Hadron Structure

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Outline of content

- Section 1: Introduction
- Section 2: How to study hadron structure?
- Section 3: Example:
  - Electromagnetic structure of proton
- Section 4: Summary

§1: What is hadron?

Reference: wikipedia.org

§1: What is hadron?

- In particle physics, a hadron is a composite particle made of quarks held together by the strong force. Hadrons are categorized into two families: baryons (made of three quarks), and mesons (made of one quark and one antiquark).

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- The best-known hadrons are protons and neutrons (both baryons), which can be found in the atomic nuclei.

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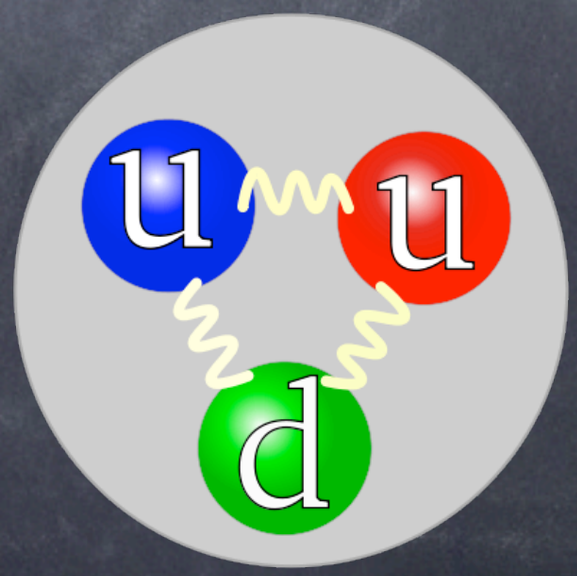
§1: What is hadron?

Hadron ← Quark (u, d, s, c, t, b)

Baryon: Proton (uud), Neutron (ddu), others...

Meson: $\pi^+(u\bar{d})$, $K^+(u\bar{s})$, others...

quantum chromodynamics (QCD) "Strong force" →



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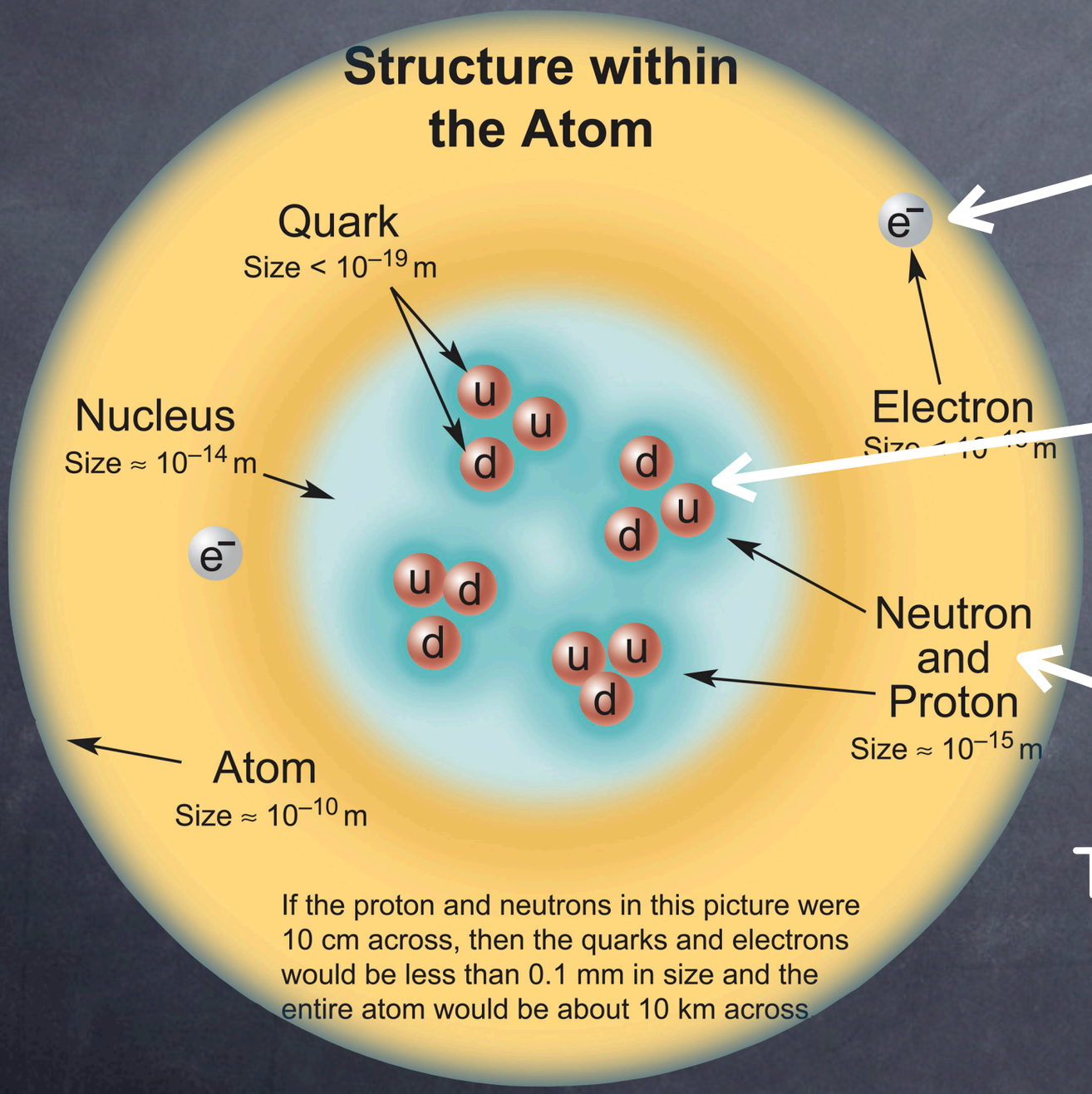

Electromagnetic force

Strong force (QCD)

The residual of strong force binds neutron and proton together.

picture taken from www.particleadventure.org

§1: What is interaction?

Example: Electromagnetic interaction

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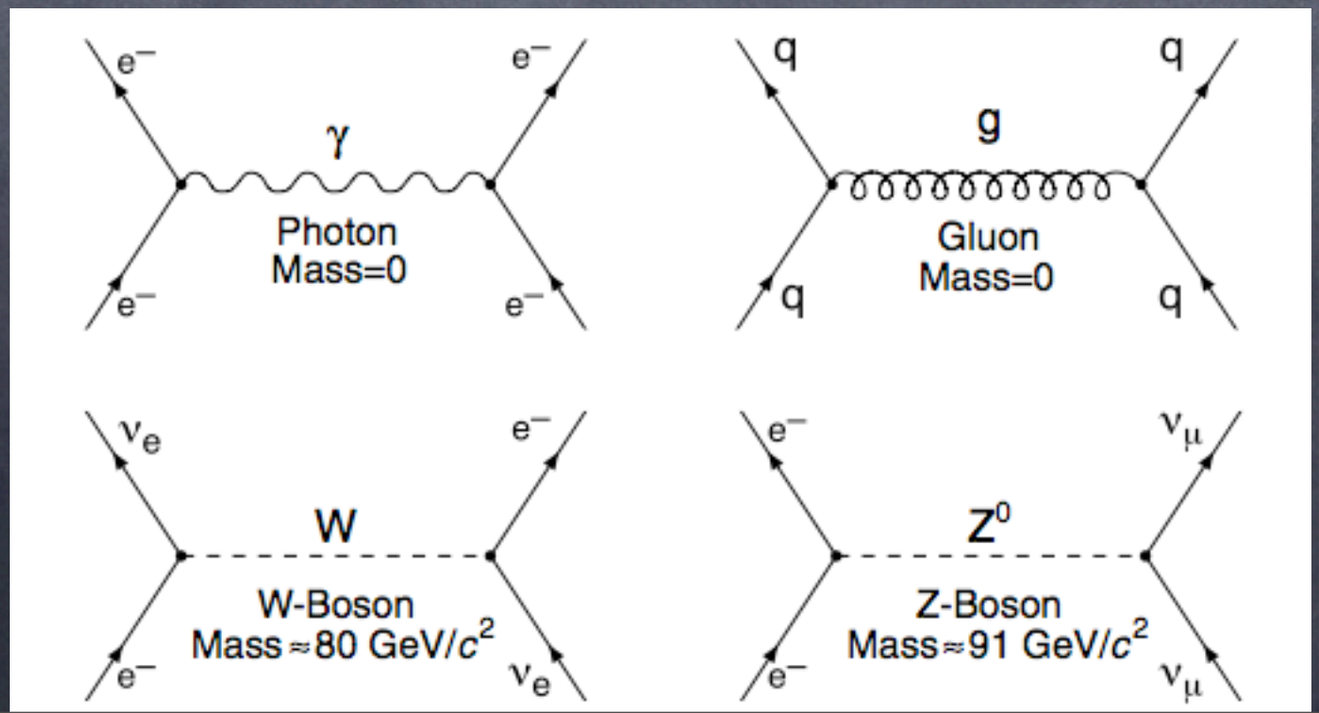

§1: How much do we know about hadrons?

They are made of quarks;
Quarks interact with strong force and EM force;
Problem solved?

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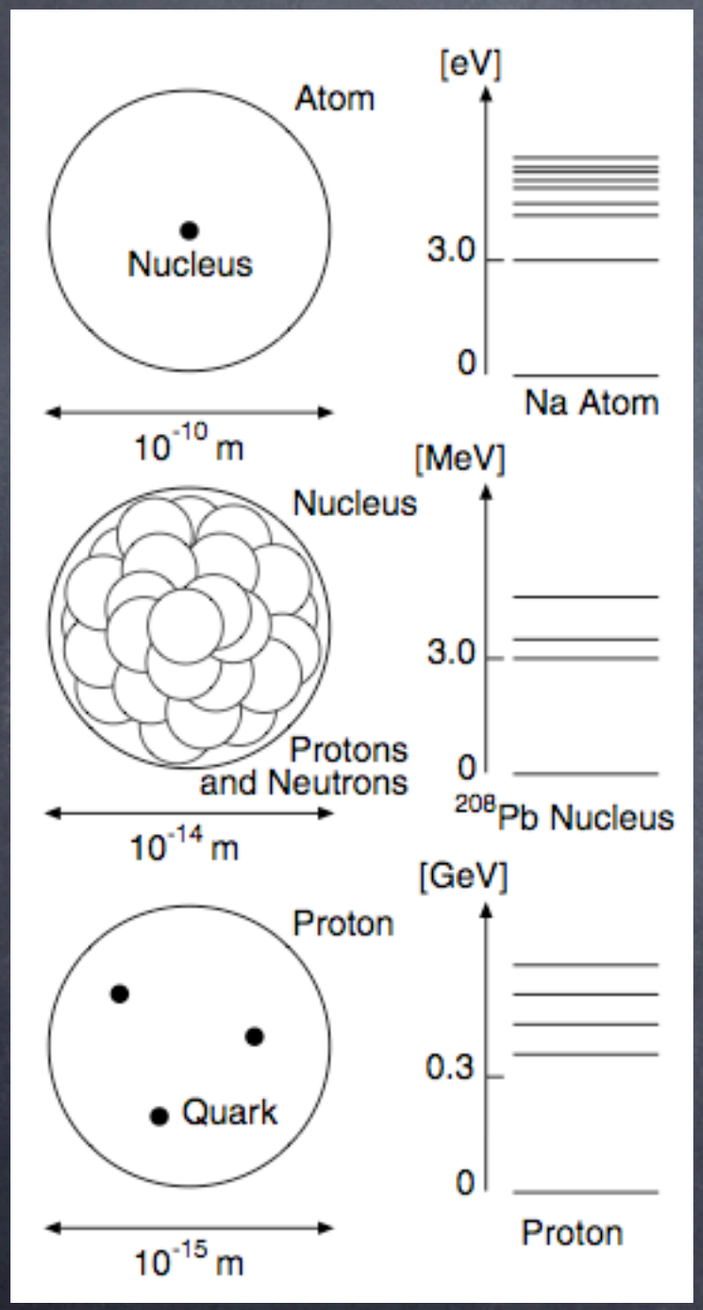
PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

picture taken from www.particleadventure.org

§1: A first glance...



Heisenberg uncertainty principle:

$\Delta x \Delta p \geq 200$[fm][MeV/c]

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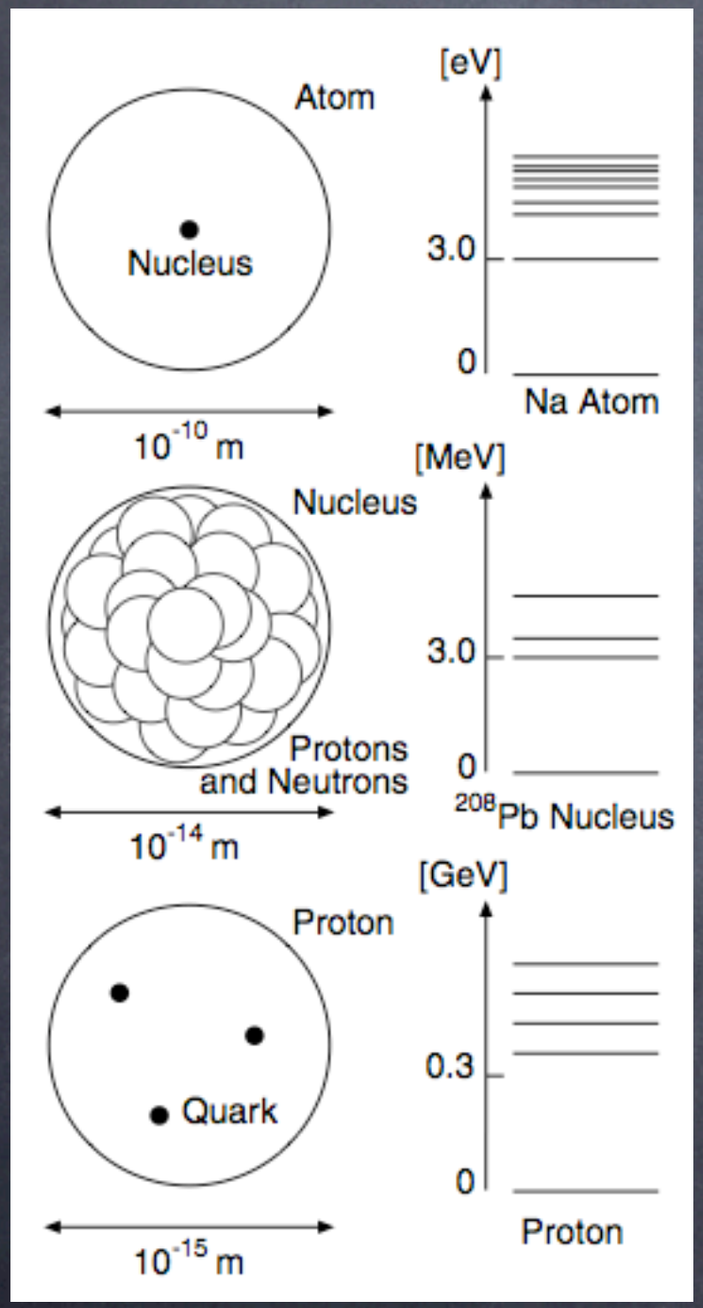

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quark inside 1fm nucleon
has 200MeV/c kinetic energy,
whose mass is several MeV.
Very dynamic!

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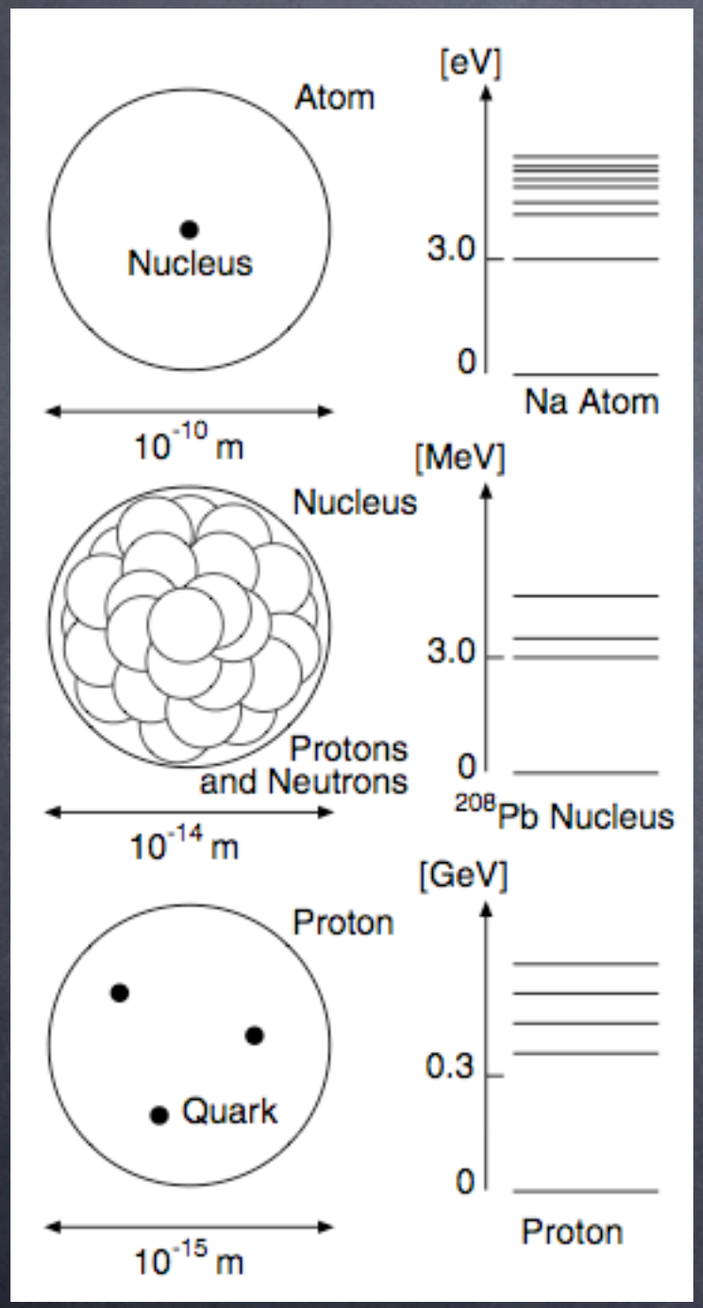

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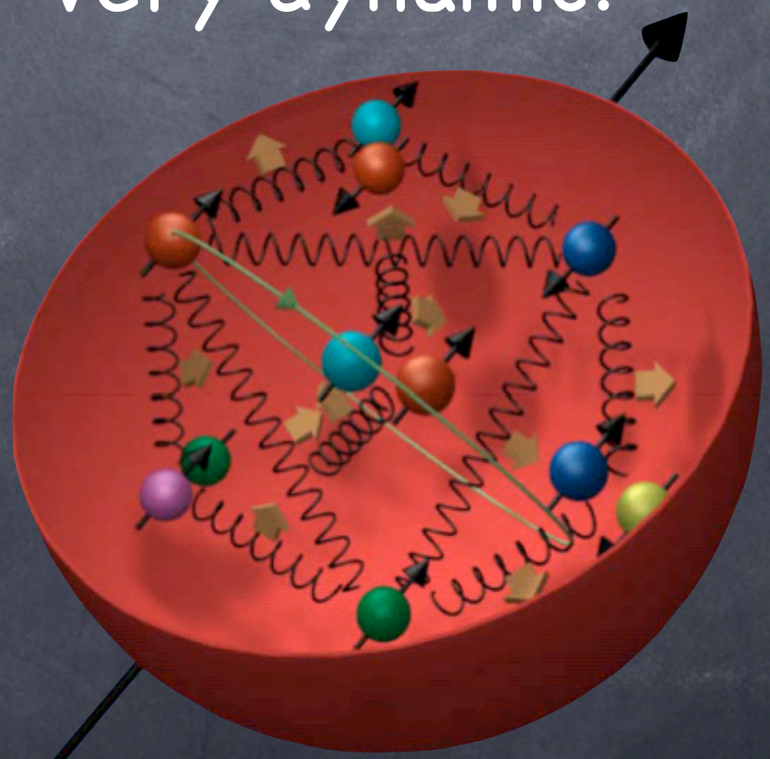
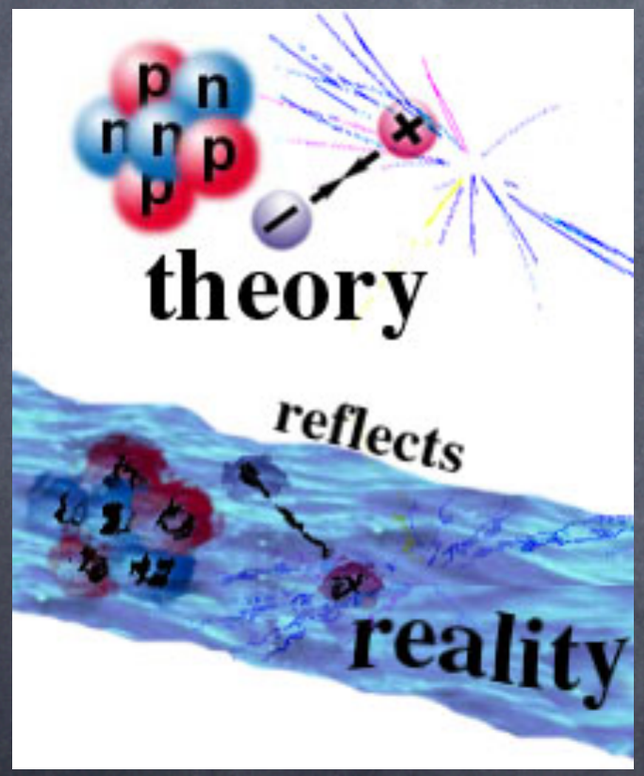


§1: A first glance...

- When we talk about hadrons, please imagine a dynamics ocean of particles instead of a peaceful lake!
- "fundamental" interaction (QCD) doesn't help.
- A bridge between real world (residual interaction) and high energy limit (perturbative QCD) to be built.
- we will focus on the ground state of hadron, particularly, proton in this talk.

§2: How to ...

