

# BTeV Physics Reach

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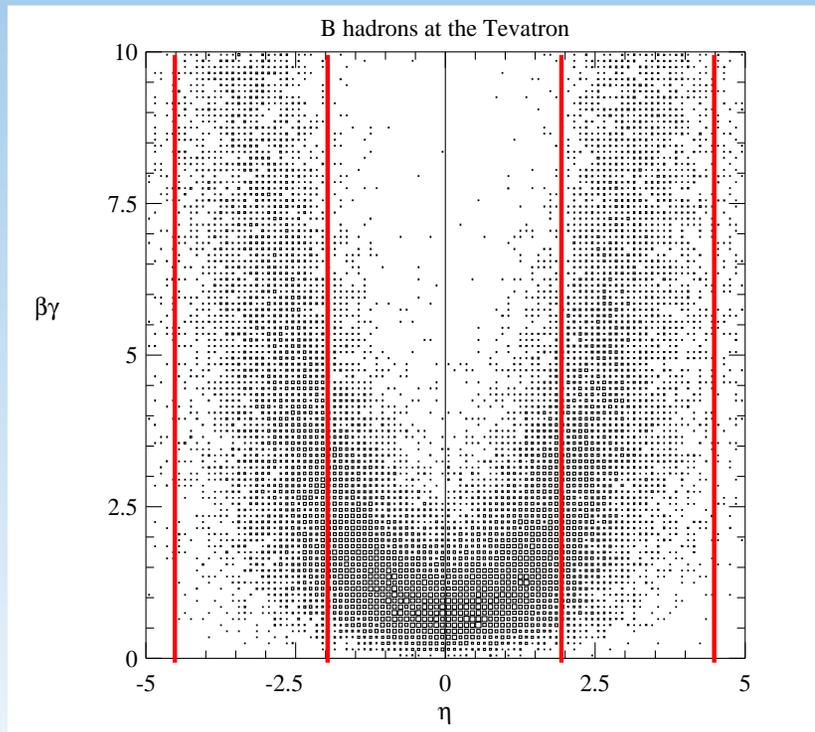
Vanderbilt University

# Outline

- The BTeV Detector
- Physics and Sensitivities
- Comparisons with Other Experiments
- BTeV Status
- Conclusion

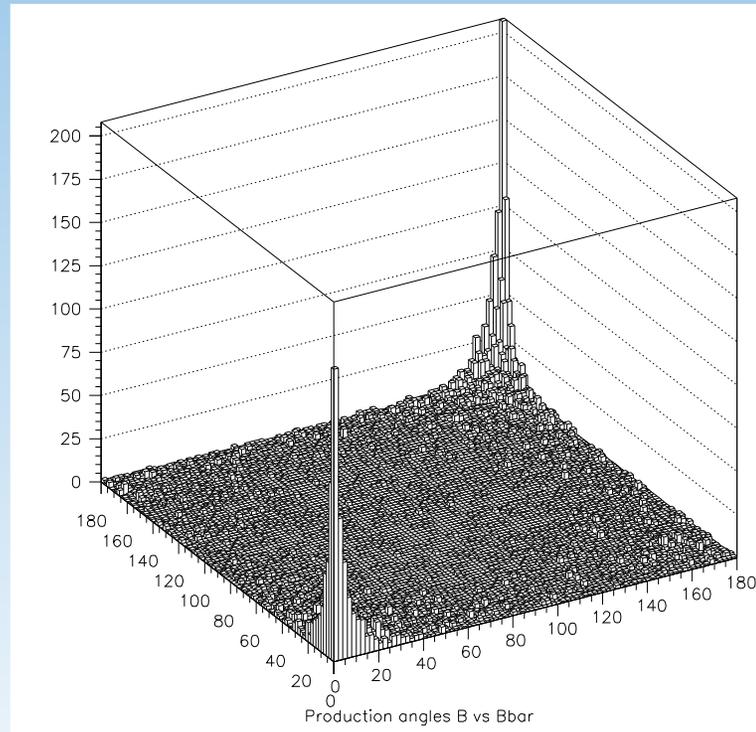
# B's in the Forward Direction

- $\sigma(b\bar{b}) \sim 100 \mu\text{b}, \sigma(c\bar{c}) \sim 1000 \mu\text{b}$
- Luminosity  $2 \times 10^{32}$ , 132/396 ns spacing  $\rightarrow \langle 2/6 \rangle$  int/cross
- $B\bar{B}$  fraction  $\approx 2 \times 10^{-3} \rightarrow 2 \times 10^{11} B\bar{B}$  pairs/year
- Interaction region  $\sigma_z = 30 \text{ cm}$



