remained unanswered:
  - ❖ What is the **force** that is binding these quarks together?
  - ❖ How do we describe it theoretically?

Quantum Chromodynamics



- Nuclei as bound states of proton and neutrons: required introduction of completely new attractive **binding force**: the '**strong nuclear force**'.
- Can now be understood in terms of more fundamental quark interactions.
- New force carrying '**gluon**' particle mediating interactions between quarks, which carry '**colour**' charge.
- Mathematical framework direct generalisation of QED. New effects:
  - ❖ **3** different colour charges (just 1 electric charge).
  - ❖ Gluon carries charge: can **self-interact**!

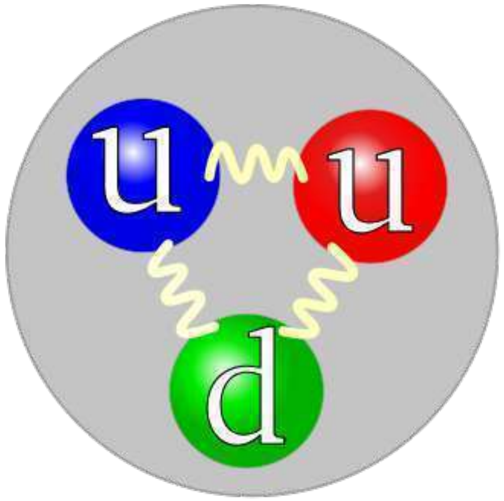



gluon-gluon scattering

QED	↔	**QCD**
Electrons	↔	**Quarks**
Photons	↔	**Gluons**
Electric Charge	↔	**Colour Charge**

What do proton collisions at the LHC look like?

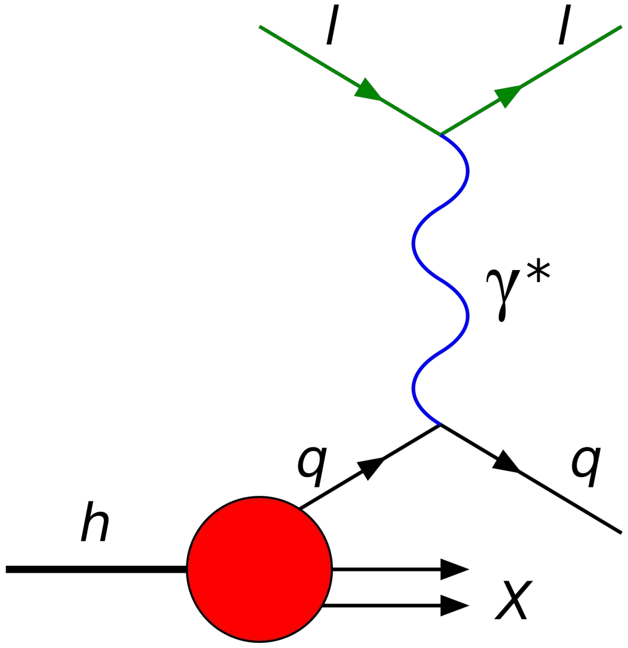
Colliding Protons



- How do we apply this model to proton collisions at the **LHC**?
- For now, stick with simpler electron-proton collision case.
- Basic idea: potentially complex **electron-proton** interaction really due to simple scattering between point-like **electron** and **quark** within proton.

Scattering Rate:

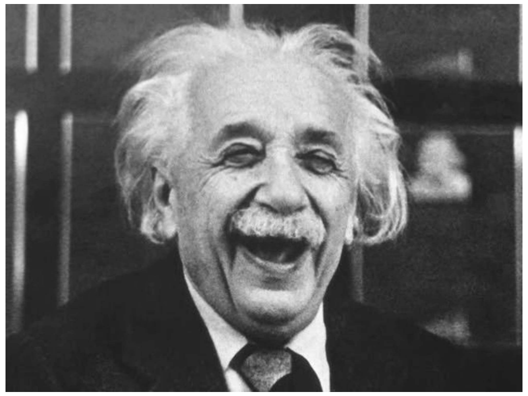
$$\sigma(ep) \sim \sigma(eq)$$

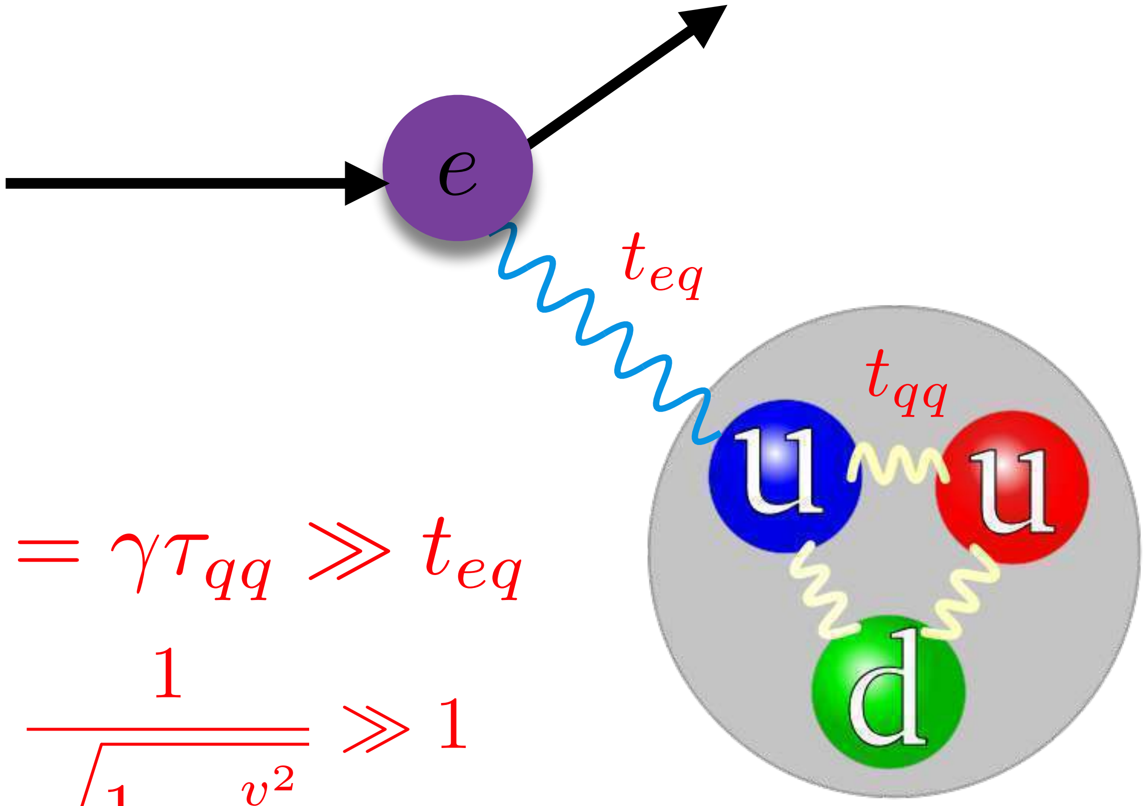


- But is this really sensible? Can we simply ignore fact that quarks is part of a complex and strongly bound system (the proton)?

Colliding Protons

- Proton at **rest**: complex system of interacting quarks ($\tau_{qq} \approx 10^{-24} s$).
- However we are interested in very **high energy** proton collisions. Proton has velocity **v ~ c**, and **relativity** comes into the game.
- What does electron 'see'? **Time dilation**: proton 'clock' much slower than when at rest, electron only sees a ~ **static snapshot** of the proton!





$$t_{qq} = \gamma \tau_{qq} \gg t_{eq}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \gg 1$$

- Electron-quark interaction time $\ll$ timescale of internal quark interactions!

Colliding Protons

- Electron scatters off a quark within the **static** proton **snapshot**. The **quark interactions** within the proton are **frozen** and can be ignored.
- Valid to consider in terms of **free** quark-electron scattering.

$$\sigma(ep) \sim \sigma(eq)$$ ✓

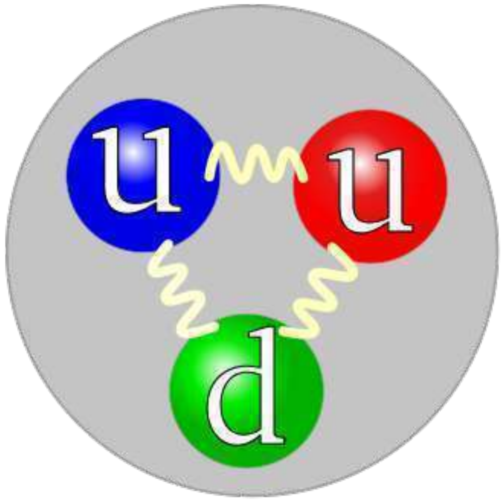
- Final element: what does the frozen distribution of quarks look like? Relevant degree of freedom: amount of proton's energy carried by quark.

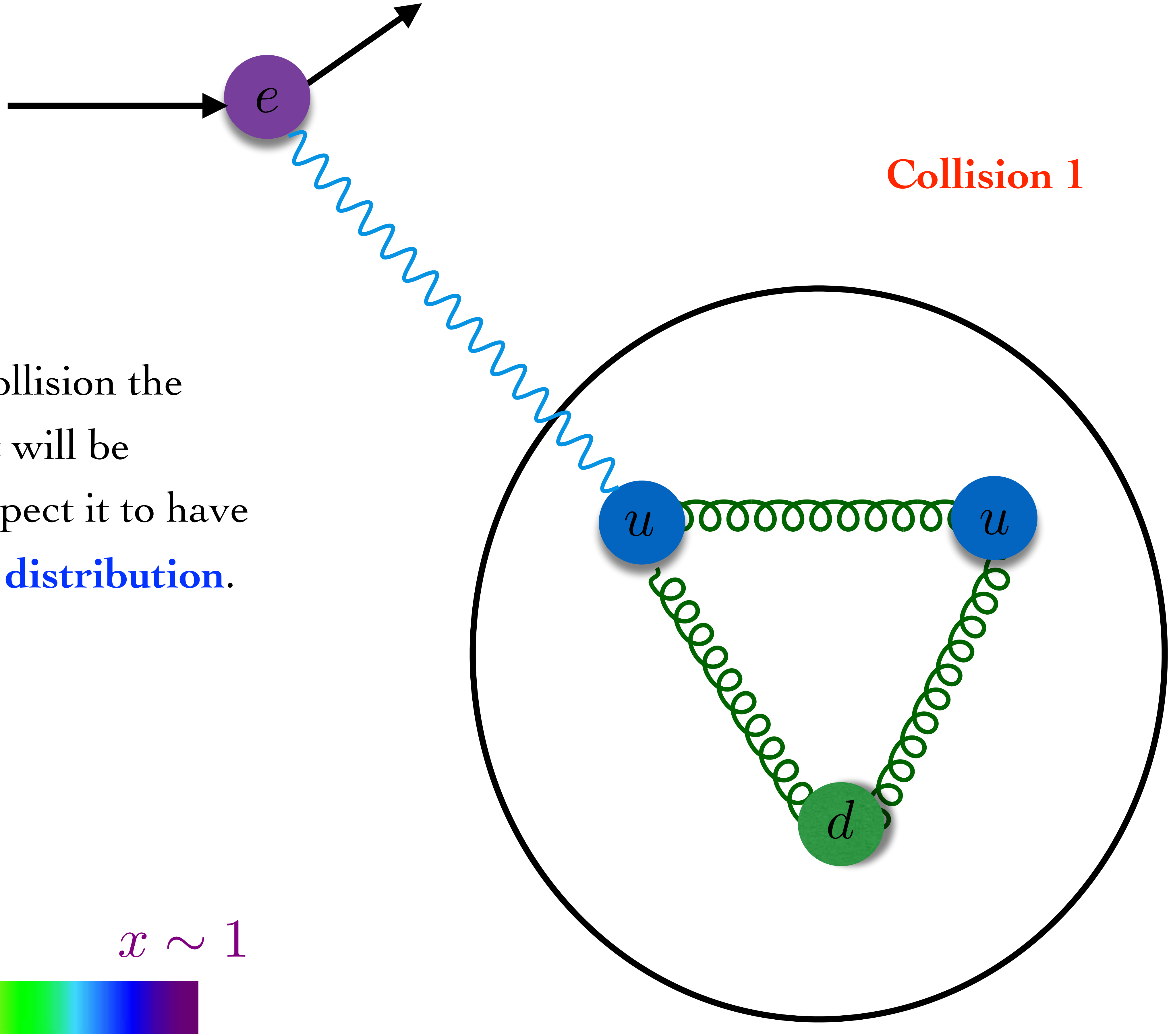
- Introduce **new variable**: $x = \frac{E_{\text{quark}}}{E_{\text{proton}}}$

$$0 < x < 1$$

quark has no energy

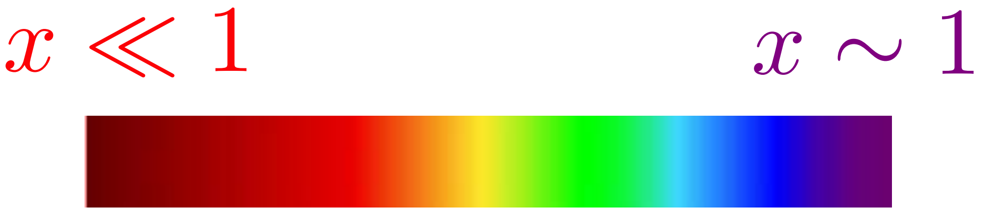
quark has all proton energy



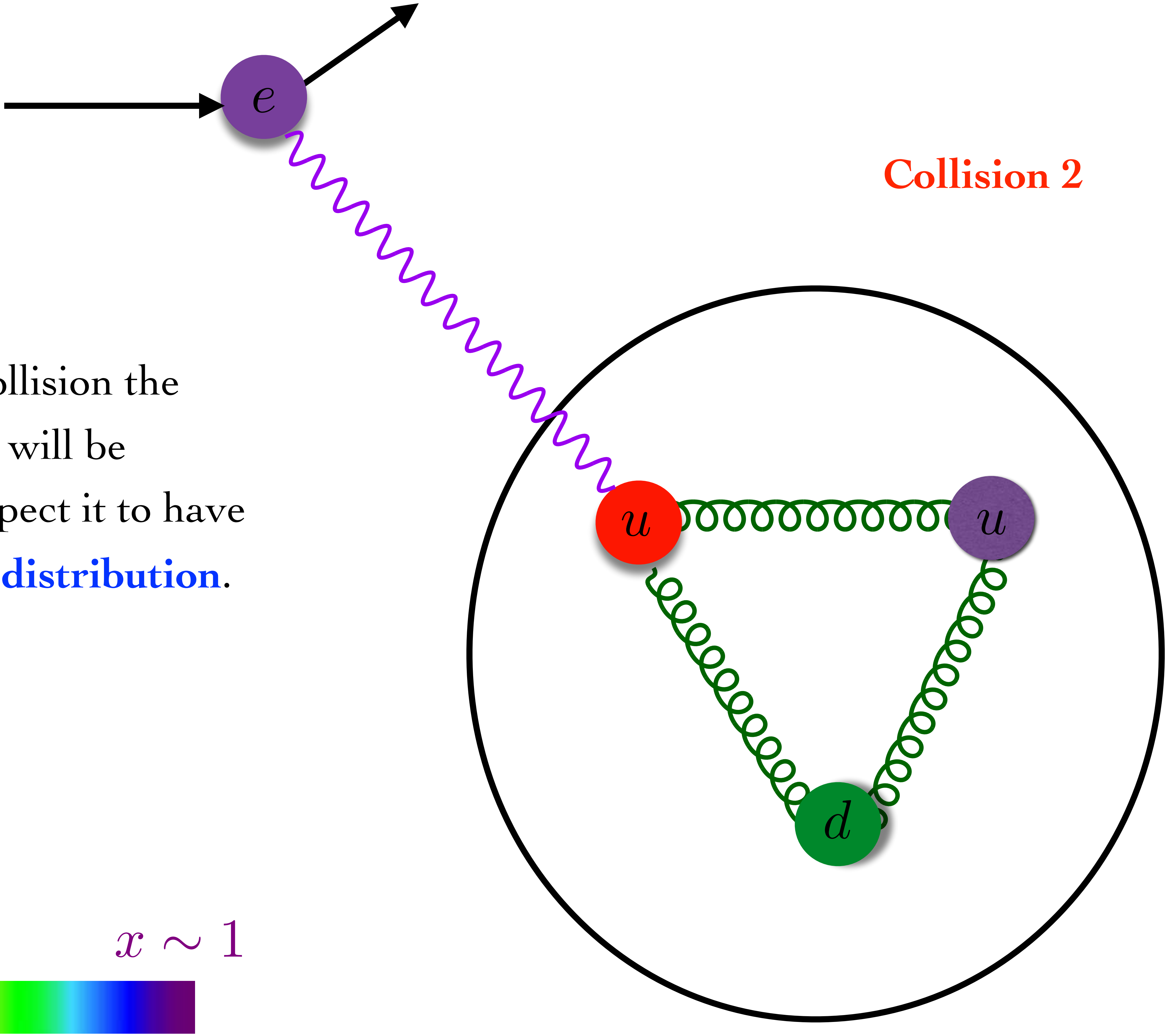


- Collision by collision the proton snapshot will be different, but expect it to have some **statistical distribution**.

