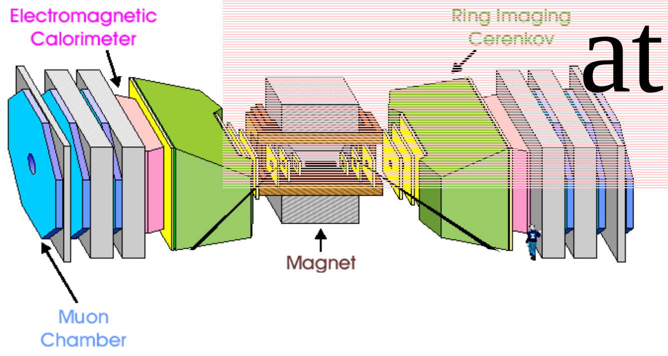
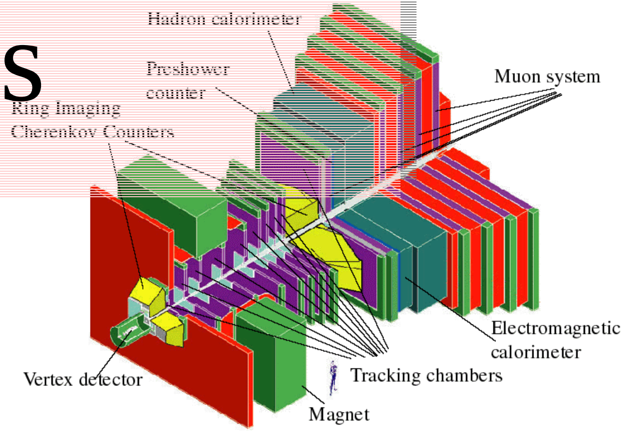
5th KEK topical conference
“Frontiers in Flavour Physics”
November 20–22, 2001
KEK, Tsukuba, Japan

Future B physics prospects at hadron colliders





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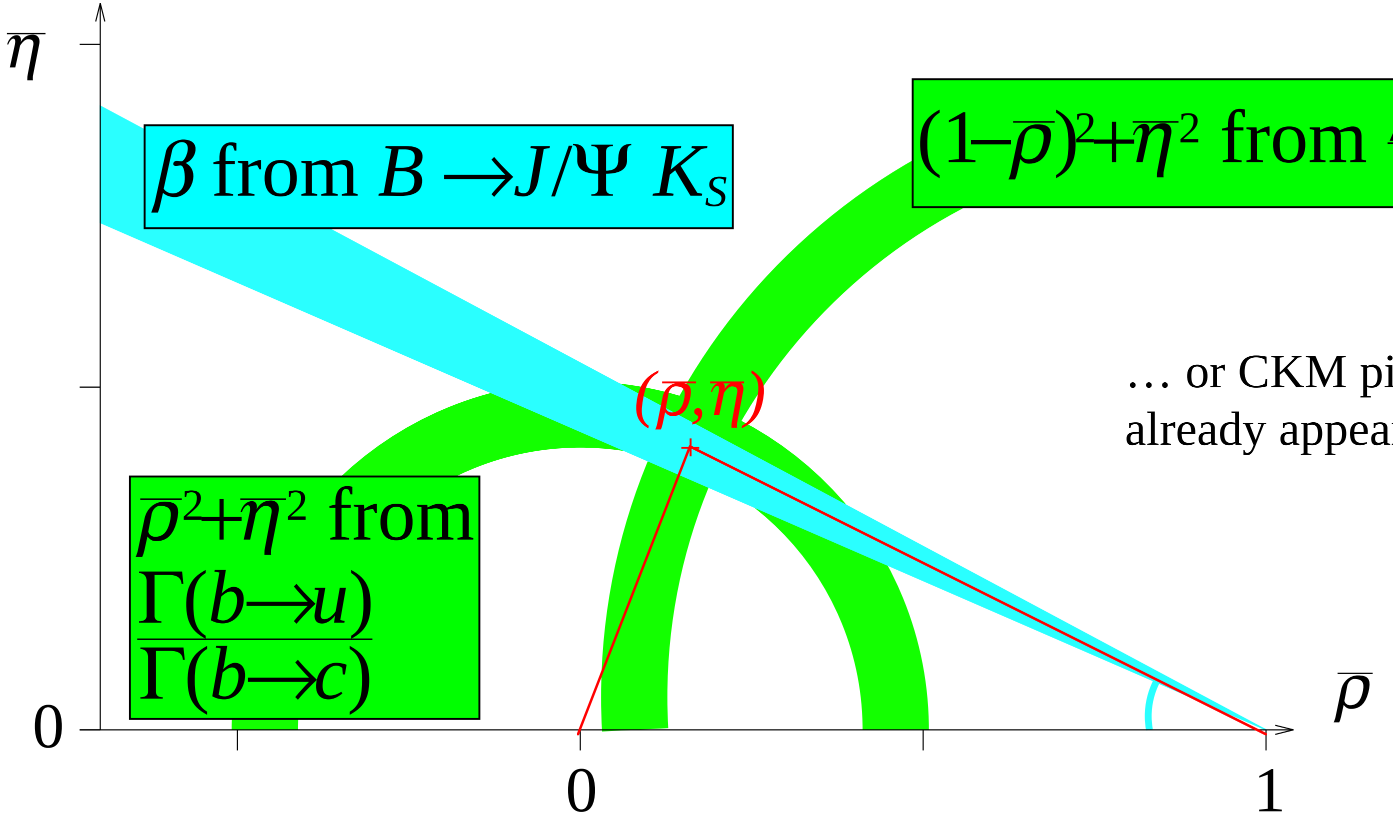
B physics and CP violation in 2006

- Experimental results from
  - —Tevatron Run IIa: CDF + D0, each 2 fb^{-1}
  - —Asym. B factories: BABAR + Belle, each 300–500 fb^{-1}
  - —“Equivalent” to several 10^8 B mesons
- Direct measurements of angles of unitarity triangle:
  - — $\sigma(\sin(2\beta)) \approx 0.03$ from $B^0 \rightarrow J/\psi\, K_S$ asymmetry
  - — no precise measurement of other angles
- Knowledge on sides of unitarity triangle
  - — $\sigma(|V_{cb}|) \approx$ few % error
  - — $\sigma(|V_{ub}|) \approx$ 5-10 % error
  - — $\sigma(|V_{td}|/|V_{ts}|) \approx$ few-5 % error (assuming $\Delta m_s < 40\ \text{ps}^{-1}$)

$$\left.\right\} \quad \sin\left[2\left(\tan^{-1}\frac{\eta}{1-\rho}\right)\right]$$

indirectly known to < 0.03

CKM triangle in 2006 (SM)

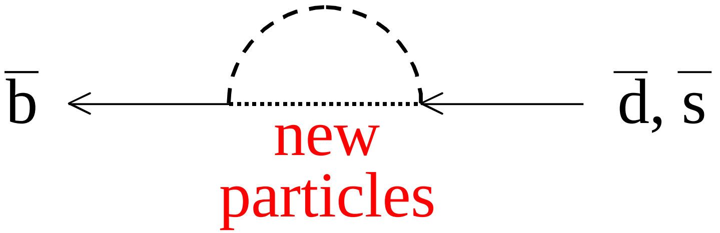


… or CKM picture might already appear inconsistent …

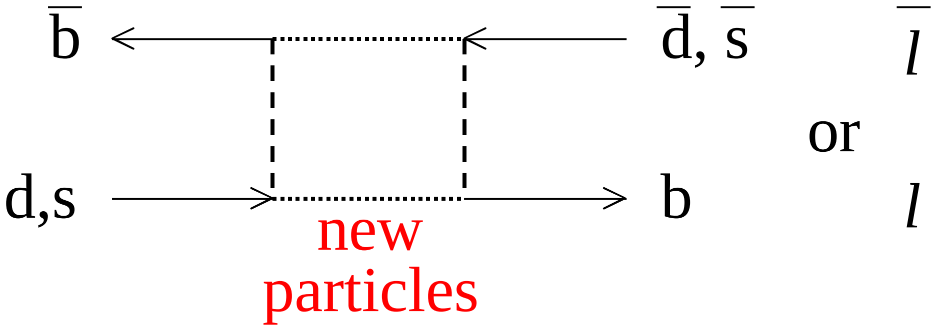
- ❑ First stringent test of CKM ansatz !
  - —Sides dominated by theoretical uncertainties
  - —More statistics would improve sin(2β)

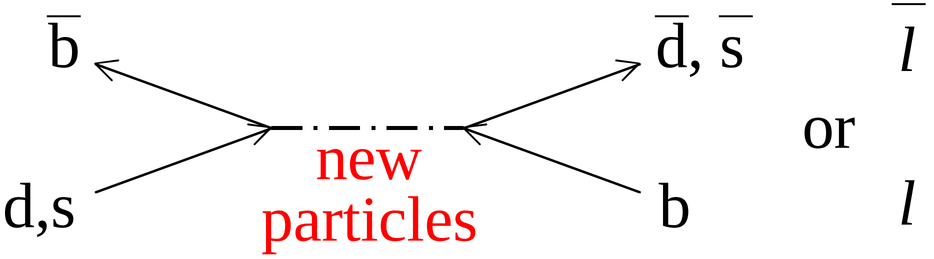
Most extensions to SM imply …

- … new physics in decays (Δb =1)
  - —Penguin loops



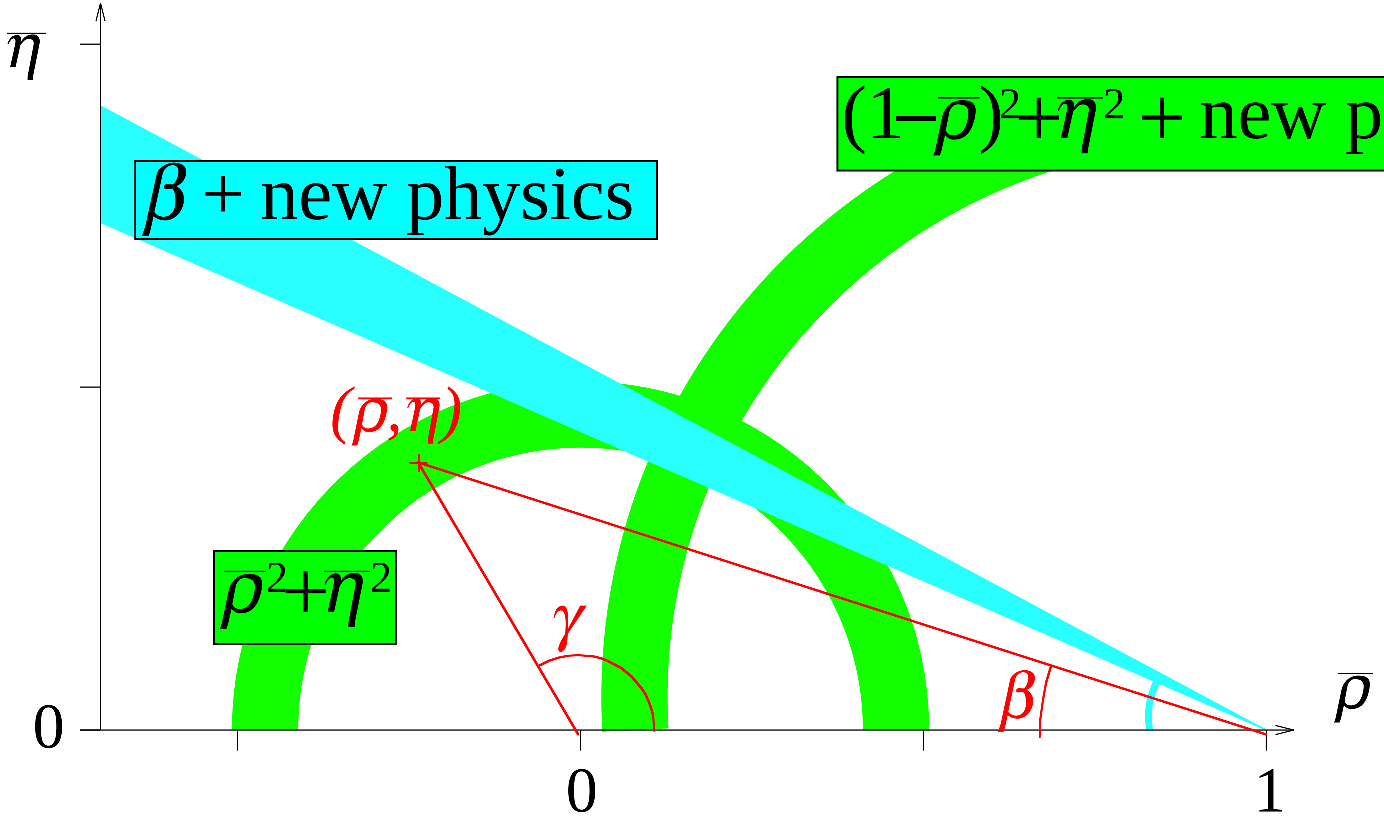
- … new physics in mixing (Δb=2)
  - —Box diagrams
  - —Tree diagrams