BTeV:  $1.9 < \eta < 4.5$

Better decay length separation



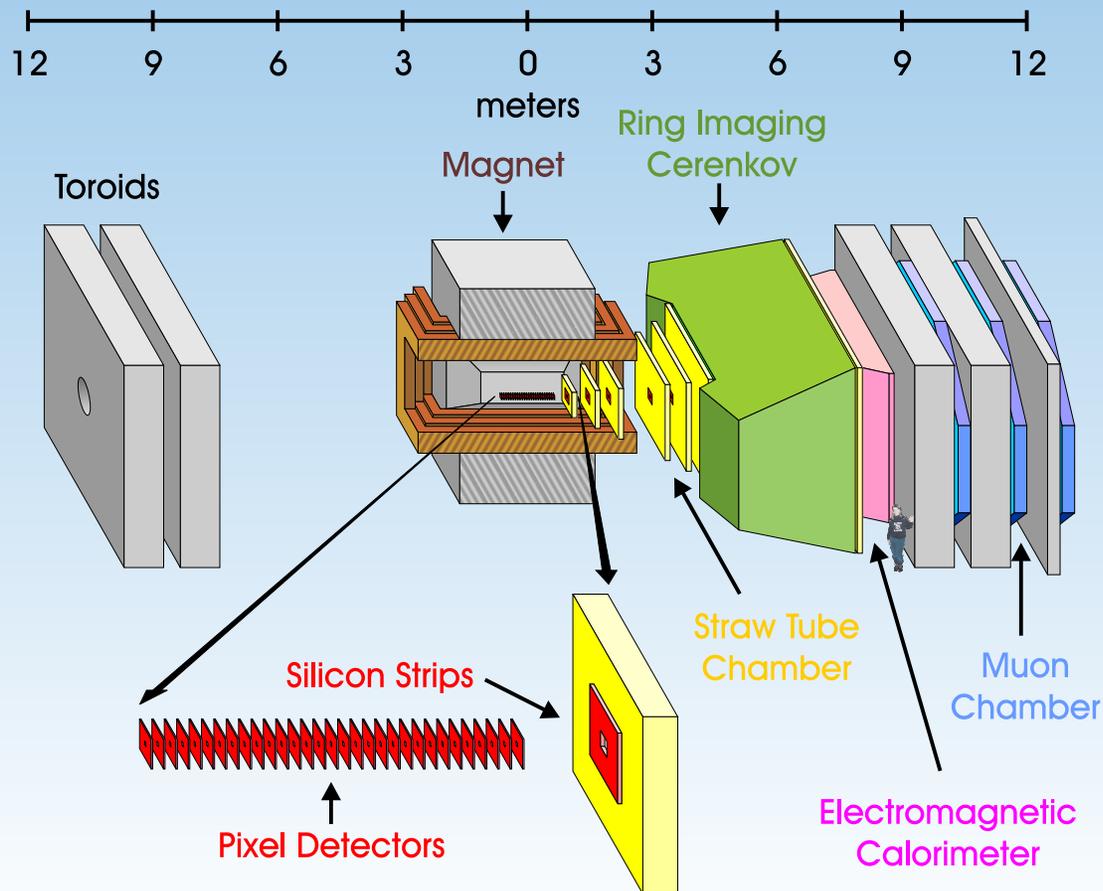
More  $B\bar{B}$  in detector

Better opp. side tagging

# The BTeV Spectrometer

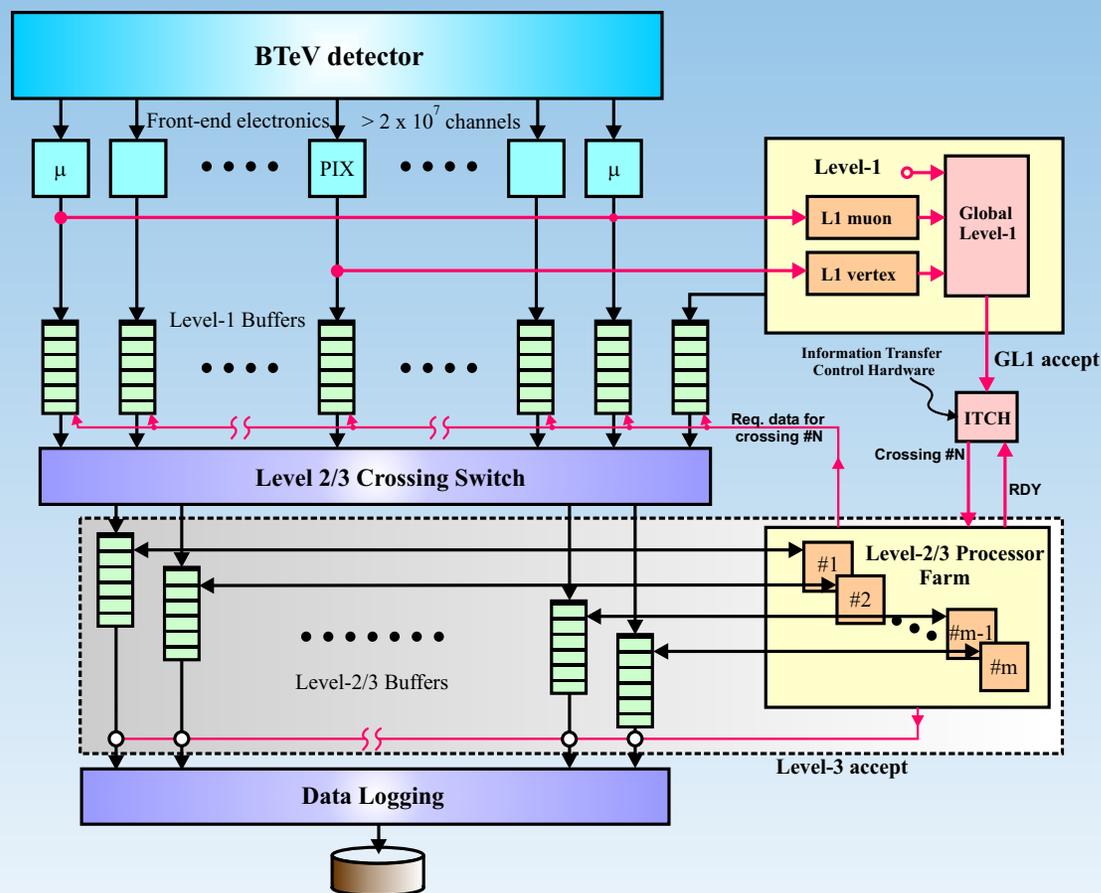
- Collider experiment, but fixed-target-like configuration
- Pixels in magnet, forward tracking with silicon & straws
- RICH particle ID,  $\text{PbWO}_4$  EM Cal., muon detection

## BTeV Detector Layout



# BTeV Trigger & DAQ

Applies computation to every crossing (up to 7.6 MHz)



- Made possible by 3D pixel space-points, low occupancy
- Pipelined with 1 TB buffer, no fixed latency
- Level 1: FPGAs and 2500 DSPs find detached vertices,  $p_T$
- Level 2/3: Farm of 2000 PCs does fast version of reconstruction
- Output rate: 4 KHz, 200 MB/s
- Data rate: 1–2 Petabytes/yr
- Considering *not* using tape

