Heavy Flavours

Saveurs Lourdes

Daniel Decamp[*] & Philippe Ghez

LAPP - Summer 2013

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[*] technical advisor/moral authority :-)

Outline

1. the Standard Model
2. from Antimatter to CP violation
3. the CKM matrix and the Flavours
4. the Beautiful Factories
5. Heavy Flavour physics today
6. Conclusion : Outlook

1 - the Standard Model

- Basic Principles
- Matter
- Forces
- Conservation laws and Symetries
- CPT
- This is IT !

the Standard Model

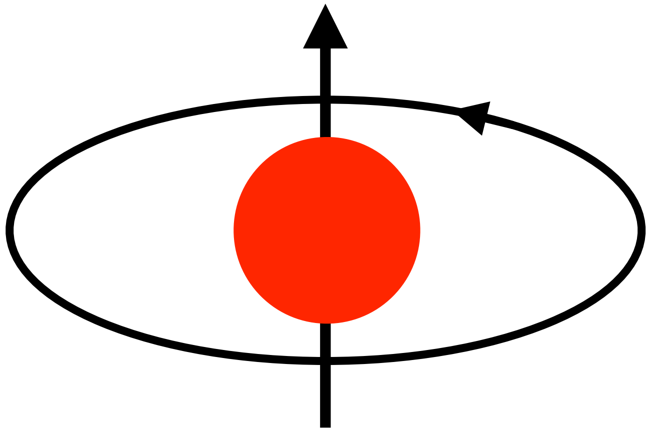
Basic Principles

- Goal : describe microscopic matter
  - matter: “particles”, motion&interactions : “forces”
  - elementary building blocks & fundamental forces
- Relativistic world
  - $E = mc^2 \rightarrow$ particles decay into other particles
- Quantic world
  - $\lambda = h/p \rightarrow$ particles AND waves (collisions/interferences)
  - $\Delta E \Delta t \geq \hbar/2 \rightarrow$ virtual interactions/states

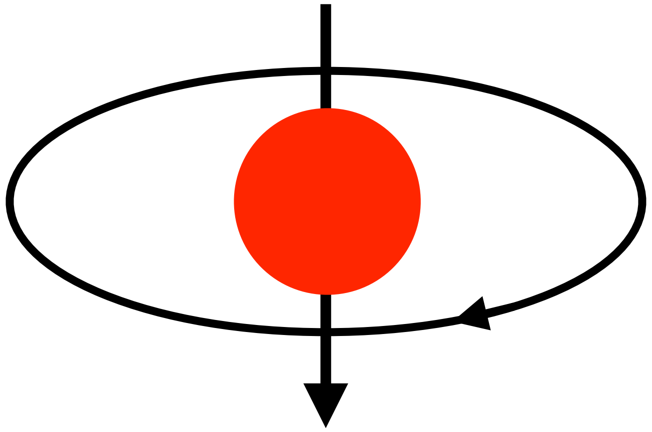
the Standard Model

Matter

- Observation :  splitting of spectral lines
- Pauli (1924) : we need (for electrons) a
  “ two-valued quantum degree of freedom “



Spin +1/2



Spin -1/2

- Spin = 1/2, 3/2, ... : FERMIONS

Matter ←→ Fermions

the Standard Model

Forces

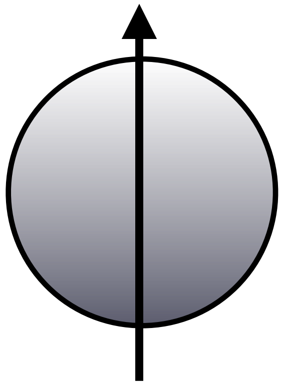
- Compton effect (1923) : light scattering on matter changes λ !
  - interaction “mediated” by exchange particles
- relativistic QM : particles ~ fields
- interacting particles ~ particle exchange
- perturbation theo. + renorm. : calculable
  - “rules” : Feynman diagrams
- Spin = 0, 1, 2, ... : BOSONS

Forces ⟵⟶ Bosons

the Standard Model

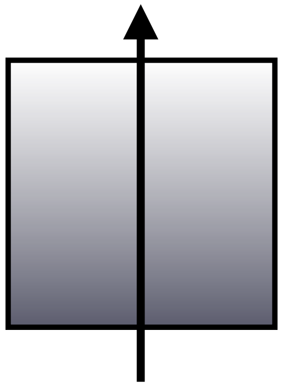
Convervation laws and Symetries

- Continuous symmetries →**+** Conservation laws



  - Energy, angular momentum, etc ...
  - Additive quantum numbers : charge, color, weak charge
  - Local gauge symetries

- Discrete symmetries →**x** Conservation laws



  - particle-antiparticle transfo. **C** : charge conjugation
  - parity (“handedness”) **P** : left-right flip
  - time reversal **T** : go backward in time

the Standard Model

CPT

	C	P	T
Space	x	**-x**	x
Time	t	t	**-t**
Momentum	p	**-p**	**-p**
Spin	s	s	**-s**
Elec. field	**-E**	**-E**	E
Magn. field	**-B**	B	**-B**

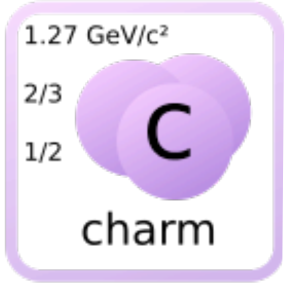
(all vectors except *h*)

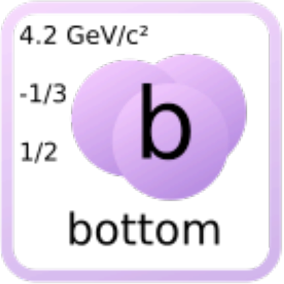
- orbital momentum :
  $L = x \wedge p$
- total angular momentum :
  $J = L + S$
- helicity :
  $h = S.p_{norm}$ ($p_{norm} = p/|p|$)
  “left-handed/right-handed”

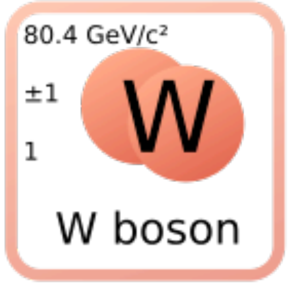
- The CPT theorem (1954):
  “ Any Lorentz-invariant local quantum field theory is invariant under the successive application of C, P and T ”
  - particles and antiparticles have equal mass and lifetime, equal magnetic moments with opposite sign, and opposite quantum numbers (OK up to ~ 10^{-18})

the Standard Model

This is IT !



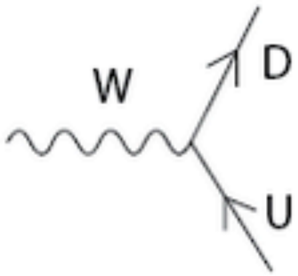




the Standard Model

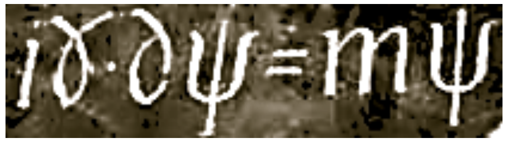
This is IT !

Standard Model Interactions
(Forces Mediated by Gauge Bosons)



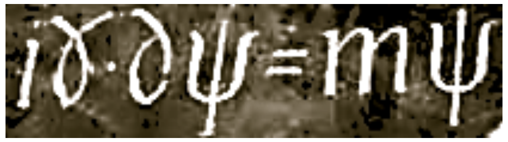
U is a up-type quark;
D is a down-type quark.

2 - from Antimatter to CP violation

–  $i\gamma\cdot\partial\psi=m\psi$	Dirac	1929	**T**
– e^+	Anderson	1932	**E**
– s	Rochester, Butler	1947	**E**
– K^0 mixing	Gell-Mann, Pais	1955	**T**
– θ-τ puzzle	Yang, Lee	1956	**E T**
– $\cancel{P}$	Wu...	1957	**E**
– ν helicity	Goldhaber...	1958	**E**
– θ_c	Cabibbo	1963	**T**
– $\cancel{CP}$ (K^0)	Cronin, Fitch...	1964	**E**

from Antimatter to CP violation

T



- from classical to quantic :

$$E=\frac{\vec{p}^{\,2}}{2m}+V \longrightarrow E=i\frac{\partial}{\partial t},p_x=-i\frac{\partial}{\partial x}$$

c = ħ = 1

- from classical to quantic&relativistic (free particle) :

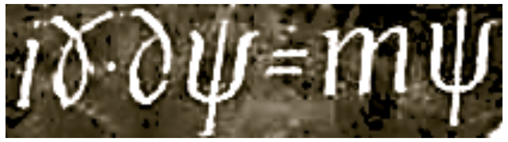
$$E^2=\vec{p}^{\,2}+m^2 \longrightarrow \text{quadratic eq. in E}$$

$$\longrightarrow E<0 \text{ solutions !}$$

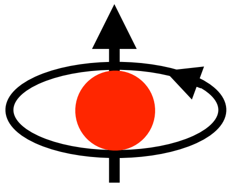
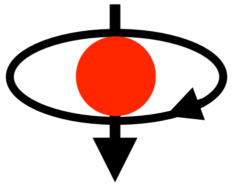
- Dirac :
  - this is a problem
  - spin cannot be included in $\Psi(x,t)$ as a simple complex nb

from Antimatter to CP violation

T



$i\gamma\cdot\partial\psi=m\psi$

- Dirac (encore !) :
  - get rid of negative energies → $\Psi = (\Psi_1, \Psi_2)$
  - don't forget spin :  and 
- BUT ... still E < 0 solutions !
  - 4 components Ψ : 2 spins + 2 signs(E)
  - E < 0 : "holes" in the (Dirac) "sea"

$$\left(\beta m + \sum_{k=1}^{3} \alpha_k p_k\right)\psi(\vec{x},t) = i\frac{\partial\psi(\vec{x},t)}{\partial t}$$

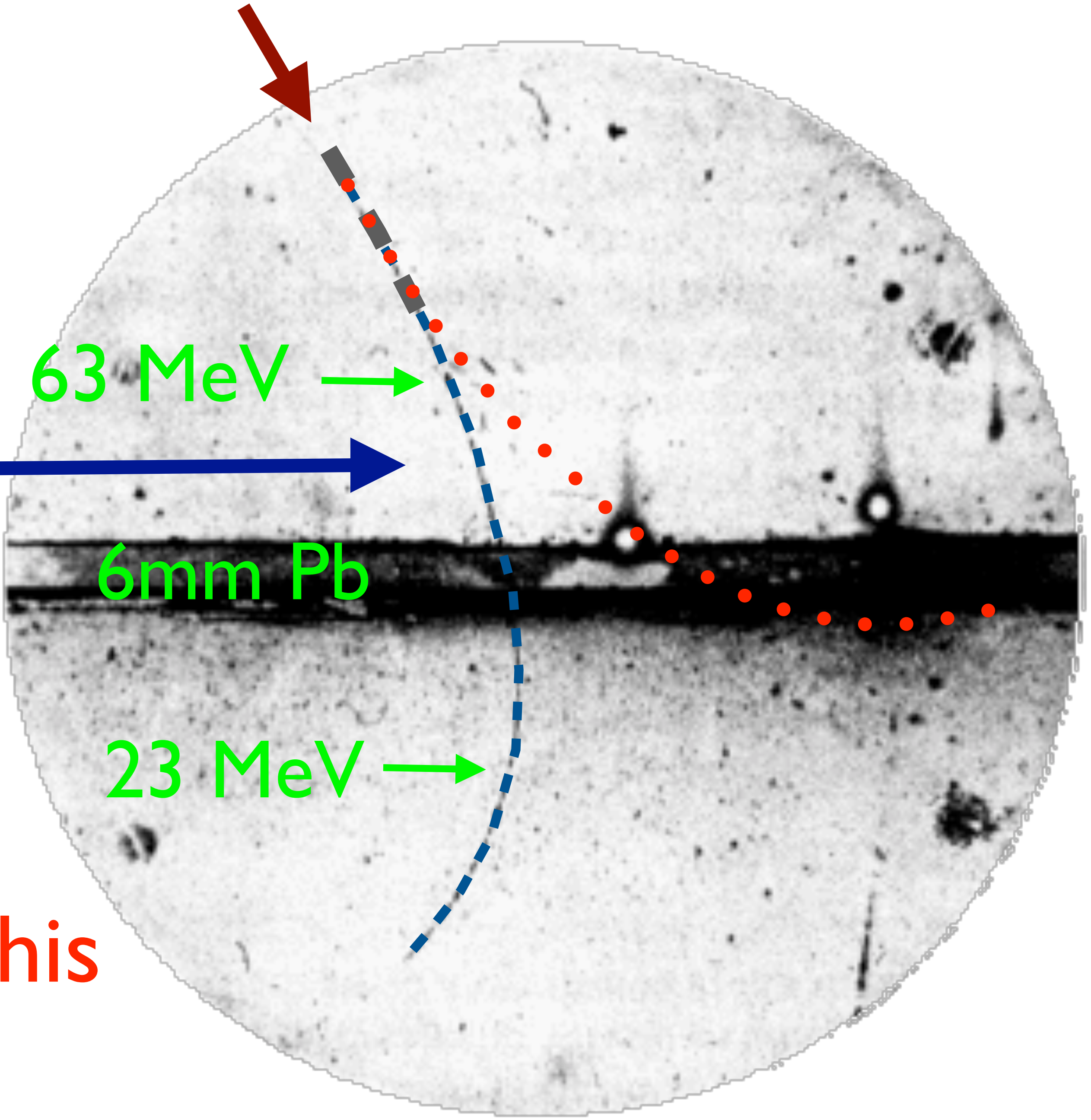
- Ψ: 4-compo. (e^-) wave function; α, β : 4x4 matrices

from Antimatter to CP violation

E

e^+

- Anderson (1932) with :
  - cosmic rays
  - vertical Wilson chamber
- he sees this
- which comes from here
- a proton would give this
- an electron would give this



First evidence of the existence of antiparticles : **Positron (e^+)**

Every particle has its own antiparticle (sometimes it is the same)

E

S

- Rochester and Butler (1947) :

Evidence for the existence of new unstable elementary particles

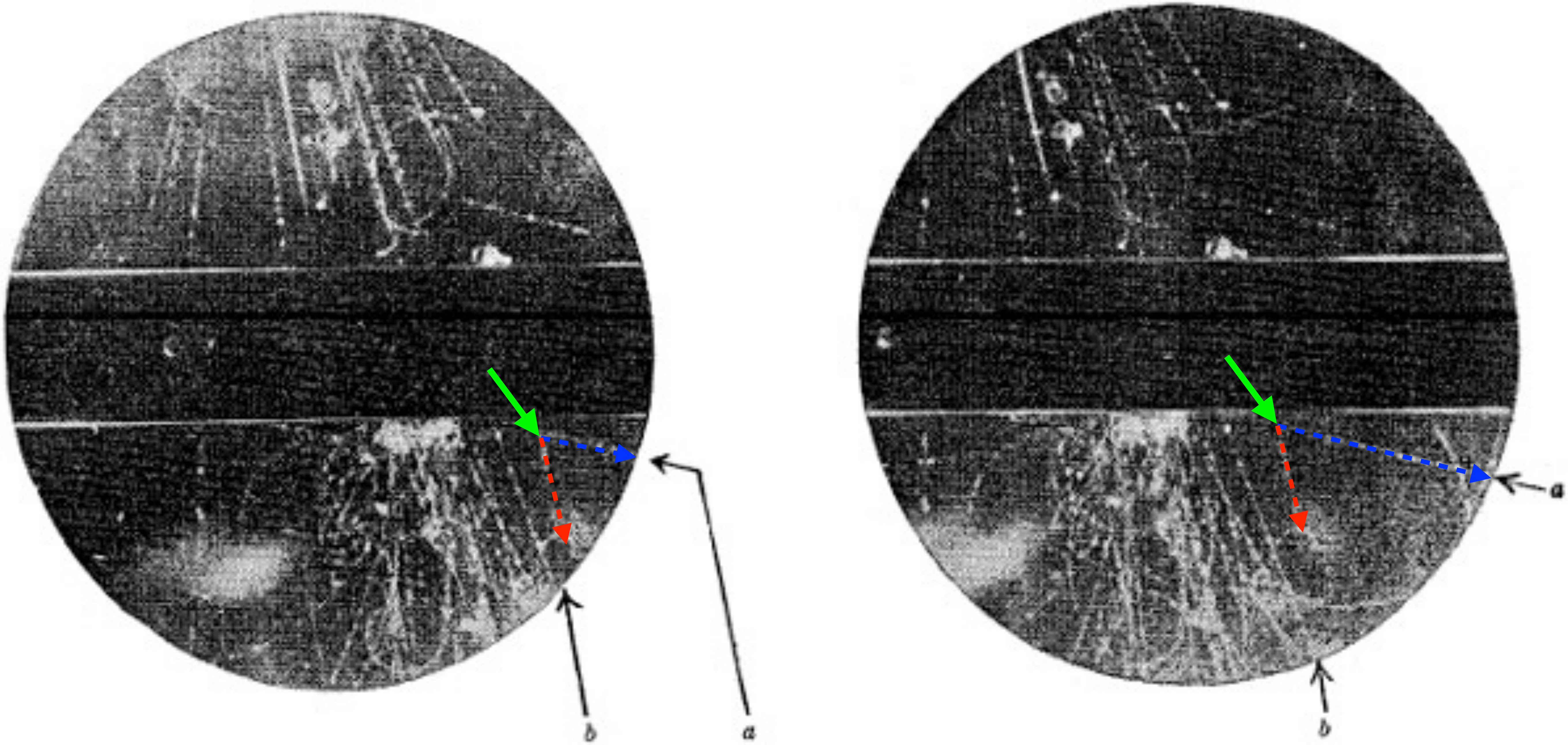
Nature 160, 855-857 (1947)

Among some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character. These photographs have been selected from five thousand photographs taken in an effective time of operation of 1,500 hours. On the basis of the analysis given below we believe that one of the forked tracks, shown in Fig. 1 (tracks *a* and *b*), represents the spontaneous transformation in the gas of the chamber of a new type of uncharged elementary particle into lighter charged particles, and that the other, shown in Fig. 2 (tracks *a* and *b*), represents similarly the transformation of a new type of charged particle into two light particles, one of which is charged and the other uncharged.

from Antimatter to CP violation

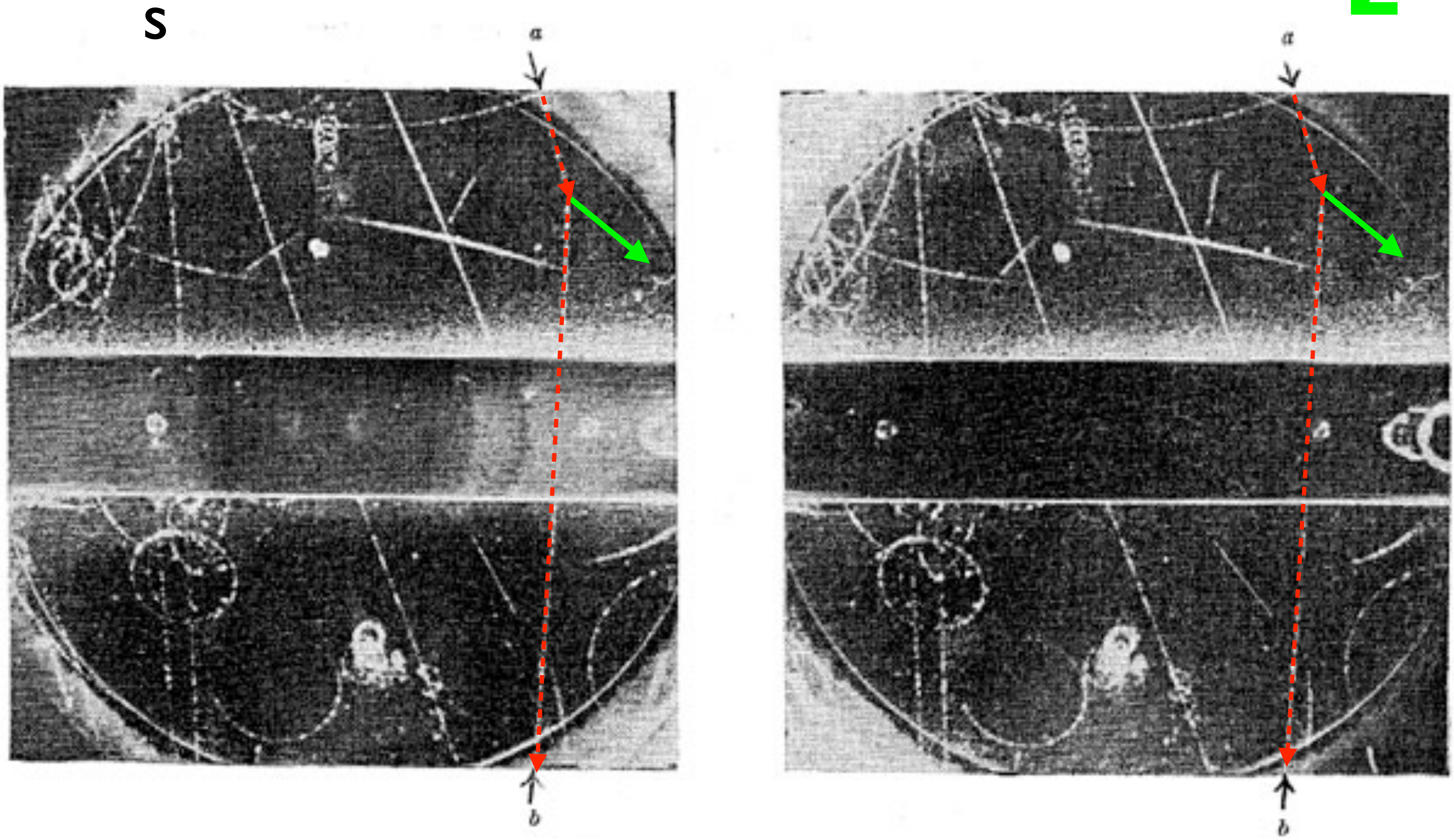
E

S



Back

from Antimatter to CP violation



from Antimatter to CP violation

E

S

- Rochester and Butler (1947) :

Evidence for the existence of new unstable elementary particles

Nature 160, 855-857 (1947)

We conclude from all the evidence that Photograph 1 represents the decay of a neutral particle, the mass of which is unlikely to be less than 770m or greater than 1,600m, into the two observed charged particles. Similarly, Photograph 2 represents the disintegration of a charged particle of mass greater than 980m and less than that of a proton into an observed penetrating particle and a neutral particle. It may be noted that no neutral particle of mass 1,000m has yet been observed; a charged particle of mass 990m ± 12 per cent has, however, been observed by Leprince-Ringuet and L'héritier.

- further observations (later) :
  - large cross-sections → strong interactions
  - long lifetime (10^{-10} s) → weak interactions !

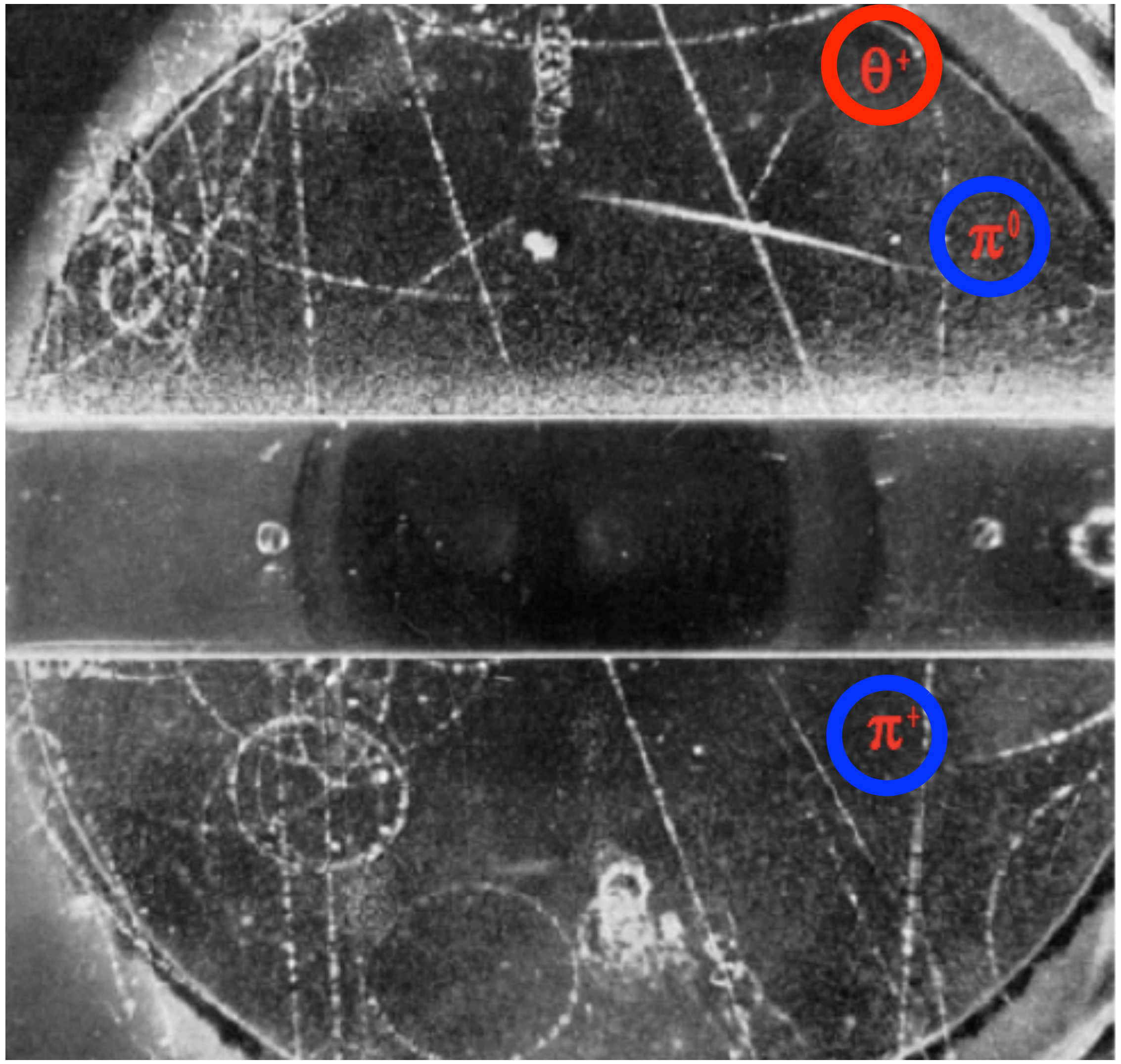
K^0 mixing

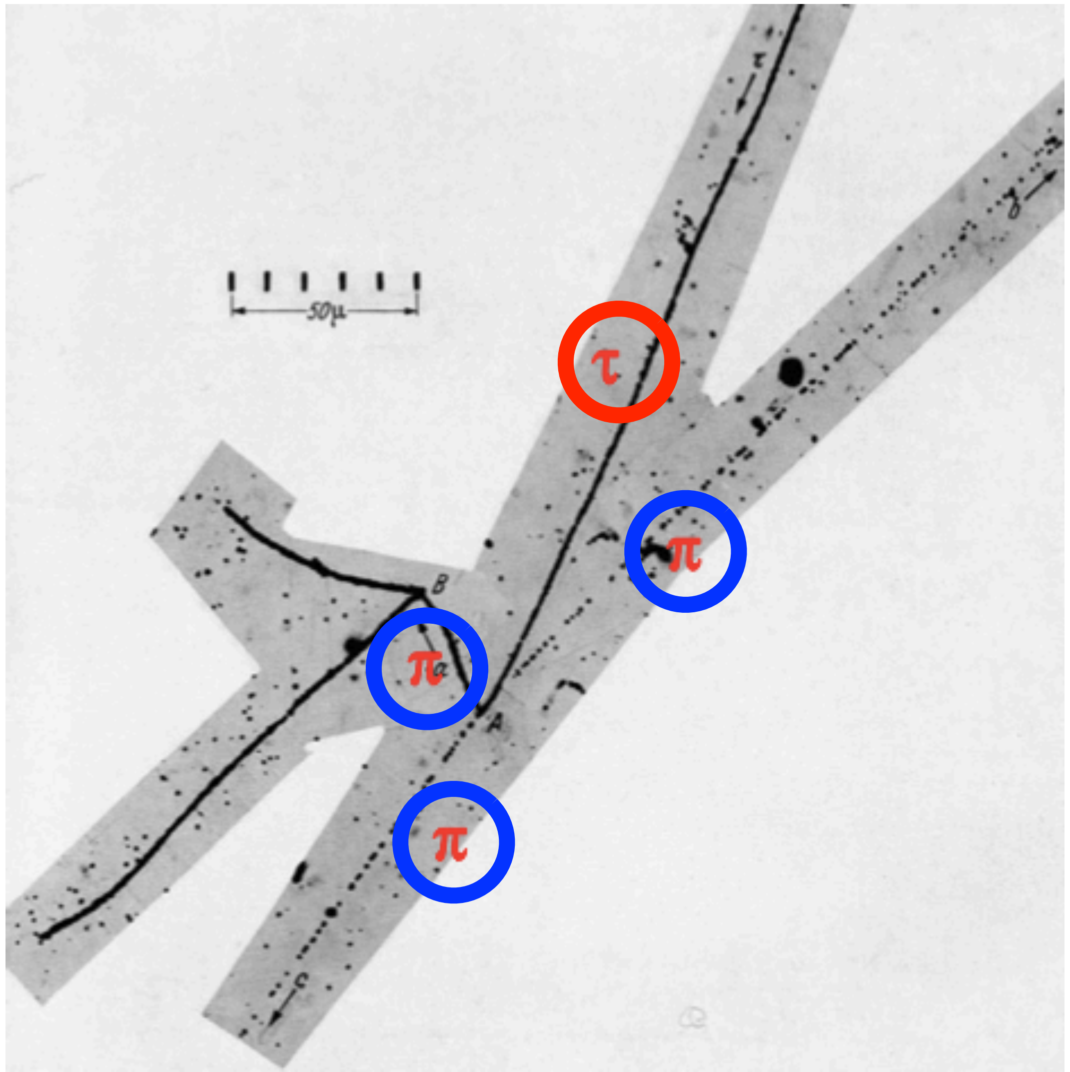
- **C** (not yet violated) !) flip quantum numbers
  - $S = +1 : K^0 \rightarrow \pi^+\pi^-$ then $S = -1 : \bar{K}^0 \rightarrow \pi^+\pi^-$
- Gell-Mann, Pais (1955) :
  - $K^0 \leftarrow\rightarrow \pi^+\pi^- \leftarrow\rightarrow \bar{K}^0$ ("**mixing**" predicted)
  - real (observed) particles are (**CP** conserved):
    $K_1 = (K^0 + \bar{K}^0) / \sqrt{2}$, $K_2 = (K^0 - \bar{K}^0) / \sqrt{2}$
- K_1 ($\pi^+\pi^-$) - **C** even - observed
- K_2 (3π) - **C** odd - predicted
  - Lederman... (1956) discovers $K^0{}_2$ ("**mixing**" observed)
  - $\tau_2 \sim 500\ \tau_1$

from Antimatter to CP violation

θ-τ puzzle

- Football : Bristol wins over Manchester 3-2





- Physics :
  - Manchester (1947) : θ → 2 π
  - Bristol (1949) : τ → 3 π

θ-τ puzzle

- THE puzzle :
  - θ and τ : ~ same masse + lifetime (same particle ?) BUT
  - **P**(θ) = -1 and **P**(τ) = +1 (1st Dalitz plot)

Is **P**arity violated ?

- THE solution : Yang, Lee (1956) : why not ?

"The conservation of parity is usually accepted without questions concerning its possible limit of validity being asked. There is actually no a priori reason why its violation is undesirable."

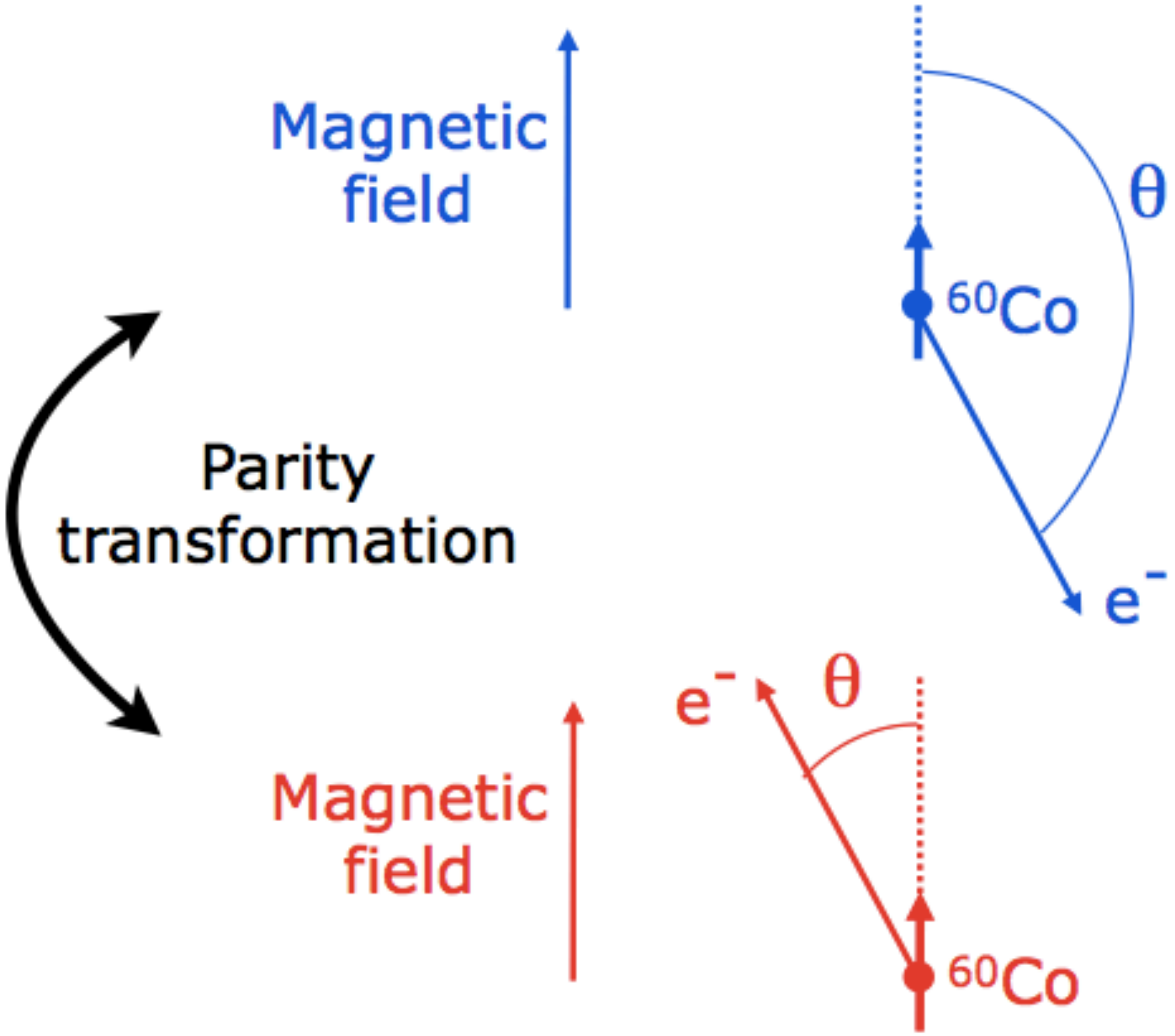
- they suggest several experiments to test it !

from Antimatter to CP violation

$\cancel{\mathbf{P}}$

E

- Principe of measurement : ${}^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni}^{*} + e^{-} + \overline{\nu} + 2\gamma$



$${}^{60}\overset{\Rightarrow\Rightarrow}{\text{Co}} \rightarrow {}^{60}\text{Ni} + \underset{\leftarrow}{\overset{\Rightarrow}{e^{-}}} + \underset{\rightarrow}{\overset{\Rightarrow}{\overline{\nu}_e}}$$

$${}^{60}\overset{\Leftarrow\Leftarrow}{\text{Co}} \rightarrow {}^{60}\text{Ni} + \underset{\leftarrow}{\overset{\Leftarrow}{e^{-}}} + \underset{\rightarrow}{\overset{\Leftarrow}{\overline{\nu}_e}}$$

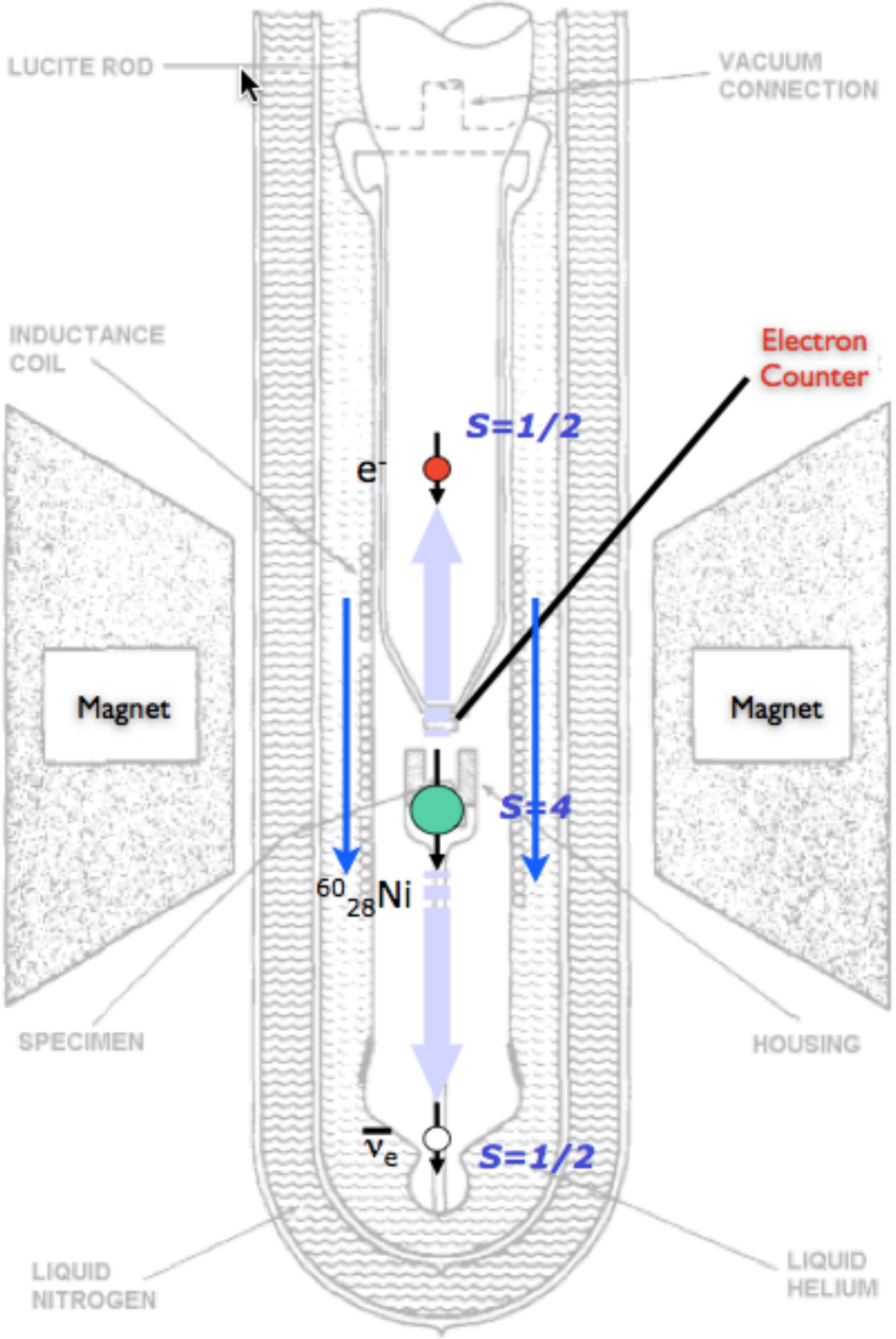
- “simply” count the e$^-$ rate when flipping $\vec{\text{B}}$
  - γ’s (conserve **P**) detected : check the Co polarization

from Antimatter to CP violation

P

E

- Experiment
  - Want spin aligned in one direction and compare to not-aligned case
  - Adiabatic demagnetization of 60Co in a magnetic field at very low temperatures (~0.01 K!). Extremely challenging in 1956!
  - Insert solenoid to polarize (20 s !)
  - ~ 7 minutes to do the measurements once polarized (heating)

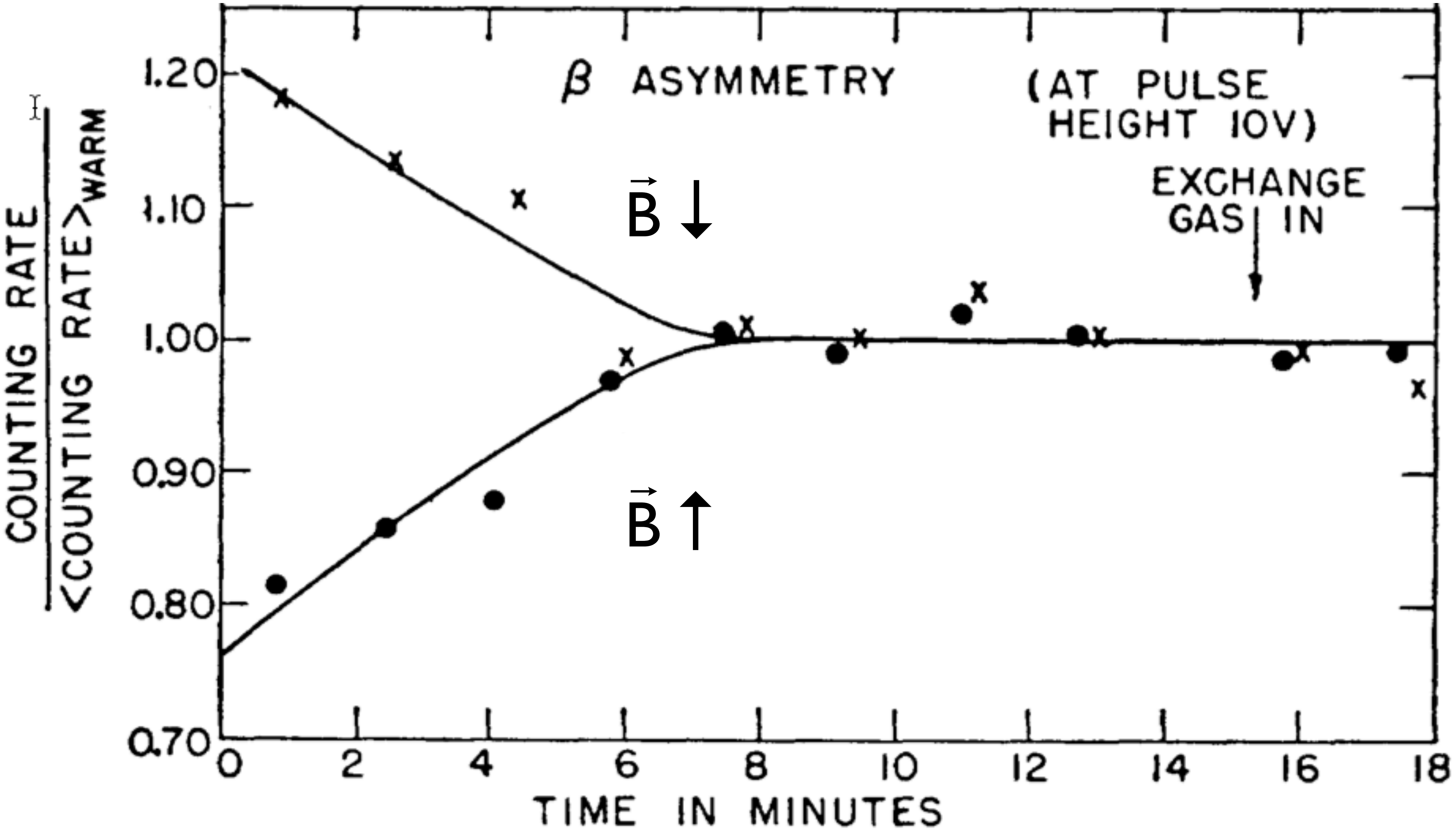


from Antimatter to CP violation

E

$\cancel{P}$

- Results



this is **Parity violation**

from Antimatter to CP violation

E

ν helicity

- the “Goldhaber” idea (1958)
  - $^{152}_{63}\mathrm{Eu} + \mathrm{e}^- \rightarrow {}^{152}_{62}\mathrm{Sm}^* + \nu_\mathrm{e}$: K capture
    - J = 0 → J = 1 , s = 0 captured e^- ⇒ Sm^* & ν_e same *h* sign
  - $^{152}\mathrm{Sm}^* \rightarrow {}^{152}\mathrm{Sm} + \gamma$: γ desexcitation
    - forward γ same *h* sign than ν_e
  - $\gamma + {}^{152}\mathrm{Sm} \rightarrow {}^{152}\mathrm{Sm}^* \rightarrow {}^{152}\mathrm{Sm} + \gamma$: resonant scattering
    - resonant scattering selects forward γ
  - select sign of *h*(γ) by (magnetically) spin flipping the e^-

from Antimatter to CP violation

E

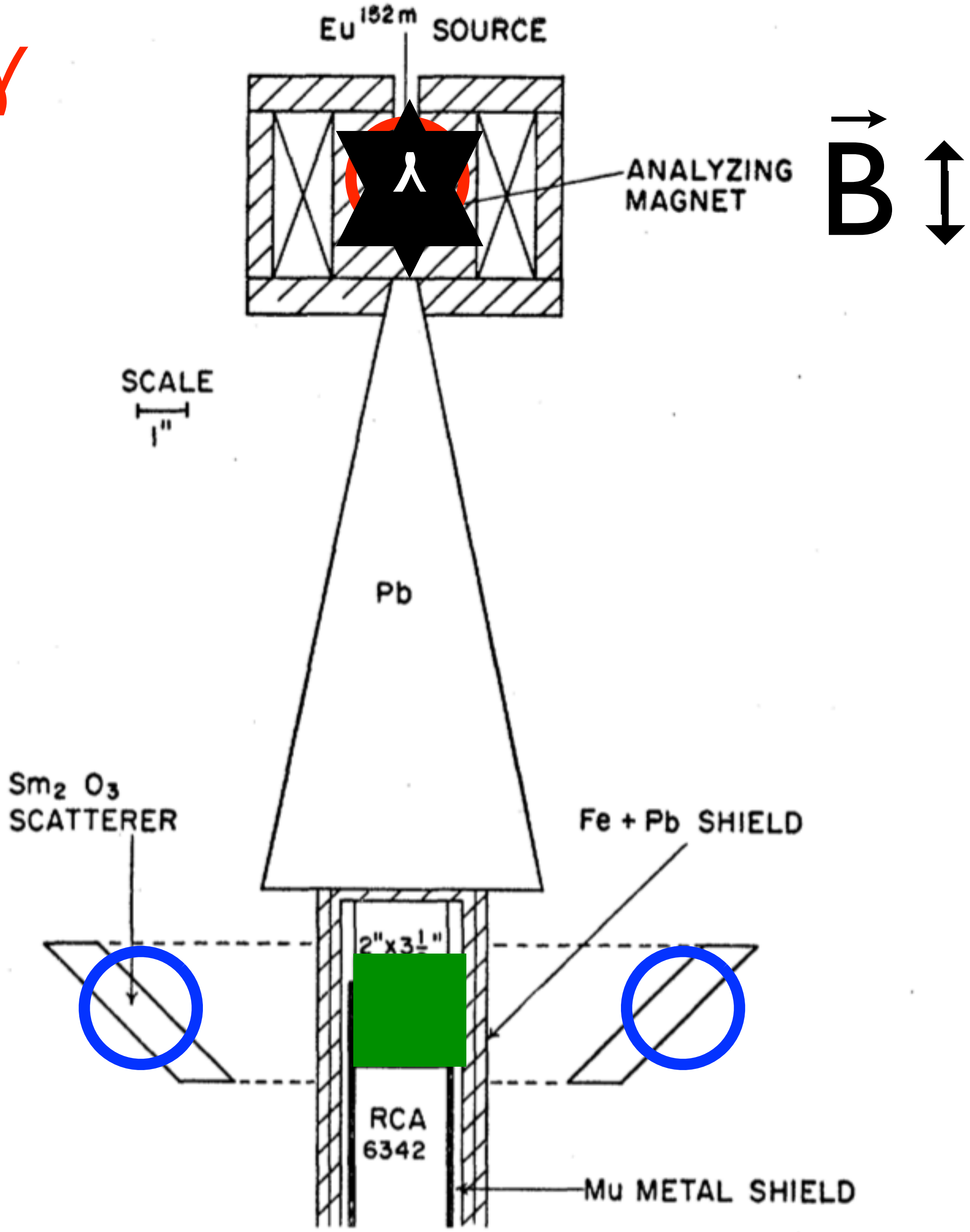
ν helicity

- the "Goldhaber" experiment (1958)
- source : Eu→Sm^*→Sm + γ
- flip e^- spin = flip $h(\nu_e)$
- capture/emit (resonant) γ
- detect γ
  - check resonant scattering
  - measure asymmetry A

Result : $A = (1.7 \pm 0.3)$ %

ν_e are left-handed !

