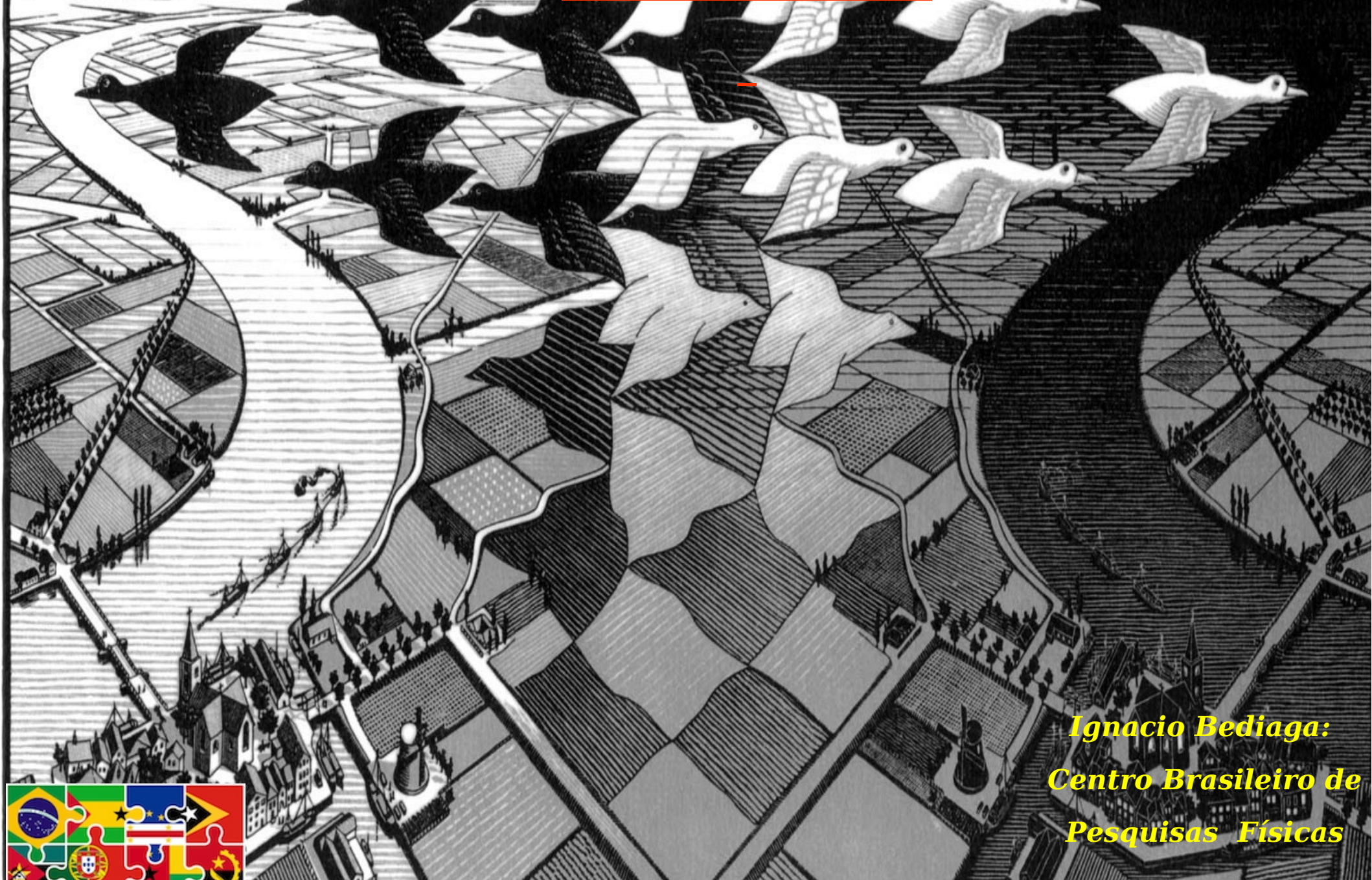




LHCb e a Assimetria Matéria-Antimatéria



*Ignacio Bediaga:
Centro Brasileiro de
Pesquisas Físicas*



“Twentieth first-Century Clouds over the electroweak theory”



“A beleza e a clareza da teoria electrofraca está obscurecida por algumas núvens”

As núvens do Pedro:

- Matéria escura e energia escura

- Porque existe mais matéria que anti-matéria no Universo?
- Porquê 3 famílias?;
- Problema da Hierarquia;
- Porque é que as massas das partículas elementares são o que são;
- Porque é que os neutrinos são muito mais leves do que os leptões carregados e os quarks;
- Será que as 3 (ou 4) forças se unificam a alguma escala?;
- Será que as partículas elementares são mesmo elementares?;



LHCb e a Assimetria Matéria-Antimatéria



Ignacio Bediaga:
Centro Brasileiro de
Pesquisas Físicas

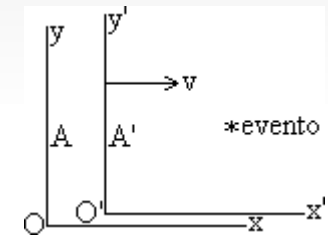
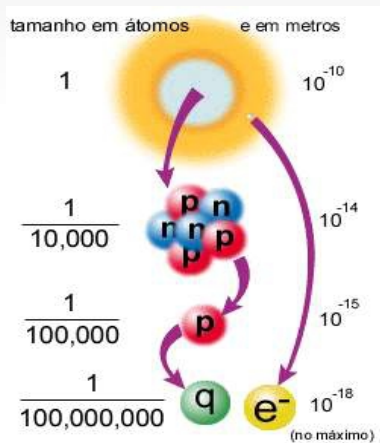


Questões gerais sobre antipartículas e as
Interações fundamentais

Gedankenexperiment Equação de Dirac (1928)

**Erwin Schrodinger e
Werner Heisenberg:
Mecânica Quântica.**

**Einstein:
Relatividade**

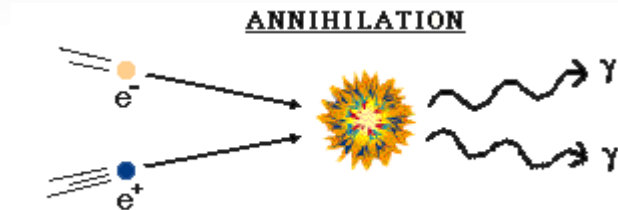
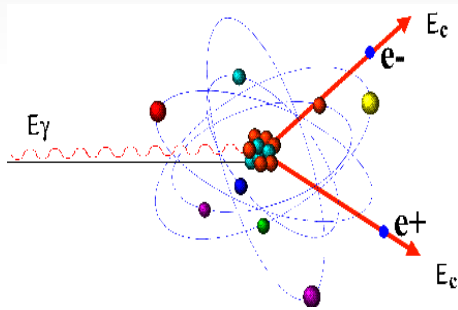


**Equação de Dirac para um
elétron relativístico**

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

Pósitron ou anti-elétron

1932 - Descoberta do pósitron ou anti-elétron, mesma massa do elétron, mas com carga positiva.



1955 - Descoberta do anti-próton, mesma massa do próton, mas com carga negativa.

Anti-Matéria

Para cada partícula de matéria temos outra de anti-matéria

Quarks	u up	c charm	t top
	d down	s strange	b bottom
	ν_e e- Neutrino	ν_μ μ - Neutrino	ν_τ τ - Neutrino
Leptons	e electron	μ muon	τ tau
			I II III
			The Generations of Matter



Quarks		Anti-quarks	
u up	d down	\bar{u}	\bar{d}
t top	b bottom	\bar{t}	\bar{b}
s strange	c charm	\bar{s}	\bar{c}
Leptons		Anti-leptons	
e electron	ν_e electron neutrino	e^+	$\bar{\nu}_e$
μ muon	ν_μ muon neutrino	$\bar{\mu}$	$\bar{\nu}_\mu$
τ tau	ν_τ tau neutrino	$\bar{\tau}$	$\bar{\nu}_\tau$

Anti-Matéria

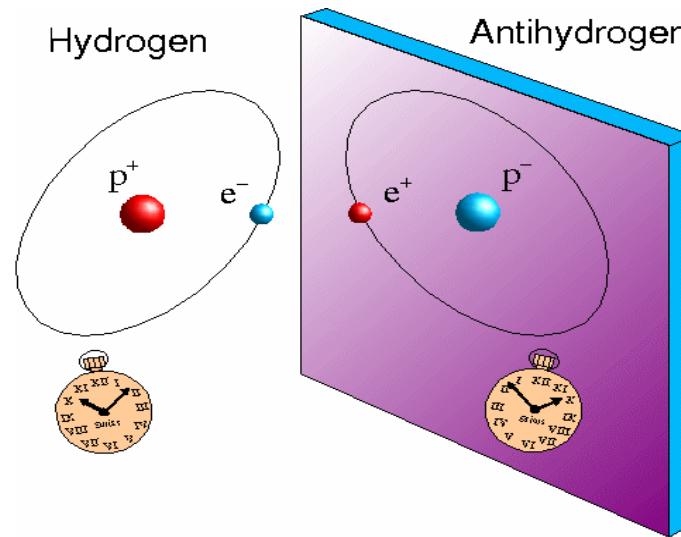
Para cada partícula de matéria temos outra de anti-matéria

Leptons	Quarks		
	u up	c charm	t top
	d down	s strange	b bottom
Leptons	ν_e e- Neutrino	ν_μ μ - Neutrino	ν_τ τ - Neutrino
	e electron	μ muon	τ tau
	I	II	III
The Generations of Matter			



Quarks		Anti-quarks	
u up	d down	\bar{u} \bar{u}	\bar{d} \bar{d}
t top	b bottom	\bar{t} \bar{t}	\bar{b} \bar{b}
s strange	c charm	\bar{s} \bar{s}	\bar{c} \bar{c}
Leptons		Anti-leptons	
e electron	ν_e electron neutrino	e^+ e^+	$\bar{\nu}_e$ $\bar{\nu}_e$
μ muon	ν_μ muon neutrino	$\bar{\mu}$ $\bar{\mu}$	$\bar{\nu}_\mu$ $\bar{\nu}_\mu$
τ tau	ν_τ tau neutrino	$\bar{\tau}$ $\bar{\tau}$	$\bar{\nu}_\tau$ $\bar{\nu}_\tau$

Átomo de anti-hidrogênio



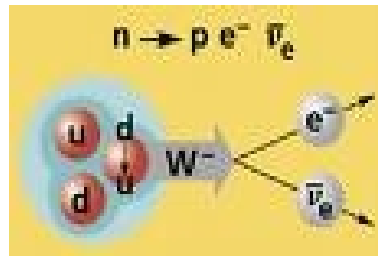
As Forças da Natureza

*Existem quatro forcas
fundamentais na
Natureza*

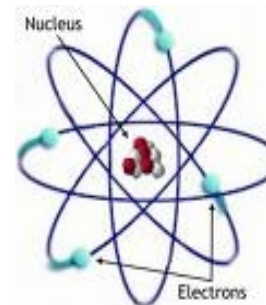
Gravitacional



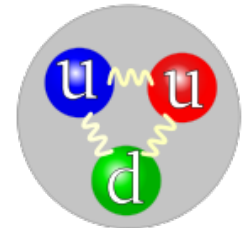
Fraca



Eletromagnética

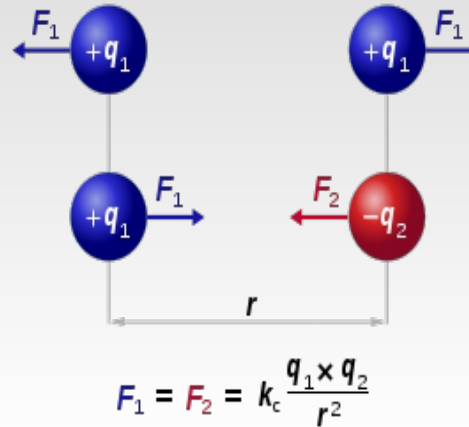


Forte



Ação de forças a distância

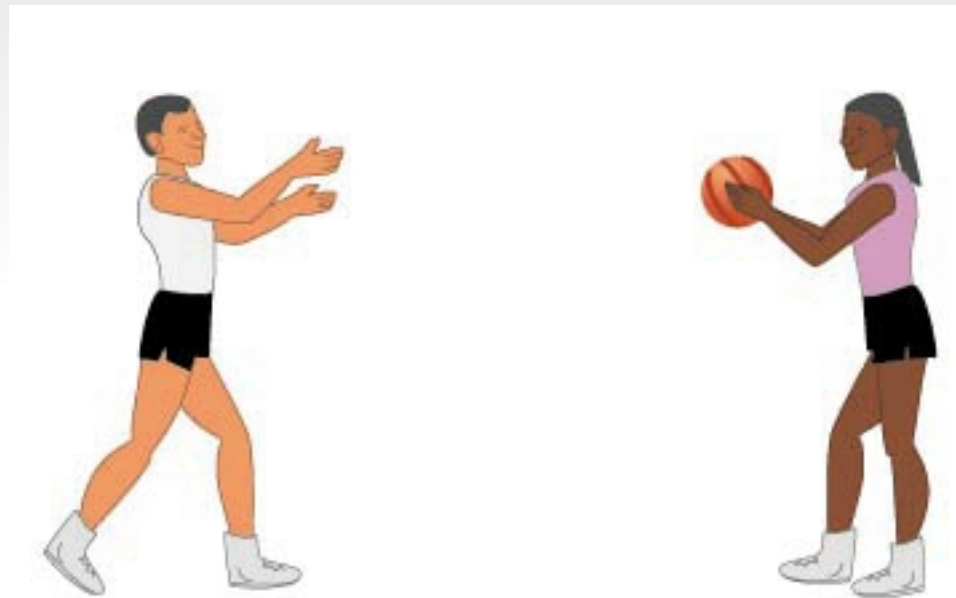
Lei de Coulomb:



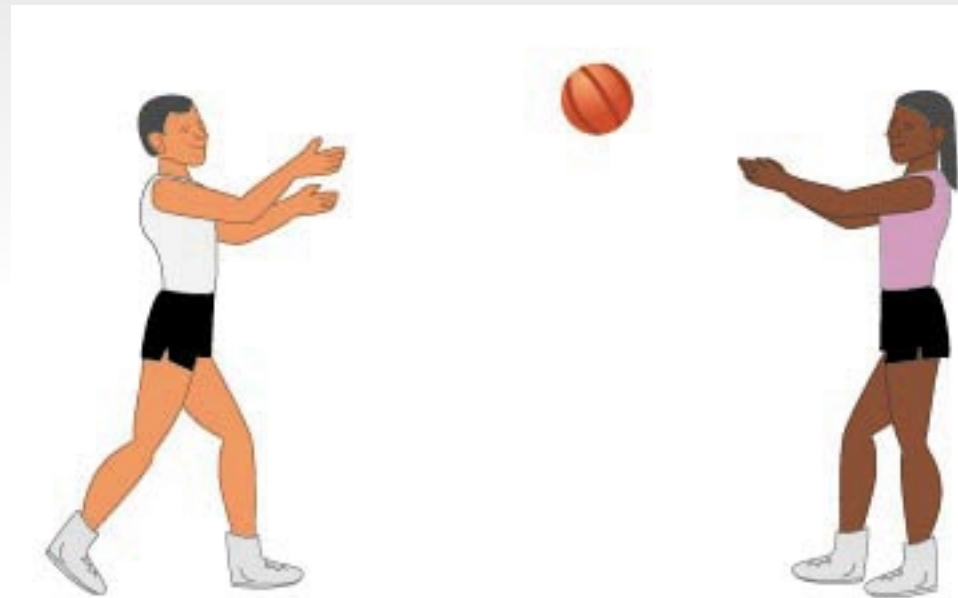
*Atração e repulsão
entre dois ímãs*

Como se transmite a força?

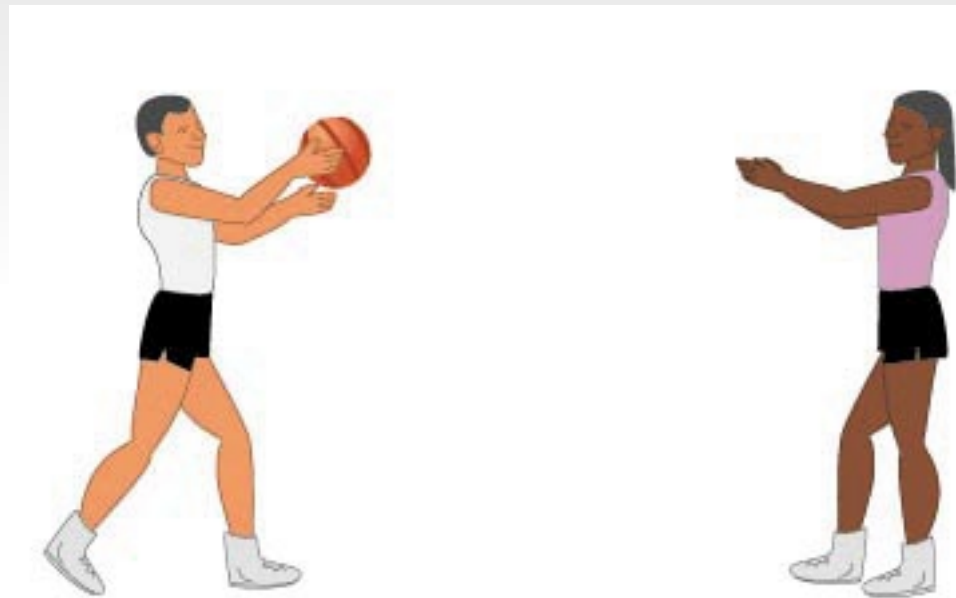
Como se transmitem as forças?



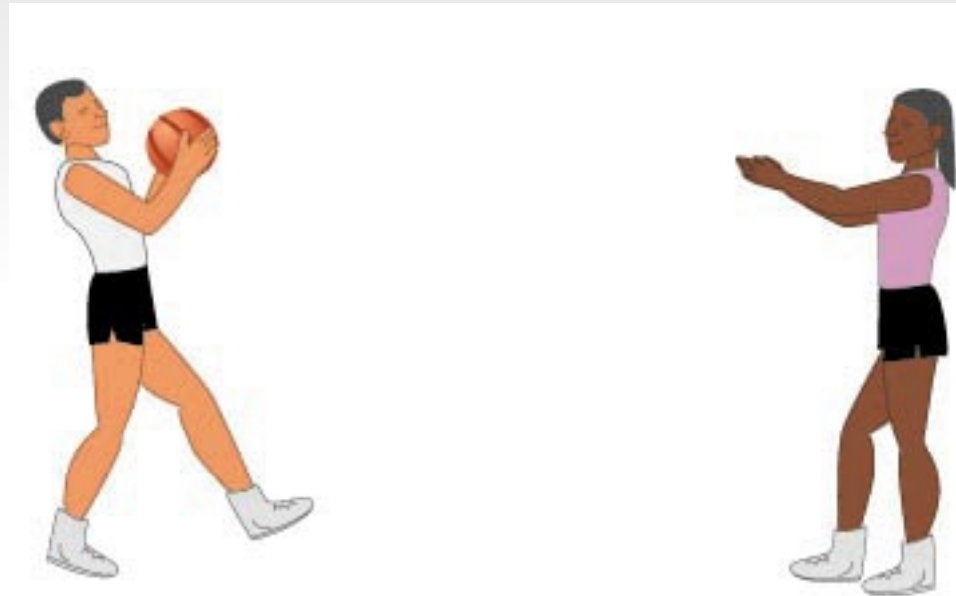
Como se transmitem as forças?



Como se transmitem as forças?

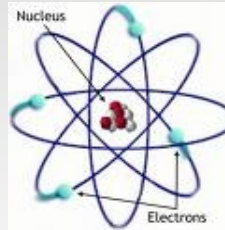


Como se transmitem as forças?



As força se transmitem através da troca de partículas.
Que partículas?

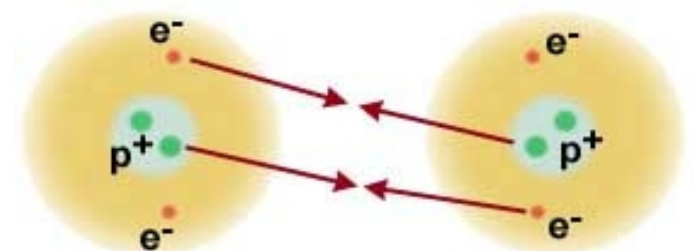
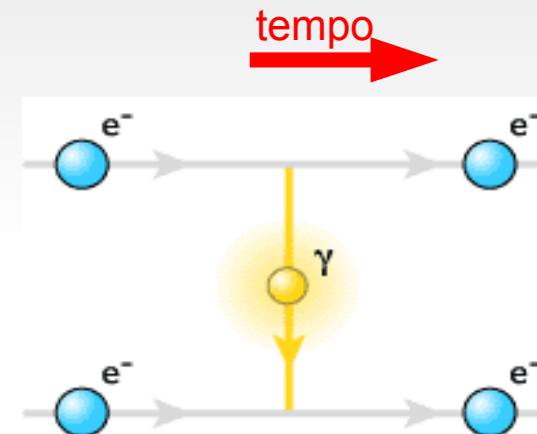
Como se transmitem as forças? Eletromagnética



Fóton γ :

Atua em todas as partícula que possuam carga elétrica.

Responsável pelo atrito, o magnetismo, a coesão das moléculas e etc.

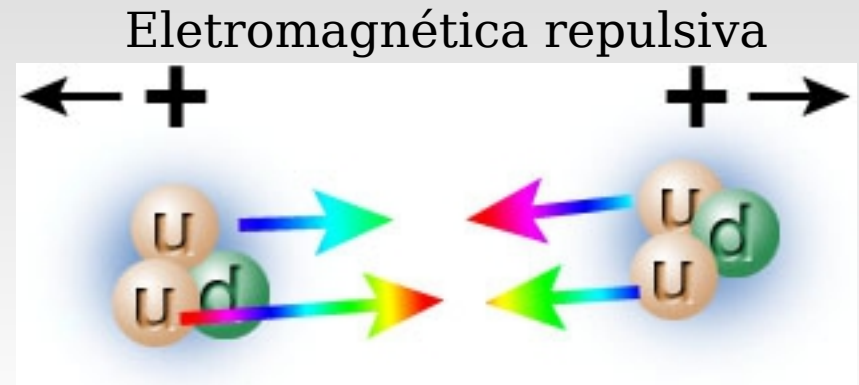


Força residual E-M em ação: Os átomos são eletricamente neutros, mas os elétrons de um são atraídos pelos prótons do outro, e vice-versa!

Como se transmitem as forças?

Forte

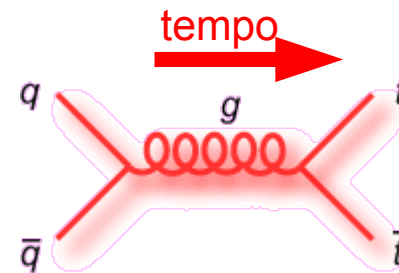
Núcleo:
Prótons e
Nêutrons



Residual forte atrativa

Força forte, tem
carga de cor e é
transmitida pelo

Glúon g



Outra interação básicas da natureza

Atua em todas as partícula que possuam carga de cor, ou seja os quarks.

Como se transmitem as forças?

Fraca

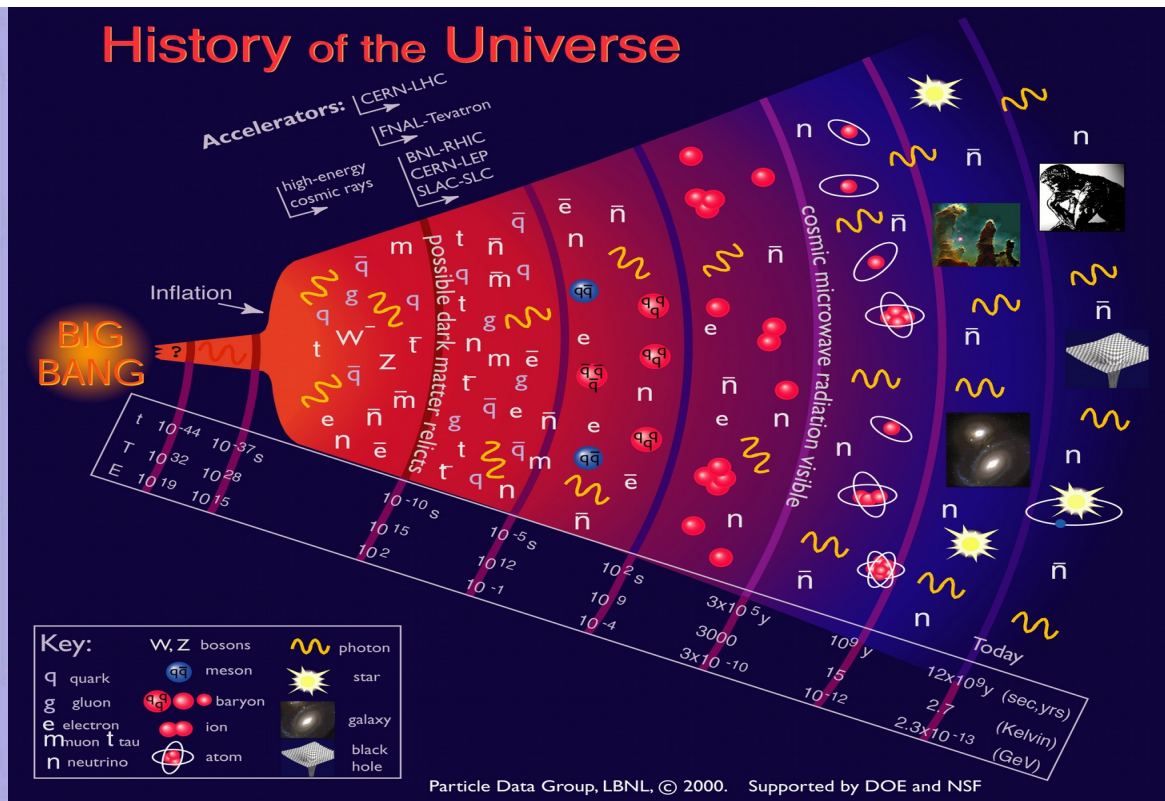
Três famílias de Quarks
e
três famílias de Leptons
no início do universo

Desintegração



Reduzidos a
uma família
de cada

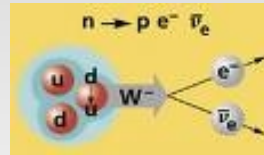
Quarks	u up	c charm	t top
	d down	s strange	b bottom
	ν_e e- Neutrino	ν_μ μ - Neutrino	ν_τ τ - Neutrino
Leptons	e electron	μ muon	τ tau
	I	II	III
	The Generations of Matter		



Quarks	u up	d down
	ν_e e- Neutrino	e electron
	I	

Como se transmitem as forças!!

Fraca



Interage com os quarks e leptons.

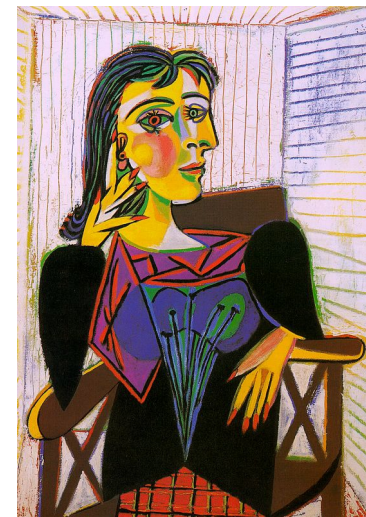
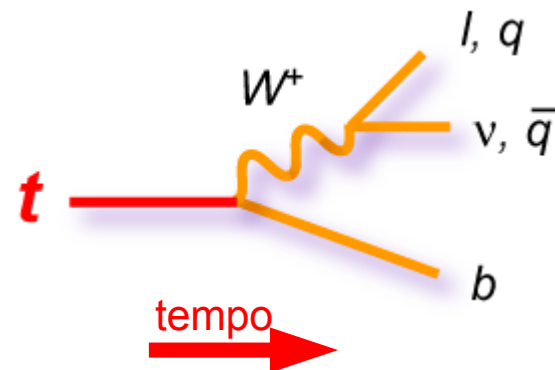
Responsável pela desintegração dos quarks e leptons pesados.

Não forma estado ligado.

A mais surpreendente das quatro forças da Natureza.

W^+ , W^- e Z^0

Outra interação
básicas da natureza



Como se transmitem as forças? Gravitacional

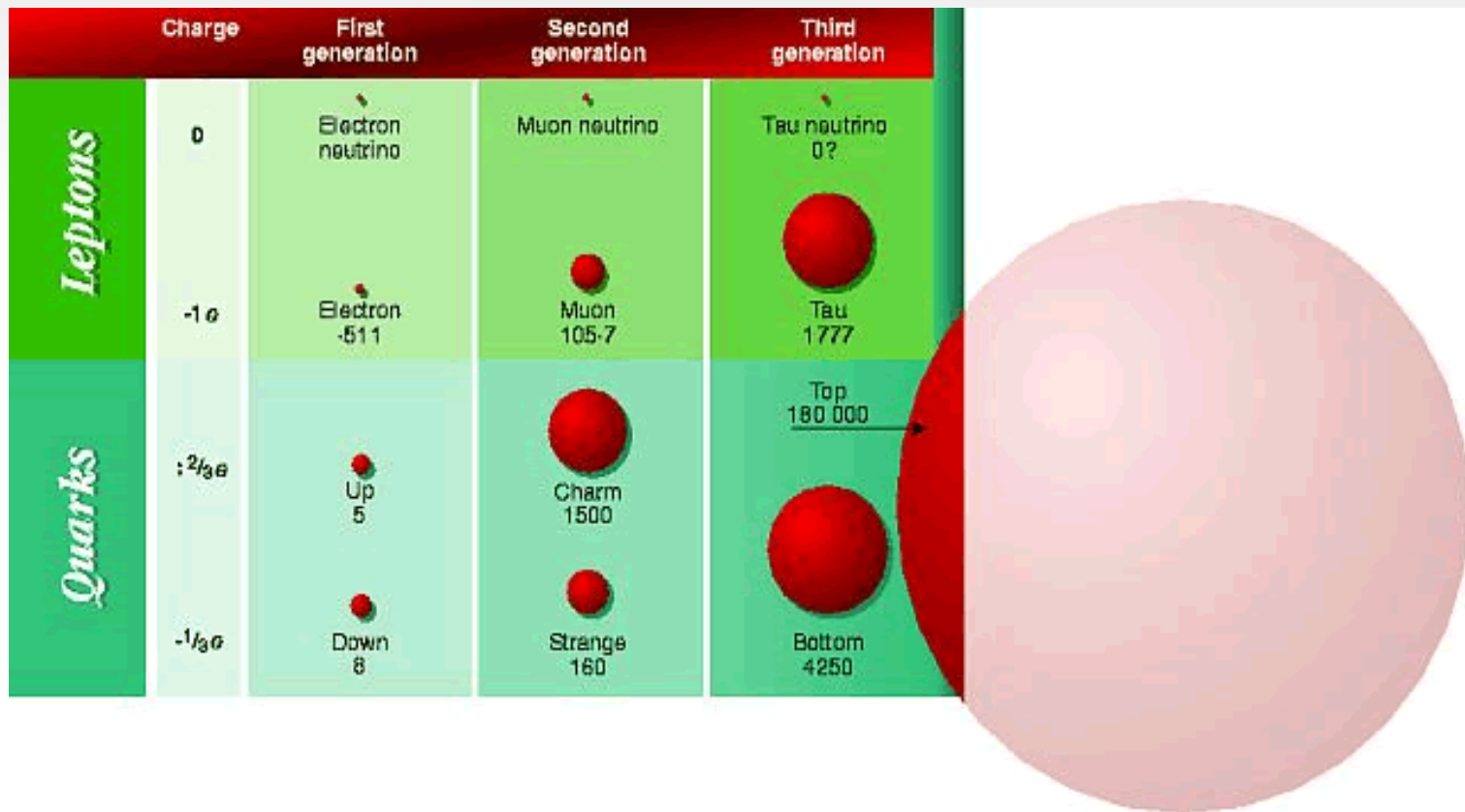


A mais universal, a mais antiga.