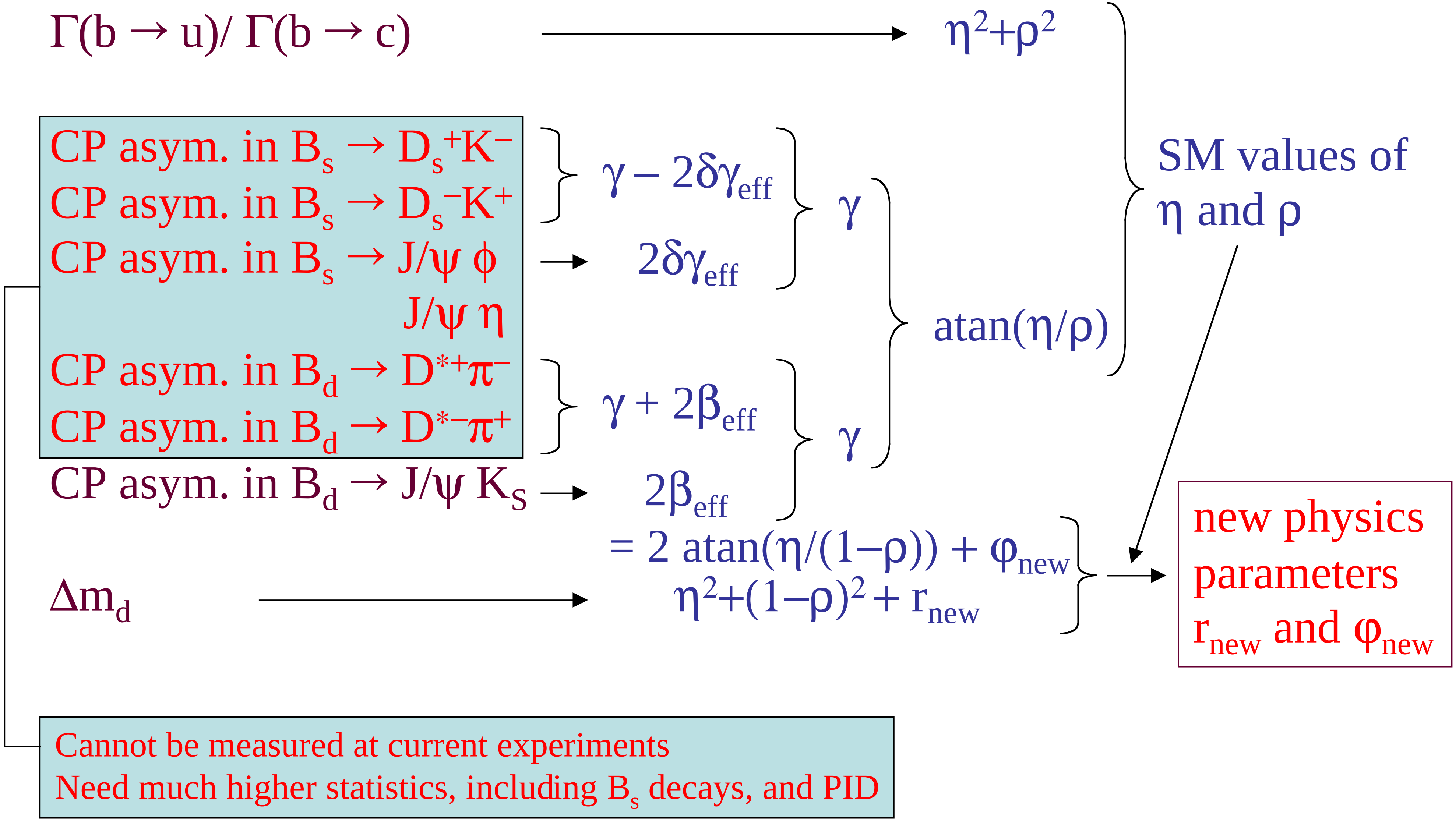
- Note: SM tree processes are not affected

CKM triangle in 2006 (new physics)



- In this case, a precise measurement of γ, independent of possible new physics in the mixing, is needed to provide evidence for the new physics

Measuring new physics in B mixing



$\Gamma(b \to u)/\ \Gamma(b \to c)$ → $\eta^2+\rho^2$

CP asym. in $B_s \to D_s^+K^-$

CP asym. in $B_s \to D_s^-K^+$

CP asym. in $B_s \to J/\psi\ \phi$

$J/\psi\ \eta$

CP asym. in $B_d \to D^{*+}\pi^-$

CP asym. in $B_d \to D^{*-}\pi^+$

CP asym. in $B_d \to J/\psi\ K_S$

Δm_d

$\gamma - 2\delta\gamma_{eff}$

$2\delta\gamma_{eff}$

$\gamma + 2\beta_{eff}$

$2\beta_{eff}$

γ

γ

atan(η/ρ)

$= 2\ \text{atan}(\eta/(1-\rho)) + \varphi_{new}$

$\eta^2+(1-\rho)^2 + r_{new}$

SM values of η and ρ

new physics parameters r_{new} and φ_{new}

Cannot be measured at current experiments

Need much higher statistics, including B_s decays, and PID

(dis)advantages of hadron colliders for B physics

10^{12} bb / year
at 2×10^{32} cm^{-2}s^{-1}

- ☺ Large bottom production cross section
  - $\sigma_{bb} = 100–500\ \mu b$ (for $\sqrt{s} = 2–14$ TeV)
- 😐 Triggering is an issue
  - $\sigma_{bb} / \sigma_{inelastic} = 0.2–0.6\%$ (for $\sqrt{s} = 2–14$ TeV)
- ☺ All b hadrons produced
  - B_u (40%), B_d (40%), B_s (10%), B_c, and b-baryons (10%)
- ☺ Many primary particles to determine b production vertex
- ☹ Many particles not associated to b hadrons
- ☹ b hadron pairs don’t evolve coherently
  - mixing dilutes tagging

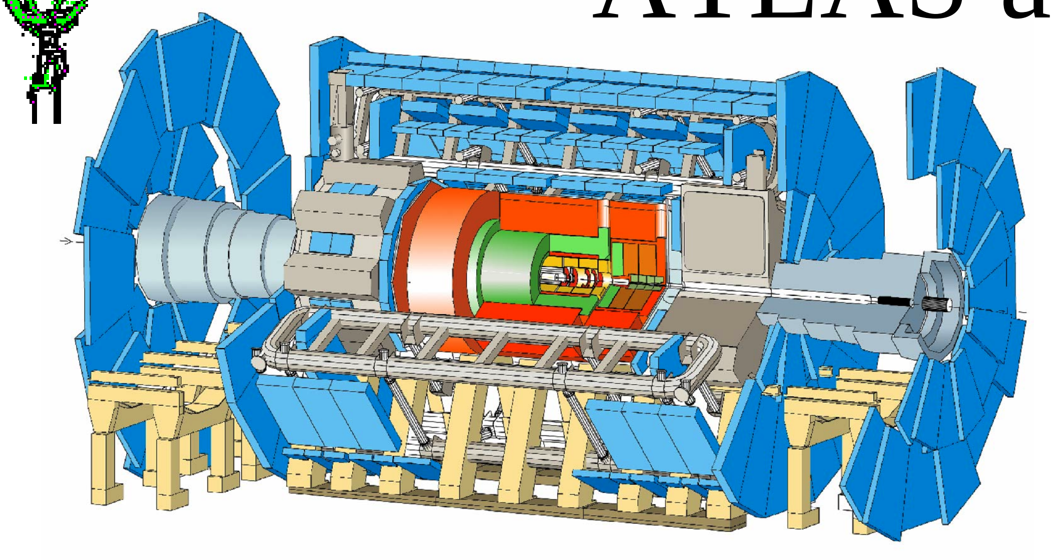
Hadron colliders (≥ 2006)

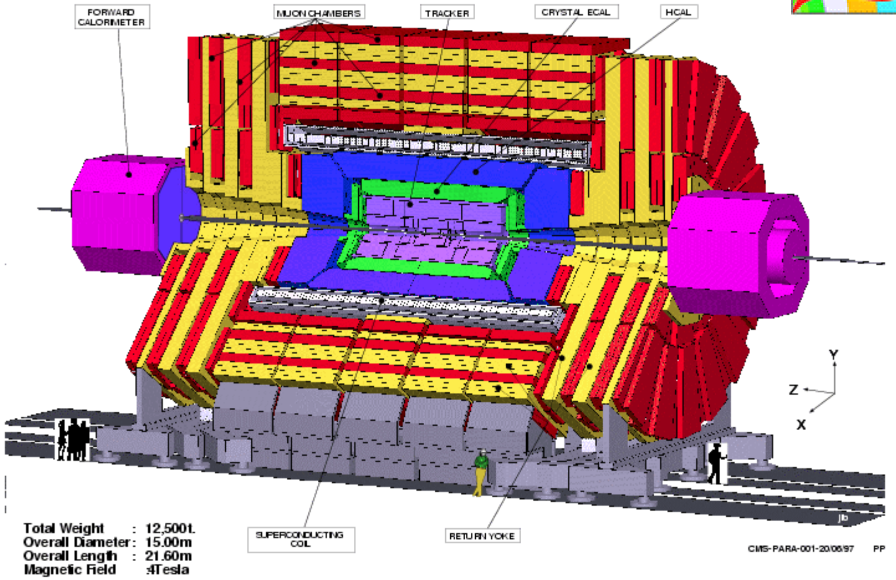
	Tevatron	**LHC**	
	proton-antiproton	proton-proton	
$\sqrt{s}$	2 TeV	14 TeV	
σ_{bb}	100 μb	500 μb	Cross sections not measured yet: large uncertainties
σ_{cc}	1mb	3.5 mb	
$\sigma_{inelastic}$	60 mb	80 mb	
σ_{total}	75 mb	100 mb	
$\omega_{bunch\ crossing}$	7.6 MHz	40 MHz	
Δt_{bunch}	132 ns	25 ns	
$\sigma_{z\ (luminous\ region)}$	30 cm	5.3 cm	
L [$cm^{-2}s^{-2}$]	2×10^{32}	2×10^{32} 10^{33} (10^{34})	
$<n_{inelastic\ pp\ interactions}$ / bx>	1.6	0.53 ~2 (20)	
		@LHCb @ATLAS/CMS	

B physics’ future at hadron colliders

- **High p_T central detectors**
  - **CDF+D0** @ Tevatron → run II started
    - See talk from V. Papadimitriou
  - **ATLAS+CMS** @ LHC → ready in 2006
    - Construction well underway
    - Most B physics during LHC’s initial low luminosity period (10^{33})
- **(forward) detectors dedicated to B physics**
  - **LHCb** @ LHC → ready in 2006
    - Proposed and approved in 1998; TDR phase, some construction started
    - Designed to do B physics at 2×10^{32} (even when ATLAS+CMS at 10^{34})
  - **BTeV** @ Tevatron → ?
    - Proposed in 2000, more aggressive approach than LHCb (technology & funding)
    - approved (stage I) at FNAL, R&D phase; waiting for funding decision …

