LHCb Experiment
-Physics and Detector-

On behalf of the LHCb collaboration

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Why is CP violation highly interesting?

- No precision test of the Standard Model in CP violation so far: we cannot exclude that CP violation is **partly** due to **new physics**.

  (Why strong ~~CP~~ is small but weak ~~CP~~ not?)

- Since CP violation is due to an "interference", it is **sensitive to a small effect** due to **new physics**.

- Cosmology (baryon genesis) suggests that an **additional source** of CP violation other than the Standard Model is needed.

A promising place to look for new Physics

CKM matrix;

in the Standard Model, CP violation is due to $\eta \neq 0$

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

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

Qualitatively, the Standard Model predicts

- $|\eta_{+-}| \neq |\eta_{00}|$

  so called Re(ε′/ε)=~10^{-3} due to CP violation in decay:

  penguins+tree

  NA31:$(2.30\pm0.65)\times10^{-3}$, E731:$(0.74\pm0.60)\times10^{-3}$

  NA48: ?, KTeV:$(2.80 \pm 0.41)\times10^{-3}$

- $Br(K_L \rightarrow \pi^0\nu\bar{\nu})\approx10^{-11}$

  so called CP violation in the interplay between decay (penguin) and oscillation (box)

  Being discussed at FNAL and BNL (CERN?)

- Very small CP violation in charged kaon decays,

etc.

In kaon system,
high precision test is rather difficult due to
theoretical uncertainties in the Standard Model
introduced by strong interactions.

↓

B-meson system

Standard way to extract the CKM elements

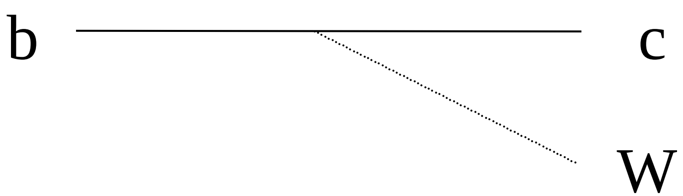
If there is nothing else but the Standard Model,

$|V_{cb}|$, $|V_{ub}|$ — B-meson decays (usually semileptonic)

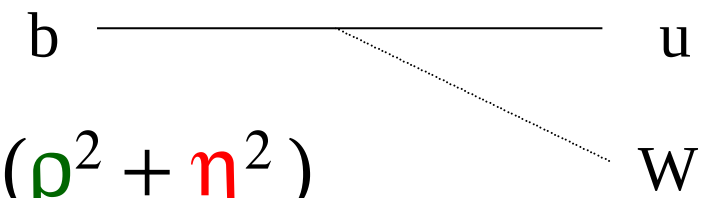
Δm_d — B_d-$\bar{B}_d$ oscillations

will fix all the Wolfenstein's parameters,

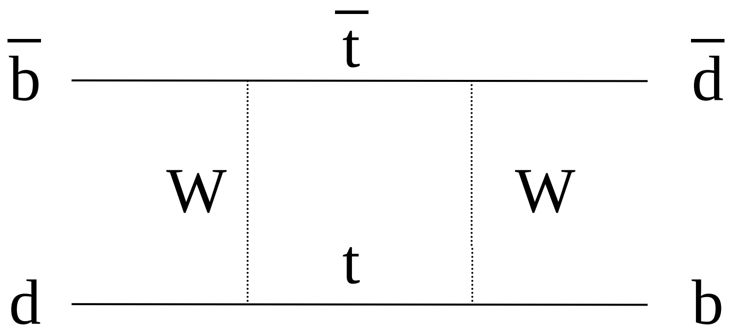
A, ρ and η (λ is well known).



