Searching for New Physics in CP-violation measurements at LHCb

Steven Blusk

Syracuse University

(on behalf of the LHCb Collaboration)

- 701 members
- 15 countries
- 52 institutes

<u>Other LHCb talks at DPF09</u>

LHC*b* Detector Status……………………..… E. Jans……27-July
Early Physics with LHCb…………..…F. Dettori……27-July
LHCb Prospects for rare Decays…..M-O. Bettler……30-July

Outline

- Introduction
- The LHC*b* Experiment
- $\sin(2\beta_s)$ in B_s mixing
- Measurements of γ
- Conclusions

➢ Not covering measurements of α, $\sin(2\beta)$ or D^0 mixing & CPV, although these are also part of the LHCb core program.

➢Rare decays covered in talk by M-O. Bettler @ 17:10 in "Beyond the Standard Model" session

Introduction

- Standard Model cannot be the final word
  - Hierarchy problem? Dark Matter? BAU? Why 3 generations? Patterns of masses & couplings? …
- New physics at the TeV energy scale (LHC)
  - New gauge fields ➔ new particles, new couplings
  - Can be probed via:
    - **Direct production** of new HEAVY particles.
    - **Loop diagrams**: $A^2 = |A_{SM}+A_{NP}|^2 = |A_{SM}|^2 + |A_{NP}|^2 + 2\,|A_{SM}||A_{NP}|\cos\phi$
      - *Heavy particles dominate in loops*
  - *Complementary approaches to uncovering New Physics*

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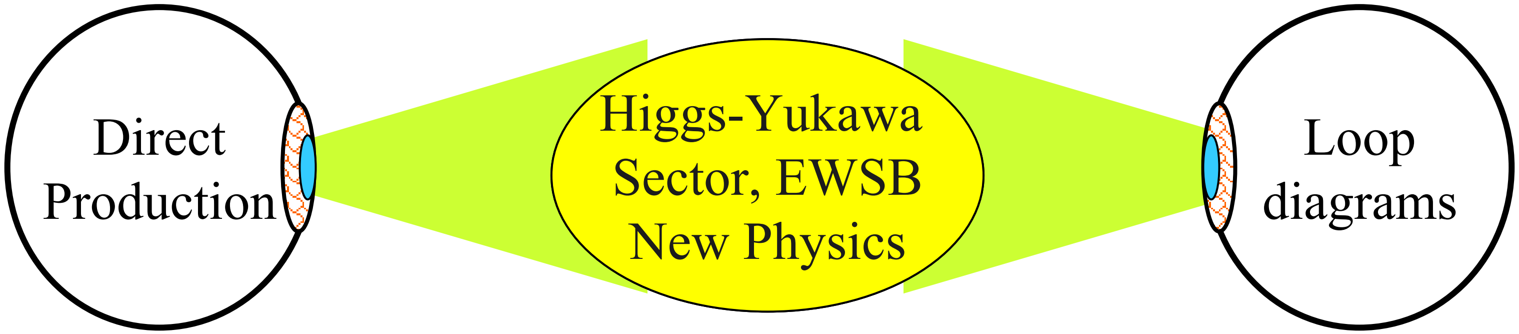
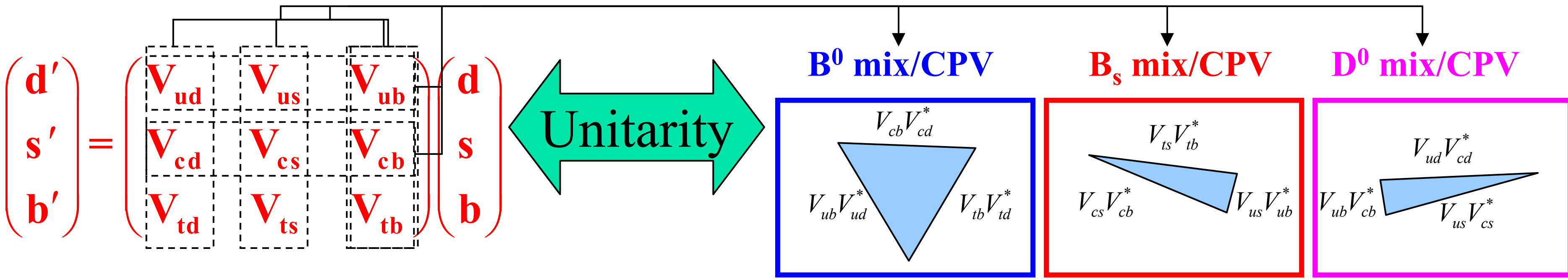


CKM & Measuring its M.E.'s

To diagonalize mass matrix, must use rotated states (3x3 Unitary → 3 angles + 1 CPV phase)



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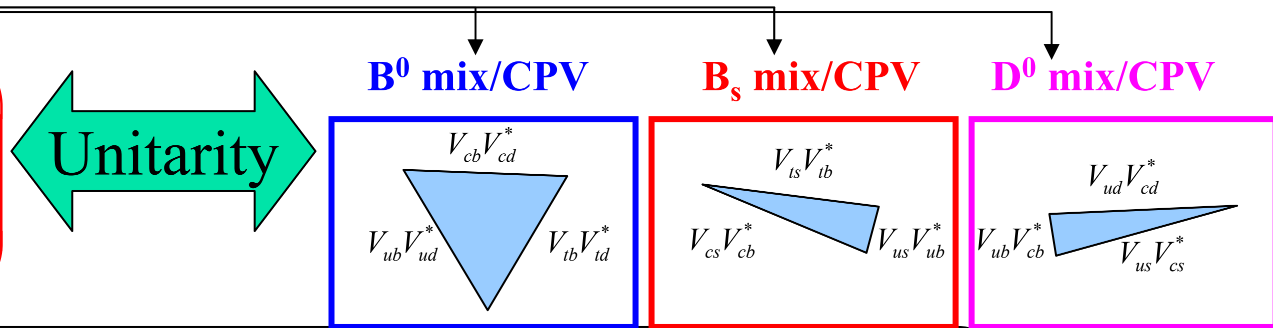
To diagonalize mass matrix, must use rotated states (3x3 Unitary → 3 angles + 1 CPV phase)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Wolfenstein parameterization (λ, A, ρ, η): A~0.8, λ~ 0.22

$$V = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2-\lambda^4/8(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2+A\lambda^4/2(1-2(\rho + i\eta)) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^5)$$

→ ρ,η in V_{ub}, V_{td}, V_{ts} → Only accessible in processes that probe these M.E.

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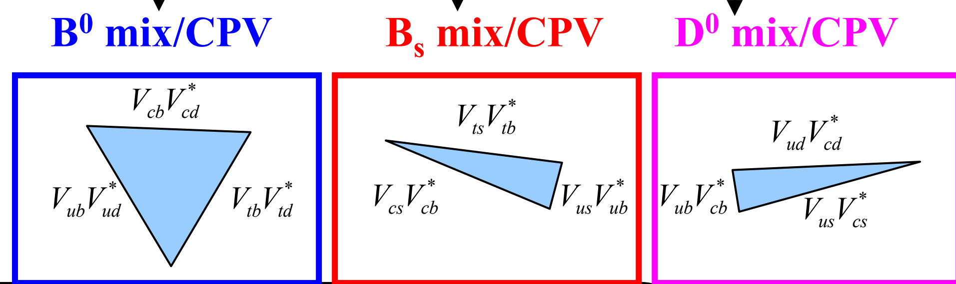
Unitarity



Wolfenstein parameterization (λ, A, ρ, η): $A \sim 0.8$, $\lambda \sim 0.22$

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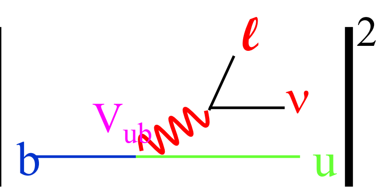
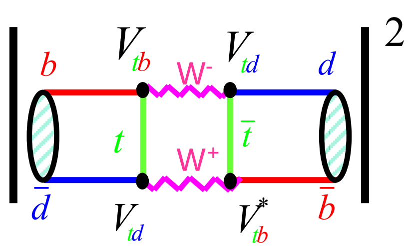
Magnitudes



$\sim |V_{ub}|^2 \propto \rho^2 + \eta^2$



$\sim |V_{tb}V_{td}^*|^2 \propto (\rho-1)^2 + \eta^2$

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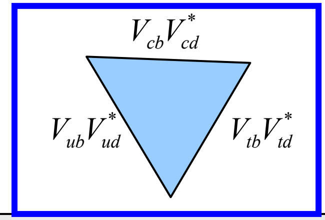
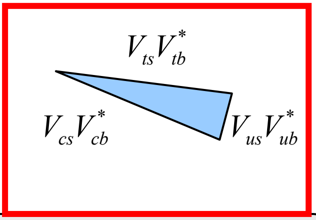
⟺ Unitarity

B^0 mix/CPV



B_s mix/CPV



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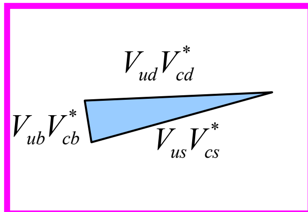

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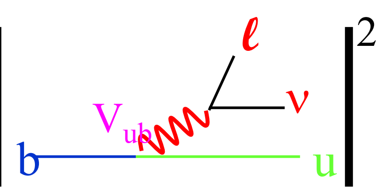

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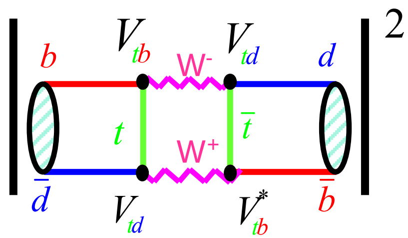

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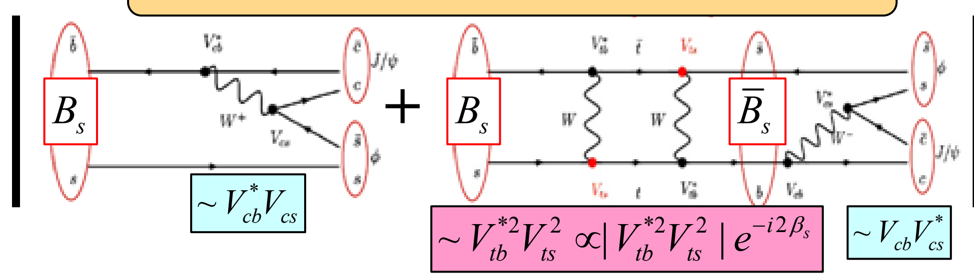
Phases



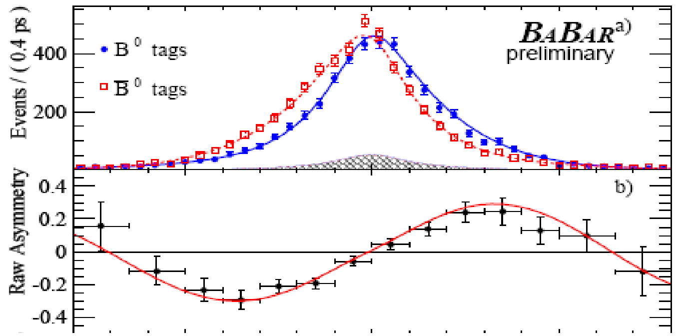
$\sim V_{cb}^* V_{cs}$

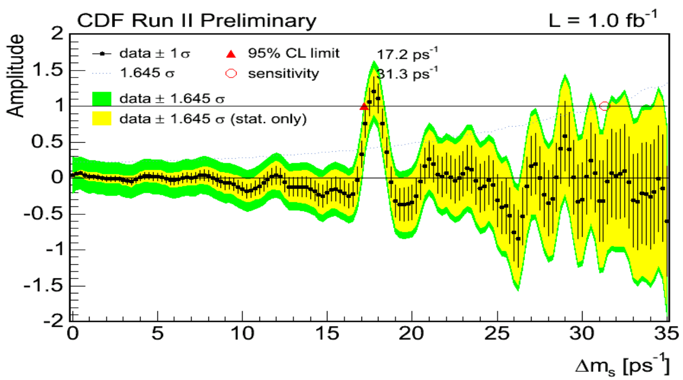
$\sim V_{tb}^{*2} V_{ts}^2 \propto |V_{tb}^{*2} V_{ts}^2| e^{-i2\beta_s}$

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

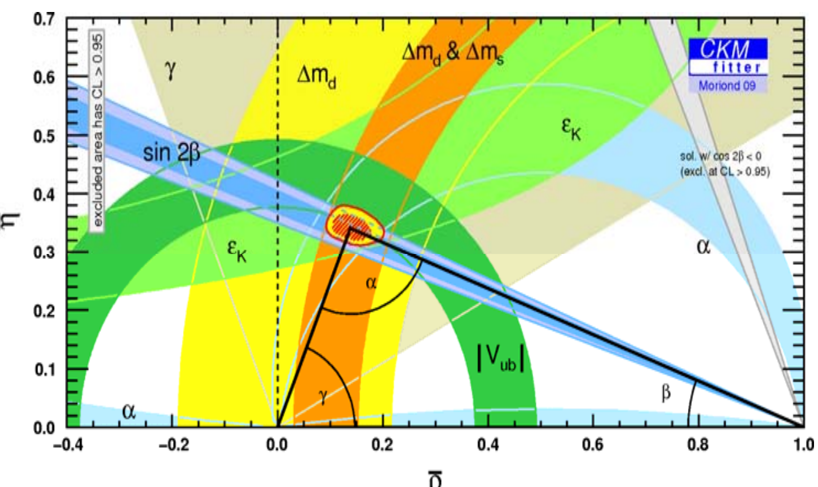
$$\beta_s = \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] \approx \lambda^2\eta \cong 0.02 \text{ [in the SM]}$$

Great progress, but much room for NP





Much learned from B-factories and Tevatron.



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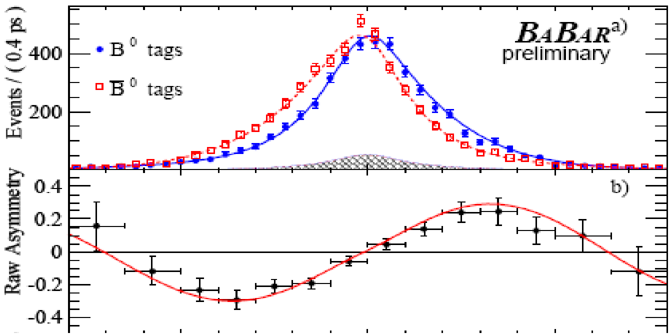

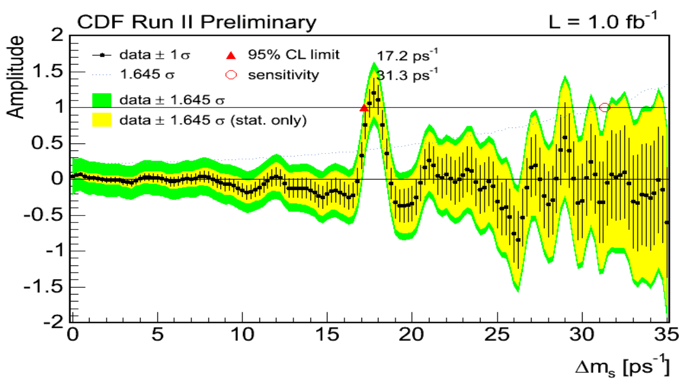

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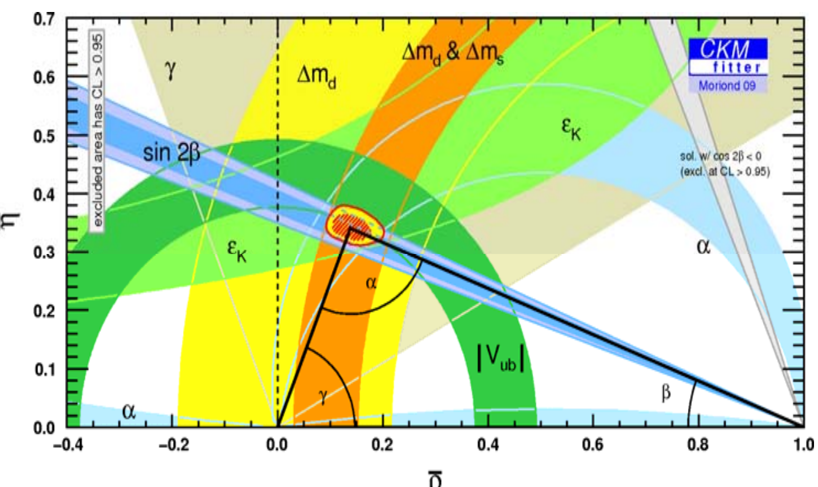

- Need more precise m'ment of B_s mixing phase
- CKM Angle γ
  - Only CKM angle that can be measured from <u>purely trees</u>
  - Indirect $\gamma = (67.8^{+4.2}_{-3.9})^{o}$ → possible NP contribution
  - Direct $\gamma = (70^{+27}_{-20})^{o}$: from Trees, but large uncertainty.
- With precise Δm_d, Δm_s, $\sin(2\beta)$ in hand, and first meas. of $\sin(2\beta_s)$, we may be seeing hints of NP.

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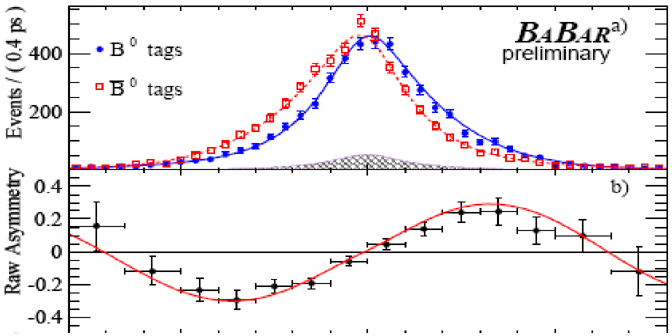

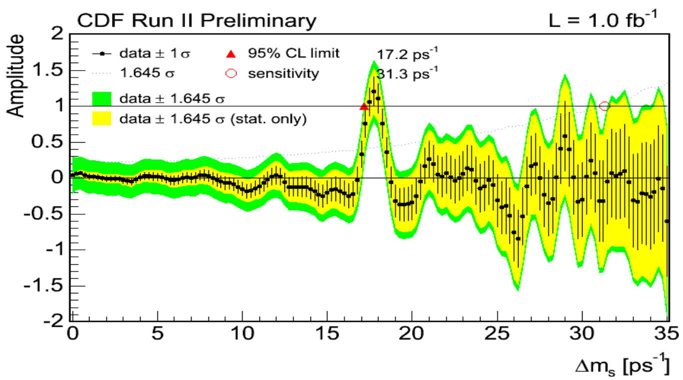

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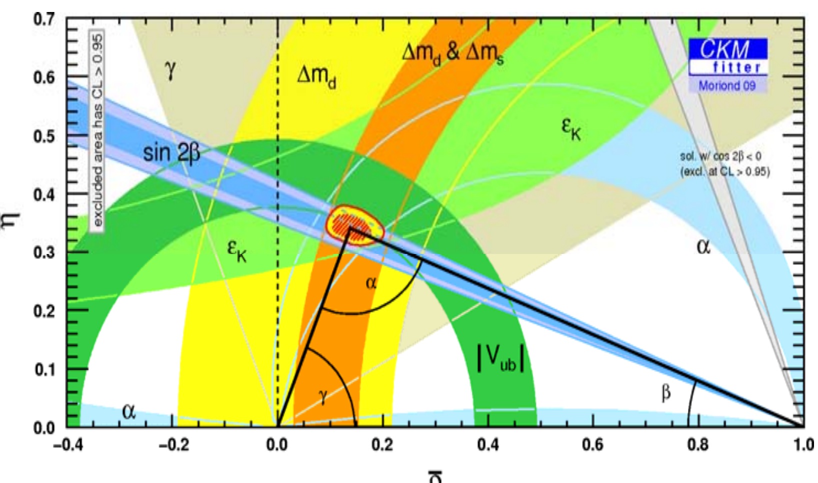

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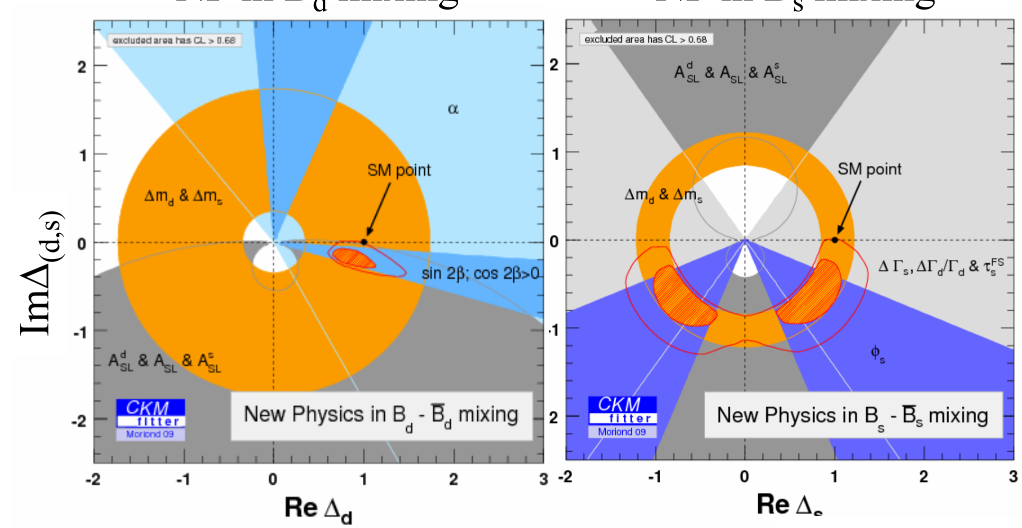
$$\frac{\langle B^0_{s,d} | M_{eff}^{SM+NP} | \overline{B}^0_{s,d} \rangle}{\langle B^0_{s,d} | M_{eff}^{SM} | \overline{B}^0_{s,d} \rangle} = |\Delta_{s,d}{}^{NP}| e^{i\phi^{NP}_{s,d}}$$

Lenz,
Nierste, arXiv.0612.167

NP in B_d mixing | NP in B_s mixing



~2σ from SM in both!