ATLAS and CMS



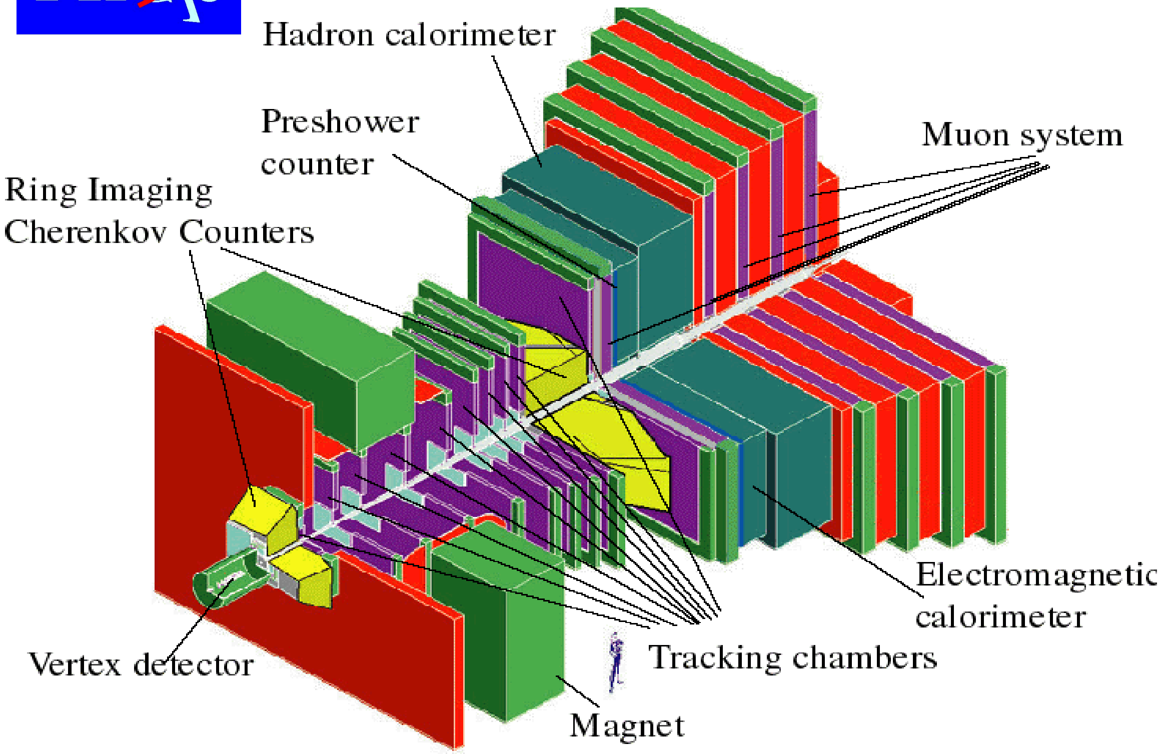


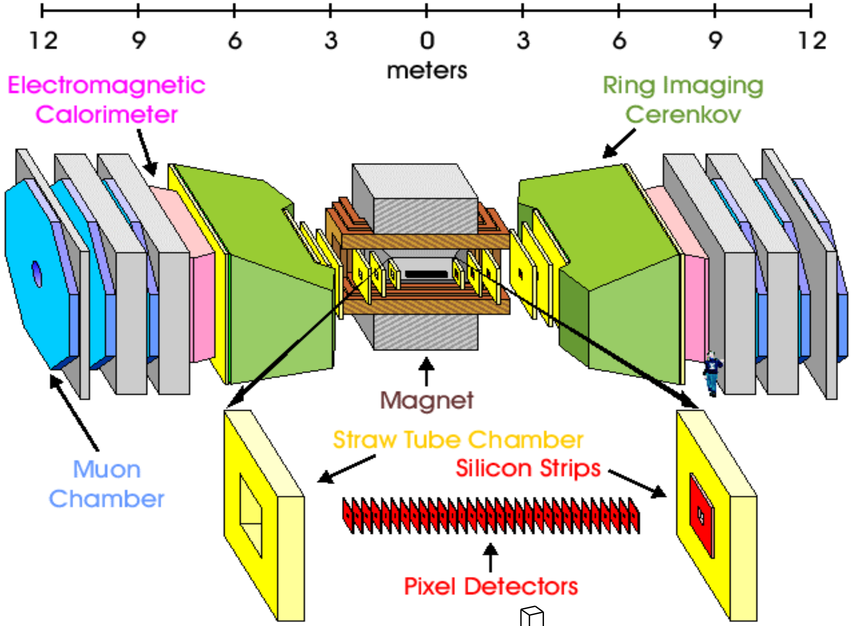
- ❑ Central detectors ($|\eta| < 2.5$)
- ❑ B physics trigger:
  - —high p_T leptons
  - —no purely hadronic trigger (must rely on tagging lepton)
- ❑ Mostly B physics using J/ψ decay modes (+ rare decays with leptons, $B_s \to \mu^+\mu^-$ …)

p_T thresholds (GeV/c):

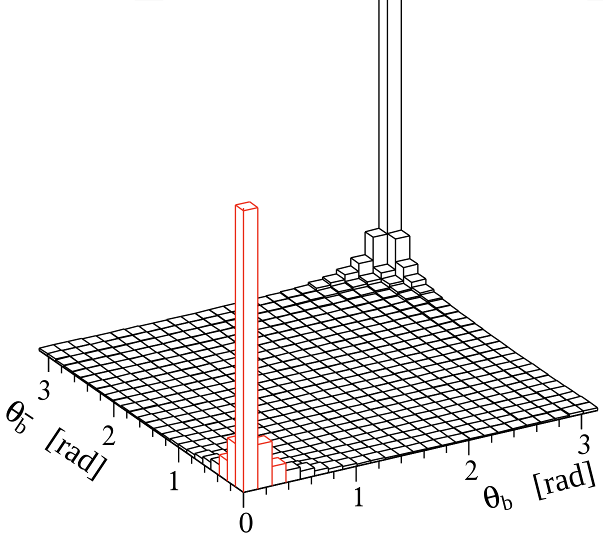
	1 μ	2 μ	1 e	2 e	μ+e
CMS	7	2–4	12	5	5+4
ATLAS	6	under study			

LHCb and BTeV





- **Forward** detectors ($1.9 < \eta < 4.9$)
  - —still very good acceptance for $b\bar{b}$ pairs
  - —large p_B, use of RICH detectors for PID
  - —vertex detectors inside beam vacuum
- Leptonic and **hadronic/vertex** triggers



LHCb and BTeV calorimeters

- Tasks:
  - Level-0 E_T trigger (e, γ, hadron)
  - Electron ID, π^0 reconstruction
- **Preshower**:
  - scintillator + $2X_0$ Pb + scintillator
- **ECAL**:
  - Pb + scintillator tiles (“shashlik”)

$$\frac{\sigma_E}{E} = \frac{0.10}{\sqrt{E\,/\,\mathrm{GeV}}} + 0.015$$

- **HCAL**:
  - Fe + scintillator tiles

$$\frac{\sigma_E}{E} = \frac{0.80}{\sqrt{E\,/\,\mathrm{GeV}}} + 0.10$$

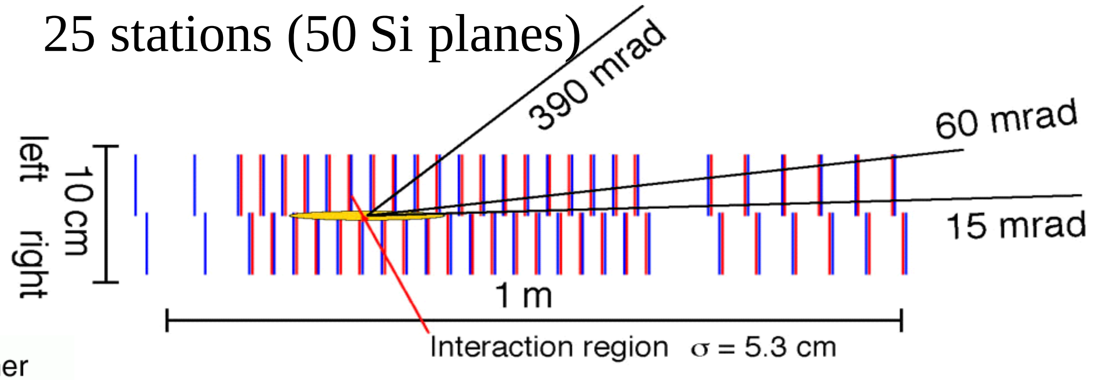
- Tasks:
  - Electron ID
  - π^0, η reconstruction
- **ECAL** only:
  - $PbWO_4$ crystals (developed by CMS) with PMT readout
  - 2×11850 crystals of ~2.6×~2.6 × 22 ($25\ X_0$) cm^3 with pointing geometry
  - very good resolution

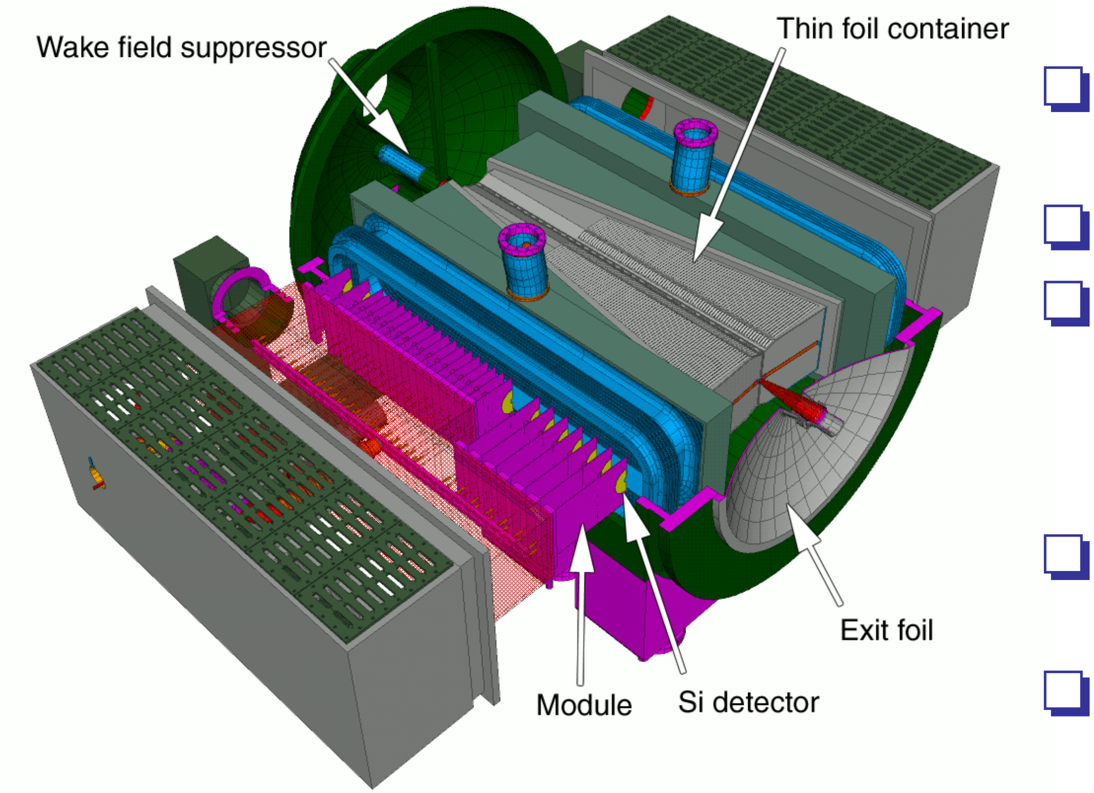
$$\frac{\sigma_E}{E} = \frac{0.016}{\sqrt{E\,/\,\mathrm{GeV}}} + 0.0055$$

LHCb vertex locator

- ❑ Online: pile-up veto
  + vertex trigger
- ❑ Offline: proper time resolution sufficient for B_s physics