A^2



$A^2\,(\rho^2 + \eta^2)$

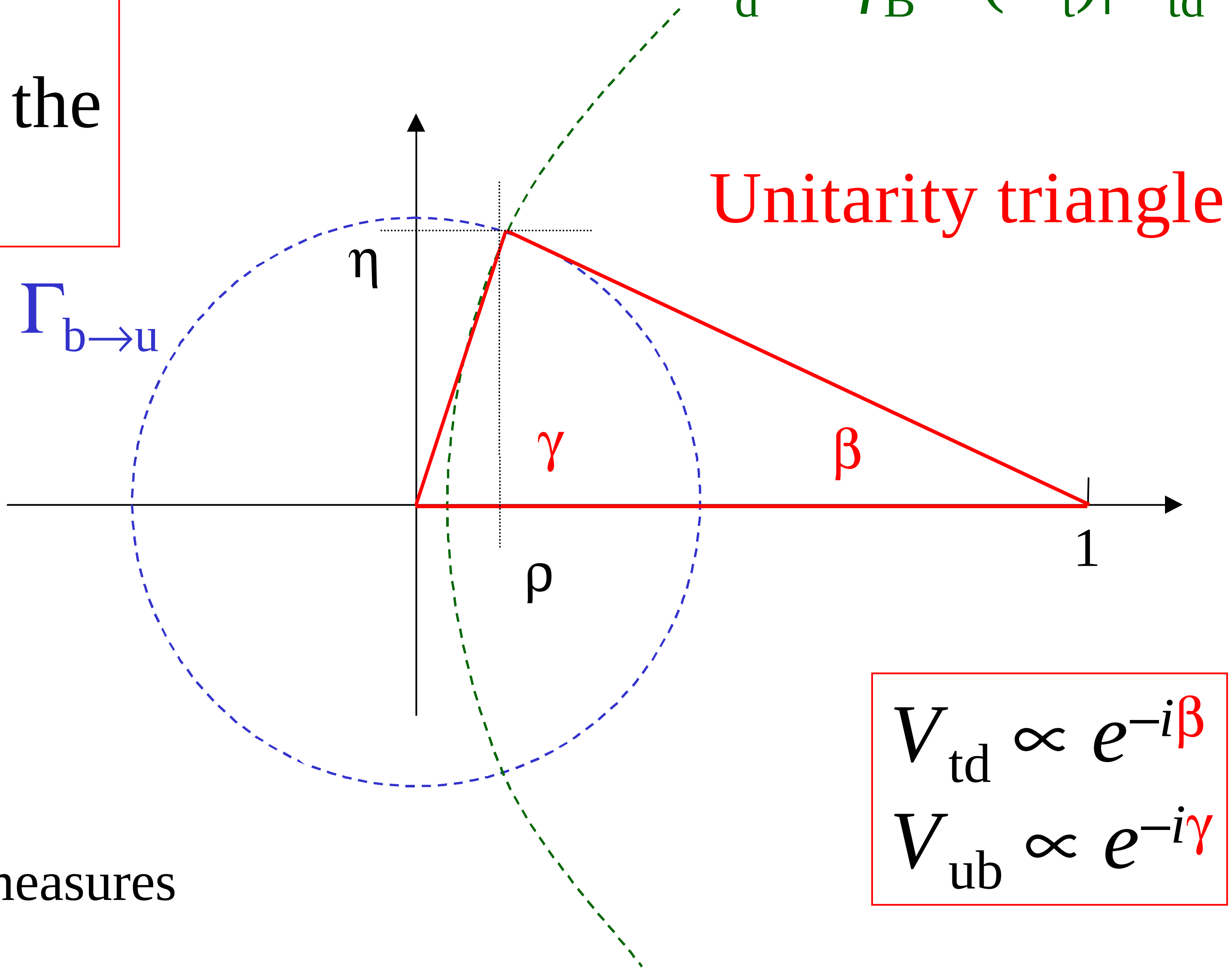


$A^2\,[(1-\rho)^2 + \eta^2]$

From the neutral kaon system $\eta > 0$

β and γ are defined by the sides

$$\Delta m_d \propto B f_B^2 F(m_t)|V_{td} V_{tb}|^2$$

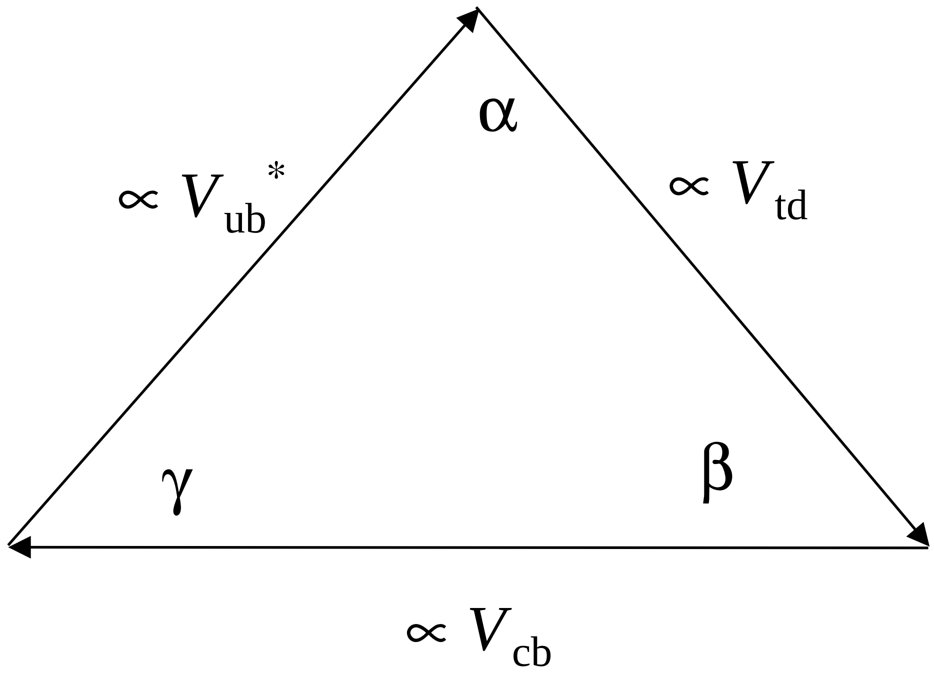


$$V_{td} \propto e^{-i\beta}$$
$$V_{ub} \propto e^{-i\gamma}$$

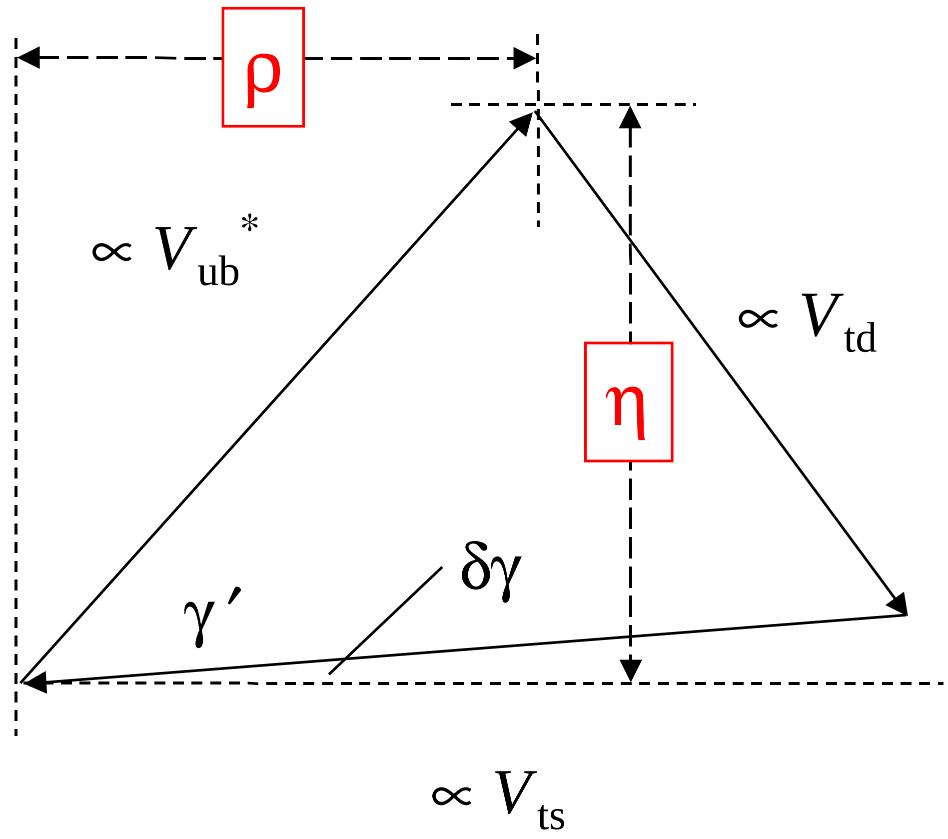
NB:
$Br(K^{\pm} \to \pi^{\pm} \nu\bar{\nu})$ measures also $|V_{td}|$

CKM Unitarity Triangles

$$V_{td}V_{tb}^{*} + V_{cd}V_{cb}^{*} + V_{ud}V_{ub}^{*} = 0$$



$$V_{td}V_{ud}^{*} + V_{ts}V_{us}^{*} + V_{tb}V_{ub}^{*} = 0$$

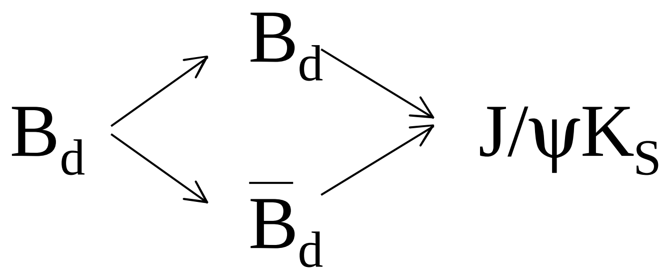


$$\arg V_{cb} = 0,\ \arg V_{ub} = -\gamma,\ \arg V_{td} = -\beta,\ \arg V_{ts} = \pi + \delta\gamma$$

CP violation in

$B_d \to J/\psi\, K_S$ v.s. $\bar{B}_d \to J/\psi\, K_S$

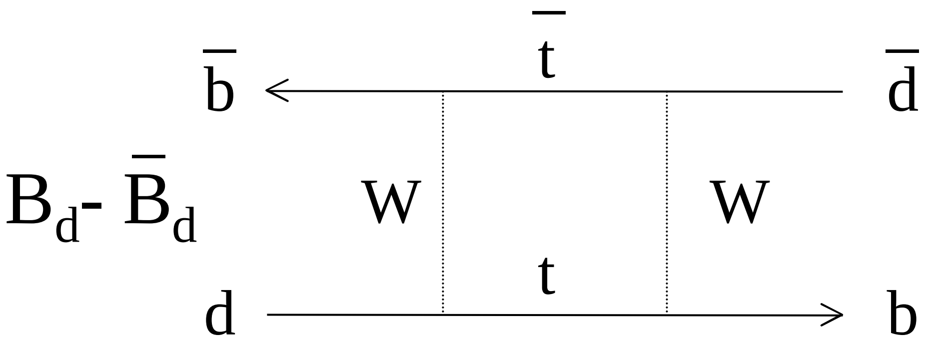
measures the phase of V_{td}, i.e. β

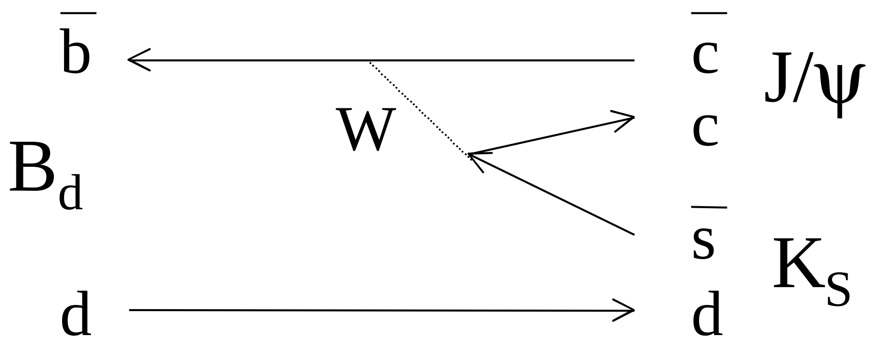


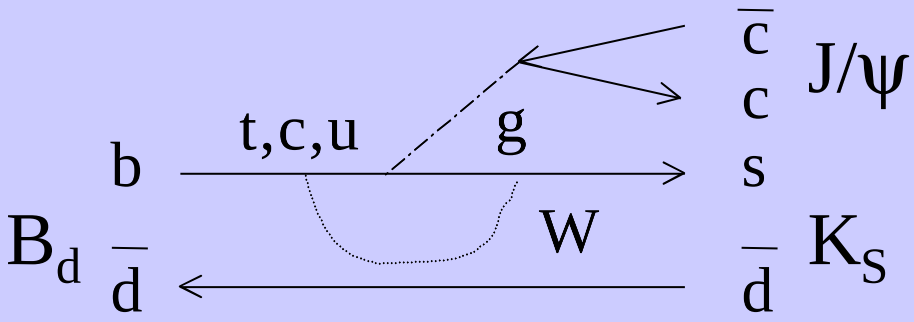
compare two β measurements = consistency test

$H_{B\text{-}\bar{B}} \propto (V_{tb}^{*}\, V_{td})^2 \propto e^{2i\beta}$

$A_{B\to J/\psi Ks} \propto V_{cb}^{*}\, V_{cs} \propto e^{0i}$







Penguin effect is negligible

By 2005, CLEO, BaBar, BELLE, CDF, D0 and HERA-B will have

- accurate $|V_{ub}|$, $|V_{cb}|$ and
- β from CP violation in $B_d \to J/\psi\, K_S$ with $\sigma \sim 0.025$

CDF(1999)
$\sin 2\beta = 0.79^{+0.41}_{-0.44}$

(Expected range in the Standard Model: $0.3 < \sin 2\beta < 0.8$)

Possibilities are

a) There will be already a sign of new physics:

- precision measurements in different decay modes in order to pin down the details of new physics.

b) Measurements look "consistent" with the Standard model.

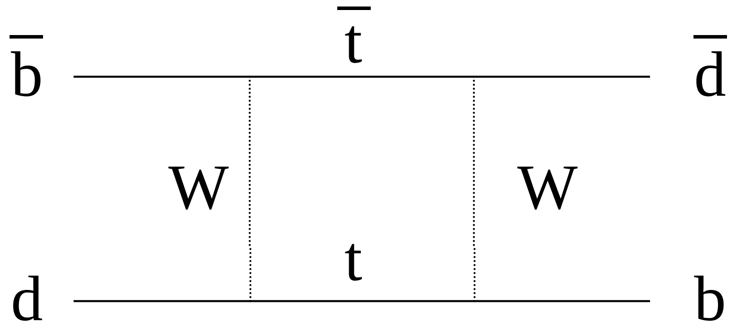
- what could happen?

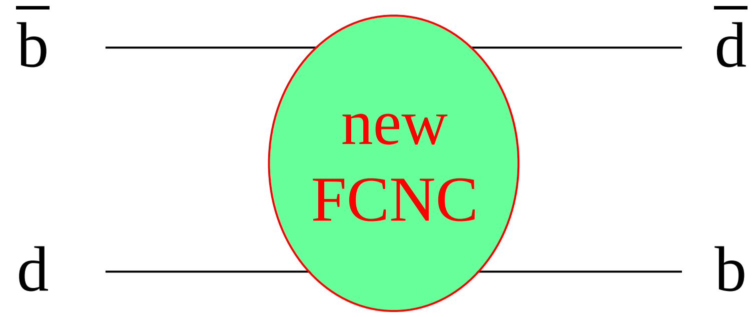
Let's make the following "interesting" scenario.