CKMFitter,
arXiv.0810.3139

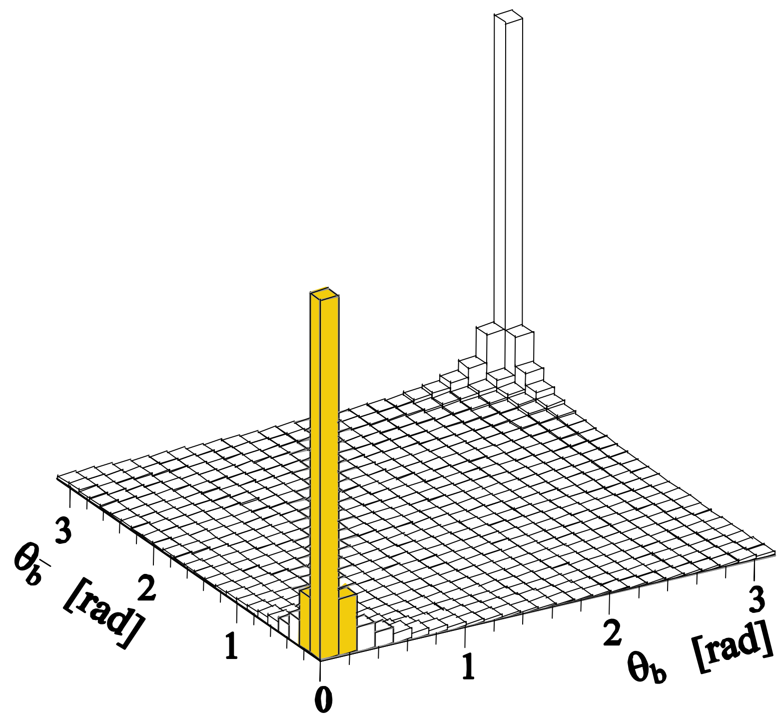
The LHCb Experiment

LHC*b* is a first <u>dedicated</u> precision heavy flavor experiment searching for **New physics** in **CP-Violation** and **Rare Decays** at a <u>hadron collider</u>

- **Beams (intentionally) less focused**
  $\mathcal{L}_{int} \sim 2 \times 10^{32} cm^{-2} s^{-1}$
  → **mostly single interaction.**

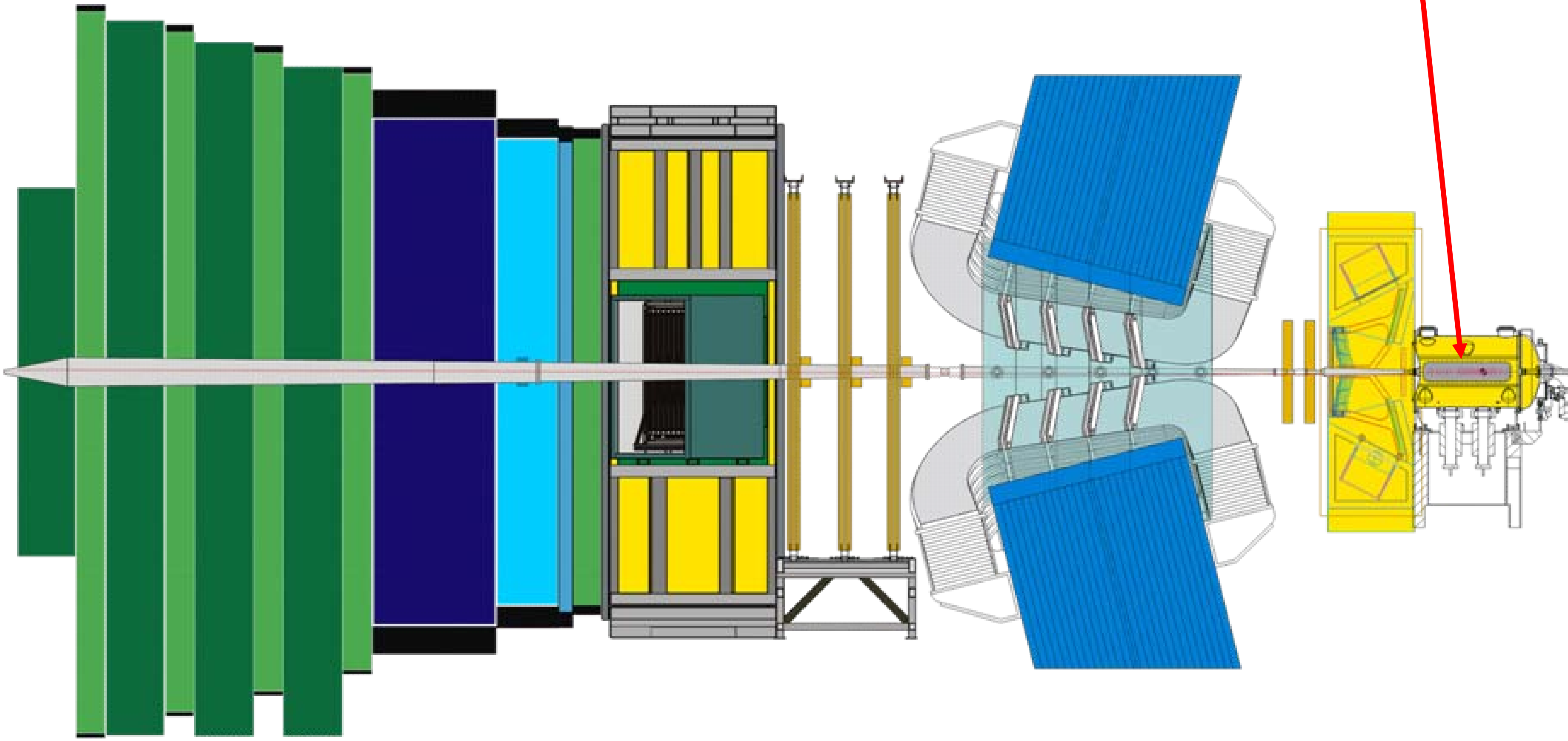
- **100K b$\bar{b}$/sec expected and all B-hadron species produced:**
  - **B^0, B^+, B_s, B_c, b-baryons.**
  - **Yields ~10^2 - 10^6 / channel per 2 fb^{-1}**

- **Forward, correlated b$\bar{b}$ production**
  Single arm forward spectrometer
  13 mrad<θ< 300 mrad (1.9<η<4.9)



The LHCb detector

VeLo
σ_{IP}~14+35/pT μm)
σ_t ~ 40 fs



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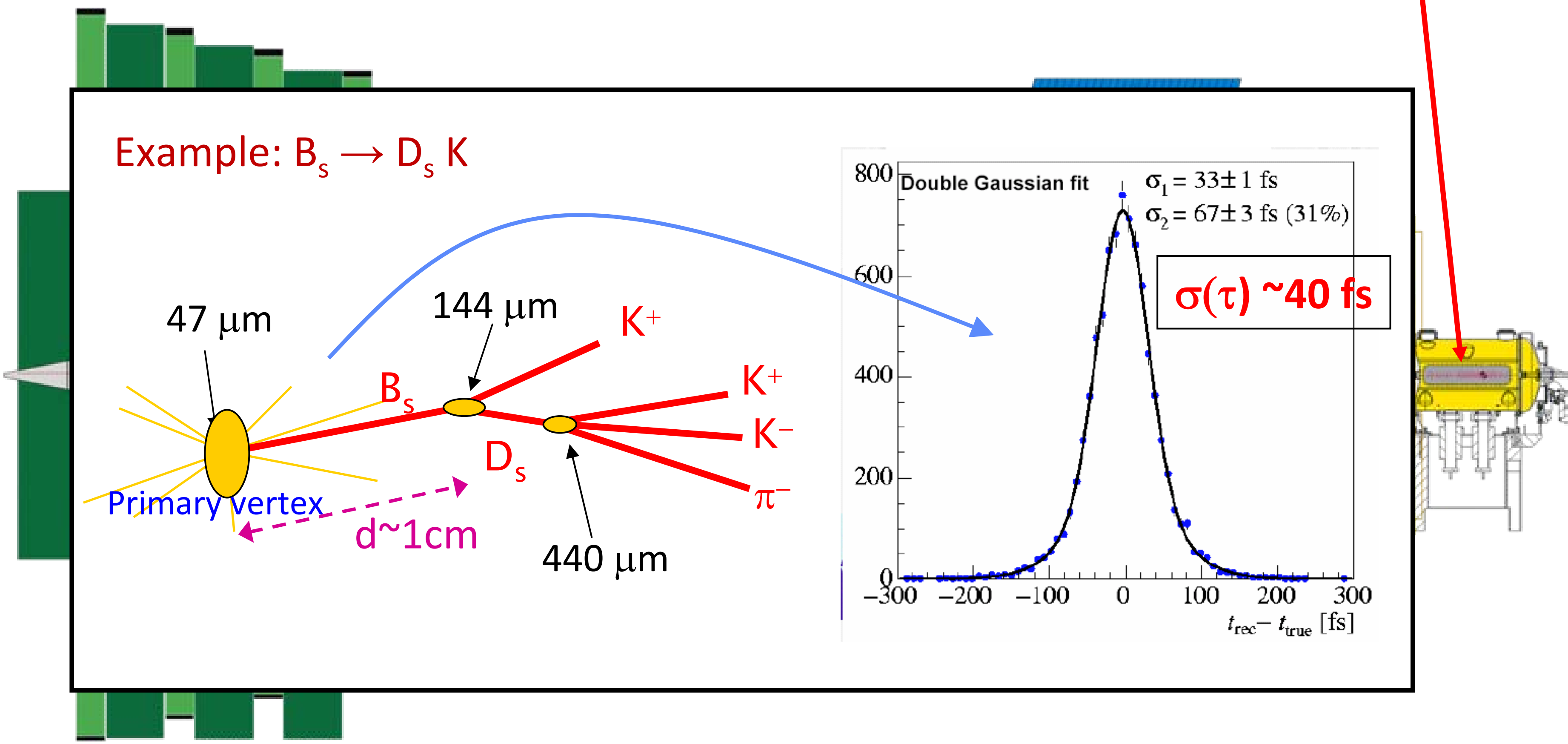

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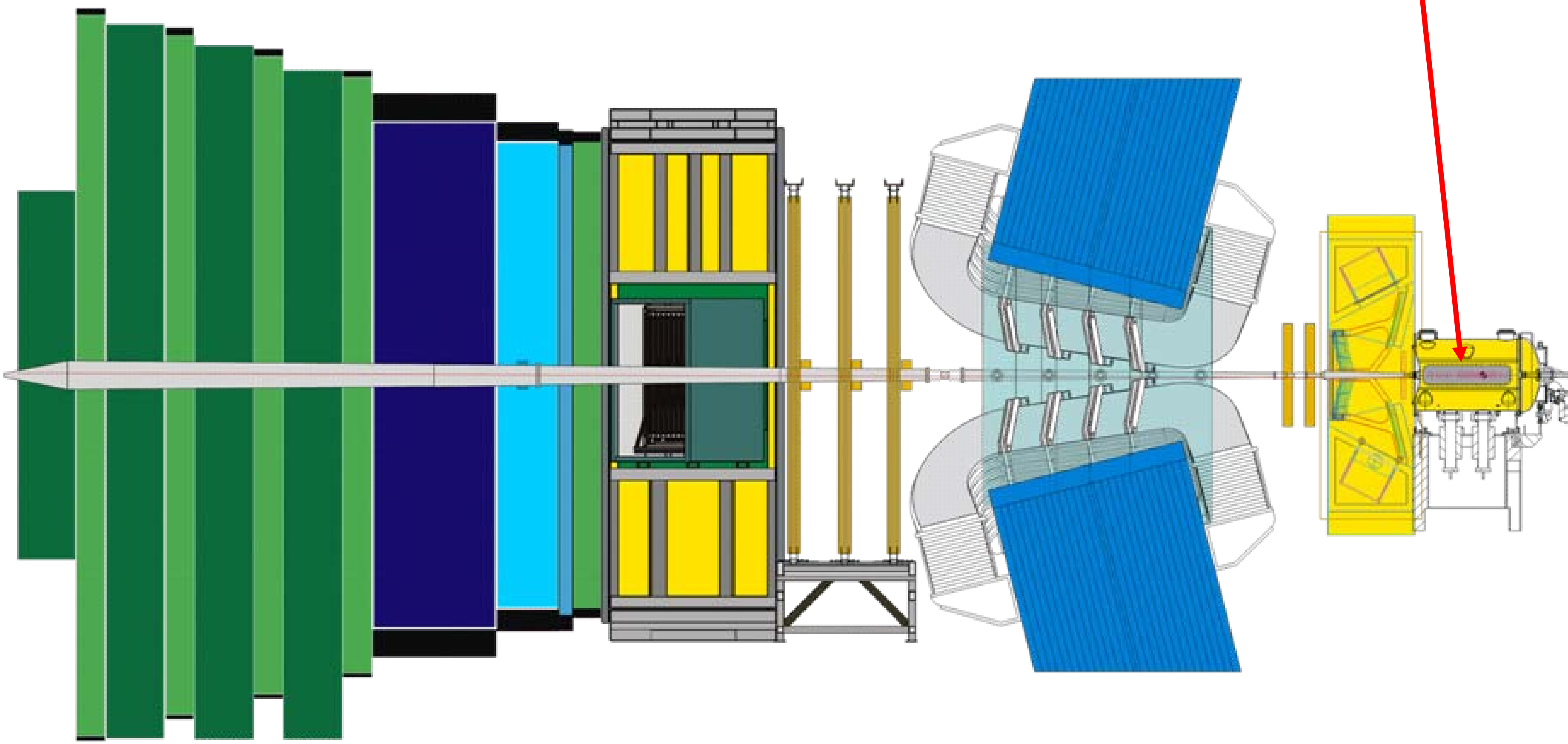

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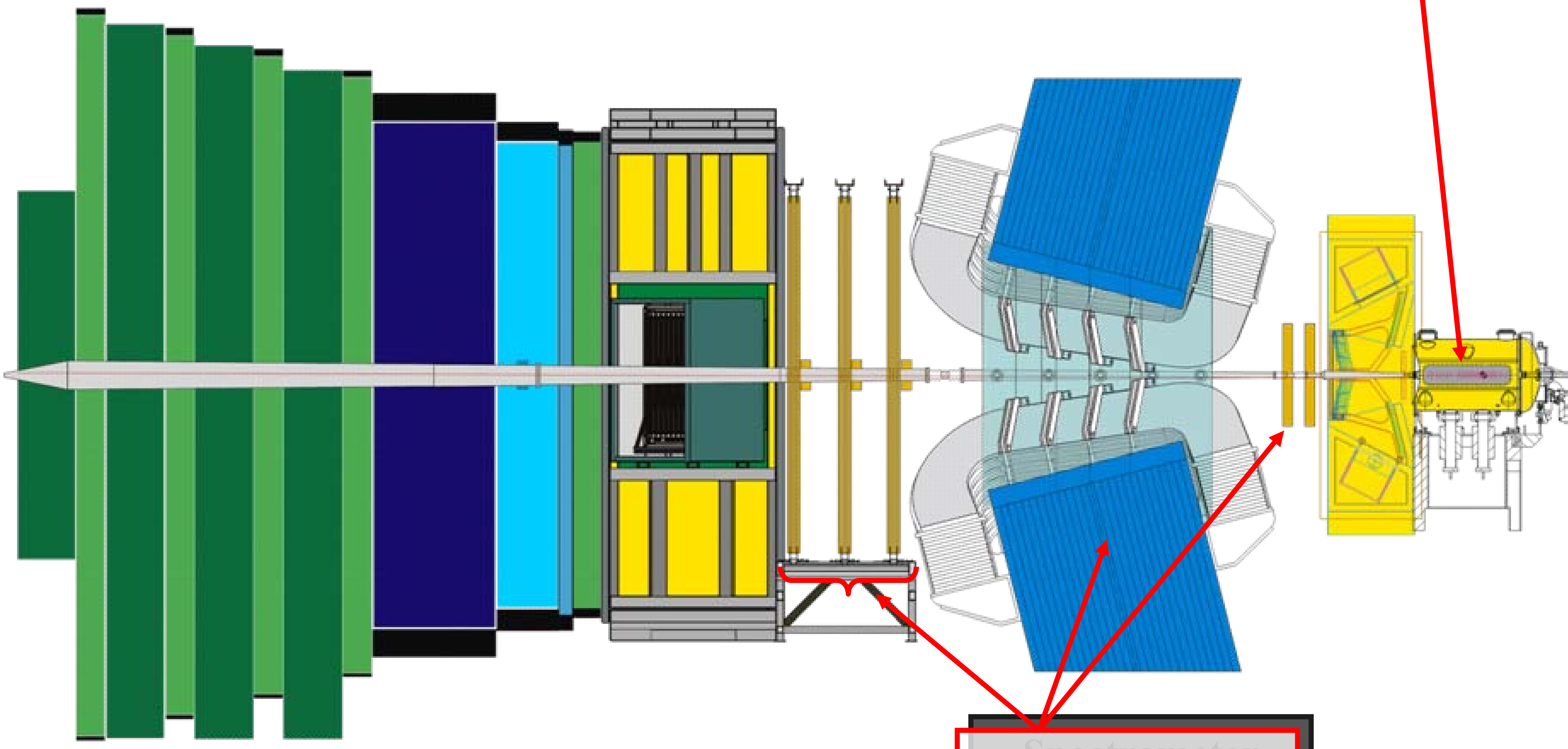

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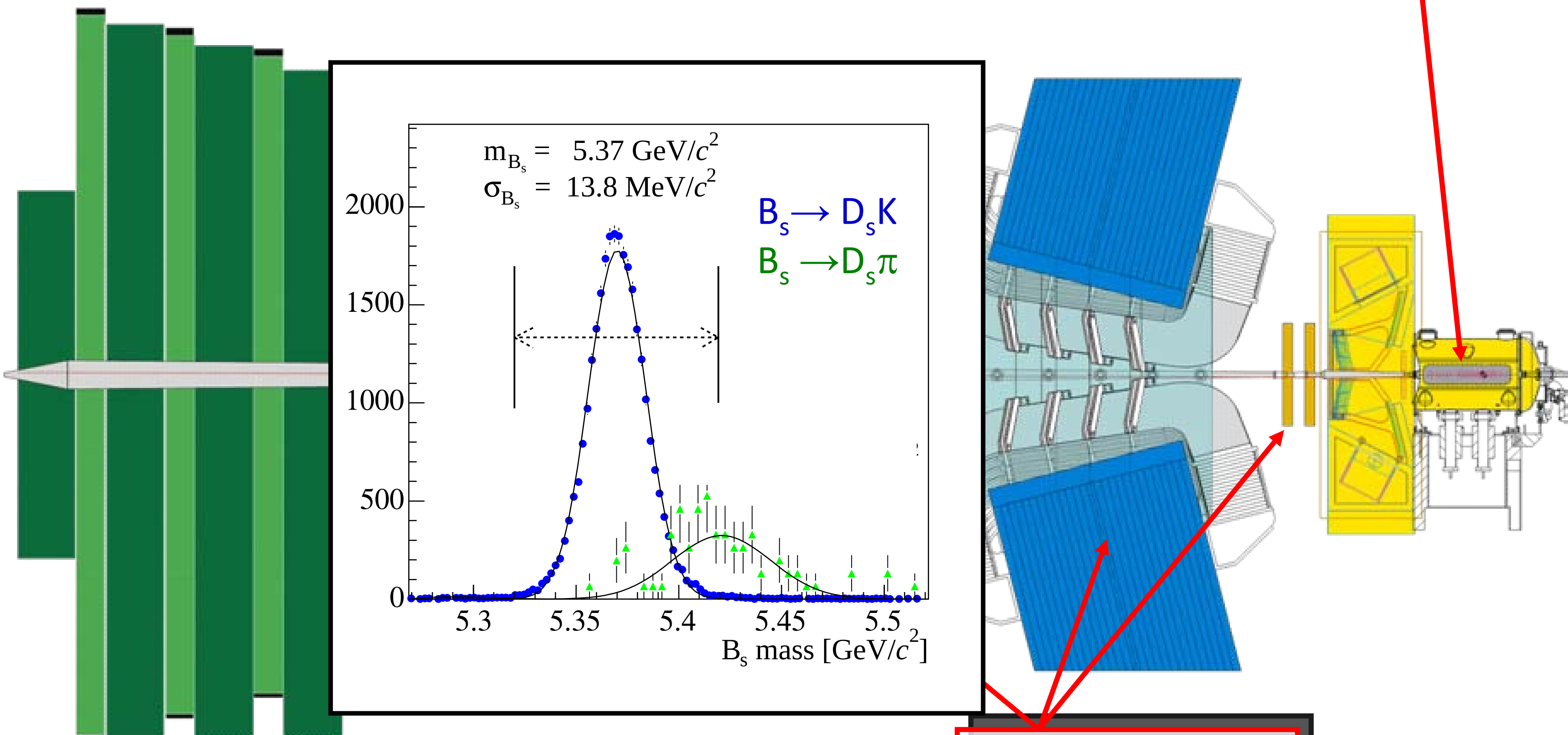
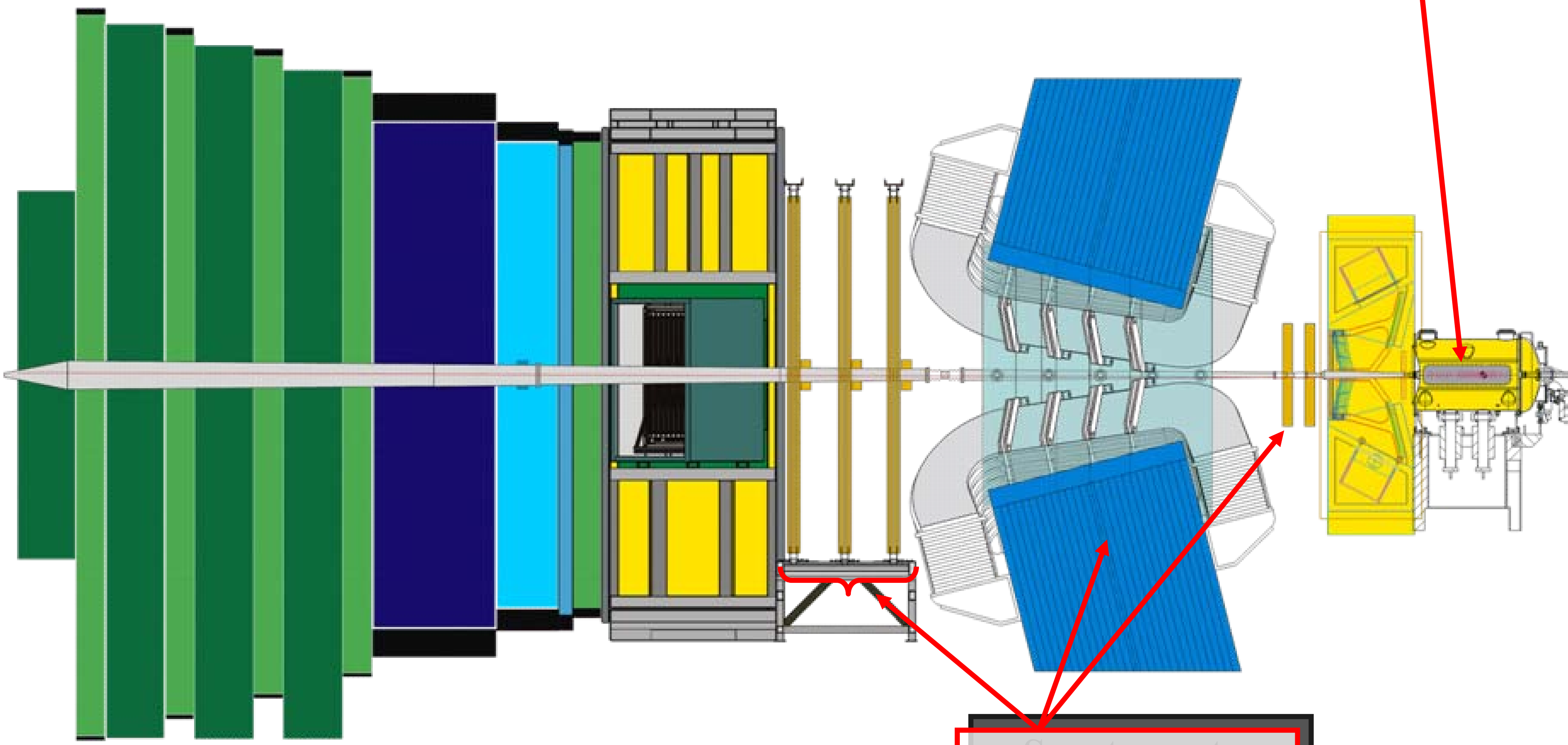