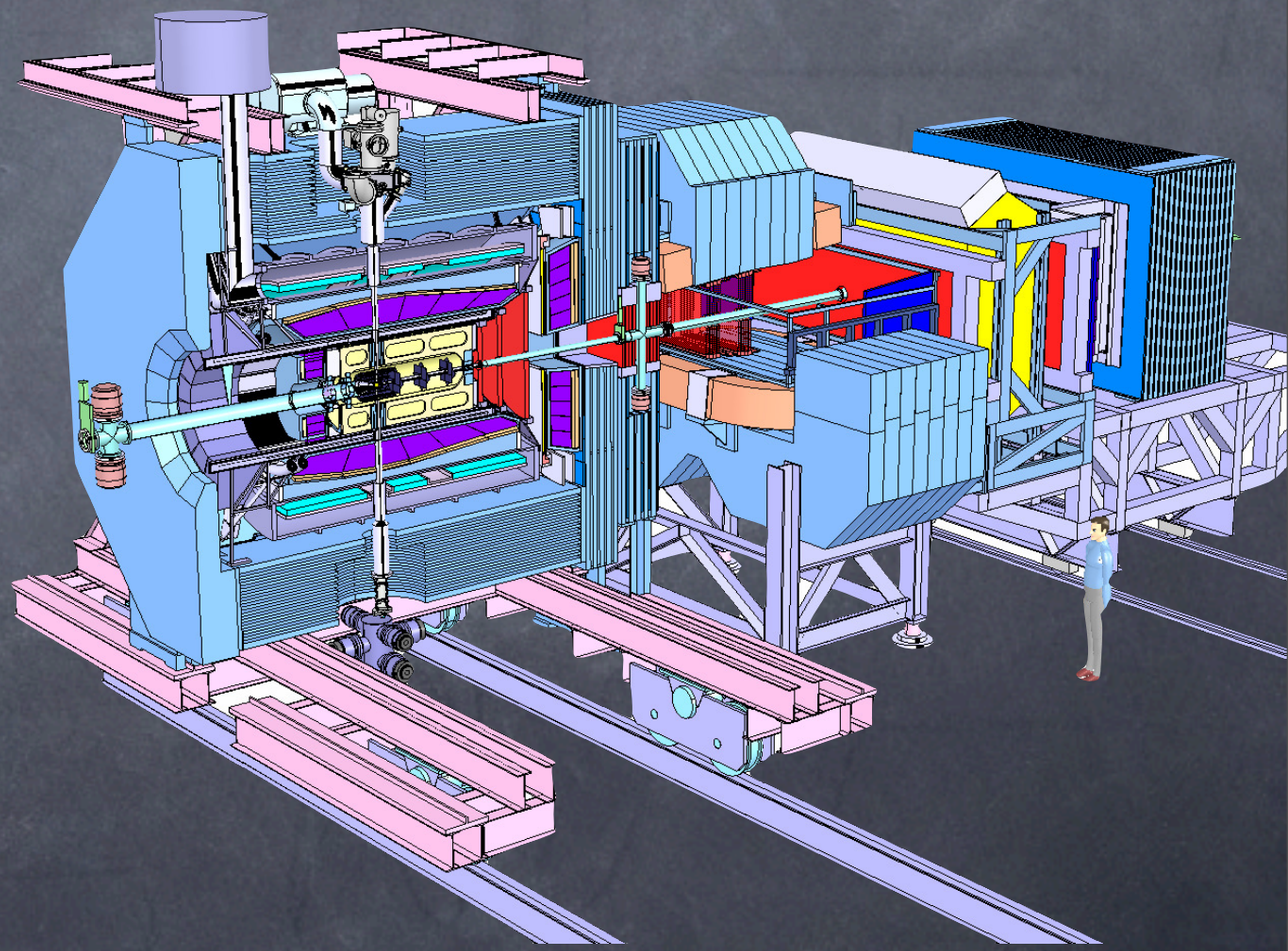
- Theory preparation



Theory is the lie that brings us nearer to the truth.

picture taken from www.particleadventure.org

- Experimental idea



Panda spectrometer

§2: Theory preparation

- Review of QM: Fermi's golden rule, cross section
- Generalization to relativistic case
- Modern view of physical world (QFT)

§2: Review of QM

- All physics contains in states of Hilbert space.
- Space representation of state (wave function) satisfies Schrödinger equation.
- A free particle wave function can be expressed into plane waves.

$$\langle x \mid \psi \rangle = \psi(x)$$

$$\frac{1}{2m}\Delta\psi = -i\frac{\partial\psi}{\partial t}, \hbar \equiv 1$$

$$\psi(x,t) = \frac{1}{\sqrt{V}}e^{(\vec{p}\vec{x}-E_k t)}$$

§2: Review of QM

- Fermi's golden rule (reaction rate):

$$W = 2\pi \mid M_{if} \mid^2 \cdot \rho(E_i)$$

- Dynamics of interaction (property of potential) is contained in the M_{if} term.

$$M_{if} = \langle \psi_f \mid V_{int} \mid \psi_i \rangle = \int \psi_f^* V_{int} \psi_i d^3x$$

- Experimentally measurable cross section.

$$\sigma = \frac{W}{(\text{Initial flux})}(\text{Number of final states})$$

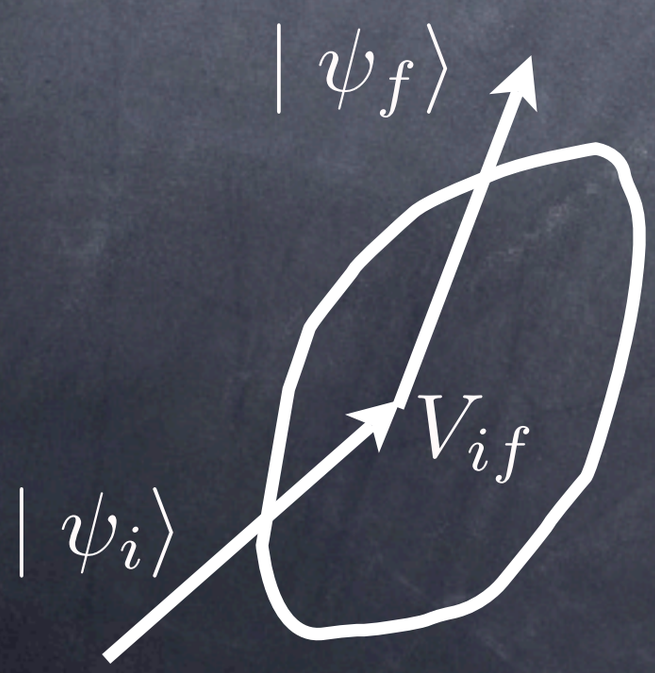
$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \frac{4Z^2\alpha^2 E'^2}{\mid q \mid^2}$$

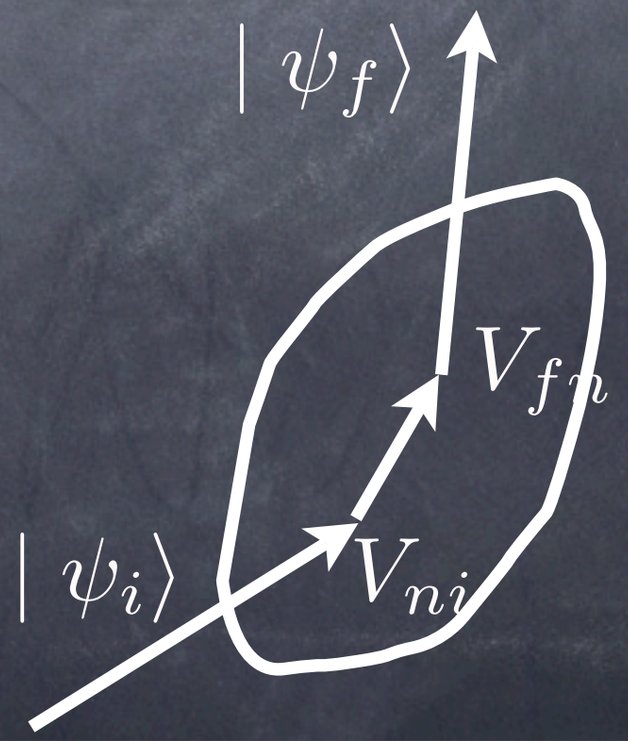
§2: Review of QM

- Perturbation expansion

$$M_{if} = \langle \psi_f \mid V_{int} \mid \psi_i \rangle = \int \psi_f^* V_{int} \psi_i d^3x$$

$$M_{if} \to V_{fi} + \sum_{n \neq i} V_{fn} \frac{1}{E_i - E_n + i\epsilon} V_{ni} + \cdots$$





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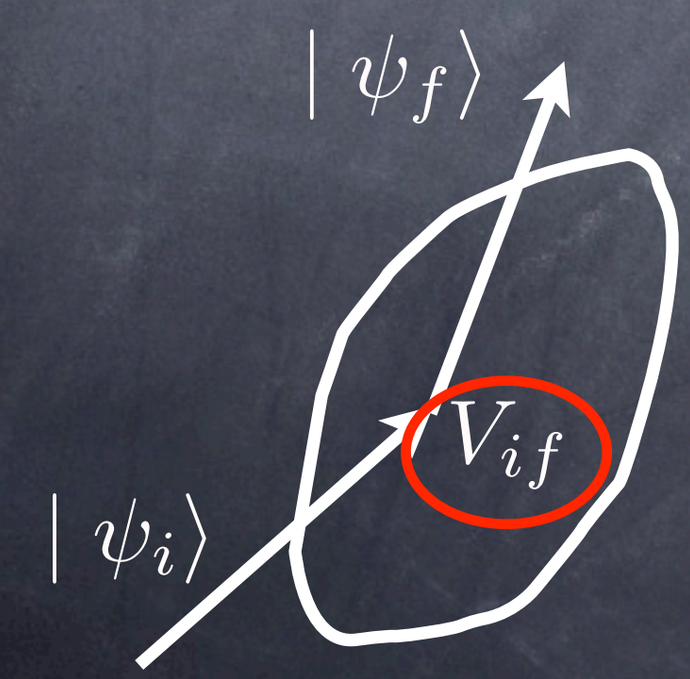
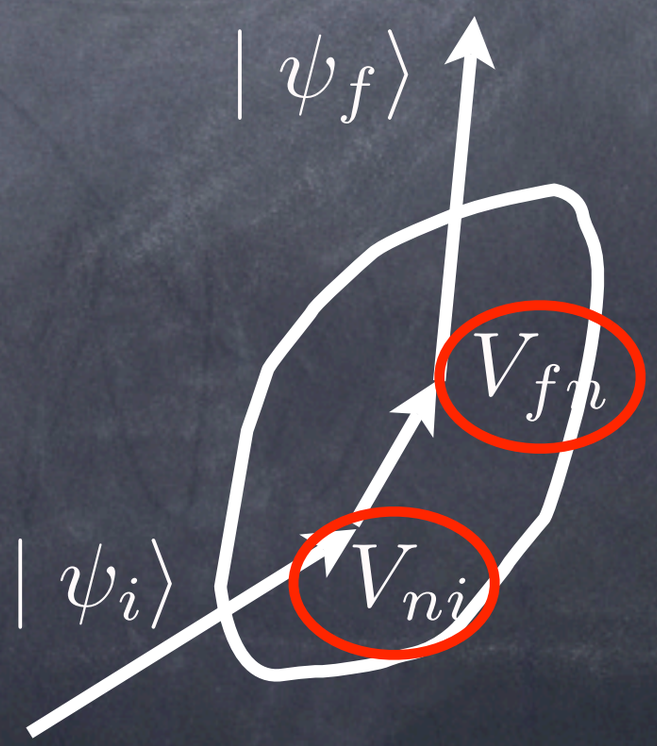


Vertex



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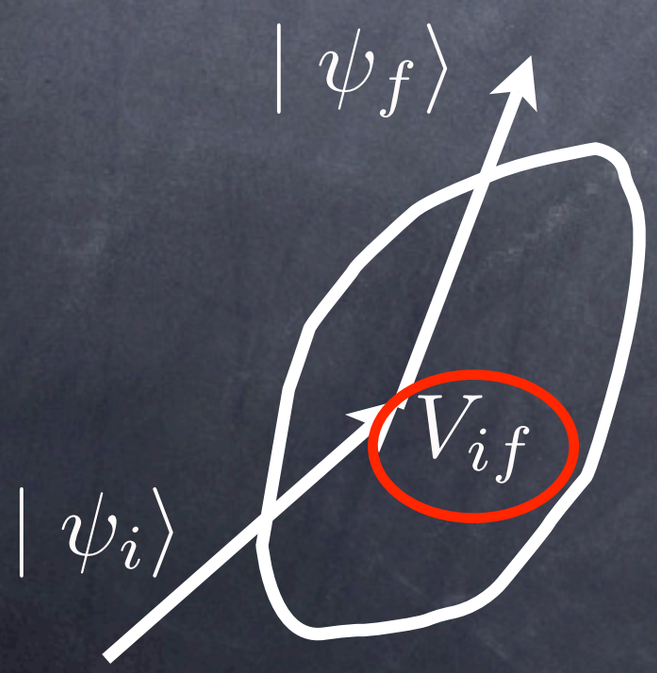
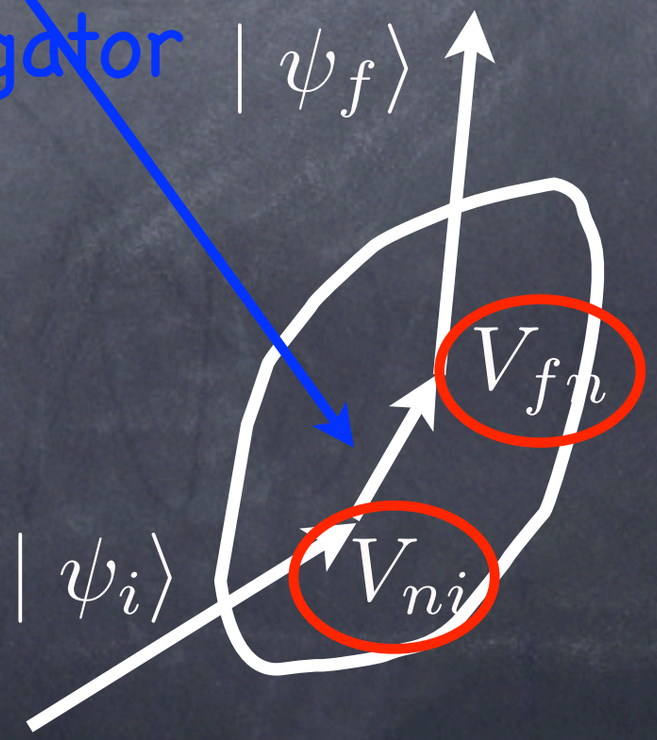
Propagator

Vertex



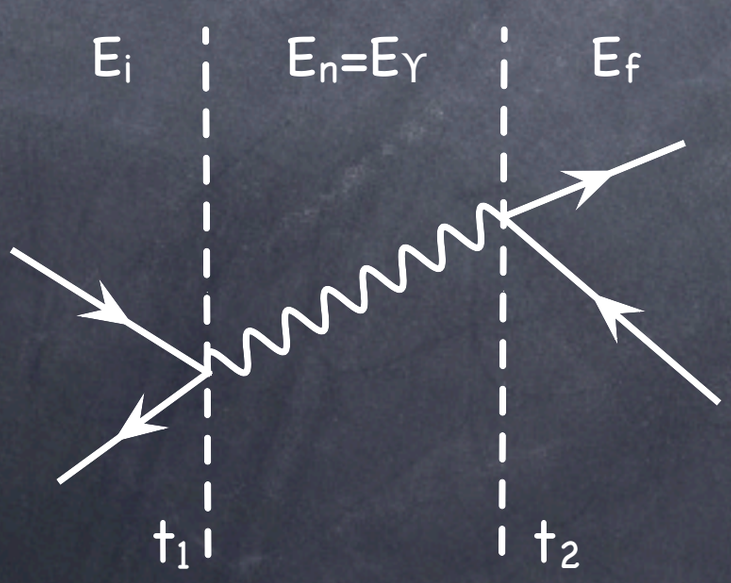


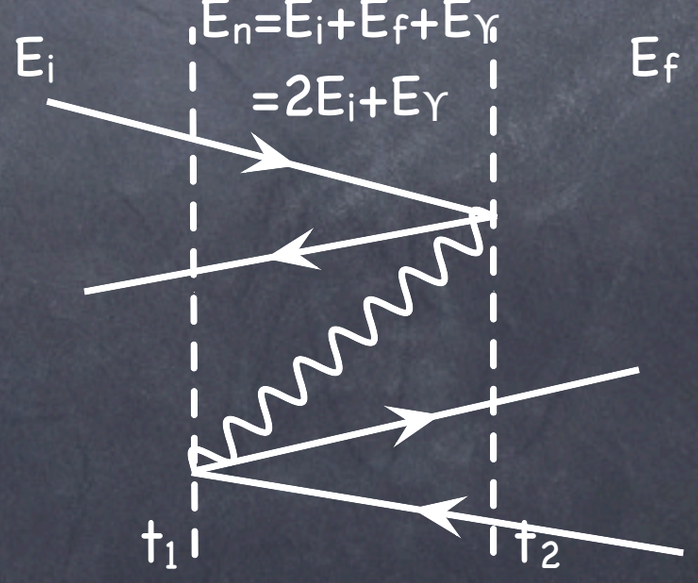
§2: Review of QM

$$\sum_{n\neq i} V_{fn}\frac{1}{E_i - E_n + i\epsilon}V_{ni}$$

$$= V_{fn}\frac{1}{E_i - E_\gamma}V_{ni} + V_{fn}\frac{1}{E_i - 2E_i - E_\gamma}V_{ni}$$

$$= V_{fn}\frac{2E_\gamma}{E_i^2 - E_\gamma^2}V_{ni} = V_{fn}\frac{2E_\gamma}{(p_A + p_B)^2 - m_\gamma^2}V_{ni}$$





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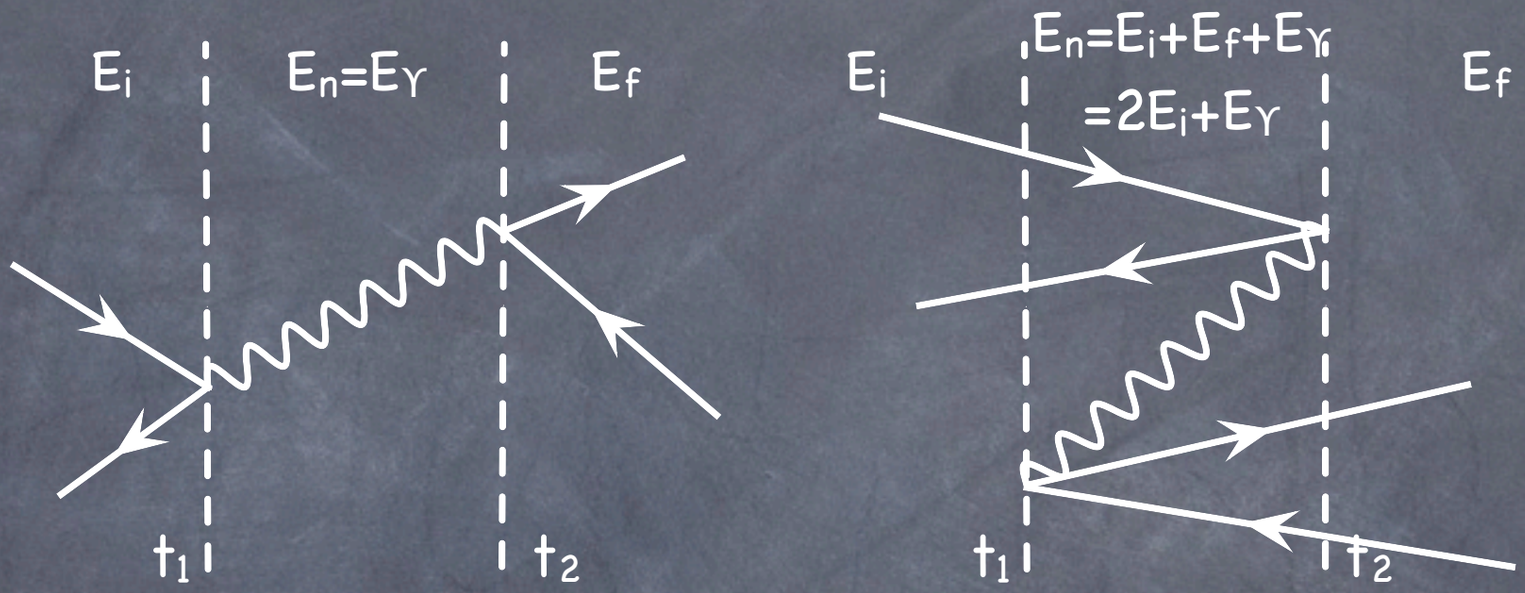

propagator

vertex

vertex

$$V_{fn}\frac{2E_\gamma}{(p_A+p_B)^2-m_\gamma^2}V_{ni}$$

p_A and p_B are 4-vector.

A general structure we will have in a theory compatible with special relativity.

