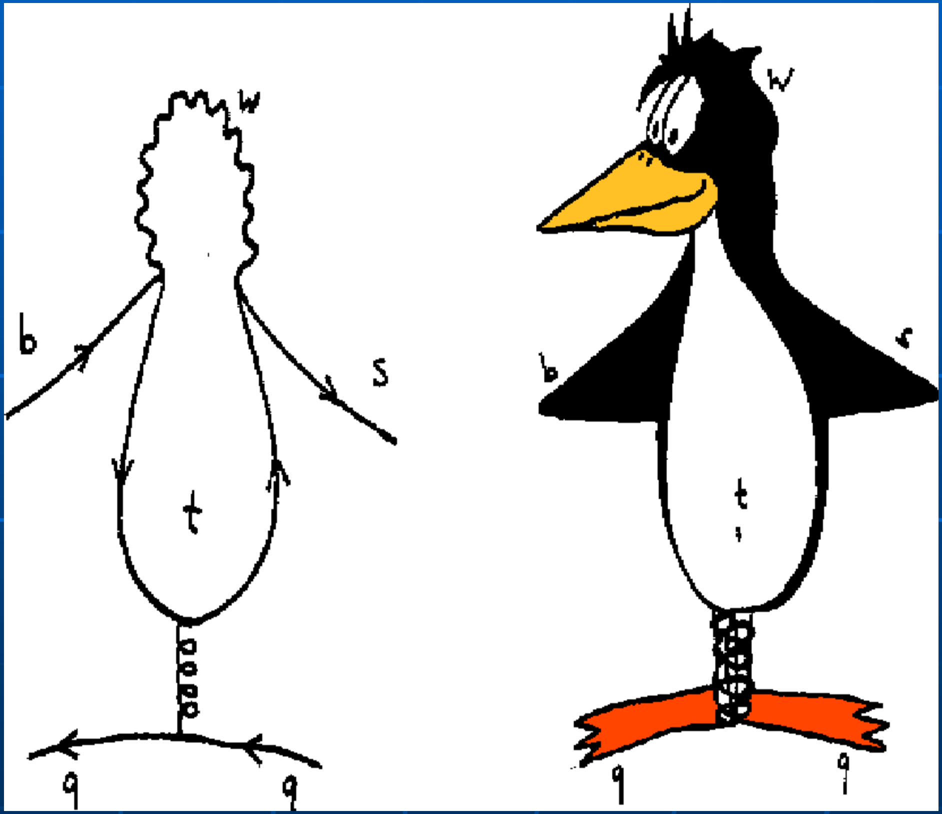
Radiative B meson Decays at BaBar

Colin Jessop

University of Notre Dame

Motivations

- Window to new Physics
- Help measure the unitarity triangle
- Test QCD technology

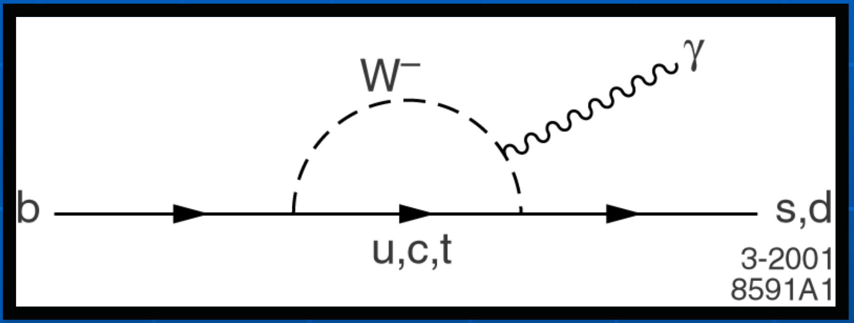


Radiative Penguin Decays

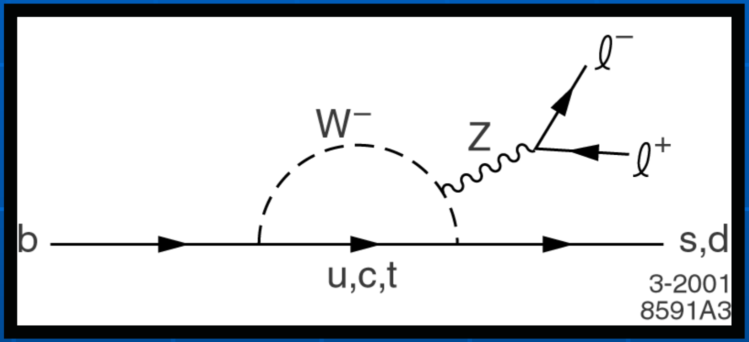
The Penguin Zoo

Several different types of penguins (not including gluonic penguins)

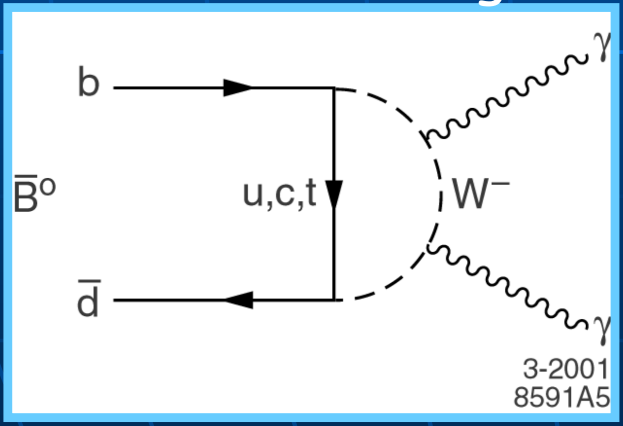
Electro-Magnetic



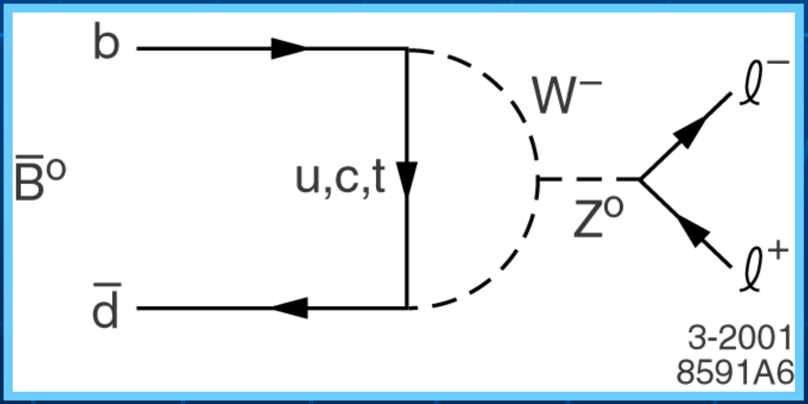
Electroweak



Vertical Electromagnetic



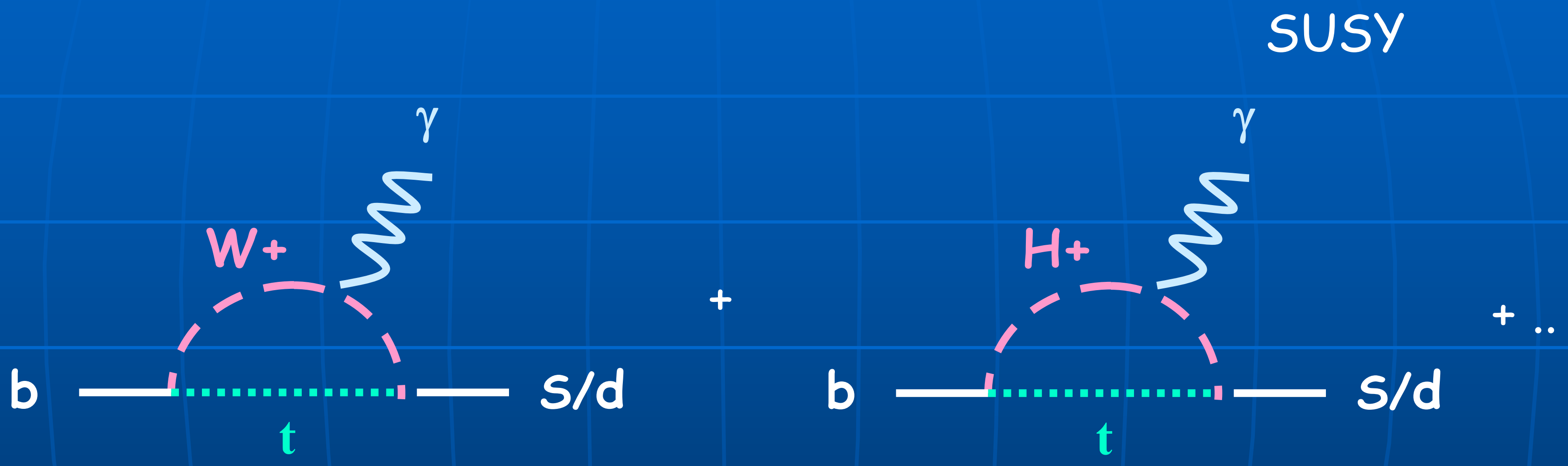
Vertical electroweak



I will focus today mostly on electromagnetic penguins. BaBar has results on all these processes

Sensitivity to New Physics

Example: If SUSY exact $B(b\to s\gamma) = 0$



New Physics enters at same order (1-loop) as Standard Model

Sensitive to many models – very extensive literature

Penguin Theory – A brief Overview

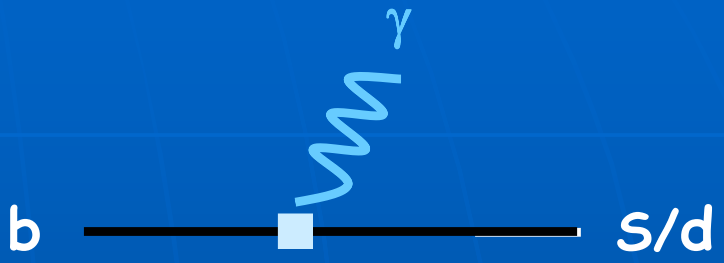
B mesons are low energy decays at scale $\mu = m_b \sim 5$ GeV

Formulate a low energy effective theory :

Generalization of Fermi Theory of β-decay.

Operator Product Expansion

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts} \sum_{i=1}^{10} C_i(\mu) Q_i(\mu)$$



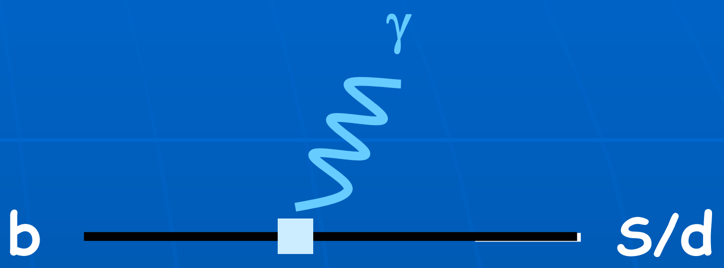
C_i : Wilson Coefficients – contains short distance (high energy) perturbative component

Q_i : Local Operators – contains long distance (low energy) non-perturbative component

μ(renormalization) scale dependence cancels in *C* and *Q*

Wilson Coefficients

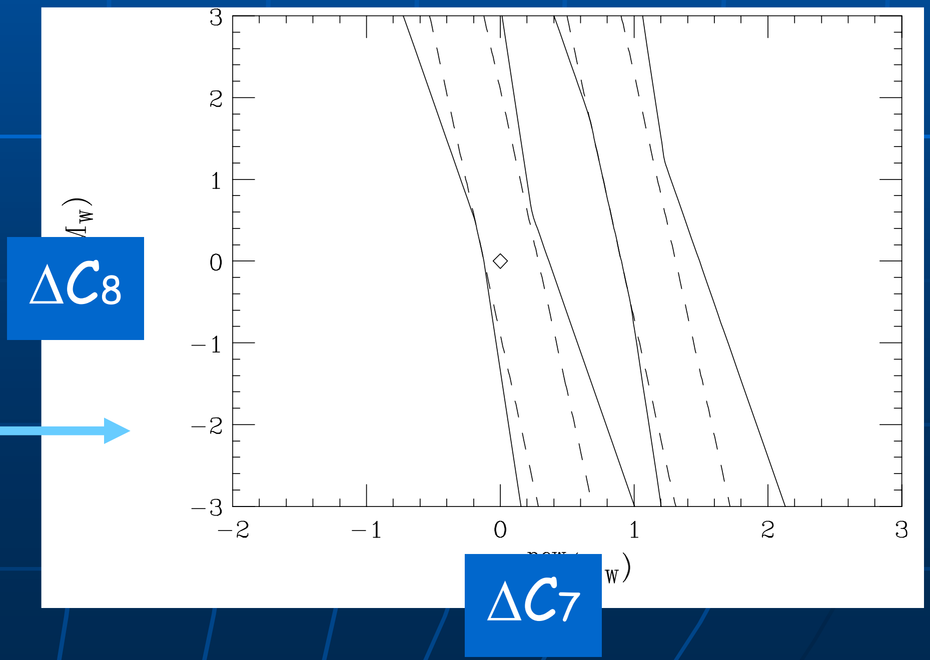
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts} \sum_{i=1}^{10} C_i(\mu) Q_i(\mu)$$



C_i i=1,2 current-current, i=3-6 gluonic penguins i=7-10 Electroweak Penguins
C_i calculated at $\mu=M_W$ and evolved down to $\mu=m_b$.

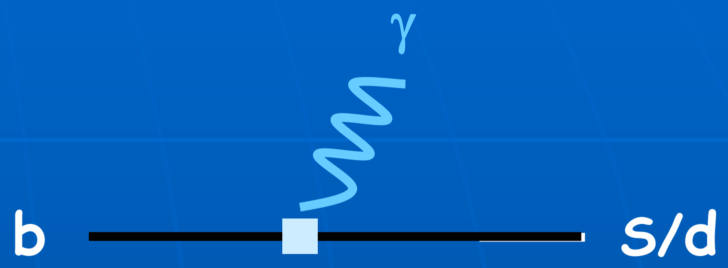
Effects of new high mass physics appear in C

e.g constraints on C_7 and C_8 from B(B->$X_s\gamma$)



Matrix Elements

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts} \sum_{i=1}^{10} C_i(\mu) Q_i(\mu)$$



<X|Q|B> are long distance (low-energy) non-perturbative component

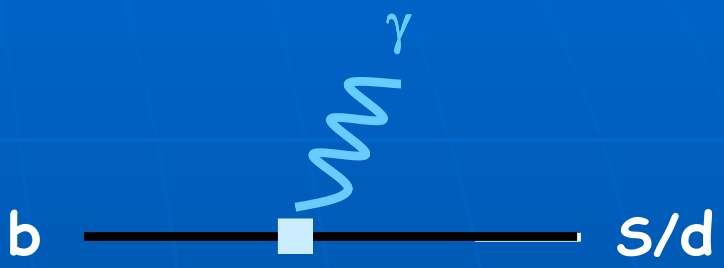
If X is exclusive state e.g | K*$\gamma >$ two possibilities

1. Lattice QCD : Lattice spacing >> compton wavelength of b -> Large errors
2. QCD sum rules: Relates resonances to vacuum structure of QCD

Neither approach gives precise estimates – limits exclusive physics.
Uncertainties cancel in ratios of modes or asymmetries.