A model for new physics

$$H_{B\text{-}\bar{B}} \propto [\{(1-\rho)^2+\eta^2\}+ r_{db}]\ e^{2i(\beta+\phi_{db})}$$

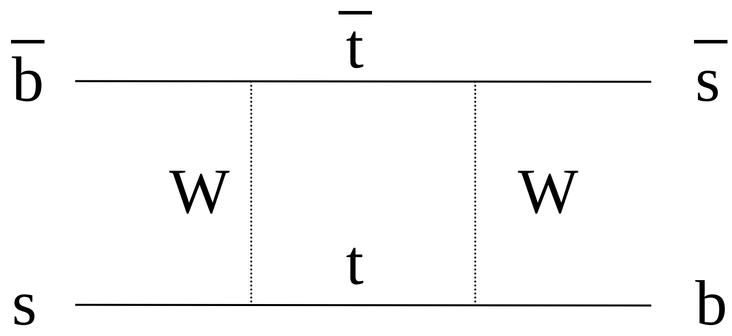
B_d- $\bar{B}_d$

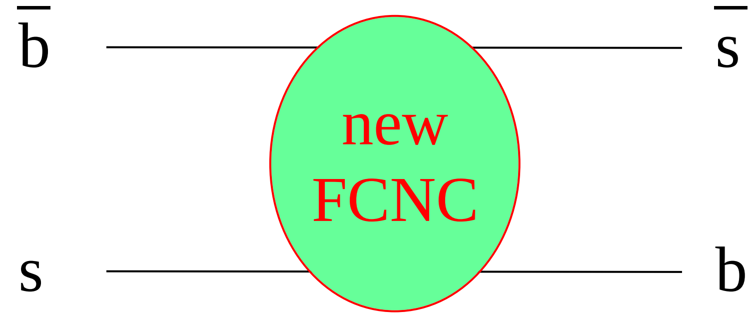




$$H_{B\text{-}\bar{B}} \propto [\ \lambda^{-2}+ r_{sb}\ ]\ e^{-2i(\delta\gamma+\phi_{sb})}$$

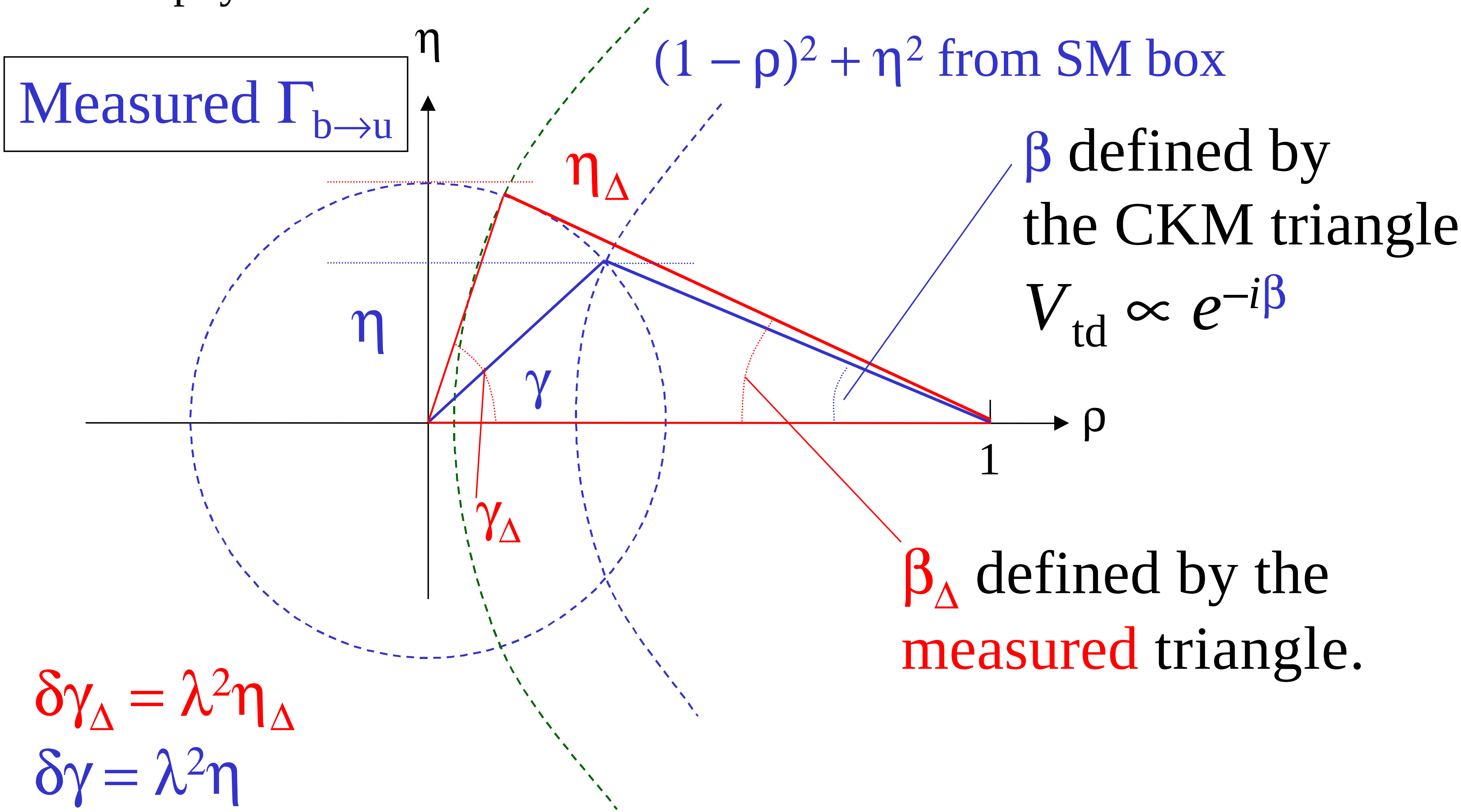
B_s- $\bar{B}_s$





semileptonic decays
are least effected by
new physics

Measured $\Delta m(B_d) \rightarrow (1-\rho)^2 + \eta^2 + r_{db}$



$\delta\gamma_\Delta = \lambda^2 \eta_\Delta$

$\delta\gamma = \lambda^2 \eta$

CP violation in

$B_d \to J/\psi\, K_S$ v.s. $B_d \to J/\psi\, K_S$

measures $\beta_{J/\psi K} = \beta + \phi_{db}$

If the model is such that numerically $\phi_{db} \approx \beta_{\Delta} - \beta$

"$\beta_{J/\psi K} = \beta_{\Delta}$"

CP measurement and triangle measurements agree with each other.

$\to$ Looks consistent with the Standard Model!

CP violation in

$B_d \to D^{*+} n\pi$ v.s. $\overline{B}_d \to D^{*-} n\pi$

$B_d \to D^{*-} n\pi$ v.s. $\overline{B}_d \to D^{*+} n\pi$

measures $2(\beta + \phi_{db}) + \gamma$

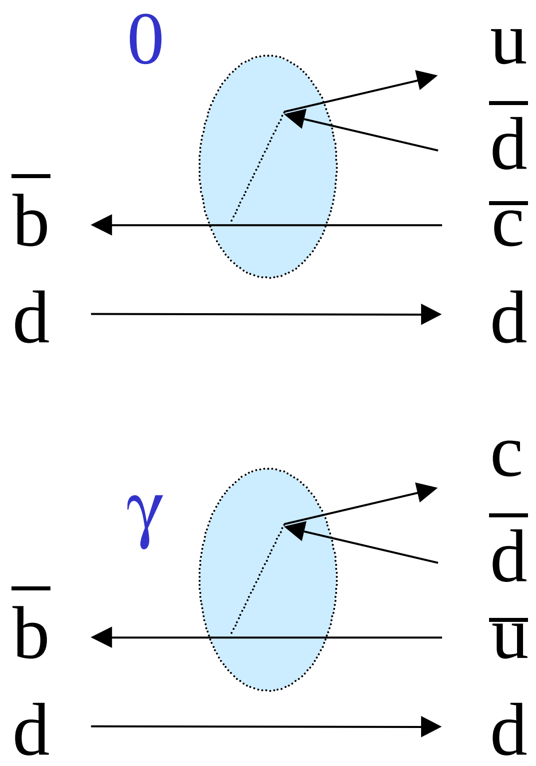
$\beta_{J/\psi K}$ is already measured $\to \gamma$

"$\gamma \neq \gamma_\Delta$"

CP measurement is

inconsistent

with triangle measurements!



$B_d \to \overline{B}_d \Rightarrow 2(\beta + \phi_{db})$

Similarly, $B_d \to \pi^+\pi^-$ and $B_d \to$ measure $\beta + \phi_{db} + \gamma$

CDF, D0 and HERA-B may be able to measure $\Delta m(\mathrm{B_s})$

$$\frac{\Delta m(\mathrm{B_d})}{\Delta m(\mathrm{B_s})} = \frac{A^2\lambda^4\left[(1-\rho)^2+\eta^2\right]+r(\mathrm{db})}{A^2\lambda^2+r(\mathrm{sb})}$$

It helps to reduce hadronic uncertainties:

$f_\mathrm{B}{}^2 B$ (~20% error, lattice calculation)

$f_\mathrm{B}{}^2 B(\mathrm{B_d})/f_\mathrm{B}{}^2 B(\mathrm{B_s})$ is much better known (~5% error)

But cannot resolve new physics.

CP violation in

$$B_s \rightarrow J/\psi\, \phi \text{ v.s. } \overline{B}_s \rightarrow J/\psi\, \phi$$

measures $\delta\gamma + \phi_{sb}$

CP violation in

$$B_s \rightarrow D_s^+ K^- \text{ v.s. } \overline{B}_s \rightarrow D_s^- K^+$$

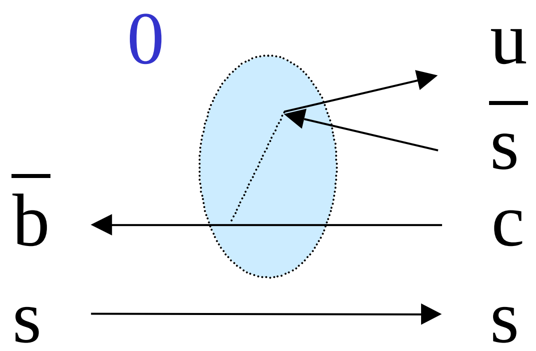
$$B_s \rightarrow D_s^- K^+ \text{ v.s. } \overline{B}_s \rightarrow D_s^+ K^-$$

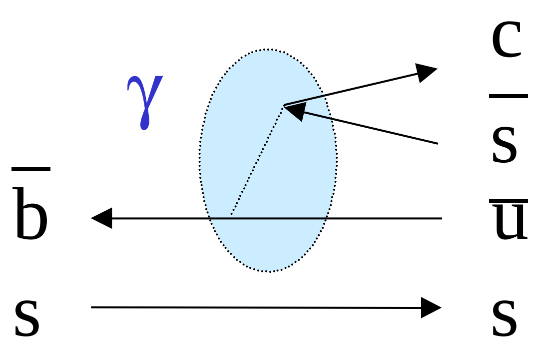
measures $2(\delta\gamma + \phi_{sb}) + \gamma$