§2: Relativity comes

- Lorentz invariant: Klein-Gordon equation
- New normalization factor

$$(\Box - m^2)\psi(x) = 0$$

$$\psi(x,t) = \frac{1}{\sqrt{V}} e^{(\vec{p}\vec{x} - Et)} = \frac{1}{\sqrt{V}} e^{(px)}$$

$$E = \sqrt{\vec{p}^2 + m^2}$$

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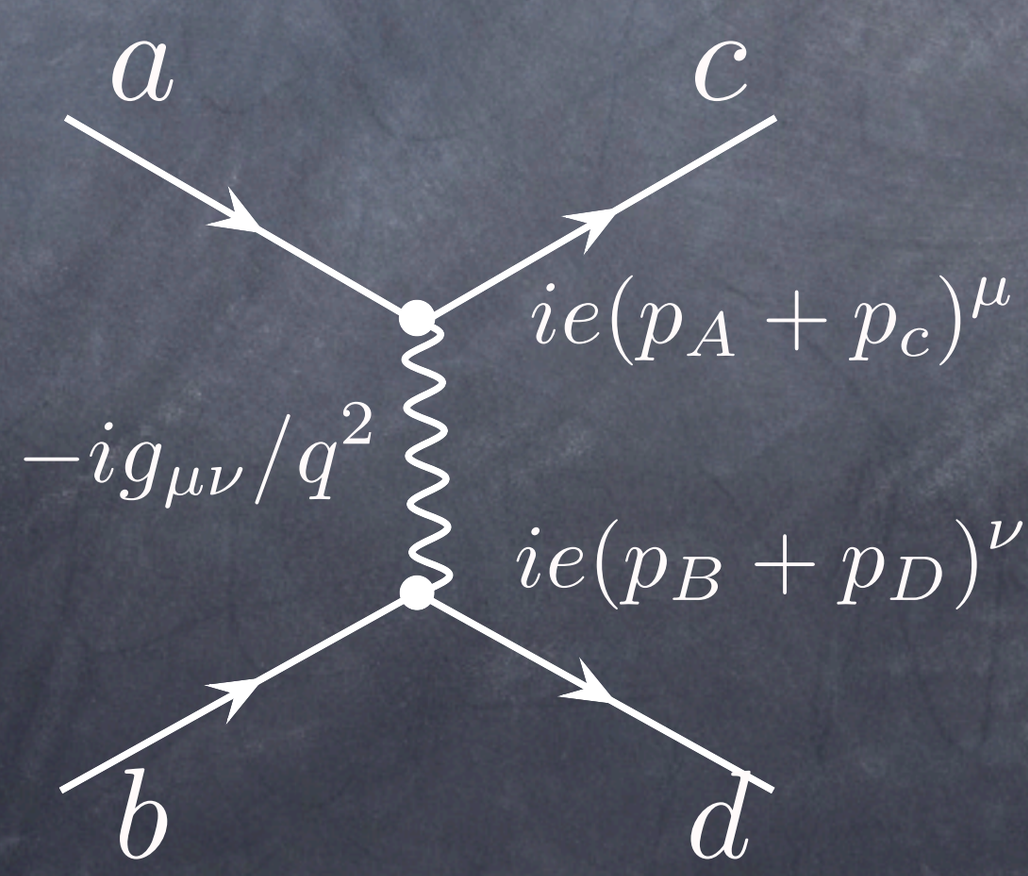
§2: Relativity comes

- Lorentz invariant amplitude: plane wave, spin=0

$$ie(p_A+p_C)^\mu \frac{-ig_{\mu\nu}}{q^2} ie(p_B+p_D)^\nu, q=p_C-p_A$$

time



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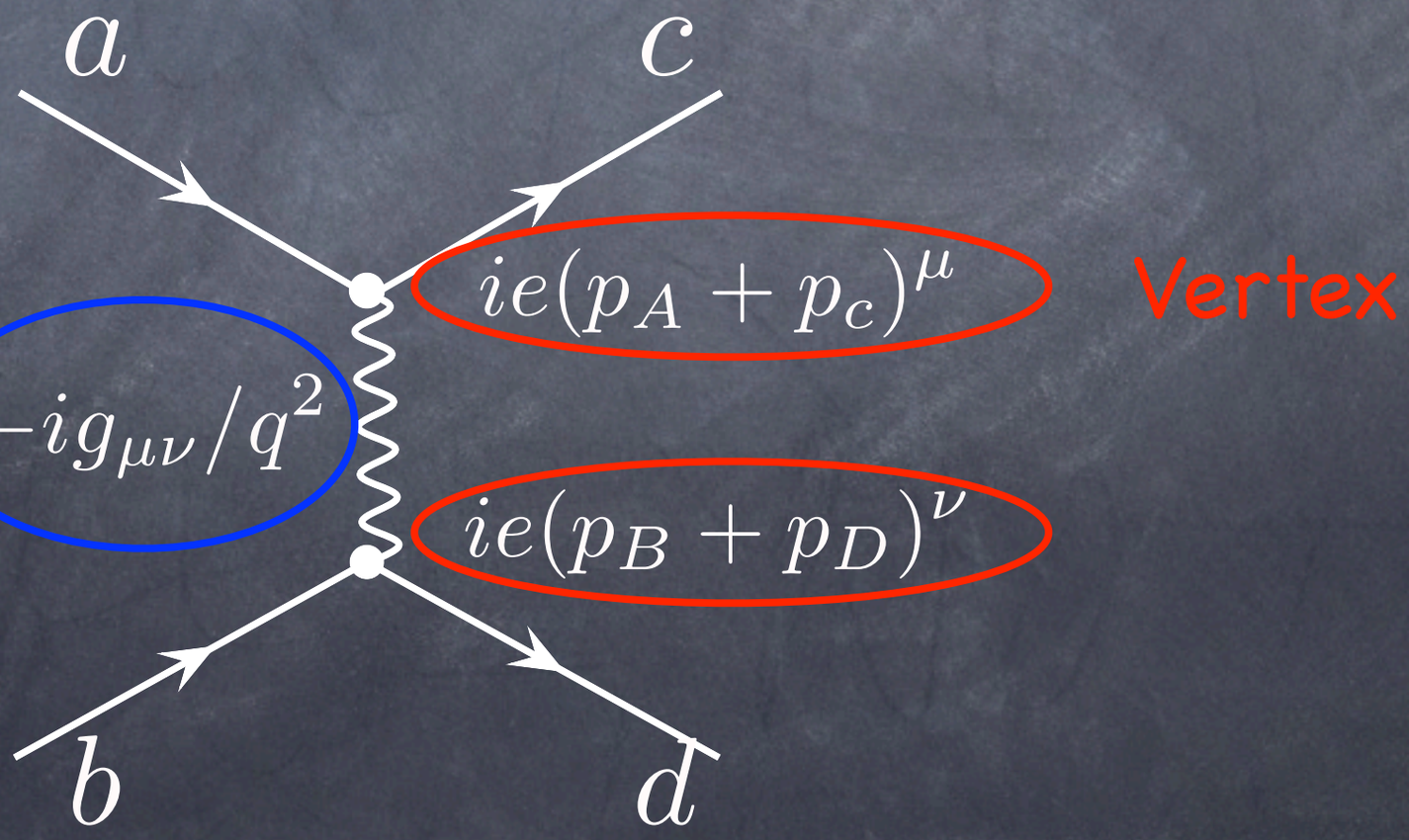


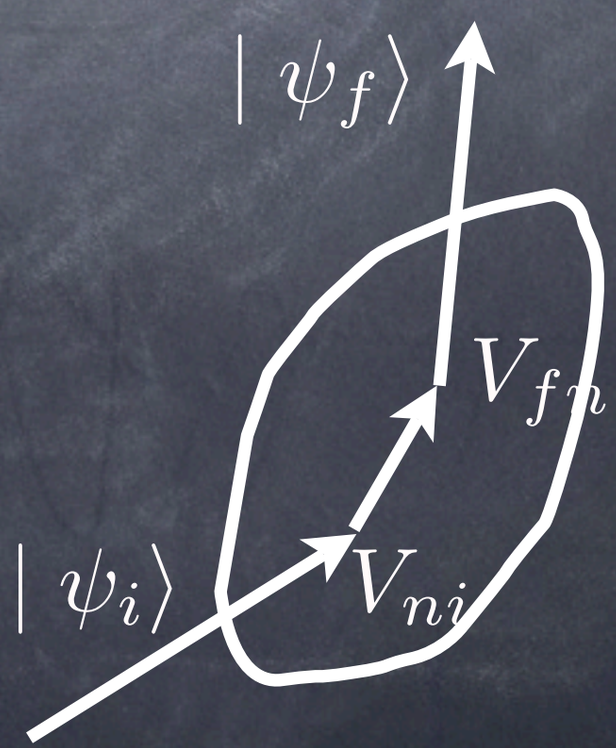
§2: Relativity comes

- A reasonable solution?

flux density

$$ie(p_A+p_C)^\mu \frac{-ig_{\mu\nu}}{q^2} ie(p_B+p_D)^\nu, q = p_C - p_A$$

$$V_{fn} \frac{2E_\gamma}{(p_A+p_B)^2 - m_\gamma^2} V_{ni}$$



§2: Relativity comes

- A reasonable solution?

Lowest order term (2nd order);
no point like interaction;
mediated by boson (propagator)

flux density

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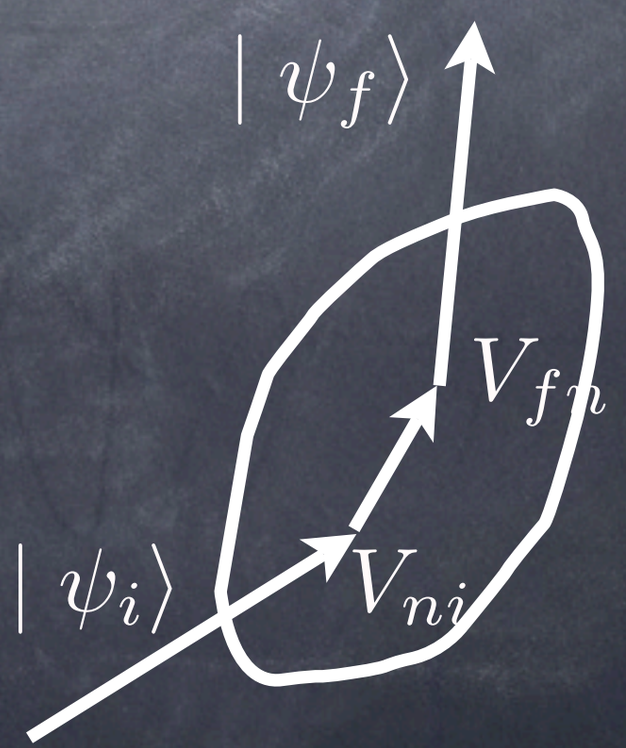

§2: Relativity comes

- Negative energy solution: $E = \pm\sqrt{\vec{p}^2 + m^2}$

flux density $\begin{cases} j^\mu(e^-) = -2e|N|^2(E,\vec{p}) \\ j^\mu(e^+) = 2e|N|^2(E,\vec{p}) \end{cases}$

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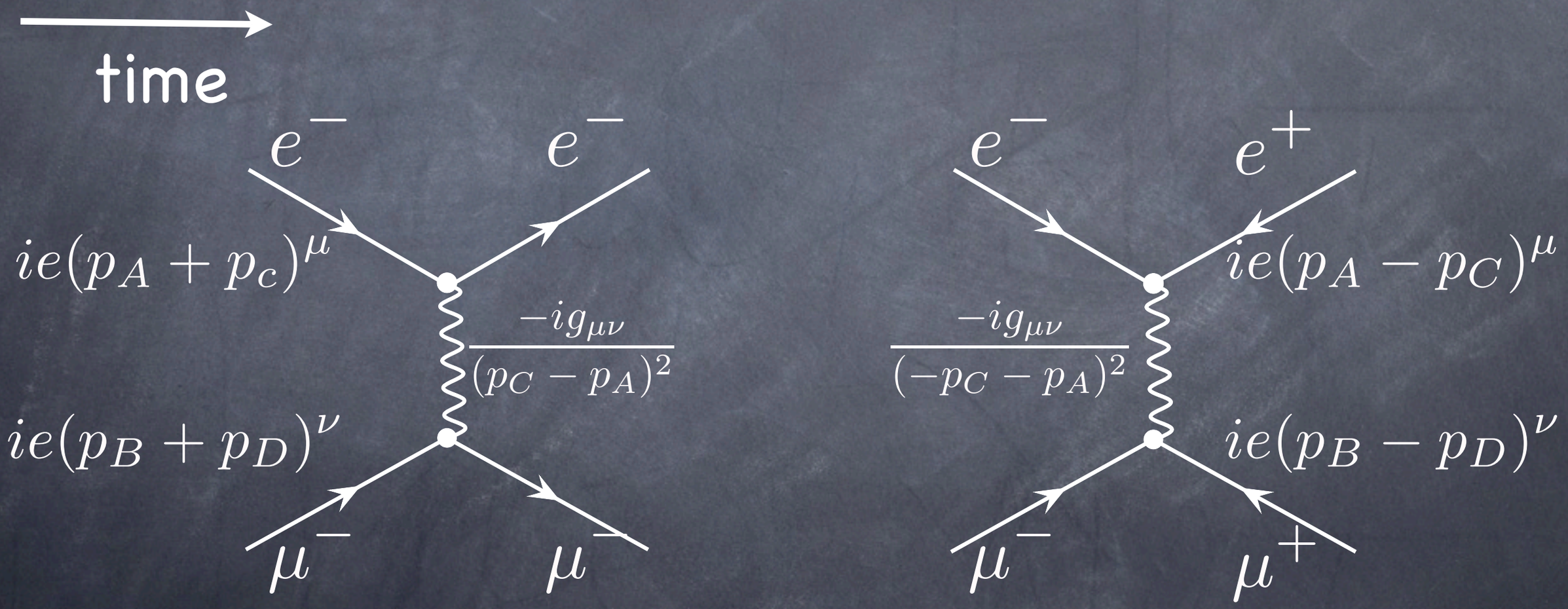
Anti-particle can be viewed as particle with negative energy going backward in time.

§2: Relativity comes

- crossing symmetry (ignore spin variable for now)



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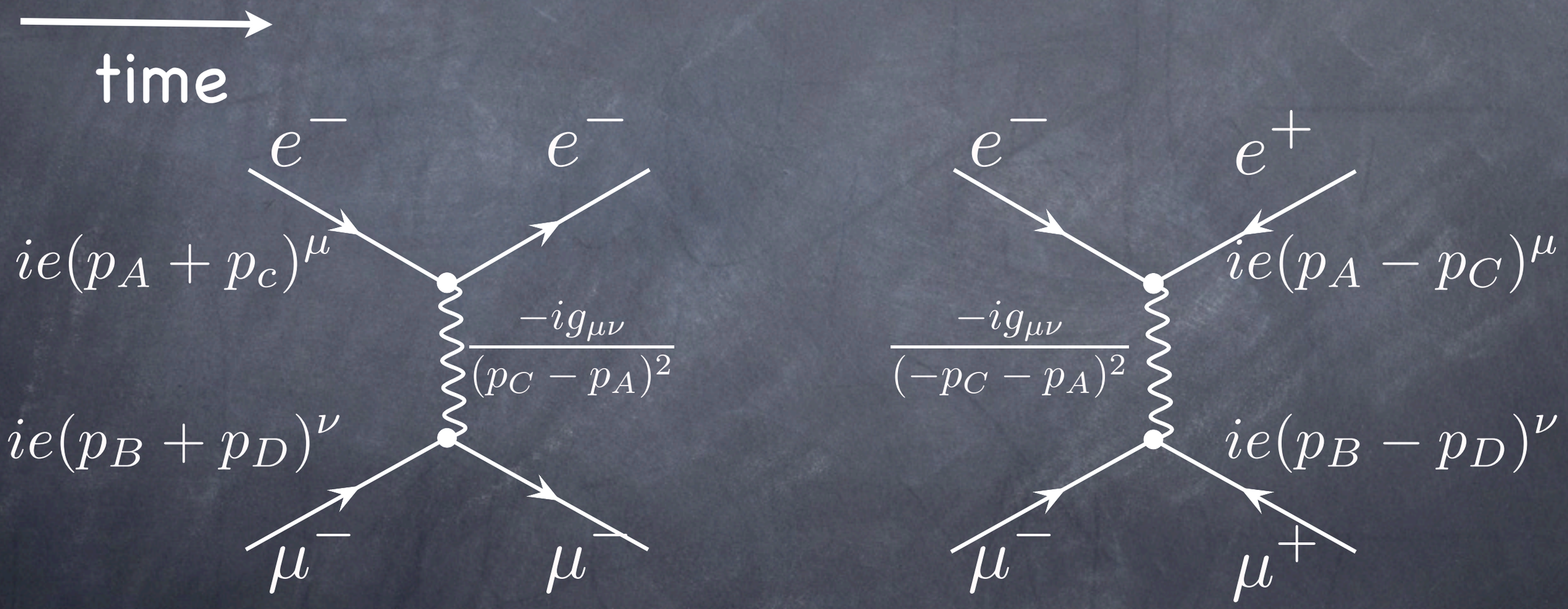


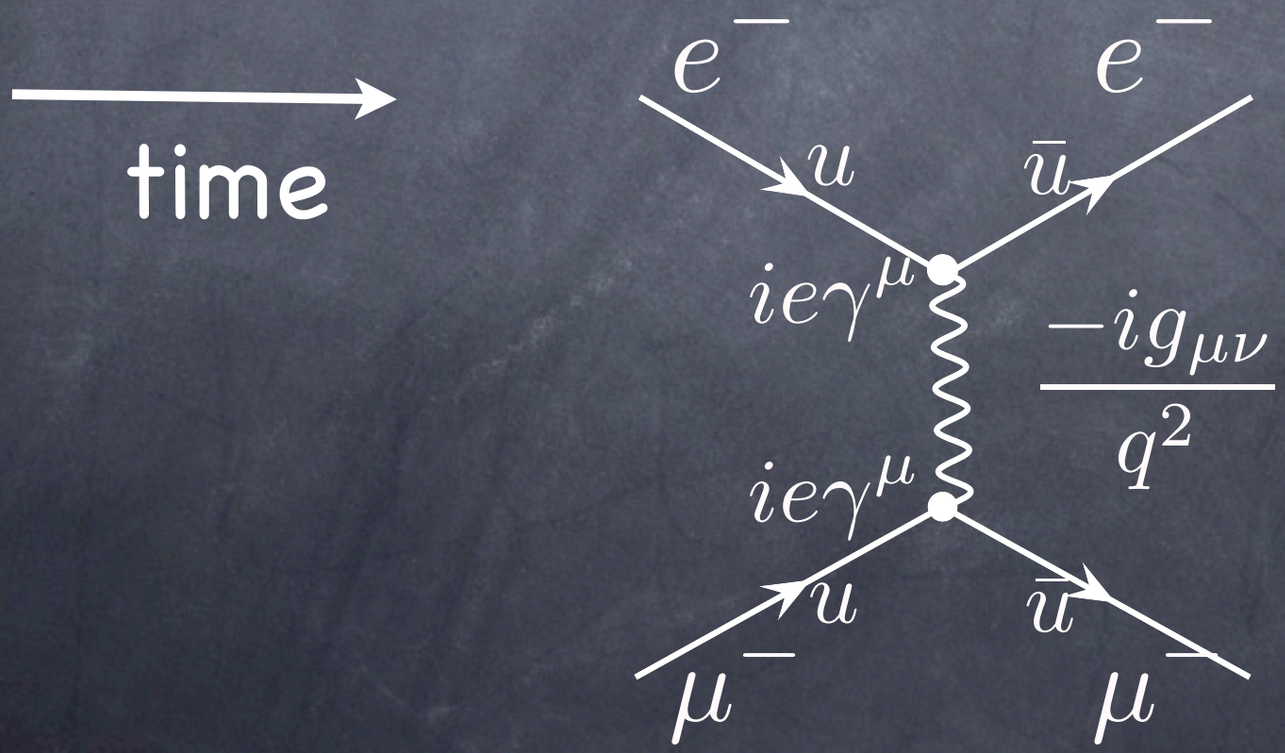
electro-muon scattering<->electron-position annihilation

They share the "same" structure.

§2: Spin comes

- Dirac equation: first order Klein-Gordon equation: $(\gamma^\mu p_\mu - m)u(\vec{p}) = 0$
- Spin structure and flux described by spinor: u(p)

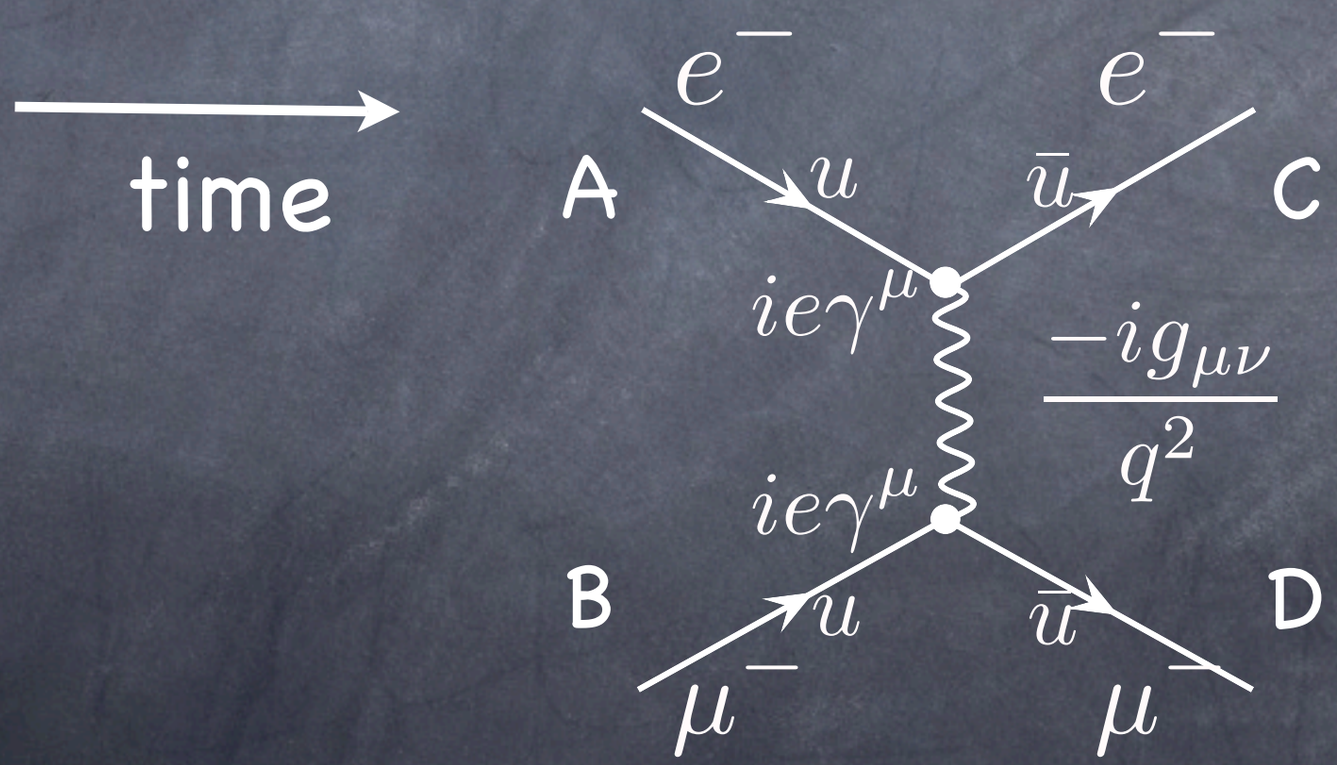
$$\psi = u(\vec{p})e^{-ipx}$$



§2: Spin comes

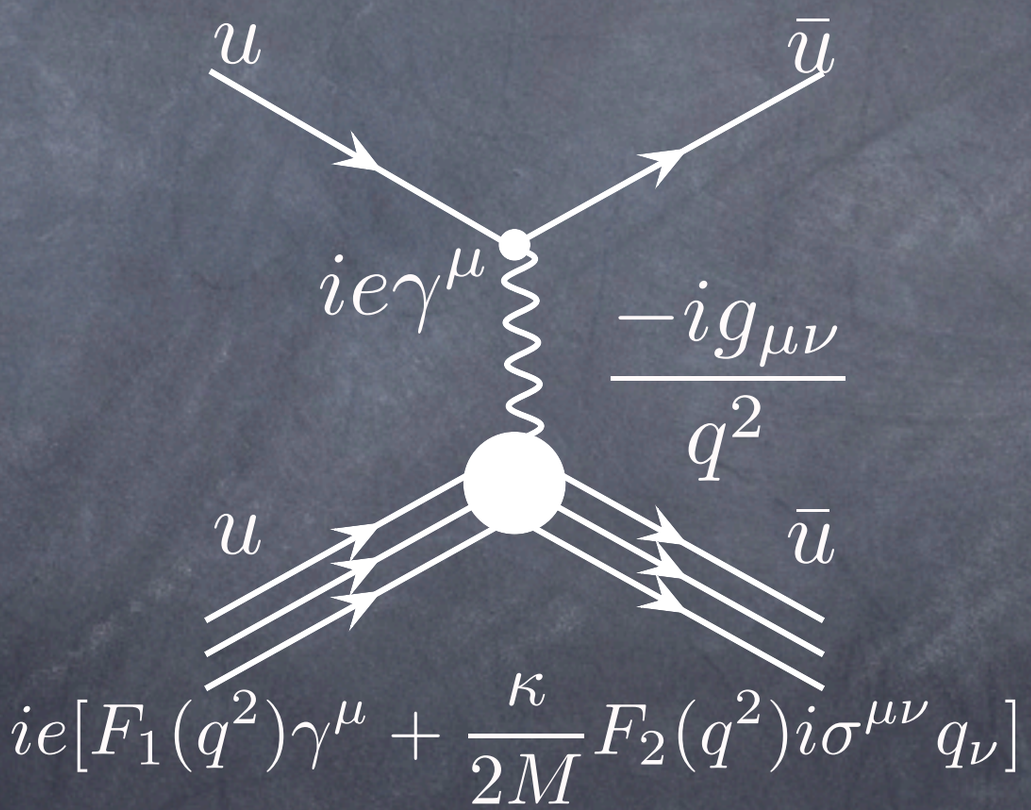
- Transition matrix element with spin:

$$M_{if} \rightarrow (ie\bar{u}_C\gamma^\mu u_A)\frac{-ig_{\mu\nu}}{q^2}(ie\bar{u}_D\gamma^\nu u_B)$$



§2: structure comes

- Particle has internal structure can be described by two independent Lorentz vectors.



