The Future of Flavor Physics at Hadron Colliders

CIPANP 2003
K. Honscheid
Ohio State University

B Physics Today

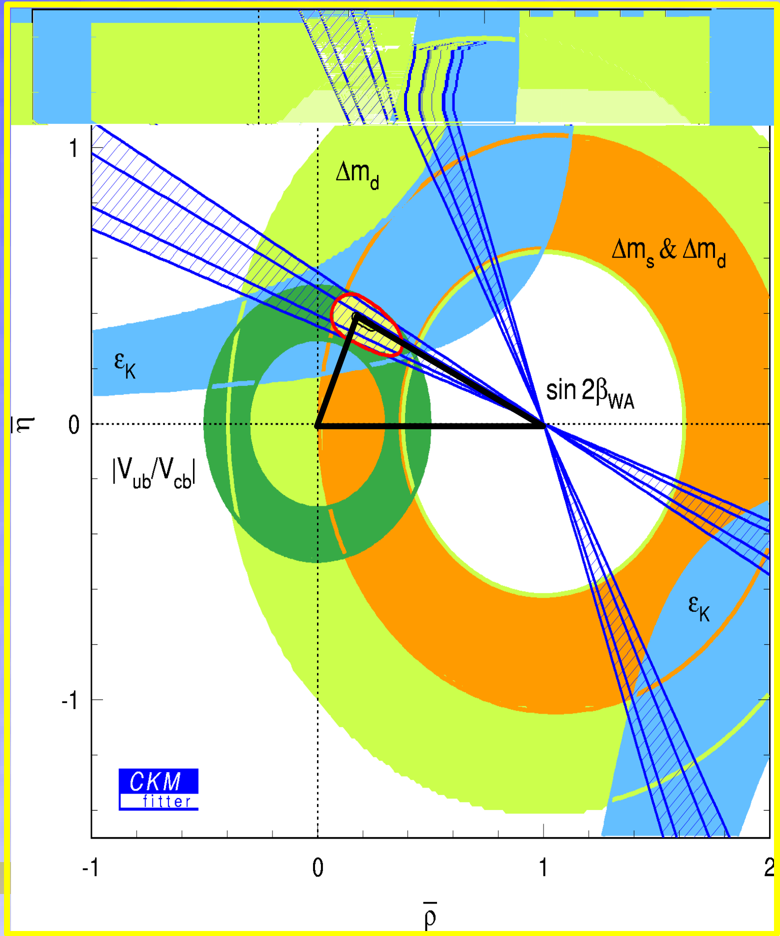
- CKM Picture okay

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

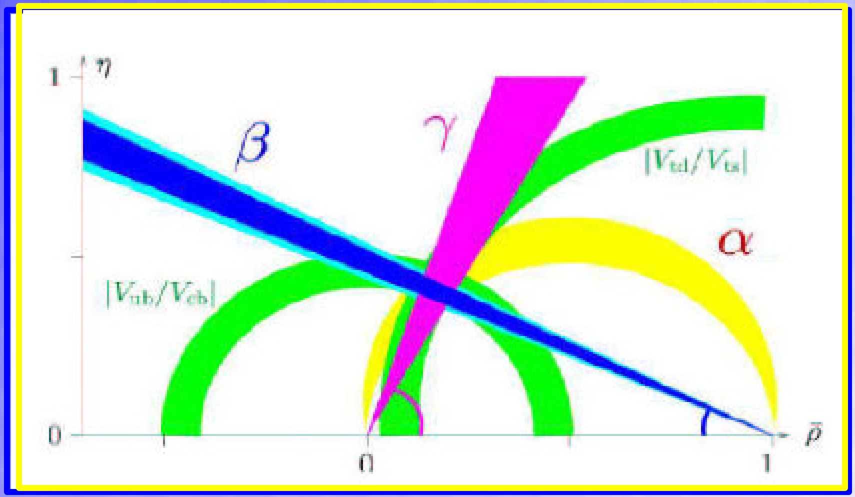
- CP Violation observed

$\sin(2\beta) = 0.734 +/- 0.054$

- No conflict with SM



Surprising B Physics

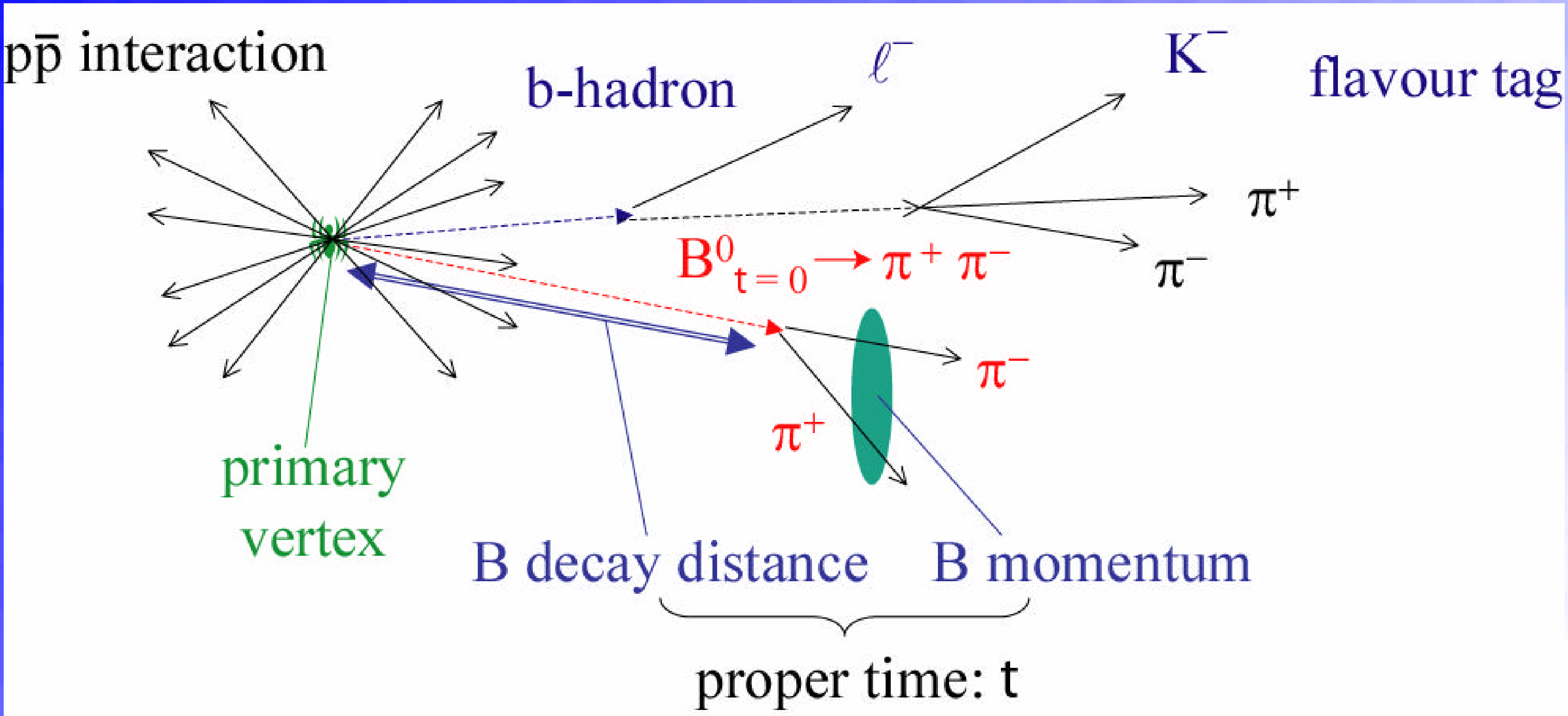
Year	Item	Theory Prediction	~Value	# B's
1983	τ_b	Too small to be observed ~ < 0.1ps	1 ps	$2x10^4$
1987	B^o-B^o mixing	Too small to see (~ < 1%) as m_{top} is believed to be ~30 GeV	20%	$2x10^5$
2001	sin(2β)	No direct prediction, but consistent with other measurements	3/4	10^7
	α,β,γ		>10^{11} b hadrons (including B_s)	

B Physics at Hadron Colliders

	Tevatron	LHC
Energy	2 TeV	14 TeV
b cross section	~100 μb	~500 μb
c cross section	~1000 μb	~3500 μb
b fraction	2×10^{-3}	6×10^{-3}
Inst. Luminosity	2×10^{32}	$>2 \times 10^{32}$
Bunch spacing	132 ns (396 ns)	25 ns
Int./crossing	<2> (<6>)	<1>
Luminous region	30 cm	5.3 cm

- Large cross sections
- Triggering is an issue
- All b-hadrons produced (B, B_s, B_c, b-baryons)

Detector Requirements

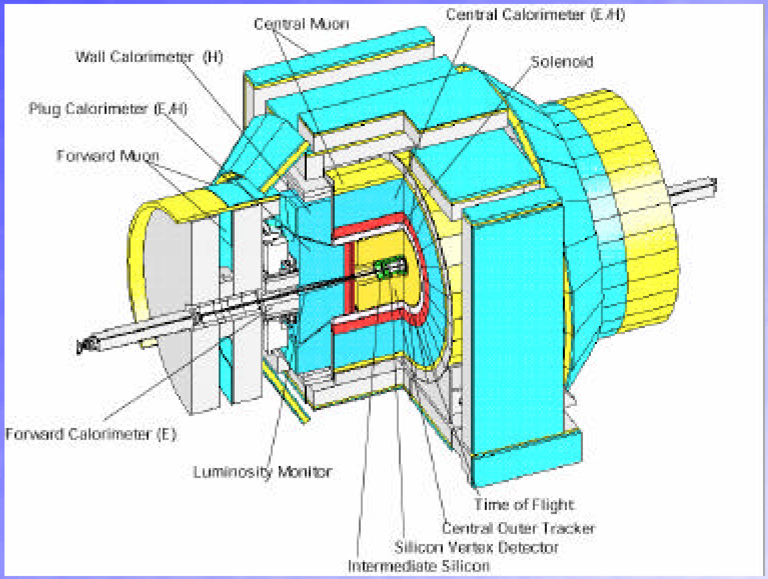


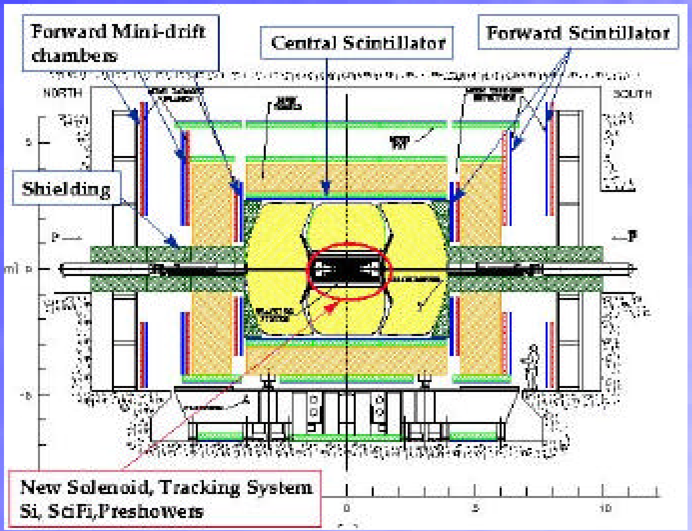
- Vertex, decay distance
- Momentum
- PID
- Neutrals (γ, π^0)

