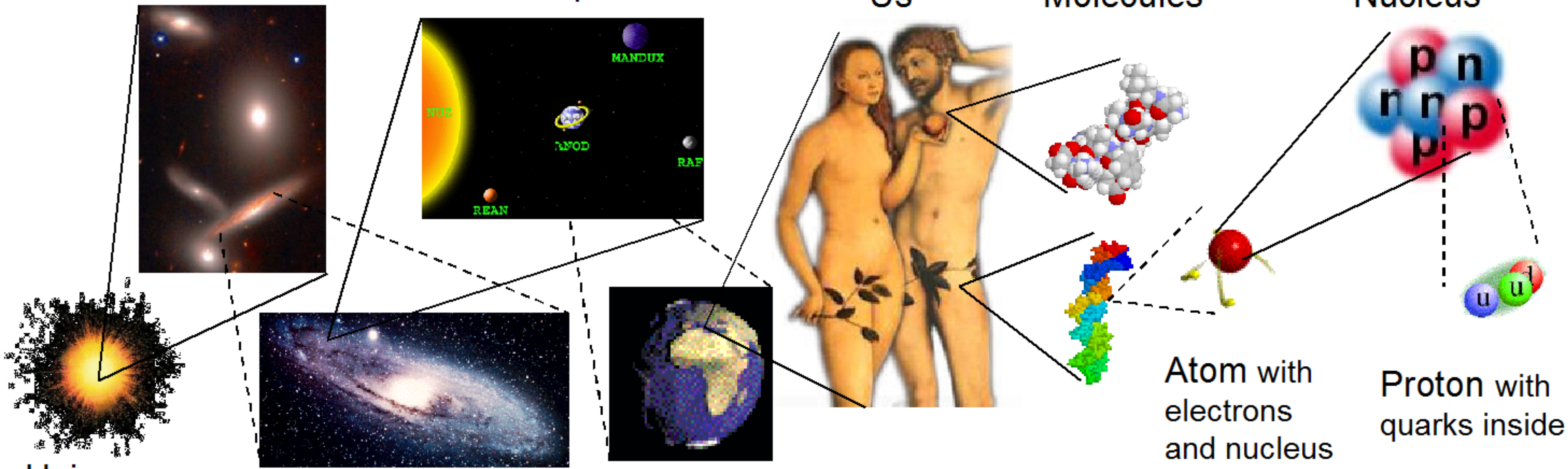
The LHCb experiment.

Physics of heavy flavor loops.

Tomasz Skwarnicki

Syracuse University

Fundamental Forces (Standard Model)



Group of galaxies

Star with planets

Us

Molecules

Nucleus

Atom with electrons and nucleus

Proton with quarks inside

Universe

Galaxy

Planet

Typical size

10^{26} 10^{23} 10^{21} 10^{13} 10^{7} 1m 10^{-9} 10^{-10} 10^{-14} 10^{-15}

Binding force

Gravity

Electromagnetic

Strong

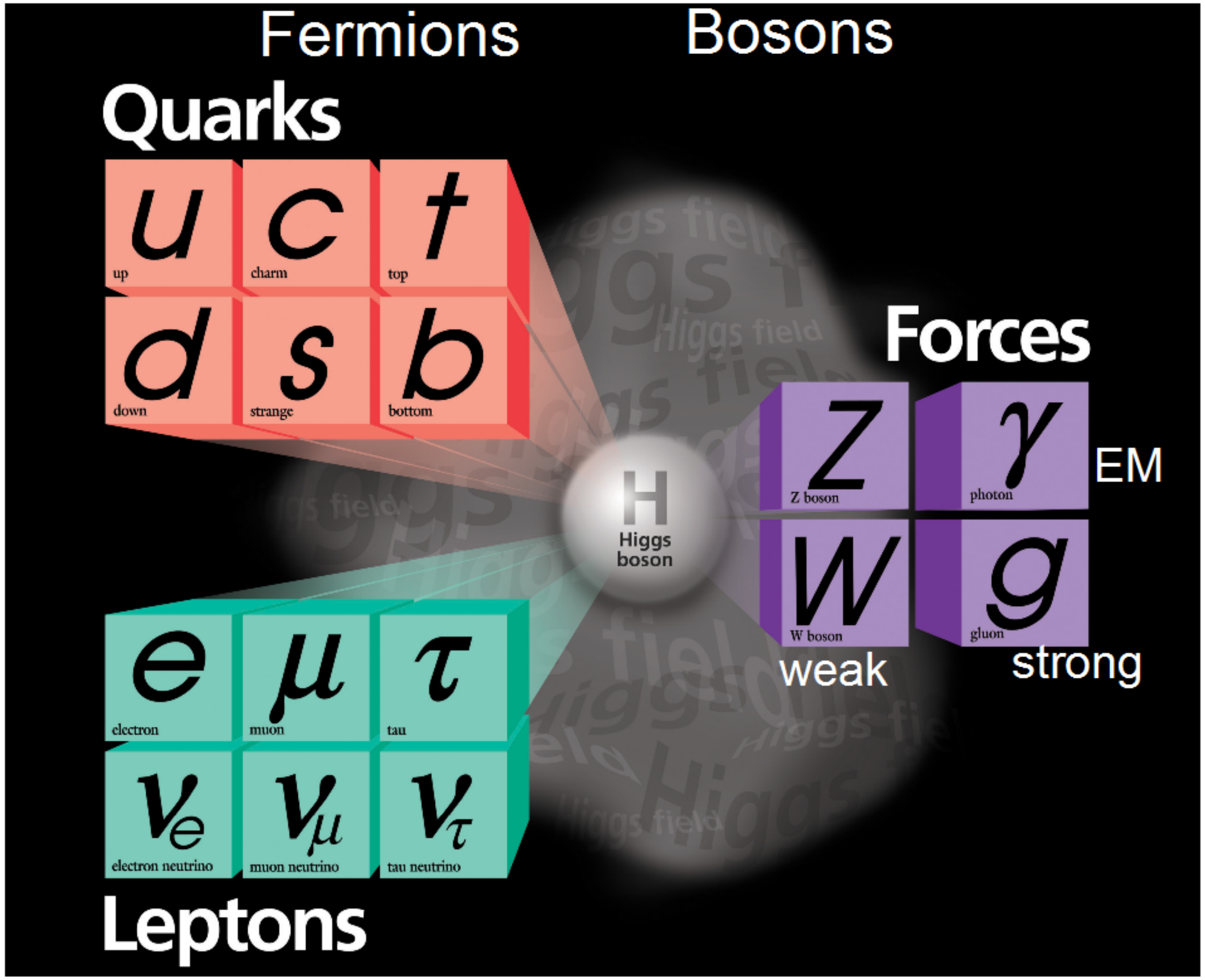
+ Weak decays of heavier quarks and leptons

Electroweak

So many phenomena, so few forces!

Can we simplify our understanding even further?
GUTs

One force in SM still to be confirmed



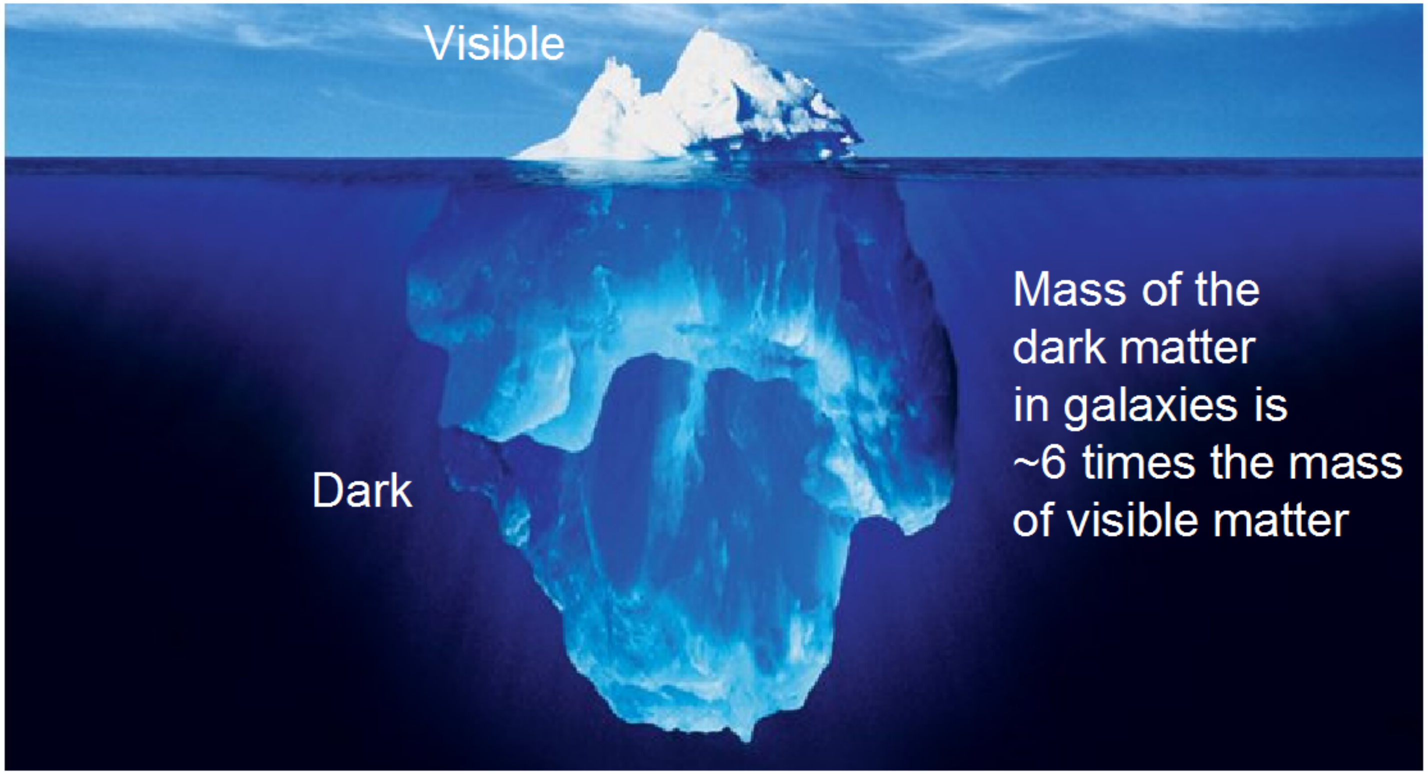
So far $M_H>114$ GeV from direct searches (LEP2).

Precision measurements in electroweak sector: $M_H=89^{+38}_{-28}$ GeV.

Higgs discovery is the main goal of LHC: pp collider with 7000 GeV x 7000 GeV

- Higgs boson breaks electroweak symmetry making W,Z bosons massive (80, 91 GeV), γ massless.
- Also gives mass to all other elementary particles.

Dark matter



Mass of the dark matter in galaxies is ~6 times the mass of visible matter

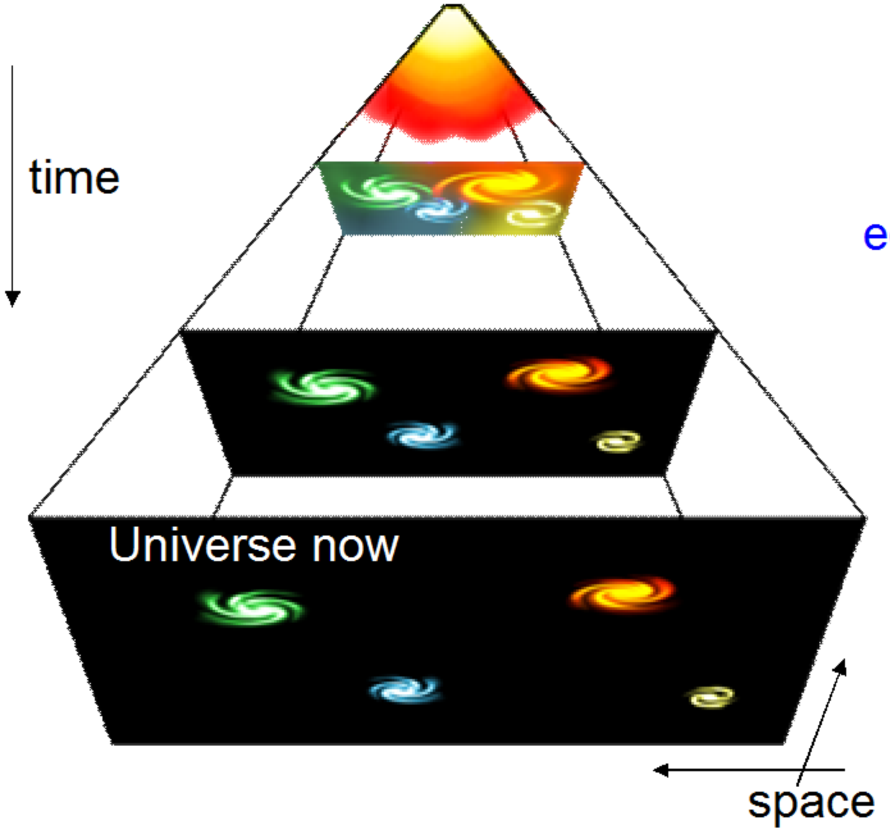
Established by studies of gravitational forces measured in galaxies.

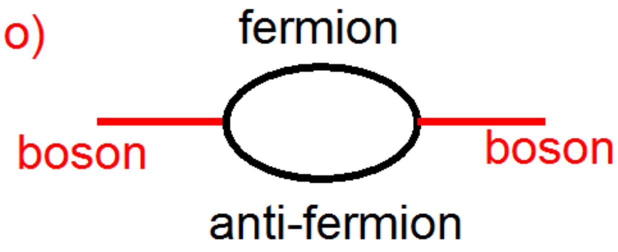
Not in SM!

- Most likely, the dark matter is due to a yet unknown stable elementary particle (which could be light or heavy), interacting with other particles by exchanging very heavy boson(s) (new force).
- There is now even a bigger problem: the Universe expands much faster than allow by our theory of gravity (Dark Energy).

Baryo-genesis

Big Bang (~14 billion years ago)





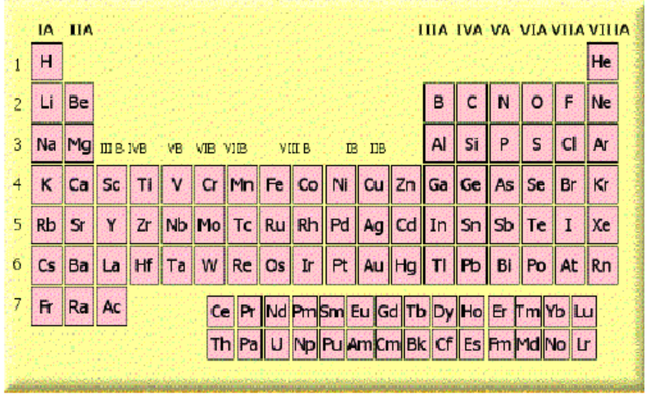
equal number of fermions and anti-fermions

only fermions survived
(anti-fermions disappeared)

- Standard Model forces don’t provide enough symmetry violation to explain disappearance of the anti-matter (we should not have been here!)
- Likely explanation: unknown forces at high energies with large (“CP-”)symmetry violation

Generation problem

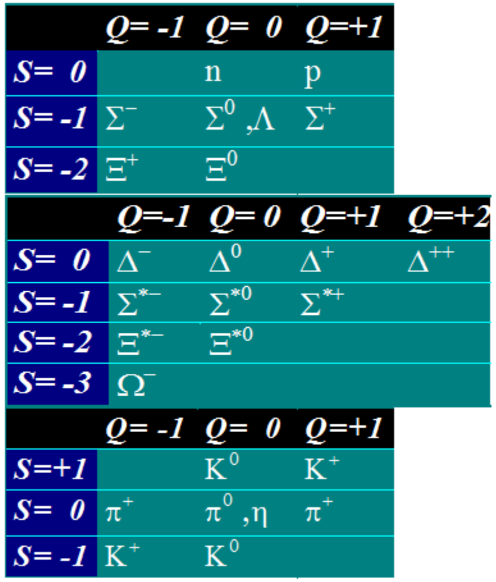
end of 19th centaury



	IA	IIA											IIIA	IVA	VA	VIA	VIIA	VIIIA
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Ac															
				Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
				Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Explained by atomic structure (nucleus + + electrons, QM and electromagnetic forces)

mid 20th centaury



	$Q=-1$	$Q=0$	$Q=+1$
$S=0$		n	p
$S=-1$	Σ^-	Σ^0 ,Λ	Σ^+
$S=-2$	Ξ^+	Ξ^0	

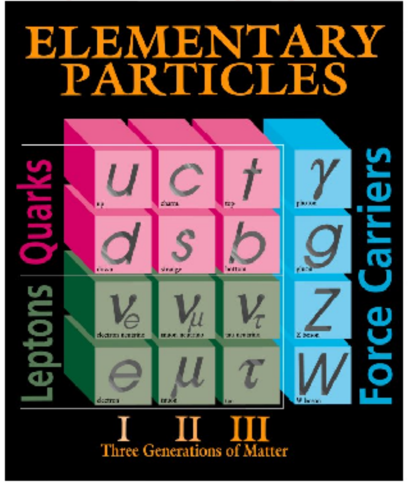
	$Q=-1$	$Q=0$	$Q=+1$	$Q=+2$
$S=0$	Δ^-	Δ^0	Δ^+	Δ^{++}
$S=-1$	Σ^{*-}	Σ^{*0}	Σ^{*+}	
$S=-2$	Ξ^{*-}	Ξ^{*0}		
$S=-3$	Ω^-			

	$Q=-1$	$Q=0$	$Q=+1$
$S=+1$		K^0	K^+
$S=0$	π^+	π^0 ,η	π^+
$S=-1$	K^+	K^0	

Explained by existence of quarks and nature of strong interactions

now

Standard Model of particle physics

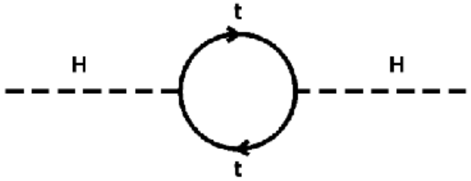


Explained by ?????

- Standard Model account for 3 generations of quarks and fermions is merely a period table!

Hierarchy Problem

- Hierarchy problem
  - SM radiative corrections to the bare Higgs mass are huge, suggesting that the effective mass itself should have been huge unless, by incredible accident (*fine tuning*), the bare mass and the corrections cancel



  - Also, why EW symmetry breaking occurs at energies lower than unification scale with gravity (Planck mass (sqrt(hc/G)~10^{19} GeV) i.e. why weak interactions are so strong compared to gravity?
- New Physics at TeV scale fixes the hierarchy problem
  - Cancellations of radiative corrections from the SM and new particles

  - The most popular extension of SM – Supersymmetry
  - Other NP scenarios possible: extra dimensions, compositeness, …

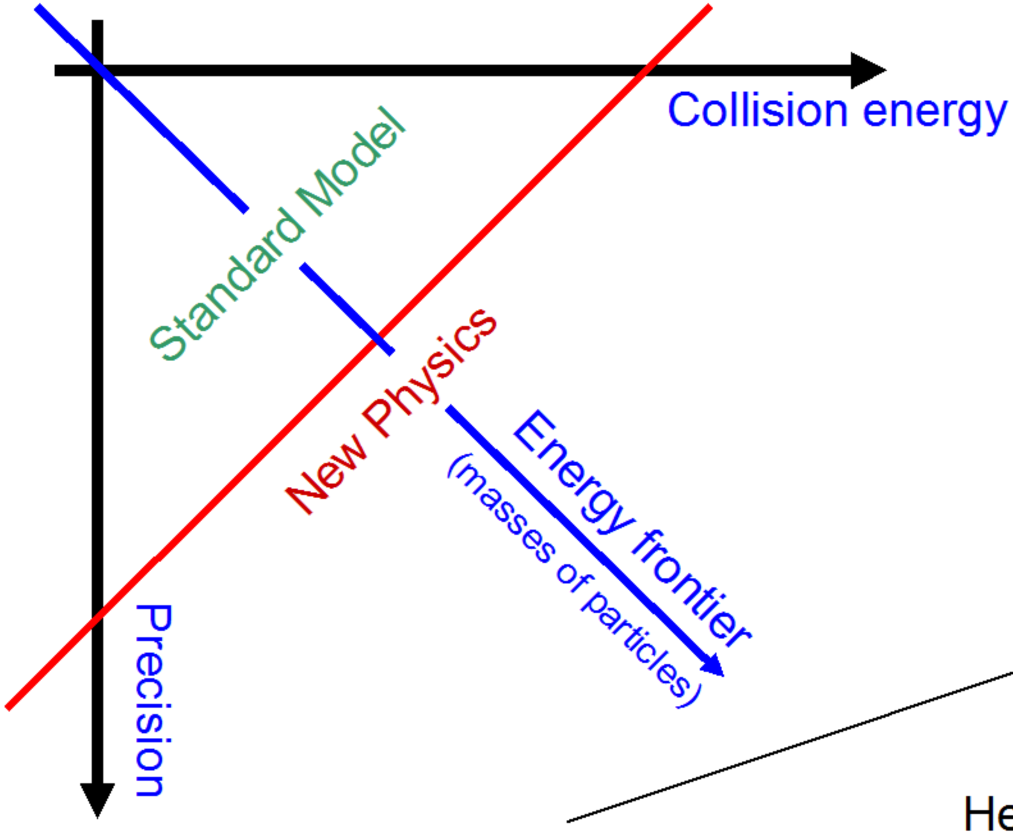
New Physics (NP)

Forces not accounted for in Standard Model exist in the nature!

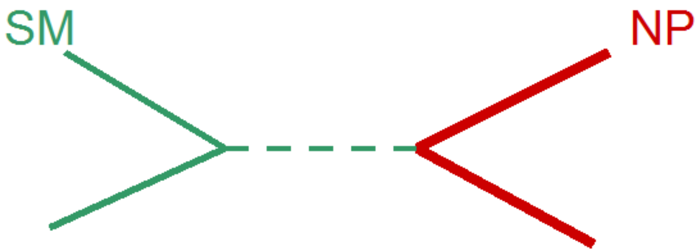
We just don't know what they are.

Need to probe higher energy scales.

Two complementary ways of advancing "energy frontier"

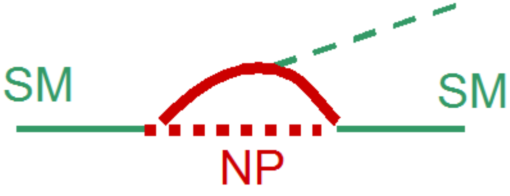


Tree diagrams, for example



Want high CM energy to exceed the production threshold

Loop diagrams, for example

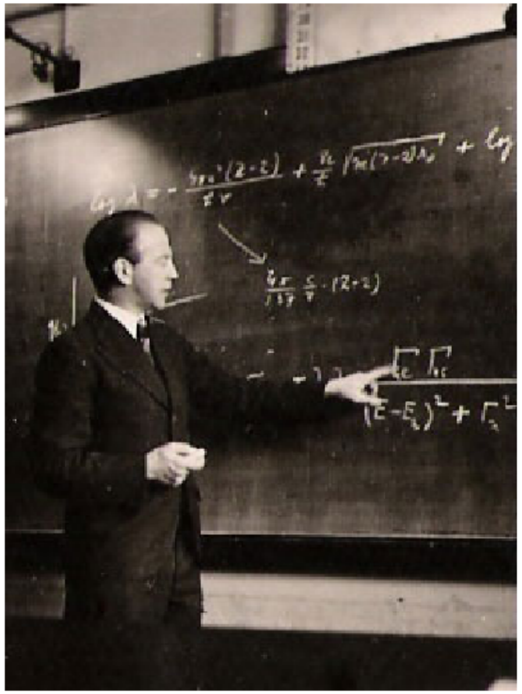


Want high precision since NP particles are highly virtual here, thus probabilities small

Heisenberg's uncertainty principle:

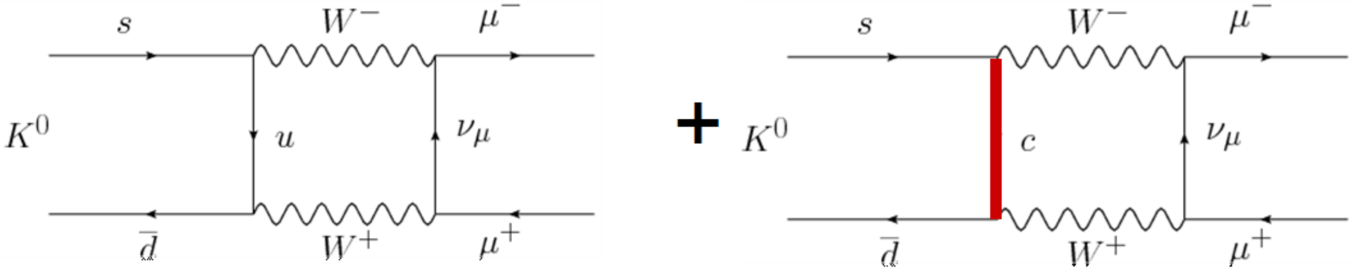
$$\Delta E \, \Delta t = \hbar/2$$

i.e. $\Delta m \, \Delta t = \hbar/2$



Loops: GIM mechanism 1970

- Standard Model at that time:
  - Known quarks **u,d,s** (eigenstates of strong interactions)
  - weak current (W) coupling **u** and **d'** = **d** $\cos\theta$ + **s** $\sin\theta$
    . (θ – Cabibbo angle: $\cos\theta=0.97$ $\sin\theta=0.22$)
- Glashow-Iliopoulos-Maiani mechanism:
  - There is also a weak current between **c** (NP!) and **s'** = - **d** $\sin\theta$ + **s** $\cos\theta$
  - Automatically no Flavor Changing Neutral Currents ($s \to d$) at tree level (desired to stay consistent with known results)
  - **c** quark in the FCNC box diagram (loop!) for $K^0_L \to \mu^+\mu^-$ decay cancels the "large" contribution from **u** quark box, and explains why not observed at 10^{-4} level



BR ~ 10^{-4}

BR « 10^{-4}

Observed in 1973
BR ~ 10^{-8}

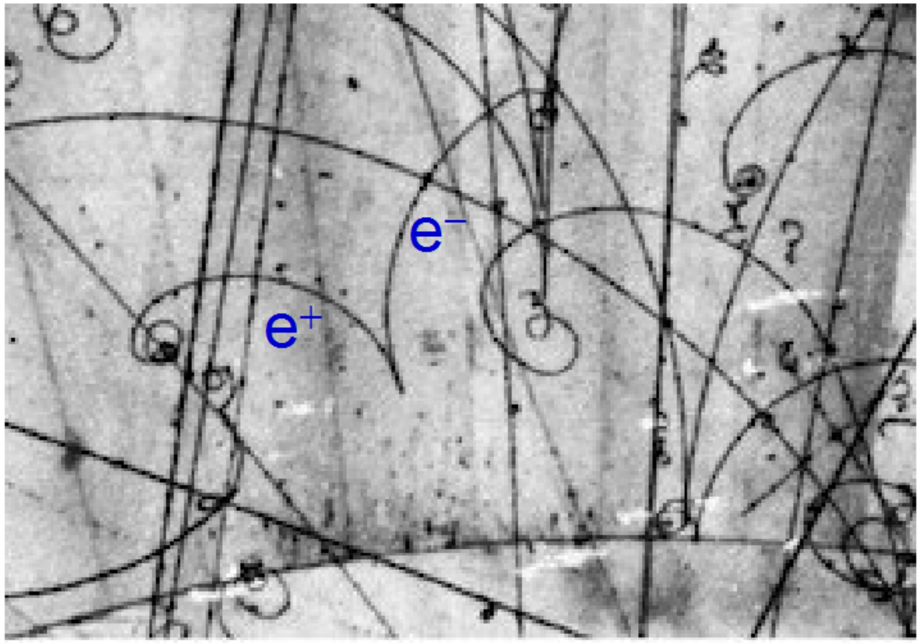
Initial non-observation of this decay meant effectively first indirect observation of c !

c quark later observed directly via tree diagram in 1974 (Ting,Richter - J/ψ)

Loops: CP violation in K^0 decays (1964)

- Standard Model at that time:
  - Electromagnetic and strong interactions **conserve** C and P symmetries
  - Weak interactions **violate** P (Wu 1956) but **conserve** CP symmetry

C symmetry



$\gamma N \rightarrow e^+e^- N$

Violation of P symmetry

"Hi, gorgeous!"