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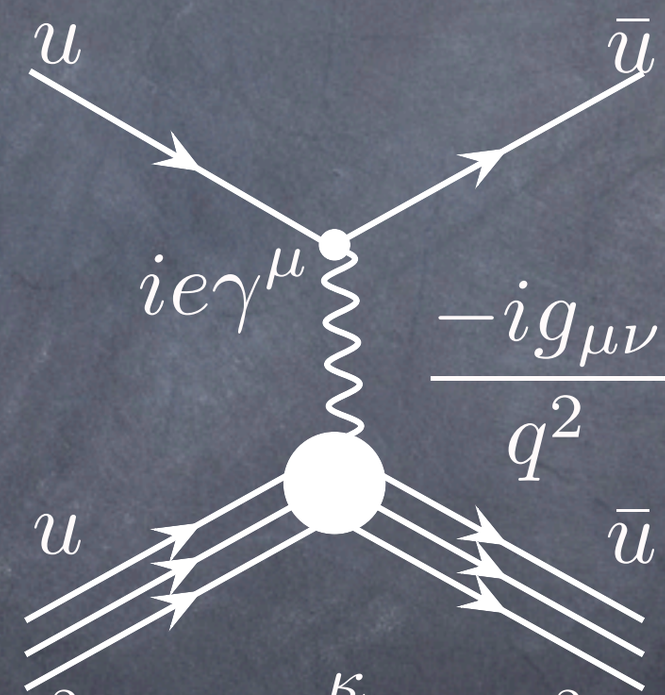


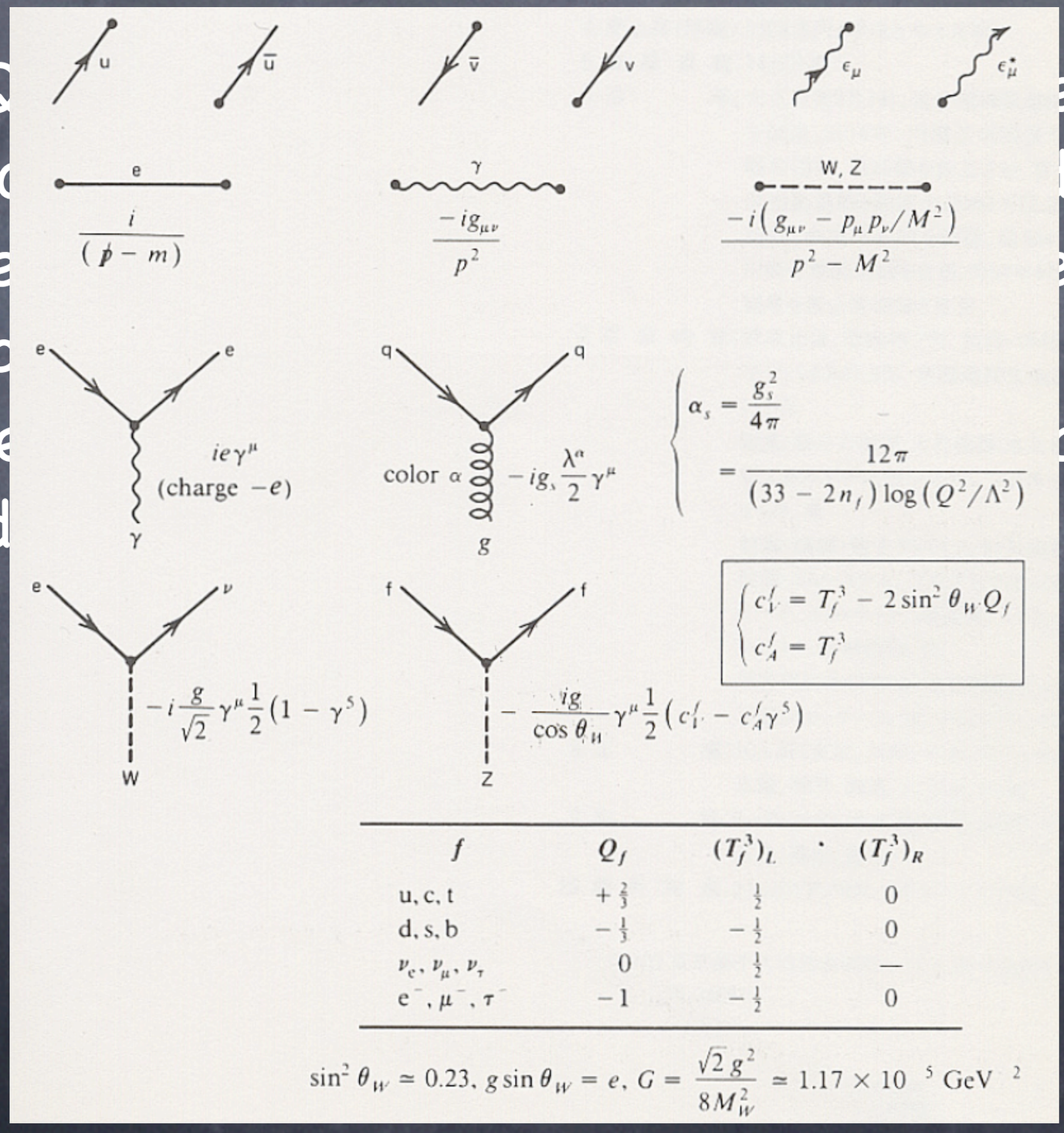
$$(ie\bar{u}_C\gamma^\mu u_A)\frac{-ig_{\mu\nu}}{q^2}(ie\bar{u}_D[F_1(q^2)\gamma^\nu + \frac{\kappa}{2M}F_2(q^2)i\sigma^{\nu\mu}q_\mu]\ u_B)$$

§2: Feynman diagram

- In QED, as in other quantum field theories, we can use the little picture invented by my colleague Richard Feynman, which are supposed to give us the illusion of understanding what is going on in quantum field theory. --- M. Gell-Mann

§2: Feynman diagram

- In Q eories, we l by my colle e supp antum unde field



f	Q_f	$(T_f^3)_L$	$(T_f^3)_R$
u, c, t	$+\frac{2}{3}$	$\frac{1}{2}$	0
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	0
ν_e, ν_μ, ν_τ	0	$\frac{1}{2}$	—
e^-, μ^-, τ^-	−1	$-\frac{1}{2}$	0

§2: QFT

- $E=mc^2$: new particle production: particle number conservation?
- In QM, "time" is not operator as "x".
- Formal solution: Quantum field theory (A quantum theory consistent with special relativity).

§2: Experimental idea

Now we have a "formalism" (Feynman diagram).
How to utilize it?

picture taken from www.particleadventure.org

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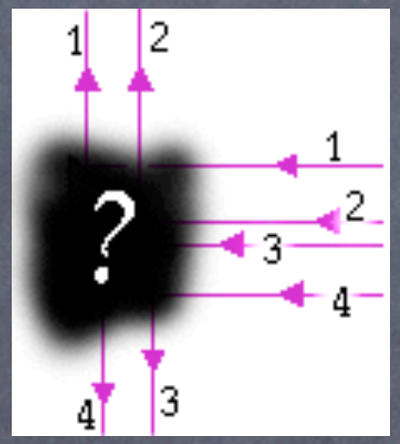

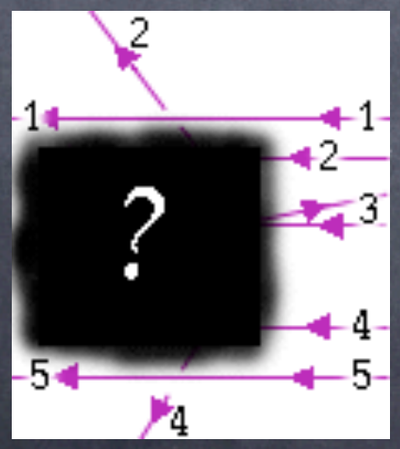

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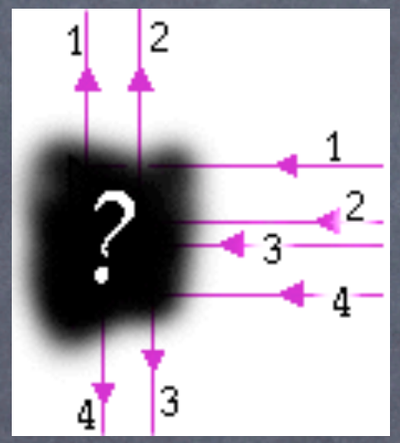
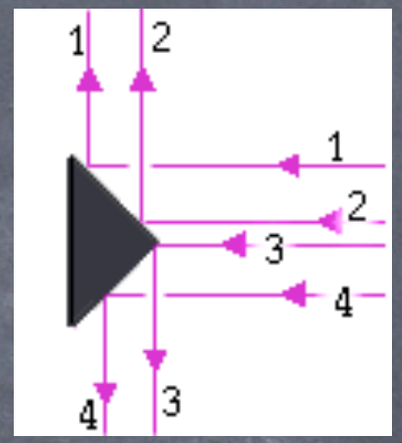
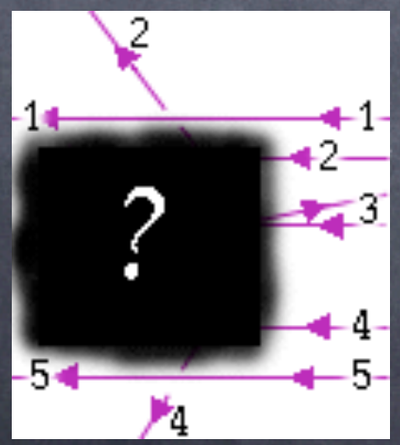
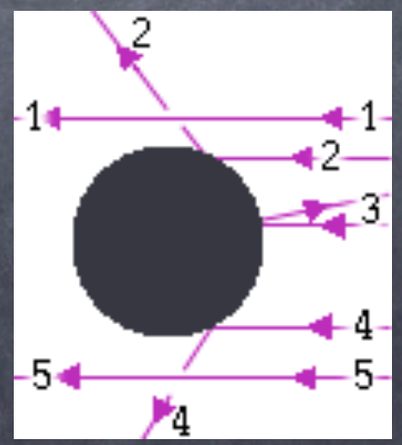




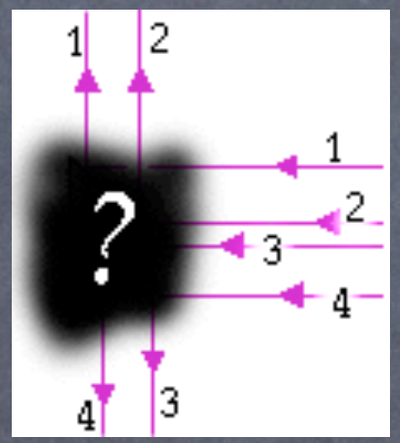


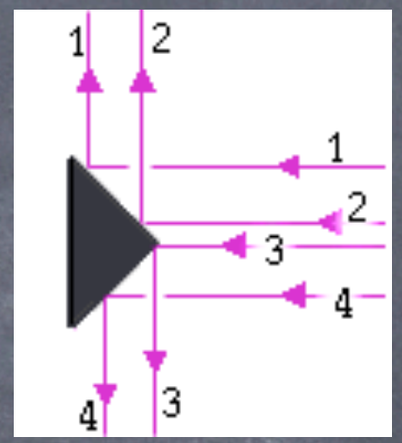


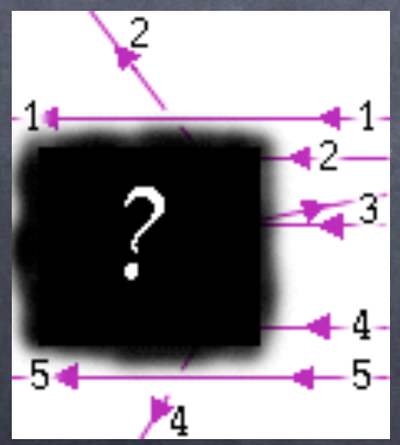
picture taken from www.particleadventure.org

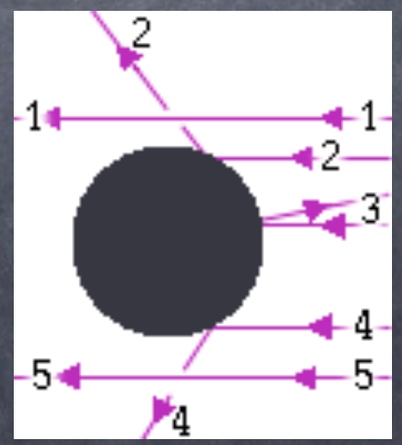
§2: Experimental idea

Now we have a "formalism" (Feynman diagram).
How to utilize it?









Investigate the shape by throwing "something" on it!

picture taken from www.particleadventure.org

§2: Experimental idea

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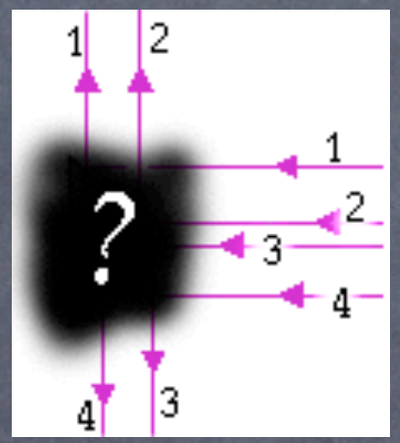
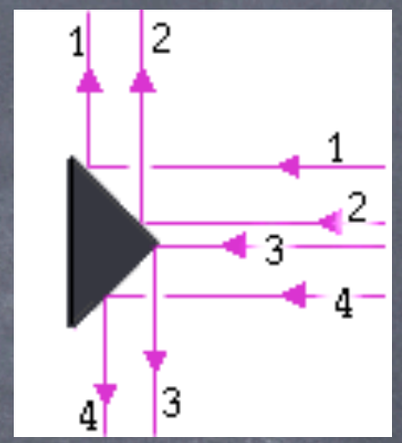
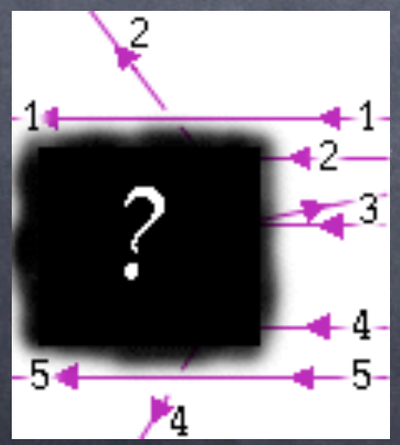
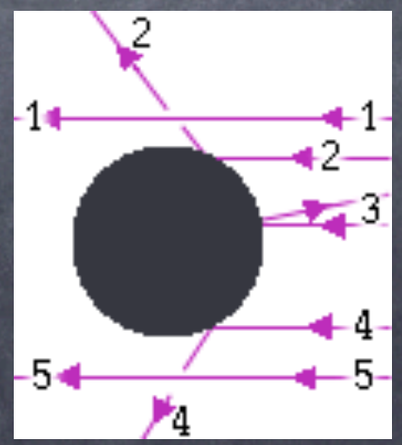
How to utilize it?









Investigate the shape by throwing "something" on it!
A more realistic example?

picture taken from www.particleadventure.org

§2: Experimental idea

- Nuclear charge distribution and form factor

  In case of point-like charged particle:

$$\left(\frac{d\sigma}{d\Omega}\right)^{*}_{Mott} = \frac{4Z^2\alpha^2E'^2}{|\,q\,|^2}\cdot\left(1-\beta^2 sin^2\frac{\theta}{2}\right)$$

If the particle's charge has distribution:

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp.} = \left(\frac{d\sigma}{d\Omega}\right)^{*}_{Mott}\cdot|\,F(q^2)\,|^2$$

§2: Experimental idea

- Nuclear charge distribution and form factor

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp.} = \left(\frac{d\sigma}{d\Omega}\right)^{*}_{Mott} \cdot \mid F(q^2) \mid^2$$

§2: Experimental idea

- Nuclear charge distribution and form factor

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp.} = \left(\frac{d\sigma}{d\Omega}\right)^{*}_{Mott} \cdot \mid F(q^2) \mid^2$$

If there is only Coulomb interaction:

$$F(q^2) = \int e^{i\vec{q}\vec{x}} f(\vec{x}) d^3x$$

Born approximation

Charge distribution

§2: Experimental idea

- Nuclear charge distribution and form factor

$$F(q^2) = \int e^{i\vec{q}\vec{x}} f(\vec{x}) d^3x$$

Born approximation

Charge distribution

§2: Experimental idea

- Nuclear charge distribution and form factor

$$F(q^2) = \int e^{i\vec{q}\vec{x}} f(\vec{x}) d^3x$$

Born approximation — Charge distribution

Form factor is Fourier transformation of the charge distribution.

§2: Experimental idea

- Nuclear charge distribution and form factor

F

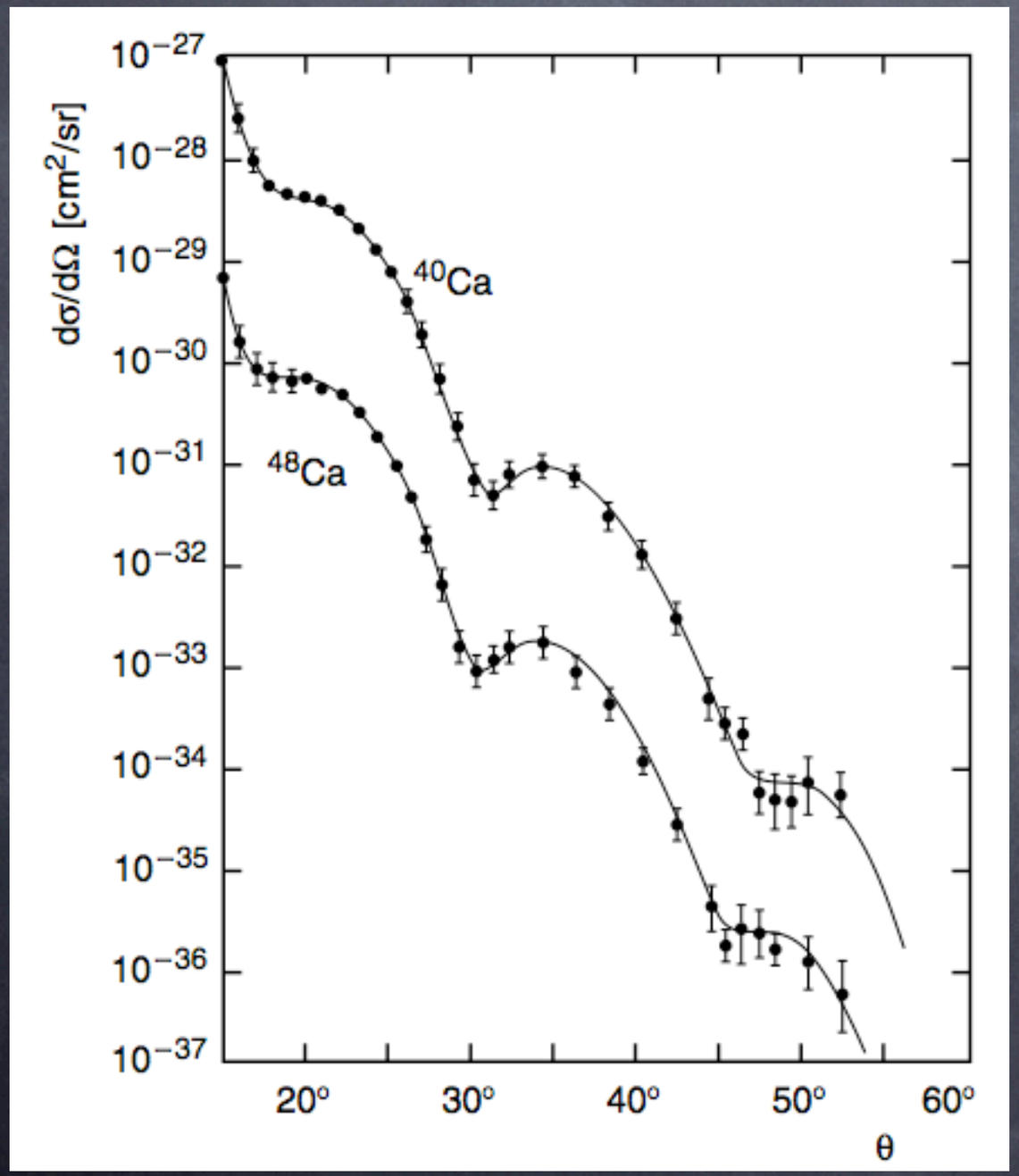
Born ap ribution

Form fac n of the

ρ(r)	$\lvert F(\boldsymbol{q}^2)\rvert$	Example
pointlike	constant	Electron
exponential	dipole	Proton
gauss	gauss	^{6}Li
homogeneous sphere	oscillating	–
sphere with a diffuse surface	oscillating	^{40}Ca
r →	$\lvert q \rvert$ →	