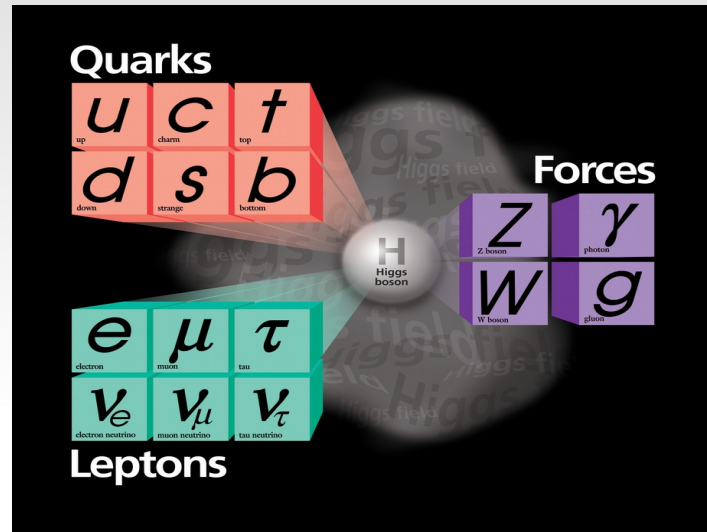
Mas é a menos conhecida das quatro forças da Natureza!

Ondas gravitacionais!

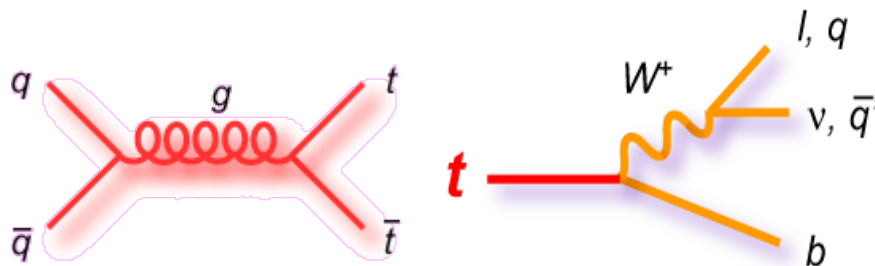
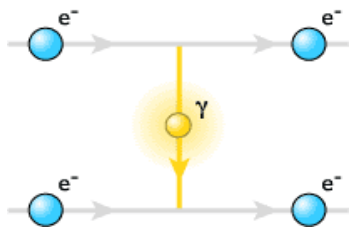
Massa dos Quarks e Leptons



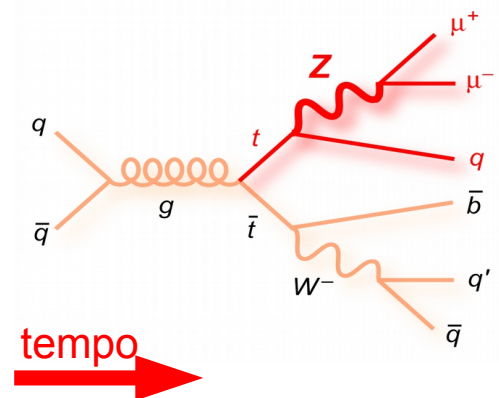
Partículas e suas Interações fundamentais.



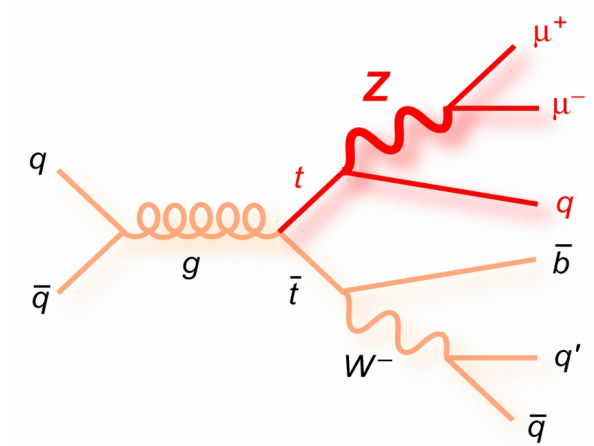
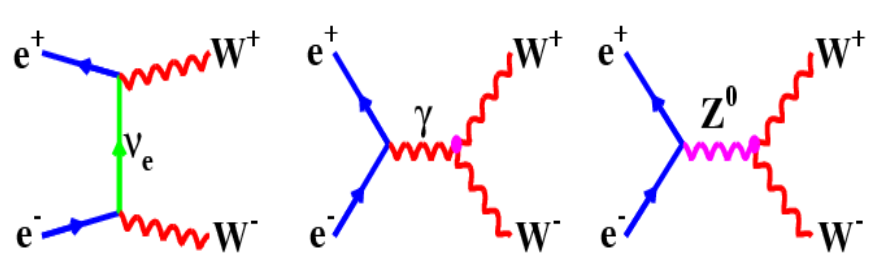
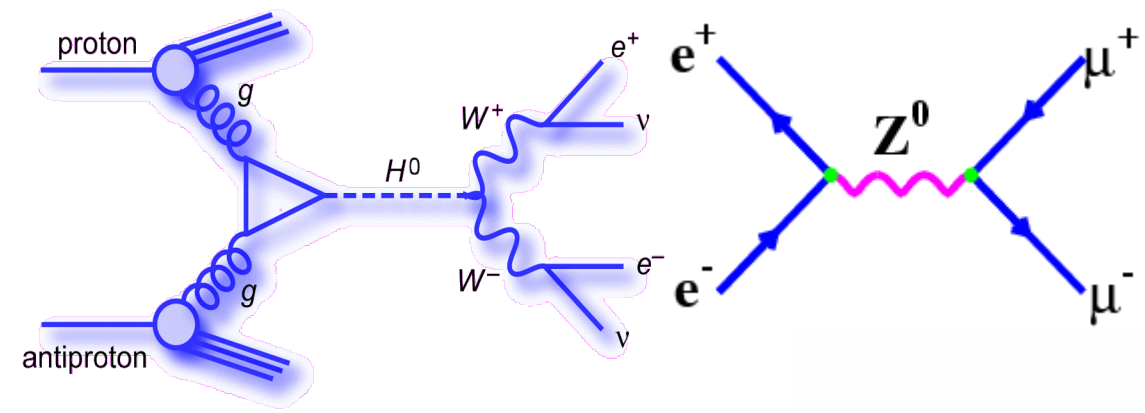
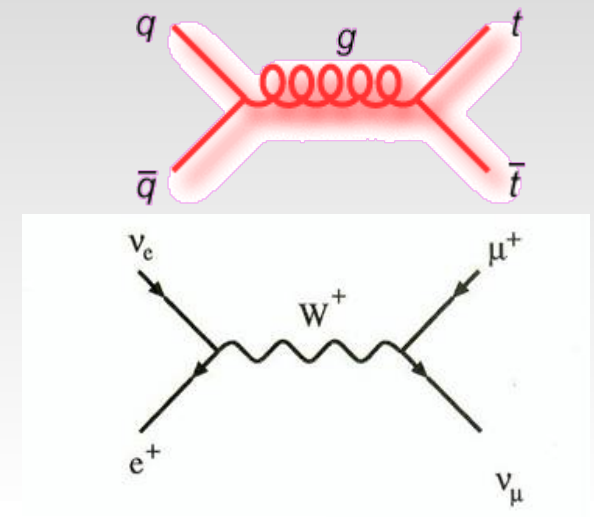
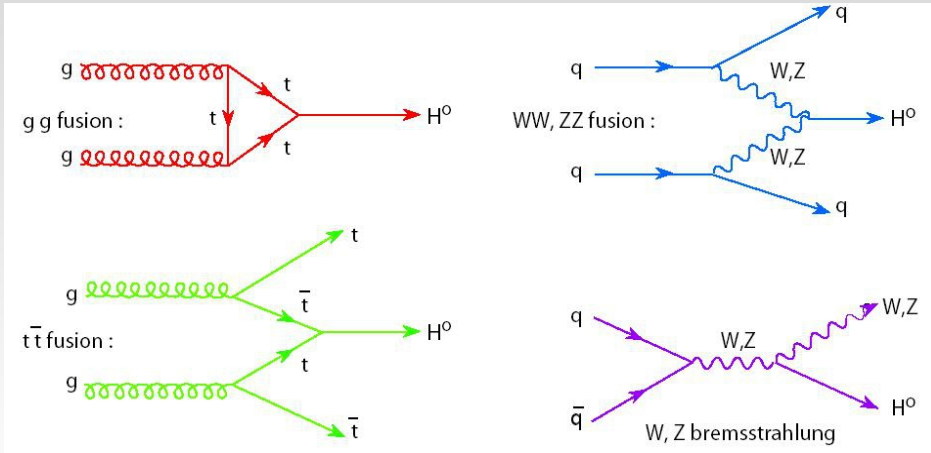
Interações básicas da natureza



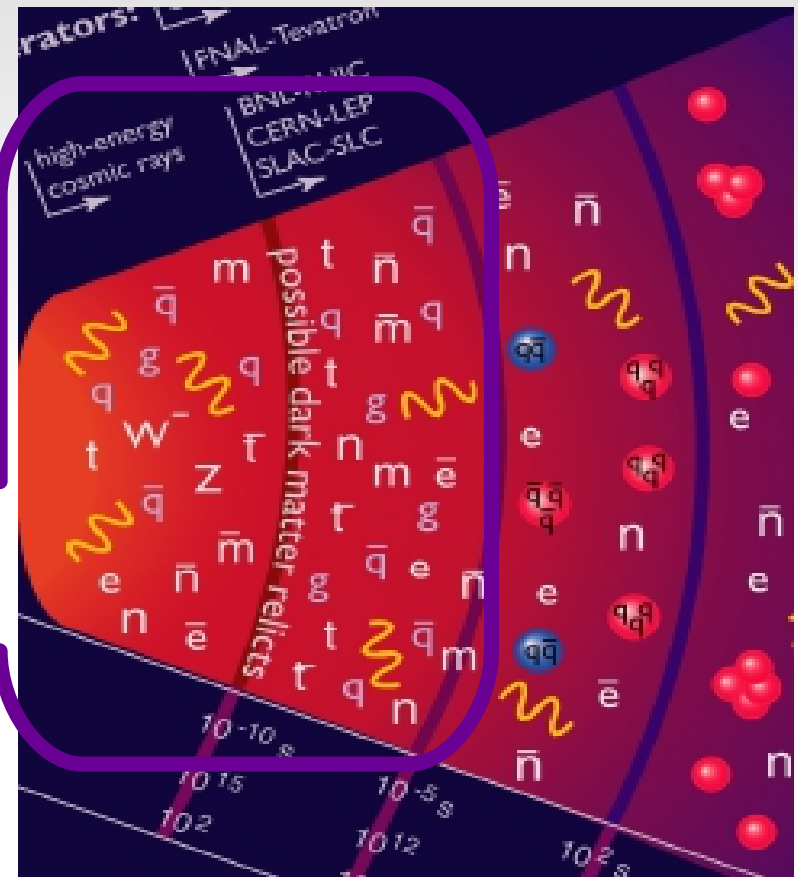
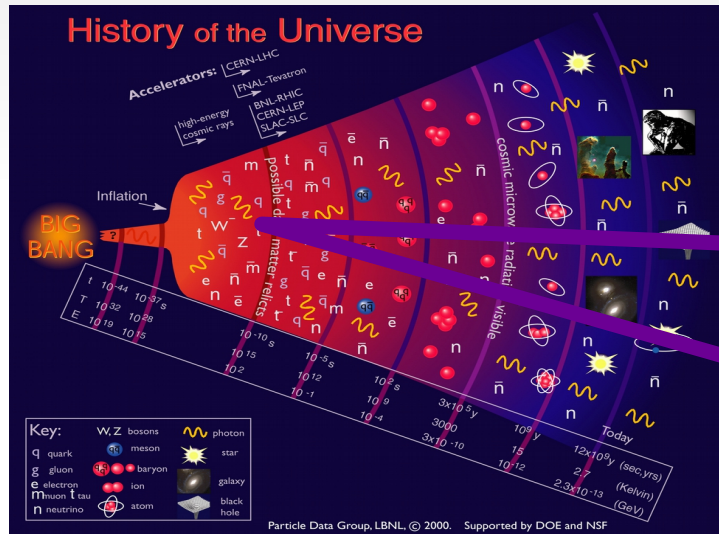
Interações combinadas



Dinâmica Matéria Anti-Matéria



Início do Universo: criação e destruição



Bósons e Fermions!

Existem dois tipos de partículas:
as transmissoras de força,
conhecidas como

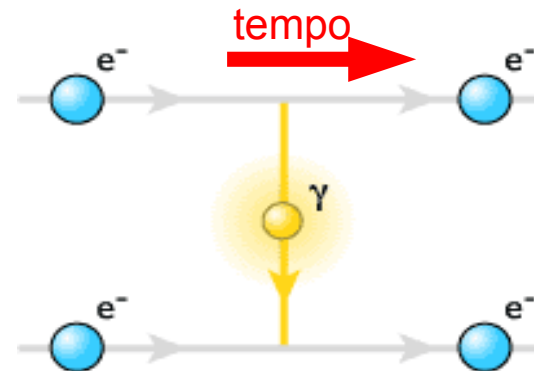
bósons

e as receptoras, conhecidas como

fermions

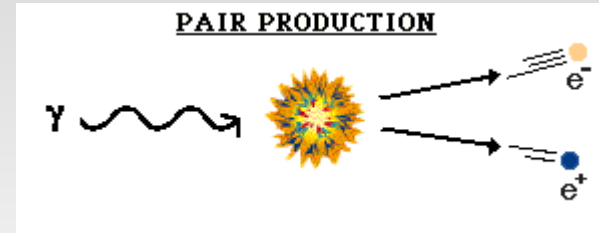
(A família dos elétrons (leptons) e a família dos quarks).

Primeira das
interações básicas da
natureza

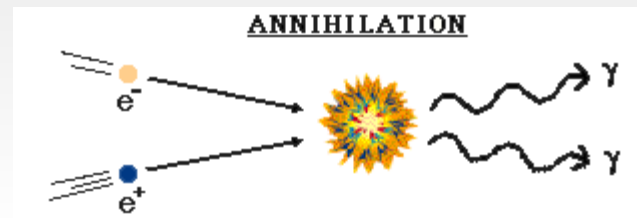


Dinâmica Matéria Anti-Matéria

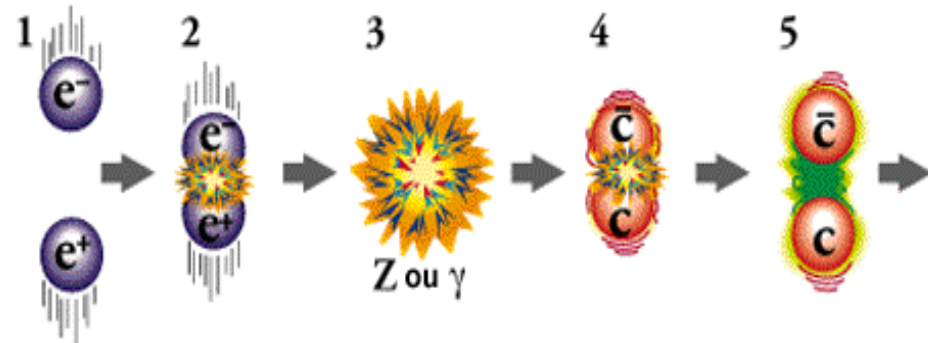
Criação
Partícula Antipartícula



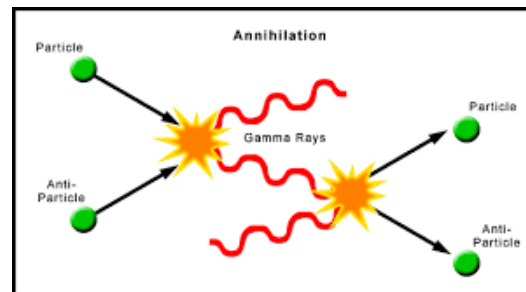
Aniquilação
Partícula Antipartícula



Aniquilação e Criação
Partícula Anti-Partícula.

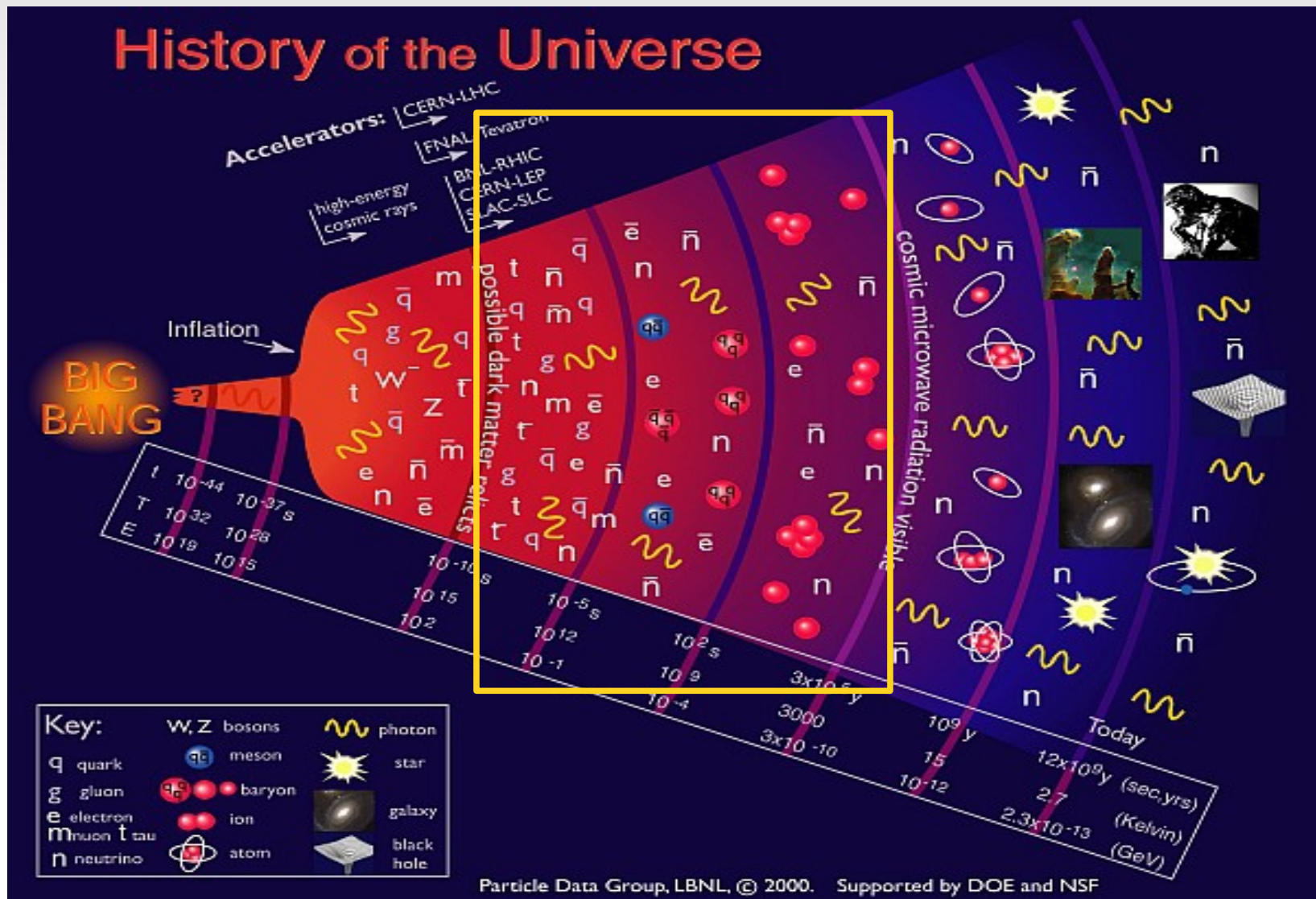


Qualquer processo de produção, por qualquer interação: sempre cria o mesmo número de partículas e antipartículas.



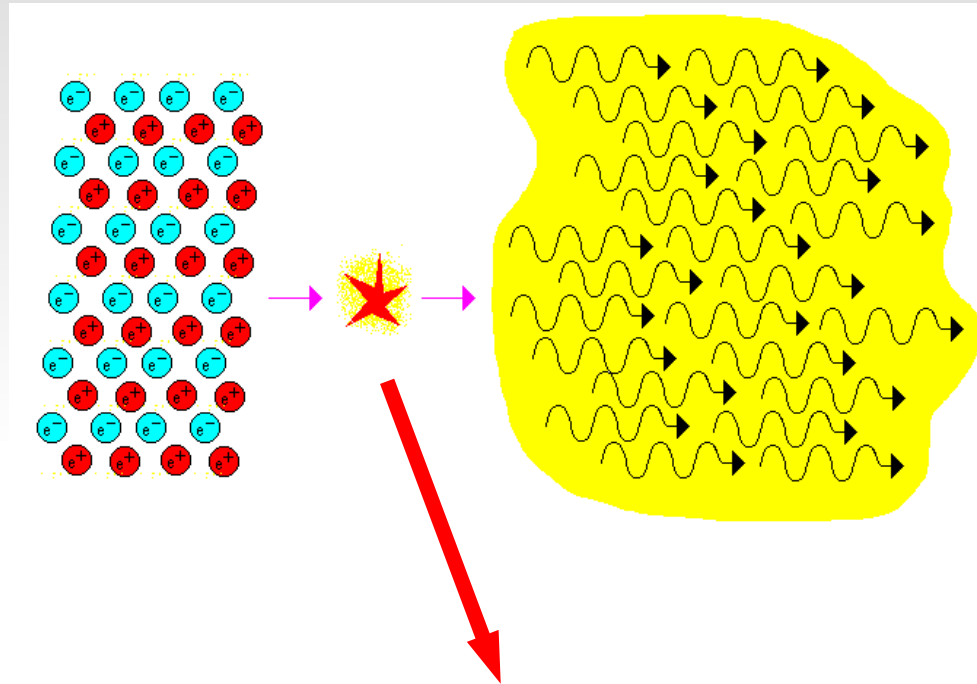
Baryogenesis

Same amount of matter
anti-matter in the beging of Universe

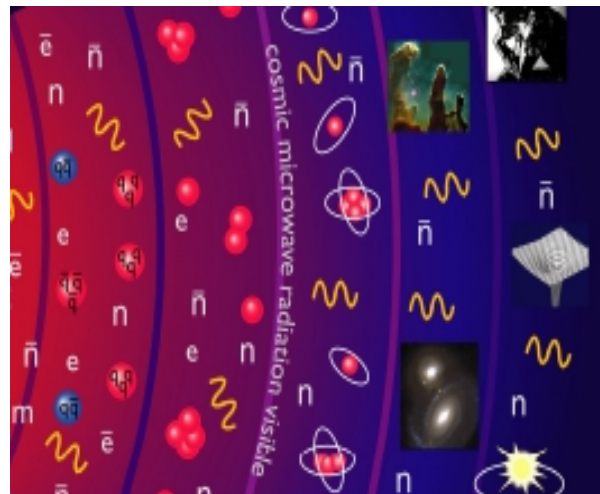


Expansão e resfriamento

Uma infinidade de pares partícula anti-partícula

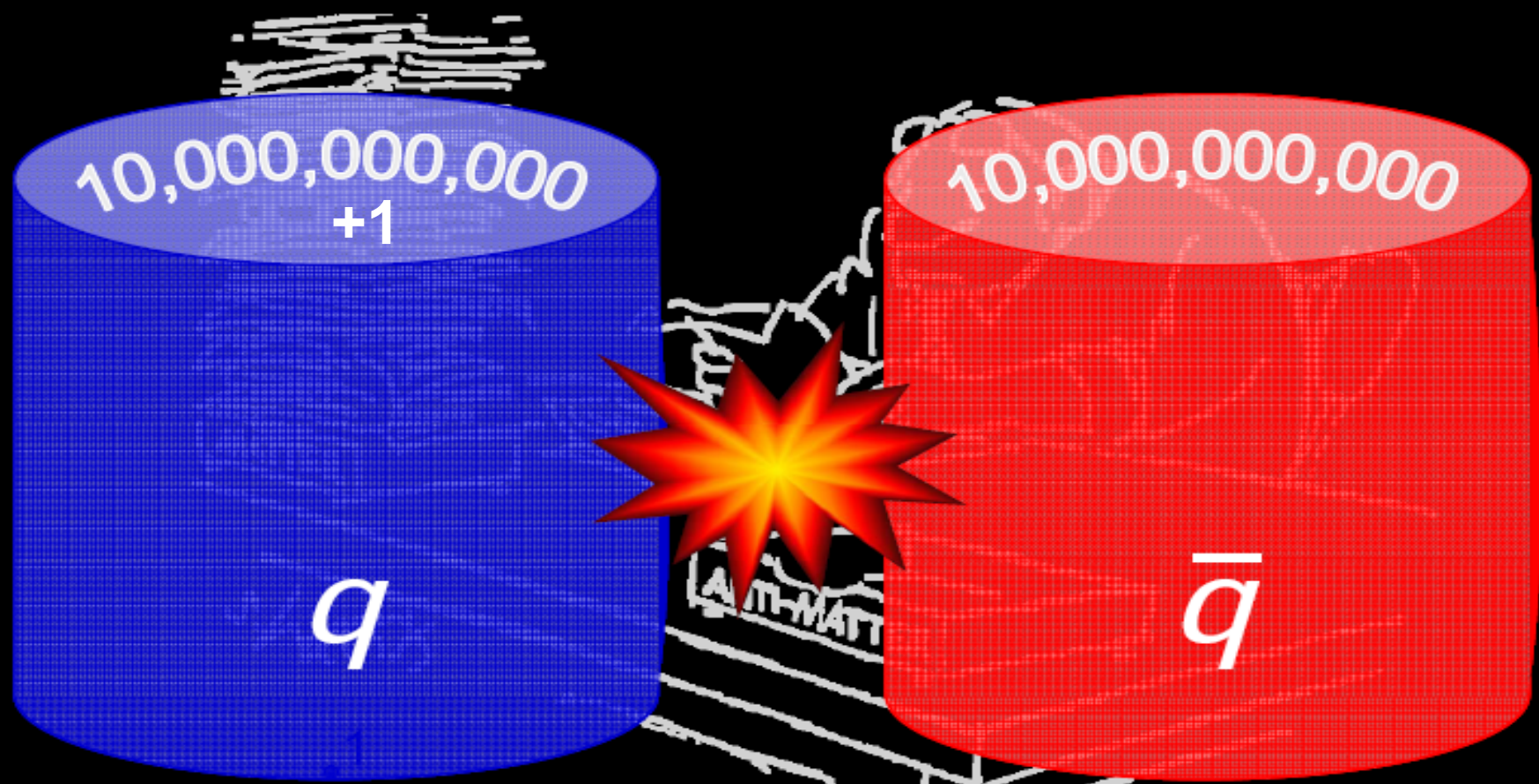


Leva a uma infinidade de Fótons com mesma energia pairando pelo Universo



$$\frac{\Delta n_{\text{baryon}}}{n_{\gamma}} = \frac{n_{\text{baryon}} - n_{\bar{\text{baryon}}}}{n_{\gamma}} \sim O(10^{-10})$$

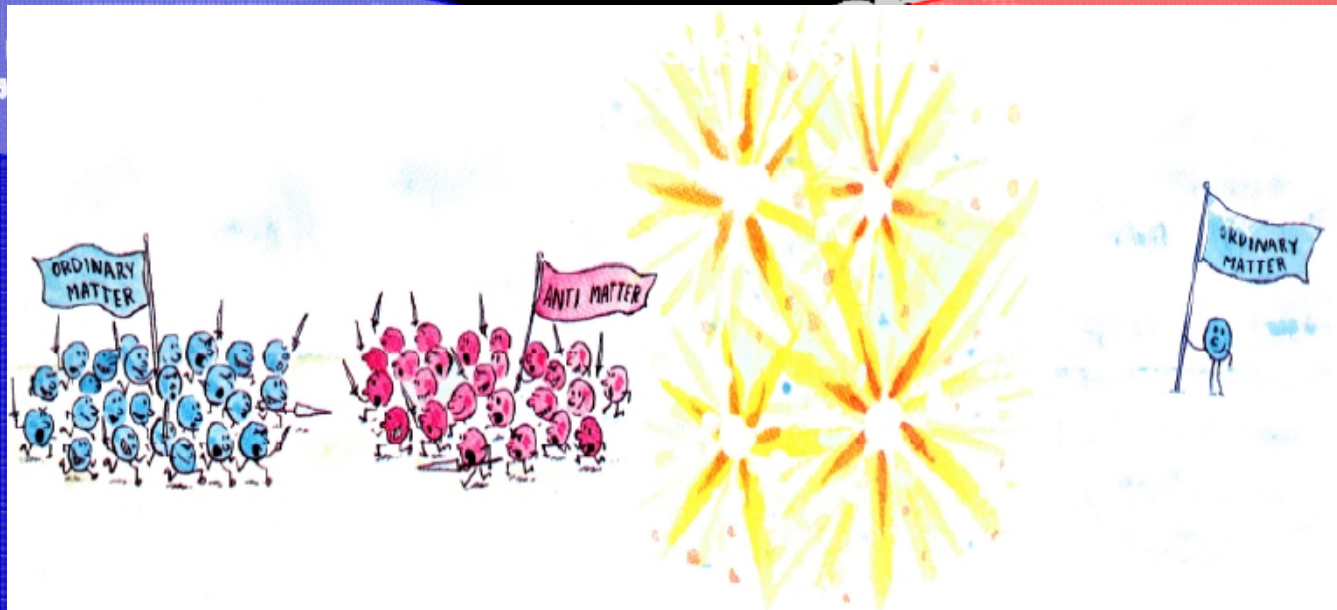
Matter-Antimatter Asymmetry



Current universe

$$\frac{\Delta n_{\text{baryon}}}{n_{\gamma}} = \frac{n_{\text{baryon}} - n_{\text{antibaryon}}}{n_{\gamma}} \sim O(10^{-10})$$