Spectrometer
Silicon + Straws
σ_p/p ~ 0.5%
$\sigma_{M(B\rightarrow hh)}$~20 MeV

The LHCb detector



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σ_{IP}~14+35/pT μm)
$\sigma_t \sim 40$ fs

Spectrometer
Silicon + Straws
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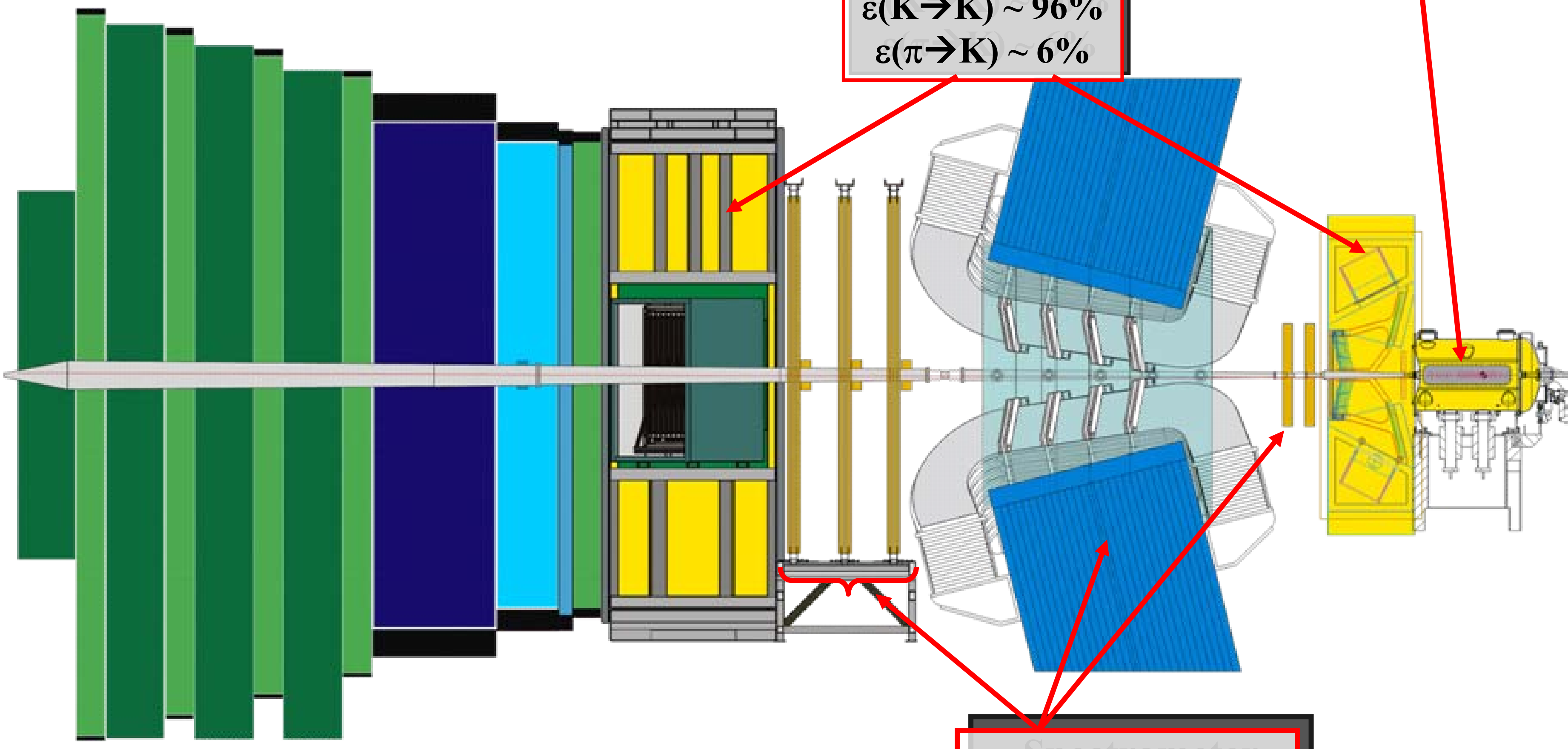
The LHCb detector

RICH 1, 2
(PID: p,K,π)
$\varepsilon(K \rightarrow K) \sim 96\%$
$\varepsilon(\pi \rightarrow K) \sim 6\%$

VeLo
$\sigma_{IP} \sim 14 + 35/pT\ \mu m)$
$\sigma_t \sim 40$ fs



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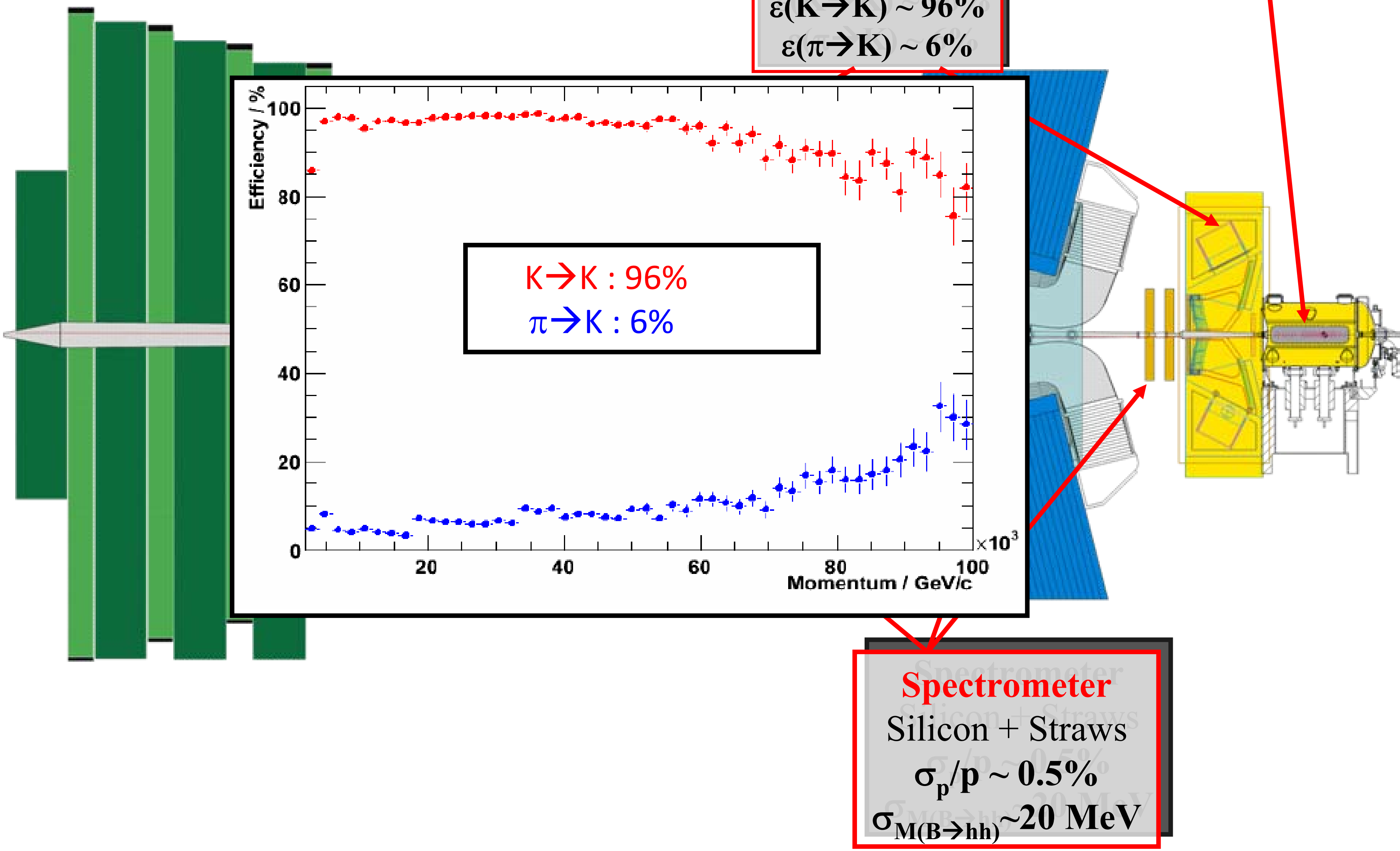

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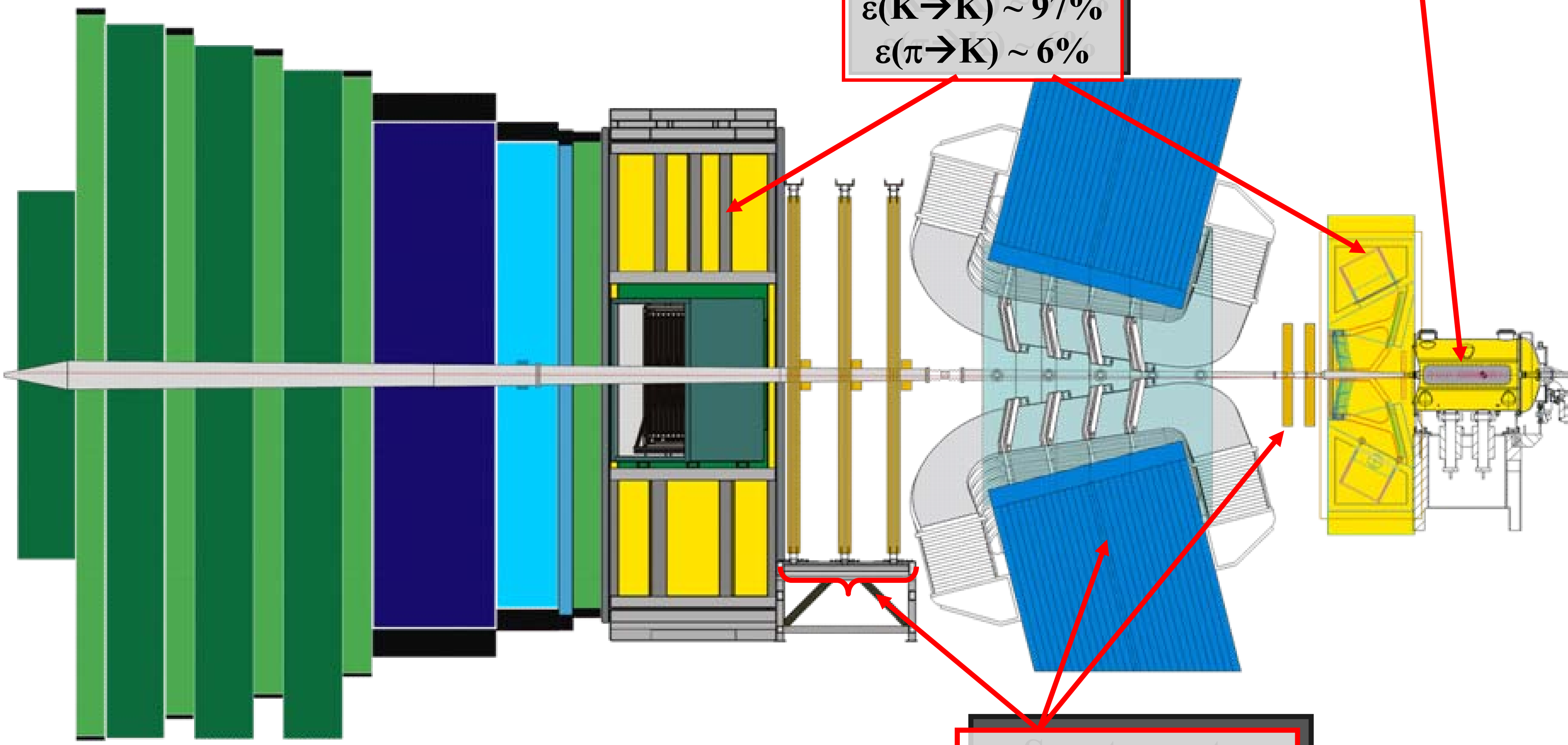

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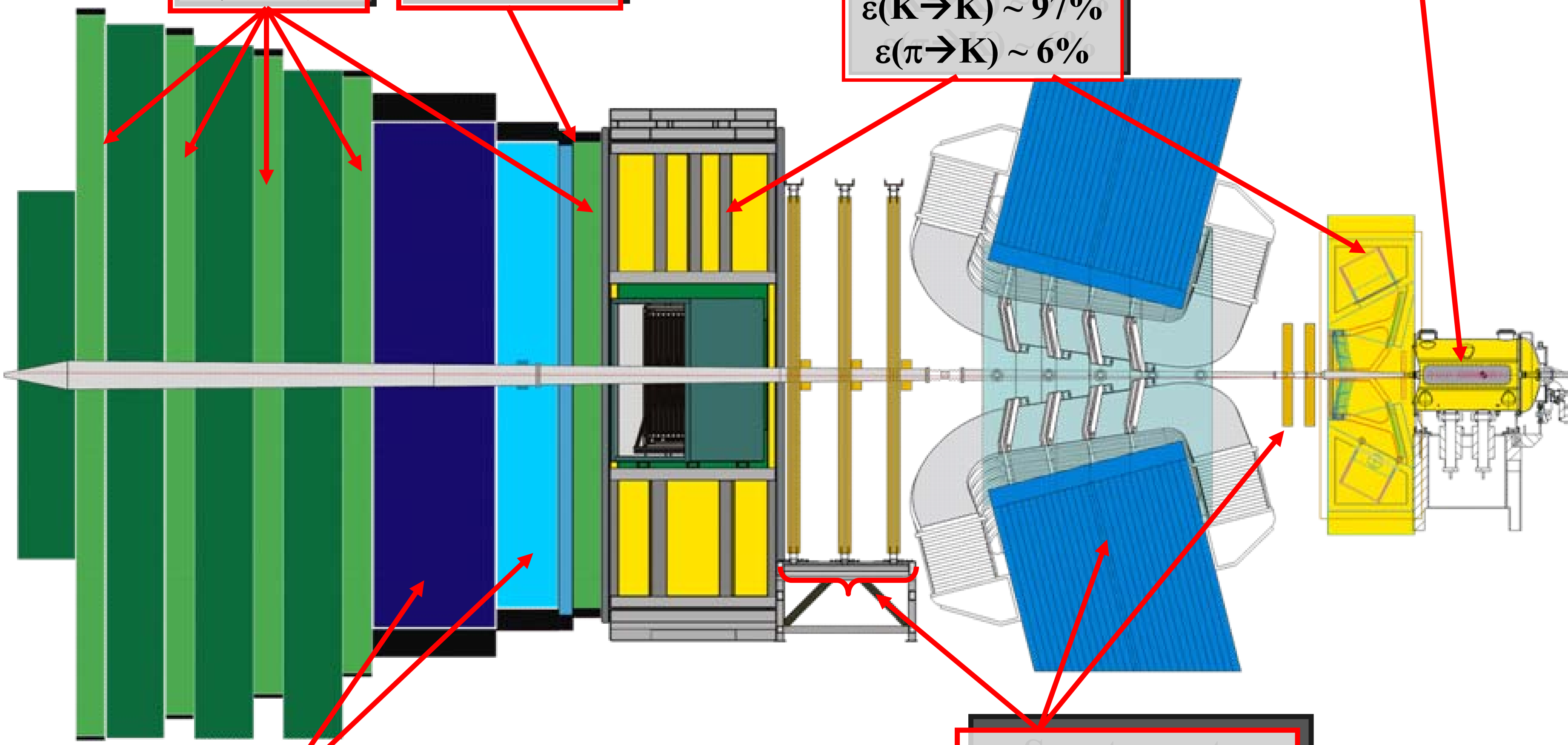


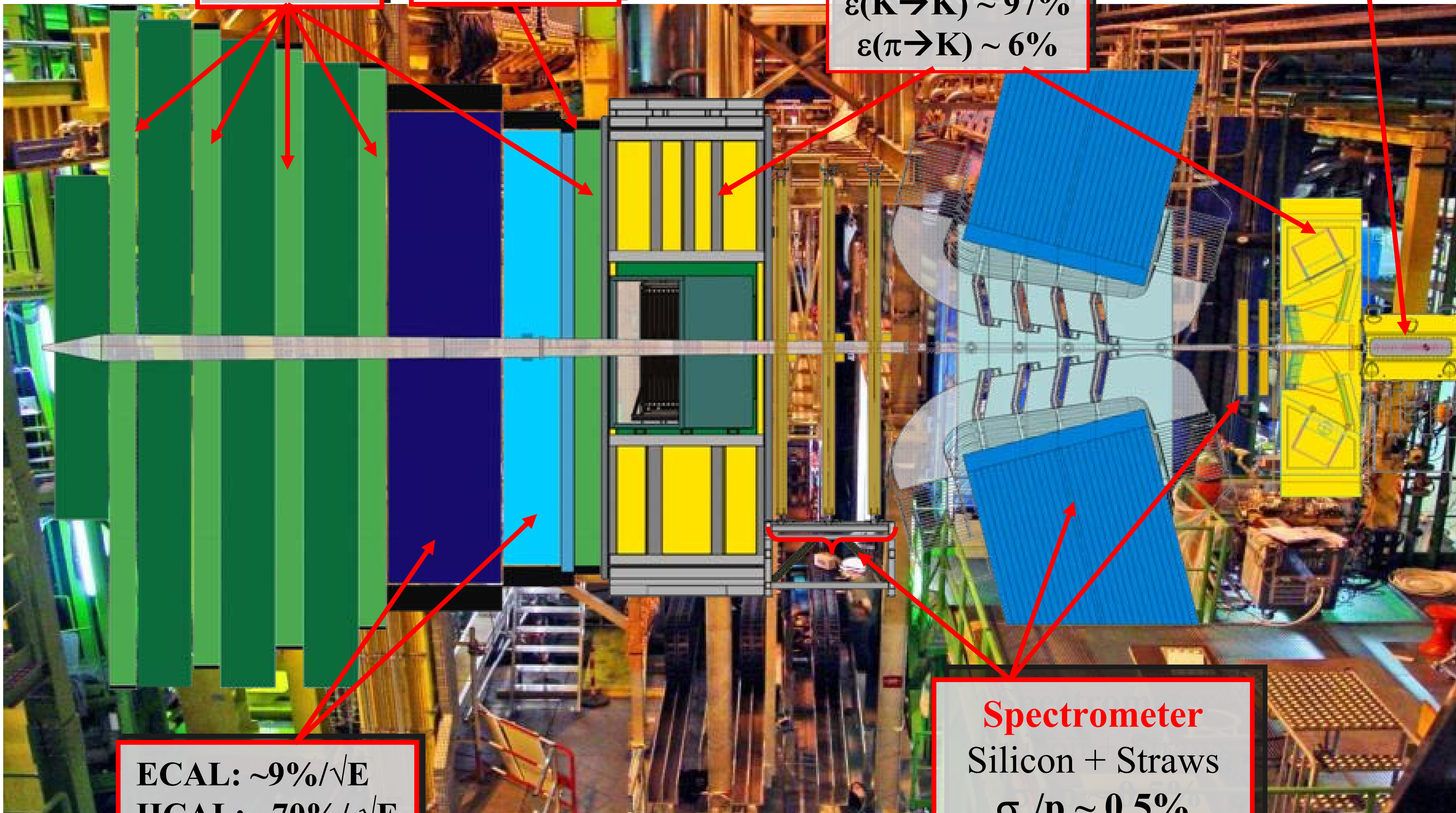
The LHCb detector

MUON
(Trigger &
μ PID)

PRS/SPD
(PID: e,γ,π^0)

RICH 1, 2
(PID: p,K,π)
$\varepsilon(K\rightarrow K) \sim 97\%$
$\varepsilon(\pi\rightarrow K) \sim 6\%$

VeLo
σ_{IP}~14+35/pT μm)
$\sigma_t \sim 40$ fs



ECAL: ~9%/√E
HCAL: ~70%/ √E
Hadronic Trigger
PID: e,γ,π^0,η,h...)

Spectrometer
Silicon + Straws
$\sigma_p/p \sim 0.5\%$
$\sigma_{M(B\rightarrow hh)}$~20 MeV

The LHCb detector

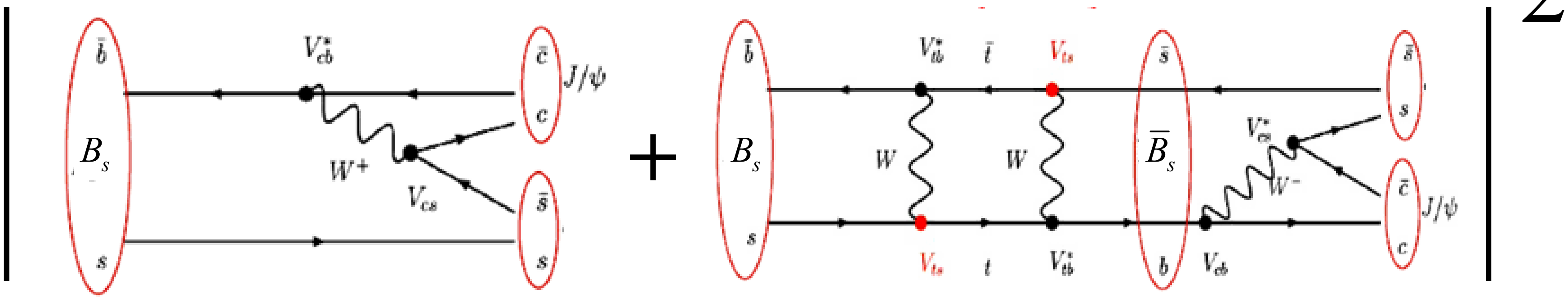
LHCb is ready for data !