Combination of two $\rightarrow \gamma$

"$\gamma \neq \gamma_\Delta$"

CP measurement is **inconsistent** with triangle measurements!





$$B_s \rightarrow \overline{B}_s \Rightarrow 2(\delta\gamma + \phi_{db})$$

Potential problems for BaBar, BELLE, CDF, D0, HERA-B

α ($\beta+\gamma$, or $2\beta+\gamma$):

$\pi^+\pi^-$	small branching fraction $<10^{-5}$
	large penguin contribution
	possible new physics effect in the decay
	need particle ID at large *p* (CDF, D0)
$\rho\pi$	time dependent Dalitz plot fit requires high statistics
	some theoretical assumption about resonances
$D^*\pi$	small asymmetries require high statistics

γ:

DK^*	small branching fractions $<<10^{-5}$
	many-fold ambiguities
D_sK	need B_s (BaBar, BELLE)
	particle ID at large *p* (CDF, D0)
	small branching fractions $<10^{-5}$

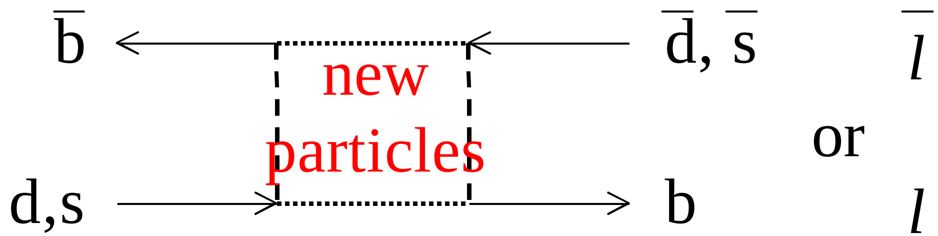
More generally new physics can appear in

$\Delta b = 1$ process

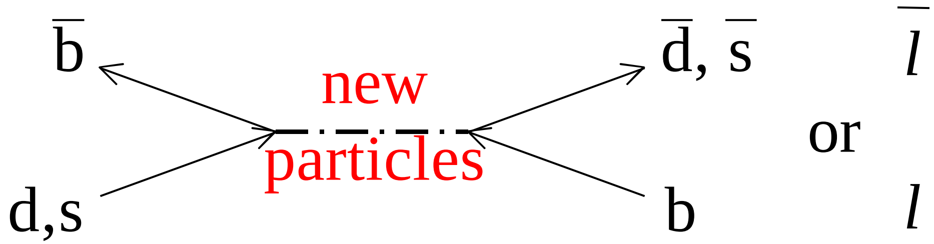
through penguin

$\Delta b = 2$ process

through box



through tree



CP violation must be studied in

B_d decays via Oscillations ⊗ b→c+W and b→u+W

B_s decays via Oscillations ⊗ b→c+W and b→u+W

$B_{d,s,u}$ decays via penguins

$B_{d,s}$ decays via box

Experimental requirements are

Small branching fractions → many $B_{d,s,u}$'s

Rapid B_s oscillations → decay time resolution

Including multi-body hadronic final states → particle ID
mass resolution
sensitive trigger

→ ***LHCb*** **experiment**

At LHC, we will have

- large $b\bar{b}$ cross section of

  ~500 μb

- "reasonable" signal/noise ratio of

  $\sigma_{b\bar{b}}/\sigma_{inelastic} \sim 5\times10^{-3}$

  This is similar to $\sigma_{cc}/\sigma_{inelastic}$ of the present fixed target charm experiments.

Overview of the Experiment

Spectrometer:

A single-arm spectrometer covering

θ_{min} = ~15 mrad (beam pipe and radiation)

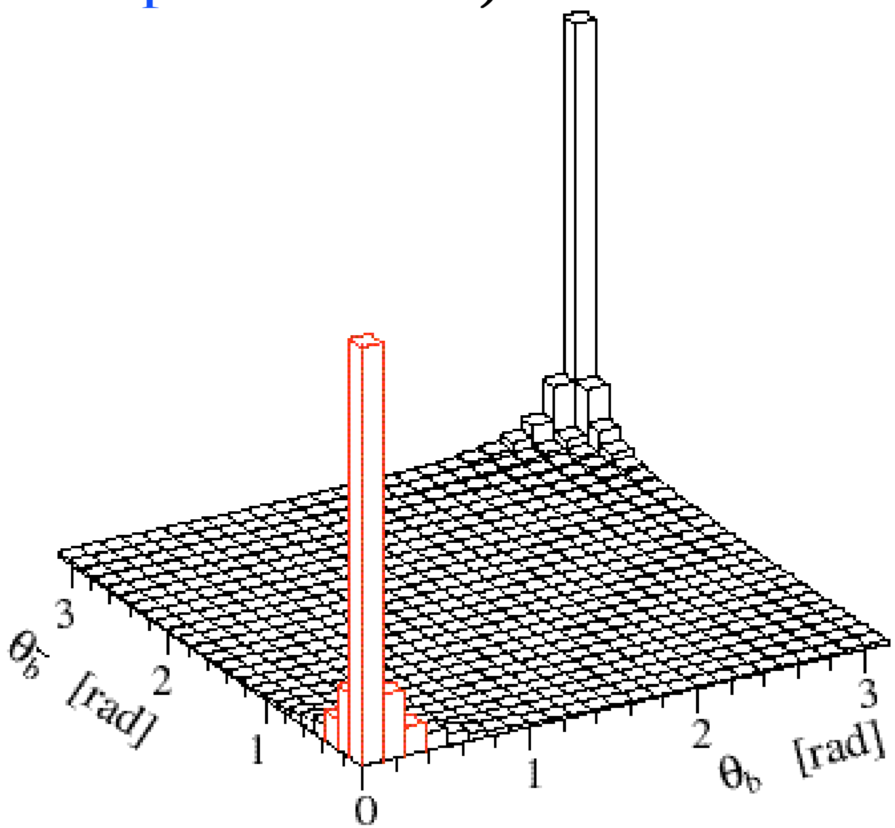
to

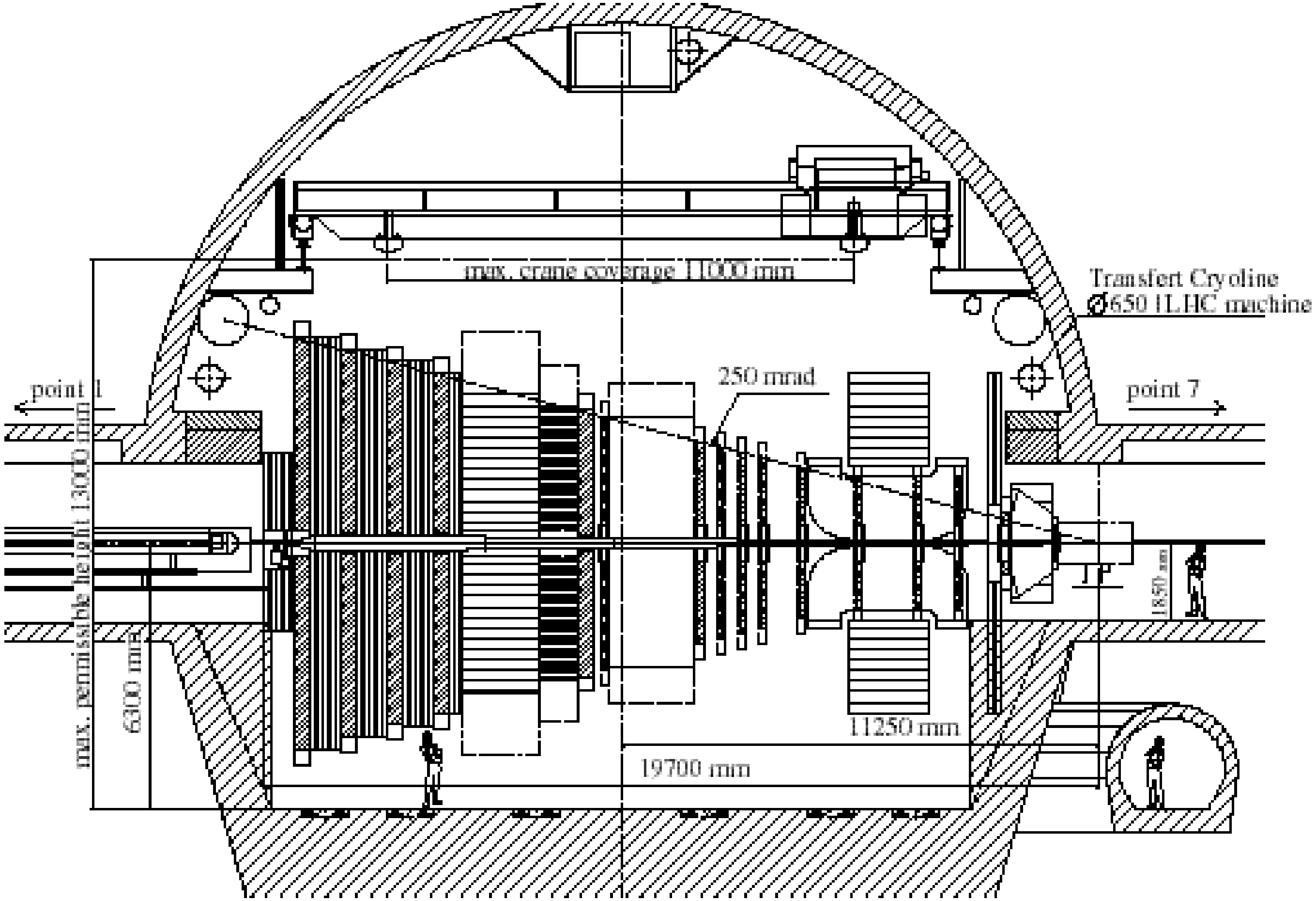
θ_{max} = ~300 mrad (cost optimisation)