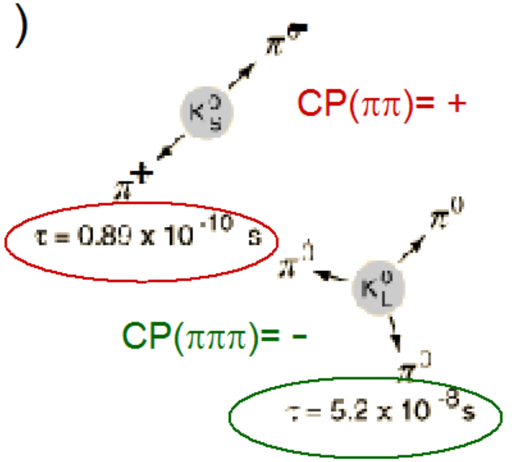
Loops: CP violation in K^0 decays

- Cronin-Fitch experiment 1964 (BNL):

$K^0 = (d\,\bar{s})$ $\overline{K^0} = (\bar{d}\,s)$

$$K_S^0 = \frac{1}{\sqrt{2}}(K^0 + \bar{K}^0)$$ CP= +

$$K_L^0 = \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0)$$ CP= -

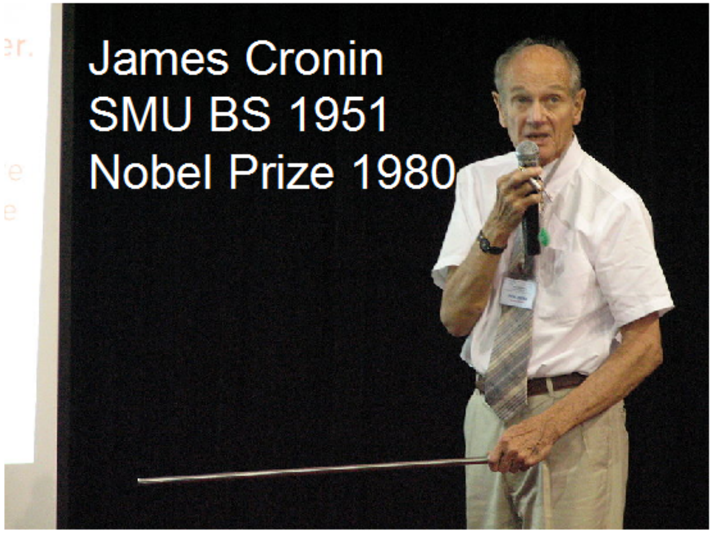


CP(ππ)= +

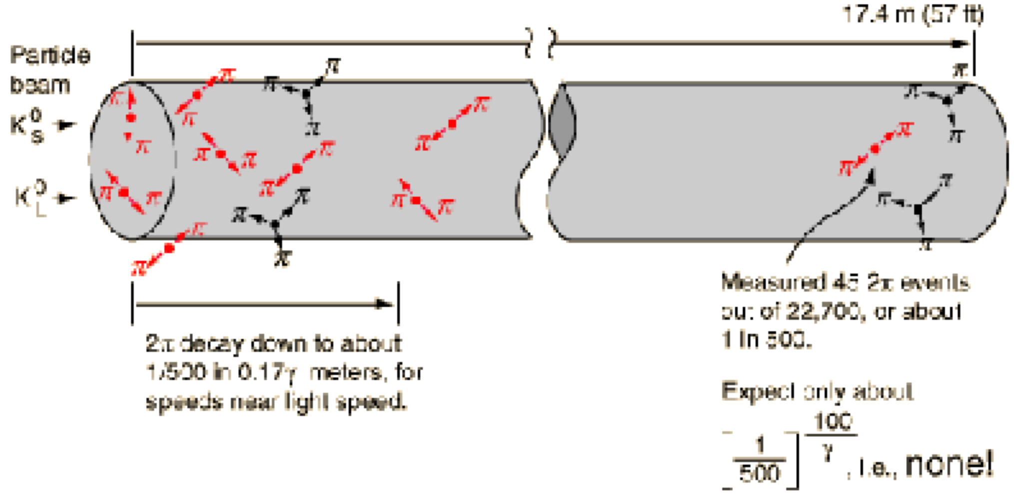
$\tau = 0.89 \times 10^{-10}$ s

CP(πππ)= -

$\tau = 5.2 \times 10^{-8}$ s



James Cronin
SMU BS 1951
Nobel Prize 1980



Measured 45 2π events out of 22,700, or about 1 in 500.

Expect only about $\left[\frac{1}{500}\right]^{\frac{100}{\gamma}}$, i.e., none!

2π decay down to about 1/500 in 0.17γ meters, for speeds near light speed.

- Decays of K^0_L mesons to ππ **violate** CP symmetry!
- Evidence for new type of force – "5th force" (NP)?

K^0_s decay quickly

K^0_L not expected to decay to ππ but it does at 0.2% level

Loops: CP violation in K^0 decays

- Kobayashi, Maskwa 1972:
  - proposed 3 quark generations to explain the Cronin-Fitch experiment without the 5th force (before the 2nd generation c quark was discovered!)

Cabibbo + GIM

$$\begin{pmatrix} u \\ c \end{pmatrix} \xleftarrow{\text{weak force}} \text{W} \rightarrow \begin{pmatrix} d' \\ s' \end{pmatrix} = V \begin{pmatrix} d \\ s \end{pmatrix}$$

+ Kobayashi,Maskawa

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix} \xleftarrow{\text{weak force}} \text{W} \rightarrow \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V \begin{pmatrix} d \\ s \\ b \end{pmatrix} \leftarrow \text{NP!}$$

To conserve probability the quark mixing matrix V must be unitary:

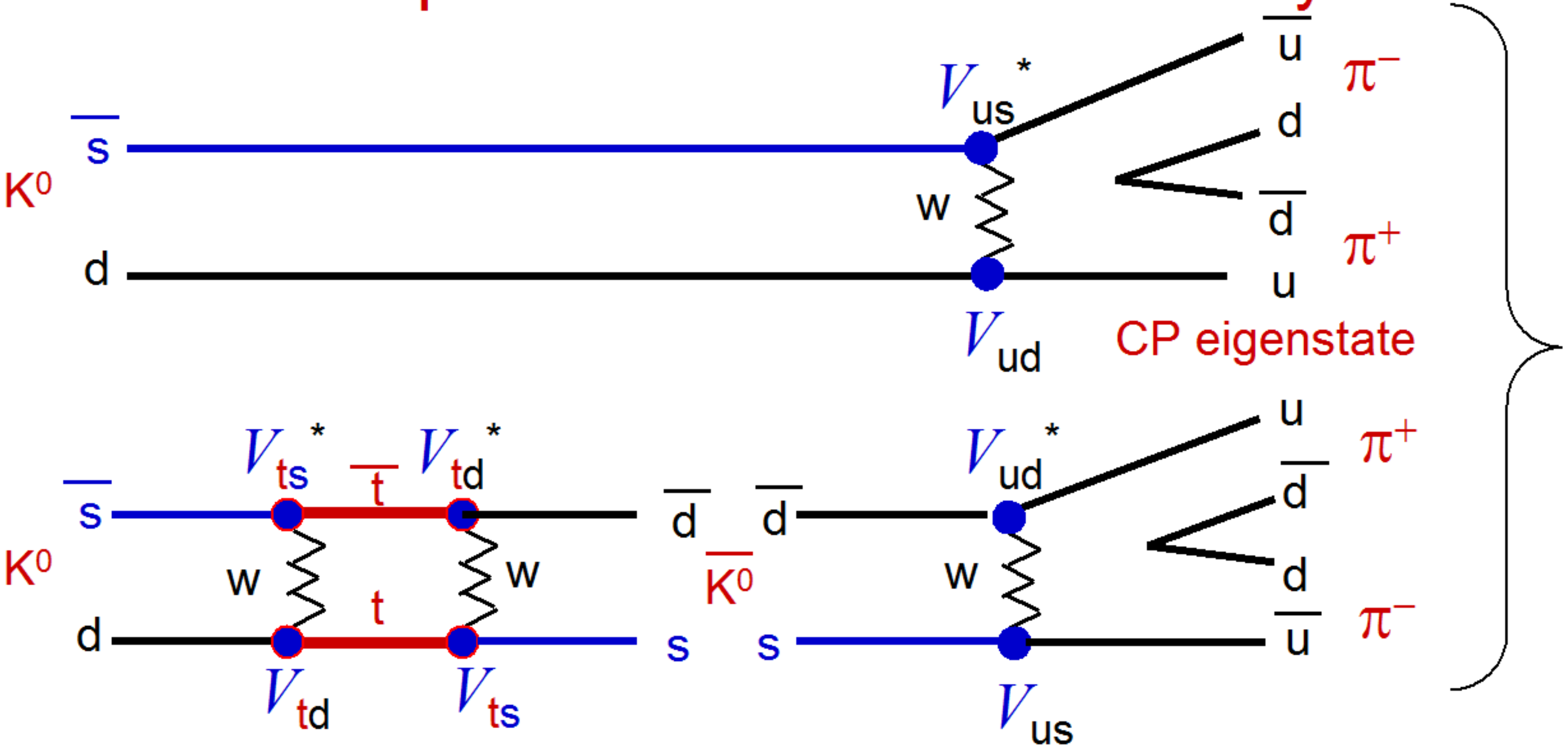
$$VV^\dagger = V^\dagger V = 1$$

V has **1 free parameter**:
rotation angle between flavors - Cabibbo angle!
All V_{ji} elements can be made real.

V has **4 free parameter**:
e.g. 3 rotation angles (Euler angles)
+ 4th must be in a complex phase.

  - the complex phases of V_{ji} not observable unless two amplitudes (i.e. processes) interfere

Loops: CP violation in K^0 decays



Impossible to tell which happened - the two processes **interfere**

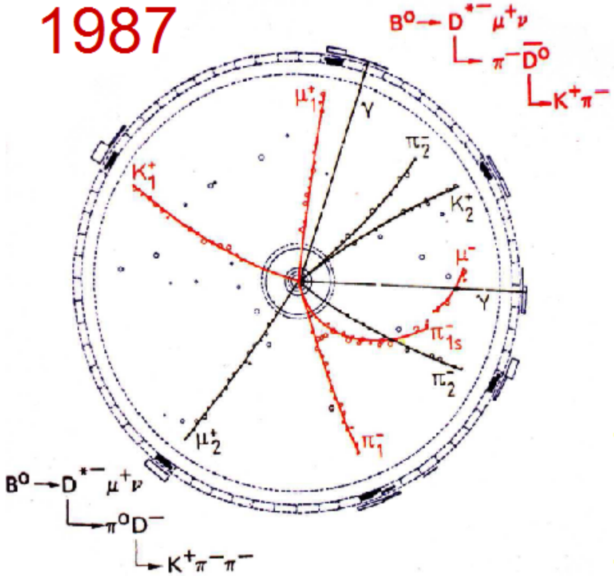
Box diagram responsible for K^0-$\overline{K^0}$ mixing

(mixing + decay: “indirect” CPV)

- The interference term produces CP violation and depends on the complex phase of the mixing diagram (ϕ_M) minus phase of decay diagram ($\phi_A \approx 0$)
- **Observation of CP violation in K^0 decays to $\pi\pi$ was effectively the first indirect observation of t quark**
- t quark observed directly via tree diagram in 1995 (CDF&D0); b quark in 1977 (Lederman Υ)

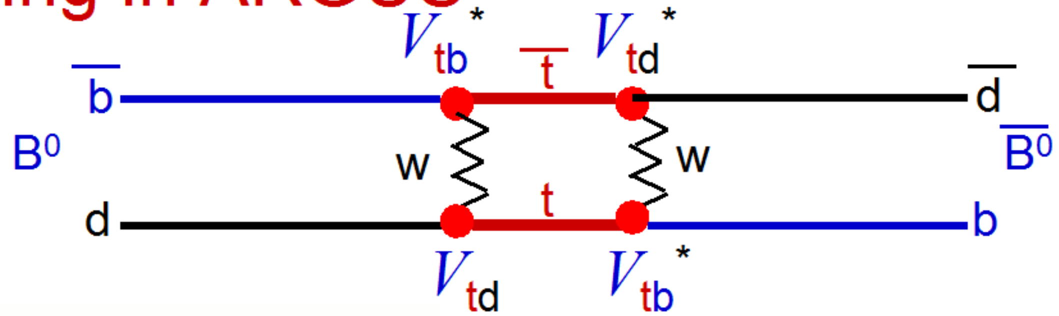
Loops: B^0-$\overline{B^0}$ Mixing in ARGUS

1987



DESY: DORIS E_{CM}=10 GeV

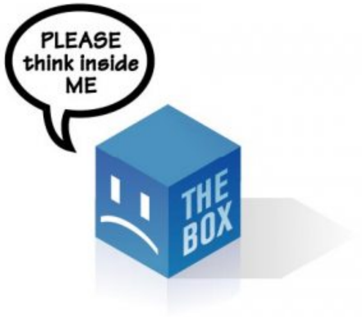
$e^+e^- \to \Upsilon(4S) \to B^0\overline{B^0}$



$$r = \frac{N(B^0B^0) + N(\overline{B}^0\overline{B}^0)}{N(B^0\overline{B}^0)} = 0.21 \pm 0.08$$

- **Big surprise** - expected to be small before the ARGUS measurement
- Sensitive to $|V_{td}|$ and top quark mass $r \sim m_t^4$
- From the ARGUS measurement $m_t > 50$ GeV contrary to the believes of that time.

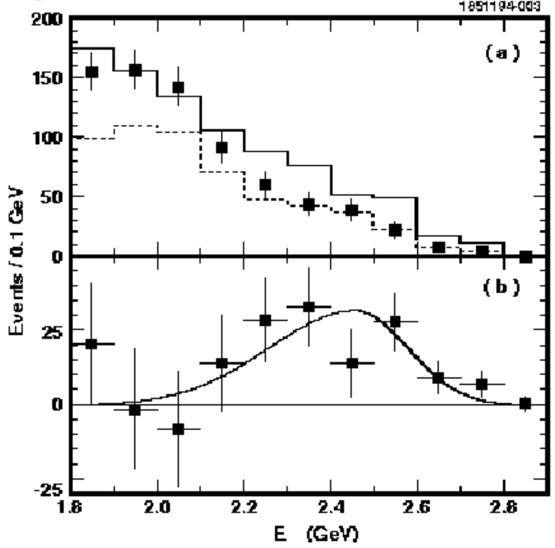
- In these times at DESY DORIS was a sideshow to higher energy PETRA!
  - e^+e^- colliders which failed to find top via direct searches:
    - PETRA (1978-90 2x17GeV), PEP (1980-90 2x14GeV), TRISTAN(1987-90 2x32 GeV), SLC (2x50GeV), LEP(1989-02 2x90GeV)
  - PEP & TRISTAN were later (~2000) rebuilt to run at $\Upsilon(4S)$ and search for New Physics in loops! **Is top&W the only thing in the box?**
- t finally discovered at Tevatron (FNAL) by CDF&D0 in 1995: m_t=171 GeV

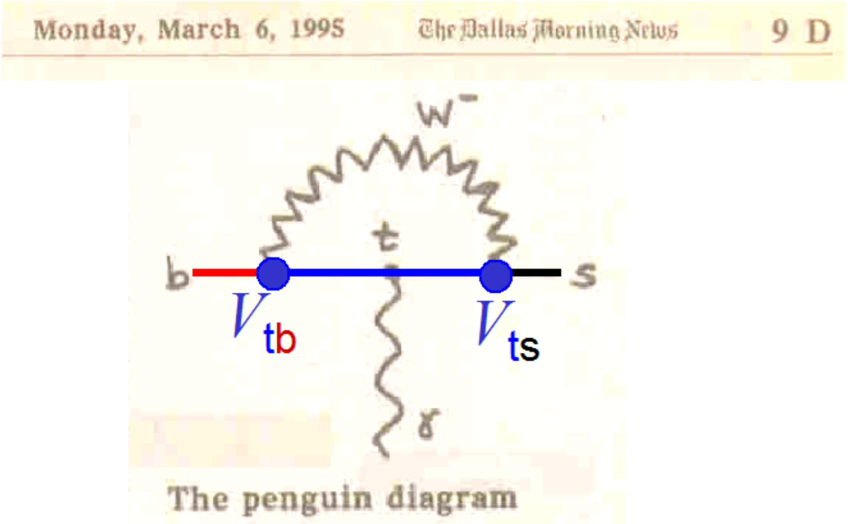


Penguin loops at CLEO-II

- First measurement of inclusive BR($b \rightarrow s\gamma$) by T.S. at SMU, 1994.
- Later also BaBar & Belle

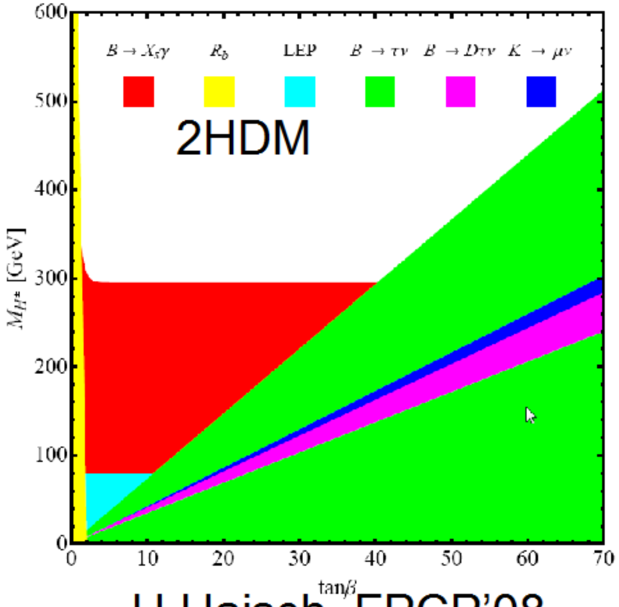
PRL,74,2885,1995
797 citations (the most among CLEO papers)




Monday, March 6, 1995 The Dallas Morning News 9 D

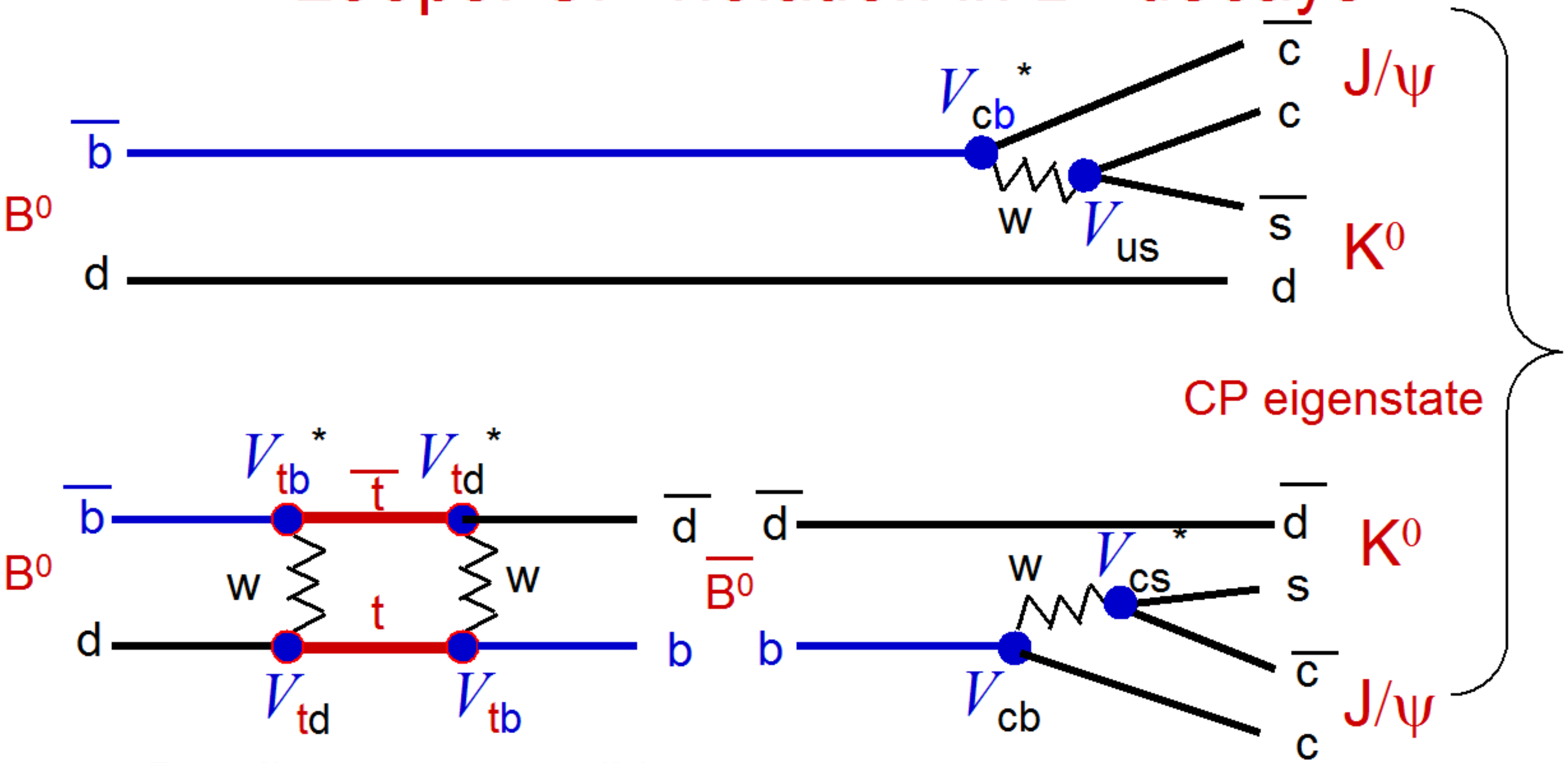
The penguin diagram

- Sensitive to $|V_{ts}|$ and NP
- One of the most elaborate SM calculations (NNLO)
- Agreement with the SM severely constrains many NP models: 2HDM, SUSY, LRSM, etc.