ϕ_s or $\sin(2\beta_s)$

Side note: 2 fb^{-1} == 1 nominal year's running at LHCb ($2x10^{32}$ cm^{-2} s^{-1})

ϕ_s (or $2\beta_s$) Anatomy

- Analogous to $B^0 \rightarrow J/\psi K_s$
- Sensitive to New Physics in B_s mixing



- $c\bar{c}$ $= J/\psi \rightarrow \mu^+\mu^-$ provides excellent trigger
- $s\bar{s}$ detected in $\phi \rightarrow K^+K^-$, $f_0(980) \rightarrow \pi^+\pi^-$, $\eta^{(\prime)} \rightarrow \gamma\gamma(\pi^+\pi^-)$

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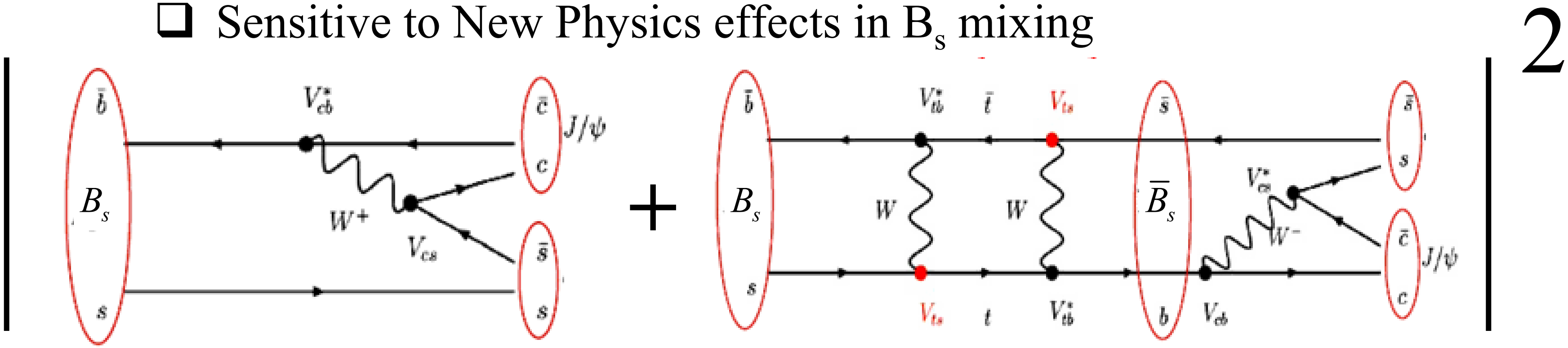

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CP Asymmetry isolates interference term

$$A_{CP}(t) = \frac{\Gamma[\overline{B}_s(t) \to f] - \Gamma[B_s(t) \to f]}{\Gamma[\overline{B}_s(t) \to f] + \Gamma[B_s(t) \to f]}$$

$$A_{CP}(t) = \frac{\eta_f sin\phi_s sin(\Delta m_s)t}{cosh(\Delta\Gamma_s t/2) - \eta_f cos\phi_s sinh(\Delta\Gamma_s t/2)}$$

***Observables**: flavor tag, t*

***Fit parameters**: $\Delta m_s, \Delta\Gamma_s, \phi_s$*

$\phi_{SM} = 0.0368 \pm 0.0017$ [SM, CKMFitter]

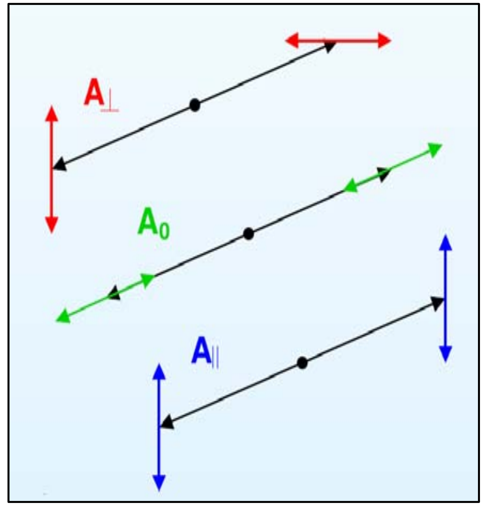
$\Gamma_s = \frac{\Gamma_H + \Gamma_L}{2}, \Delta\Gamma_s = \Gamma_L - \Gamma_H; \Delta m_s = M_H - M_L$

η_f = CP eigenvalue

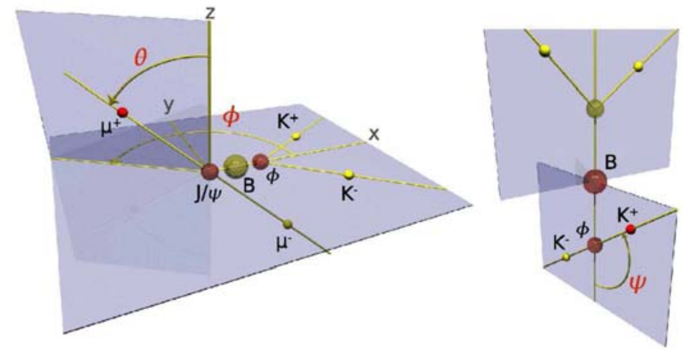
$\sin(2\beta_s)$ in $B_s \to J/\psi\phi$

- $0^- \to 1^{--}\, 1^{-}$
- 3 independent amplitudes
  - L=0, 2 CP+
  - L=1 CP-

$$\eta_{CP} = (-1)^L$$



- Must disentangle CP=±1.
- Sensitive to angular distributions

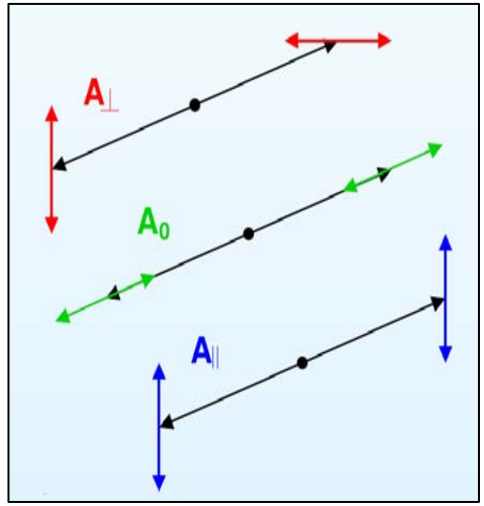


Transversity angles

$\sin(2\beta_s)$ in $B_s \rightarrow J/\psi\phi$

- ❑ $0^- \rightarrow 1^{--}\,1^{--} \rightarrow L=0,1,2$ permitted
- ❑ 3 independent amplitudes
  - ❑ L=0,2 CP+
  - ❑ L=1 CP-

$\left.\right\}\ \eta_{CP} = (-1)^L$



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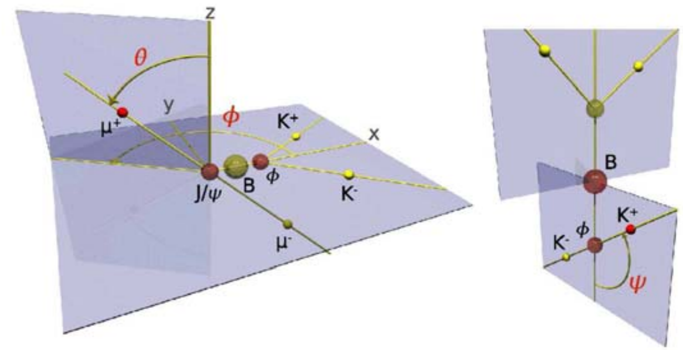
- ❑ Sensitive to angular distributions



Transversity angles

$$\frac{\partial^4\Gamma(B_s \rightarrow J/\psi\phi)}{\partial t\,\partial\cos\theta\, d\phi\,\partial\cos\psi} = g(\vec{f},\vec{o})$$

More Fit parameters : $\vec{f}$

$\phi_s, \Delta m_s, \Delta\Gamma_s, \Gamma_s + (R_\perp, R_\parallel, \delta_\perp, \delta_\parallel)$

$$R_\perp = \frac{|A_\perp(0)|^2}{|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2};$$

$$R_\parallel = \frac{|A_\parallel(0)|^2}{|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2};$$

$$\delta_\perp = \arg(A_\perp(0)A_0^*(0))$$

$$\delta_\parallel = \arg(A_\parallel(0)A_0^*(0))$$

Observables : $\vec{o}$

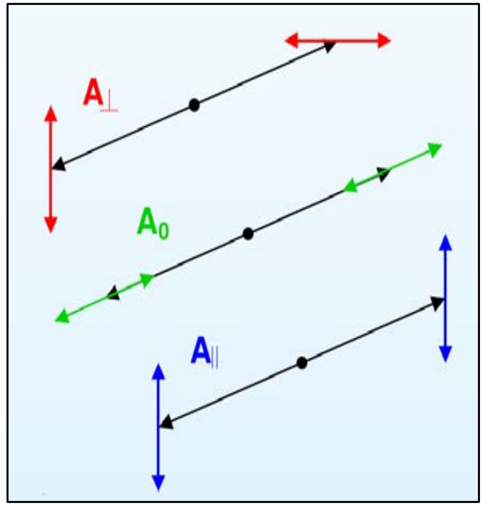
flavor tag, t

$+ (\cos\theta, \phi, \cos\psi)$

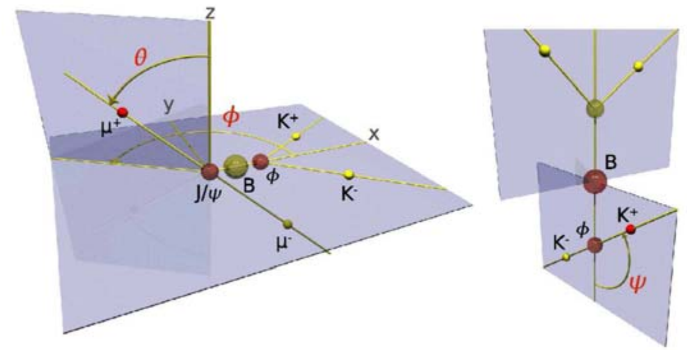
sin(2β_s) in $B_s \rightarrow J/\psi\phi$

- $0^- \rightarrow 1^{--}\,1^{--} \rightarrow L=0,1,2$ permitted
- 3 independent amplitudes
  - L=0,2 CP+
  - L=1 CP-

$$\eta_{CP} = (-1)^L$$



- Must disentangle CP=±1.
- Sensitive to angular distributions



Transversity angles

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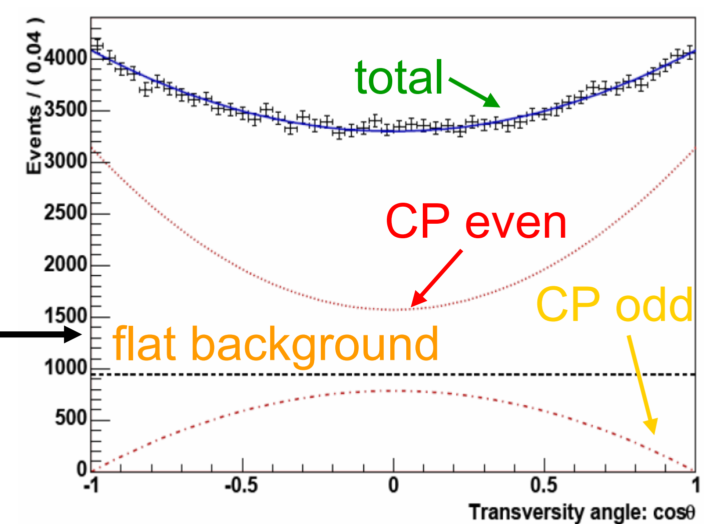


$B_s \rightarrow J/\psi\phi$ —— ϕ_s Analysis

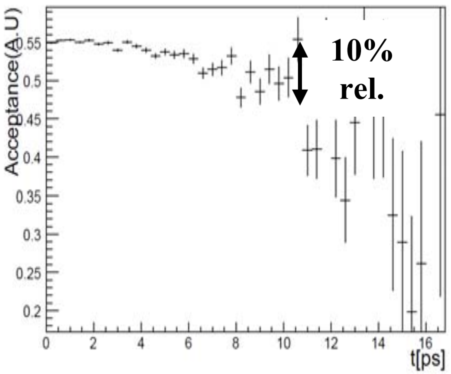
Signal: $B_s \rightarrow J/\psi\phi$

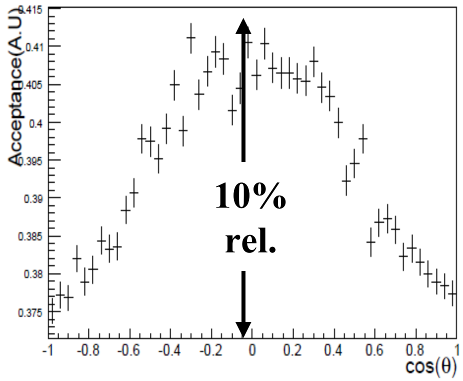
Control channels:

- Acceptance: $B \rightarrow J/\psi K^{*0}$
- Tagging: $B \rightarrow J/\psi K^*$, $B^+ \rightarrow J/\psi K^+$, $B_s \rightarrow D_s^+\pi^-$
- Background: Sidebands

	Signal ($2\ fb^{-1}$)	B/S	
		bb	Prompt ψ
$B_s \rightarrow J/\psi\phi$	117k	0.5	1.6
$B \rightarrow J/\psi K^*$	489k	1.5	5.2
$B \rightarrow J/\psi K^+$	942k	0.3	1.6

Example acceptance plots (note zero suppression)





$B_s \rightarrow J/\psi\phi$ —— ϕ_s Analysis

Signal: $B_s \rightarrow J/\psi\phi$

Control channels:

- Acceptance: $B \rightarrow J/\psi K^{*0}$
- Tagging: $B \rightarrow J/\psi K^{*}$, $B^{+} \rightarrow J/\psi K^{+}$, $B_s \rightarrow D_s^{+}\pi^{-}$
- Background: Sidebands

	Signal ($2\ fb^{-1}$)	B/S	
		bb	Prompt ψ
$B_s \rightarrow J/\psi\phi$	117k	0.5	1.6
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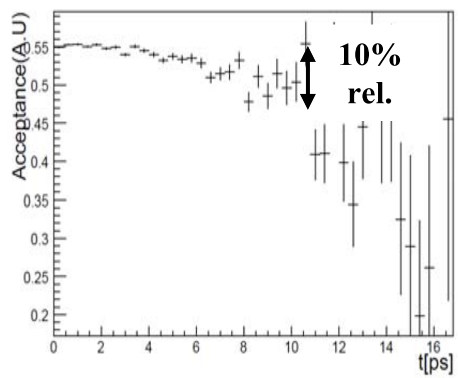

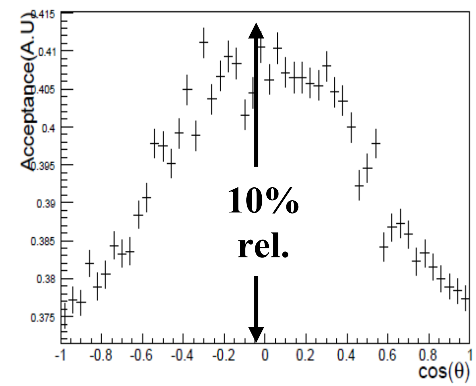

✦ Likelihood fit:

- **6 observables** *m, t, cosθ, φ, cosψ, tag*
- **7 free parameters** :

  ϕ_s, $\Delta\Gamma_\sigma$, Γ_σ, $R_\perp$, $R_\parallel$, $\delta_\perp$, $\delta_\parallel$

  Detector parameters fixed

[Inclusion of S-wave component leads to ~10-20% reduction in resolution]

$B_s \to J/\psi\phi$ — ϕ_s Analysis

Signal: $B_s \to J/\psi\phi$

Control channels:

- ❑ Acceptance: $B \to J/\psi K^{*0}$
- ❑ Tagging: $B \to J/\psi K^*$, $B^+ \to J/\psi K^+$, $B_s \to D_s^+\pi^-$
- ❑ Background: Sidebands

	Signal (2 fb^{-1})	B/S	
		bb	Prompt ψ
$B_s \to J/\psi\phi$	117k	0.5	1.6
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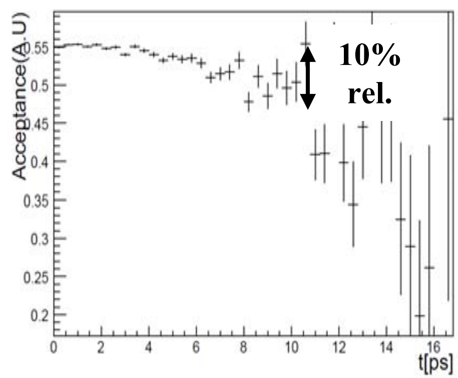
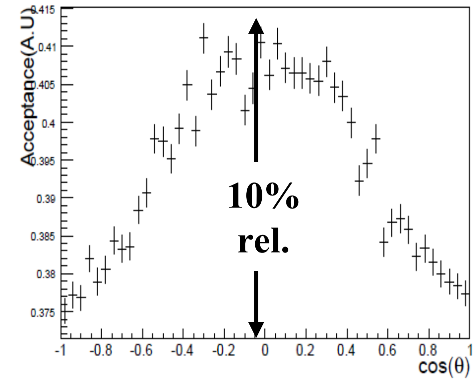
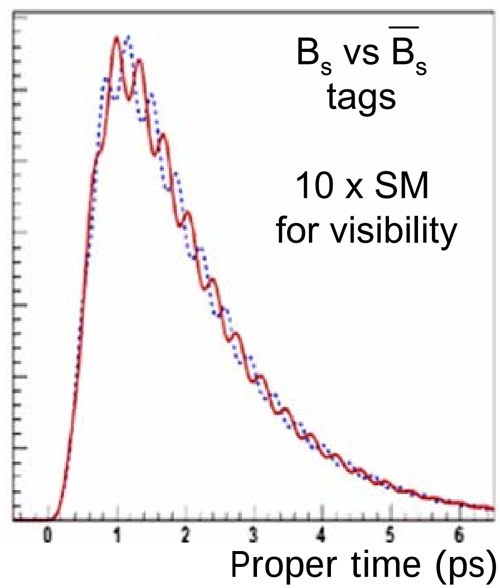
Example acceptance plots (note zero suppression)





Asymmetry $\propto \sin 2\beta_s \times \sin \Delta m_s t$



- ❑ **$\sigma(2\beta_s) \sim 0.07$** with just **0.5 fb^{-1}**

2 fb^{-1}

- ❑ $\sigma(2\beta)_s \sim 0.035$
- ❑ If $2\beta_s \gtrsim 0.2$

5σ NP discovery in 1st year of data!

$B_s \to J/\psi f_0(980), f_0 \to \pi^+\pi^-$

- See poster by L. Zhang at FPCP09
- Also, S. Stone and L. Zhang, Phys. Rev. D 79, 074024 (2009).

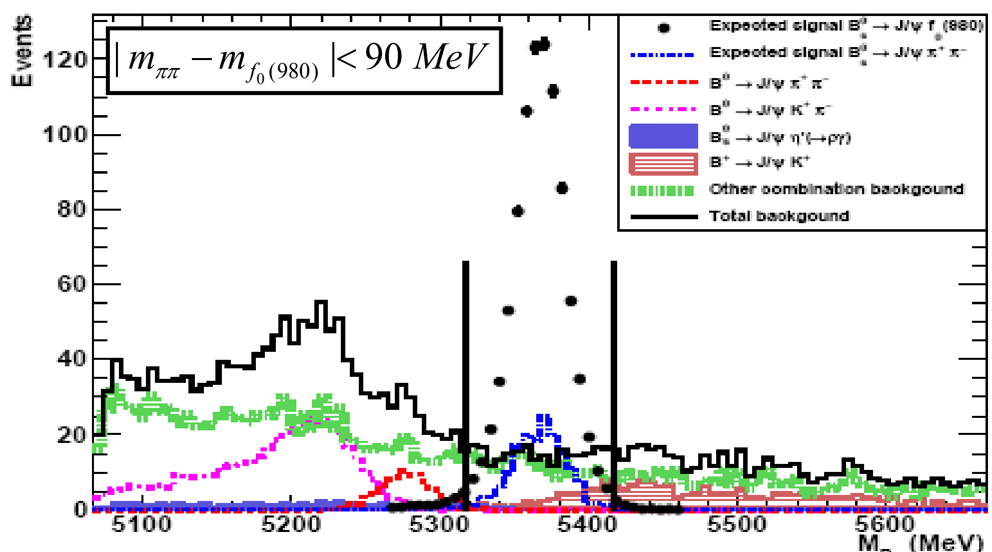
- $s\bar{s}$ can form $f_0(980)$

- Estimate: $$\frac{\Gamma(B_s \to J/\psi f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\psi\phi, \phi \to K^+K^-)} = \frac{\Gamma(D_s \to f_0(980)e\nu, f_0 \to \pi^+\pi^-)}{\Gamma(D_s \to \phi e\nu, \phi \to K^+K^-)}\bigg|_{q^2=0} = (42 \pm 11)\%$$

based on the similar energy available for the (ss) system.

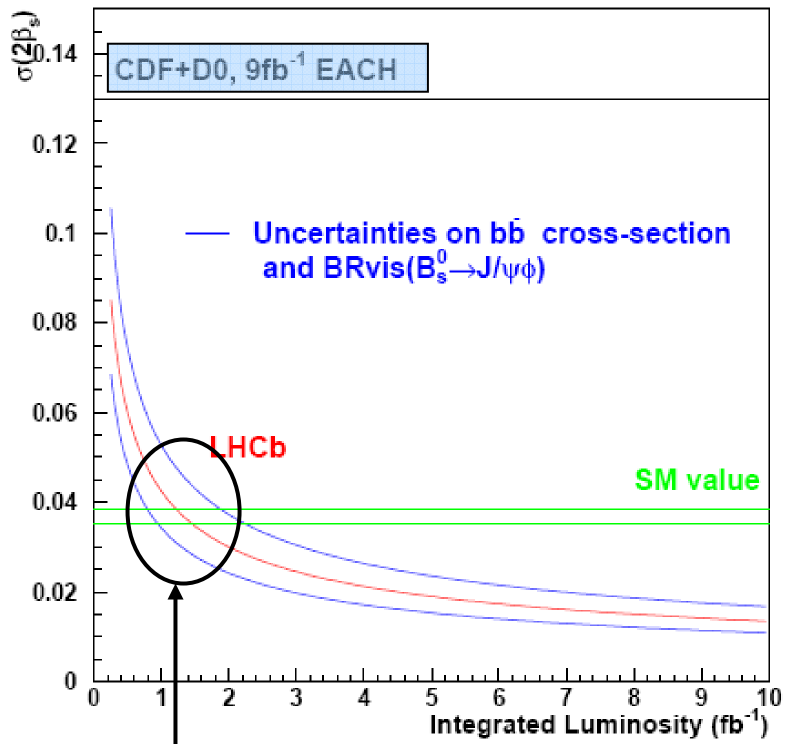
- No angular analysis needed
  → increased single-event sensitivity

- This mode looks very promising for LHCb



ϕ_s mixing Summary (2 fb^{-1})

Decay	Yield (2 fb^{-1})	$\sigma(\phi_s)$ (2 fb^{-1})
*$J/\psi\phi$	117K	**0.035**
$J/\psi f_0(980)$	Not public yet	
$J/\psi\eta_{\gamma\gamma}$	~9K	0.11
$J/\psi\eta'_{\rho\gamma}$	~4K	0.09
$D_s^+D_s^-$	~4K	0.13



For 10 fb^{-1}, scale down error by ~2.2

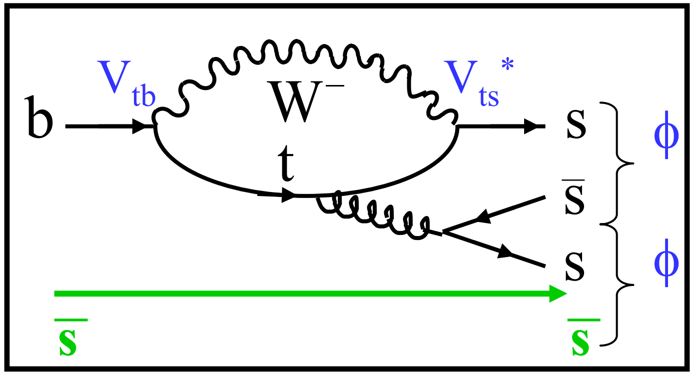
- ❑ Sensitive to SM value before/by end of year 1 (2 fb^{-1}) !
- ❑ NP discover could come before if $\sin(2\beta_s)$ large-ish

* $Inputs: \phi_s = 0.037, \Delta\Gamma_s = 0.084\ ps^{-1}, |A_0|^2 = 0.56, |A_{\parallel}|^2 = 0.21, |A_{\perp}|^2 = 0.23, \delta_{\parallel} = -2.9, \delta_{\perp} = 2.9,$

$LHCb - ROADMAP3 - 001$

$B_s \rightarrow \phi\phi$

- **Penguin loop diagram.**
  => Interference of direct decay and mixing



- V_{ts} appears in both decay and mixing.
  => cancellation of SM contribution of amplitudes
  => $(V_{tb}V^*_{ts}/V^*_{tb}V_{ts})$ $(V^*_{tb}V_{ts}/V_{tb}V^*_{ts}) = 1$
  mixing decay
  => But, new physics unlikely to cancel

- Prediction of CP violation in SM < 1%.
  => **Observation of *any* CP violation is signature for NP.**

- Again, $P \rightarrow VV$ ➔ angular analysis required.