Inclusive Matrix Elements

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts} \sum_{i=1}^{10} C_i(\mu) Q_i(\mu)$$



If X is an inclusive state

$$\langle X | Q | B \rangle = 1 + \mathrm{O}(\cancelto{0}{\frac{1}{m_b}}) + \mathrm{O}(\frac{1}{m_b^2}) + \ldots$$

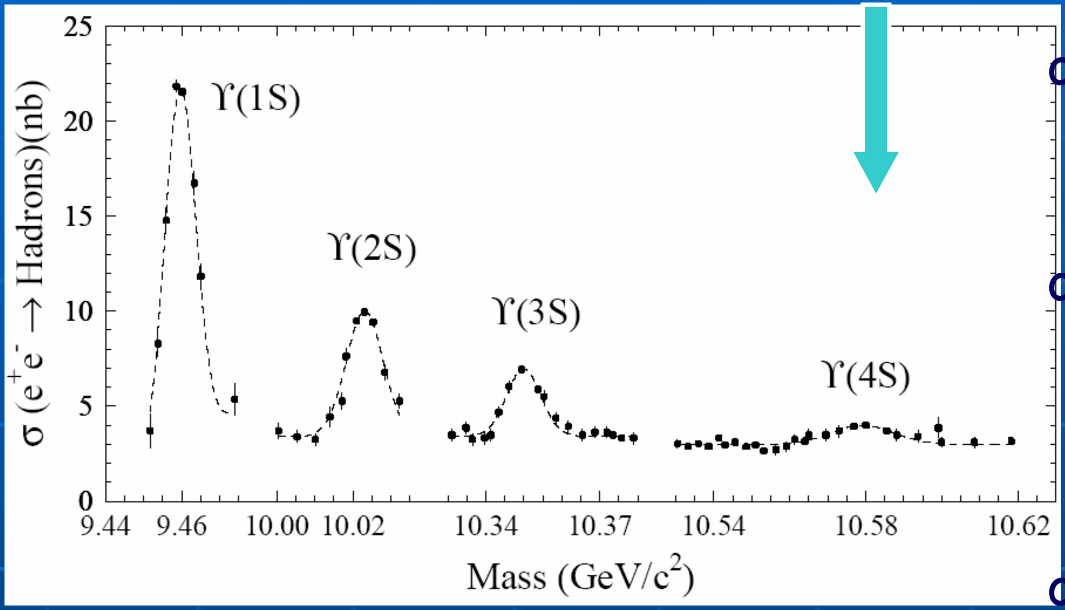
Leading term is short distance quark contribution and non-perturbative effects appears at $1/m_b^2$ –i.e (O(1%)) corrections

Inclusive measurements are much more sensitive to new physics

General Considerations

	Exclusive		Inclusive
Mode (#Events in~400fb-1)	B->K*γ O(500)	B->$\rho/\omega\gamma$ O(50)	B->Xsγ O(5000)
Backgrounds	Small	Large	Large
Theory Uncertainty	Large 30-50%	Medium (in ratios) 15%	Small 7%

B factories: e+e- → Y(4S) → BB

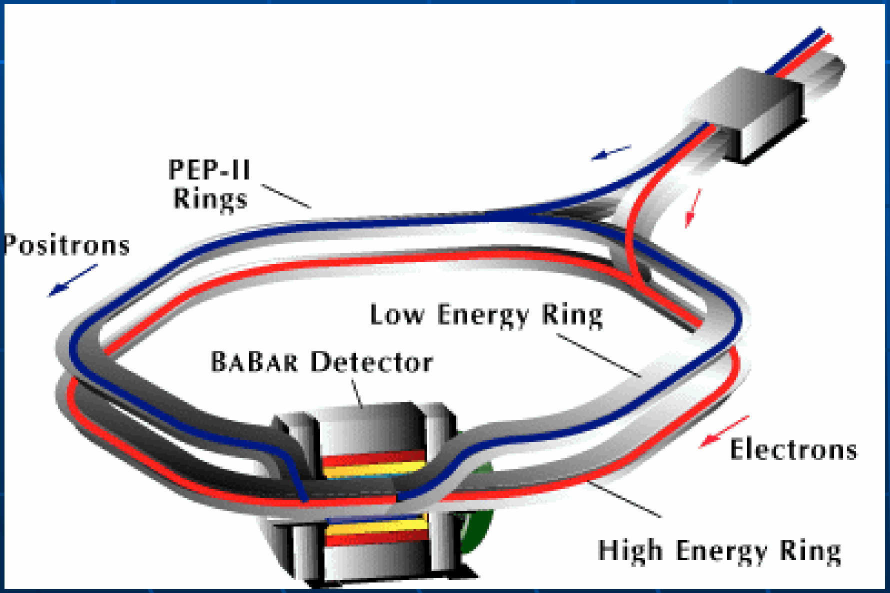


- B factories operate at the Y(4S) resonance (10.58 GeV)
- hadronic cross-sections: udsc:bb = 3.4:1.1 nb
- in the Y(4S) frame the B mesons are practically at rest

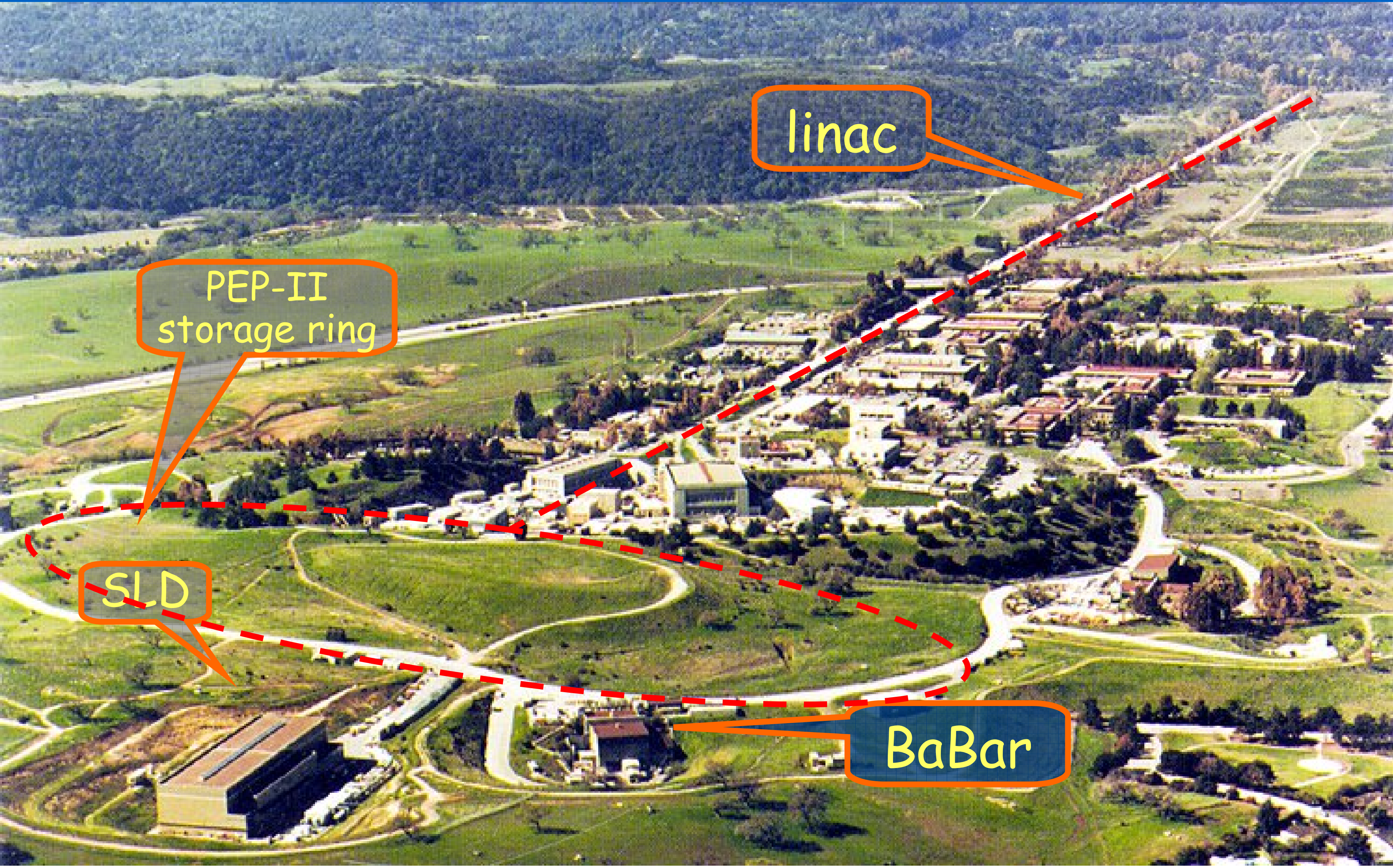
→ PEP-II is an asymmetric collider

9.0 GeV electrons vs

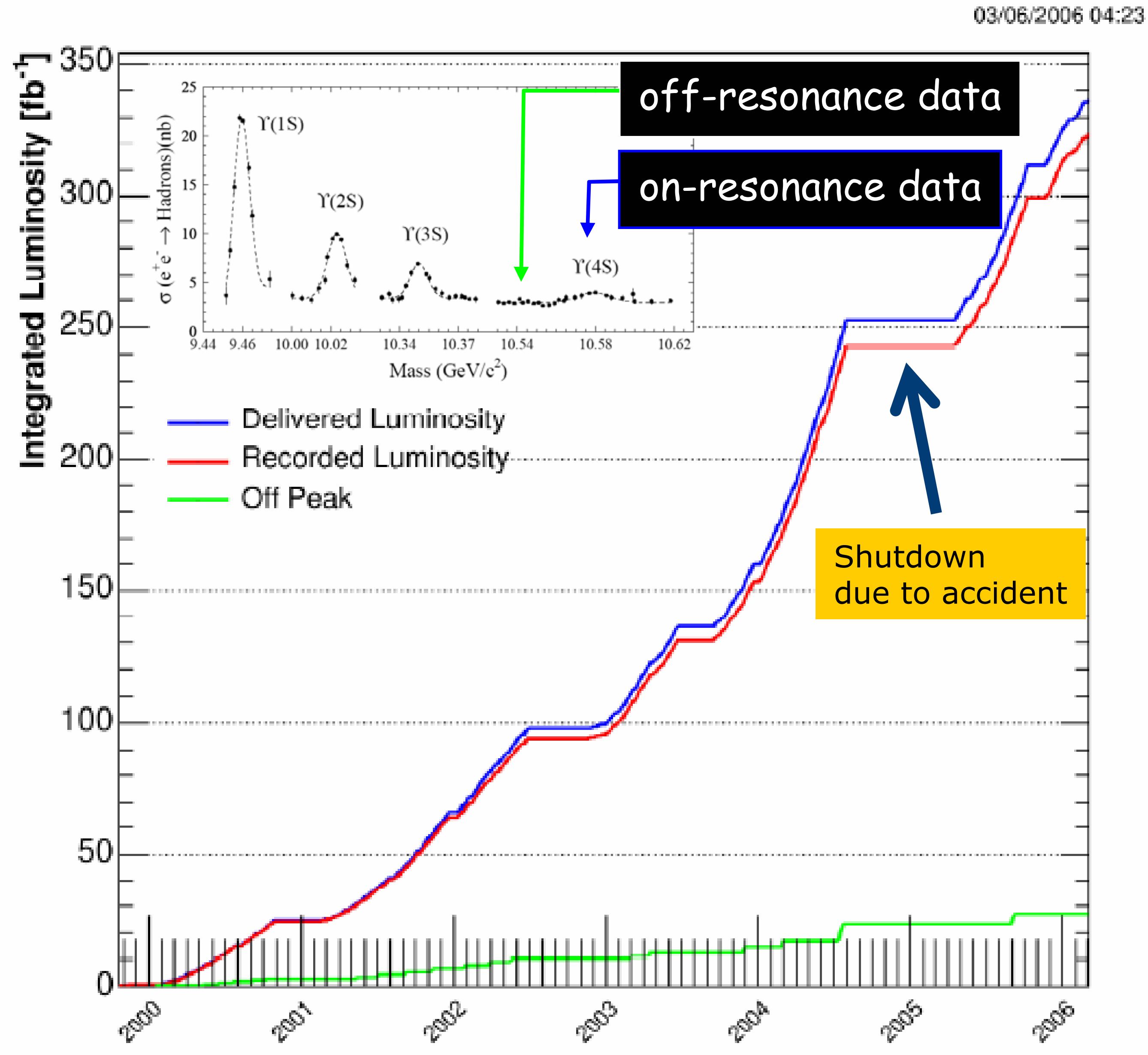
3.1 GeV positrons



PEP-II and BaBar at SLAC



Integrated luminosity



off-resonance data

on-resonance data

Shutdown
due to accident

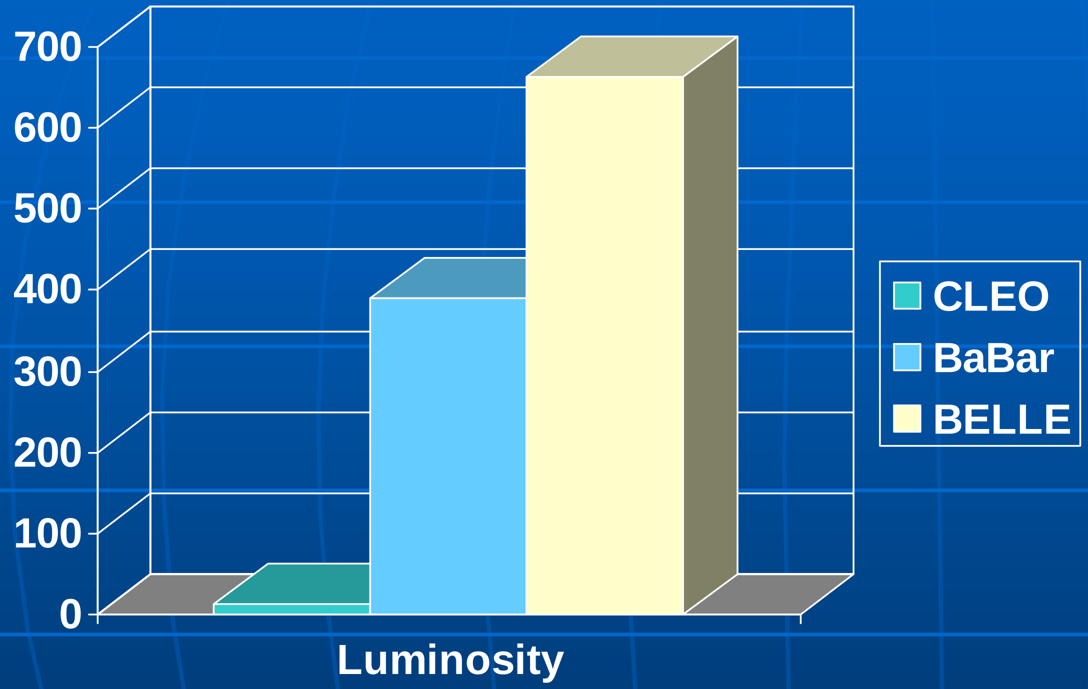
Currently 10 BB event per second.

since 2000 BaBar has recorded 430M BB events

about 8% of data is taken below the Y(4S) resonance

results presented here are based on
$90\ fb^{-1}$ - $340\ fb^{-1}$
on-resonance data

Other B meson experiments



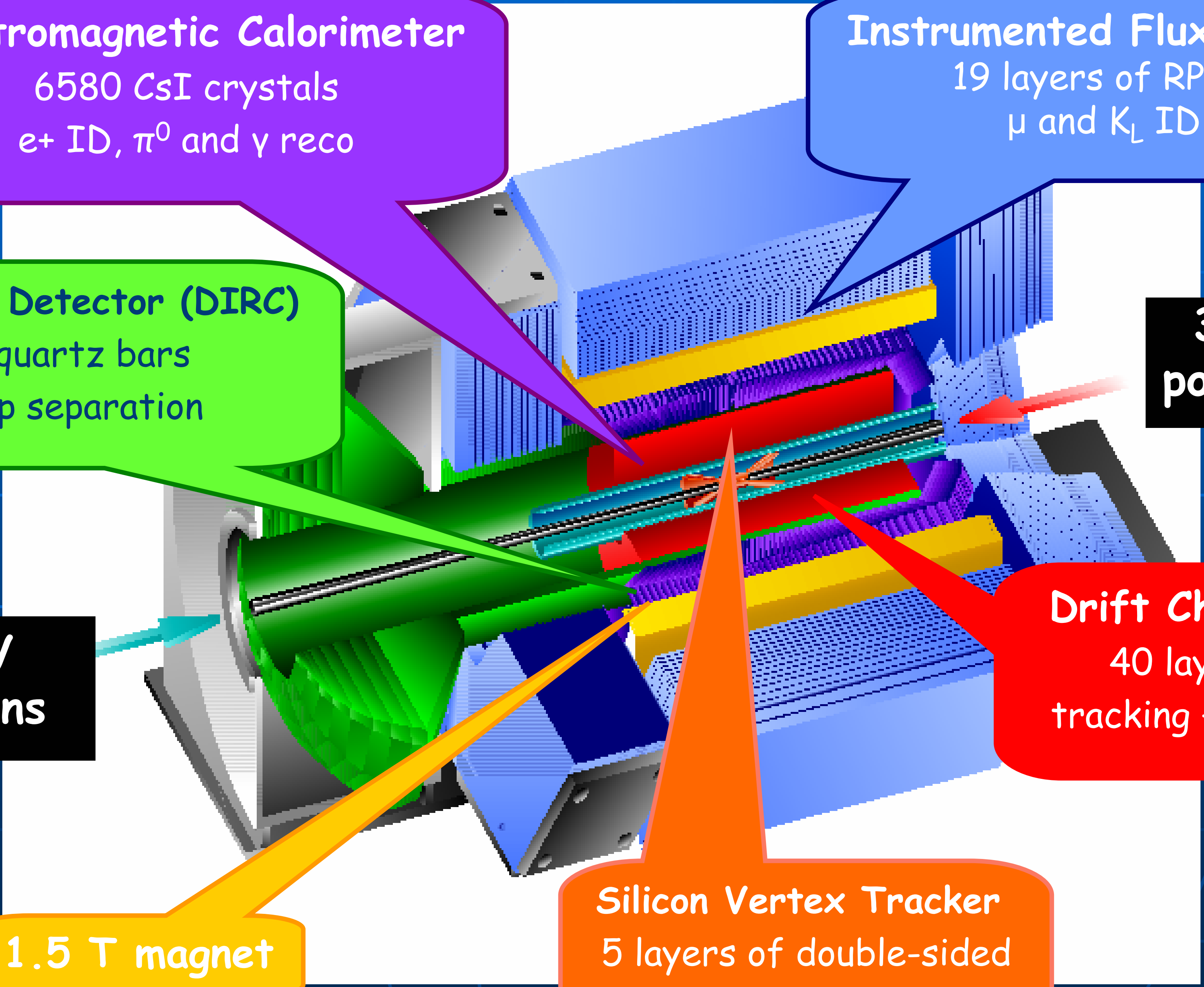
CLEO did much of the pioneering work. Stopped in 2001

BaBar forced to shut down for a year in 2004-2005 by DOE safety after accident

Though BELLE has larger datasets BaBar remains competitive

BaBar will stop running in 2008. Hope for 1000 fb-1 at that time.