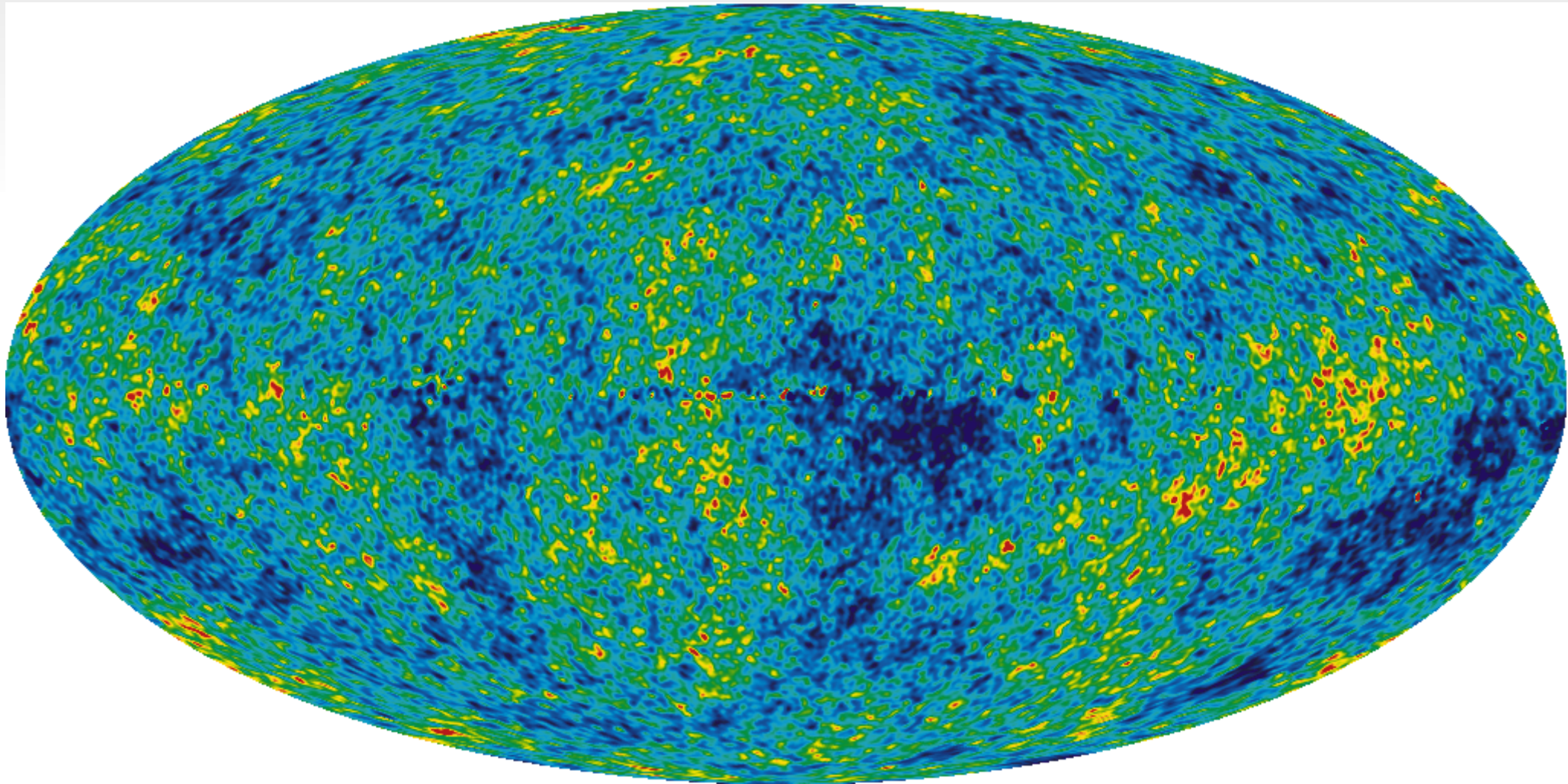
Matter-Antimatter Asymmetry



Current universe

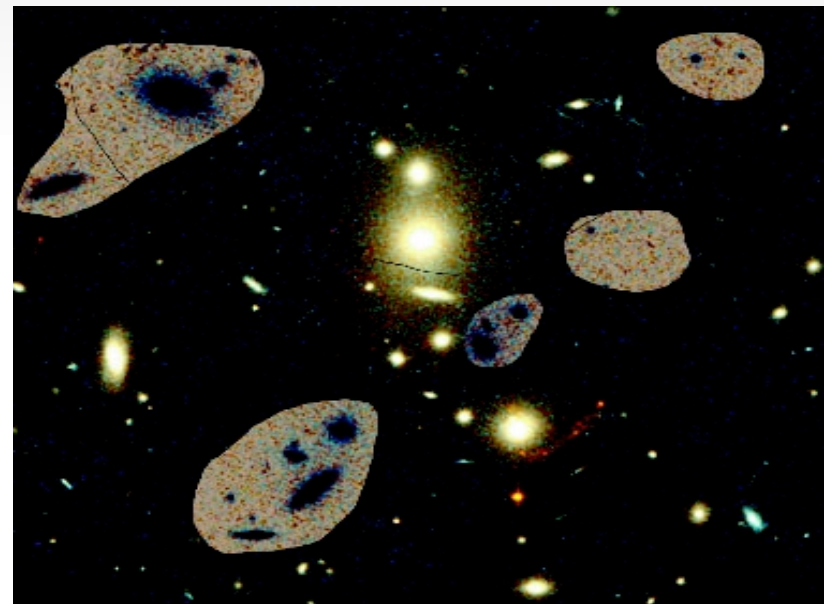
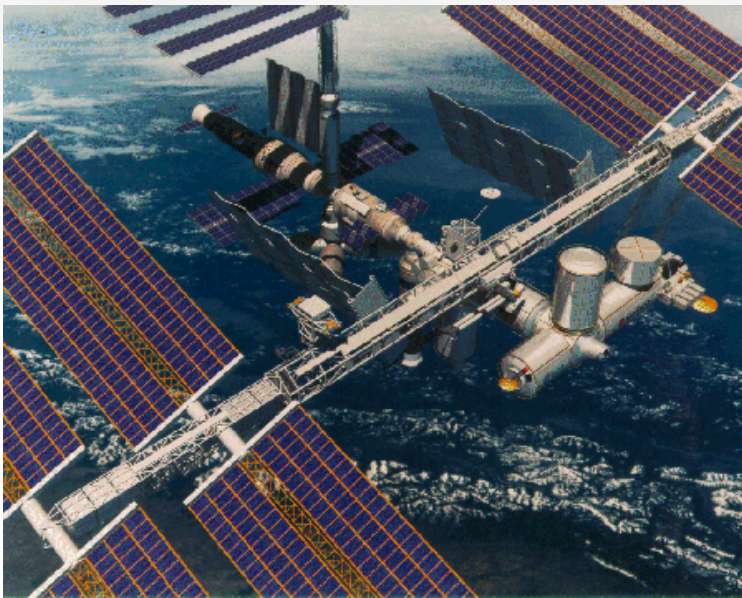
Radiação de fundo

2.7248 a 2.7252 K⁰ Menos de 0.01% de variação



Onde esta a Anti-Matéria?

- ▶ Balões com detectores de anti-partículas.
- ▶ Radio telescópios, satélites com detecção de raios gamma e raios X.



- ▶ Nenhuma evidência de anti-matéria em ~ 1 Bilhão de anos luz

Questões gerais sobre
a violação de ~~CP~~.

Condições de Sakharov

Para a produção da assimetria entre a matéria e a anti-matéria, observada no universo atual, são necessárias duas condições:

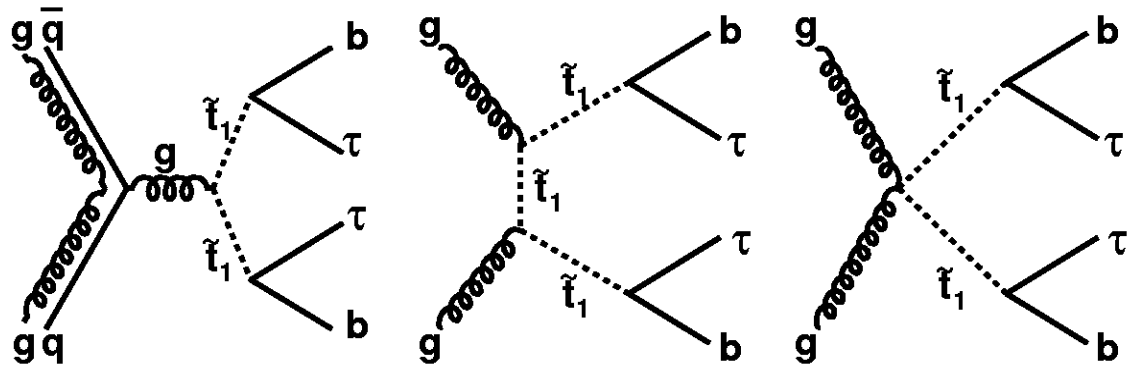
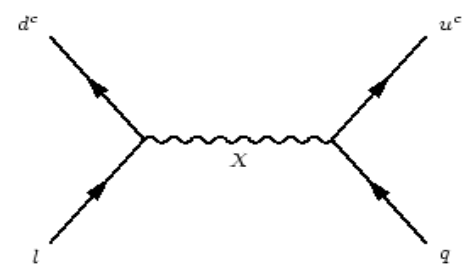
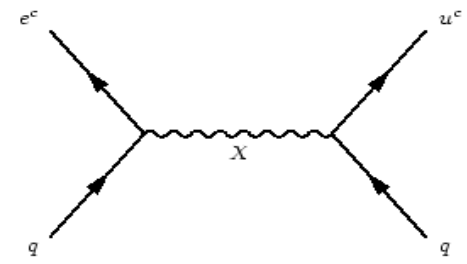
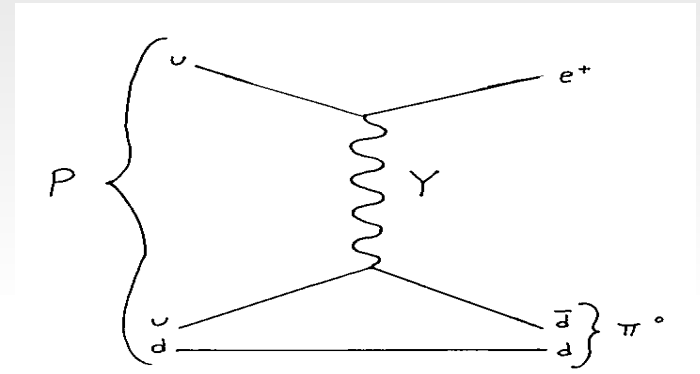
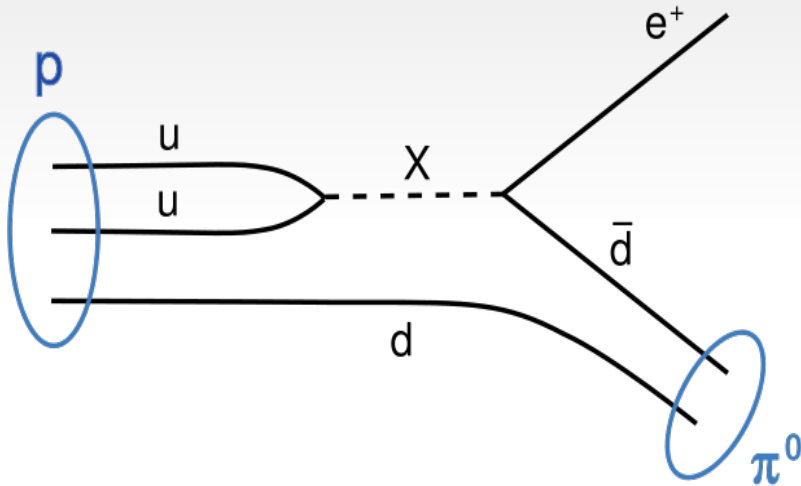
- ▶ O número bariônico ser violado.
- ▶ Violação de C e de CP

Estas duas condições seriam possíveis, segundo Sakharov, somente em um sistema fora do equilíbrio termodinâmico, ou seja no Universo em forte expansão.



Violação do número Barionico

Processos onde: o número de quarks, menos o número de anti-quarks, é diferente entre o estado inicial e final.



Negative experimental results: Particle Data Group

p DECAY MODES	Partial mean life (10^{30} years)	Co
Antilepton + meson		
$N \rightarrow e^+ \pi$	$> 158 (n), > 1600 (p)$	
$N \rightarrow \mu^+ \pi$	$> 100 (n), > 473 (p)$	
$N \rightarrow \nu \pi$	$> 112 (n), > 25 (p)$	
$p \rightarrow e^+ \eta$	> 313	
$p \rightarrow \mu^+ \eta$	> 126	
$n \rightarrow \nu \eta$	> 158	
$N \rightarrow e^+ \rho$	$> 217 (n), > 75 (p)$	
$N \rightarrow \mu^+ \rho$	$> 228 (n), > 110 (p)$	
$N \rightarrow \nu \rho$	$> 19 (n), > 162 (p)$	
$p \rightarrow e^+ \omega$	> 107	
$p \rightarrow \mu^+ \omega$	> 117	
$n \rightarrow \nu \omega$	> 108	
$N \rightarrow e^+ K$	$> 17 (n)$	
$p \rightarrow e^+ K_S^0$	> 120	
$p \rightarrow e^+ K_L^0$	> 51	
$N \rightarrow \mu^+ K$	$> 26 (n)$	
$p \rightarrow \mu^+ K_S^0$	> 150	
$p \rightarrow \mu^+ K_L^0$	> 83	
$N \rightarrow \nu K$	$> 86 (n)$	
$n \rightarrow \nu K_S^0$	> 51	
$p \rightarrow e^+ K^*(892)^0$	> 84	
$N \rightarrow \nu K^*(892)$	$> 78 (n)$	
Antilepton + mesons		
$p \rightarrow e^+ \pi^+ \pi^-$	> 82	
$p \rightarrow e^+ \pi^0 \pi^0$	> 147	
$n \rightarrow e^+ \pi^- \pi^0$	> 52	
$p \rightarrow \mu^+ \pi^+ \pi^-$	> 133	
$p \rightarrow \mu^+ \pi^0 \pi^0$	> 101	
$n \rightarrow \mu^+ \pi^- \pi^0$	> 74	
$n \rightarrow e^+ K^0 \pi^-$	> 18	
Lepton + meson		
$n \rightarrow e^- \pi^+$	> 65	
$n \rightarrow \mu^- \pi^+$	> 49	
$n \rightarrow e^- \rho^+$	> 62	
$n \rightarrow \mu^- \rho^+$	> 7	
$n \rightarrow e^- K^+$	> 32	
$n \rightarrow \mu^- K^+$	> 57	
Lepton + mesons		
$p \rightarrow e^- \pi^+ \pi^+$	> 30	
$n \rightarrow e^- \pi^+ \pi^0$	> 29	
$p \rightarrow \mu^- \pi^+ \pi^+$	> 17	
$n \rightarrow \mu^- \pi^+ \pi^0$	> 34	
$p \rightarrow e^- \pi^+ K^+$	> 75	
$p \rightarrow \mu^- \pi^+ K^+$	> 245	
Antilepton + photon(s)		
$p \rightarrow e^+ \gamma$	> 670	
$p \rightarrow \mu^+ \gamma$	> 478	
$n \rightarrow \nu \gamma$	> 28	
$p \rightarrow e^+ \gamma \gamma$	> 100	
$n \rightarrow \nu \gamma \gamma$	> 219	

There is no baryon number violation at low temperature.

Condições de Sakharov

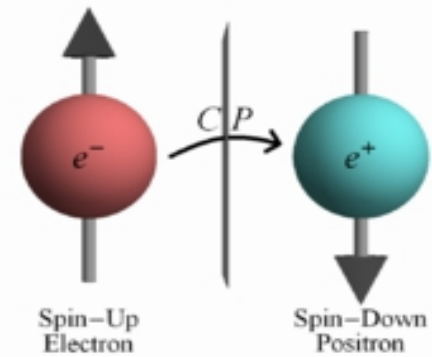
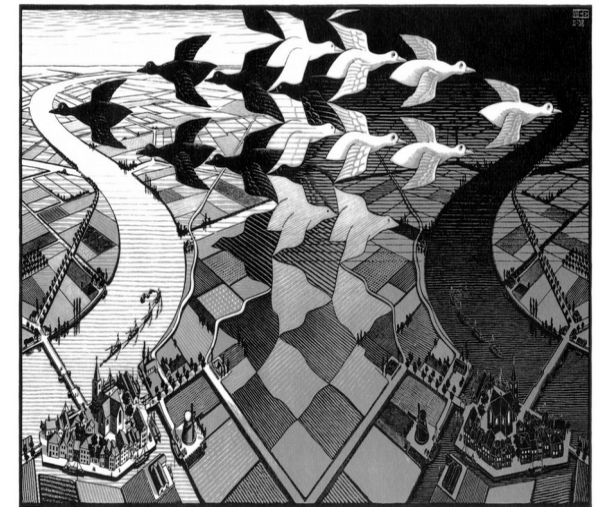
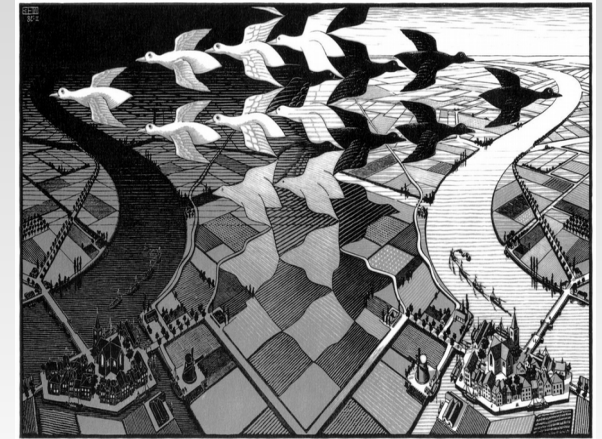
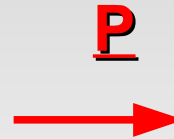
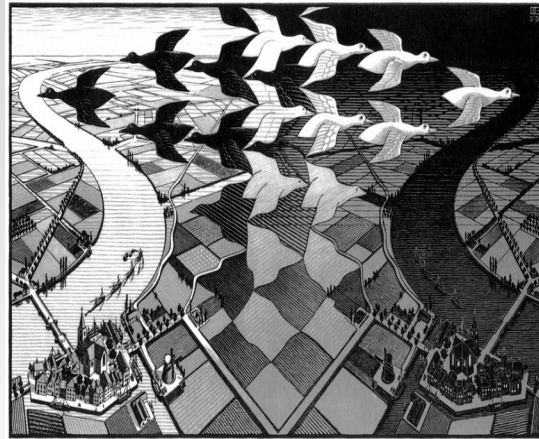
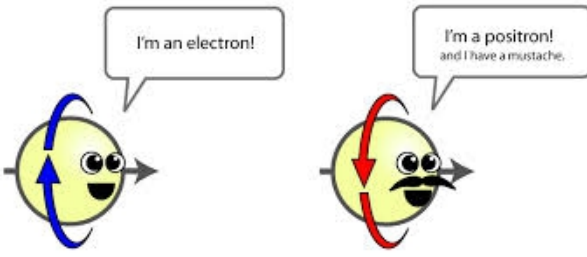
Para a produção da assimetria entre a matéria e a anti-matéria, observada no universo atual, são necessárias duas condições:

- ▶ O número bariônico ser violado.
- ▶ Violação de C e de CP

Estas duas condições seriam possíveis, segundo Sakharov, somente em um sistema fora do equilíbrio termodinâmico, ou seja no Universo em forte expansão.



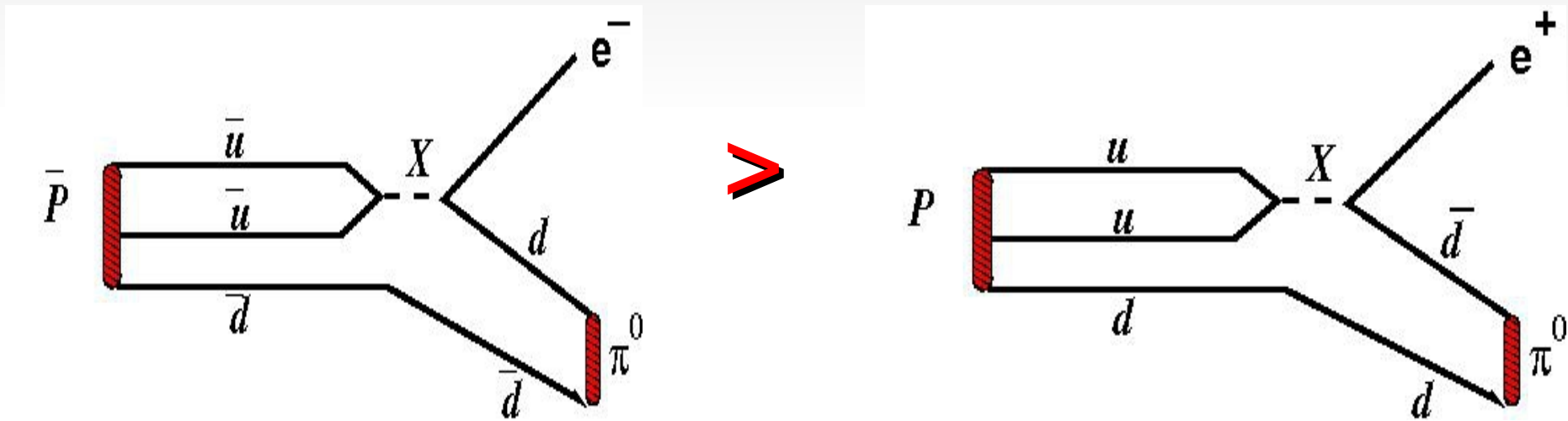
CP Symmetry



Landau: CP symmetry must be the responsible by the transformation matter anti-matter.

Violação de CP

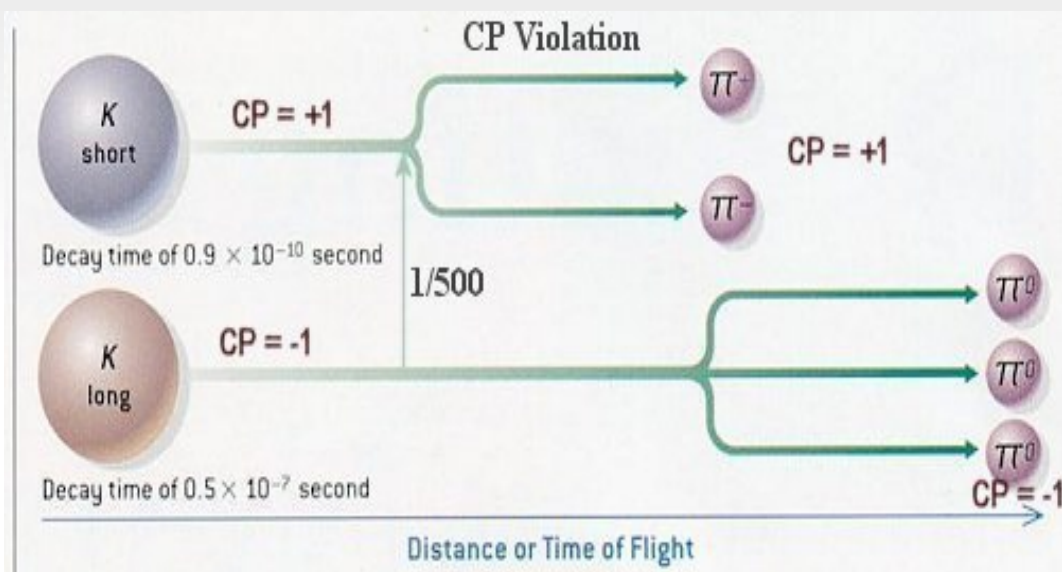
Desintegração do próton seria menor que a do antipróton



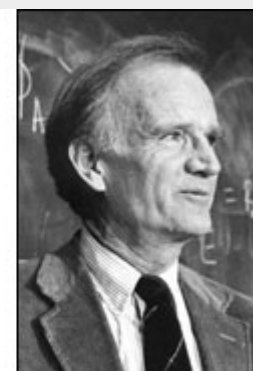
Isto daria conta do fato de que a soma das cargas elétrica do Universo é zero



~~CP~~ asymmetry observation: 52 years!



James Cronin



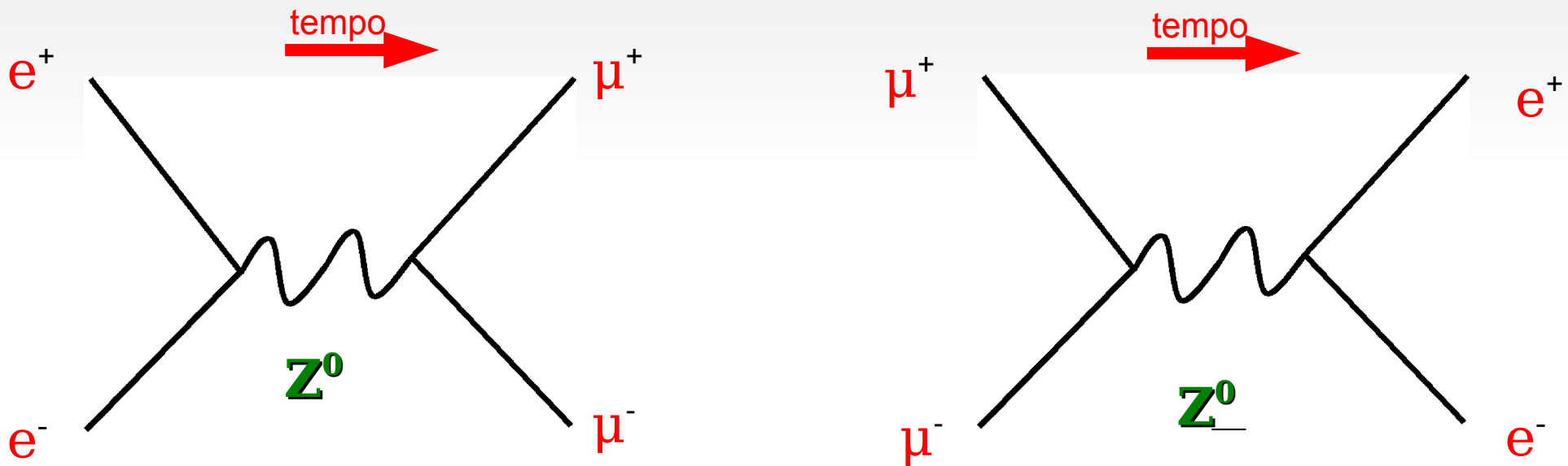
Val Fitch

1/500 over K_{long} going to two pions, violating ~~CP~~

Teorema de CPT

Se aplica a qualquer teoria invariante de Lorentz, onde os observáveis são representados por operadores hermitianos.

Violação de CP → Irreversibilidade.



Transformação em tempo deve ser descrita por uma transformação unitária e complexa $e^{-iEt} \rightarrow T \rightarrow e^{iEt}$.

Violação de CP implica na existência de uma fase.

Kobayashi-Maskawa Nobel de 2008



Matriz de Cabibbo de mistura 2X2: não permite violação de CP, falta o termo complexo.

2 ^ 3 famílias de quarks

Matriz de mistura 2X2 > 3X3,
permite um termo complexo que
poderia explicar a violação de CP

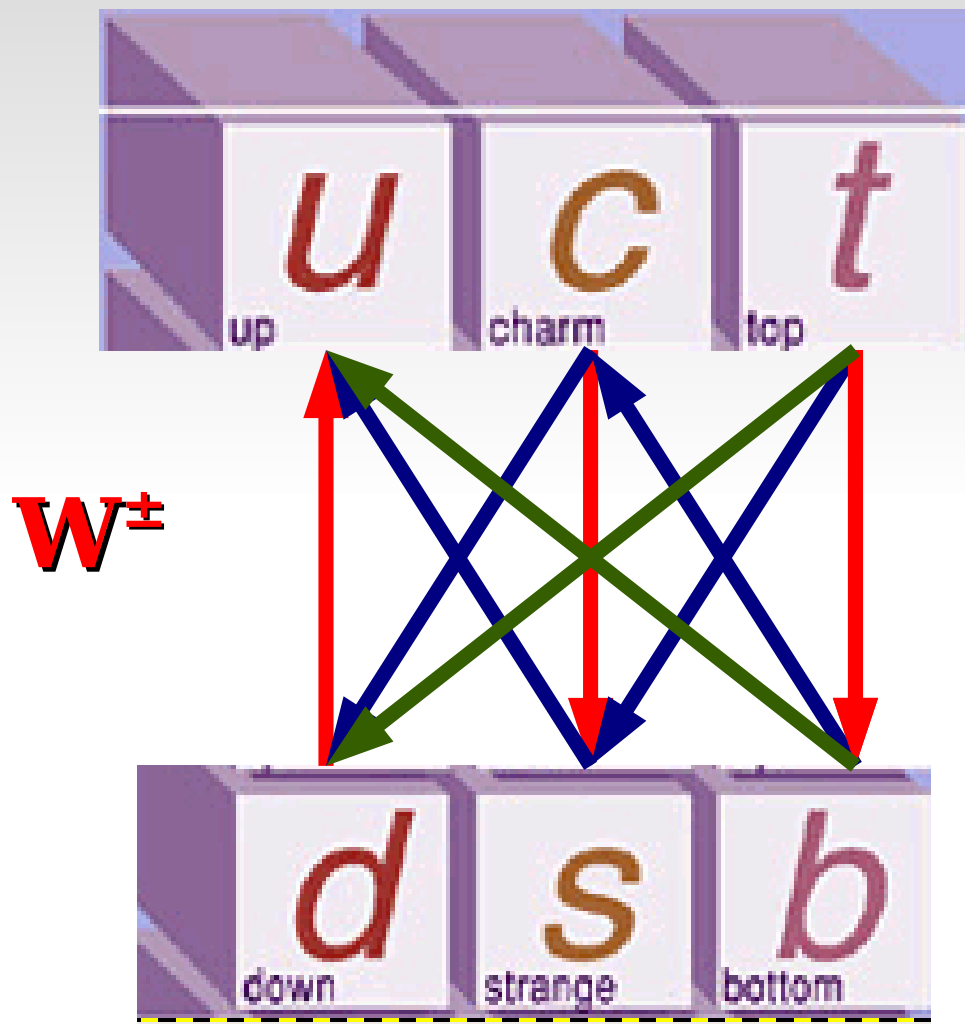
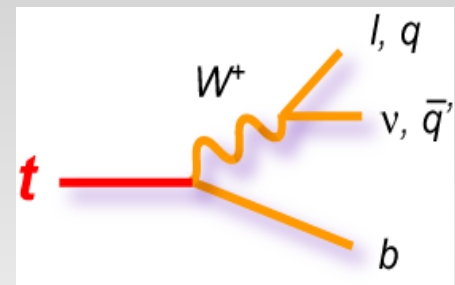
	d	s	b	
u	V_{ud}	V_{us}	V_{ub}	u
c	V_{cd}	V_{cs}	V_{cb}	c
t	V_{td}	V_{ts}	V_{tb}	t

Kobayashi e Maskawa
propuseram dois novos
quarks o **b** e **t**





CabbiboKobayashiMaskawa Matrix



High probability



Middle probability



Low probability

Cabibbo Kobayashi-Maskawa:
4 parameters, 3 angles and **one phase.**

Quarks e Leptons

Três famílias de Quarks e
três famílias de Leptons.
Todas já produzidas e observadas em
aceleradores.