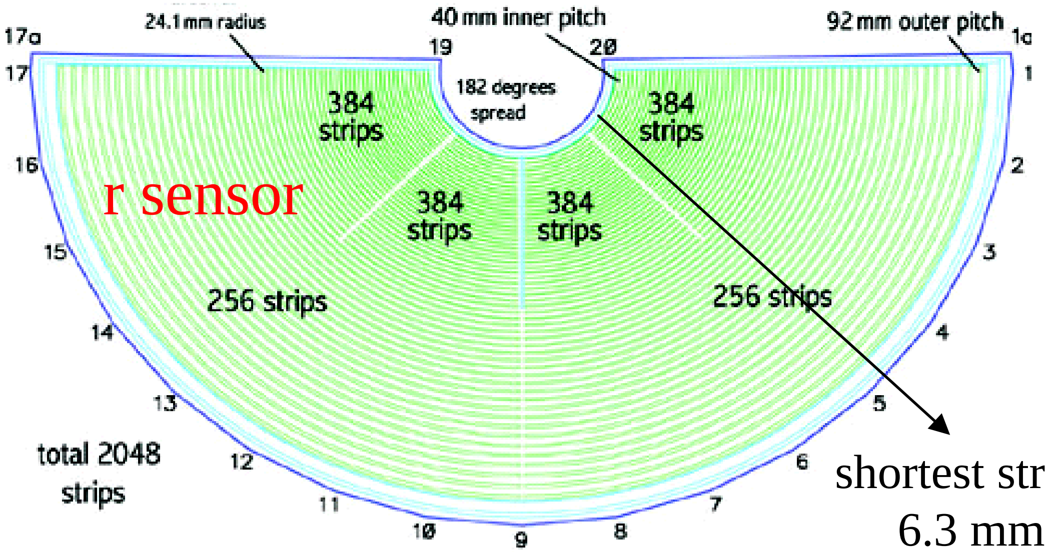
25 stations (50 Si planes)



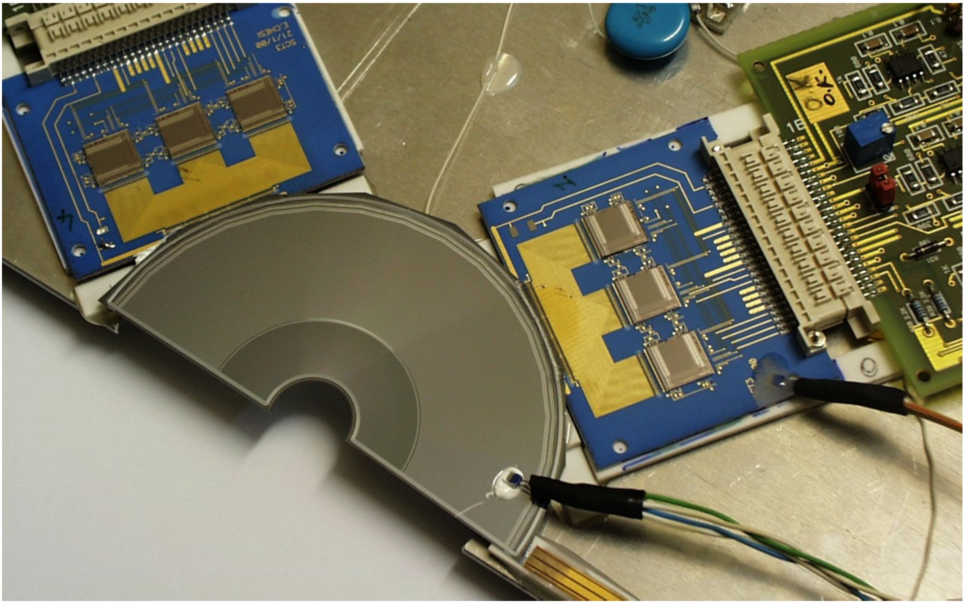


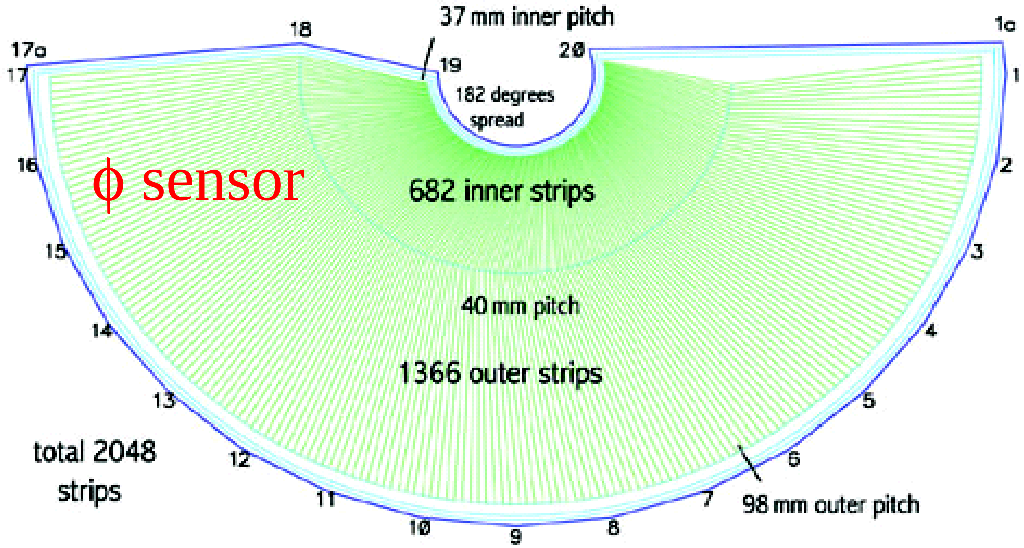
- ❑ Many stations for full coverage, but only ~200k channels
- ❑ Inside vacuum tank
- ❑ Sufficiently rad-hard to be very close to beams
  - — Active Si at 8 mm where ~10^{14} $n_{eq}/cm^2/y$ is expected
- ❑ Sensors on each side retractable during beam setup
- ❑ Each half in Al box (250 µm thick) acting as RF shield

LHCb vertex locator



shortest strip: 6.3 mm



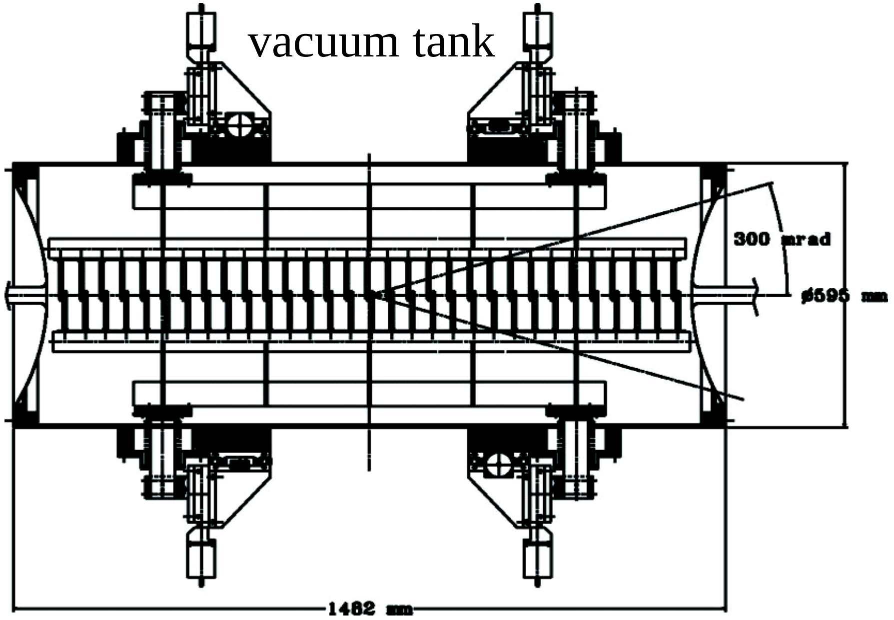


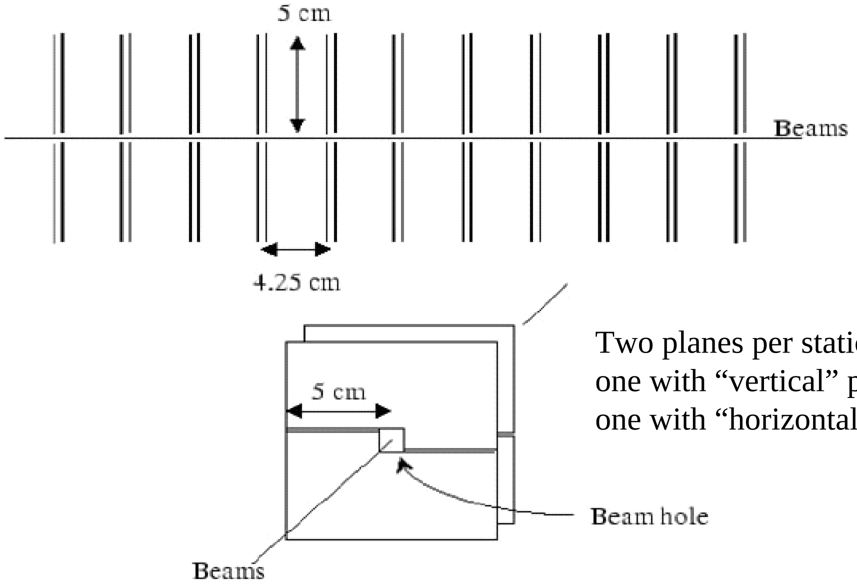
- *r*- and ϕ-measuring small Si strips ("striplets")
- varying pitch, occupancy < 1%
- 300 µm, n-on-n, double metal layer
- Analogue readout with STCA–VELO (DMIL) or BEETLE (0.25µm)

BTeV pixel detector

31 stations (62 Si planes)

Heart of BTeV trigger,
used at first level of triggering





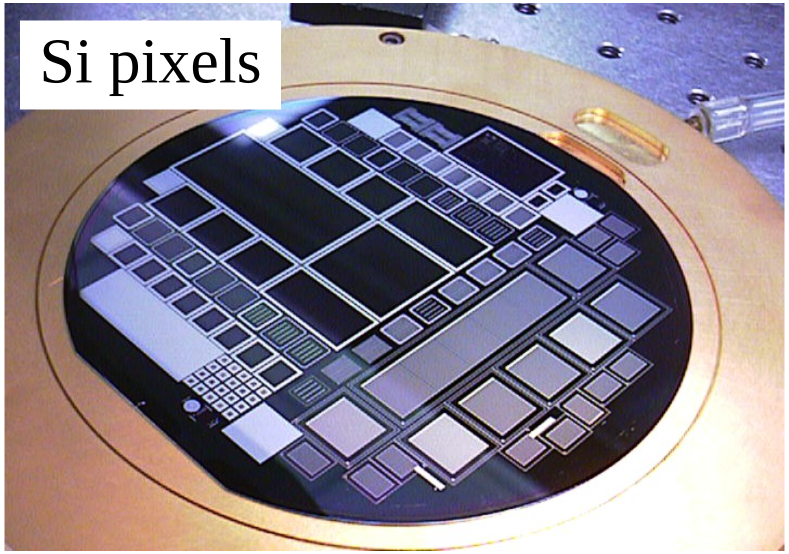
Two planes per station:
one with “vertical” pixels
one with “horizontal” pixels

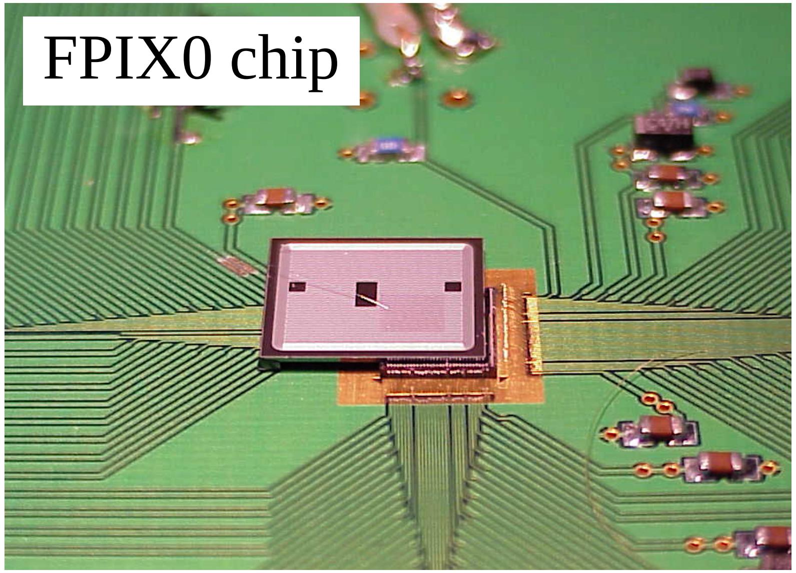
- ❑ Located in dipole field
- ❑ “3-dimensional” hits
- ❑ Radiation hard

But ...