§2: Experimental idea

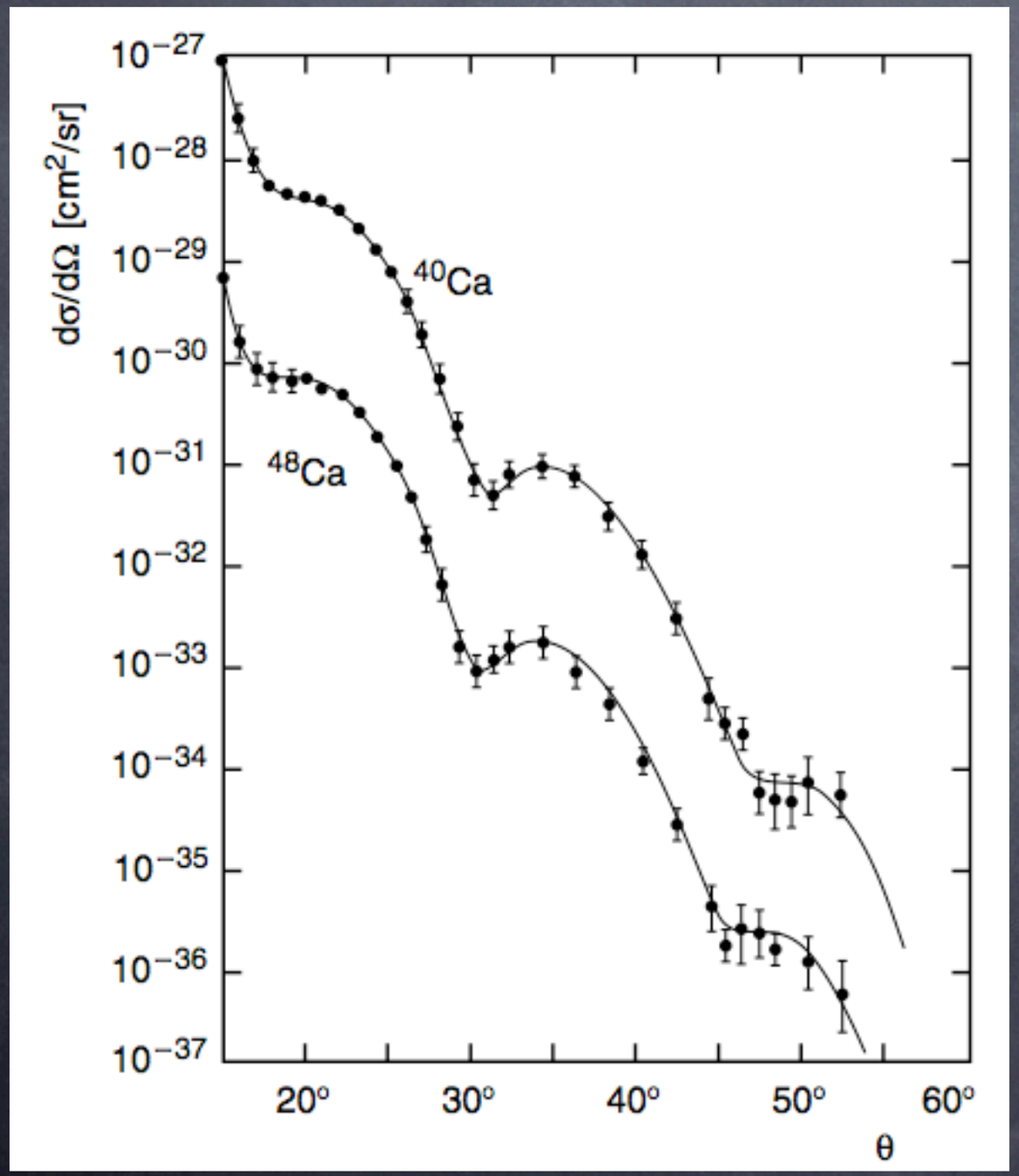
- Nuclear charge distribution



$$\left(\frac{d\sigma}{d\Omega}\right)_{exp.} = \left(\frac{d\sigma}{d\Omega}\right)^{*}_{point} \cdot \mid F(q^2) \mid^2$$

§2: Experimental idea

- Nuclear charge distribution



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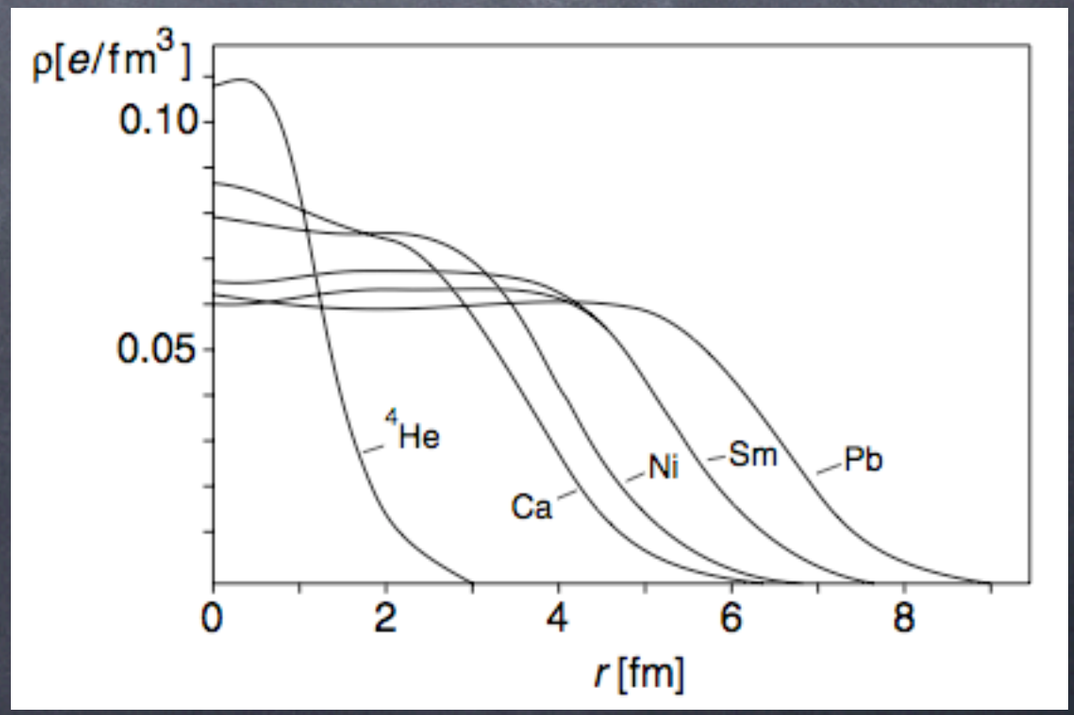
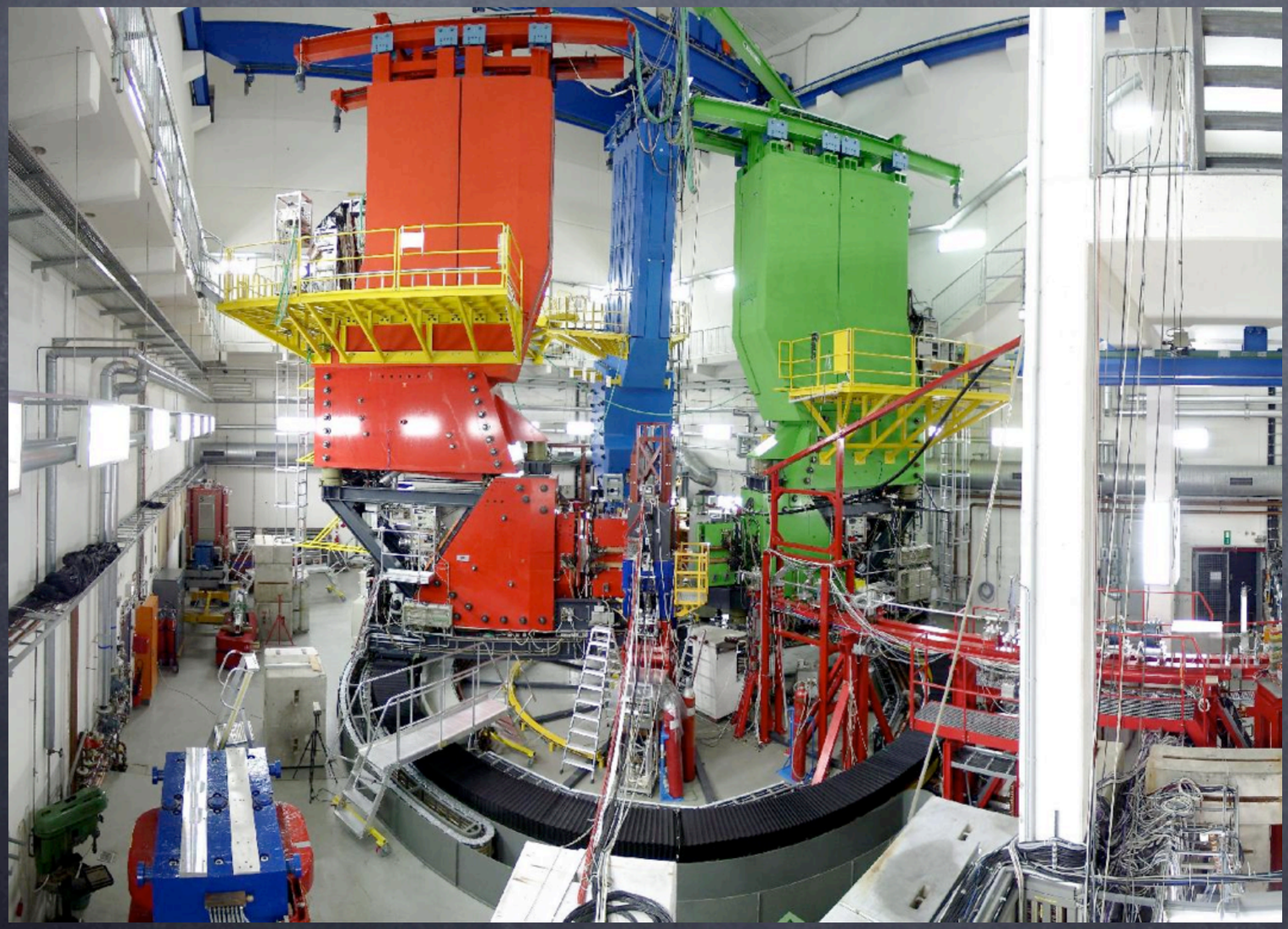


§2: Experimental idea

- Since Rutherford, scattering experiment has been the main method of discovery.



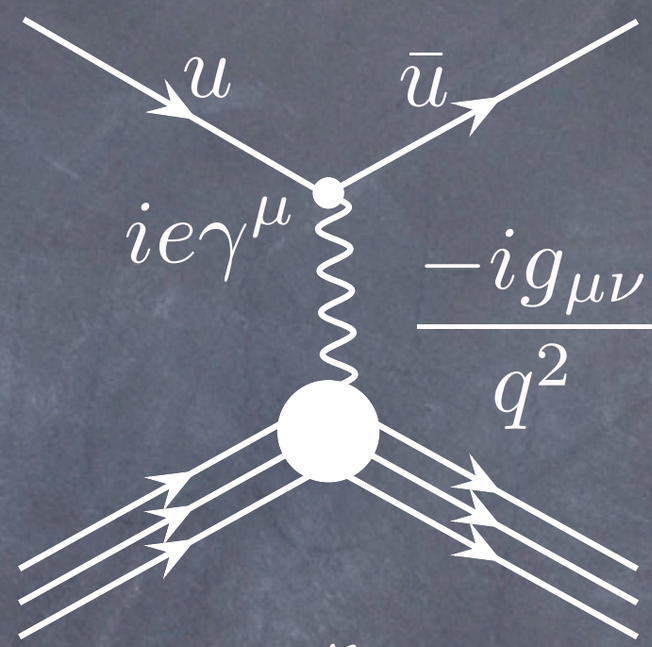
Three-arm spectrometer at MAMI, Mainz Univ.

§3: Example

- Electromagnetic structure of proton
- Future project at PANDA, FAIR facility

§3: EM structure of proton

Recall:

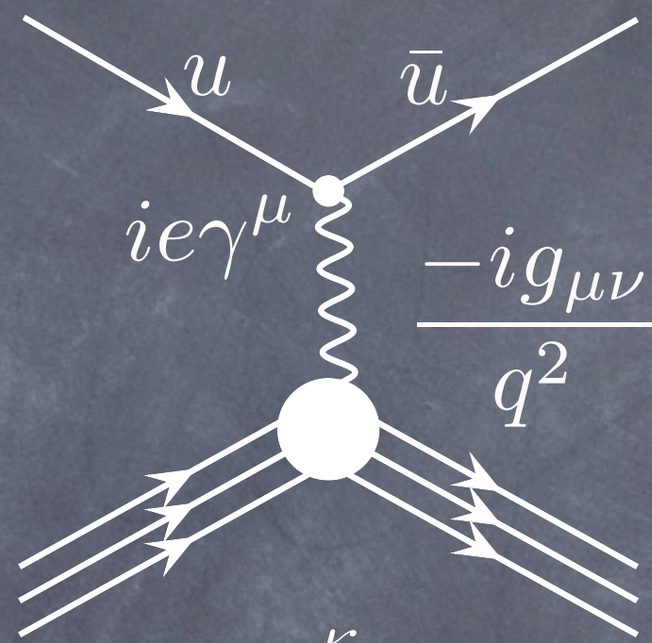


$$ie[F_1(q^2)\gamma^\mu + \frac{\kappa}{2M}F_2(q^2)i\sigma^{\mu\nu}q_\nu]$$

When q^2 is approaching 0, $F_1(0) = 1 \quad F_2(0) = 1$ because photon can only "see" proton as a "point-like" particle.

§3: EM structure of proton

Recall:



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§3: EM structure of proton

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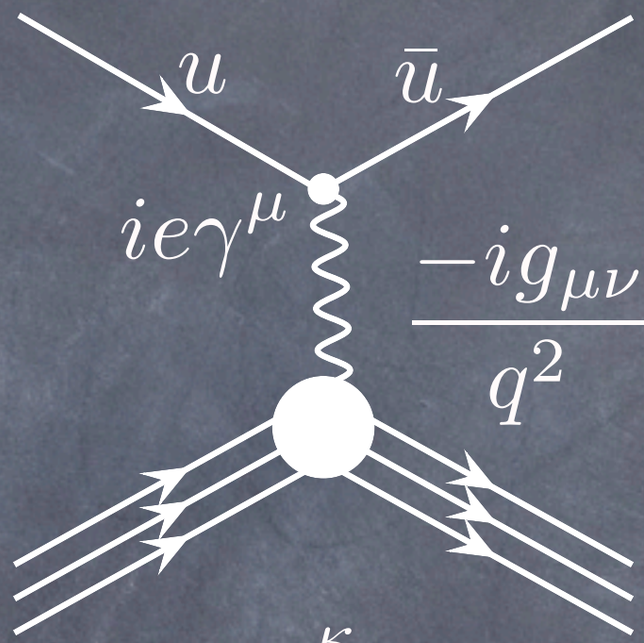

$$ie[F_1(q^2)\gamma^\mu + \frac{\kappa}{2M}F_2(q^2)i\sigma^{\mu\nu}q_\nu]$$

$$(ie\bar{u}_C\gamma^\mu u_A)\frac{-ig_{\mu\nu}}{q^2}(ie\bar{u}_D[F_1(q^2)\gamma^\nu + \frac{\kappa}{2M}F_2(q^2)i\sigma^{\nu\mu}q_\mu]\ u_B)$$

§3: EM structure of proton

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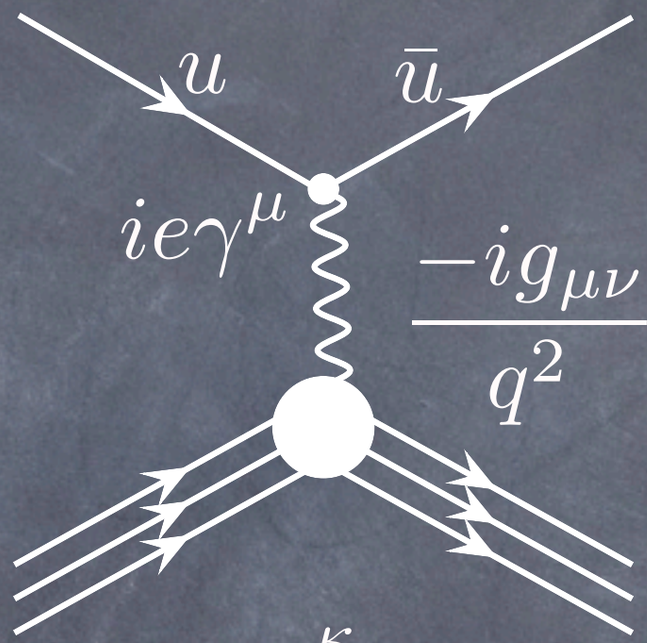

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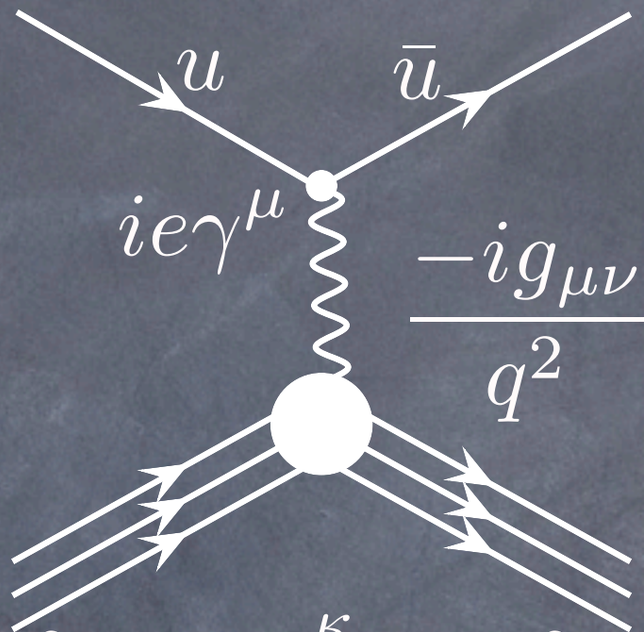
By summing up all possible spin states and taking care of phase space:

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp.} = \left(\frac{\alpha^2}{4E^2 sin^4\frac{\theta}{2}}\right)\frac{E'}{E}\left\{\left(F_1^2 - \frac{\kappa^2 q^2}{4M^2}F_2^2\right)cos^2\frac{\theta}{2} - \frac{q^2}{2M^2}(F_1+\kappa F_2)^2 sin^2\frac{\theta}{2}\right\}$$

§3: EM structure of proton

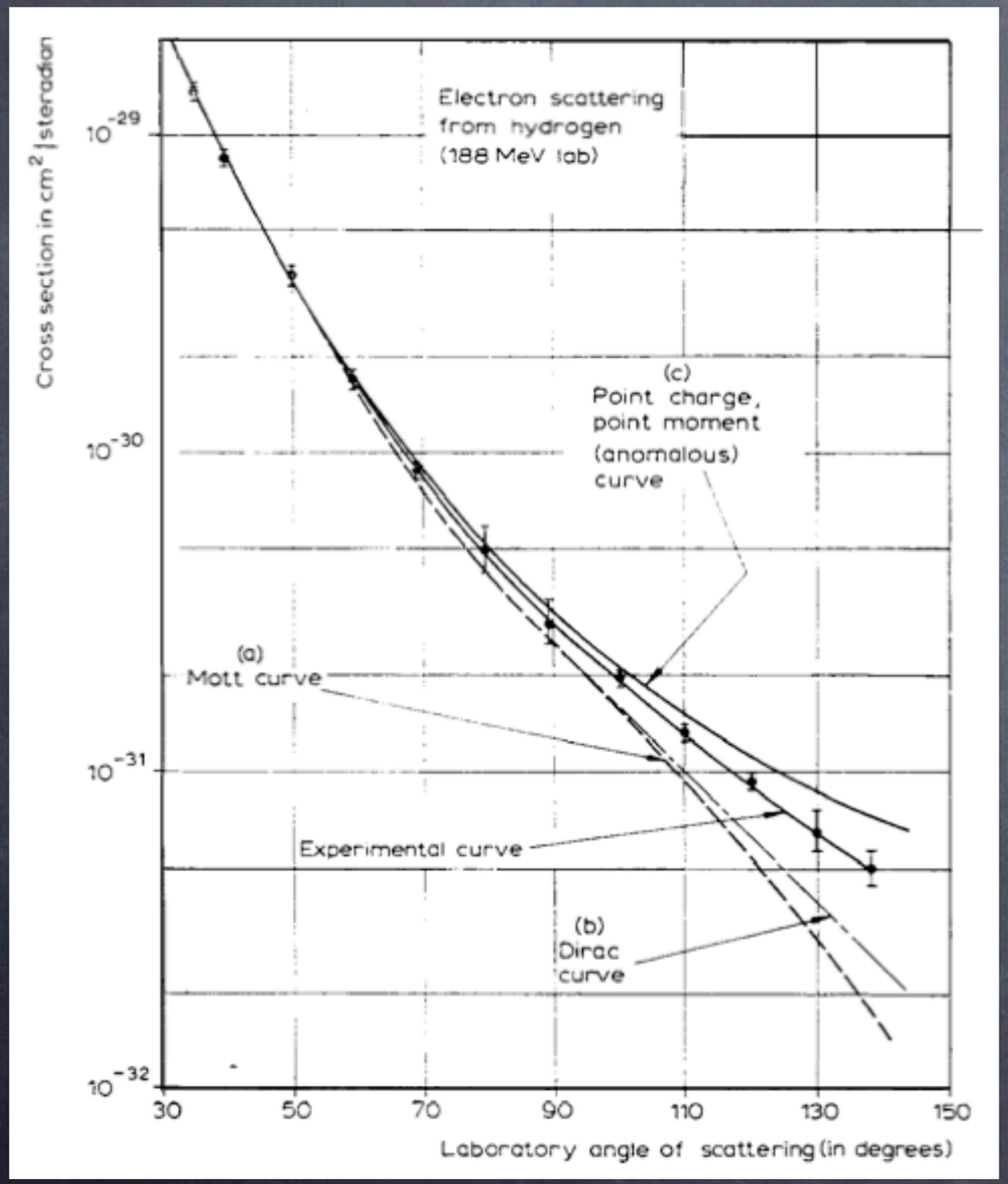


$$ie[F_1(q^2)\gamma^\mu + \frac{\kappa}{2M}F_2(q^2)i\sigma^{\mu\nu}q_\nu]$$

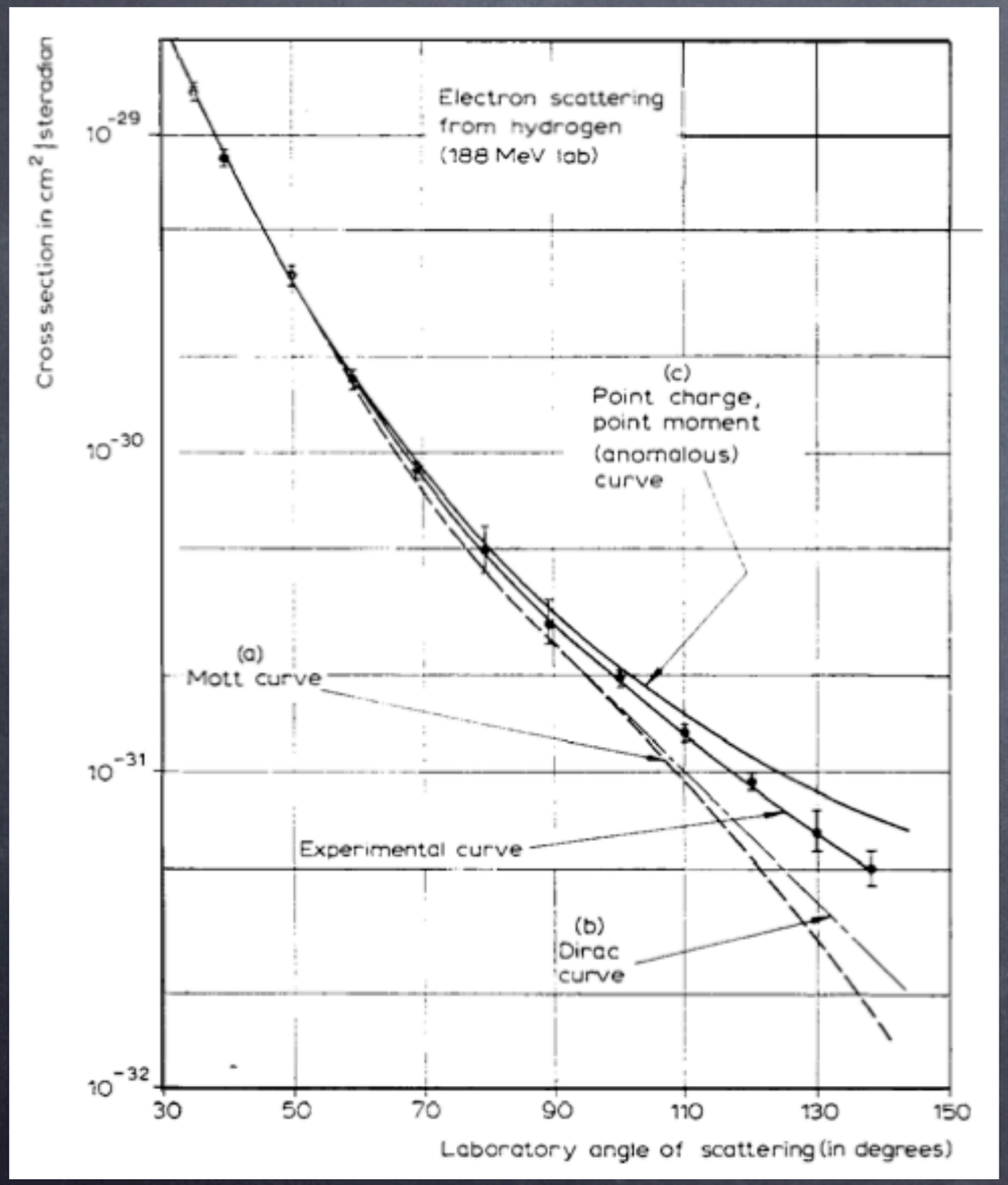
Robert Hofstadter,
Nobel prize for measuring proton and neutron form factor, 1961