U.Haisch, FPCP'08

Loops: CP violation in B^0 decays



Impossible to tell which happened - the two processes **interfere**

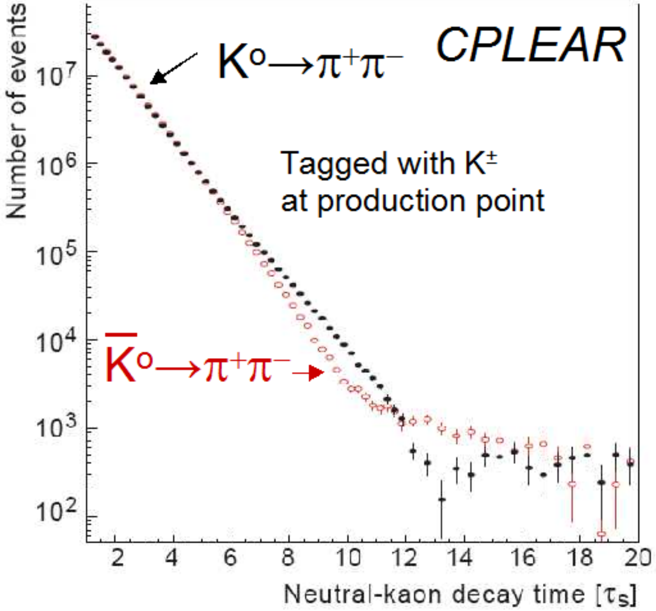
Box diagram responsible for B^0-$\overline{B^0}$ mixing

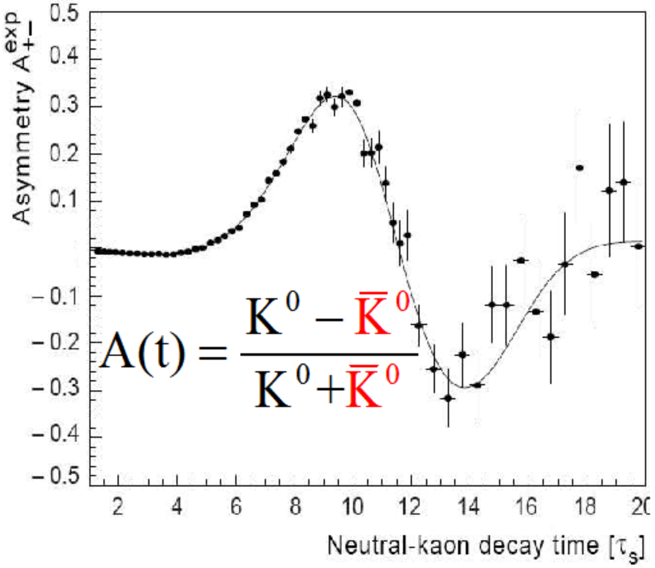
(mixing + decay: “indirect” CPV)

- Sizeable mixing frequency made this measurement feasible
- Because of rather short B^0 lifetime it was necessary to build asymmetric e^+e^- colliders, to make them live longer in the lab frame (PEP II: BaBar, KEK-B: Belle)

Indirect CPV in B^0 decays

Modern version of Cronin-Fitch

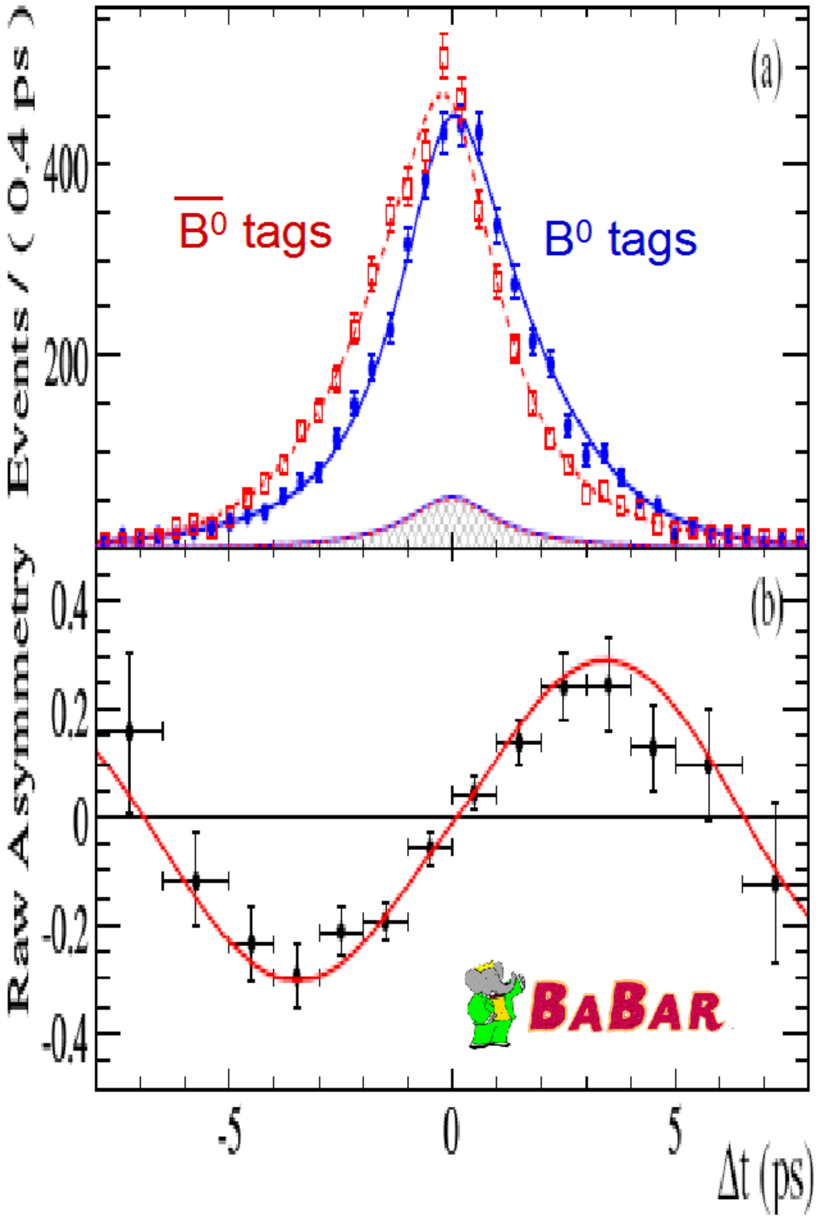




$$A(t) = \frac{K^0 - \overline{K}^0}{K^0 + \overline{K}^0}$$

For B's measure Δt between B^0 & $\overline{B}^0$ decay in $e^+e^- \to B^0\overline{B}^0$

$B^o \to J/\psi\ K^0_S$ + similar



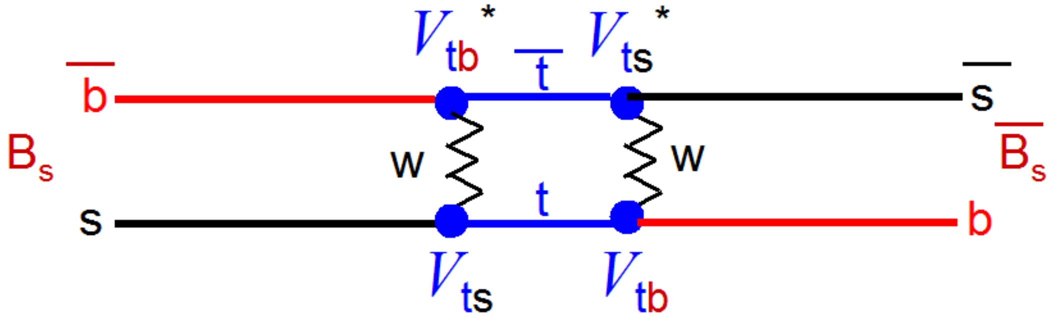
$\Delta\Gamma = \Gamma_s - \Gamma_L$

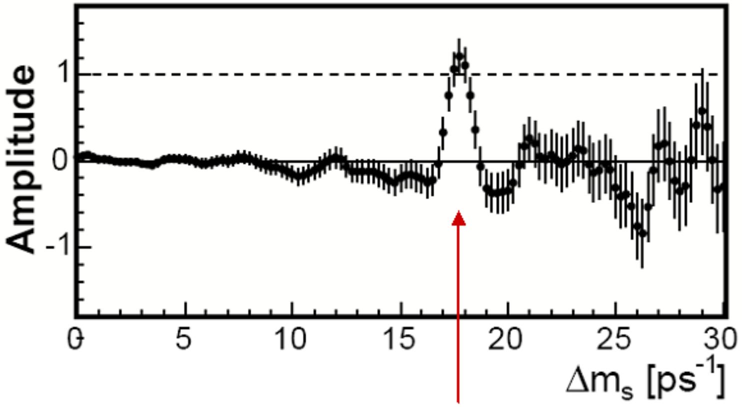
← large

very small →

Bs mixing

- In e^+e^- B_s produced only above $\Upsilon(4S)$. Production cross-section much smaller than for B^0,$B^\pm$ at the $\Upsilon(4S)$ peak.
- Large numbers of B_s's produced at Tevatron (and LHC) CDF measured B_s-$\overline{B}_s$ mixing frequency in 2006





$\Delta m = M_L - M_s$

frequency of oscillations sensitive to $|V_{ts}|$

CKM – emerging picture

- In SM the matrix must be unitary: 4 independent parameters to describe it (many choices how to define them)
- Wolfenstein's choice (1983) most convenient to depict its measured structure

$$\begin{array}{cc} & \begin{array}{ccc} \mathrm{d} & \qquad\qquad \mathrm{s} & \qquad\qquad \mathrm{b} \end{array} \\ \begin{array}{c} \mathrm{u} \\ \mathrm{c} \\ \mathrm{t} \end{array} & V=\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}+\delta V \end{array}$$

Good to λ^3~1%

$\lambda=0.226\pm0.001$ ($\sin\theta_C$)

$A=0.81\pm0.02$

ρ,η see next

$$\delta V=\begin{pmatrix} 0 & 0 & 0 \\ -iA^2\lambda^5\eta & 0 & 0 \\ A\lambda^5(\rho+i\eta)/2 & -A\lambda^4(1/2-\rho-i\eta) & 0 \end{pmatrix}$$

Complex phase η mostly in V_{td}, V_{ub} then a bit in V_{ts}

$\lambda^0=1$

$\lambda^1=0.23$

$\lambda^2=0.051$

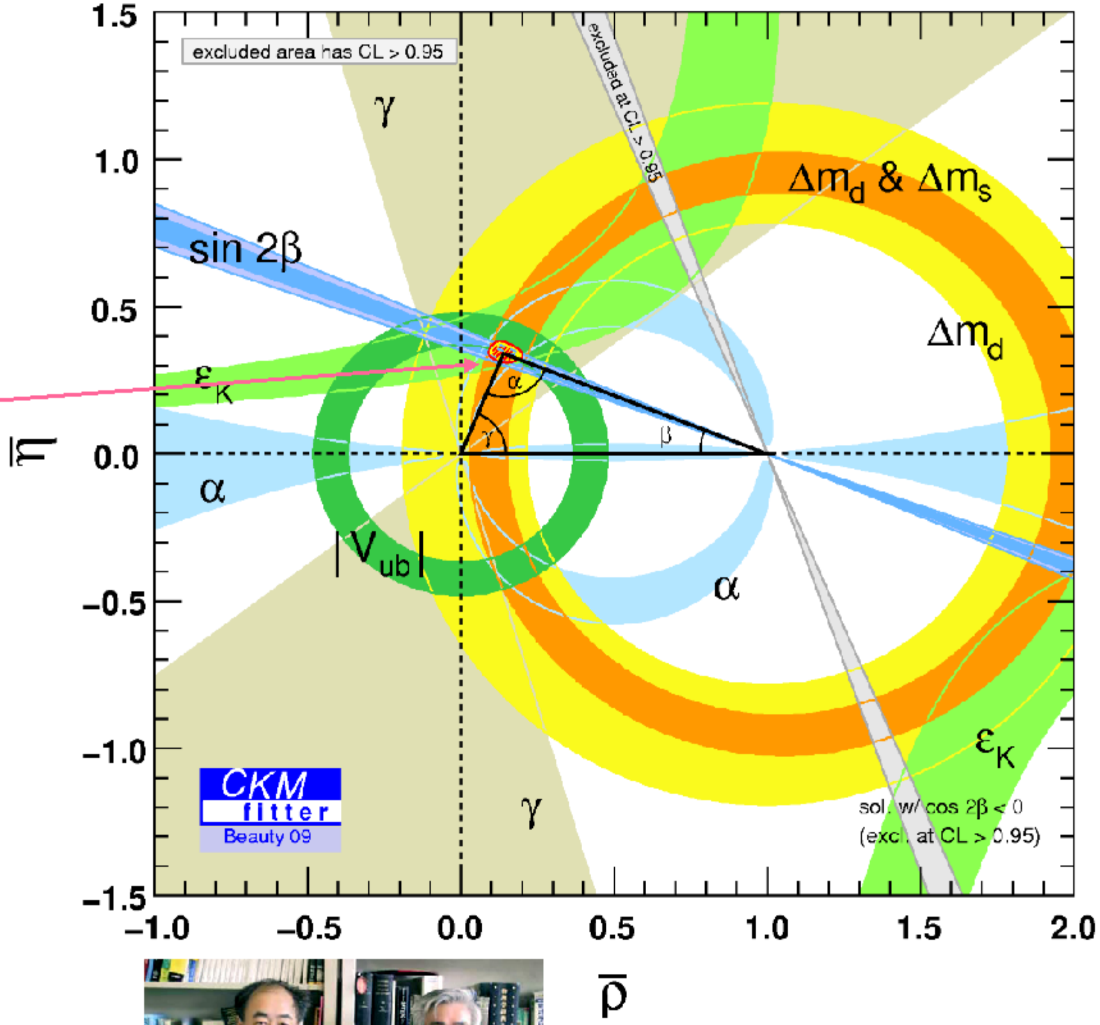
$\lambda^3=0.012$

$\lambda^4=0.0026$

$\lambda^5=0.0006$

Test of SM via CKM unitarity

- CKM Fitter results using CP violation in J/ψ K_S, $\rho^+\rho^-$, DK^-, K_L, & V_{ub}, V_{cb} & Δm_q
- Similar situation using UTFIT
- The overlap region includes CL>95%
- The fact that the overlap region exists means all measurements so far are consistent with the SM
- NP scenarios must now fit into the narrow overlap region

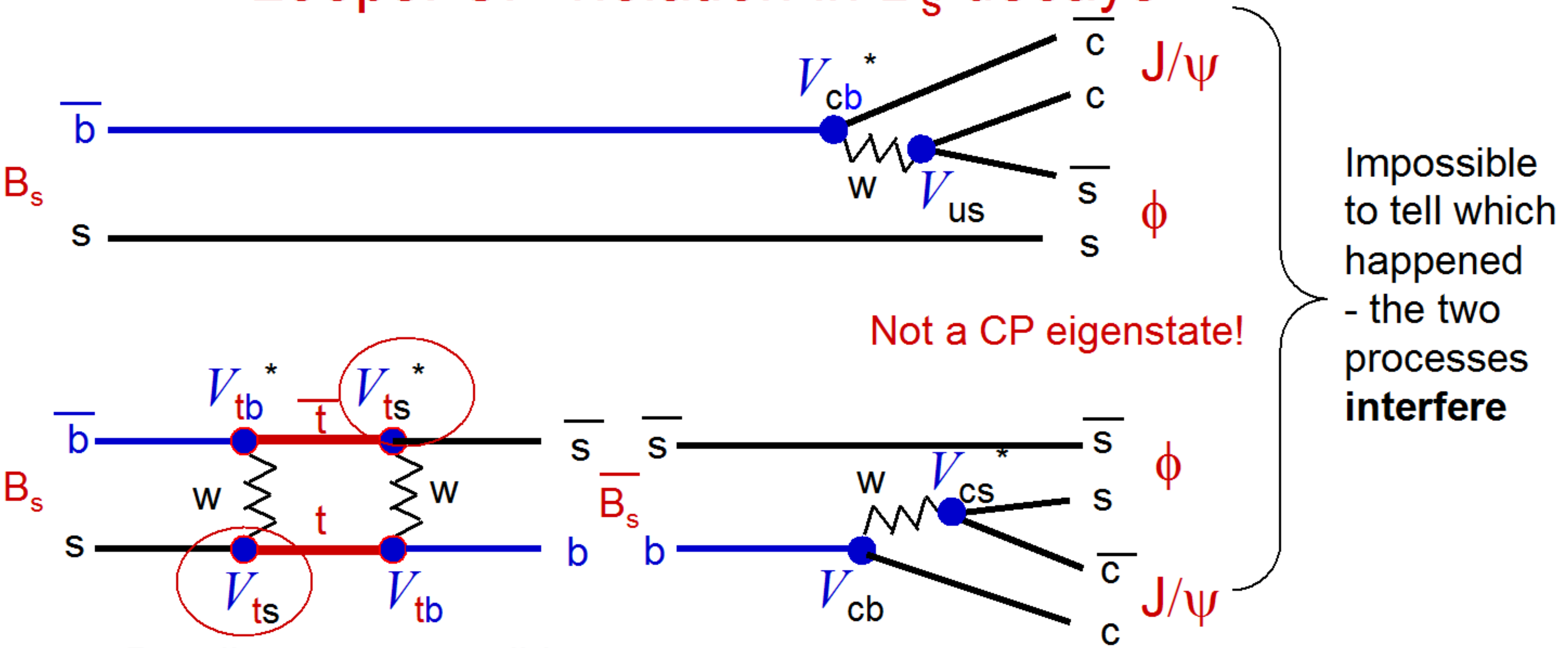


Kobayashi & Maskawa
Nobel Prize 2008

Note: $\bar\rho = \rho(1-\lambda^2/2)$

$\bar\eta = \eta(1-\lambda^2/2)$

Loops: CP violation in B_s decays



Not a CP eigenstate!

Impossible to tell which happened - the two processes **interfere**

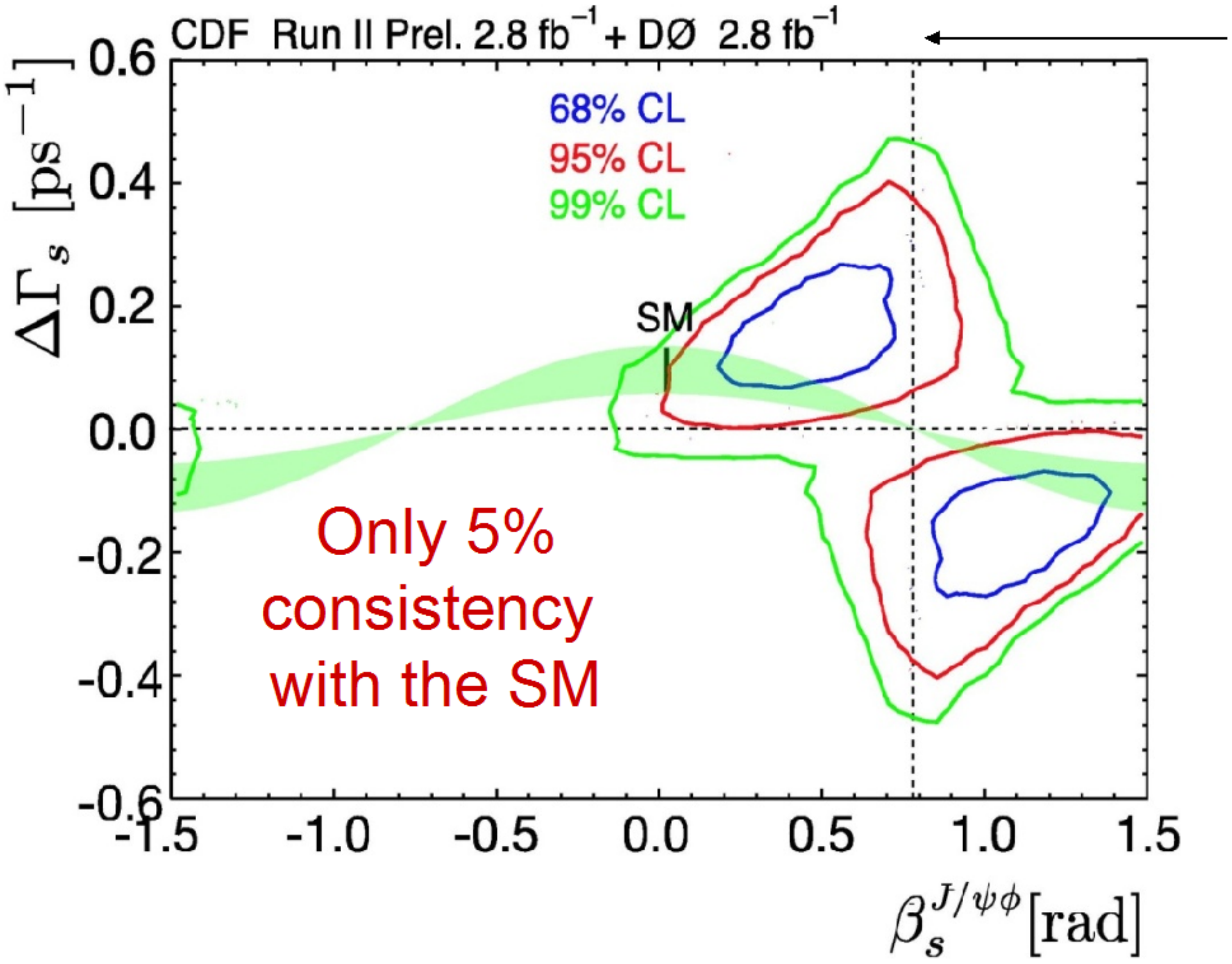
Box diagram responsible for B^0-$\overline{B^0}$ mixing

(mixing + decay: “indirect” CPV)

- The only non-negligible CKM phase is from V_{ts} ($\sim\lambda^4$) – very small. Excellent place to look for phases from NP particles!
- Different helicity amplitudes lead to different CP values of the final state. Analysis of the angular correlation is performed to deconvolute.

Phase of B_s mixing diagram

- The SM prediction of the phase depends also on $\Delta\Gamma$. Measure both from the time evolution.



$= -\phi_s/2$

Only 5% consistency with the SM

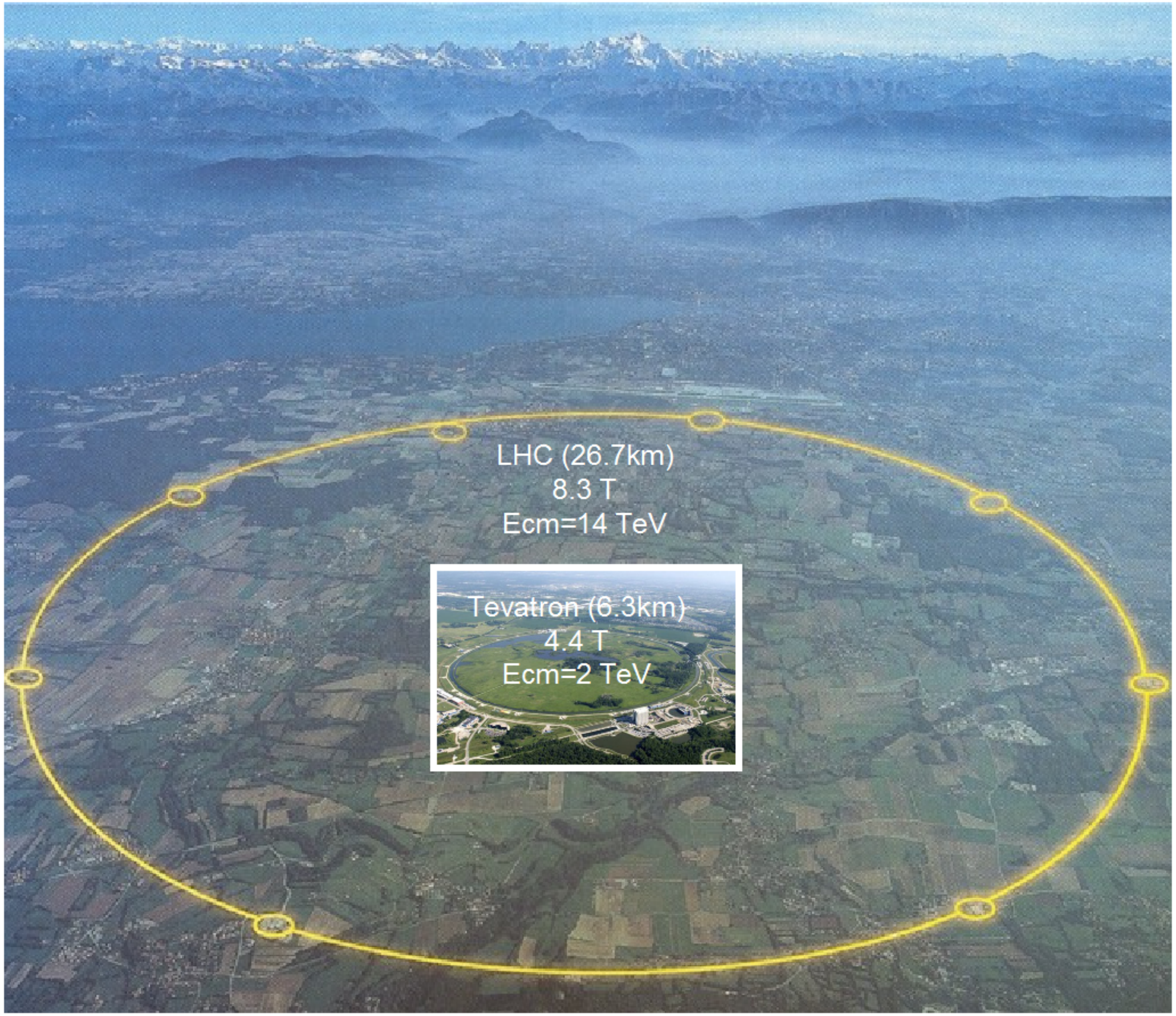
Pretty sizable integrated luminosity for hadron collider!

Would be good to shrink the experimental errors **a lot**.