(and **C** is violated ...)



from Antimatter to CP violation

θ_c

- Nicola Cabibbo (1963)
  - known : e ν_e μ ν_μ (“leptons”) and u d s (“quarks” = “trick”)
  - known :

↑	0	ν_e	ν_μ	+2/3	**u**		**W^+**
W^-	-1	**e**	**μ**	-1/3	**d**	**s**	↓

- BUT lifetimes (“g”) problems :
  - $g_1(l^- \rightarrow W^- \nu_l) > g_2(d \rightarrow W^- u) >> g_3(s \rightarrow W^- u)$
  - universality of the couplings ???
- Trick :
  - $g_1 = g, g_2 = g\cos\theta_c, g_3 = g\sin\theta_c$

from Antimatter to CP violation

θ_c

T

- and it "works" !!!
  - $\Gamma(K \rightarrow \mu\nu)/\Gamma(\pi \rightarrow \mu\nu) \Rightarrow \tan^2\theta_c \Rightarrow \theta_c \sim 0.257$
  - then : $g(l^- \rightarrow W^- \nu_l) = g(d \cos\theta_c + s \sin \theta_c)$
  - describes correctly FCCC (... almost)
- consequences :
  - d (weak interaction) ≠ d (mass eigenstates)
  - $(\nu_e\ e)_L$, $(\nu_\mu\ \mu)_L$, $(u\ d')$ with $d' = d \cos\theta_c + s \sin \theta_c$
  - same for s → Cabibbo matrix $\left(\frac{d'}{s'}\right) = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \left(\frac{d}{s}\right)$

... there is more to come ...

from Antimatter to CP violation

~~CP~~ (K^0)

E

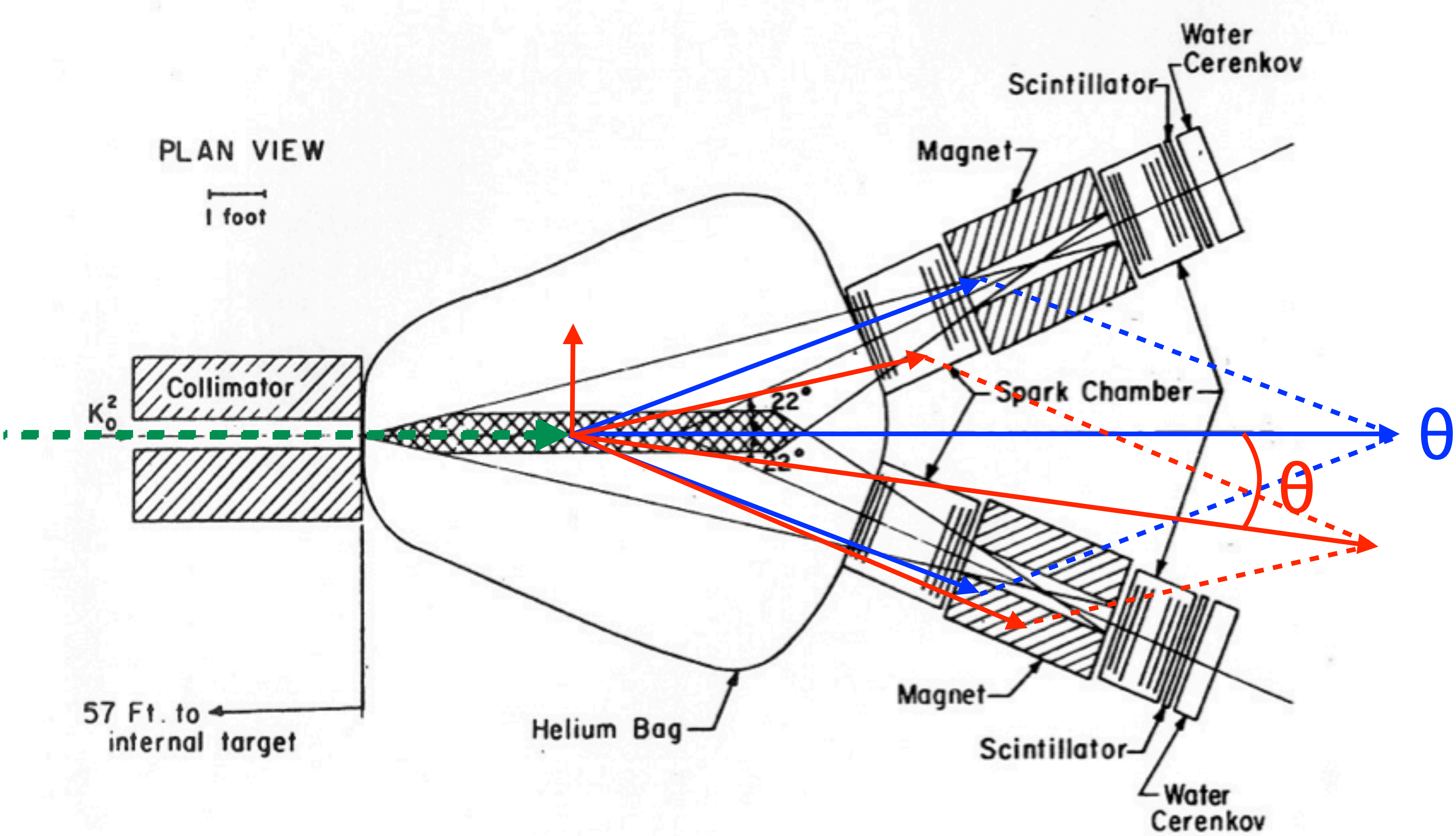
- **P** broken/**C** broken → **CP** looks like The "good" symmetry !
- use K^0 and wait ...
  - until short-lived K^0 ("K_1") has disappeared
- then check that "K_2" is **CP** odd
  - reminder : 2π = even, 3π = odd

from Antimatter to CP violation

E

$\cancel{CP}$ (K^0)

- Cronin&Fitch (1964) - Experiment

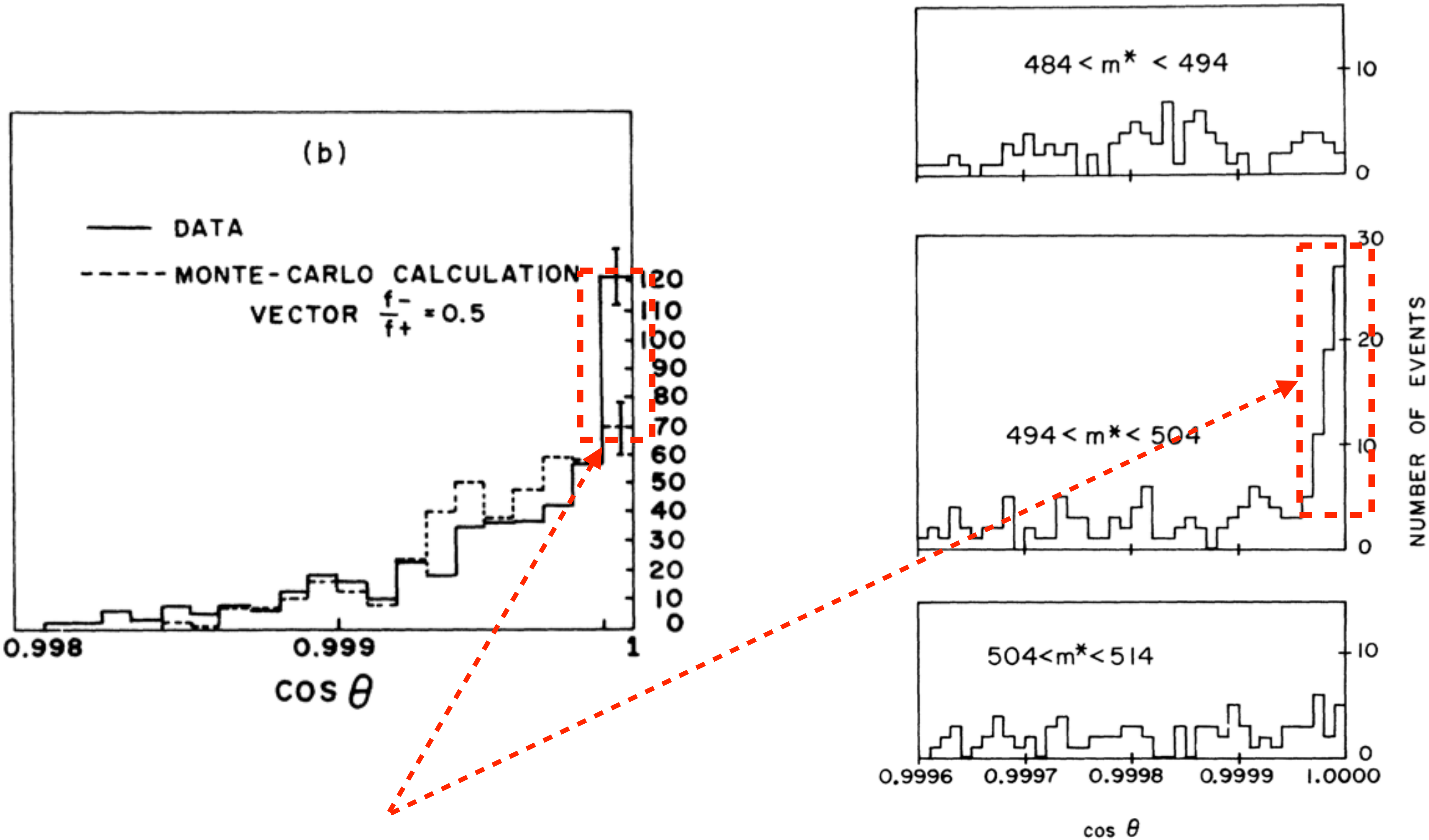


from Antimatter to CP violation

E

$\cancel{CP}$ (K^0)

- Cronin&Fitch (1964) - Results



excess ! (~ 30 evts)

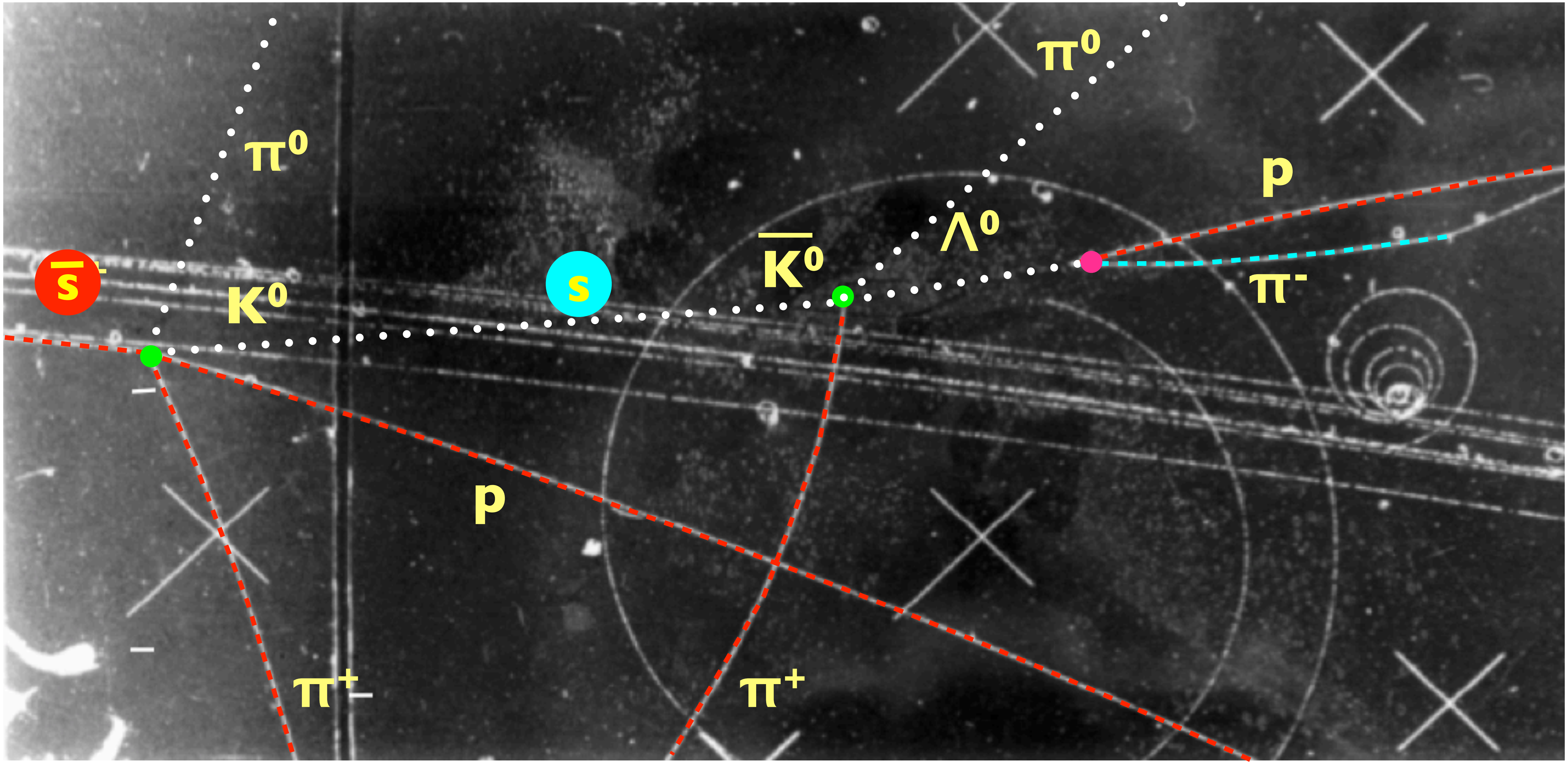
3 - the CKM matrix and the Flavours

interlude : seeing K^0 mixing in bubbles		...	**E**
Quarks	Gell-Mann, Zweig	1964	**T**
GIM	Glashow, Illiopolous, Maiani	1970	**T**
CKM matrix - 1	Kobayashi, Maskawa	1973	**T**
interlude : modern particle physics detectors			**E**
c	Ting..., Richter...	1974	**E**
τ	Perl...	1975	**E**
b	Lederman...	1977	**E**
B^0_d mixing	ARGUS	1987	**E**
t	CDF, D0	1995	**E**

the CKM matrix and the Flavours

seeing the K^0 mixing in bubble chambers

E



- - - - - - + tracks
- - - - - - - tracks
· · · · · · · · · neutrals (w&b → b&w)

● collision vertex (on p)
● desintegration vertex

Quarks

- proposed (indeptly) by Gell-Mann&Zweig (1964)
  - main motivation : put some order in the hadron zoo !
    - classify (remember Mendeleïev)
- How to classify ?
  - classify : Spin
  - classify : Isospin
    - introduced by Heisenberg (1932) : p ~ n → p↑(+1/2) , n↓(-1/2)
    - related to B, S, Q : $Q = I_3 + \frac{B+S}{2}$ (Gell-Mann, Nakano, Nishijima ~ 1956)
  - insensitivity to “flavour” (strange or not strange)
- Consequences ...

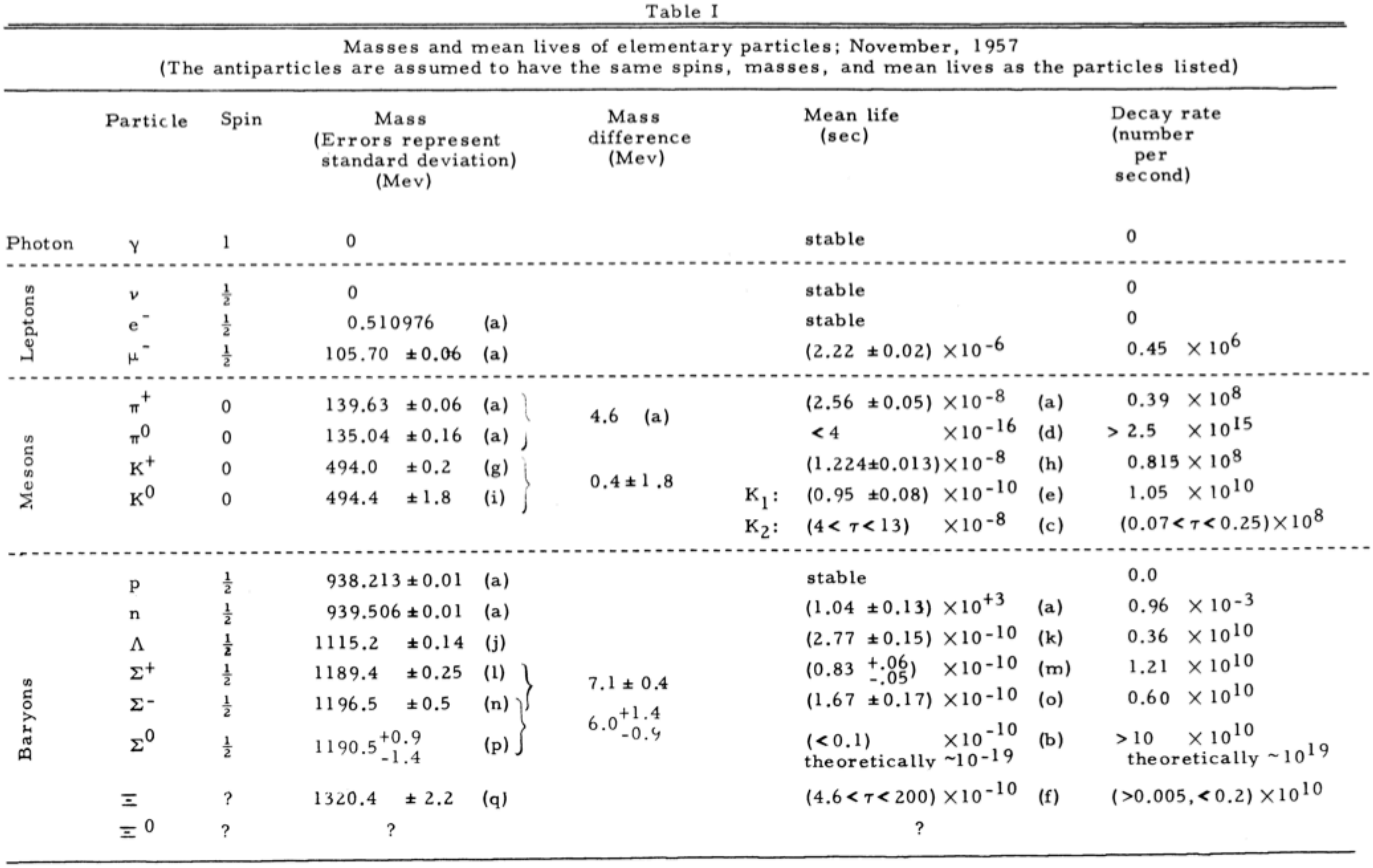


Table I

Masses and mean lives of elementary particles; November, 1957
(The antiparticles are assumed to have the same spins, masses, and mean lives as the particles listed)

	Particle	Spin	Mass (Errors represent standard deviation) (Mev)		Mass difference (Mev)		Mean life (sec)		Decay rate (number per second)
Photon	γ	1	0				stable		0
Leptons	ν	$\frac{1}{2}$	0				stable		0
	e^-	$\frac{1}{2}$	0.510976	(a)			stable		0
	μ^-	$\frac{1}{2}$	105.70 ±0.06	(a)			$(2.22 \pm 0.02) \times 10^{-6}$		0.45×10^{6}
Mesons	π^+	0	139.63 ±0.06	(a)	4.6 (a)		$(2.56 \pm 0.05) \times 10^{-8}$	(a)	0.39×10^{8}
	π^0	0	135.04 ±0.16	(a)			$< 4 \times 10^{-16}$	(d)	$> 2.5 \times 10^{15}$
	K^+	0	494.0 ±0.2	(g)	0.4 ± 1.8		$(1.224 \pm 0.013) \times 10^{-8}$	(h)	0.815×10^{8}
	K^0	0	494.4 ±1.8	(i)		K_1:	$(0.95 \pm 0.08) \times 10^{-10}$	(e)	1.05×10^{10}
						K_2:	$(4 < \tau < 13) \times 10^{-8}$	(c)	$(0.07 < \tau < 0.25) \times 10^{8}$
Baryons	p	$\frac{1}{2}$	938.213 ± 0.01	(a)			stable		0.0
	n	$\frac{1}{2}$	939.506 ± 0.01	(a)			$(1.04 \pm 0.13) \times 10^{+3}$	(a)	0.96×10^{-3}
	Λ	$\frac{1}{2}$	1115.2 ±0.14	(j)			$(2.77 \pm 0.15) \times 10^{-10}$	(k)	0.36×10^{10}
	Σ^+	$\frac{1}{2}$	1189.4 ±0.25	(l)	7.1 ± 0.4		$(0.83\ ^{+.06}_{-.05}) \times 10^{-10}$	(m)	1.21×10^{10}
	Σ^-	$\frac{1}{2}$	1196.5 ±0.5	(n)	$6.0^{+1.4}_{-0.9}$		$(1.67 \pm 0.17) \times 10^{-10}$	(o)	0.60×10^{10}
	Σ^0	$\frac{1}{2}$	$1190.5^{+0.9}_{-1.4}$	(p)			$(< 0.1) \times 10^{-10}$ theoretically $\sim 10^{-19}$	(b)	$> 10 \times 10^{10}$ theoretically $\sim 10^{19}$
	Ξ	?	1320.4 ± 2.2	(q)			$(4.6 < \tau < 200) \times 10^{-10}$	(f)	$(> 0.005, < 0.2) \times 10^{10}$
	Ξ^0	?	?				?		

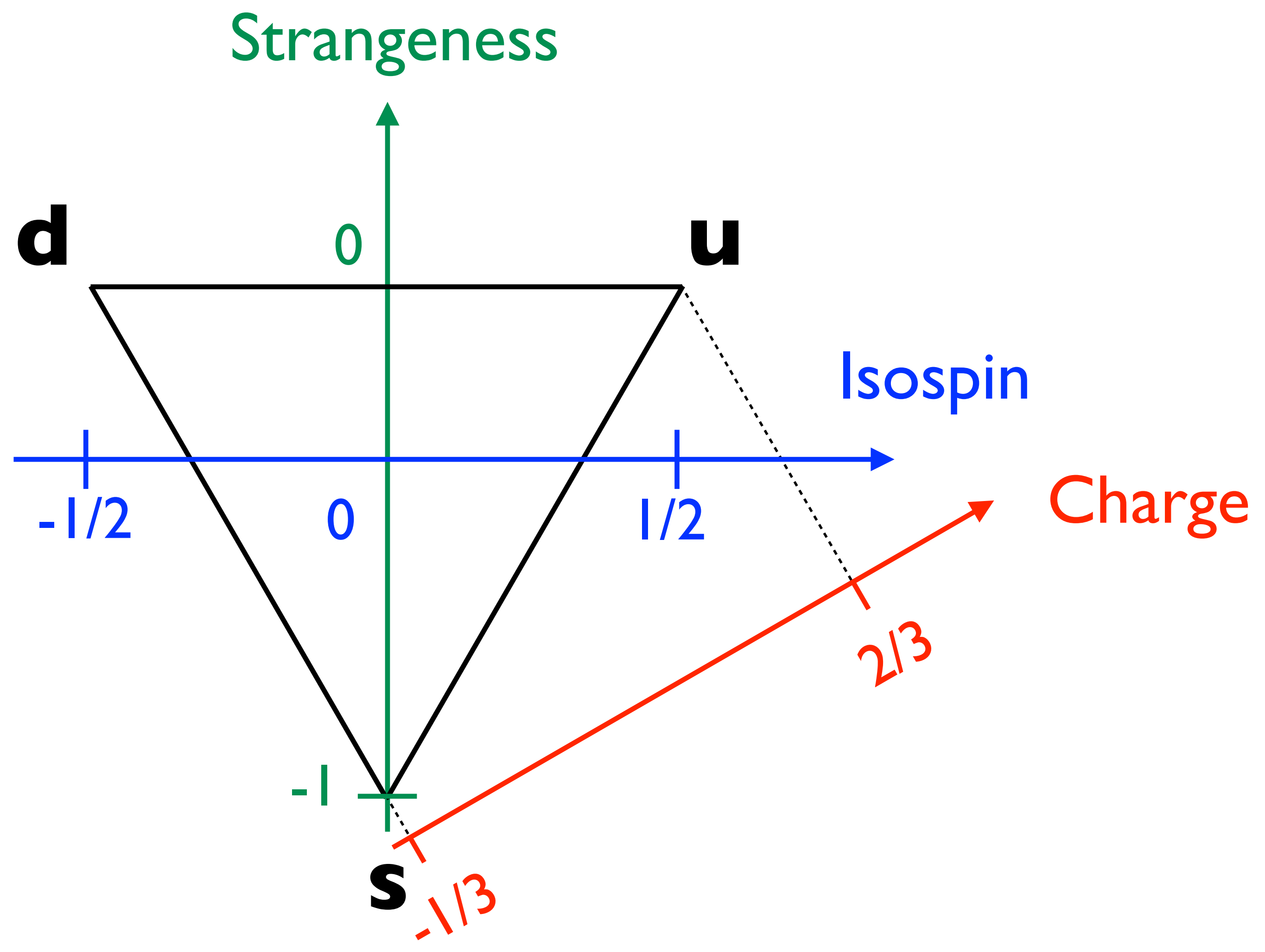
and the Δ (I = 3/2 (++,+,0,-)) being discovered

back

the CKM matrix and the Flavours

Quarks

- This is the building block :

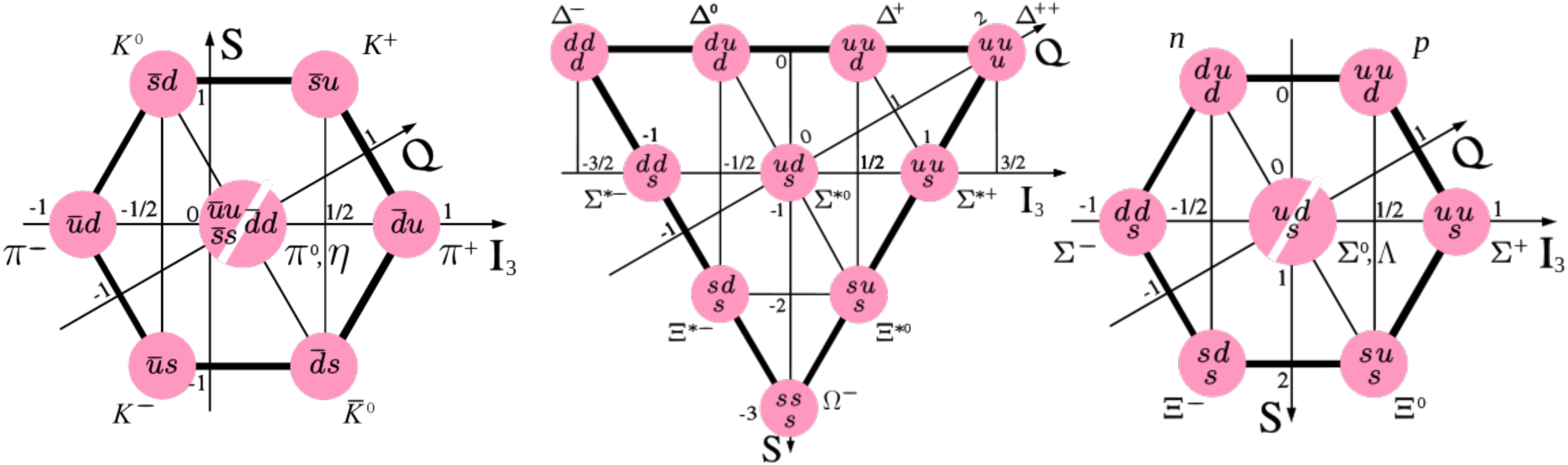


- “collateral damages”
  - fractional charges !!!
  - what is the “charge” of the strong interaction ???

the CKM matrix and the Flavours

Quarks

- and these are some blocks



  - I_3 @ S=0 (meson octet), S = -1 (baryon decuplet), S = 1 (baryon octet)

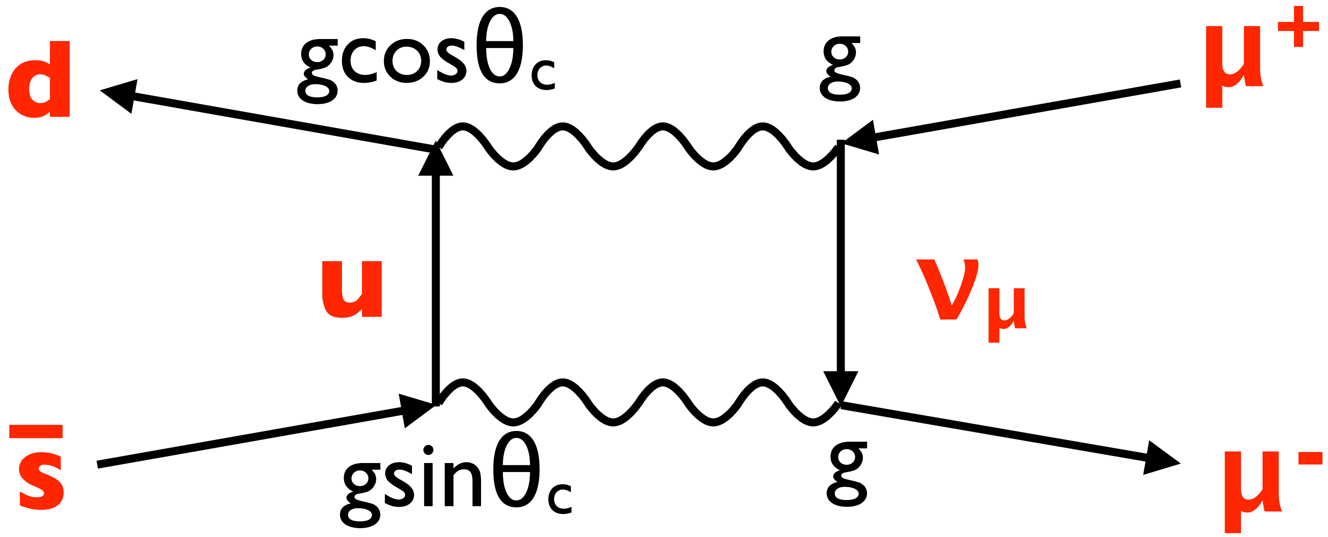
- Ω⁻ was not existing → predicted
  - discovered in 1964 !
  - don't you remember Mendeleïev :-)

the CKM matrix and the Flavours

T

GIM

- remember : $(\nu_e\ e)_L$, $(\nu_\mu\ \mu)_L$, (u d’)
  - d’ = d $\cos\theta_c$ + s $\sin\theta_c$
- there should be an s’ = -d $\sin\theta_c$ + s $\cos\theta_c$
  - but if (u d’) then (**x** s’)
- without **x** :



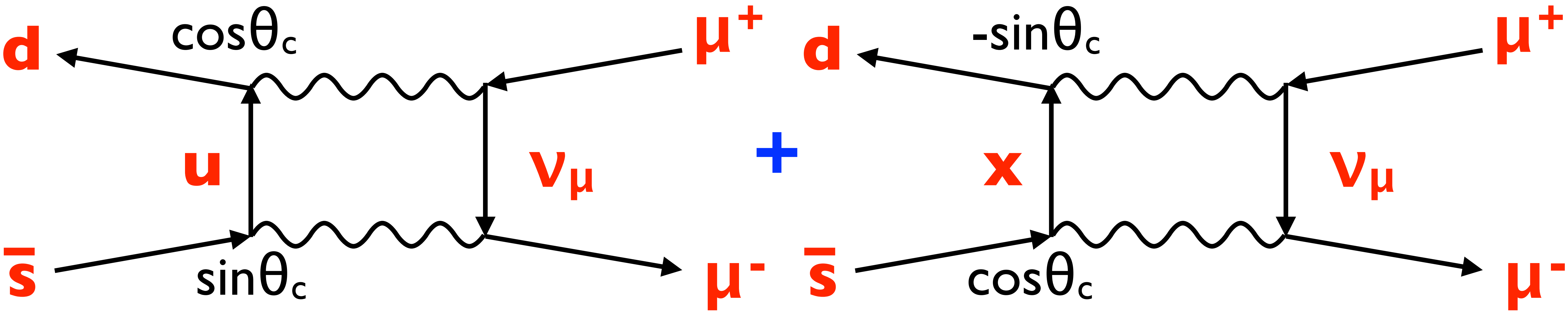
  - $Br(K_L \to \mu^+\mu^-) \sim 7\times10^{-9} << g^8\sin^2\theta_c\cos^2\theta_c$

the CKM matrix and the Flavours

T

GIM

- with **x** , add a new (-) amplitude :



- almost fully destructive → $Br(K_L \rightarrow \mu^+\mu^-)$ OK !
- almost : $m_u \neq m_x$!

“We propose a model of weak interactions in which the currents are constructed out of four basic quark fields (...) The model features a remarkable summetry between leptons and quarks”

Glashow, Iliopoulos, Maiani (1970)

the CKM matrix and the Flavours

GIM

- This is it :

$$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L,\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L$$

$$\begin{pmatrix}u\\ d'\end{pmatrix}_L,\begin{pmatrix}c\\ s'\end{pmatrix}_L$$

- “x” is called **c**harm
- last little tiny problem: does **c** exist ?

the CKM matrix and the Flavours

CKM : the idea

> “It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields”

Kobayashi, Maskawa (1973)

- the Cabibbo matrix $V = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$ describes the (weak) transitions from 1 flavour to an other
  - with 4 flavours ~ 2 “generations”
- can it explain CP ? → NO !
- what do we need to explain it ?

T

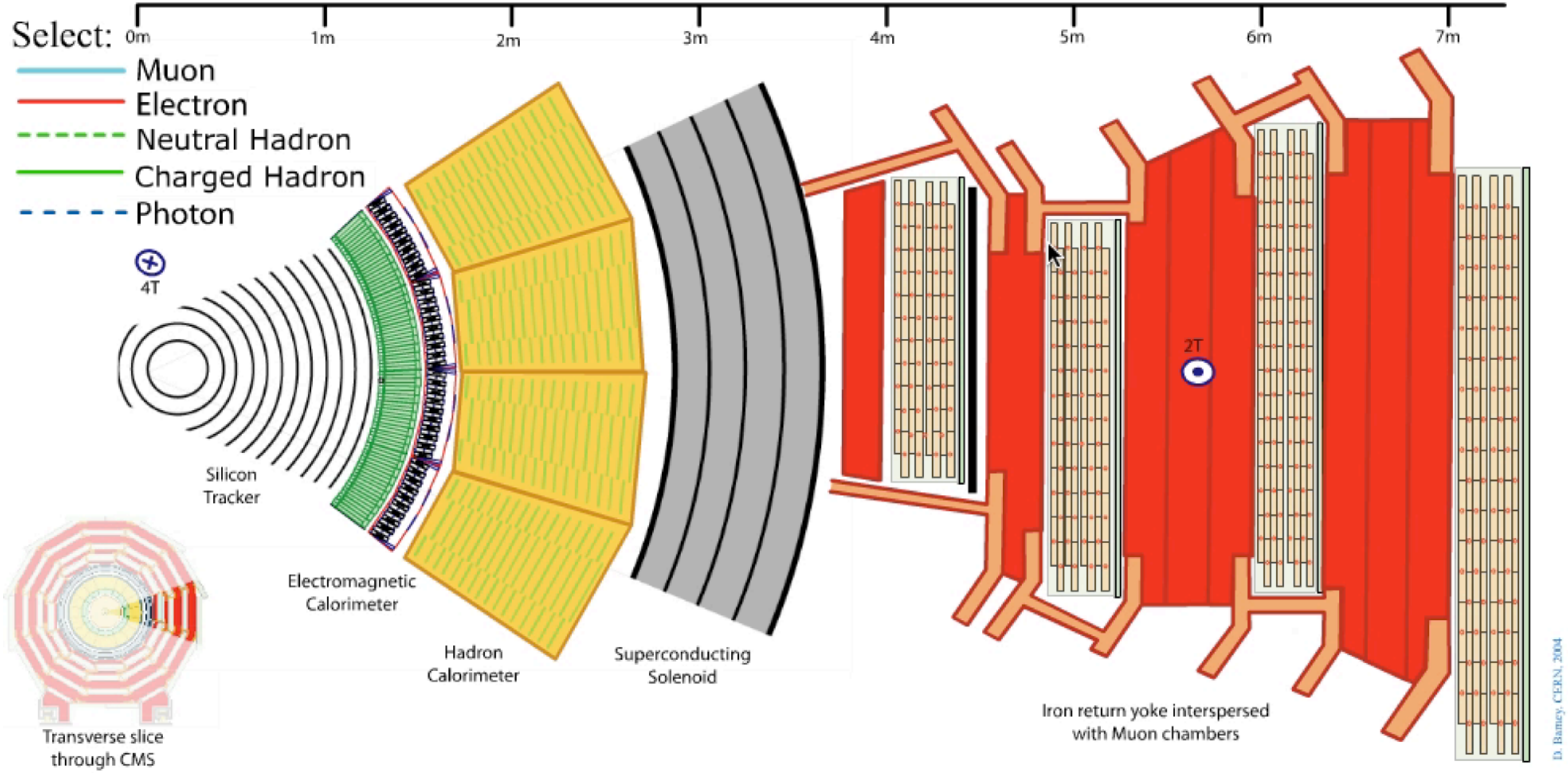
CKM : the idea

- V is a 2x2 matrix and $|V|^2$ are transition probabilities → V should be unitary !
  - V elements have to be complex
    - Schrödinger equation invariant under **T** only if Hamiltonian is real
    - **T** is violated (~ **CP**) → H complex → V complex
  - $VV^\dagger = 1 \Leftrightarrow \sum_{j=1}^{N} V_{ij}V^*_{jk} = \delta_{ik}$ → many constraint on Vij
  - with N = 2 → 1 angle (θ_c)
  - with N = 3 → 3 angles + 1 phase → $\cancel{\mathrm{CP}}$
- this 3x3 complex matrix is called the **CKM** matrix
  - 3x3 → would there be a 3rd generation ?

the CKM matrix and the Flavours

interlude : modern particle physics detectors

E



the CKM matrix and the Flavours

E

C ... experimentalists strike back !

- 12 November 1974 (publication day) : **J**
- J.J. Aubert et al. (cocorico)

- 30 GeV p on Be target
- e^+e^- 2-arms spectrometer

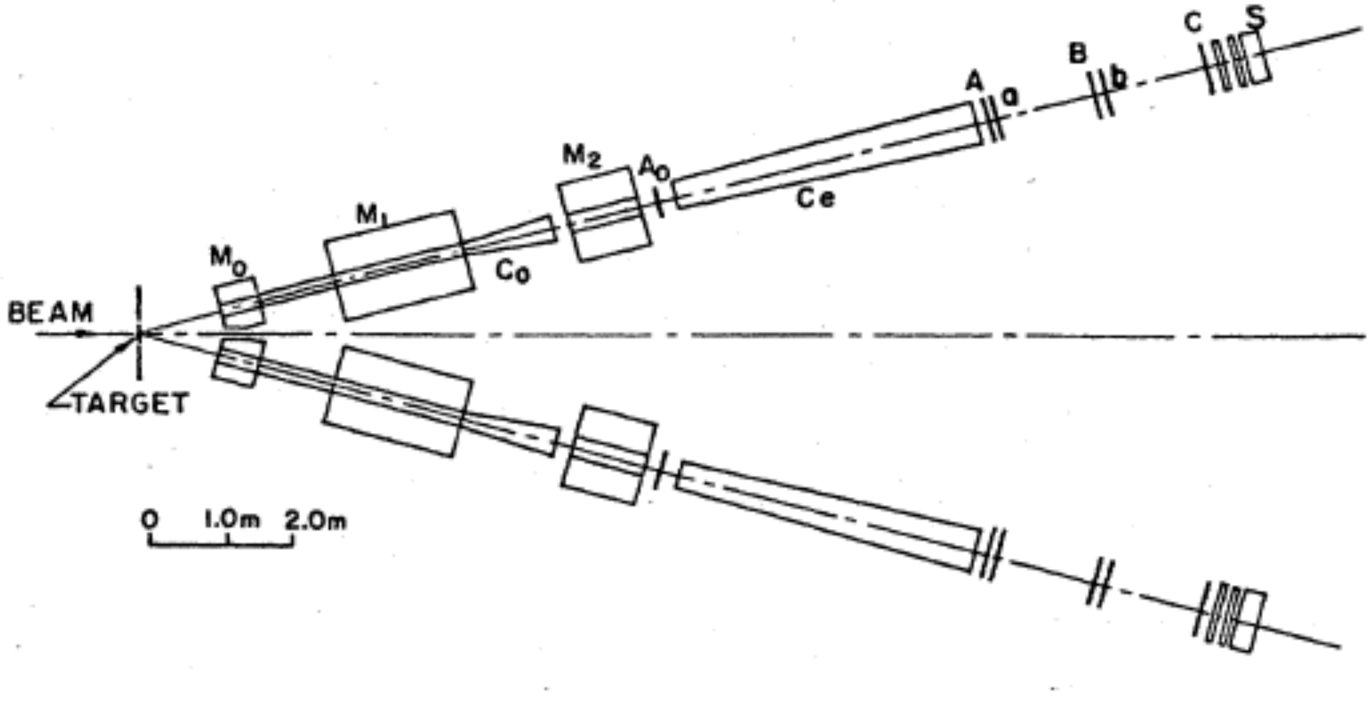
  $p + p \to e^+ + e^- + x$
- M's : dipole magnets
- A_0 A, B, C : 8000-wires proportionnal chambers
- a,b : hodoscopes
- S : lead-glass counters
- C_B, C_0, C_e : C counters

Acceptance :

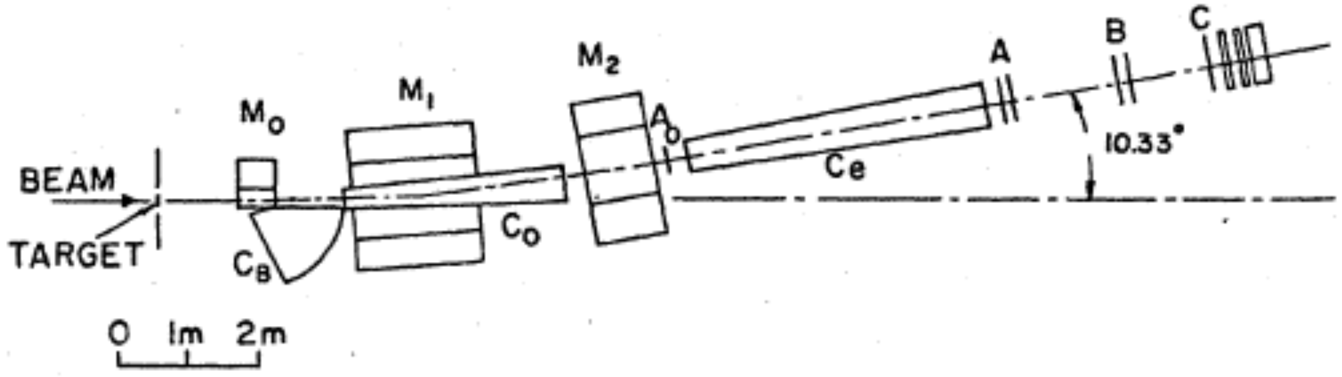
$\Delta\theta = \pm 1°$

$\Delta\Phi = \pm 2°$

$\Delta m = 2$ GeV



(a) Plan view



(b) Side view

the CKM matrix and the Flavours

E

C ... experimentalists strike back !