Sensitivity:

- **2 fb^{-1}** : Signal ~ **4K events**, $0.4 < B/S < 2.1$ at 90% CL $\sigma(2\beta_s)_{\phi\phi}$ ~ 0.13 rad
- **10 fb^{-1}: ~20K events** ~ 0.06 rad

γ Measurements in LHCb

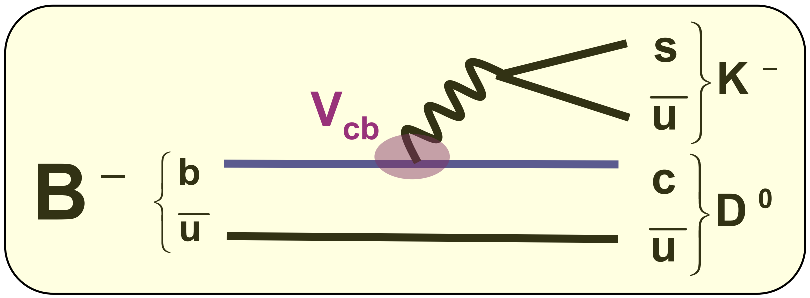
- **$B^+ \rightarrow \overset{(-)}{D}{}^0 K^+$ TREE, No Mixing -** ★★★★★ γ_{SM}
  - $D^0/\bar{D}^0 \rightarrow f_{CP}$, *e.g.* K^+K^-, $\pi^+\pi^-$ (GLW):
  - $D^0/\bar{D}^0 \rightarrow$ CF, DCS *e.g.* $K^-\pi^+$, $K^+\pi^-$ (ADS) + 3-body, 4-body
  - $D^0/\bar{D}^0 \rightarrow$ CF multi-body, e.g. $D^0 \rightarrow K_s\pi^+\pi^-$, $K_sK^+K^-$ (GGSZ)
  - $D^0 \rightarrow$ 4-body, e.g. $K^+K^-\pi^+\pi^-$
- **$B^0 \rightarrow \overset{(-)}{D}{}^0 K^{*0*}(K^+\pi^-)$ Tree, Self-tagging -** ★★★★★ γ_{SM}
  - Much the same issues/techniques as in B^+ decay
  - Time-dependent analysis not required.
  - Dalitz analysis to extract **D^0K^{*0*} amplitude (T. Gershon, PRD79, 051301 (2009))**
- **$B_s \rightarrow D_sK$ & $B^0 \rightarrow D\pi$** ★★★★★ $\gamma_{SM}+\phi_s$
  - Time-dependent analysis necessary
  - Simultaneous fit with $B_s \rightarrow D_s\pi$
- **γ with Penguins**
  - **$B \rightarrow \pi^+\pi^-/K^+K^-$** ★★★★ γ_{SM+NP}
  - $B \rightarrow K\pi\pi$ and other 3 body modes

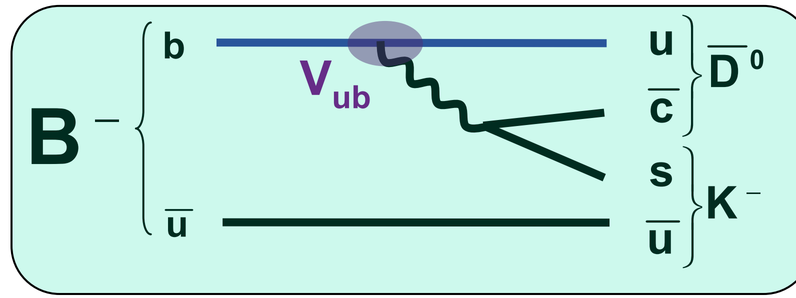
GLW: Gronau & London, PLB253, 483 (1991), Gronau and Wyler, PLB265, 172 (1991) and Dunietz, PLB270, 75 (1991).
ADS: Atwood, Duietz & Soni, PRL78, 3257 (1997)
GGSZ: Giri, Grossman, Soffer, & Zupan PRD 68, 054018 (2003); also Atwood, Dunietz and Soni, PRD63 036005 (2001)

More details in LHCb-2008-031, and references therein

γ in $B^- \rightarrow \overset{(-)}{D^0} K^-$

- Interference between two $O(\lambda^3)$ diagrams → large interference term
- But, one $b \rightarrow c(\bar{u}s)$ is color favored , the other $b \rightarrow u(\bar{c}s)$ is color suppressed





$$\frac{A(B \rightarrow \bar{D}^0 K^-)}{A(B \rightarrow D^0 K^-)} = r_B e^{i\delta_B} e^{-i\gamma} \qquad r_B \sim 0.1$$

γ in $B^- \to \overset{(-)}{D^0} K^-$

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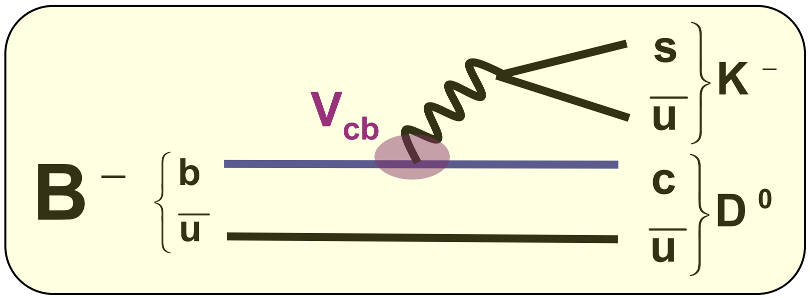
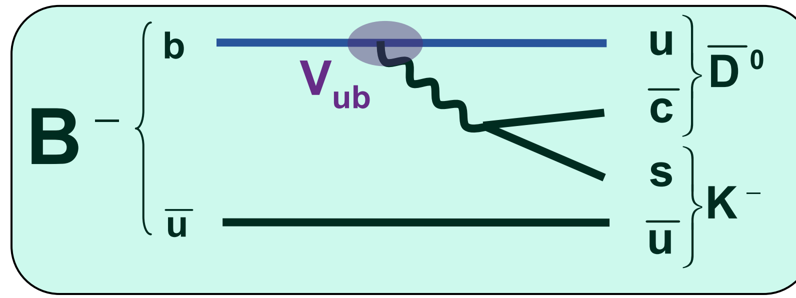




$$\frac{A(B \to \bar{D}^0 K^-)}{A(B \to D^0 K^-)} = r_B e^{i\delta_B} e^{-i\gamma}$$

$r_B \sim 0.1$

GLW: Use $D^0 \to f_{CP}$

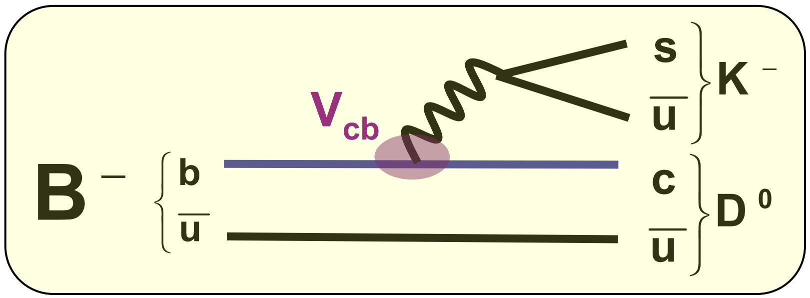
$$\Gamma(B^- \to (h^+h^-)_D K^-) = N_{hh}(1 + r_B^2 + 2r_B \cos(\delta_B - \gamma))$$
$$\Gamma(B^+ \to (h^+h^-)_D K^+) = N_{hh}(1 + r_B^2 + 2r_B \cos(\delta_B + \gamma))$$

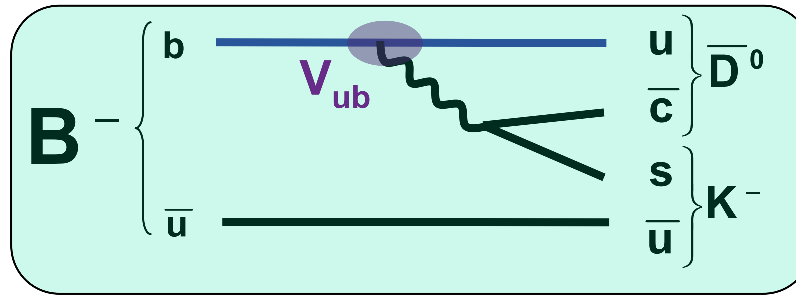
Sensitivity to γ through interference in $D^0/\overline{D^0} \to$ CP final states

☺ Large-ish rates
☹ Small interference $\propto r_B$

γ in $B^- \to \overset{(-)}{D^0} K^-$

- Interference between two $O(\lambda^3)$ diagrams → large interference term
- But, one $b \to c(\bar{u}s)$ is color favored , the other $b \to u(\bar{c}s)$ is color suppressed





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Sensitivity to γ through interference in $D^0/\overline{D^0} \to$ CP final states

☺ Large-ish rates
☹ Small interference $\propto r_B$

ADS: Interference between CF & DCS Decays

$$(1)\ \Gamma(B^- \to (K^-\pi^+)_D K^-) = N_{K\pi}(1 + (r_B r_D^{K\pi})^2 + 2r_B r_D^{K\pi}\cos(\delta_B - \delta_D^{K\pi} - \gamma))$$
$$(2)\ \Gamma(B^- \to (K^+\pi^-)_D K^-) = N_{K\pi}(r_B^2 + (r_B r_D^{K\pi})^2 + 2r_B r_D^{K\pi}\cos(\delta_B + \delta_D^{K\pi} - \gamma))$$
$$(3)\ \Gamma(B^+ \to (K^-\pi^+)_D K^+) = N_{K\pi}(r_B^2 + (r_B r_D^{K\pi})^2 + 2r_B r_D^{K\pi}\cos(\delta_B + \delta_D^{K\pi} + \gamma))$$
$$(4)\ \Gamma(B^+ \to (K^+\pi^-)_D K^+) = N_{K\pi}(1 + (r_B r_D^{K\pi})^2 + 2r_B r_D^{K\pi}\cos(\delta_B - \delta_D^{K\pi} + \gamma))$$

☺ Large interference in (2) & (3) → Enhanced sensitivity to γ
☹ Low rates (DCSD)

ADS/GLW Two-Body Combined

$$\Gamma(B^- \to (h^+h^-)_D K^-) = N_{hh}(1 + r_B^2 + 2r_B\cos(\delta_B - \gamma))$$
$$\Gamma(B^+ \to (h^+h^-)_D K^-) = N_{hh}(1 + r_B^2 + 2r_B\cos(\delta_B + \gamma))$$

GLW

Include both $D^0 \to KK, \pi\pi$

$$\Gamma(B^- \to (K^-\pi^+)_D K^-) = N_{K\pi}(1 + (r_B r_D^{K\pi})^2 + 2r_B r_D^{K\pi}\cos(\delta_B - \delta_D^{K\pi} - \gamma))$$
$$\Gamma(B^- \to (K^+\pi^-)_D K^+) = N_{K\pi}(r_B^2 + (r_B r_D^{K\pi})^2 + 2r_B r_D^{K\pi}\cos(\delta_B + \delta_D^{K\pi} - \gamma))$$
$$\Gamma(B^+ \to (K^-\pi^+)_D K^-) = N_{K\pi}(r_B^2 + (r_B r_D^{K\pi})^2 + 2r_B r_D^{K\pi}\cos(\delta_B + \delta_D^{K\pi} + \gamma))$$
$$\Gamma(B^+ \to (K^+\pi^-)_D K^+) = N_{K\pi}(1 + (r_B r_D^{K\pi})^2 + 2r_B r_D^{K\pi}\cos(\delta_B - \delta_D^{K\pi} + \gamma))$$

ADS

6 unknowns : $r_B, \delta_B, \delta_D^{K\pi}, \gamma, N_{K\pi}, N_{hh}$

But additional constraints:

$$N_{hh} = \frac{\varepsilon_{hh}}{\varepsilon_{K\pi}} \frac{B_{hh}}{B_{K\pi}} N_{K\pi}$$

$CLEO-c : \delta_D^{K\pi} = (22^{+11+9}_{-12-11})^o$

$r_D^{K\pi} \sim 0.06$ **well measured**

Mode	Yield	B/S
$B^\pm \to D_{fav}(K\pi)K^\pm$	31k	0.6
$B^\pm \to D_{sup}(K\pi)K^\pm$	600	0.6
$B^\pm \to D_{CP}(KK)K^\pm$	3.2k	1.2
$B^\pm \to D_{CP}(\pi\pi)K^\pm$	1.1k	3.2

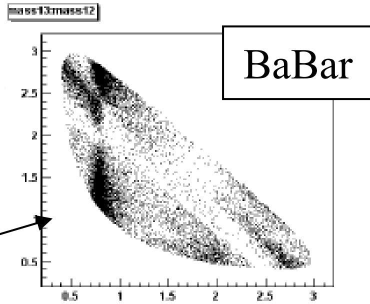
LHCb-2009-011

$2\ fb^{-1}$

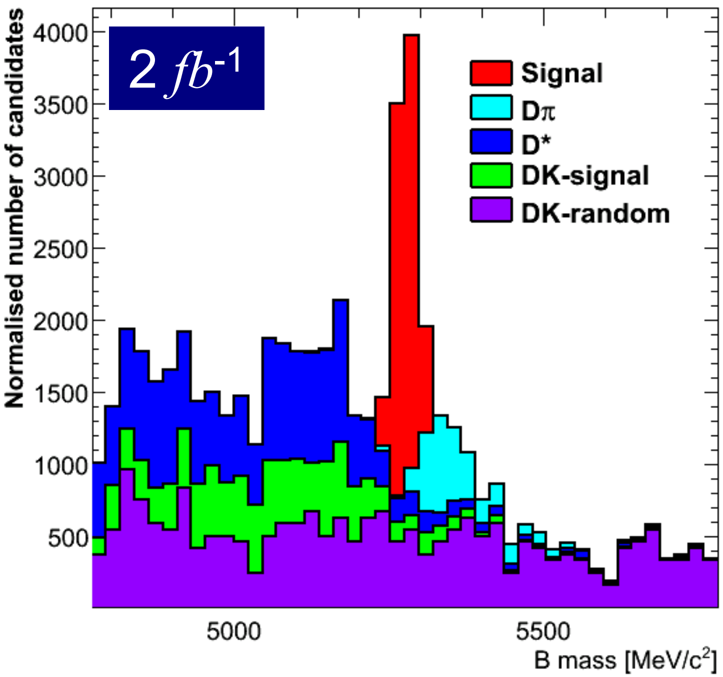
$\sigma_\gamma \sim 10\text{-}11^o$ for $2\ fb^{-1}$
$\sim 5^o$ for $10\ fb^{-1}$
for $r_B = 0.10$

γ in $B^+ \to D^0(K_s\pi^+\pi^-)K^+$

$$\Gamma(B^+ \to D^0(K_S\pi\pi)K^+) = |f_D|^2 + r_B^2|\bar{f}_D|^2 + 2|f_D||\bar{f}_D| r_B \cos(\Delta\delta_D - (\delta_B + \gamma))$$
$$\Gamma(B^- \to D^0(K_S\pi\pi)K^-) = |\bar{f}_D|^2 + r_B^2|f_D|^2 + 2|f_D||\bar{f}_D| r_B \cos(\Delta\delta_D + (\delta_B + \gamma))$$



- CF, common final state: Much larger BFs.
- Interference between the $D^0 \to K_s\pi\pi$ and $\overline{D^0} \to K_s\pi^+\pi^-$.
- Relative strong phase shift $\Delta\delta_D = \delta_D(m_-^2, m_+^2) - \delta_D(m_+^2, m_-^2)$
  - Using flavor-tagged $D^0 \to K_s\pi\pi \to$ ~7-9° model uncertainty
  - Use QC $\psi(3770) \to D^0D^0$ from CLEO-*c* ~2° model uncertainty! (PRD**78**, 092007 (2008))



Signal / 2 fb^{-1}: ~ **5K**
B/S : ~ **0.5**

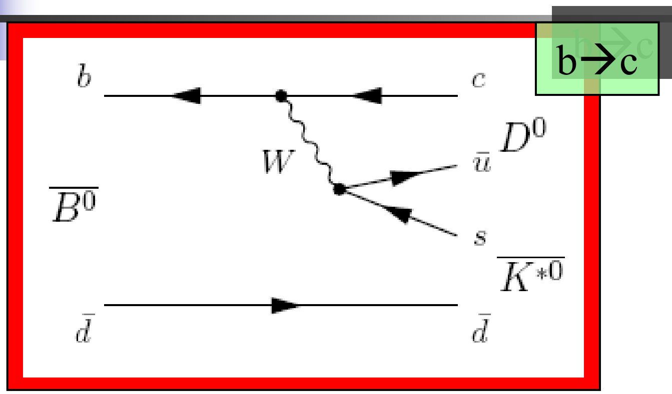
σ_γ ~12-13° / 2 fb^{-1}

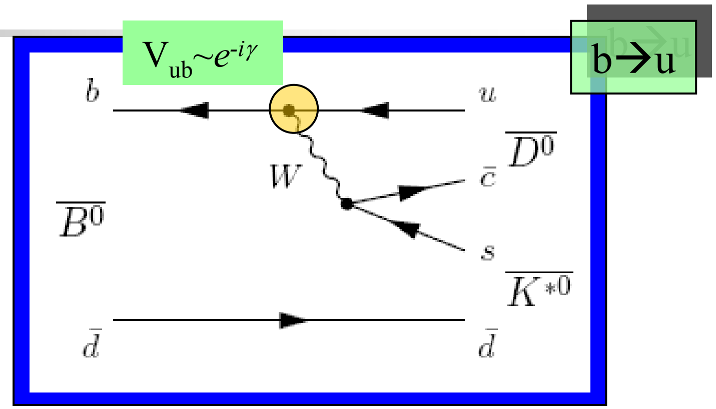
σ_γ ~ 6° / 10 fb^{-1}

LHCb-2008-028

T. Gershon, PRD79, 051301 (2009))

γ in $B^0 \to \overset{(-)}{D^0} K^{*0}$

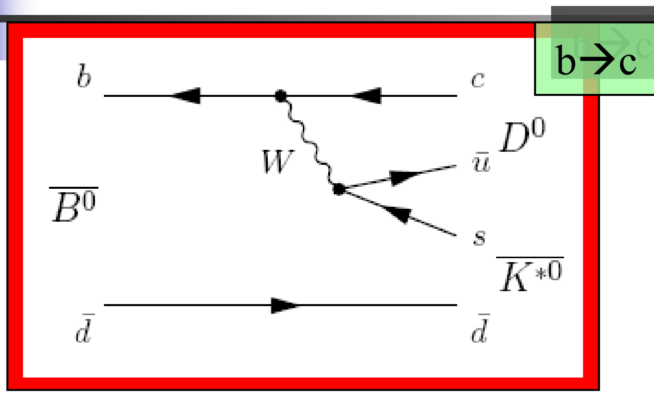


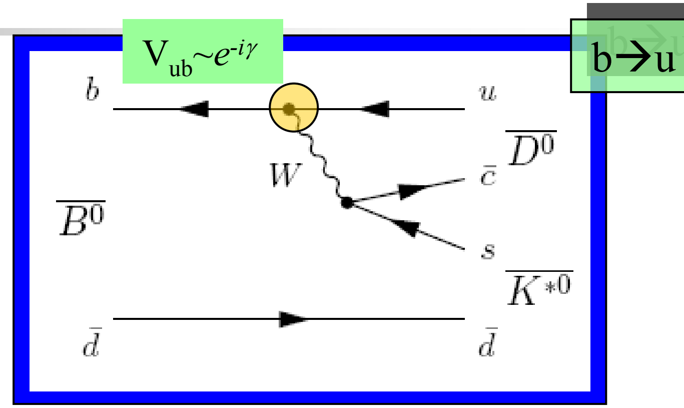


- $B^0 \to \overset{(-)}{D^0} K^{*0}$, $K^{*0} \to K^+\pi^-$ <u>not accessible</u> in B^0 decay → self tagging.
- Both diagrams color suppressed!
  - $r_B \sim 0.4$ compared to ~0.1 in $B^+ \to D^0K^+$ → larger interference term

T. Gershon, PRD79, 051301 (2009))

γ in $B^0 \to \overset{(-)}{D^0} K^{*0}$





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The amplitudes in CF, DCS, and CP final states

$$A\left(\overline{B^0} \to D^0(K^-\pi^+)K^{*0}\right)_{CF} = A_{K^*}\left(1 + r_B e^{i(\delta_B+\gamma)} r_D e^{i\delta_D}\right)$$

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T. Gershon, PRD79, 051301 (2009))