* but only in Europe

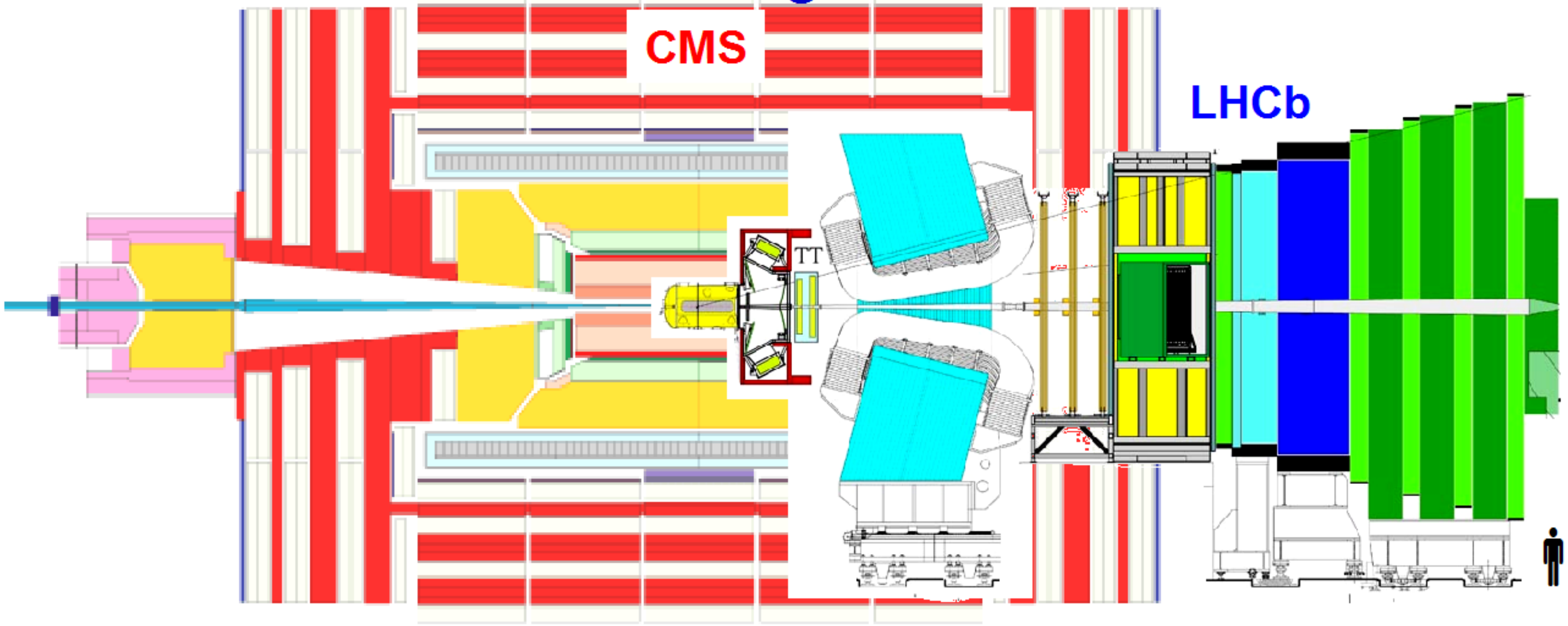
~~(BTeV)~~

Increase $b\bar{b}$ cross-section

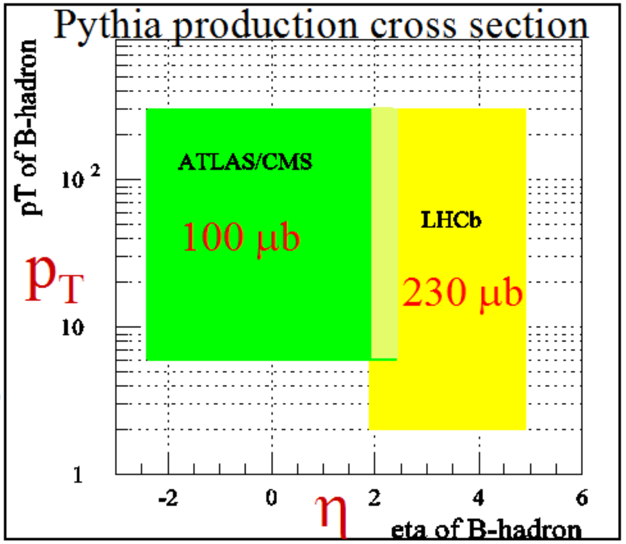


- Gain a factor of ~5 in cross section at 14 TeV
- Less (~3) for initial 2 years of running, since Ecm=7 TeV
- Also gain in $b\bar{b}$ being a larger fraction of total inelastic cross-section:
  - LHC ~1% vs Tevatron ~0.3%
  - Important especially for **triggering**

Use forward region

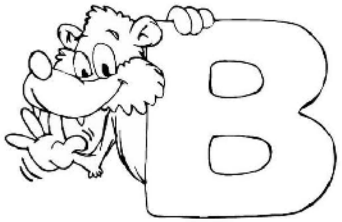


- Capture both b and $\bar{b}$ in **affordable** (75M CHF) solid angle (at $\mathcal{L}=2\times10^{32}/\mathrm{cm}^2\mathrm{s}$, we get 10^{12} B hadrons in 10^7 sec; 20kHz)
- Single arm to have space for more detector layers: Particle ID (K/π/p separation) tagging efficiency
- Large forward momentum of B daughters:
  - Can detect/trigger on muons with much lower Pt thresholds
  - Smaller multiple scattering in vertex detector:
    - Helps triggering on displaced vertices (B lifetime)
    - Excellent proper time resolution (40 fs)



B trigger happy!

Triggers
at
L ~ 2 10^{32} cm^{-2}s^{-1}



	CDF	LHCb
Bunch crossing rate	**2 350 kHz**	**40 000 kHz**
Bunch spacing	396 ns	25 ns
Interactions / crossing	***(at 3 10^{32}) 10.0***	**(at 2 10^{32}) 1.2**
Stage 1	L1	L0
Output rate	**30 kHz**	**1 000 kHz**
Latency	5.5 μs	4.0 μs
Type	Hardware (tracks,mu,ecal)	Hardware (hcal,mu,ecal)
Single μ	Pt>4 GeV	Pt>1.3 GeV
Dimoun	Pt1>2.0 & Pt2>2.0 GeV	Pt1+Pt2>1.3 GeV
Stage 2	L2	HLT1
Output rate	**1 kHz**	**30 kHz**
Execution time	20 μs	~5 000 μs
Type	Hardware (tracks, IP)	Computer Farm (tracks,IP)
Stage 3	L3	HLT2
Output rate	**150 Hz**	**2 000 Hz**
Event size	250 kB	35 kB
Type	Computer farm	Computer Farm (full event reco)
Fraction of bandwidth for heavy flavors	small	all

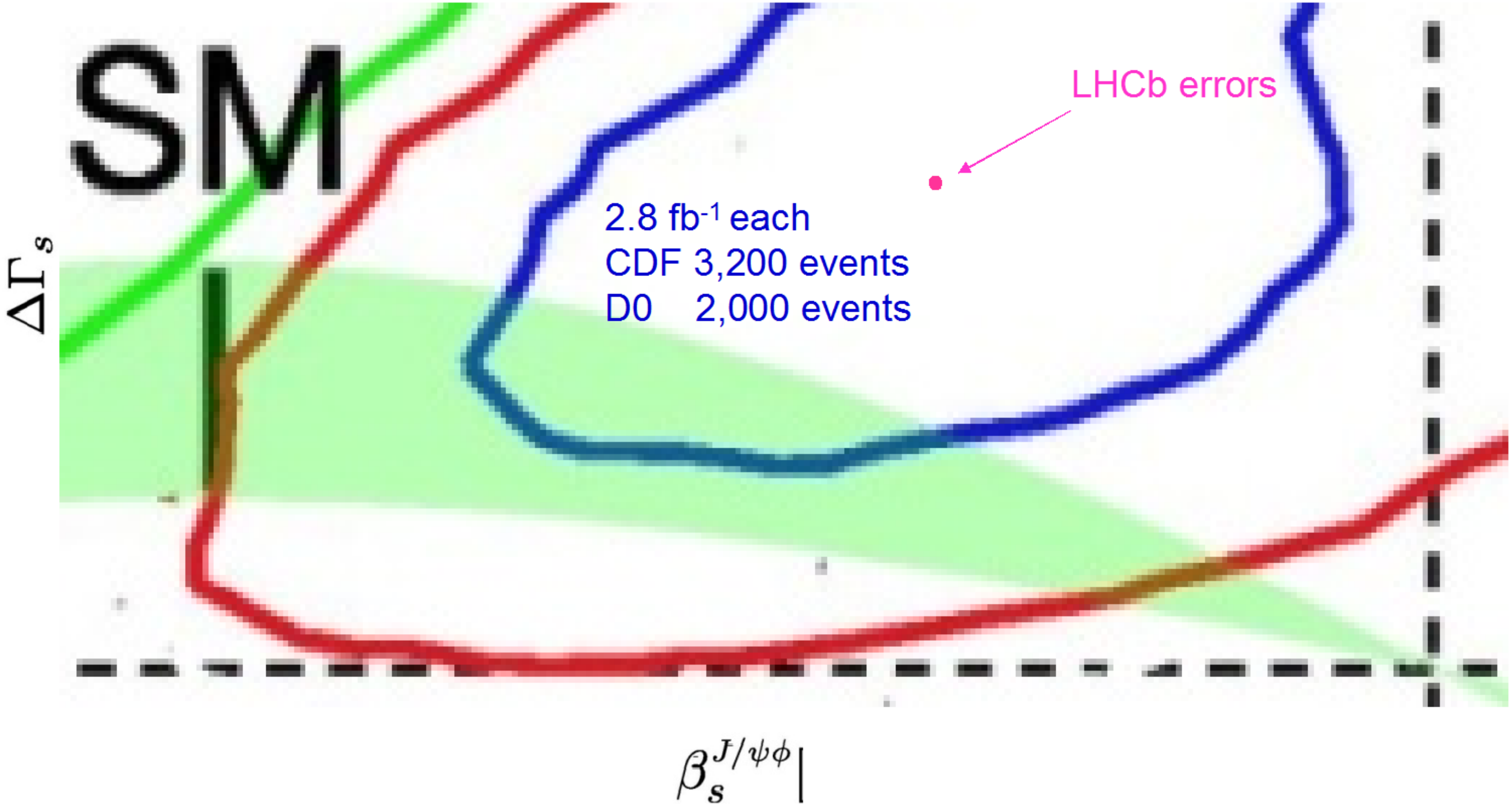
- LHCb is the first dedicated hadron collider b-experiment

BB gun

B hunting

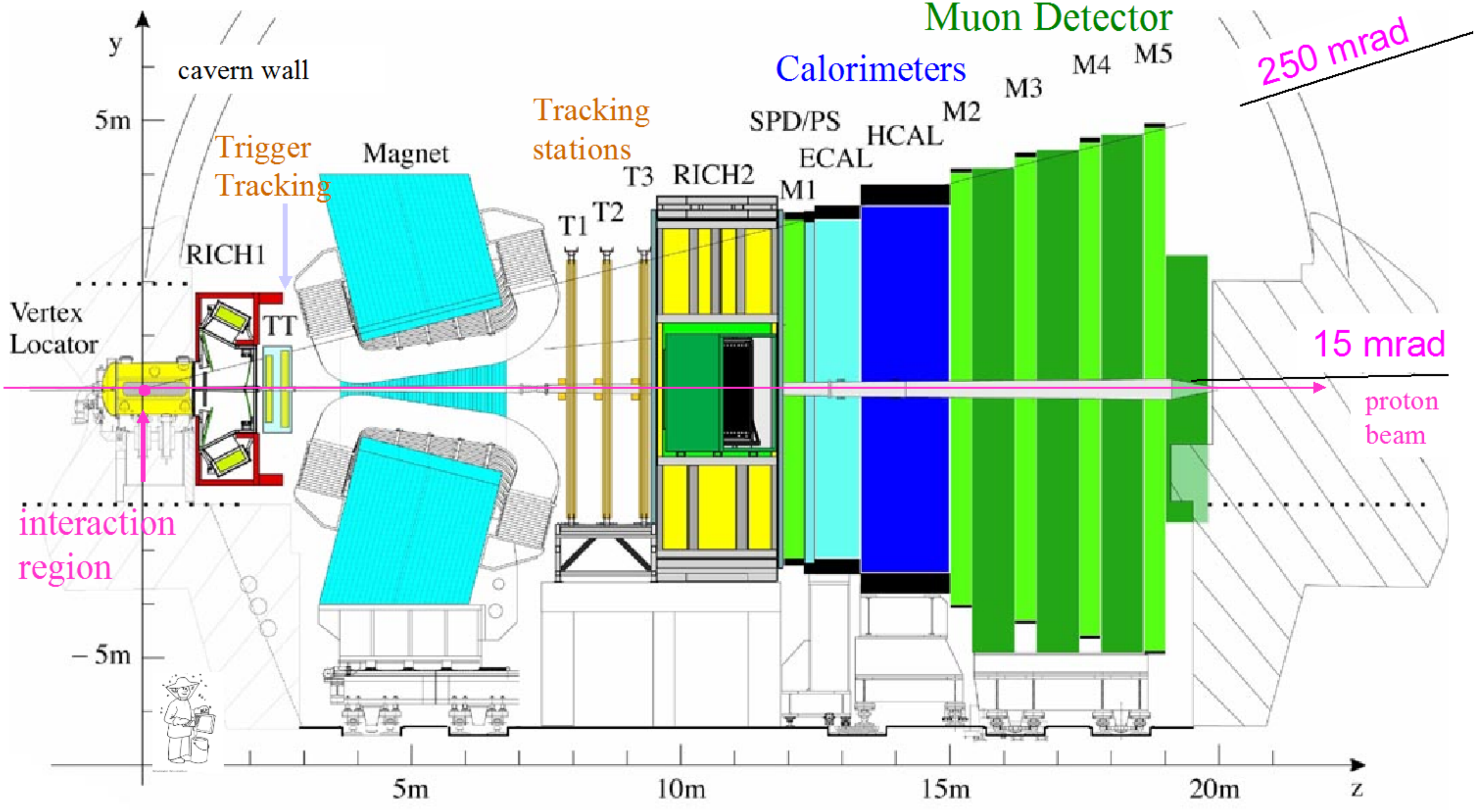
LHCb sensitivity to β_s

- LHCb will get 131,000 such events in 2 fb^{-1}. Projected errors are ±0.03 rad in $2\beta_s$ & ±0.013 in $\Delta\Gamma_s/\Gamma_s$



2.8 fb^{-1} each
CDF 3,200 events
D0 2,000 events

The LHCb Detector



Vertexing

Tracking

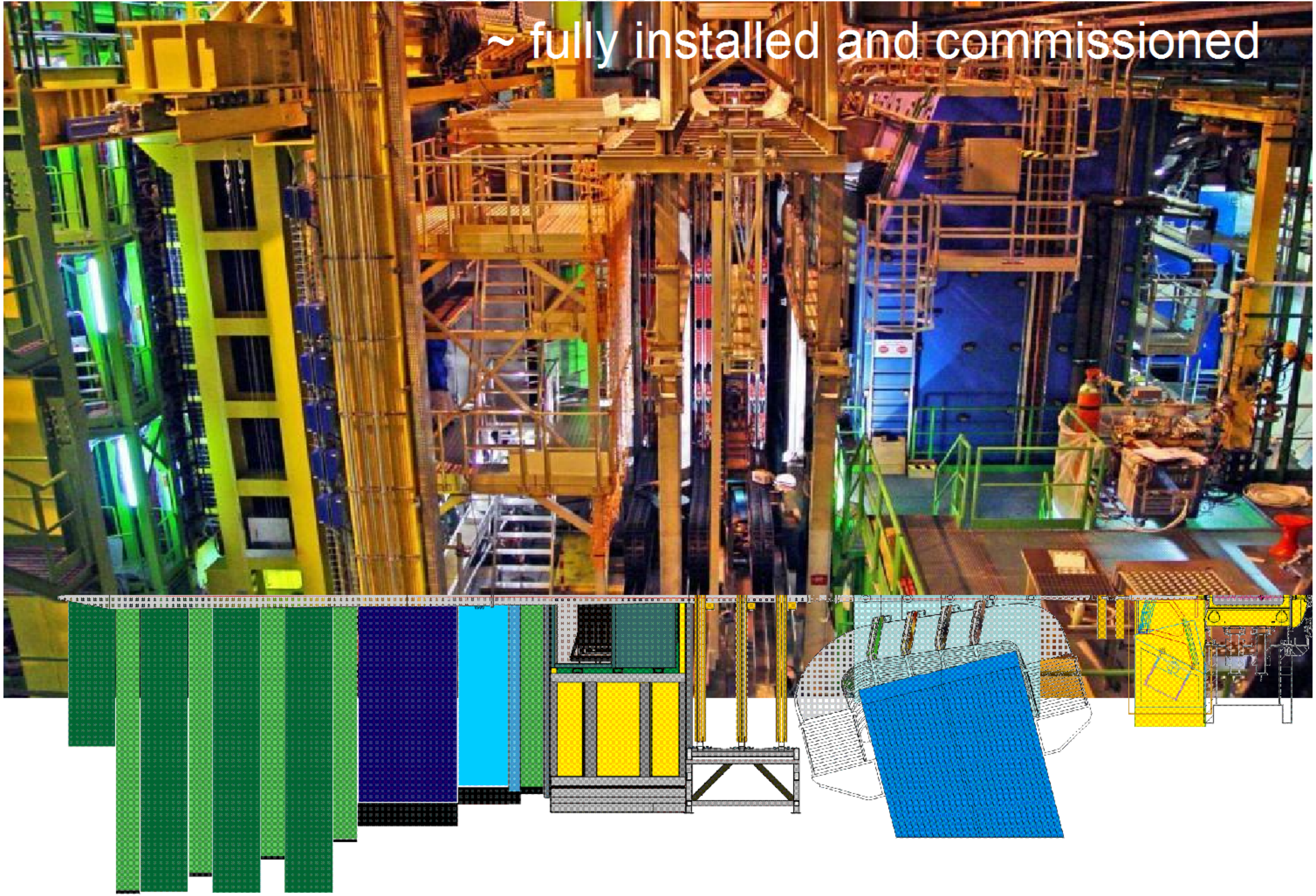
e/γ

μ

Hadron triggering

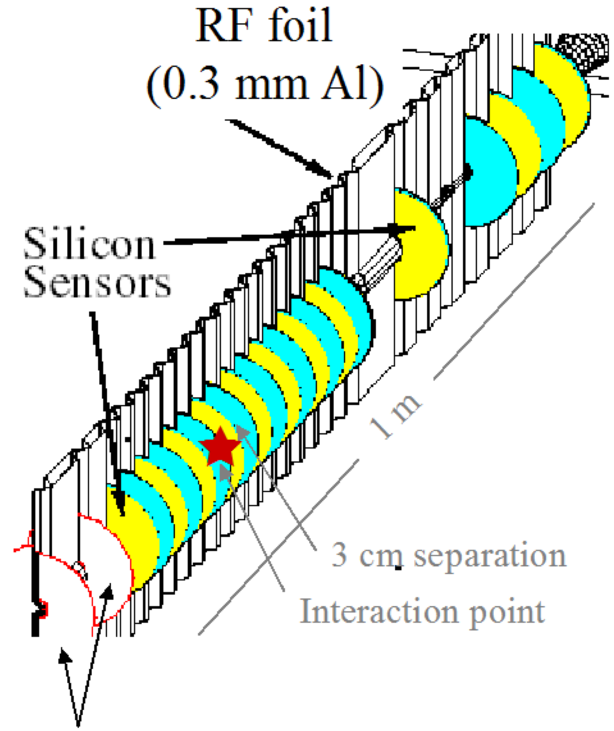
K/π/p Identification

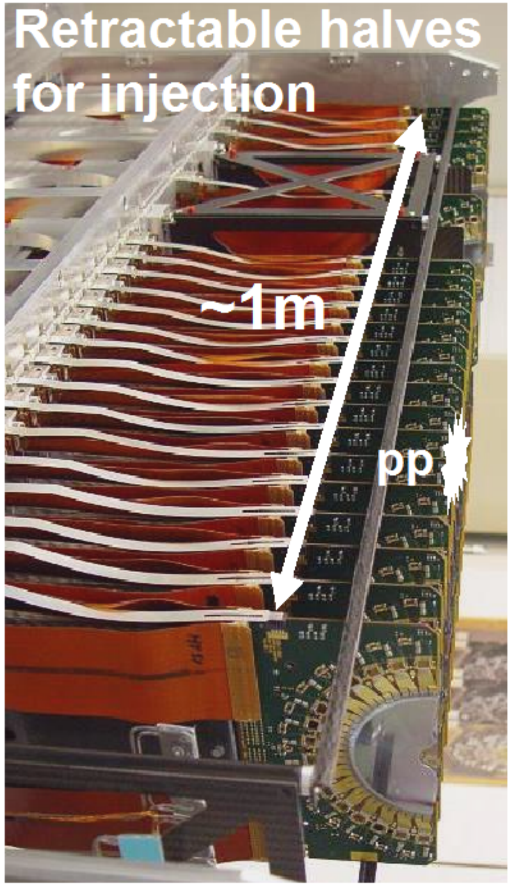
LHCb Detector Status

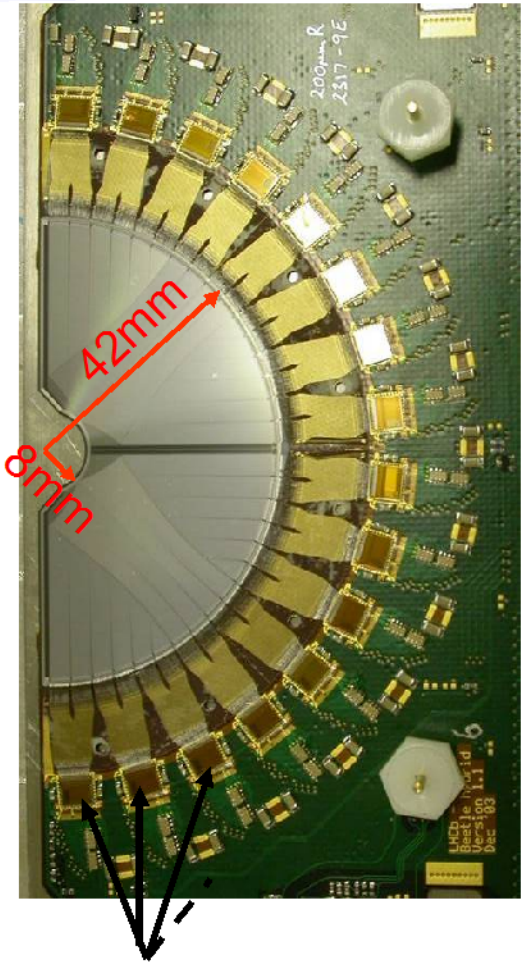


~ fully installed and commissioned

Vertex Detector (VELO)





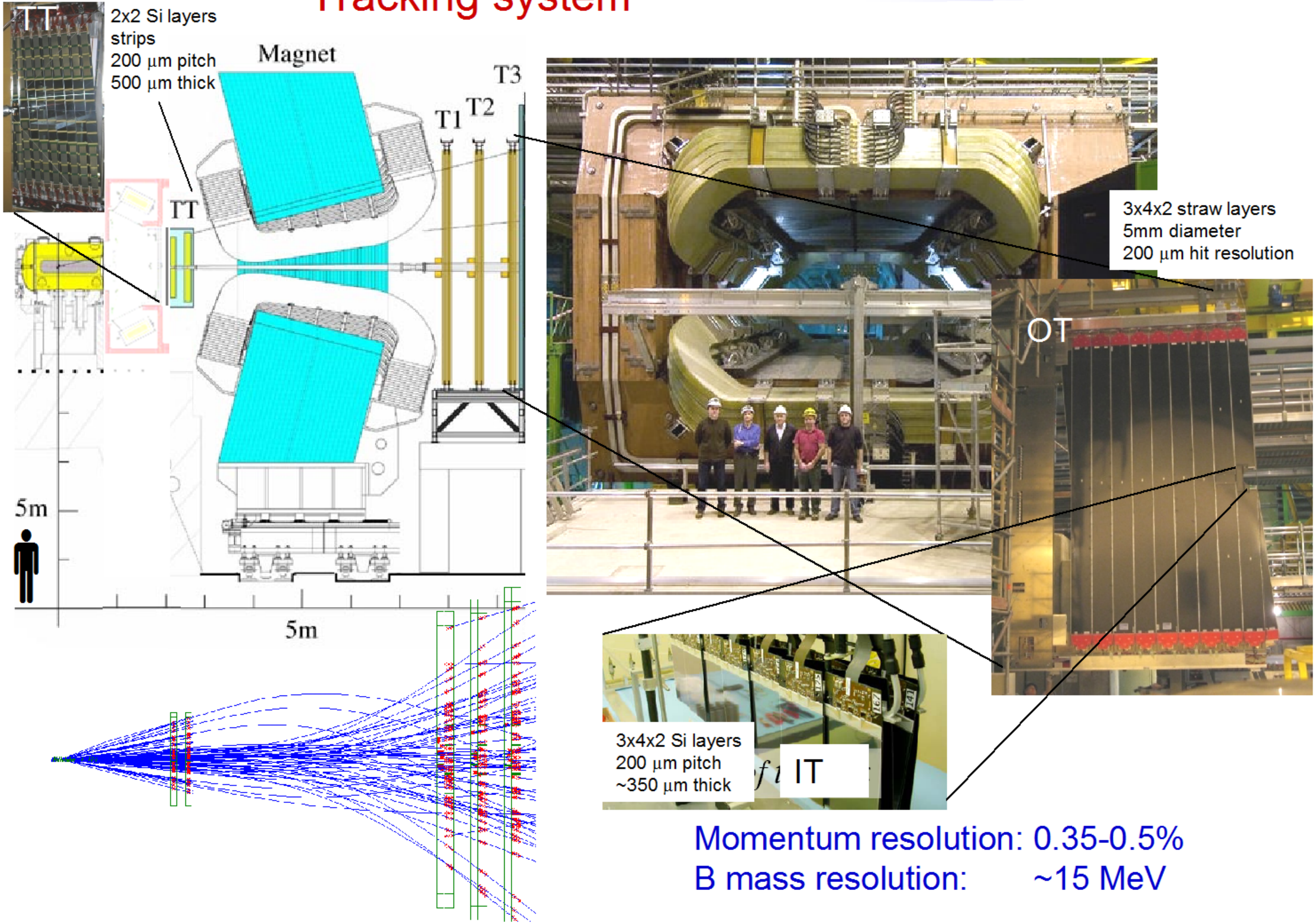


21 stations

- R and ϕ layer each
- n$^+$n type
- 2048 strips/sensor
- Strip pitch varies from 40µm to 100µm