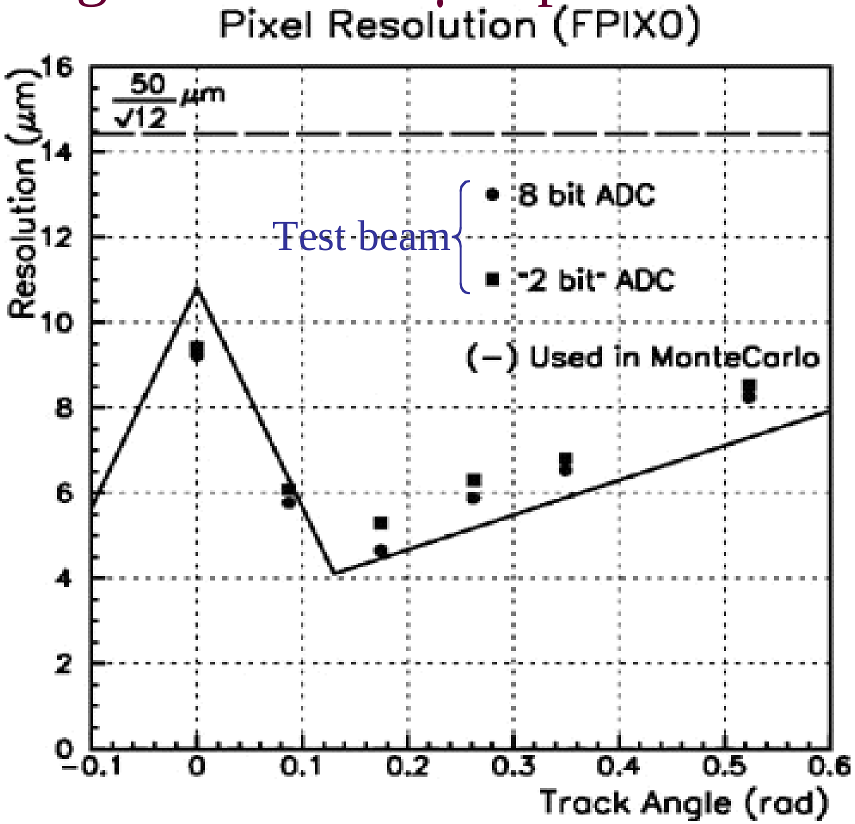
- ❑ 30M channels !
- ❑ Electronics inside acceptance
  → larger radiation length
  (~2% per station)

BTeV pixel detector





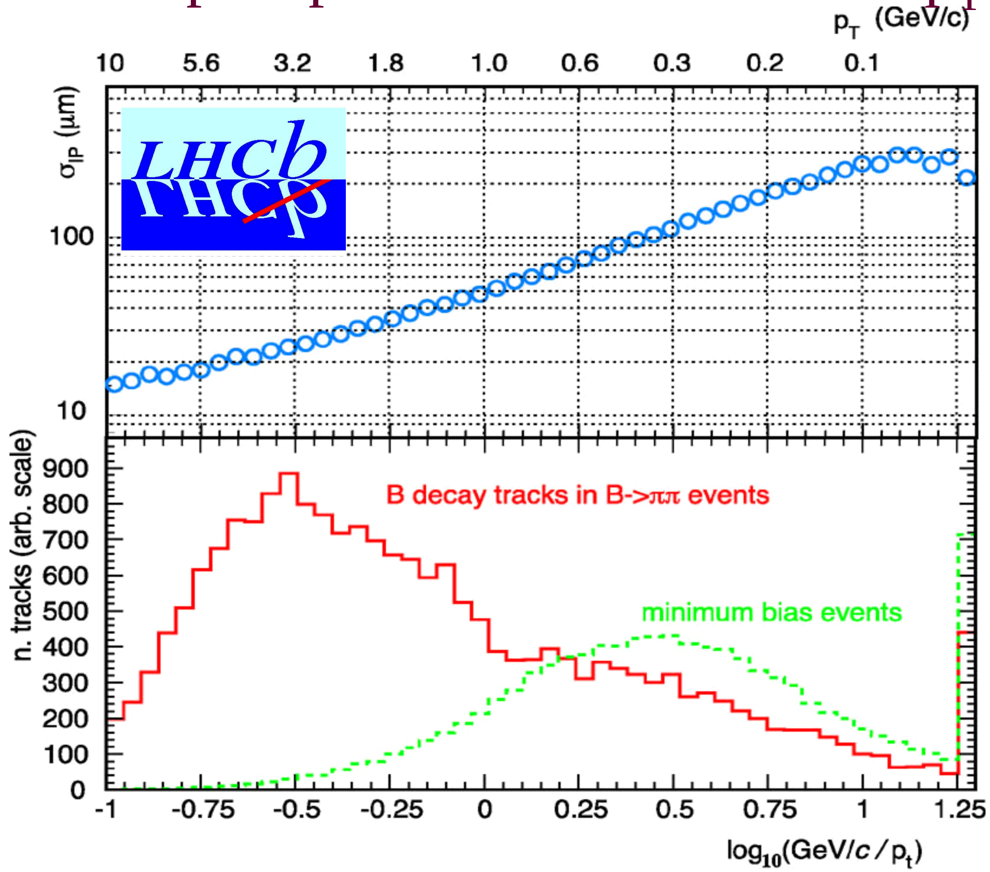
- 250 μm thick 1×5 cm^2 pixel detector
- 25k rectangular 50×400 μm pixels



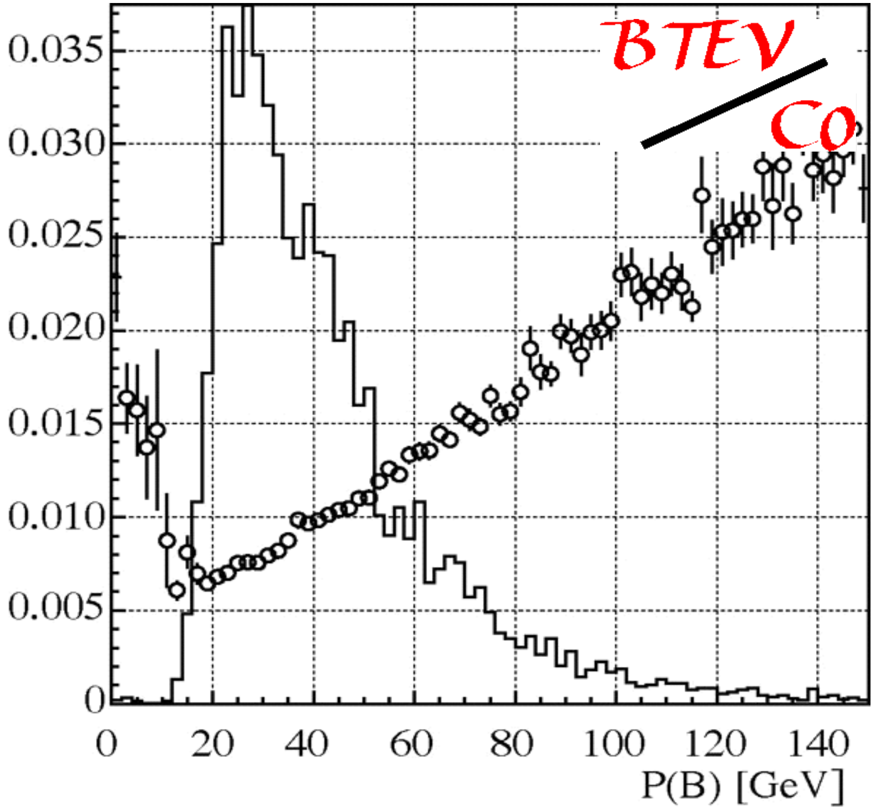
- 3 bit analogue readout
- 200 μm thick bump bonded chip (FPIX2)

Vertexing resolution

Impact parameter resolution vs p_T



Decay length resolution [cm]
for B $\rightarrow \pi^+\pi^-$ decays



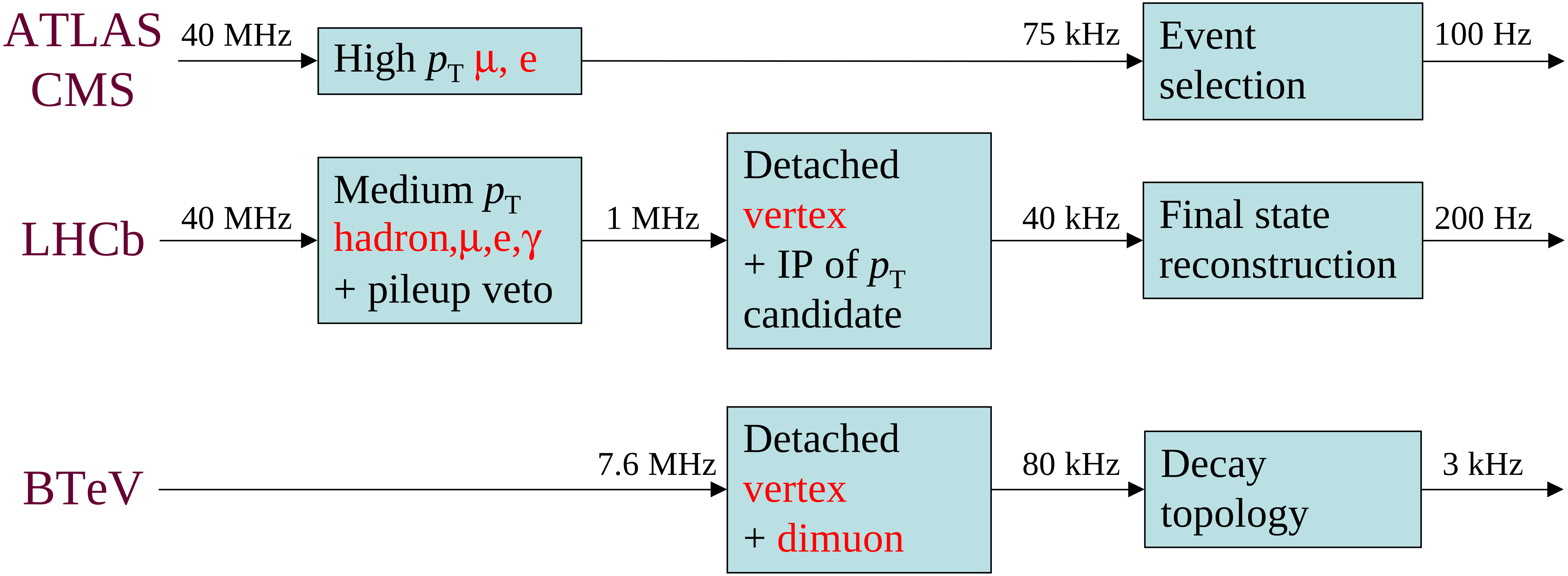
Excellent proper time resolution avoids significant damping of B_s oscillations
(5σ measurement of Δm_s up to 48 ps^{-1} using one year of **$B_s \rightarrow D_s^-\pi^+$** data with **$\sigma_t$=43 fs**)

Trigger schemes

p_T and E_T triggers
(muon + calorimeters)

vertex triggers
(Si vertex detector)

confirmation
and event filters



ATLAS CMS: 40 MHz → High p_T μ, e → 75 kHz → Event selection → 100 Hz

LHCb: 40 MHz → Medium p_T hadron,μ,e,γ + pileup veto → 1 MHz → Detached vertex + IP of p_T candidate → 40 kHz → Final state reconstruction → 200 Hz

BTeV: 7.6 MHz → Detached vertex + dimuon → 80 kHz → Decay topology → 3 kHz

Low-level triggers

LHCb

40 MHz ↓ (12.4 MHz of inel. interactions)

L0 Medium p_T hadron,μ,e,γ + pileup veto

calo+μ+pileup veto:
5×10^4 channels
hardware, synchronous
fixed latency =4 μs
reduction factor ~40
(only ~10 from p_T cut)

1 MHz ↓

L1 Detached vertex + IP of p_T candidate *

Si strips: 2×10^5 channels
processors, asynchronous
fixed latency =1.7 ms
reduction factor ~25

40 kHz ↓

BTeV

7.6 MHz ↓

L1 Detached vertex + dimuon

Si pixels: 3×10^7 channels
hardware+processors, asynchronous
variable latency ~150 μs
reduction factor ~100