i.e. η = ~1.88 to ~4.89

has an equal $b\bar{b}$ acceptance

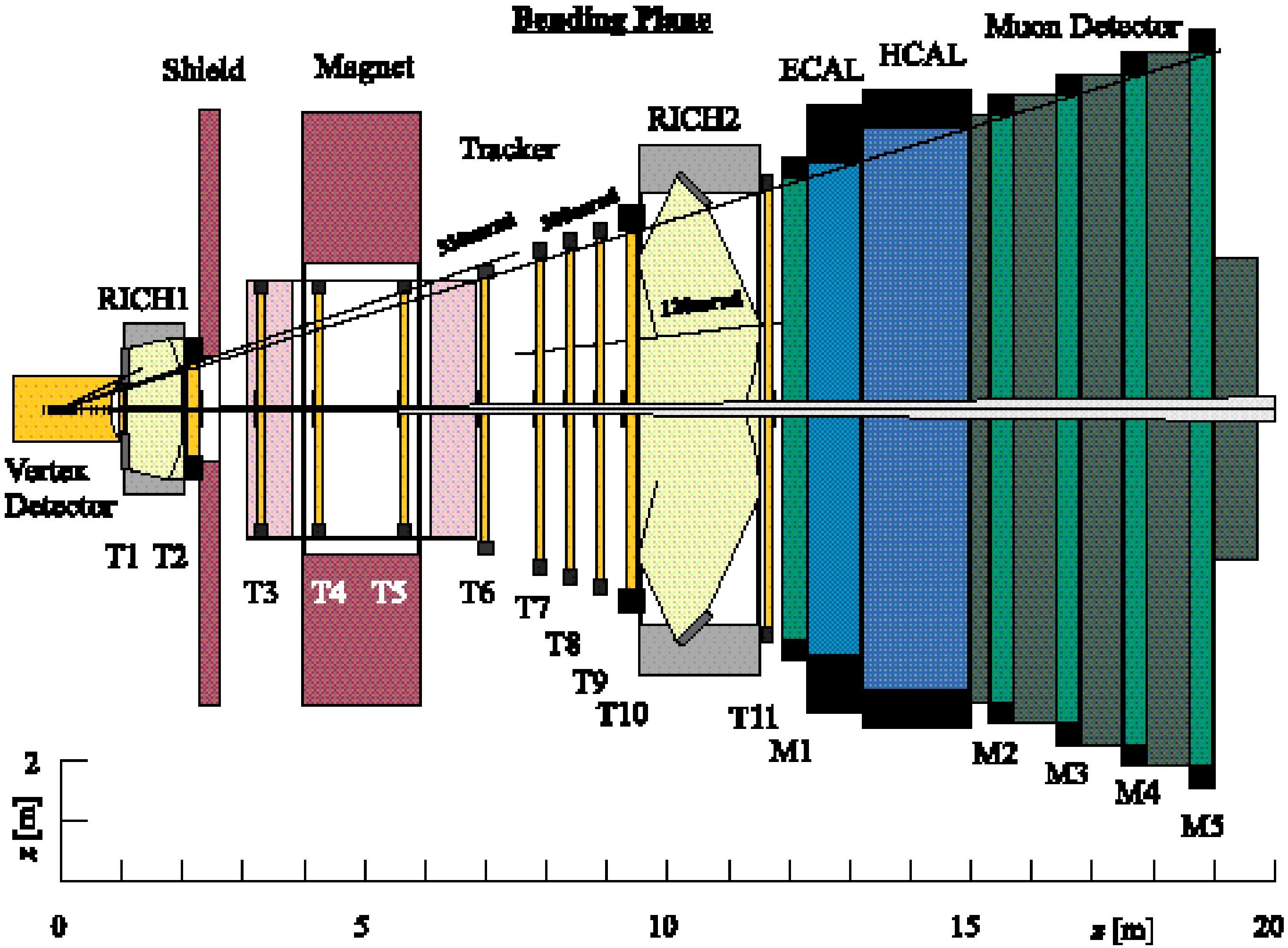
as a large central detector.




max. crane coverage 11000 mm
Transfert Cryoline
Ø650 LHC machine
point 1
point 7
250 mrad
max. permissible height 13000 mm
6300 mm
1850 mm
11250 mm
19700 mm

IP 8

The LHCb Detector



The LHCb Detector (Technical Proposal)

Vertex detector:

Si r-ϕ strip detector, single-sided, 150μm thick, analogue readout

Tracking system:

Outer; drift chamber with honeycomb technology

Inner; Micro Strip Gas Chamber with Gaseous Electron Multiplier
or Micro Cathode Strip Chamber (backup solution Si)

RICH system:

RICH-1; Aerogel (n = 1.03) C_4F_{10} (n = 1.0014)

RICH-2; CF_4 (n = 1.0005)

Photon detector; Hybrid Photon Diodes (backup solution PMT)

Calorimeter system:

Preshower; Single layer Pb/Si (14/10 mm)

Electromagnetic; Shashilik type 25X_0 10% resolution

Hadron; ATLAS design tile calorimeter 7.3λ 80% resolution

Muon system:

Multi-gap Resistive Plate Chamber and Cathode Pad Chamber

Physics capability of the LHCb detector is due to:

- Trigger efficient for both leptons and hadrons

  high p_T hadron trigger $\Rightarrow$ 2 to 3 times increase in

  $\pi\pi, K\pi, D^*\pi, DK^*, D_s\pi, D_sK$ …

  $D_s\pi$: ATLAS=3k, CMS=4.2k, LHCb=34k /year

- Particle identification e/μ/π/K/p

  $\pi\pi, K\pi, D^*\pi, DK^*, D_s\pi, D_sK$

- Good decay time resolution

  e.g. 43 fs for $B_s \rightarrow D_s\pi$, 32 fs for $B_s \rightarrow J/\psi\phi$

  ATLAS($D_s\pi$)=73 fs, CMS($J/\psi\phi$)=68 fs

- Good mass resolution

  e.g. 11 MeV for $B_s \rightarrow D_s\pi$, 17 MeV for $B_d \rightarrow \pi^+\pi^-$

  ATLAS($D_s\pi$)=40 MeV, CMS($\pi^+\pi^-$)=31 MeV

particle ID + mass resolution $\Rightarrow$ redundant background rejection

LHCb Trigger Efficiency

for reconstructed and correctly tagged events

	L0(%)				L1(%)	L2(%)	Total(%)
	μ	e	h	all			
$B_d \to J/\psi(ee)K_S$ + tag	17	**63**	17	72	42	81	**24**
$B_d \to J/\psi(\mu\mu)K_S$ + tag	**87**	6	16	88	50	81	**36**
$B_s \to D_s K$ + tag	15	9	**45**	54	56	92	**28**
$B_d \to DK^*$	8	3	31	37	59	95	21
$B_d \to \pi^+\pi^-$ + tag	14	8	**70**	76	48	83	**30**

- trigger efficiencies are ~ 30%
- hadron trigger is important for hadronic final states
- lepton trigger is important for final states with leptons

Importance of particle identification

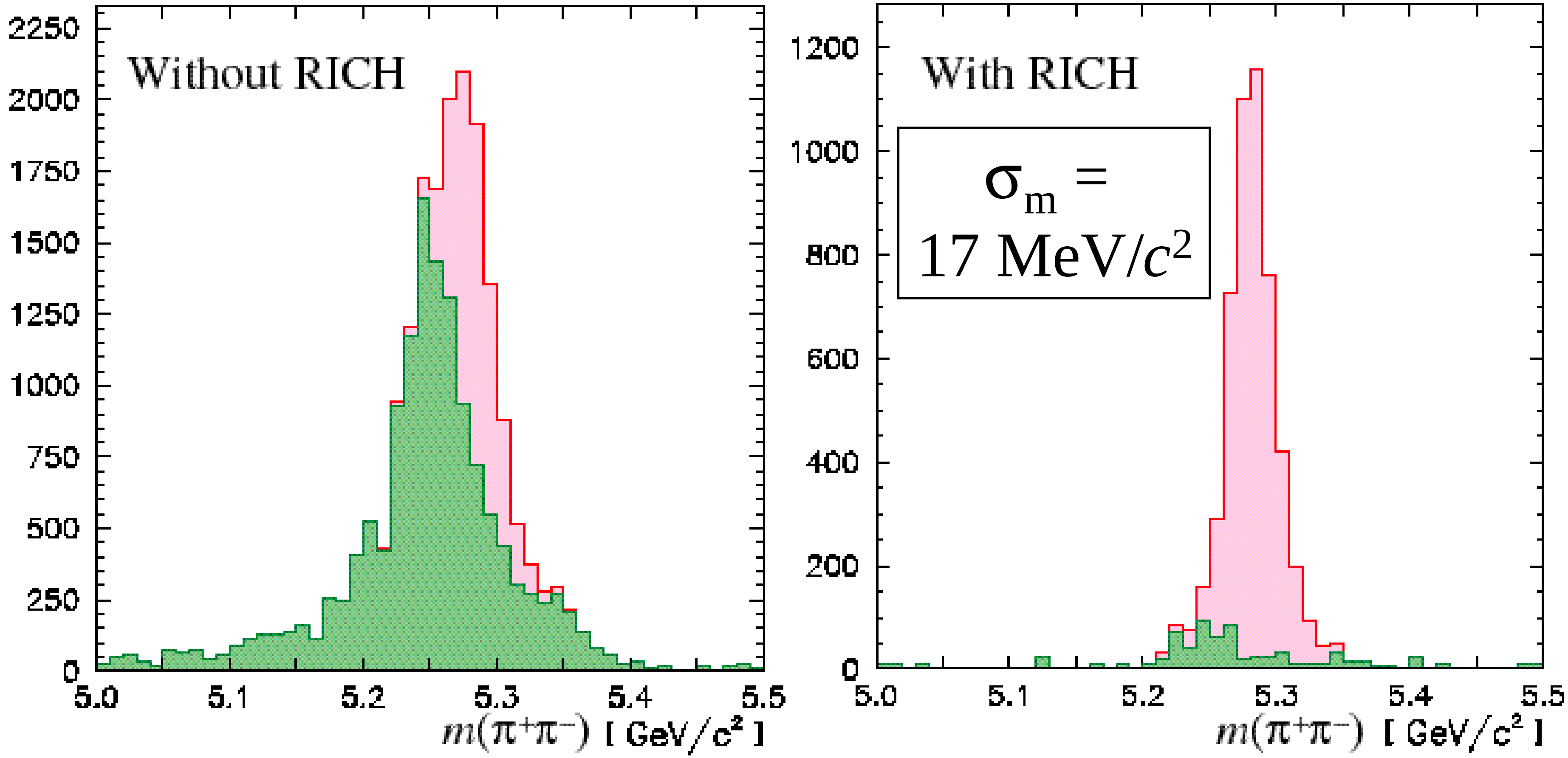
Br: $B_d \to \pi^+\pi^- = 0.7\times10^{-5}$, $\to K^\pm\pi^\mp = 1.5\times10^{-5}$