Impact Parameter (IP) resolution: ~30 µm
Primary Vertex resolution: ~45 µm
Decay time resolution: ~40 fs

Tracking system



2x2 Si layers
strips
200 μm pitch
500 μm thick

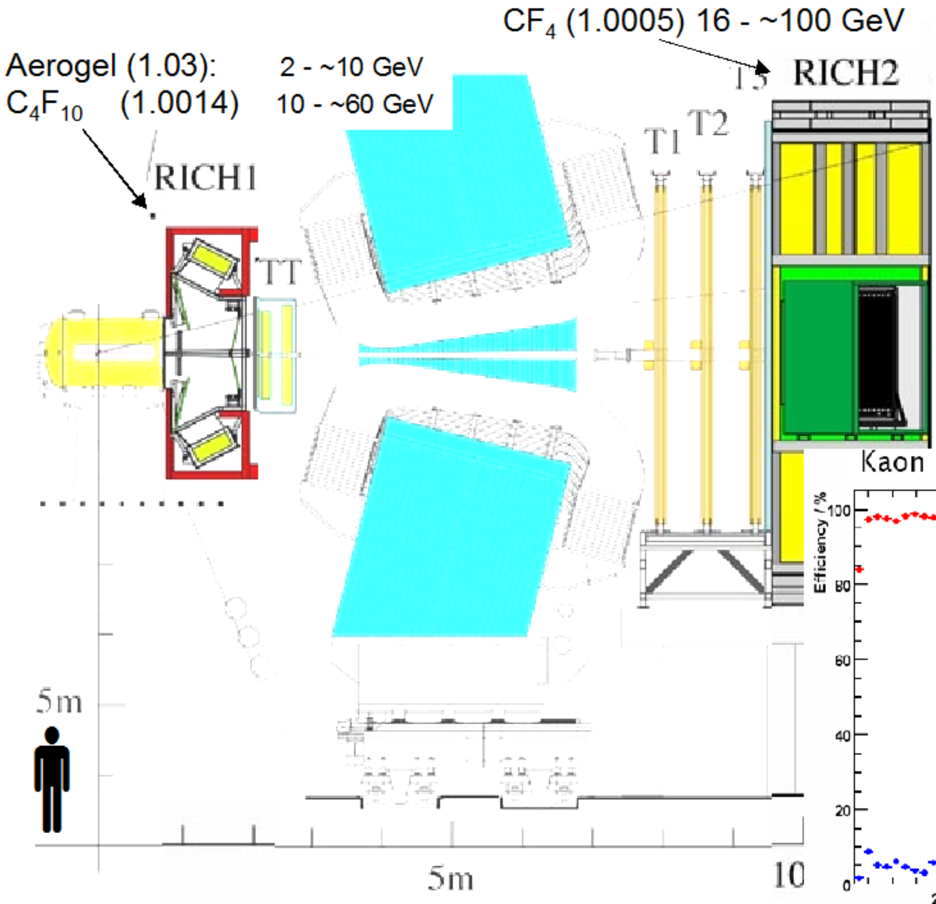
3x4x2 straw layers
5mm diameter
200 μm hit resolution

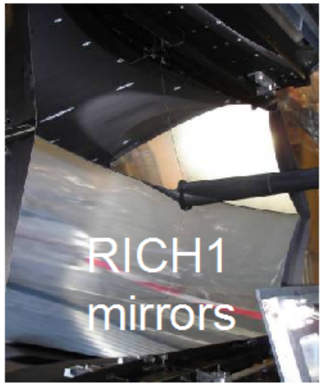
3x4x2 Si layers
200 μm pitch
~350 μm thick

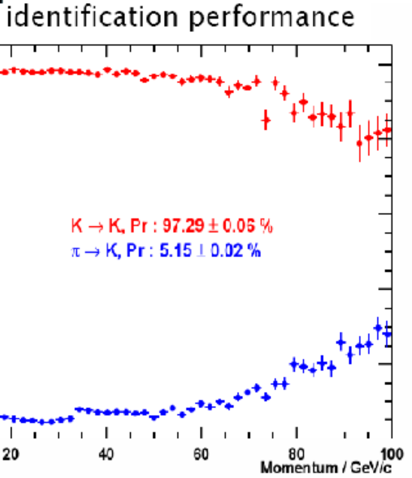
Momentum resolution: 0.35-0.5%

B mass resolution: ~15 MeV

Particle identification

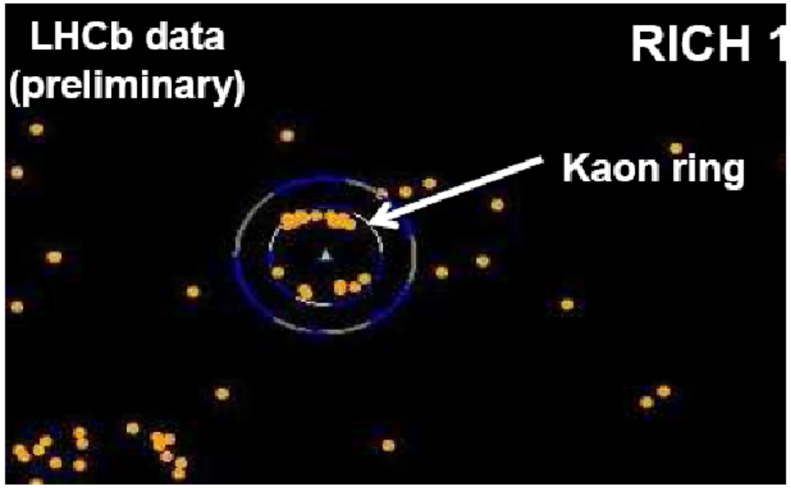


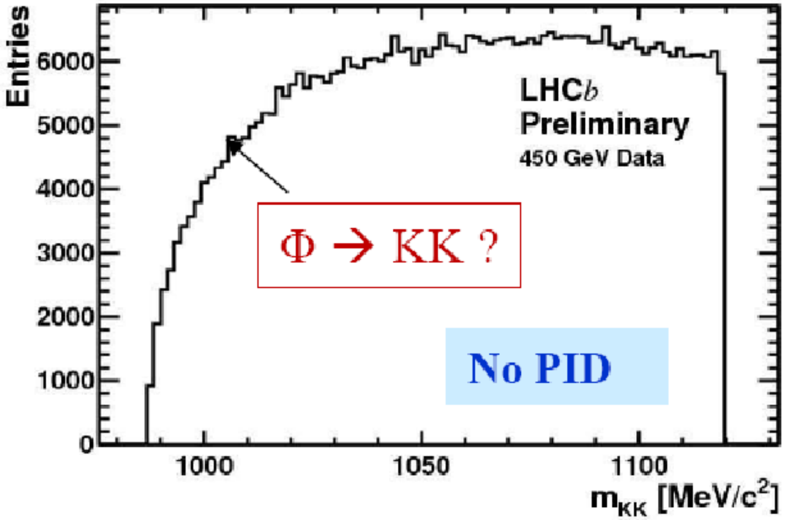


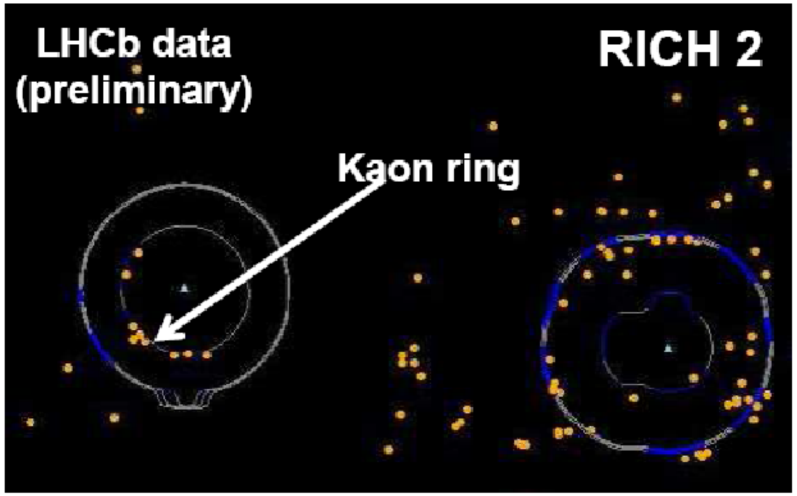


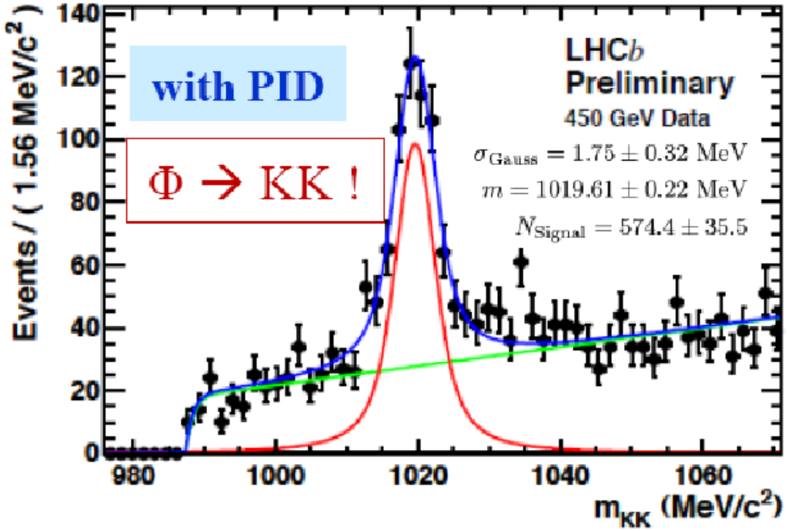
- **Good π/K/p separation is a unique feature compared to central detectors:**
  - Important for background suppression in B and D reconstruction and for **flavor tagging:** εD^2 ~ 6% (4%) for B_s (B^0)

Cherenkov rings in Dec.2009 0.9TeV data

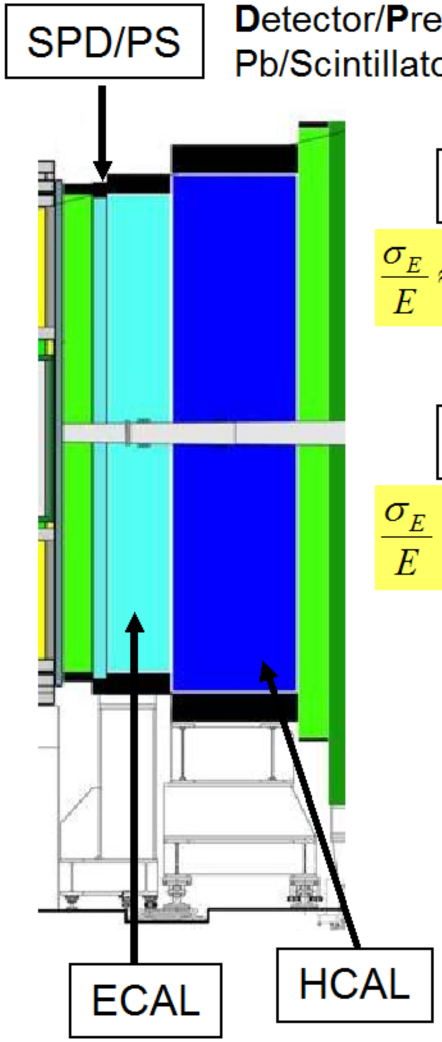








Calorimeters



Scintillating **P**ad **D**etector/**Pre**Shower Pb/Scintillator, 2.5 X_0

ECAL

$$\frac{\sigma_E}{E} \approx \frac{9.5\%}{\sqrt{E}} \oplus 0.8\%$$

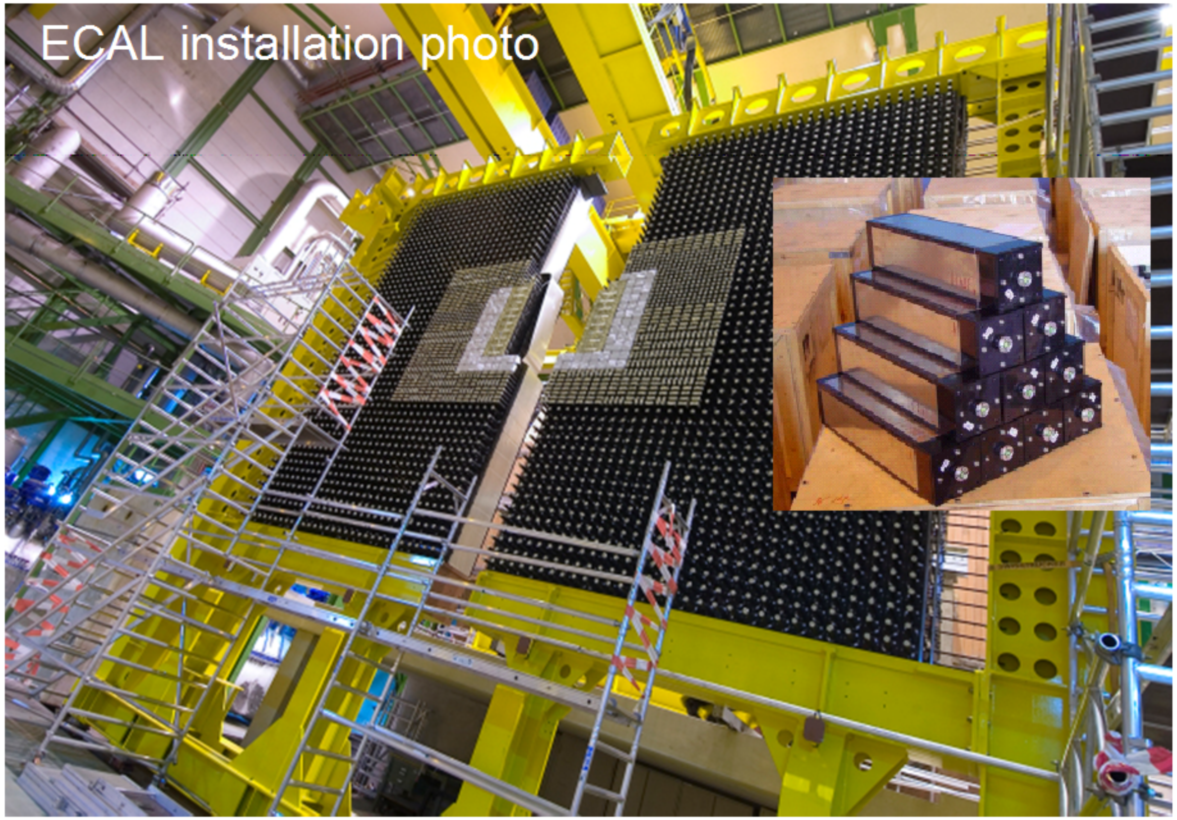
HCAL

$$\frac{\sigma_E}{E} \approx \frac{70\%}{\sqrt{E}} \oplus 10\%$$

ECAL: Pb-Scintillator Shashlik, 25 X_0

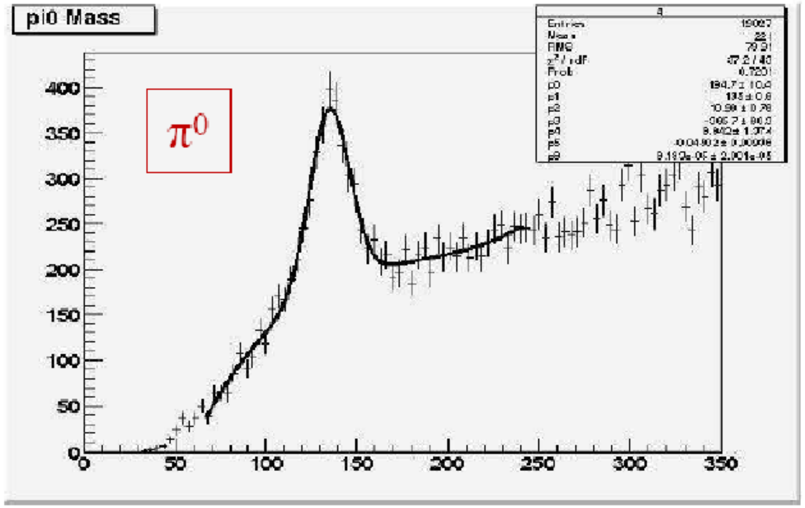
HCAL: Fe/Scintillator tiles, 5.6 λ_0

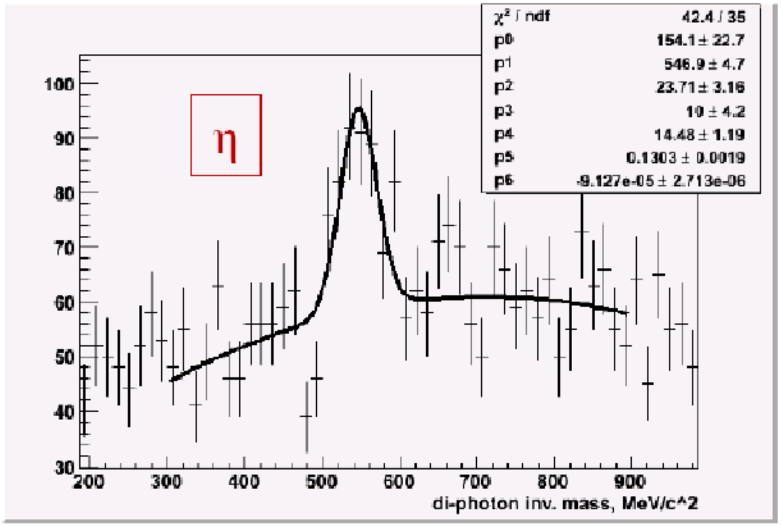
PMT readout


ECAL installation photo

- HCAL: hadron L0 trigger (Et>~3.6 GeV)
- ECAL: e,γ L0 trigger (Et>~2.7 GeV)
  - Offline: e ID; γ,π^0 reconstruction; jets

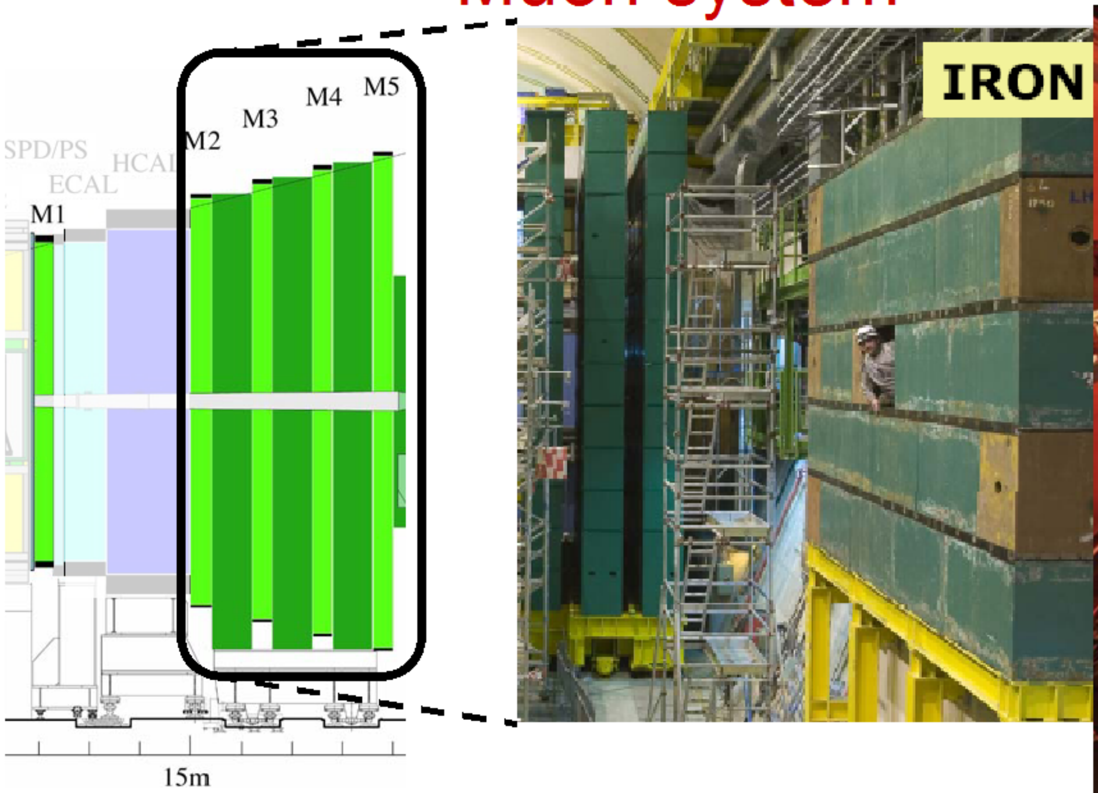
Di-photons in Dec.2009 0.9TeV data

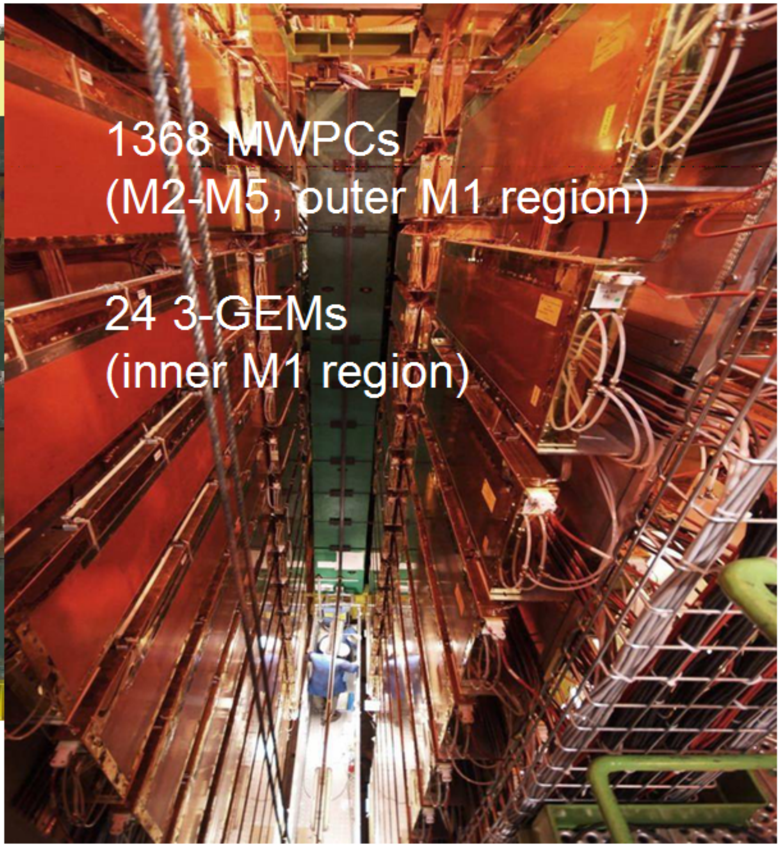




- LHCb preliminary

Muon system



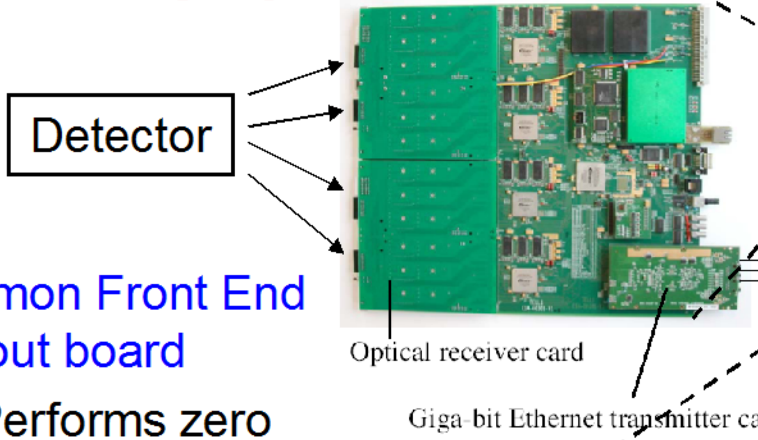


1368 MWPCs
(M2-M5, outer M1 region)

24 3-GEMs
(inner M1 region)

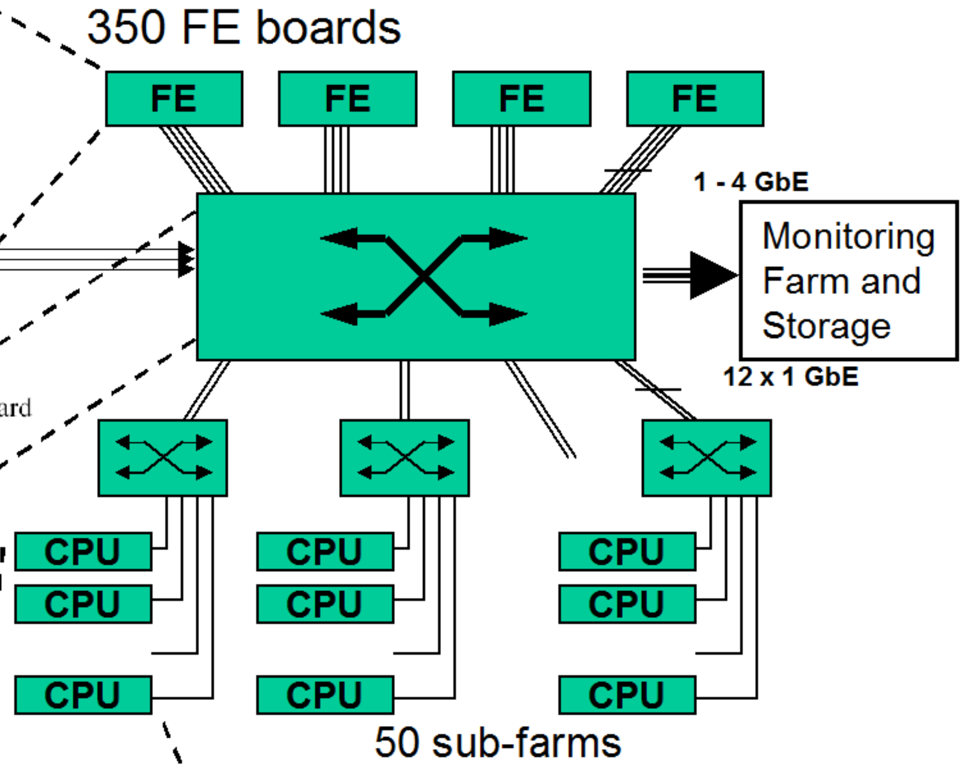
- L0 Muon Trigger:
  - Single- and Di-Muon: $p_{t1}+(p_{t2})>1.3$ GeV ($\sigma_p/p \sim 20\%$)
- Low reconstruction thresholds in offline:
  - $p>3$ GeV, $p_t>0.5$ GeV