# Efficiencies and Tagging

Triggering on  $\geq 2$  tracks detached by  $> 6\sigma$ , we select 1% of crossings and have these efficiencies ( $\langle 2 \rangle$  int./crossing):

Decay	$\epsilon(\%)$	Decay	$\epsilon(\%)$
$B^0 \rightarrow \pi^+ \pi^-$	63	$B^0 \rightarrow K^+ \pi^-$	63
$B_s^0 \rightarrow D_s^+ K^-$	74	$B^0 \rightarrow J/\psi K_S^0$	50
$B^- \rightarrow D^0 K^-$	70	$B_s^0 \rightarrow J/\psi K^*$	68
$B^- \rightarrow K_S^0 \pi^-$	27	$B^0 \rightarrow K^* \gamma$	63

- Dilution  $D \equiv (N_{\text{right}} - N_{\text{wrong}})/(N_{\text{right}} + N_{\text{wrong}})$
- Effective tagging efficiency =  $\epsilon D^2$
- BTeV studies use
  - Opposite side  $K^\pm$
  - Opposite side leptons & jet charge
  - Same side  $\pi^\pm$  (for  $B^0$ ),  $K^\pm$  (for  $B_s^0$ )
- Conclusion  $\epsilon D^2(B^0) = 0.10$ ,  $\epsilon D^2(B_s^0) = 0.13$ , diff. from same side tagging

## SM Description of $\mathcal{CP}$

So far the Standard Model description of  $\mathcal{CP}$  has held up well. No discrepancies have emerged.

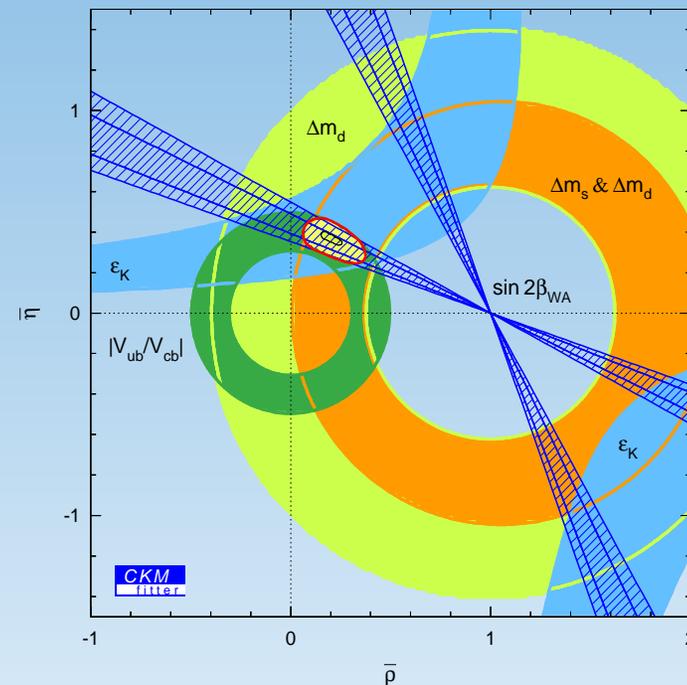
Assume in 2008–9:

- $\Delta m(B_d)/\Delta m(B_s)$  to 5% from CDF & DØ
- $\sin 2\beta$  to 0.02 from 1000  $\text{fb}^{-1}$  from BABAR & Belle

Except  $\sin 2\beta$ , theory errors dominate

But, we know there is “New Physics:” Dark matter, baryon asymmetry,  $\nu$  mixing. May have visible effects in  $b$  sector

BTeV’s challenge will be to test New Physics as an additional source of  $\mathcal{CP}$ .



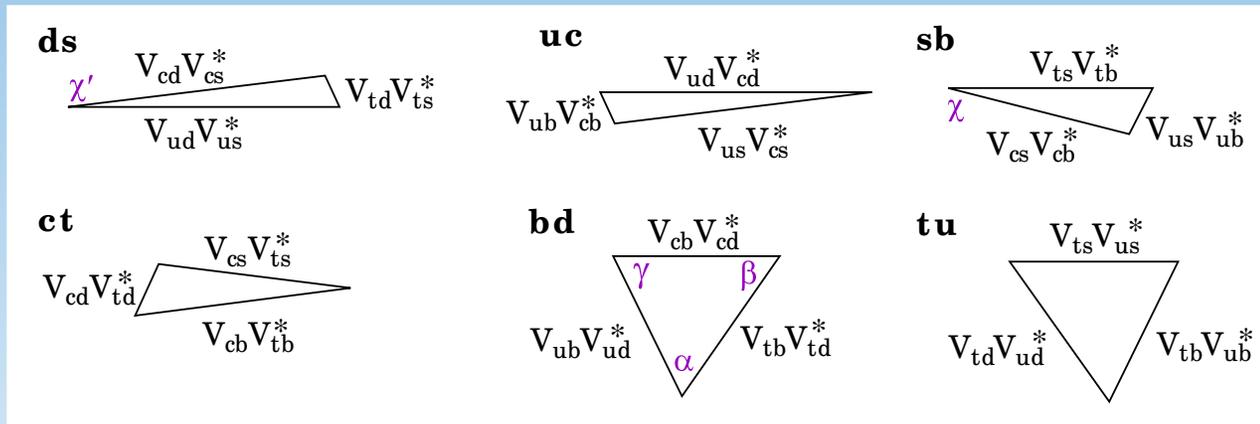
# Unitarity and CKM triangles

Unitarity constraints of the CKM matrix allow us to create 6 triangles with equal areas; defined by only four angles:  $\beta$ ,  $\gamma$ ,  $\chi$ , and  $\chi'$  instead of  $A$ ,  $\lambda$ ,  $\rho$ , and  $\eta$ .

$$\beta = \arg \left[ -\frac{V_{tb}V_{td}^*}{V_{cb}V_{cd}^*} \right]$$

$$\gamma = \arg \left[ -\frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}} \right]$$

etc.