80 kHz ↓

Efficiencies for signal events passing offline selection

	LHCb (TP) L0*L1	**LHCb** (now) L0*L1	**BTeV** L1
$\mathbf{B^0 \to J/\psi\, K_S}$	0.88*0.50	0.88*0.90=**0.79**	**0.50**
$\mathbf{B^0 \to \pi^+\pi^-}$	0.76*0.48	0.76*0.72=**0.55**	**0.63**
$\mathbf{B_s \to D_s^- K^+}$	0.54*0.56	0.54*0.70=**0.38**	**0.74**

* added since TP
(LHCb event yields not updated
yet for new L1 efficiencies)

Ring Imaging Cherenkov detectors

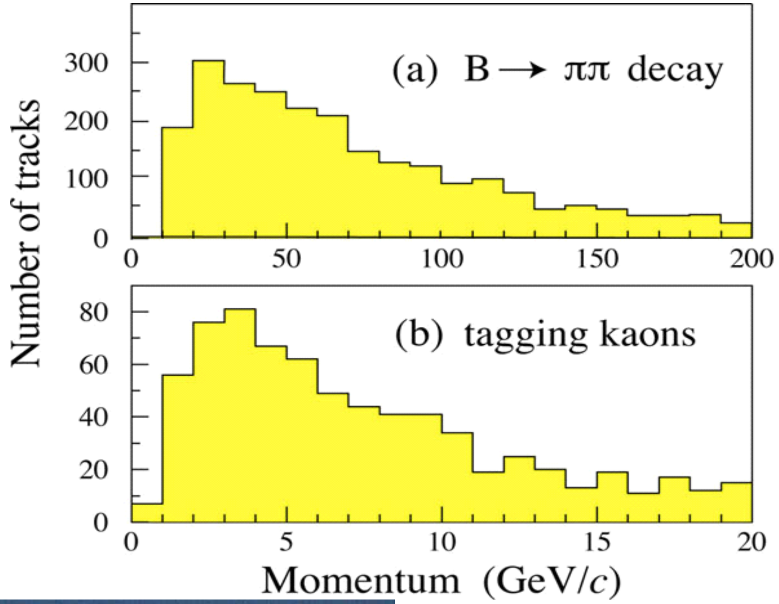
- BTeV:

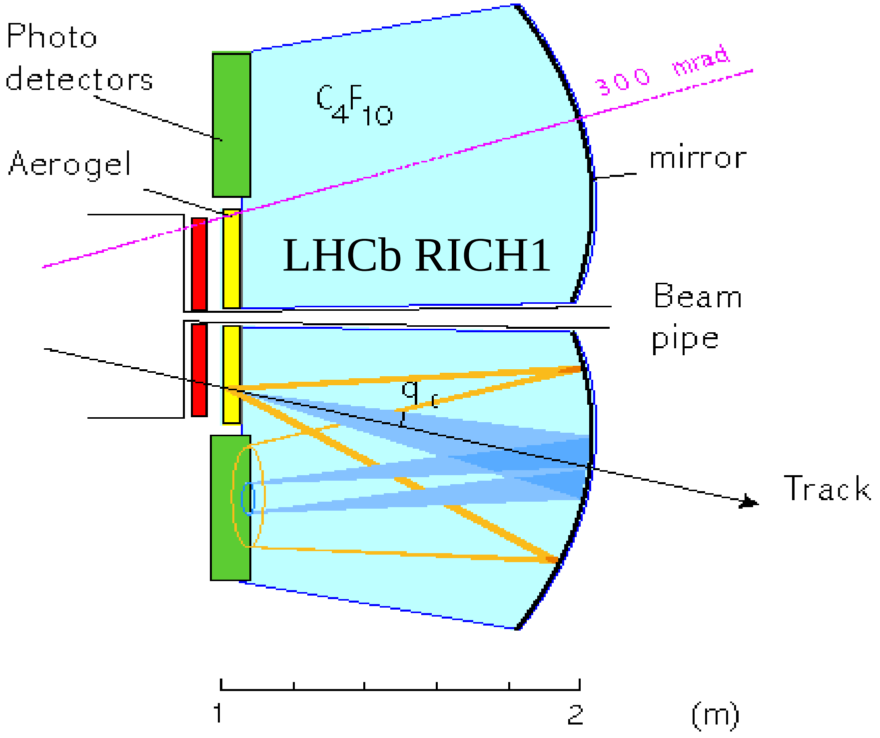
  2 radiators in 1 RICH
  to cover $3 < p < 70$ GeV/c

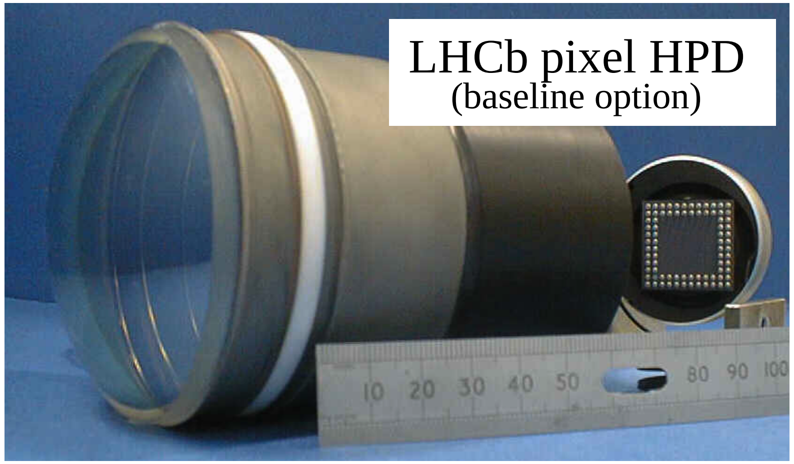
- LHCb:

  3 radiators in 2 RICHes
  to cover $1 < p < 100$ GeV/c

	refr. index n	threshold (GeV/c)	
		π	K
aerogel	1.03	0.6	2.0
C_4F_{10}	1.0014	2.6	9.3
CF_4	1.0005	4.4	15.6






LHCb pixel HPD
(baseline option)

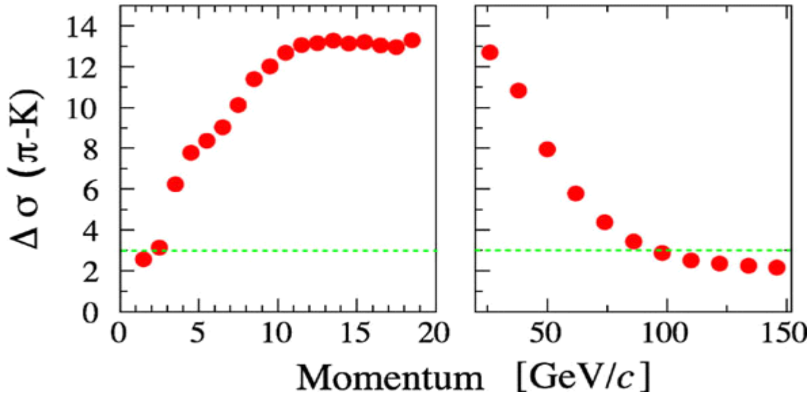
1024 Si pixels
(500µm x 500µm)

Prototype chip
available

87 mm diam. phototube with pixel detector
bump-bonded to encapsulated binary electronics

Particle identification

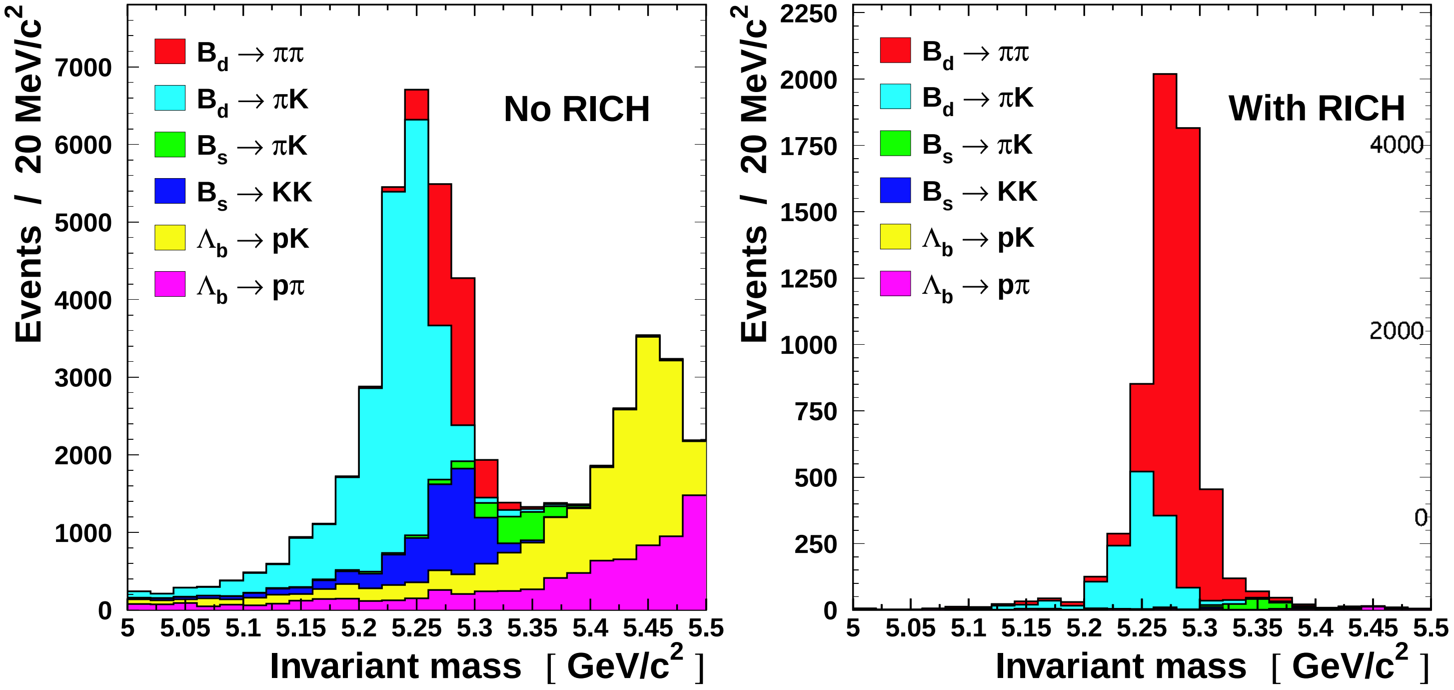
LHCb K–π separation for true π



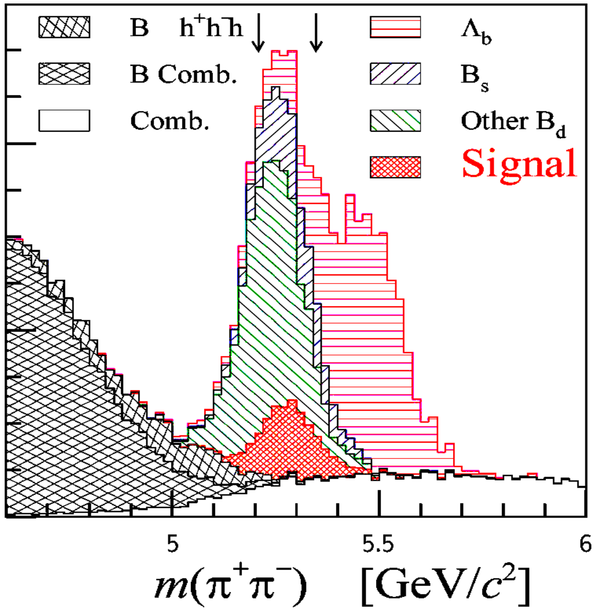
- Very important for many exclusive channels

Example: $B^0 \rightarrow \pi^+\pi^-$

LHCb



ATLAS



Flavour tagging at production

- Needed for many CP violation measurements
- Methods used/studied so far:

	ATLAS CMS	**LHCb**	**BTeV**
Other b tagging			
Lepton from b→l	yes*	yes*	yes
Kaon from b→c→s	–	yes*+	yes+
Vertex or jet charge	yes	Still to be studied	yes
Same b tagging			
B** or B–π correlation	yes		yes
B_s–K correlation	–		yes+
Jet charge	yes		

* can fire p_T trigger

+ possible thanks to good PID

- LHCb and BTeV expected to reach similar tagging power:
  - —LHCb TP: εD^2=6.4% based on study of lepton and kaon tags alone
  - —BTeV TP: εD^2=10% assumed