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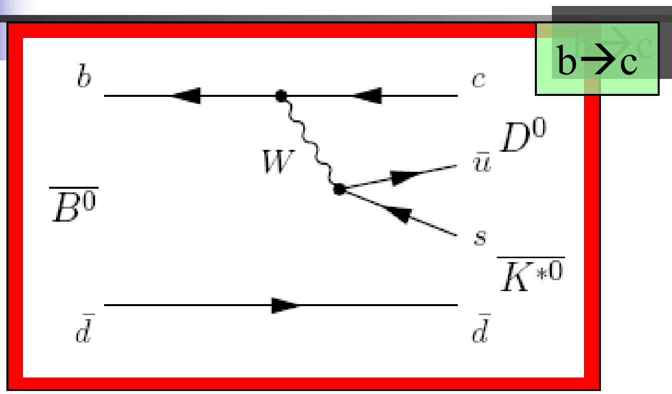

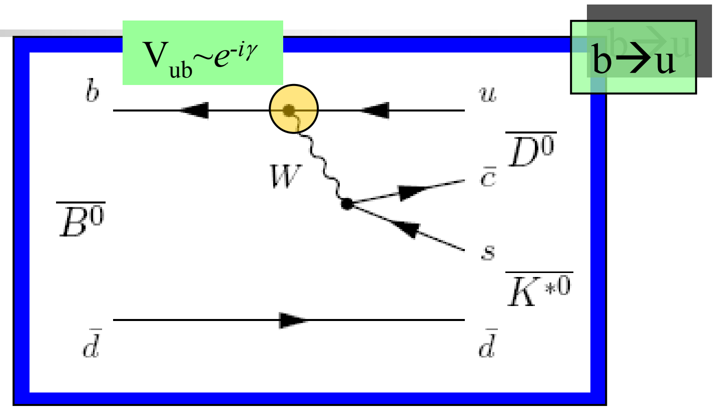

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- 4 amplitude ratios
- 3 unknowns: r_B, δ_B and γ!
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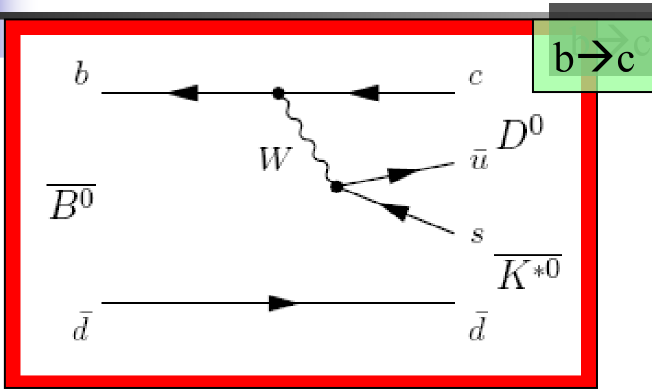

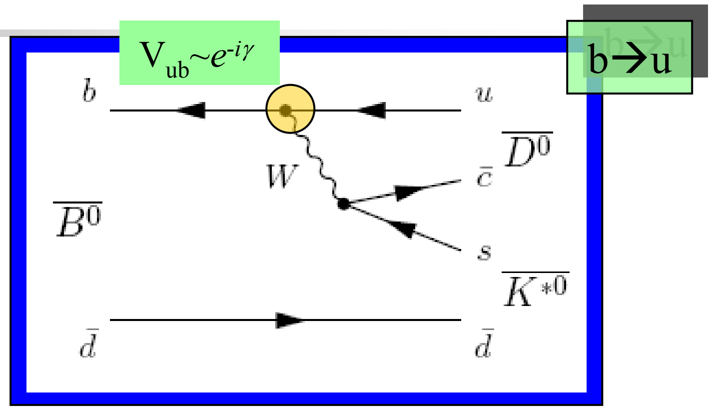

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- 4 amplitude ratios
- 3 unknowns: r_B, δ_B and γ!
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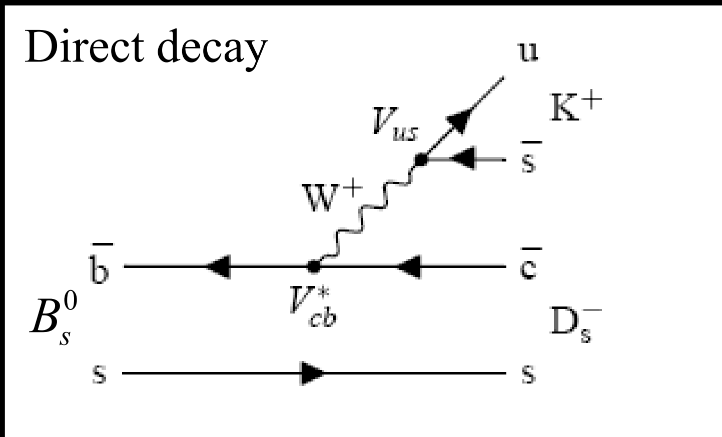
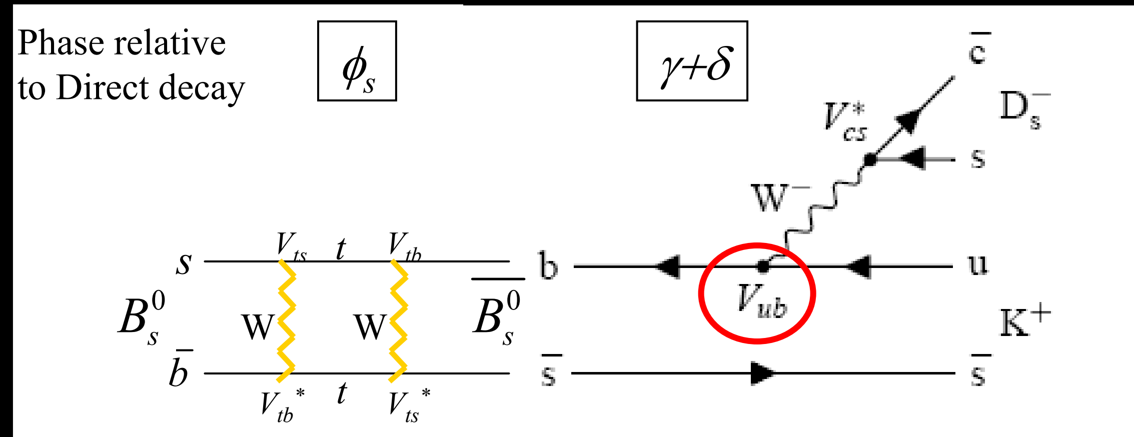
This mode looks extremely promising for LHCb, may provide the greatest sensitivity to γ !

γ in $B_s \rightarrow D_s K$



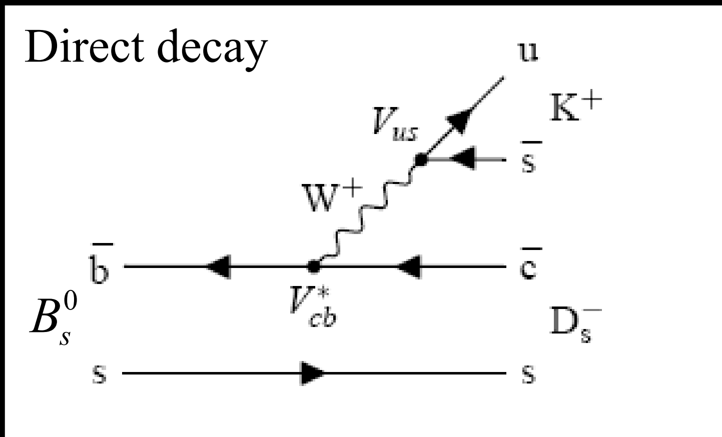


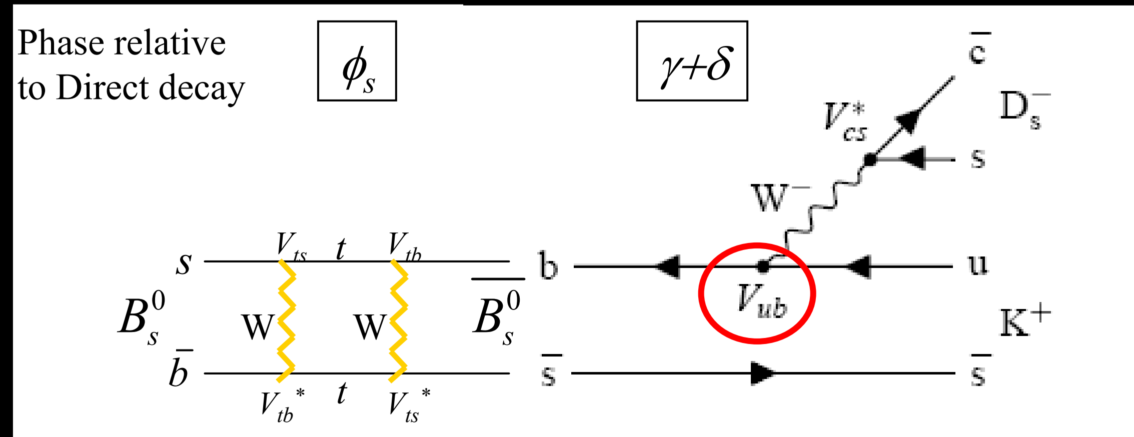
- 4 time-dependent rates, 3 fit parameters ($|\lambda|$, δ, $\gamma+\phi_s$)

$$\Gamma(B_s^0 \to D_s^- K^+) = \frac{|A|^2}{2} e^{-t/\tau}[(1+|\lambda|^2)\cosh(\Delta\Gamma_s t/2) + (1-|\lambda|^2)\cos(\Delta m_s t) - 2|\lambda|\cos(\delta+(\gamma+\phi_s))\sinh(\Delta\Gamma_s t/2) - 2|\lambda|\sin(\delta+(\gamma+\phi_s))\sin(\Delta m_s t)]$$

$$|\lambda| = \left|\frac{\bar{A}_f}{A_f}\right| = \left|\frac{V_{ub}V_{cs}}{V_{cb}V_{us}}\right| \sim 0.4$$

γ in $B_s \to D_s K$





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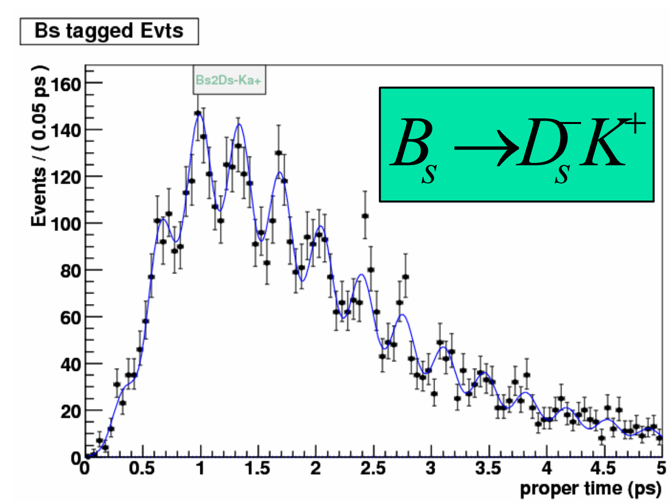
- Simultaneous fit for $B_s \to D_s K$, $D_s\pi$
- $D_s\pi$ ~140K/2 fb^{-1}, constrains: ω_{mistag}, Δm_s, $\Delta\Gamma_s$, Γ_s
- ~50% of events with no flavor tag included, provide some additional sensitivity.

$B_s \to D_s K$: Signal ~ 7K/2 fb^{-1}, B/S ~ 0.7

$$\sigma_{\gamma+\phi_s} \sim 11^0 / 2\ fb^{-1} \quad (\sim 5^0 / 10\ fb^{-1})$$



- $B_s \to D_s K^*$, $B_s \to D_s(K\pi\pi)$ will also add sensitivity

LHCb-2007-059

γ from $B\rightarrow\pi\pi,KK$

- CPV from interference between T&P with & without mixing

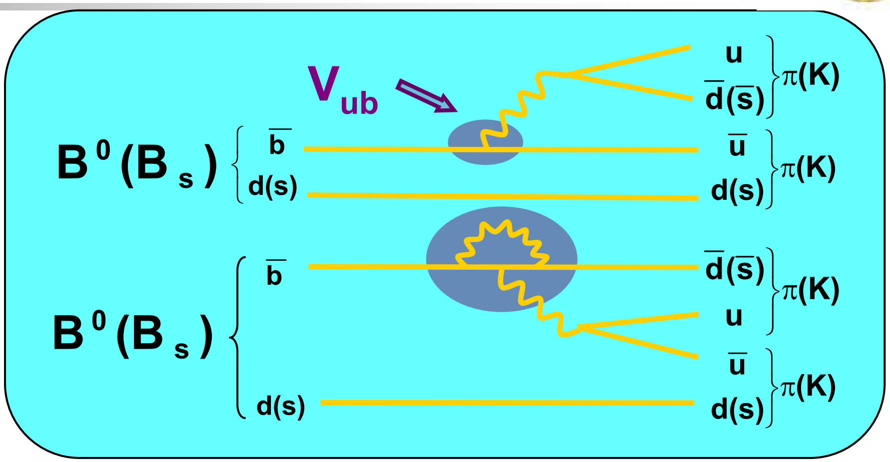
$$A_f^{CP}(t)=\frac{A_f^{dir}\cdot\cos(\Delta m\cdot t)+A_f^{mix}\cdot\sin(\Delta m\cdot t)}{\cosh\left(\frac{\Delta\Gamma}{2}\cdot t\right)-A_f^{\Delta\Gamma}\cdot\sinh\left(\frac{\Delta\Gamma}{2}\cdot t\right)}$$

$$A_{\pi\pi}^{dir}(d,\theta,\gamma),\quad A_{\pi\pi}^{mix}(d,\theta,2\beta,\gamma)$$

$$d_{\pi\pi}e^{i\theta_{\pi\pi}}=\frac{1}{R_{\pi\pi}}\left(\frac{r_P^{\pi\pi}}{1+r_P^{\pi\pi}}\right),\quad r_P^{\pi\pi}=\frac{P_{\pi\pi}^c}{T_{\pi\pi}}-\frac{P_{\pi\pi}^t}{T_{\pi\pi}}$$

3 unknowns, 2 measurements.. ?
Add $B_s\rightarrow K^+K^-$ and invoke U-spin symmetry

$$U-spin: d_{KK}=\left(\frac{1-\lambda^2}{\lambda^2}\right)d_{\pi\pi},\quad \theta_{KK}=\theta_{\pi\pi}$$



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LHCb-2007-059

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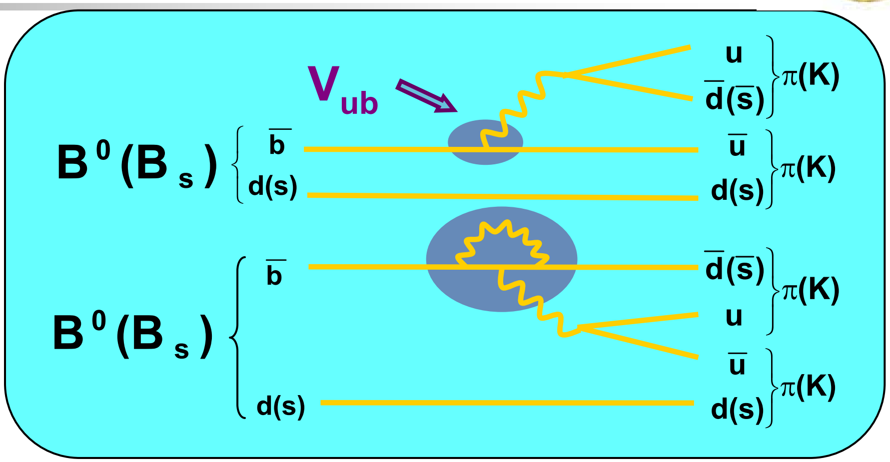

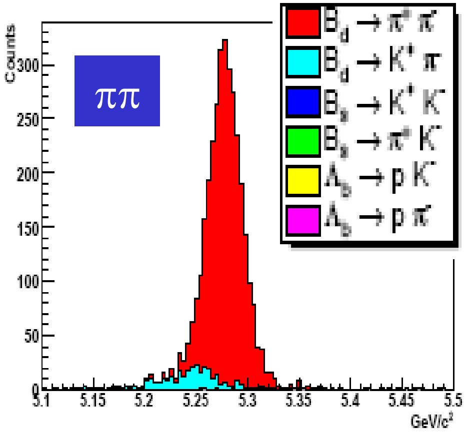

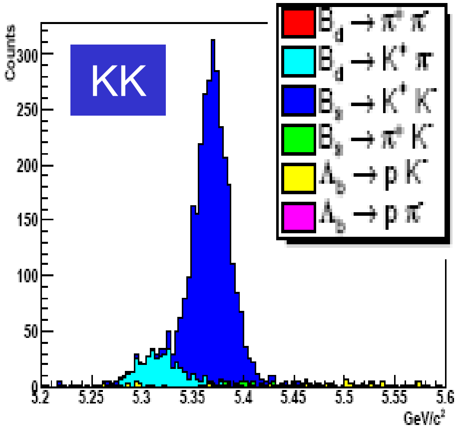

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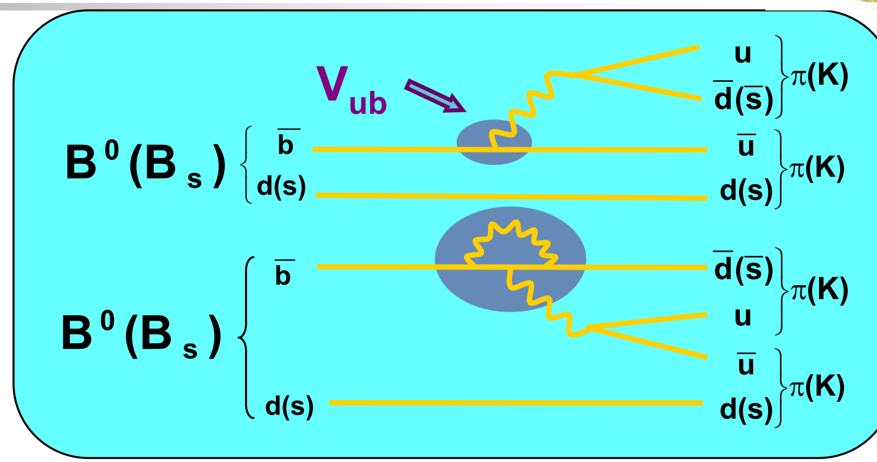

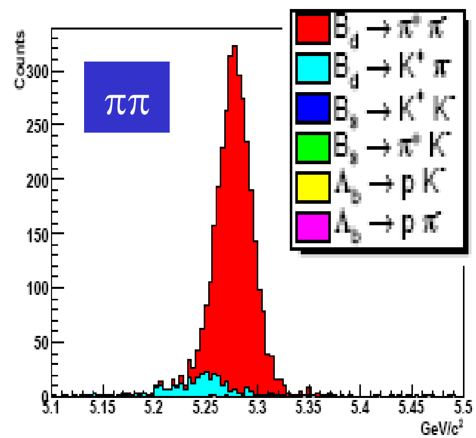

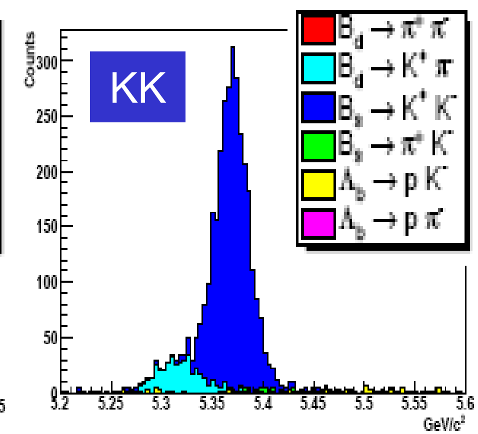

Mode	Sig. yield (untagged)	B/S
$B^0\to\pi\pi$	36k	0.5
$B_s\to KK$	36k	0.15
$B^0\to K\pi$	140k	< 0.06
$B_s\to\pi K$	10k	1.9

2 fb^{-1}

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LHCb-2007-059

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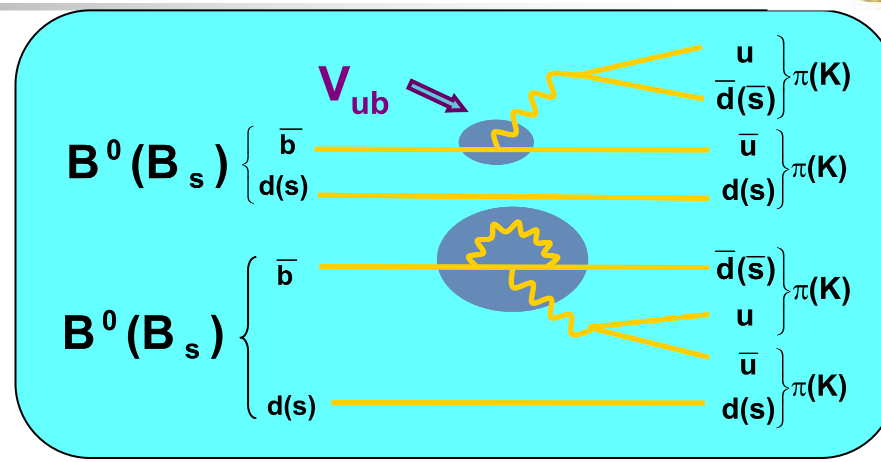

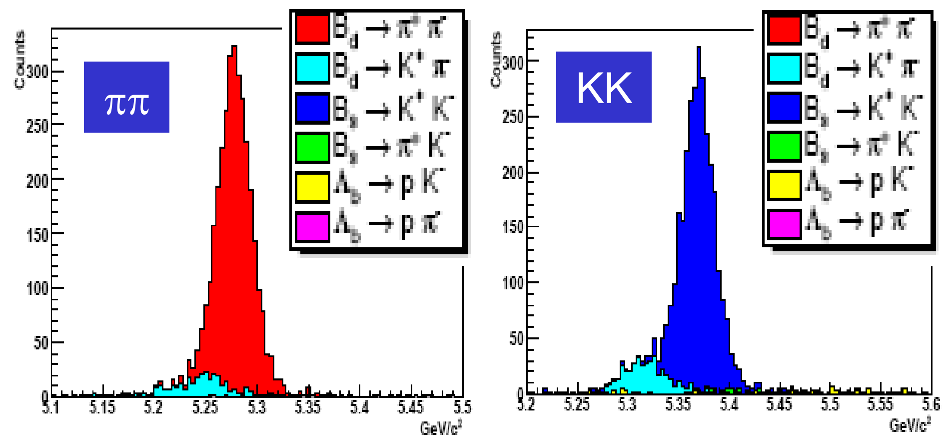

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Input: 2β & $2\beta_s$

Allow for ±20% U-spin breaking

$\sigma_\gamma \sim 10^o$ / 2 fb^{-1}
$\sim 5^o$ / 10 fb^{-1}

γ Summary

Decay	$\sigma_\gamma(^o)$ (2 fb^{-1})
TREES ONLY	
$B^+ \rightarrow D^0K^+$, 2-body ADS/GLW+$D^0 \rightarrow K\pi\pi\pi$	~8
$B^+ \rightarrow D^0(K_s\pi\pi)K^+$	~13
$B^0 \rightarrow D^0K^{*0}$, 2-bodyADS/GLW	~18
Global Fit (Trees)	**~6^o**
TIME-DEPENDENT	
$B_s \rightarrow D_sK$	**~11^o**
TIME DEPENDENT & PENGUINS	
$B_{(s)} \rightarrow \pi\pi,KK$	**~10^o**