The BaBar detector



Electromagnetic Calorimeter
6580 CsI crystals
e+ ID, π^0 and γ reco

Instrumented Flux Return
19 layers of RPCs
μ and K_L ID

Cherenkov Detector (DIRC)
144 quartz bars
K, π, p separation

3 GeV positrons

9 GeV electrons

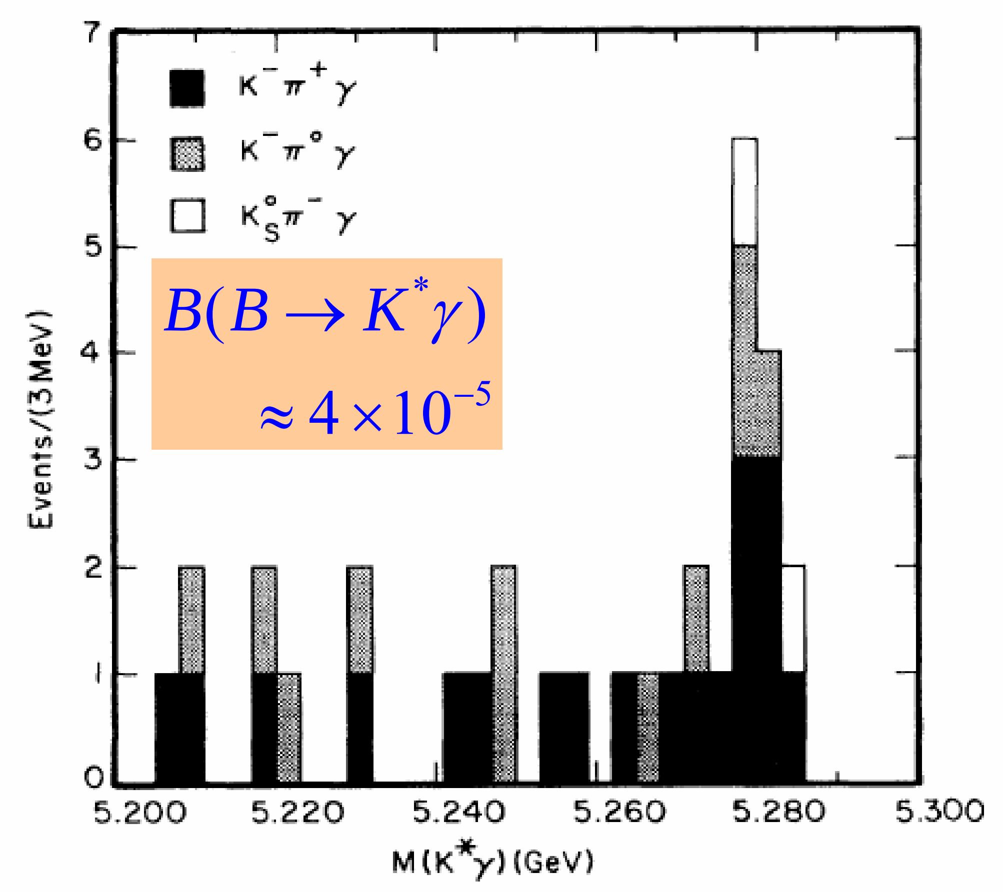
Drift Chamber
40 layers,
tracking + dE/dx

1.5 T magnet

Silicon Vertex Tracker
5 layers of double-sided
silicon strips

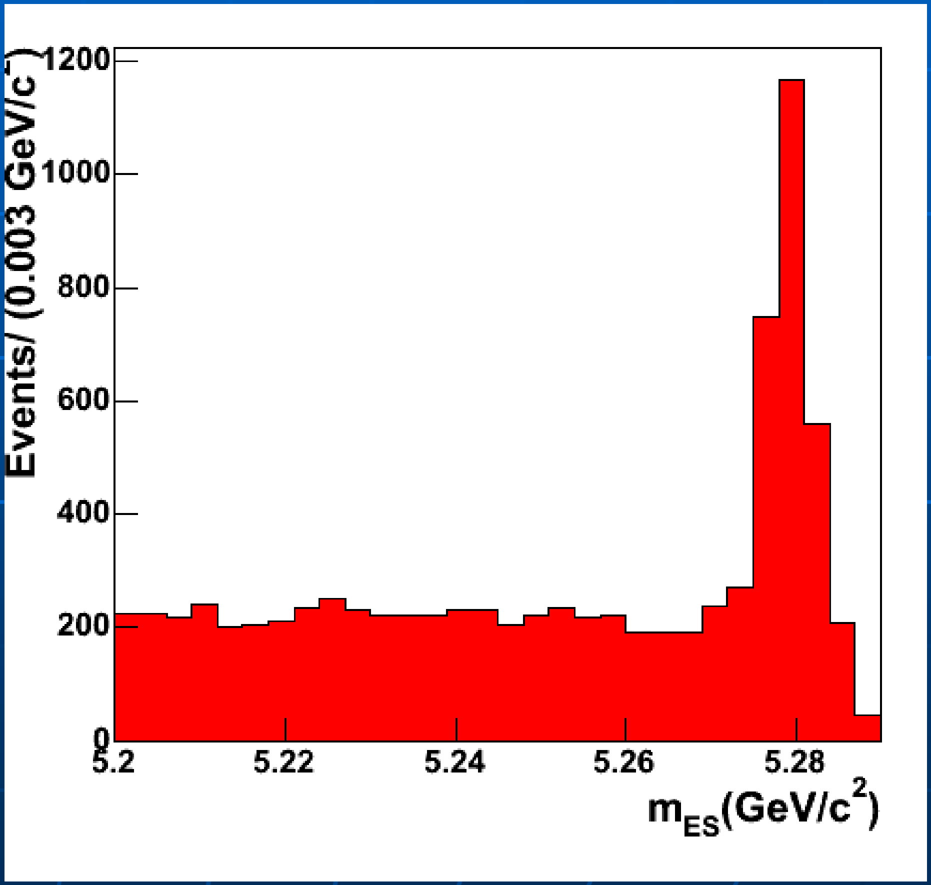
Radiative penguin decays of *B* mesons

CLEO Observation of *B*→*K γ *1993***



$$B(B \to K^*\gamma) \approx 4\times 10^{-5}$$

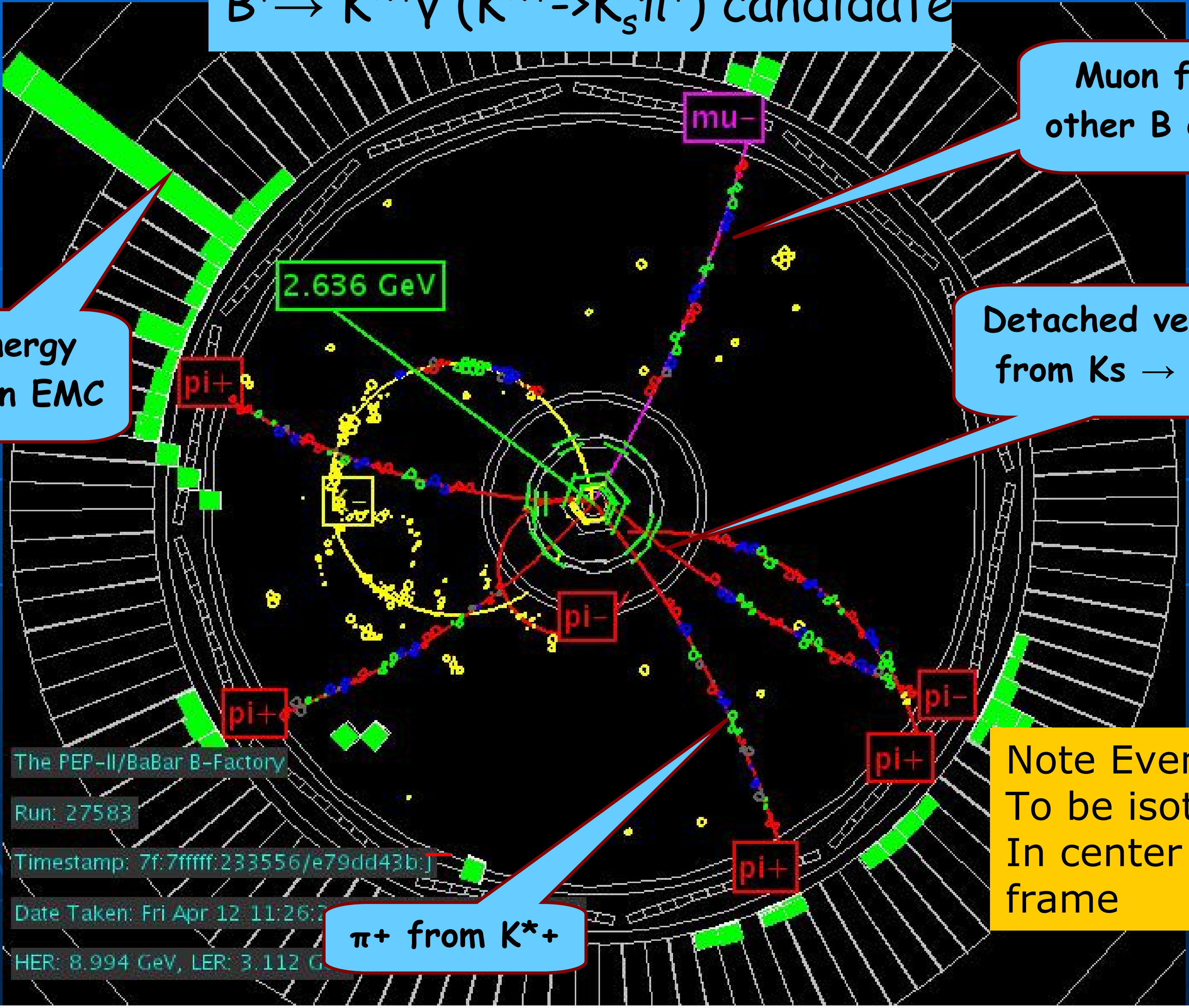
BaBar *B*→*K γ *2006***



First observation of penguins by CLEO. Now it’s a background !

Radiative penguin portrait

$B^+ \rightarrow K^{*+}\gamma$ (K^{*+}->$K_s\pi^+$) candidate



The PEP-II/BaBar B-Factory

Run: 27583

Timestamp: 7f:7fffff:233556/e79dd43b:]

Date Taken: Fri Apr 12 11:26:

HER: 8.994 GeV, LER: 3.112 G

Muon from other B decay

High energy photon in EMC

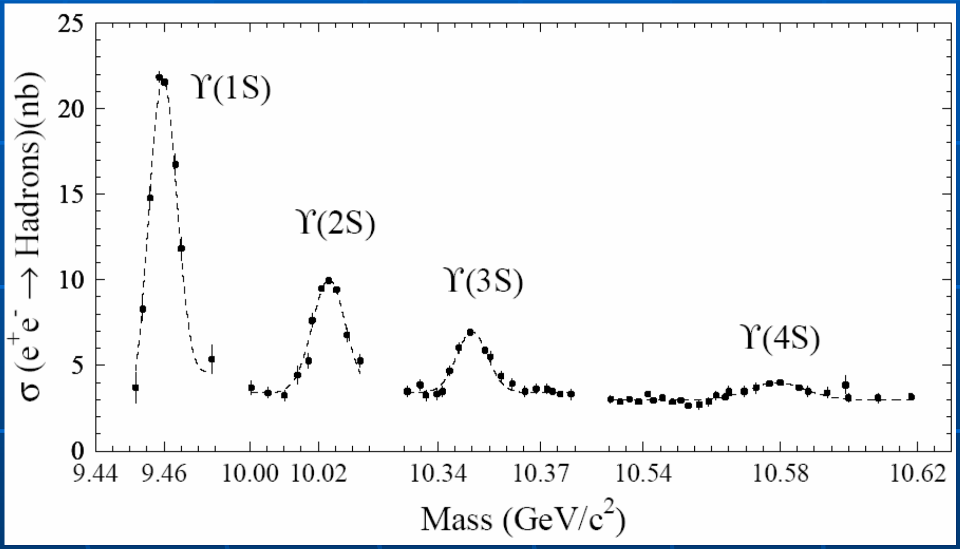
Detached vertex from Ks → ππ

π+ from K*+

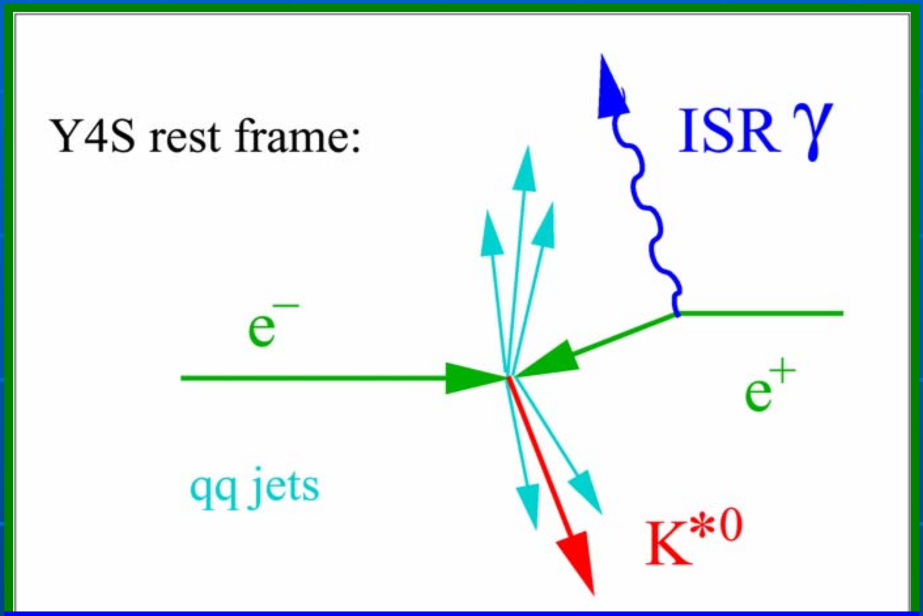
Note Event tends To be isotropic In center of mass frame

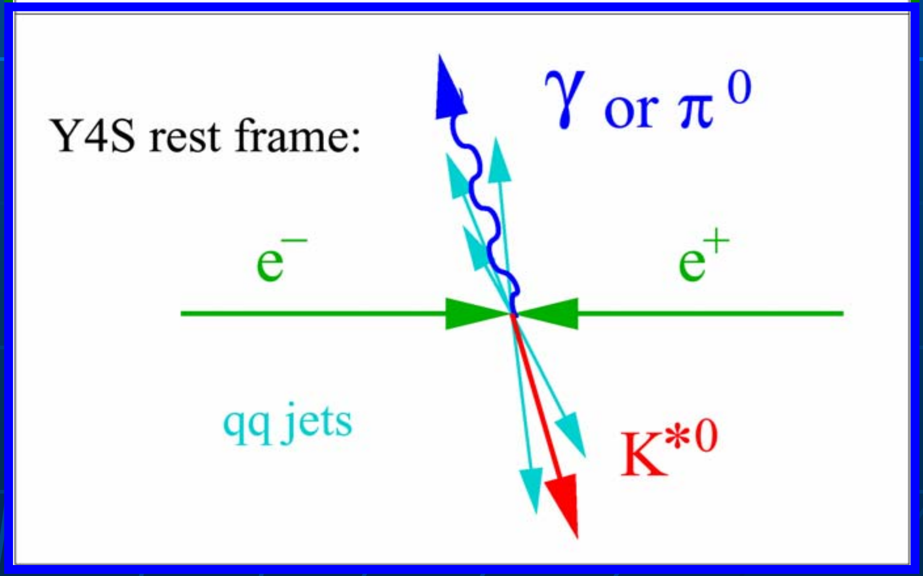
Continuum Backgrounds

Production of u,d,s,c quark and τ pairs underneath ϒ(4s)