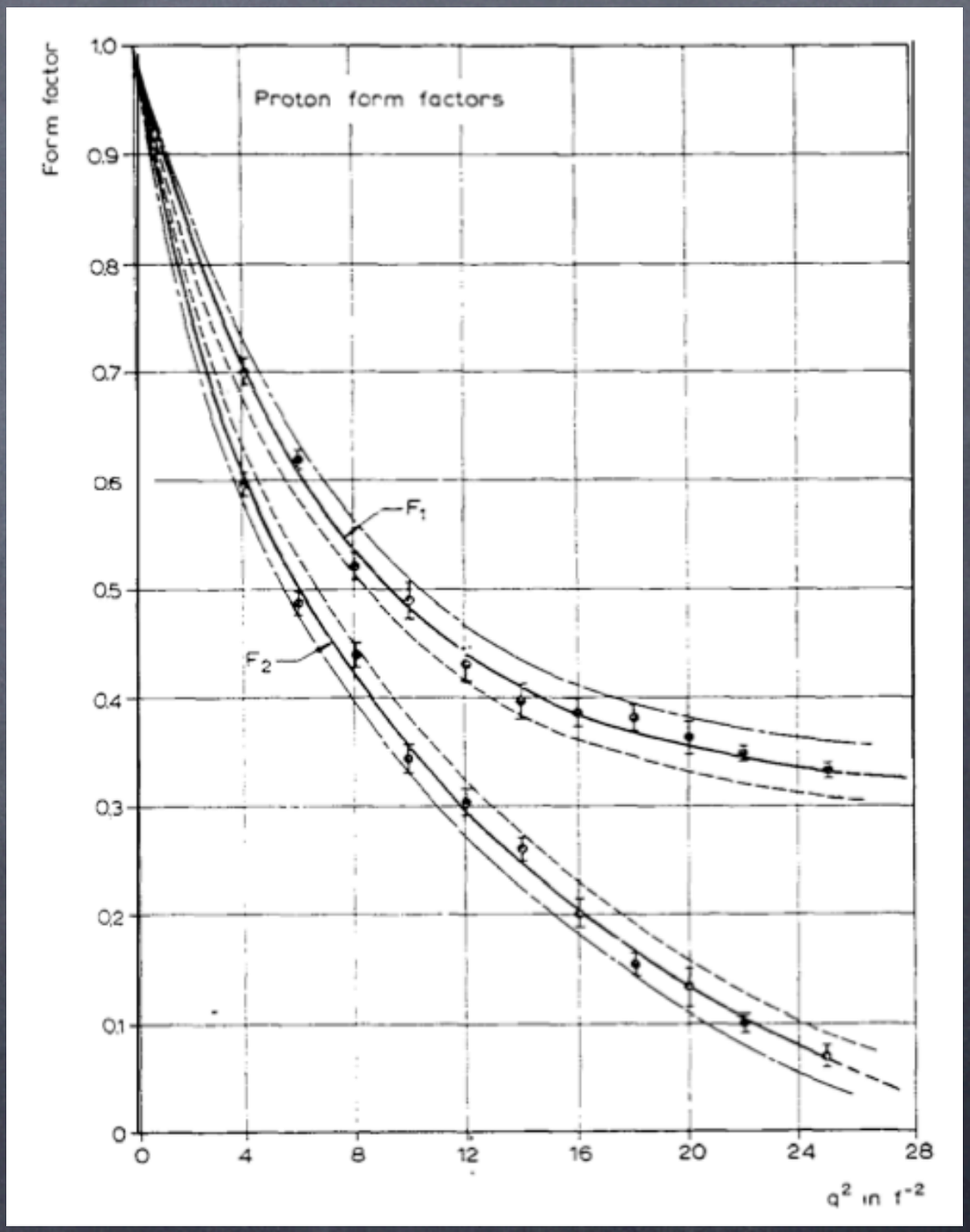
§3: EM structure of proton

§3: EM structure of proton

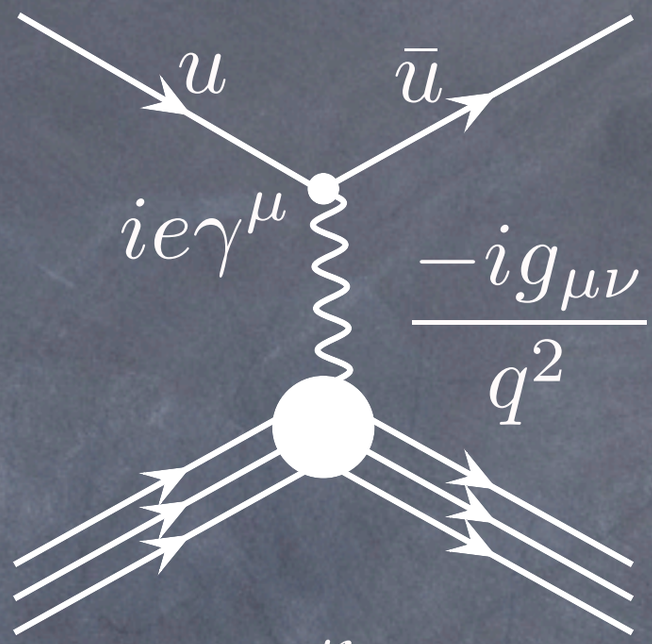


§3: EM structure of proton





§3: EM structure of proton



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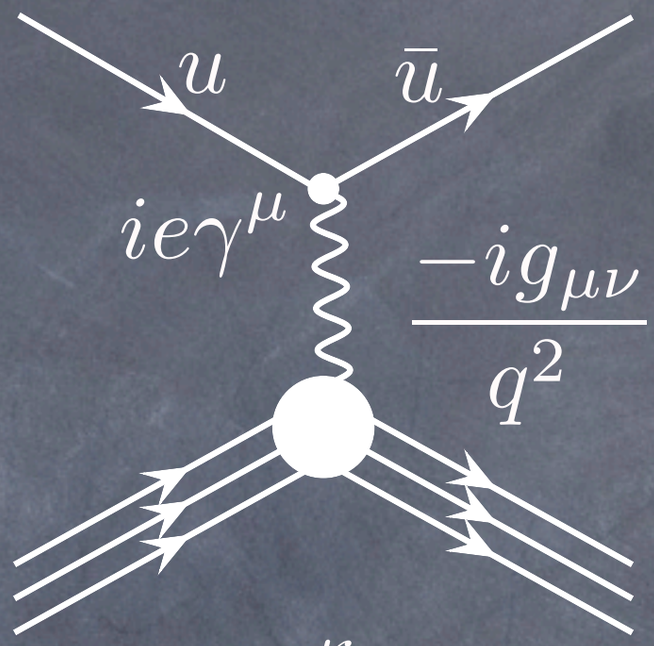
Sachs form factor $\begin{cases} G_E \equiv F_1 + \dfrac{\kappa q^2}{4M^2}F_2 \\ G_M \equiv F_1 + \kappa F_2 \end{cases}$

§3: EM structure of proton



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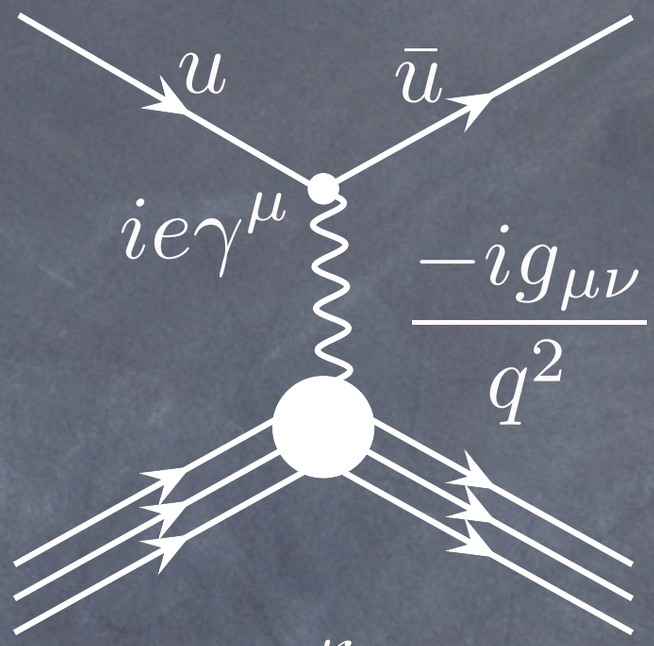
When $q^2=0$, G_E and G_M are proton charge and magnetic moment, respectively.

§3: EM structure of proton



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Rosenbluth formula:

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp.} = \left(\frac{\alpha^2}{4E^2 sin^4\frac{\theta}{2}}\right)\frac{E'}{E}\left(\frac{G_E^2+\tau G_M^2}{1+\tau}cos^2\frac{\theta}{2} + 2\tau G_M^2 sin^2\frac{\theta}{2}\right), \tau = \frac{q^2}{4M^2}$$

§3: EM structure of proton

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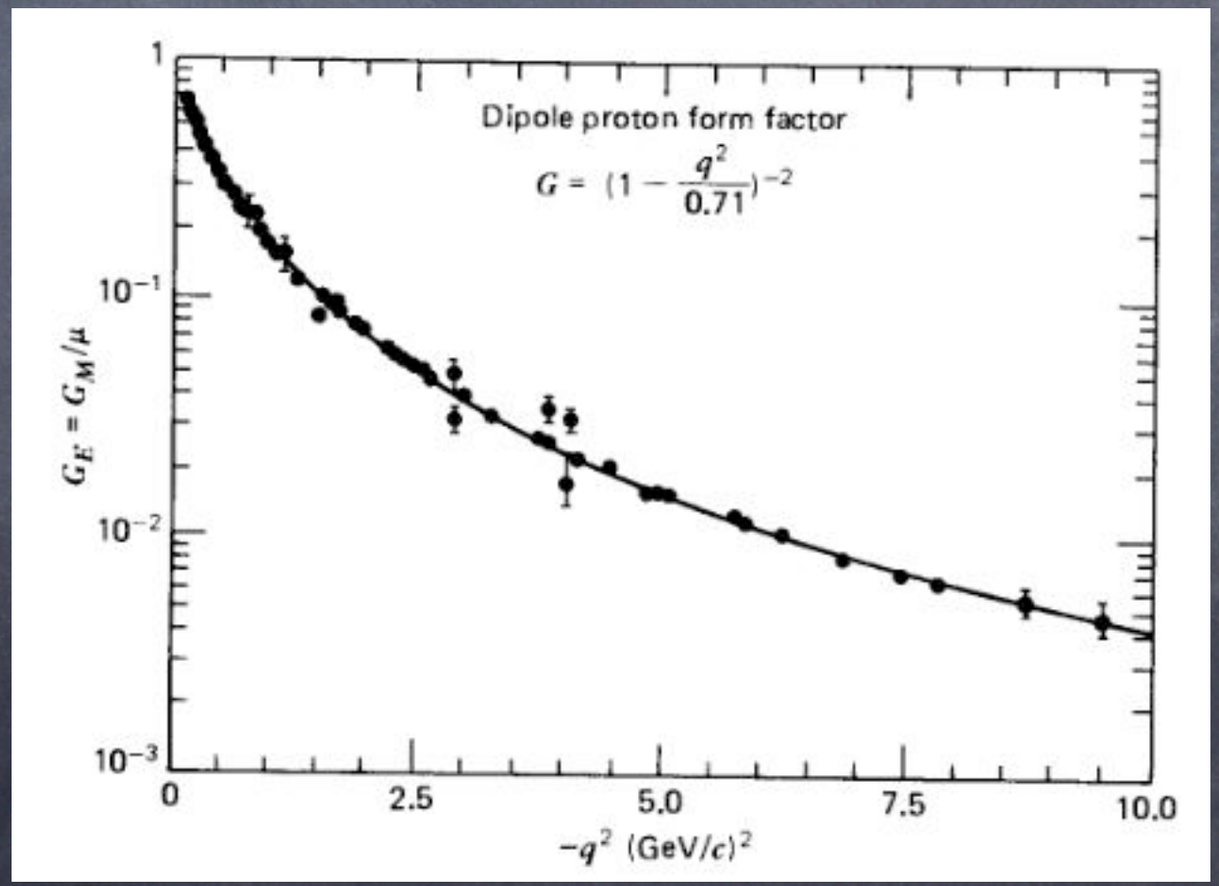

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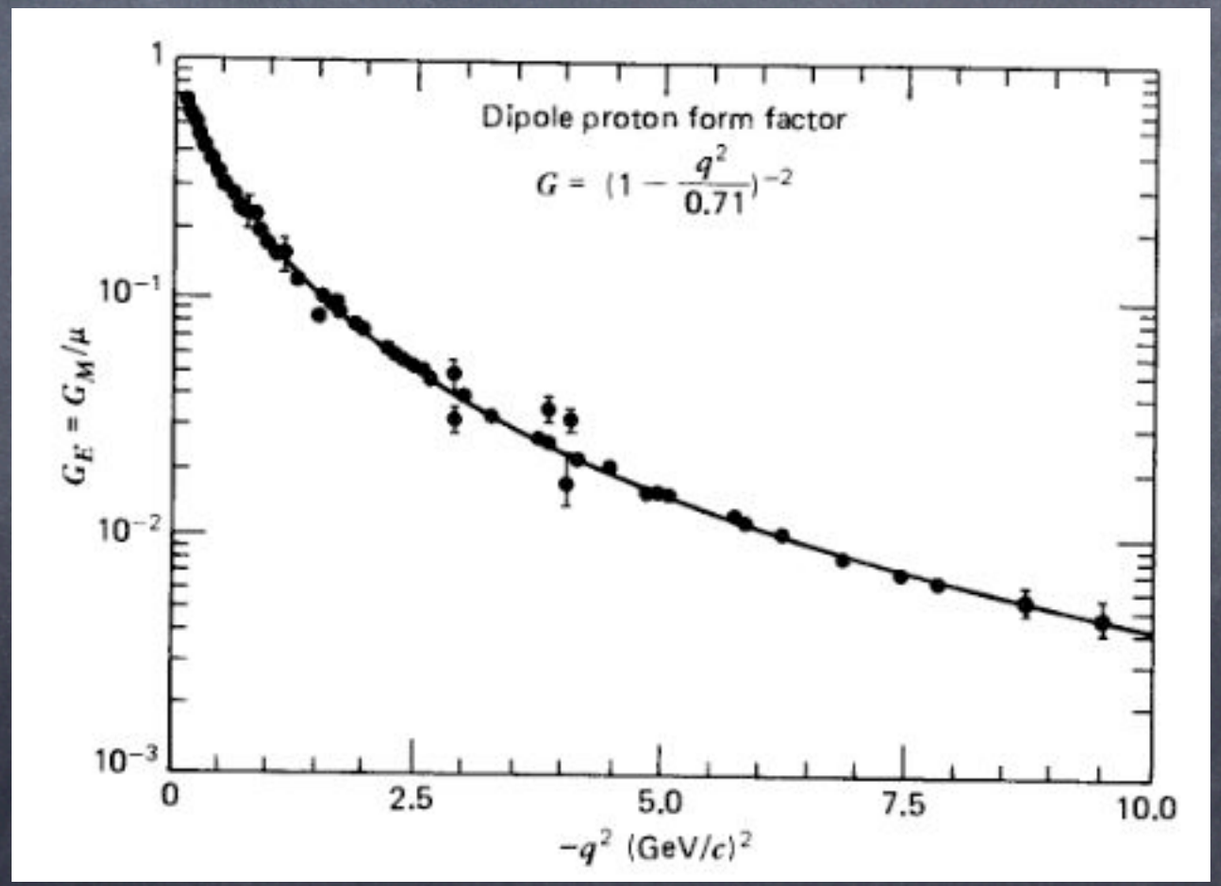
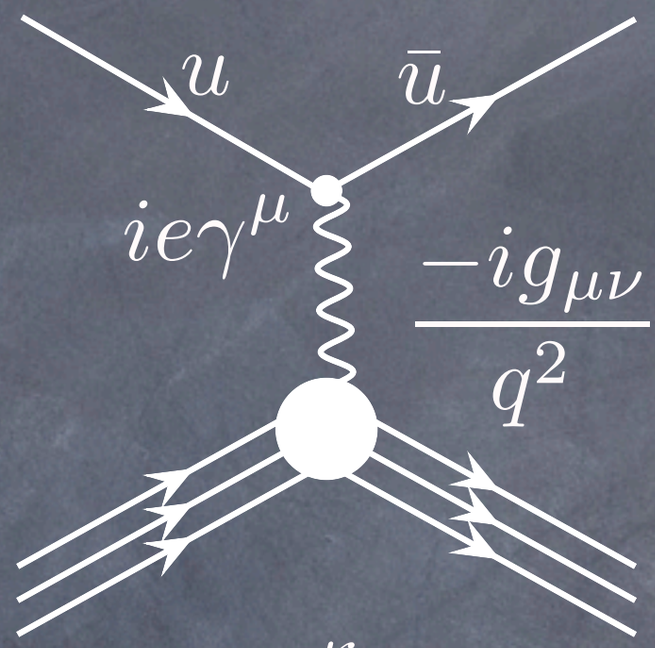


Exponential distribution of proton charge (0.8 fm)!

§3: EM structure of proton



$$ie[F_1(q^2)\gamma^\mu + \frac{\kappa}{2M}F_2(q^2)i\sigma^{\mu\nu}q_\nu]$$

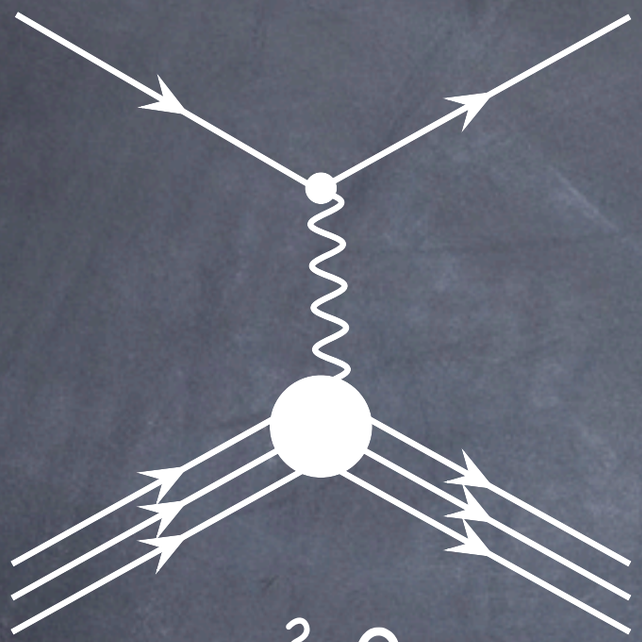
elastic ep scattering;

space-like region ($q^2<0$);

spacial distribution of proton charge

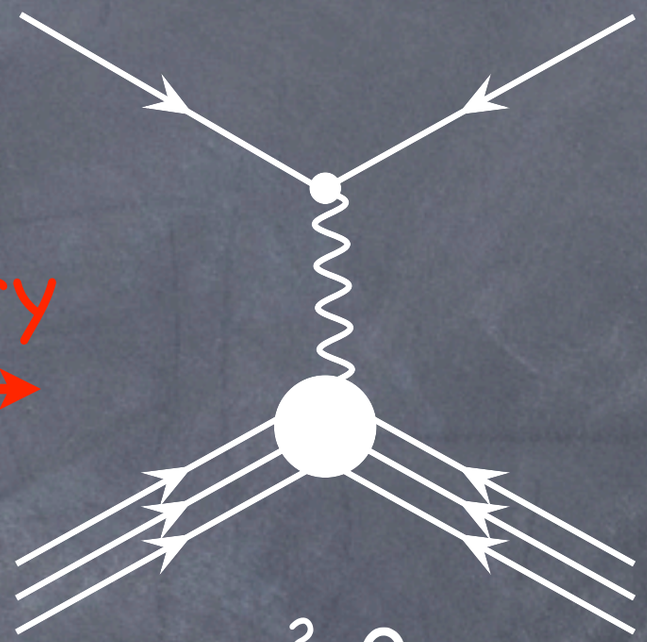
What about time-like region ($q^2>0$)?