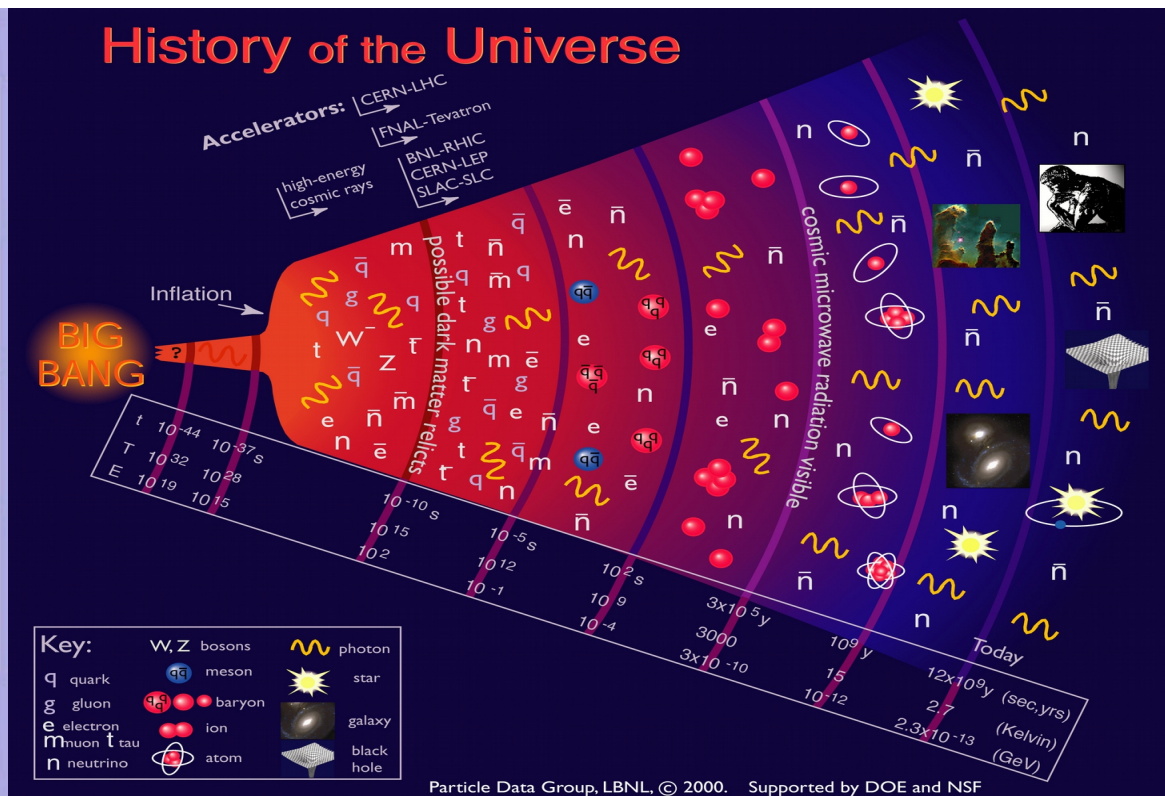
Quarks

<i>u</i> up	<i>c</i> charm	<i>t</i> top
<i>d</i> down	<i>s</i> strange	<i>b</i> bottom

Leptons

ν_e e- Neutrino	ν_μ μ - Neutrino	ν_τ τ - Neutrino
<i>e</i> electron	μ muon	τ tau

I II III
The Generations of Matter



Quarks

<i>u</i> up
<i>d</i> down

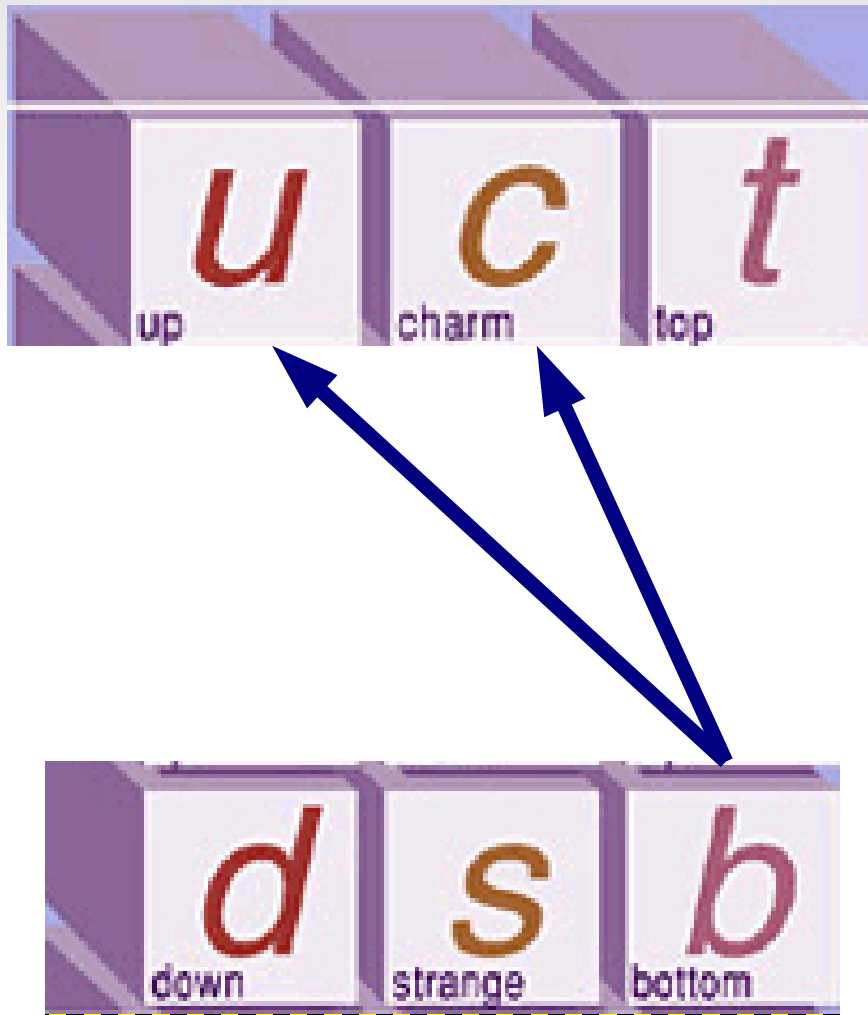
Leptons

ν_e e- Neutrino
<i>e</i> electron

I

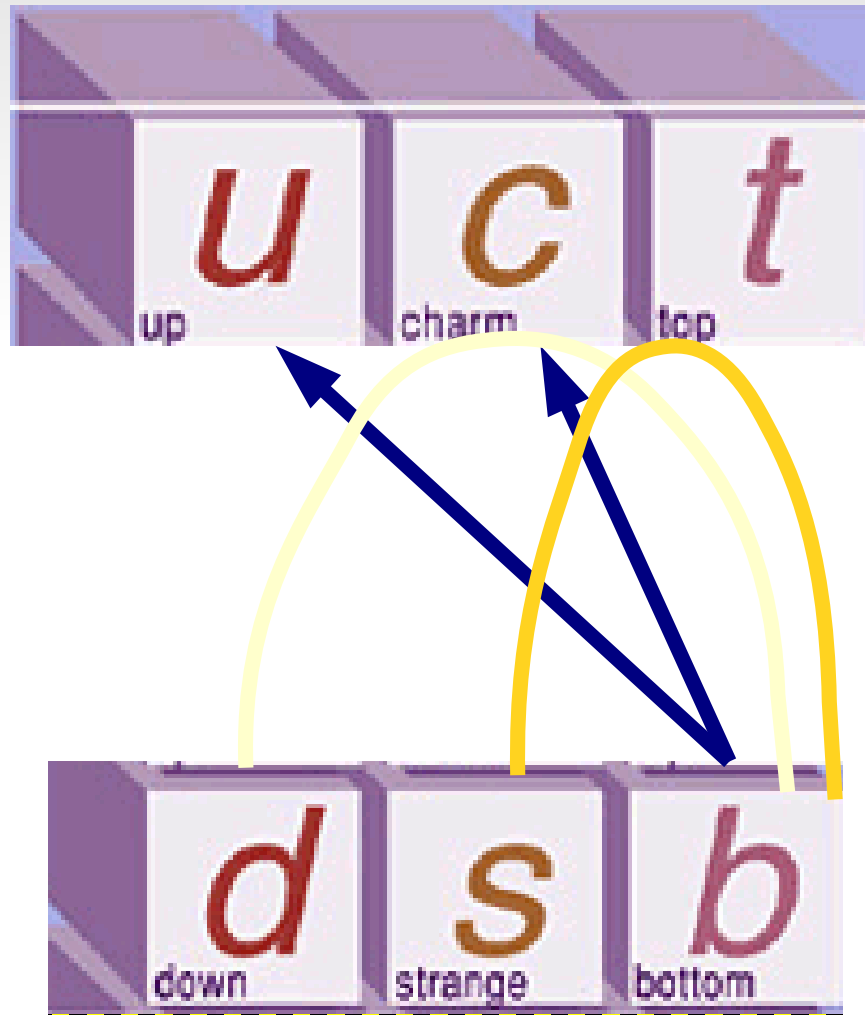
Quark *b*: maior fonte de violação de CP

Decaimentos de partículas envolvendo o quark *b*, apresentam forte componente de violação de CP



b quark is the biggest source of CP violation in the CKM matrix.

I. Bigi e A. Sanda

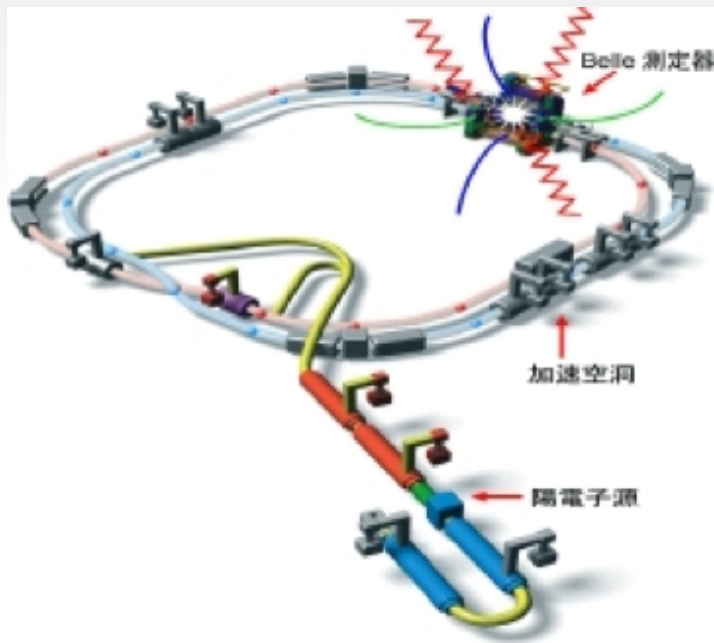




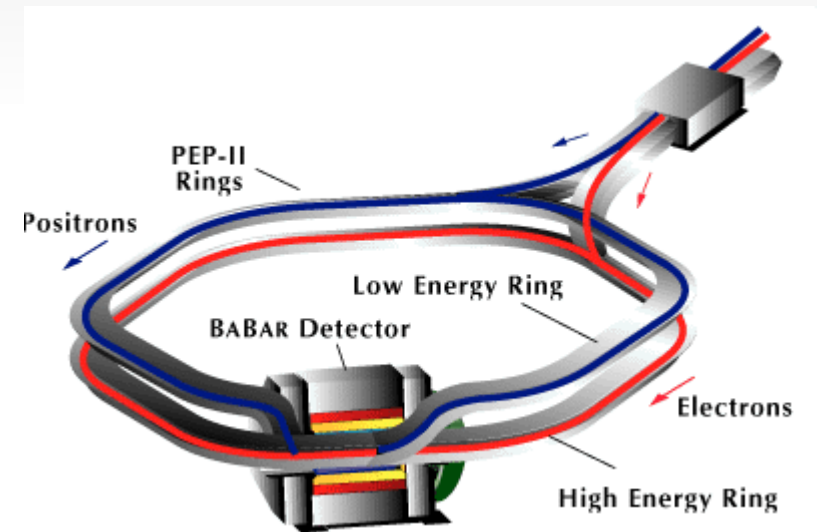
Belle and BaBar Collaborations



KEK Japão



PEP II- Stanford-EUA

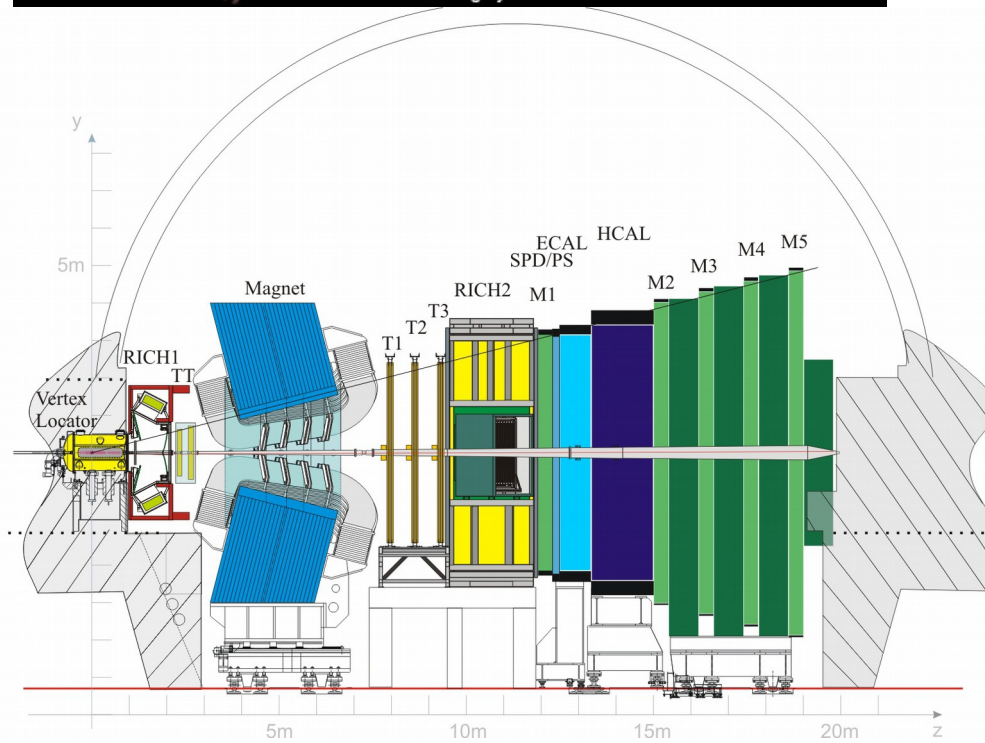
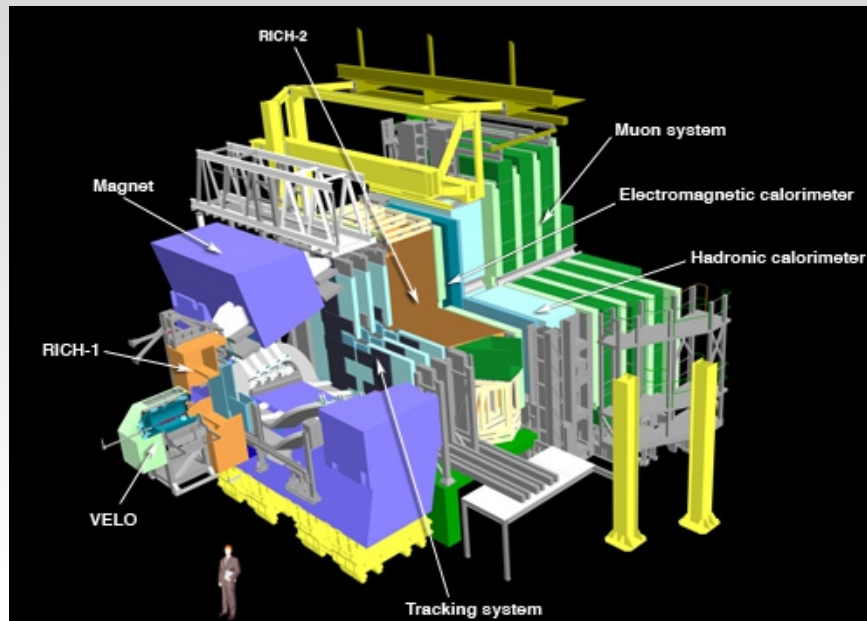


657 millions of B's mesons

383 millions of B's mesons



Detector LHCb



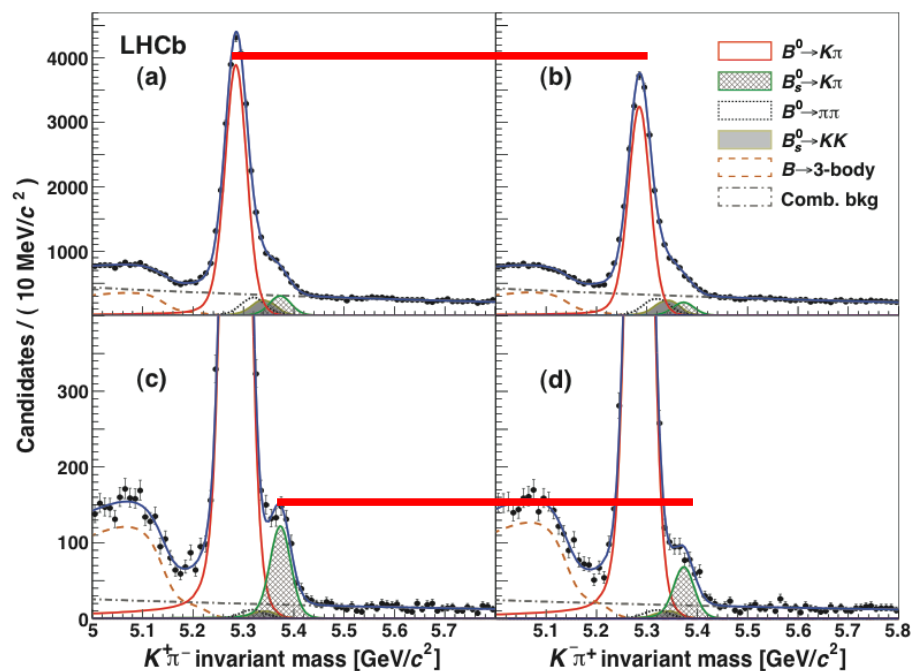


Directly CP violation for : $B^0 \rightarrow K^+ \pi^-$ e $B_s^0 \rightarrow K^+ \pi^-$

LHCb: *Phys. Rev. Lett.* 110, 221601 (2013)

Directly CP violation:

simple counting of events between charge conjugates final states.



$$A_{CP}(B^0 \rightarrow K^+ \pi^-) = \frac{|\langle K^+ \pi^- | T | B^0 \rangle|^2 - |\langle K^- \pi^+ | T | \bar{B}^0 \rangle|^2}{|\langle K^+ \pi^- | T | B^0 \rangle|^2 + |\langle K^- \pi^+ | T | \bar{B}^0 \rangle|^2}$$

$$A_{CP}(B^0 \rightarrow K^+ \pi^-) = -0.080 \pm 0.007 (\text{stat}) \pm 0.003 (\text{syst}),$$

$$A_{CP}(B_s^0 \rightarrow K^+ \pi^-) = 0.27 \pm 0.04 (\text{stat}) \pm 0.01 (\text{syst}).$$

~~CP~~ Violation.

Anti-particles decays rate bigger than particle.

◆ Maximum CP asymmetry in the standard model

Jarlskog determinant :

$$\det [S_u S_d] = 2i J v(S_u) v(S_d) = 2i J (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)$$

J is an invariant whose magnitude is proportional to the area of any of unitary triangles produced by CKM matrix $J = \sin(\theta_{12}) \sin(\theta_{13}) \sin(\theta_{23}) \sin(\delta_{cp}) \approx 10^{-5}$

The maximum CP violation from standard model CP is given by:

$$\det [S_u S_d] / T^{12}$$

“sphaleron”: phase weak transition temperature estimative change from 1 to 100GeV

$$\det [S_u S_d] / T^{12} \approx 10^{-10} \text{ to } 10^{-19}$$

$N(\text{barions})/N(\text{photons}) \approx 10^{-10}$ observed in the Universe.

- ◆ **Need a comprehension of the range and dynamics of this asymmetry.**

Observação de Violação da Simetria de ~~CP~~

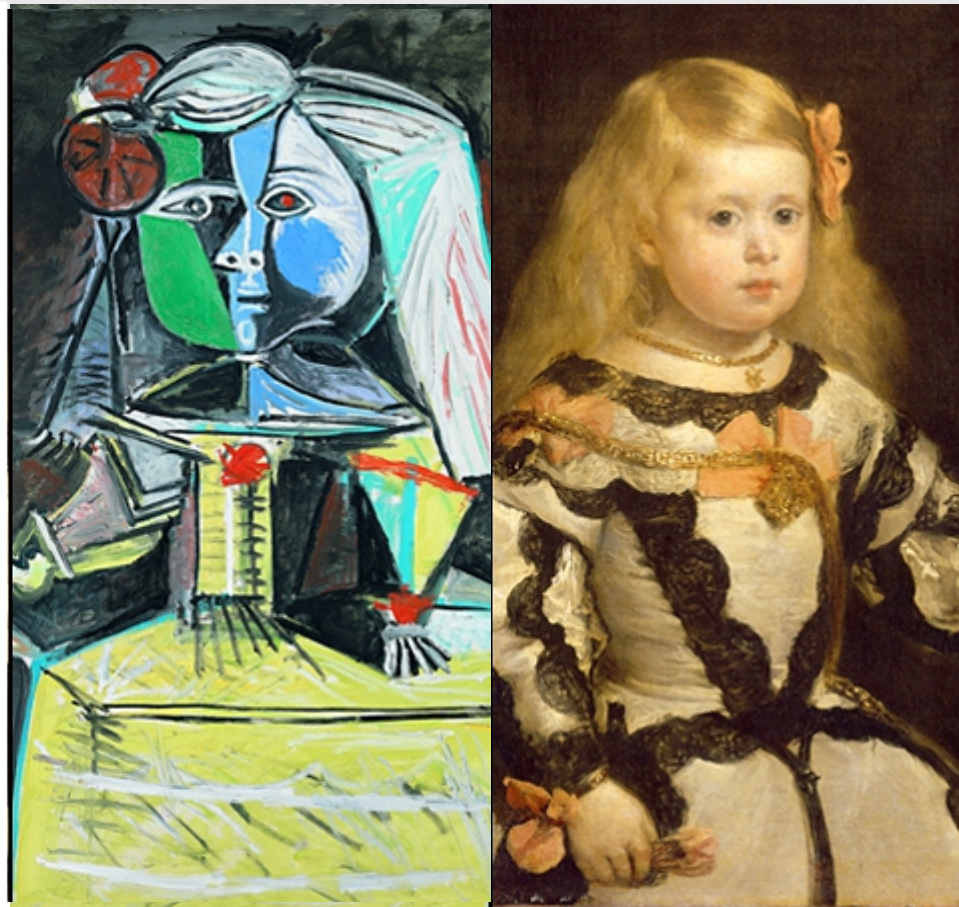
- ▶ Violação de CP nos decaimentos dos mésons K's e B's, podem ser explicados pelo Modelo Padrão
- ▶ Entretanto ela não explica toda a violação de CP necessária para entender a assimetria matéria anti-matéria do Universo

$$\text{Universe: } \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 10^{-9} \sim 10^{-10}$$

$$\text{Standard Model: } \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = \sim 10^{-20}$$

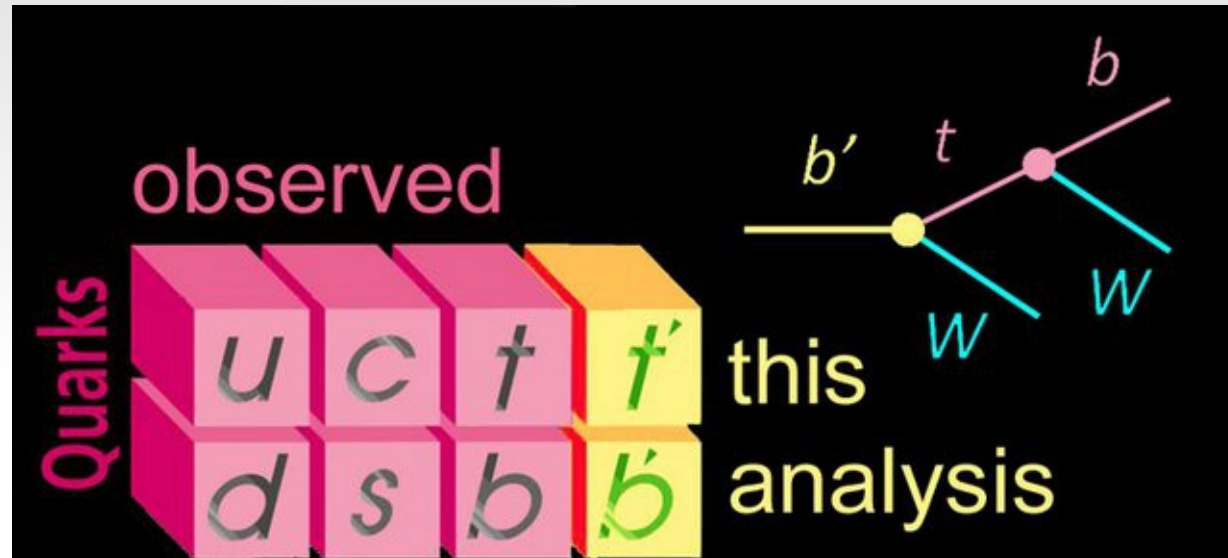
- ▶ Novas fontes de violação de CP são necessárias

*Necessária uma nova fonte importante
de violação de CP*



Las Meninas de Velásquez a Picasso

New sources of CP violation ?



New matrix
Cabibbo-Kobayashi-
Maskawa



$$V_{CKM}^{4 \times 4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ud_4} \\ V_{cd} & V_{cs} & V_{cb} & V_{cd_4} \\ V_{td} & V_{ts} & V_{tb} & V_{td_4} \\ V_{u_4d} & V_{u_4s} & V_{u_4b} & V_{u_4d_4} \end{pmatrix}$$

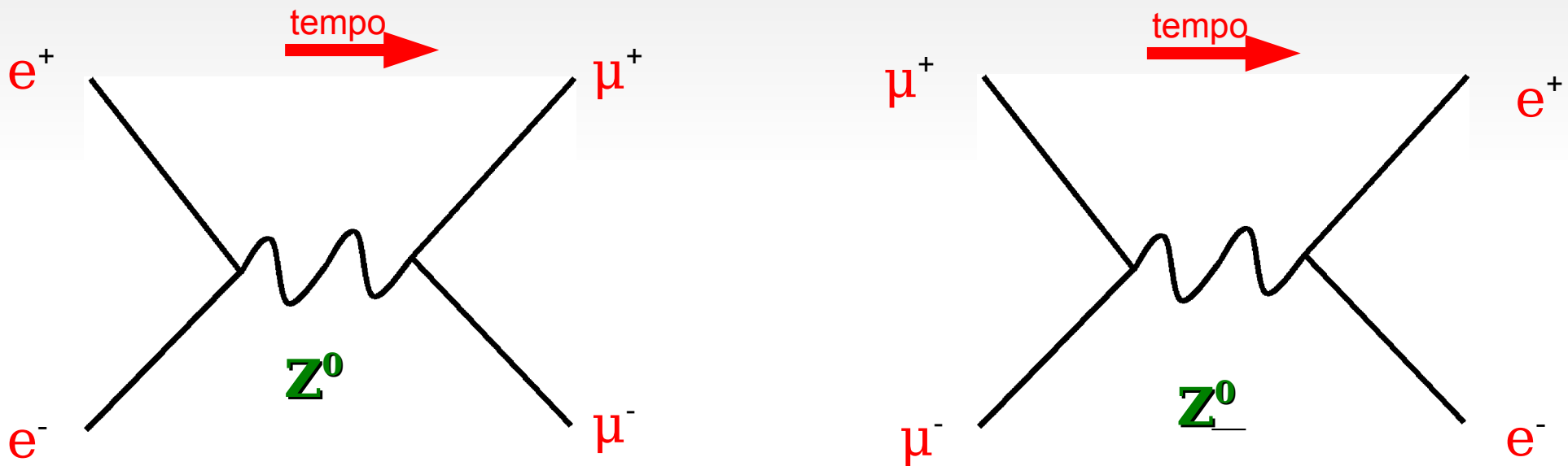
Cabibbo Kobayashi-Maskawa:
4 parameters, 3 angles and one phase.
9 parameters, 6 angles and 3 phases.

Dinâmica para a
Violação de ~~CP~~

Teorema de CPT

Se aplica a qualquer teoria invariante de Lorentz, onde os observáveis são representados por operadores hermitianos.

Violação de CP → Irreversibilidade.

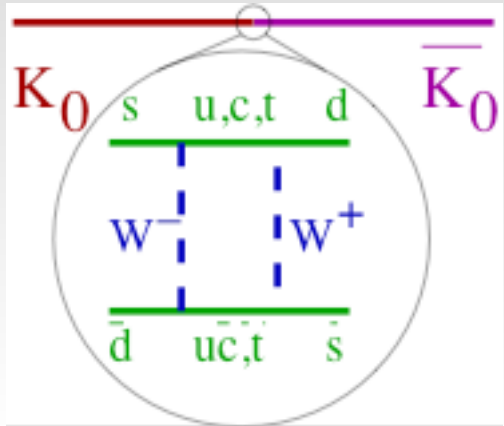


Transformação em tempo deve ser descrita por uma transformação unitária e complexa $e^{-iEt} \rightarrow T \rightarrow e^{iEt}$.

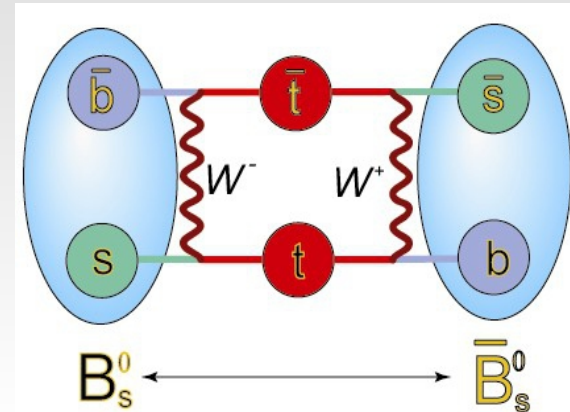
Violação de CP implica na existência de uma fase.