- $\beta$  well measured in  $B$  decays,  $\alpha$  and  $\gamma$  more difficult ( $\alpha + \beta + \gamma = \pi$ )
- $\chi$  small,  $CP$  violation in  $B_s^0$  decays
- $\chi'$  very small,  $CP$  violation in  $K$ 's

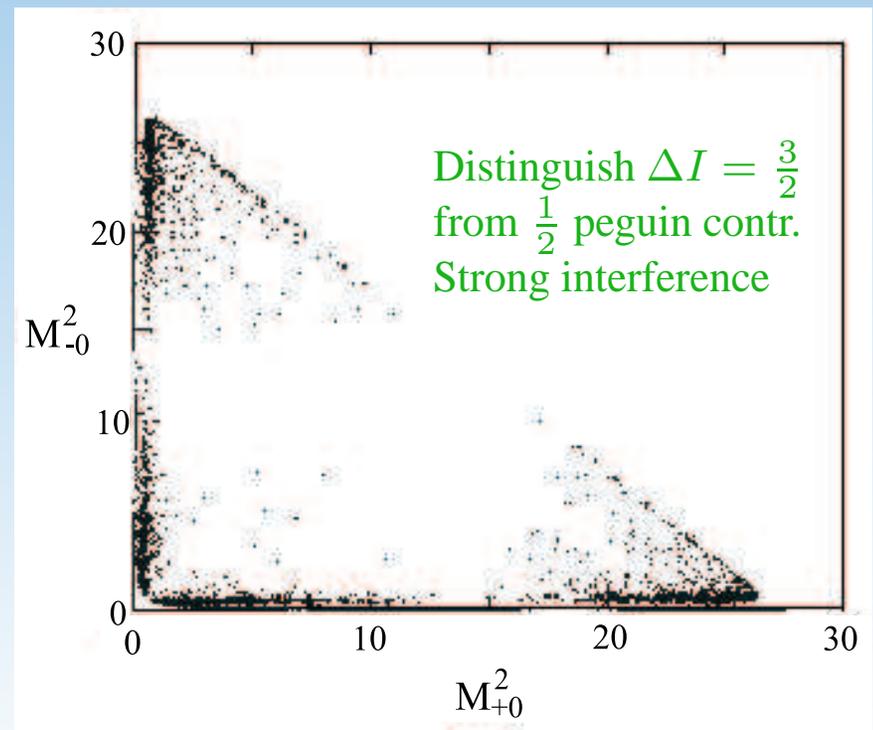
# Measuring $\alpha$

Most accessible in  $B^0 \rightarrow \pi^+ \pi^-$

- Problem: Penguin contamination is  $\sim 40\%$
- Can salvage by also measuring  $B^+ \rightarrow \pi^+ \pi^0$  and  $B^0 \rightarrow \pi^0 \pi^0$  (very difficult)

Model indep. with  $B^0 \rightarrow \rho \pi$   
Dalitz gives  $\sin 2\alpha$ ,  $\cos 2\alpha$

- Measured BRs:
  - $B^0 \rightarrow \rho^\pm \pi^\pm$ :  $\approx 3 \times 10^{-5}$
  - $B^0 \rightarrow \rho^0 \pi^0$ :  $< 0.5 \times 10^{-5}$
  - $\gtrsim B^0 \rightarrow \pi^+ \pi^-$
- Challenging analysis, 9 parameter fit



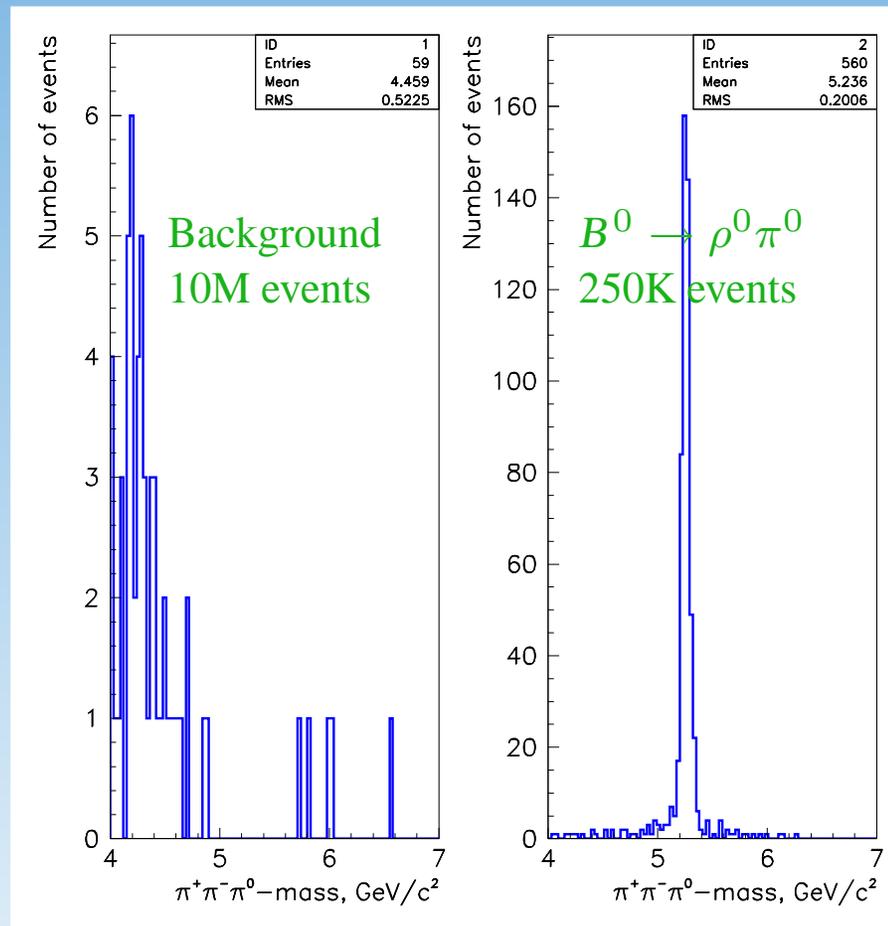
## $B^0 \rightarrow \rho\pi$ in BTeV

For one yr of running:

	$\rho^\pm \pi^\mp$	$\rho^0 \pi^0$
BR ( $\times 10^{-5}$ )	2.8	0.5
$\epsilon$	0.0014	0.0011
Sig./ $10^7$ s	5400	776
$\epsilon D^2$	0.10	0.10
Tagged/yr	540	78
Sig/BG	4.1	0.3

Depending on value of  $\alpha$ ,  
measured to  $1.4\text{--}4.3^\circ$  in  $1.4 \times 10^7$  s

Also includes various assumptions of BG composition, Penguin amplitudes



# Measuring $\chi$

$\sin 2\chi$  is the  $CP$  asymmetry of  $B_s^0$  decays

In the Standard model, phases and magnitudes are correlated:

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

where  $\lambda \equiv \left| \frac{V_{us}}{V_{ud}} \right| = 0.2205 \pm 0.0018$

Analysis:

- $B_s^0 \rightarrow J/\psi\phi$ 
  - Mixed  $CP$  final state, needs angular analysis
- $B_s^0 \rightarrow J/\psi\eta^{(\prime)}$ 
  - Definite  $CP$  final state
  - Less data, simpler analysis, more difficult recon.

# $B_s^0$ Mixing, measurement of $x_s$

$$\begin{aligned}x_{d/s} &\equiv \frac{\Delta m_{d/s}}{\Gamma_{d/s}} \\ &= \frac{G_F^2}{6\pi^2} B_{B_{d/s}} f_{B_{d/s}}^2 m_{B_{d/s}} \tau_{B_{d/s}} |V_{tb}^* V_{t(d/s)}|^2 m_t^2 F \left( \frac{m_t^2}{m_W^2} \right) \eta_{\text{QCD}}\end{aligned}$$

Combined with  $x_d$ ,  $x_s$  is a measure of  $|V_{td}/V_{ts}|$ . Many theoretical uncertainties cancel  $\rightarrow$  better measurement in  $(\rho, \eta)$  plane

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2$$

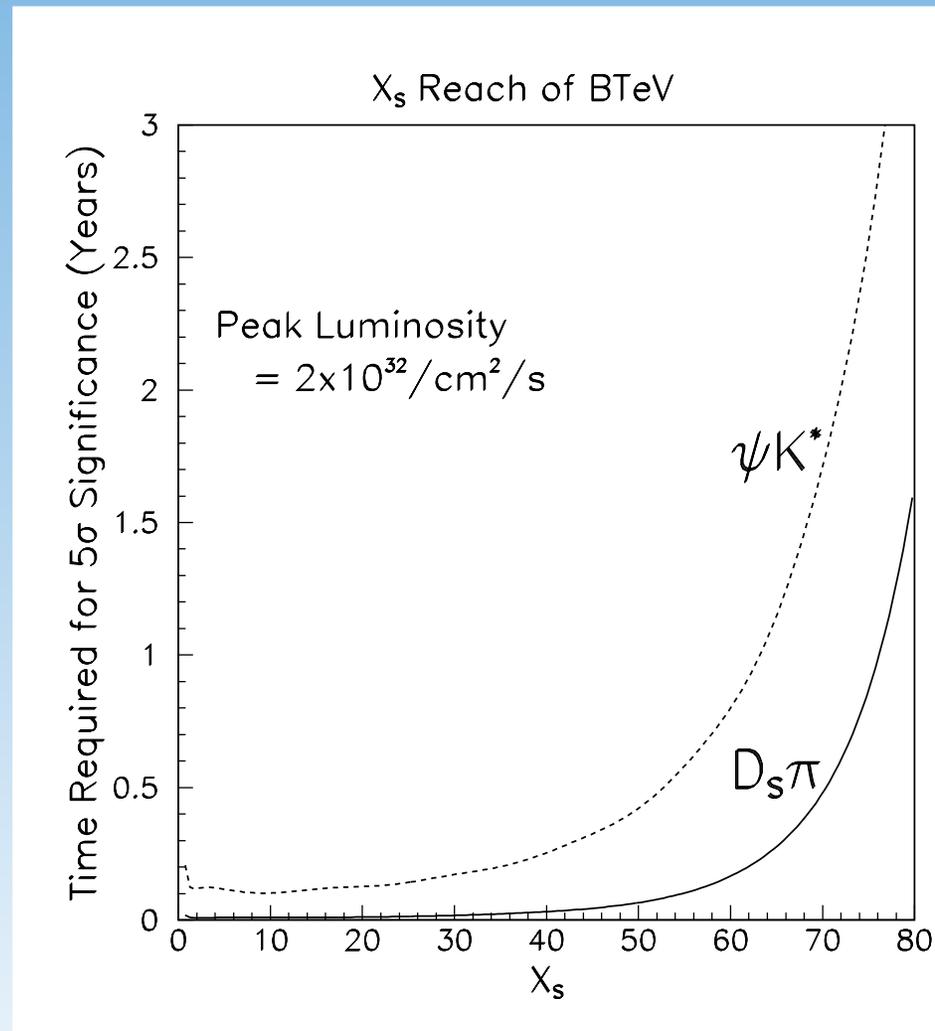
$$\xi = \frac{f_{B_s}}{f_{B_d}} \sqrt{\frac{B_{B_s}}{B_{B_d}}} = 1.24 \pm 0.04 \pm 0.06 \text{ (lattice best value)}$$

## BTeV's $x_s$ sensitivity

In the SM,  $x_s$  should be  $\lesssim 40$ .

BTeV's best channel is  $B_s^0 \rightarrow D_s^+ \pi^-$  and gives us sensitivity up to  $x_s = 80$  in about three years running.

“Discovery” is  $5\sigma$  significance.