§3: EM structure of proton



$q^2<0$

crossing symmetry



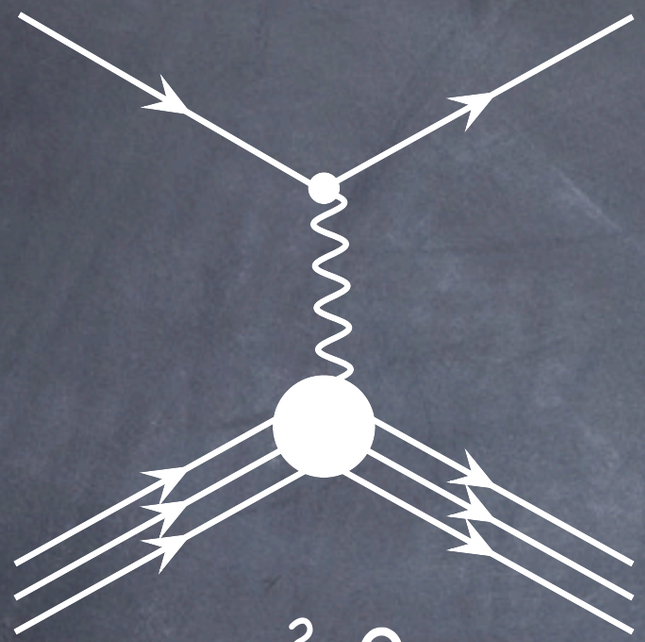
$q^2>0$

electron-positron collider or proton anti-proton annihilation; time-like region ($q^2>0$): dynamics

By summing up all possible spin states and taking care of phase space:

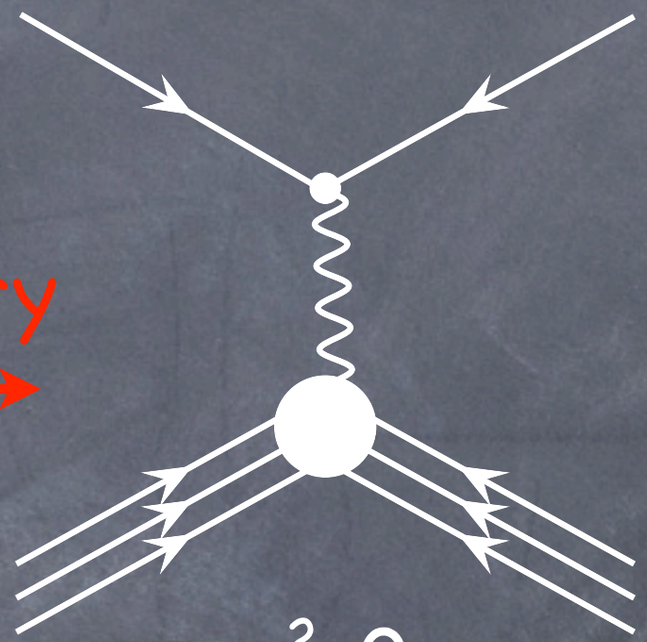
$$\frac{d\sigma}{dcos\theta} = \frac{\pi\alpha^2}{8M^2\sqrt{\tau(\tau-1)}}\left[|G_M|^2\left(1+cos^2\theta\right)+\frac{|G_E|^2}{\tau}(1-cos^2\theta)\right], \tau = \frac{q^2}{4M^2}$$

§3: EM structure of proton



$q^2<0$

crossing symmetry



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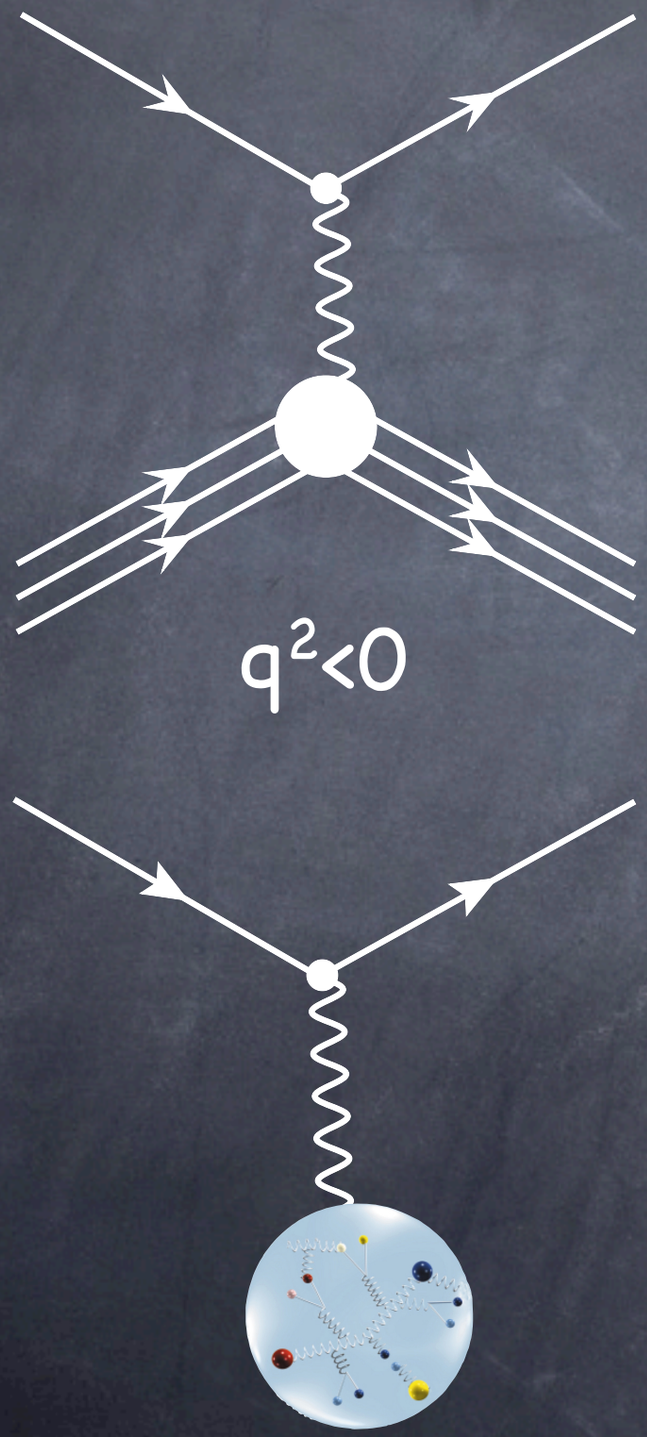
§3: EM structure of proton



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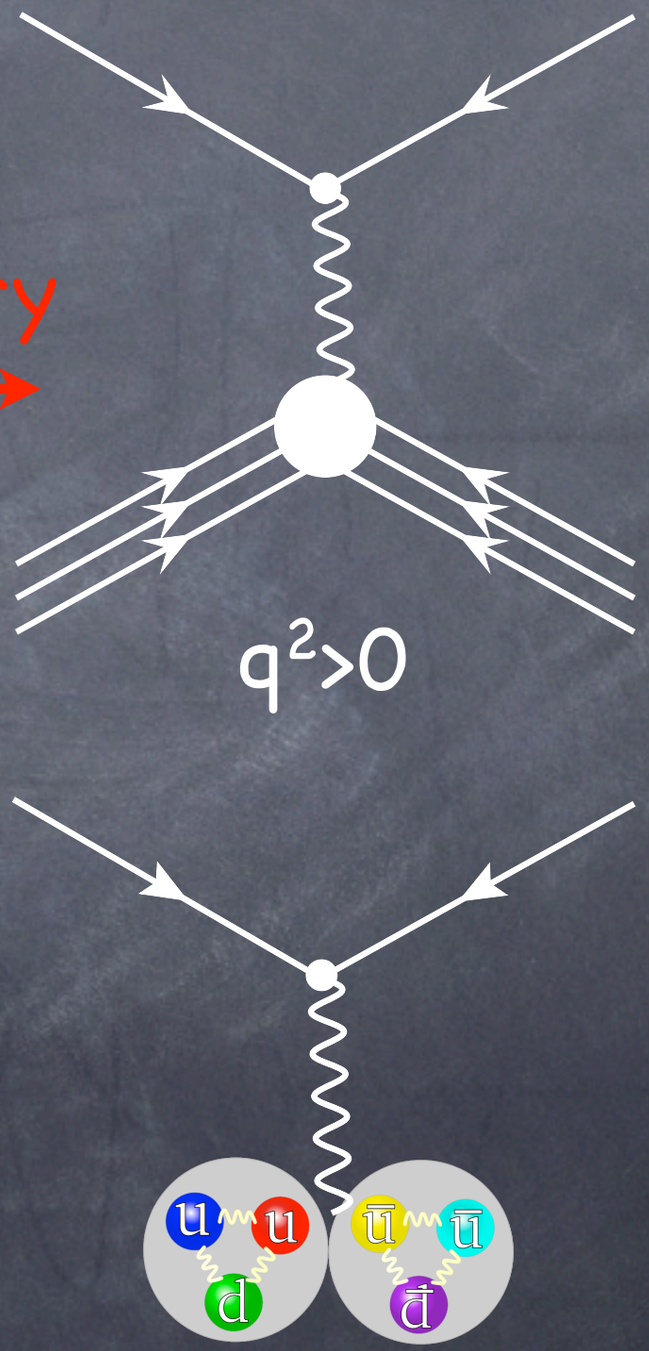


$q^2>0$

§3: EM structure of proton

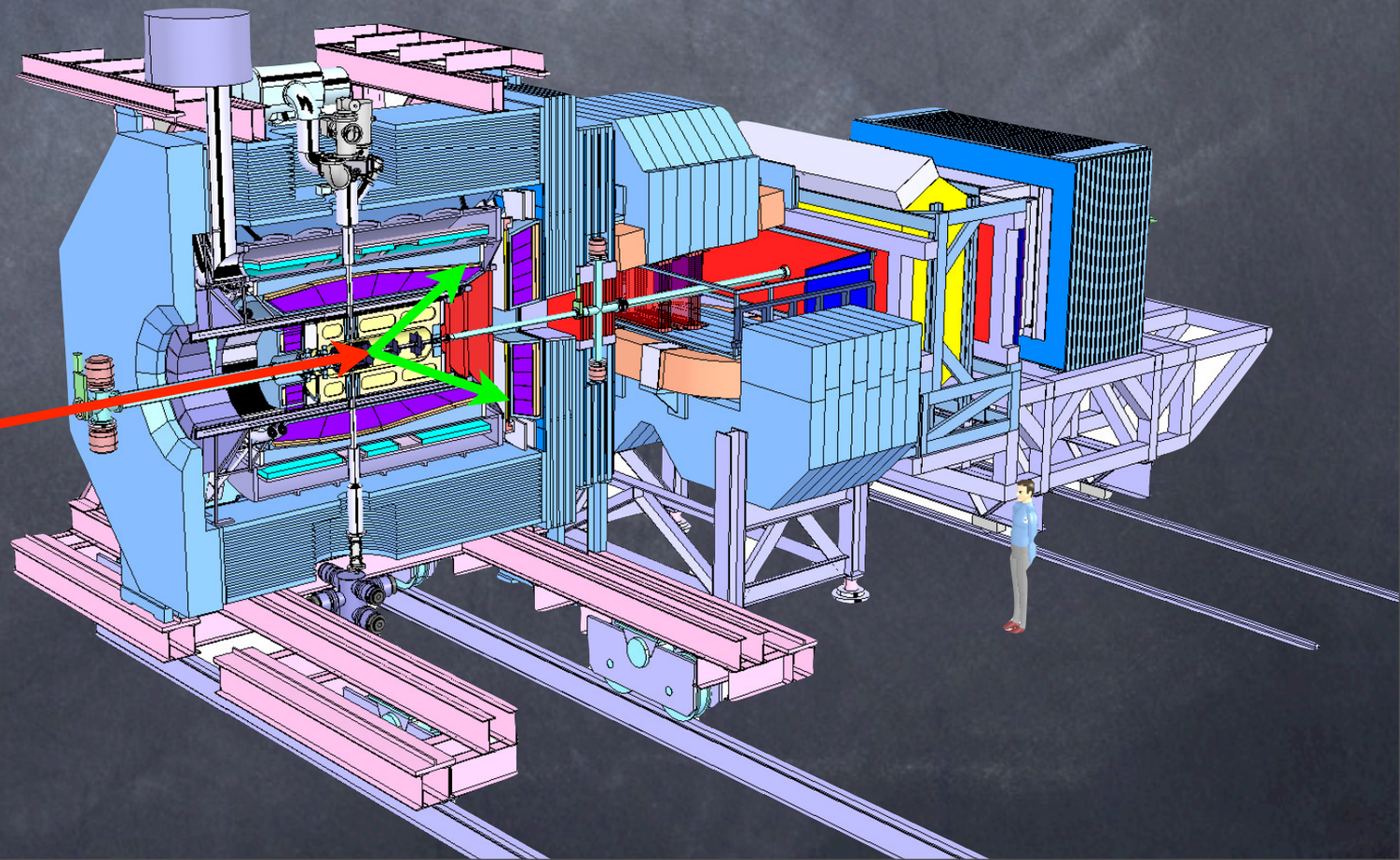
PANDA:

proton anti-proton annihilate into electro positron,

time-like region ($q^2>0$)

$$\frac{d\sigma}{dcos\theta} = \frac{\pi\alpha^2}{8M^2\sqrt{\tau(\tau-1)}}\left[|G_M|^2\left(1+cos^2\theta\right)+\frac{|G_E|^2}{\tau}(1-cos^2\theta)\right], \tau = \frac{q^2}{4M^2}$$

$$\bar{p}+p \rightarrow e^+ + e^-$$



§3: EM structure of proton

Wait a second! what's PANDA?

§3: EM structure of proton

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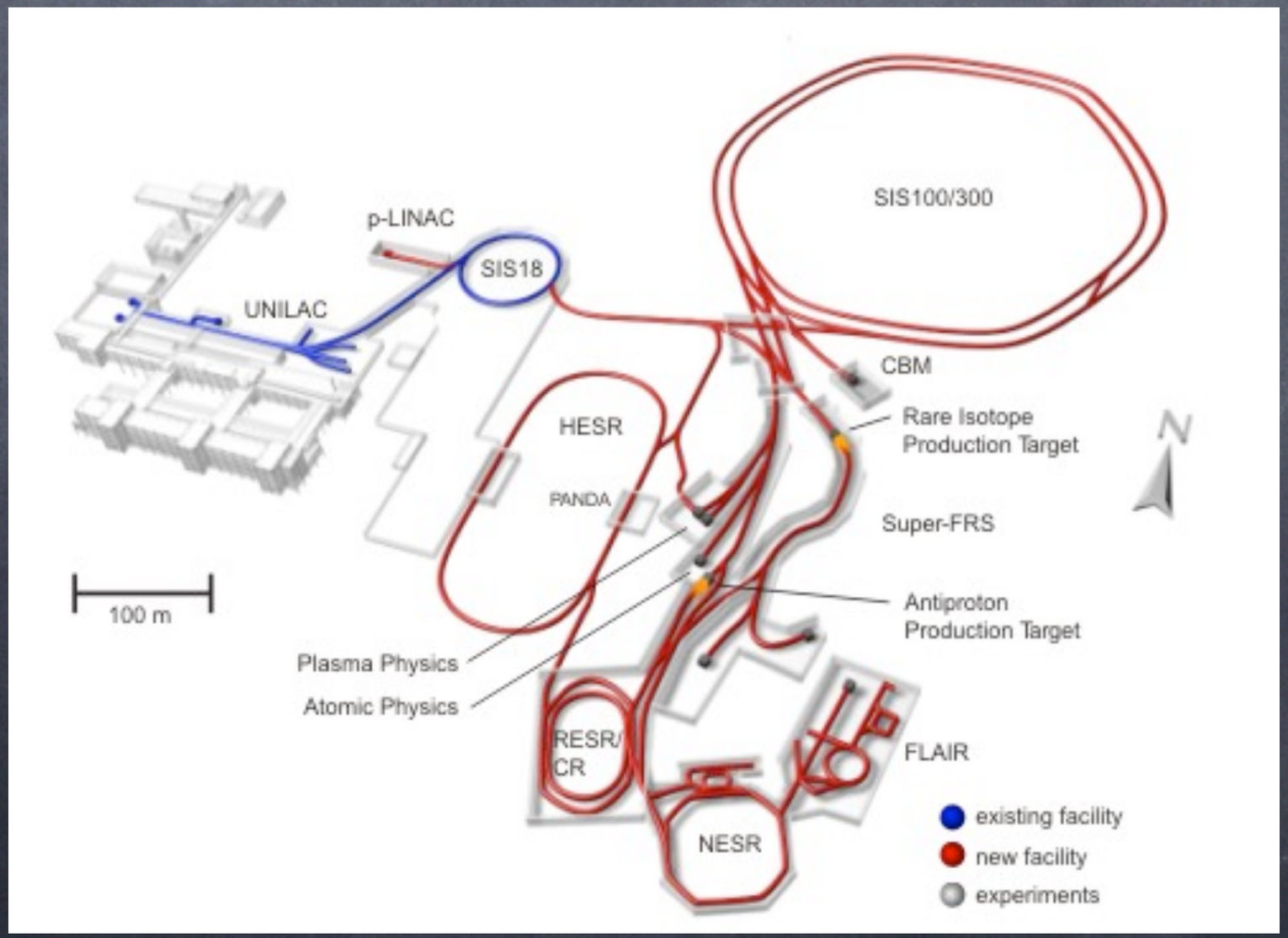
Anti-proton annihilation at Darmstadt

§3: EM structure of proton

Wait a second! what's PANDA?

Anti-proton annihilation at Darmstadt



§3: EM structure of proton

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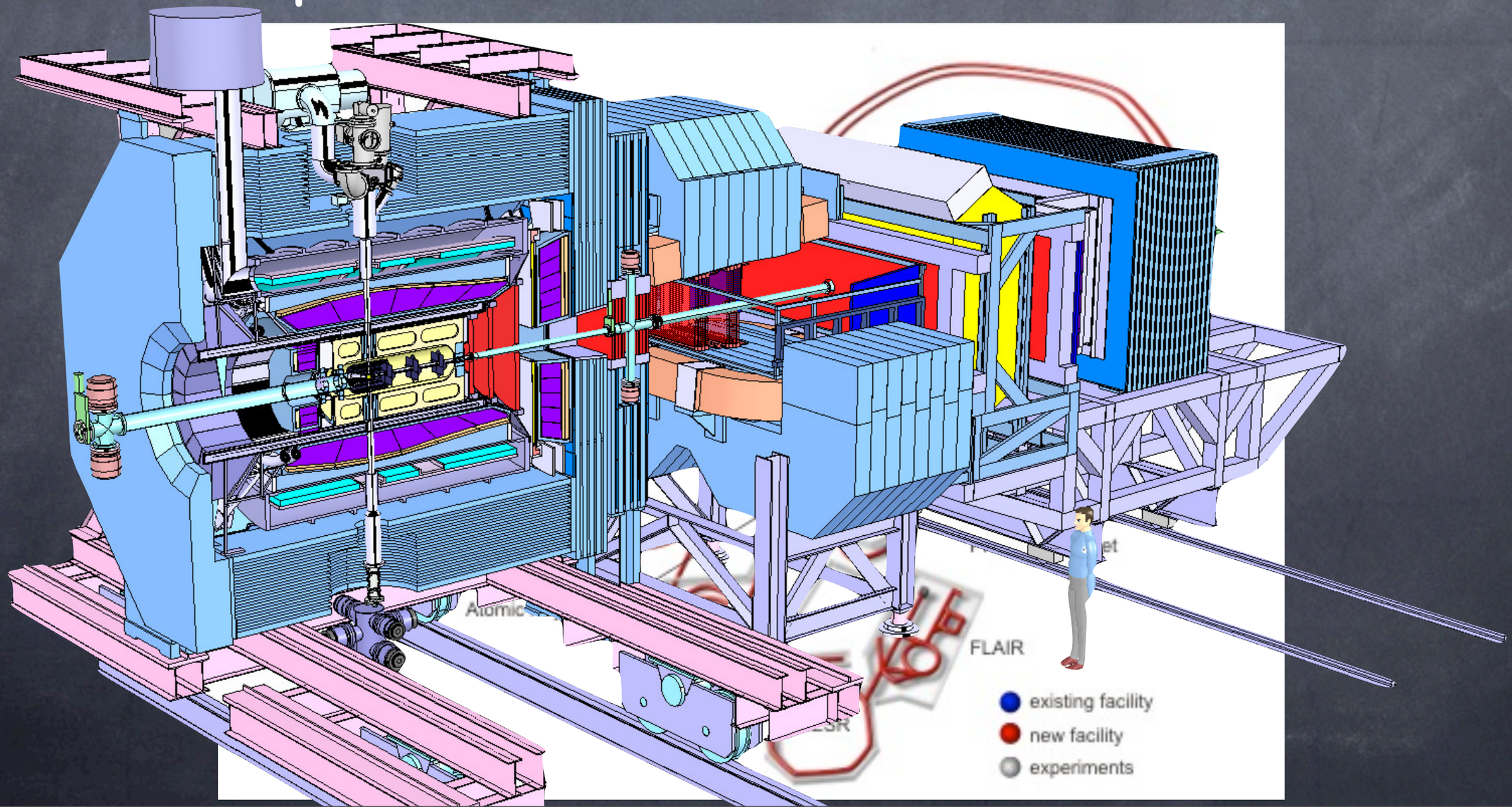
Anti-proton annihilation at Darmstadt



§3: EM structure of proton

Measure this reaction at PANDA???

$$\bar{p} + p \rightarrow e^+ + e^-$$

§3: EM structure of proton

Measure this reaction at PANDA???

$$\bar{p} + p \rightarrow e^+ + e^-$$

Measurement: How to determine what did you get?

§3: EM structure of proton

Measure this reaction at PANDA???

$$\bar{p} + p \rightarrow e^+ + e^-$$

Measurement: How to determine what did you get?

PID: particle identification (mass, charge, life time, ...)

§3: EM structure of proton

Measure this reaction at PANDA???

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PID: particle identification (mass, charge, life time, ...)

That's all!

§3: EM structure of proton

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§3: EM structure of proton

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§3: EM structure of proton

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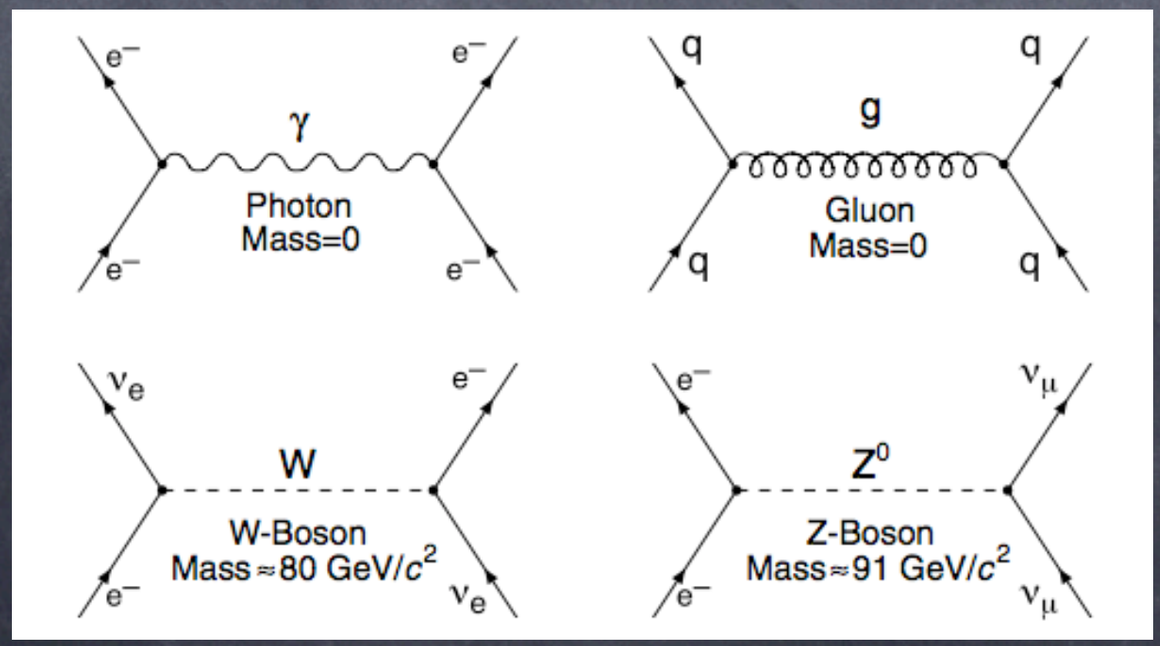

§3: EM structure of proton

No, because there are other interactions compete with this reaction channel.

$$\bar{p} + p \rightarrow \pi^+ + \pi^-$$

10^6 times more yields than

$$\bar{p} + p \rightarrow e^+ + e^-$$

Need to pick up the one that you want from one million!