Particle and anti-particle oscillation

$$K^0 \rightleftharpoons \bar{K}^0$$



$$B_s^0 \rightleftharpoons \bar{B}_s^0$$

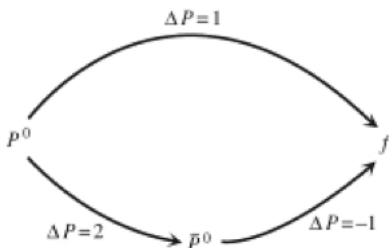


CP violation: Neutral particle and anti-particle decaying into a same final state: (P.ex. $\pi^+\pi^-$, J/ψ or K^+K^-)

Master Equation:

$$\langle \alpha | T(t) | P^0 \rangle = e^{-(\Gamma/2 - i\Delta m)t} [T(P^0 \rightarrow \alpha) \cos \Delta m t + q/p T(\bar{P}^0 \rightarrow \alpha) \sin \Delta m t]$$

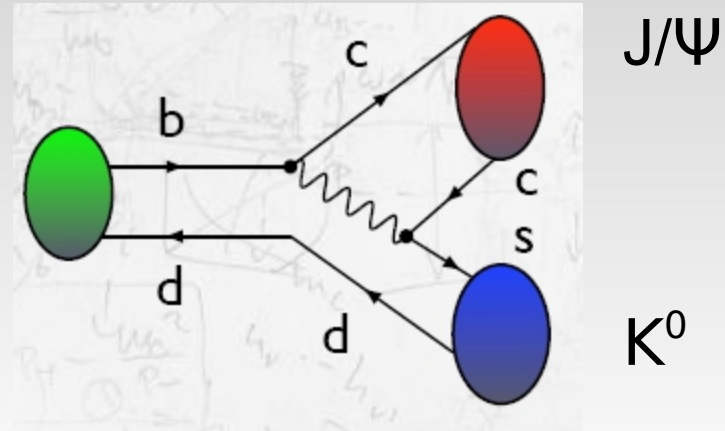
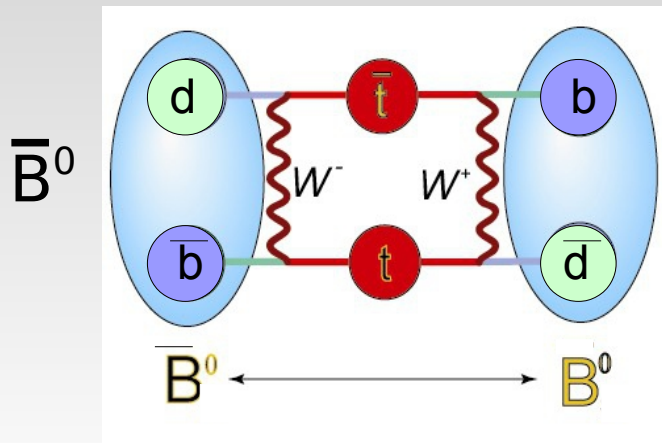
$$\langle \alpha | T(t) | \bar{P}^0 \rangle = e^{-(\Gamma/2 - i\Delta m)t} [T(\bar{P}^0 \rightarrow \alpha) \cos \Delta m t + p/q T(P^0 \rightarrow \alpha) \sin \Delta m t]$$



IF $q/p \neq p/q \rightarrow$ CP violation.

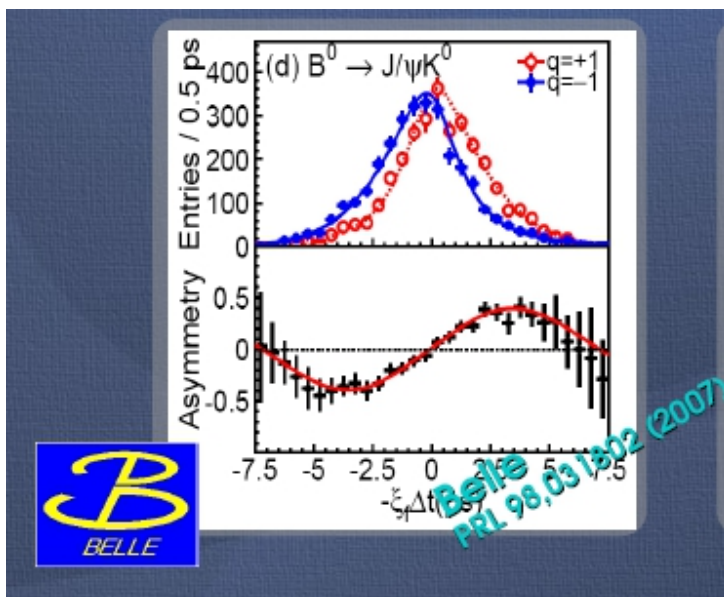
Δm mass difference between B^0 and \bar{B}^0

~~CP~~ violation dynamic to $B^0 \rightleftharpoons \bar{B}^0$ oscillation



$$\frac{\Gamma(B^0(t) \rightarrow J/\psi K_S) - \Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S)}{\Gamma(B^0(t) \rightarrow J/\psi K_S) + \Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S)} = \sin(2\beta) \sin(\Delta m t)$$

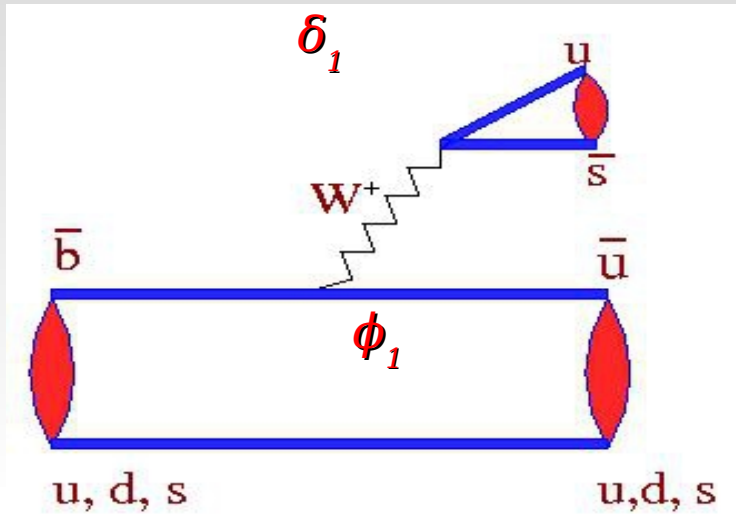
$\Gamma(B^0(t) \rightarrow J/\psi K_S)$ is the probability to B^0 decay in the $J/\psi K_S$ final state at the time t .



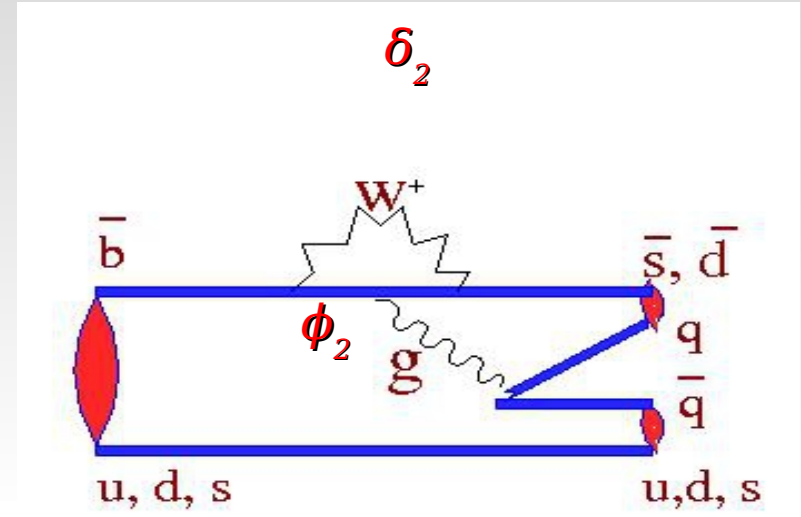
$$\sin 2\beta = 0.68 \pm 0.025 \pm 0.020$$

Directly CP violation:

Single final state like $B^0 \rightarrow K^+ \pi^-$ decay,
with different rate to particle and anti-particle.



Interference \Rightarrow ~~CP~~



Phases ϕ_i change sign with charge conjugate operation: weak phase.

Phases δ_i no change sign with charge conjugate operation: strong phase.

$$\langle f|T|i\rangle = A_1 e^{i(\delta_1 + \phi_1)} + A_2 e^{i(\delta_2 + \phi_2)},$$

$$\langle \bar{f}|T|\bar{i}\rangle = A_1 e^{i(\delta_1 - \phi_1 + \theta)} + A_2 e^{i(\delta_2 - \phi_2)} \dots$$

$$|\langle f|T|i\rangle|^2 - |\langle \bar{f}|T|\bar{i}\rangle|^2 = -4A_1 A_2 \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2).$$

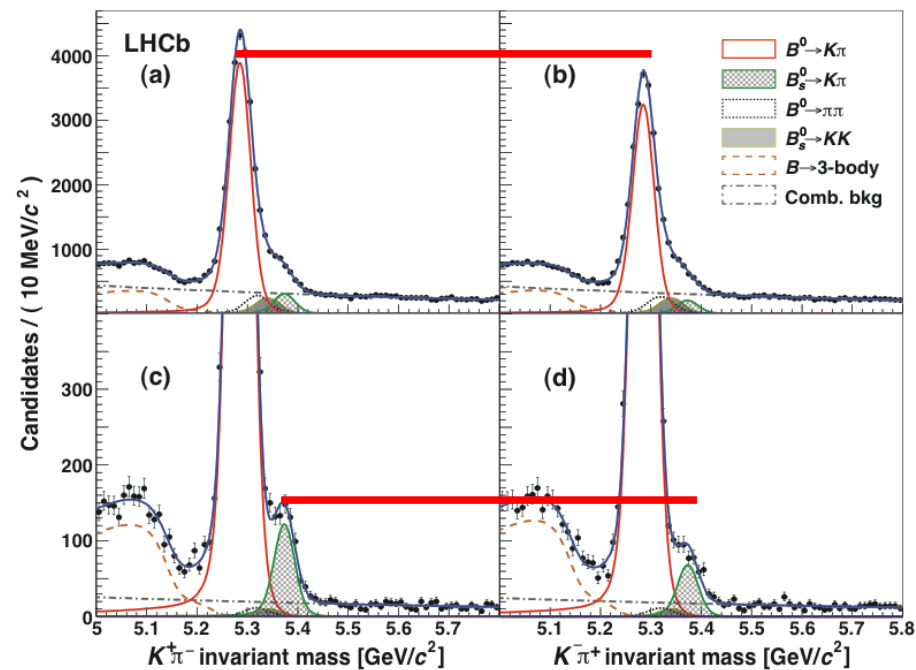
Directly CP violation: two amplitudes with different strong and weak phase.

Directly CP violation for : $B^0 \rightarrow K^+ \pi^-$ e $B^0 \rightarrow K^+ \pi^-$ _s

LHCb: *Phys. Rev. Lett.* 110, 221601 (2013)

Directly CP violation:

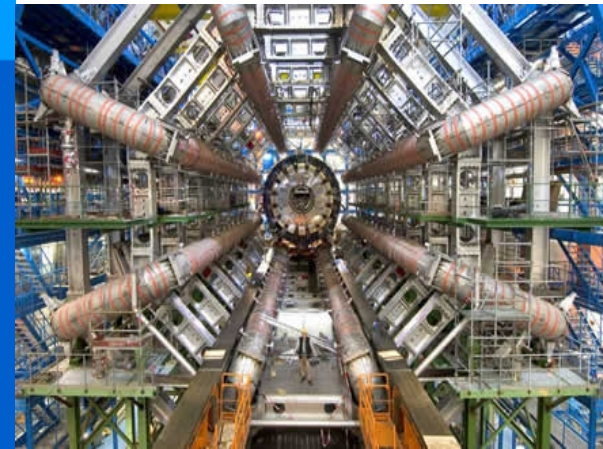
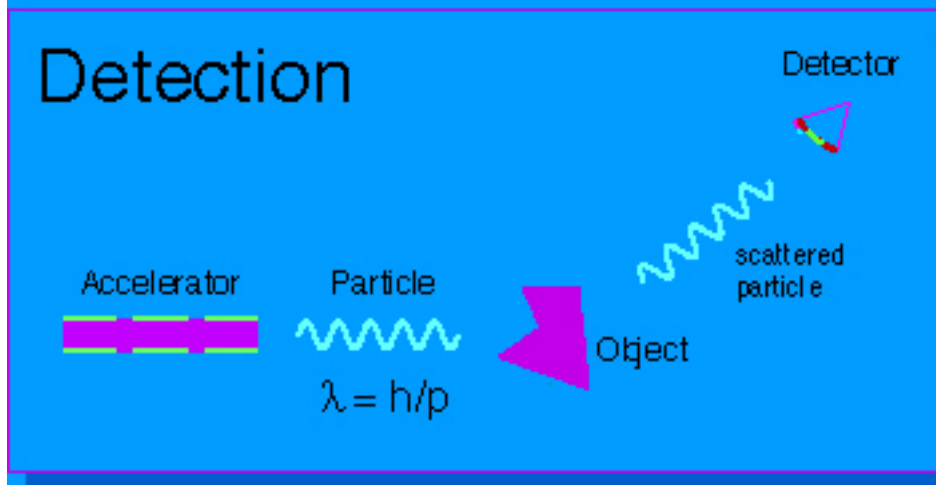
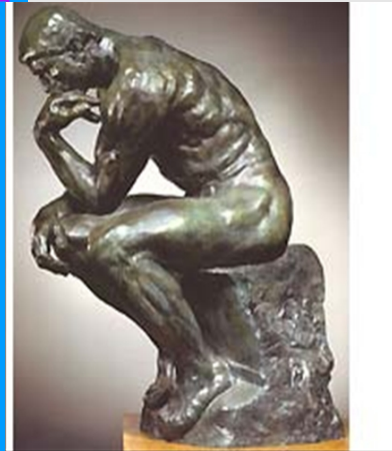
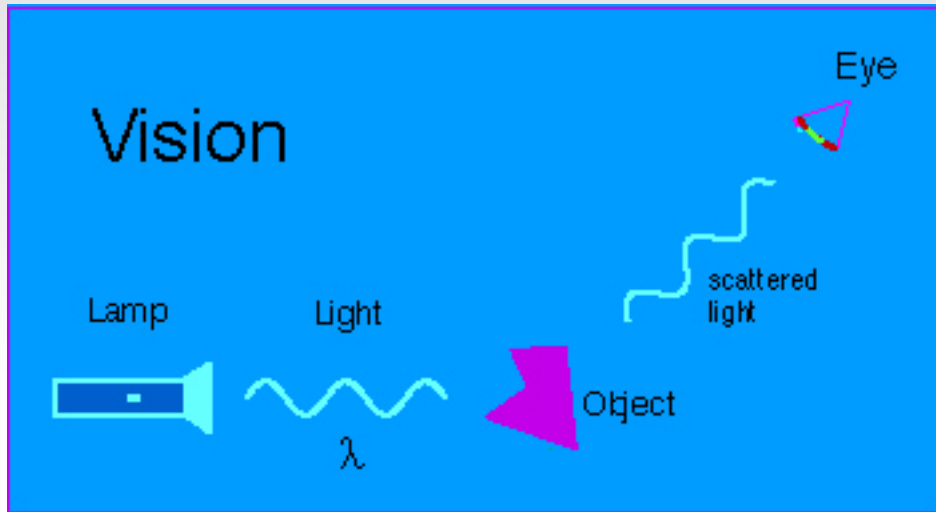
simple counting of events between charge conjugates final states.



$$A_{cp}(B^0 \rightarrow K^+ \pi^-) = \frac{|\langle K^+ \pi^- | T | B^0 \rangle|^2 - |\langle K^- \pi^+ | T | \bar{B}^0 \rangle|^2}{|\langle K^+ \pi^- | T | B^0 \rangle|^2 + |\langle K^- \pi^+ | T | \bar{B}^0 \rangle|^2}$$

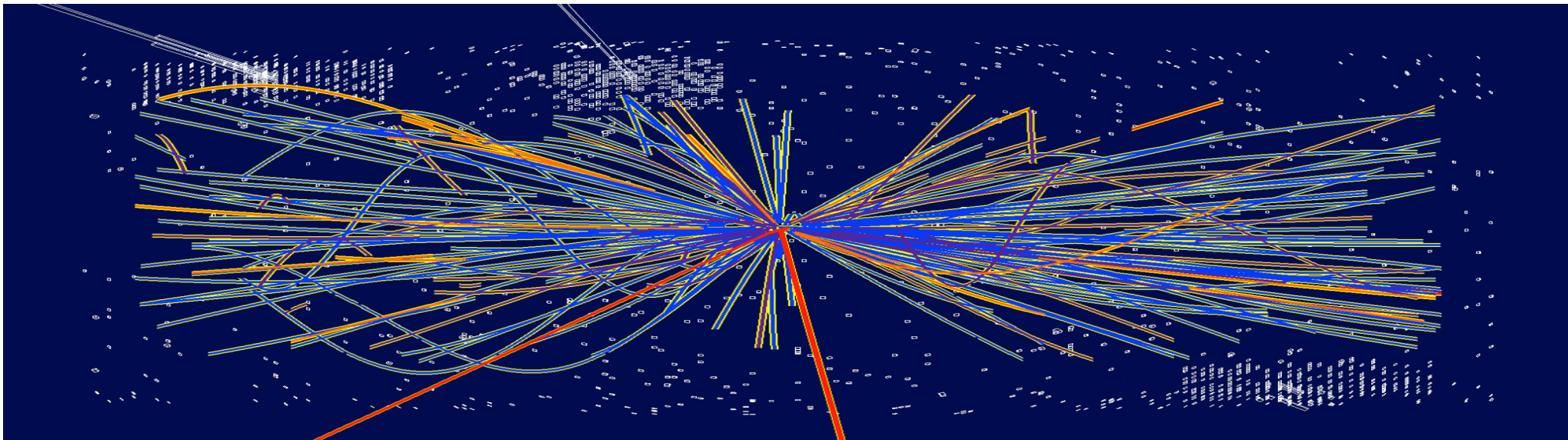
Particle detection

Observação de partículas



Metas do aparato LHC

- ▶ *Energia no centro de massa 13000GeV
(6500 GeV contra 6500 GeV)*
- ▶ *40 milhões de colisões por segundo/detector*
- ▶ *Um ordem maior em energia e duas em quantidade de
colisões que o Tevatron do Fermilab*
- ▶ *Criação de cerca de 100 partículas por colisão*

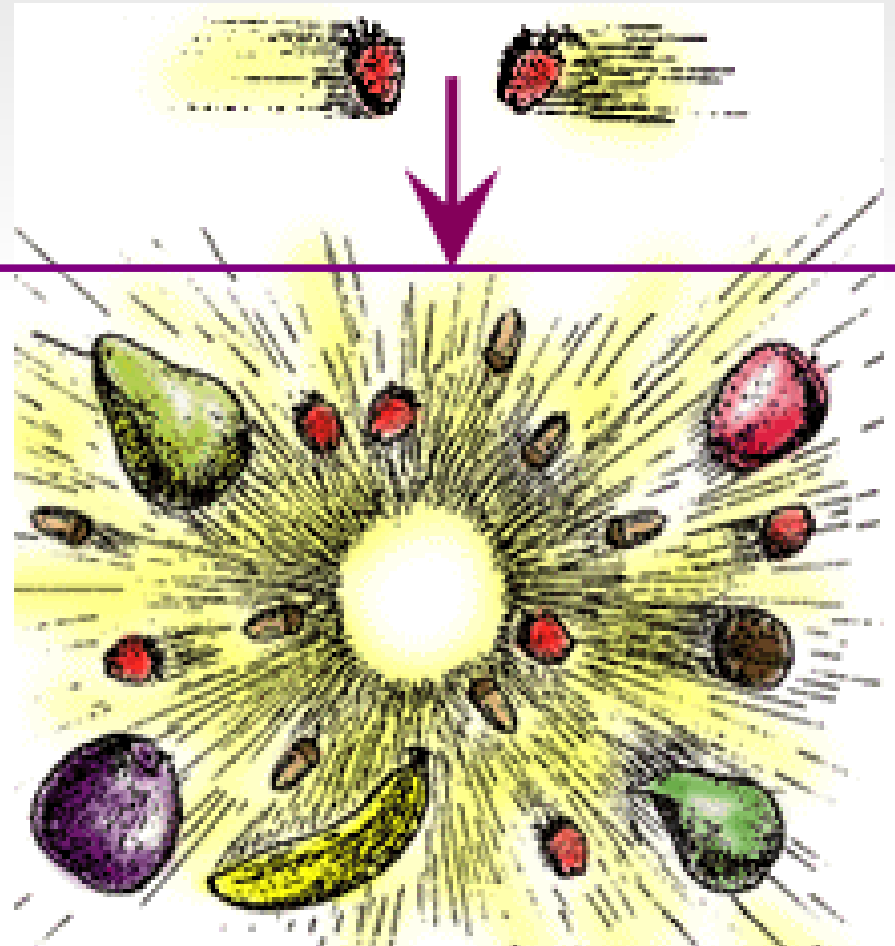




How can we observe particle with little lifetime?

- ◆ Collision

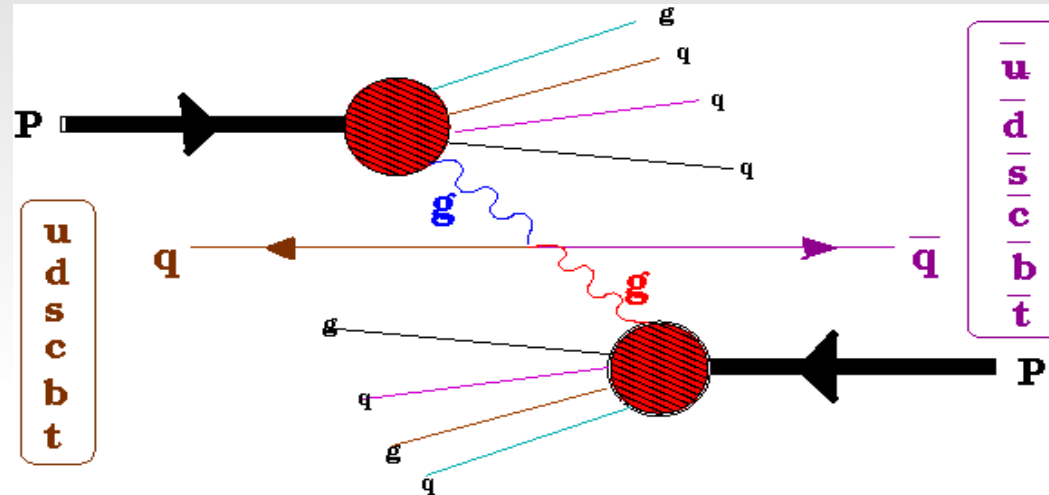
*Energy given in the
accelerator → Mass*



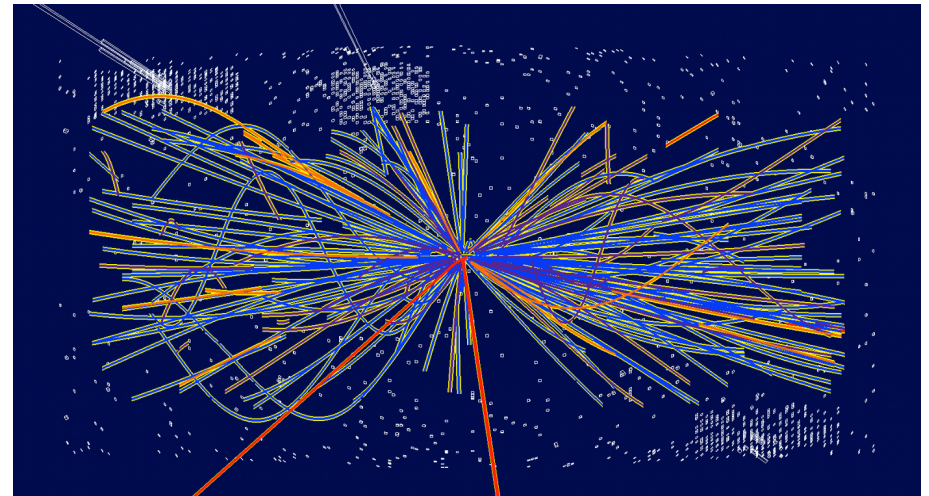
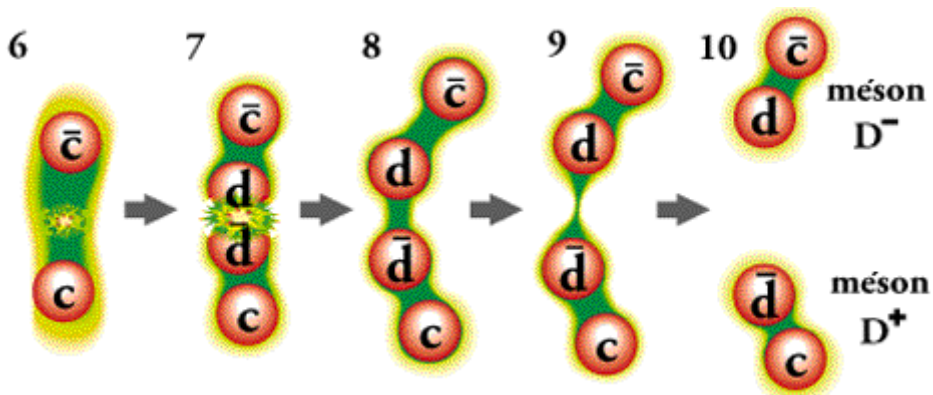


Particle observation.

High energy particle collision.

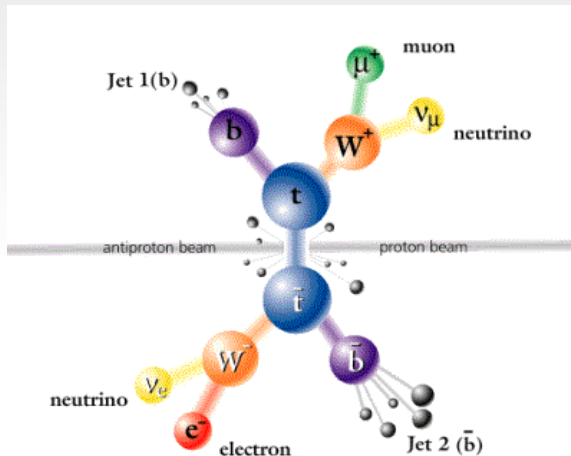


Hadronization: quarks to hadrons.

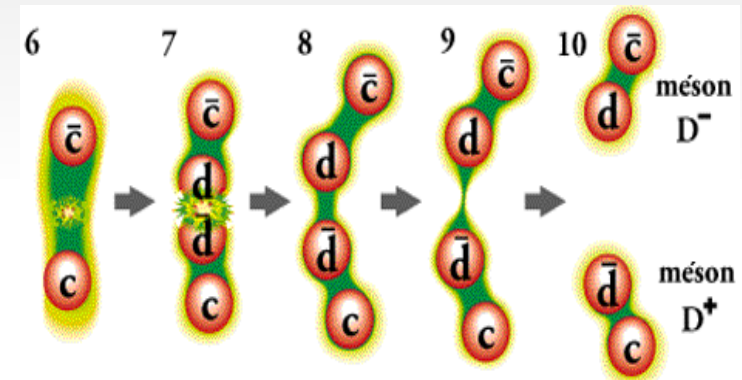


Desintegração-criação e hadronização

- ◆ Dezenas de possíveis desintegrações-criações



- ◆ Dezenas de hadronizações



- ◆ Centenas de possibilidades de observação.