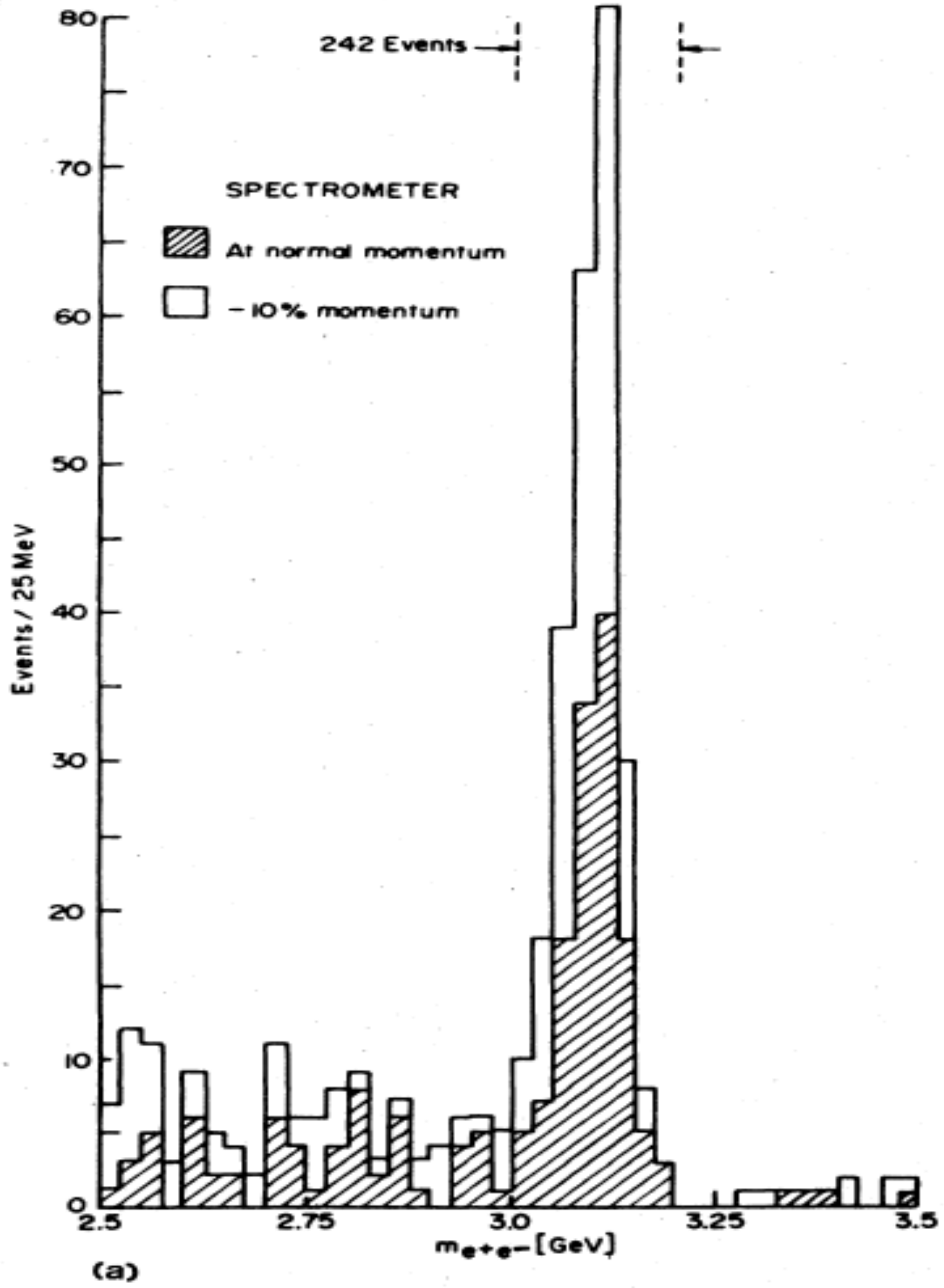
- 12 November 1974 (publication day) : **J**
- J.J. Aubert et al. (cocorico)

" We report the observation of a heavy particle J, with mass m = 3.1 GeV and width approximatively zero "

" The most striking feature of J is the possibility that it may be one of the theoretically suggested charmed particles ..."

" It is also important to note the absence of an e^+e^- continuum, which contradicts the preditions of parton models* ..."

* Drell-Yann !



the CKM matrix and the Flavours

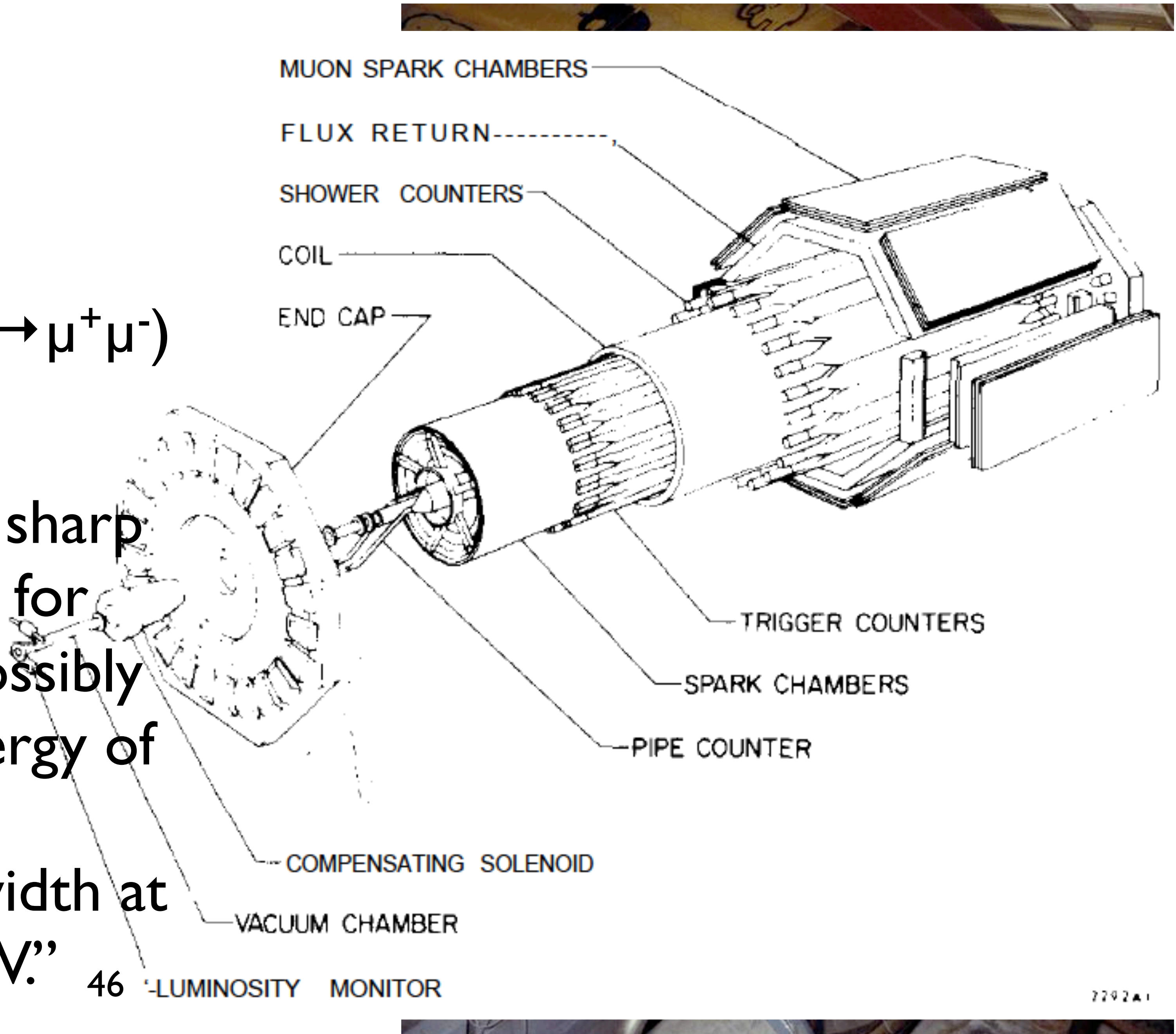
E

C ... experimentalists strike back !

- 13 November 1974 (publication day) : Ψ
- J.E. Augustin et al. (cocorico)

- scan [m] differently !
- SPEAR : 2 - 8 GeV e^+e^-
  - can vary E_{cm} !
- to study :
  $\sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-)$
- measure X-sections !

> "We have observed a very sharp peak in the cross-section for $e^+e^- \rightarrow$ hadrons, e^+e^- and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV."



the CKM matrix and the Flavours

E

C ... experimentalists strike back !

c discovery

=

there is a 4th quark

(GIM were right !)

the CKM matrix and the Flavours

E

τ ... experimentalists strike back !

- same machine : SPEAR = e^+e^-
  - E_{cm} = 4.8 GeV
- ~ first large solid angle detector
  - Mark I (2.6π)
- looking for “new heavy leptons”
  - count total charge seen
  - count “prongs”
  - count nb of γ’s
  - estimate coplanarity

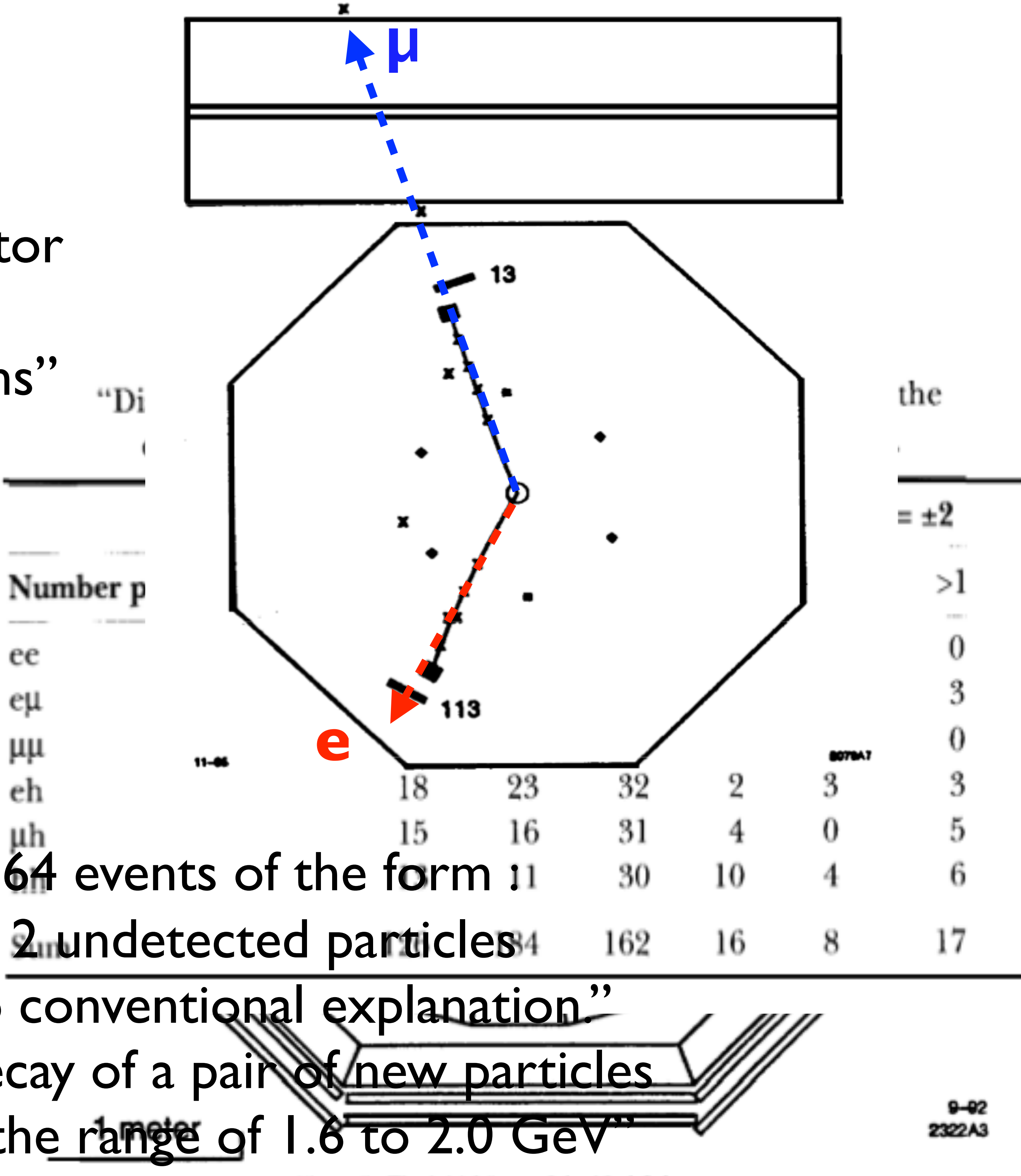


Figure 5. The initial form of the Mark I detector.

“We have found 64 events of the form :

$e^+e^- \to e^\pm\mu^\mp + \geq 2$ undetected particles

for which we have no conventional explanation.”

“(...) production and decay of a pair of new particles each having a mass in the range of 1.6 to 2.0 GeV”

the CKM matrix and the Flavours

E

τ ... experimentalists strike back !

τ discovery

=

there is a 3rd lepton

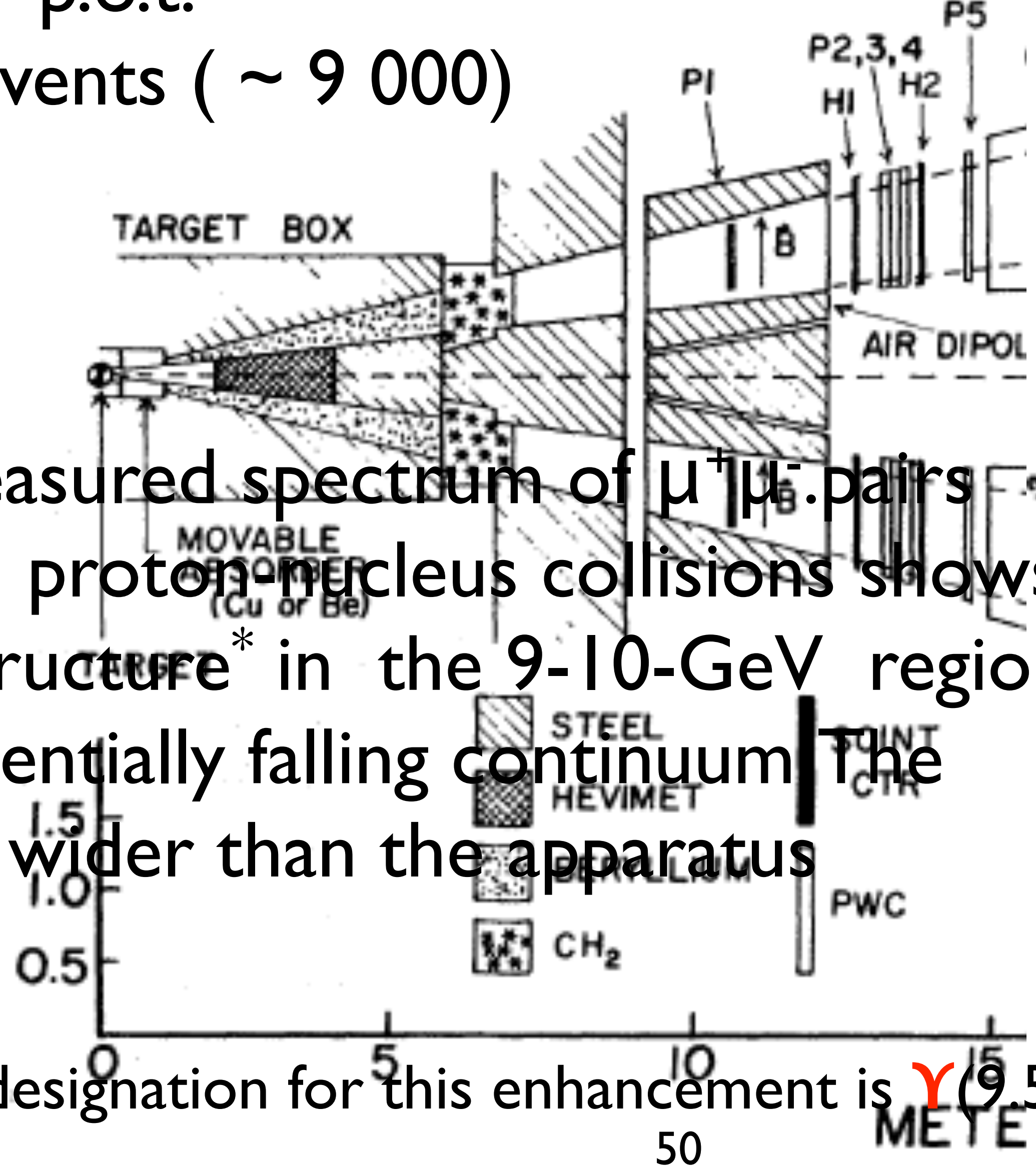
(KM were probably right !)

the CKM matrix and the Flavours

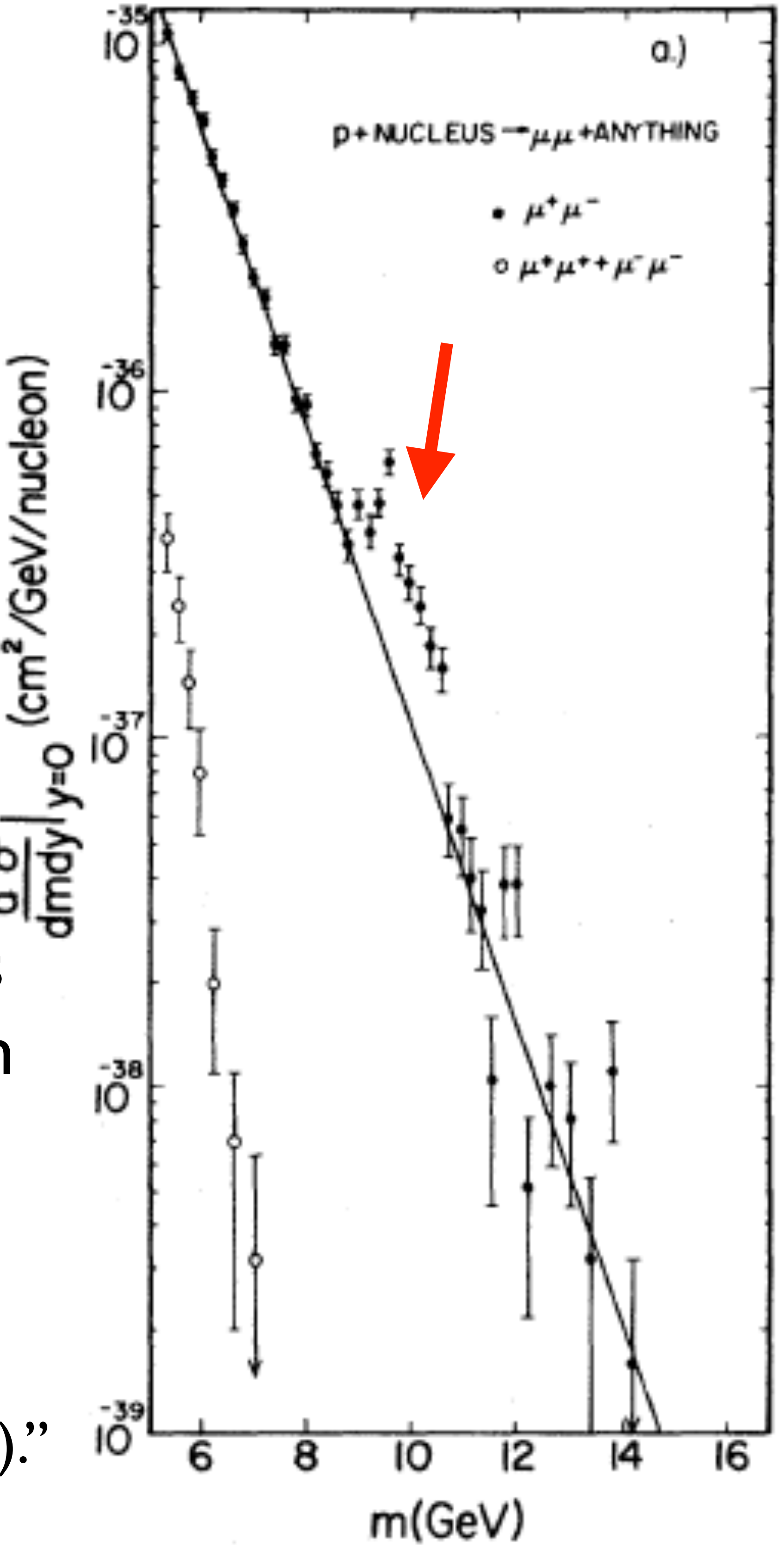
E

b ... experimentalists strike back !

- once again : 2-arms spectrometer
- looking for $m_{\mu\mu} > 5$ GeV
- filter hadrons with Be
- NEW machine : 400 GeV protons !
  - 1.6 x 10^{16} p.o.t.
  - a lot of events (~ 9 000)



“(...) the measured spectrum of $\mu^+\mu^-$ pairs produced in proton-nucleus collisions shows significant structure* in the 9-10-GeV region on an exponentially falling continuum. The structure is wider than the apparatus resolution.”



* “(...) a reasonable designation for this enhancement is Υ(9.5).”

the CKM matrix and the Flavours

b ... experimentalists strike back !

E

b discovery

=

there is a 5th quark

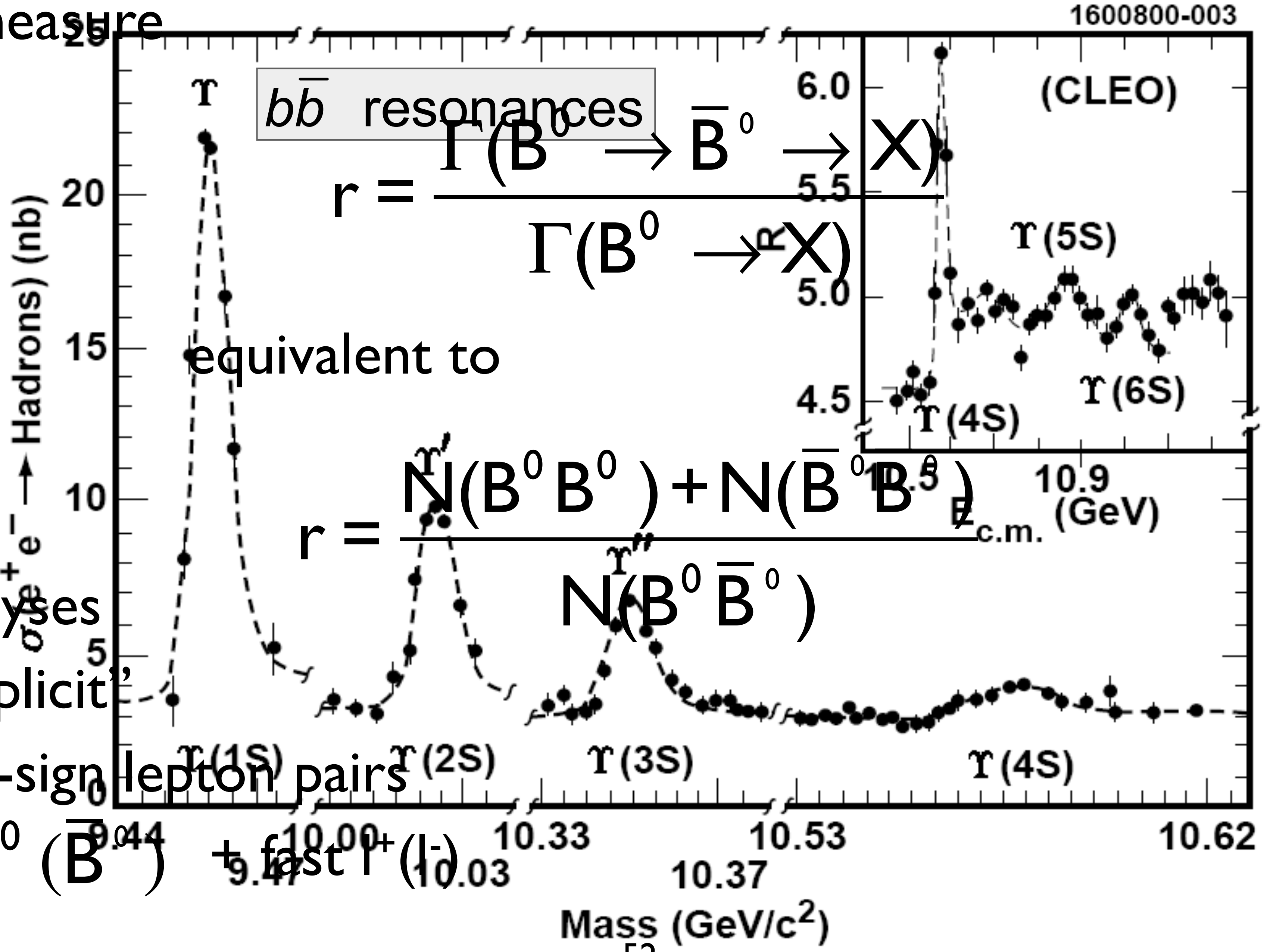
(KM were absolutely right !)

the CKM matrix and the Flavours

E

B^0_d mixing ... experimentalists strike back !

- reminder : $B^0_d = "B^0" = \bar{b}d \, , \bar{B}^0_d = \bar{B}^0 = b\bar{d}$
- $B^0 \sim K^0$ → mixing ; BUT lifetimes very similar (≠ K^0)
- e^+e^- → Υ(4S) is good : enough E for Υ(4S) → $B^0\bar{B}^0$
- will measure



$$r = \frac{\Gamma(B^0 \to \bar{B}^0 \to X)}{\Gamma(B^0 \to X)}$$

equivalent to

$$r = \frac{N(B^0B^0) + N(\bar{B}^0\bar{B}^0)}{N(B^0\bar{B}^0)}$$

- 3 analyses
  - "explicit"
  - like-sign lepton pairs
  - l B^0 ($\bar{B}^{*+}$) + fast l^+ (l^-)

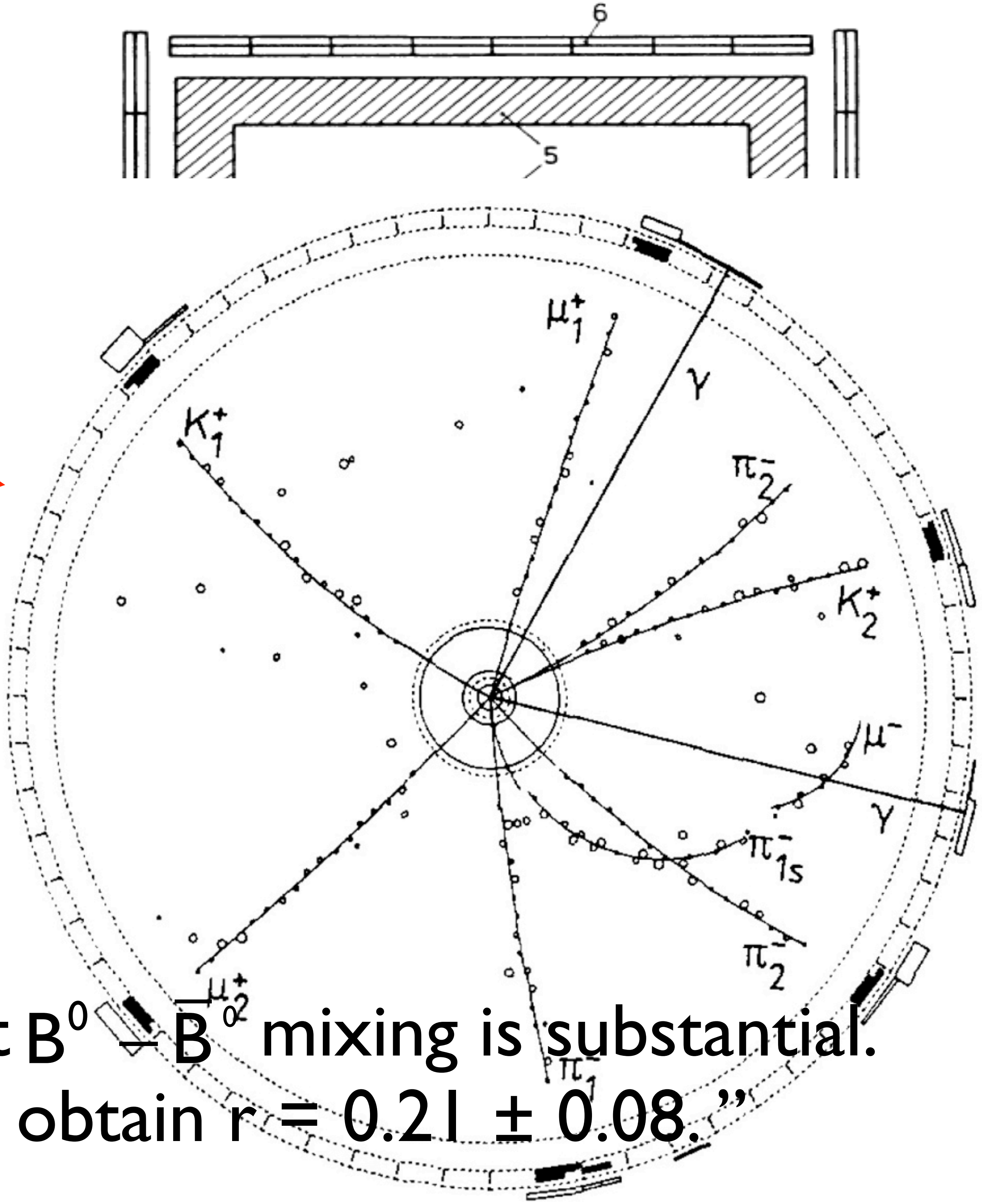
the CKM matrix and the Flavours

E

B^0_d mixing ... experimentalists strike back !

- machine : DORIS II → $e^+e^- \sim 5 + 5$ GeV
- detector : ARGUS
- 88 000 $\Upsilon(4S)$ events ~ 103 pb^{-1}

- 24.8 events with like-sign dilepton
- 4.1 events with B^0 + fast lepton
- 1 "explicit" event
  - $B^0_1 \rightarrow D^{*-}_1 \mu^+_1 \nu_1$
    $D^{*-}_1 \rightarrow \pi^-_1 \bar{D}^0$
    $\bar{D}^0 \rightarrow K^+_1 \pi^-_1$
  - $B^0_2 \rightarrow D^{*-}_2 \mu^+_2 \nu_2$
    $D^{*-}_2 \rightarrow \pi^0 D^-$
    $D^- \rightarrow K^+_2 \pi^-_2 \pi^-_2$



" This leads to the conclusion that $B^0 - \bar{B}^0$ mixing is substantial. For the mixing parameter we obtain r = 0.21 ± 0.08. "

the CKM matrix and the Flavours

E

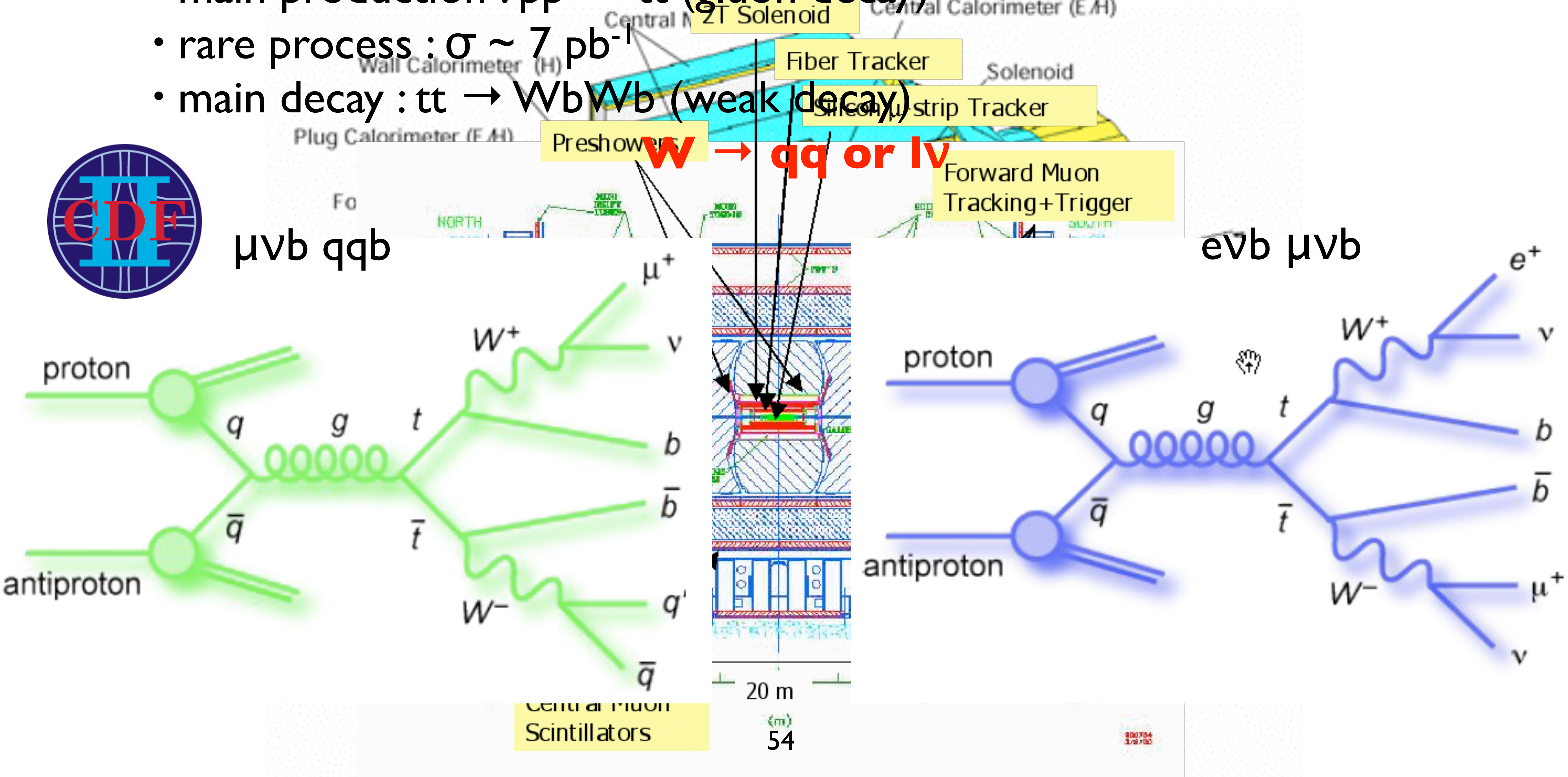
t ... experimentalists strike back !

- machine : “Tevatron” = $p\bar{p}$ @ E_{CM} = 1.8 TeV
- detectors : CDF/D0
  - “modern” = ~ 4π with “everything” inside
- main production : $p\bar{p} \rightarrow t\bar{t}$ (gluon decay)
- rare process : σ ~ 7 pb^{-1}
- main decay : tt → WbWb (weak decay)

W → qq or lν

μνb qqb

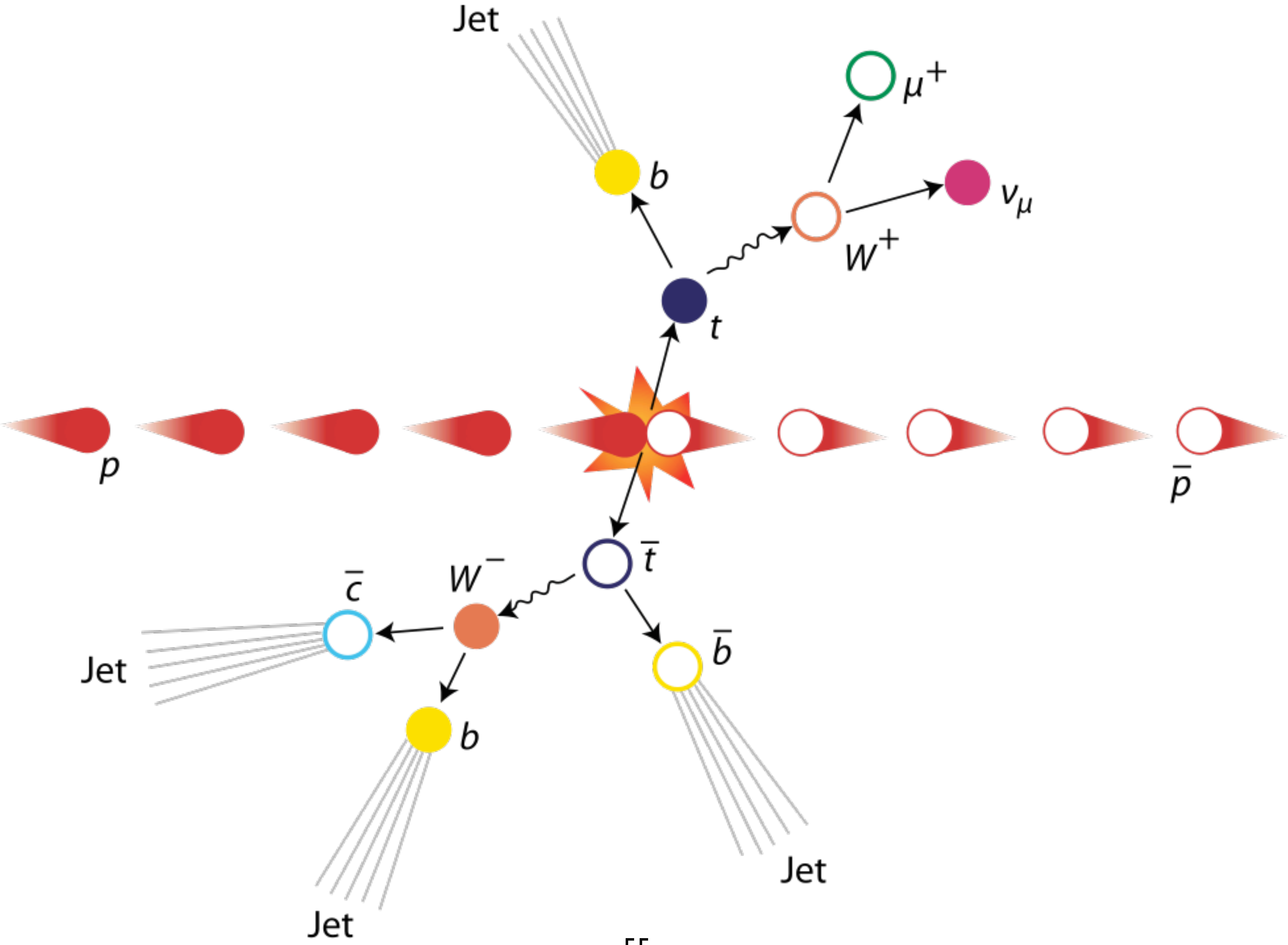
eνb μνb



the CKM matrix and the Flavours

E

t ... experimentalists strike back !



the CKM matrix and the Flavours

E

t ... experimentalists strike back !

- analyses ⇔ topologies
- example 1 : 2 (s.l.) W → 2l + 2ν + 2 bjets
  - 2 high p_T leptons
  - 2 b-quark jets
  - missing transverse E_T
    - D0 : topological selection to separate Signal/Background and b-tagging analyses
    - CDF : topological selection and selection with b-quark jet identification (b-tag)
- example 2 : 1 (s.l.) W → l + ν + qq + 2 bjets
  - 1 high p_T lepton
  - 2 b-quark jets
  - 2 light quark jets
  - missing transverse E_T
    - D0 : topological (likelyhood) and b-tagging analyses
    - CDF : topological (neural net.) and selection and b-tagging analyses

the CKM matrix and the Flavours

E

t ... experimentalists strike back !

- results :
  - CDF : 5 σ evidence, $m_{top} = 176 \pm 8 \pm 10$ GeV
  - D0 : 4.6 σ evidence, $m_{top} = 199\ ^{+19}_{-21} \pm 22$ GeV

Have the FNAL experiments found the top quark ?

Well ...

→ B. Pietrzyk - Moriond 1994 - Top searches summary :

$$m_T = 174 \pm 11\ ^{+17}_{-19} \text{ GeV}$$

the CKM matrix and the Flavours

t ... experimentalists strike back !

E

t discovery

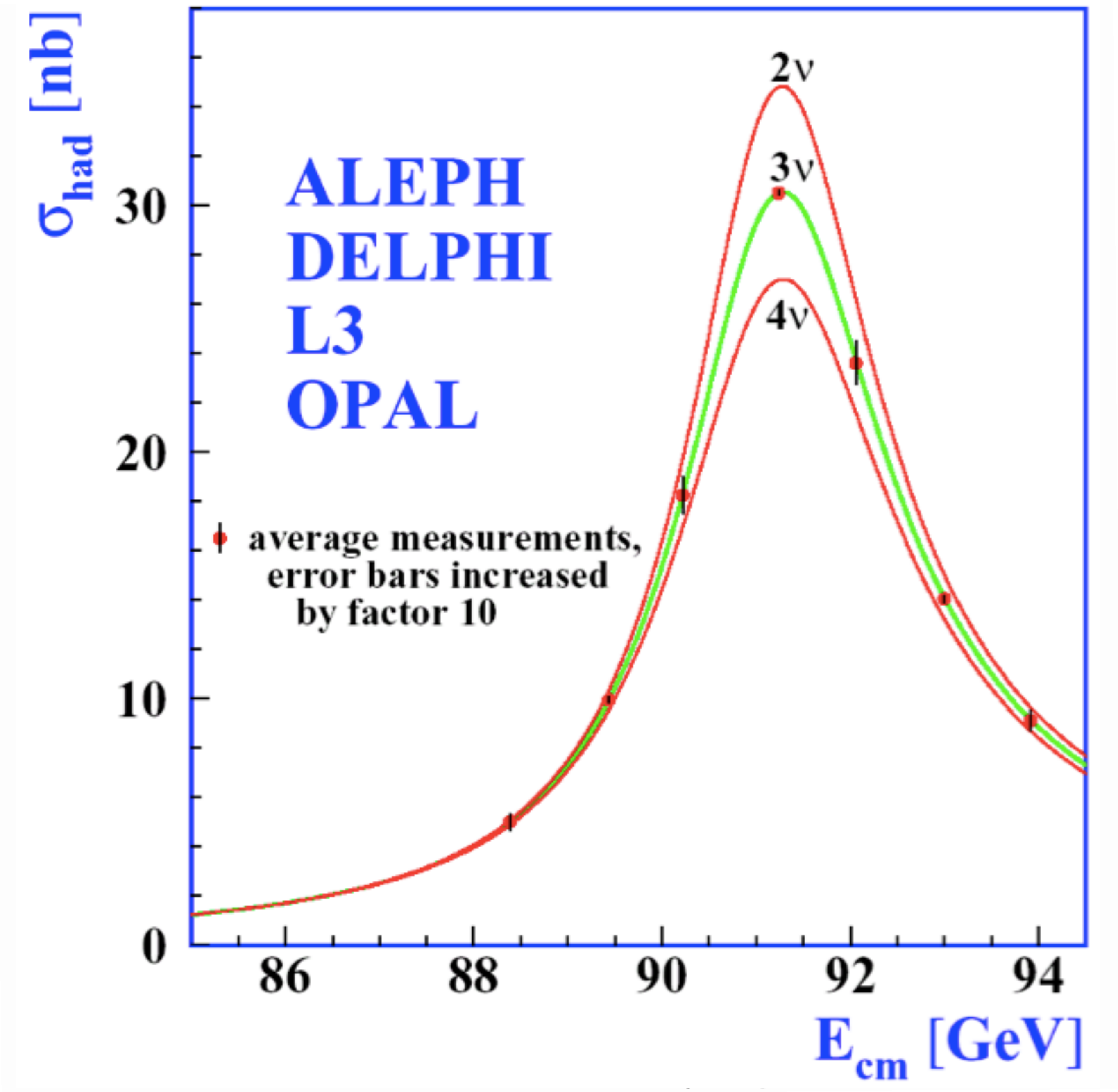
=

All fermions are there !

if you don't believe it ...

the CKM matrix and the Flavours

t ... experimentalists strike back !