10 fb^{-1}:

- γ Trees: ~ 3^o
- γ Time-dependent: ~5^o
- **γ Combined: ~ (1.9 – 2.7)^o** (depending on r_B, δ_B)
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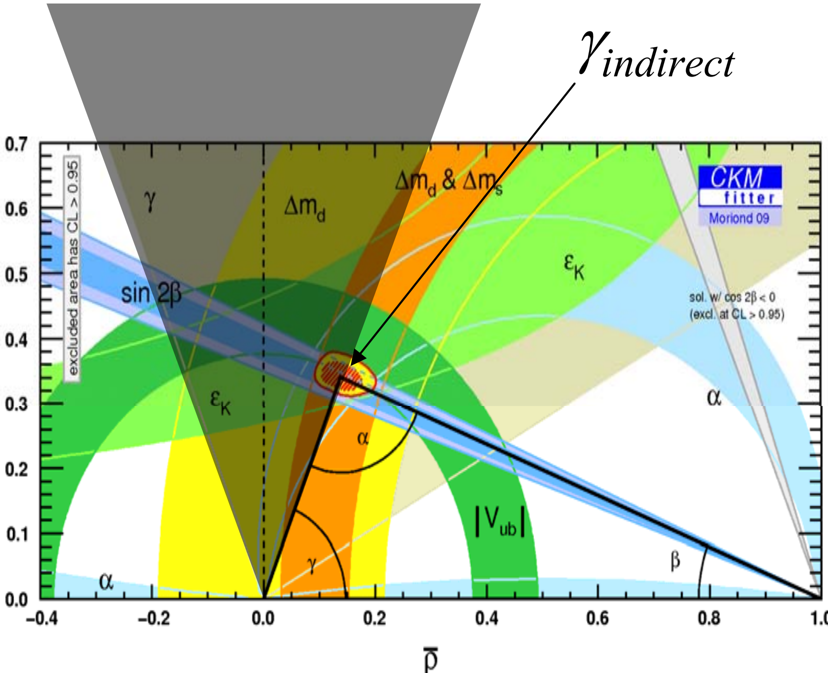
2010



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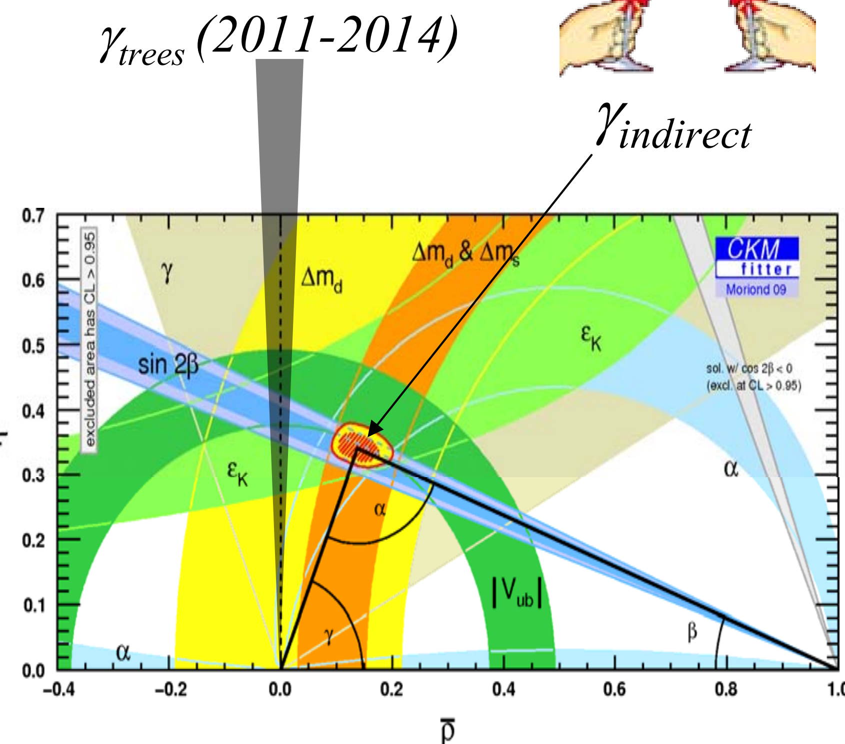

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- New Physics is not only about producing new particles.
  - Although that would clearly be tremendous!
- New Physics should couple non-trivially with flavor.
  - Should lead to modified rates, CPV asymmetries, angular distributions, etc
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- LHCb expects to expose these differences, if they are observable
- Measurements of $\sin(2\beta_s)$ and γ could reveal NP within just 1 nominal year.
- Also expect to break new ground in CPV in D^0 decays
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Special thanks to Wayne State and the organizing committee

The next few years should be quite exciting!

Backups

$B_s \to J/\psi\phi$ Differential Rate

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\, d\cos\theta\, d\varphi\, d\cos\psi} \equiv \frac{d^4\Gamma}{dt\, d\Omega} \propto \sum_{k=1}^{6} h_k(t) f_k(\Omega)$$

k	$h_k(t)$	$\bar{h}_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0(t)\rvert^2$	$\lvert \bar{A}_0(t)\rvert^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\lvert \bar{A}_\parallel(t)\rvert^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\lvert A_\perp(t)\rvert^2$	$\lvert \bar{A}_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im\{A_\parallel^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\}$	$-\sin^2\psi\sin 2\theta\sin\varphi$
5	$\Re\{A_0^*(t)A_\parallel(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_\parallel(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
6	$\Im\{A_0^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$

$$|A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right]$$

$$|A_\parallel(t)|^2 = |A_\parallel(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right]$$

$$|A_\perp(t)|^2 = |A_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right]$$

$$\Im\{A_\parallel^*(t)A_\perp(t)\} = |A_\parallel(0)||A_\perp(0)|e^{-\Gamma_s t}\Big[-\cos(\delta_\perp-\delta_\parallel)\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp-\delta_\parallel)\cos\Phi\sin(\Delta m_s t)\Big]$$

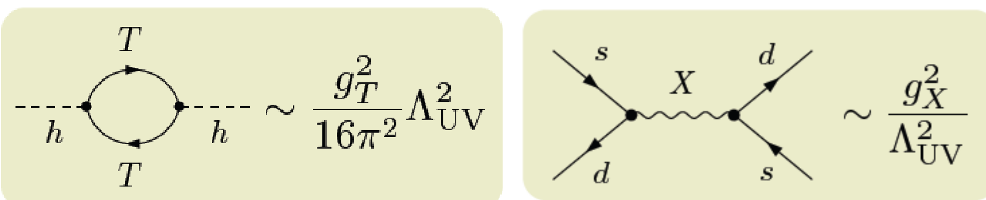
$$\Re\{A_0^*(t)A_\parallel(t)\} = |A_0(0)||A_\parallel(0)|e^{-\Gamma_s t}\cos\delta_\parallel\Big[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\Big]$$

$$\Im\{A_0^*(t)A_\perp(t)\} = |A_0(0)||A_\perp(0)|e^{-\Gamma_s t}\Big[-\cos\delta_\perp\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\delta_\perp\cos(\Delta m_s t) - \cos\delta_\perp\cos\Phi\sin(\Delta m_s t)\Big]$$

What has B Physics taught us

- Explosion of results over the last ~8 years. CKM describes major part of flavor-changing and CP violating effects.
  - New Physics a correction to LO CKM
- Surprising we haven't seen larger effects by now

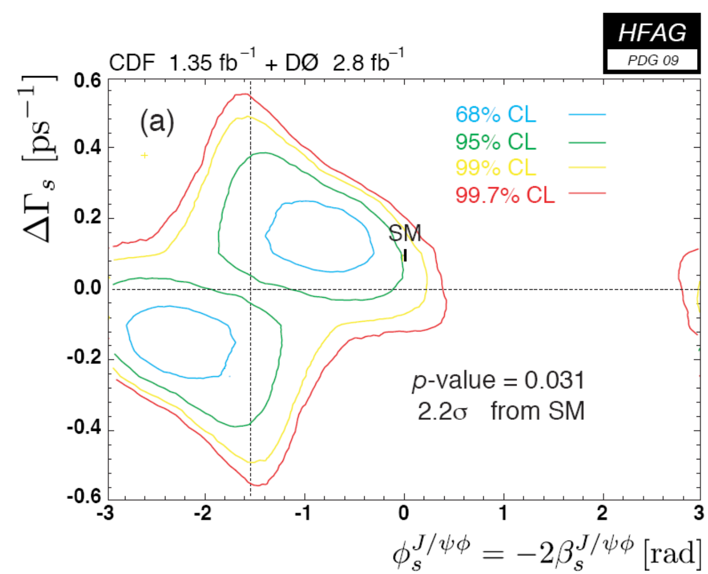
M. Neubert, FPCP09



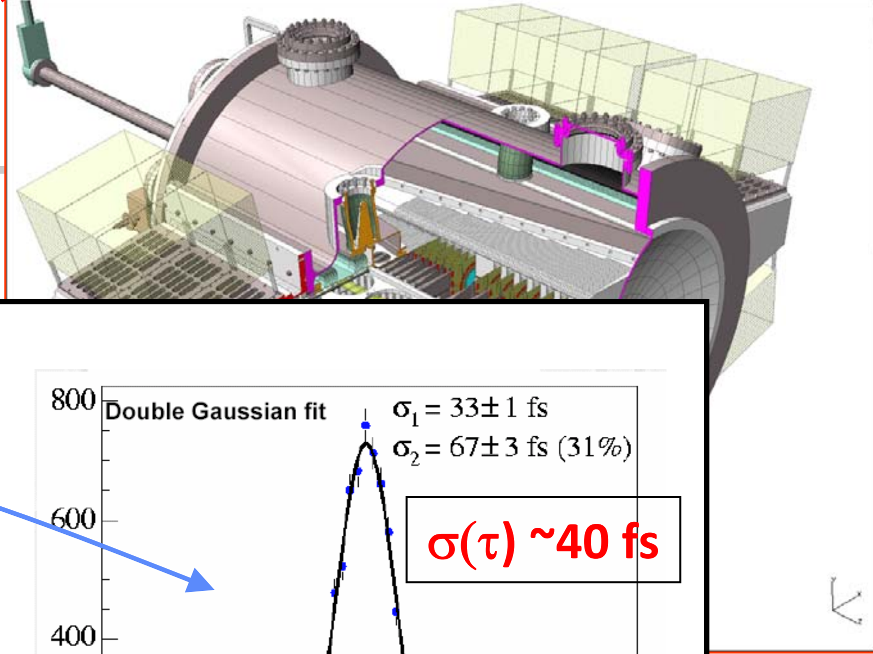
Widely disparate scales?
Minimal Flavor Violation?

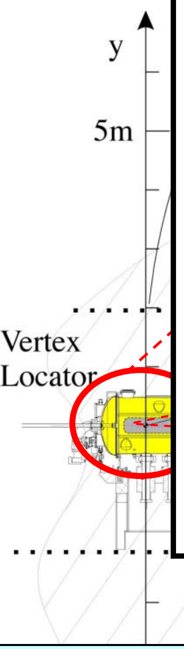
$\Lambda_{Higgs} \lesssim 1$ TeV $\longrightarrow$ increasing energy scale $\longrightarrow$ $\Lambda_{flavor} \gtrsim 10^3$ TeV

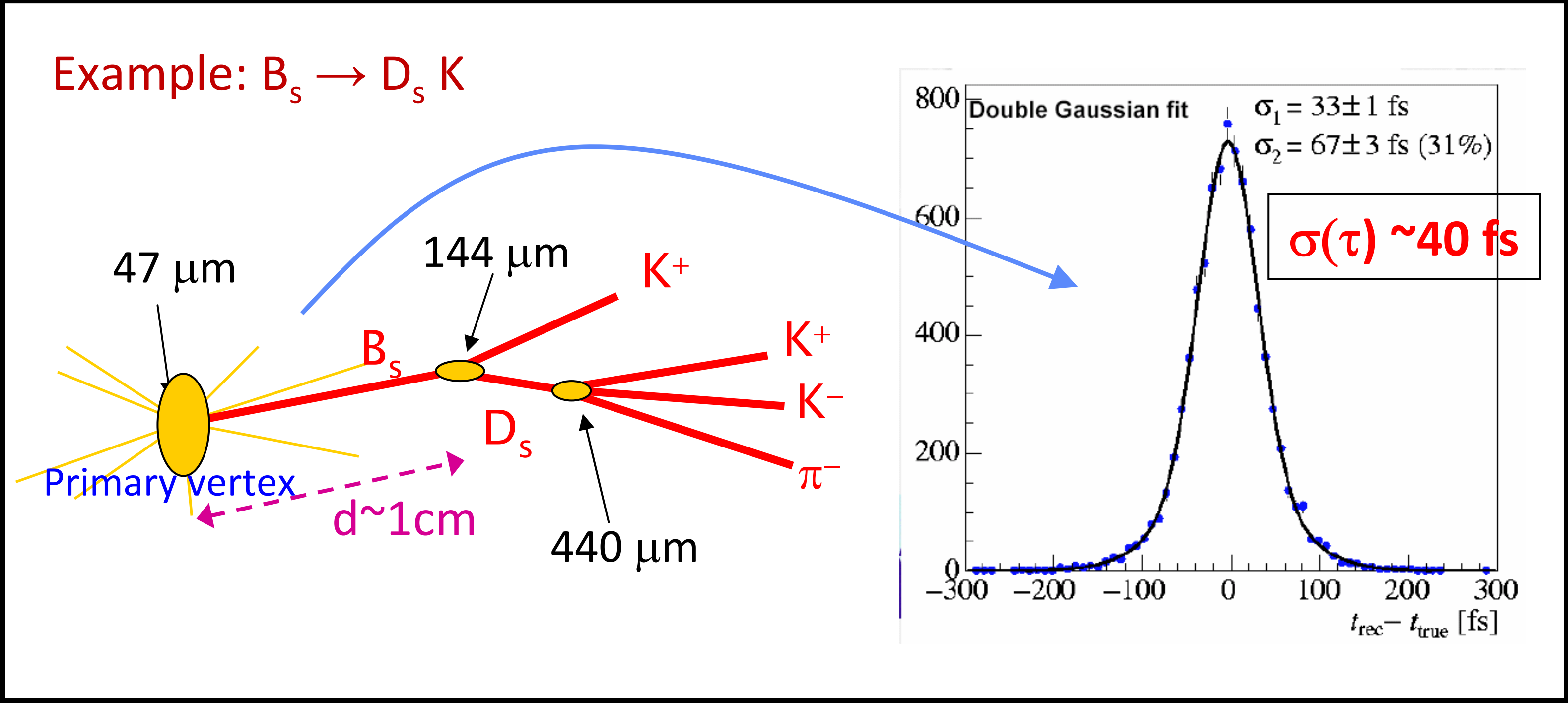
- But, there are tantalizing hints that New Physics may be around the corner
  - E.g. 2.2σ tension in $2\beta_s$ from the Tevatron

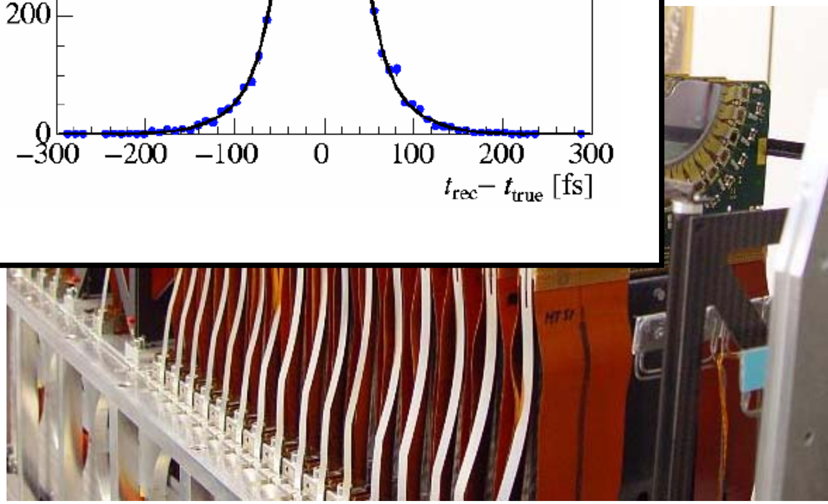


B-Vertex Measurement









Vertex Locator (Velo)

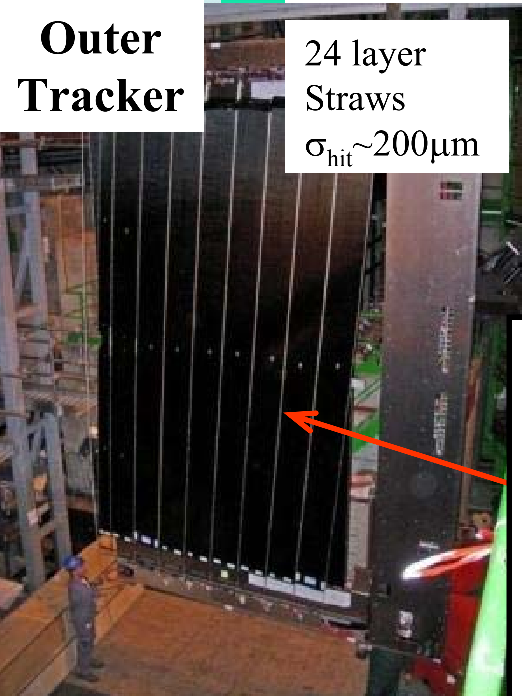
21 stations of silicon strip detectors (r-ϕ)

~ 8 μm hit resolution

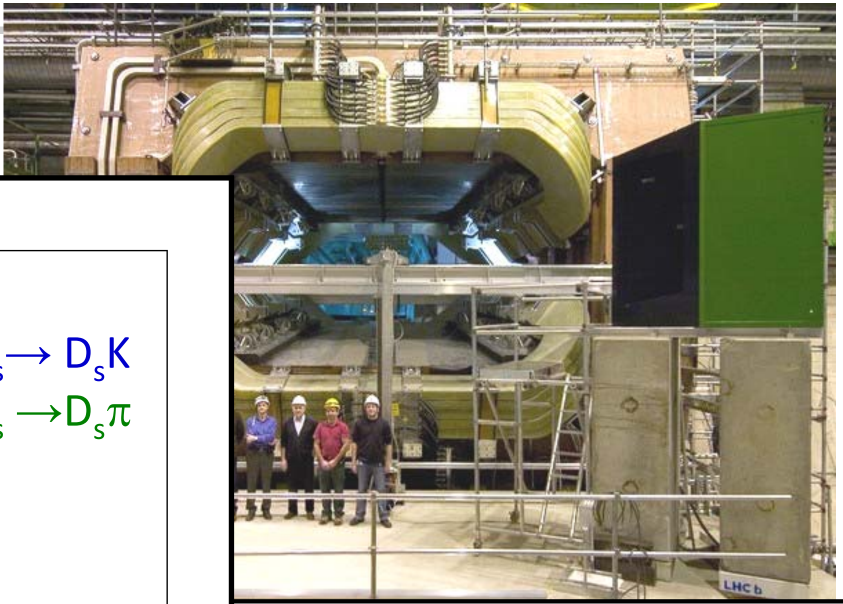
~25 μm IP resolution

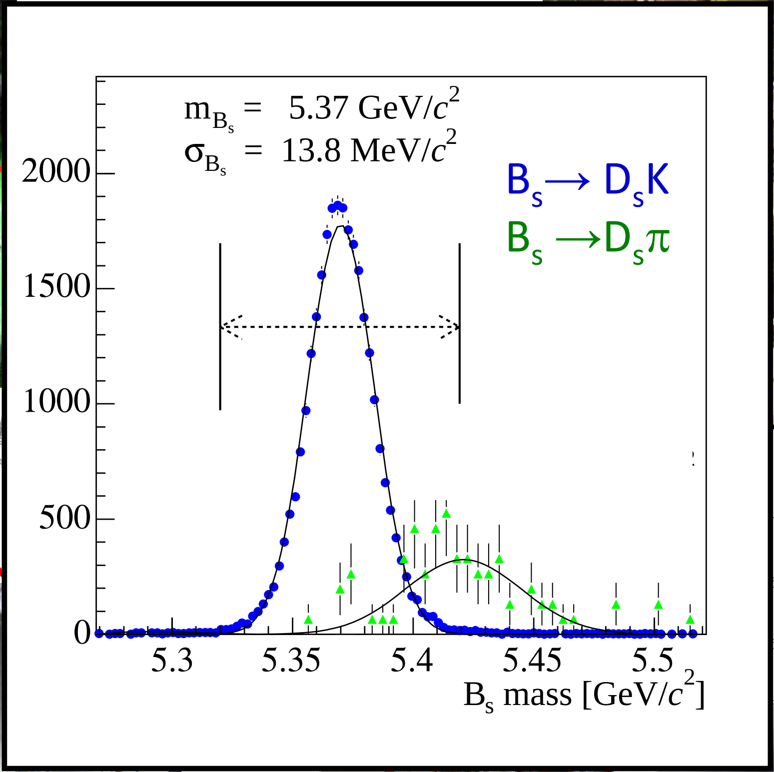
- Trigger on large IP tracks
- Measurement of decay distance (time)