FE and HLT Farm



- Common Front End readout board
  - Performs zero suppression
  - Event formatting for DAQ
- Single Core Router:
  - 1MHz input event rate
  - Total throughput: 50 GB/s

Force10 E1200, 1260 GbE ports



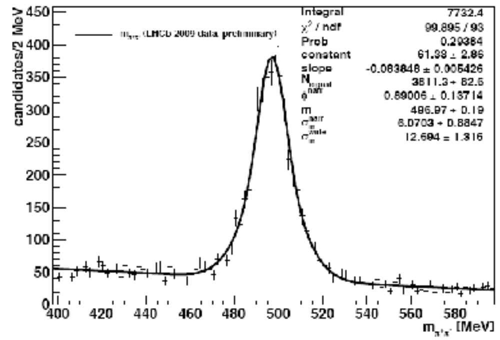
- HLT Farm
  - ~2000 computer boxes (multicore)
  - Up to 44 boxes/rack
  - Executing High Level Triggers code:
    - Same software framework as offline
    - HLT1 + HLT2 in one processing pass
  - 2kHz data logging rate (~0.25 GB/s)

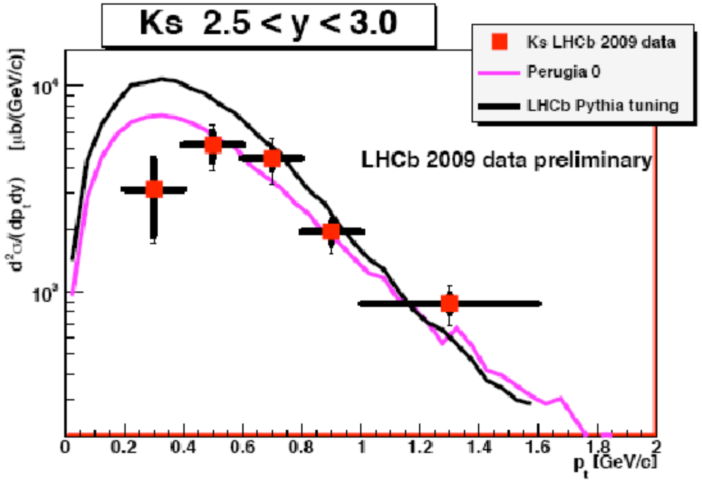
First collision data – inclusive K^0_s

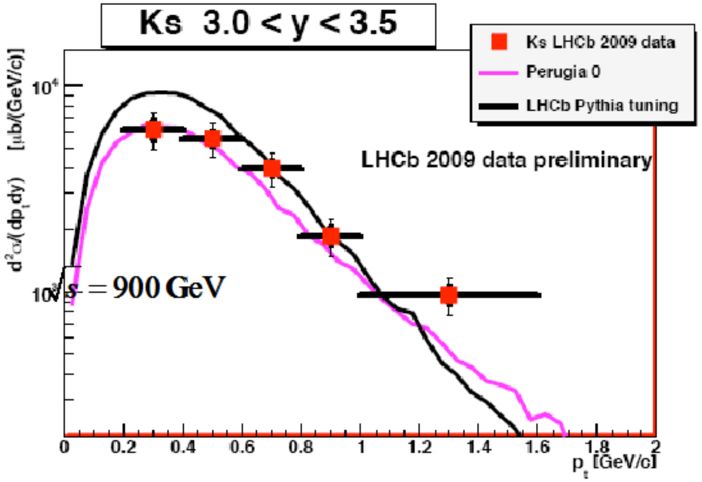
13 runs taken Dec 11-15,2009
(vertex detector only partially closed)
~0.4M minimum bias triggers

- Including $L_{int}=6.8\pm1.0\ \mu b^{-1}$

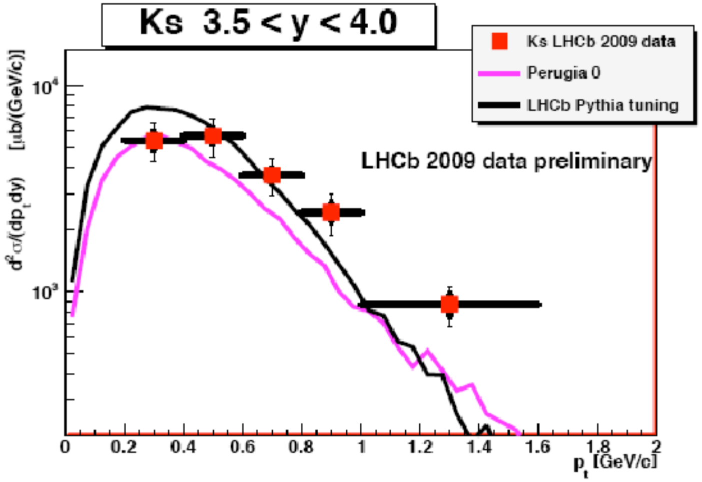
$$\sqrt{s} = 900\ \text{GeV}$$







(for more details see M. Knecht at Moriond, 2010)



-Crosses: LHCb DATA 2009 Preliminary
-Bold error bars: statistical errors
-Thin error bars: syst. including 15% on lumi
-BLACK curve: LHCb PYTHIA tuning
-PINK curve: Perugia 0 PYTHIA tuning

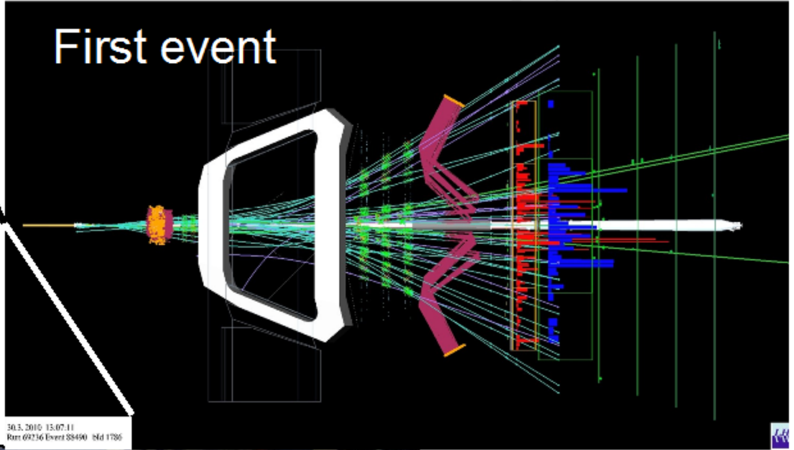
Cross-sections reasonably consistent with PYTHIA predictions

First high energy collisions

- Beginning of extended running at

$$\sqrt{s} = 7.0\,\mathrm{TeV}$$

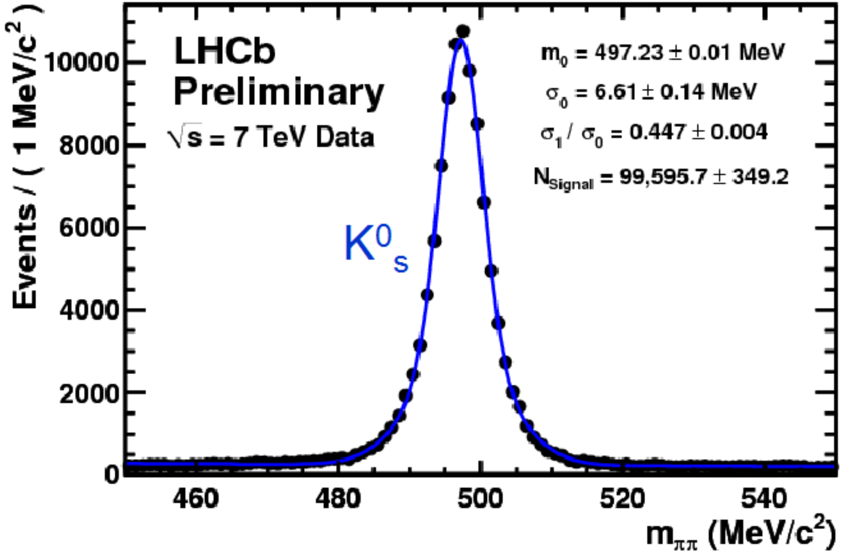
LHCb Event Display

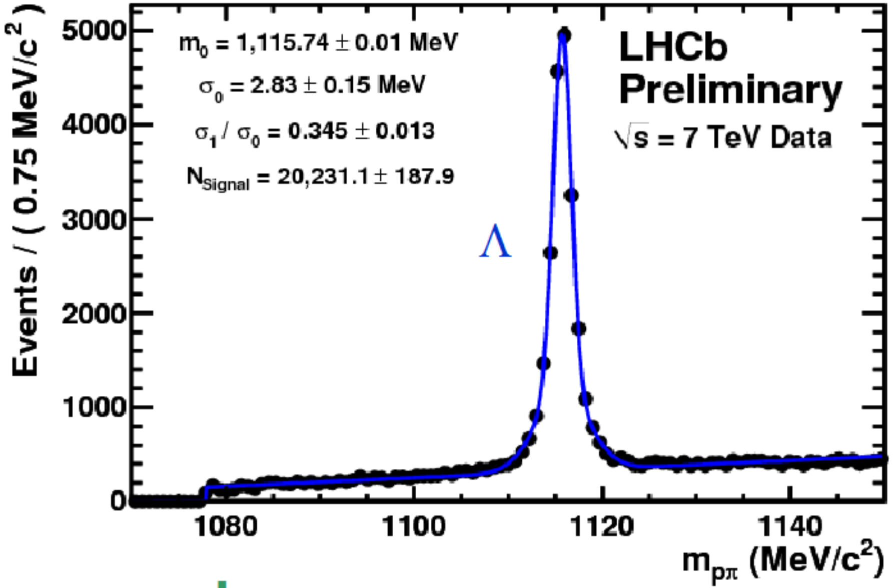


30.3. 2010 13:07:11
Run 69236 Event 88490 bId 1786

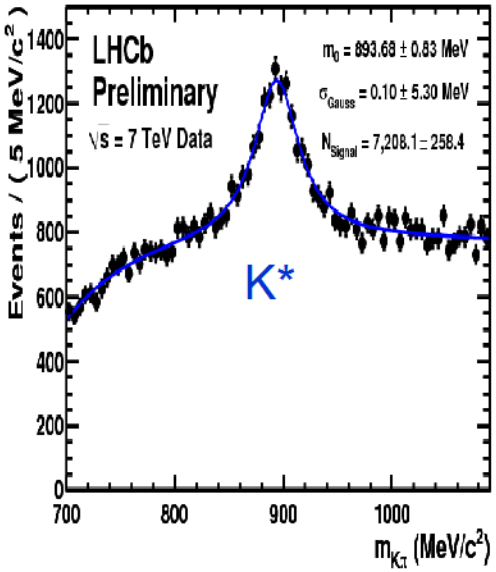
First plots from 7 TeV data – strange peaks

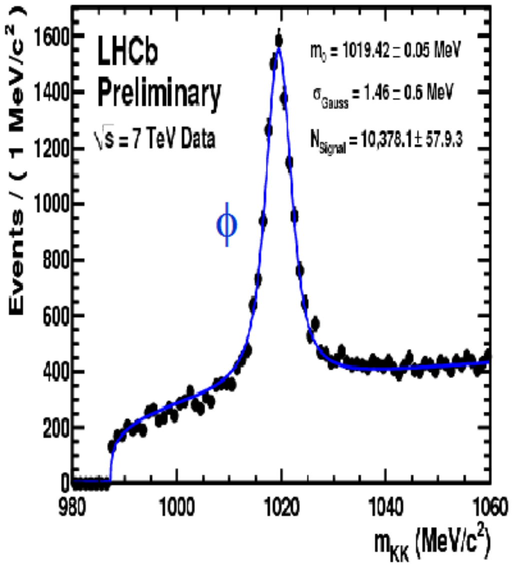
(~10M events; L ~65 μb^{-1})

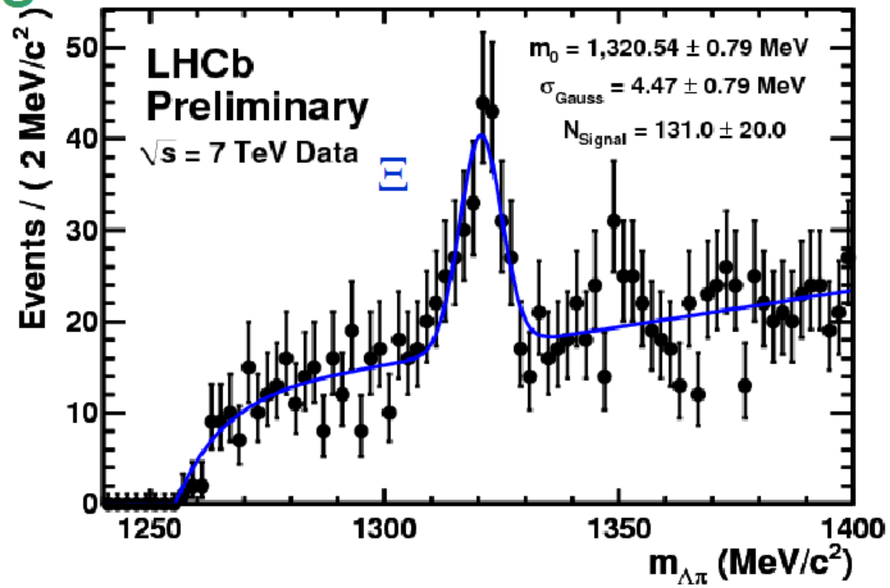




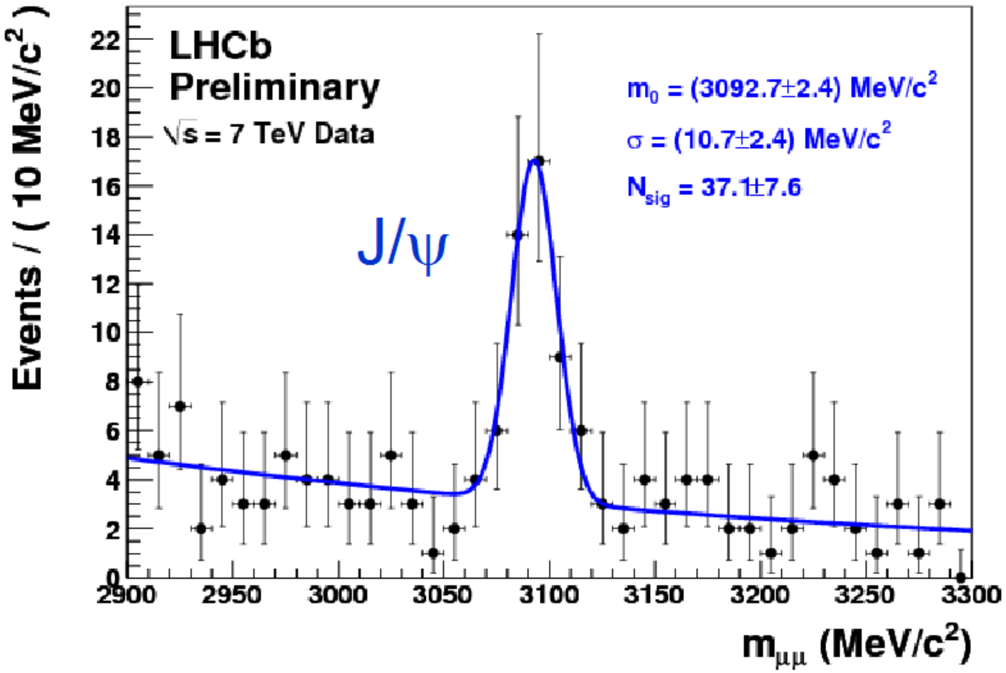
- Detector alignment is in progress!





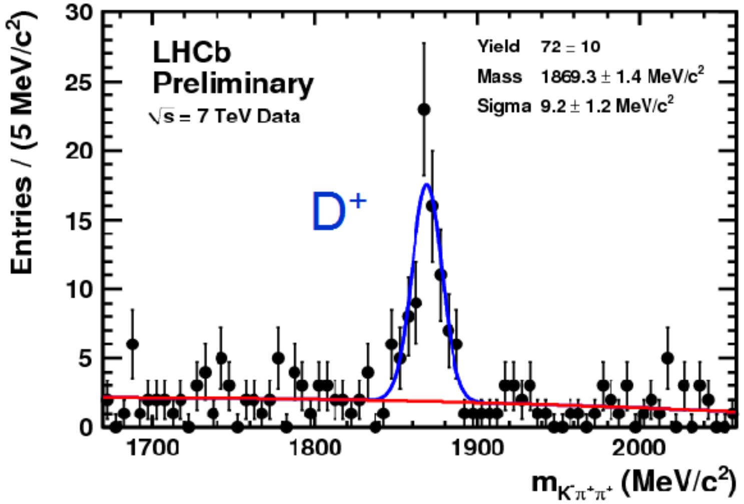


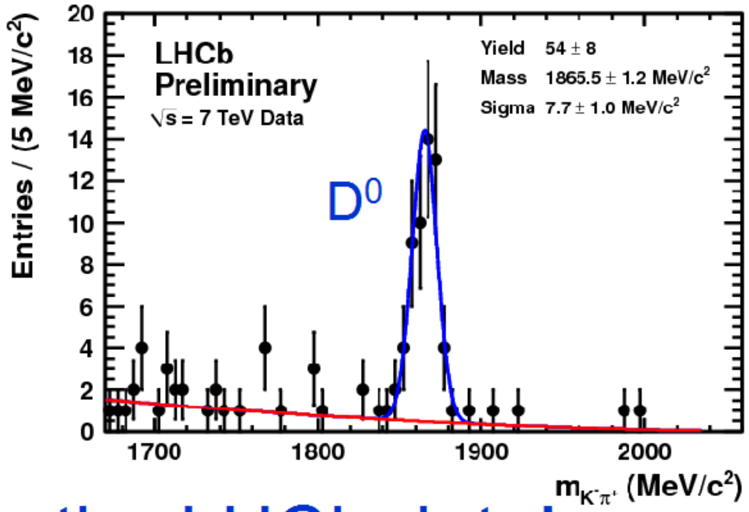
First plots from 7 TeV data – charm peaks



L~160 μb^{-1}

L~110 μb^{-1}



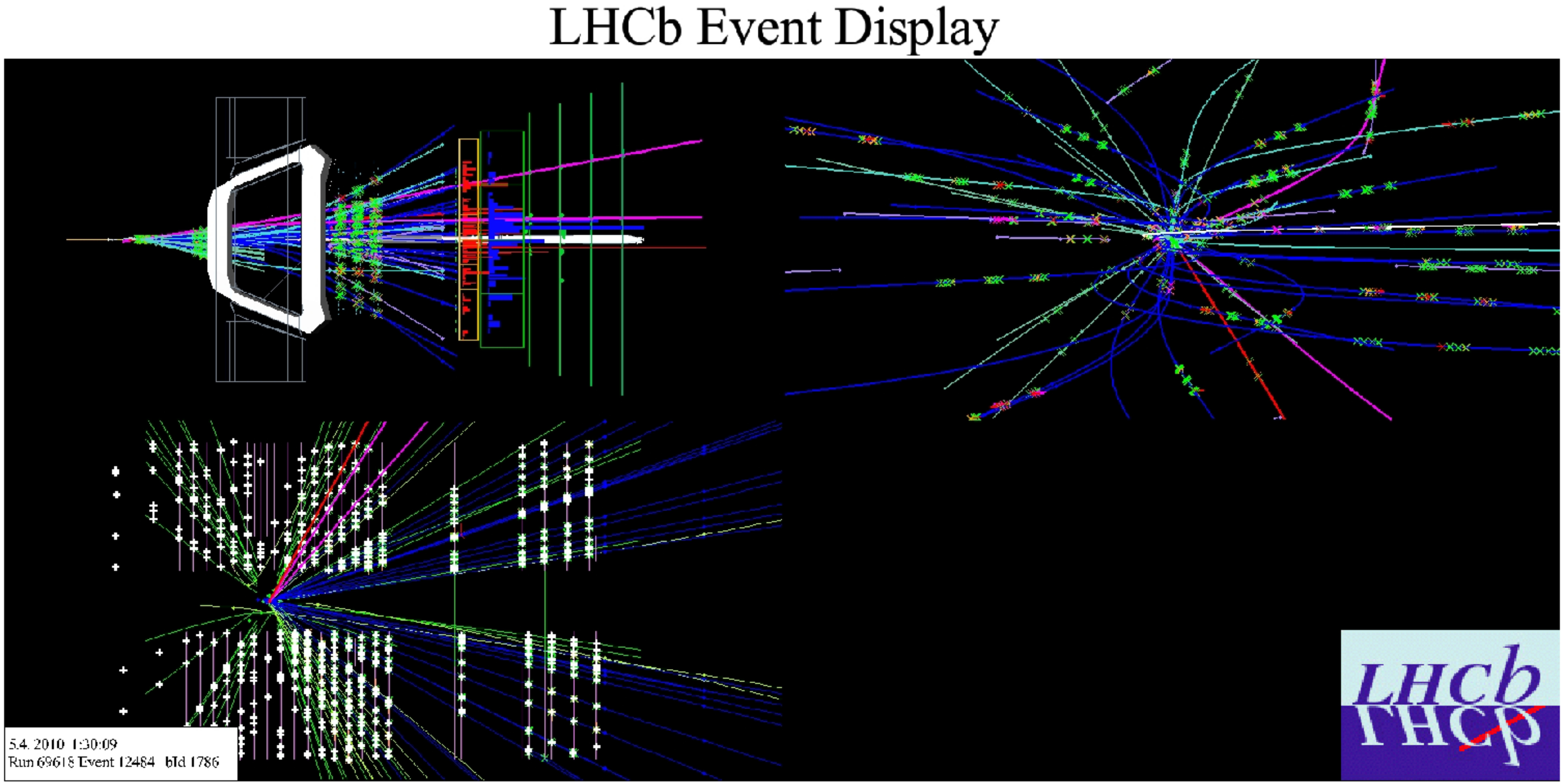


- First heavy flavors seen in the LHCb data!