Original Paper : ALEPH (1989), D.Decamp et al. : $N_\nu = 3.27 \pm 0.30$

Today value : $N_\nu = 2.92 \pm 0.05$

4 - the Beautiful Factories

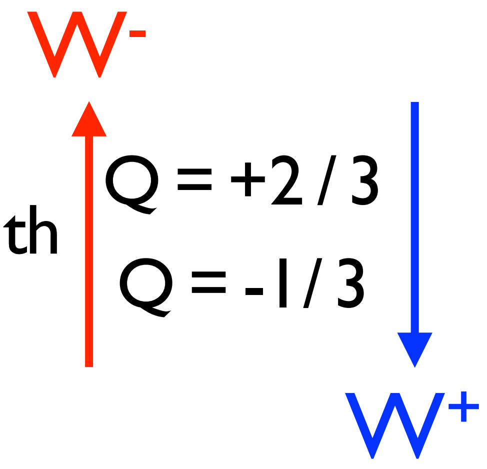
– CKM matrix - 2		...	**T**
– Mixing & Oscillations		...	**T**
– Triangle - status 1	CKMfitter	1995	**??**
– 🐧 & B factories	PEPII, KEKB	1999	**E**
– ~~CP~~ (B^0_d)	BaBar (Belle)	2001	**E**
– B^0_s oscillations	CDF	2006	**E**

the Beautiful Factories

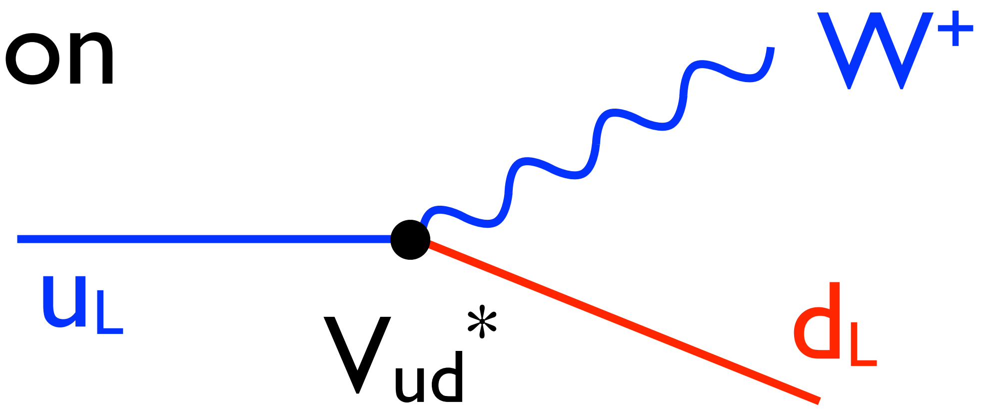
CKM matrix - 2/writing the elements

- reminder :
  - Mass eigenstates ≠ Flavour eigenstates
  - 3x3 unitary matrix, 4 parameters (3 angles, 1 phase)
- now we can write it with the 3 L doublets :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \times \begin{pmatrix} d \\ s \\ b \end{pmatrix} \text{ and } \begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \text{ with } \begin{matrix} Q = +2/3 \\ Q = -1/3 \end{matrix}$$



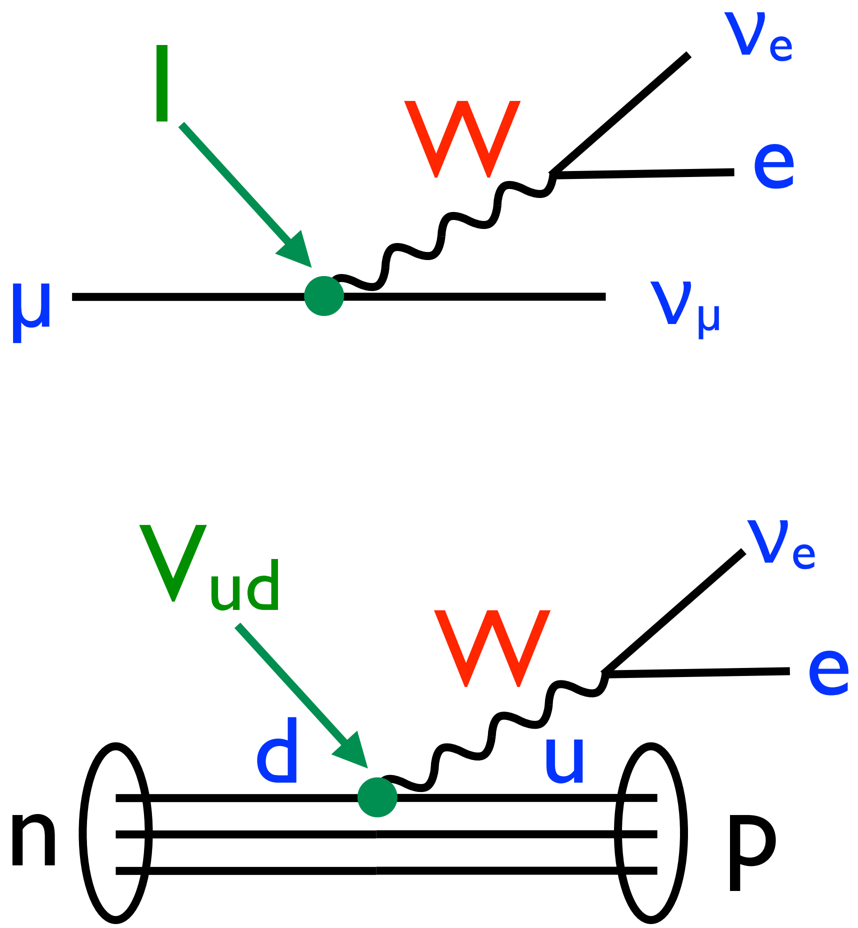
- matrix elements by definition
  - Vij for particles
  - Vij* for antiparticles



the Beautiful Factories

CKM matrix - 2/measuring the elements

- matrix elements determination (example 1)



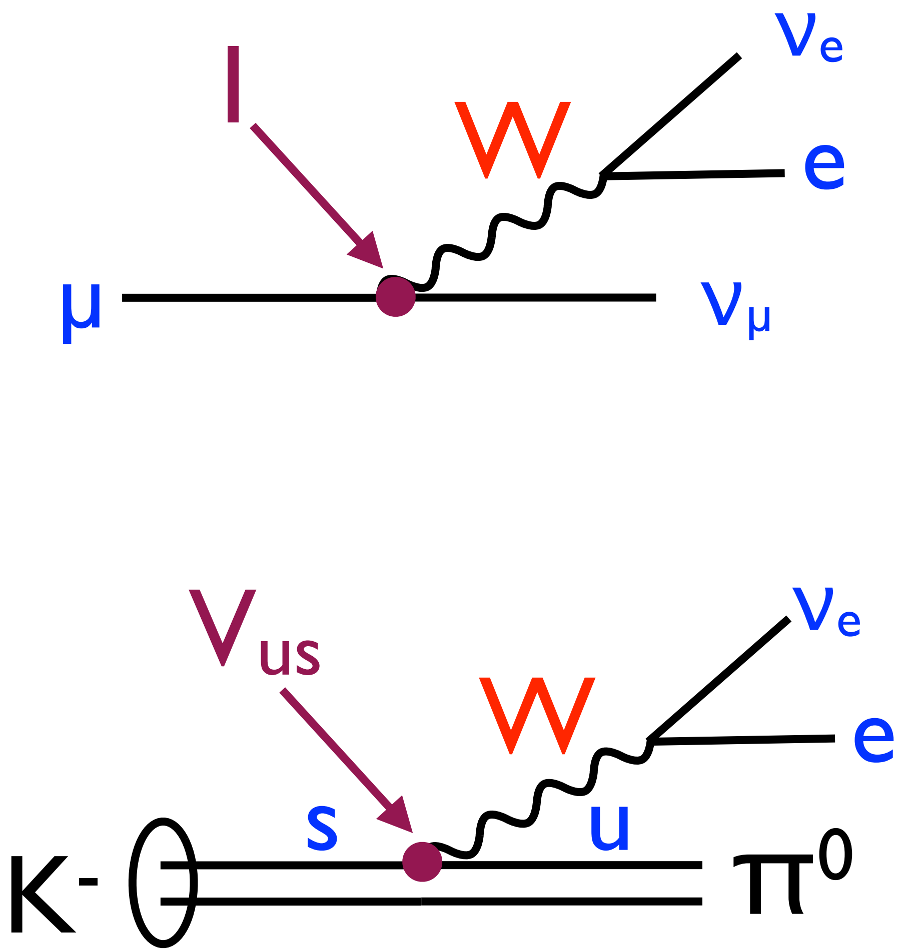
$$\begin{pmatrix} \boxed{V_{ud}} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{ud}|^2 \sim$ neutron decay rate / muon decay rate

$|V_{ud}| \sim 1$

CKM matrix - 2/measuring the elements

- matrix elements determination (example 2)



$$\begin{pmatrix} \boxed{V_{ud}} & \boxed{V_{us}} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

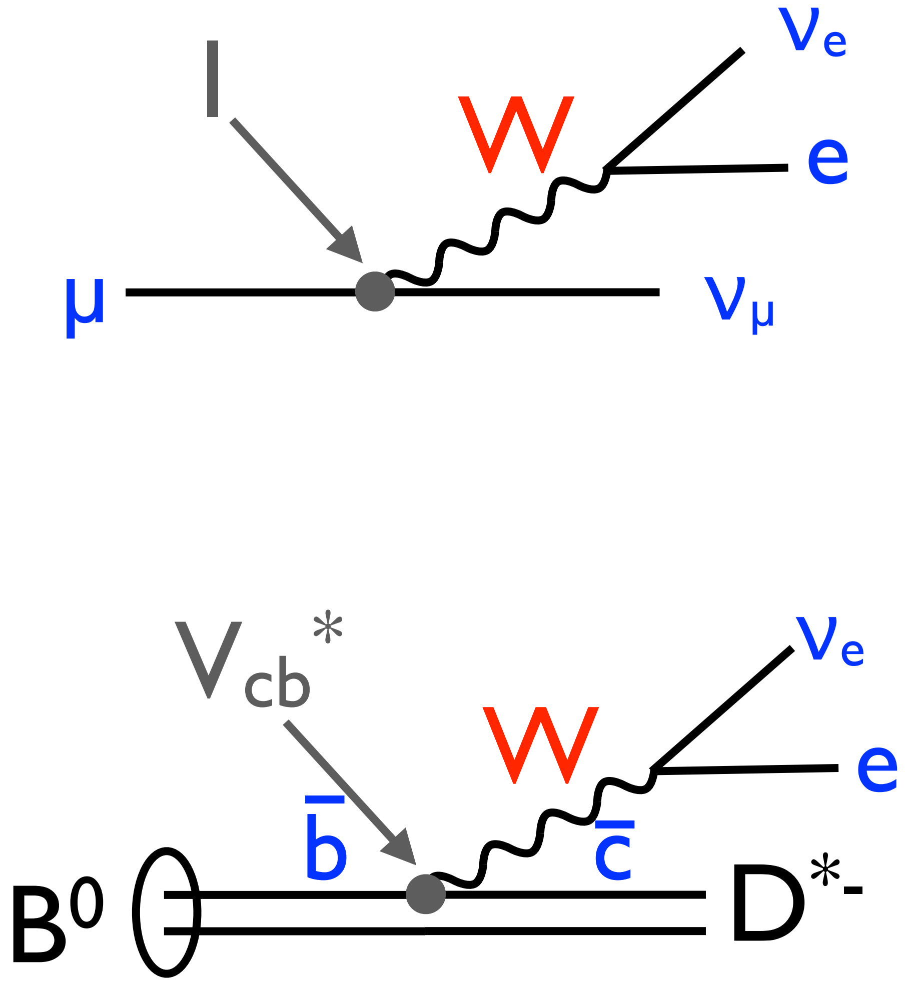
$|V_{us}|^2 \sim K^-$ semileptonic decay rate / muon decay rate

$|V_{us}| \sim 0.22\ (= \sin\theta_c = \lambda)$

the Beautiful Factories

CKM matrix - 2/measuring the elements

- matrix elements determination (example 3)



$$\begin{pmatrix} \boxed{V_{ud}} & \boxed{V_{us}} & V_{ub} \\ V_{cd} & V_{cs} & \boxed{V_{cb}} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

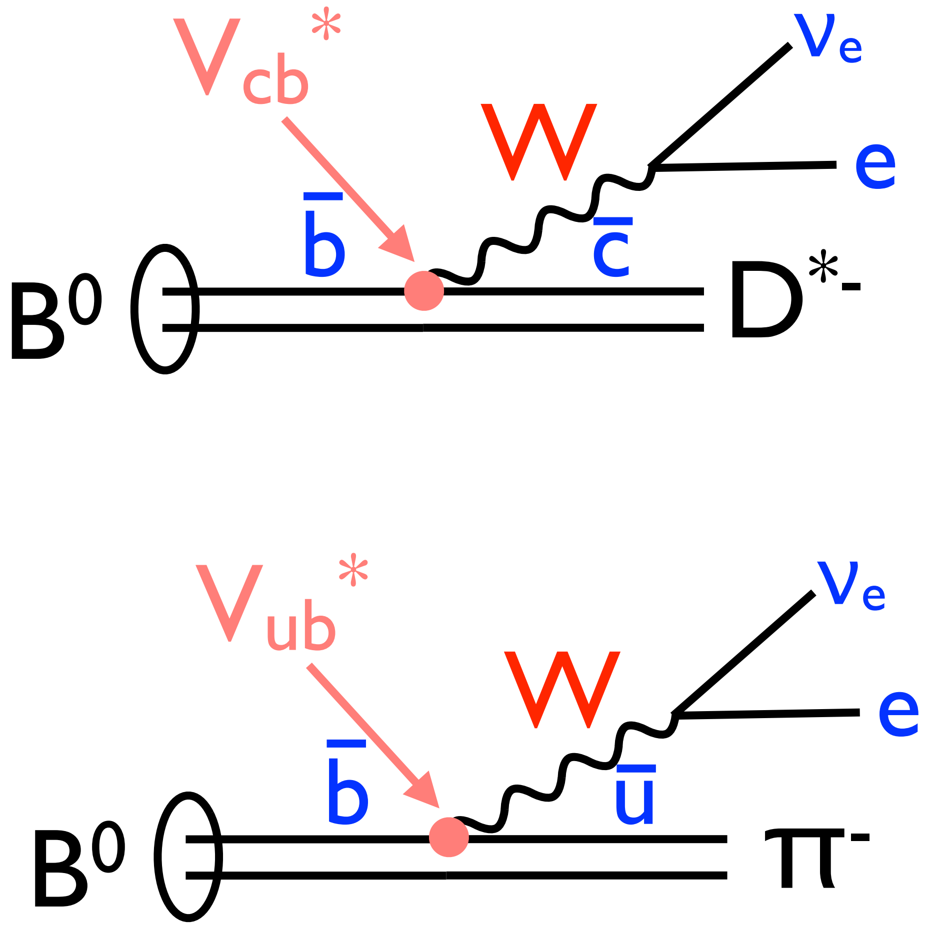
$|V_{cb}|^2 \sim B^0 \rightarrow D^{*-} l^+ \nu$ decay rate / muon decay rate

$|V_{cb}| \sim 0.04 \sim \sin^2\theta_c\ (\lambda^2)$

the Beautiful Factories

CKM matrix - 2/measuring the elements

- matrix elements determination (example 4)



$$\begin{pmatrix} \boxed{V_{ud}} & \boxed{V_{us}} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & \boxed{V_{cb}} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Decay rates of $B^0 \rightarrow D^{*-} l^+ \nu$ / $B^0 \rightarrow \pi^- l^+ \nu \sim |V_{cb}/V_{ub}|^2$

$|V_{ub} / V_{cb}| = 0.090 \pm 0.025$

CKM matrix - 2/parametrizing the elements

- parametrizations
  - Wolfenstein (1983) : write matrix elements as powers of λ
  - put latest results and a complex term

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

  - transitions on diagonal ~ 1 → 1
  - transitions 1st → 2nd family ~ λ → small
  - transitions 2nd → 3rd family ~ λ^2 → very small
  - transitions 1st → 3rd family ~ λ^3 → very very small
  - (ρ - iη) → complex (**CP** violation)

the Beautiful Factories

CKM matrix - 2/applying unitarity

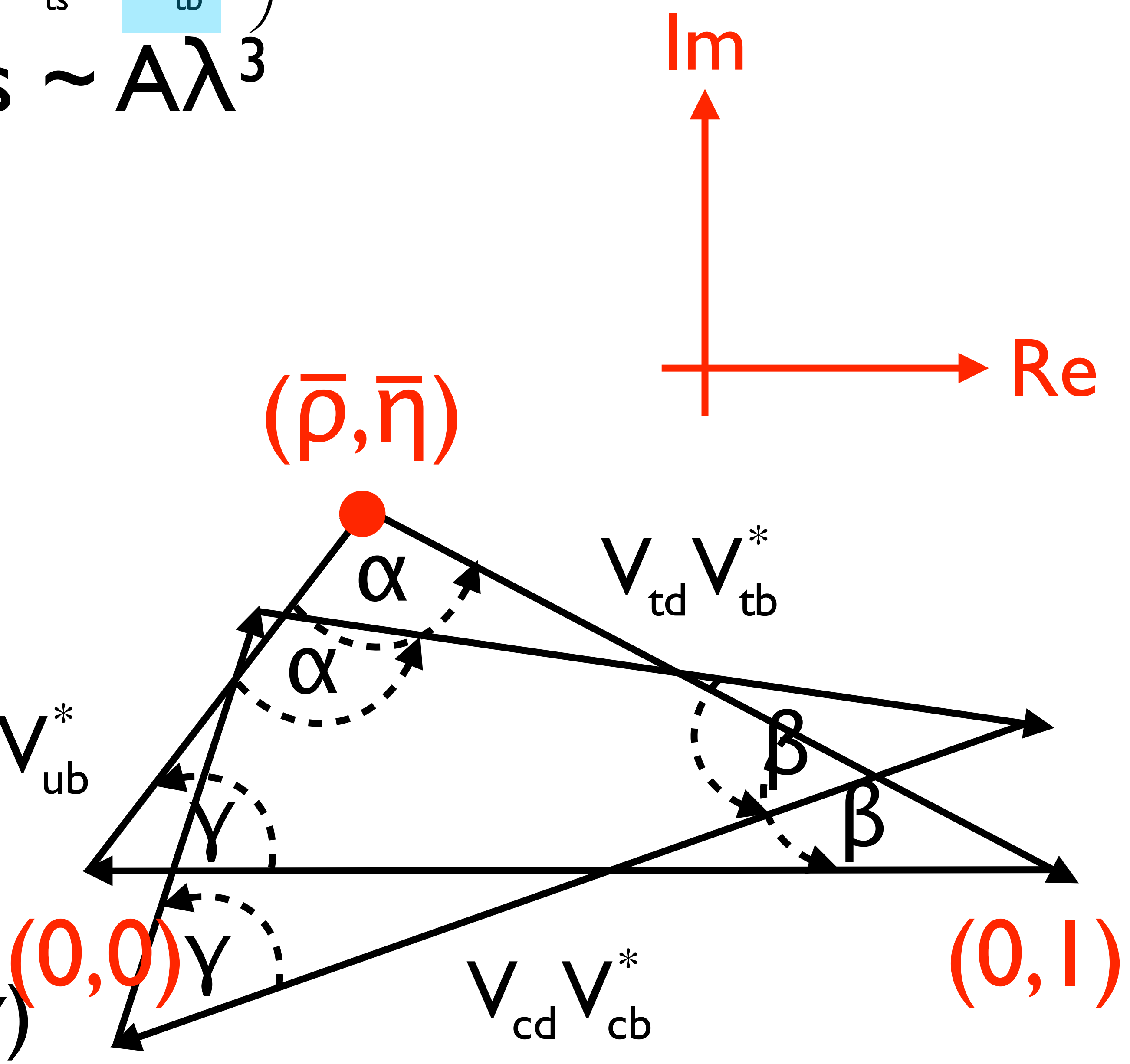
- reminder : CKM matrix is (complex) unitary)
- consequences :
  - Σproba = 1 $$|V_{id}|^2 + |V_{is}|^2 + |V_{ib}|^2 = 1, \forall i \in \{u, c, t\}$$
  - Column x Column* $$\sum_{j=1}^{3} V_{ij} V_{kj}^{*} = 0, \forall i \neq k \{1, 2, 3\}$$
  - Line x Line* $$\sum_{j=1}^{3} V_{ji} V_{jk}^{*} = 0, \forall i \neq k \{1, 2, 3\}$$
- each of the 6 $VV^* = 0$ → 1 triangle in complex plane
  - area of all triangles are equal and is a phase convention
  - they are “equivalent” BUT not equally “interesting” ...

CKM matrix - 2/defining the Unitarity Triangle

- unitarity of the "bd" triangle :

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}^{*} \rightarrow V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

- each term of the sum is ~ $A\lambda^3$
  - "best" (= largest) case
- sides of the triangle
- angles of the triangle
- phase convention
- normalization
- "simplication" ($\alpha=\pi-\beta-\gamma$)
  - remember : $(\beta,\gamma,\bar{\rho},\bar{\eta}) \sim f(A,\lambda,\rho,\eta)$ ~ 3 angles + 1 complex phase



the Beautiful Factories

Mixing & Oscillation/first steps

- reminder : mixing predicted in 1955 (then observed)
  - (**CP** conserved) : $$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right), \quad [CP = +1]$$ $$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right), \quad [CP = -1]$$
- but $\cancel{\textbf{CP}}$: physical (mass) eigenstates ≠ CP eigenstates !
  - $(K_1, K_2) \rightarrow (K_S, K_L)$

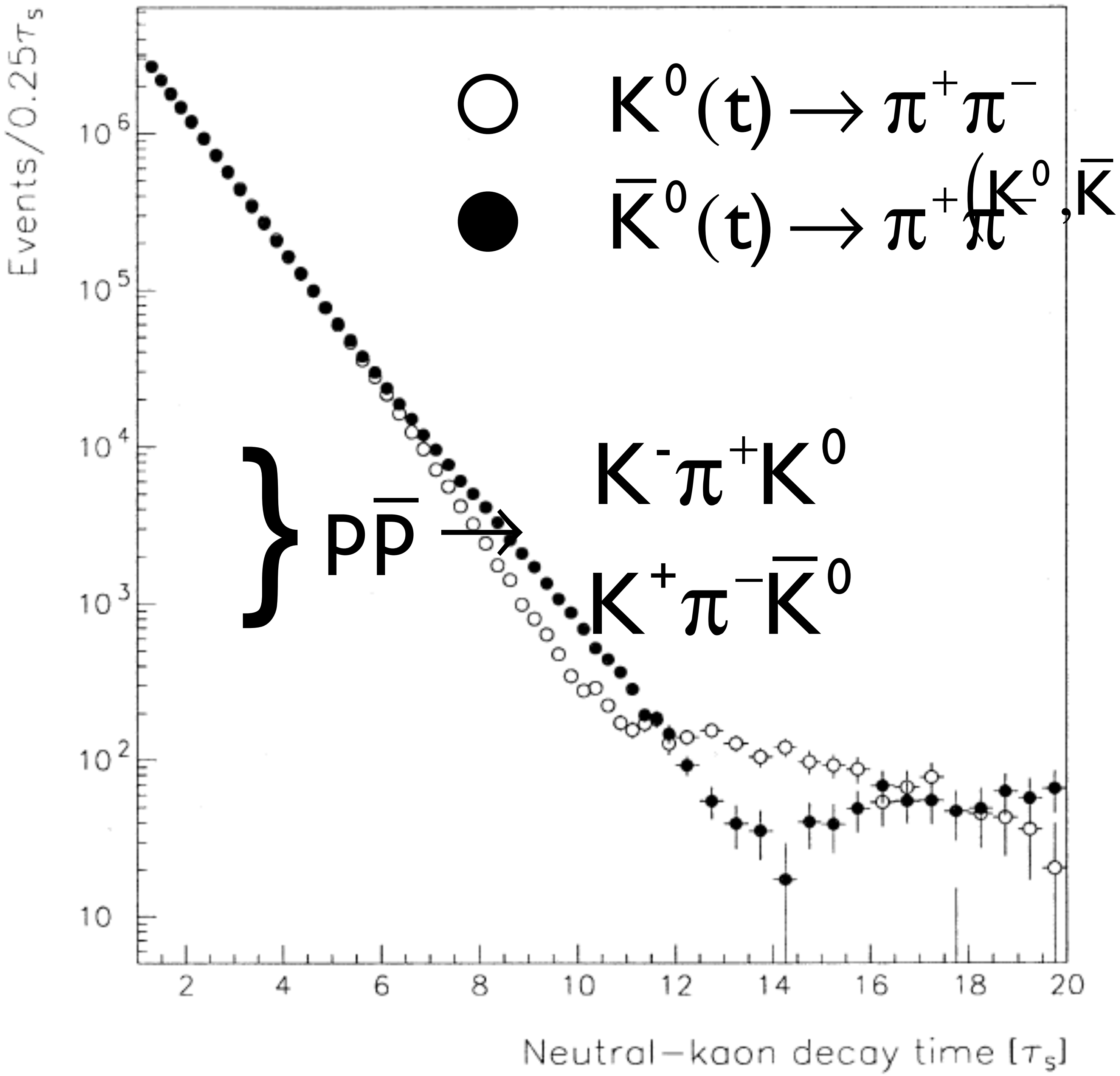
$$\begin{pmatrix} |K_S\rangle \\ |K_L\rangle \end{pmatrix} = \frac{1}{\sqrt{1+|\varepsilon|^2}}\begin{pmatrix} |K_1\rangle + \varepsilon|K_2\rangle \\ \varepsilon|K_1\rangle + |K_2\rangle \end{pmatrix} = \sqrt{\frac{1}{2}}\begin{pmatrix} p & q \\ p & -q \end{pmatrix}\begin{pmatrix} |K^0\rangle \\ |\bar{K}^0\rangle \end{pmatrix}$$

  - $|q/p| = |(1-\varepsilon)/(1+\varepsilon)| \sim 0.995 \neq 1$
  - how does this evolve with time ? interferences ?

the Beautiful Factories

Mixing & Oscillation/one experiment

- CPLEAR (1999) :
  - time evolution of $(K^0, \bar{K}^0)$
  - (clever) method :
    - flavour tagged with
    - $p\bar{p}$ at rest !
- results :
  - ● ≠ ○ !
  - non-exp. compone
  - oscillations



○ $K^0(t) \rightarrow \pi^+\pi^-$

● $\bar{K}^0(t) \rightarrow \pi^+\pi^-$

$$\left.\begin{matrix} \\ \\ \end{matrix}\right\} p\bar{p} \rightarrow \begin{matrix} K^-\pi^+K^0 \\ K^+\pi^-\bar{K}^0 \end{matrix}$$

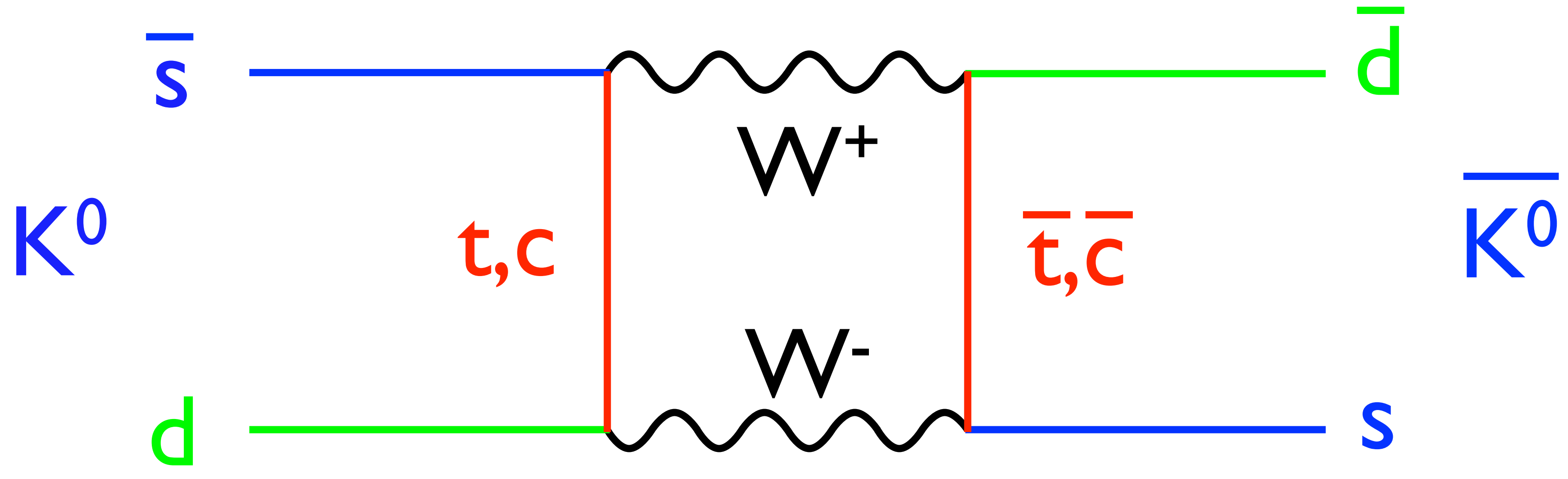
Fig. 1. The measured decay rates for K^0 (open circles) and $\bar{K}^0$ (solid circles) after acceptance correction and background subtraction.

the Beautiful Factories

Mixing & Oscillation/box

T

- it's weak decays : ~~C , P , Strangeness~~
- described by "box" diagram ($\Delta S = 2$)



- $\Delta m = m(K_L)-m(K_S) = 3.5\ 10^{-12}$ MeV > 0 $\rightarrow K^0 \rightleftarrows \overline{K^0}$
- how do we (time) describe this ?

the Beautiful Factories

Mixing & Oscillation/time evolution

- write time dependence

$$|K(t)\rangle = g(t)|K^0\rangle + h(t)|\bar{K}^0\rangle$$

- with Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} |K^0(t)\rangle \\ |\bar{K}^0(t)\rangle \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} |K^0(t)\rangle \\ |\bar{K}^0(t)\rangle \end{pmatrix}$$

  - $M - i/2\Gamma$: 2x2 matrix ; off-diagonal : Δm, $\Delta\Gamma \neq 0$ → mixing
  - observe K_S,K_L → $\Delta m = m(K_L)-m(K_S)$, Γ_S, Γ_L
- results : time-dependent intensities

the Beautiful Factories

Mixing & Oscillation/interferences and violations

- Rates in terms of observables ($\cancel{\mathbf{CP}}$ neglected)

$$I_{K^0}(t) \sim e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S+\Gamma_L)t/2}\cos(\Delta m.t)$$

$$I_{\bar{K}^0}(t) \sim e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S+\Gamma_L)t/2}\cos(\Delta m.t)$$

  - cos() due to interference !

- Rates in terms of **CP** violation
  - 3 terms : $\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right|$, $\left|\frac{p}{q}\right|$, $I\left(\frac{p}{q}\frac{\bar{A}_f}{A_f}\right)$ with $A_f = \langle f|H_W|K^0\rangle$
    - **CP** in decay (term ≠ 1)
    - **CP** in mixing (term ≠ 1)
    - **CP** in interference mixing/decay (term ≠ 0)

the Beautiful Factories

Triangle - status 1 (1995-2001)

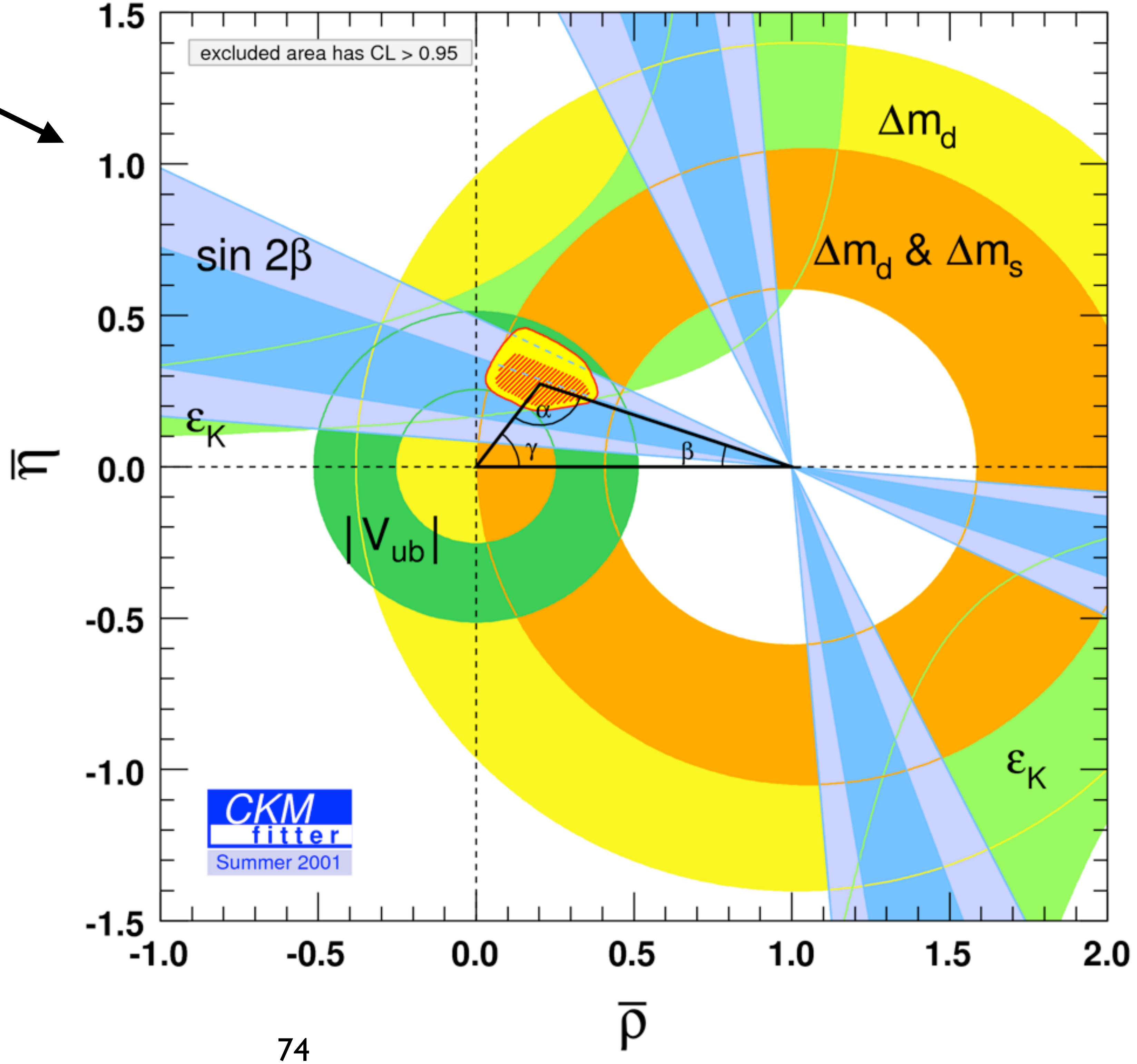
??

from now on : (bd) triangle

$$\alpha = \arg\left(\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right)$$

$$\beta = \arg\left(\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right)$$

$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$$



the Beautiful Factories

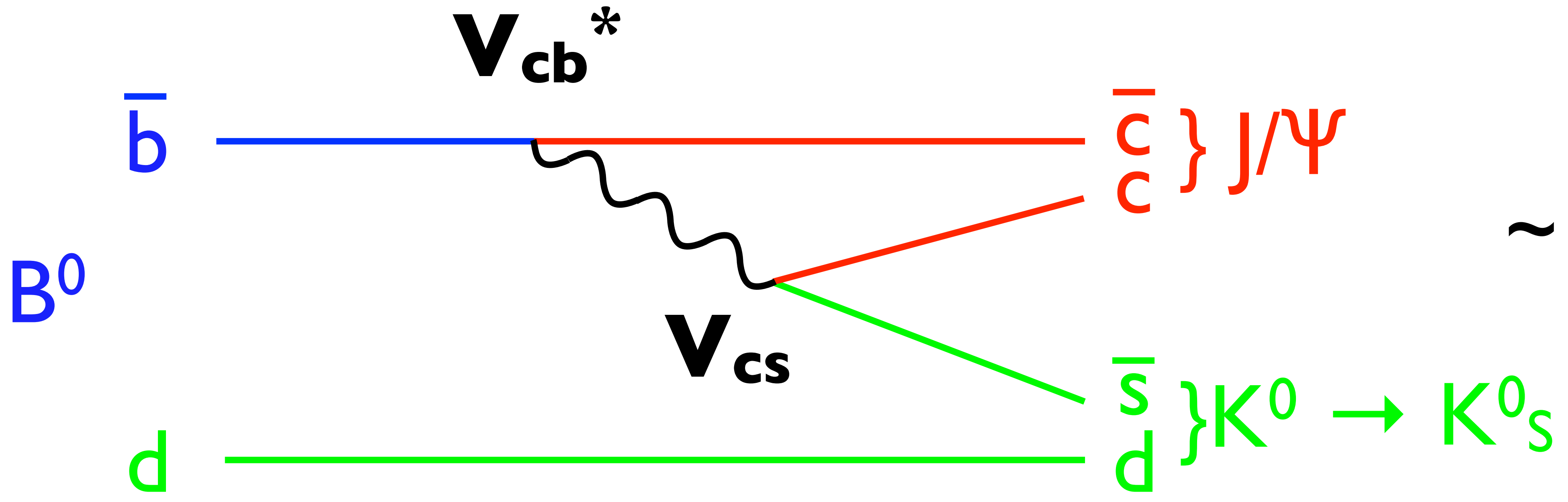
& B Factories

E

- $e^+e^- \rightarrow \Upsilon(4S)$ is good
  - measure B^0 / $\bar{B}^0$ decays → overconstrain UT !
- many possible decays but 1 golden decay

$$B^0 \rightarrow J/\Psi\, K^0_S$$

  - $J/\Psi \rightarrow l^+l^-$:“easy” , $K^0_S \rightarrow \pi^+\pi^-$:“easy”



$\sim V_{cs}V_{cb}^*$

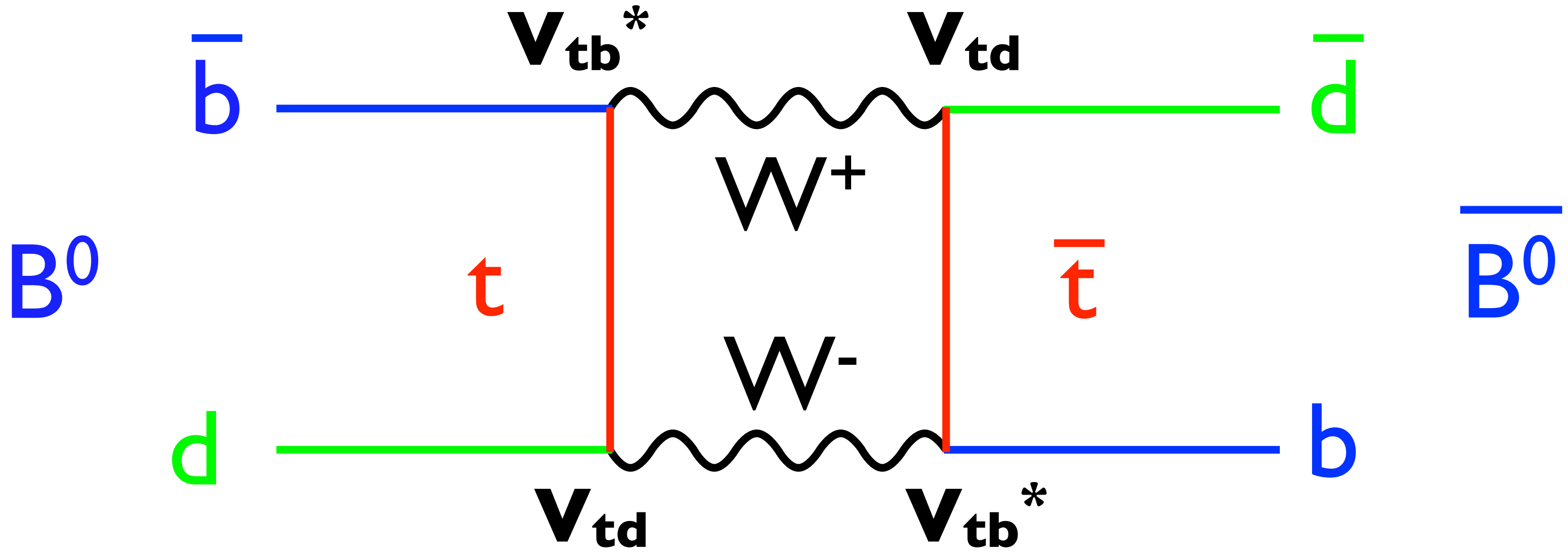
  - and there is more ...

the Beautiful Factories

& B Factories

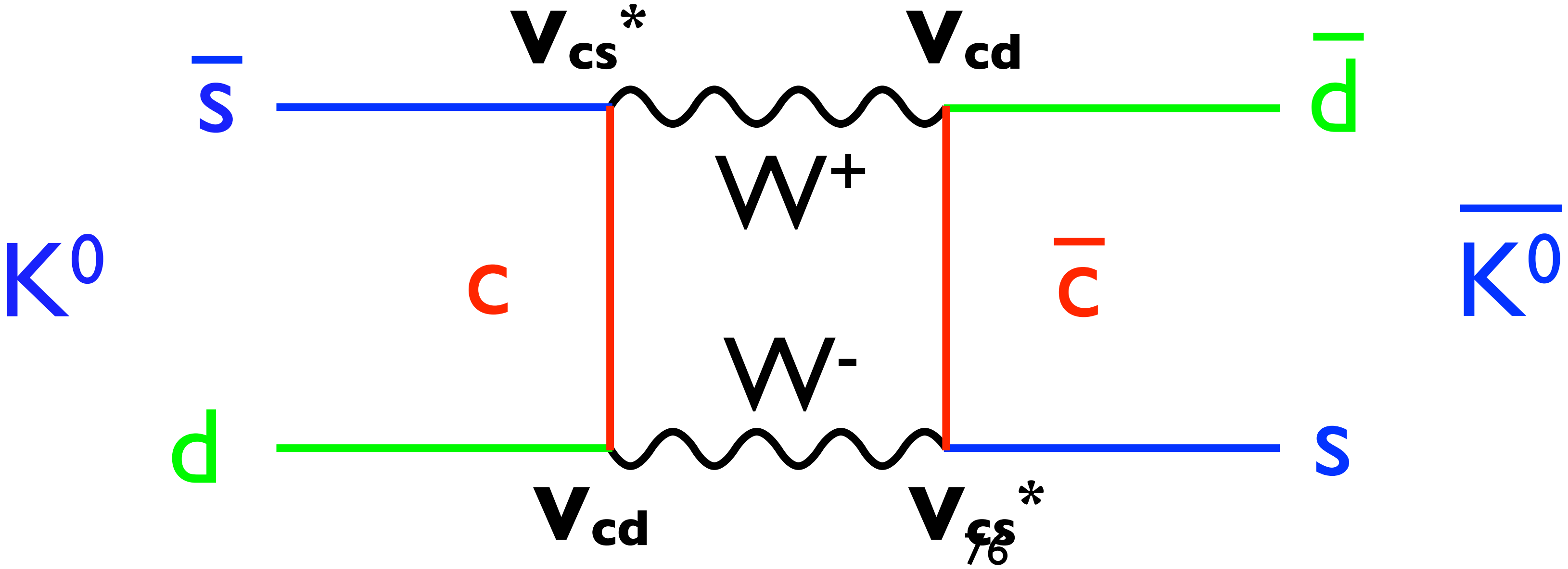
E

- more $B^0 \rightarrow J/\Psi\ K^0_S$
  - B^0 also can mix and decay to **CP** eigenstates !



$\sim\ (V_{td}V_{tb}^*)^2$

  - then K^0 must mix for interference !



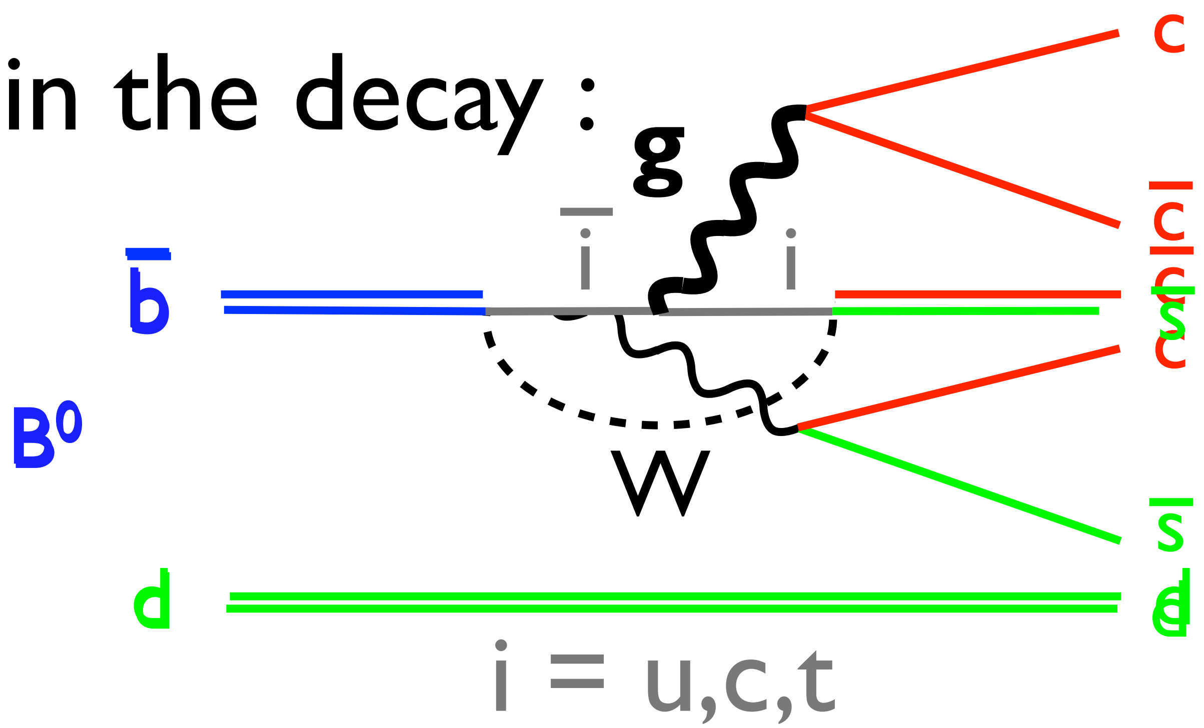
$\sim\ (V_{cd}V_{cs}^*)^2$

the Beautiful Factories

🐧 & B Factories

E

- summarizing $B^0 \rightarrow J/\Psi\ K^0_S$
  - B^0 mixing → B^0 decay → K^0 mixing !!!
- and 🐧 in the decay :



  - rates $\sim V_{cb}V_{cs}^*$ (real), $V_{tb}V_{ts}^*$ (real), $V_{ub}V_{us}^*$ (γ)
- observable : $A_{CP}(t) = \dfrac{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S) - \Gamma(B^0(t) \rightarrow J/\psi K_S)}{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S) + \Gamma(B^0(t) \rightarrow J/\psi K_S)}$
  - $= \sin(2\beta).\sin(\Delta m.t)$
  - need to measure the decay time ≠ between the 2 B's !!!

the Beautiful Factories

& B Factories - 1999

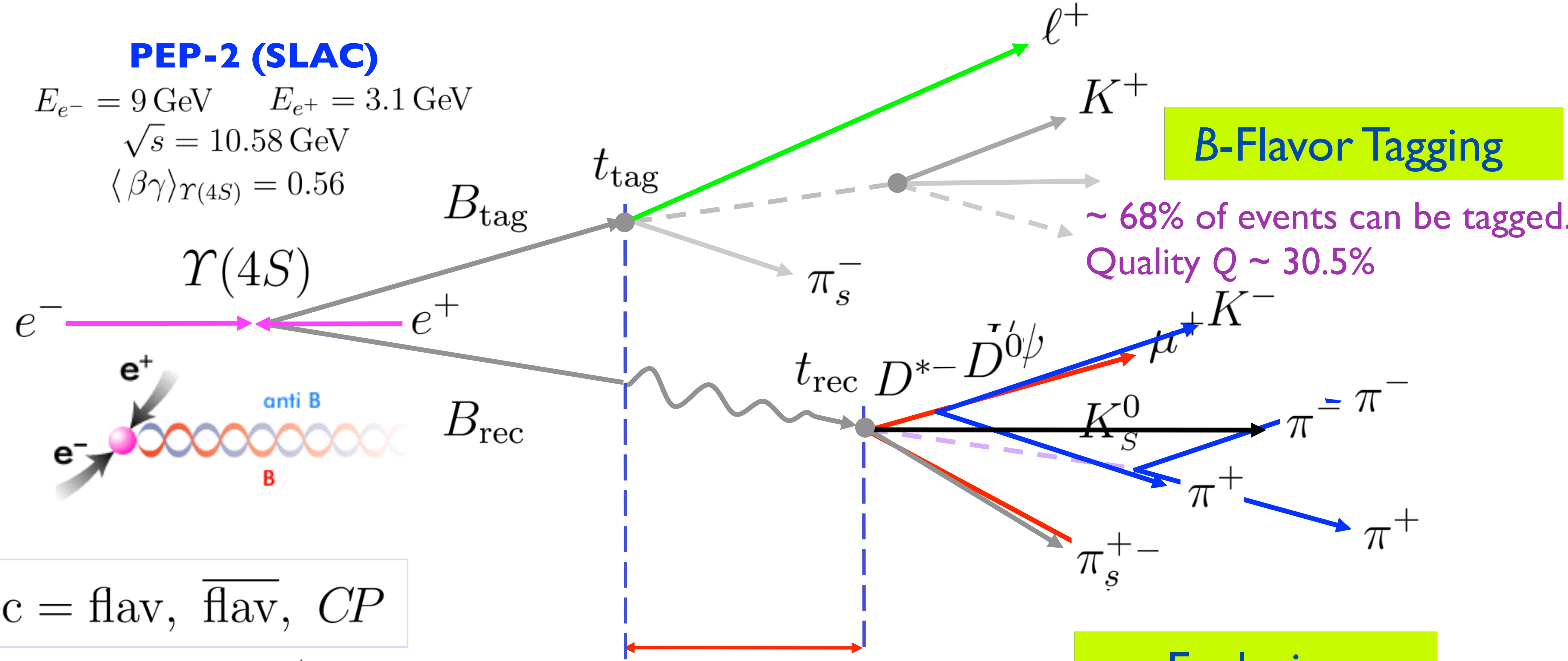
E

- but $\tau(B) \sim 1.5\ 10^{-12}s \rightarrow$ make it live longer !
- Oddone simple/clever idea
  - remember Einstein : “time dilatation” → give B’s high speed
    - produce high speed $\Upsilon(4S)$
    - ... with **asymetric e^+e^- collisions** !
- they are called “B Factories”
  - PEP-II (SLAC) : 9 GeV e^- x 3.1 GeV e^+
  - KEKB (Tsukuba) : 8 GeV e^- x 3.5 GeV e^+
- for both : $E_{CM} = 10.58$ GeV
    - coherent B pairs production and P-wave decay
    - $\Upsilon(4S)$ boot : $\beta\gamma = 0.56/0.42 \rightarrow$ B’s decay length = ~ 200-250μm

the Beautiful Factories

CP (B^0_d) - Analyses in B factories

E



PEP-2 (SLAC)

$$E_{e^-} = 9\,\mathrm{GeV} \qquad E_{e^+} = 3.1\,\mathrm{GeV}$$

$$\sqrt{s} = 10.58\,\mathrm{GeV}$$

$$\langle\beta\gamma\rangle_{\Upsilon(4S)} = 0.56$$

B-Flavor Tagging

~ 68% of events can be tagged.