$$x = \frac{E_{\text{quark}}}{E_{\text{proton}}}$$



Collision 2



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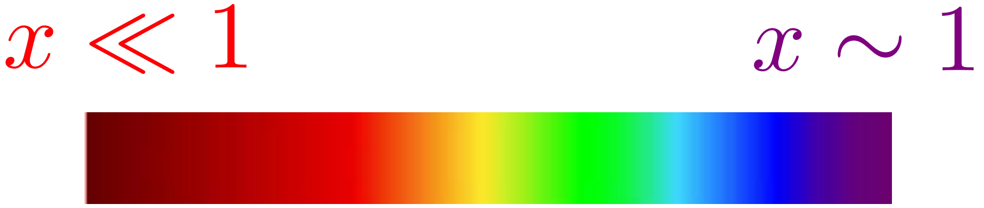
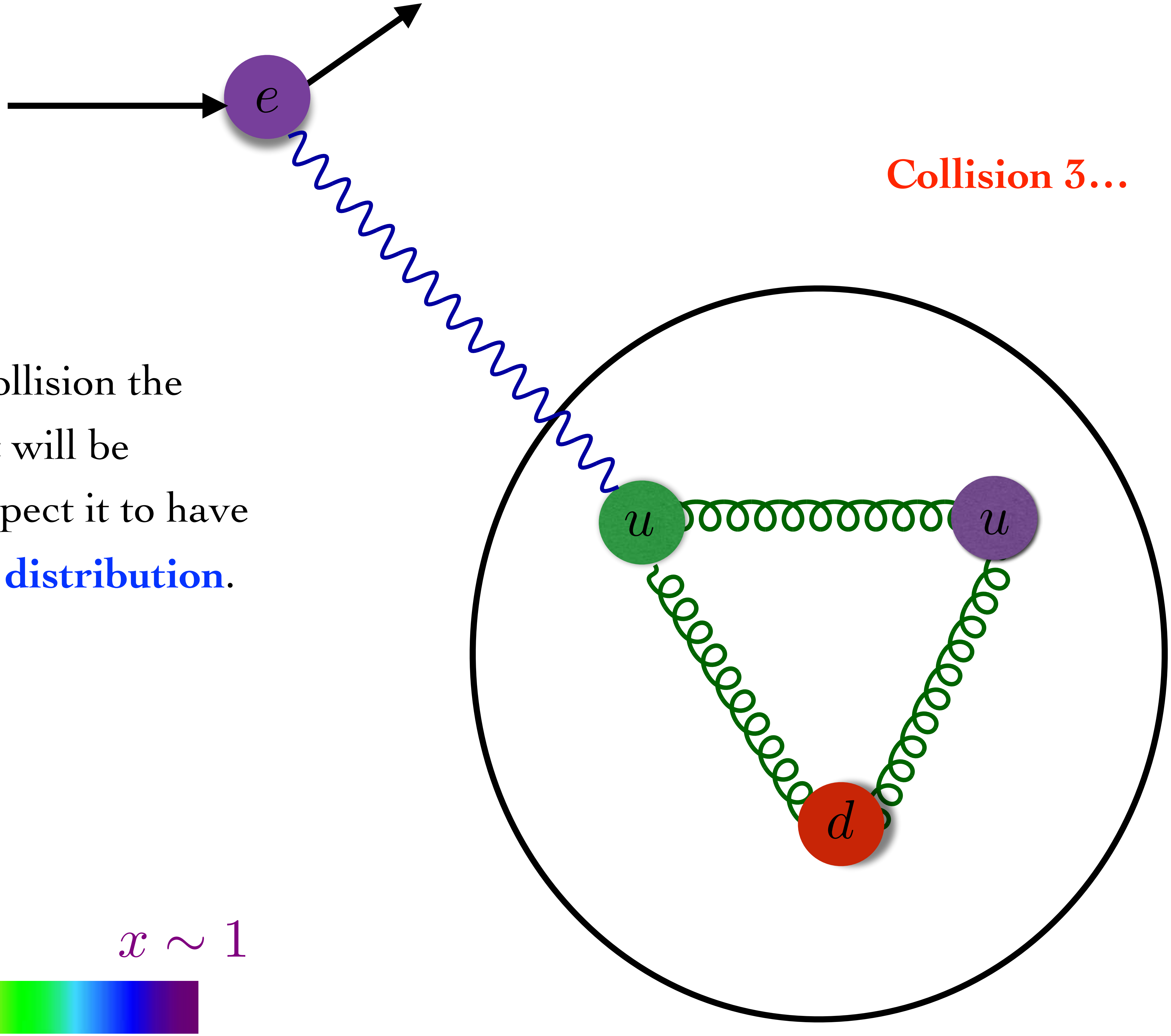


Collision 3…

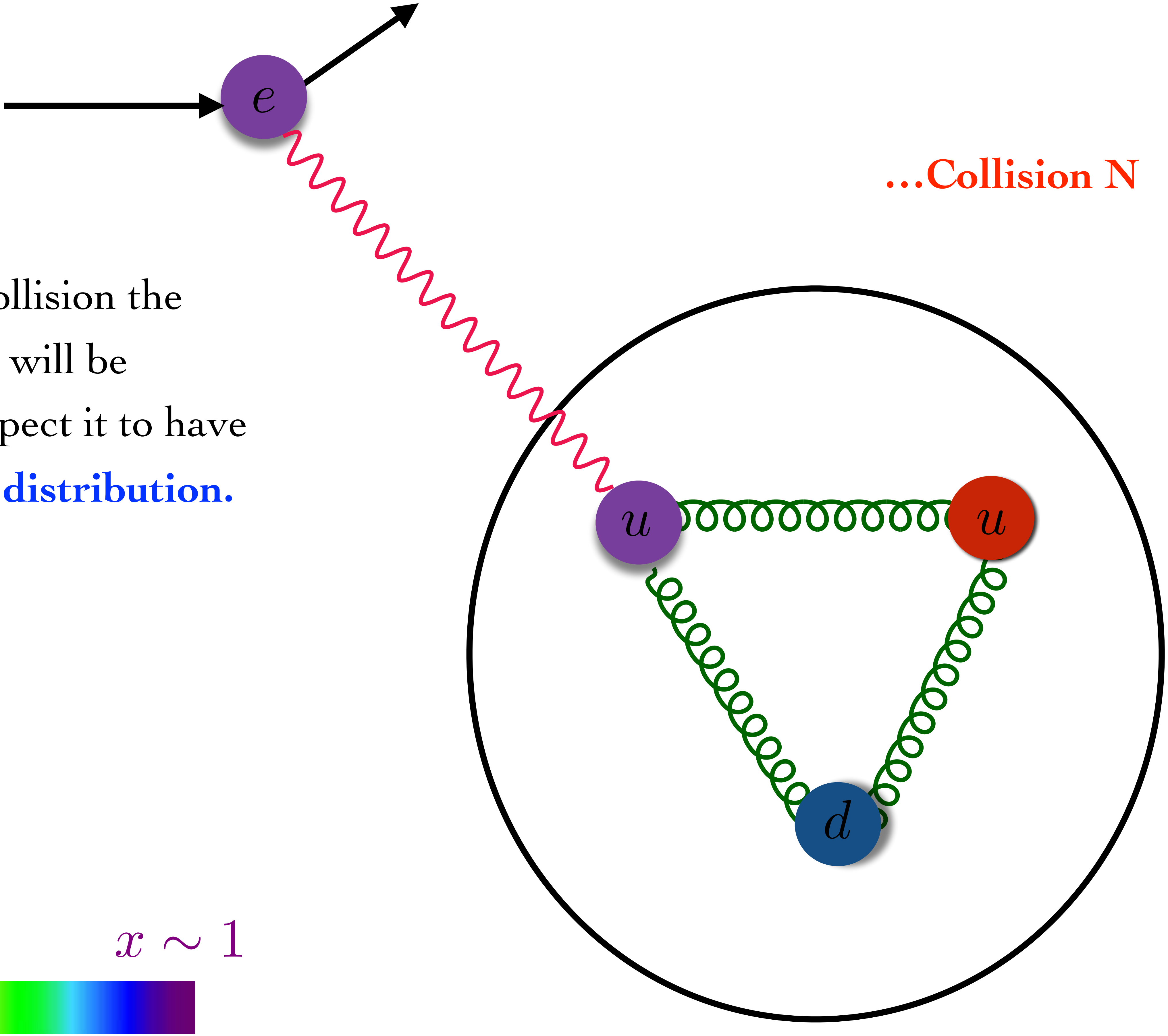


- Collision by collision the proton snapshot will be different, but expect it to have some **statistical distribution**.

$$x = \frac{E_{\text{quark}}}{E_{\text{proton}}}$$

$x \ll 1$ $\qquad$ $x \sim 1$

…Collision N



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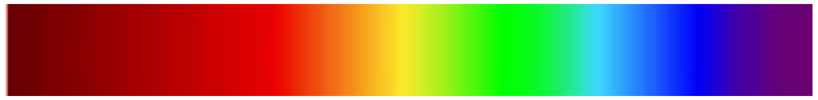


Mapping out the Proton

- **Statistical distribution** known as '**Parton Distribution Function**' (**PDF**).

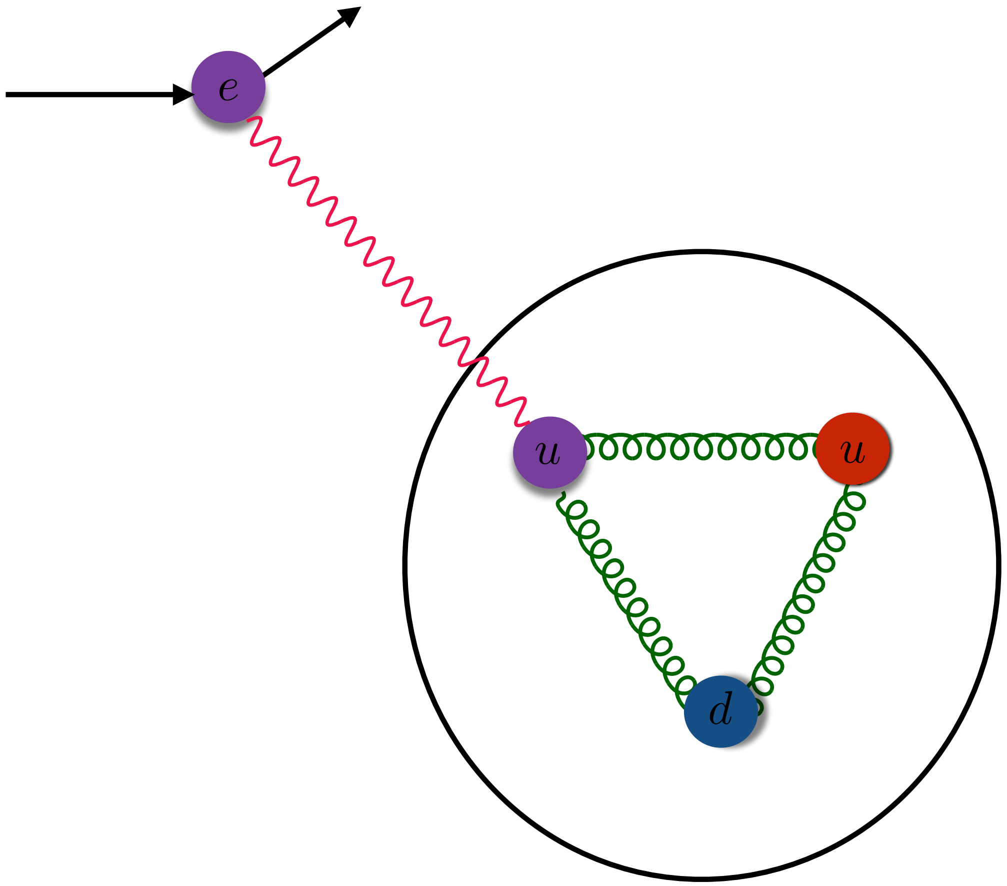
$f(x)$: **Probability of finding a quark with energy fraction x in proton snapshot.**

Electron-proton scattering rate:

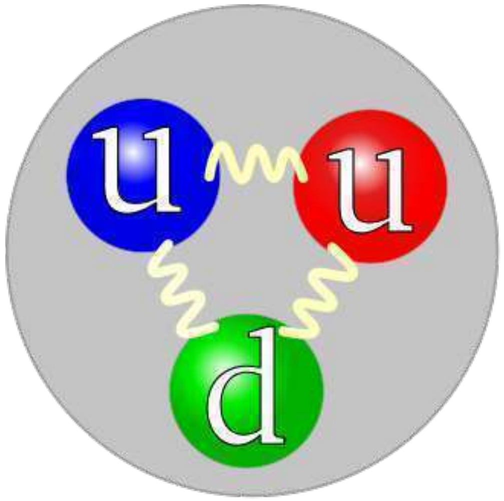
$$\sigma_{ep} = \int_0^1 \mathrm{d}x\, f_q(x)\, \sigma_{eq}(x)$$

- Electron energy and scattering angle directly related to quark x and photon resolution.

⟶ By scanning over these, can **map out** entire distribution!