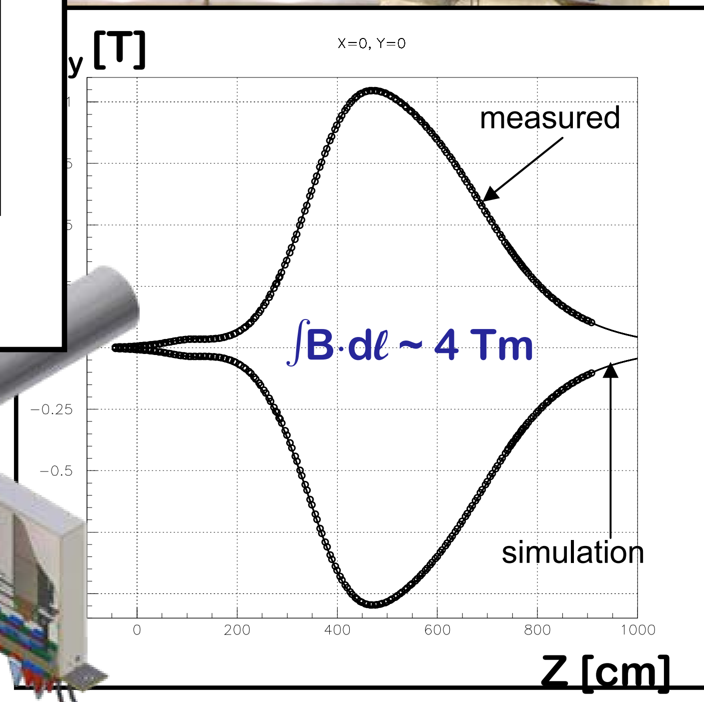
Momentum measurement

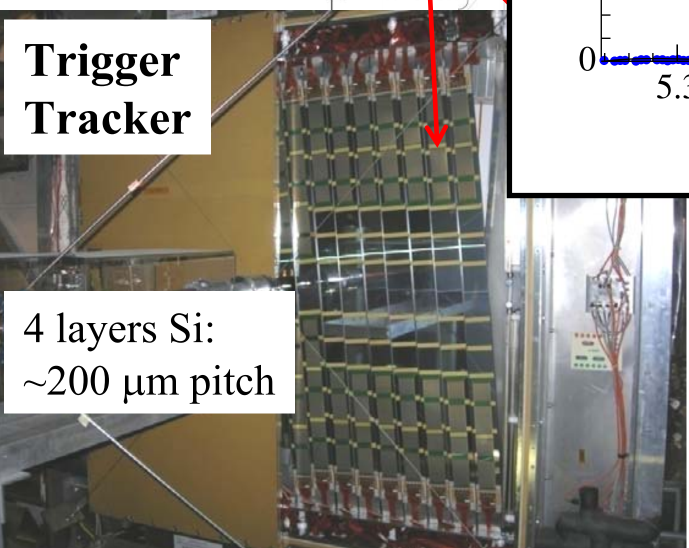


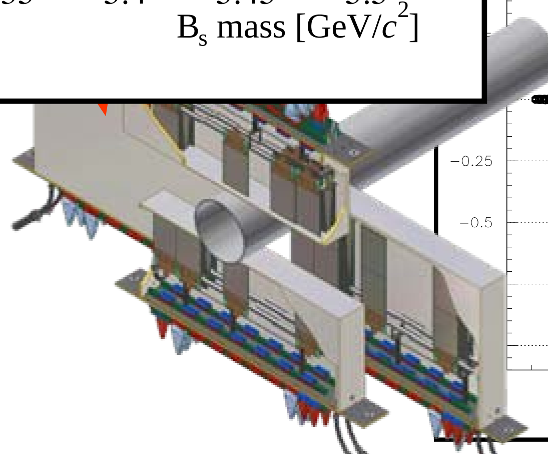
σ_p/p~0.5%





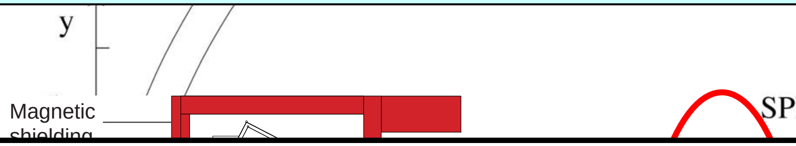


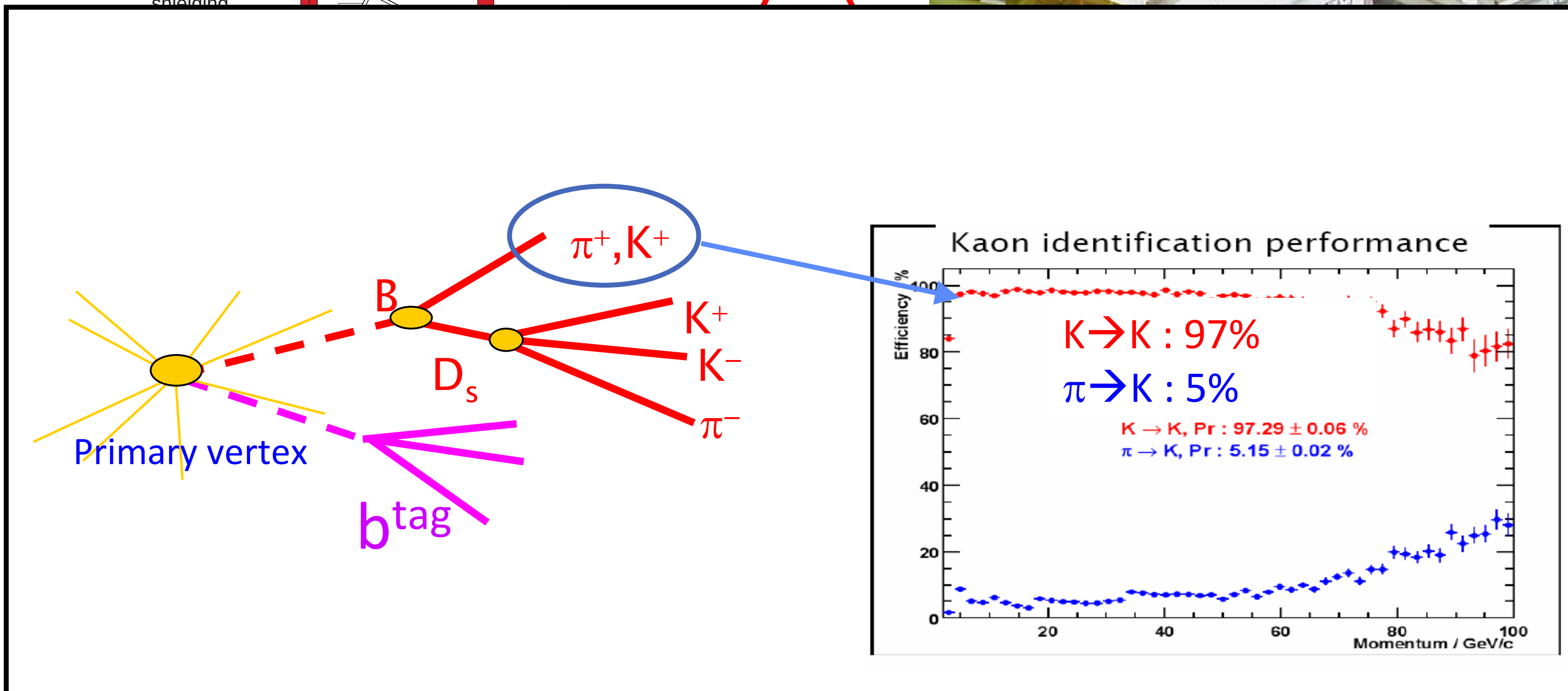




Particle Identification

RICH: p/K/π identification using Cherenkov angle (rings)



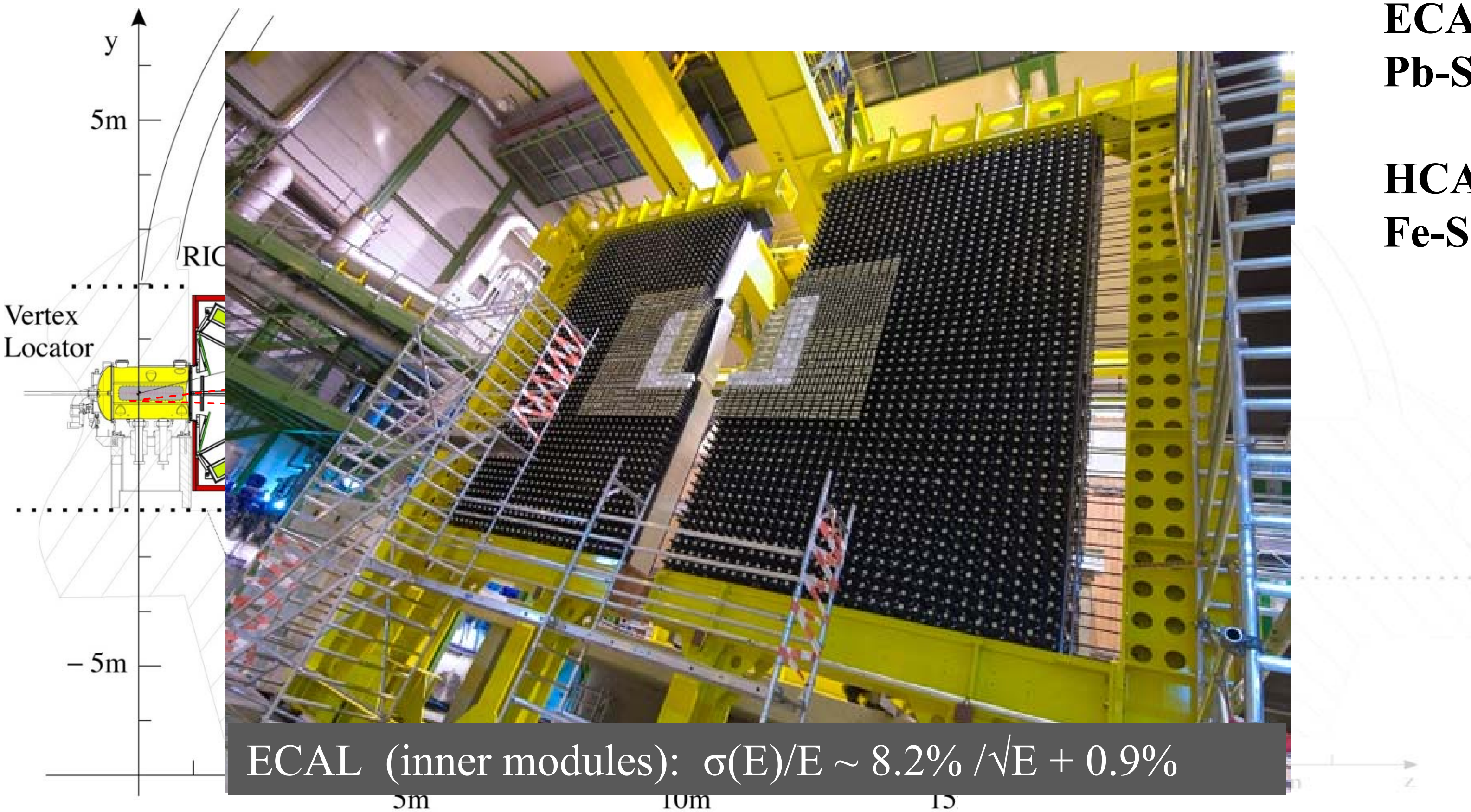


RICH1: 5 cm aerogel n=1.03

4 m^3 C_4F_{10} n=1.0014

RICH2: 100 m^3 CF_4 n=1.0005

ECAL & HCAL: L0 trigger & Particle ID



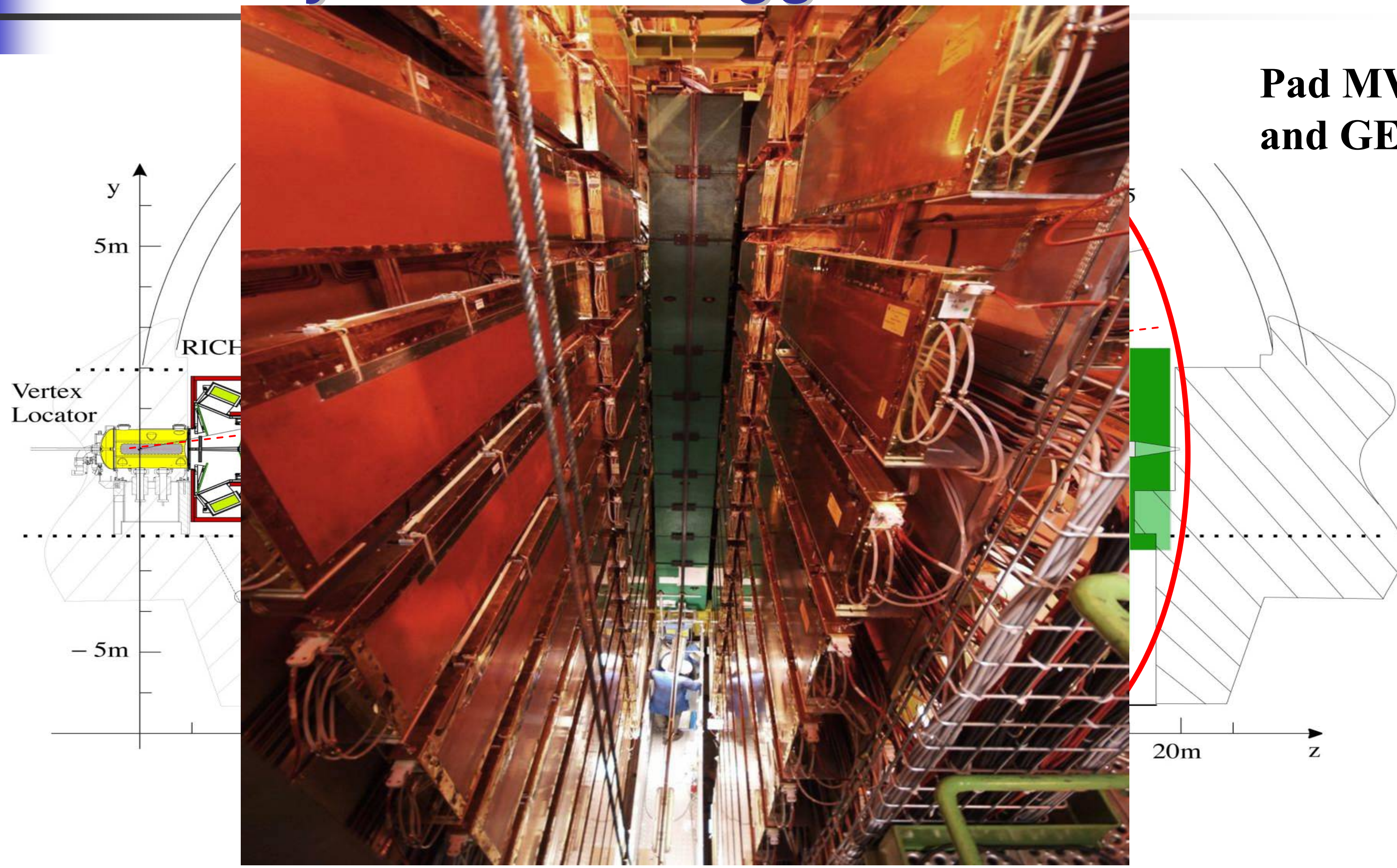
ECAL: Pb-Scint.

HCAL Fe-Scint.

- Level 0 trigger: high E_T electron and hadron
- Identify electrons, hadrons, π^0, γ

Muon System: L0 trigger & Particle ID

Pad MWPCs and GEMs



Muon system:

•Level 0 trigger: High P_t muons

LHCb trigger

Detector

↓

40 MHz

L0: high p_T ~ 1-4 GeV (μ, di-μ, e, γ, *h, di-h…*) [hardware]

↓

1 MHz

16000 core online farm

↓

HLT1: Confirm L0 w/ tracking in ROI; p_T, IP cuts

↓

~30 kHz

↓

HLT2: full reconstruction of event

- **Inclusive selections**
  - Ex: Single high p_T μ, di-μ, J/ψ, *2h, 3h, 4h*
- **Exclusive selections :**
  - Ex: $B_{(s)} \rightarrow D_{(s)} h^{(*)}$, $\phi\phi$, $K^* \ell\ell$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-$, K^+K^-,

↓

To tape: 35 kB @ 2 kHz

Additional ADS: $B^+ \to D^0(K^-\pi^+\pi^-\pi^-, K^-\pi^+\pi^0)K$

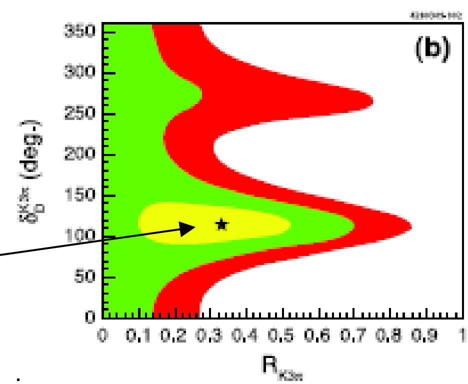
$$\Gamma(B^- \to (K^-\pi^+\pi^+\pi^-)_D K^-) \propto 1 + r_B r_D^{K3\pi} + 2 r_B r_D^{K3\pi} R_{K3\pi} \cos(\delta_B - \delta_D^{K3\pi} - \gamma), \quad (1)$$

$$\Gamma(B^- \to (K^+\pi^-\pi^+\pi^-)_D K^-) \propto r_B^2 + (r_D^{K3\pi})^2 + 2 r_B r_D^{K3\pi} R_{K3\pi} \cos(\delta_B + \delta_D^{K3\pi} - \gamma), \quad (2)$$

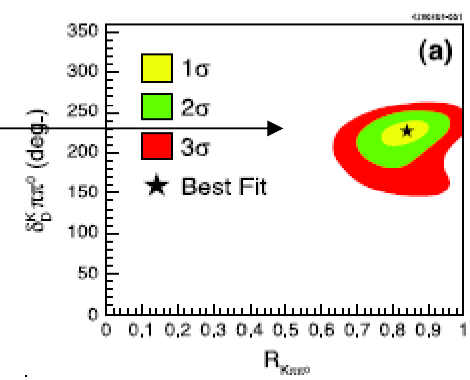
$$\Gamma(B^+ \to (K^+\pi^-\pi^+\pi^-)_D K^+) \propto 1 + r_B r_D^{K3\pi} + 2 r_B r_D^{K3\pi} R_{K3\pi} \cos(\delta_B - \delta_D^{K3\pi} + \gamma), \quad (3)$$

$$\Gamma(B^+ \to (K^-\pi^+\pi^+\pi^-)_D K^+) \propto r_B^2 + (r_D^{K3\pi})^2 + 2 r_B r_D^{K3\pi} R_{K3\pi} \cos(\delta_B + \delta_D^{K3\pi} + \gamma). \quad (4)$$

- Interference over the $D^0 \to K^-\pi^+\pi^-\pi^+$ Dalitz
  - $R_{K3\pi}$ is the Coherence factor [0-1] → Bigger is better !
  - $\delta_{K3\pi}$ is the strong phase diff. averaged over the Dalitz plot
  - These have been measured with CLEO-c
    - Low coherence in $B^+ \to D^0(K\pi\pi\pi)K^+$, but does help in global fit to constrain r_B.



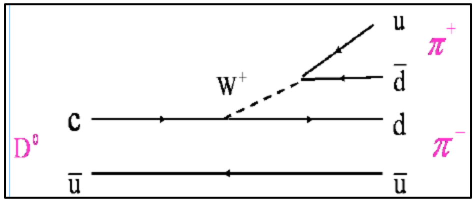
- $D^0 \to K\pi\pi^0$ has large coherence and BF~14%! investigations underway…stay tuned …

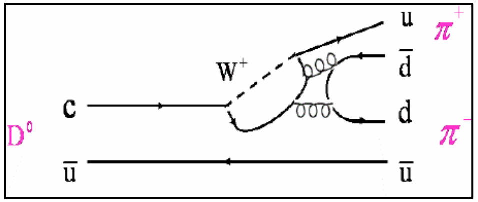


See: arXiv.0903.4853

CPV in D^0 Decays

- CPV in D^0 decays expected to be at the level 10^{-3}.
- **~10^8** $D^{*+} \rightarrow D^0(hh')\pi_s^+$ / 2 fb^{-1} (~50% from B, 50% prompt)
- Any CPV at the level of even 1% would be a signal for NP.
- One example: CPV in SCS decays





$$A_{CP} = \frac{\Gamma(D^0 \to KK(\pi\pi)) - \Gamma(\overline{D}^0 \to KK(\pi\pi))}{\Gamma(D^0 \to KK(\pi\pi)) + \Gamma(\overline{D}^0 \to KK(\pi\pi))}$$

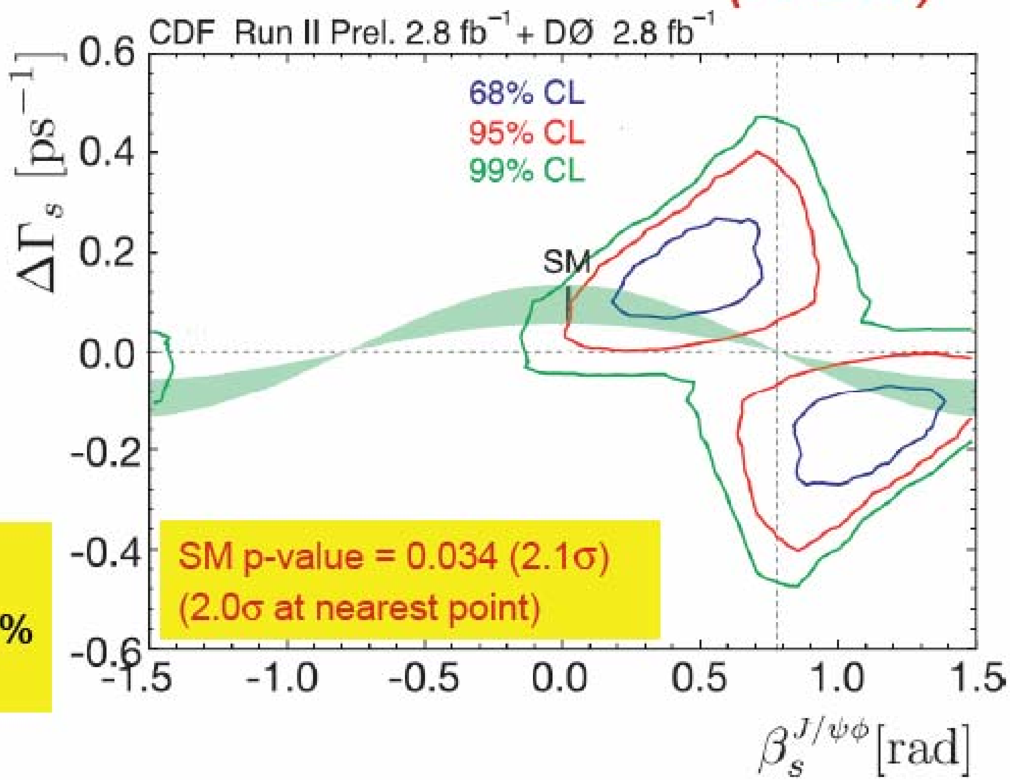
$< 0.1\%$ in SM

	A_{cp}(%)	N (K^+K^-)	N ($\pi^+\pi^-$)	Data set
BaBar	0.26 ± 0.36 ± 0.08	69696	30679	384 fb^{-1}
Belle	0.01 ± 0.30 ± 0.15	111000	49000	540 fb^{-1}
HFAG	0.123 ± 0.248			
LHCb	~ 0.04 % order (stat)	8 x 10^6	3 x 10^6	10 fb^{-1}

G. Punzi, EPS09, Krakow

Combined Tevatron result *(NEW)*

- Full inclusion of systematics and non-Gaussian effects
- No constraints. Make available to combination groups.



$\beta_s^{J/\psi\phi}$ range:
[0.27,0.59] U [0.97,1.30] @68%
[0.10,1.42] @95%

- Compared to HFAG 2008:
  Larger CDF sample + Better accounting for tails ⇒ same level of SM agreement.
- Both CDF and D0 currently working on **2x** samples.
- Expect improved precision by ***simultaneous fit*** of CDF and D0 samples.