Quality Q ~ 30.5%

$$\mathrm{rec} = \mathrm{flav},\ \overline{\mathrm{flav}},\ CP$$

$$f_{\rm flav} = D^{*-}\pi^+, \ldots$$

$$f_{CP} = J/\psi\, K^0_S,\ J/\psi\, K^0_L, \ldots$$

$$\Delta t \equiv t_{\rm rec} - t_{\rm tag}$$

Exclusive
B Meson
Reconstruction

$$\mathrm{tag} = B^0,\ \overline{B}^0$$

$$f_{B^0} = X\ell^+\nu,\ XK^+,\ X\pi_s^-, \ldots$$

Vertexing &
Time Difference
Determination

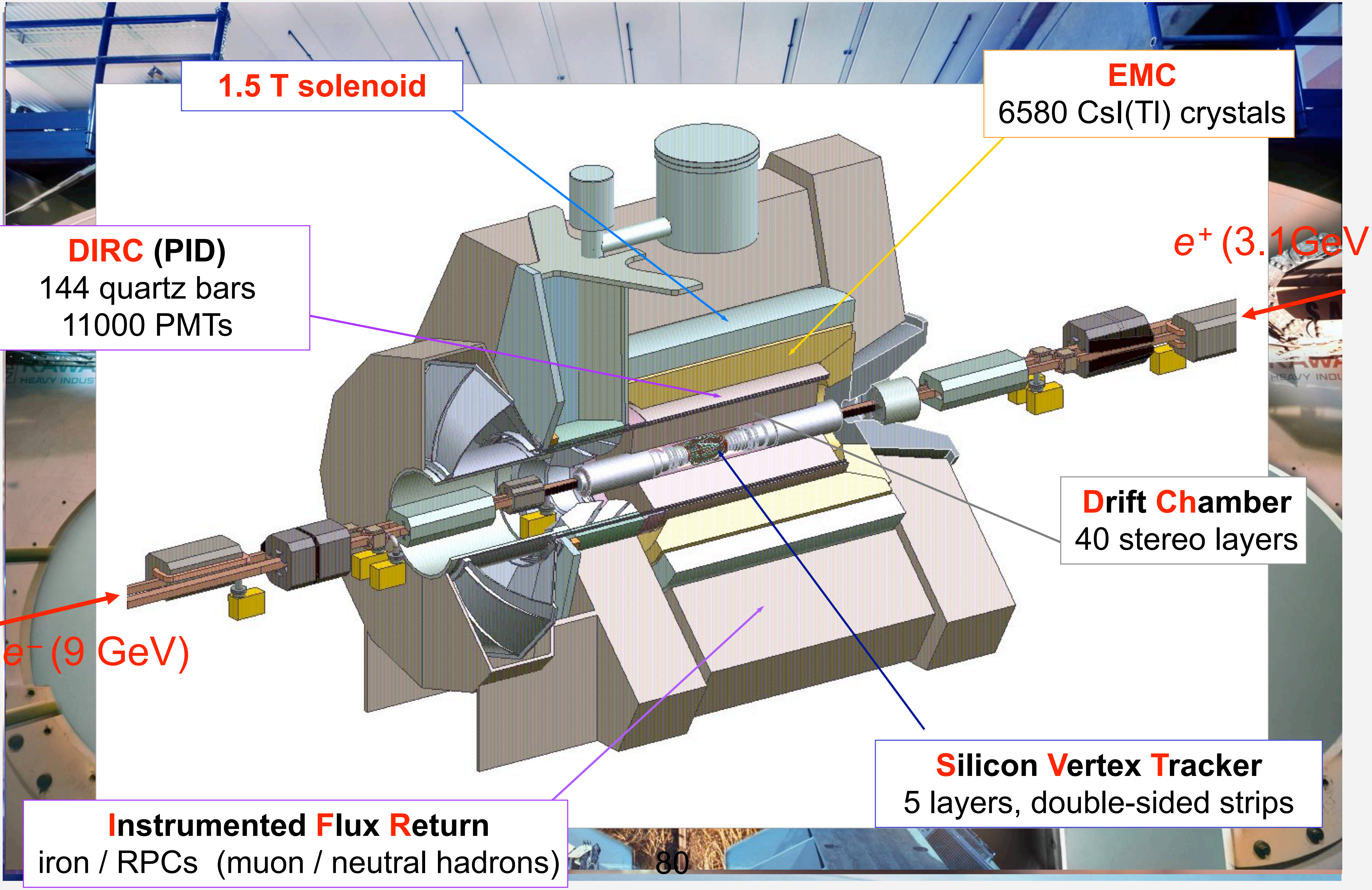
$$\Delta t \approx \Delta z / c \langle\beta\gamma\rangle_{\Upsilon(4S)}$$

$$\langle\Delta z\rangle_{B\bar{B}} \approx 260\,\mu\mathrm{m}$$

the Beautiful Factories

~~CP~~ (B^0_d) - BaBar

E



1.5 T solenoid

EMC
6580 CsI(Tl) crystals

DIRC (PID)
144 quartz bars
11000 PMTs

e^+ (3.1GeV)

Drift Chamber
40 stereo layers

e^- (9 GeV)

Silicon Vertex Tracker
5 layers, double-sided strips

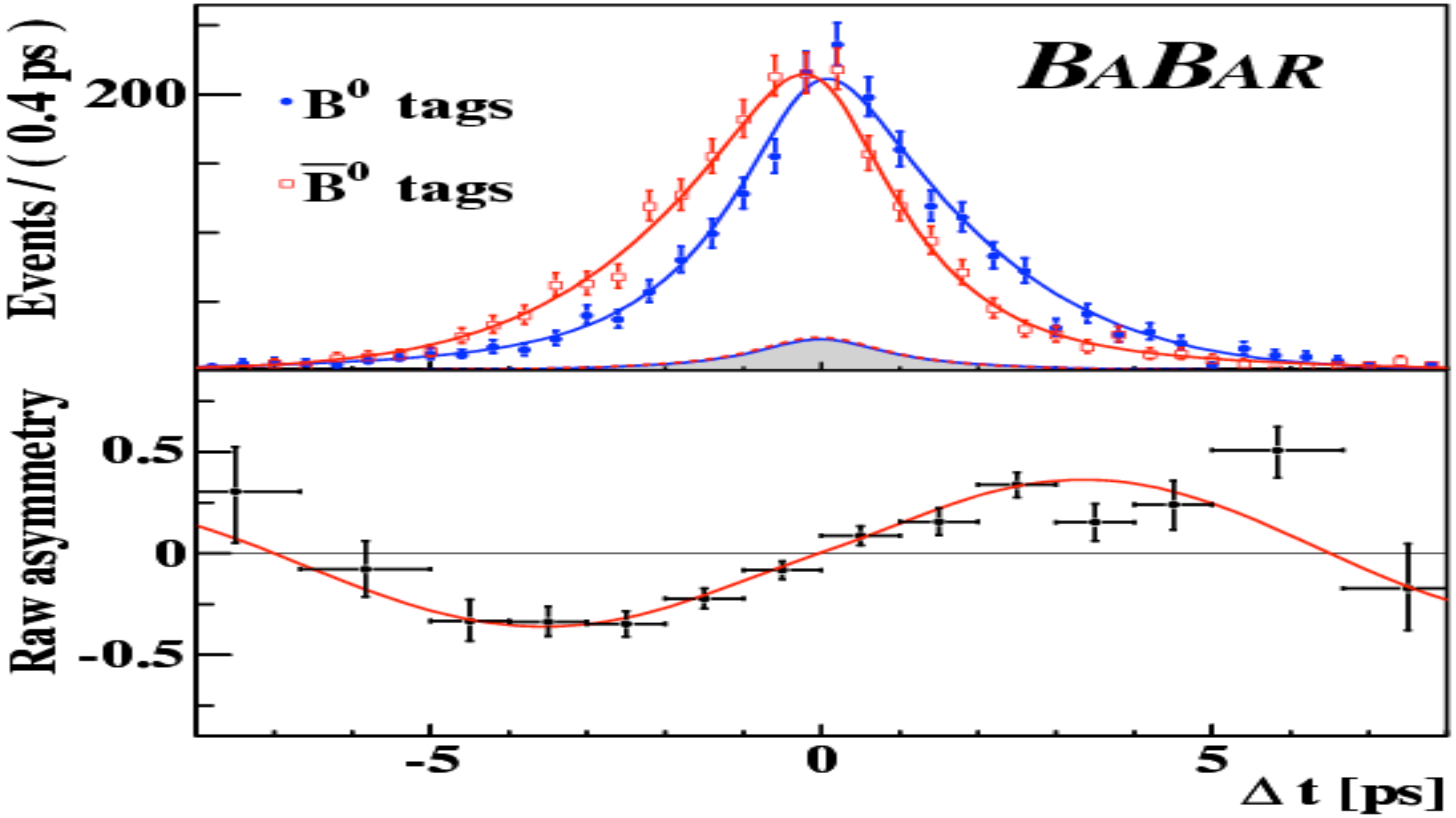
Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)

the Beautiful Factories

E

$\cancel{\mathrm{CP}}$ $(B^0{}_d)$ - BaBar - 2001

- observable : $A_{f_{CP}}(t) = \dfrac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$
  - **CP** in interference mixing/decay
  - can be written : $S_{f_{CP}} \sin(\Delta m.t) - C_{f_{CP}} \cos(\Delta m.t)$
    - $S_{f_{CP}} = \sin(2\beta)$, $C_{f_{CP}} = 0$ for B→ J/ψ K^0, Φ, ...

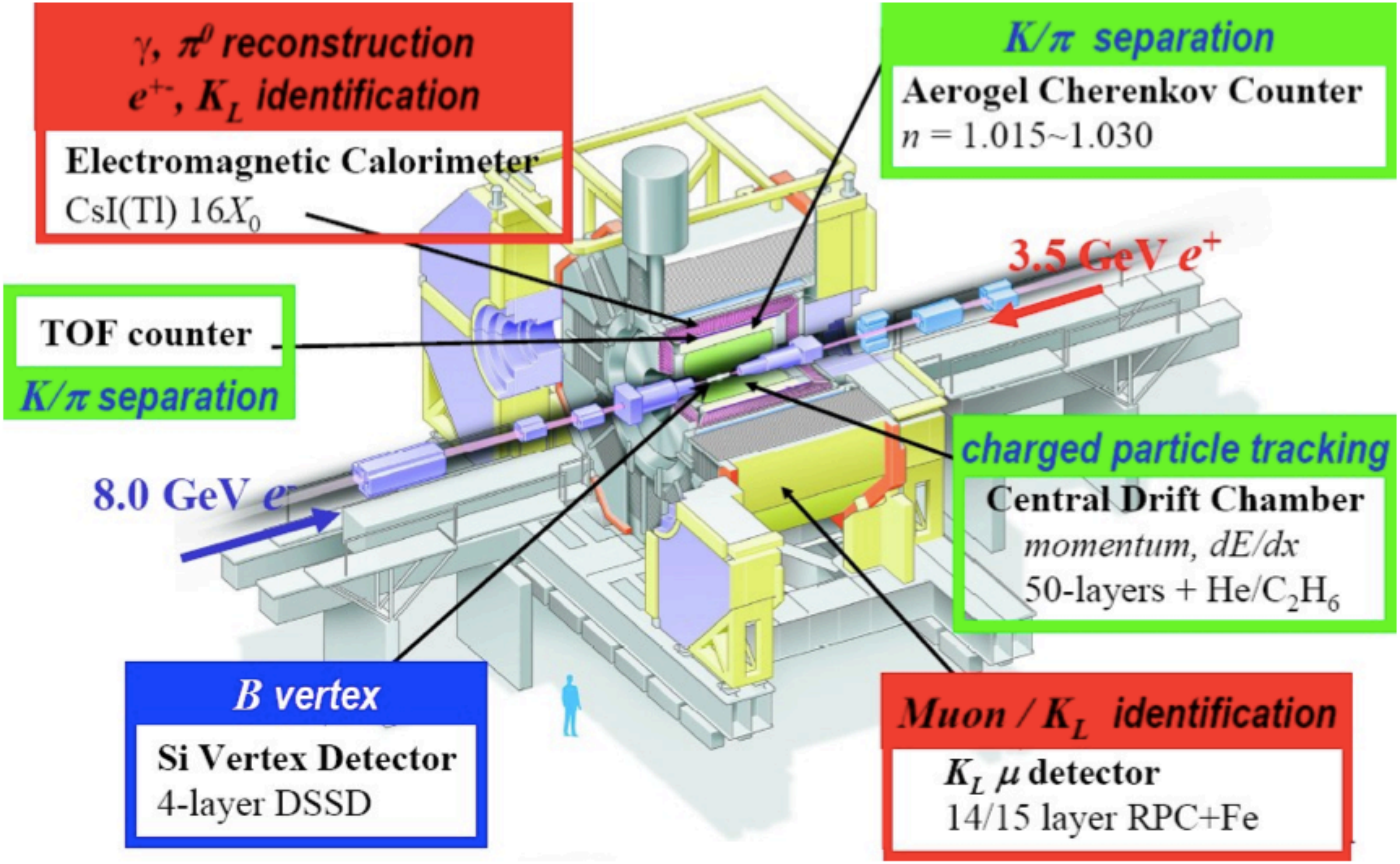


2001 results : sin(2β) = 0.34±0.20(stat)±0.05(sys)

the Beautiful Factories

Belle

E



γ, π^0 reconstruction
e^{+-}, K_L identification

Electromagnetic Calorimeter
CsI(Tl) $16X_0$

K/π separation

Aerogel Cherenkov Counter
$n = 1.015\sim1.030$

TOF counter
K/π separation

3.5 GeV e^+

8.0 GeV e^-

charged particle tracking

Central Drift Chamber
momentum, dE/dx
50-layers + He/C_2H_6

B vertex

Si Vertex Detector
4-layer DSSD

Muon / K_L identification

K_L μ detector
14/15 layer RPC+Fe

B^0_s oscillations - CDF - 2006

- reminder : CDF = $p\bar{p}$ @ $\sqrt{s}$ = 1.96 TeV
- results for 1 fb^{-1}
- 36000 fully reconstructed hadronic B_s
- 37000 partially reconstructed semi-leptonic B_s
- Measurements :

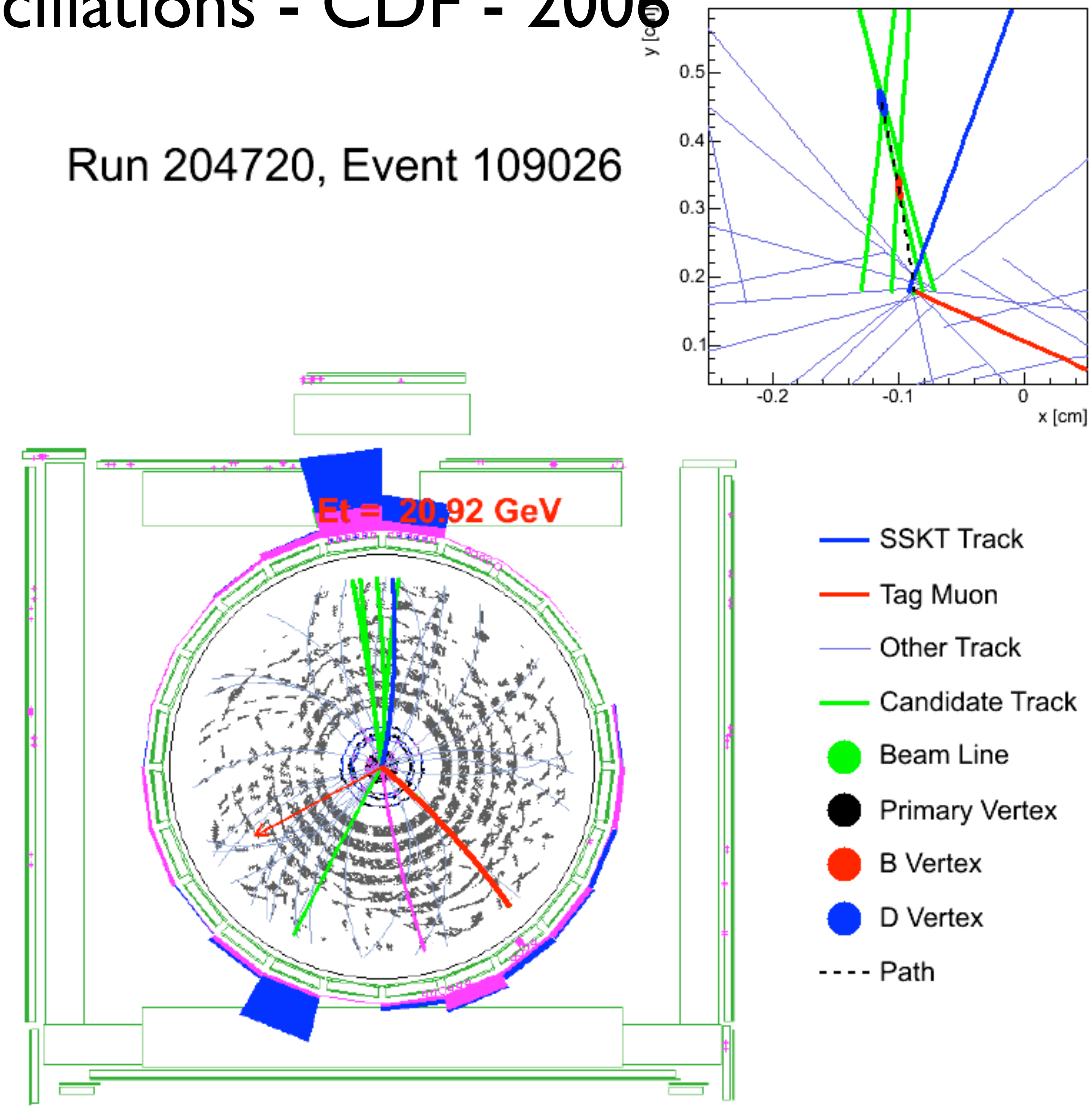
  probability as a function of proper decay time that a B_s decays with same/opposite flavor than at production

- Signal consistent with B_s^0 - $\bar{B}_s^0$ oscillations

the Beautiful Factories

E

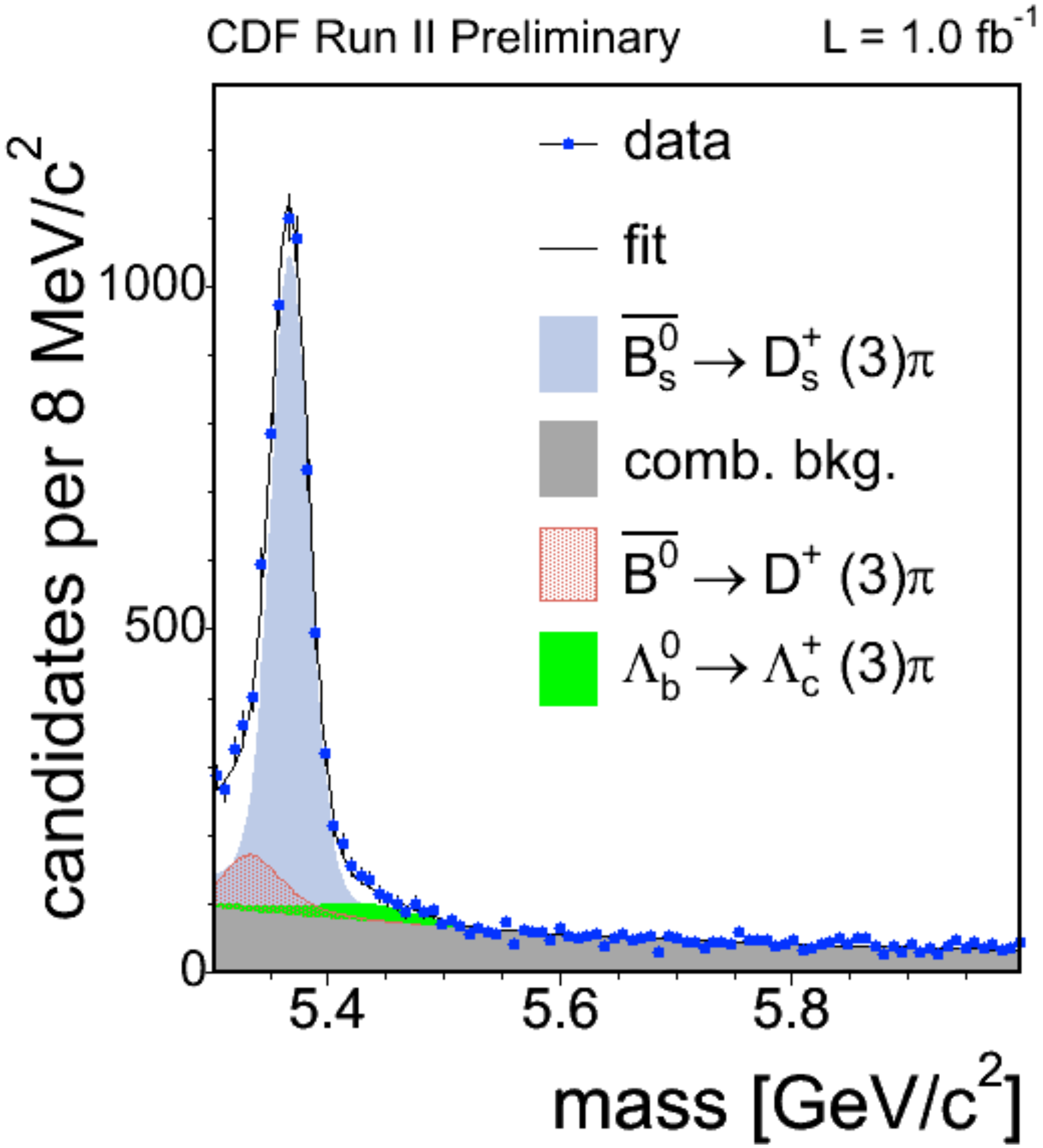
B^0_s oscillations - CDF - 2006

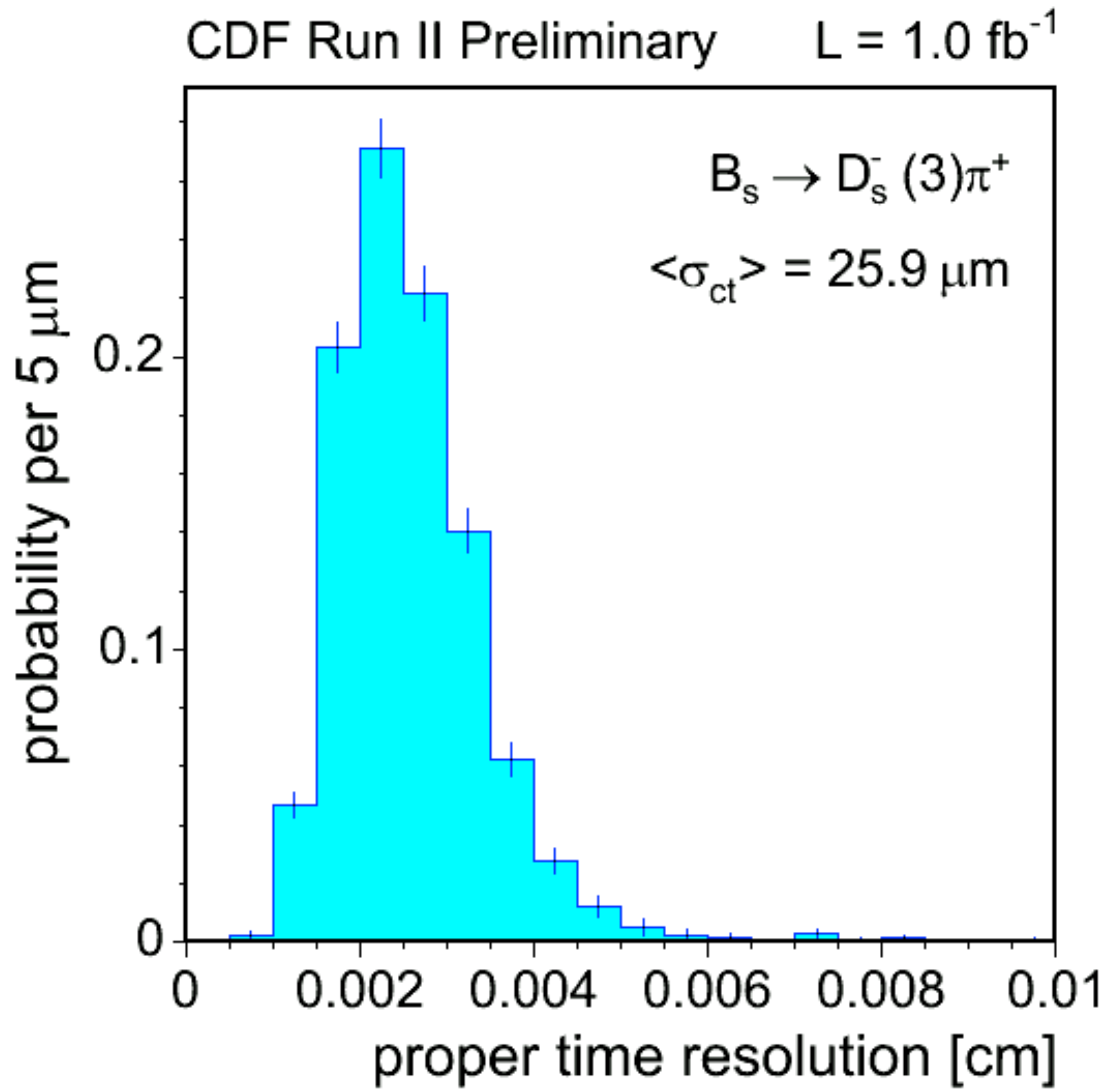


the Beautiful Factories

B^0_s oscillations - CDF - 2006

E





$$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{sys})\ \text{ps}^{-1}$$

Results :

$$\frac{|V_{td}|}{|V_{ts}|} = 0.0260 \pm 0.0007(\text{exp})\ {}^{+0.0081}_{-0.0060}\ (\text{theor})$$

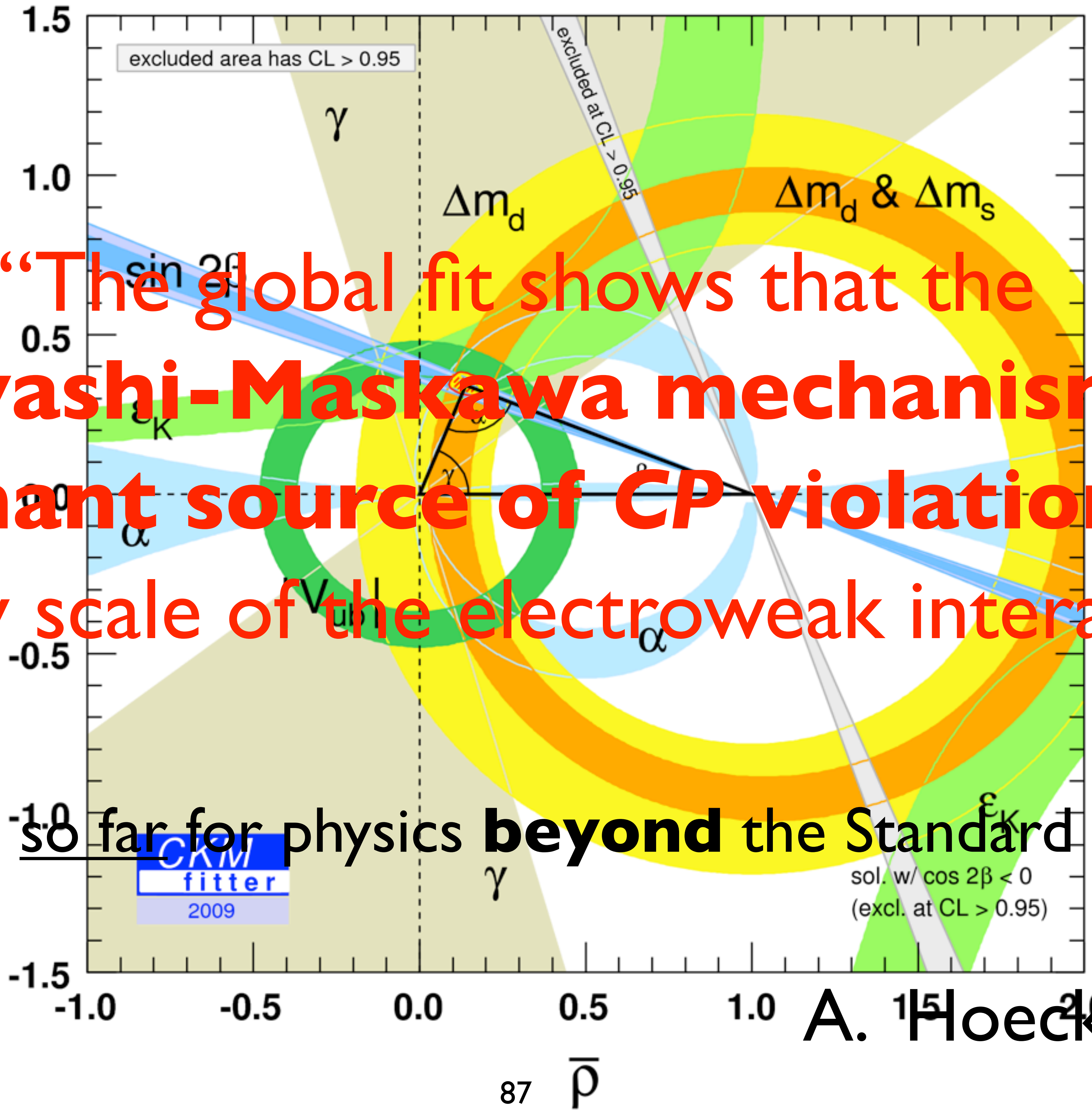
5 - Heavy Flavour physics today

- CKM status before LHC
- a beautiful experiment : LHCb
- LHCb on CKM
- LHCb on Penguins
- LHCb on Rare decays

Heavy Flavour physics today

CKM status before LHC

E



"The global fit shows that the **Kobayashi-Maskawa mechanism** is the **dominant source of *CP* violation** at the energy scale of the electroweak interaction"

"No need so far for physics **beyond** the Standard Model"

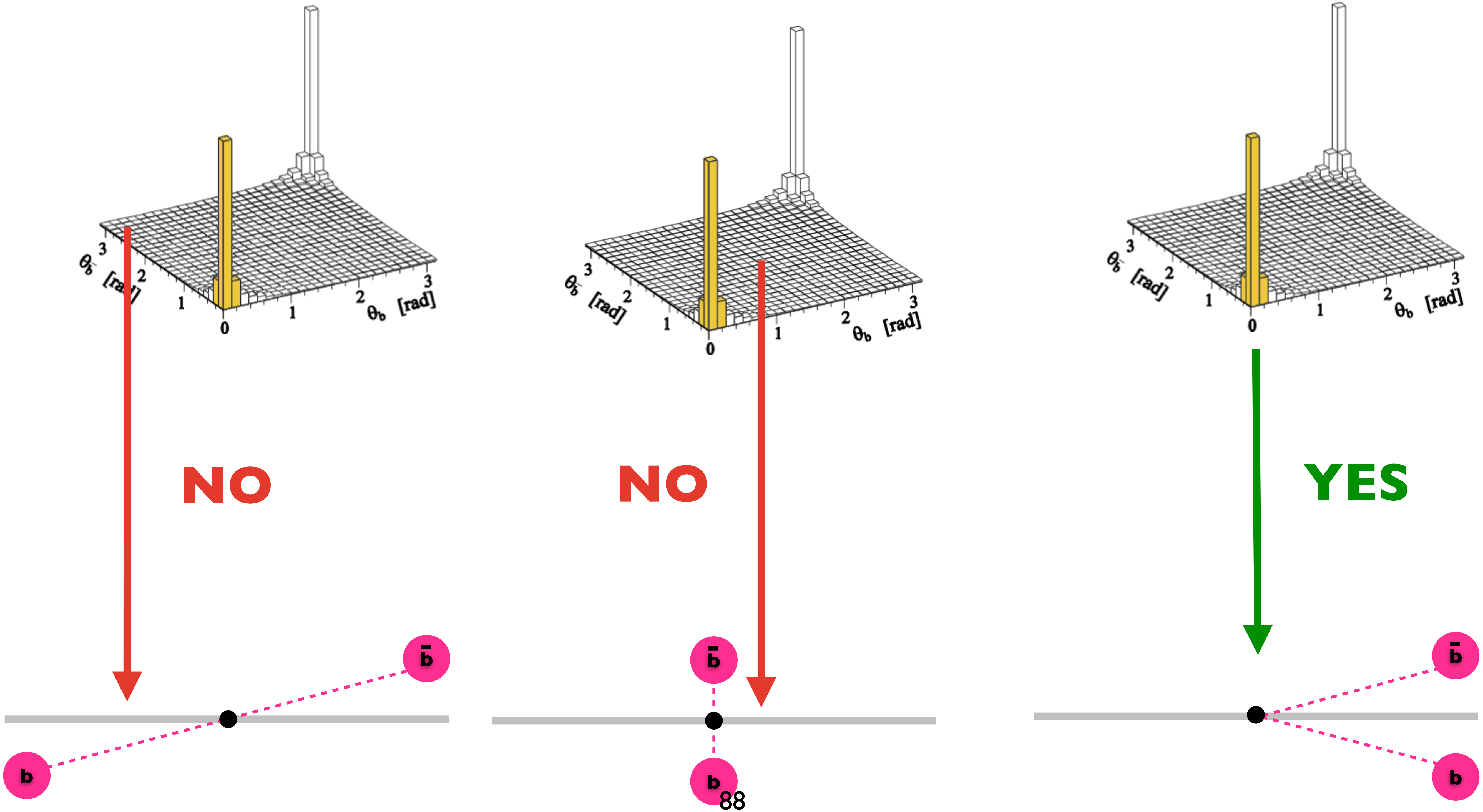
A. Hoecker (2008)

Heavy Flavour physics today

E

a beautiful experiment : LHCb

- beauty is at small angle :

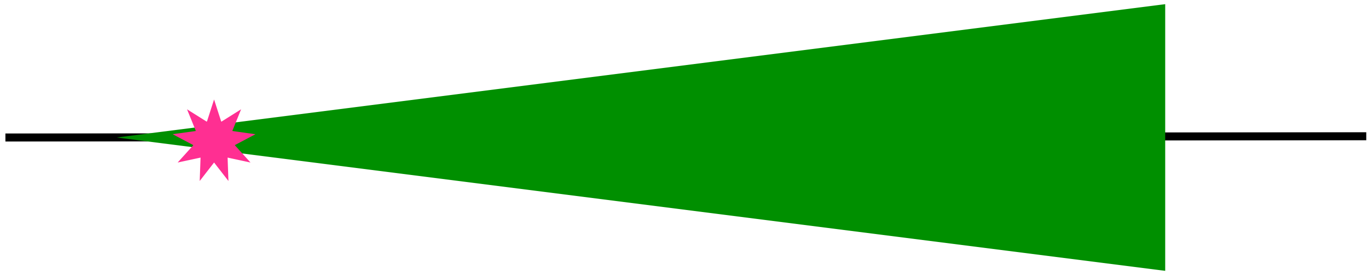


Heavy Flavour physics today

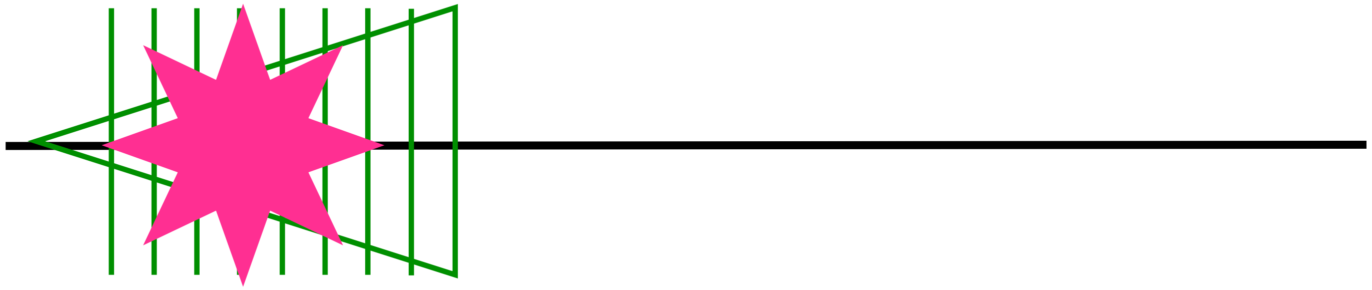
E

a beautiful experiment : LHCb

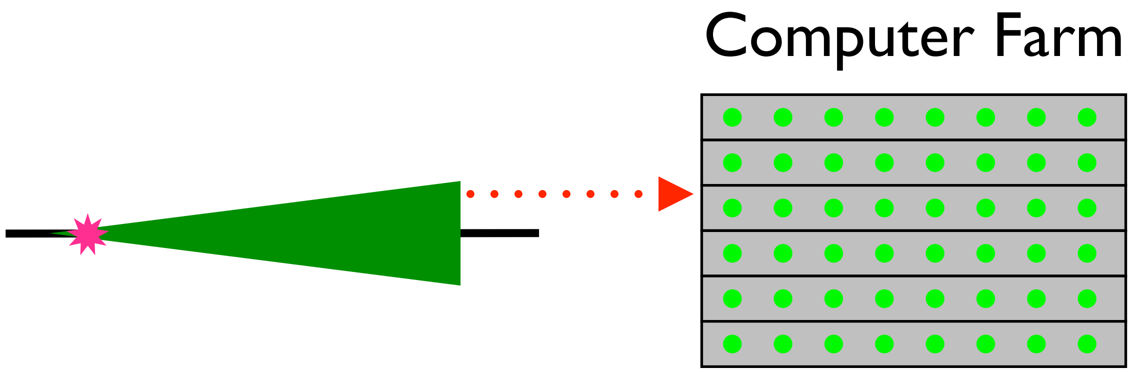
- constrains :
  - forward



  - small lifetime



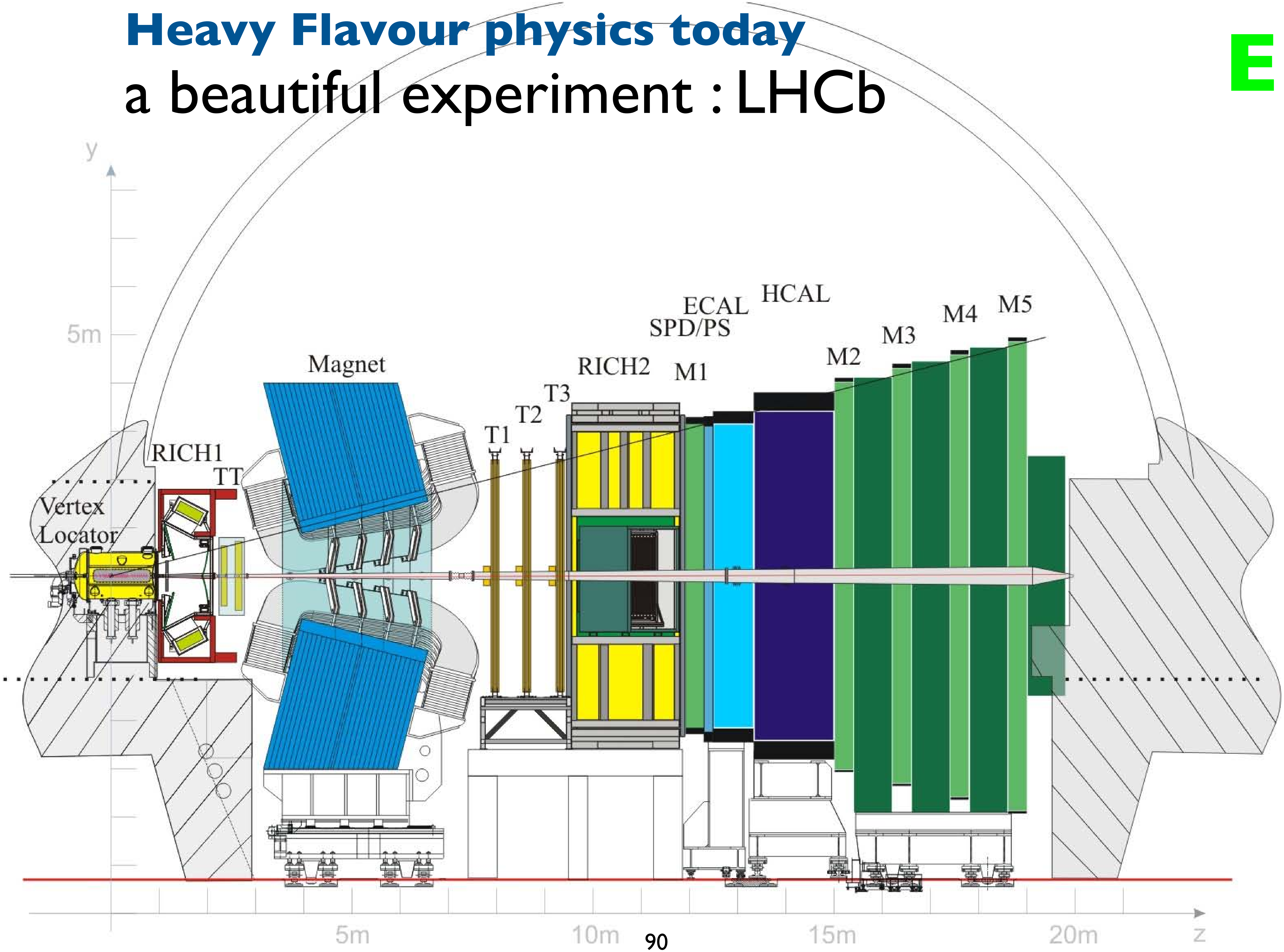
  - frequent



Heavy Flavour physics today

a beautiful experiment : LHCb

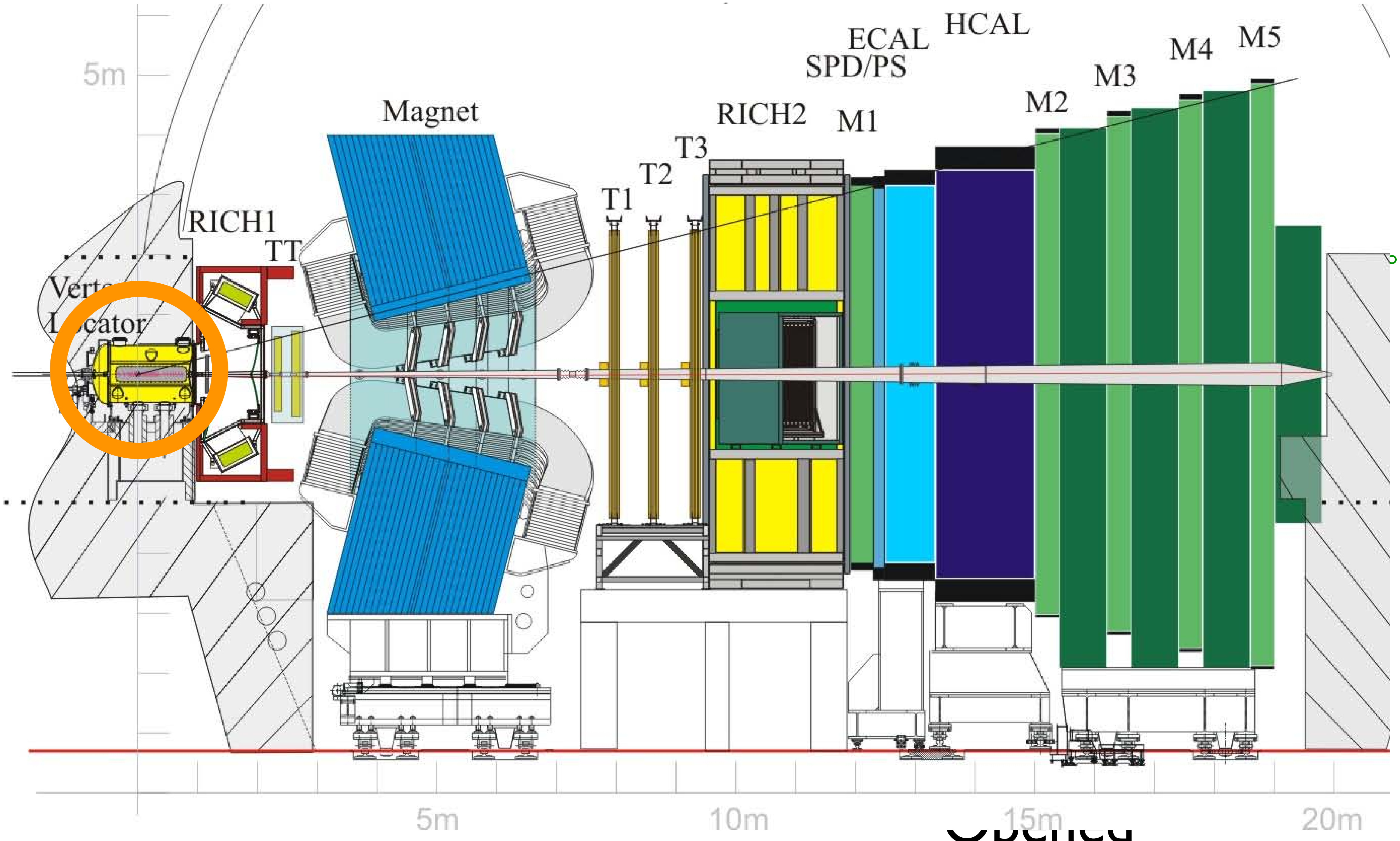
E



Heavy Flavour physics today

a beautiful experiment : LHCb

E

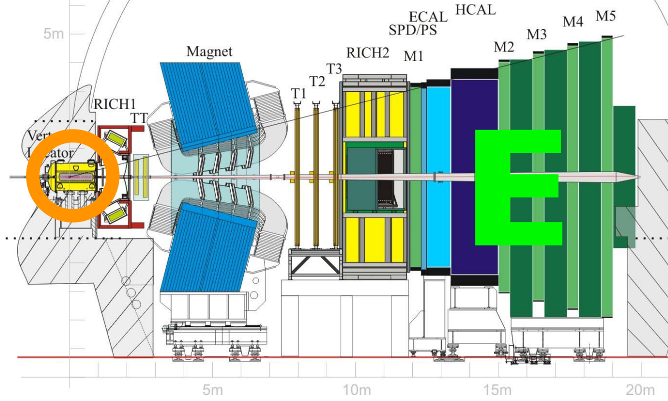


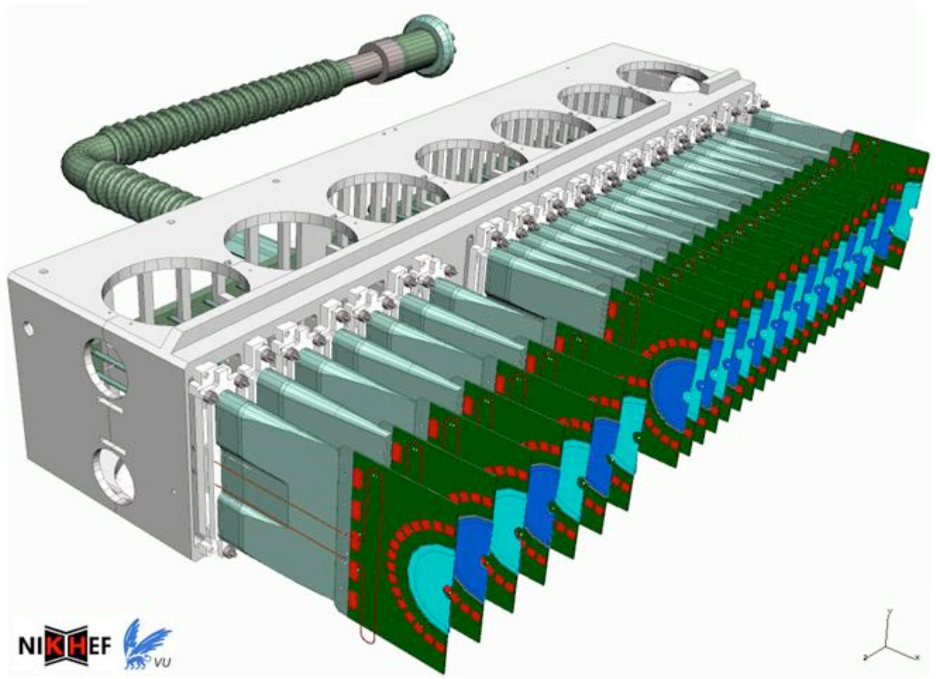
Opened

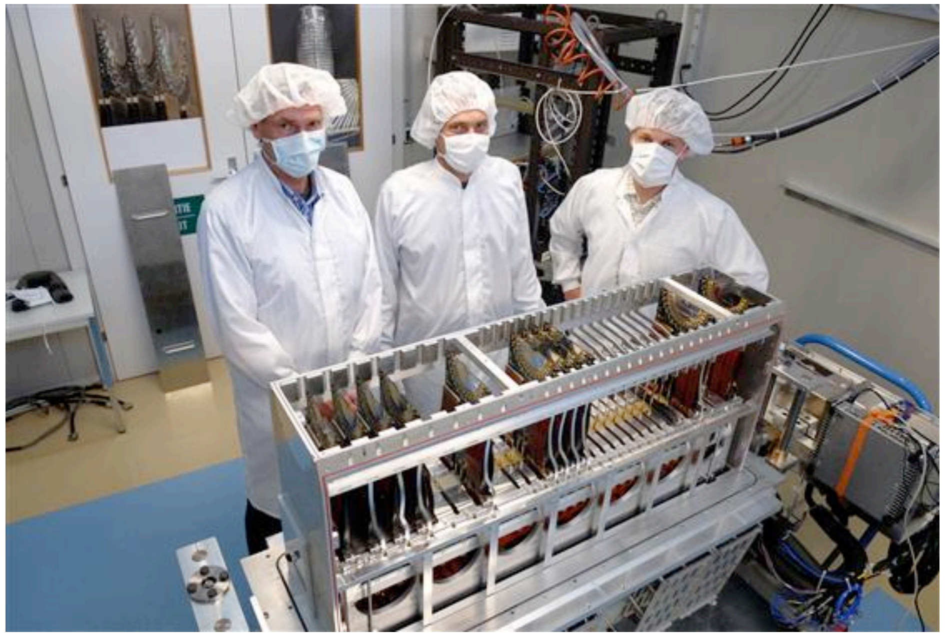
(only when stable beam)