The Proton 'Sea'



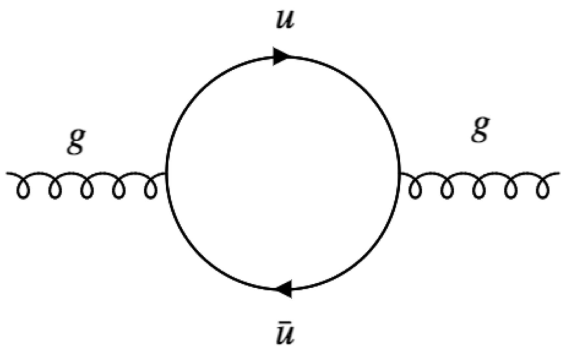
- So far have only considered possibility of electron-quark scattering. Seems sensible given basic **uud** picture of proton. But is this the **whole story?**

- **No!** In fact proton is a much more complex object than basic uud picture would predict. **Uncertainty principle**:

$$\Delta E \Delta t \sim \hbar$$

$\longrightarrow$ Quark-antiquark pairs can snap in and out of existence if:

$$\Delta t < \frac{\hbar}{2 m_q c^2}$$



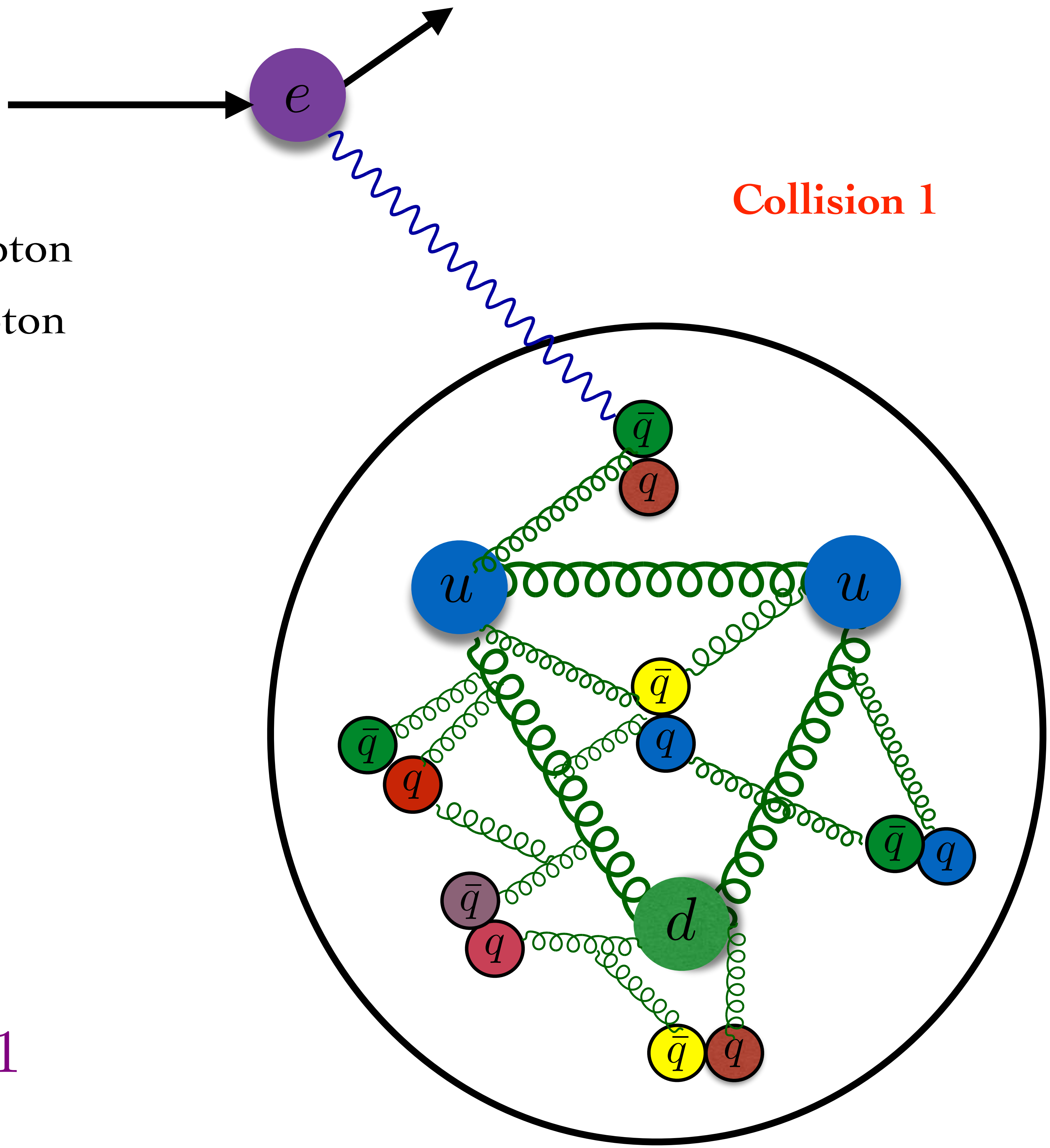
- Proton is in fact filled with a '**sea**' of **quark-antiquark pairs** snapping in and out of existence. In addition to so-called '**valence**' **uud**.

- Back to the electron-proton collision: this seething proton sea is also ~ **frozen** in the proton snapshot.

$\longrightarrow$ Electron can scatter off these frozen quark-antiquark pairs!

$$x = \frac{E_{\text{quark}}}{E_{\text{proton}}}$$

$x \ll 1$ $x \sim 1$



Collision 1

Collision 2…

- Back to the electron-proton collision: this seething proton sea is also ~ **frozen** in the proton snapshot.

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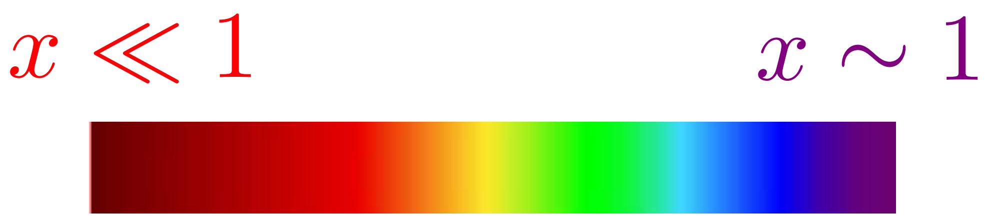
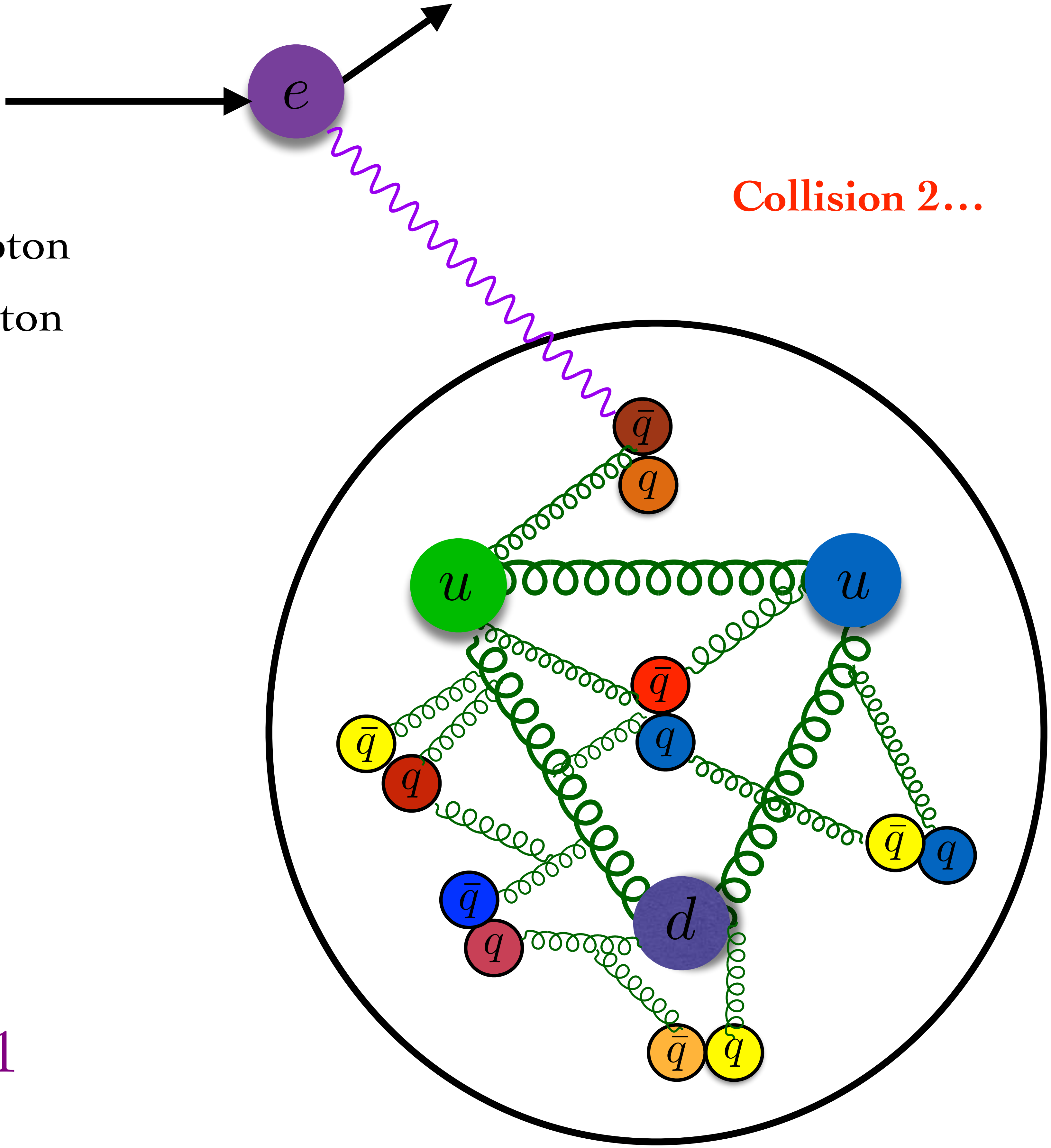
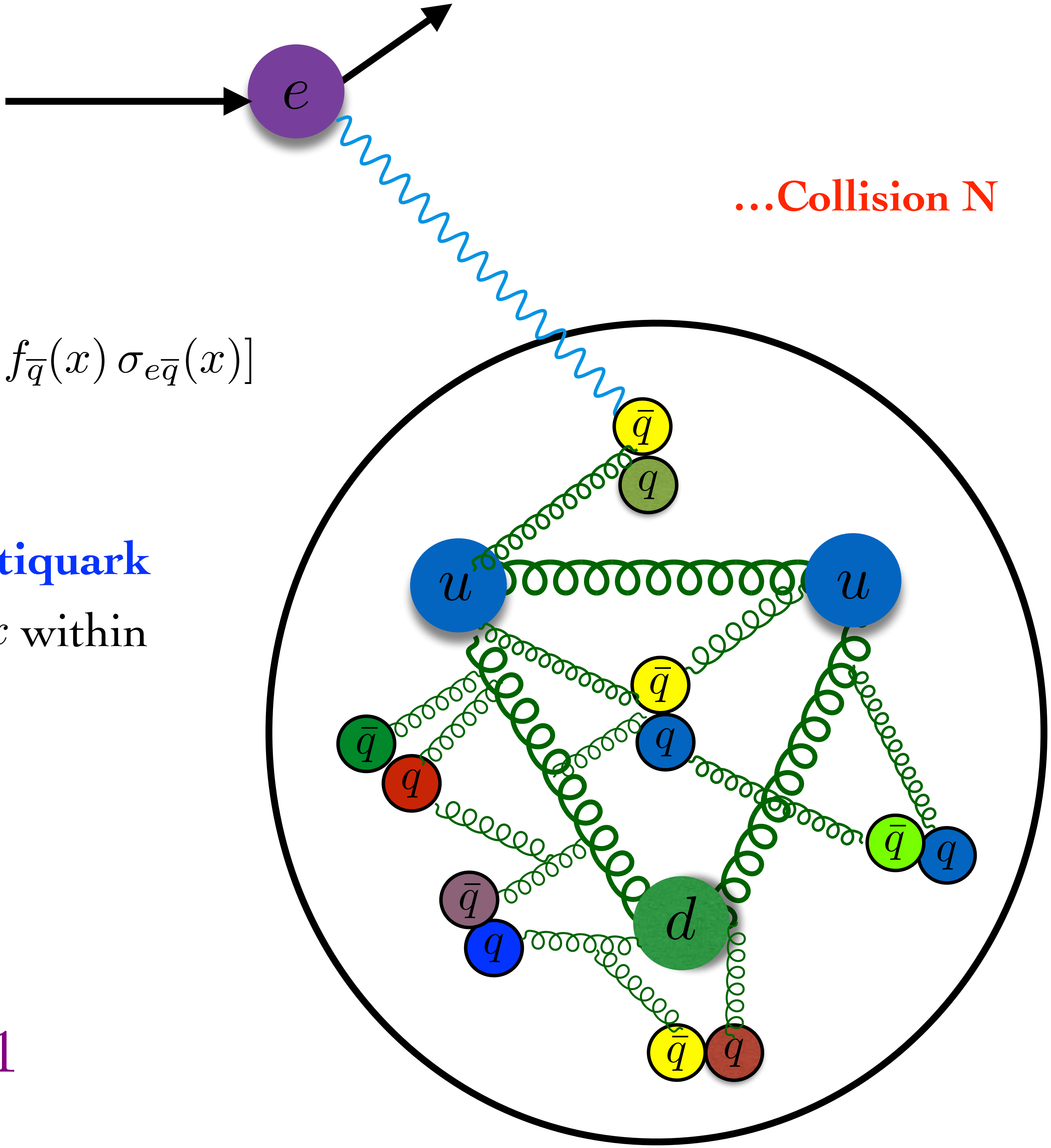




…Collision N



- Scattering rate becomes:

$$\sigma_{ep} = \int_0^1 \mathrm{d}x \left[f_q(x)\, \sigma_{eq}(x) + f_{\bar{q}}(x)\, \sigma_{e\bar{q}}(x) \right]$$

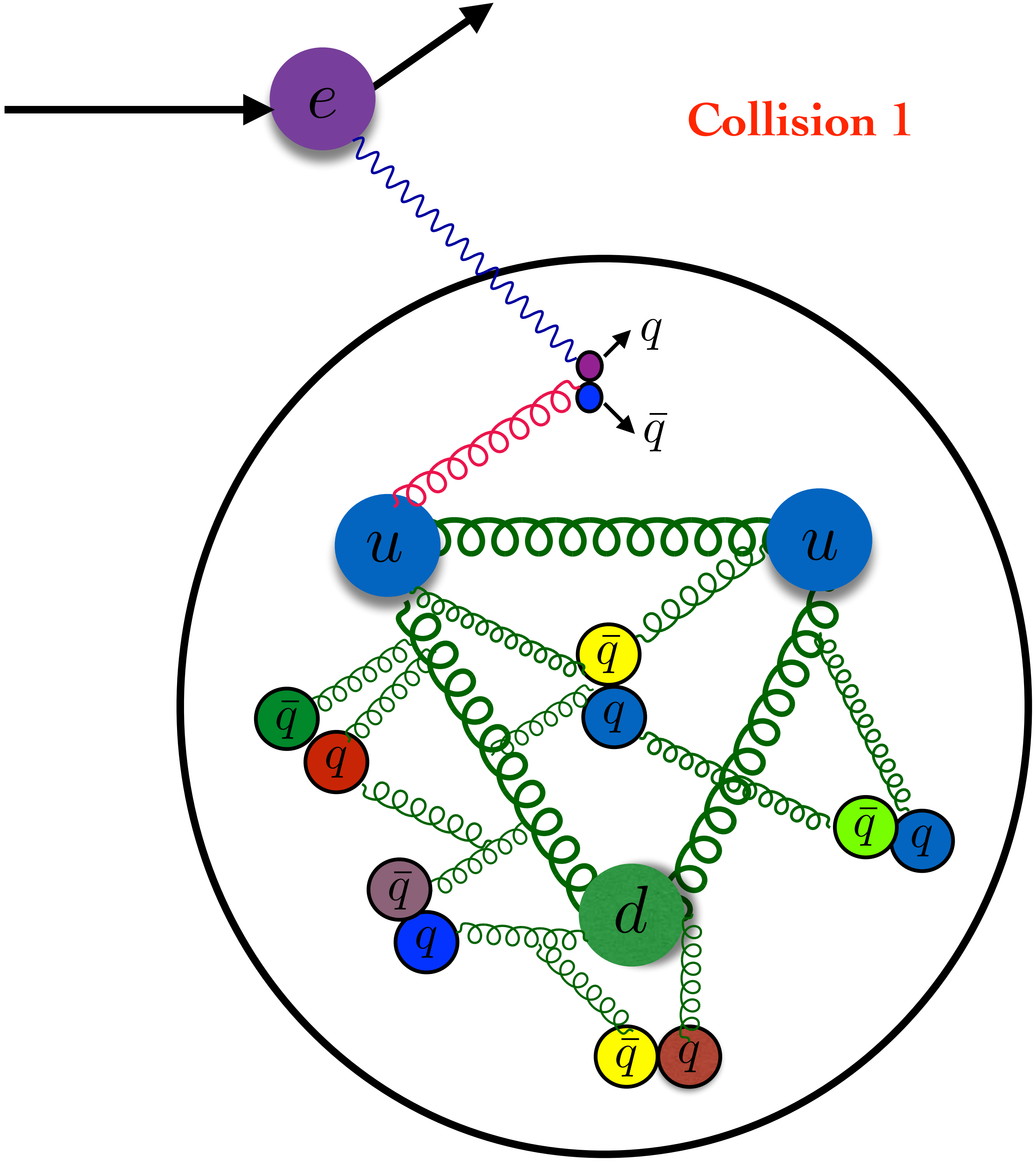
$f_{\bar{q}}(x)$: Probability to find **antiquark** with energy fraction x within proton snapshot.

$$x = \frac{E_{\text{quark}}}{E_{\text{proton}}}$$

$x \ll 1$ $x \sim 1$

The Gluon Content of the Proton

- Sea of **gluons** constantly being exchanged between the quark constituents of proton, binding it together.
- Can also scatter off these objects!