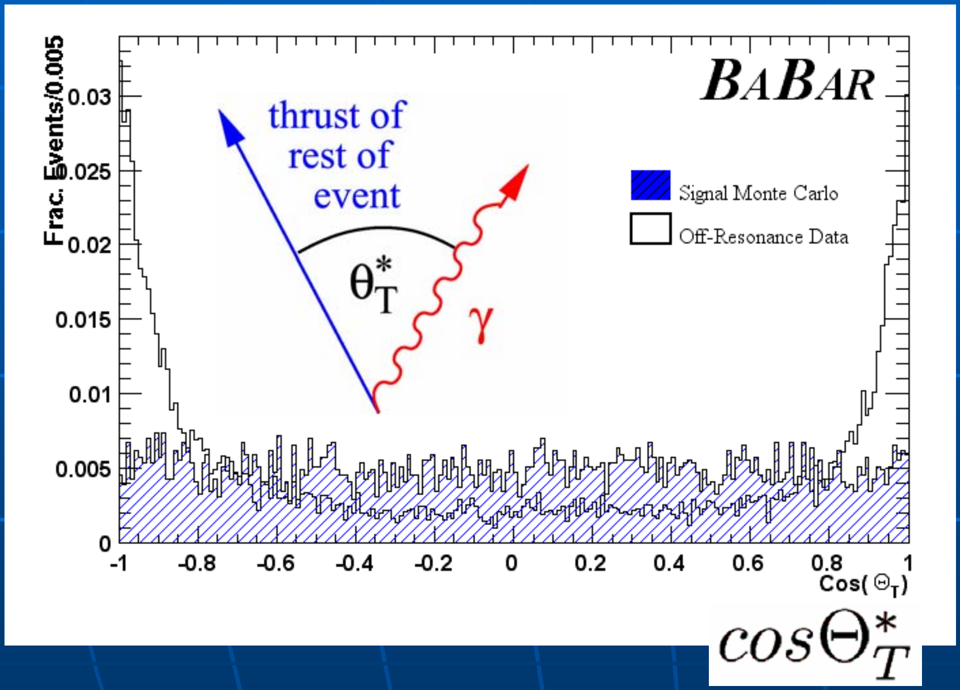
Lorentz boost makes a jet-like topology





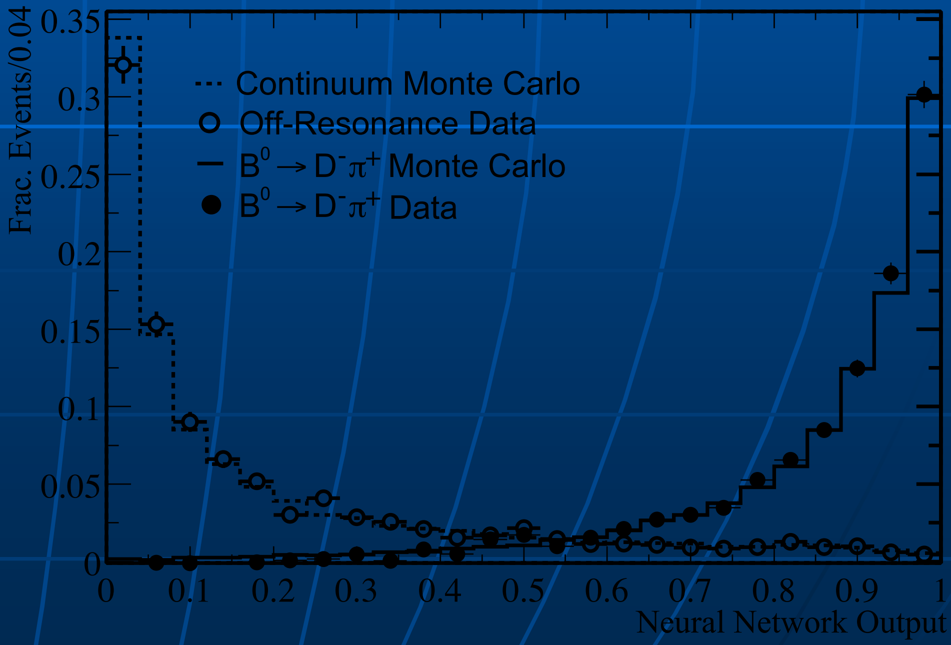
Event Shape Variables

Construct "Shape" variables to distinguish between isotropy and jets

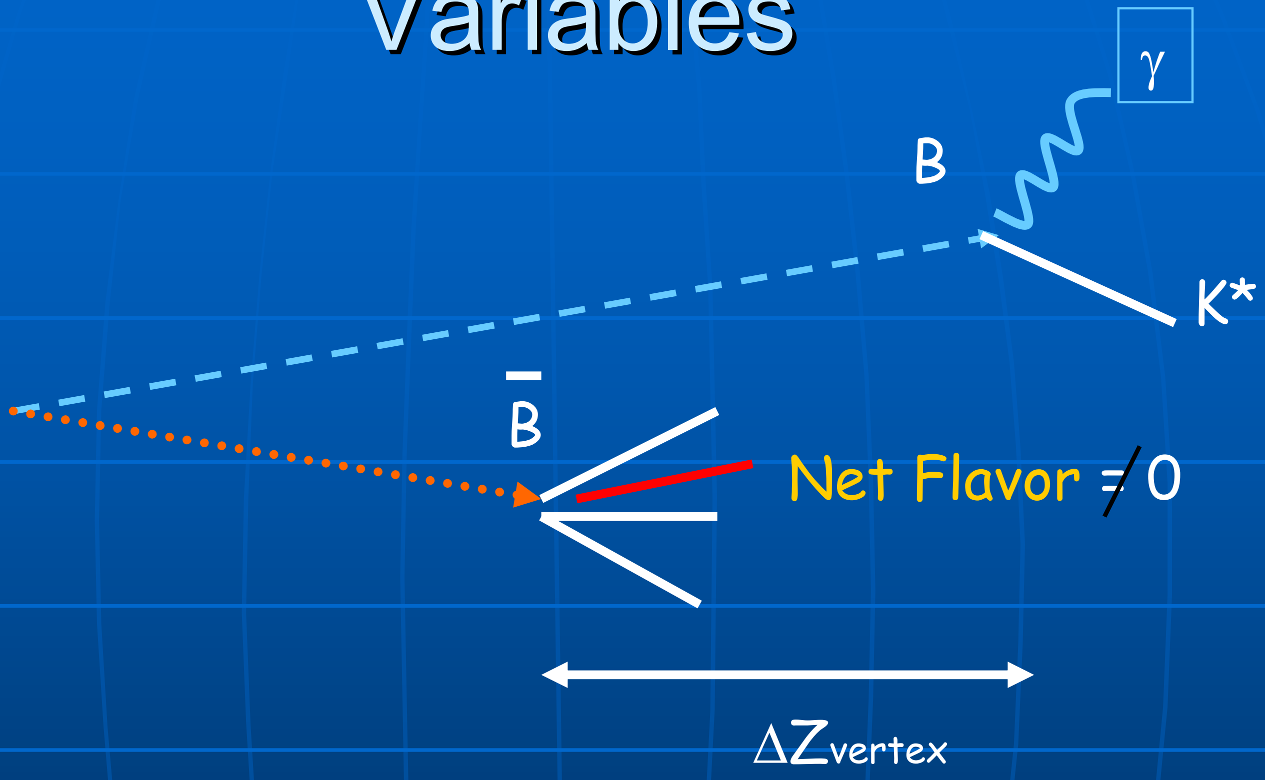


Angle between thrust and photon

Neural net combination of suite of topology variables effective with multicomponent background



Additional Continuum separation Variables

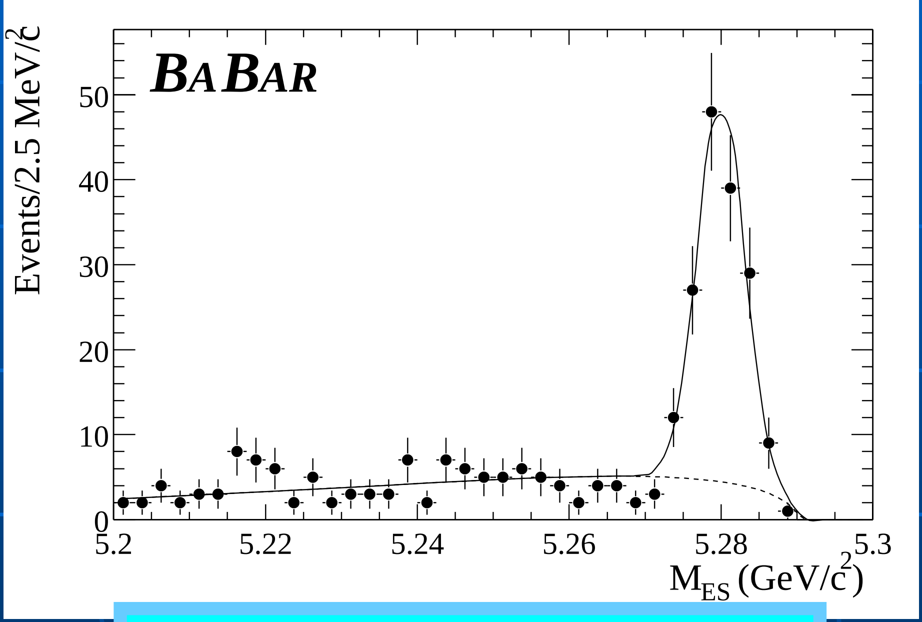


B's have lifetime and decay weakly. uds decays promptly and strongly

Net Flavor = $(N(e^+) - N(e^-)) + (N(\mu^+) - N(\mu^-)) + (N(k^+) - N(k^-))$

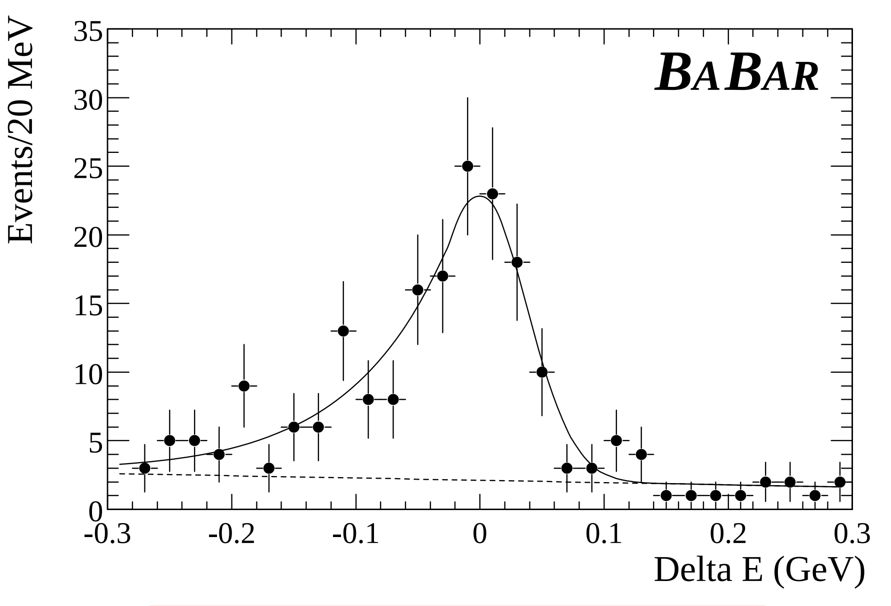
Signal Variables for Exclusive Reconstruction analyses

Beam Constrained Mass



$$M_{ES} = \sqrt{\left(E_{beam}^{*2} - p_B^{*2}\right)}$$

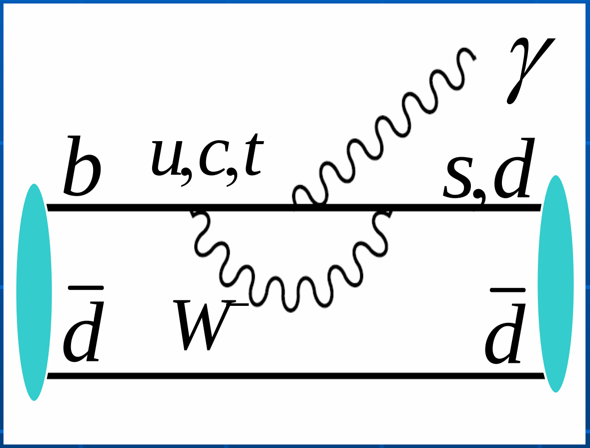
Reconstructed Energy - beam Energy



$$\Delta E^* = E_B^* - E_{beam}^*$$

Sensitivity can be enhanced by performing two dimensional likelihood fits to signal and background.

A Colony of Penguins

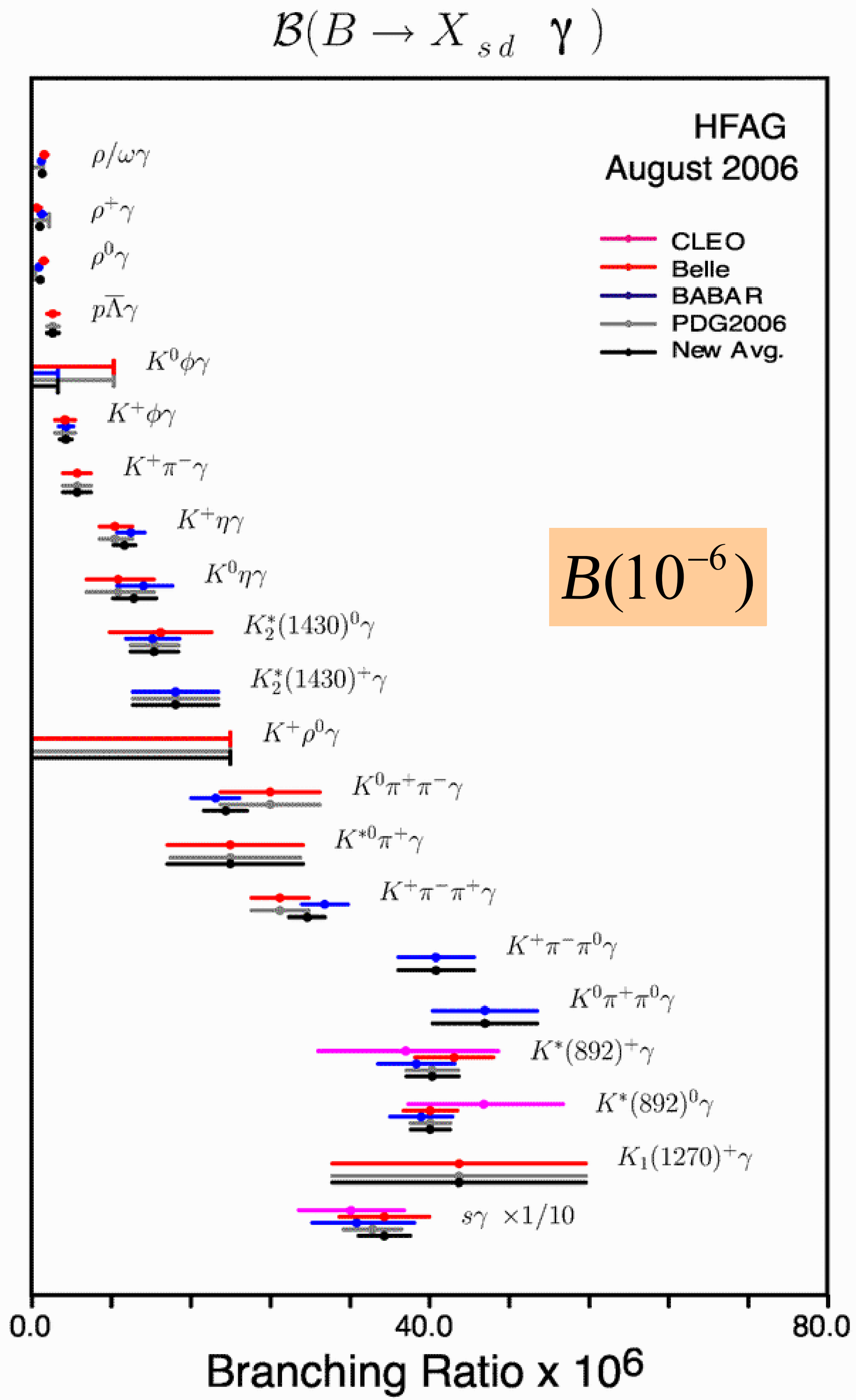


ρ,ω

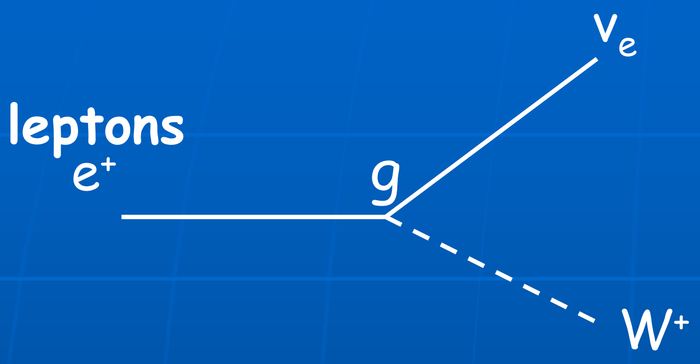
dd (V_{td})