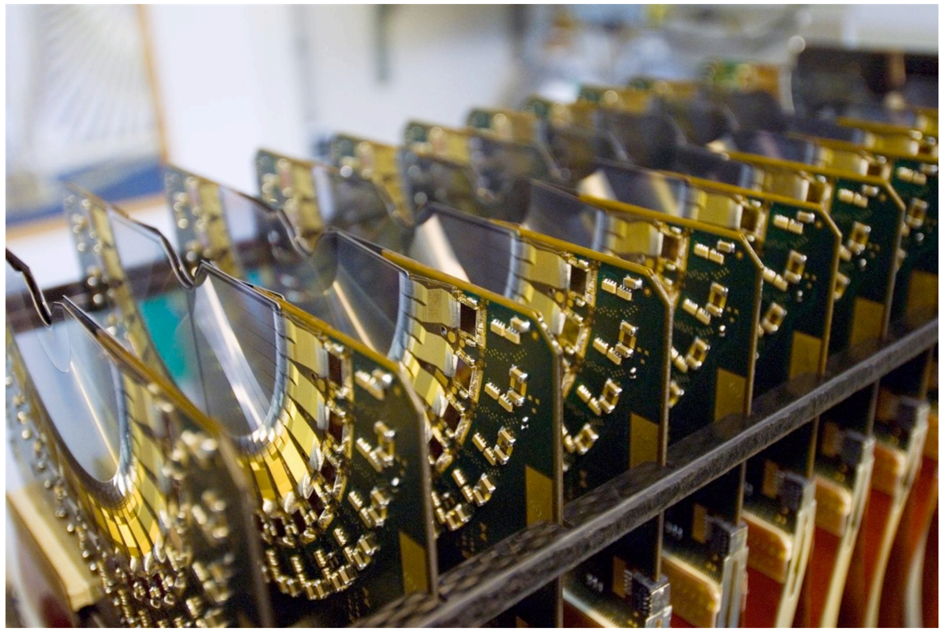
Heavy Flavour physics today

a beautiful experiment : LHCb







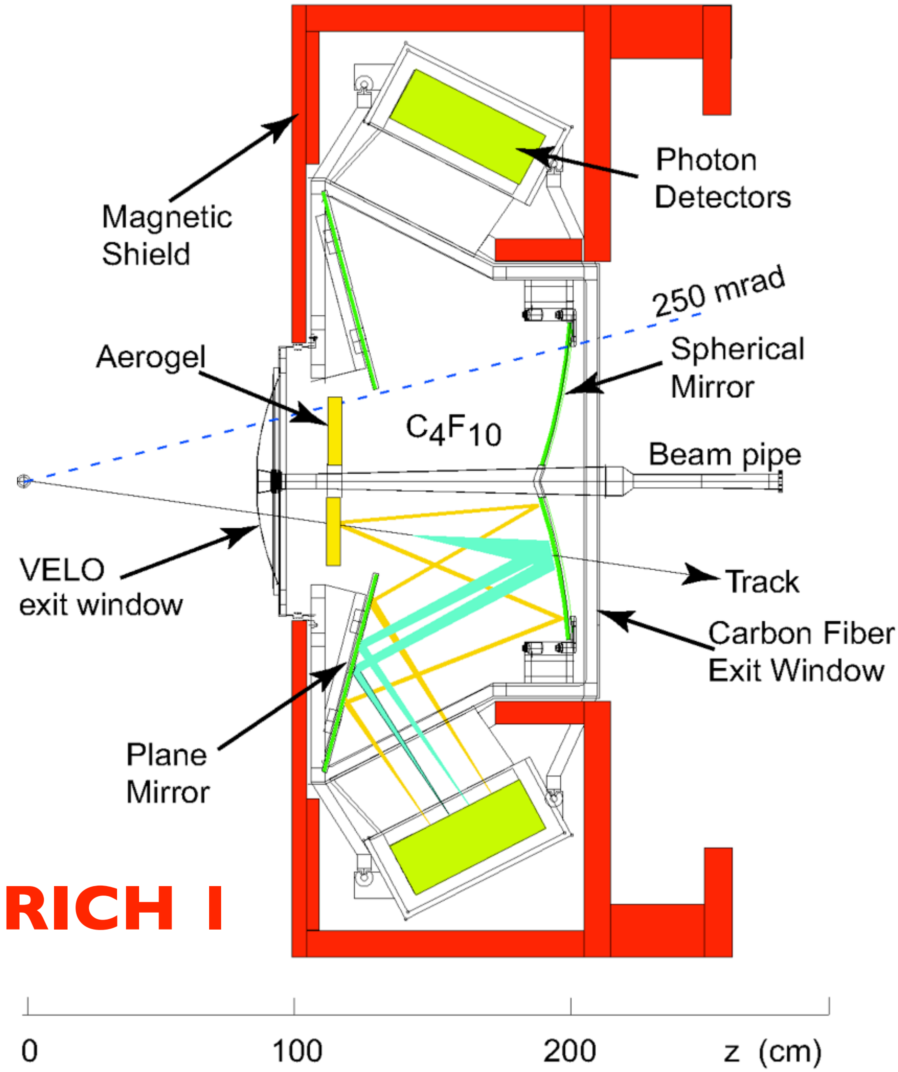


Silicium microstrips
R pitch : 40-102 µm
φ pitch : 36-97 µm
172 000 channels
Vacuum
Cooled @ -5°C

Heavy Flavour physics today

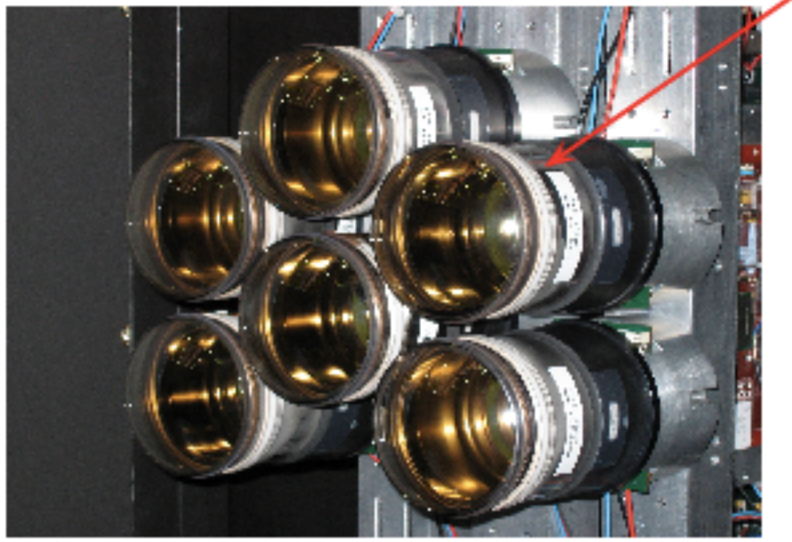
a beautiful experiment : LHCb

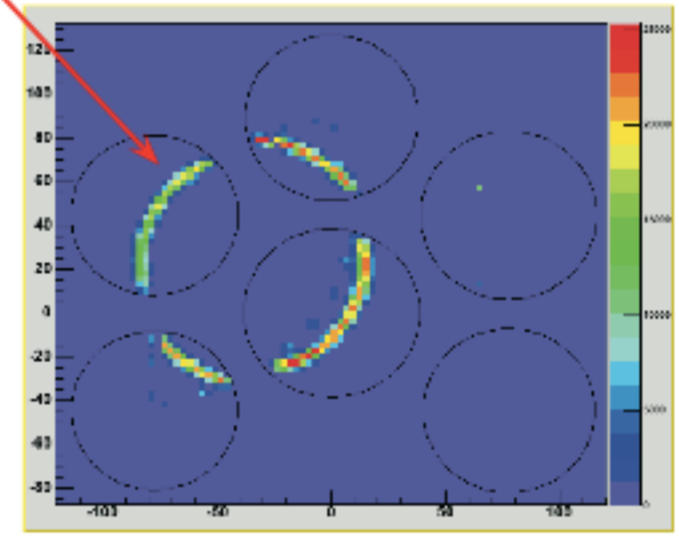
E



RICH 1

Hybrid Photon Detector





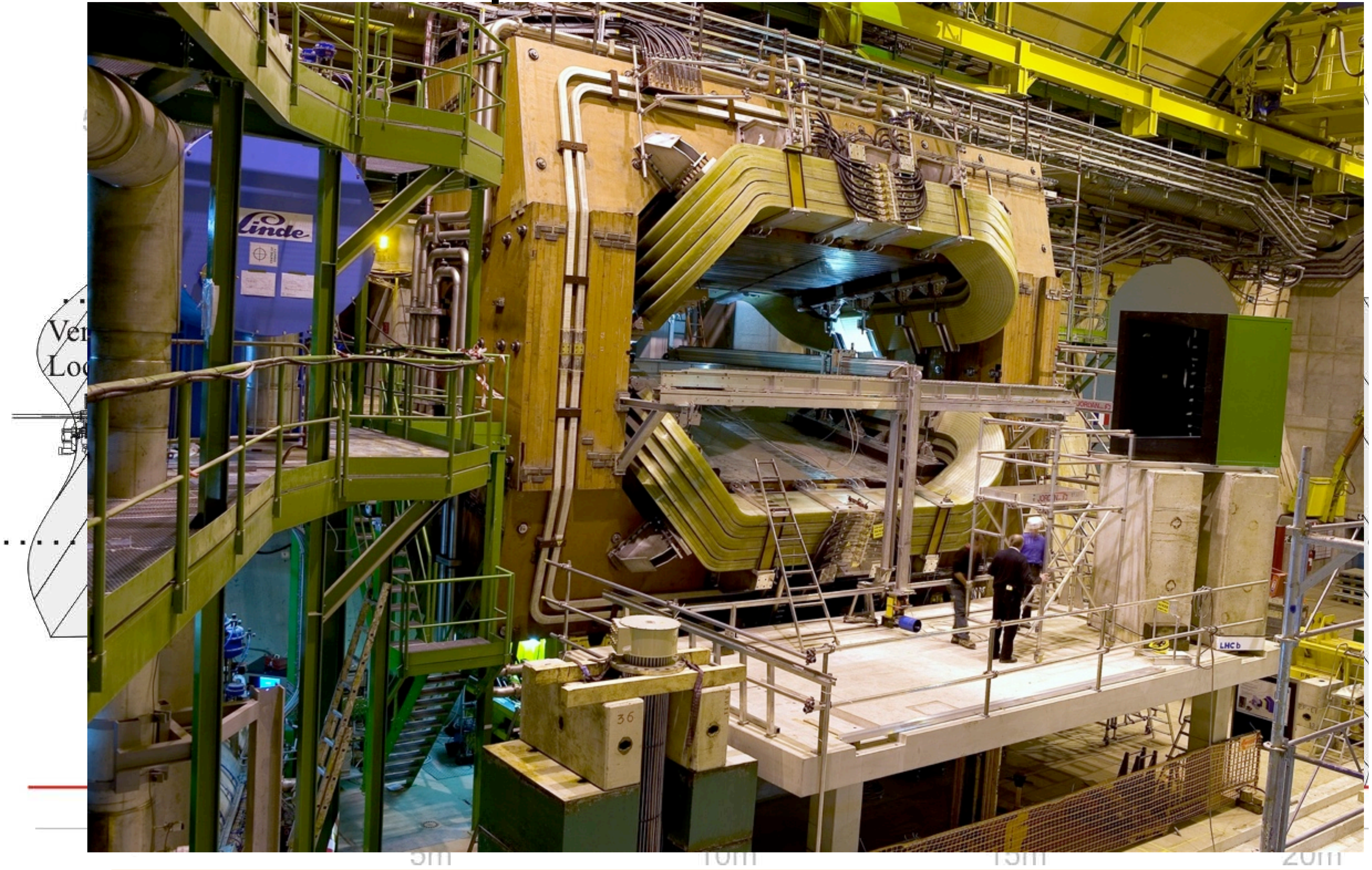
RICH 1
$2 < p < 60$ GeV/c
25-300 mrad
5 cm Aerogel
85 cm C_4F_{10}

RICH 2
$17 < p < 100$ GeV/c
10-120 mrad
~ 20 cm CF_4

Heavy Flavour physics today

a beautiful experiment : LHCb

E

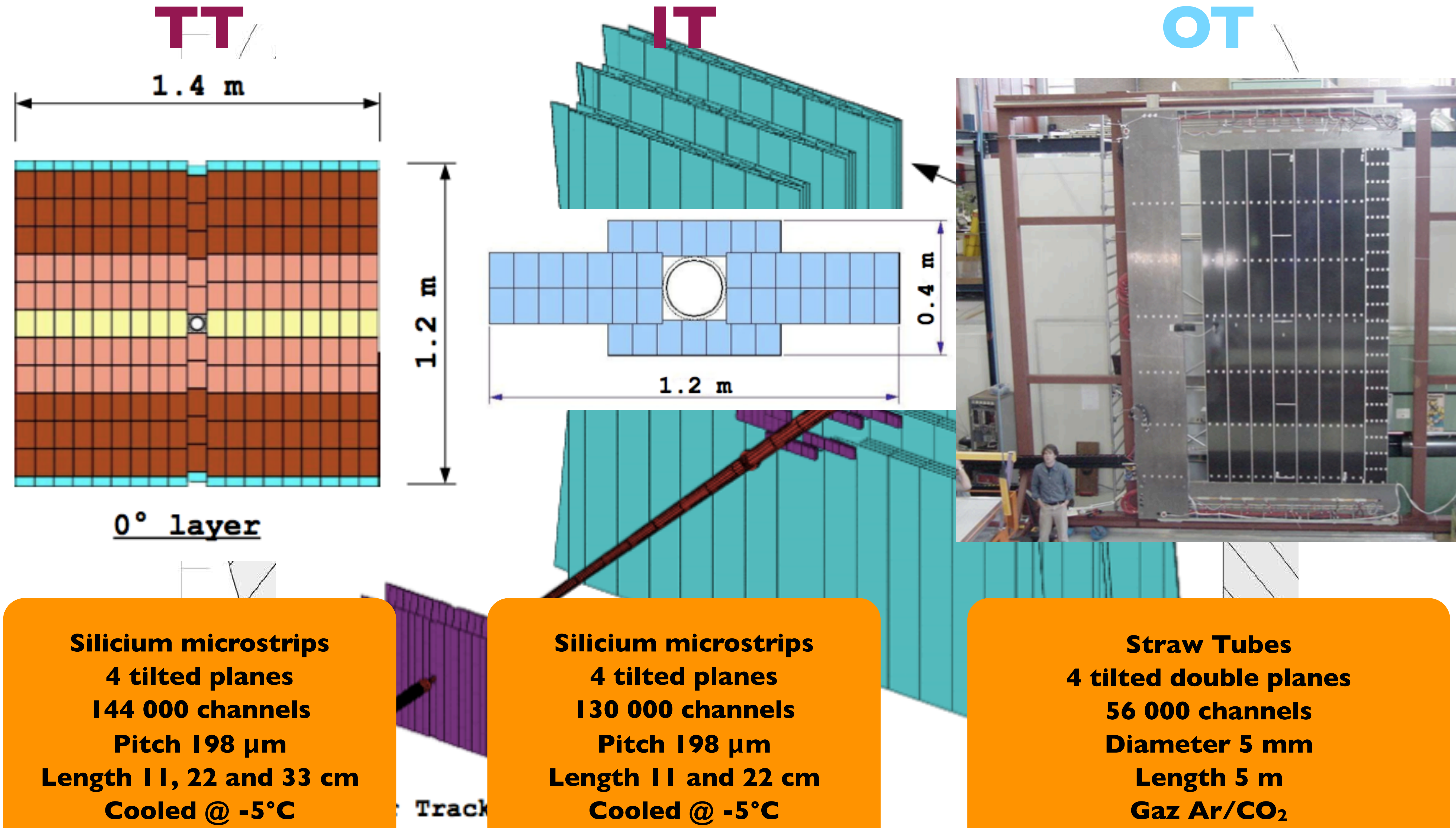


Dipole - Vertical Field (4Tm) - Can Switch Direction

Heavy Flavour physics today

a beautiful experiment : LHCb

E



Silicium microstrips
4 tilted planes
144 000 channels
Pitch 198 µm
Length 11, 22 and 33 cm
Cooled @ -5°C

Silicium microstrips
4 tilted planes
130 000 channels
Pitch 198 µm
Length 11 and 22 cm
Cooled @ -5°C

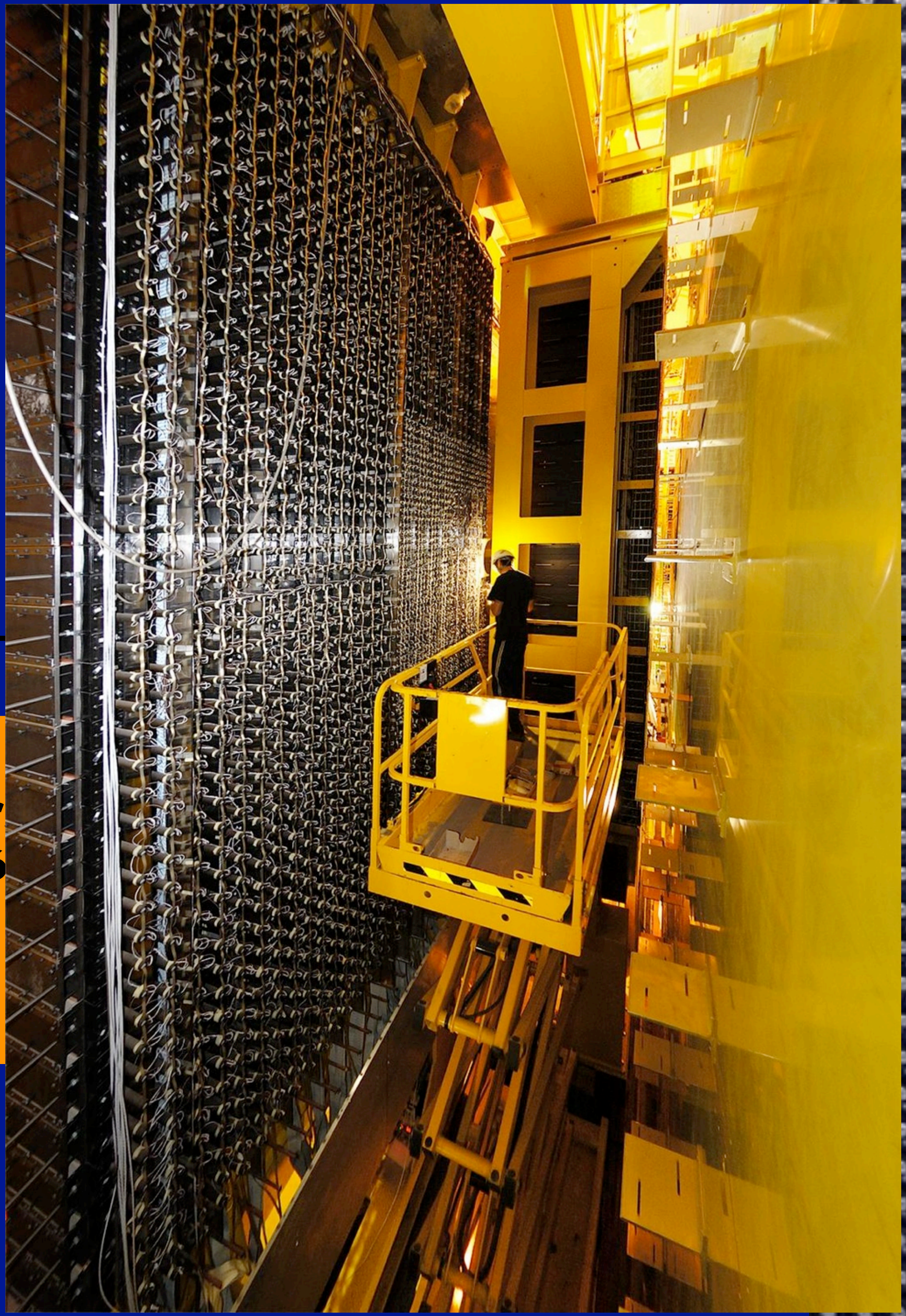
Straw Tubes
4 tilted double planes
56 000 channels
Diameter 5 mm
Length 5 m
Gaz Ar/CO$_2$

Heavy Flavour physics today

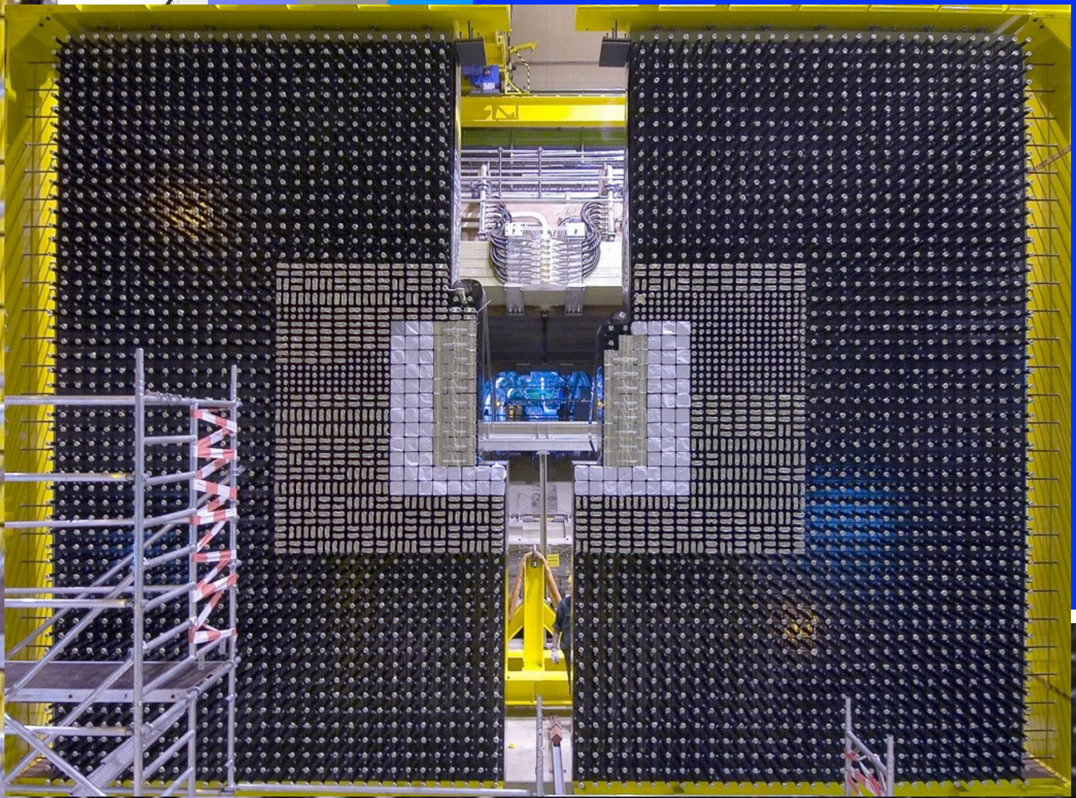
a beautiful experiment : LHCb

E

Pb



Fer
6

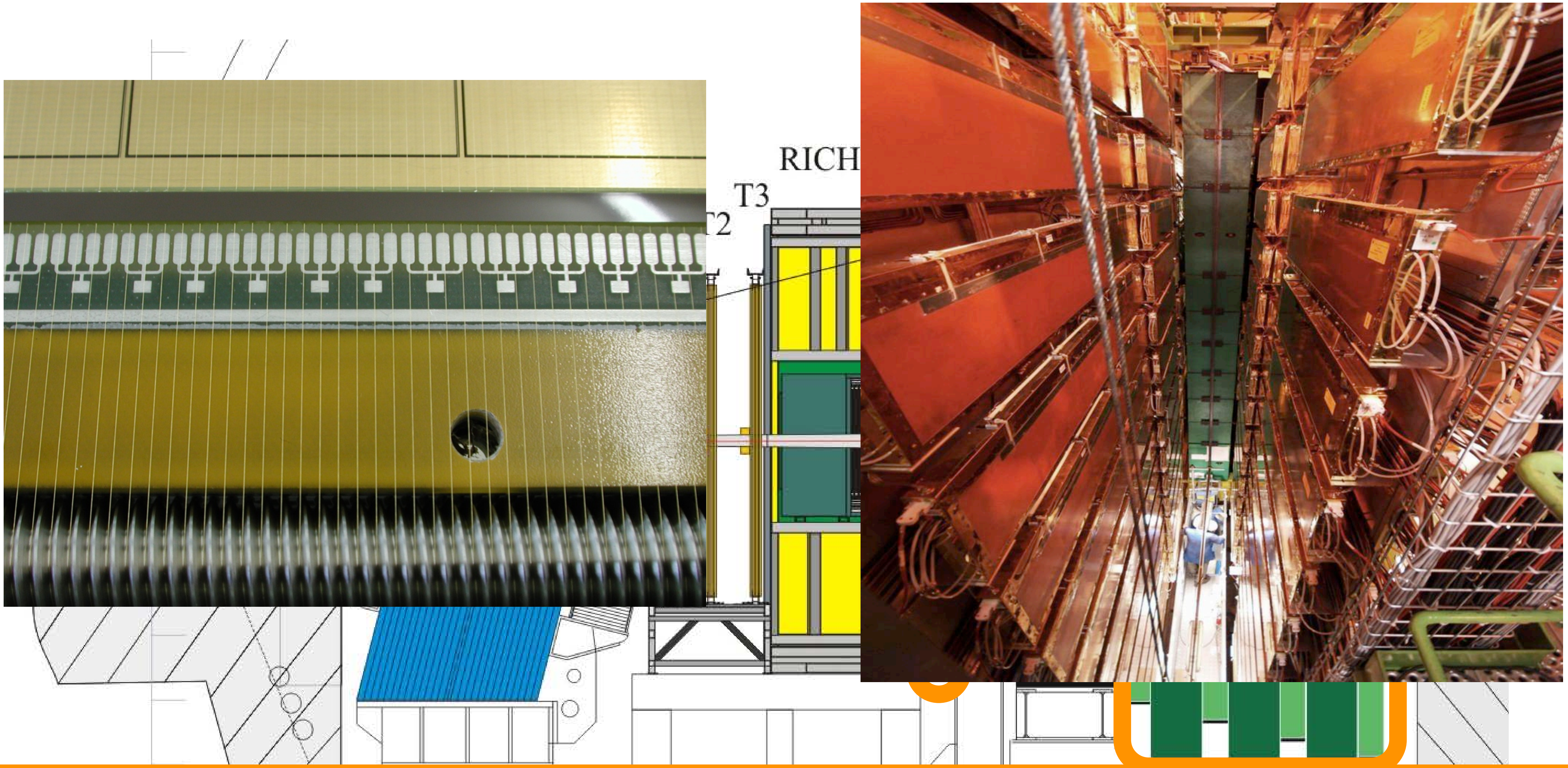


HCAL

Heavy Flavour physics today

a beautiful experiment : LHCb

E

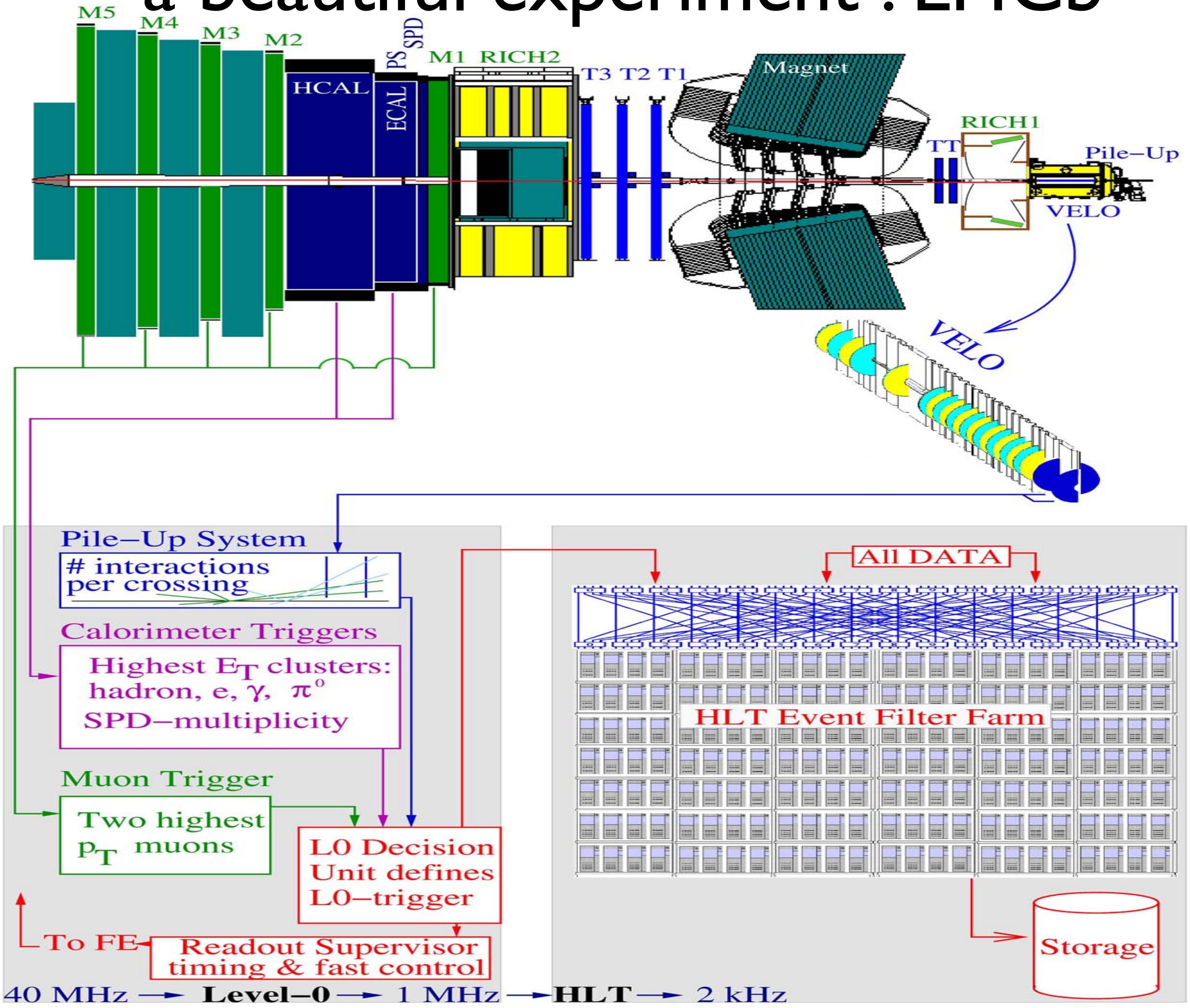


1368 chambers : MWPC 4 “gaps”, 24 GEM
Wires (~ 3 millions) : 2 mm / 250 à 310 mm
Gaz : 5 mm, Ar/CO2/CF4 (40:50:10)
26 000/120 000 logical channels/physical

Heavy Flavour physics today

a beautiful experiment : LHCb

E



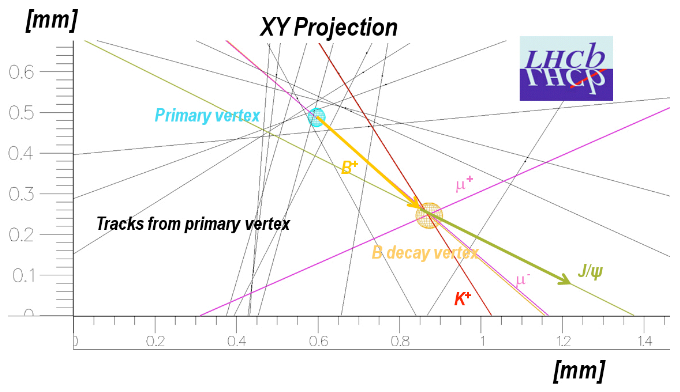
HLT :
1350 CPU

Heavy Flavour physics today

a beautiful experiment : LHCb

E

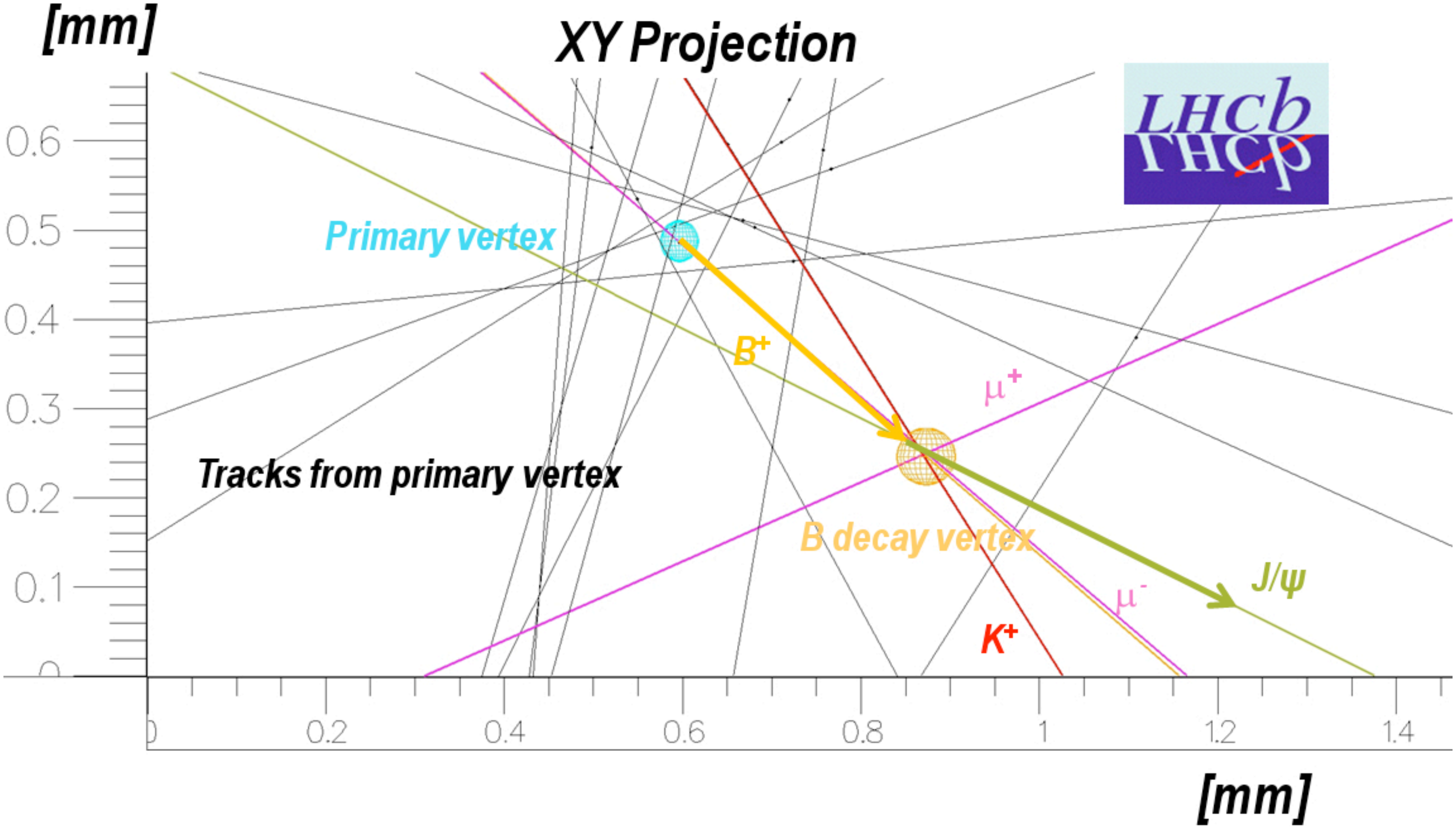
VELO



Heavy Flavour physics today

a beautiful experiment : LHCb

E

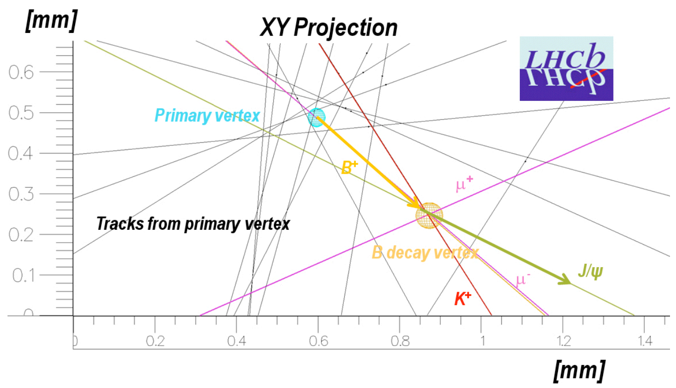


Heavy Flavour physics today

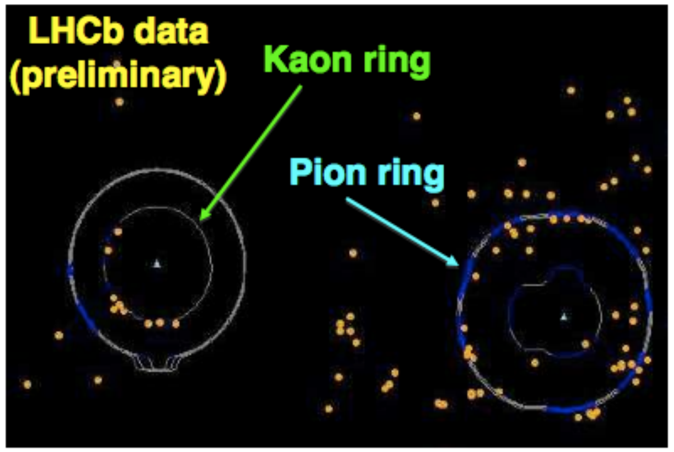
a beautiful experiment : LHCb

E

VELO



RICH

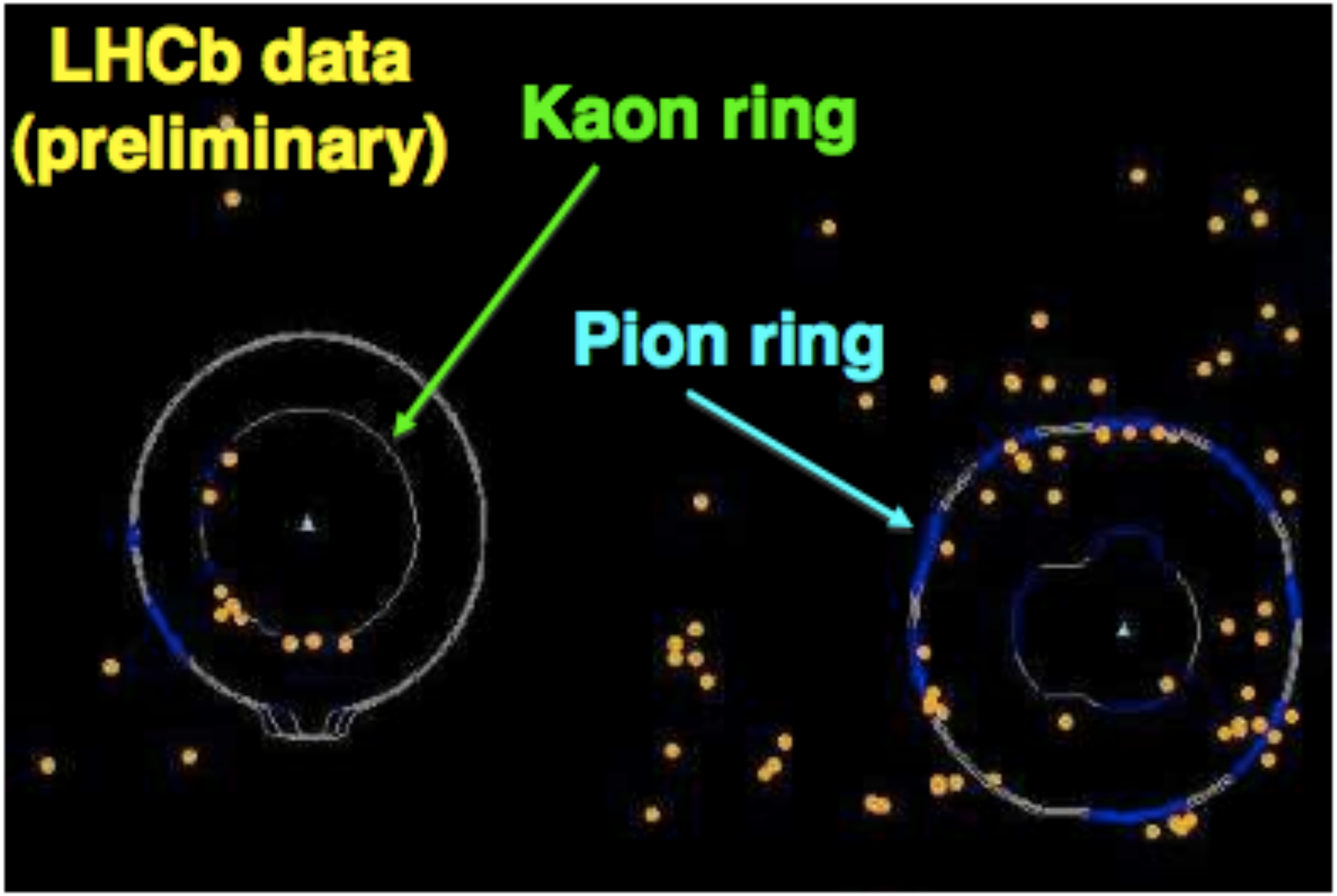


RICH2 panel: single pp-interaction event

Heavy Flavour physics today

a beautiful experiment : LHCb

E



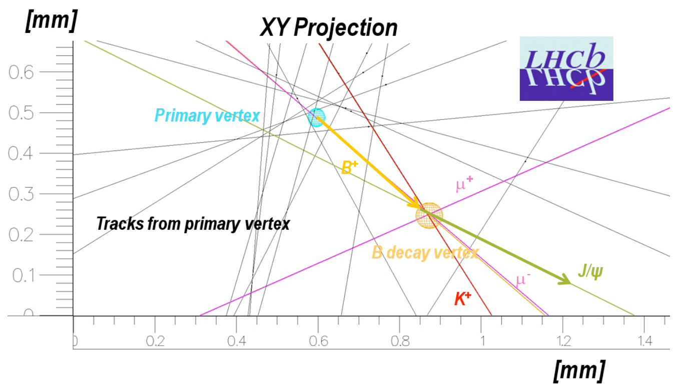
RICH2 panel: single pp-interaction event