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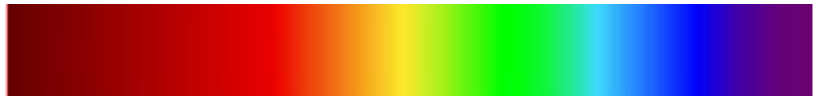
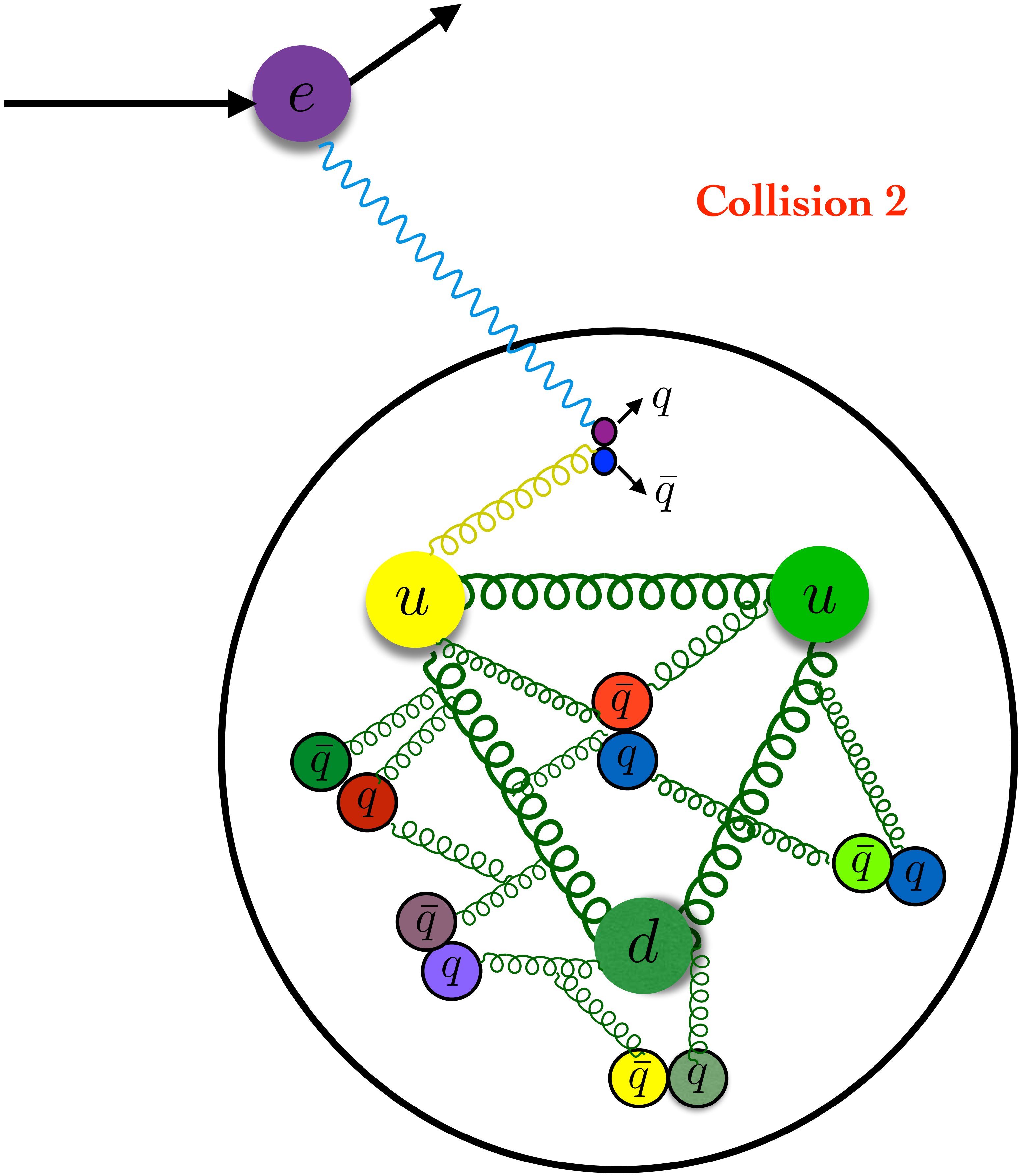


Collision 2



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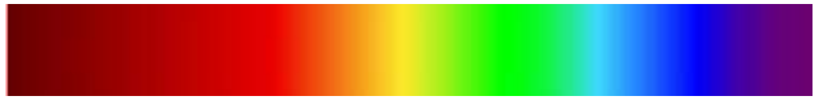
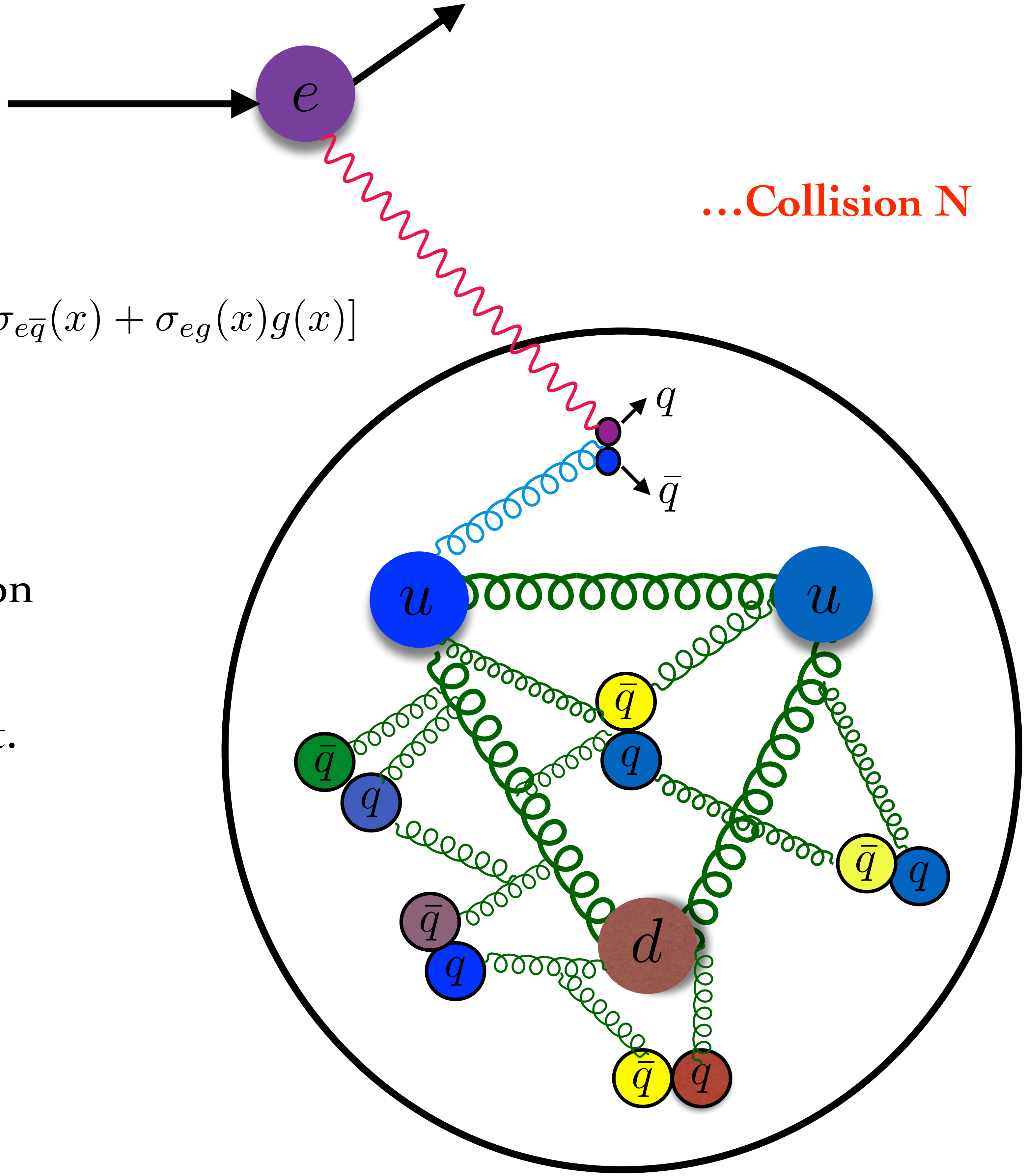


…Collision N

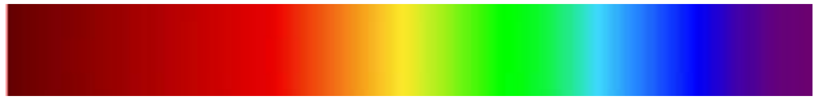


$$\sigma_{ep} = \int_0^1 \mathrm{d}x \, [f_q(x)\,\sigma_{eq}(x) + f_{\bar{q}}(x)\,\sigma_{e\bar{q}}(x) + \sigma_{eg}(x)g(x)]$$

$g(x)$: Probability to find gluon with energy fraction x within proton snapshot.

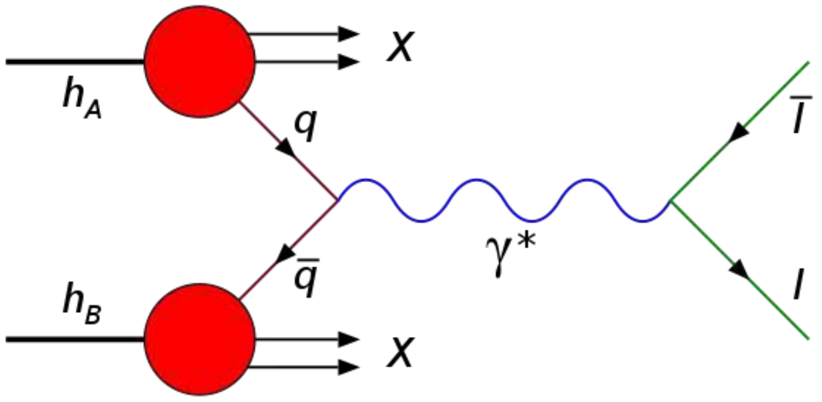
$$x = \frac{E_{\text{quark}}}{E_{\text{proton}}}$$

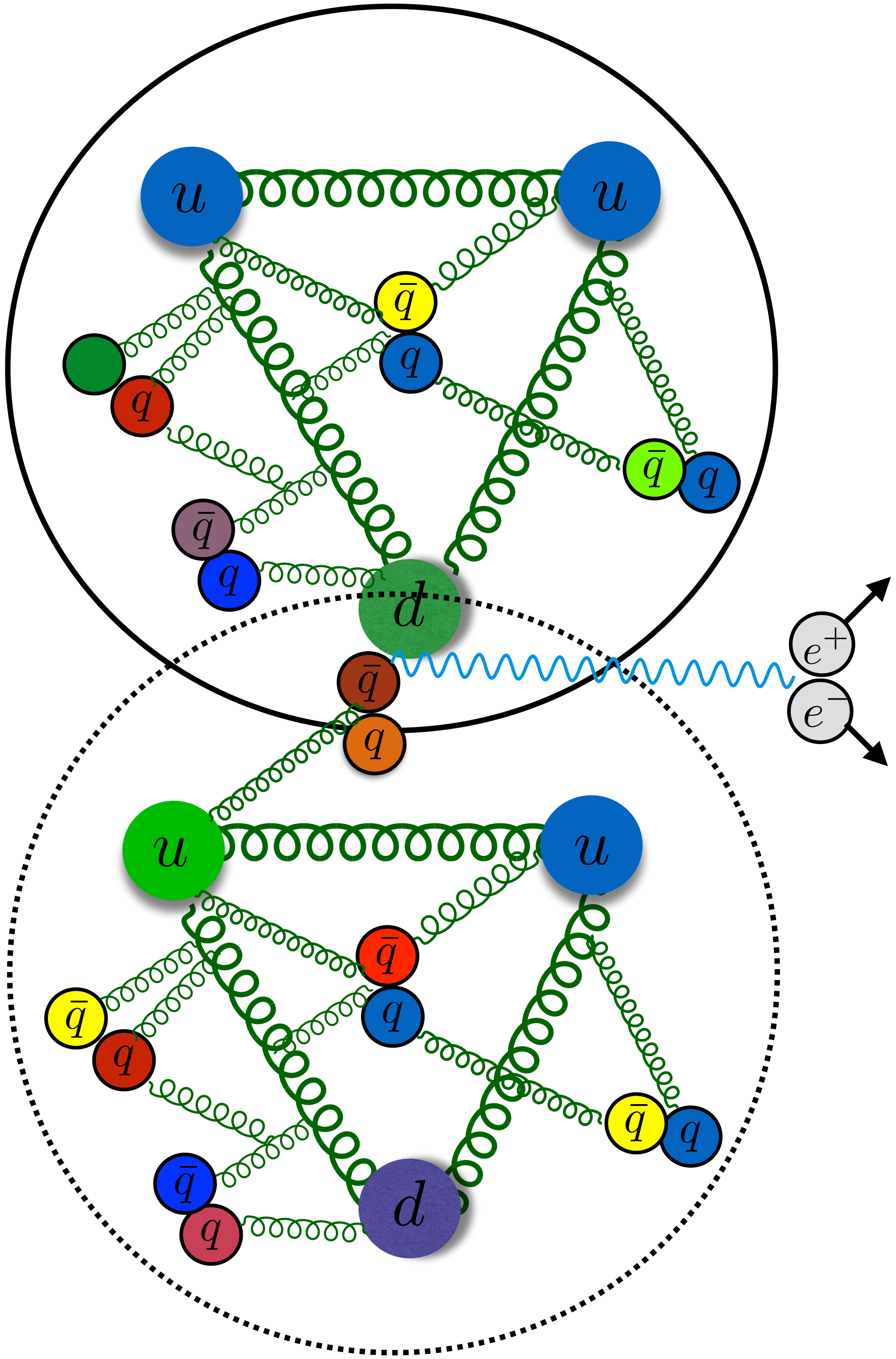
$x \ll 1$ $x \sim 1$



Proton-Proton Collisions

- How does this picture change in the case of **proton-proton** collisions at the **LHC**? Answer: **not too much**.
- Proton-proton scattering = scattering of point-like **quark/gluons**.
- For example, simple so-called ‘**Drell-Yan**’ process, leading to production of an electron-positron pair.

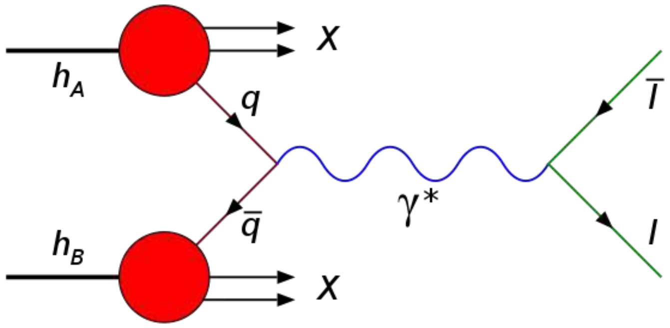




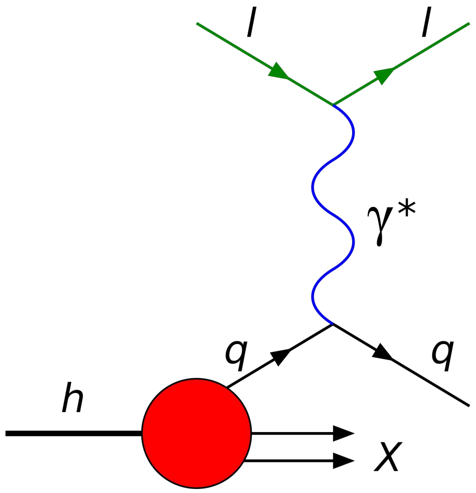
$$\sigma^{DY} \sim \sigma(\bar{q}q \to e^+e^-) \otimes q(x_1) \otimes \overline{q}(x_2)$$

Extracting PDFs

- How do we actually **determine** these **PDFs**?
- **PDFs:** distribution of proton constituents, due to complex strong interactions. With current theoretical tools we **cannot predict** them.
- What we can do: determine them experimentally in processes we understand well and use to predict processes such as **Higgs** production.