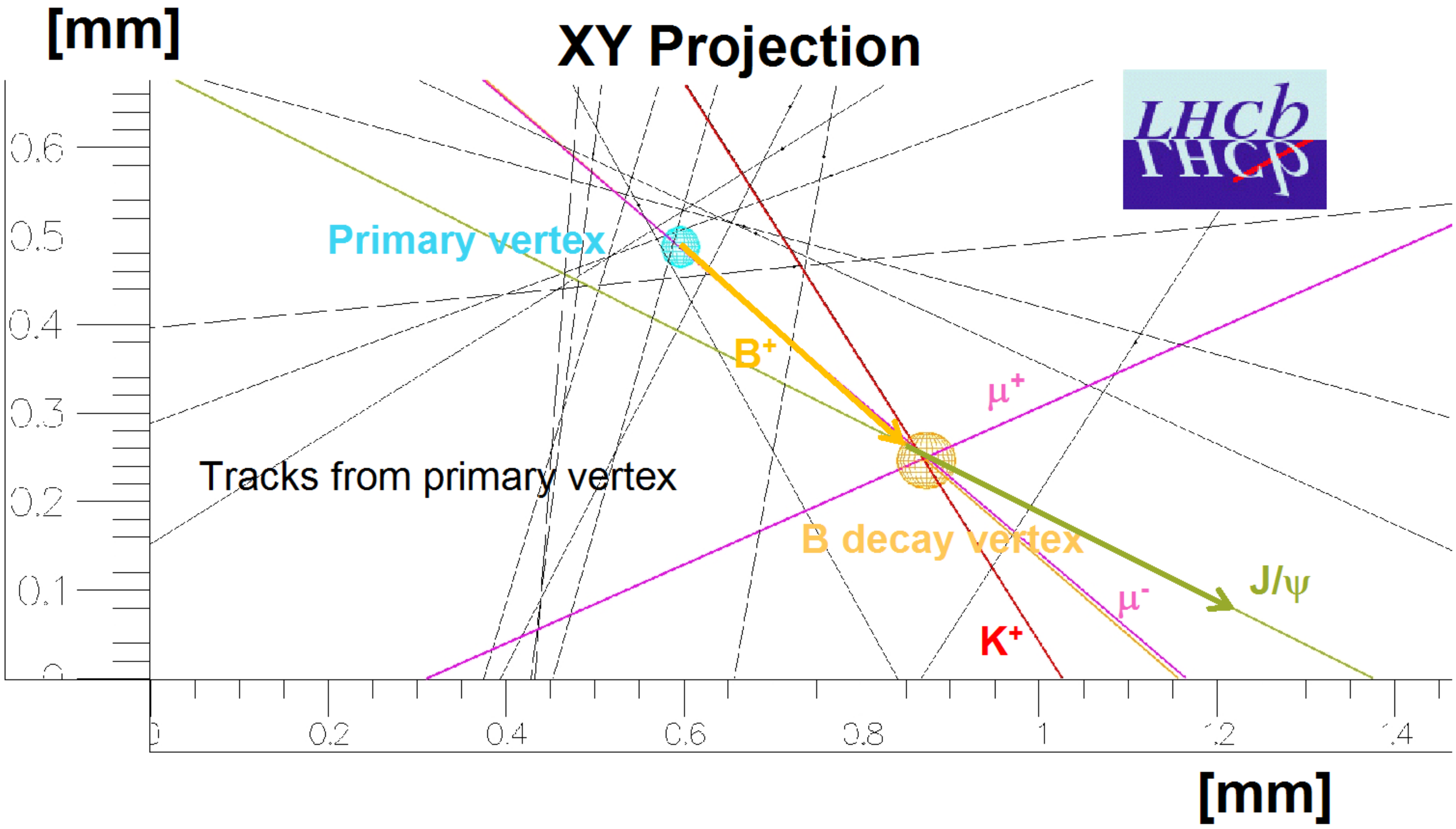
First B event from 7 TeV data – $B^+ \rightarrow J/\psi\ K^+$

B Mass = (5326.7±10.9) MeV/c^2
Momentum: p = 62.7 GeV/c, p_T = 10.48 GeV/c
Cos(α) = 0.9999, dist = 2.03mm

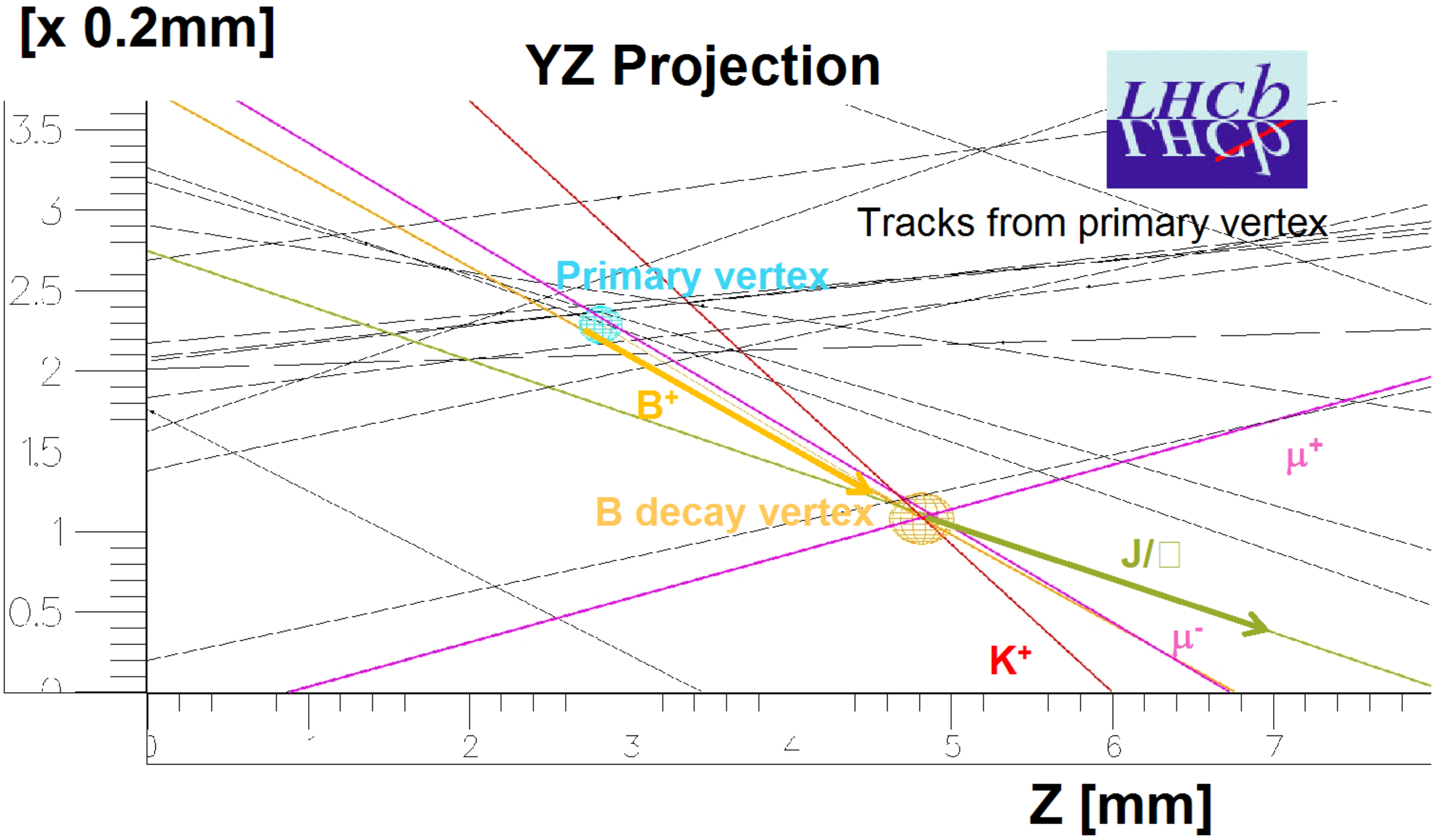
Muons are magenta, kaon is red



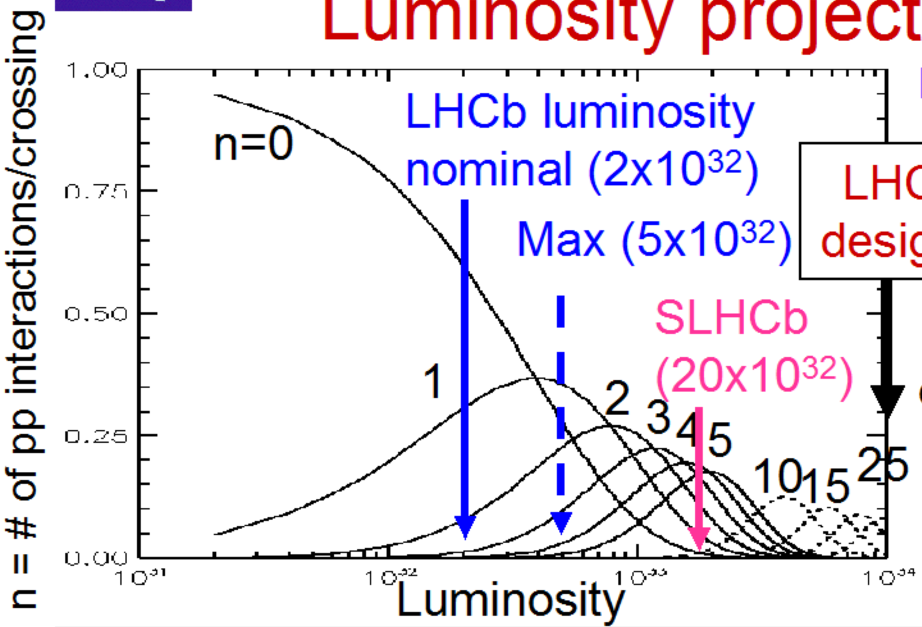
First B event from 7 TeV data – $B^+ \rightarrow J/\psi K^+$



First B event from 7 TeV data – $B^+ \rightarrow J/\psi\ K^+$



Luminosity projections



LHCb design luminosity is $2x10^{32}$ $cm^{-2}s^{-1}$

- –Little pile-up (n=0.5)
- –Less radiation damage
- –Smaller occupancies
- –Less confusion (n=1.2 for triggered event)
- –Easier triggering

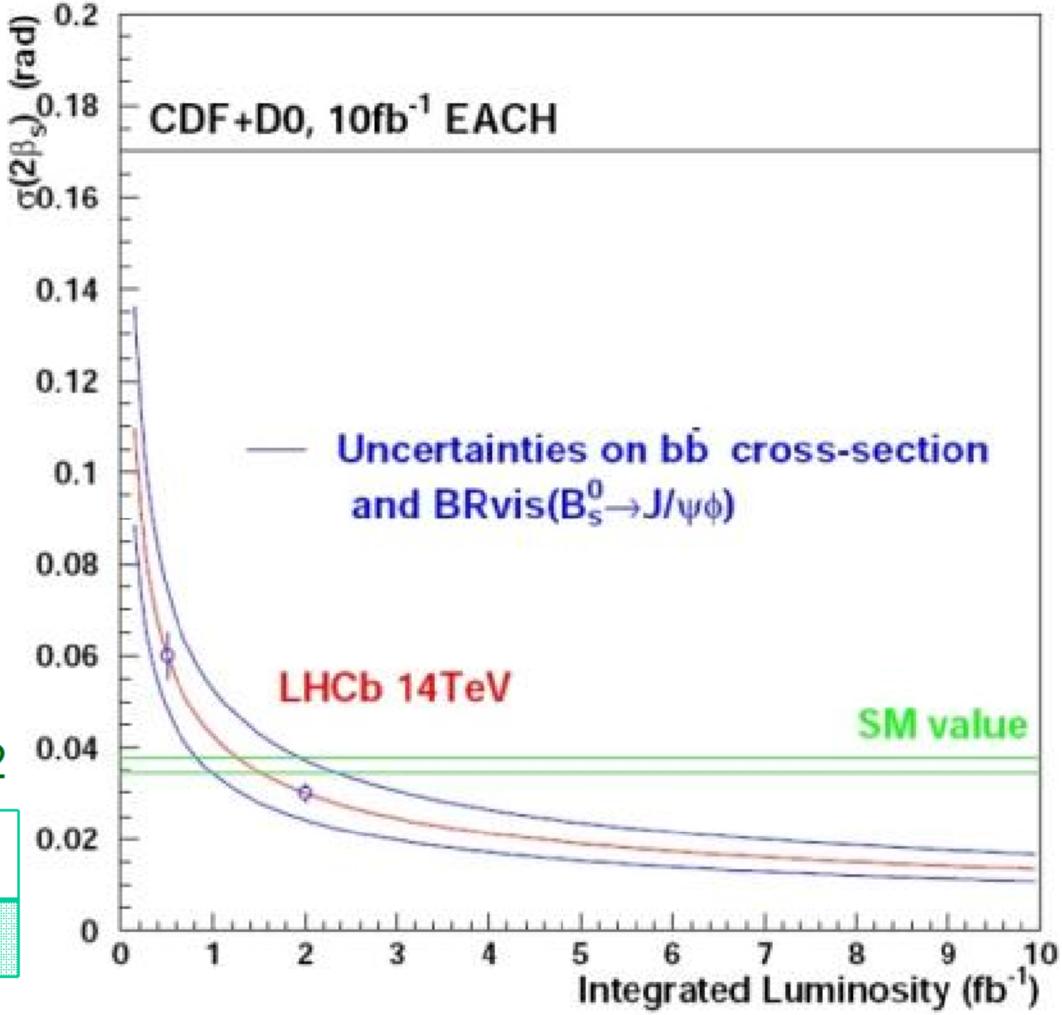
can run up to $5x10^{32}$ $cm^{-2}s^{-1}$ but gain only in muons

Beams will be defocused when LHC delivers Luminosity larger than desired.

Year	Months	Ecm TeV	β* m	I_b p/bunch	$N_{bunches}$	Peak L 10^{32} $cm^{-2}s^{-1}$	Lumi / Year fb^{-1}		Sum fb^{-1}
							LHC	LHCb	LHCb
2010	8	7	2.5	7 10^{10}	720	1.2	0.5	0.5	0.5
2011	8	7	2.5	7 10^{10}	720	1.2	0.8	0.8	1.3
2012									
2013	6	13	1.0	1.1 10^{11}	720	14.0	7.0	2.0	3.3
2014	7	14	1.0	1.1 10^{11}	1404	30.0	16.0	2.0	5.3

LHCb physics reach will saturate at ~10 fb-1 : SuperLHCb in 2016? 100 fb-1

Loops in LHCb: phase of B_s mixing



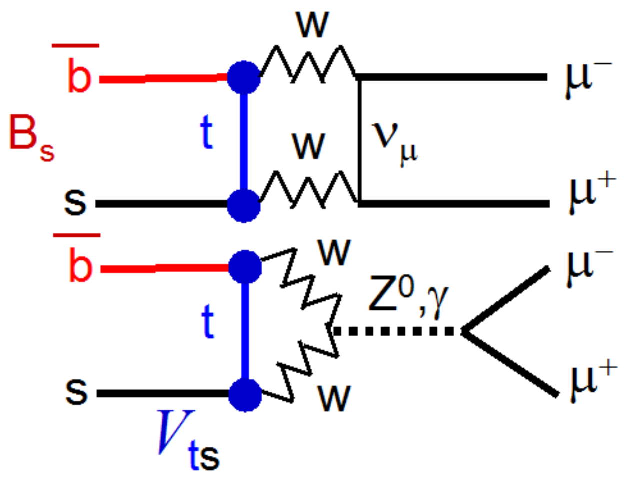
SM ϕ_s=-0.036±0.002

	LHCb	SLHCb	SM
σ	0.01	~0.003	0.002

- One of the best predicted CPV phases in the SM.
- LHCb will have sensitivity to observe SM CPV.
- Need 100 fb^{-1} (SLHCb) to fully exploit this window to NP.

Loops in LHCb: BR($B_s \to \mu^+\mu^-$)

SM

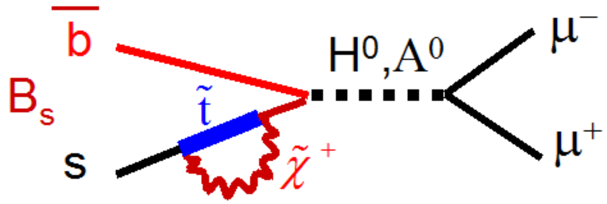


$$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^{-9}$$

Small with small theoretical error!

NP

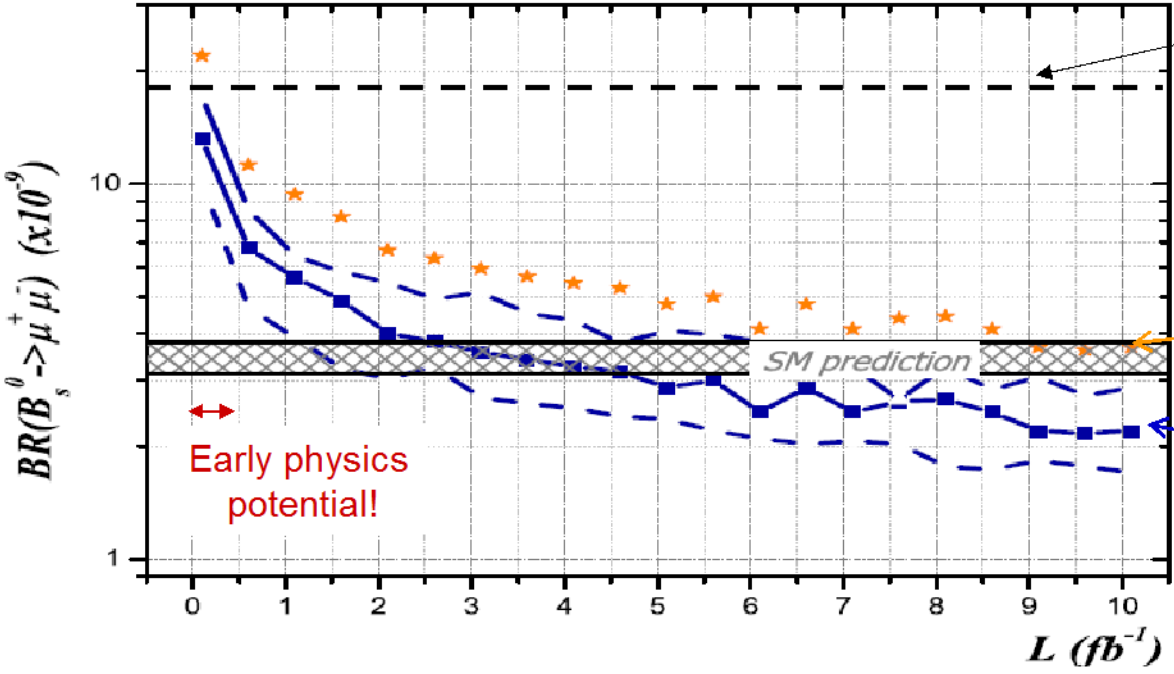
e.g. SUSY



~ $\tan^6\beta$

Could be strongly enhanced.

In some models negative interference with the SM.



CDF+D0 UL expected 9 fb^{-1}

5σ

3σ observation

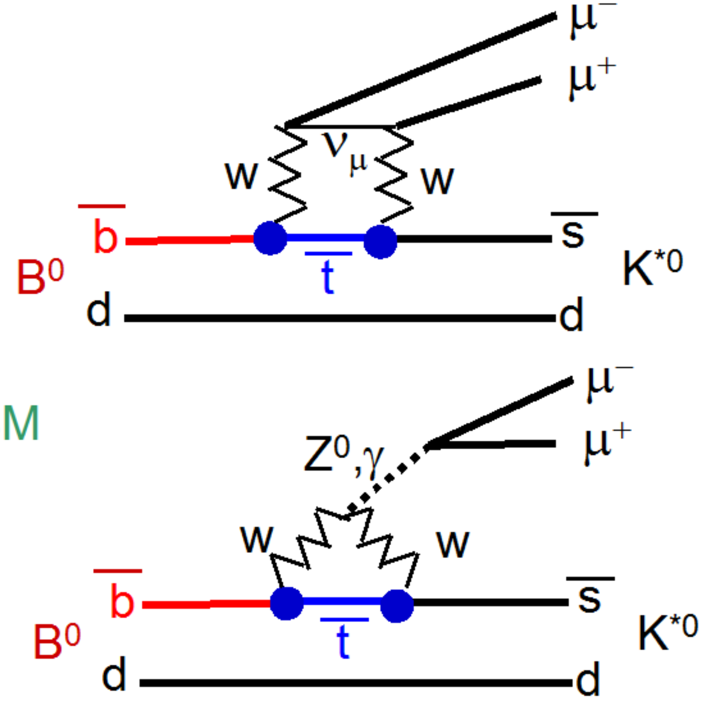
Bkg: b → μ^- X & b → μ^+ X

is under control:

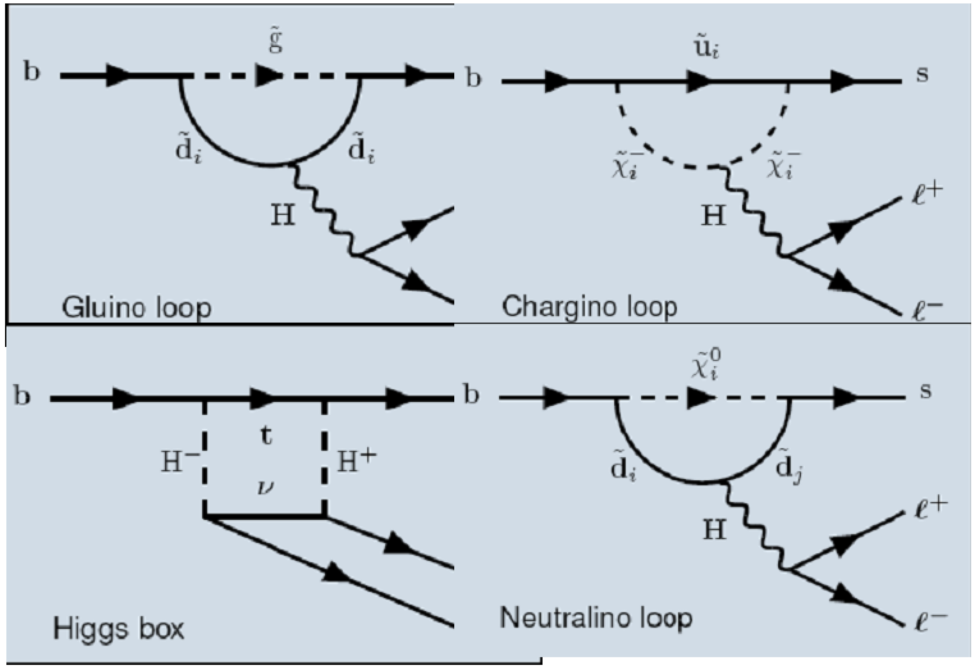
need ~100 fb^{-1} to reach theoretical limitations (SLHCb)

Loops in LHCb: B→K*$\mu^+\mu^-$

SM



NP e.g. SUSY



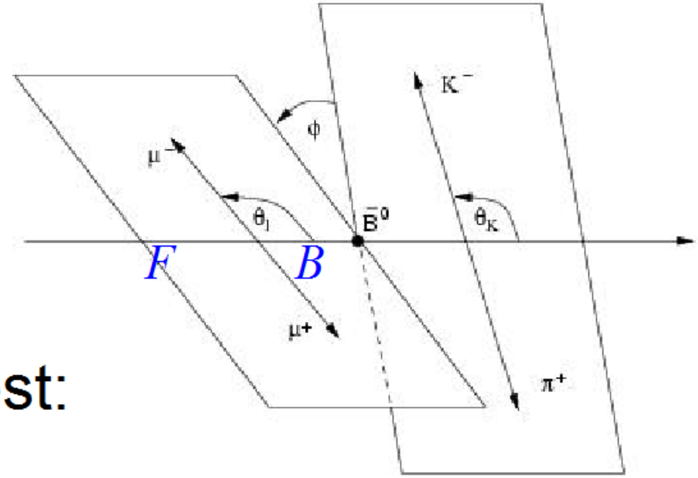
Already observed by Belle, BaBar and CDF !

Belle PRL,103 (2009) 657M BB 625 fb^{-1} $BR(B \to K^* l^+ l^-) = (1.07 \pm 0.11 \pm 0.09) \times 10^{-6}$

CDF (Prel.) Note 10047 (2009) 4.4 fb^{-1} $BR(B_s \to \phi l^+ l^-) = (1.44 \pm 0.33 \pm 0.46) \times 10^{-6}$

Loops in LHCb: $B \to K^* \mu^+ \mu^-$

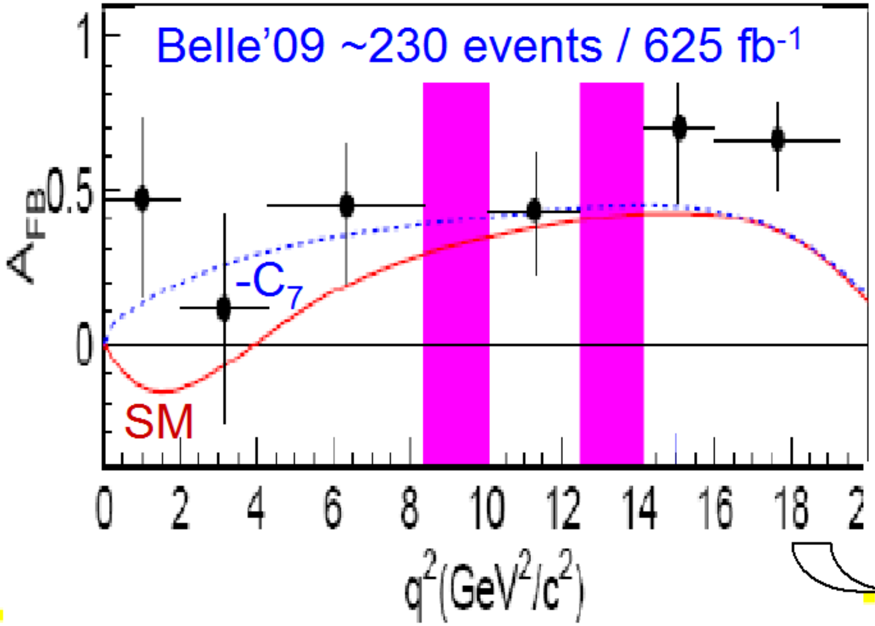
- Described by three angles (θ_l, ϕ, θ_K) and di-μ invariant mass q^2



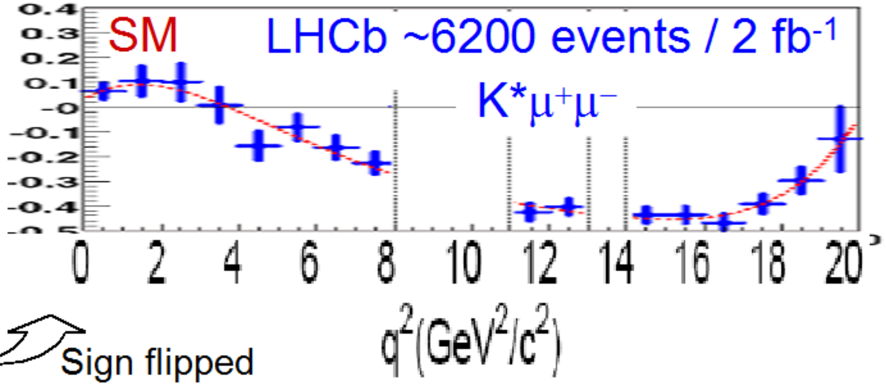
- ☐ Forward-backward asymmetry

  A_{FB} of θ_l distribution of particular interest:
  - Varies between different NP models →
  - At $A_{FB} = 0$, the dominant theoretical uncertainty from $B_d \to K^*$ form-factors cancels at LO

$$A_{FB}\left(q^2\right) = \frac{N_F - N_B}{N_F + N_B}$$



(CDF ~100 $K^*\mu^+\mu^-$ + ~27 $\phi\mu^+\mu^-$ / 4.4 fb^{-1})



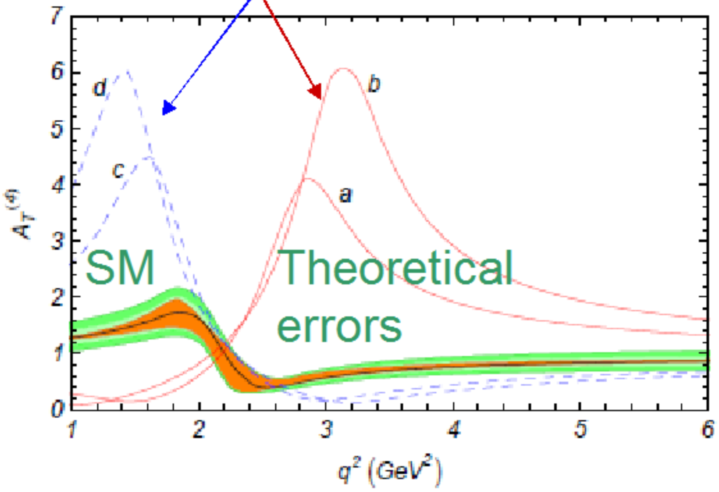
Sign flipped

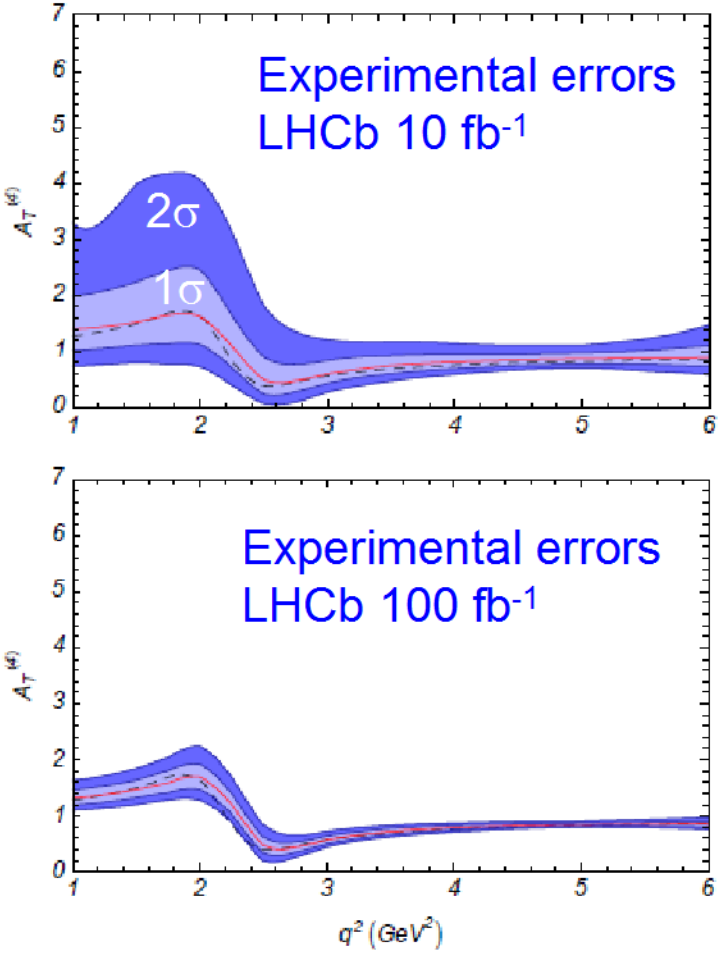
Loops in LHCb: $B \to K^* \mu^+ \mu^-$

- Even more sensitivity using transverse asymmetries

U.Egede et al., JHEP 11, 32 (2008).