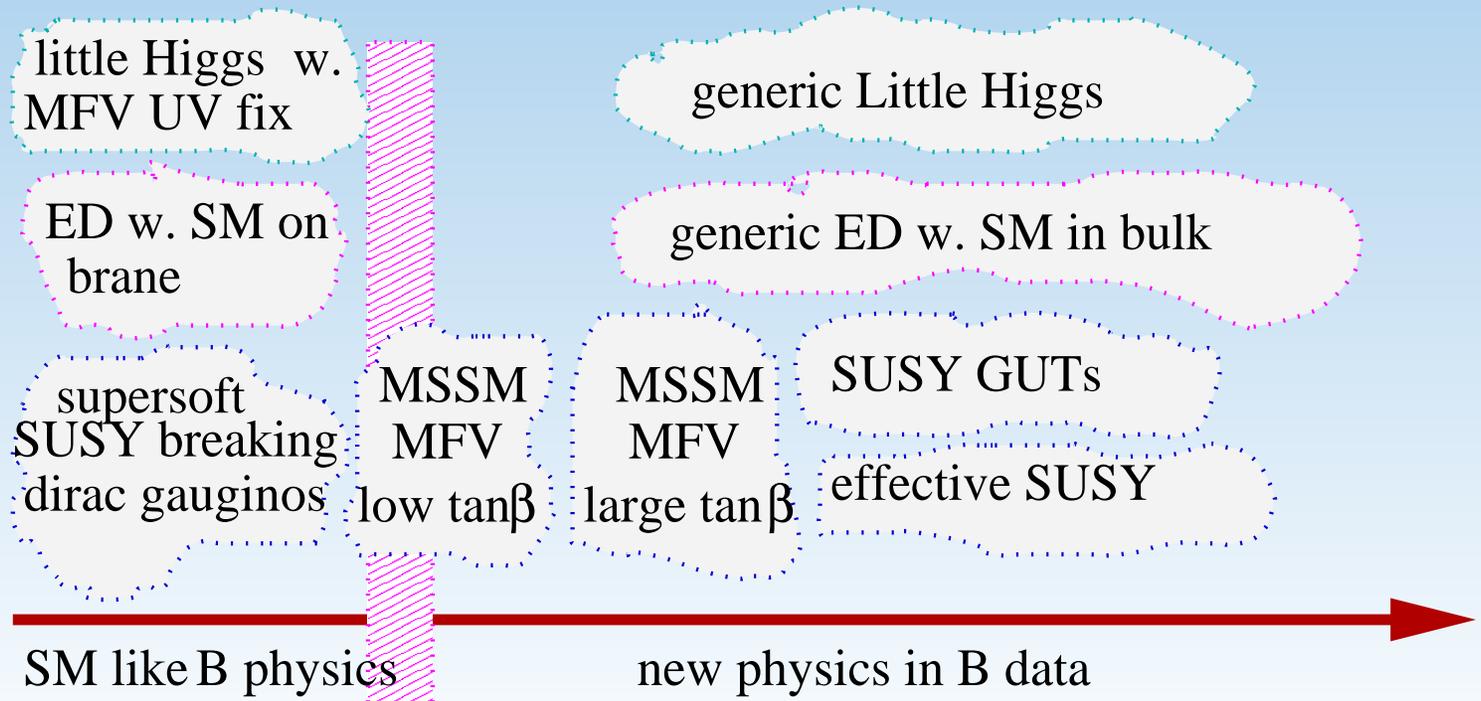


2-arm sensitivity,  $\sim \frac{1}{2}$  for 1-arm

# New Physics

From Masiero & Vives (hep-ex/0104027): *“the relevance of SUSY searches in rare processes is not confined to the usually quoted possibility that indirect searches can arrive ‘first’ ... in signaling the presence of SUSY. Even after the possible direct production and observation of SUSY particles, the importance of FCNC and CP violation in testing SUSY remains of utmost relevance. They are and will be complementary to the Tevatron and LHC establishing low energy supersymmetry as the response to the electroweak breaking puzzle.”*

We would replace “SUSY” with “New Physics”



From Hiller–hep/ph/0207121

# Example: MSSM

- In general, SUSY adds 80 constants, 43 new phases
- In MSSM, two new phases (hep-ph/9911321):
- $\theta_D$  ( $B^0$  mixing),  $\theta_A$  ( $B^0$  decay)
- $\phi_{K\pi}$  (combination  $\rightarrow \mathcal{CP}$  in  $D^0$  mixing)
- Predictions of  $\theta_D, \theta_A$  vary,  $\mathcal{O}(0.1-1)$

Decay	SM	MSSM
$B^0 \rightarrow J/\psi K_S^0$	$\sin 2\beta$	$\sin 2(\beta + \theta_D)$
$B^0 \rightarrow \phi K_S^0$	$\sin 2\beta$	$\sin 2(\beta + \theta_D + \theta_A)$
$D^0 \rightarrow K^- \pi^+$	0	$\sim \sin \phi_{K\pi}$

Two obvious signatures: Different  $CP$  asymmetries in  $B^0 \rightarrow J/\psi K_S^0$  and  $B^0 \rightarrow \phi K_S^0$  and  $\mathcal{CP}$  in  $D^0 \rightarrow K^- \pi^+$ .