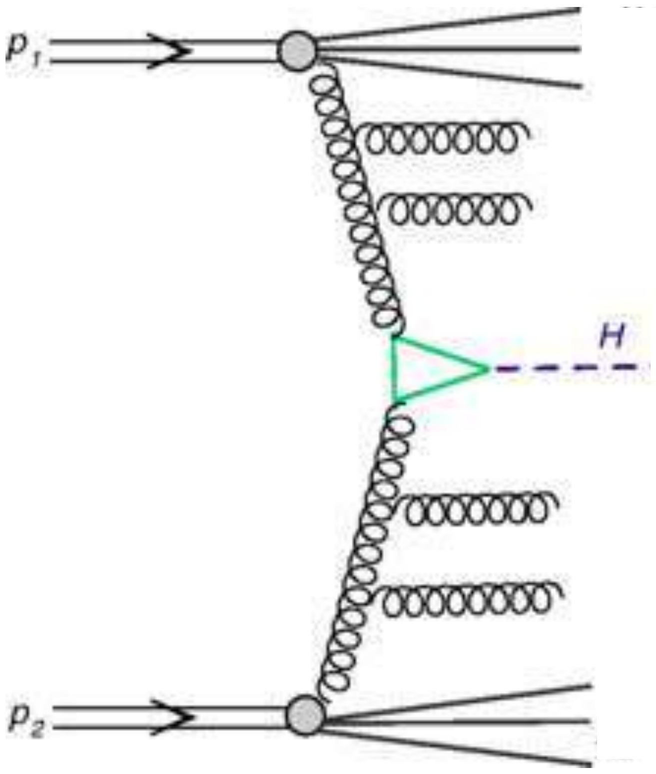


$+$



$+\cdots$

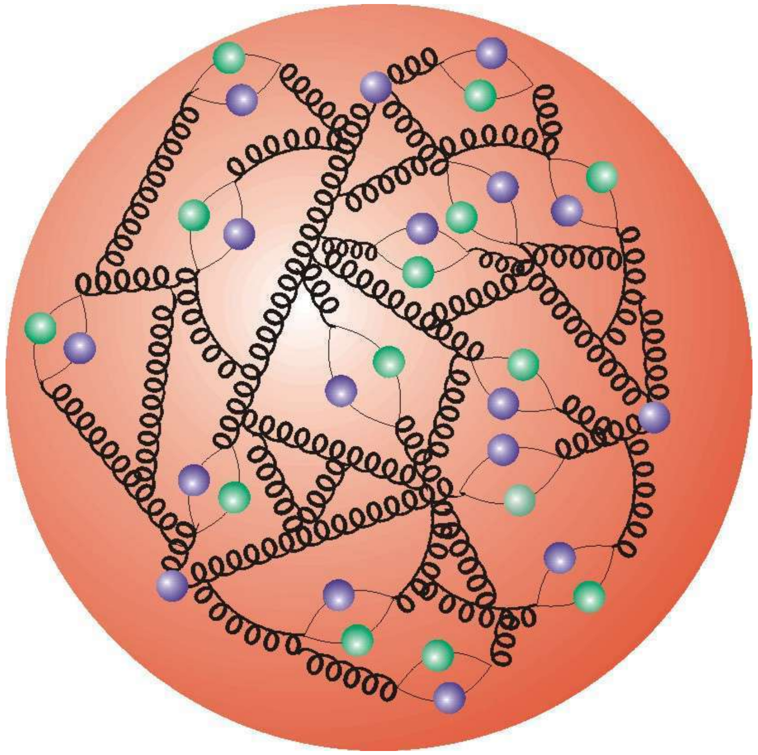
$\Rightarrow$



The Proton Today

- Proton: a complex quantum-mechanical system. Active and ongoing programme of research to **map** it out:

  - How much of proton energy is carried by **gluons**? How much is in the quark **sea**?
  - How significant are **heavier** (strange, charm, bottom, top…) **quarks**?
  - How do each of these vary with x ?
  - How well do we understand the connection between the proton and high-energy collisions?



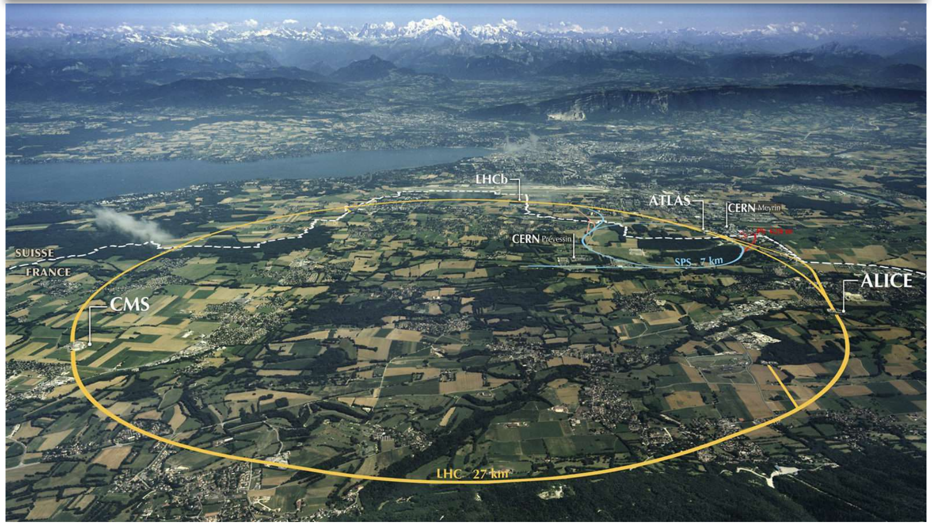
- To probe the Higgs and stress test the Standard Model at the LHC we need to address these questions as **precisely** as we can.

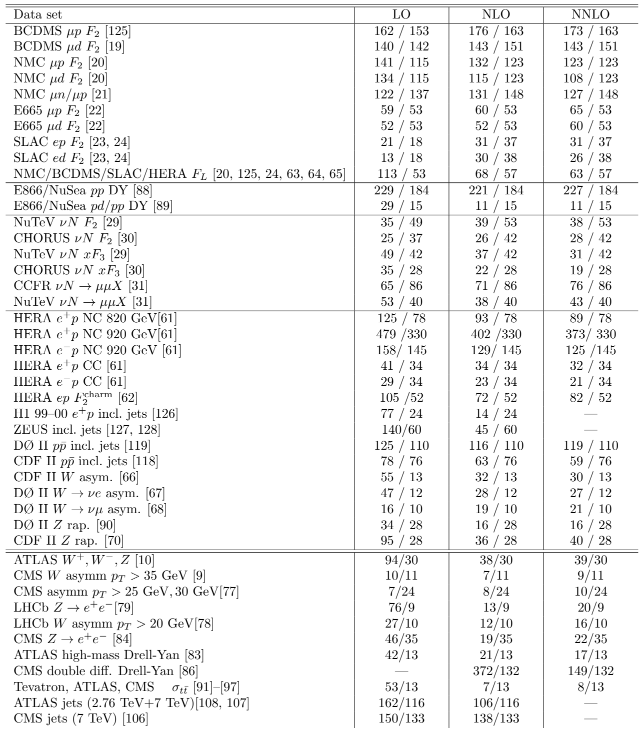
Global PDF Fits

- Since the discovery of quarks, a vast array of data on proton collisions has been collected, from different **colliders** and via difference **processes**.

- Combining all of this we can perform a '**Global Fit**' to PDFs, allowing us to pin down proton structure with **precision**.

LHC@CERN





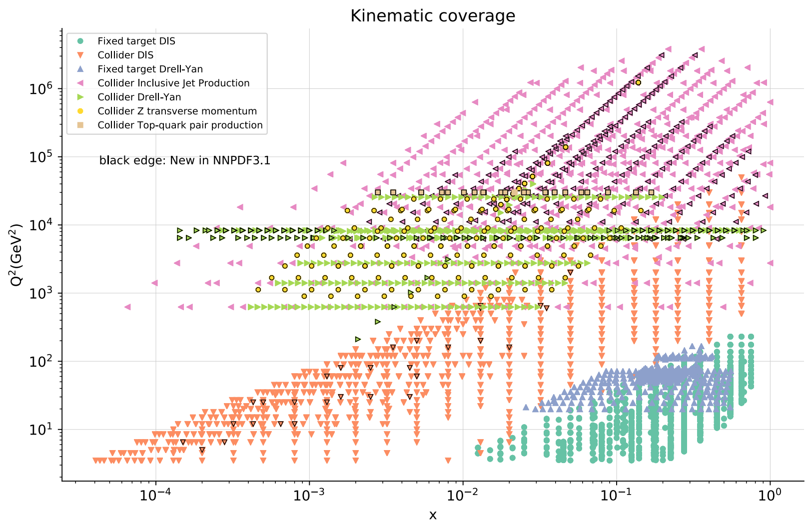
Data set	LO	NLO	NNLO
BCDMS μp F_2 [125]	162 / 153	176 / 163	173 / 163
BCDMS μd F_2 [19]	140 / 142	143 / 151	143 / 151
NMC μp F_2 [20]	141 / 115	132 / 123	123 / 123
NMC μd F_2 [20]	134 / 115	115 / 123	108 / 123
NMC $\mu n/\mu p$ [21]	122 / 137	131 / 148	127 / 148
E665 μp F_2 [22]	59 / 53	60 / 53	65 / 53
E665 μd F_2 [22]	52 / 53	52 / 53	60 / 53
SLAC ep F_2 [23, 24]	21 / 18	31 / 37	31 / 37
SLAC ed F_2 [23, 24]	13 / 18	30 / 38	26 / 38
NMC/BCDMS/SLAC/HERA F_L [20, 125, 24, 63, 64, 65]	113 / 53	68 / 57	63 / 57
E866/NuSea pp DY [88]	229 / 184	221 / 184	227 / 184
E866/NuSea pd/pp DY [89]	29 / 15	11 / 15	11 / 15
NuTeV νN F_2 [29]	35 / 49	39 / 53	38 / 53
CHORUS νN F_2 [30]	25 / 37	26 / 42	28 / 42
NuTeV νN xF_3 [29]	49 / 42	37 / 42	31 / 42
CHORUS νN xF_3 [30]	35 / 28	22 / 28	19 / 28
CCFR $\nu N \to \mu\mu X$ [31]	65 / 86	71 / 86	76 / 86
NuTeV $\nu N \to \mu\mu X$ [31]	53 / 40	38 / 40	43 / 40
HERA e^+p NC 820 GeV[61]	125 / 78	93 / 78	89 / 78
HERA e^+p NC 920 GeV[61]	479 /330	402 /330	373/ 330
HERA e^-p NC 920 GeV [61]	158/ 145	129/ 145	125 /145
HERA e^+p CC [61]	41 / 34	34 / 34	32 / 34
HERA e^-p CC [61]	29 / 34	23 / 34	21 / 34
HERA ep F_2^{charm} [62]	105 /52	72 / 52	82 / 52
H1 99–00 e^+p incl. jets [126]	77 / 24	14 / 24	—
ZEUS incl. jets [127, 128]	140/60	45 / 60	—
DØ II $p\bar{p}$ incl. jets [119]	125 / 110	116 / 110	119 / 110
CDF II $p\bar{p}$ incl. jets [118]	78 / 76	63 / 76	59 / 76
CDF II W asym. [66]	55 / 13	32 / 13	30 / 13
DØ II $W \to \nu e$ asym. [67]	47 / 12	28 / 12	27 / 12
DØ II $W \to \nu\mu$ asym. [68]	16 / 10	19 / 10	21 / 10
DØ II Z rap. [90]	34 / 28	16 / 28	16 / 28
CDF II Z rap. [70]	95 / 28	36 / 28	40 / 28
ATLAS W^+, W^-, Z [10]	94/30	38/30	39/30
CMS W asymm $p_T > 35$ GeV [9]	10/11	7/11	9/11
CMS asymm $p_T > 25$ GeV, 30 GeV[77]	7/24	8/24	10/24
LHCb $Z \to e^+e^-$[79]	76/9	13/9	20/9
LHCb W asymm $p_T > 20$ GeV[78]	27/10	12/10	16/10
CMS $Z \to e^+e^-$ [84]	46/35	19/35	22/35
ATLAS high-mass Drell-Yan [83]	42/13	21/13	17/13
CMS double diff. Drell-Yan [86]	—	372/132	149/132
Tevatron, ATLAS, CMS $\sigma_{t\bar{t}}$ [91]–[97]	53/13	7/13	8/13
ATLAS jets (2.76 TeV+7 TeV)[108, 107]	162/116	106/116	—
CMS jets (7 TeV) [106]	150/133	138/133	—