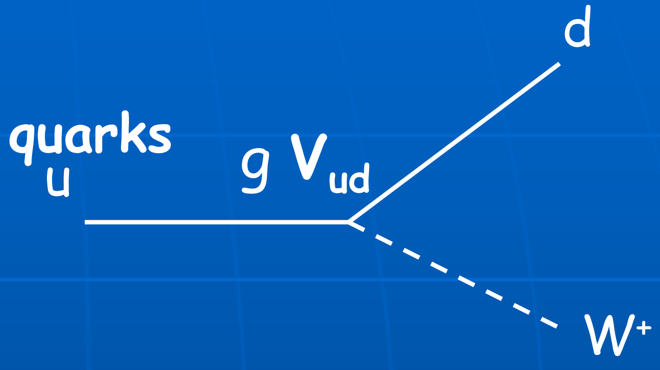
sd (V_{ts})

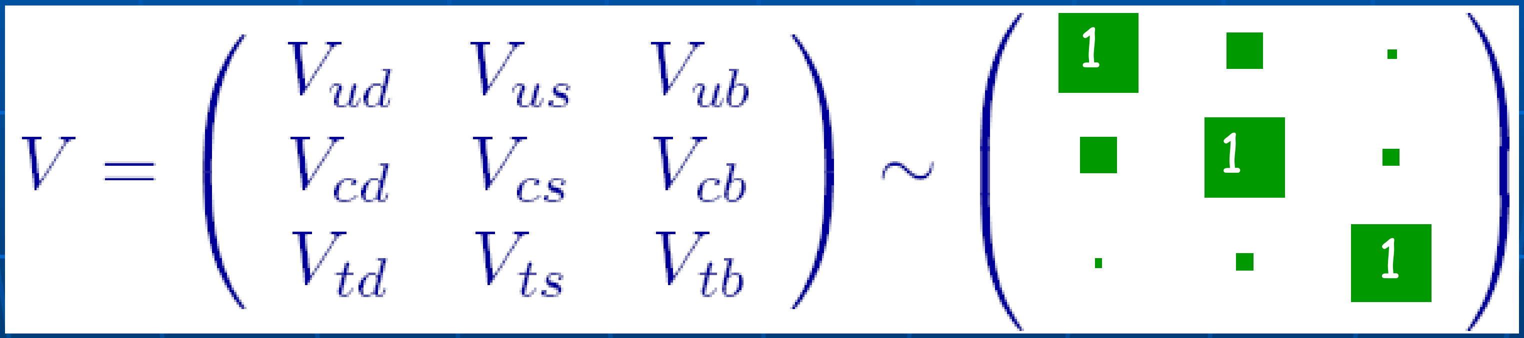
K*(892)
K_1(1270)
K_2(1430)
…



The CKM matrix







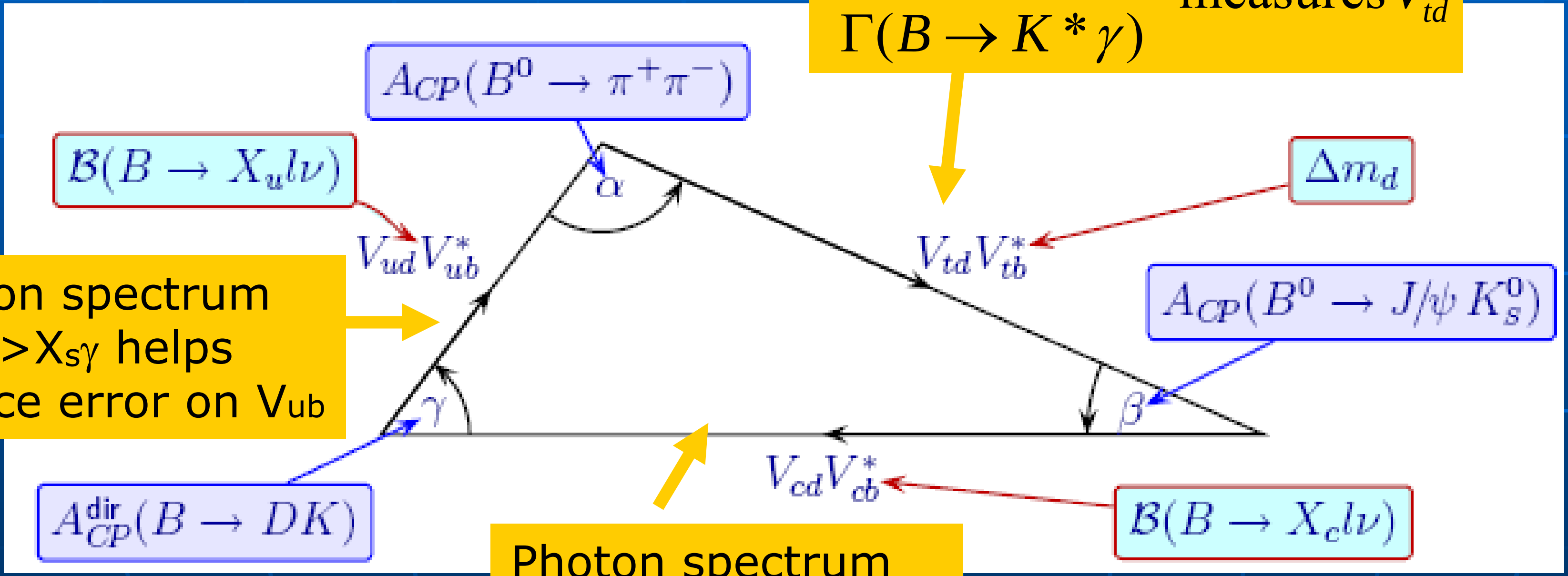
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim$$

Standard model explanation of CP violation is a single phase in the CKM matrix V.

The unitarity triangle

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

$\frac{\Gamma(B \to \rho\gamma, \omega\gamma)}{\Gamma(B \to K^*\gamma)}$ measures V_{td}



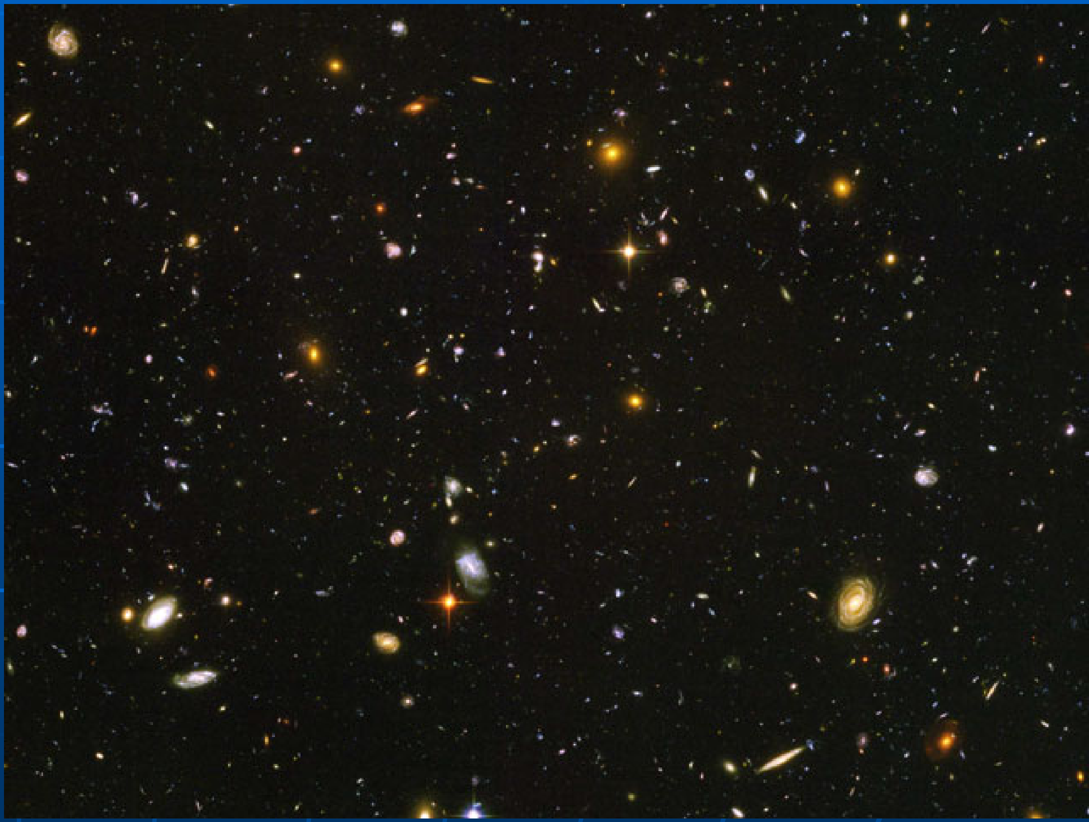
Photon spectrum in B->$X_s\gamma$ helps reduce error on V_{ub}

Photon spectrum in B->$X_s\gamma$ helps reduce error on V_{bc}

Overconstraining the triangle may reveal new sources of CP violation.

Matter-Antimatter Asymmetry in Universe

CP violation is an essential component of the presumed mechanism for generating this asymmetry

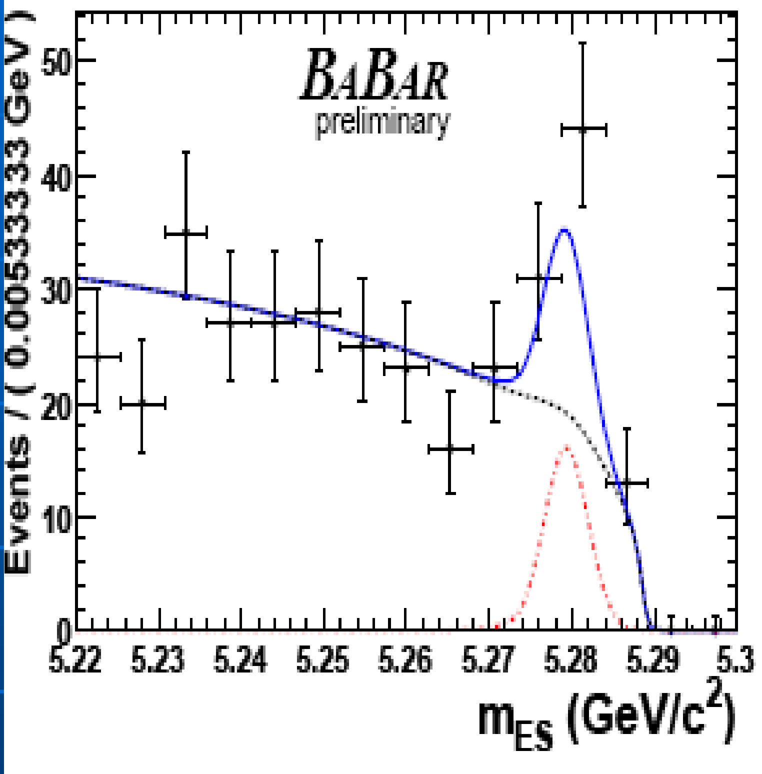


But: The Standard model has insufficient CP violation to account for the observed asym.

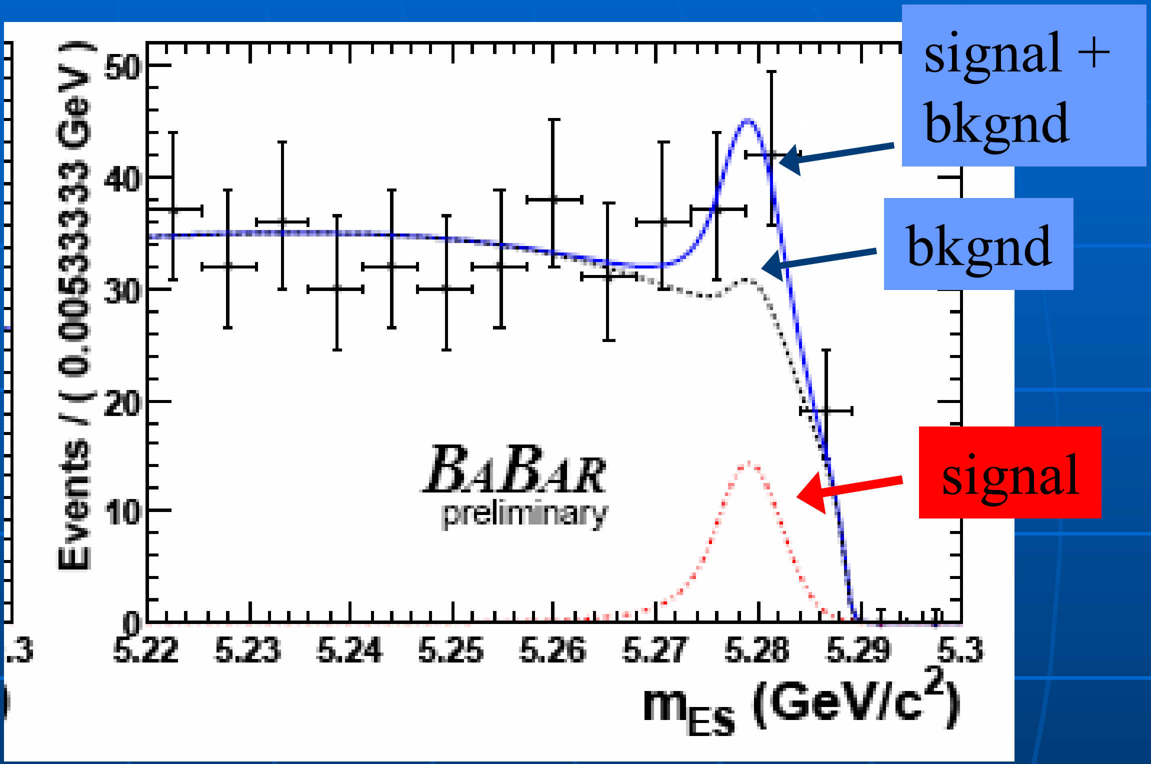
Presumably extra CP violation comes from new physics that couples to quarks or leptons

Measurement of $b \rightarrow d\,\gamma$ Decays

$B^0 \rightarrow \rho^0\gamma$



$B^+ \rightarrow \rho^+\gamma$



signal + bkgnd

bkgnd

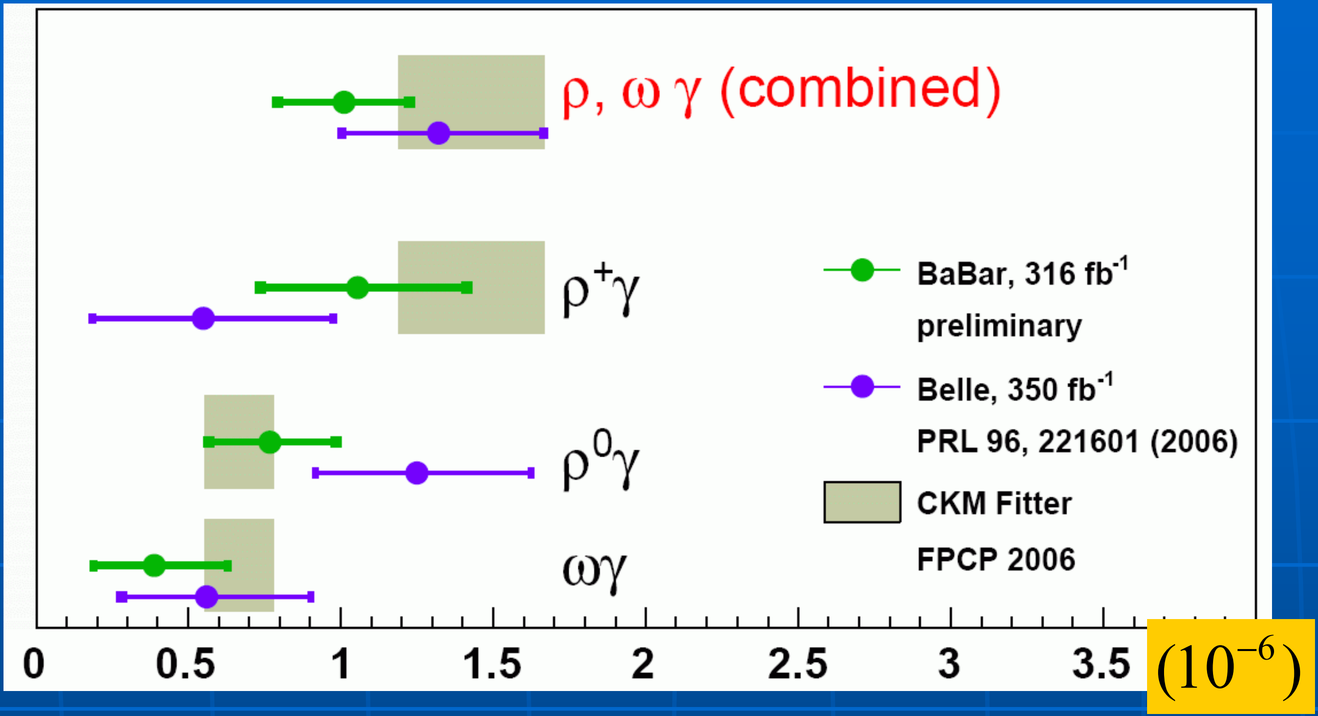
signal

Mass projections from 4d fit

6.3 sigma observation

BABAR, hep-ex/0607099, 347 M BB

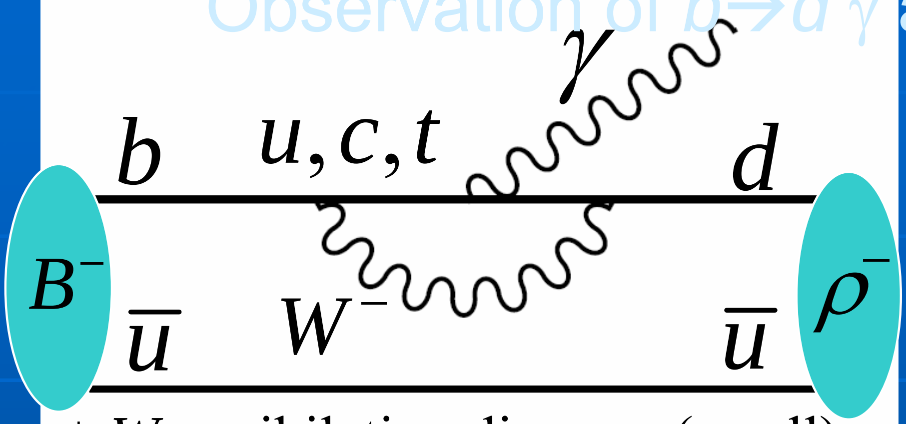
Comparison of *b→d* γ Branching Fractions