Nenhuma observação direta, para vidas médias menores 10^{-10} s



Reconstrução do evento;

Massa invariante e/ou massa faltante e/ou jatos

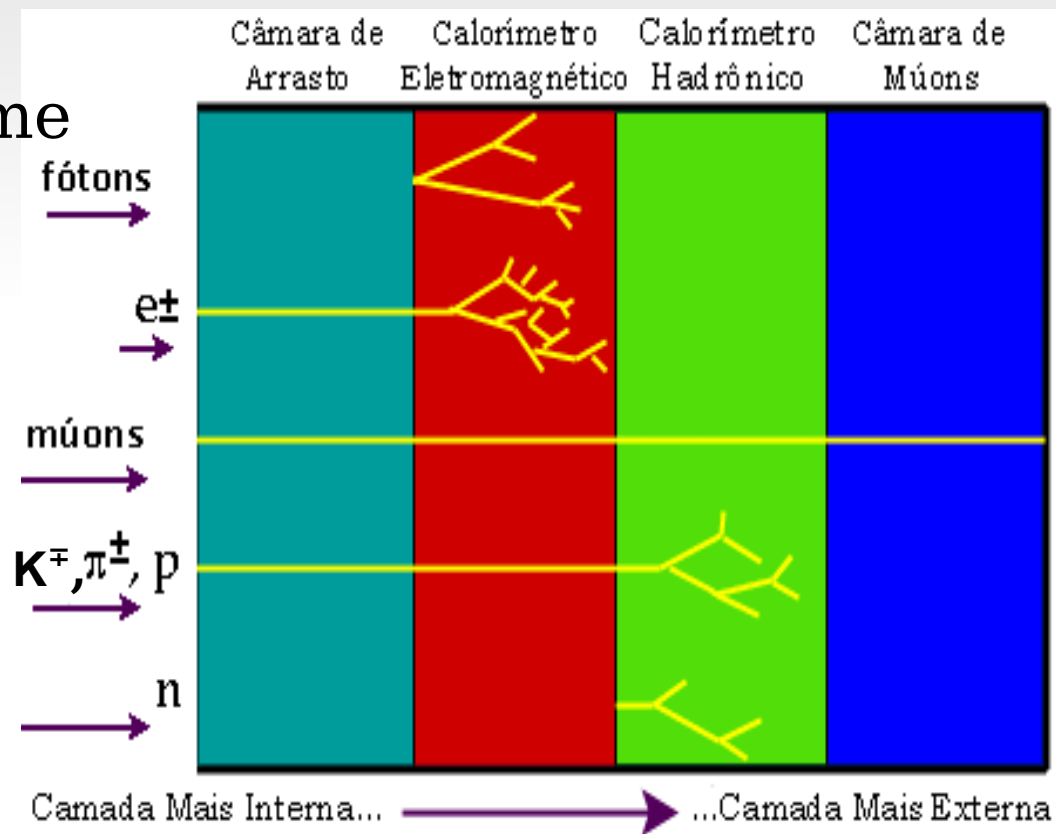


Directly observation

- Charged particles with lifetime less than 10^{-10} s:

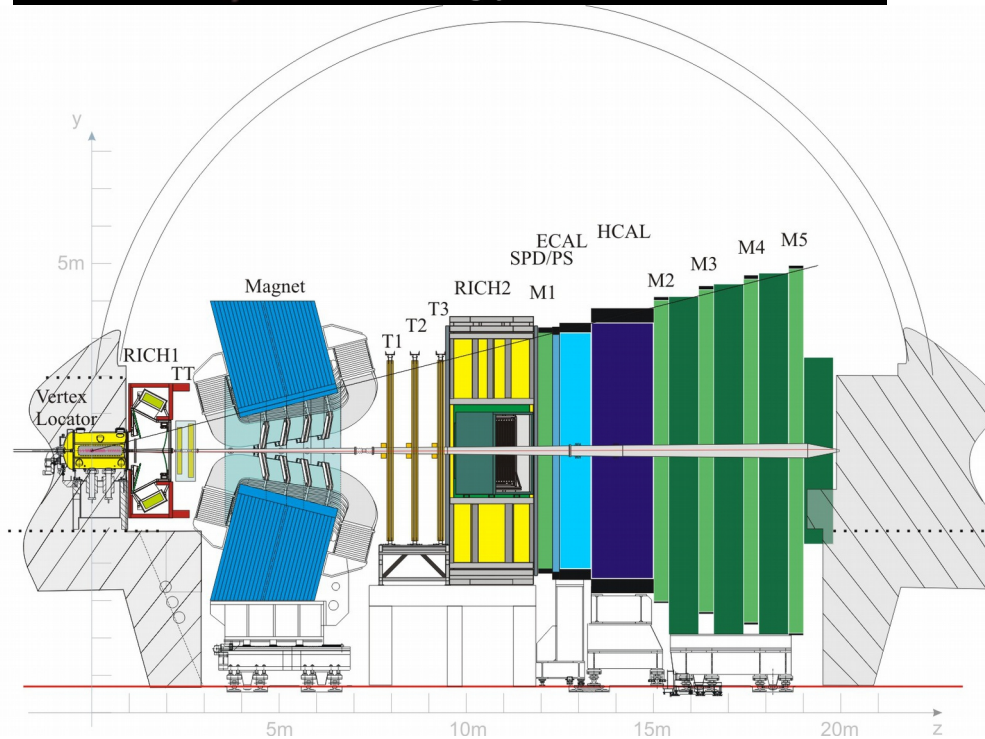
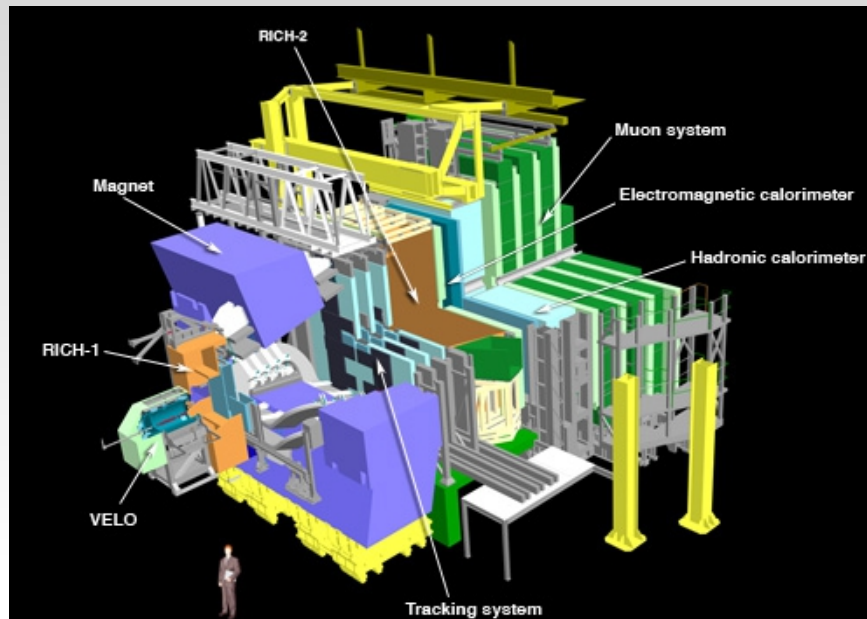
- **proton, electron, muon, meson π e meson K**

- Neutral particles:
fóton, nêutron and K^0



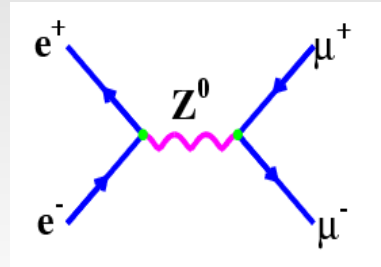


Detector LHCb

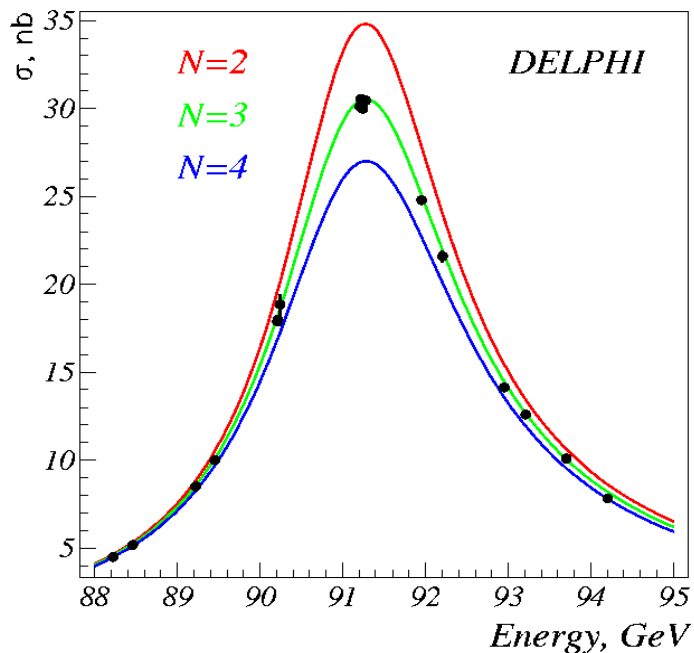


Conservação da energia

- Desintegração do bóson $Z^0 \rightarrow \mu^+ \mu^-$



- O quadrimomento do Z^0 é igual a soma dos quadrimomentos do μ^+ mais a do μ^-



- Natureza das partículas
- Energia total de cada μ
- Análise estatística



Mass equation

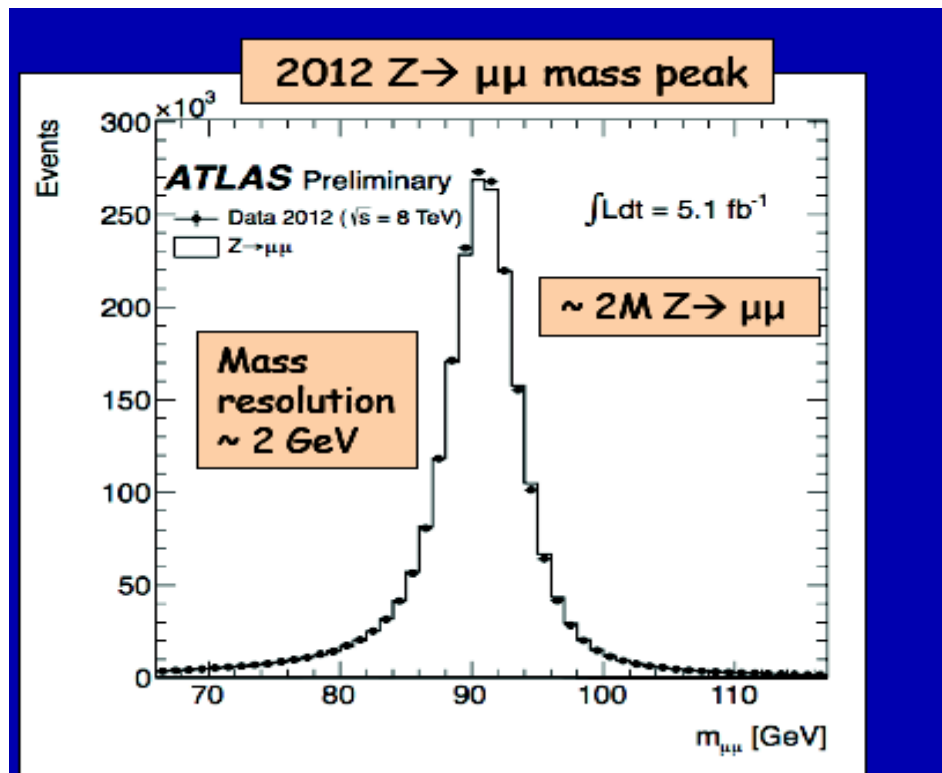
- ▶ Gauge boson desintegration



Quadri-momentum conservation $M_z^2 = (P_{\nu Z})^2 = (P_{\nu}^{\mu^+} + P_{\nu}^{\mu^-})^2 \quad \underline{C=1}$

$$M_{\mu^+\mu^-}^2 = (P_{\mu^+}^{\nu} + P_{\mu^-}^{\nu})^2 = m_{\mu^+}^2 + m_{\mu^-}^2 + 2E_{\mu^+} \cdot E_{\mu^-} + 2\vec{P}_{\mu^+} \cdot \vec{P}_{\mu^-}$$

$$= m_{\mu^+}^2 + m_{\mu^-}^2 + 2\sqrt{|\vec{P}_{\mu^+}|^2 + m_{\mu^+}^2} \cdot \sqrt{|\vec{P}_{\mu^-}|^2 + m_{\mu^-}^2} + 2\vec{P}_{\mu^+} \cdot \vec{P}_{\mu^-}$$

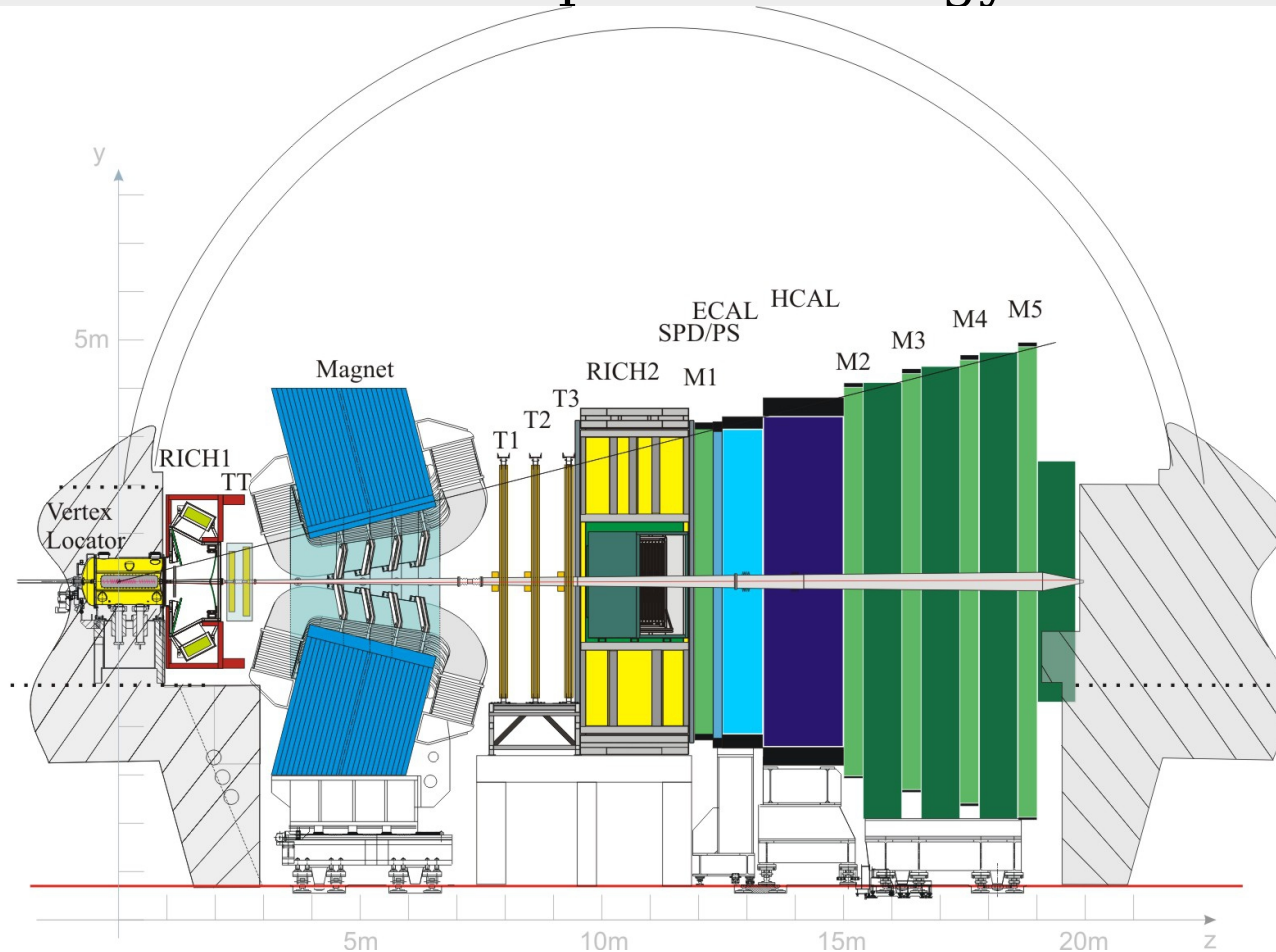


$$BW = \left| \frac{\sqrt{m_{Z^0} \Gamma}}{m_{Z^0}^2 - M_{\mu^+\mu^-}^2 - im_{Z^0} \Gamma} \right|^2$$



Events observation

- ▶ Nature of the particles
- ▶ Tri-momentum of the charges particles
- ▶ Neutral particle energy



Informação produzida no ATLAS

150 Milhões de sensores

Leitura destes: 40 Milhões de vezes por segundo





LHC Computer Grid



WLCG
Worldwide LHC Computing Grid

5/16/2011 2:00:00



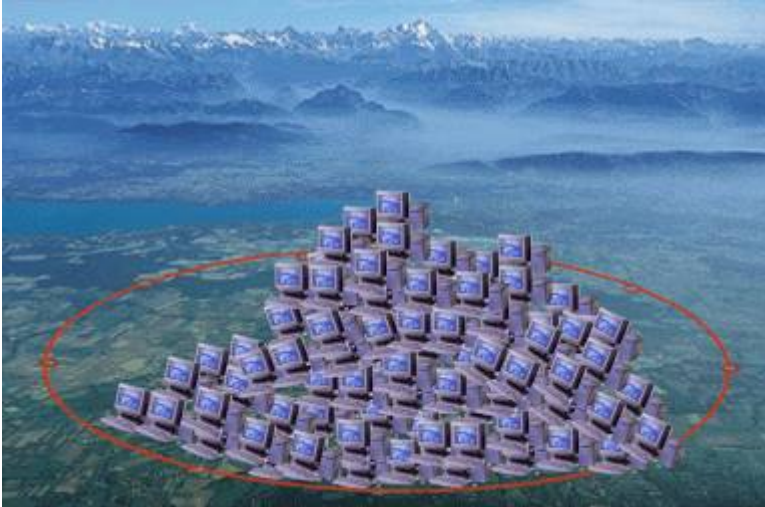
US Dept. of State Geographer
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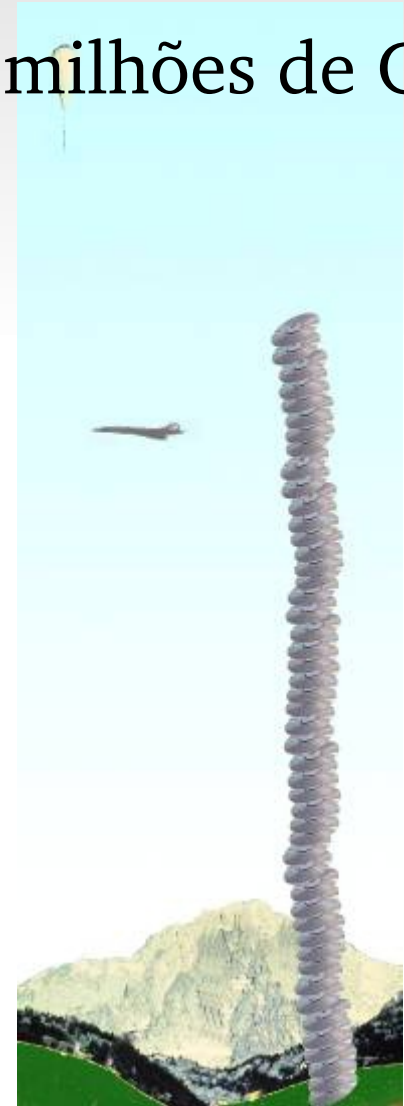
Altitude do ponto de visão 14409,53 km

Onde processar e guardar essa informação?

- ▶ 200 Mil computadores



- ▶ 20 milhões de CD's

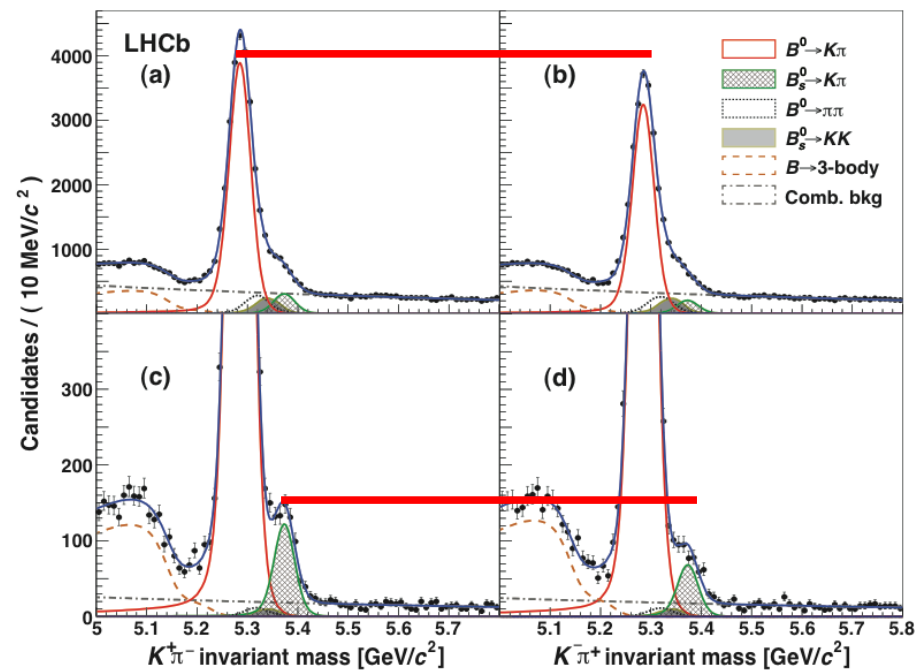


Directly ~~CP~~ violation for : $B^0 \rightarrow K^+ \pi^-$ e $B^0 \rightarrow K^+ \pi^-$ _s

LHCb: *Phys. Rev. Lett.* 110, 221601 (2013)

Directly CP violation:

simple counting of events between charge conjugates final states.



$$A_{cp}(B^0 \rightarrow K^+ \pi^-) = \frac{|\langle K^+ \pi^- | T | B^0 \rangle|^2 - |\langle K^- \pi^+ | T | \bar{B}^0 \rangle|^2}{|\langle K^+ \pi^- | T | B^0 \rangle|^2 + |\langle K^- \pi^+ | T | \bar{B}^0 \rangle|^2}$$

*Participação Brasileira
na análise dos dados:*

Decaimento em três corpos.



Participação Brasileira

CBPF

IF-UFRJ

PUC-Rio

♦ Professores/pesquisadores	15
♦ Tecnólogos e tecnologistas	7
♦ Alunos de doutoramento	4
♦ Aluno de mestrado	7
♦ Pós – doutores	4
♦ Total	37

Violação de CP em desintegração
do B em três corpos.

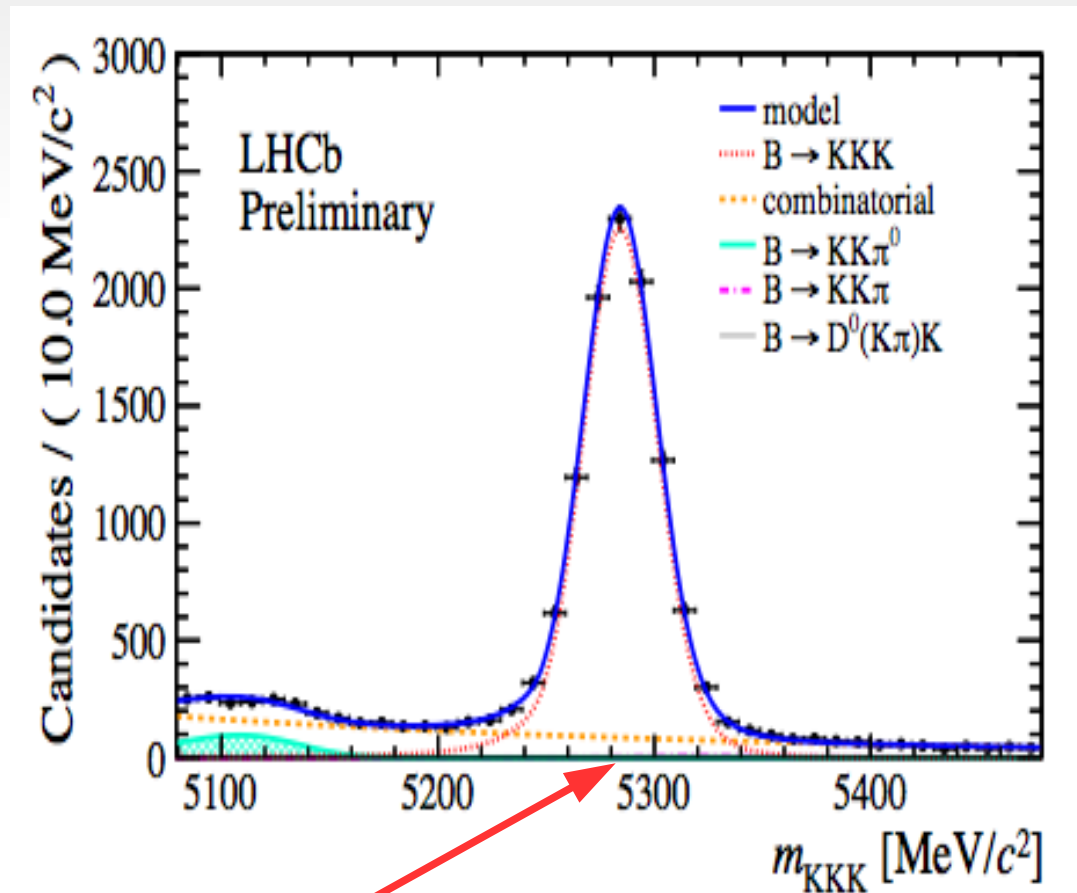


Invariant mass

$$B^\mp \rightarrow K^\mp K^- K^+$$

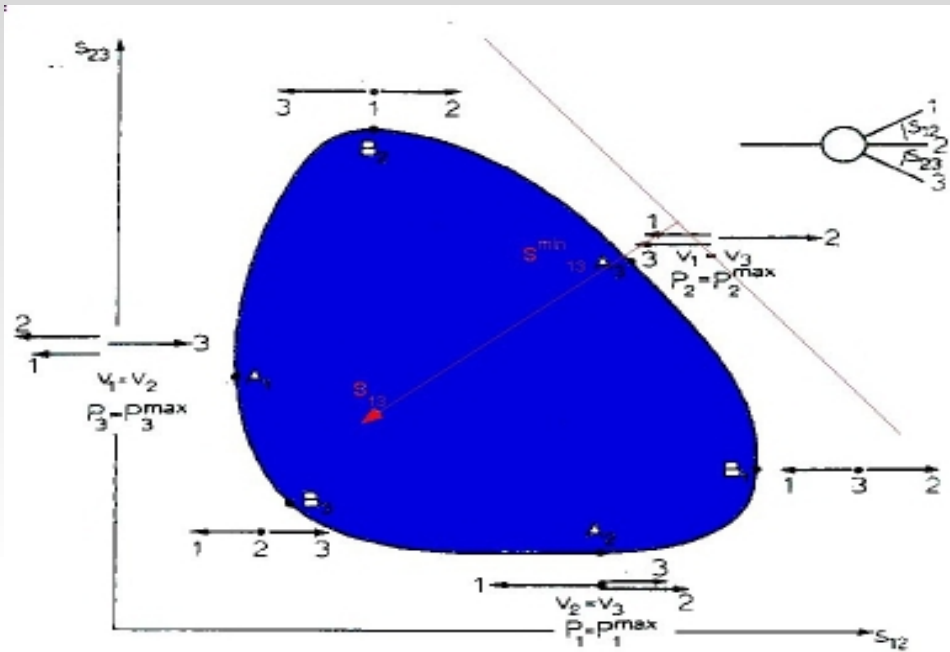
momentum
conservation

$$M_B^2 = (P_B^\nu)^2 = (P_{K^+}^\nu + P_{K^-}^\nu + P_{K^+}^\nu)^2$$



B^\mp Mass = 5278 MeV

Dalitz Plot



$$s_{12} = M_{12}^2 = (p_1^\nu + p_2^\nu)^2$$

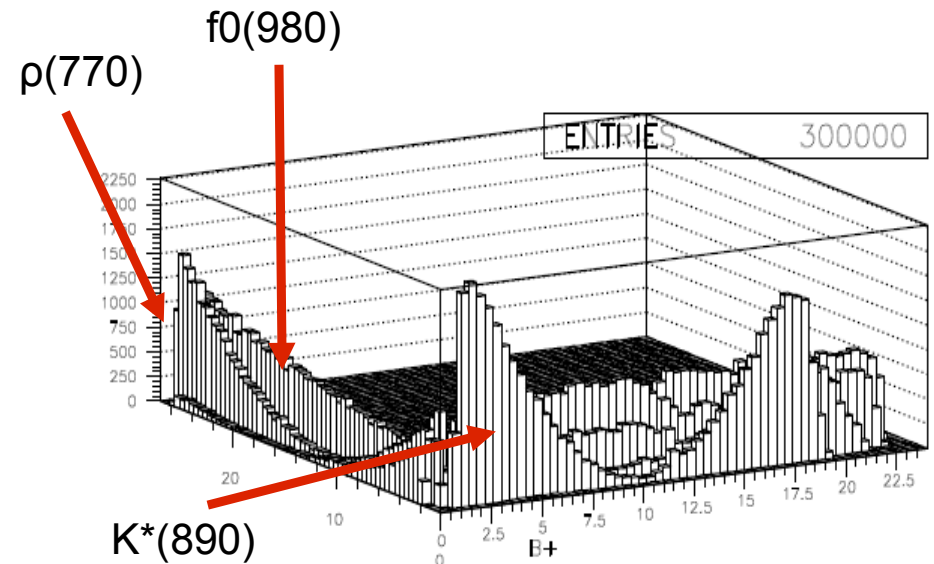
$$s_{13} = M_{13}^2 = (p_1^\nu + p_3^\nu)^2$$

$$s_{23} = M_{23}^2 = (p_2^\nu + p_3^\nu)^2$$

Flat phase space where it is write the dynamics.

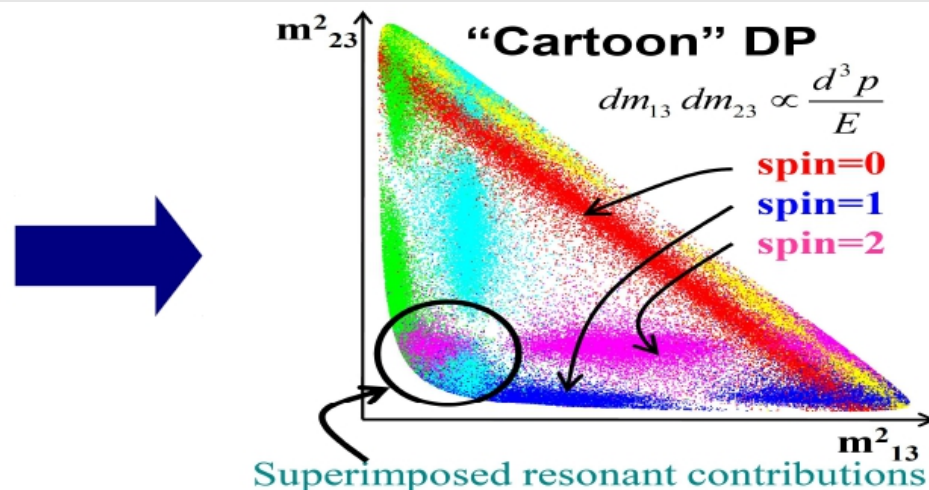
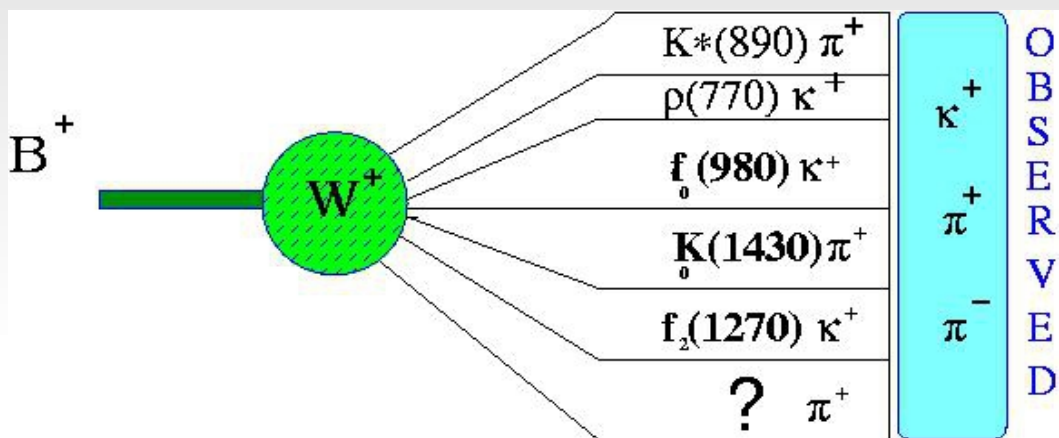
$$d\Gamma(s_{12}, s_{23}) = \frac{1}{(2\pi)^3 32 M_B^3} |\mathcal{M}|^2 ds_{12} ds_{23}$$

$|M|^2 \Rightarrow$ resonances



Charmless three body B charge decays

Study the B decays and their intermediary states:



- $B^\pm \rightarrow \pi^\pm \pi^+ \pi^-$
- $B^\pm \rightarrow \pi^\pm K^+ K^-$
- $B^\pm \rightarrow K^\pm K^+ K^-$
- $B^\pm \rightarrow \pi^\pm p^- p$
- $B^\pm \rightarrow K^\pm p^- p$

Interference between intermediary states with different weak phases imply in CP violation.