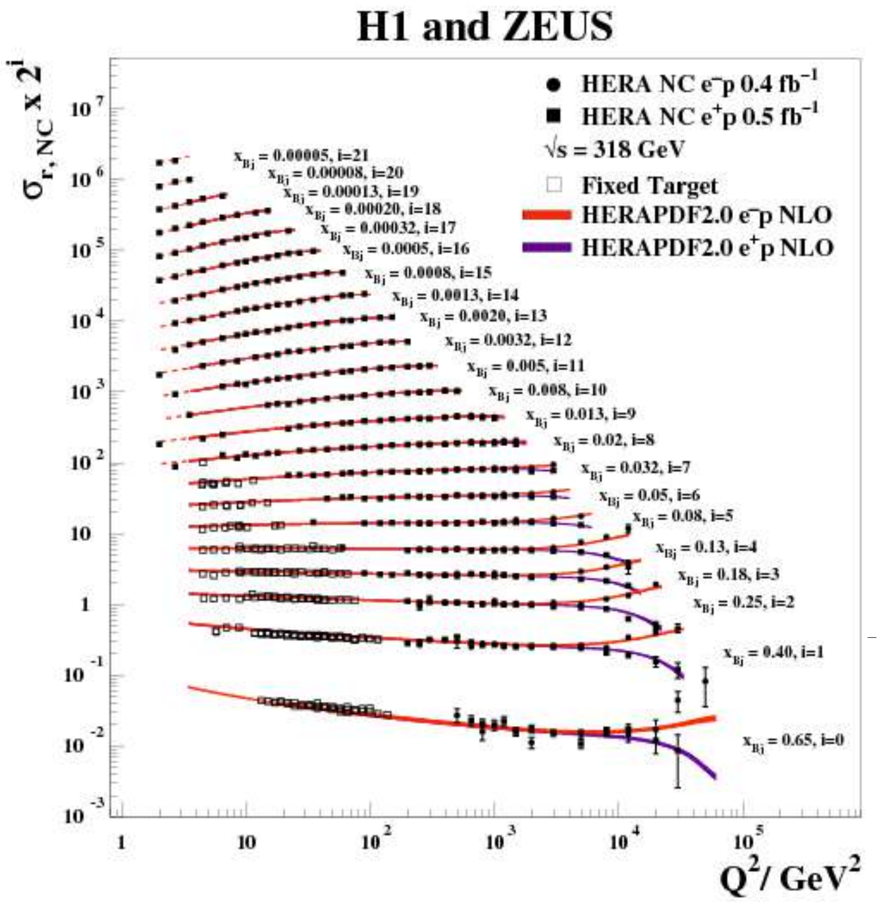
Tevatron@Chicago

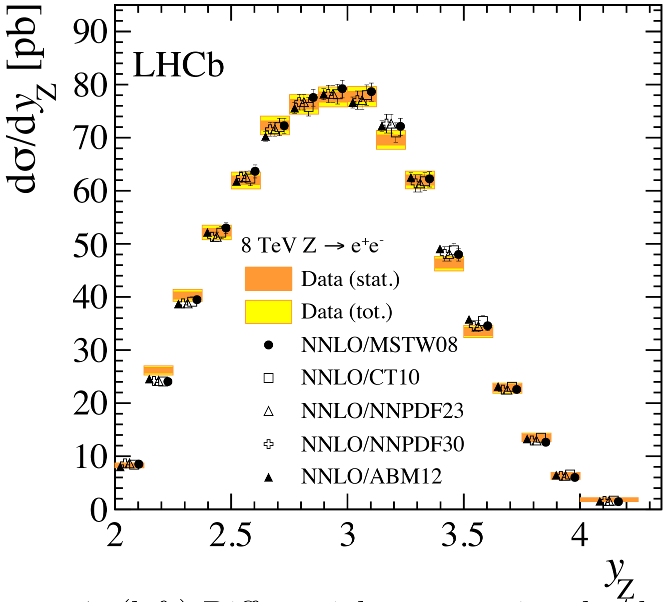
HERA@Hamburg

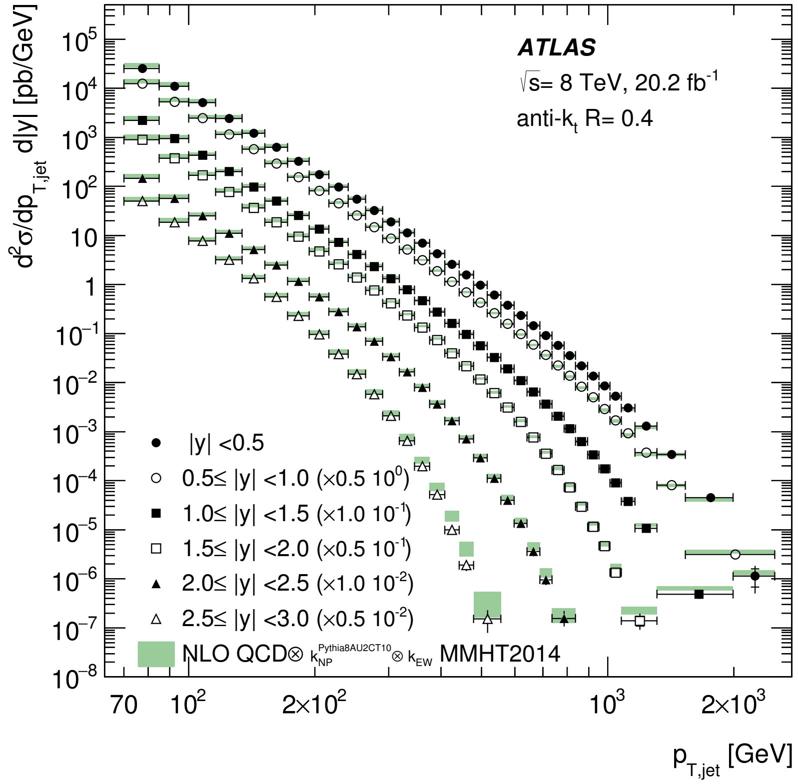
Where are we now?

- The wealth of available high precision data is unprecedented.

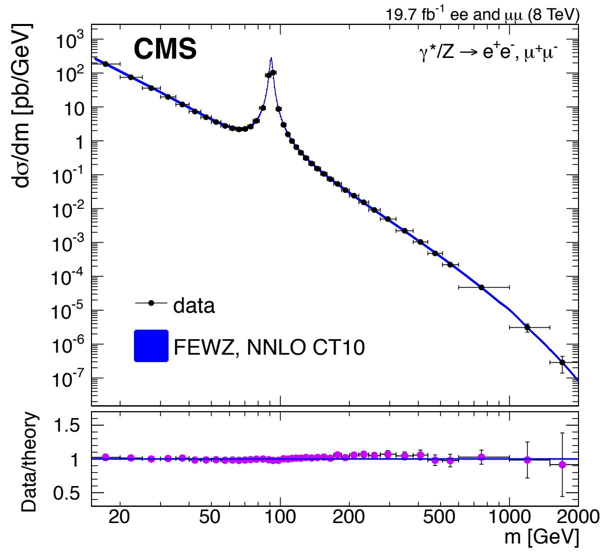








- There is **a lot**! And much of it these days comes from **LHC** itself.

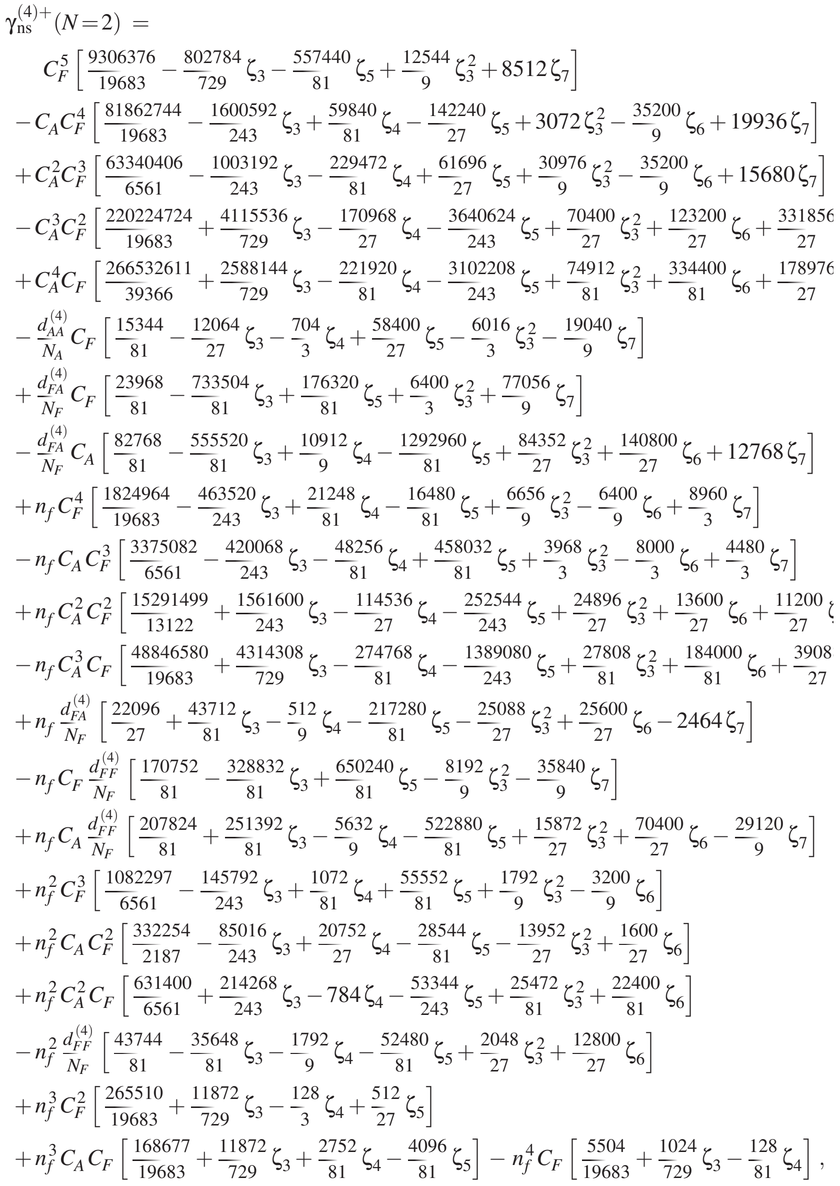


Where are we now?

- The **theoretical calculations** for the processes entering PDF fits are certainly keeping up with the data!

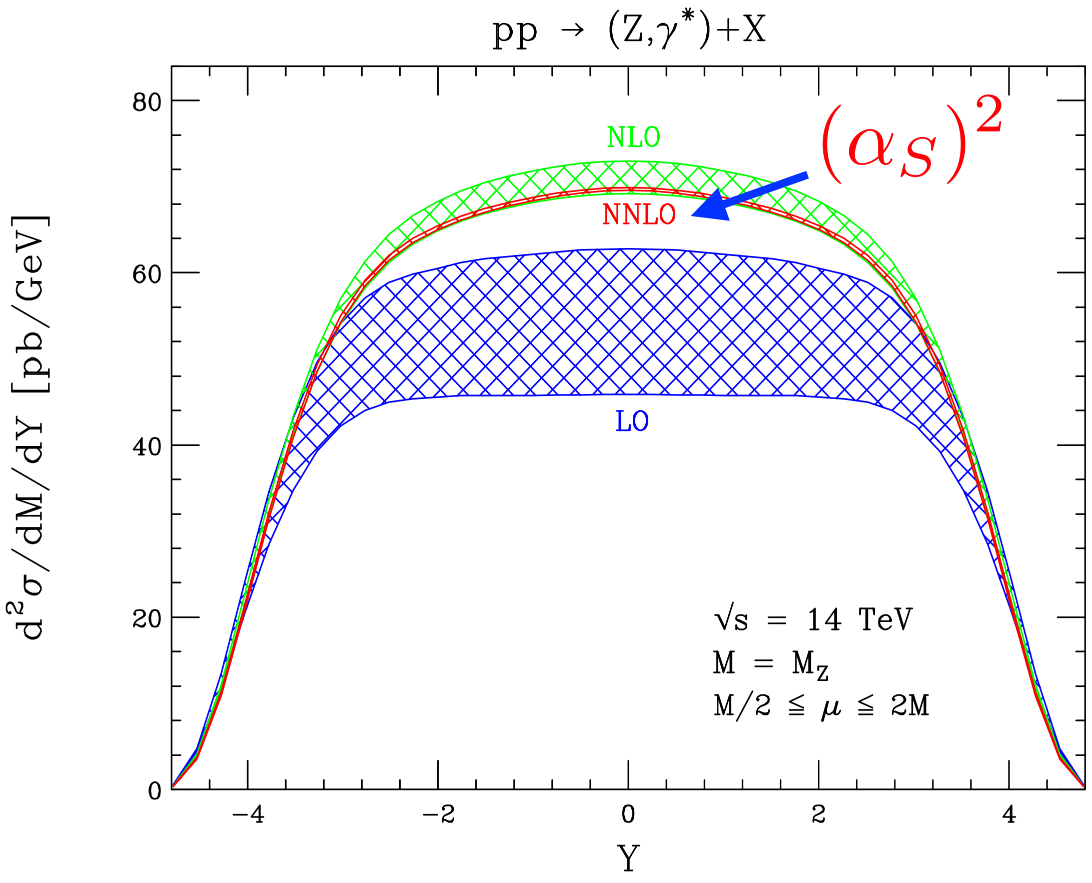
$(\alpha_S)^5$

Five-loop contributions to low-N non-singlet anomalous dimensions in QCD



$$
\begin{aligned}
\gamma_{\rm ns}^{(4)+}(N\!=\!2) \;=\;
& C_F^5\left[\frac{9306376}{19683}-\frac{802784}{729}\zeta_3-\frac{557440}{81}\zeta_5+\frac{12544}{9}\zeta_3^2+8512\zeta_7\right]\\
&-C_AC_F^4\left[\frac{81862744}{19683}-\frac{1600592}{243}\zeta_3+\frac{59840}{81}\zeta_4-\frac{142240}{27}\zeta_5+3072\zeta_3^2-\frac{35200}{9}\zeta_6+19936\zeta_7\right]\\
&+C_A^2C_F^3\left[\frac{63340406}{6561}-\frac{1003192}{243}\zeta_3-\frac{229472}{81}\zeta_4+\frac{61696}{27}\zeta_5+\frac{30976}{9}\zeta_3^2-\frac{35200}{9}\zeta_6+15680\zeta_7\right]\\
&-C_A^3C_F^2\left[\frac{220224724}{19683}+\frac{4115536}{729}\zeta_3-\frac{170968}{27}\zeta_4-\frac{3640624}{243}\zeta_5+\frac{70400}{27}\zeta_3^2+\frac{123200}{27}\zeta_6+\frac{331856}{27}\right.\\
&+C_A^4C_F\left[\frac{266532611}{39366}+\frac{2588144}{729}\zeta_3-\frac{221920}{81}\zeta_4-\frac{3102208}{243}\zeta_5+\frac{74912}{81}\zeta_3^2+\frac{334400}{81}\zeta_6+\frac{178976}{27}\right.\\
&-\frac{d_{AA}^{(4)}}{N_A}C_F\left[\frac{15344}{81}-\frac{12064}{27}\zeta_3-\frac{704}{3}\zeta_4+\frac{58400}{27}\zeta_5-\frac{6016}{3}\zeta_3^2-\frac{19040}{9}\zeta_7\right]\\
&+\frac{d_{FA}^{(4)}}{N_F}C_F\left[\frac{23968}{81}-\frac{733504}{81}\zeta_3+\frac{176320}{81}\zeta_5+\frac{6400}{3}\zeta_3^2+\frac{77056}{9}\zeta_7\right]\\
&-\frac{d_{FA}^{(4)}}{N_F}C_A\left[\frac{82768}{81}-\frac{555520}{81}\zeta_3+\frac{10912}{9}\zeta_4-\frac{1292960}{81}\zeta_5+\frac{84352}{27}\zeta_3^2+\frac{140800}{27}\zeta_6+12768\zeta_7\right]\\
&+n_fC_F^4\left[\frac{1824964}{19683}-\frac{463520}{243}\zeta_3+\frac{21248}{81}\zeta_4-\frac{16480}{81}\zeta_5+\frac{6656}{9}\zeta_3^2-\frac{6400}{9}\zeta_6+\frac{8960}{3}\zeta_7\right]\\
&-n_fC_AC_F^3\left[\frac{3375082}{6561}-\frac{420068}{243}\zeta_3-\frac{48256}{81}\zeta_4+\frac{458032}{81}\zeta_5+\frac{3968}{3}\zeta_3^2-\frac{8000}{3}\zeta_6+\frac{4480}{3}\zeta_7\right]\\
&+n_fC_A^2C_F^2\left[\frac{15291499}{13122}+\frac{1561600}{243}\zeta_3-\frac{114536}{27}\zeta_4-\frac{252544}{243}\zeta_5+\frac{24896}{27}\zeta_3^2+\frac{13600}{27}\zeta_6+\frac{11200}{27}\right.\\
&-n_fC_A^3C_F\left[\frac{48846580}{19683}+\frac{4314308}{729}\zeta_3-\frac{274768}{81}\zeta_4-\frac{1389080}{243}\zeta_5+\frac{27808}{81}\zeta_3^2+\frac{184000}{81}\zeta_6+\frac{3908}{27}\right.\\
&+n_f\frac{d_{FA}^{(4)}}{N_F}\left[\frac{22096}{27}+\frac{43712}{81}\zeta_3-\frac{512}{9}\zeta_4-\frac{217280}{81}\zeta_5-\frac{25088}{27}\zeta_3^2+\frac{25600}{27}\zeta_6-2464\zeta_7\right]\\
&-n_fC_F\frac{d_{FF}^{(4)}}{N_F}\left[\frac{170752}{81}-\frac{328832}{81}\zeta_3+\frac{650240}{81}\zeta_5-\frac{8192}{9}\zeta_3^2-\frac{35840}{9}\zeta_7\right]\\
&+n_fC_A\frac{d_{FF}^{(4)}}{N_F}\left[\frac{207824}{81}+\frac{251392}{81}\zeta_3-\frac{5632}{9}\zeta_4-\frac{522880}{81}\zeta_5+\frac{15872}{27}\zeta_3^2+\frac{70400}{27}\zeta_6-\frac{29120}{9}\zeta_7\right]\\
&+n_f^2C_F^3\left[\frac{1082297}{6561}-\frac{145792}{243}\zeta_3+\frac{1072}{81}\zeta_4+\frac{55552}{81}\zeta_5+\frac{1792}{9}\zeta_3^2-\frac{3200}{9}\zeta_6\right]\\
&+n_f^2C_AC_F^2\left[\frac{332254}{2187}-\frac{85016}{243}\zeta_3+\frac{20752}{27}\zeta_4-\frac{28544}{81}\zeta_5-\frac{13952}{27}\zeta_3^2+\frac{1600}{27}\zeta_6\right]\\
&+n_f^2C_A^2C_F\left[\frac{631400}{6561}+\frac{214268}{243}\zeta_3-784\zeta_4-\frac{53344}{243}\zeta_5+\frac{25472}{81}\zeta_3^2+\frac{22400}{81}\zeta_6\right]\\
&-n_f^2\frac{d_{FF}^{(4)}}{N_F}\left[\frac{43744}{81}-\frac{35648}{81}\zeta_3-\frac{1792}{9}\zeta_4-\frac{52480}{81}\zeta_5+\frac{2048}{27}\zeta_3^2+\frac{12800}{27}\zeta_6\right]\\
&+n_f^3C_F^2\left[\frac{265510}{19683}+\frac{11872}{729}\zeta_3-\frac{128}{3}\zeta_4+\frac{512}{27}\zeta_5\right]\\
&+n_f^3C_AC_F\left[\frac{168677}{19683}+\frac{11872}{729}\zeta_3+\frac{2752}{81}\zeta_4-\frac{4096}{81}\zeta_5\right]-n_f^4C_F\left[\frac{5504}{19683}+\frac{1024}{729}\zeta_3-\frac{128}{81}\zeta_4\right],
\end{aligned}
$$