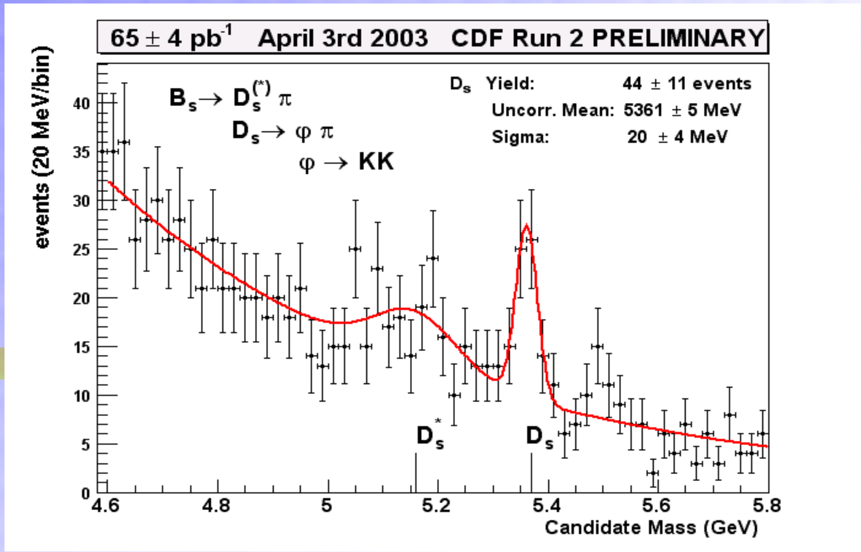
From F. Teubert

CDF and D0

- CDF pioneered B physics at hadron collider.
- New for Run II
  - TOF (Particle ID)
  - Detached Vertex Trigger
  - Improved tracking
- D0 enters B physics
- New for Run II
  - Tracking
  - Detached Vertex Trigger (soon)





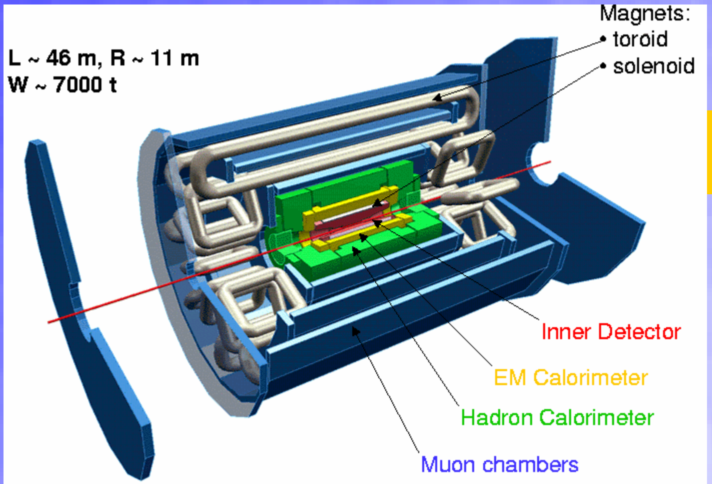


Atlas and CMS

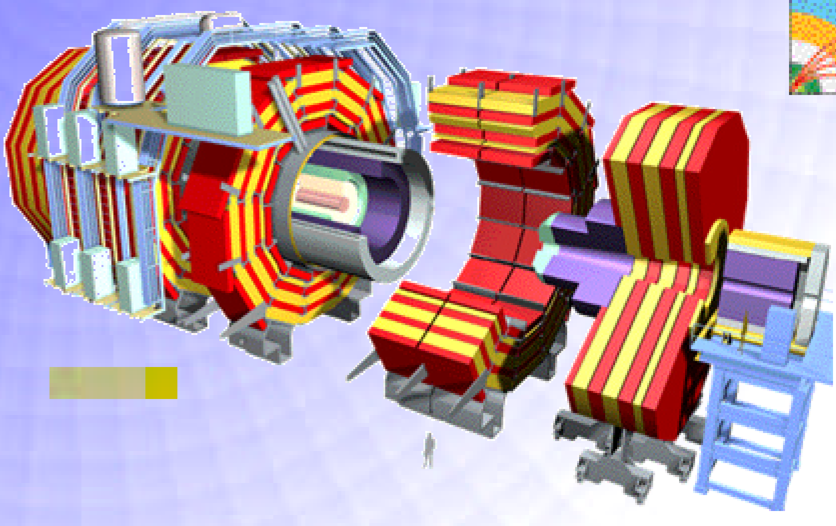
- **Acceptance**
  - $|\eta| < 2.5$
- **Particle ID**
  - ATLAS v.limited π-K separation, ~0.8σ from TRD
- **Di-lepton trigger**
- **Vertexing**
  - Special pixel B layer R~5cm
- **"Low" luminosity running**
  - Lumi 10^{33} $cm^{-2}s^{-1}$
  - Only $30fb^{-1}$ (3 years)
  - Specialist B triggers
- **BUT : DAQ Bandwidth**

  only 100 evts/s to

  tape for ALL physics



ATLAS



From N. Harnew

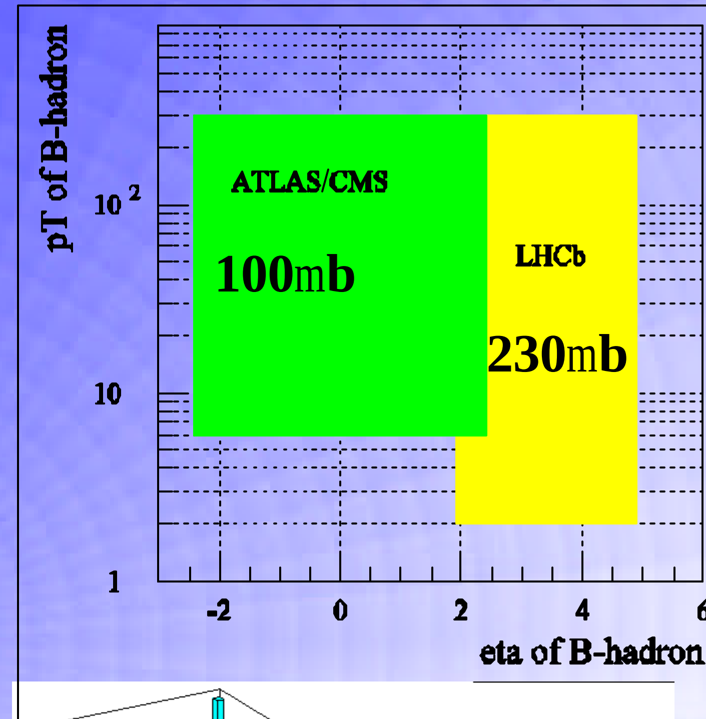
Forward vs. Central Geometry

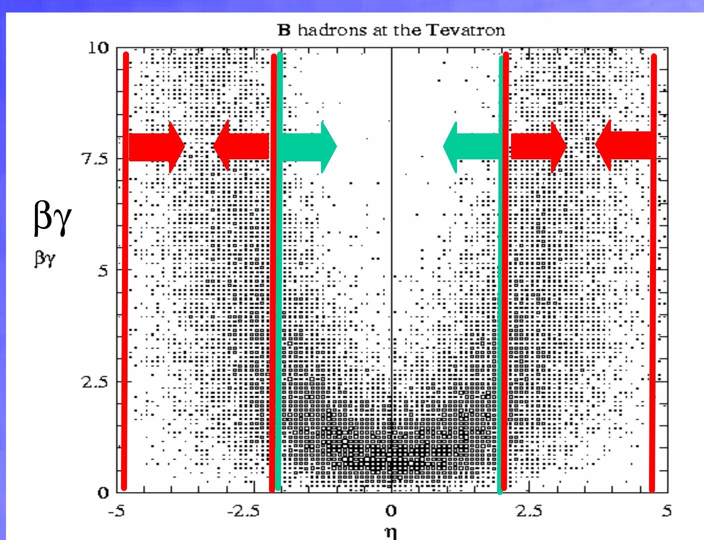
Multi-purpose experiments require large solid angle coverage.

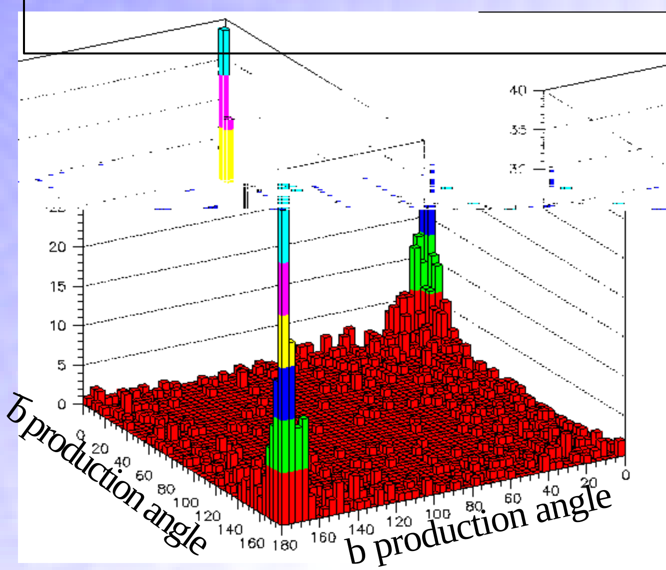
→ Central Geometry
(CDF, D0, Atlas, CMS)

Dedicated B experiments can take advantage of

→ Forward geometry
(BTeV, LHCb)