Phases in amplitude analysis

Signature of the phase difference between two interfering resonances

$$|\mathcal{M}|^2 = |a_{\pi^+\pi^-}|^2 + |a_{\pi^+\pi^0}|^2 + 2|a_{\pi^+\pi^-} a_{\pi^+\pi^0}|$$

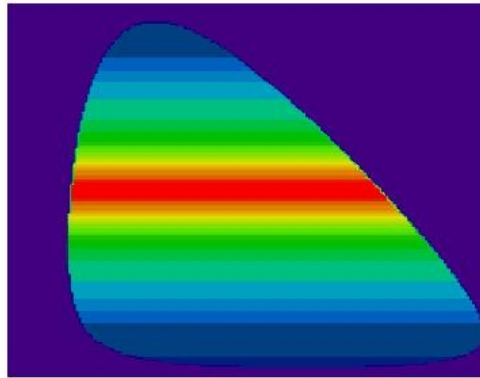


Figure 1: $|a_{\pi^+\pi^-}| = 1, |a_{\pi^+\pi^0}| = 0$

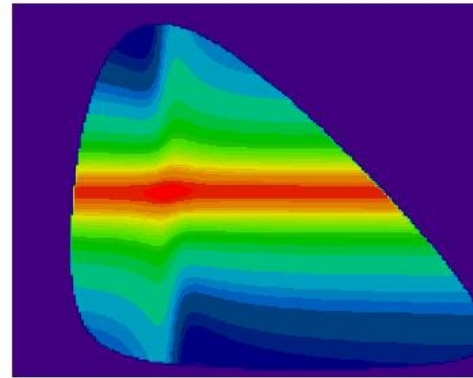


Figure 2: $|a_{\pi^+\pi^-}| = 1, |a_{\pi^+\pi^0}| > 0$

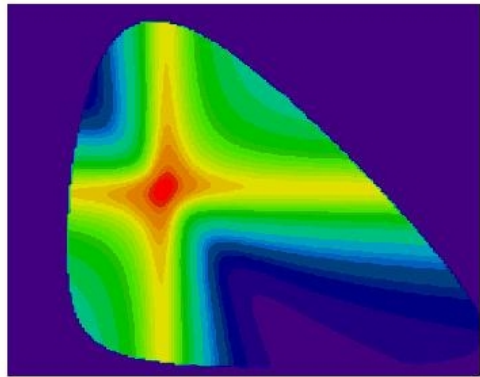


Figure 3: *
 $|a_{\pi^+\pi^-}| = |a_{\pi^+\pi^0}| = 1, \Delta\Phi = 0^\circ$

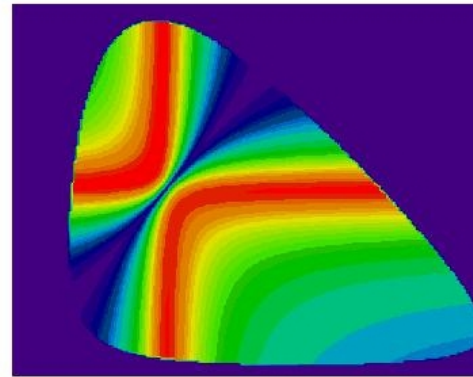


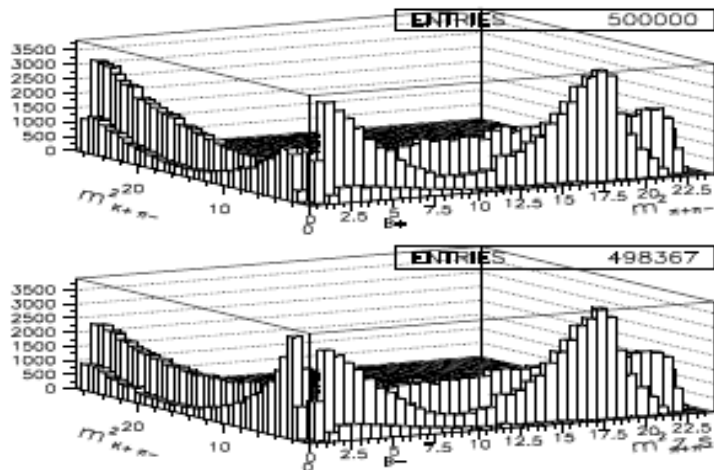
Figure 4: *
 $|a_{\pi^+\pi^-}| = |a_{\pi^+\pi^0}| = 1, \Delta\Phi = 90^\circ$

Search for sources of ~~CP~~ in $B^+ \rightarrow hhh$:

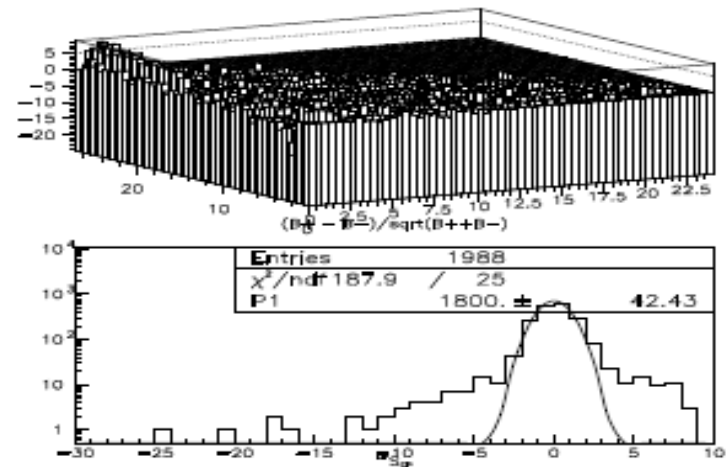
Weak phase change signal for charge conjugated decays,

then interference pattern are different for each Dalitz plane.

$$B^+ \neq B^- \Rightarrow \text{CP}$$



DP ? CP





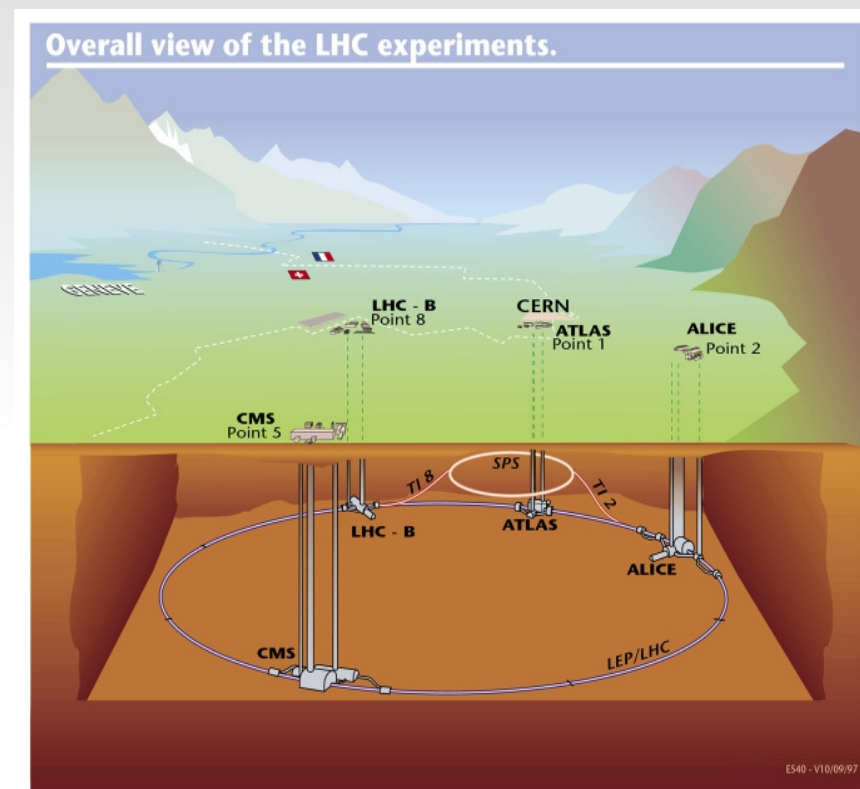
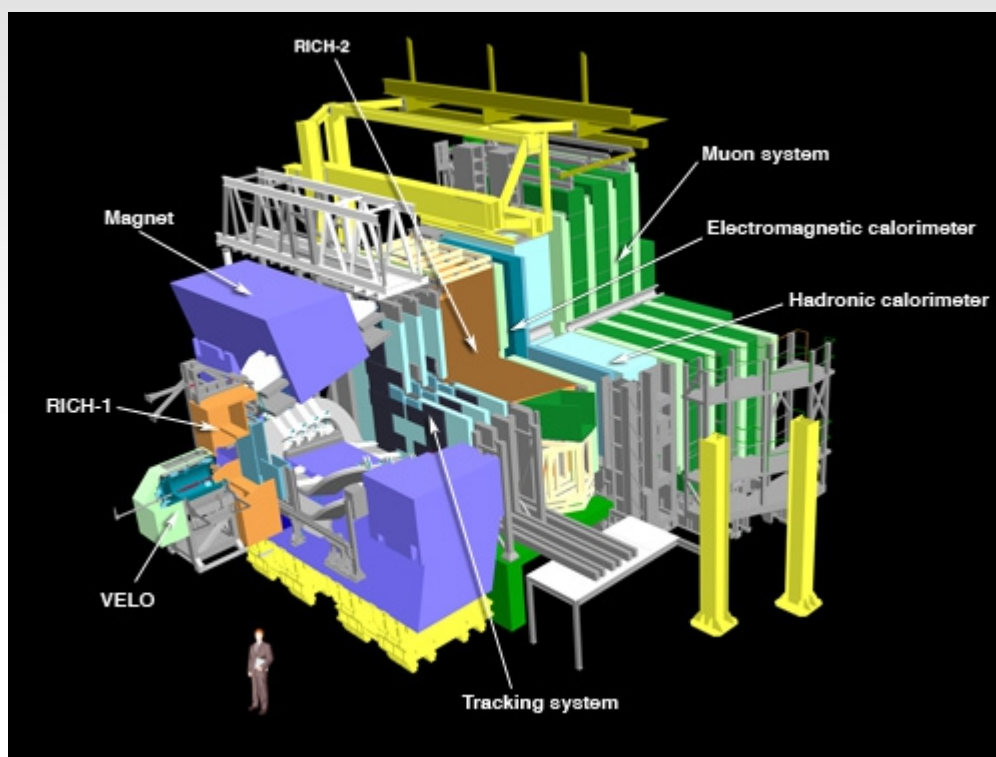
Evidence of CP violation in
 $B^+ \rightarrow K + \pi^+ \pi^-$ and $B^+ \rightarrow K + K + K^-$

Final results

with LHCb 2011 +2012 data

hep/ex-1408.5373, Phys.Rev. D90 (2014) no.11, 112004

LHCb collaboration at LHC



Ten times more B's than Belle and Babar already produced, in one year data taking.

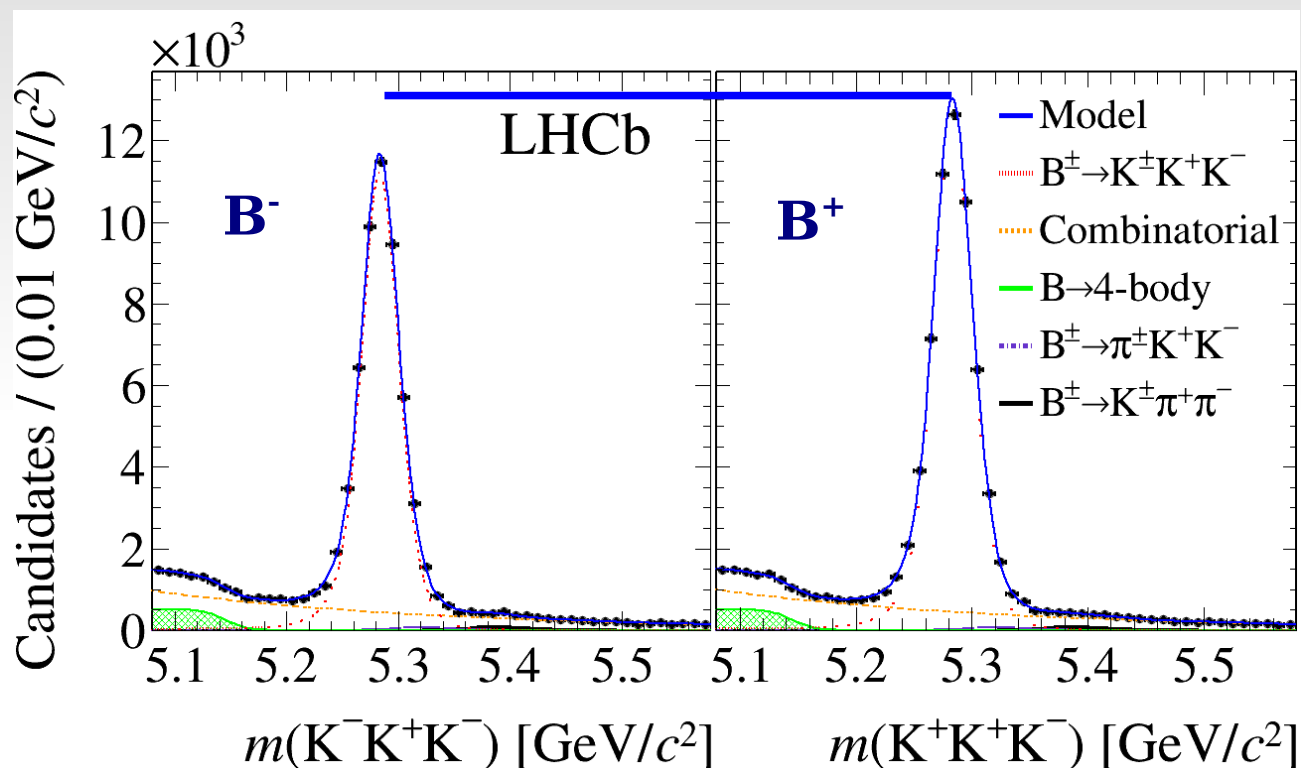
800 collaborators, more than 50 institutions, total cost 100M CHF.

Total charge asymmetry for



hep/ex-1408.5373, Phys.Rev. D90 (2014) no.11, 112004

$$N(B^-) + N(B^+) = 109.240 \pm 556$$



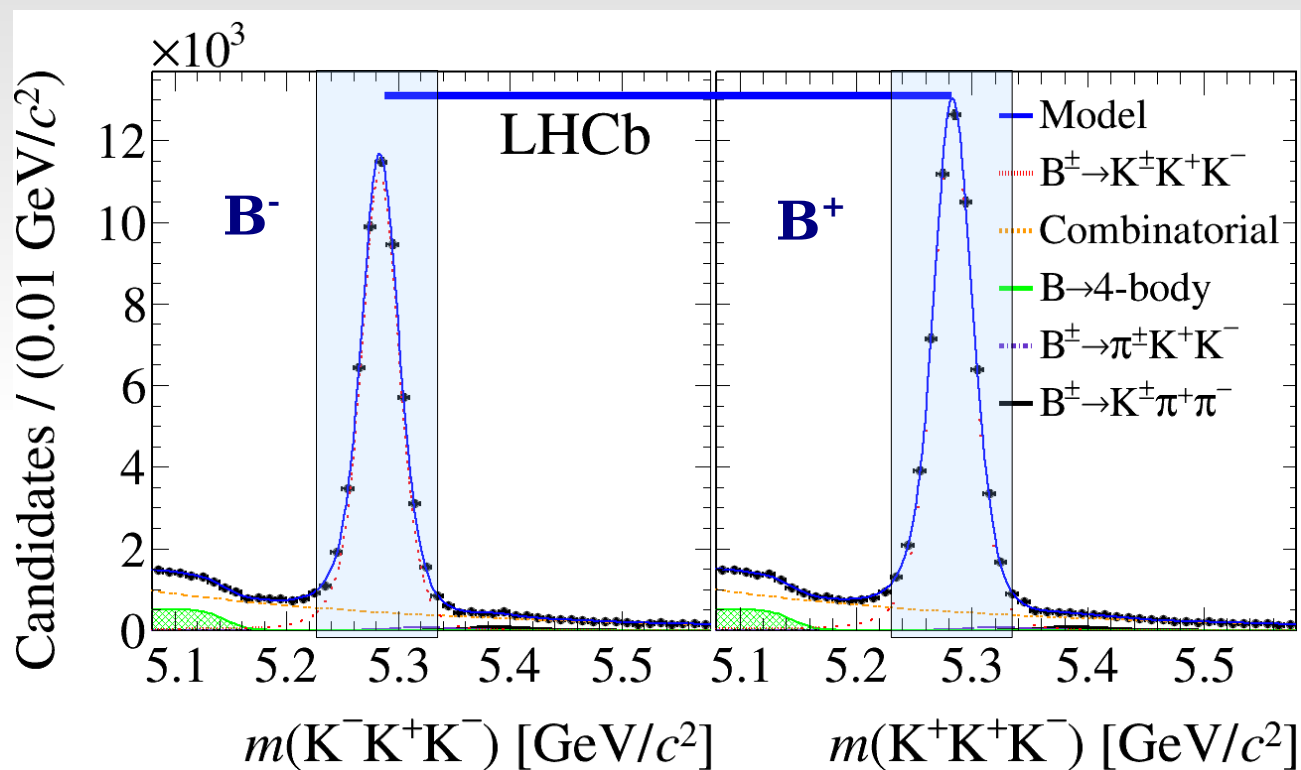
Total charge asymmetry:

$$ACP = \frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)} = -3.6 \pm 0.4(\text{sta}) \pm 0.4(\text{sys})\%$$

Plus an error of 0.7% from the control channel $B^- \rightarrow J/\Psi K^-$

Total charge asymmetry for $B^\mp \rightarrow K^\mp K^+ K^-$

$$N(B^-) + N(B^+) = 109.240 \pm 556$$



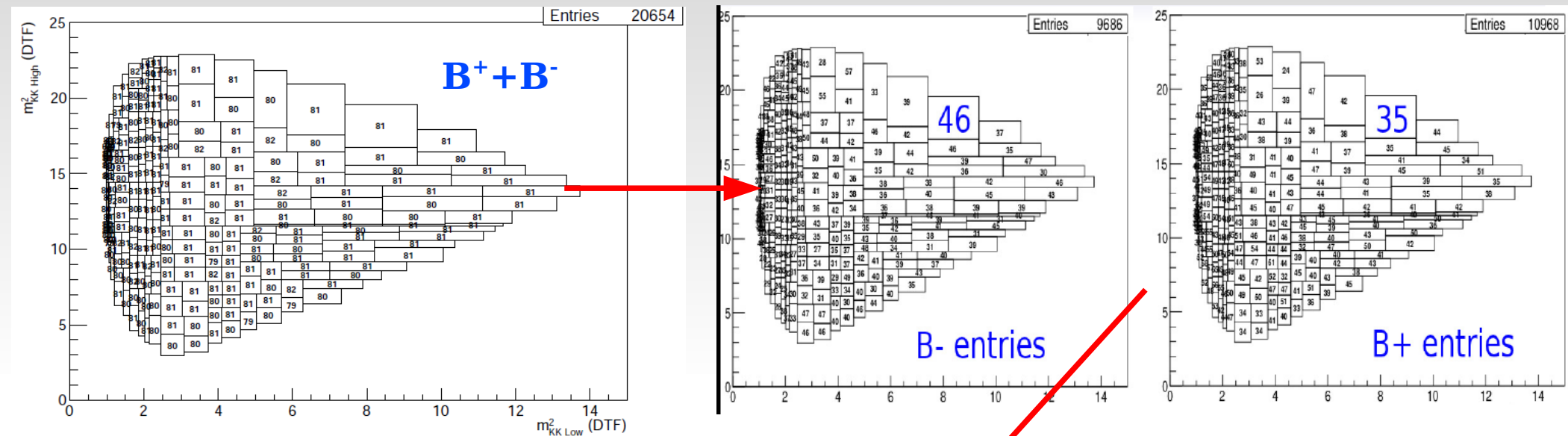
Total charge asymmetry:

$$ACP = \frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)} = -3.6 \pm 0.4(\text{sta}) \pm 0.4(\text{sys})\%$$

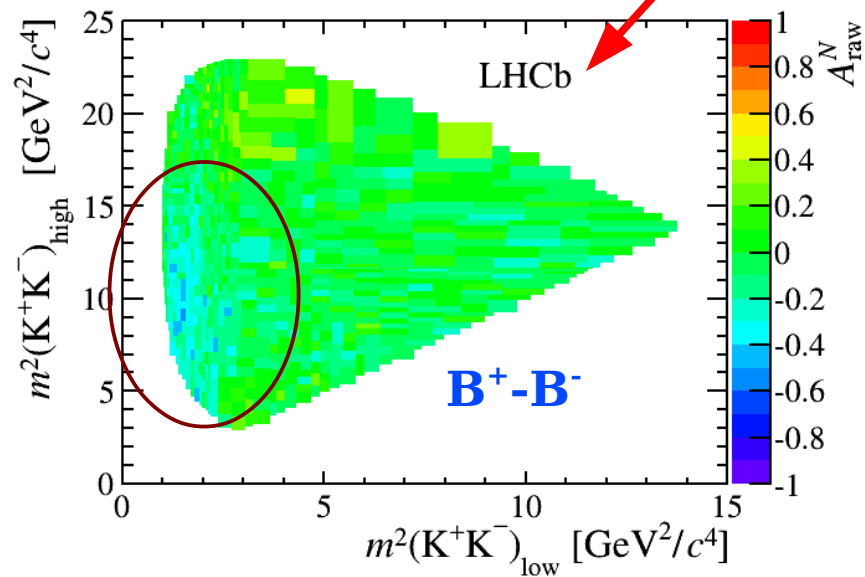
Plus an error of 0.7% from the control channel $B^- \rightarrow J/\psi K^-$

$B^+ - B^-$ Dalitz differences

$M^2_{K^+K^-}$ Vs $M^2_{K^+K^-}$ phase space distribution



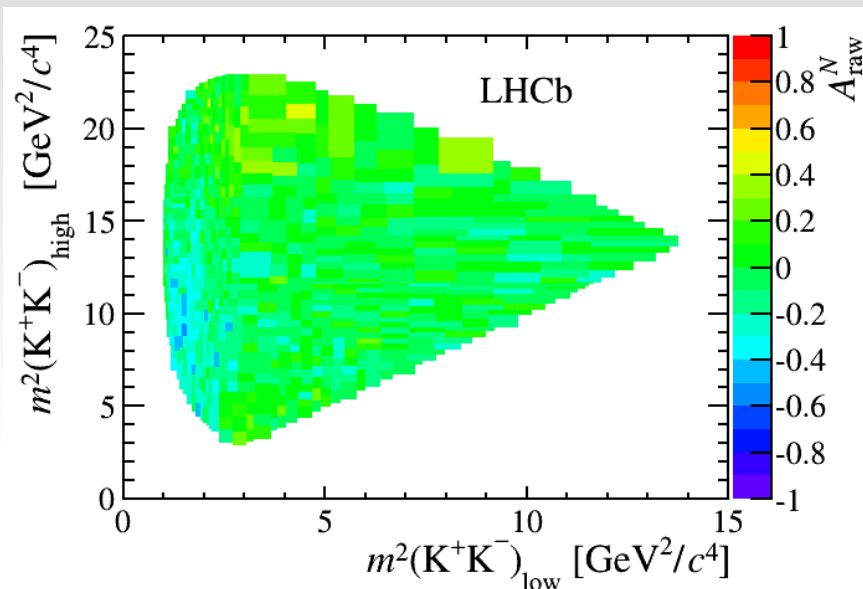
Dalitz Map of the CP violation



$B^+ - B^-$ Dalitz differences

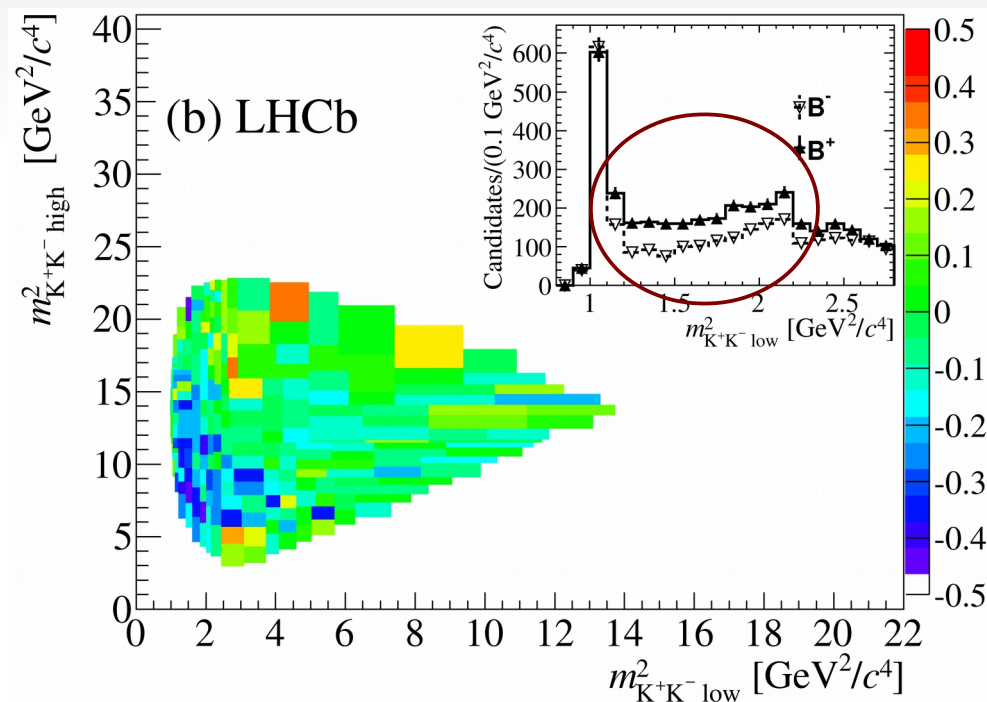
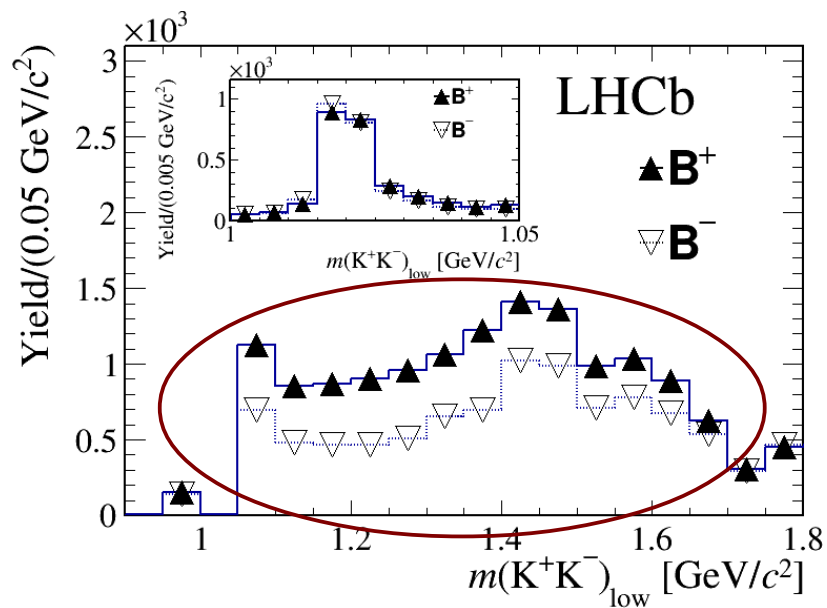
$M^2_{K^+K^-}$ Vs $M^2_{K^+K^-}$ phase space distribution

2011 + 2012 data



2011 data: old analysis and reconstruction.

LHCb: PRL 111, 101801 (2013)

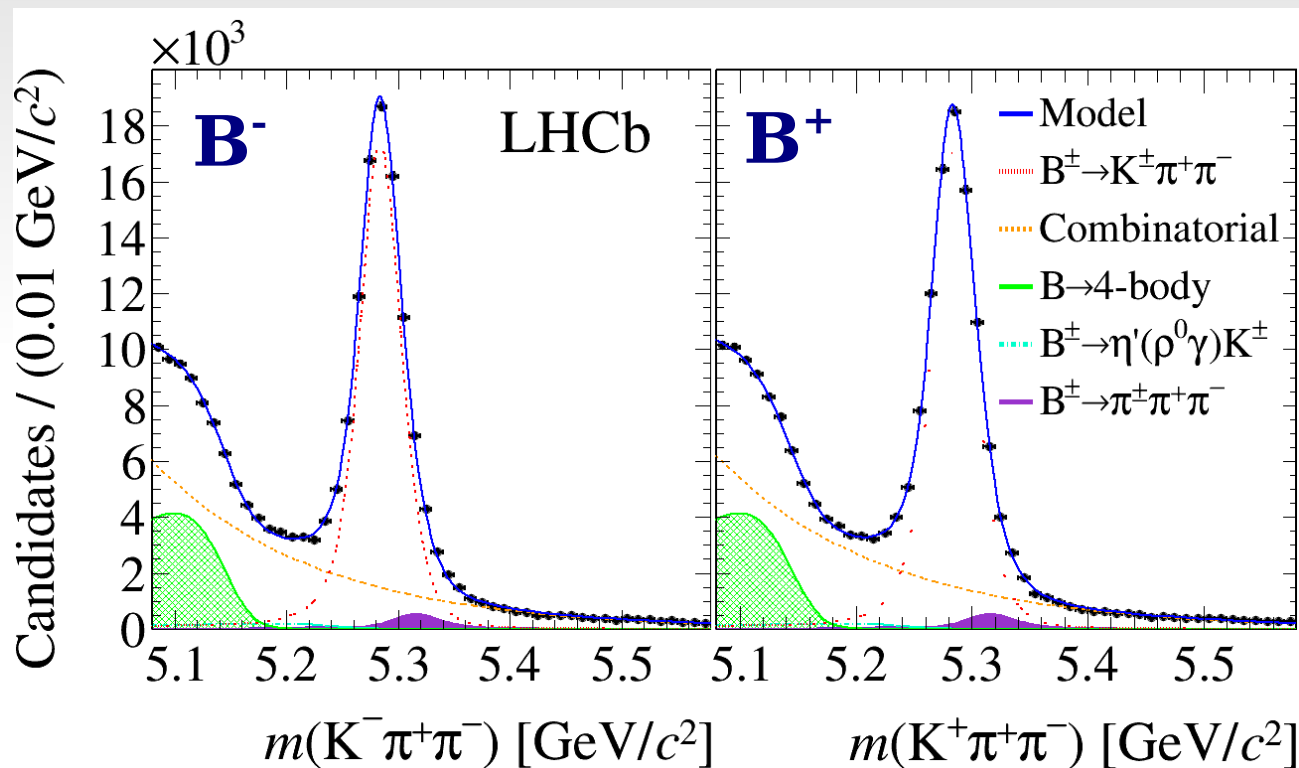


Total charge asymmetry for



hep/ex-1408.5373, Phys.Rev. D90 (2014) no.11, 112004

$$N(B^{-}) + N(B^{+}) = 181\,074 \pm 556$$



Total charge asymmetry:

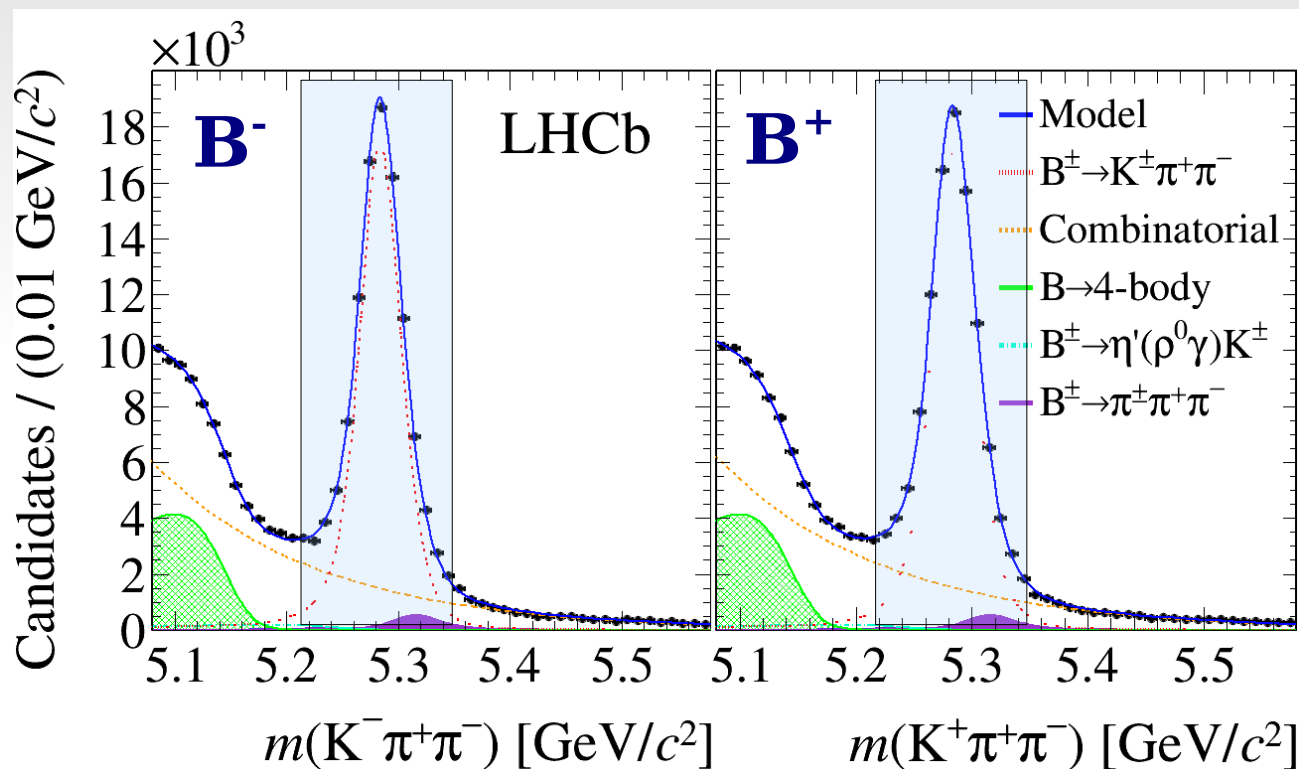
$$ACP = \frac{N(B^{-}) - N(B^{+})}{N(B^{-}) + N(B^{+})} = 2.5 \pm 0.4(\text{sta}) \pm 0.4(\text{sys})\%$$