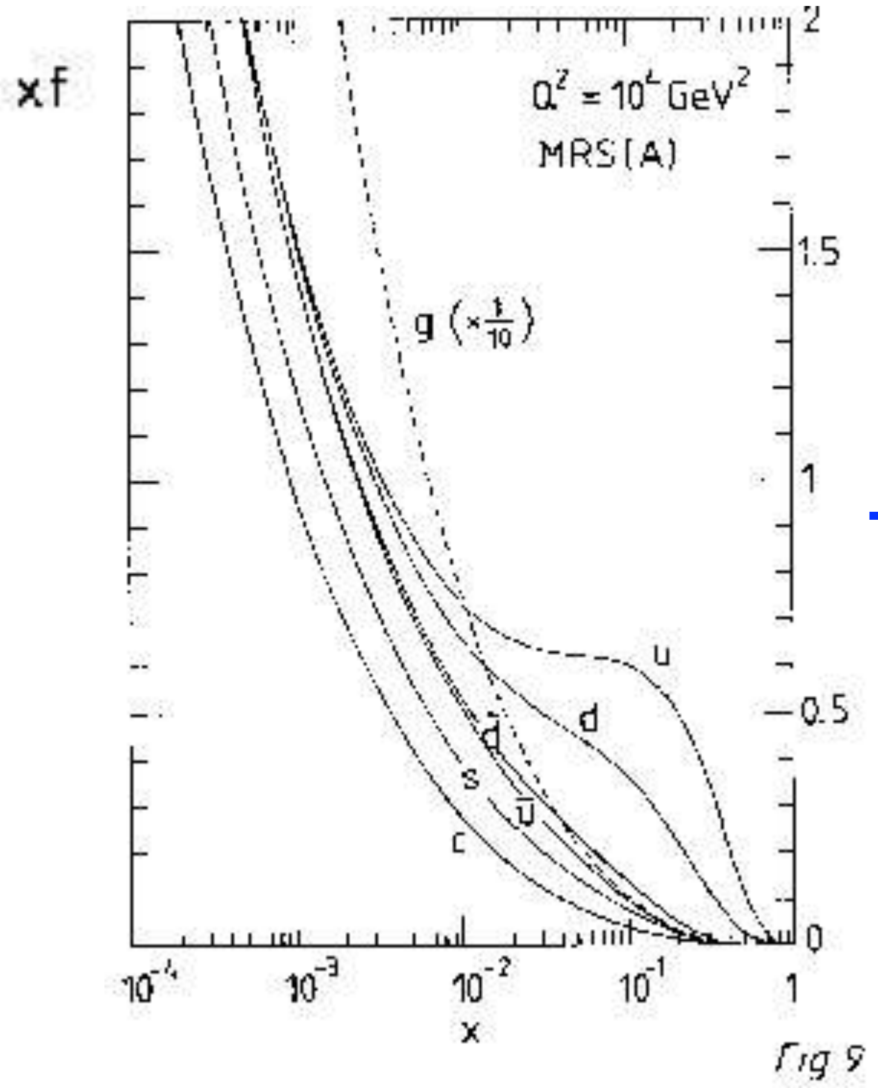
+ 1.5 more pages!



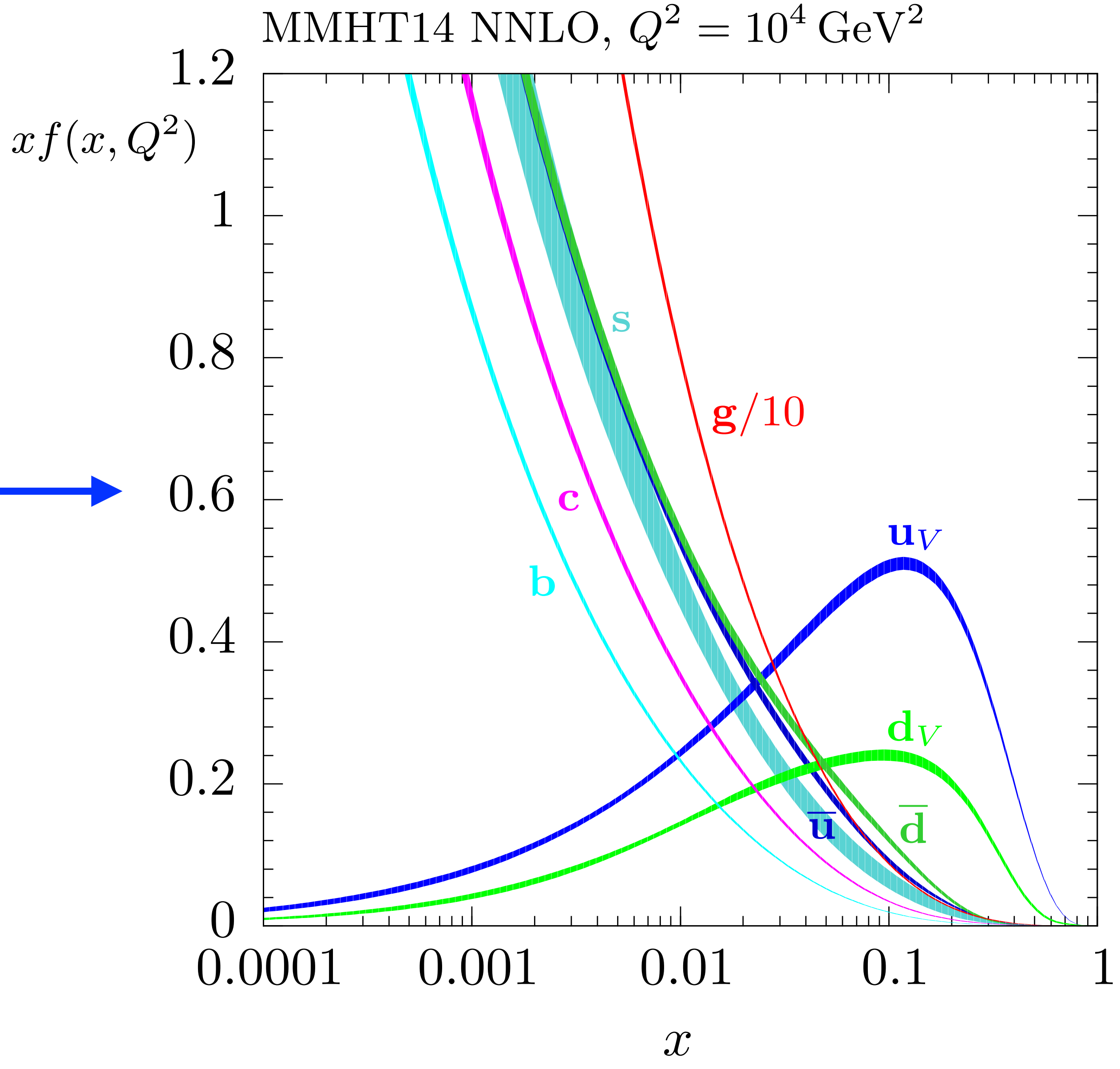
Where are we now?

- Data and theory at **unprecedented level of precision** provide unique opportunity to really pin down proton structure like never before.

~ 2 decades after quark discovery.
Still only rough picture.



Today: Precision Physics!



- Taking a closer look…

The Proton Backbone

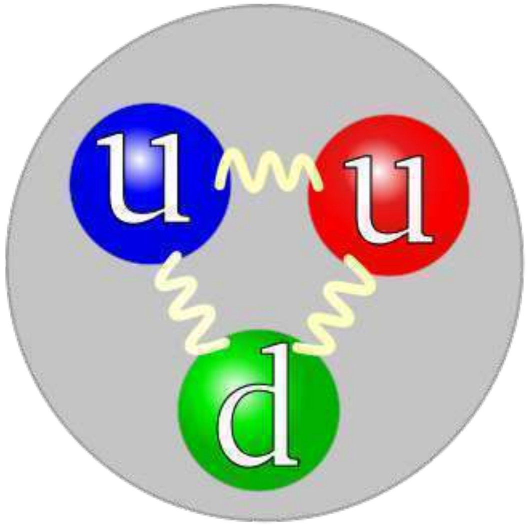
- Within our precise mapping, many features present…

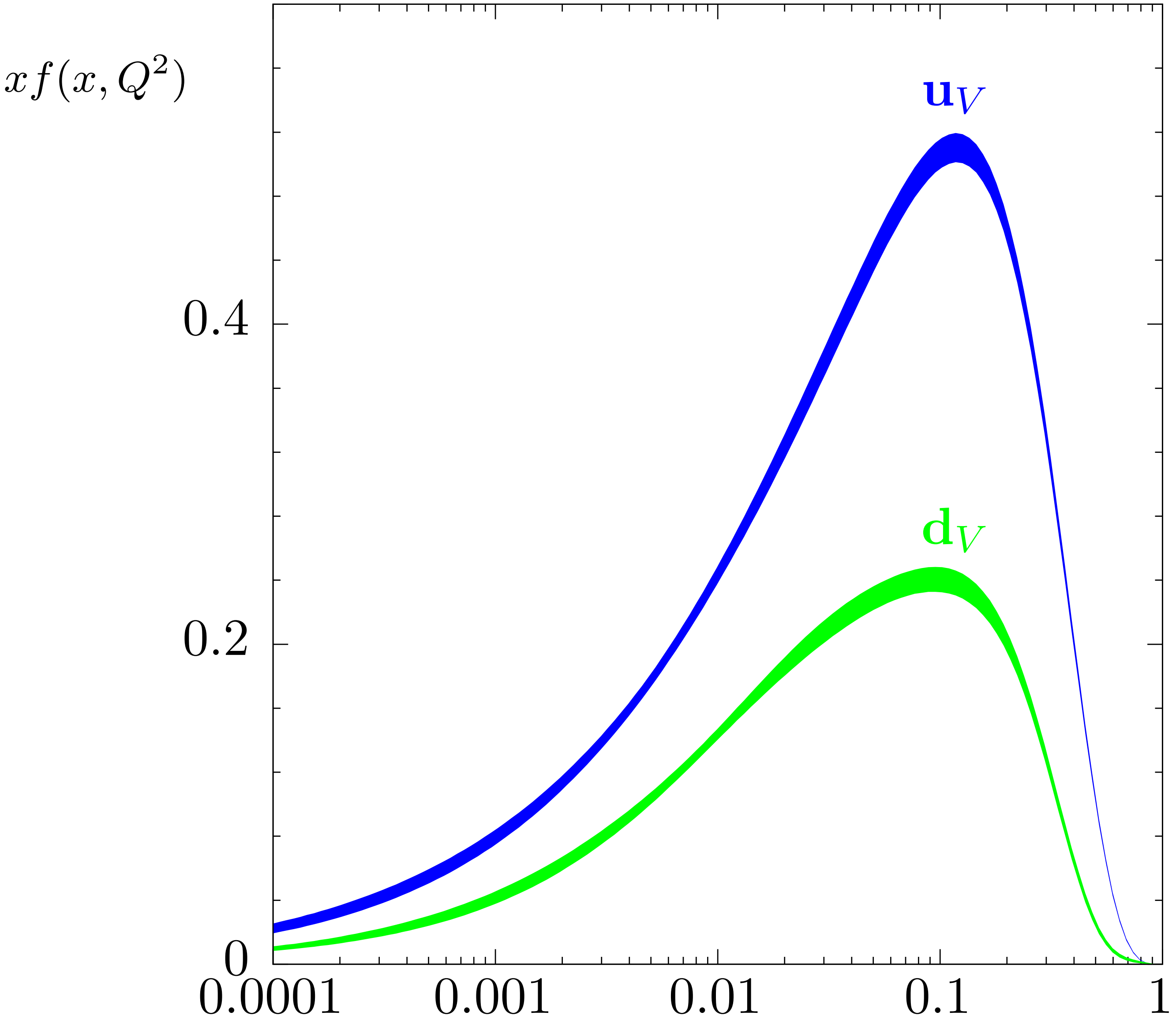
$u - \overline{u},\ d - \overline{d}$

- ‘Valence’ up and down quark structure consistent with basic **uud** picture.

- $u_V \approx 2d_V$

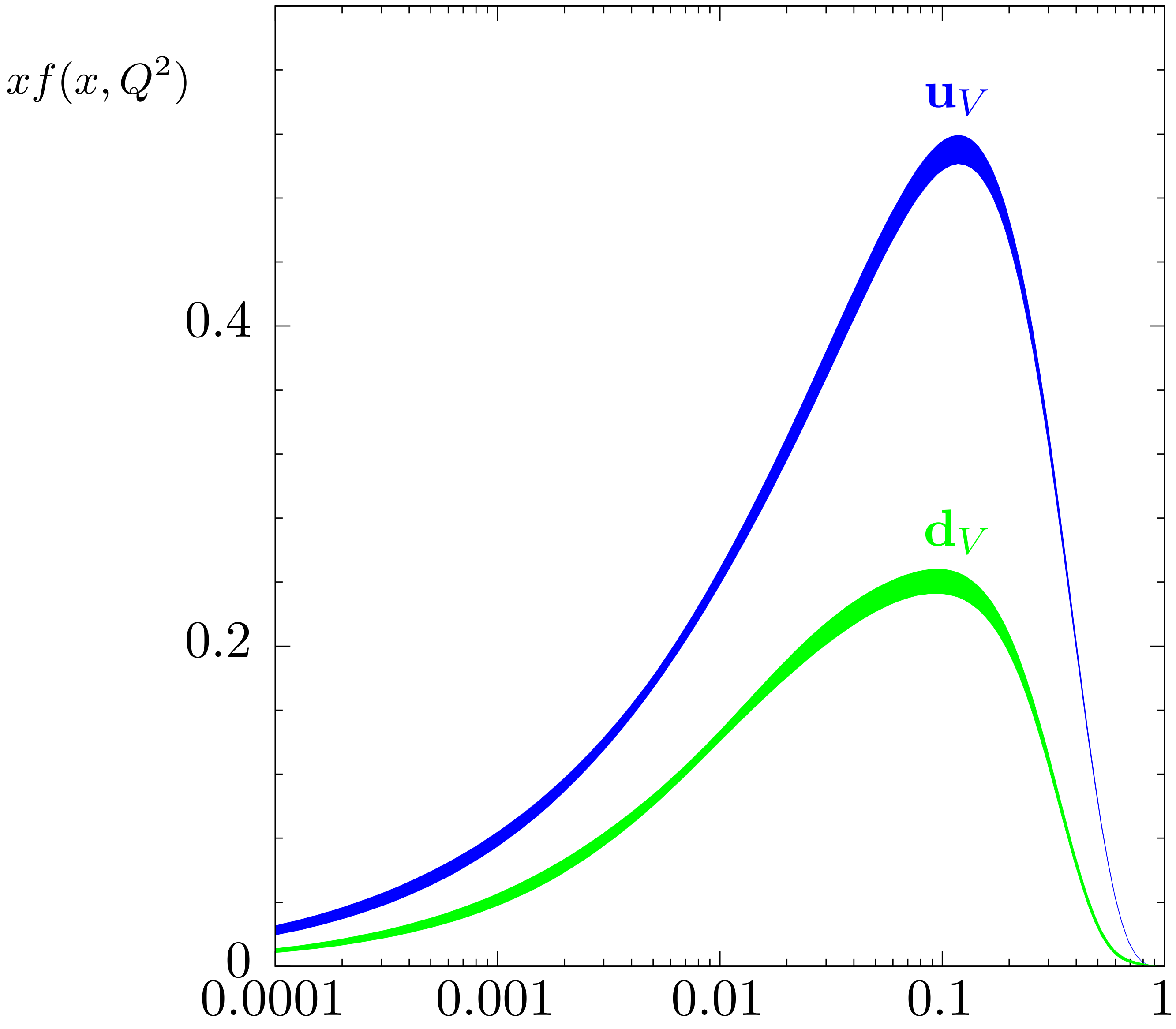
- Peaked at $x \approx \frac{1}{3}$.