# Sensitivities in One Year

Decay Mode	BR ( $10^{-6}$ )	# Events	S/B	Parameter	Error (Value)
$B_s^0 \rightarrow D_s^+ K^-$	300	7 500	7	$\gamma - 2\chi$	$8^\circ$
$B_s^0 \rightarrow D_s^+ \pi^-$	3000	59 000	3	$x_s$	(75)
$B^0 \rightarrow J/\psi K_S^0, J/\psi \rightarrow \ell^+ \ell^-$	445	168 000	10	$\sin 2\beta$	0.017
$B^0 \rightarrow J/\psi K^0, K^0 \rightarrow \pi \ell \nu$	7	250	2.3	$\cos 2\beta$	$\sim 0.5$
$B^- \rightarrow D^0(K^+ \pi^-)K^-$	0.17	170	1		
$B^- \rightarrow D^0(K^+ K^-)K^-$	1.1	1 000	$> 10$	$\gamma$	$13^\circ$
$B_s^0 \rightarrow J/\psi \eta$	330	2 800	15		
$B_s^0 \rightarrow J/\psi \eta'$	670	9 800	30	$\sin 2\chi$	0.024
$B^0 \rightarrow \rho^+ \pi^-$	28	5 400	4.1		
$B^0 \rightarrow \rho^0 \pi^0$	5	780	0.3	$\alpha$	$\sim 4^\circ$
$B^- \rightarrow K_S^0 \pi^-$	12.1	4 600	1		$< 4^\circ +$
$B^0 \rightarrow K^+ \pi^-$	18.8	62 100	20	$\gamma$	theory err.
$B^0 \rightarrow \pi^+ \pi^-$	4.5	14 600	3		0.03
$B_s^0 \rightarrow K^+ K^-$	17	18 900	3	$\alpha, \gamma$	0.02

Model dependent checks may be useful for resolving ambiguities

# Measurement Requirements

BTeV provides:

- Large samples of tagged  $B^+$ ,  $B^0$ ,  $B_s^0$  decays, unbiased  $b$  and  $c$  decays
- Efficient trigger, well understood acceptance and reconstruction
- Excellent vertex and momentum resolutions
- Excellent particle ID and  $\gamma$ ,  $\pi^0$  reconstruction

Quantity	Decay Mode	Vertex Trigger	$K \pi$ Sep.	$\gamma$ Det.	Decay Time $\sigma$
$\sin 2\alpha$	$B^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$	✓	✓	✓	
$\cos 2\alpha$	$B^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$	✓	✓	✓	
$\sin \gamma$	$B_s^0 \rightarrow D_s^+ K^-$	✓	✓		✓
$\sin \gamma$	$B^0 \rightarrow D^0 K^-$	✓	✓		
$\sin 2\chi$	$B_s^0 \rightarrow J/\psi\eta, J/\psi\eta'$		✓	✓	✓
$\sin 2\beta$	$B^0 \rightarrow J/\psi K_S^0$				
$\cos 2\beta$	$B^0 \rightarrow J/\psi K^0, K^0 \rightarrow \pi\ell\nu$		✓		
$x_s$	$B_s^0 \rightarrow D_s^+ \pi^-$	✓	✓		✓
$\Delta\Gamma$ for $B_s^0$	$B_s^0 \rightarrow J/\psi\eta^{(\prime)}, K^+K^-, D_s^+ \pi^-$	✓	✓	✓	✓

# BTeV Compared to *B*-factories

- No  $B_s^0$ ,  $B_c^+$ ,  $\Lambda_b^0$  at *B*-factories
- Tevatron  $\sigma$   $10^5$  higher than  $e^-e^+$ 
  - *B*-factory:  $\mathcal{L} = 10^{34} \rightarrow 1.1 \times 10^8 B^0/10^7 \text{ s}$
  - BTeV:  $\mathcal{L} = 2 \times 10^{32} \rightarrow 1.5 \times 10^{11} B^0/10^7 \text{ s}$
- Reconstruction and tagging efficiency is sometimes  $50\times$  better at  $e^+e^-$
- BTeV is able to overcome this with high cross section
- Many modes BTeV collects  $30\times e^+e^-$  statistics/yr
- Assume *B*-factories reach  $> 500 \text{ fb}^{-1}$ , currently  $\sim 130$
- Super-KEK: Plan to upgrade to  $\mathcal{L} = 10^{35}$  in 2007, still not competitive with BTeV in  $B\bar{B}$