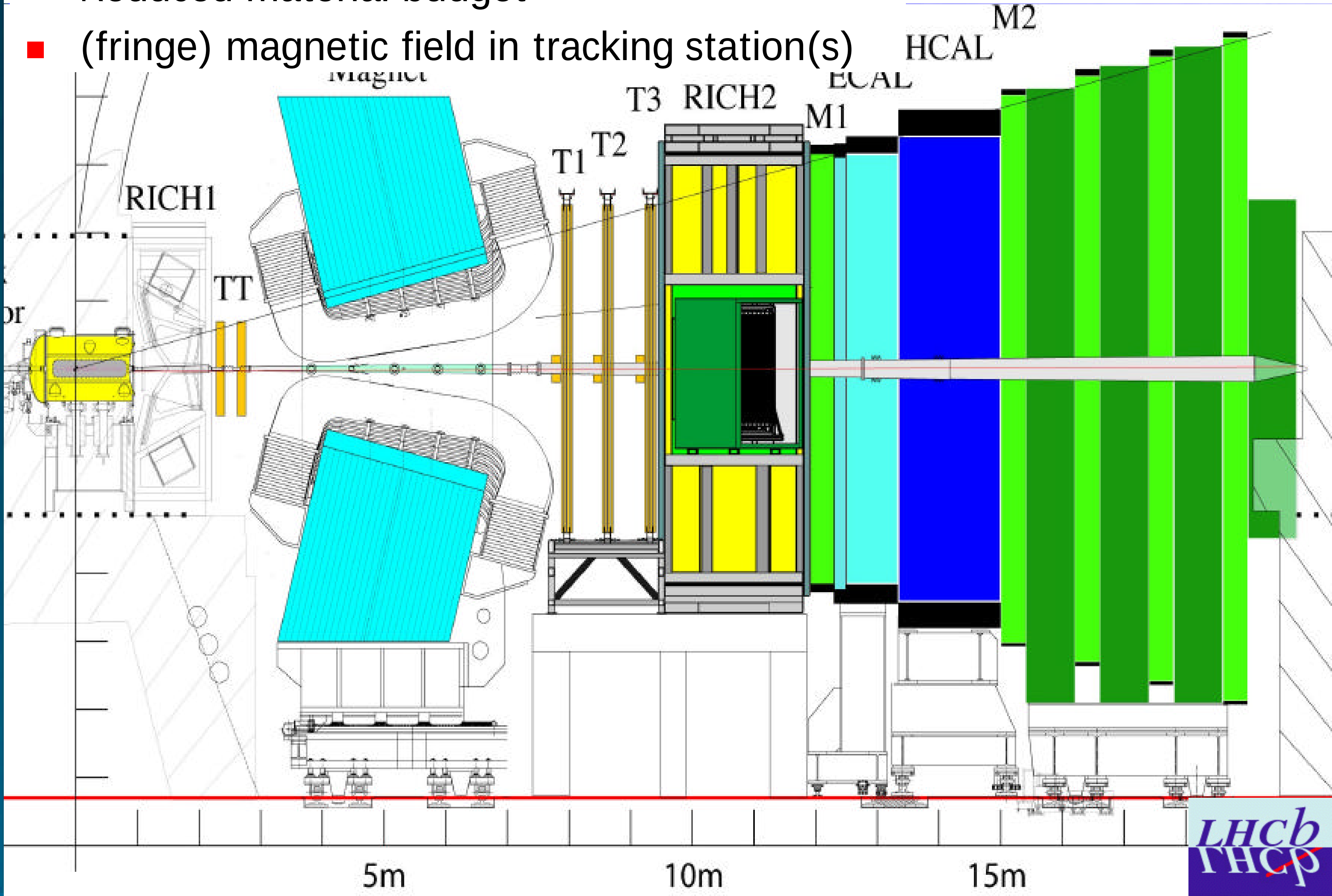






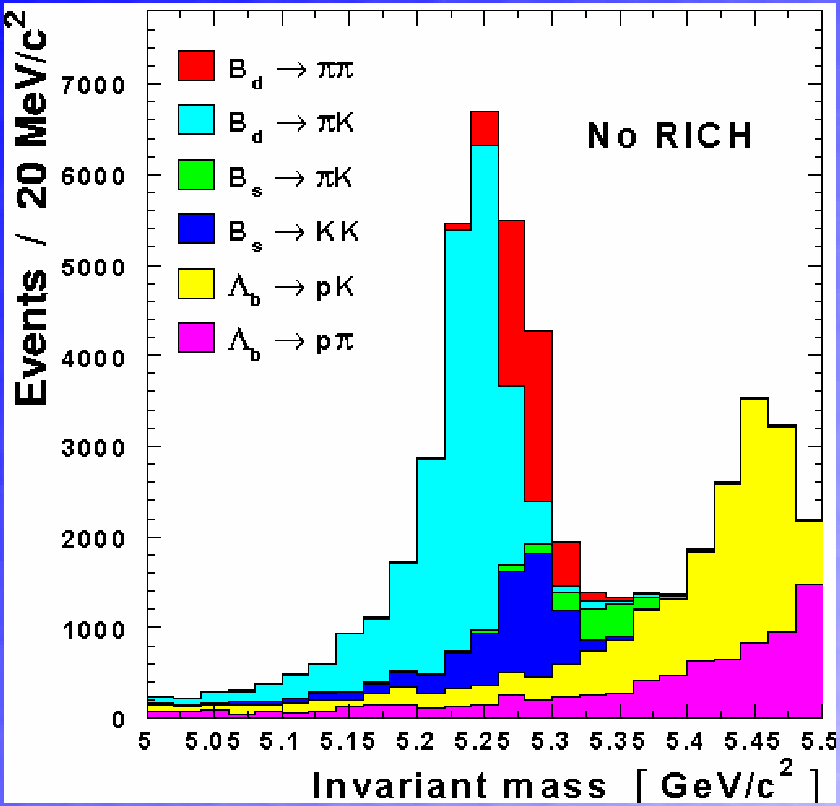
LHCb Light

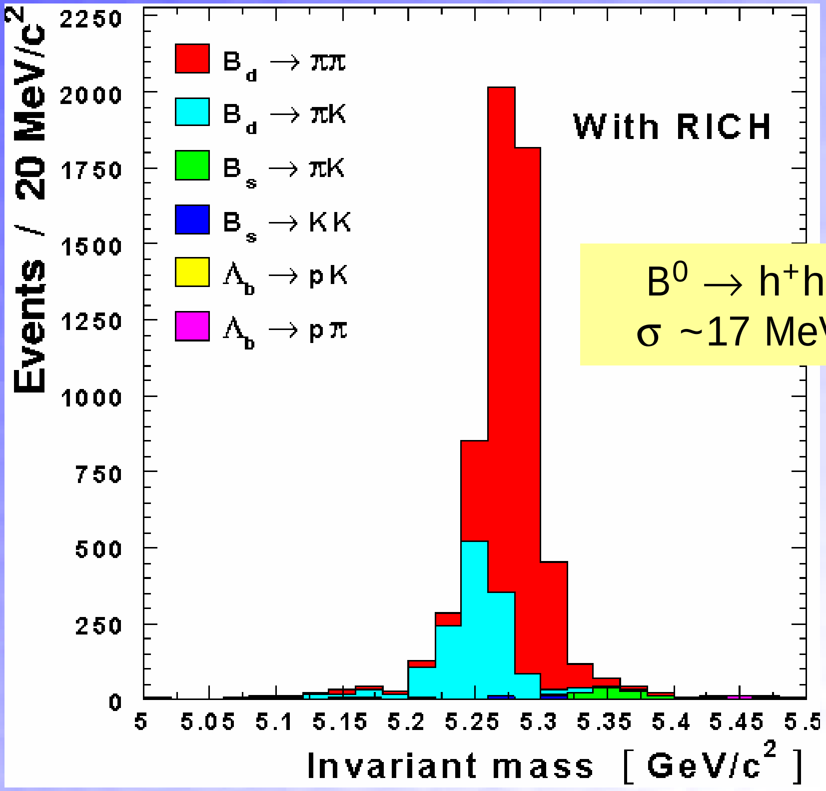
- No tracking stations in magnet region
- Reduced material budget
- (fringe) magnetic field in tracking station(s)



The Importance of Particle ID

For example: B-> $\pi^+\pi^-$





$B^0 \rightarrow h^+h^-$
σ ~17 MeV

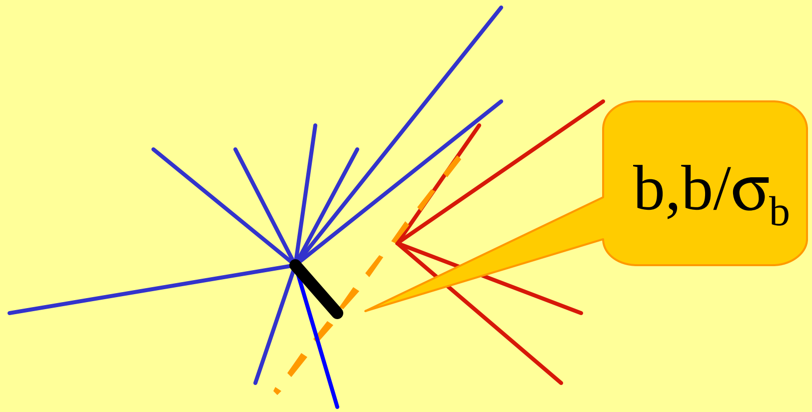
Purity = 84% ; Efficiency = 90%

CIPANP2003
K. Honscheid
Ohio State

The BTeV Detector

Detached Vertex Trigger

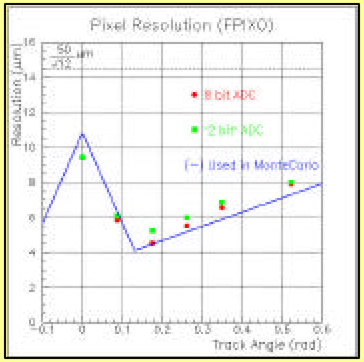
- **Find the primary vertex**
- **Identify tracks which miss it**
- **Calculates the significance of detachment**
- **For EVERY crossing**



CLEO/BaBar/BELLE-like performance in a hadron Collider environment!

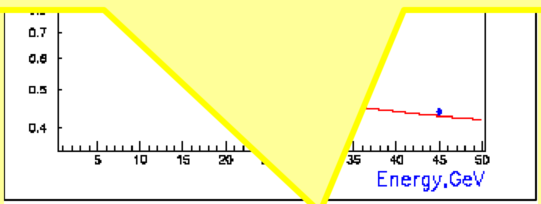
Detector

- 60 pixel planes
- inside magnet
- σ = 5-10 μm



fs

$\sigma(\pi \to \gamma\gamma) \sim 3$ MeV

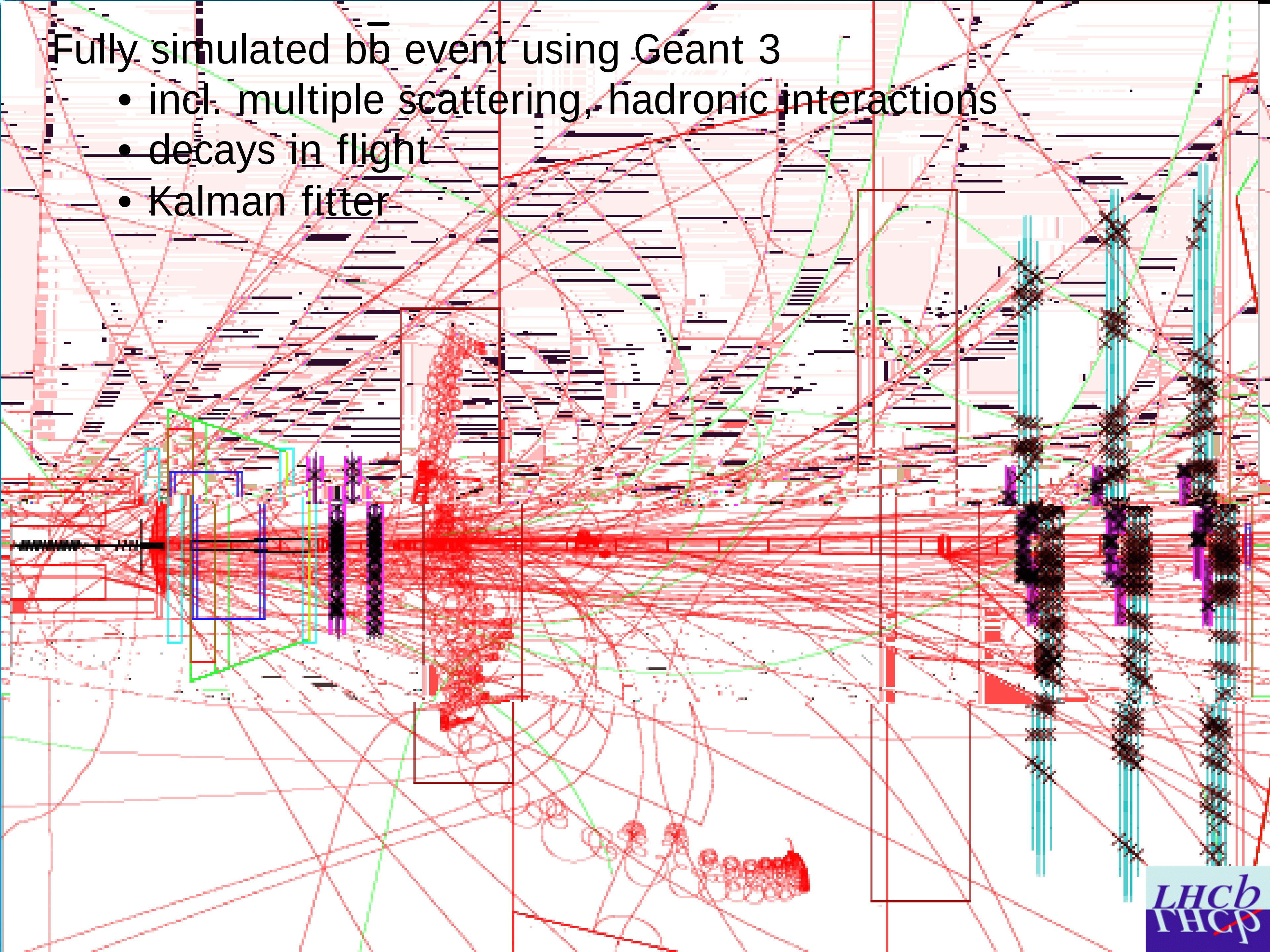


Muon Chamber

Electromagnetic Calorimeter

Fully simulated b$\bar{b}$ event using Geant 3

- incl. multiple scattering, hadronic interactions
- decays in flight
- Kalman fitter



Efficiencies and Tagging

- For a requirement of at least 2 tracks detached by more than 6σ, we trigger on only 1% of the beam crossings and achieve the following trigger efficiencies for these states (<2> int. per crossing):

Decay	efficiency(%)	Decay	efficiency(%)
$B \to \pi^+\pi^-$	63	$B^o \to K^+\pi^-$	63
$B_s \to D_s K$	74	$B^o \to J/\psi\ K_s$	50
$B^- \to D^o K^-$	70	$B_s \to J/\psi K^*$	68
$B^- \to K_s \pi^-$	27	$B^o \to K^* \gamma$	40