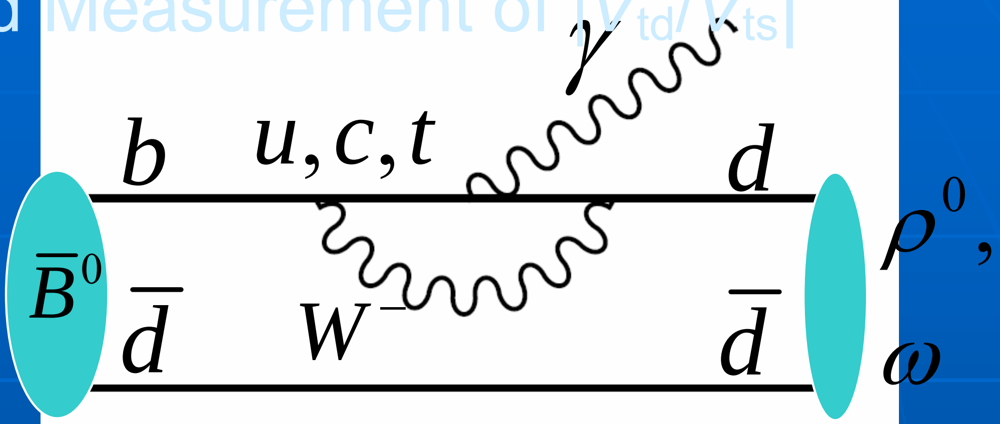
CKM fitter includes CDF B_s mixing result.
Error on CKM Fitter prediction includes uncert. on $B \to V\gamma$ form-factor ratio.

Mode	***BABAR* (10^{-6})** **(6.3 σ signif.)**	**Belle (10^{-6})** **(5.1σ signif.)**
$B^+ \to \rho^+\gamma$	$1.06^{+0.35}_{-0.31} \pm 0.09$	$0.55^{+0.43+0.12}_{-0.37-0.11}$
$B^0 \to \rho^0\gamma$	$0.77^{+0.21}_{-0.19} \pm 0.07$	$1.17^{+0.35+0.09}_{-0.31-0.08}$
$B^0 \to \omega\gamma$	< 0.84 (90% C.L.)	$0.58^{+0.34+0.14}_{-0.31-0.10}$
$B \to (\rho^+, \rho^0, \omega)_{I\text{-avg}}\gamma$	$1.01 \pm 0.21 \pm 0.08$	$1.32^{+0.34+0.10}_{-0.31-0.09}$

Observation of $b\to d\,\gamma$ and Measurement of $|V_{td}/V_{ts}|$



+ W annihilation diagram (small)



$$\frac{B(B\to\rho\gamma)}{B(B\to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{\left(m_B^2-m_\rho^2\right)^3}{\left(m_B^2-m_{K^*}^2\right)^3}\underbrace{\left(\frac{T_1^\rho(0)}{T_1^{K^*}(0)}\right)^2}_{1/\xi^2}\left(1+\Delta R\right)$$

$$\xi \equiv \frac{T_1^{K^*}(0)}{T_1^\rho(0)} = 1.17 \pm 0.09$$

Ball and Zwicky, JHEP 0604, 046 (2006)

$$\Delta R = 0.1 \pm 0.1$$

Ali, Lunghi, Parkhomenko, PLB 595, 323 (2004)

$$\Gamma(B\to\rho^+\gamma) = 2\frac{\tau_{B^+}}{\tau_{B^0}}\Gamma(B\to\rho\gamma) = 2\frac{\tau_{B^+}}{\tau_{B^0}}\Gamma(B\to\omega\gamma)$$

I-spin (ρ), quark model (ω). Expect small I-spin violation:(1.1+/-3.9)%.

Extracting $|V_{td}/V_{ts}|$ from $b \to d\,\gamma$ Decays

Belle, PRL 96, 221601 (2006).

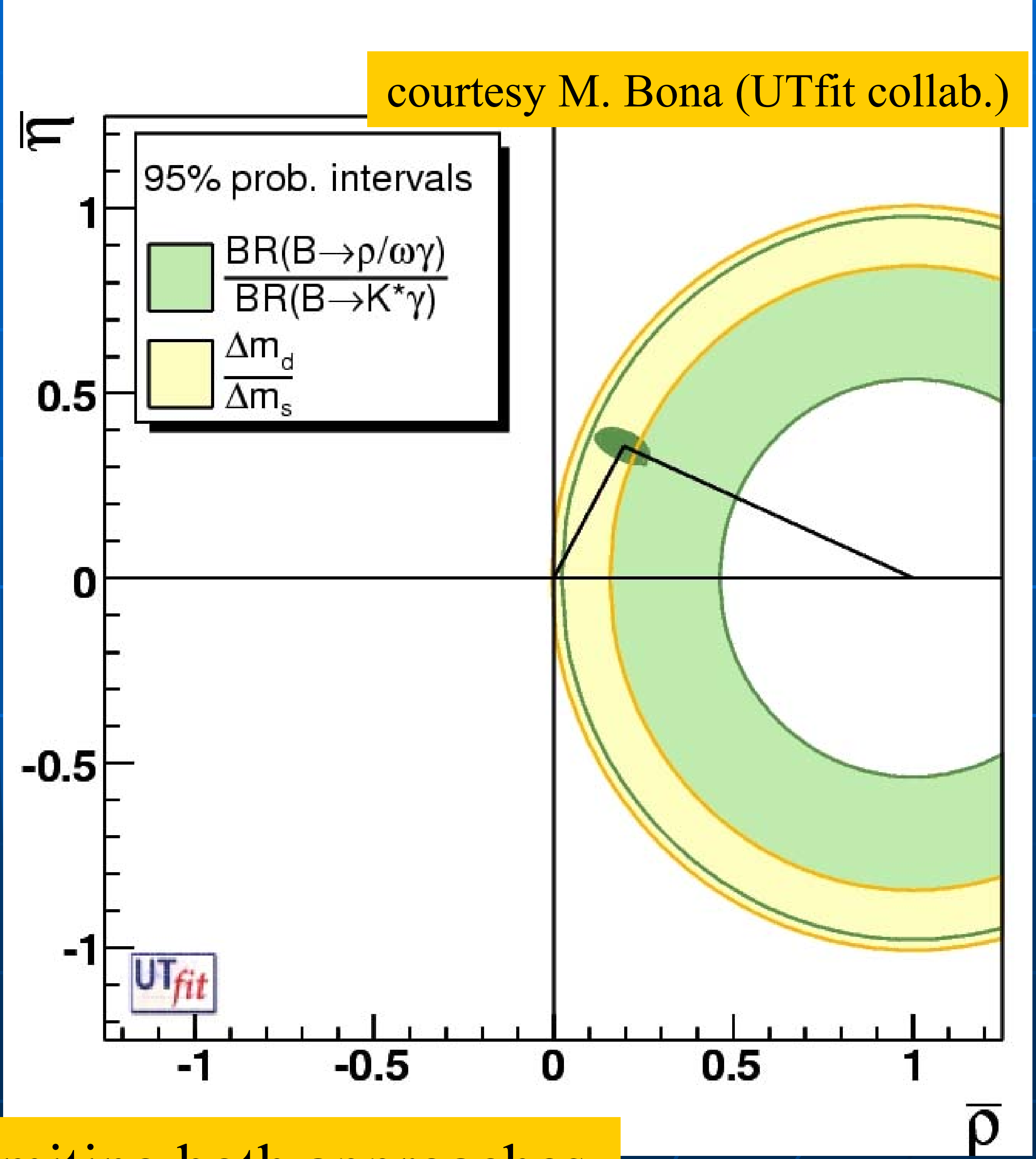
$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.199^{+0.026+0.018}_{-0.025-0.015}$$

BABAR, hep-ex/0607099 (preliminary)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.171^{+0.018+0.017}_{-0.021-0.014}$$

CDF, hep-ex/0606027 (preliminary)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.208^{+0.001+0.008}_{-0.002-0.006}$$



courtesy M. Bona (UTfit collab.)

Consistent within errors.

Theoretical uncertainties limiting both approaches.

Inclusive Penguins: $\Gamma(B\text{->}Xs\gamma)$

$$\Gamma(B \rightarrow X_s\gamma) = \Gamma(b \rightarrow s\gamma) + \Delta^{non-pert}$$

Quark-hadron duality

The non-perturbative corrections are a few percent.

Recently a new NNLO calculation for B(B->$X_s\gamma$) has been completed

$$B(B \rightarrow X_s\gamma) = 3.15 \pm 0.23 \times 10^{-4}$$

(Misiak,Asatrian,Bieri,Czakon,Czarnecki,Ewerth,Ferroglia,Gambino
Gorbahn,Greub,Haisch,Hovhannisyan,Hurth,Mitov,Poghosyan,Slusarczyh)

Major undertaking involving thousands of diagrams. New precise Calculation has renewed interest in the field

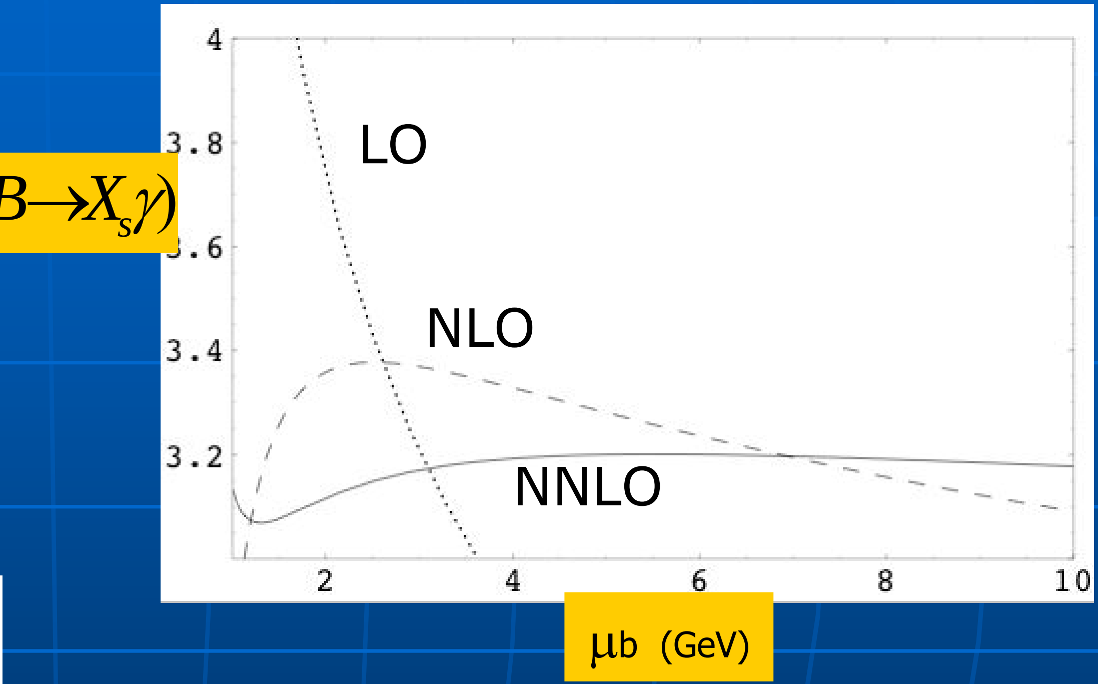
Compare to NLO: $B(B \rightarrow X_s\gamma) = 3.61 \pm 0.43 \times 10^{-4}$

Theory Errors on B(B->Xsγ)

Theory errors from choice of Renormalization scales

As go to higher orders this is reduced as expected.

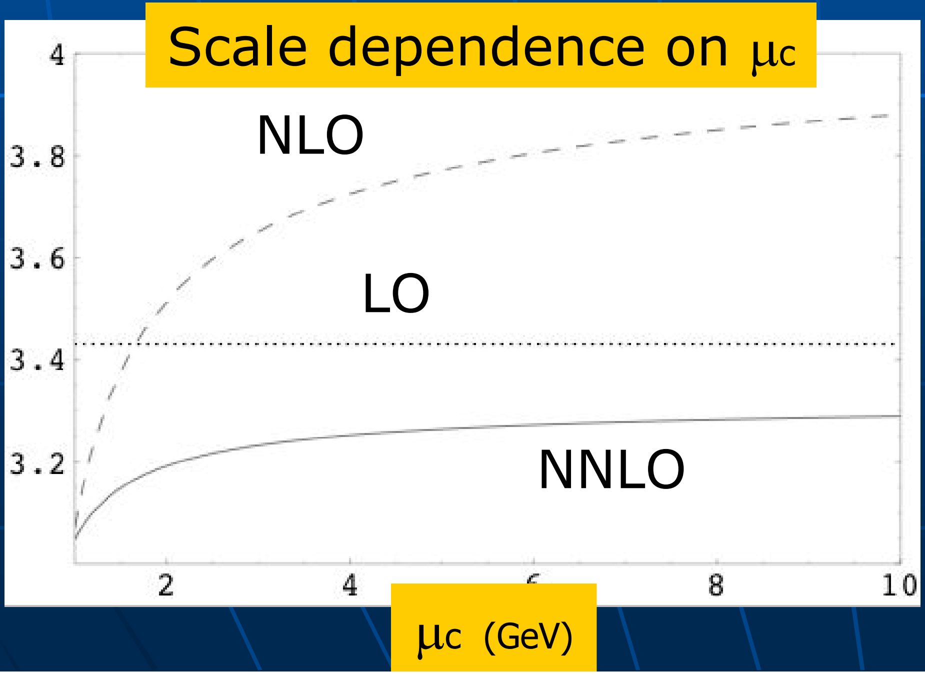
Scale dependence on μb



At NLO the choice of charm quark renormalization scale had been a Problem.