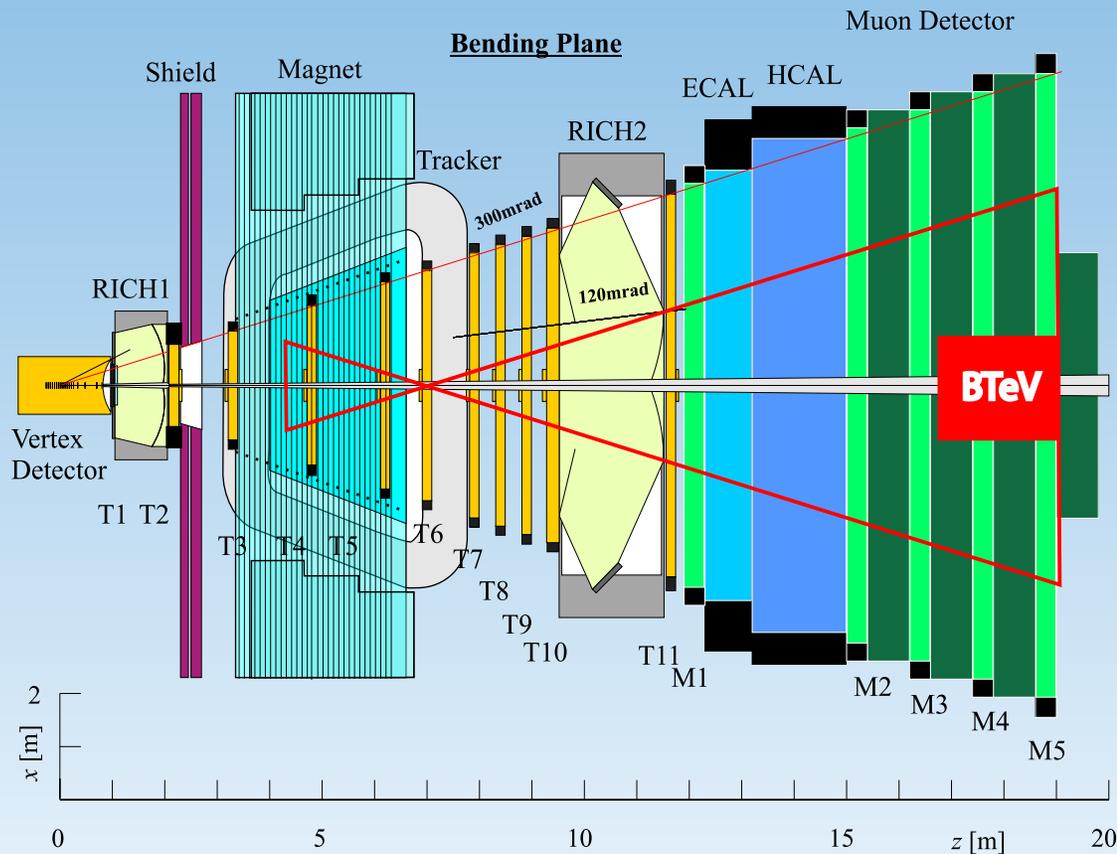
## Comparison to LHCb

Strongest competitor to BTeV. Recently re-optimized to reduce material in spectrometer.

### LHCb advantages:

- $\sigma_{b\bar{b}} = 5 \times \text{BTeV}$
- $\sigma_{\text{tot}} = 1.6 \times \text{BTeV}$
- $\langle \text{Int./Cross} \rangle < 1$

But, BTeV has many advantages too.



LHCb before re-optimization

# BTeV Advantages over LHCb

- 132 or 396 ns crossing time vs. 25 ns
- Lower BTeV  $p \rightarrow$  shorter detector (hall length  $\sim$ same)
  - Only one RICH needed, less  $B$ -field
  - Smaller size  $\rightarrow$  better detectors/\$\$
- Better EM calorimeter — more comprehensive studies
- DAQ has  $20\times$  rate,  $5\times$  more  $b$  decays to “tape”
- Pixel detector allows vertexing at L1
  - Unbiased selection of  $b$  and  $c$  decays
  - Will have physics that becomes interesting “on tape”
- Multiple interactions per crossing OK
  - Longer interaction region, pixel vertexing
- Vertex detector in  $B$ -field can reject low-momentum tracks

# Comparisons with LHCb

Comparisons with prelim. (April 2003) LHCb-light #s. BTeV #s scaled to LHCb BR's.

Mode	BR ( $10^{-5}$ )	LHCb Untagged		BTeV
		TDR	Light	
$B_s^0 \rightarrow D_s^+ \pi^- (x_s)$	300	86 000	72 000	59 000
$B_s^0 \rightarrow D_s^+ K^- (\gamma - 2\chi)$	23	6 000	8 000	5 900

Comparisons with LHCb TDR #s. (Light #s will be similar)

Mode	BR	LHCb		BTeV	
		Yield	S/B	Yield	S/B
$B_s^0 \rightarrow J/\psi \eta^{(\prime)} (\chi)$	$1.0 \times 10^{-3}$	—	—	12 650	> 15
$B^0 \rightarrow \rho^+ \pi^- (\alpha)$	$2.8 \times 10^{-5}$	2 140	0.8	5 400	4.1
$B^0 \rightarrow \rho^0 \pi^0 (\alpha)$	$0.5 \times 10^{-5}$	880	0.05?	776	0.3

BTeV does better with  $\gamma, \pi^0$ , more comprehensive data set

# History and Status of BTeV

- December 1997: BTeV becomes R&D project
- May 1999: Preliminary TDR
- May 2000: Proposal for 2-arm BTeV, \$130M + \$50M
  - Unanimously approved by PAC, June 2000
- March 2002: One arm descoped detector proposed, offline computing supplied by universities: \$122M + \$0M
  - Unanimously approved by PAC
- October 2002: Fermilab (Temple) cost review
- March 2003: Review by P5
- Assuming a positive P5 report, a Temple (internal) and Lehman review will follow
- Construction, commissioning 2007–8, data taking 2009

# Conclusions

- Plenty of physics not covered
  - Other non-SM tests: Extra dimensions, SO(10)
  - FCNC decays
  - $b$  baryons,  $B_c$  mesons
  - Copious amounts of charm
- We will make key measurements in  $B_s^0$  decays and states with  $\gamma$ 's; our ability to record all  $b$  states gives us the broadest possible scope and significant advantages over other experiments
- BTeV will make critical contributions to our knowledge of  $\mathcal{CP}$  and move from initial observations to determining if the SM description is complete. **BTeV is not just doing SM physics; it can reveal or help explain new phenomena**
- Part of a high precision flavor program to complement and interpret any NP discoveries at Tevatron or LHC

# Backup Slides

# 396 ns Bunch Crossing

- BTeV was designed for  $\mathcal{L} = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  at 132 ns  
→  $\langle 2 \rangle$  interactions/crossing
- Now expect  $\mathcal{L} \sim 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  at 396 ns ( $\langle 6 \rangle$  int./cross)  
or  $\mathcal{L} \sim 1.3 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  at 396 ns ( $\langle 4 \rangle$  int./cross)
- Verified performance by repeating many simulations at  $\langle 4 \rangle$   
and  $\langle 6 \rangle$  int./cross (without re-optimizing code)
- Key potential problem areas (trigger, EMCAL, RICH) all  
hold up well based on simulations
- On going work to fully understand the impact of a change  
to 396 ns, *e.g.* optimizing charge collection for pixel  
readout

# Change from Two Arms to One

Between our first and second PAC approvals, BTeV was rescoped. However, we also found better ways to do physics, so the effect was not as drastic on our ability to achieve our physics goals:

- Loss of one arm: factor = 0.5
- Gains in dileptons:
  - RICH ID of  $\mu$ 's
  - Proposal:  $\mu^+\mu^-$  only, now  $e^+e^-$  too
  - Factor = 2.4 (or 3.9) for (di)lepton ID
- DAQ retains full bandwidth, loosen triggers: factor = 1.15
- Same-side  $K^\pm$  tagging for  $B_s^0$  only: factor = 1.3
- Bottom line: w.r.t. proposal, factors from 0.58–2.9, most physics is same or better with new assumptions