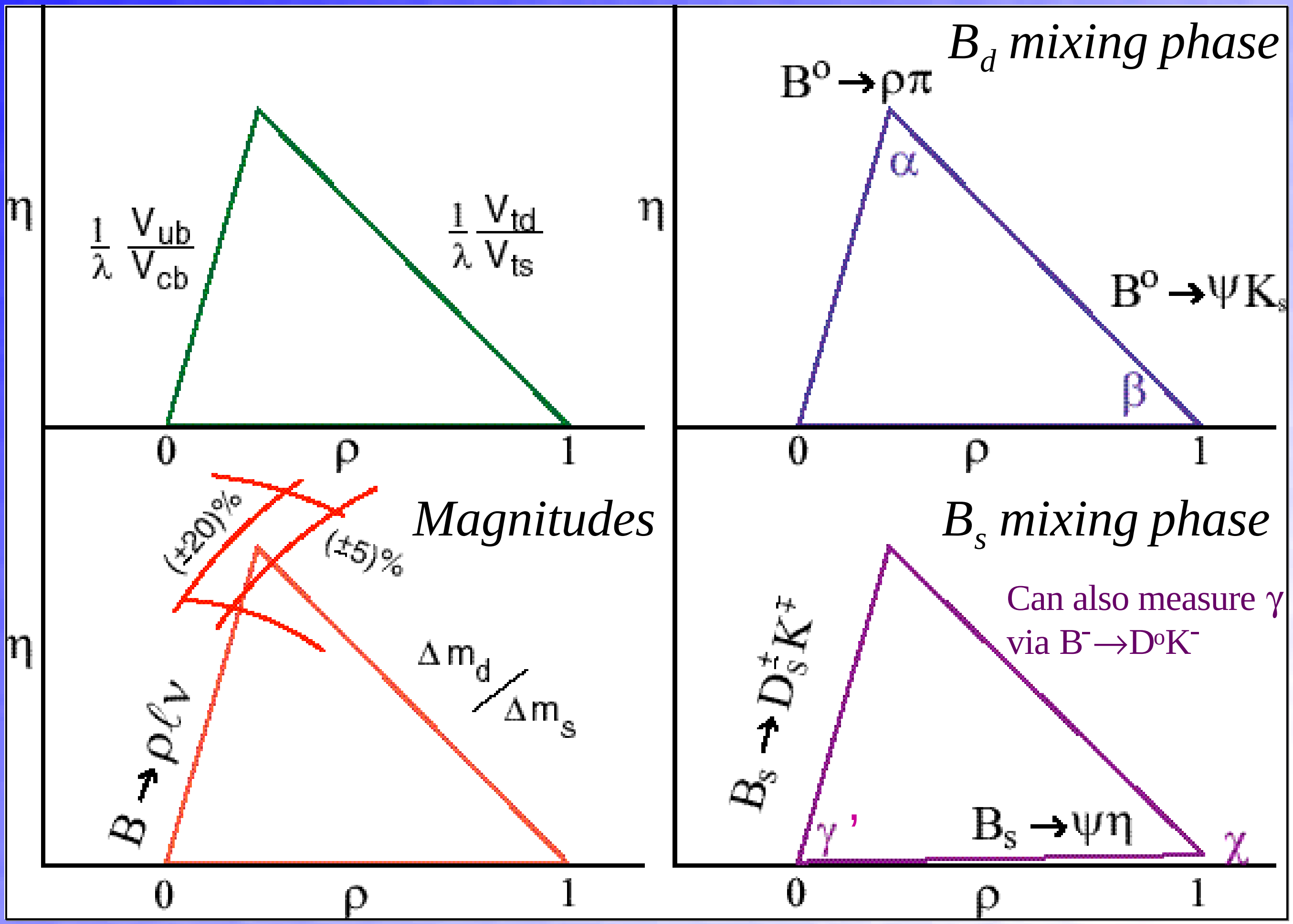
- $\varepsilon \equiv$ efficiency; D $\equiv$ Dilution or $(N_{right}-N_{wrong})/(N_{right}+N_{wrong})$
- Effective tagging efficiency $\equiv \varepsilon D^2$
- Extensive study for BTeV uses
  - Opposite sign $K^\pm$
  - Jet Charge
  - Same side $\pi^\pm$ (for B^o) or $K^\pm$ for (B_s)
  - Leptons
- Conclusion: εD^2 (B^o) = 0.10, εD^2 (B_s) = 0.13 (difference due to same side tagging)

The Physics Goals

- There is New Physics out there:
  - Baryon Asymmetry of Universe & by Dark Matter
  - Hierarchy problem
  - Plethora of fundamental parameters
  - ...
- B Experiments at Hadron Colliders are well positioned to:
  - Perform precision measurements of CKM Elements with small model dependence.
  - Search for New Physics via ~~CP~~ phases
  - Search for New Physics via Rare Decays
  - Help interpret new results found elsewhere (LHC, neutrinos)
  - Complete a broad program in heavy flavor physics
    - Weak decay processes, *B*'s, polarization, Dalitz plots, QCD...
    - Semileptonic decays including Λ_b
    - b & c quark Production
    - Structure: B(s) spetroscopy, b-baryon states
    - B_c decays

Part 1: Is the CKM Picture correct?

- Use different sets of measurements to define apex of triangle *(adopted from Peskin)*
- Also have ε_K (CP in K_L system)

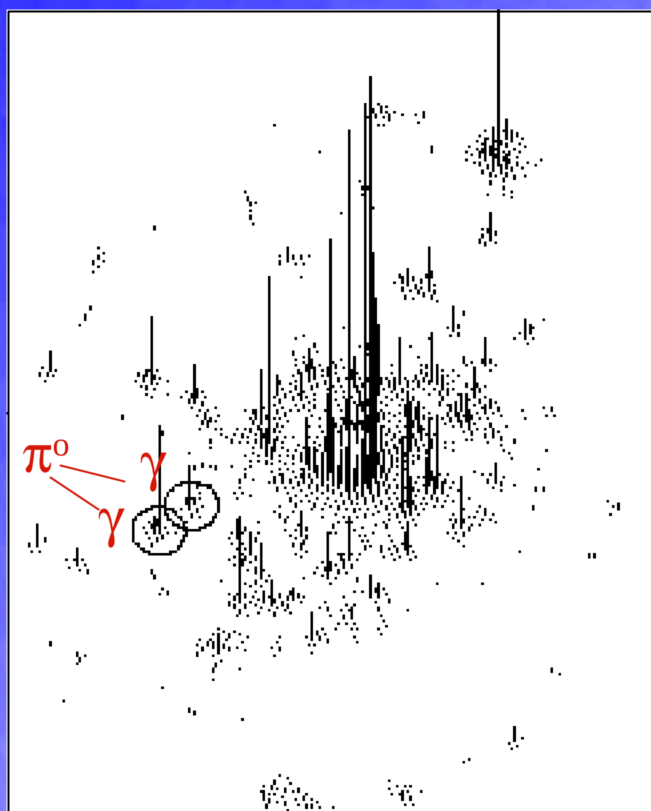


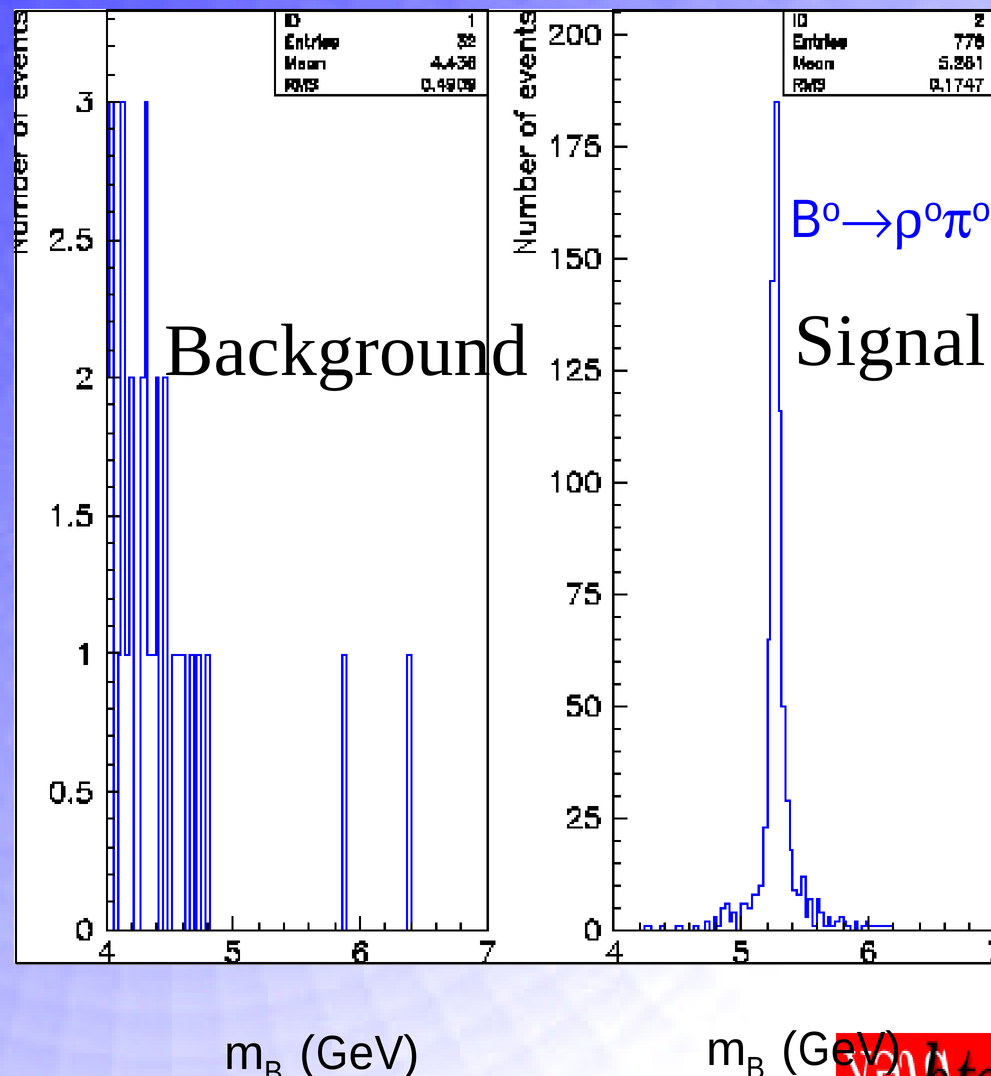
Measuring a Using Bº® rp ® p+p-pº

- A Dalitz Plot analysis gives **both** sin(2α) and cos(2α) (Snyder & Quinn)
- Measured branching ratios are:
  - $B(B^- \to \rho^o \pi^-) = \sim 10^{-5}$
  - $B(B^o \to \rho^- \pi^+ + \rho^+ \pi^-) = \sim 3 \times 10^{-5}$
  - $B(B^o \to \rho^o \pi^o) < 0.5 \times 10^{-5}$
- Snyder & Quinn showed that 1000-2000 tagged events are sufficient
- Not easy to measure
  - π^0 reconstruction
- Not easy to analyze

Yields for Bº® r p

- Based 9.9x10^6 background events
- $B^o \rightarrow \rho^+\pi^-$
  5400 events, S/B = 4.1
- $B^o \rightarrow \rho^o\pi^o$
  780 events, S/B = 0.3