$B_s \to K^+K^- = 1.5\times10^{-5}$, $\to K^\pm\pi^\mp = 0.7\times10^{-5}$

All combinations

Background

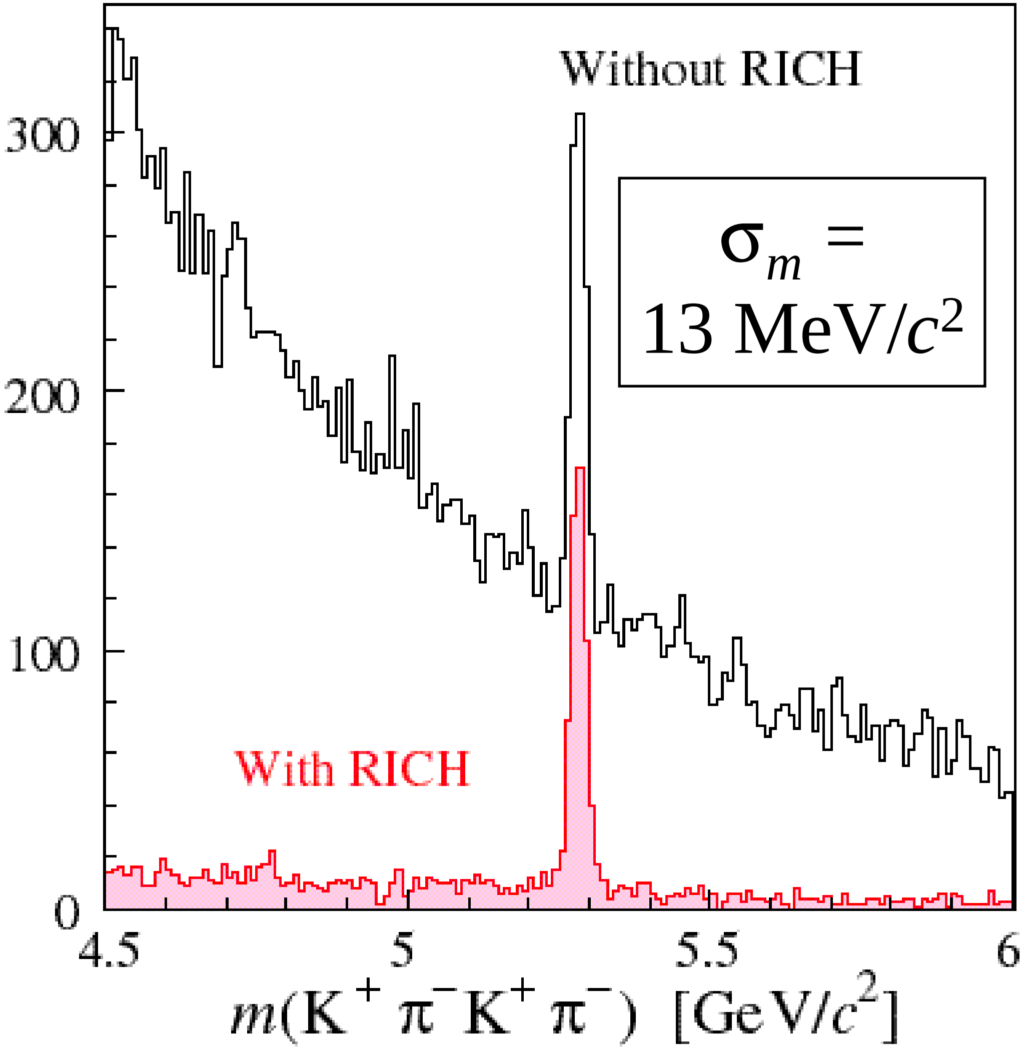
eff. = 85%



Very small visible branching fractions

(10^{-7}~10^{-8})

Importance of particle identification

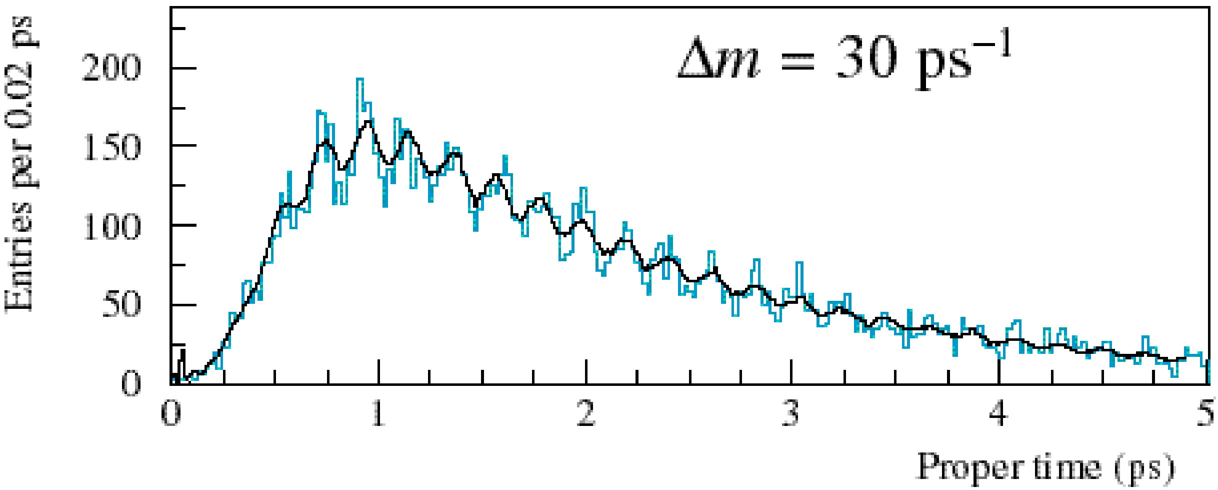


With signal events

B_s-$\bar{B}_s$ oscillations with $B_s \to D_s \pi$

120 k reconstructed and tagged events

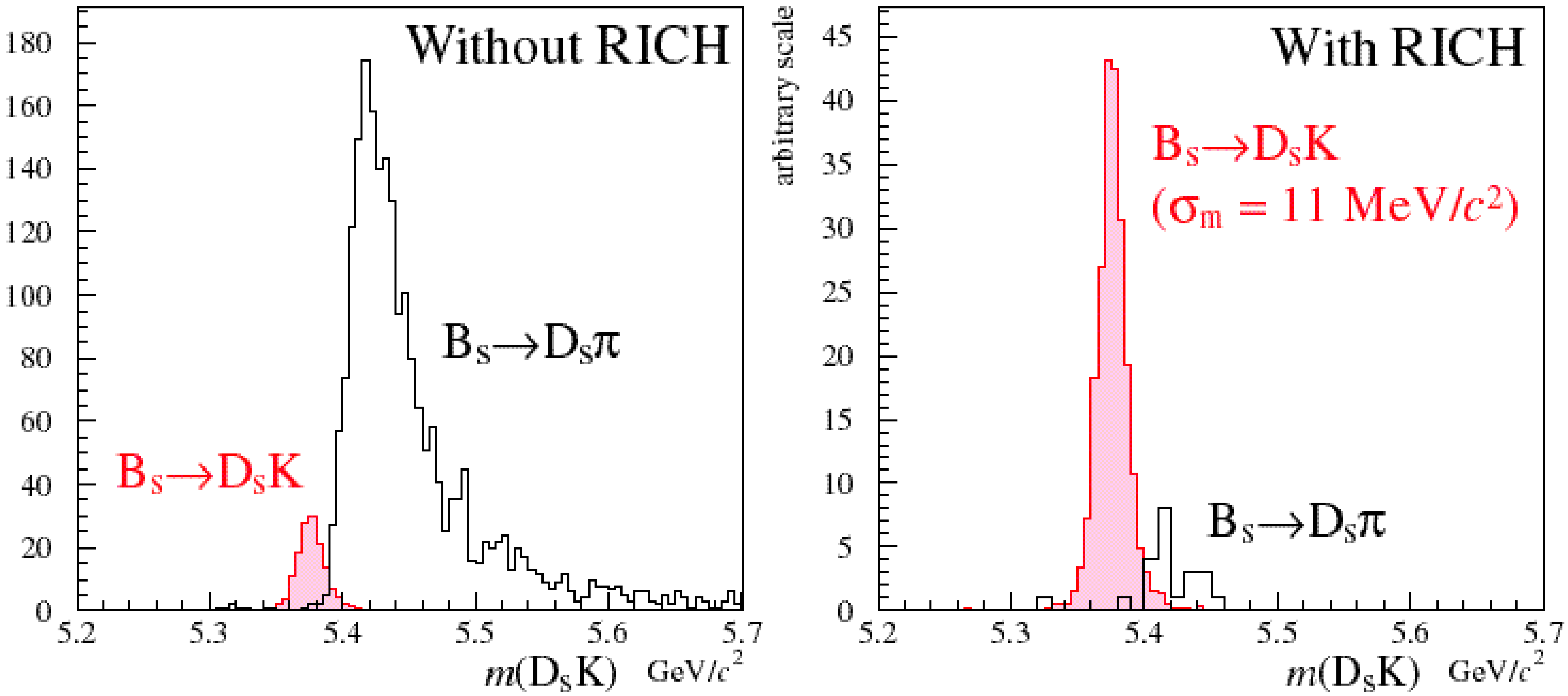
measurements of Δm_s with a significance >5: up to 48 ps^{-1} ($x_s = 75$)



$B_s \to D_sK$

Major background: $B_s \to D_s\pi$ (No CP violation)

Importance of particle identification and mass resolution



Performance figures are supported in particular by:

- GEANT detector simulation

- Low luminosity (2×10^{32} $cm^2 s^{-1}$) needed

- Flexible and robust early level trigger

  Level-0: High p_t e, μ, h, Level-1: Vertex

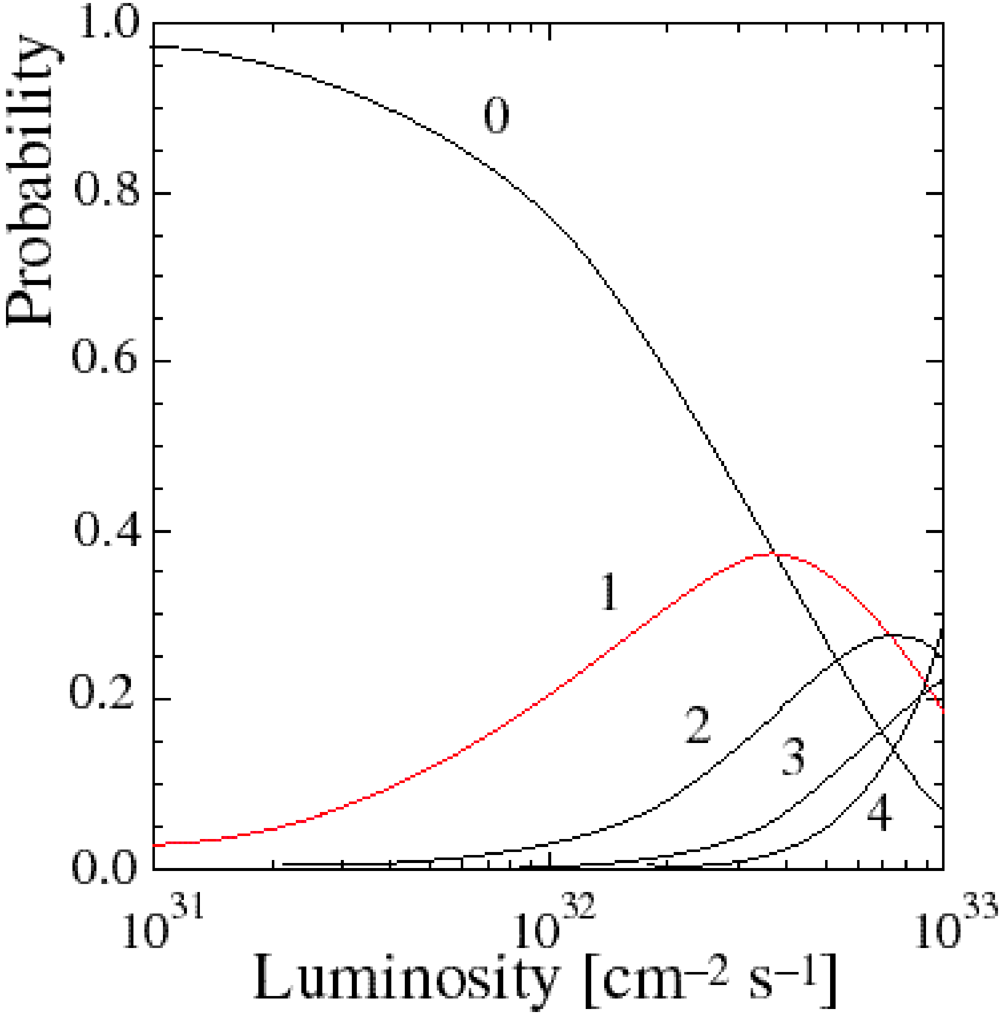
- Conservative approach to the detector

Optimal Running luminosity is determined by

# of bunch crossing with one pp interaction

vs

radiation damage, detector occupancy, bunch-bunch pile-up, etc.



LHCb
Average running luminosity
2×10^{32} cm^{-2} s^{-1}
(tuneable)

4.5×10^{11} $B^0+\bar{B}^0$ in one year

1.3×10^{11} $B_s^0+\bar{B}_s^0$

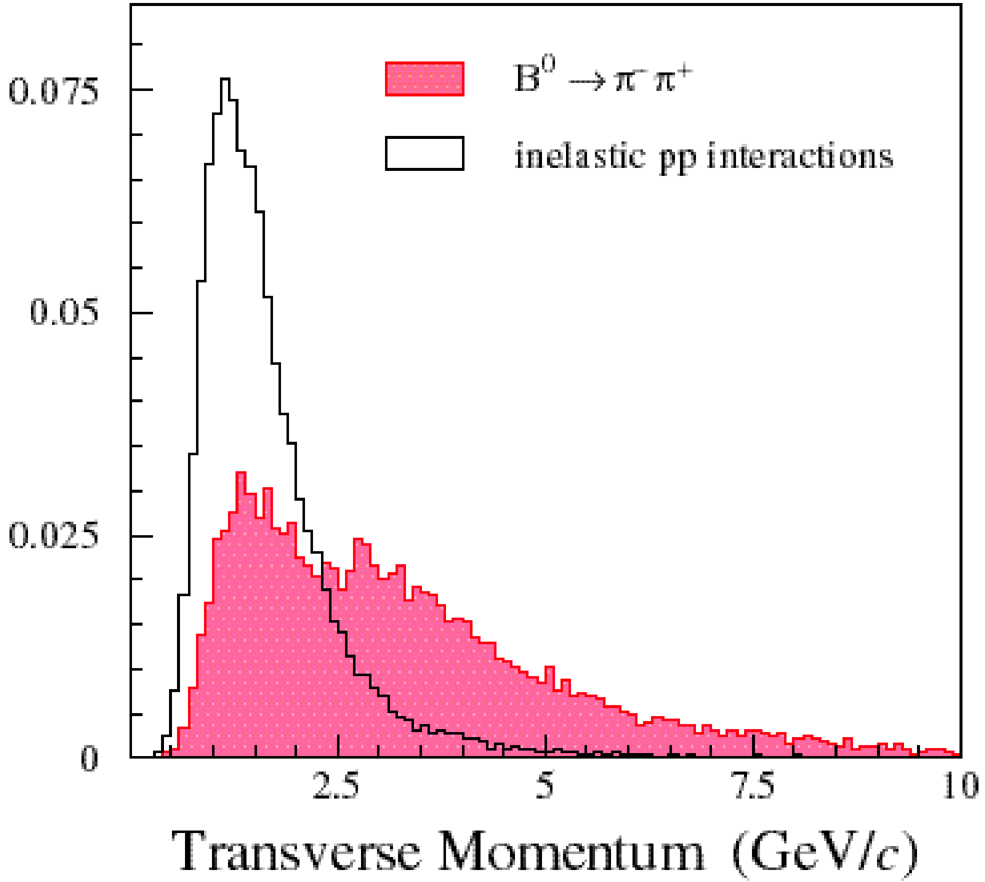
Trigger:

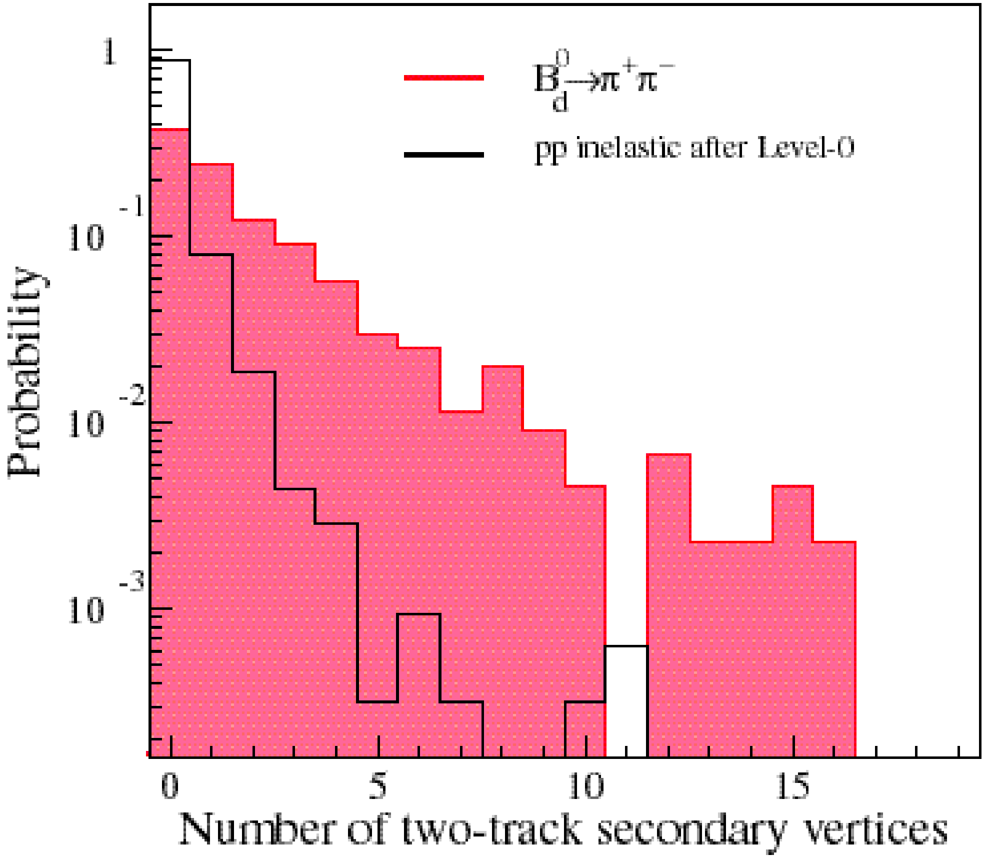
Flexible: Multilevel with different ingredients