β from $B^0 \to J/\psi\, K_S$

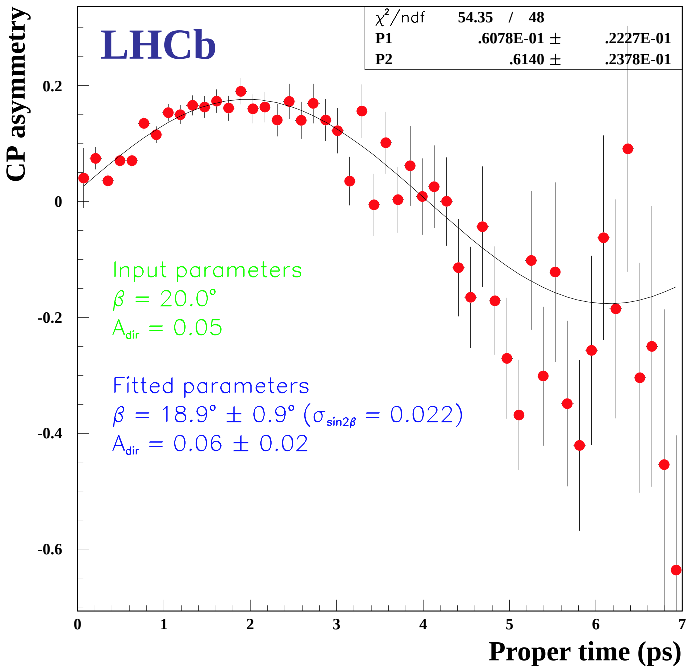
- ❑ Huge statistics (especially ATLAS & CMS)
- ❑ Can also fit for A_{dir} (expected ≈ 0 in SM)

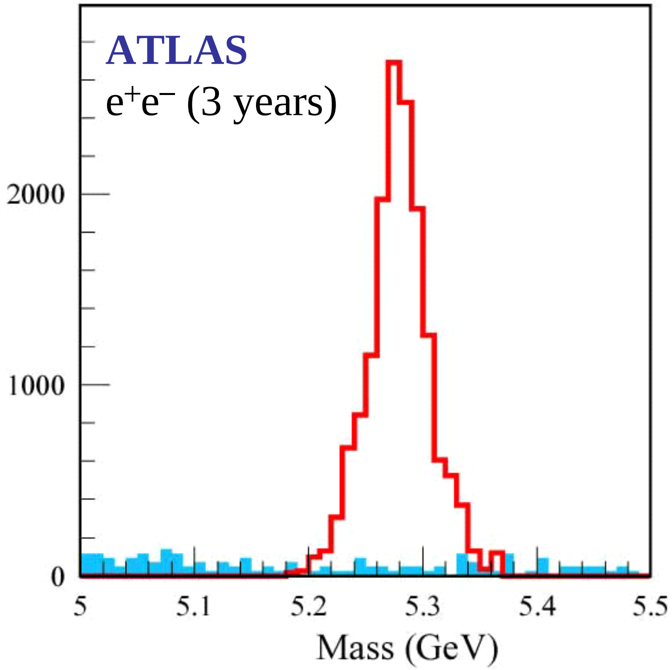
$$A_{\mathrm{CP}}(t) = A_{\mathrm{dir}} \cos(\Delta m_d\, t) - \sin(2\beta)\sin(\Delta m_d\, t)$$

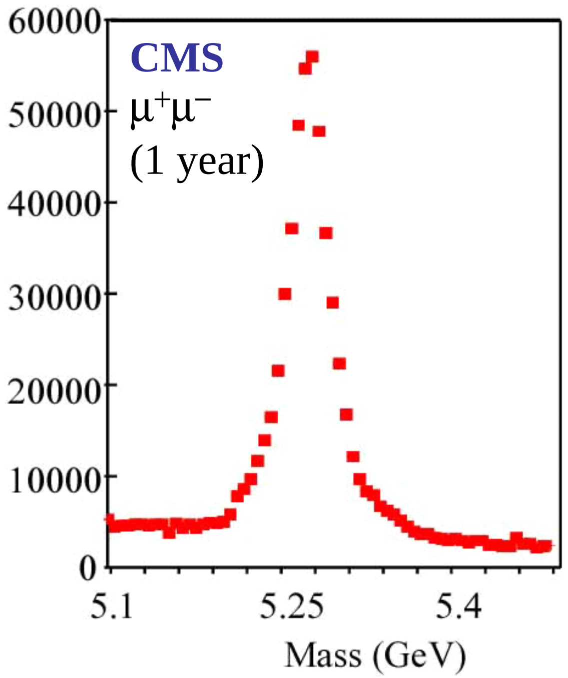
- ❑ LHCb & BTeV:
  compare with Penguin decay $B^0 \to \phi\, K_S$

Reach in 10^7 s

	σ(sin(2β))
ATLAS	0.017
CMS	0.015
LHCb	<0.021
BTeV	0.025





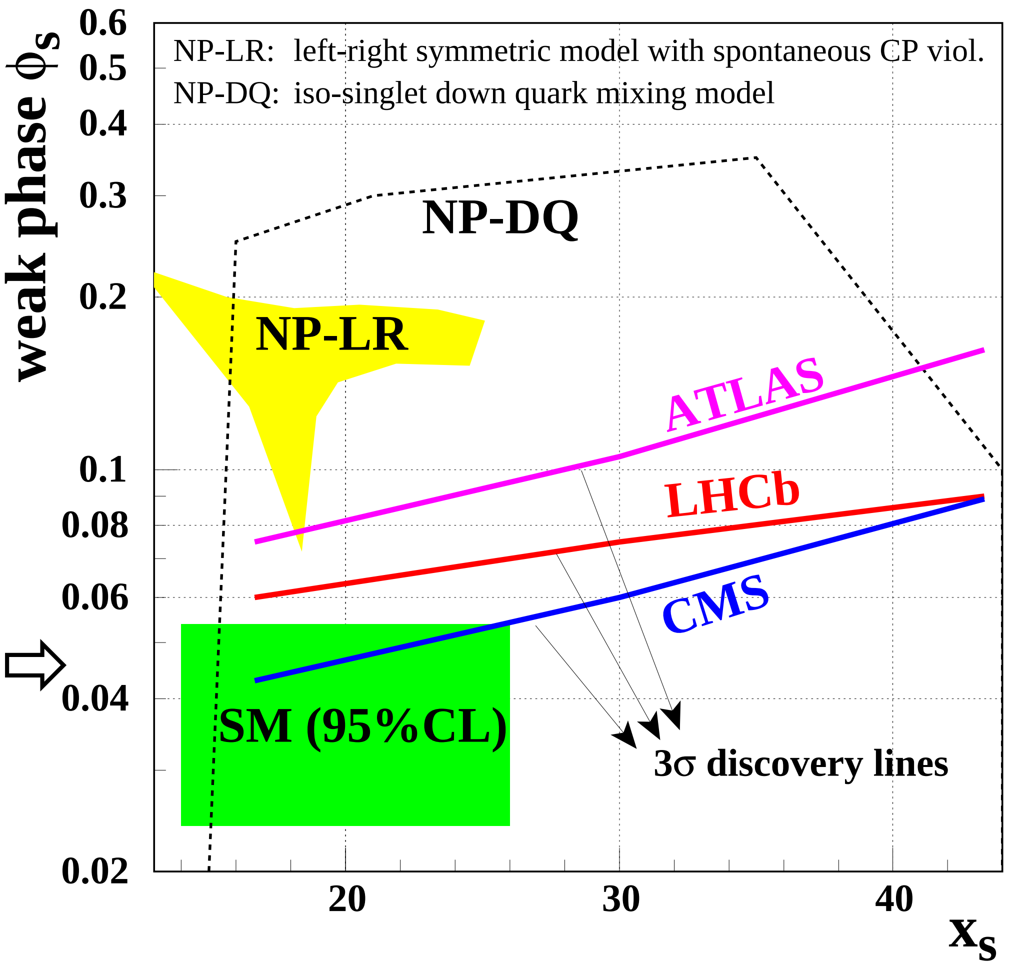


B_s mixing phase from $B_s \to J/\psi\ \phi$, $J/\psi\ \eta$

- Strange counterpart of $B^0 \to J/\psi\ K_S$
- SM prediction of B_s mixing phase is small $\phi_s = 2\delta\gamma = 2\lambda^2\eta = O(10^{-2})$
- Sensitive probe for new physics

- $J/\psi\ \phi$ is not pure CP final state
  - — can reach $\sigma(\phi_s) \approx 0.02$ in 1 year, under assumptions on the strong phases
  - — need angular analysis for clean extraction

	Signal (untagged)	Backgr.	σ_t
LHCb (5 years)	>370k evts	3%	31 fs
ATLAS (3 years)	300k evts	15%	63 fs
CMS (3 years)	600k evts	10%	63 fs



- $J/\psi\ \eta^{(\prime)}$ is pure CP=–1
  - — need photon detection
  - — BTeV: $\sigma(\phi_s) = 0.033$ in 1 year

$B^0 \to \pi^+\pi^-$ asymmetry, etc ...

$$A_{\mathrm{CP}}(t) = A_{\mathrm{dir}} \cos(\Delta m_d\, t) + A_{\mathrm{mix}} \sin(\Delta m_d\, t)$$

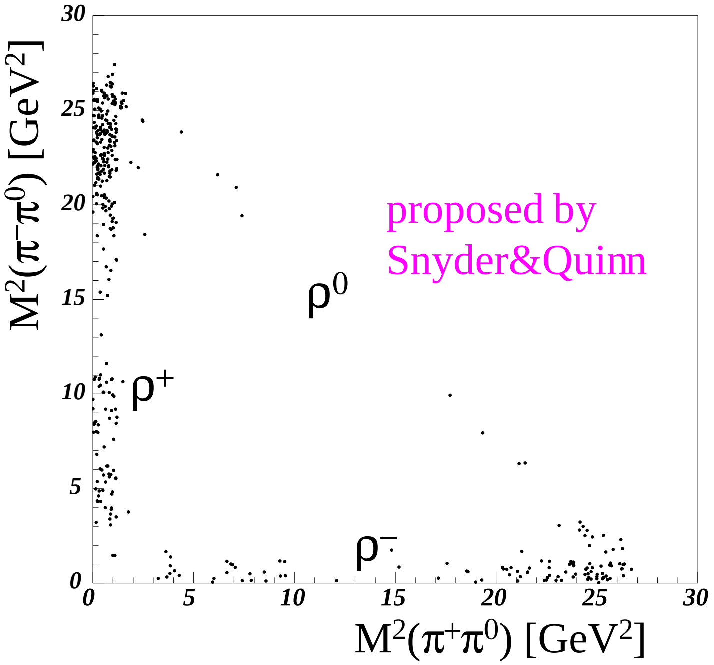
- A_{dir} and A_{mix} can be measured
  - e.g. ±0.08 with 1 year at LHCb

but Penguin “pollution” hampers α extraction

$B^0 \to \pi^+ \pi^-$ annual yield

	Tagged	Untagged	S/B
ATLAS	2.3k		0.17
CMS	0.9k		1.2
LHCb	4.9k	>12.3k	>1
BTeV		23.8k	3

- Study of $B^0 \to (\rho^+\pi^-, \rho^-\pi^+, \rho^0\pi^0) \to \pi^+ \pi^- \pi^0$ (time-dependent analysis of Dalitz plot) to extract α, Penguin and tree terms
  - BTeV/LHCb claim 10.8/>3.3k untagged per year
  - more study needed to quote σ(α) (5–10° ?)