Heavy Flavour physics today

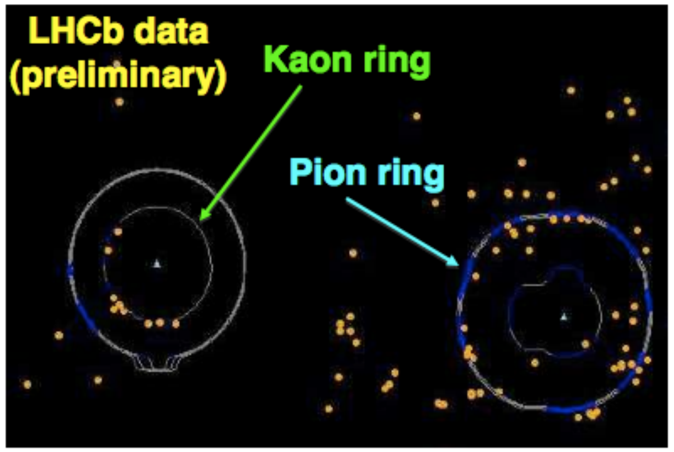
a beautiful experiment : LHCb

E

VELO

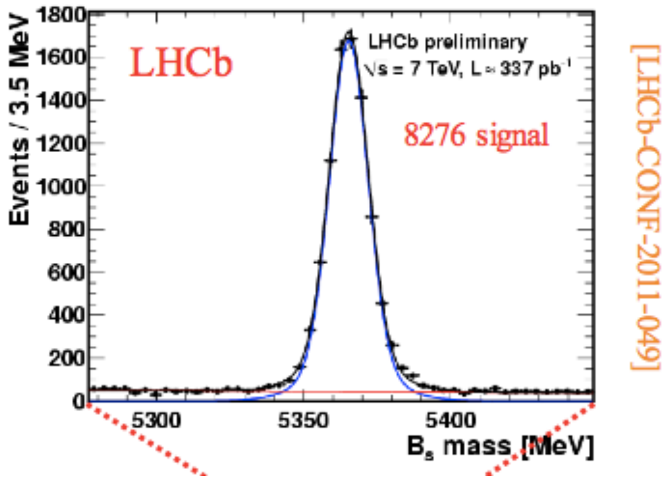


RICH



RICH2 panel: single pp-interaction event

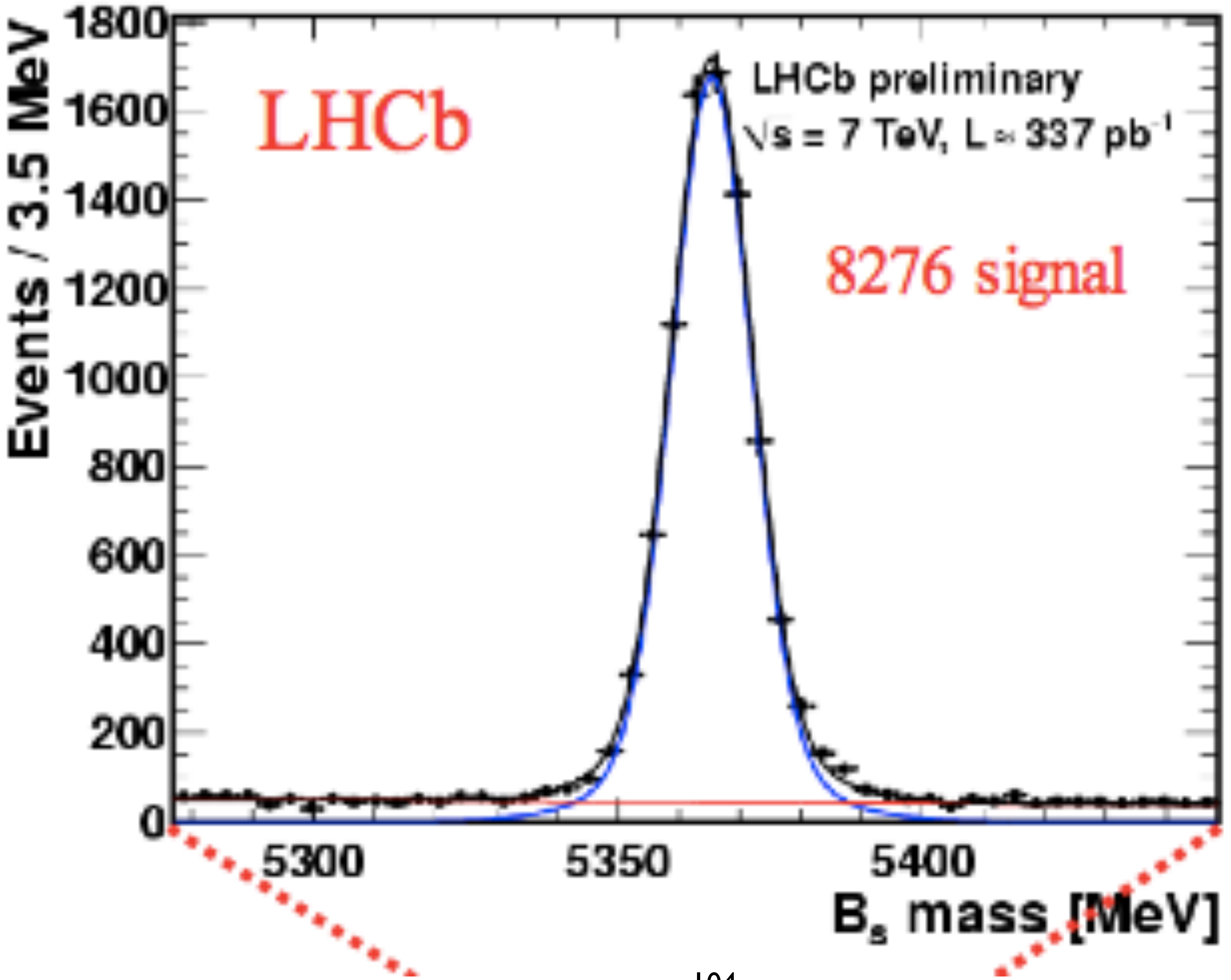
TRACK



Heavy Flavour physics today

a beautiful experiment : LHCb

E



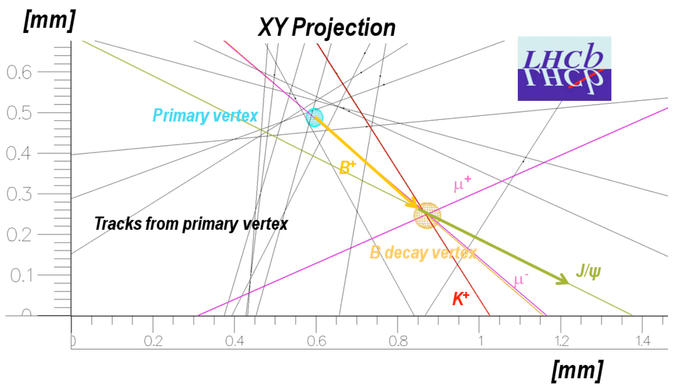
[LHCb-CONF-2011-049]

Heavy Flavour physics today

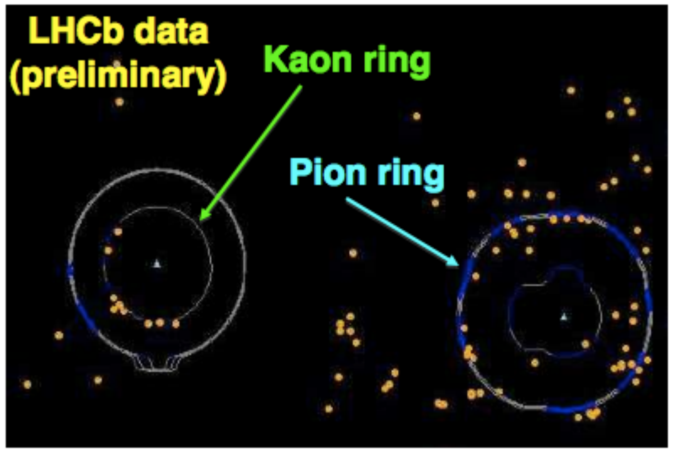
a beautiful experiment : LHCb

E

VELO

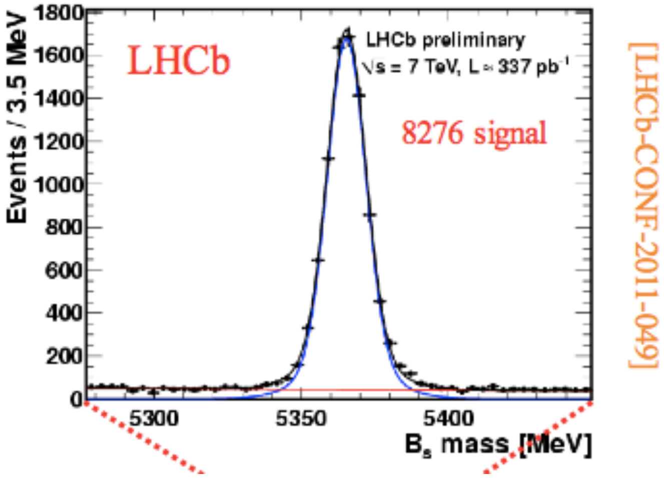


RICH

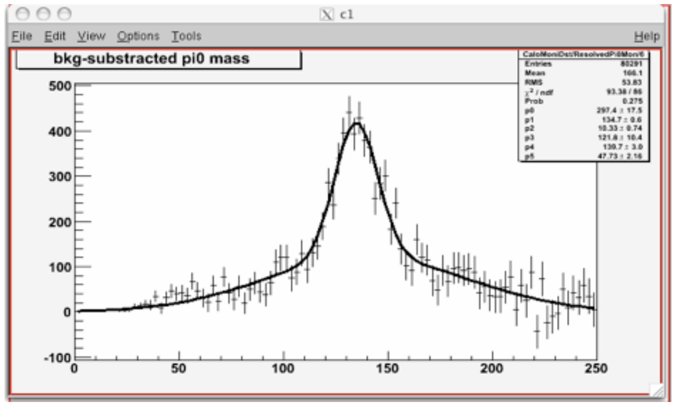


RICH2 panel: single pp-interaction event

TRACK



CALO

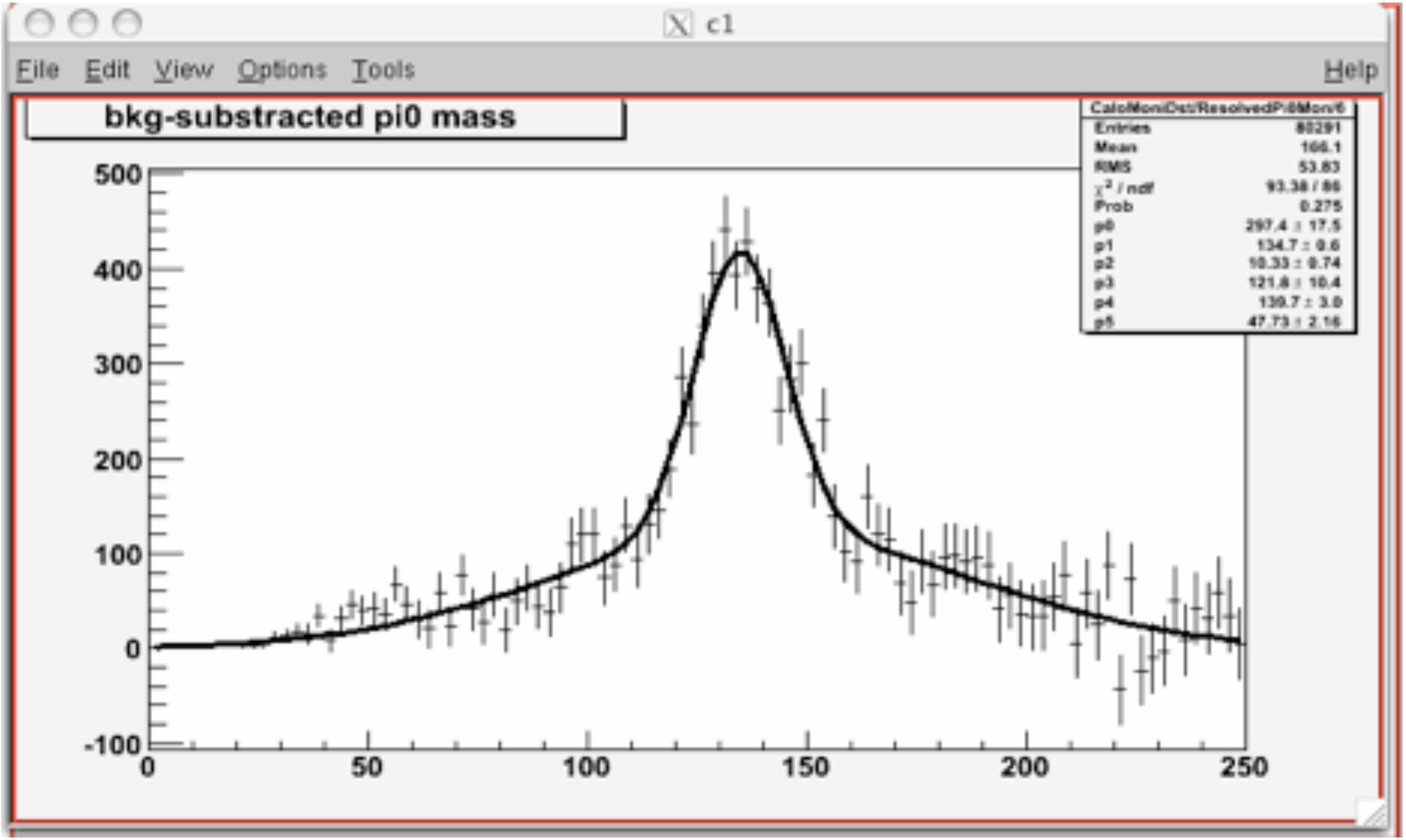


CaloMoniDst/ResolvedPi0Mon/6	
Entries	80291
Mean	106.1
RMS	53.83
χ^2 / ndf	93.38 / 86
Prob	0.275
p0	297.4 ± 17.5
p1	134.7 ± 0.6
p2	10.33 ± 0.74
p3	121.8 ± 10.4
p4	139.7 ± 3.0
p5	47.73 ± 2.16