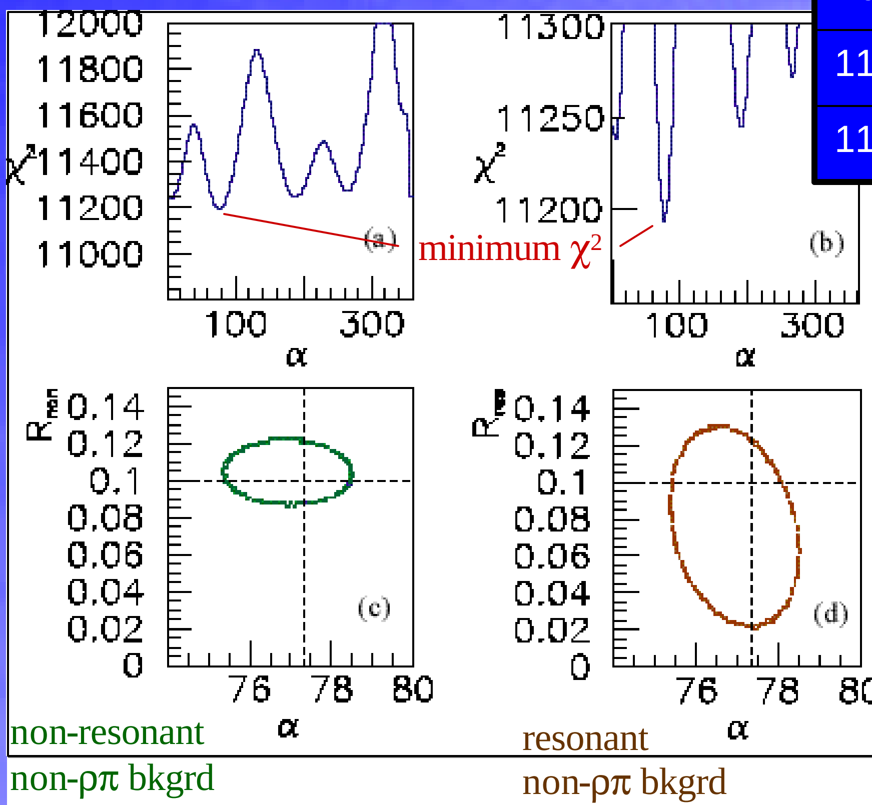




Our Estimate of Accuracy on a

- Geant simulation of $B^o \to \rho\pi$, (for 1.4×10^7 s)

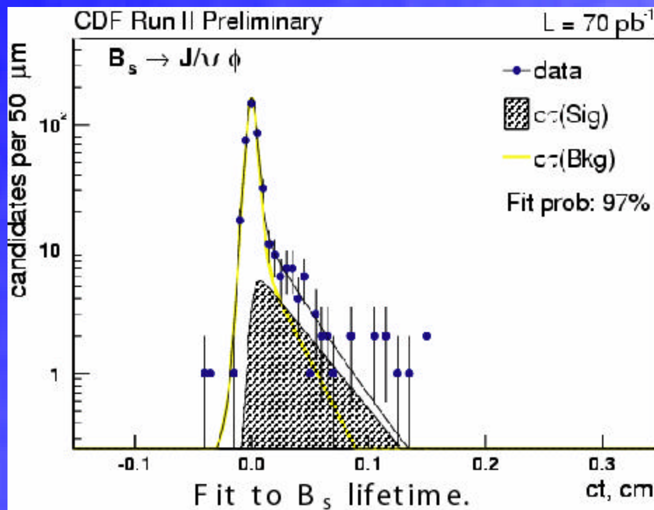
α (gen)	R_{res}	R_{non}	α (recon)	$\Delta\alpha$
77.3°	0.2	0.2	77.2°	1.6°
77.3°	0.4	0	77.1°	1.8°
93.0°	0.2	0.2	93.3°	1.9°
93.0°	0.4	0	93.3°	2.1°
111.0°	0.2	0.2	111.7°	3.9°
111.0°	0.4	0.2	110.4°	4.3°

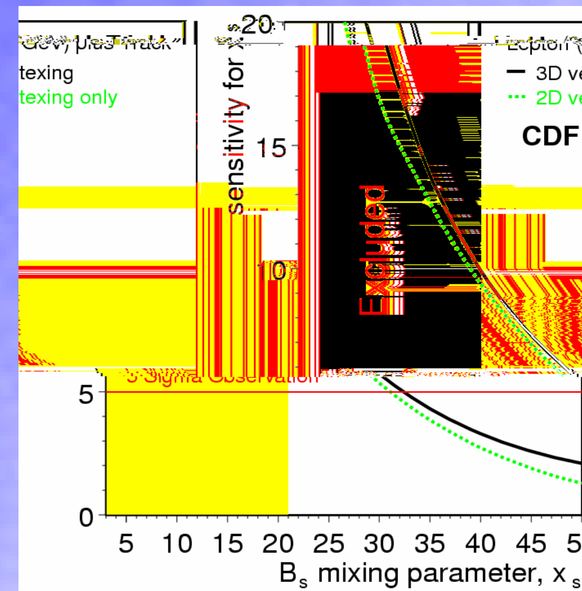


Example:
1000 $B^o \to \rho\pi$ signal + backgrounds
With input $\alpha = 77.3^o$

B_s Mixing (V_{td}/V_{ts})

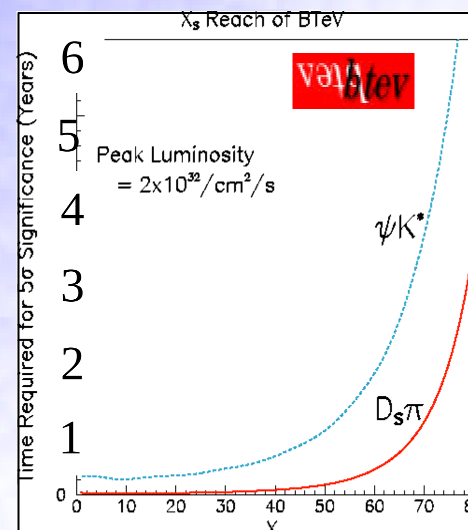
- Δm_s ($\sim x_s$) = $\Delta\Gamma \cdot C$ where C can be calculated inside the S. M.
- CDF sensitive to x_s ~ 30





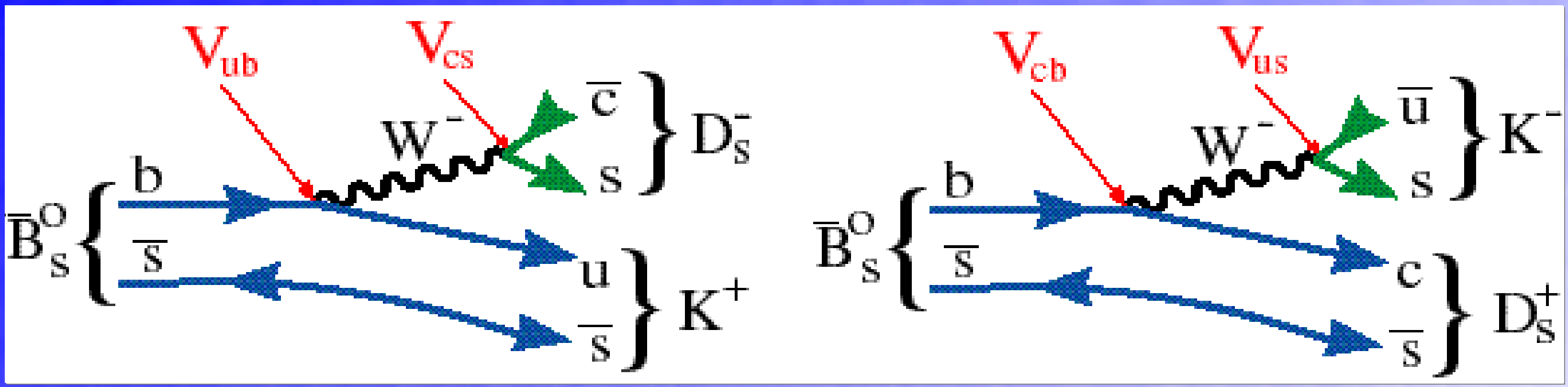
- $\Delta\Gamma/\Gamma$: $B_s \to \psi\phi$ seen
  Expect $\sigma(\Delta\Gamma/\Gamma)$ ~ 2% after Run II

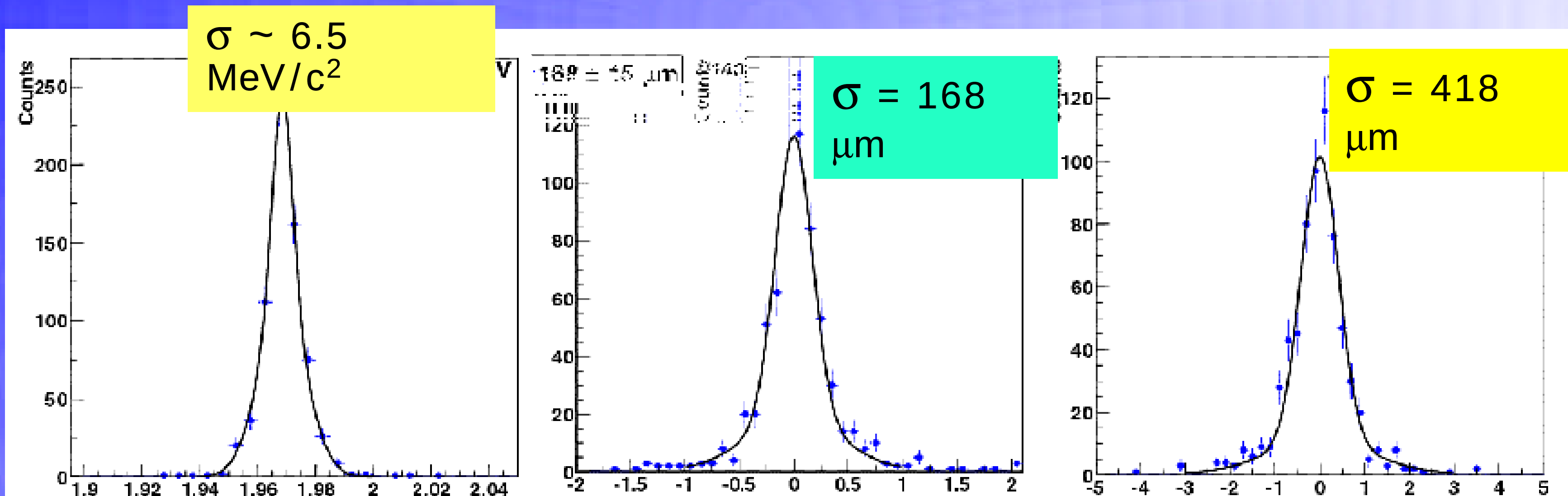
- BTeV reaches sensitivity to x_s of 80
  in 3.2 years



One of several ways to determine γ: $B_s \to D_s^{\pm} K^{\mp}$

- Theoretically clean, BR ~ 10^{-4}





D_s mass (GeV)

B_s vtx resolution (mm)

D_s vtx resolutio

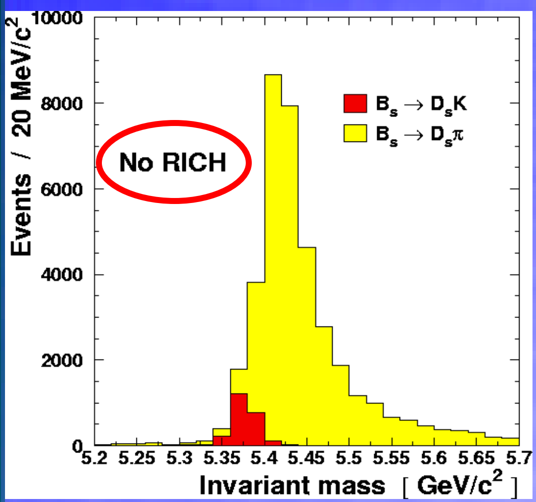
γ from $B_s \to D^-_s K^+$, $D^+_s K^-$ (II)

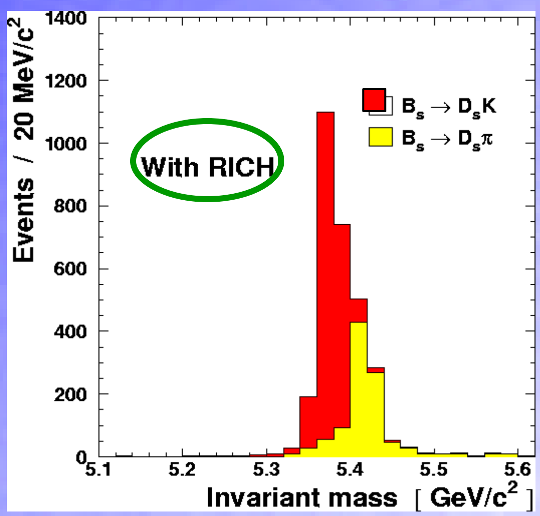
Needed:

- ✓ Hadronic trigger
- ✓ K/π separation
- ✓ Good proper time resolution

❑ From the measurement of 4 time-dependent asymmetries one gets g-2dg

❑ 2 same order tree level amplitudes ($\propto\lambda^3$) : large asymmetries, NP contributes unlikely





Sensitivity depends upon

- relative amplitudes
- strong phase difference
- values of γ, Δm_s , $\Delta\Gamma_s / \Gamma_s$

For $\Delta m_s = 20\ ps^{-1}$:

s(g) ~ **10°**

For $\Delta m_s = 30\ ps^{-1}$:

s(g) ~ **12°**

In one year: 8k $B_s \to D_s^{\pm} K^{\pm}$ reconstructed events

From M. Musy

Measuring c

- In the SM the phases and magnitudes are correlated:

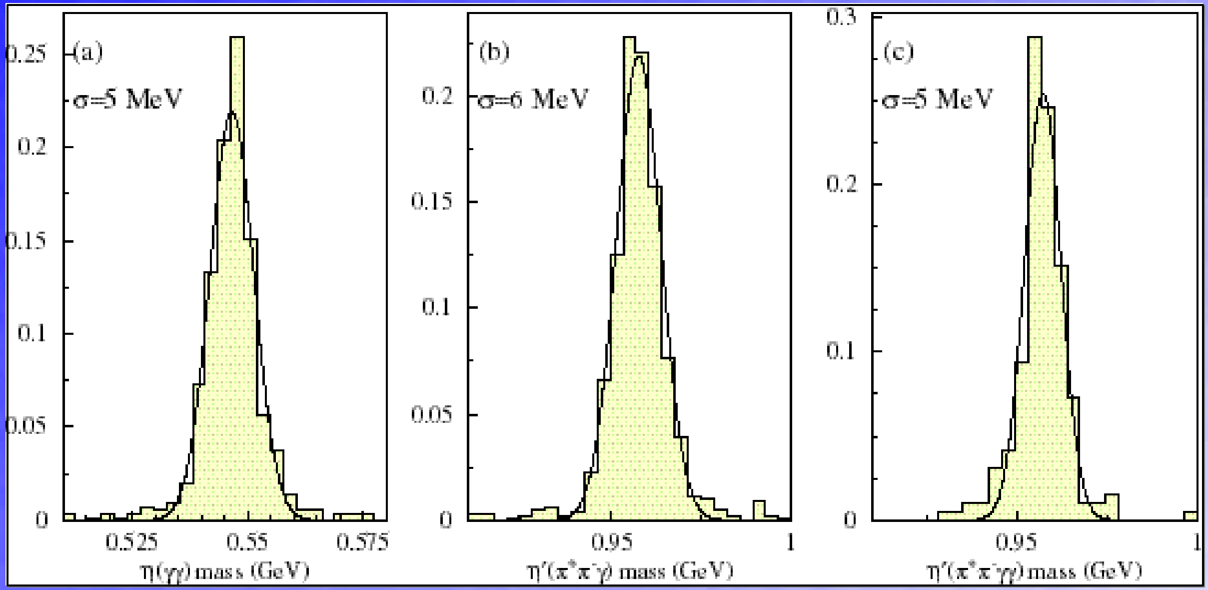
$$\sin\chi = \lambda^2 \frac{\sin\beta \sin\gamma}{\sin(\beta+\gamma)}$$

Silva & Wolfenstein (hep-ph/9610208)
Aleksan, Kayser & London

- $\lambda = |V_{us}|$ = 0.2205±0.0018
- χ is the phase of V_{ts} -> B_s Mixing
- Good: B_s->$J/\psi\phi$ plus non-trivial angular analysis
- Better: B_s -> CP eigenstate such as
  $B_s \to J/\psi\eta^{(\prime)}$, $\eta\to\gamma\gamma$, $\eta'\to\rho\gamma$

Measuring c II

- BTeV can reconstruct η and η’



- Yield in one year
  - $B_s \rightarrow J/\psi\ \eta$: 2,800 events with S/B = 15
  - $B_s \rightarrow J/\psi\ \eta'$: 9,800 events with S/B = 30
  - Error on $\sin(2\chi)$ = 0.024
  - With $\chi \sim 2^{o}$ a precision measurement will require a few years.

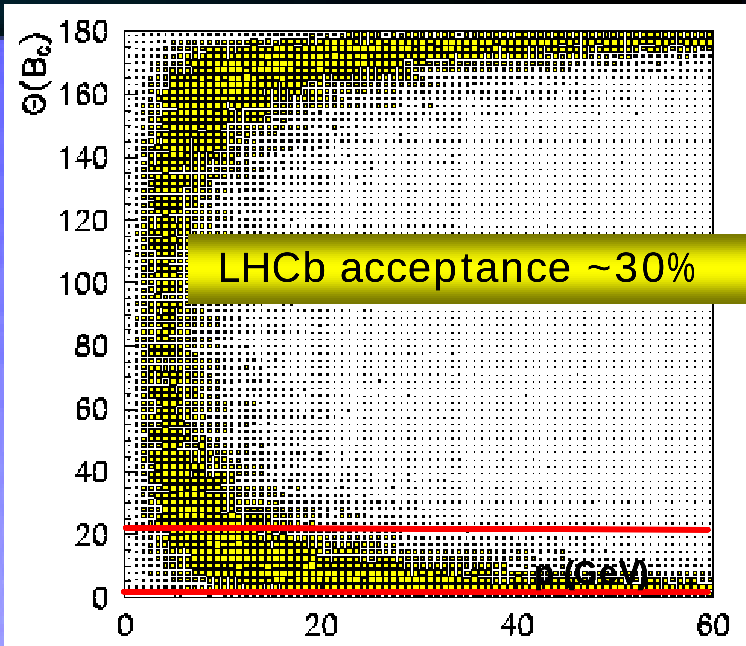
Physics Reach (CKM) in 10^7 s

Reaction	$\mathcal{B}$(B) ($\times10^{-6}$)	# of Events	S/B	Parameter	Error or (Value)
$B_s \to D_s K^-$	300	7500	7	$\gamma - 2\chi$	8^o
$B_s \to D_s \pi^-$	3000	59,000	3	x_s	(75)
$B^o \to J/\psi K_S$ $J/\psi \to \ell^+ \ell^-$	445	168,000	10	$\sin(2\beta)$	0.017
$B^o \to J/\psi K^o$, $K^o \to \pi \ell \nu$	7	250	2.3	$\cos(2\beta)$	~0.5
$B^- \to D^o (K^+\pi^-) K^-$	0.17	170	1		
$B^- \to D^o (K^+K^-) K^-$	1.1	1,000	>10	γ	13^o
$B_s \to J/\psi \eta$,	330	2,800	15		
$B_s \to J/\psi \eta'$	670	9,800	30	$\sin(2\chi)$	0.024
$B^o \to \rho^+\pi^-$	28	5,400	4.1		
$B^o \to \rho^o\pi^o$	5	780	0.3	α	$\sim 4^o$

Reaction	$\mathcal{B}$(B) ($\times10^{-6}$)	# of Events	S/B	Parameter	Error
$B^- \to K_S \pi^-$	12.1	4,600	1		$<4^o$ +
$B^o \to K^+\pi^-$	18.8	62,100	20	γ	Theory err.
$B^o \to \pi^+\pi^-$	4.5	14,600	3	Asymmetry	0.030
$B^o \to K^+ K^-$	17	18,900	6.6	Asymmetry	0.020

B_c mesons

- CDF: m_{Bc} = 6.4 +/- 0.4 GeV
  t_{Bc} ~ 0.5 ps
- BTeV/LHCb: Precision measurements of mass, lifetime
- Search for CPV in $B_c \to J/\psi D^+$ or $B_c \to D_s D$



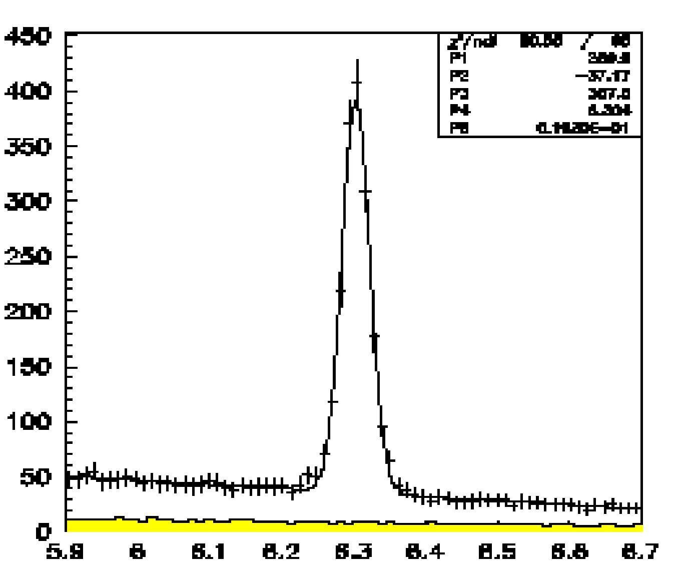
<u>LHCb preliminary study</u>

$\sigma(pp \to B_c)$ ~300 nb $\Rightarrow$ 10^9 B_c/ year

$B_c \to J/\psi\ \pi$ (BR ~10^{-2})

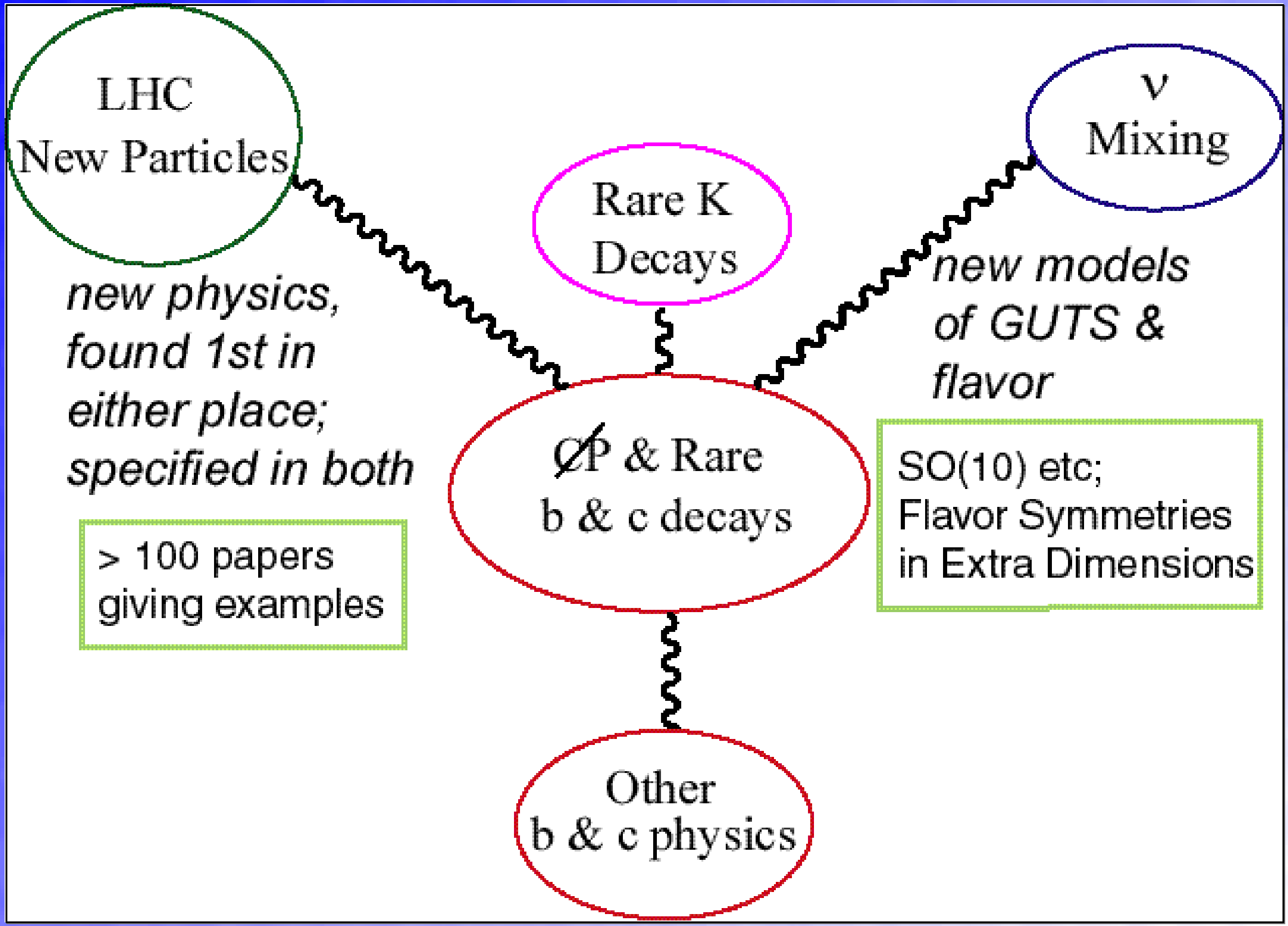
ε ~ 2% ⇨ **12k events/year**

Background from $B \to J/\psi$ X and prompt J/ψ reduced cutting on the distance between primary vertex and B_c vertex