proposed by Snyder&Quinn

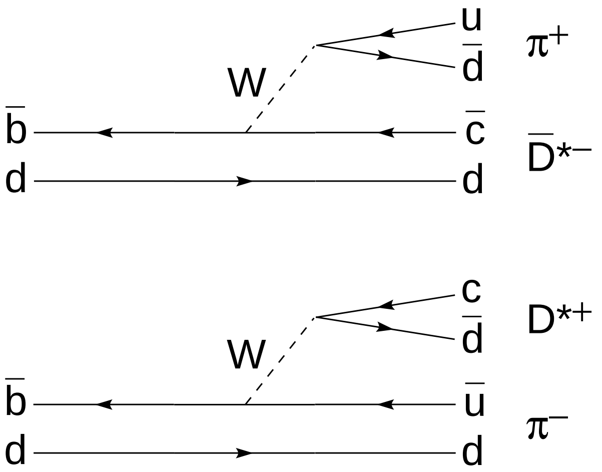
- Measure A_{dir} and A_{mix} for $B_s \to K^+K^-$
  - e.g. ±0.11 with 1 year at LHCb (if Δm_s=20 ps^{-1})

and combine with $B^0 \to \pi^+\pi^-$ results to extract γ assuming U-spin symmetry
  - LHC claim σ(γ) ~ 5° after 1 year

proposed by Fleischer

γ from $B^0 \to D^{*-}\pi^+$, $D^{*+}\pi^-$

- Small interference between two tree decays, with and without prior B^0 mixing
- Extract γ+2β and Δ^{strong} simultaneously from the two time-dependent asymmetries
- Use 2β from $J/\psi\, K_S$ to obtain value of γ insensitive to possible new physics in mixing



$V^*_{cb}V_{ud} \propto \lambda^2$

↖

+ strong phase difference Δ

↙

$V^*_{ub}V_{cd} \propto \lambda^4 e^{i\gamma}$

assumed amplitude ratio $|\eta| = 0.02$

Need

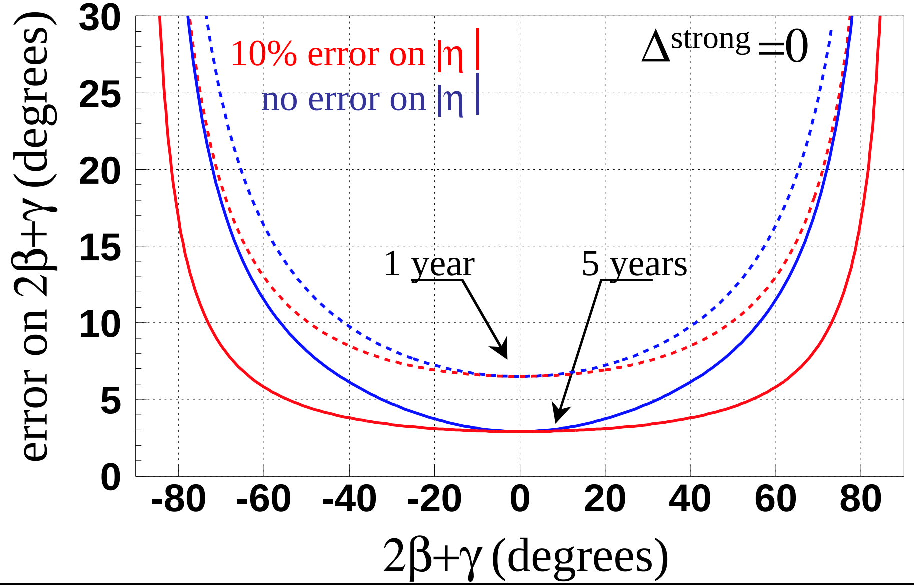
✓ high stats

- LHCb study:
  - — use both exclusive and inclusive reconstruction of neutral D from D*

	Annual yield (untagged)	S/B	$\sigma(m_B)$ MeV	$\sigma(t_B)$ ps
B→ D*(D(Kπ) π) π	183 k	5.6	13.6	60
B→ D*(D(incl)π) π	1150 k	4.4	220	170

$\boxed{\sigma(\gamma) = O(10°)}$ (1 year)

depends on 2β+γ and Δ^{strong}



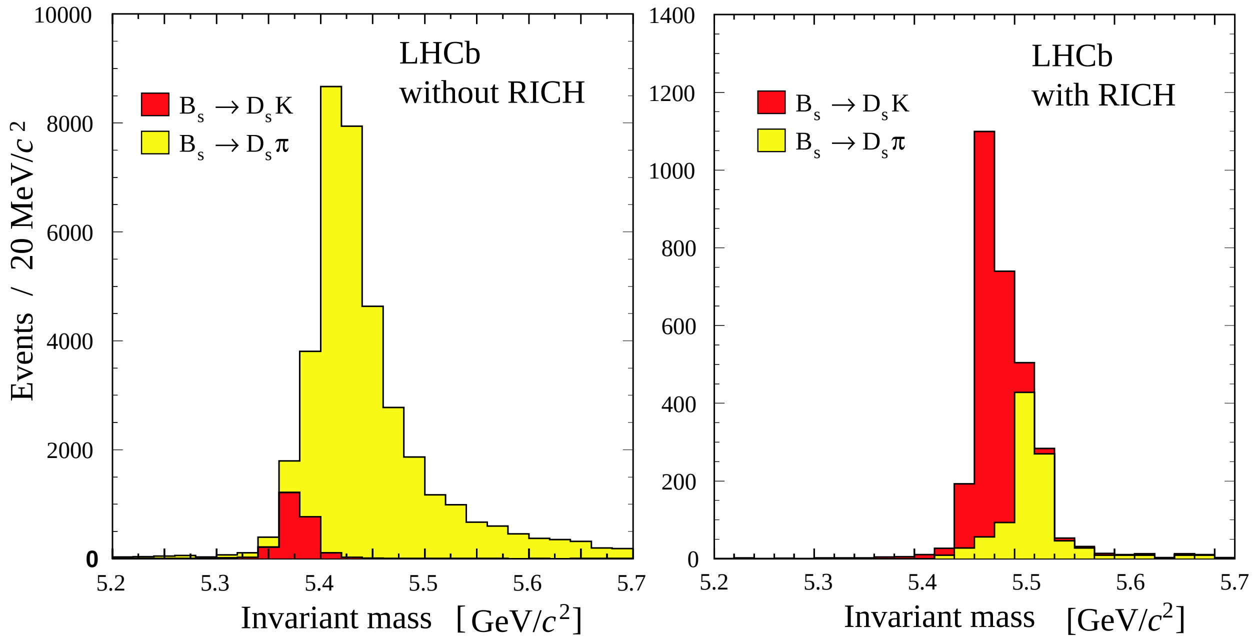
γ from $B_s \to D_s^-K^+, D_s^+K^-$

- Strange counterpart of $B^0 \to D^{*-}\pi^+, D^{*+}\pi^-$
- Here measure $\gamma - 2\delta\gamma$, and take $2\delta\gamma$ from $J/\psi\ \phi$
- Important differences:
  - — Asymmetry larger because two tree amplitudes of similar order ($\propto\lambda^3$)
  - — Proper time resolution more important
  - — Background from Cabibbo-allowed $D_s^-\pi^+$

Need very good
- ✓ hadronic trigger efficiency
- ✓ K/π separation
- ✓ proper time resolution

	Annual yield * (untagged)	S/B	$\sigma(m_B)$ MeV	$\sigma(t_B)$ ps
LHCb	6.4 k	12	11	43
BTeV	9.7 k	7	17	43

* using common BR assumptions (as in LHCb TP)



Sensitivity on γ depends on:
- amplitude ratio
- strong phase difference
- γ
- Δm_s

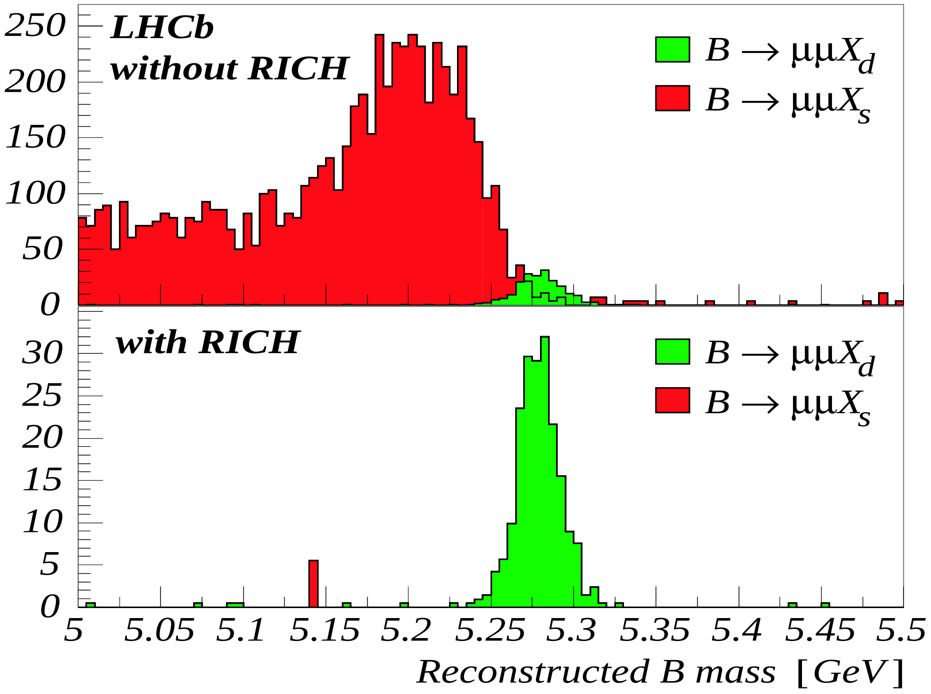
For Δm_s = 20 ps^{-1}:

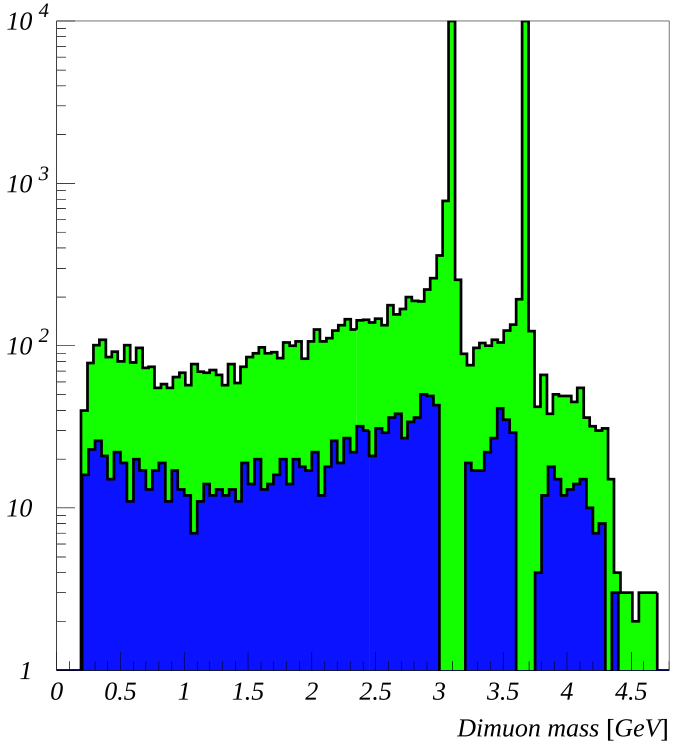
$\sigma(\gamma) = O(10°)$

(1 year, each expt)

$|V_{td}|/|V_{ts}|$ from $B \to \mu^+\mu^- X_{s,d}$

- ❑ $B \to \mu^+\mu^- X_{s,d}$ involve loop & box with V_{td}, V_{ts}
- ❑ Ratio of inclusive rates with “non-resonant” dimuon mass allows extraction of $|V_{td}|/|V_{ts}|$ with small theoretical error of *O*(1%)





New preliminary
LHCb study

	Annual yield	S/B
$B^0, B^\pm \to \mu^+\mu^- X_s$	16 k	15
$B^0, B^\pm \to \mu^+\mu^- X_d$	0.6 k	1

⇒ Relative error on $|V_{td}|/|V_{ts}|$ of ~11%

- ❑ After several years, this method may become competitive with $\Delta m_d/\Delta m_s$

Summary

- B physics at hadron colliders, currently performed at **Tevatron**, will get a big boost once **LHC** turns on (2006)
  - ✓ huge statistics: 10^{12} bb / year at 2×10^{32} cm^{-2}s^{-1} including B$_s$ mesons
- Dedicated detectors (**LHCb**, **BTeV**) aim for best
  - …trigger efficiency (hadron and vertex triggers)
  - …proper time resolution
  - …particle identification
- Clean extraction of angle γ after one year
  - 👍 several independent measurements with *O*(10°) precision
- Confront with other measurements involving loops/boxes
  - ☺ if new physics shows up, measure its parameters