Heavy Flavour physics today

a beautiful experiment : LHCb

E



bkg-substracted pi0 mass

```
CaloMoniDst/ResolvedPi0Mon/6
Entries        80291
Mean           106.1
RMS            53.83
χ² / ndf     93.38 / 86
Prob           0.275
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```
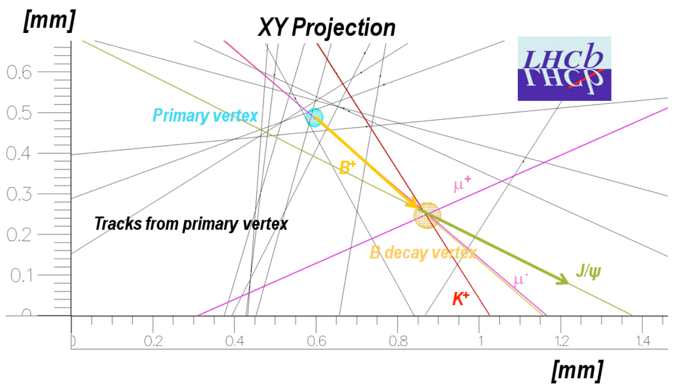

Heavy Flavour physics today

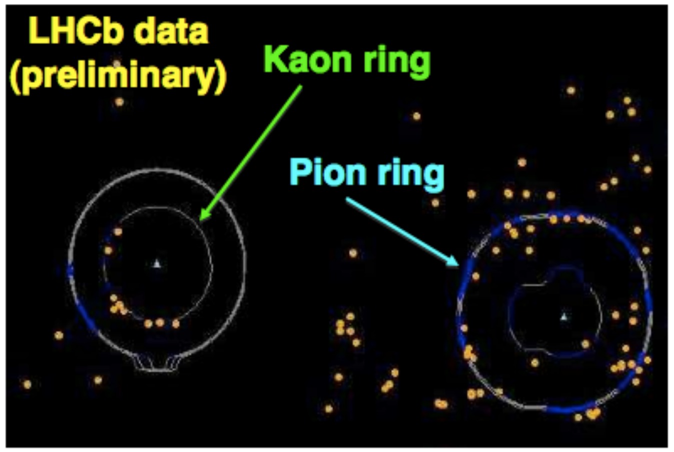
a beautiful experiment : LHCb

E

VELO

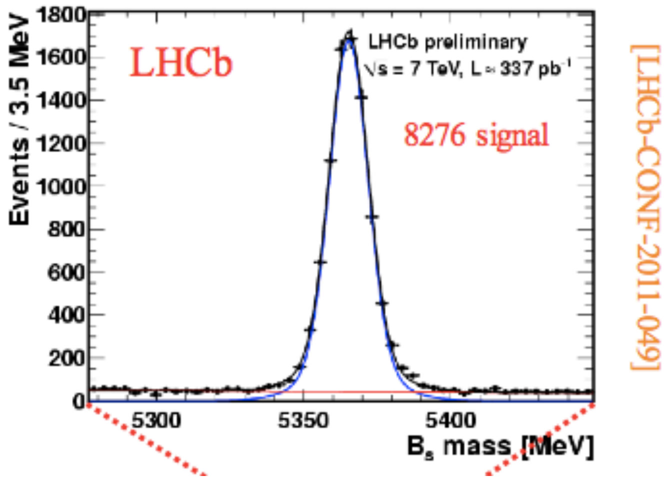


RICH

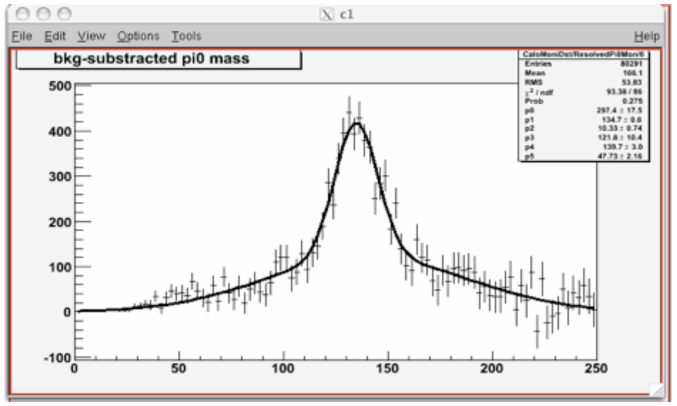


RICH2 panel: single pp-interaction event

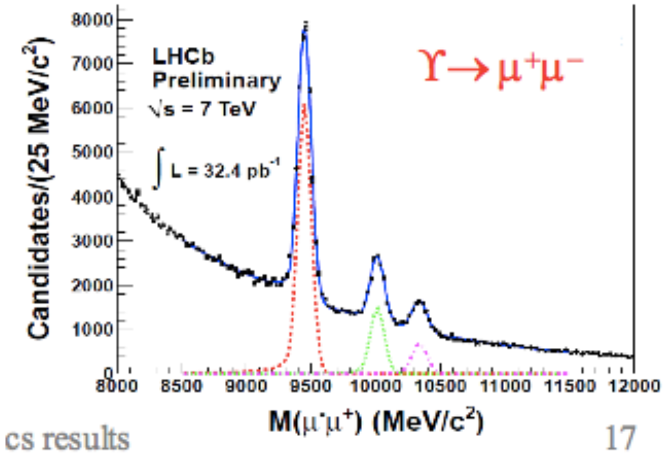
TRACK



CALO



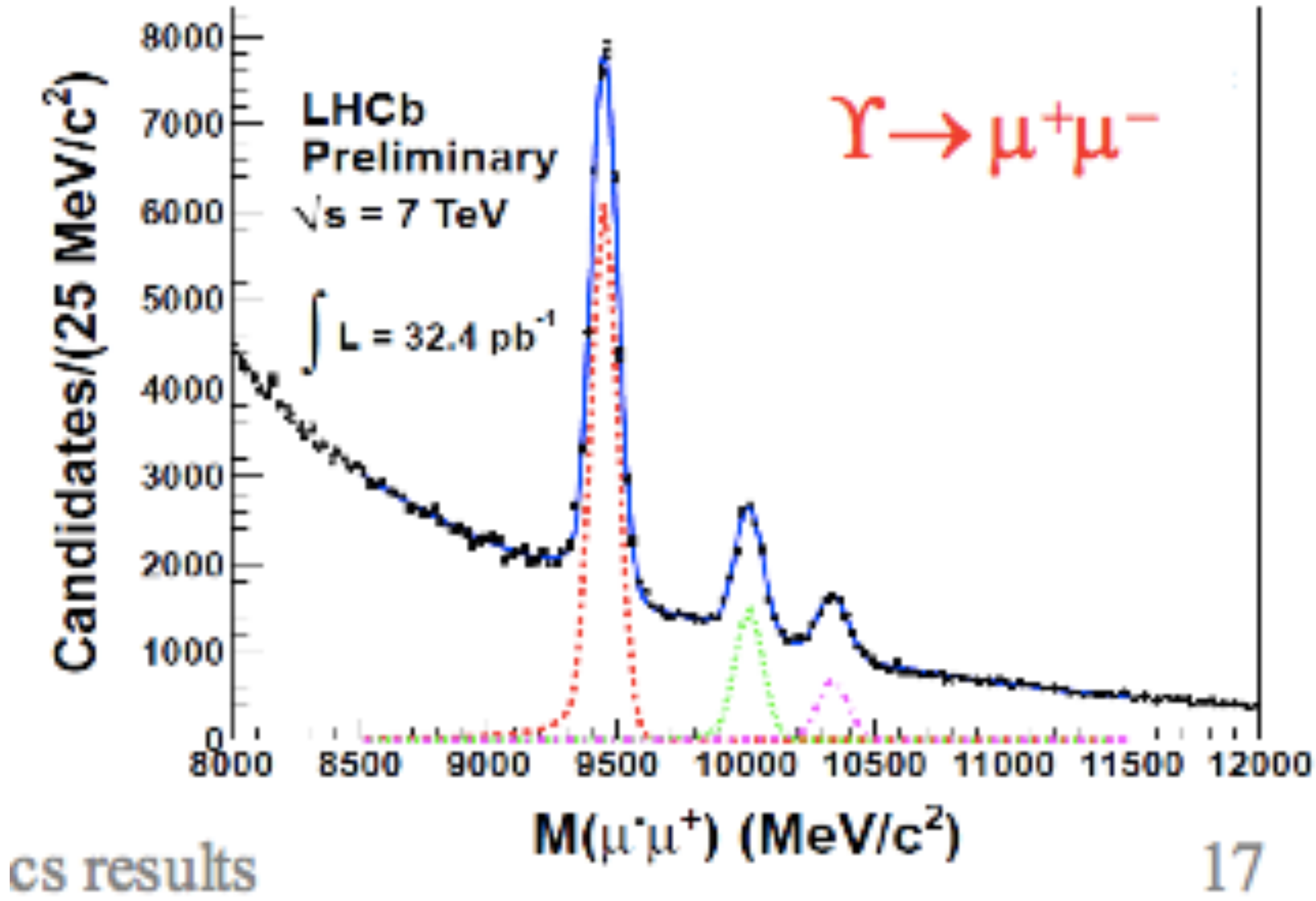
MUON



Heavy Flavour physics today

a beautiful experiment : LHCb

E

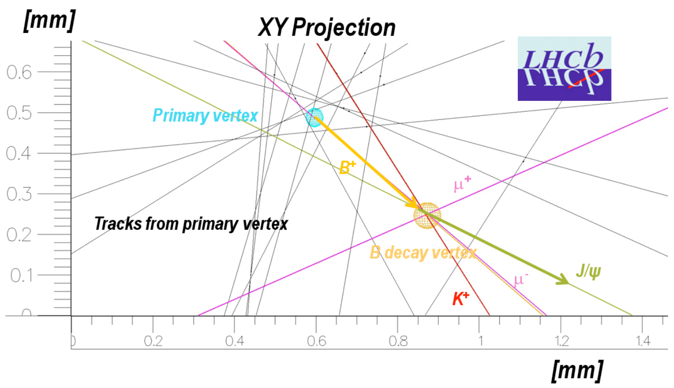


Heavy Flavour physics today

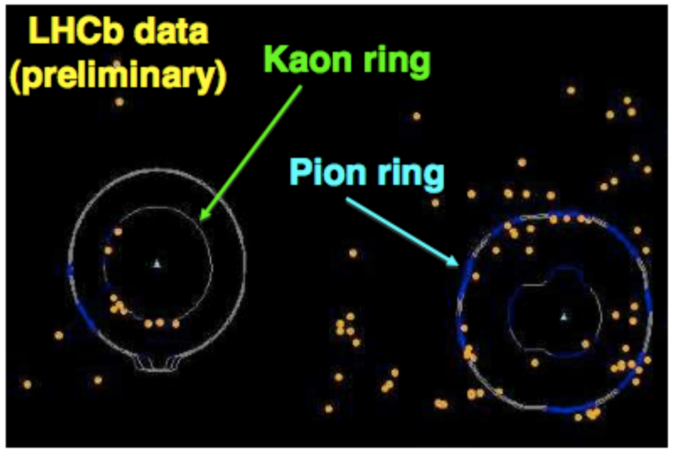
a beautiful experiment : LHCb

E

VELO

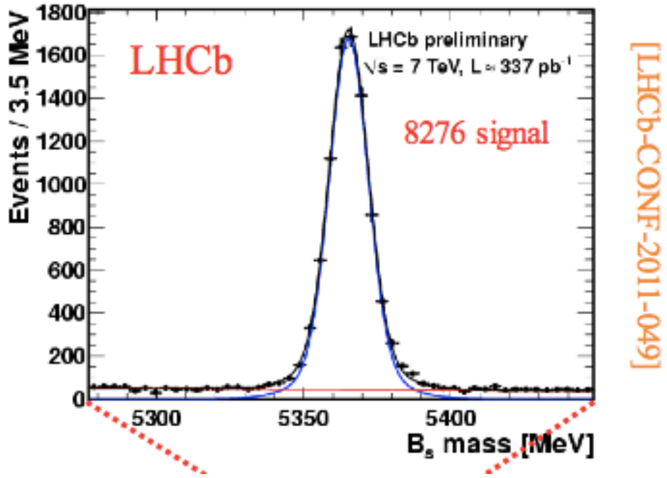


RICH

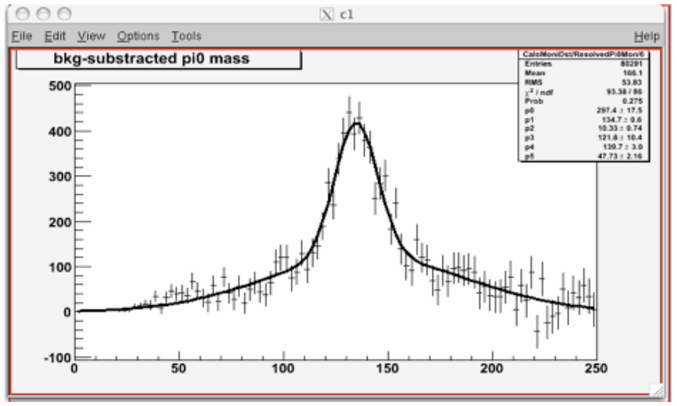


RICH2 panel: single pp-interaction event

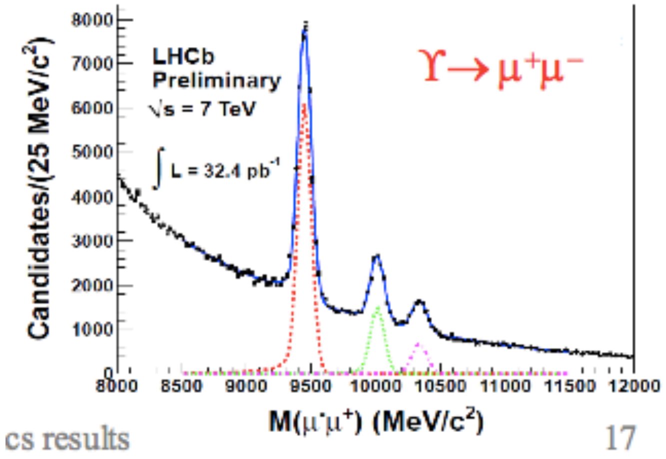
TRACK



CALO



MUON



DAQ

2011 :

~ 10 M collisions / s

~ 800 000 L0 / s

~ 3 000 bb / s

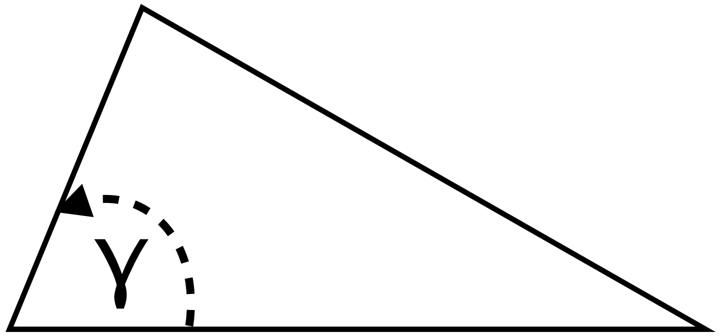
~ 10 m bb recorded and analysed !

Heavy Flavour physics today

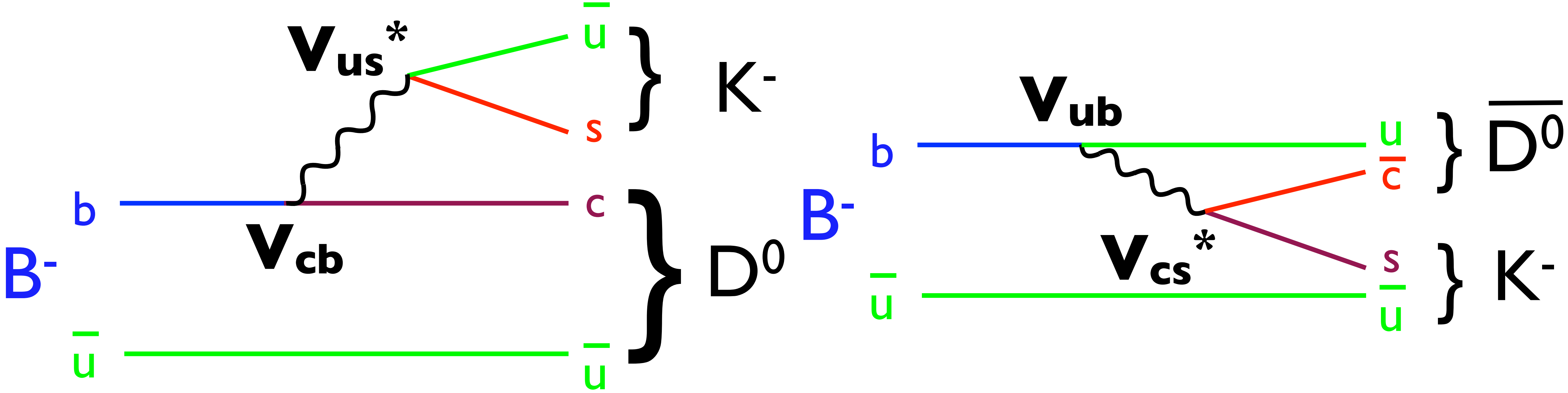
E

LHCb on CKM

- measuring the γ angle :



- diagrams : no 🐧 contribution → "clean"



- b→c (V_{cb}) & b→u (V_{ub}) interferences
- difficult but allow to access γ (V_{ub})

LHCb on CKM

- measuring the γ angle : observable

$$R_{CP+} = \frac{\Gamma(B^- \to [h^+h^-]_D K^-) + \Gamma(B^+ \to [h^+h^-]_D K^+)}{1/2\left[\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)\right]} = 1 + r_B^2 + 2r_B\cos\delta_B\cos\gamma$$

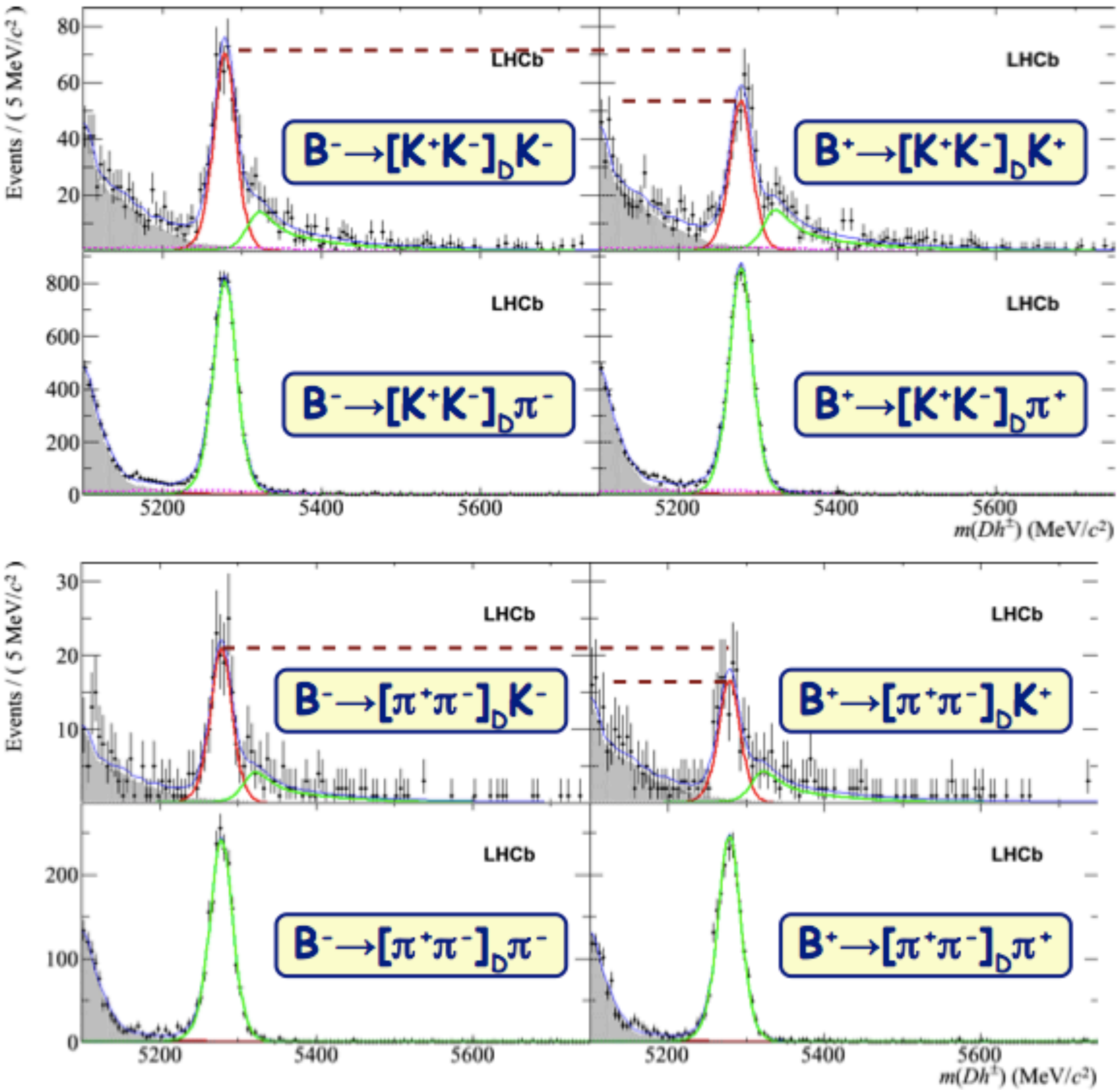
$$A_{CP+} = \frac{\Gamma(B^- \to [h^+h^-]_D K^-) - \Gamma(B^+ \to [h^+h^-]_D K^+)}{1/2\left[\Gamma(B^- \to [h^+h^-]_D K^-) + \Gamma(B^+ \to [h^+h^-]_D K^+)\right]} = + \frac{2r_B\cos\delta_B\cos\gamma}{R_{CP+}}$$

Heavy Flavour physics today

LHCb on CKM

E

- measuring the γ angle : results



$$A_{CP+} = (14.5 \pm 3.2 \pm 1.0)\,\%$$

[PLB 713 (2012) 351]

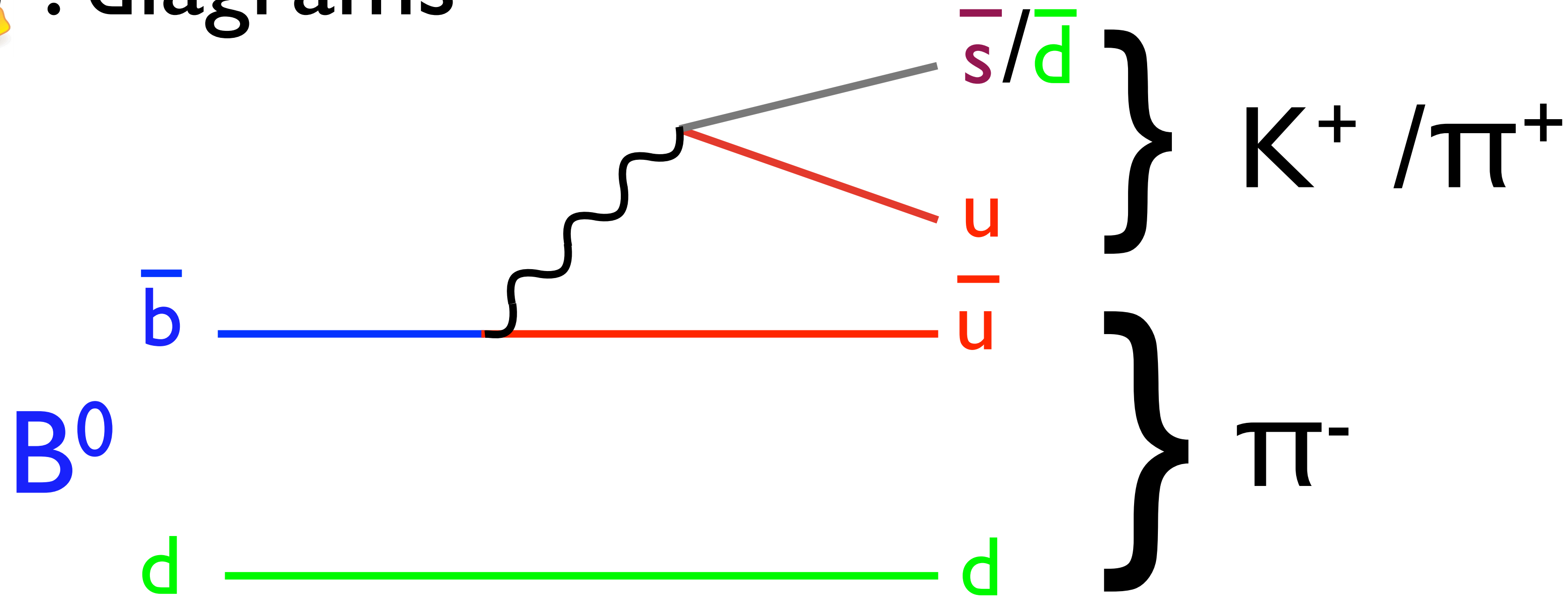
LHCb result (LHCb-CONF-2013-006)

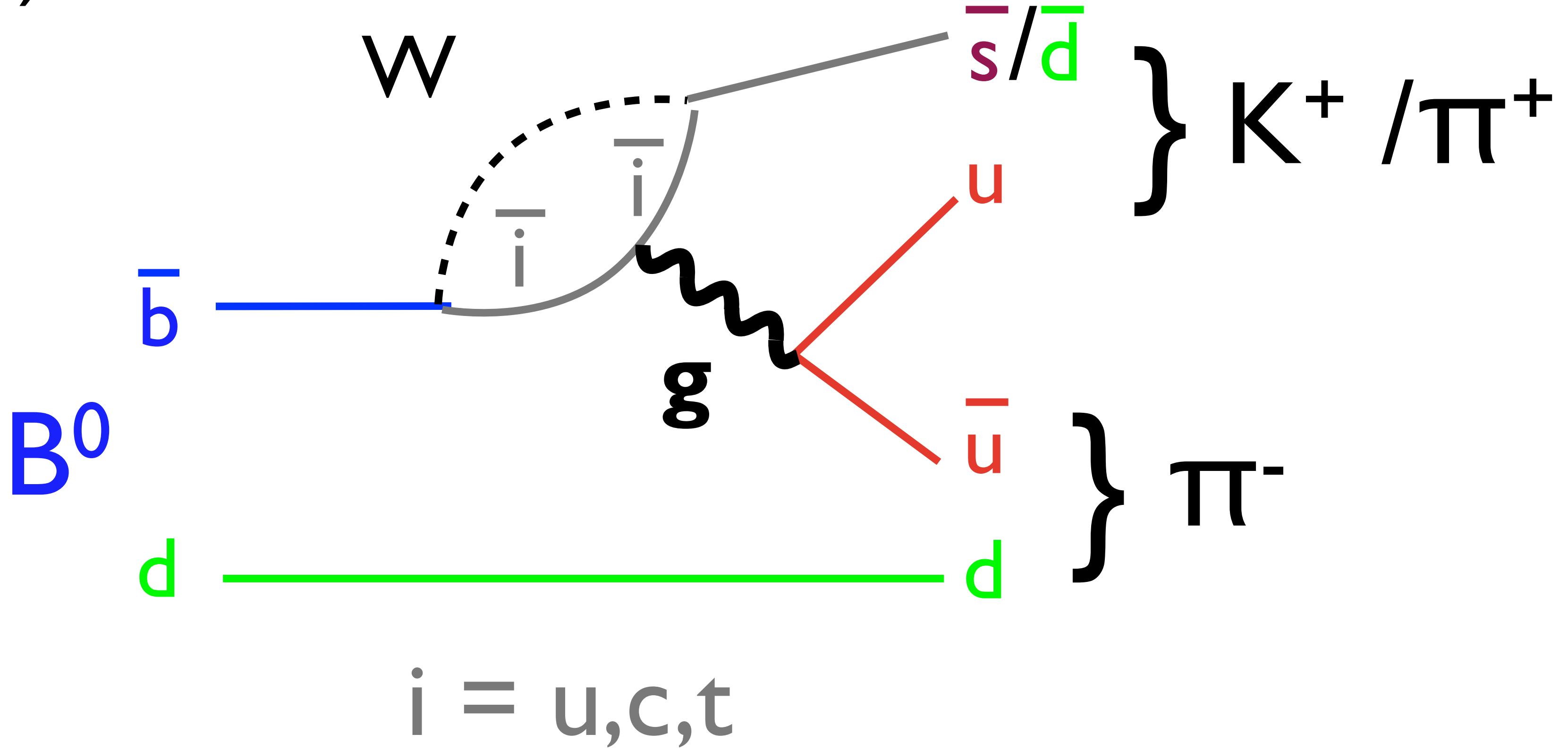
$\gamma = (67 \pm 12)^\circ$

CKMFitter: $\gamma = (68.0^{+4.1}_{-4.6})^\circ$

LHCb on Penguins

- gamma with 🐧 : diagrams
- also with B^0_s
  - put s for d
  - get K^- for π^-
- b→u (V_{ub}) (tree)
  &
  b→s (or d) 🐧
  interferences
- measure A_{CP}
  as f(t) or integ.

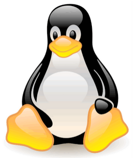




Heavy Flavour physics today

LHCb on Penguins

E

- gamma with  : observables

$$A_{CP}(t) = \frac{\Gamma(B^0_{(s)}(t=0) \rightarrow f) - \Gamma(\overline{B}^0_{(s)}(t=0) \rightarrow f)}{\Gamma(B^0_{(s)}(t=0) \rightarrow f) + \Gamma(\overline{B}^0_{(s)}(t=0) \rightarrow f)}$$

$$= \frac{A_f^{dir} \cos(\Delta m_{(s)} t) + A_f^{mix} \sin(\Delta m_{(s)} t)}{\cosh(\frac{\Delta\Gamma_{(s)}}{2} t) - A_f^{\Delta\Gamma} \sinh(\frac{\Delta\Gamma_{(s)}}{2} t)}$$

- Mixing induced CP violation : A_f^{mix}
- CP violation in decay : $A_f^{dir} \rightarrow \gamma$

Heavy Flavour physics today

E

LHCb on Penguins

- gamma with 🐧 : results

$B^0 \to K^+\pi^-$

$B^{0bar} \to K^-\pi^+$

A_{CP} =

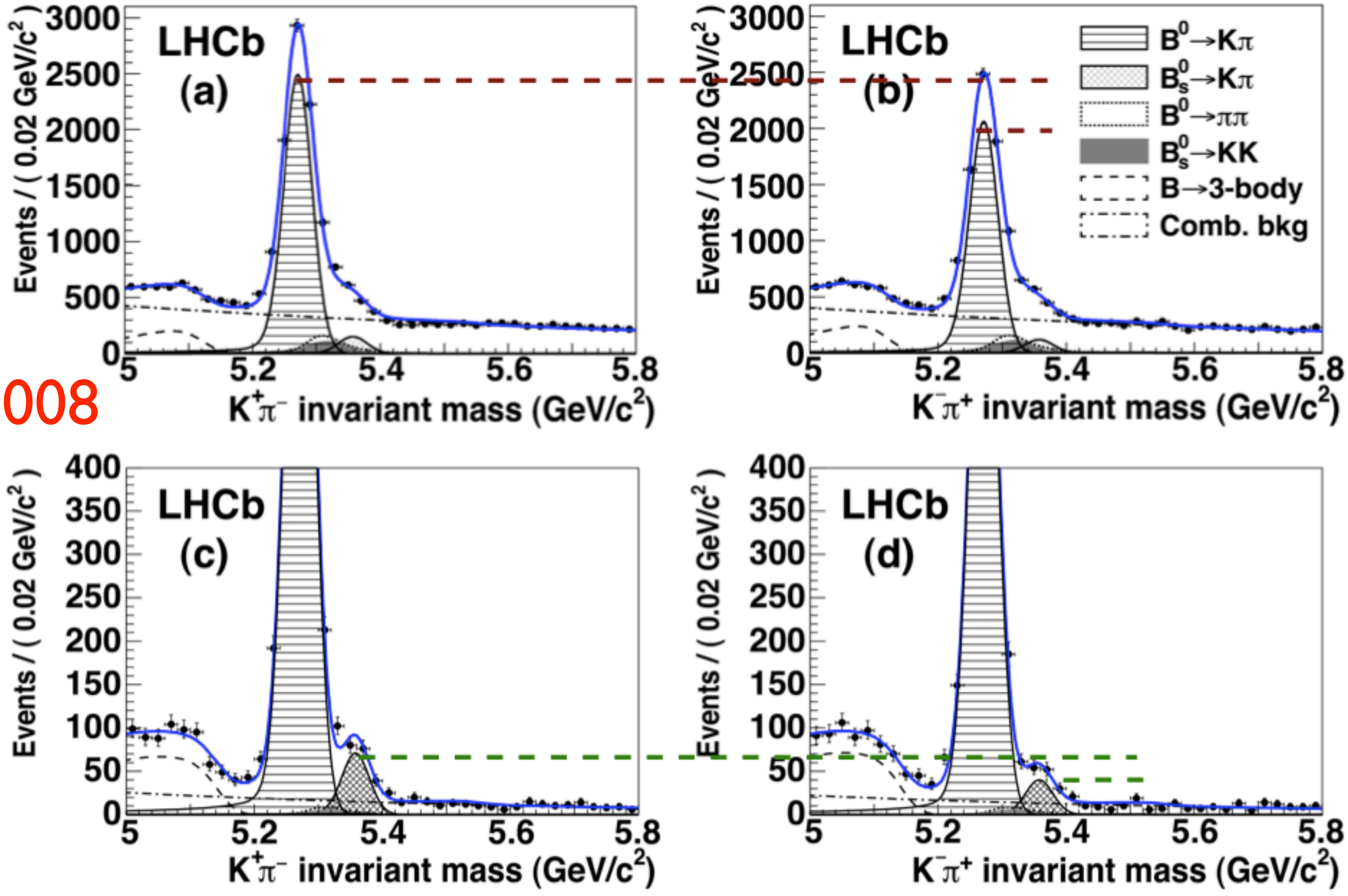
-0.088±0.011±0.008

$B^0_s \to K^-\pi^+$

$B^0{}_s{}^{bar} \to K^+\pi^-$

A_{CP} =

0.27±0.08±0.02



Heavy Flavour physics today

LHCb on rare decays

E

- $B^0_{(s)} \rightarrow \mu\mu$
  - b → s(d) = FCNC : best place for **NP**
  - extremely well (SM) known but
  - ... very small : many suppression effects !
- Predictions (SM) :
  - $Br(B^0_s \rightarrow \mu\mu) = (3.23 \pm 0.27) \times 10^{-9}$
  - $Br(B^0_d \rightarrow \mu\mu) = (1.07 \pm 0.10) \times 10^{-10}$
  - ~ 1 (B^0_s) or 0.1 (B^0_d) in a BILLION B^0 decay !

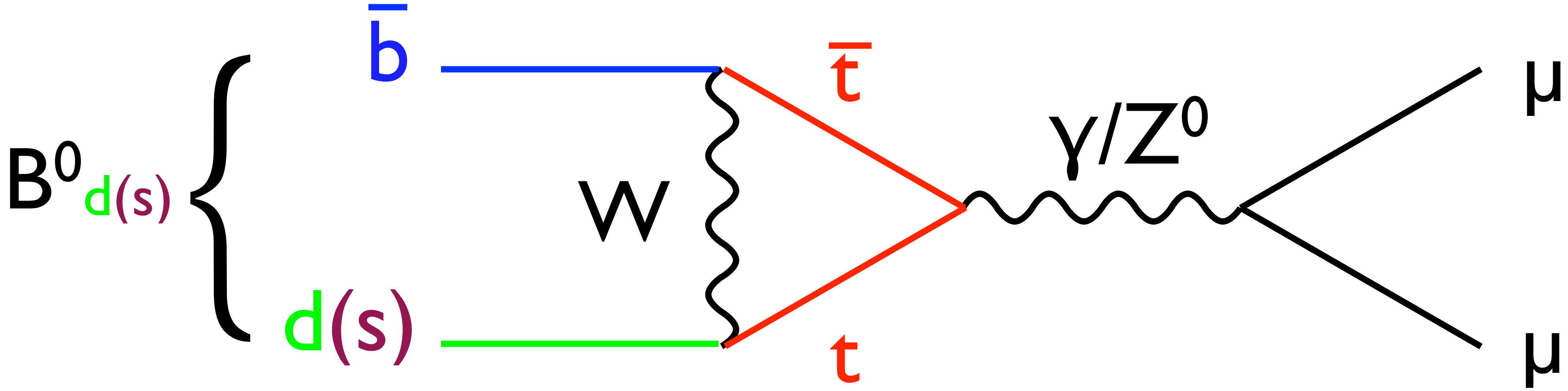
Heavy Flavour physics today

LHCb on rare decays

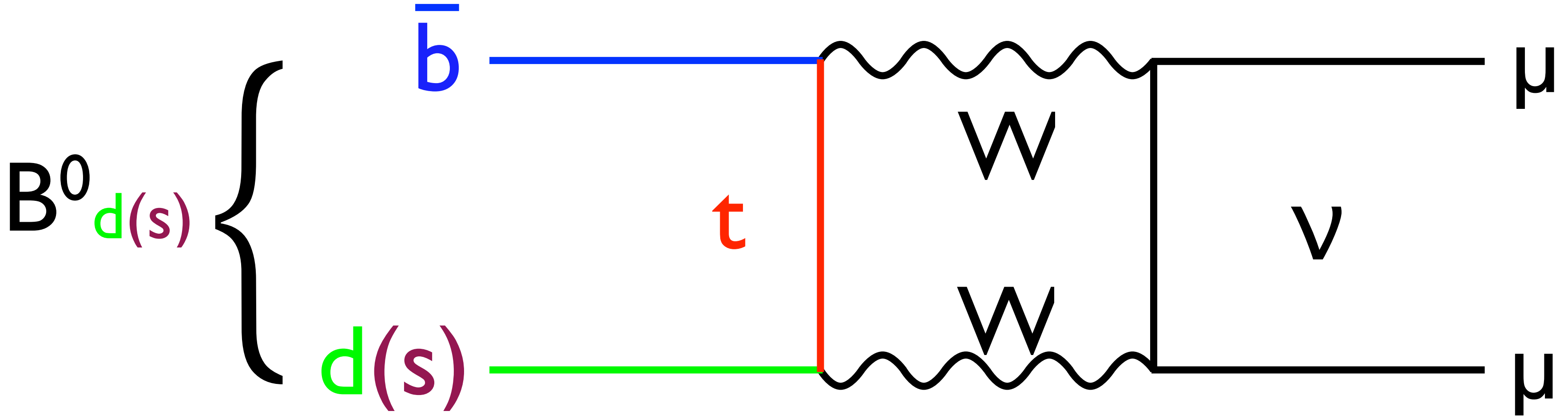
E

- $B^0_{d(s)} \rightarrow \mu\mu$: graphs

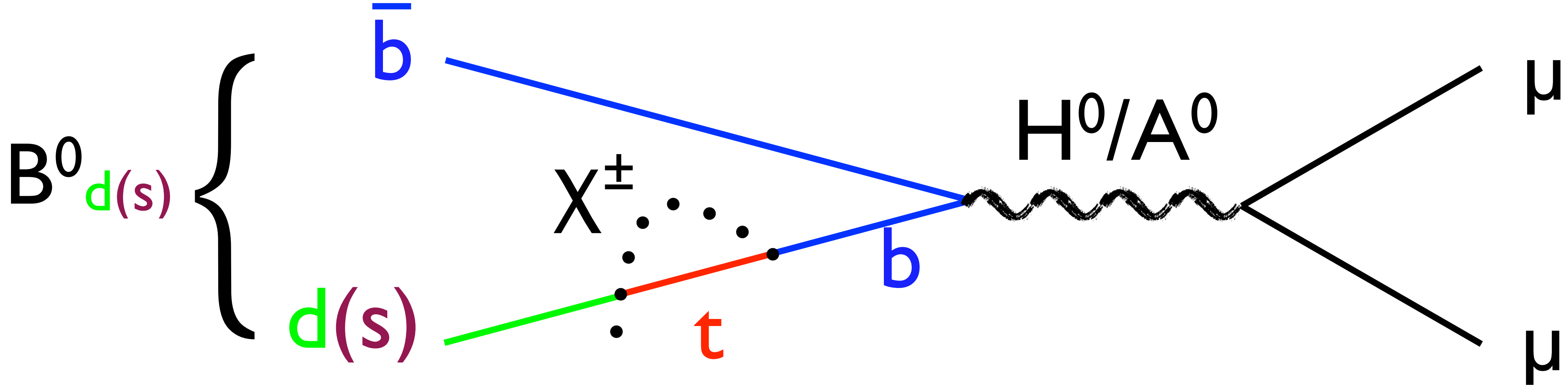
SM : FCNC



SM : FCCC



NP



Heavy Flavour physics today

LHCb on rare decays

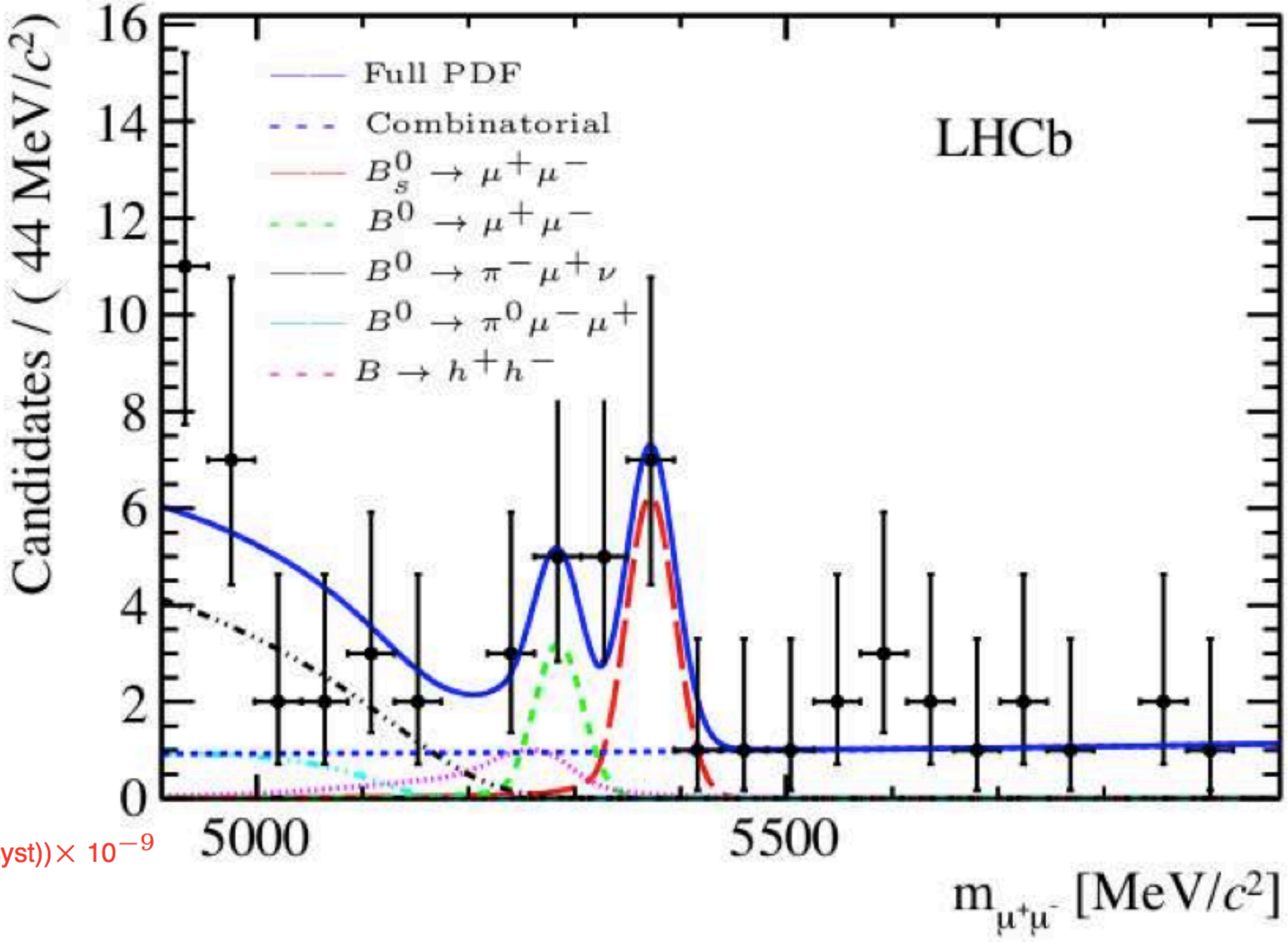
E

- $B^0_{d(s)} \rightarrow \mu\mu$: results as of

LAST WEEK !

also CMS :

~ same sensit.



$\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}(\mathrm{stat})^{+0.3}_{-0.1}(\mathrm{syst}))\times 10^{-9}$

$\to 4\,\sigma$

$\mathrm{BR}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95% CL

$\mathrm{BR}(B^0 \to \mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1}(\mathrm{stat})^{+0.6}_{-0.4}(\mathrm{syst}))\times 10^{-10}$

$\to 2.0\,\sigma$

Heavy Flavour physics today

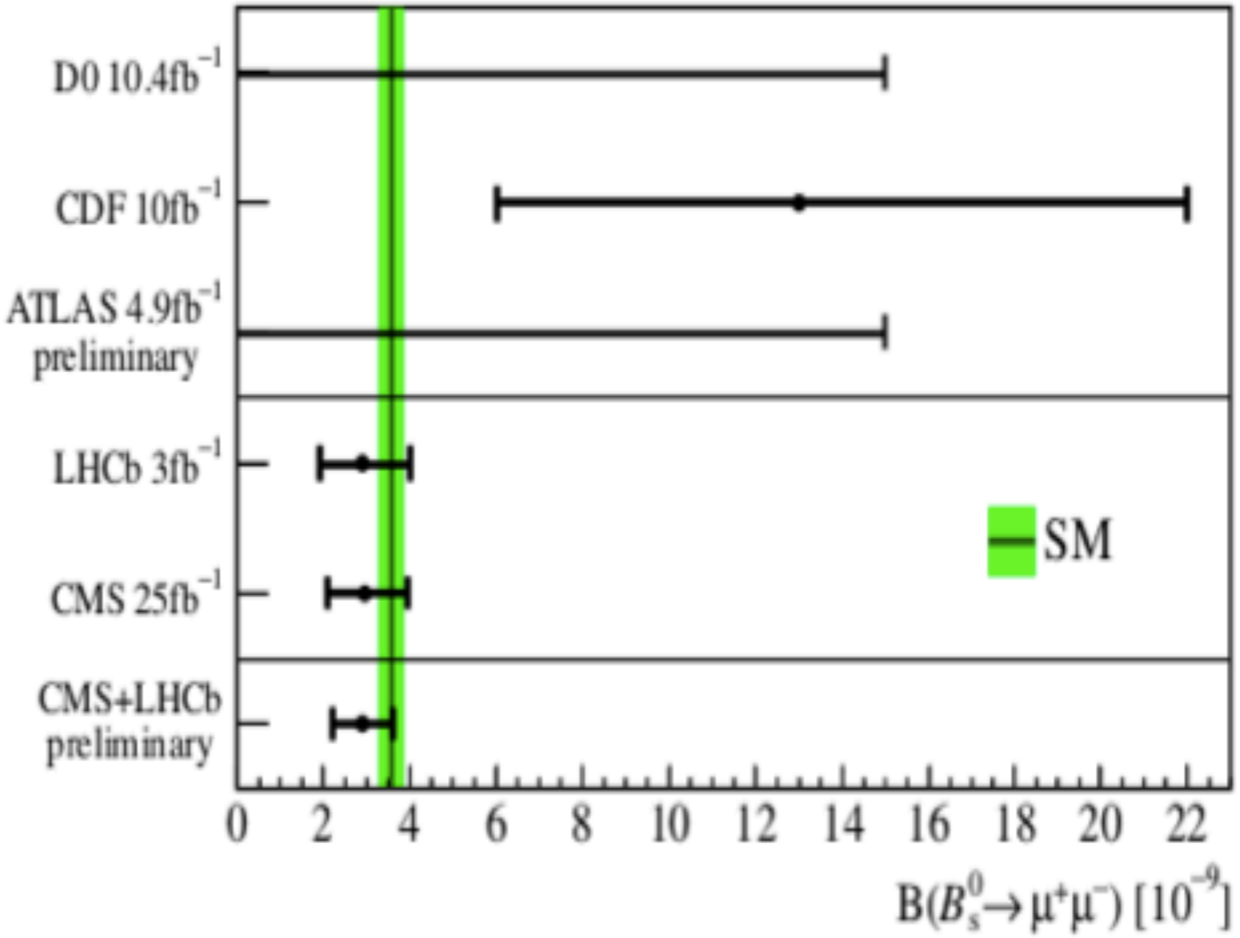
LHCb on rare decays

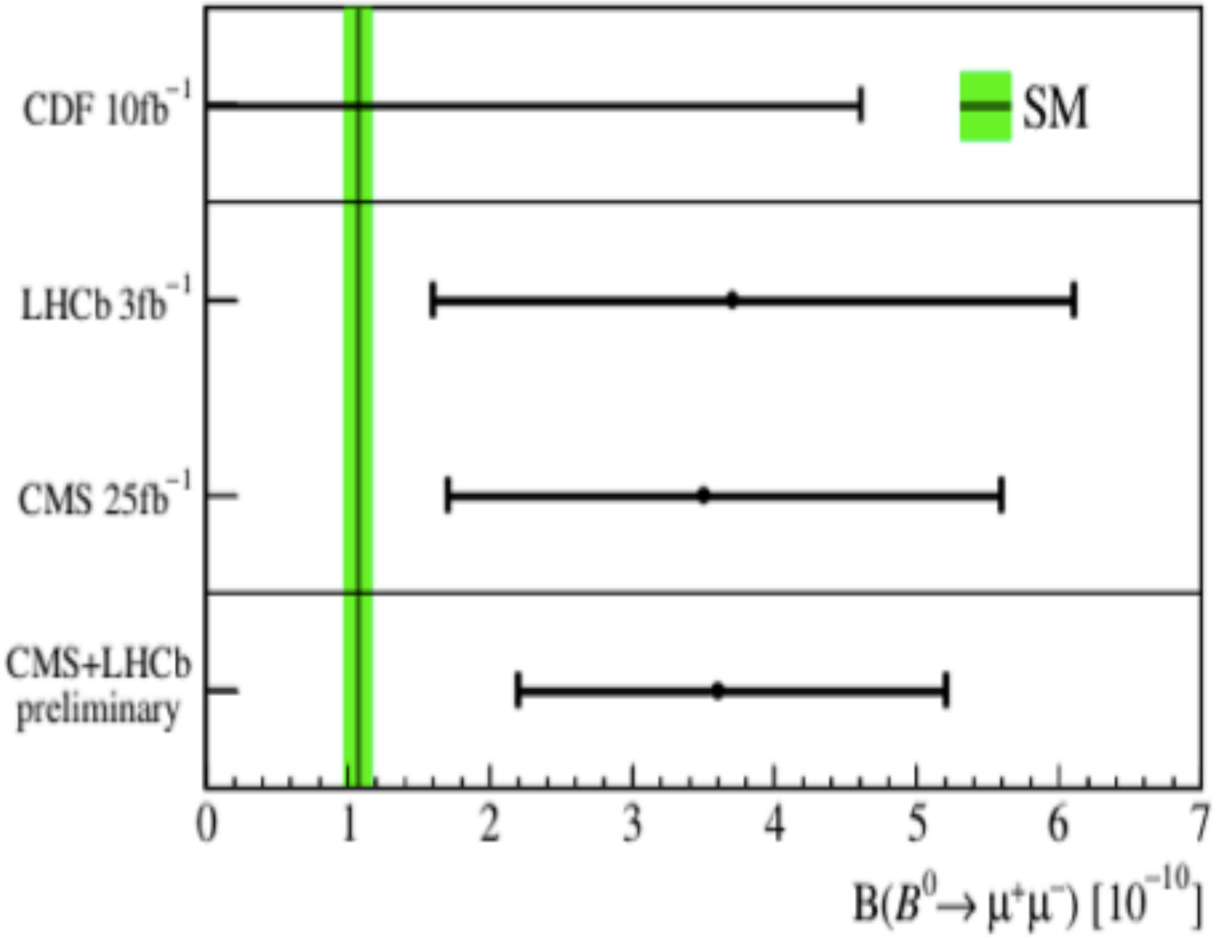
E

- $B^0_{d(s)} \rightarrow \mu\mu$: results as of LAST WEEK !
- World average :

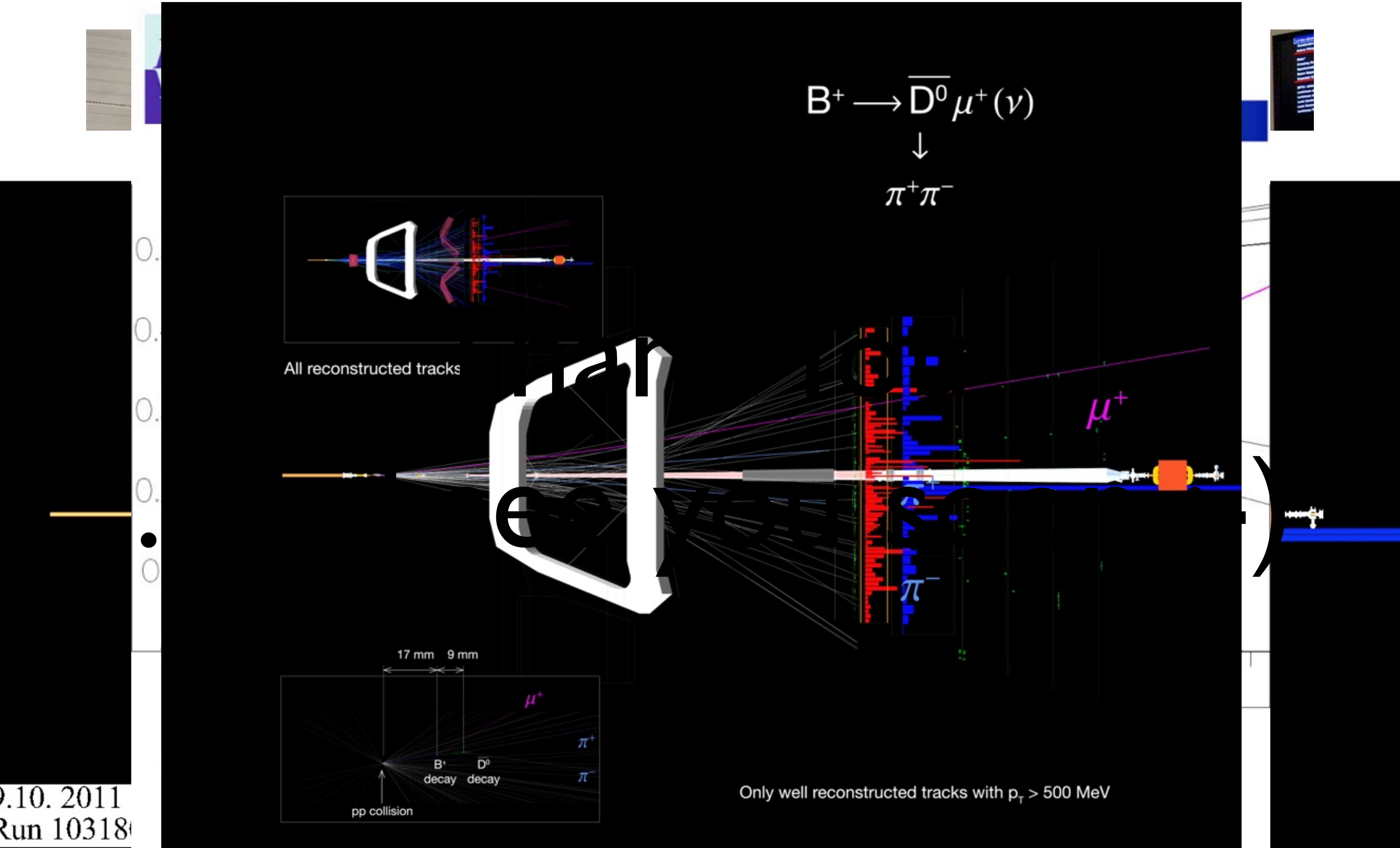
Observation:

$$\mathrm{BR}(B_s \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$





6 - Conclusion



Extra sub-chapters for chapter 4

(prepared but not presented)

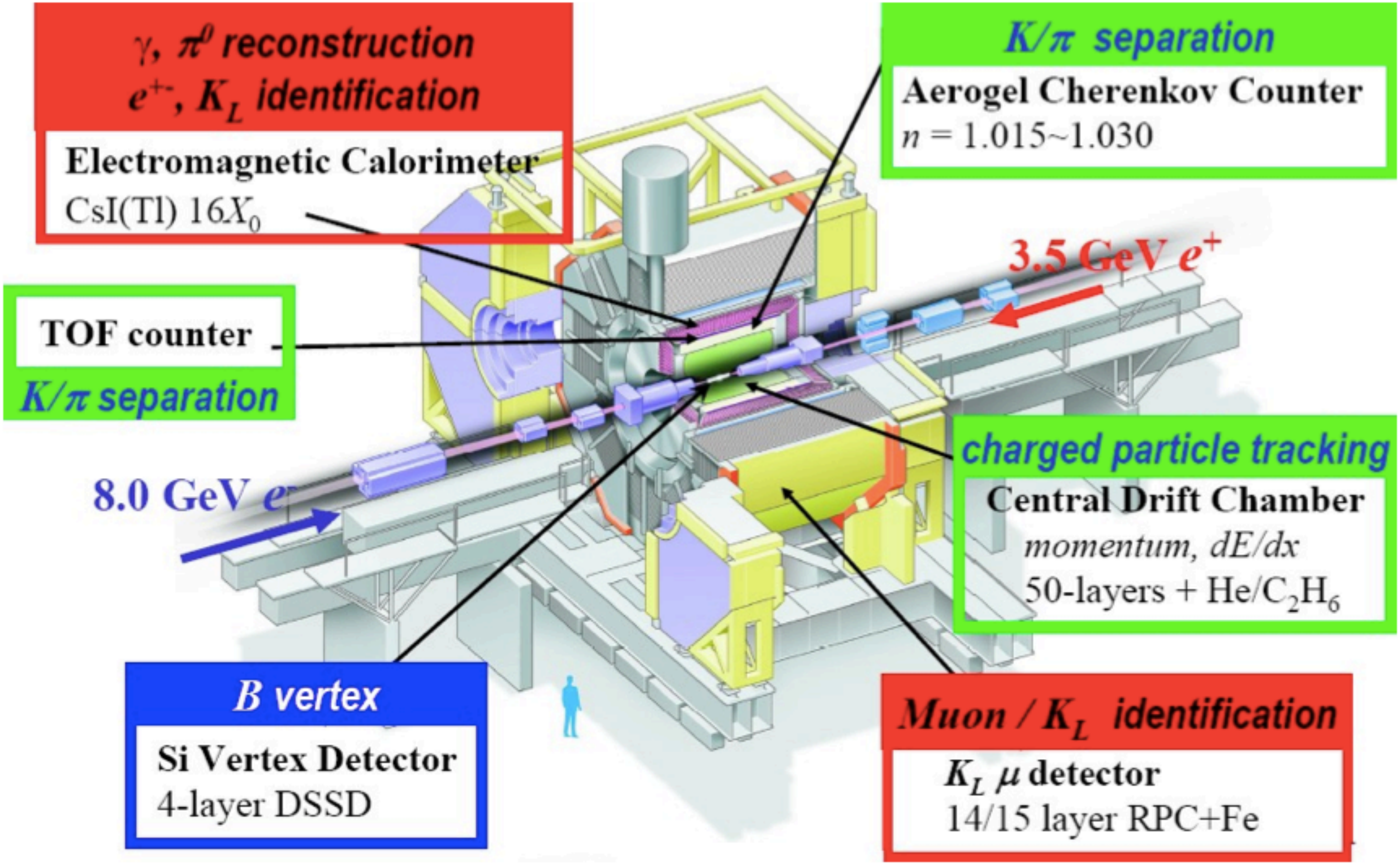
4 - the Beautiful Factories

– CKM matrix - 2		…	**T**
– Mixing & Oscillations		…	**T**
– Triangle - status 1	CKMfitter	1995	**??**
– 🐧 & B factories	PEPII, KEKB	1999	**E**
– $\cancel{CP}$ (B^0_d)	BaBar (Belle)	2001	**E**
– Direct $\cancel{CP}$ (B^0_d)	Belle (BaBar)	2004	**E**
– B^0_s oscillations	CDF	2006	**E**
– D^0 mixing	BaBar (Belle)	2007	**E**

the Beautiful Factories

Direct $\cancel{CP}$ (B^0_d) - Belle

E



γ, π^0 reconstruction
e^{+-}, K_L identification

Electromagnetic Calorimeter
CsI(Tl) $16X_0$

K/π separation

Aerogel Cherenkov Counter
$n = 1.015$~1.030

TOF counter
K/π separation

charged particle tracking

Central Drift Chamber
momentum, dE/dx
50-layers + He/C_2H_6

B vertex

Si Vertex Detector
4-layer DSSD

Muon / K_L identification

K_L μ detector
14/15 layer RPC+Fe

the Beautiful Factories

Direct $\not{CP}$ (B^0_d) - Belle - 2004

E

- observable :

$$P_{\pi\pi}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1+q.\left\{S_{\pi\pi}\sin(\Delta m_d \Delta t)+A_{\pi\pi}\cos(\Delta m_d \Delta t)\right\}\right]$$

with $\Delta t = t_{\pi\pi} - t_{tag}$ and q : B flavour of tagged B

"We report the first observation of CP-violating asymmetries in $B^0 \to \pi^+\pi^-$ decays based on a 140 fb^{-1} data sample (...). We reconstruct one neutral B meson as a $B^0 \to \pi^+\pi^-$ CP eigenstate and identify the flavor of the accompanying B meson from its decay products. (...) The fit yields the CP-violating asymmetry amplitudes

$A_{\pi\pi} = +0.58 \pm 0.15(\text{stat}) \pm 0.07(\text{syst})$

$S_{\pi\pi} = -1.00 \pm 0.21(\text{stat}) \pm 0.07(\text{syst})$

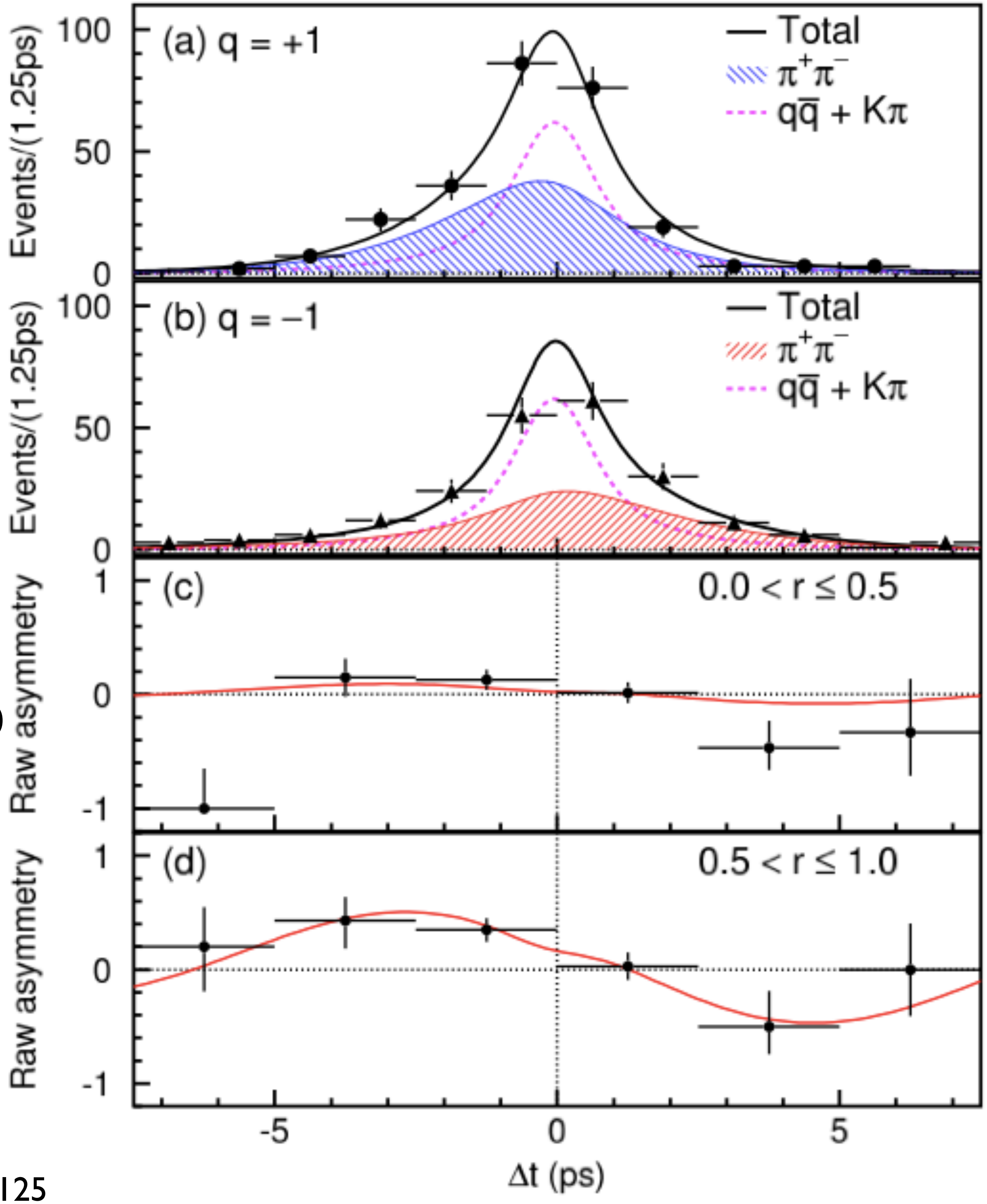
(...) We also find evidence for direct CP violation with a significance at or greater than 3.2 standard deviations for any $S_{\pi\pi}$ value."

the Beautiful Factories

Direct $\cancel{CP}$ $(B^0{}_d)$ - Belle - 2004

E

- Results :
- r : evt/evt MC flavor dilution
  - r = 0 fully ambiguous
  - r = 1 fully unambiguous
- Δt distributions for the 483 $B^0 \to \pi^+\pi^-$
- (a) 264 candidates with q = +1, i.e. the tag side is identified as B^0
- (b) 219 candidates with q = −1.
- (c) Asymmetry, A, in each Δt bin with $0 < r \leq 0.5$ and
- (d) with $0.5 < r \leq 1.0$.



D^0 mixing - BaBar - 2007

- $D^0 = \bar{u}c$, $\bar{D}^0 = u\bar{c}$
  - $D^0 \rightarrow K^-\pi^+$: "Cabibbo-favored" (CF) , "right sign" (RS)
  - $\bar{D}^0 \rightarrow K^+\pi^-$: "Doubly Cabibbo-suppressed" (DCS), "wrong sign" (WS)
    - $D^0 \rightarrow \bar{D}^0 \rightarrow K^+\pi^-$: rate ~ 0.3%
    - mixing followed by CF : rate ~ 10^{-4}
- Identify D^0 charge conjugation
  - at production and at decay :

$$D^{*\pm} \rightarrow \pi_s^{\pm} D^0, D^0 \rightarrow K^{\mp}\pi^{\pm}$$

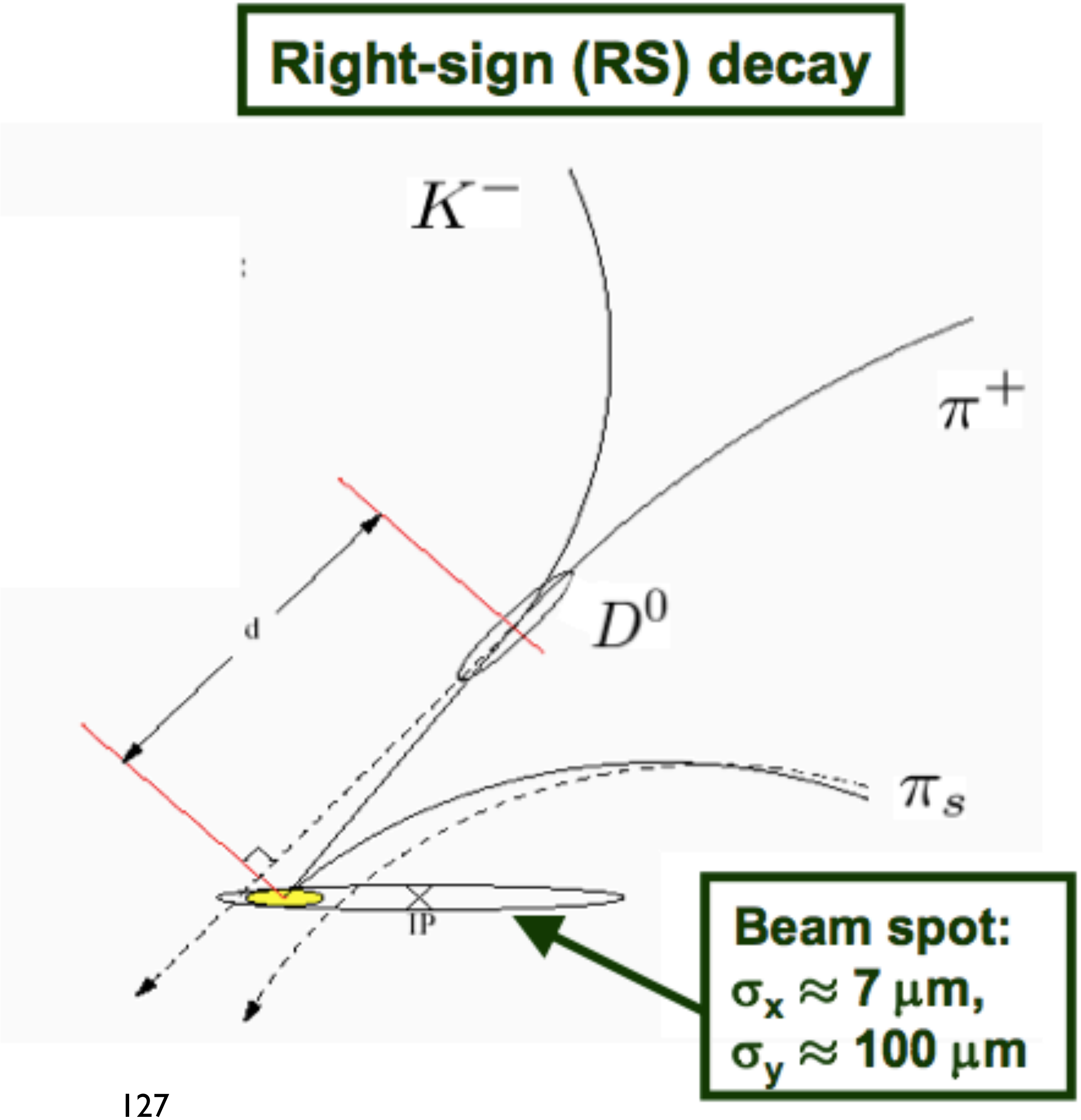
- Use beamspot to constrain the vertex fits

the Beautiful Factories

D^0 mixing - BaBar - 2007

E

- Analysis
  - constrained fit to full decay chain
  - kinematic cuts for D^0 and D^{*+}
- Data : 384 fb^{-1}
  - 1 229 000 RS
    - S/B ~ 99/1
  - 64 000 WS
    - S/B ~ 1/1
- Sophisticated statistical analysis

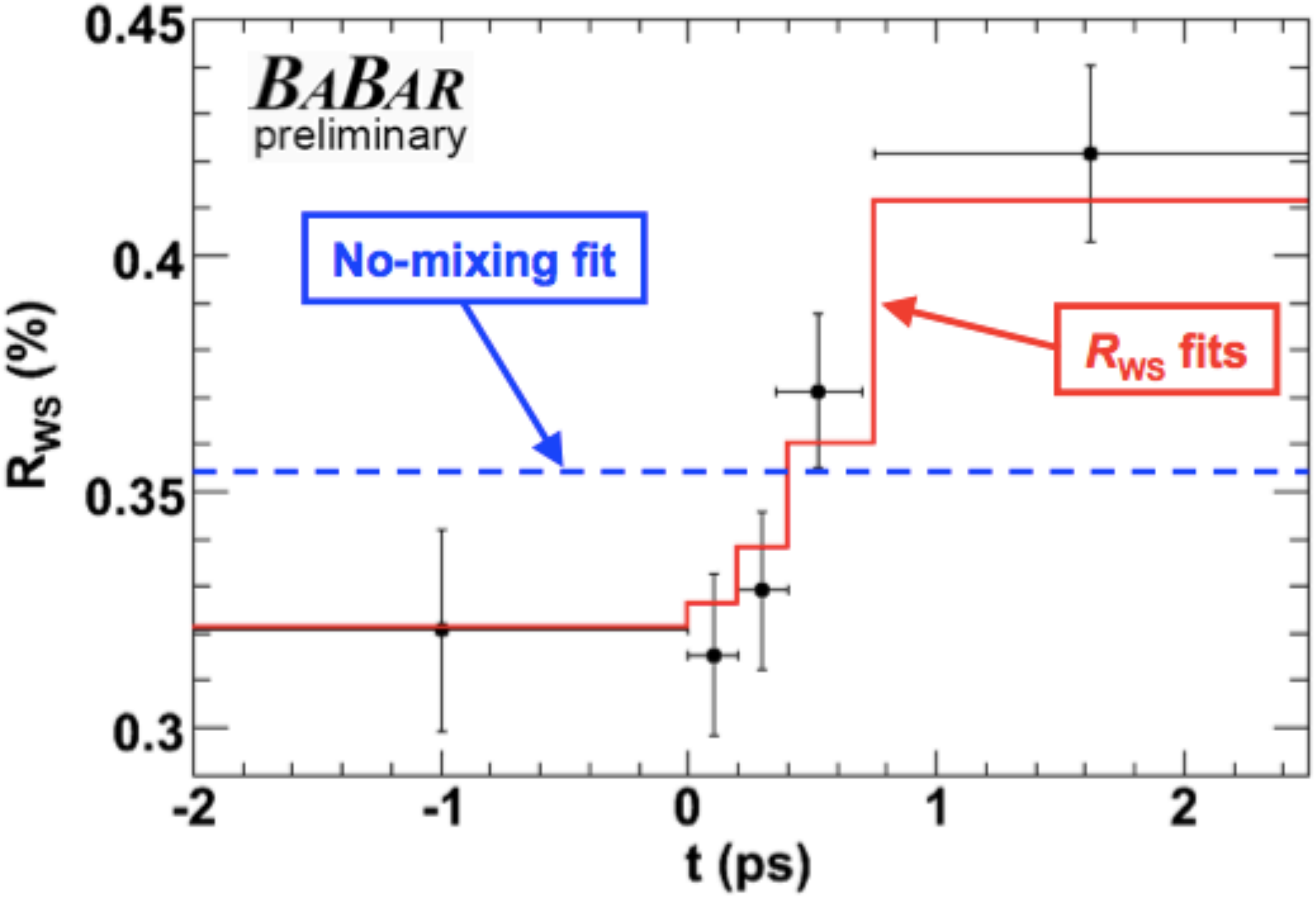


Right-sign (RS) decay

Beam spot:
$\sigma_x \approx 7\ \mu m$,
$\sigma_y \approx 100\ \mu m$

D^0 mixing - BaBar - 2007

- Results :



Dashed line: standard R_{WS} fit (χ^2=24).
Solid, red line: independent R_{WS} fits to each time bin (χ^2 = 1.5).

- Quantitatively : mixing established @ 3.9 σ (stat. + syst.)