Robust: Evenly spread selectivities over all the levels

Efficient: High p_T leptons and hadrons

Detached decay vertices



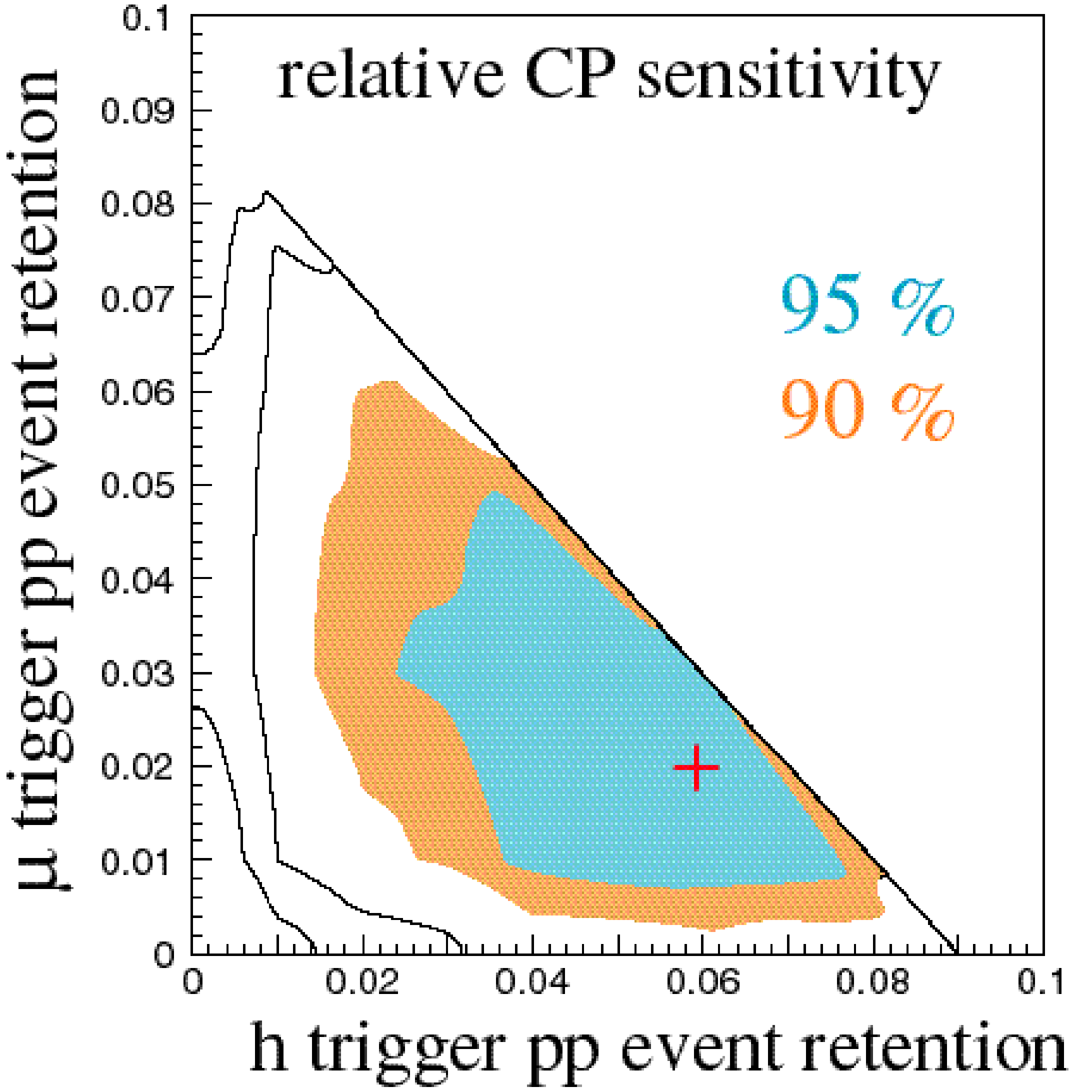


Level	Characteristics	Sub-detector		
Level-0	high p_T			in-put
	:e	ECAL	(60k	40 MHz
	:h	E+HCAL	channels)	
	:μ	Muon		latency
	pile-up	Pile-up		3.2 μs
	on-detector → off-detector electronics (1 TB/s)			
Level-1	sec. vertices	Vertex	(220k)	1 MHz
	high p_T	Trackers+L0-Seed		<256 μs
	off-detector → event buffer (2-4 GB/s)			
Level-2	refined	Vertex		40 kHz
	sec. vertices	+ Trackers		10 ms
Level-3	partial and full	All		5 kHz
	reconstruction of			200 ms
	final states		To tape = 200 Hz	

Trigger operating point can be adjusted to the running condition without loss in physics.

Example:

Thresholds for three different L0 trigger components can be adjusted depending on the running condition.



Example of "shopping list":	LHCb	ATLAS/CMS
$B_d \to J/\psi K_S$	✓	✓
$B_s \to J/\psi\phi$	✓	✓
$B_s \to D_S K$	✓	✗ (PID)
$B_d \to DK^*$	✓	✗ (PID,Trigger)
$B_d \to D^*\pi$	✓	✗ (PID)
$B_d \to \pi\pi$	✓	✗ (PID)
$B_d \to K\pi$ ($\not{C}\not{P}$ in gluonic penguin)	✓	✗ (PID)
$B_d \to \rho\pi$	✓	?
(BaBar 160 events, LHCb 670 events / year)		
$B_s \to K^*\gamma$ ($\not{C}\not{P}$ in radiative penguin)	✓	?
$B_s \to K^* l^+ l^-$ ($\not{C}\not{P}$ in radiative penguin)	✓	✓
B_s oscillations, x_s up to	75	38
$B_s \to \mu^+\mu^-$	✓	✓

The *LHCb* Experiment

Brazil

Finland

France

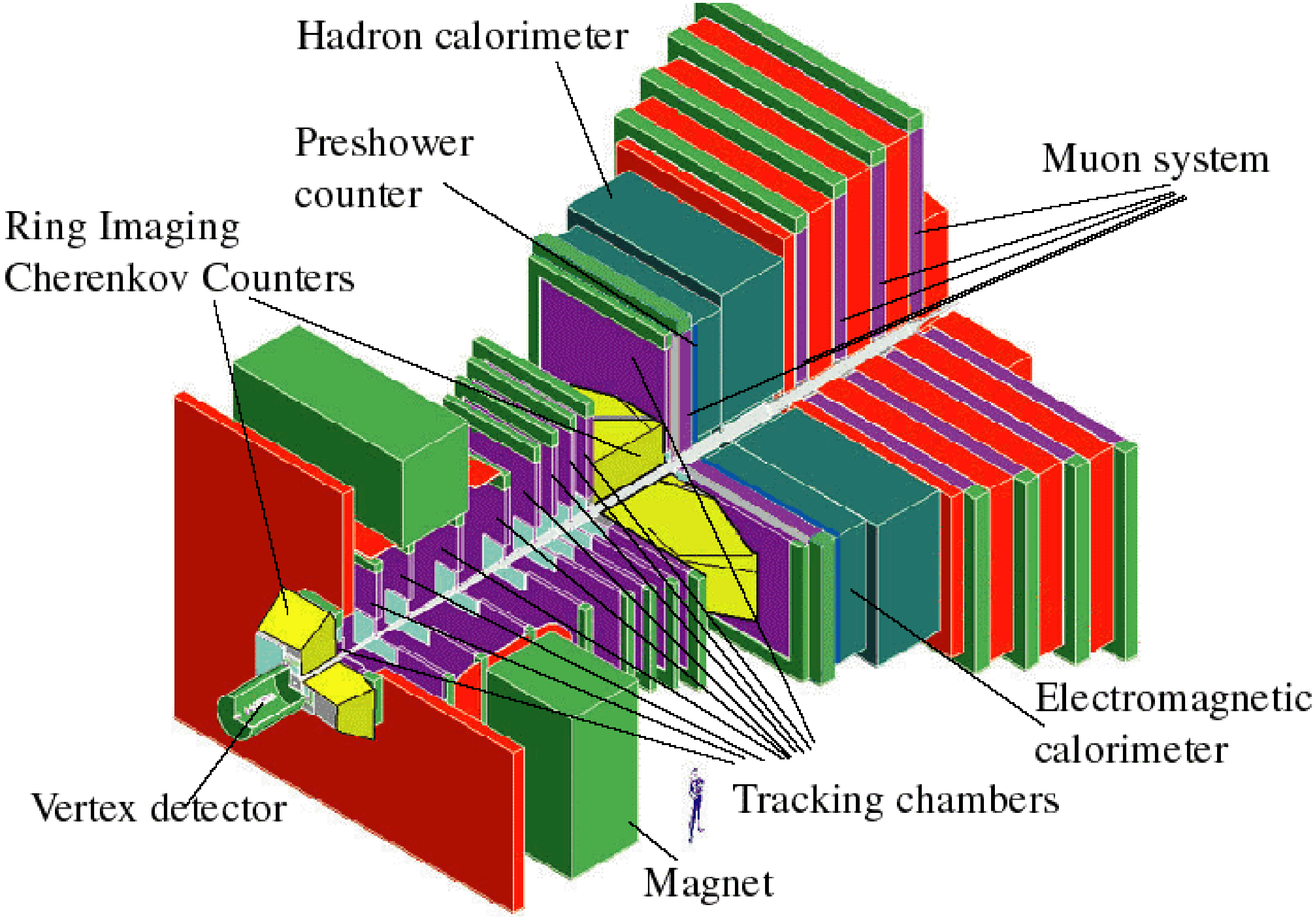
Germany

USA

Ukraine

UK

Switzerland



Italy

Poland

PRC

Netherlands

Romania

Russia

Spain

The *LHCb* Collaboration (24.3.99)

Finland:	Espoo-Vantaa Inst. Tech.
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Poland:	Cracow Inst. Nucl. Phys., Warsaw Univ.
Spain:	Univ. Barcelona, Univ. Santiago de Compostela
Switzerland:	Univ. Lausanne
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Brazil:	UFRJ
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Russia:	INR, ITEP, Lebedev Inst., IHEP, PNPI(Gatchina)
Romania:	Inst. of Atomic Phys. Bucharest
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Conclusions

- The LHCb experiment can fully exploit the large B-meson yields at LHC with its flexible, robust and efficient trigger.
- Low required luminosity, 2×10^{32}, guarantees physics results from the beginning of the LHC operation. Locally tuneable luminosity ensures long physics programme.
- The LHCb detector can be constructed in an existing experimental area with a modest cost. Its open geometry allows easy access to the detector for adjusting to the machine condition and upgrading.
- With the particle identification capability, excellent mass and decay time resolutions, LHCb can study many different B-meson decay modes with a high precision which is essential to reveal physics beyond the Standard Model in rare processes.