M($J/\psi(\mu\mu)\ \pi$) GeV/c^2

Part II: Search for New Physics



For a nice overview see: S. Stone "BTeV Physics" at http://doe-hep.hep.net/P5StoneMarch2003.pdf

First Example: Supersymmetry

- Supersymmetry: In general 80 constants & 43 phases
- MSSM: 2 phases (Nir, hep-ph/9911321)
- New Physics in B^o mixing: θ_D , B^o decay: θ_A, D^o mixing: $\phi_{K\pi}$

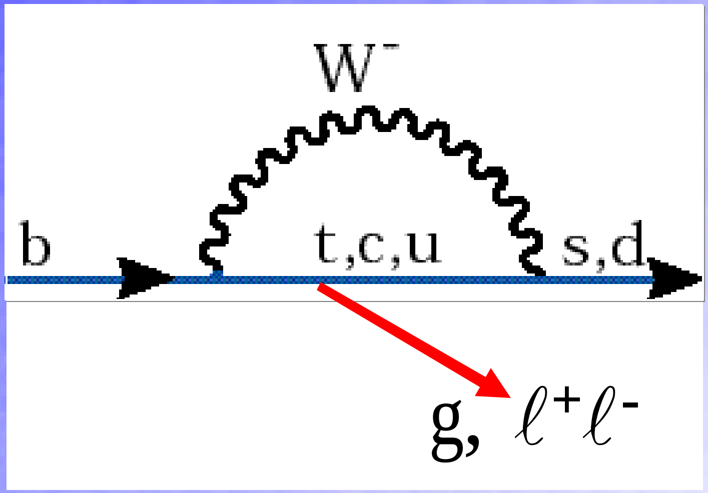
Process	Quantity	SM	New Physics
$B^o \to J/\psi K_s$	CP asym	$\sin(2\beta)$	$\sin 2(\beta+\theta_D)$
$B^o \to \phi K_s$	CP asym	$\sin(2\beta)$	$\sin 2(\beta+\theta_D+\theta_A)$
$D^o \to K^- \pi^+$	CP asym	0	$\sim\sin(\phi_{K\pi})$

Difference $\Rightarrow$ NP

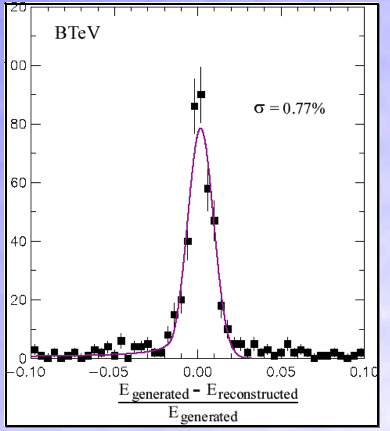
New Physics

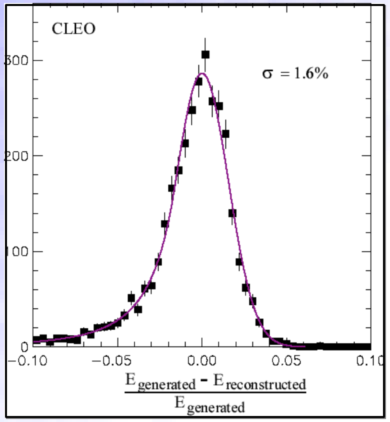
Rare b Decays

- Search for New Physics in Loop diagrams
  - New fermion like objects in addition to t, c or u
  - New Gauge-like objects in addition to W, Z or g



- Inclusive Rare Decays including
  - $b \to s\gamma$
  - $b \to d\gamma$
  - $b \to s\ell^+\ell^-$
- Exclusive Rare Decays such as
  - $B \to \rho\gamma$, $K^*\gamma$
  - $B \to K^*\ell^+\ell^-$
    Dalitz plot & polarization





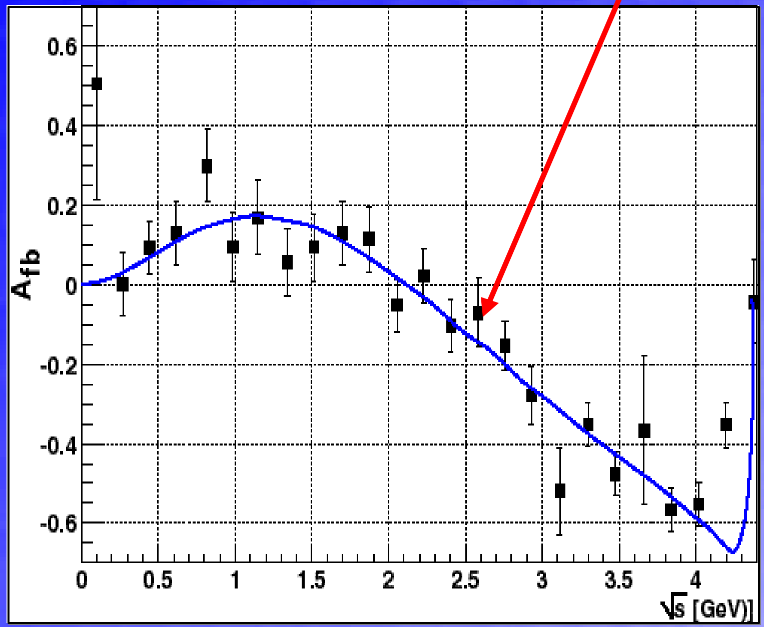
$B^o \to K^*\gamma$

Yield, S/B for Rare b Decays

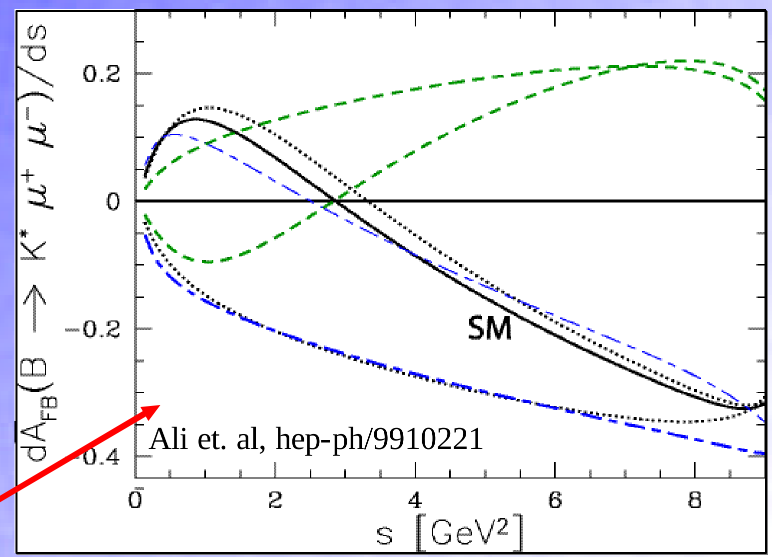
Reaction	*B* (10^{-6})	Signal	S/B	Physics
$B^o \to K^{*o}\mu^+\mu^-$	1.5	2530	11	Polarization; Rate
$B^- \to K^-\mu^+\mu^-$	0.4	1470	3.2	Rate
$b \to s\mu^+\mu^-$	5.7	4140	0.13	Rate; Wilson coefficents

Polarization in Bº®K*ºm$^+$m$^-$

- BTeV data compared to Burdman et al calculation

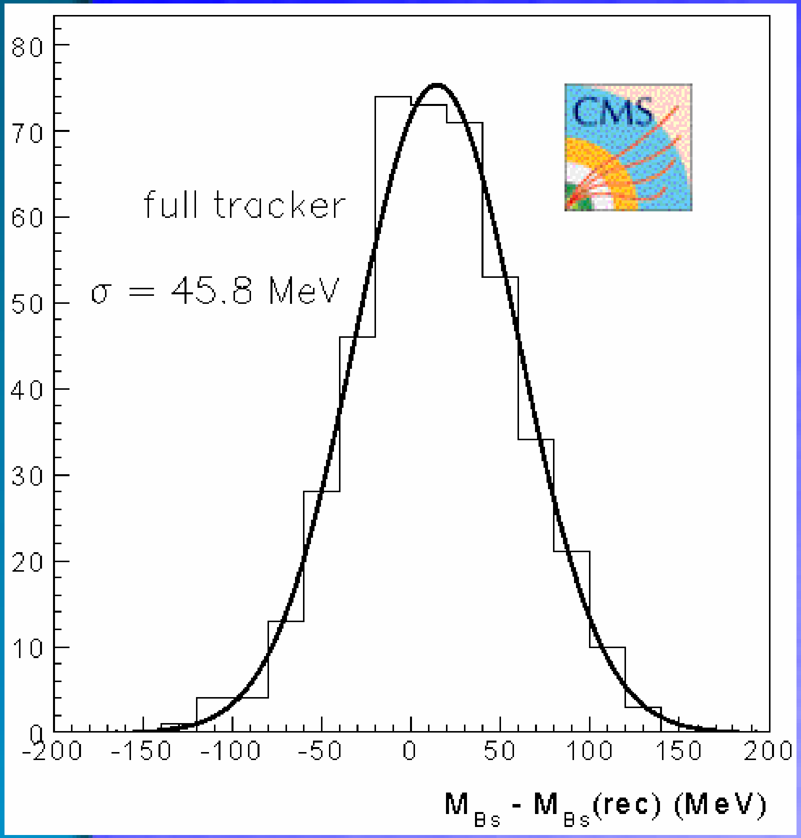


- Dilepton invariant mass distributions, forward-backward asymmetry discriminate among the SM and various supersymmetric theories.
(Ali, Lunghi, Greub & Hiller, hep-ph/0112300)



- One year for $K^* \ell^+ \ell^-$, enough to determine if New Physics is present

Rare Leptonic Decays



B_s^0 ® m^+m^-

Standard Model BR ~ 4×10^{-9}

Here the General Purpose Detectors have an advantage : high p_T di-muon triggering at high (1×10^{34}) luminosity.