Plus an error of 0.7% from the control channel $B^{-} \rightarrow J/\Psi K^{-}$

Total charge asymmetry for



$$\mathbf{N(B^-) + N(B^+) = 181\,074 \pm 556}$$



Total charge asymmetry:

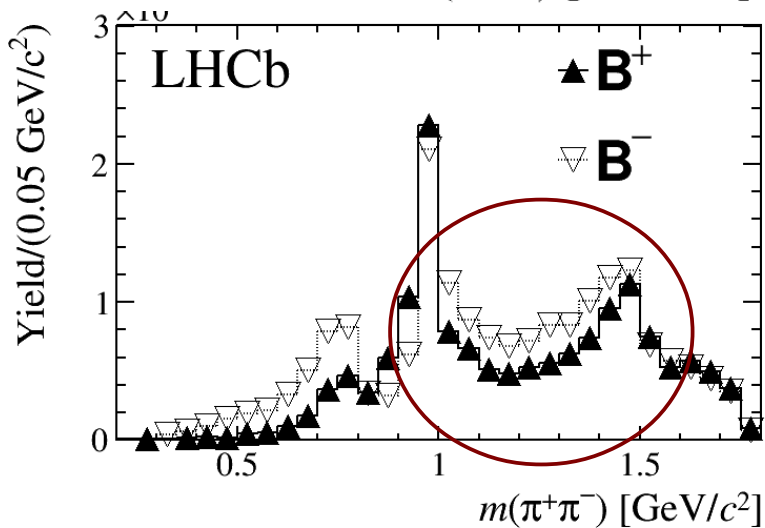
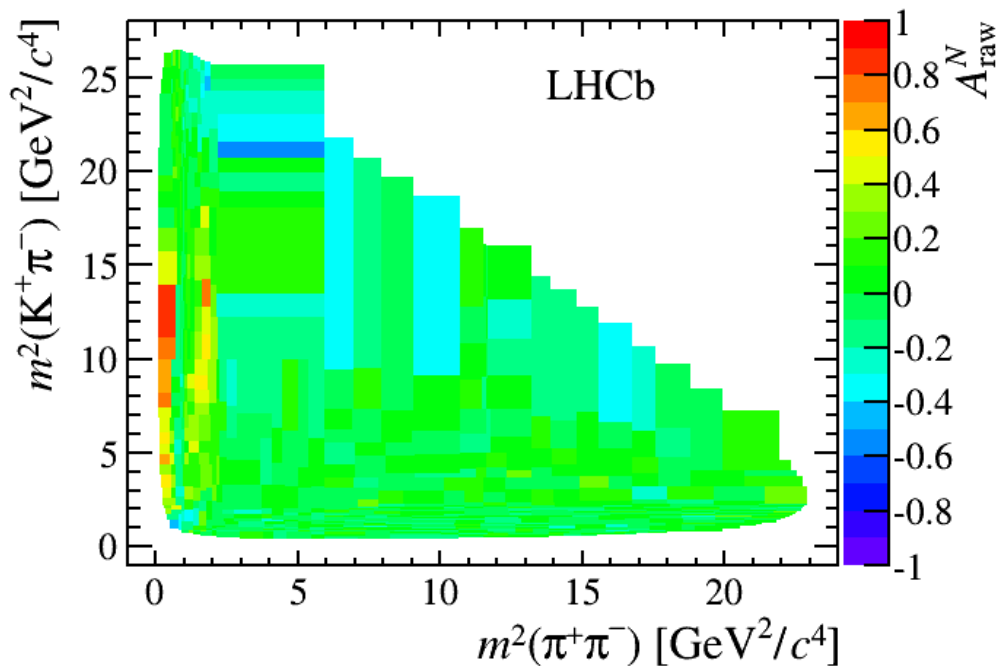
$$\text{ACP} = \frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)} = 2.5 \pm 0.4(\text{sta}) \pm 0.4(\text{sys})\%$$

Plus an error of 0.7% from the control channel $B^- \rightarrow J/\Psi K^-$

B⁺ - B⁻ Dalitz differences

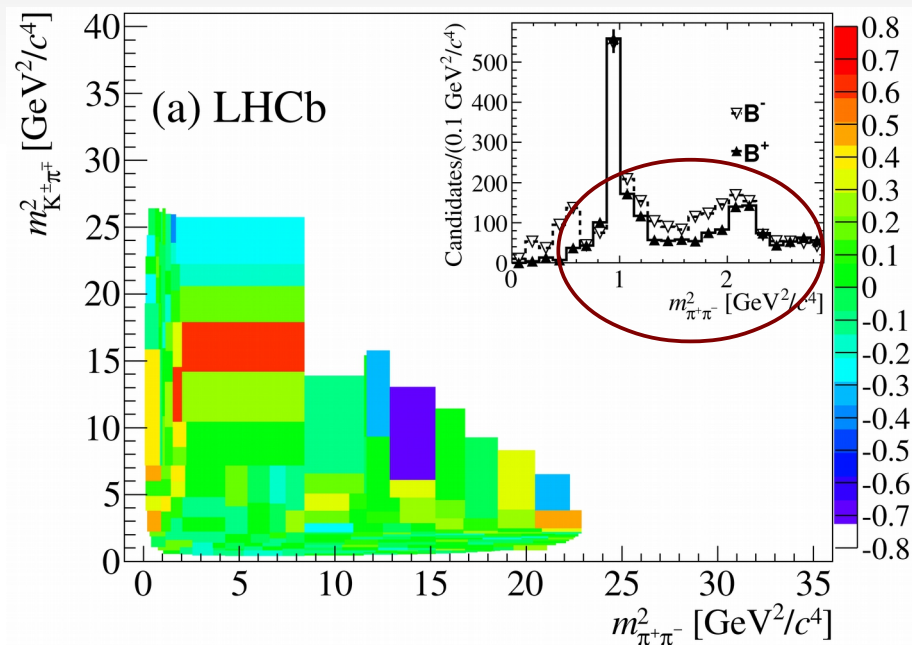
Low $M^2_{\pi K}$ and High $M^2_{\pi\pi}$ phase space distribution

2011 +2012 data



2011 data:
old analysis and
reconstruction.

LHCb: PRL 111, 101801 (2013)





Evidence of CP violation in

$B^+ \rightarrow \pi^+ K^+ K^-$ and $B^+ \rightarrow \pi^+ \pi^+ \pi^-$

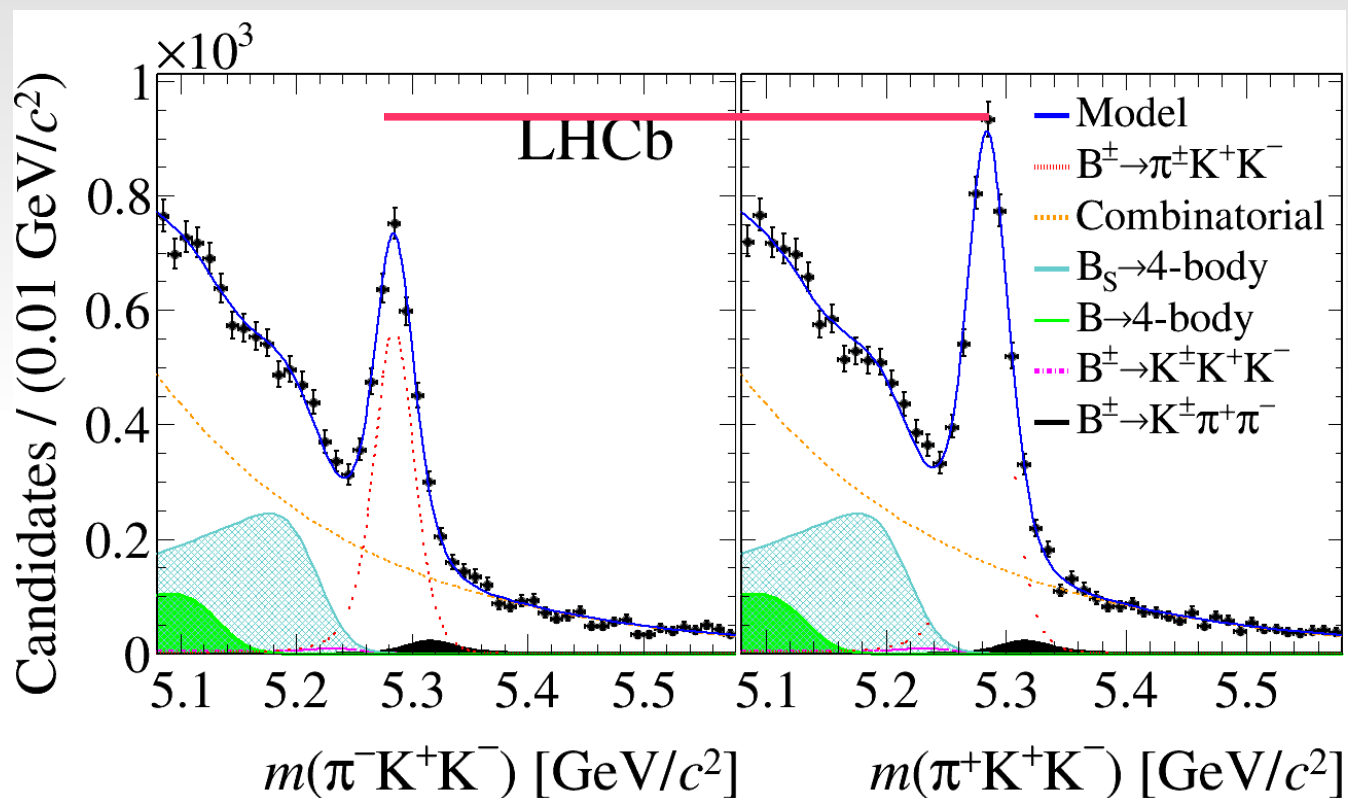
Final results
with LHCb 2011 +2012 data
[hep/ex-1408.5373](https://arxiv.org/abs/hep-ex-1408.5373)

Total charge asymmetry for



hep/ex-1408.5373, Phys.Rev. D90 (2014) no.11, 112004

$$\mathbf{N(B^-) + N(B^+) = 6161 \pm 172}$$



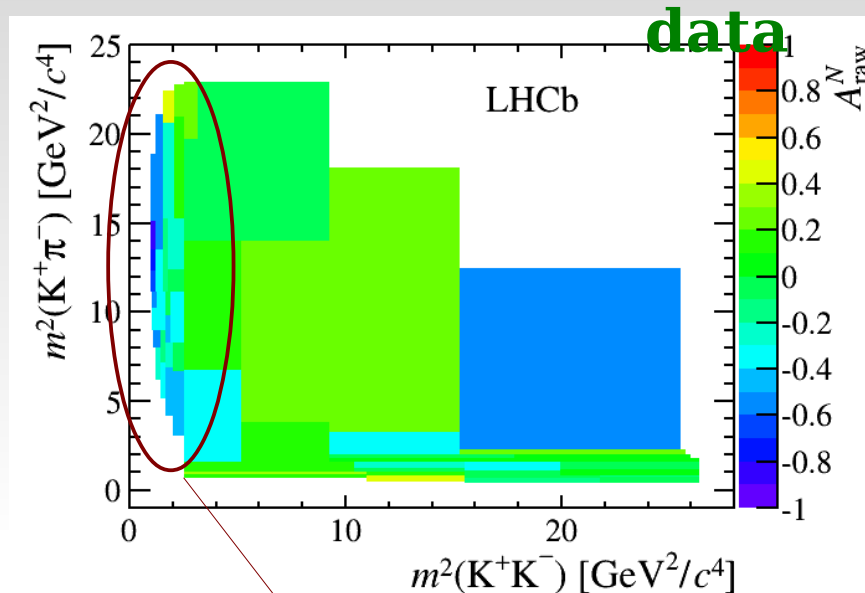
Total charge asymmetry:

$$\text{ACP} = \frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)} = 12.3 \pm 1.7(\text{sta}) \pm 1.2(\text{sys})\%$$

Plus an error of 0.7% from the control channel $B^- \rightarrow J/\Psi K^-$

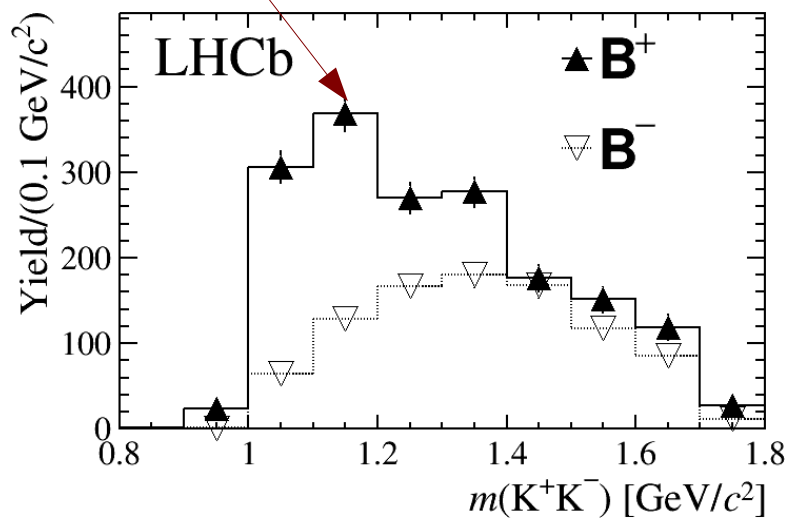
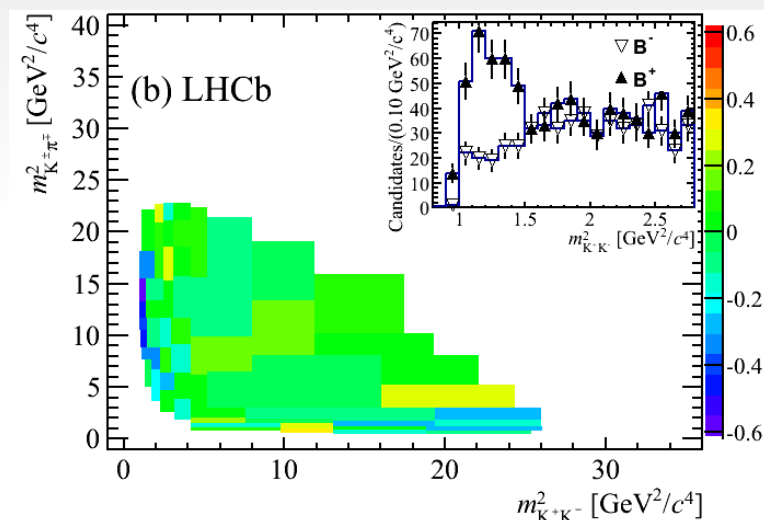
$B^\pm \rightarrow \pi^\mp K^+ K^-$ Dalitz plot

2011 + 2012



2011 data: old analysis and reconstruction.

LHCb: PRL 112, 011801 (2014)



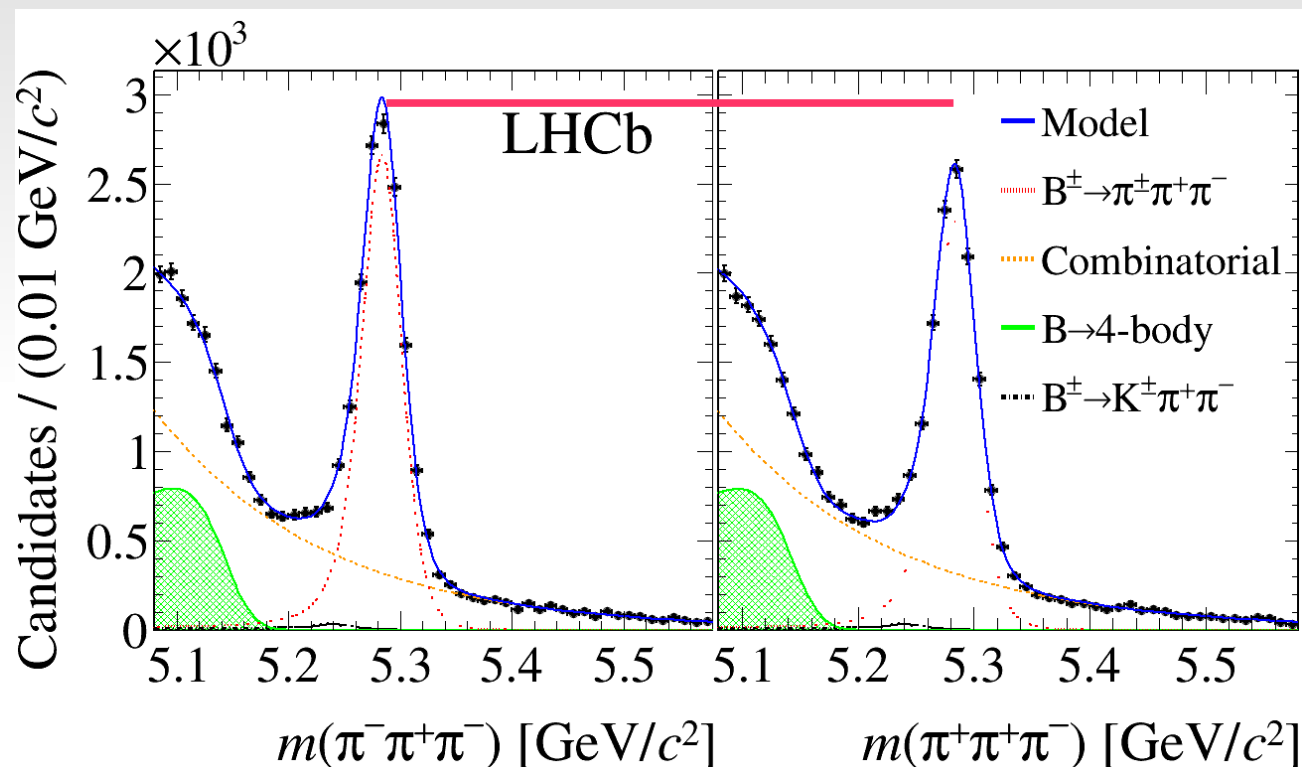
ACP \sim 33%

Total charge asymmetry for



hep/ex-1408.5373, Phys.Rev. D90 (2014) no.11, 112004

$$N(B^{-}) + N(B^{+}) = 24907 \pm 222$$



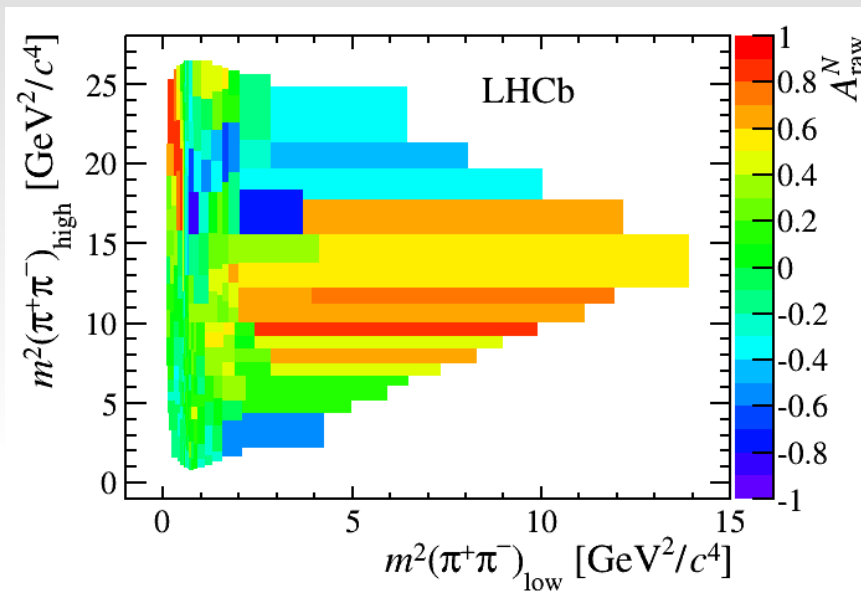
Total charge asymmetry:

$$ACP = \frac{N(B^{-}) - N(B^{+})}{N(B^{-}) + N(B^{+})} = 5.8 \pm 0.8(\text{sta}) \pm 0.9(\text{sys})\%$$

Plus an error of 0.7% from the control channel $B^{-} \rightarrow J/\Psi K^{-}$

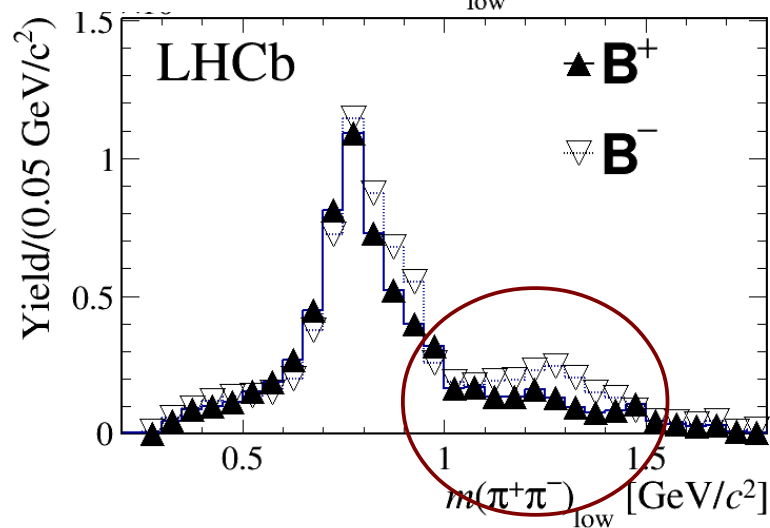
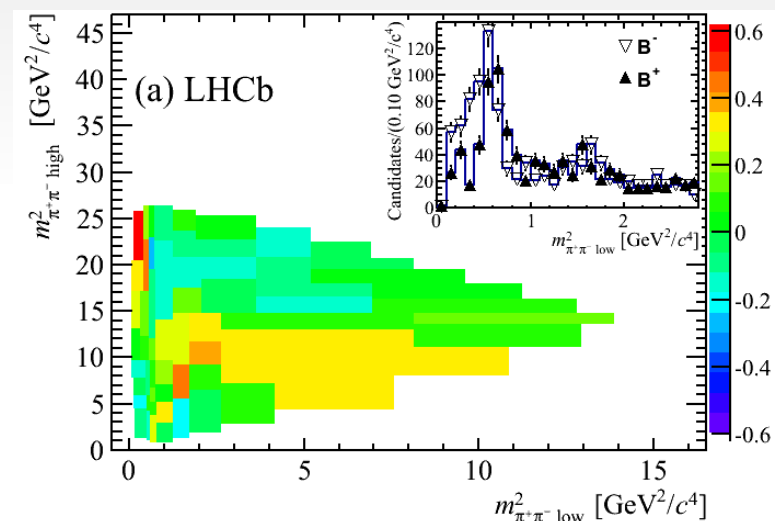
$B^\mp \rightarrow \pi^\mp \pi^+ \pi^-$ Dalitz plot

2011 + 2012 data



2011 data: old analysis and reconstruction.

LHCb: PRL 112, 011801 (2014)

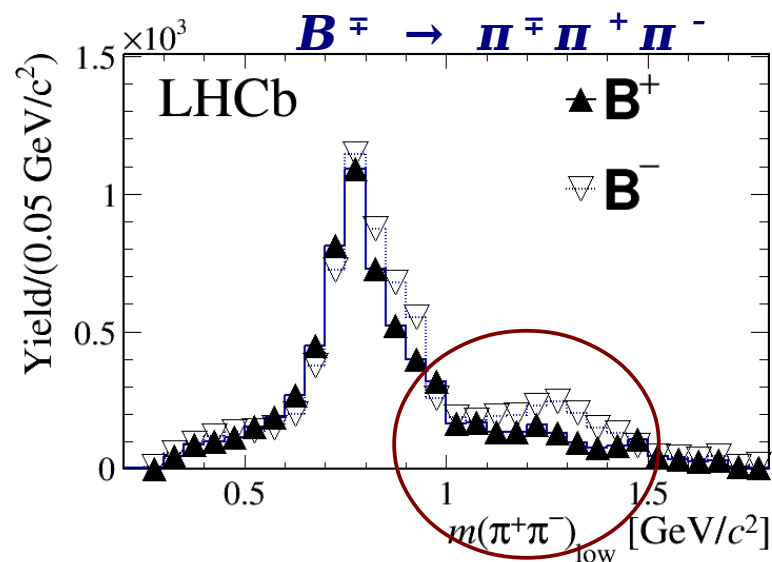
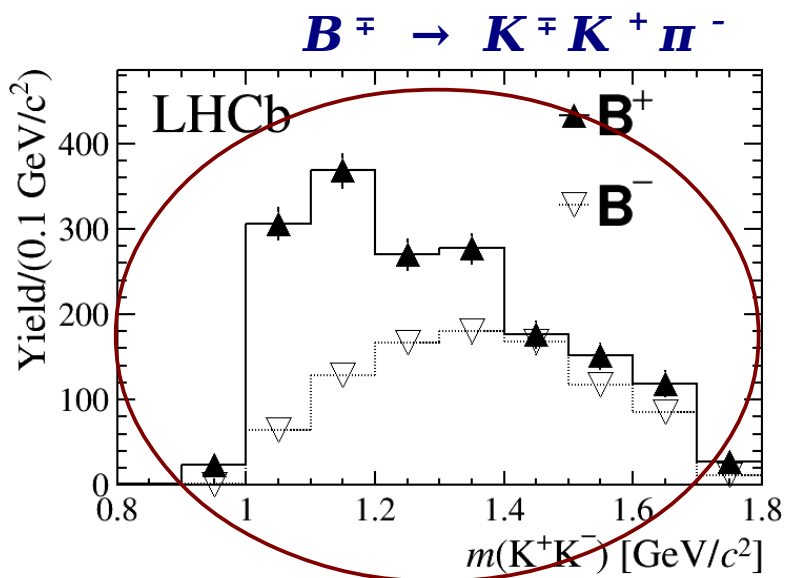
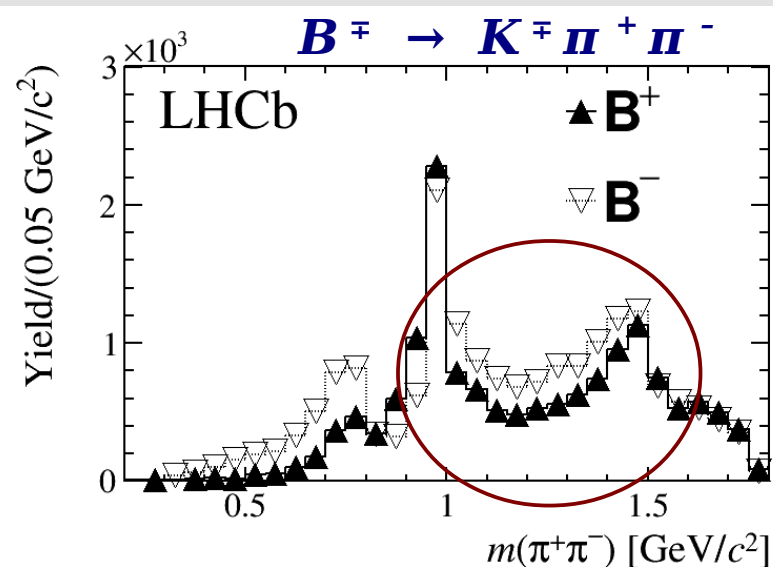
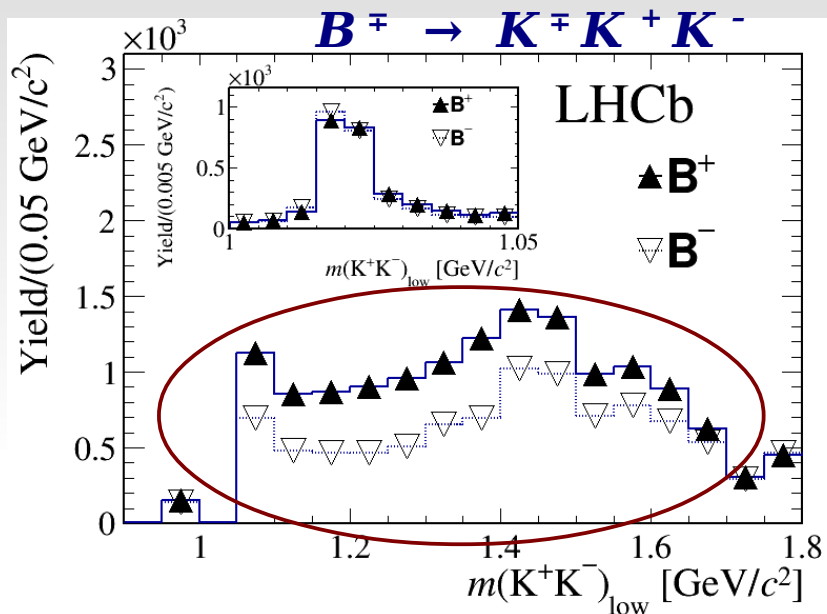


Final state interaction

$$\pi^+ \pi^- \rightarrow K^+ K^-$$

2011 + 2012 data

hep/ex-1408.5373 Phys.Rev. D90 (2014) no.11, 112004





Remarks of the experimental results.



- ◆ Global ~~CP~~ observed in all 4 channels
- ◆ positive ~~CP~~ in $B^{\mp} \rightarrow K^{\mp} \pi^+ \pi^-$ and $B^{\mp} \rightarrow \pi^{\mp} \pi^+ \pi^-$
- ◆ negative in $B^{\mp} \rightarrow \pi^{\mp} K^+ K^-$ and $B^{\mp} \rightarrow K^{\mp} K^+ K^-$.
- ◆ ~~CP~~ not uniform in the Dalitz plot: similar large ~~CP~~ in the low $K^+ K^-$ and $\pi^+ \pi^-$ invariant mass regions, re-enforcing the idea of the presence of the re-scattering $\pi^+ \pi^- \rightarrow K^+ K^-$.