New calculation resolves this issue and errors are now understood

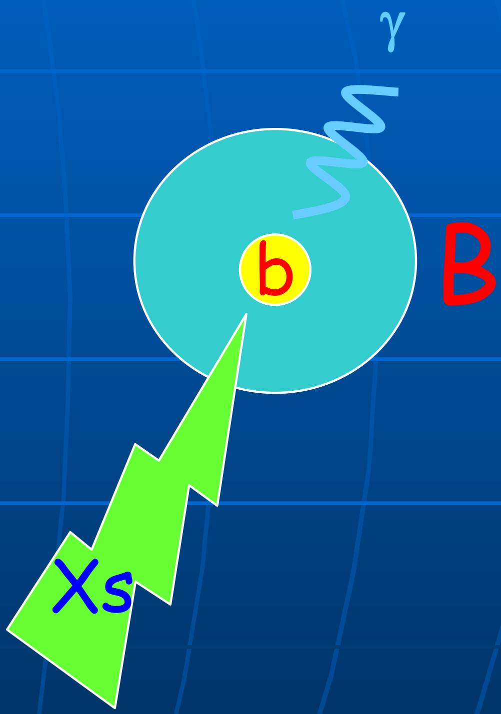
Scale dependence on μc



Quark-Hadron duality

Quarks

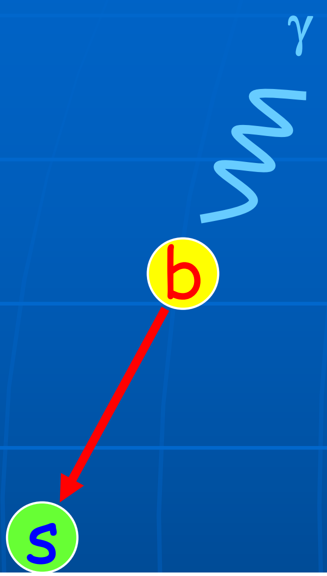
Hadrons

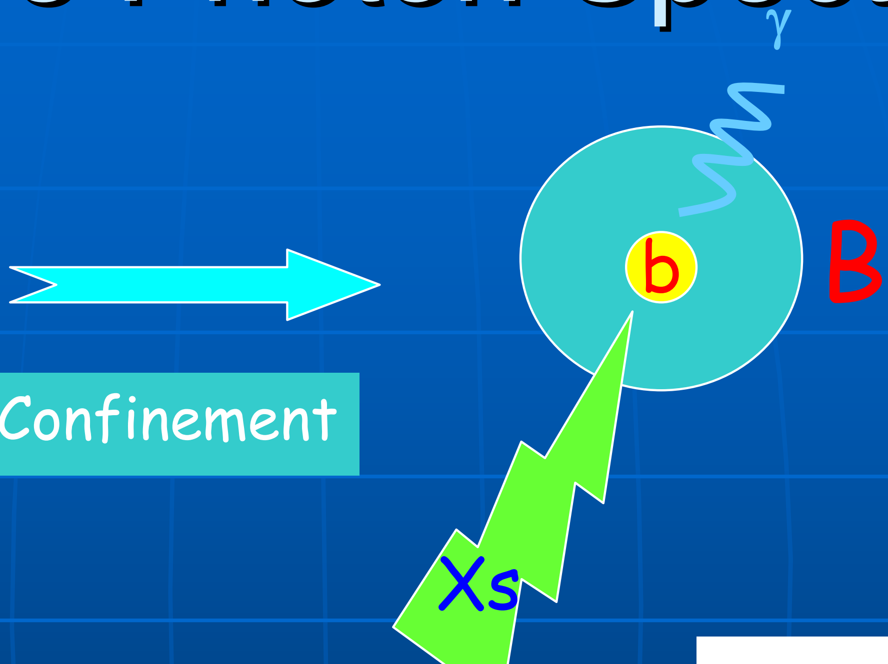


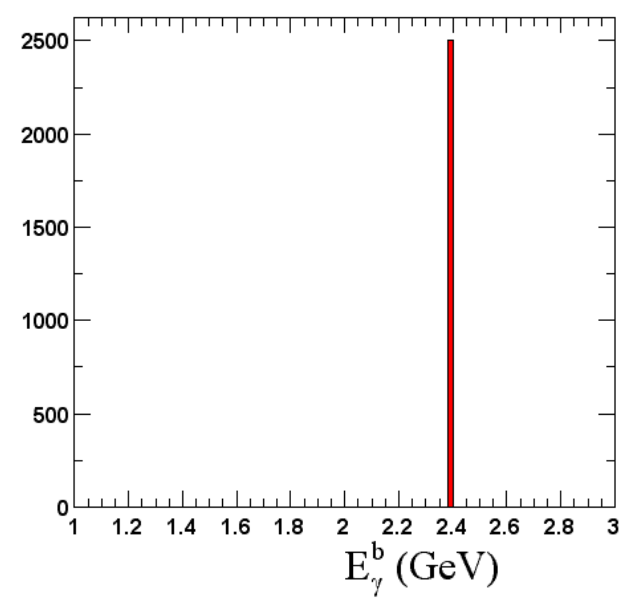
$$\mathcal{B}(b \rightarrow s\gamma) = \mathcal{B}(B \rightarrow X_s\gamma)$$

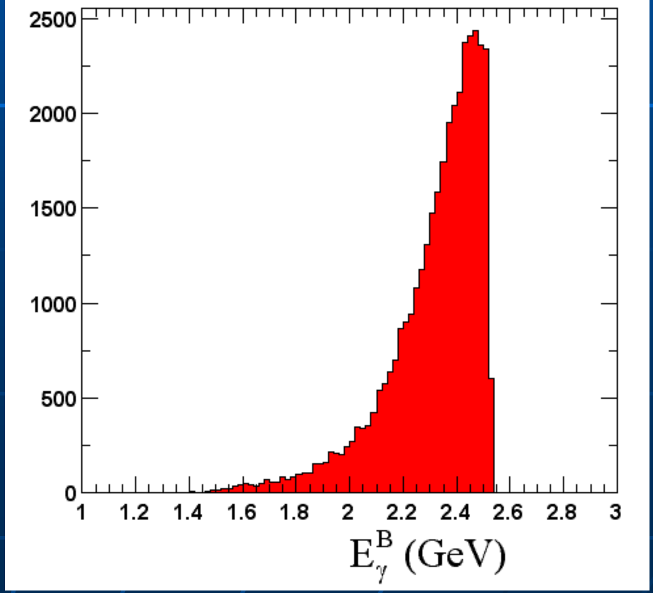
A fully inclusive measurement can be related directly to quark calculation

Inclusive Photon Spectrum



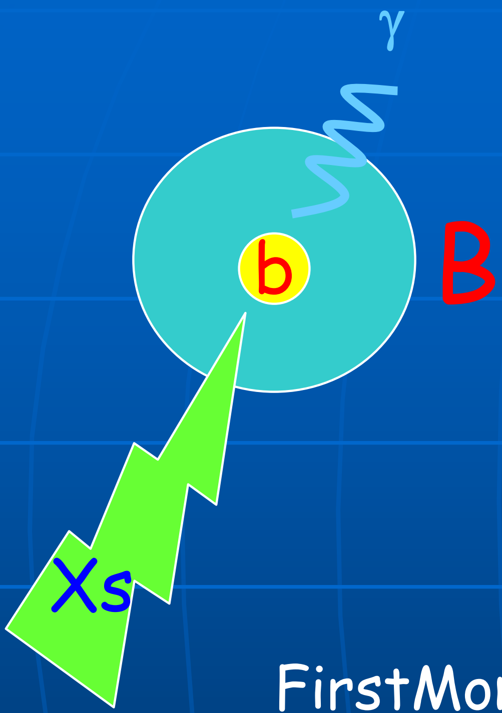


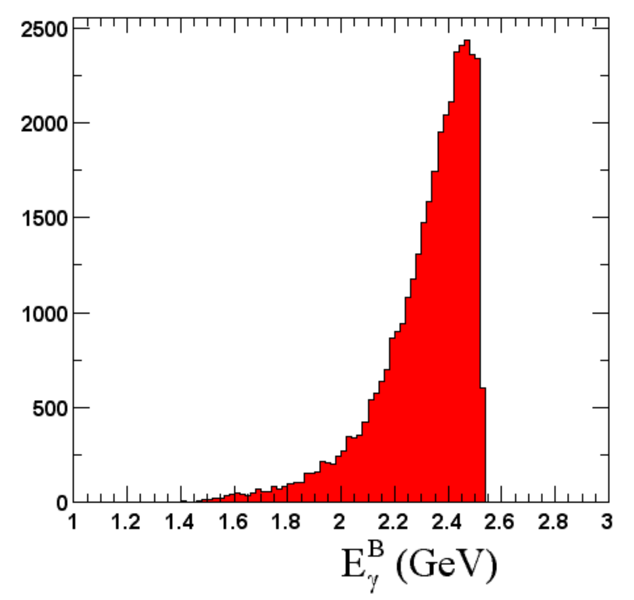




To be fully inclusive must measure all the photon spectrum

Inclusive Photon Spectrum





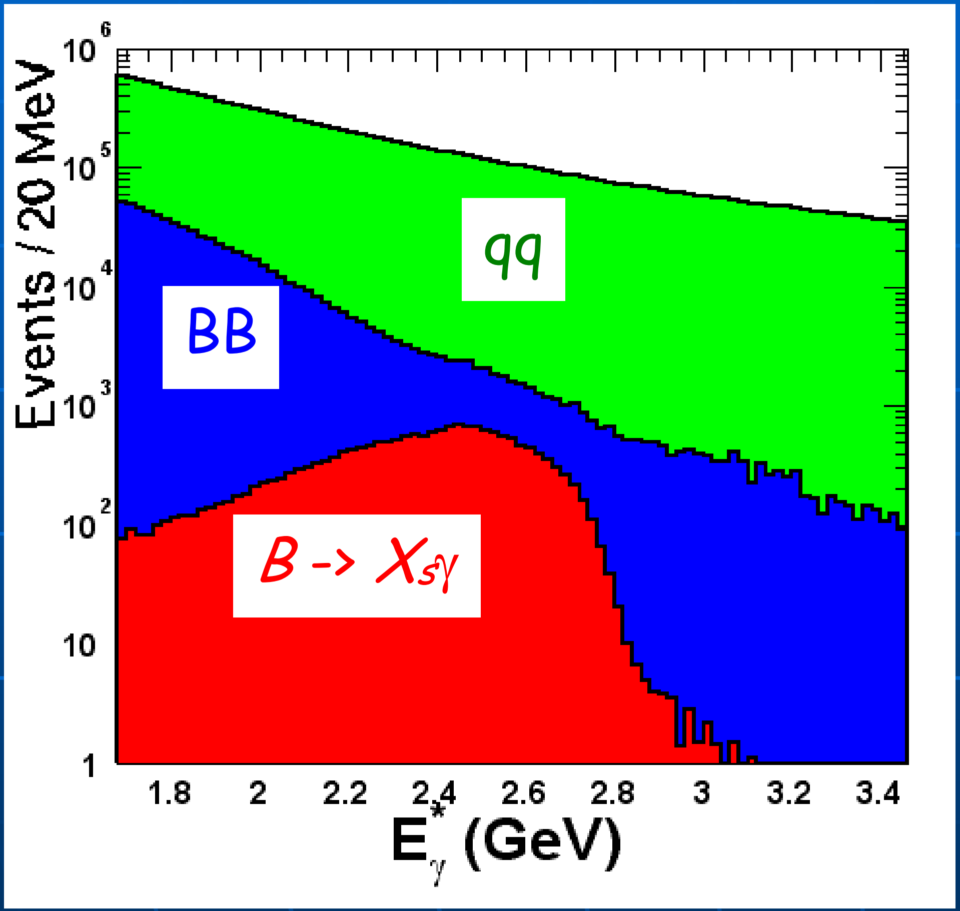
First Moment: $\left\langle E_\gamma^B \right\rangle \approx \frac{m_b}{2}$

Second Moment: $\left\langle E_\gamma^{B2} \right\rangle - \left\langle E_\gamma^B \right\rangle^2 \approx$ (Kinetic energy of b)^2

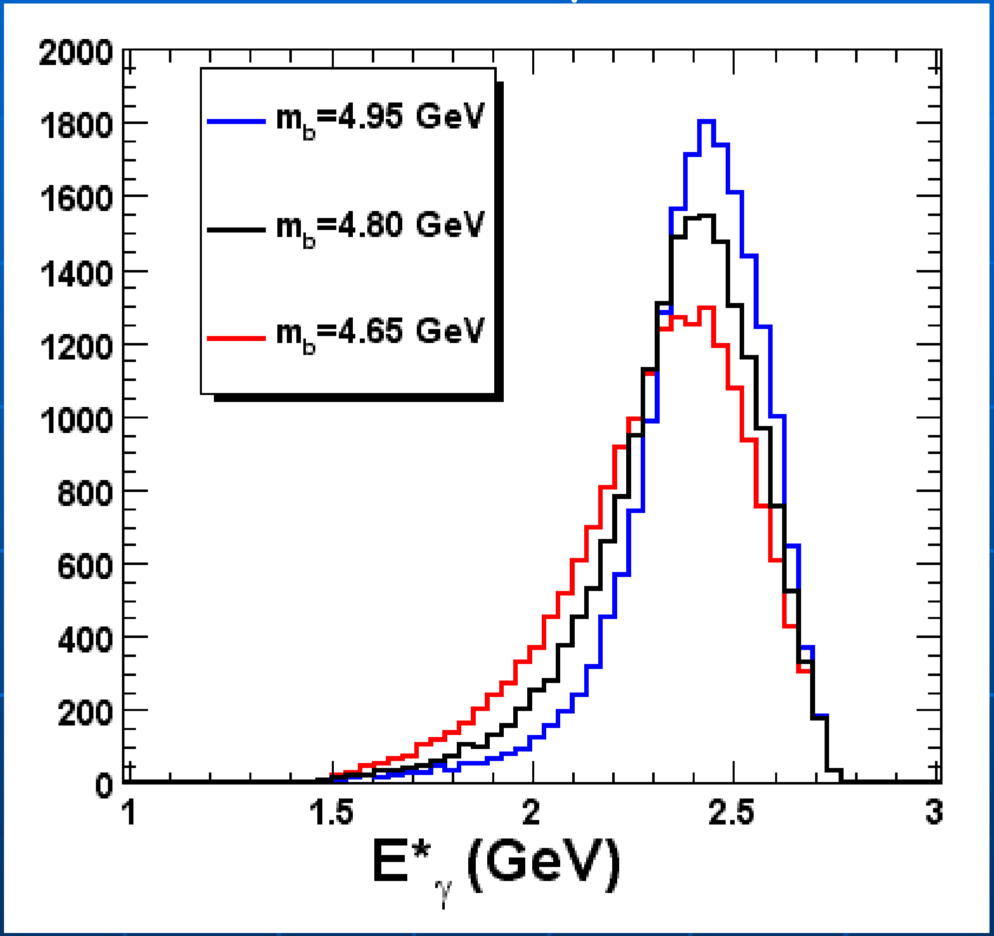
Information about motion of b-quark should be universal – i.e like a structure function and so can be applied to other inclusive processes

Experimental Challenge

Monte Carlo : Just require γ



γ Model Dependence

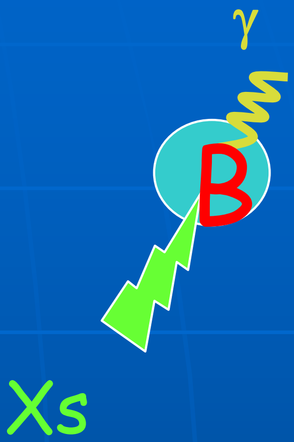


Note additional BB background

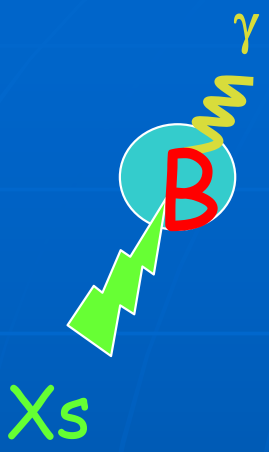
To reduce large backgrounds without cutting on γ or Xs
i.e a fully inclusive measurement

Two Methods for inclusive $B \rightarrow X_s\ \gamma$

Differ in treatment of Xs



Method	Advantages	Disadvantages
Fully inclusive **don't reconstruct X_s**	Closest correspondence to inclusive $\mathcal{B}(B \rightarrow X_s\ \gamma)$.	More Backgrounds
Sum of exclusive $B \rightarrow K\ n(\pi)\ \gamma$	Less background due to additional kinematic constraints. Better E_γ resolution.	More model dependence due to finite set of explicitly reconstructed $B \rightarrow X_s\ \gamma$ decays.