§3: EM structure of proton

Thanks to the excellent tracking capability of PANDA spectrometer, which makes it possible.

From simulation: event generator, particle propagation, detector response, tracking, particle identification...

§3: EM structure of proton

Monte-Carlo method implemented in C++.
GEANT4, ROOT from CERN
PANDARoot from GSI

Geant 4

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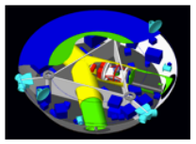
Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. The two main reference papers for Geant4 are published in *Nuclear Instruments and Methods in Physics Research* A 506 (2003) 250-303, and *IEEE Transactions on Nuclear Science* 53 No. 1 (2006) 270-278.

Applications

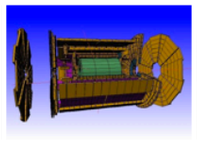
A sampling of applications, technology transfer and other uses of Geant4

User Support



Getting started, guides and information for users and developers

Results & Publications



Validation of Geant4, results from experiments and publications

Collaboration

Who we are: collaborating institutions, members, organization and legal information

News

- *25 June 2010* - **Release 9.4 BETA** is available from the Beta download area.
- *22 April 2010* - **Patch-01** to **release 9.3** is available from the download area.
- *16 March 2010* - 2010 planned developments.
- *19 February 2010* - **Patch-03** to **release 9.2** is available from the archive download area.

Events

- 7th Geant4 Space Users' Workshop, Seattle (USA), **18-20 August 2010**.
- Geant4 Technical Forum, CERN, Geneva (Switzerland), **2 September, 2010**.
- 3rd Monte Carlo Conference, MC2010, Hitotsubashi Memorial Hall, Tokyo (Japan), **17-20 October 2010**.
- 15thGeant4 Collaboration Workshop at ESA/ESTEC, Noordwijk, The Netherlands, **4-8 October, 2010**

- **Past events**

Applications | User Support | Results & Publications | Collaboration | Site Map

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Last updated: 03 Aug 2010

ROOT

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Screenshots

Get a taste of ROOT's capabilities by sampling some screenshots.

Download

Go ahead and download the latest build of ROOT.

Documentation

Get the inside scoop on how to fully utilize ROOT. Also, search the Reference Guide, the HowTo's and the user forums.

What's New

- March 31, 2010, 15:34 Patch release 5.22/00i
- January 22, 2010, 17:44 Patch release 5.22/00g
- January 20, 2010, 12:14 Patch release 5.26/00a
- December 15, 2009, 10:21 Production release 5.26/00

Recent blog posts

- New server and code poetry
- C++ 0x draft published

Patch release 5.26/00c

patch release

The patch release of ROOT 5.26/00c is now available.

The SVN tag for this version is **v5-26-00c**.

For what is fixed in this patch release see the patch release notes.

Read more

Development release 5.27/04

development release

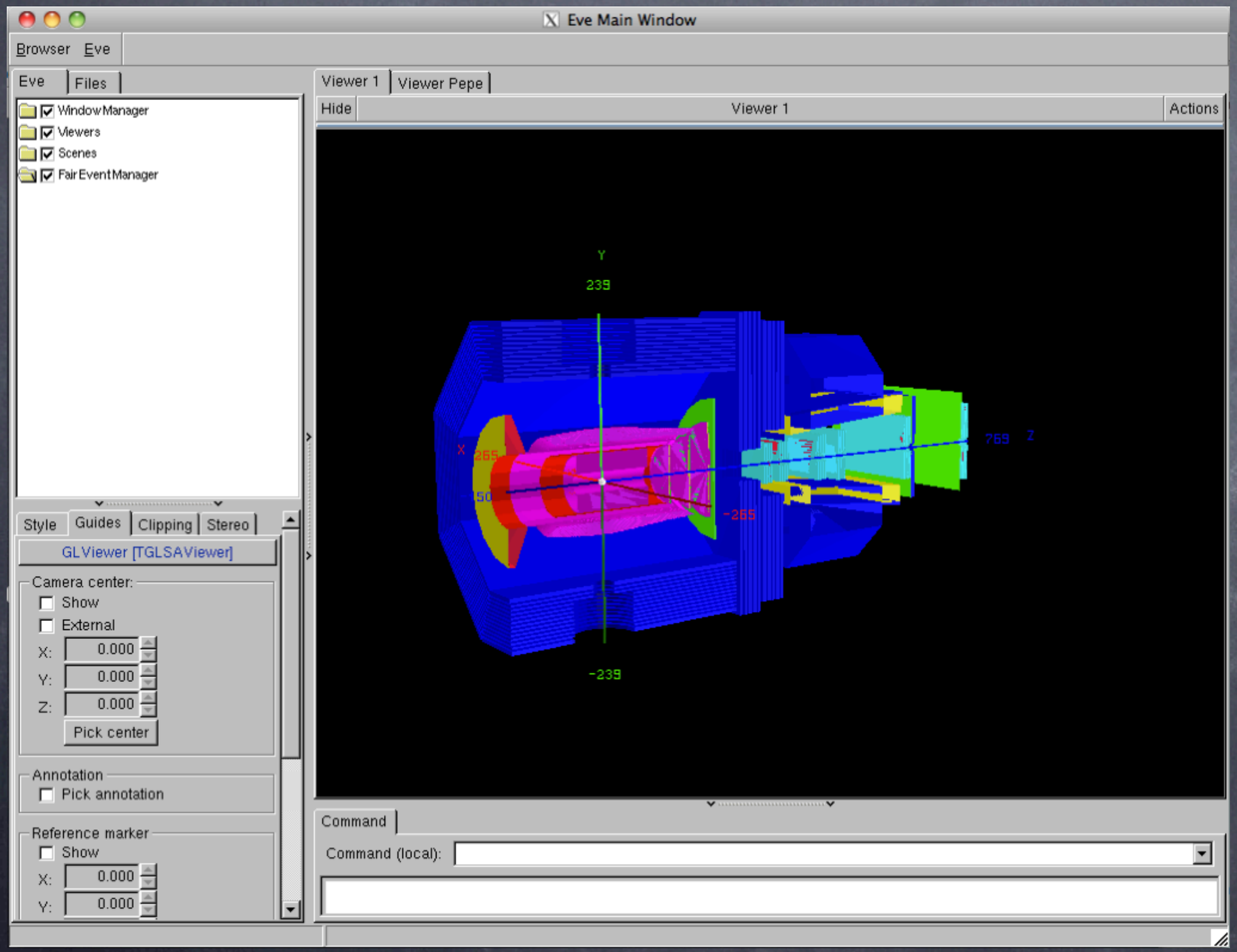
The development release of ROOT 5.27/04 is now available.

The SVN tag for this version is **v5-27-04**.

See the release notes for what is new in the version 5.27/04 development release.

Read more

§3: EM structure of proton



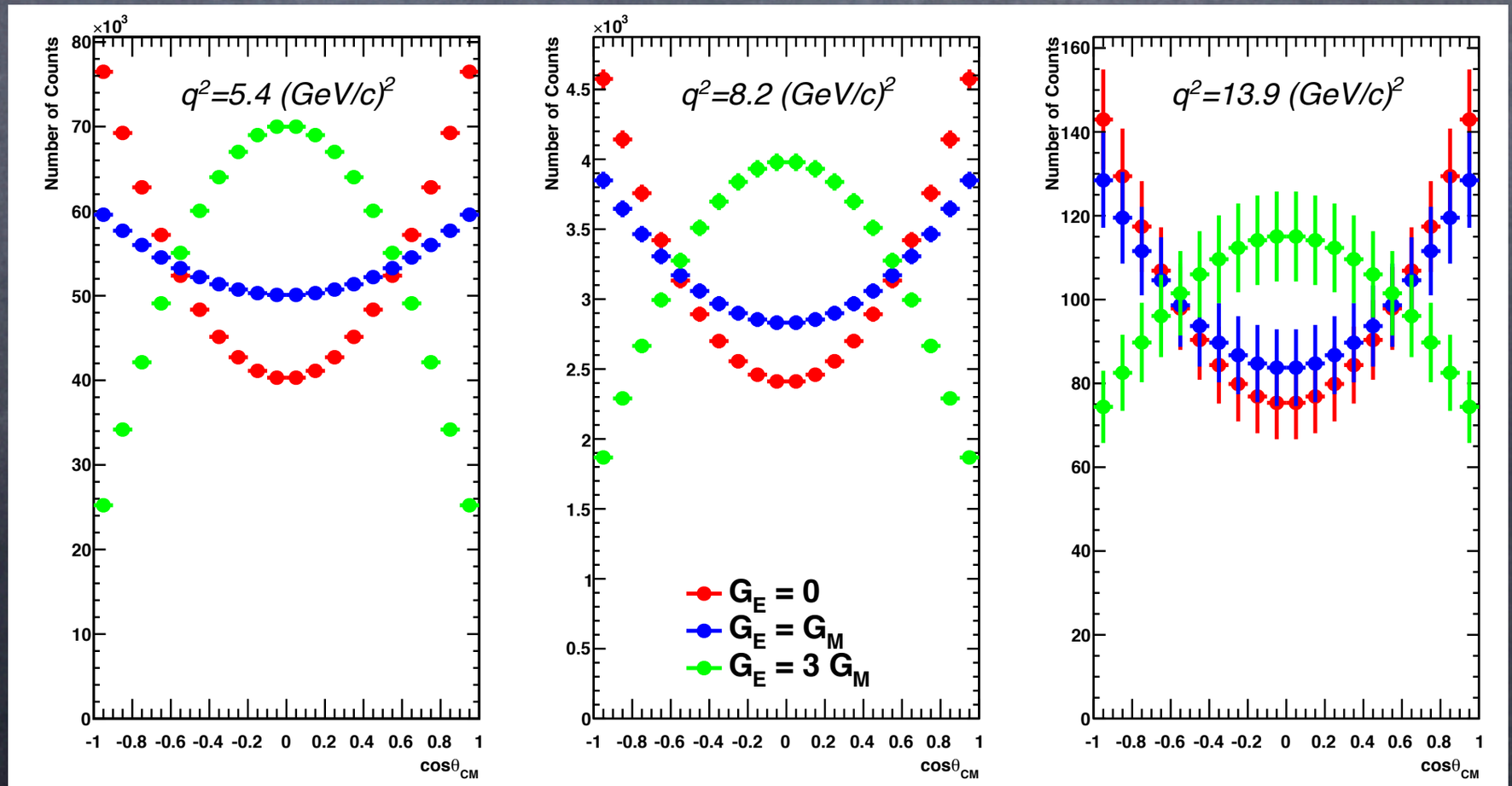
Everything is in "computer space".

§3: EM structure of proton

A taste of how does it work:

$$\frac{d\sigma}{dcos\theta} = \frac{\pi\alpha^2}{8M^2\sqrt{\tau(\tau-1)}}\left[|G_M|^2\left(1+cos^2\theta\right)+\frac{|G_E|^2}{\tau}(1-cos^2\theta)\right], \tau = \frac{q^2}{4M^2}$$

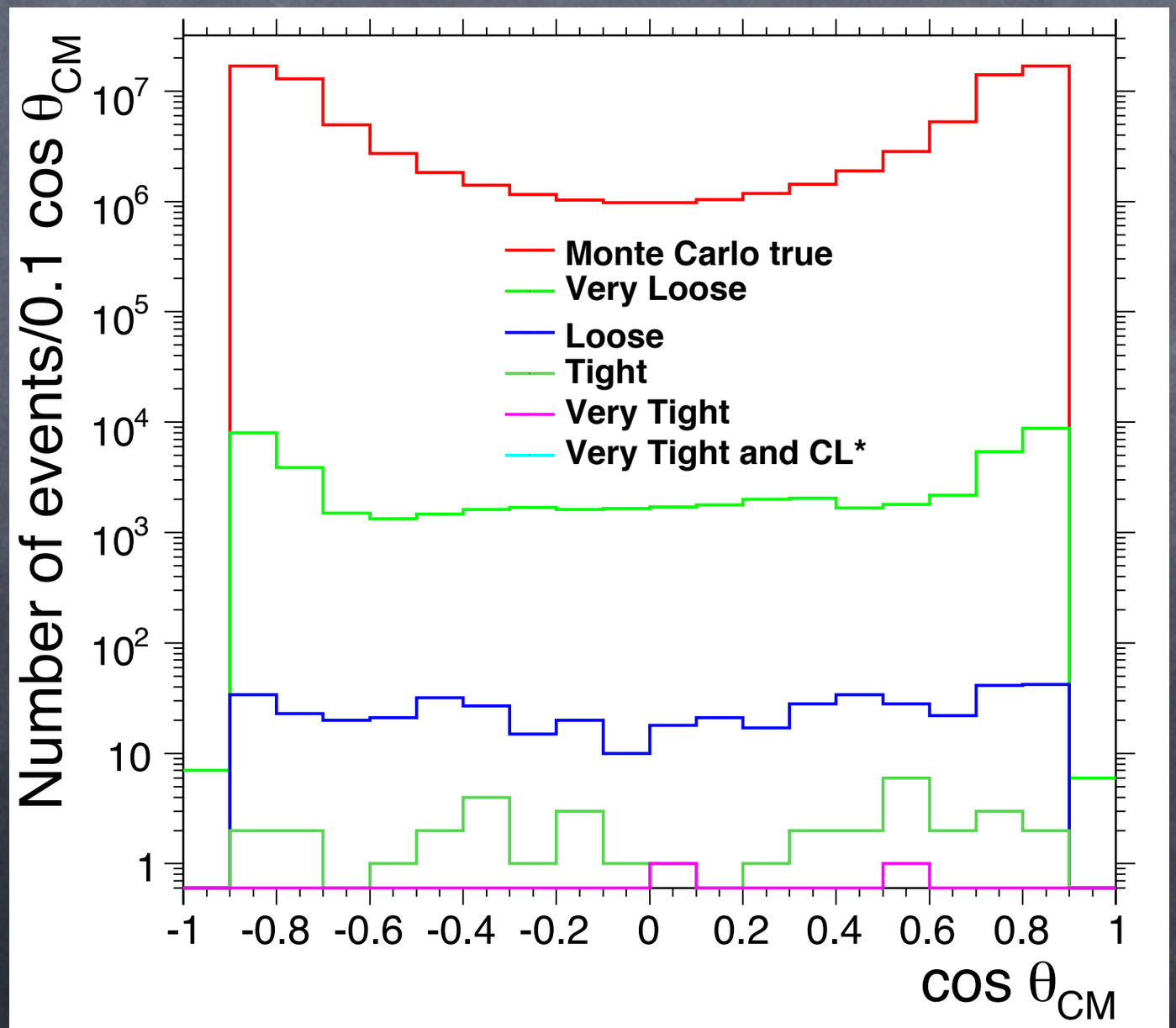
Event generation



§3: EM structure of proton

A taste of how does it work:

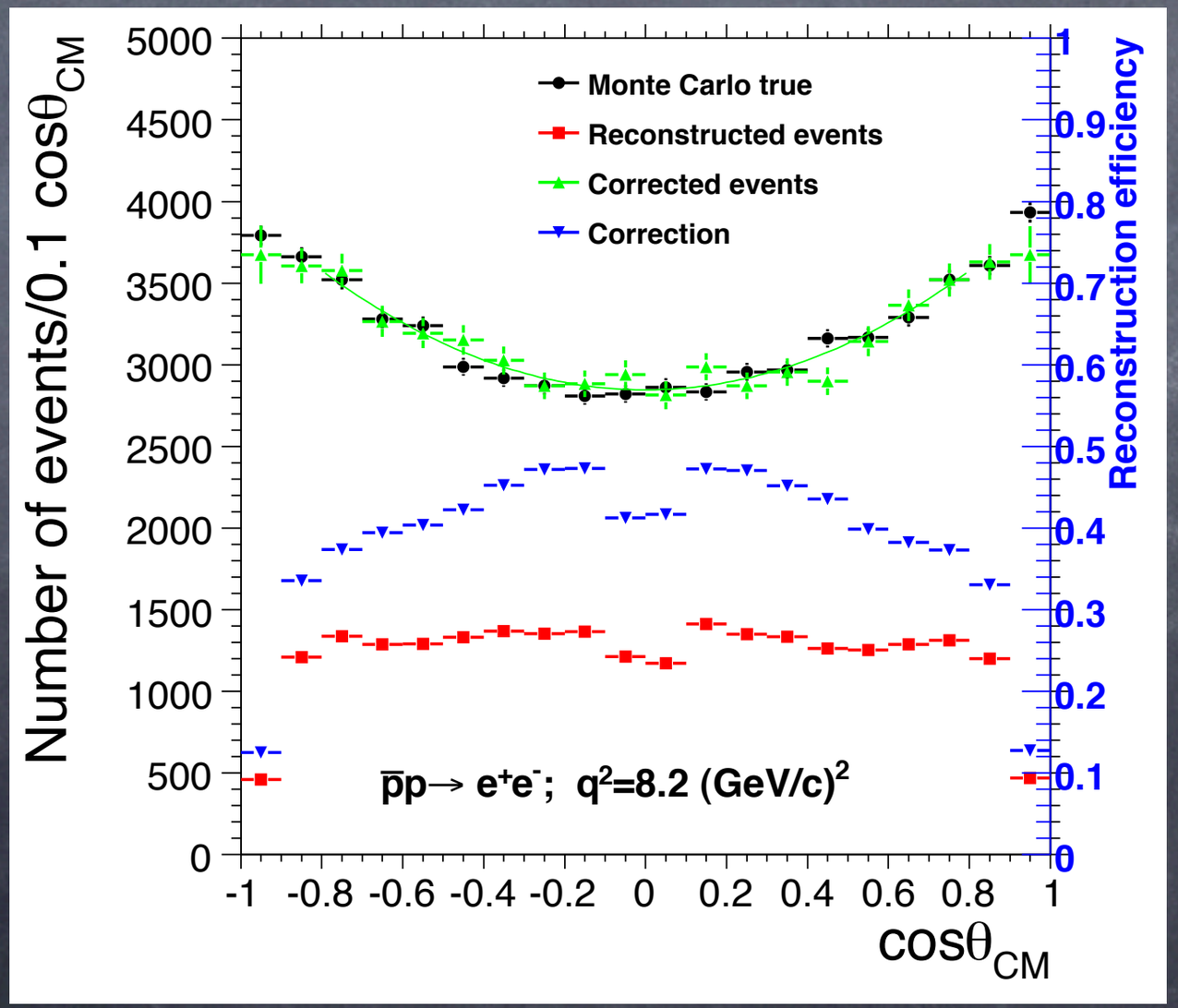
Background generation & suppression



§3: EM structure of proton

A taste of how does it work:

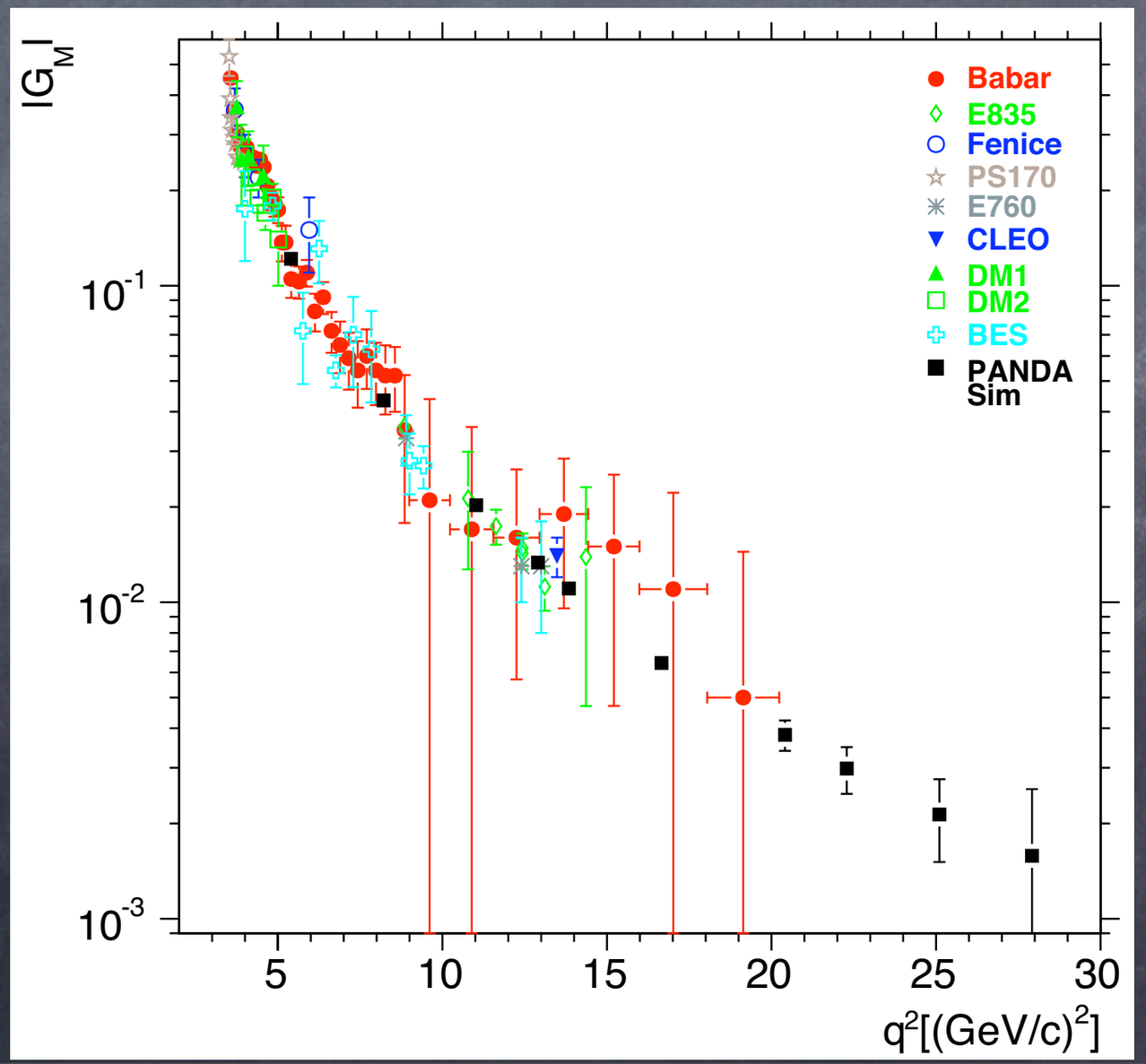
Event reconstruction



§3: EM structure of proton

A taste of how does it work:

Expected results from PANDA



§4: Summary

- Introduction to Feynman diagram.
- GSI (PANDA) will play an important role in the study of hadron physics.
- Hadron physics needs young talents to contribute (hardware, software, physics...).

§4: References

- Book list for further reading:
  - Quarks and Leptons, by F. Halzen, A. Martin
  - Particles and nuclei, by B. Povh
  - Quantum field theory, by M. Srednicki

- Thanks for your attention!
- Hope to see you at GSI even after this summer!