Gluons

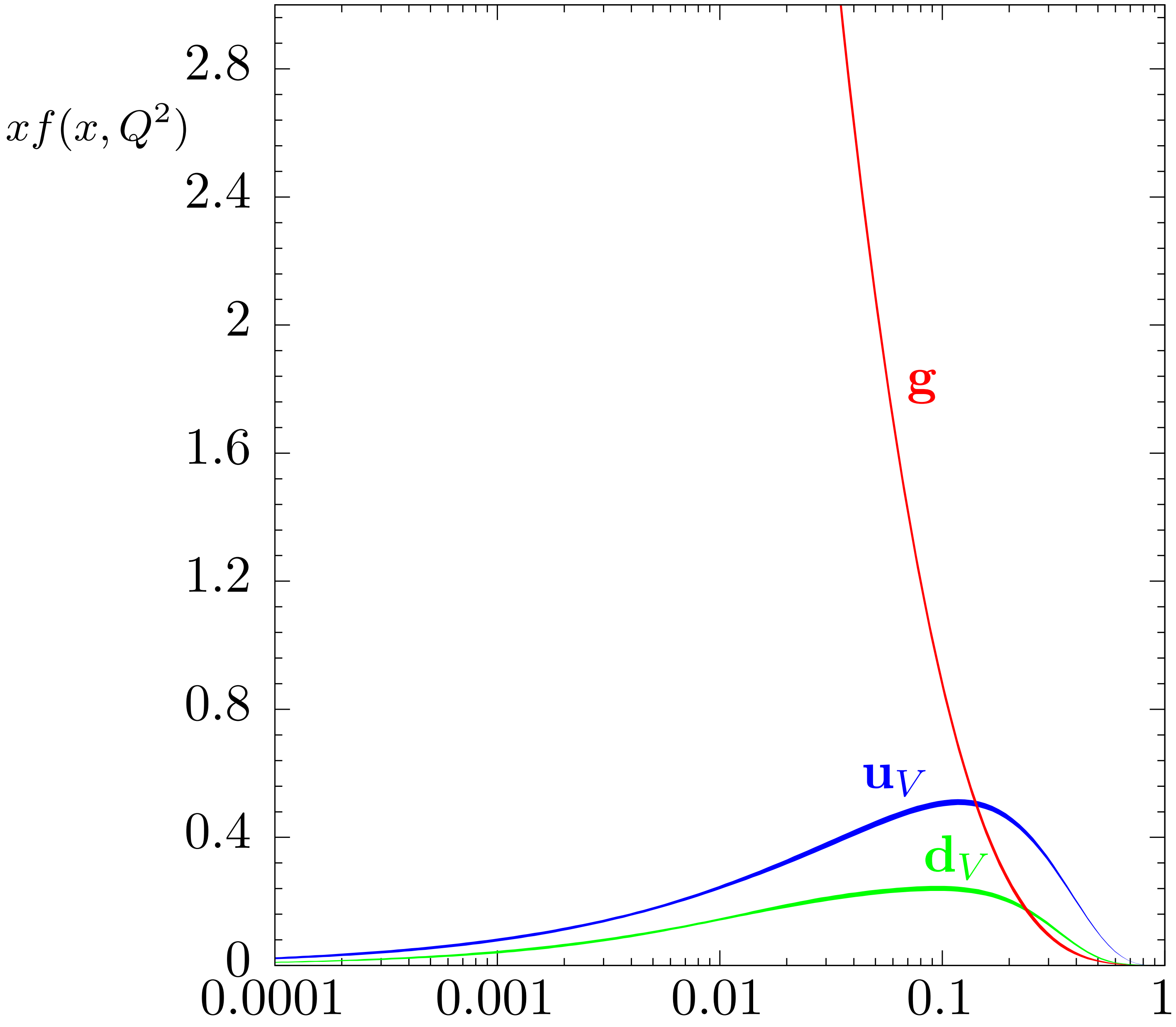
- What happens when we add gluons into the picture?



Gluons!

- Contribution from gluons is absolute huge!
- In fact, roughly **50%** of proton energy carried by gluons.
- LHC a gluon-gluon collider: crucial for Higgs physics.

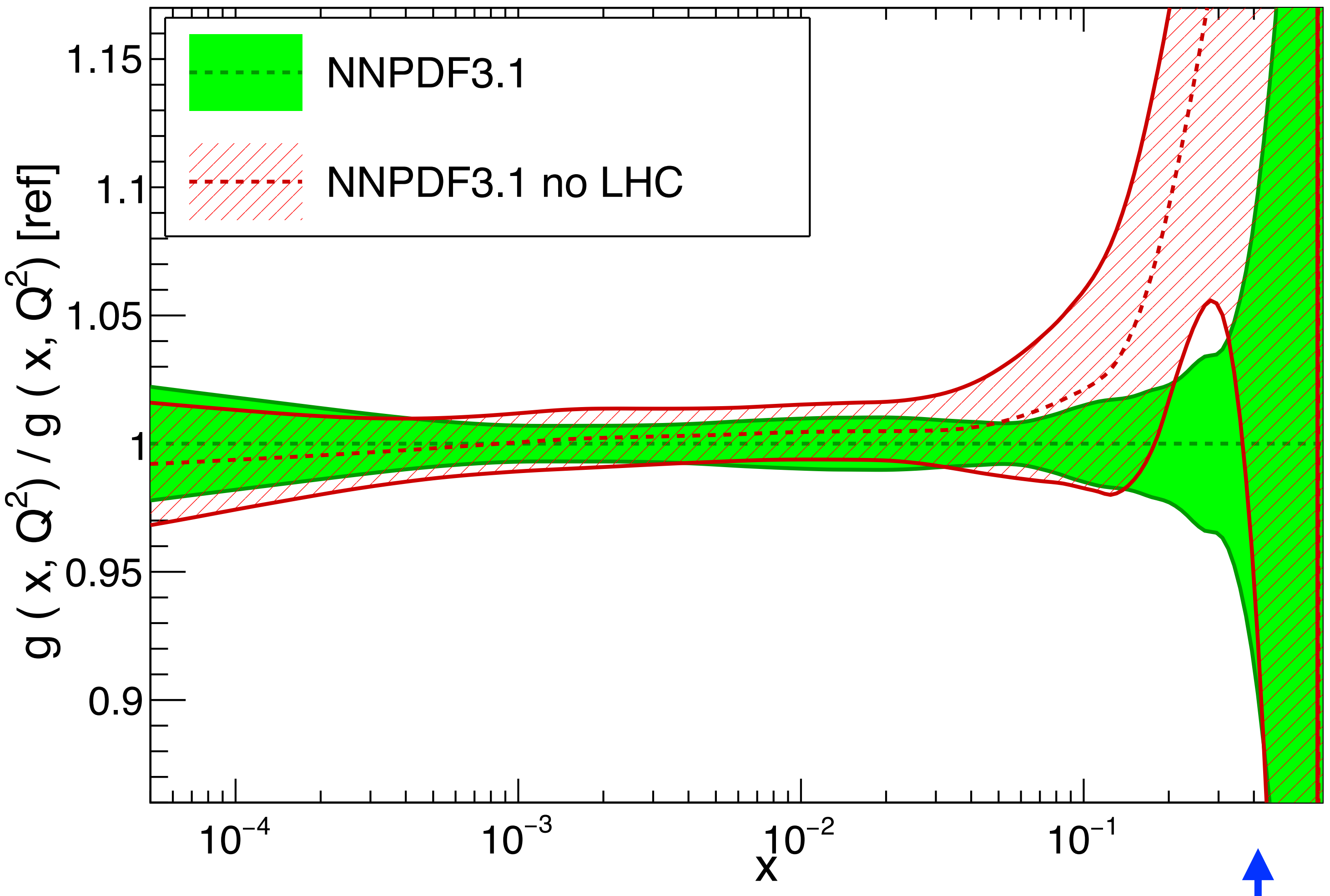
(Fabrizio 's talk)



The Gluon: Zooming In

- **Roughly** 50% of proton energy carried by gluons. Research today: pinning this statement down with **high precision**.

NNPDF3.1 NNLO, Q = 100 GeV



- Modern fits now achieve ~ **1%** level precision in many regions.
- Not always the case. Key question: how can we best exploit **LHC** to push into less understood regions?

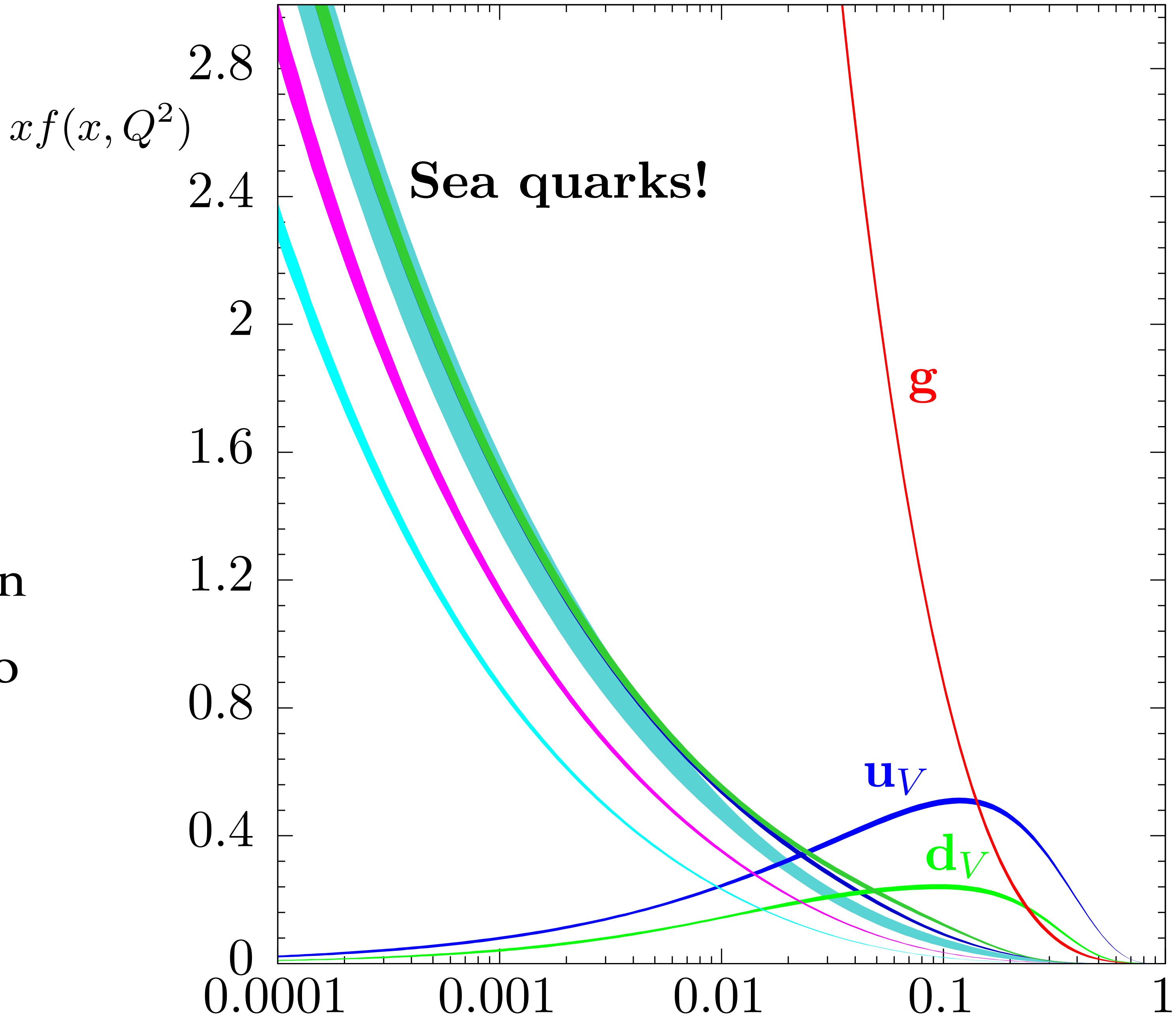
Higgs

Physics beyond the Standard Model

The Quark Sea

- Quark sea completely dominant over ‘valence’ **uud** in many regions.

- Crucial to pin these down precisely- direct relevant to LHC physics.

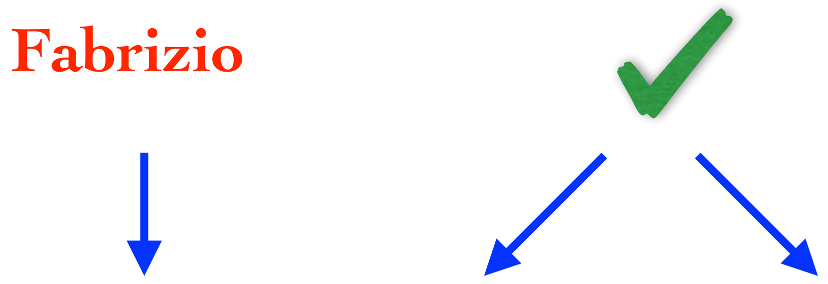


What next?

- Data and theory at **unprecedented level of precision** provide unique opportunity to really pin down proton structure. But also a challenge:
    - ❖ Dealing with **complex**/computationally expensive **theory** effectively.
    - ❖ Dealing with cases where data and theory **do not agree** to the high precision standard we require.
    - ❖ Re-evaluating foundations: are PDF uncertainties **accurate** as well as precise? Other 'theory' **uncertainties/biases** hidden in fits?
    - ❖ Perhaps we can calculate PDFs after all!? Applying numerical '**lattice**' techniques to predict PDFs, rather than fitting them.
- …and much more besides. Ensuring that our knowledge of PDFs matches requirements for understanding in detail the Higgs at the LHC.

Higgs Production at the LHC

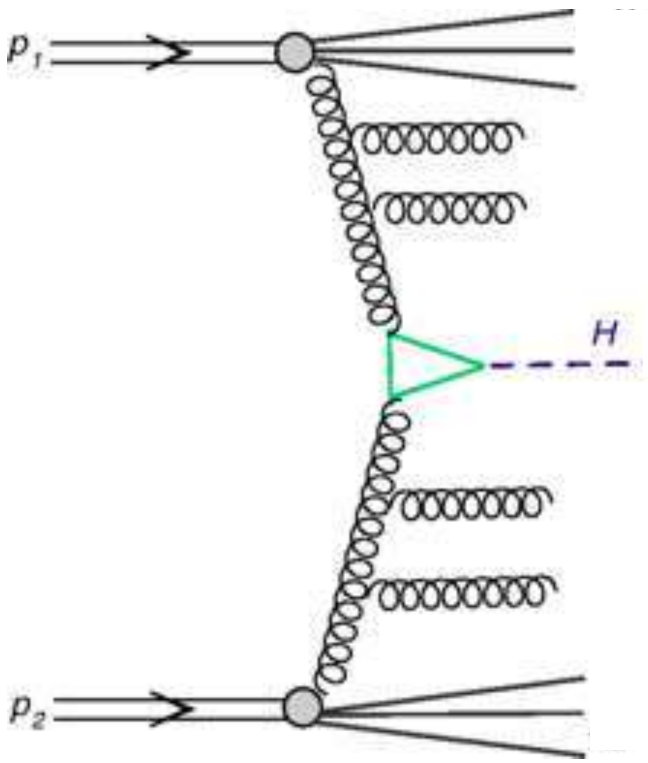
- We have all we need to go from protons to collisions at the **LHC**.
- Key idea: LHC is not really a proton-proton collider. It is a quark-quark, gluon-gluon… collider.



Fabrizio

✓

$$\sigma(pp \to h + X) \sim \sigma(gg \to h) \otimes g(x_1, Q^2) \otimes g(x_2, Q^2) \ ,$$



- **Next question:** how do we predict the rate of Higgs boson production from quark-quark, gluon-gluon… collisions? On to Fabrizio…

Thank you for listening!