CMS : 100 fb^{-1} (10^7s at 10^{34} $cm^{-2}s^{-1}$)

~26 signal events

6.4 events background

Muon trigger :

2 m's with pT > 4 GeV

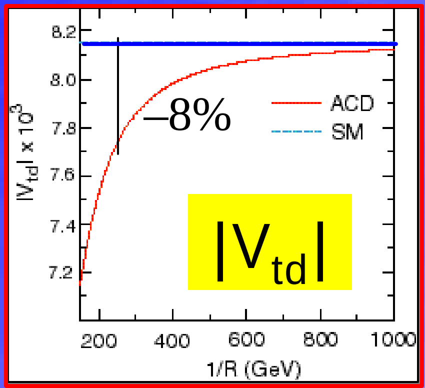
| h| < 2.4

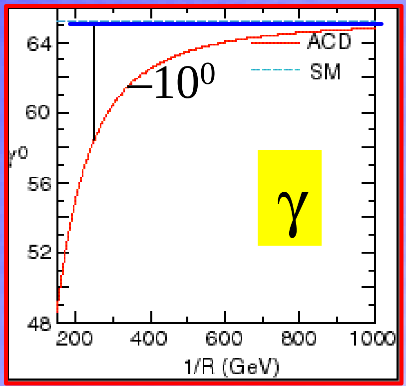
Search also for B_d^0 ® m^+m^-

Standard Model BR ~ 1×10^{-10}

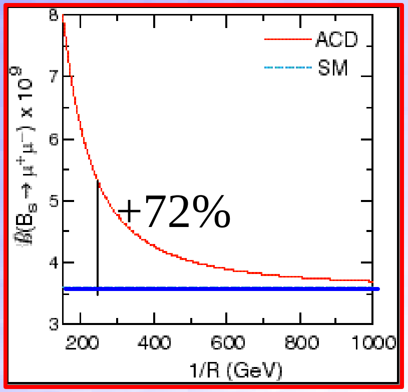
Another Example: Extra Dimensions

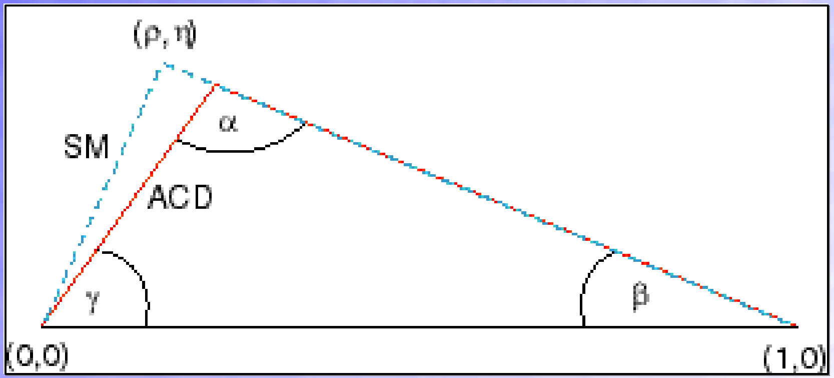
- Aranda & Lorenzo Diaz-Cruz, “Flavor Symmetries in Extra Dimensions” (hep-ph/0207059) (Buras et al. hep-ph/0212143)
- Extra spatial dimension is compactified at scale 1/R = 250 GeV on up
- No effect on $|V_{ub}/V_{cb}|$, $\Delta M_d/\Delta M_s$, $\sin(2\beta)$





$B_s \to \mu\mu$





Summary

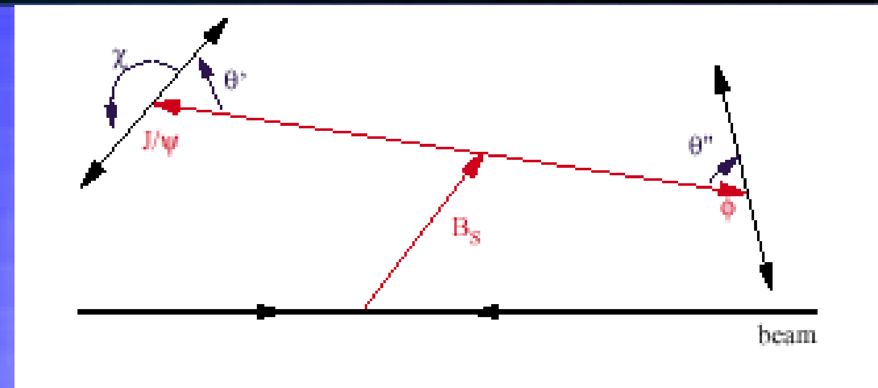
- Heavy quark physics at hadron colliders provides a unique opportunity to
  - measure fundamental parameters of the Standard Model with no or only small model dependence
  - discover new physics in CP violating amplitudes or rare decays.
  - interpret new phenomena found elsewhere (e.g. LHC)
- Some scenarios are clear others will be a surprise

➡ This program requires a general purpose B detector like BTeV and LHCb with
  - an efficient, unbiased trigger and a high performance DAQ
  - a superb charged particle tracking system
  - good particle identification
  - excellent photon detection

Additional Transparencies from BTeV and LHCb Studies

$\delta\gamma$ (= χ) from $B_s \to J/\psi\ \phi$

- **In SM** $f_s = -2dg = -2l^2h \sim$ **10^{-2}**
- **Sensitive to New Physics effects in the B_s-B_s system**



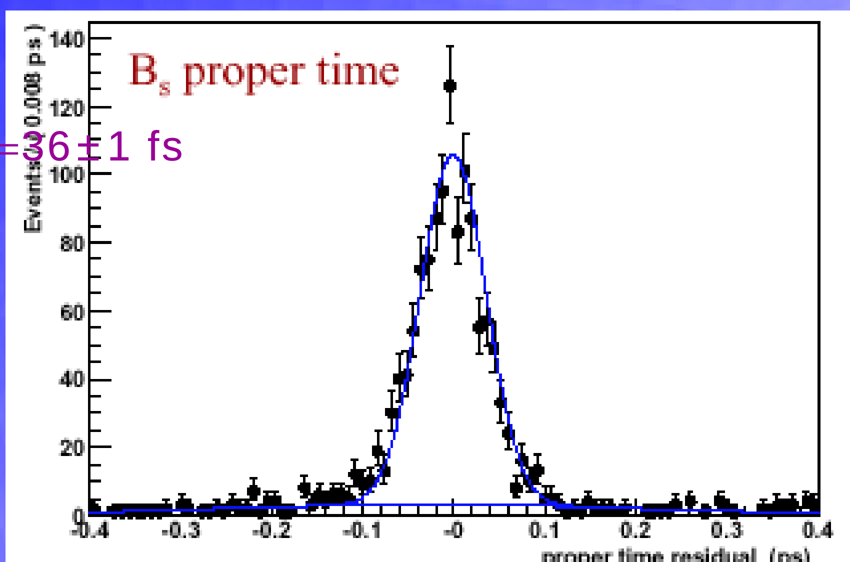
In one year:

109 k events $B_s \to J/\psi\ (\mu^+\mu^-)\ \phi$

19 k events $B_s \to J/\psi\ (e^+e^-)\ \phi$

$J/\psi\ \phi$ is not CP eigenstate:

needs fit to angular distributions of decay final states as a function of proper time



$\sigma = 36 \pm 1$ fs

Assuming $\Delta m_s = 20\ \text{ps}^{-1}$:

$s\ (2dg) \sim$ **2º**

From M. Musy

Current status of LHCb Physics Reach in 1 year ($2fb^{-1}$)

	Channel	Yield	Precision*
b	B_d ® J/y K_s	119 k	s(b) » 0.6^o
g	B_s ® D_sK B_d ® pp, B_s ® KK	8 k 27 k, 35 k	s(g) » 10^o s(g) » 3^o
a	B_d ® p^+p^-	27 k	s(a) » 5^o - 10^o
2dg	B_s ® J/y f	128 k	s(2dg) » 2^o
$\|V_{td}/V_{ts}\|$	B_s ® D_sp	72 k	Dm_s up to 58 ps^{-1}
rare decays	B_d ® K^* g	20 k	

All numbers will be updated together with more channels in the re-optimization LHCb TDR (September 2003)

From M. Musy

A simplified trigger comparison

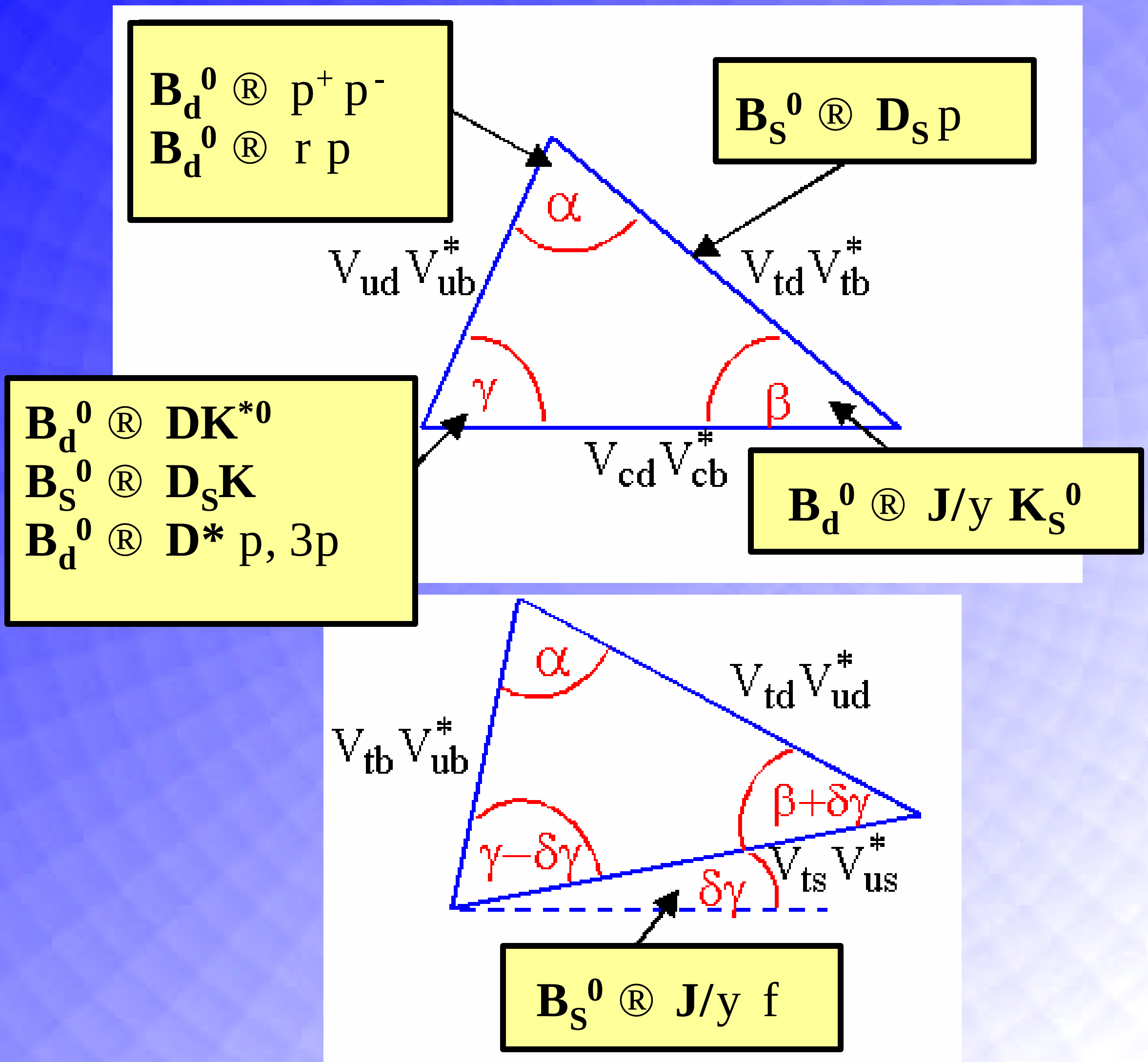
	[illegible]	[illegible]
High p_T, high E_T	10* MHz	
Impact parameter	1 MHz	7.6 MHz
Decay topology		80 kHz
Physics algorithms	40 kHz	
To tape	200 Hz	4 kHz

* Rate of events with visible collisions

	ATLAS	CMS
Muon trigger	40 MHz	40 MHz
$J/\psi \to \mu^+\mu^-$, $D_s \to \phi\pi$, $B \to \pi^+\pi^-$	23kHz	
Physics algorithms	1 kHz	4 kHz
To tape	10 Hz	10 Hz

From U. Egede

Unitarity Triangles



$\delta\gamma = \chi$

From N. Harnew