SUSY models consistent with the current data

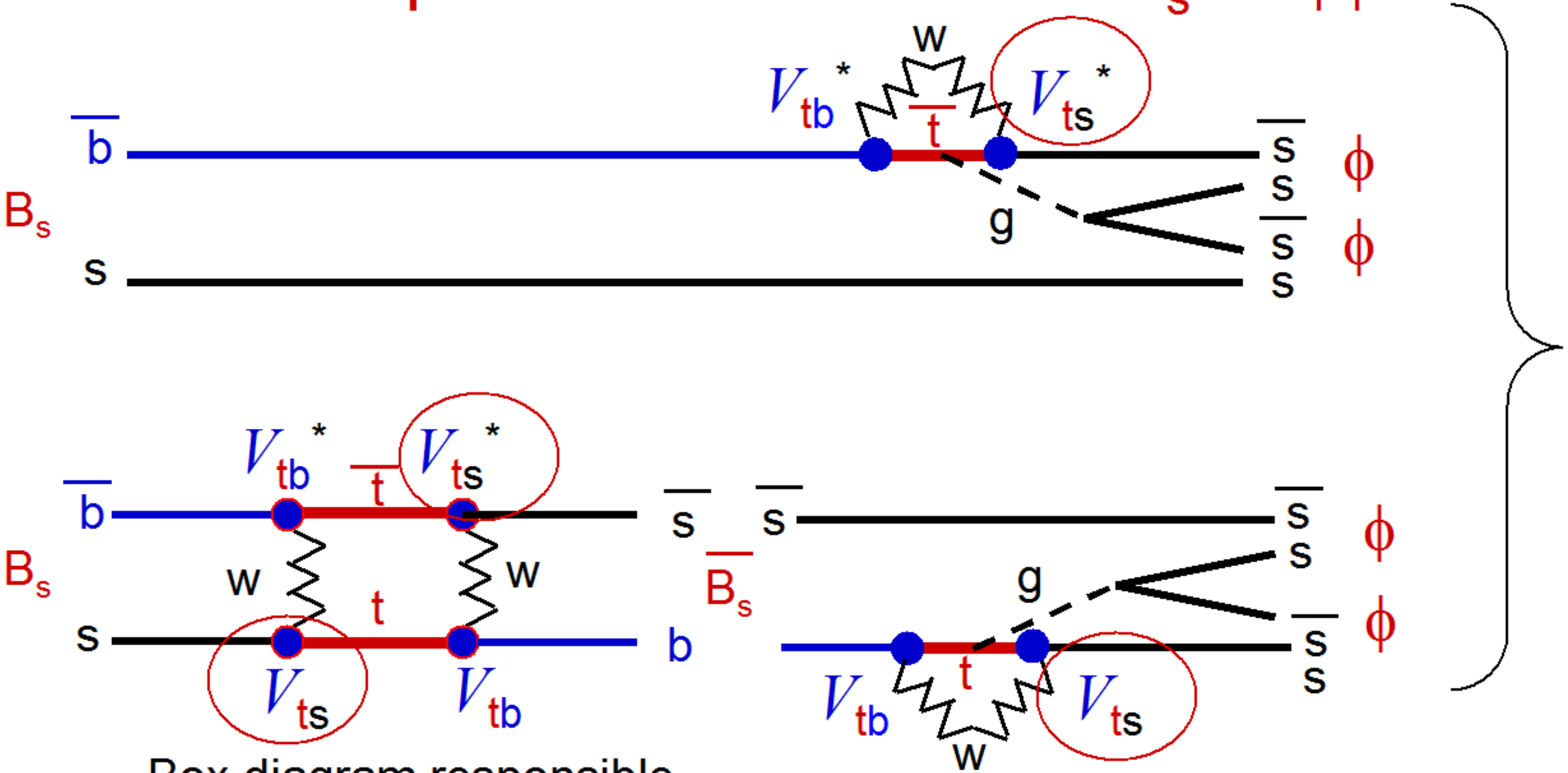



Experimental errors LHCb 10 fb^{-1}

Experimental errors LHCb 100 fb^{-1}

Need SLHCb to reach the limit of sensitivity to NP imposed by the theoretical errors.

Loops: Indirect CPV with $B_s \to \phi\phi$



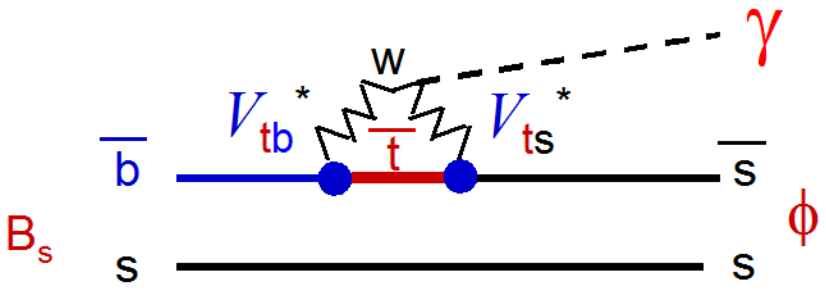
Impossible
to tell which
happened
- the two
processes
interfere

Box diagram responsible
for B_s-$\bar{B}_s$ mixing

(mixing + decay: "indirect" CPV)

- Phases of the mixing and penguin decay exactly the same: ϕ_M-ϕ_D=0. No CPV in SM!
- Excellent place to look for phases from NP particles in the gluonic penguin diagram.
- LHCb will measure this phase to ±0.03 (10 fb^{-1}). SLHCb highly desired!
- Measurement of ϕ_M (β_d) for $B^0 \to \phi K_s$ to ±0.1 (10 fb^{-1}) compare with β_d from $B^0 \to J/\psi K_s$

Loops: CPV with $B_s \rightarrow \gamma\phi$



In SM photon from $b \rightarrow s\gamma$ is left-handed, from $\bar{b} \rightarrow \bar{s}\gamma$ right-handed.

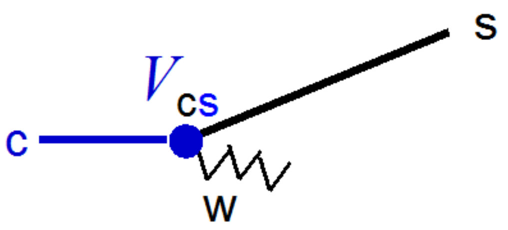
- ➔ φγ final states in B_s and $\bar{B}_s$ do not interfere
- ➔ interference of mixing-decay cannot occur

$$A_{CP}(t) = \frac{\Gamma(\bar{B}_S \rightarrow \phi\gamma) - \Gamma(B_S \rightarrow \phi\gamma)}{\Gamma(\bar{B}_S \rightarrow \phi\gamma) + \Gamma(B_S \rightarrow \phi\gamma)} = 0 \quad \text{in SM}$$

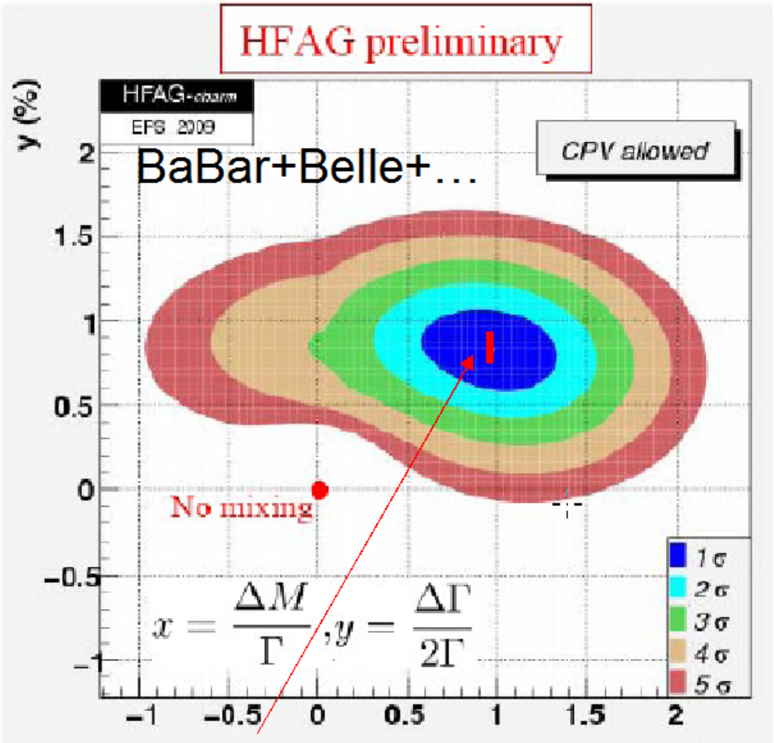
Measuring time-dependent CP asymmetry
is a probe for NP with right handed currents.

Channel	Yield (10 fb^{-1})	B/S
$B_s \rightarrow \phi\gamma$	55k	<0.55

Mixing and CPV in charm decays



- $m_c >> m_s$, $|V_{cs}|$~1, thus c quark dominant decays within the same quark generation (unlike for s, b quarks)
- Contributions from the SM loop diagrams (e.g. mixing via the box diagram) extremely small



Rotated by strong phase δ

D0 mixing established >5σ (however individual measurements not as significant)

Can be accommodated in SM via long distance diagrams (tree diagrams, with virtual hadrons in intermediate states). Very difficult to predict, thus cannot establish or rule out NP.

No complex phases in CKM elements involved. SM CPV in mixing expected to be extremely small (~10^{-6}).

CPV: Good place to look for NP, especially models in which couplings to up type quarks are enhanced.

LHCb 10 fb^{-1} $B \to D^{*+}X$, $D^{*+} \to \pi^+_{tag} D^0$, $D^0 \to \pi^+ K^-$ (DCS or $\overline{D^0} \to \pi^+ K^-$): Yield(t)

CPV Asymmetry up to ±4x10^{-4} (stat.) using $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$

Other measurements of CPV

- With 2 fb^{-1}

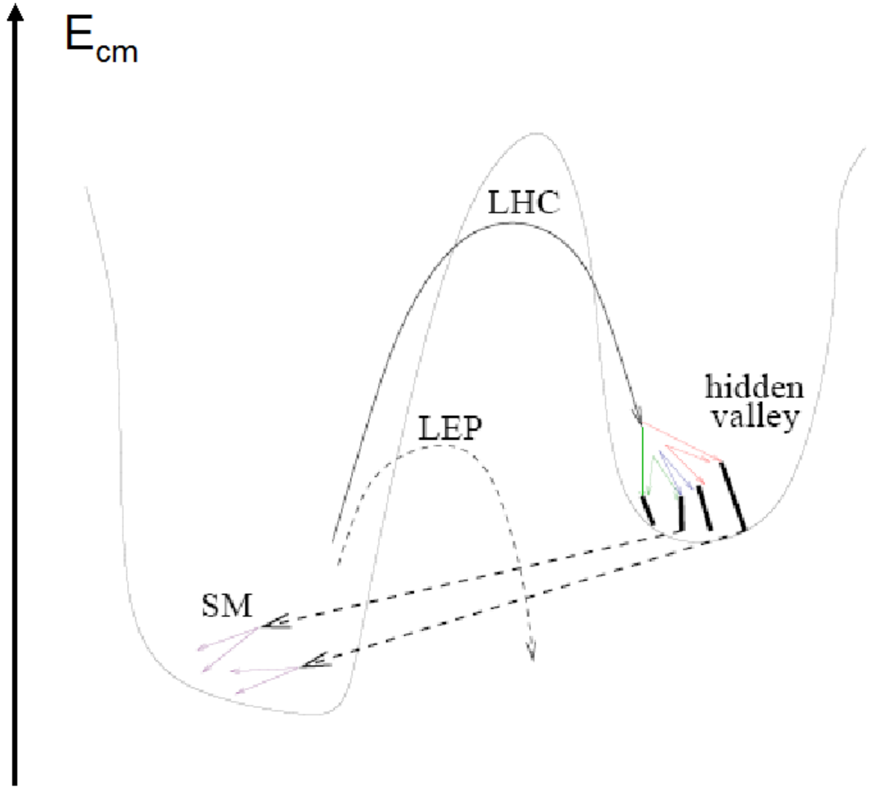
	Channel	**Yield**	**B/S**	**Precision**
γ	$B_s \to D_s^{-+} K^{+-}$	5.4k	< 1.0	$\sigma(\gamma) \sim 14^\circ$
	$B_d \to \pi^+ \pi^-$	36k	0.46	$\sigma(\gamma) \sim 4^\circ$
	$B_s \to K^+ K^-$	36k	< 0.06	
	$B_d \to D^0\,(K\pi, KK)\,K^{*0}$	3.4 k, 0.5 k, 0.6 k	<0.3, <1.7, < 1.4	$\sigma(\gamma) \sim 7^\circ - 10^\circ$
	$B^- \to D^0\,(K^-\pi^+, K^+\pi^-)\,K^-$	28k, 0.5k	0.6, 4.3	$\sigma(\gamma) \sim 5^\circ - 15^\circ$
	$B^- \to D^0\,(K^+K^-, \pi^+\pi^-)\,K^-$	4.3 k	2.0	
	$B^- \to D^0\,(K_S\pi^+\pi^-)\,K^-$	1.5 - 5k	< 0.7	$\sigma(\gamma) \sim 8^\circ - 16^\circ$
α	$B_d \to \pi^+ \pi^- \pi^0$	14k	< 0.8	$\sigma(\alpha) \sim 10^\circ$
	$B \to \rho^+\rho^0, \rho^+\rho^-, \rho^0\rho^0$	9k, 2k, 1k	1, <5, < 4	
β	$B_d \to J/\psi(\mu\mu)K_S$	216k	0.8	$\sigma(\sin 2\beta) \sim 0.022$

LHCb and direct NP searches

- We are not competitive with ATLAS/CMS for SM Higgs, and NP searches with missing E_t
- However LHCb detector has some unique features:
  - Muon triggers with low Pt thresholds
  - Long vertex detector
  - Much larger trigger bandwidth (2 kHz) thanks to small event size
  - Also RICHes, acceptance at large η
- LHCb is sensitive to “Exotic” particles decaying into leptons or quark jets, especially with lifetimes in the range of $500>\tau>1$ ps.
- Show one example: “Hidden Valley” Higgs decays

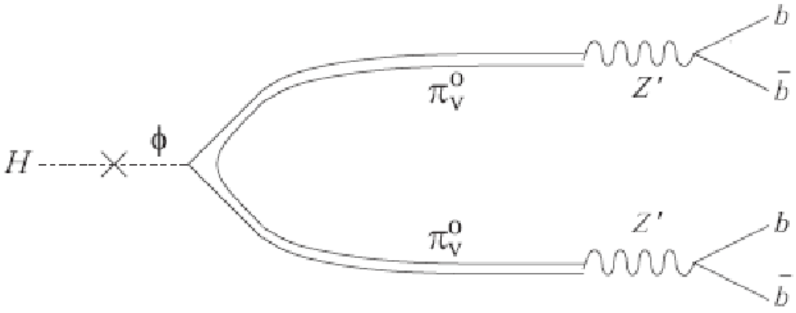
Hidden Valleys

- New heavy Gauge sectors can augment the Standard Model (SM) as well SUSY etc.
- These sectors arise naturally in String theory
- It takes energy to excite them
- They couple to SM via Z′ or heavy particle loops
- From Strassler & Zurek [hep-ph/604261]

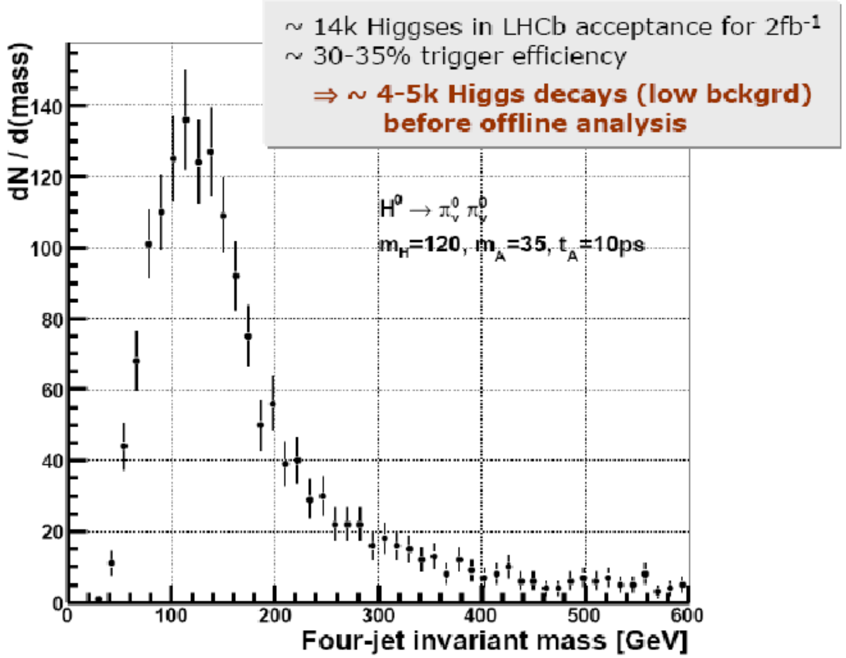


Search for Exotic Higgs Decays

- Hidden Valley provides new scalars π^o_v, allowing $H^o \to \pi^o_v\, \pi^o_v \to b\bar{b}$, with possibly long lifetimes.
- Machanism for Higgs to evade searches at LEP2 – reconciles the indirect and direct Higgs probes.

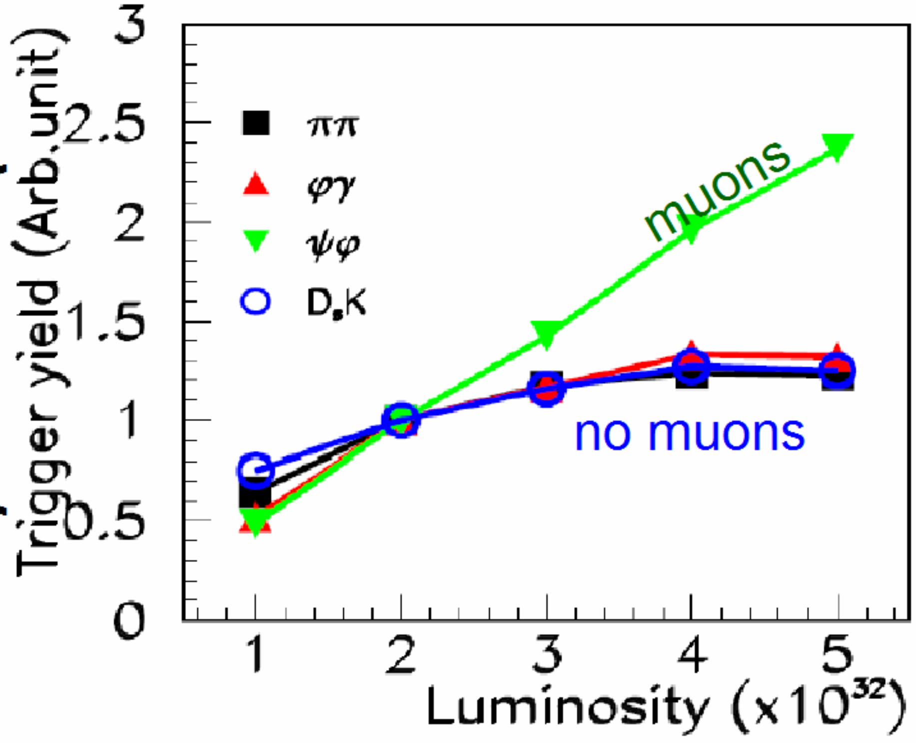


- For "light" Higgs, b-jets are "soft". LHCb can still trigger on them.
- Expect a few thousands of them triggered & reconstructed in 2 fb^{-1}


~ 14k Higgses in LHCb acceptance for 2fb^{-1}
~ 30-35% trigger efficiency
⇒ ~ 4-5k Higgs decays (low bckgrd) before offline analysis

Why LHCb upgrade?

- Will reach ~10 fb^{-1} in ~5 years (hopefully will discover signs of NP).
- Need ~100 fb^{-1} to reach theoretical limits of sensitivity in many channels. Collecting data for 50 years not practical.
- LHCb luminosity limited by the detector not LHC!
  - Radiation damage (spec was <20 fb^{-1}) especially in VELO.
  - No gain from increased luminosity for channels relying on L0 hadron trigger



SuperLHCb

- **Eliminate hardware L0 trigger. Readout all detectors at 40MHz to HLT farm.**
- Use software triggers only:
  - MU, HCAL with lower Et threshold, followed by VELO tracking (confirmation, IP) and VELO-TT Pt measurement, before tracking through the magnet.
- New radiation hard VELO (pixels!)
- Need new FE for all subdetectors (40 MHz).
- Need new RICH photo-detectors (present HPDs are integrated with 10MHz readout chip) – MaPMTs.
- Possibly also:
  - New T-stations to reduce occupancy in straws (larger IT).
  - Enhance low momentum K/π separation with TORCH (ToF detector timing Cerenkov photons radiated in quartz).
- Timeline: EOI (Apr.08), LOI (Dec.10), installation 2016?

Upgrade summary

- ATLAS and CMS will hopefully observe NP via direct production!
- Observing effects of these particles in loops will help determine nature of new interactions.
- We hope to see these effects in 10 fb^{-1}
- Upgrading will allow us to precisely measure these effects, and in most of the search windows hit the theoretical limitations.
- For many NP scenarios loops probe energy scales larger than directly reachable.
  - It is possible NP will be first seen in the loops
  - In depressing scenario in which no NP is seen at LHC, loops will set scale for new energy scales to be reached.

Upgraded Sensitivities (100 fb^{-1})

Observable	Sensitivity
$CPV(B_s \to \phi\phi)$	0.01-0.02
$CPV(B_d \to \phi K_s)$	0.025-0.035
$CPV(B_s \to J/\psi\phi)$ $(2\beta_s)$	0.003
$CPV(B_d \to J/\psi K_s)$ (2β)	0.003-0.010
$CPV(B \to DK)$ (γ)	$<1^o$
$CPV(B_s \to D_s K)$ (γ)	$1\text{-}2^o$
$B(B_s \to \mu^+\mu^-)$	5-10% of SM
$A_{FB}(B \to K^*\mu^+\mu^-)$	Zero to ± 0.07 GeV^2
$CPV(B_s \to \phi\gamma)$	0.016-0.025
Charm mixing x'^2	$2x10^{-5}$
Charm mixing y'	$2.8x10^{-4}$
Charm CP y_{CP}	$1.5x10^{-4}$

Conclusion

- Loop processes are a crystal ball of high energy physics:
  - Spectacular successes in the past
  - Tight constraints on NP physics at energy scales extending beyond those probed by tree diagrams
  - Hunt for NP in loops at LHCb has just started

From Wikipedia:
Seers, wizards, sorcerers, psychics, gypsies, fortune tellers, and all other types of diviners also used crystal balls to "see" into the past, present, or future.

LHCb collboration:
800 physicist,
54 instititutions,
15 countries