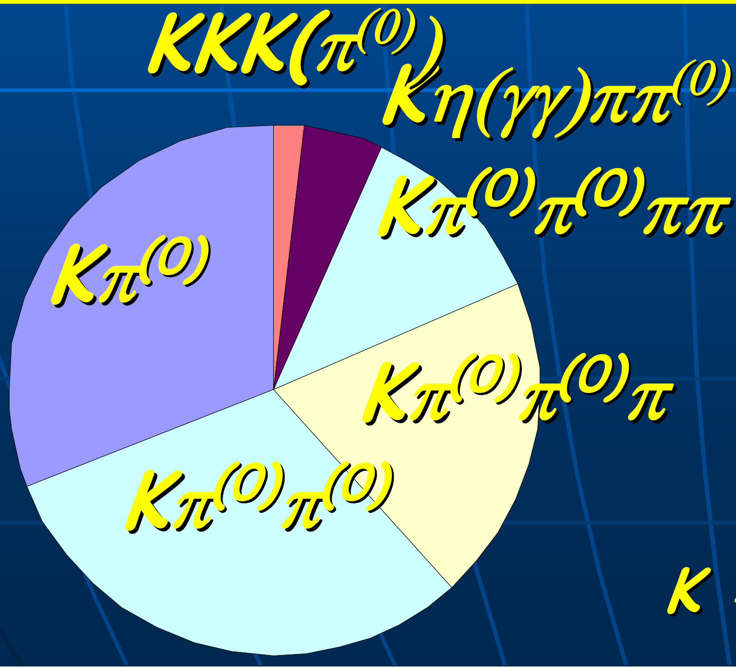
Technique 1 – Semi-Inclusive

Exclusively Reconstruct as many of the final states of Xs as possible:

Fundamental problem is that composition of final states must be guessed - large systematic

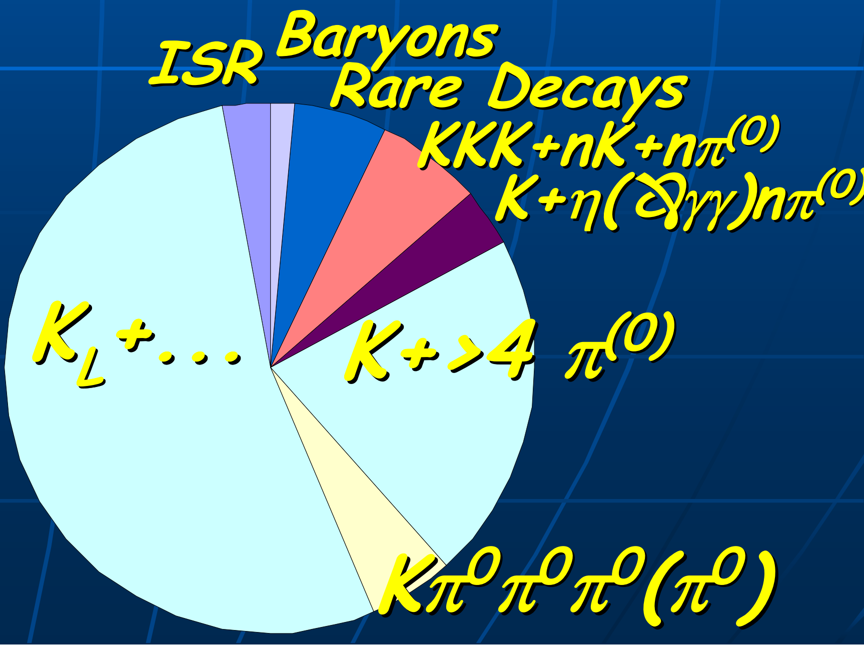
~55%

Reconstructed Final States



~45%

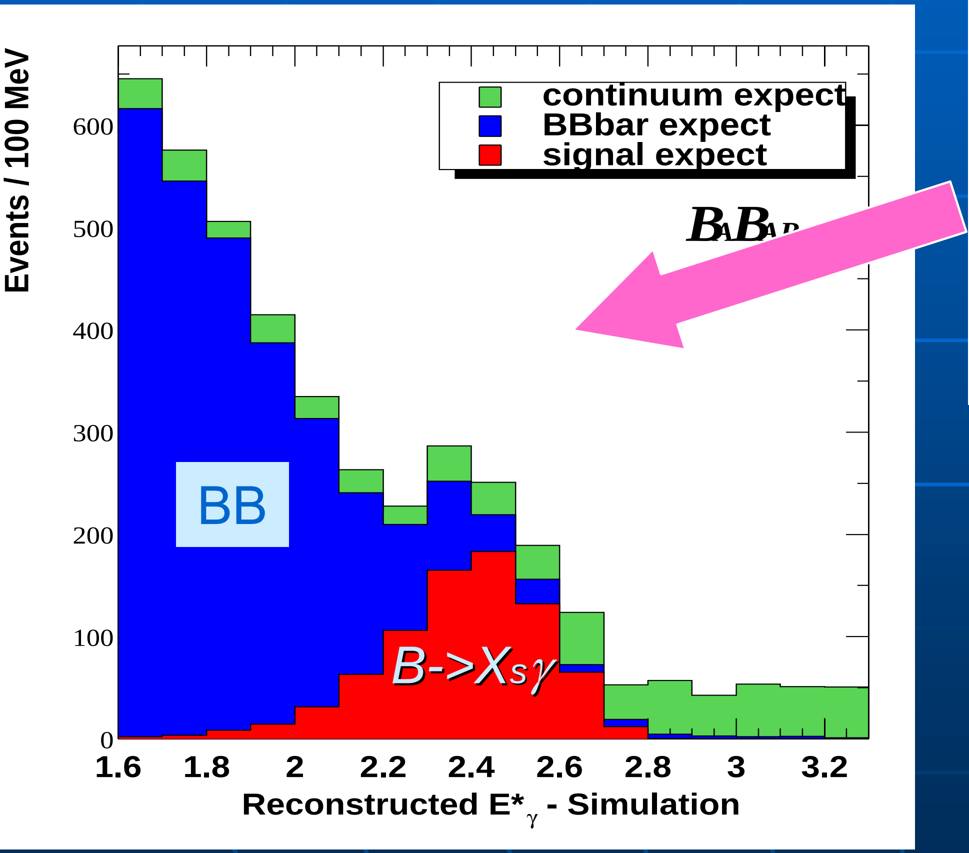
Missing Final States

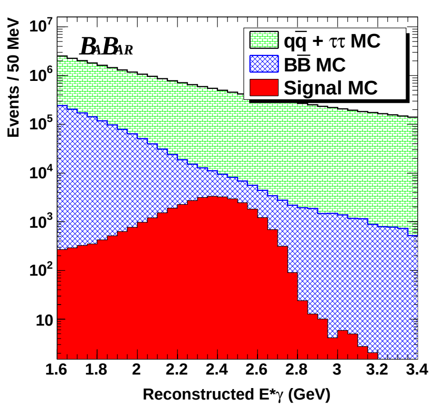


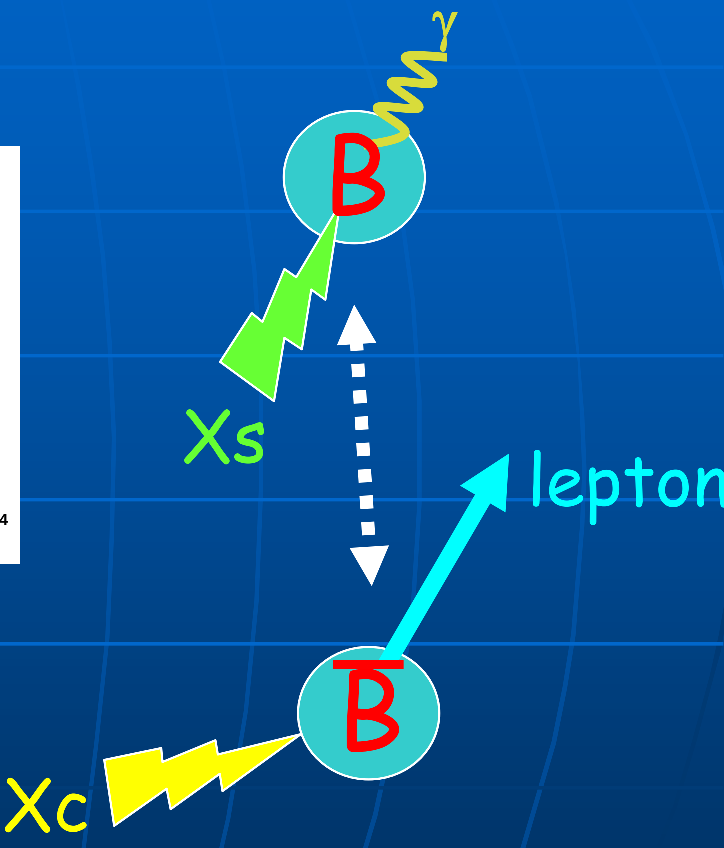
$K = K^{\pm},\ K_s$

Technique II “Fully Inclusive”: *B -> $X_s\gamma$*

Suppress continuum background by
requiring a “lepton tag” from recoiling B
(5% Efficiency for x1200 reduction in background)



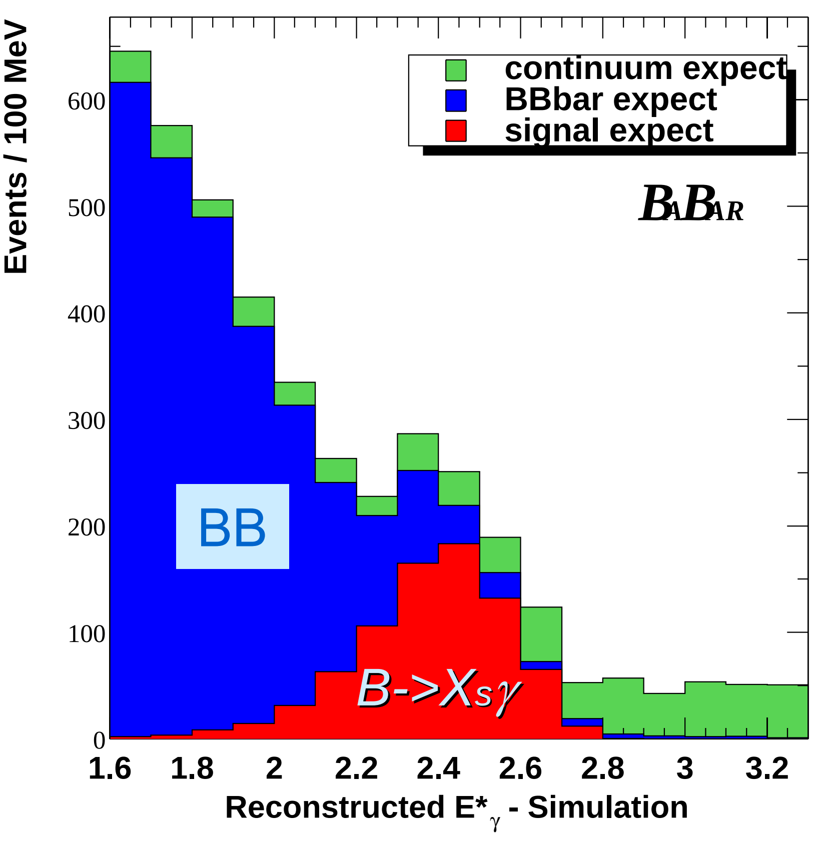




Remaining continuum subtracted with off-resonance data -> statistical uncertainty

Multi-component BB background

Fully Inclusive BB background



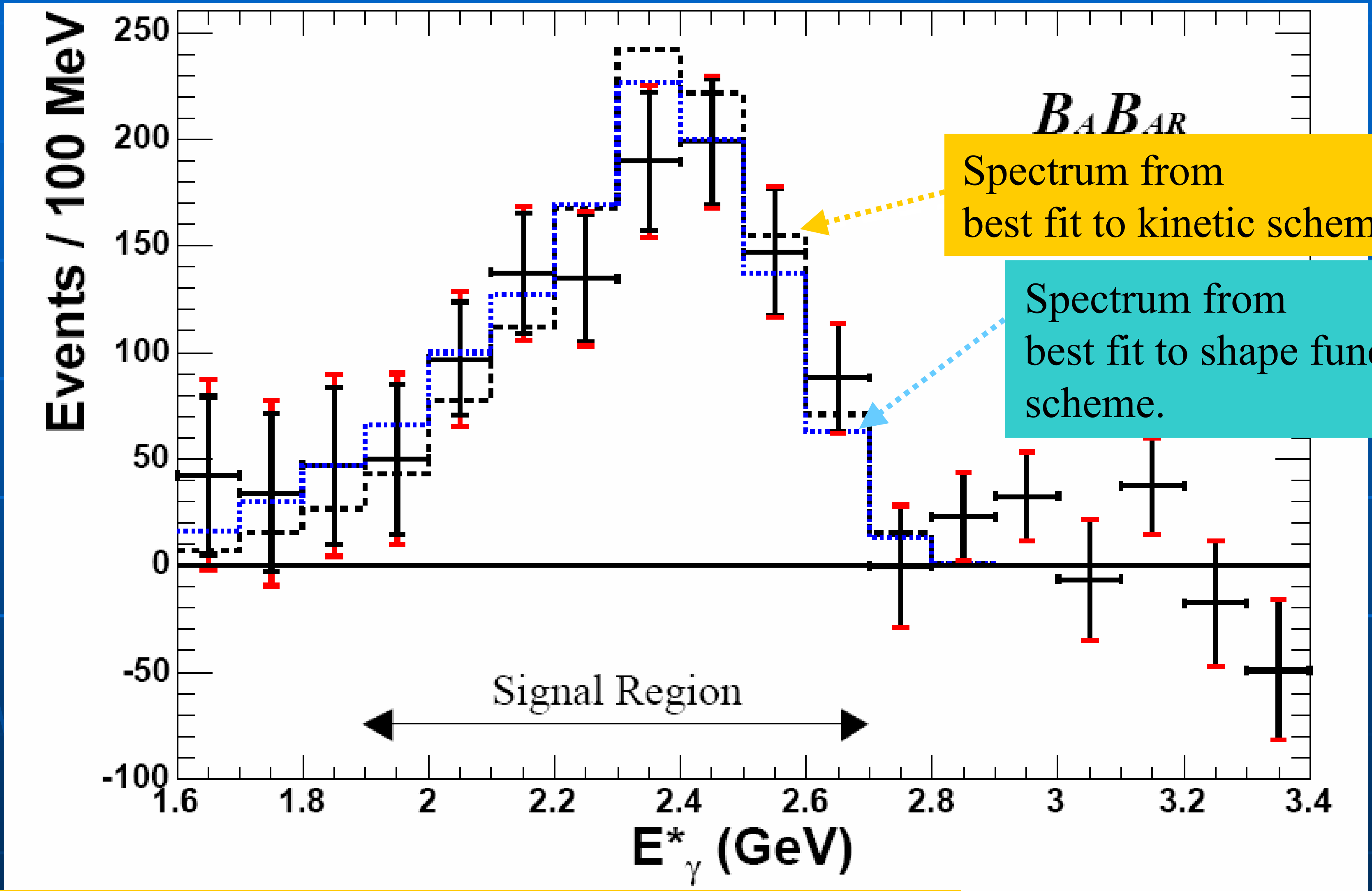
Component	%
π^0	64
η^0	17
$\bar{n}$	8
$e^\pm$	4
ω & η'	3
Other	4

Each BB component measured independently in data. Precision of these measurements is dominant systematic.

BABAR Fully Inclusive B→ X_s γ, w/lepton tag

(PRL Oct 23 2006)

88.5×10^6 $B\overline{B}$ events



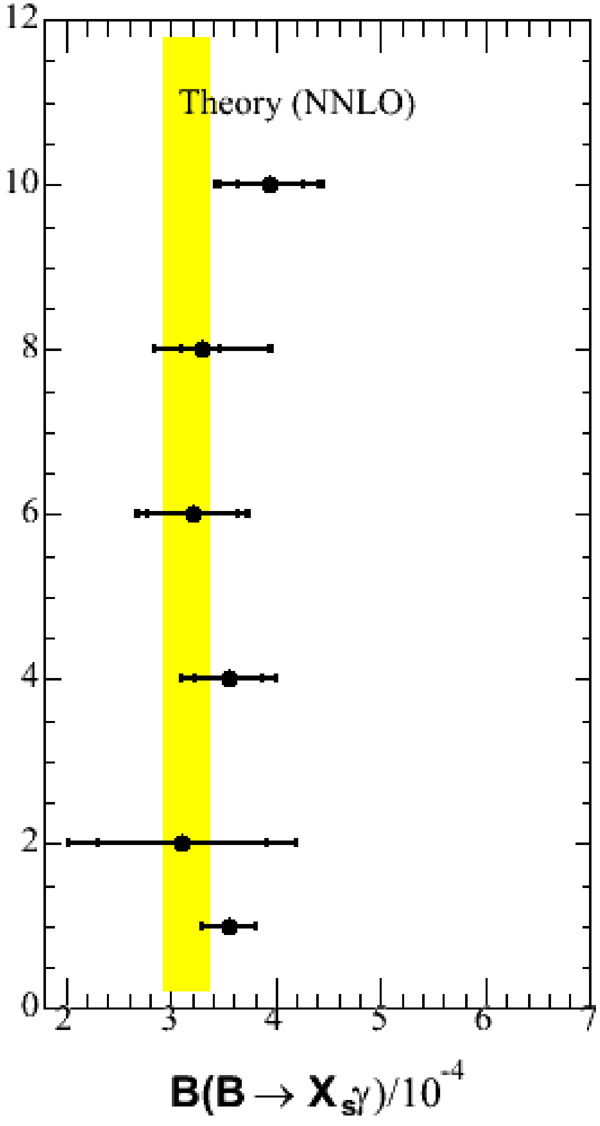
Spectrum from best fit to kinetic scheme.

Spectrum from best fit to shape function scheme.

$B(B \rightarrow X_s\gamma) = (3.67 \pm 0.29 \pm 0.34 \pm 0.29) \times 10^{-4}$ $E_\gamma > 1.9$ GeV (measured)

$B(B \rightarrow X_s\gamma) = (3.94 \pm 0.31 \pm 0.36 \pm 0.21) \times 10^{-4}$ $E_\gamma > 1.6$ GeV (extrapolated, kinetic scheme)

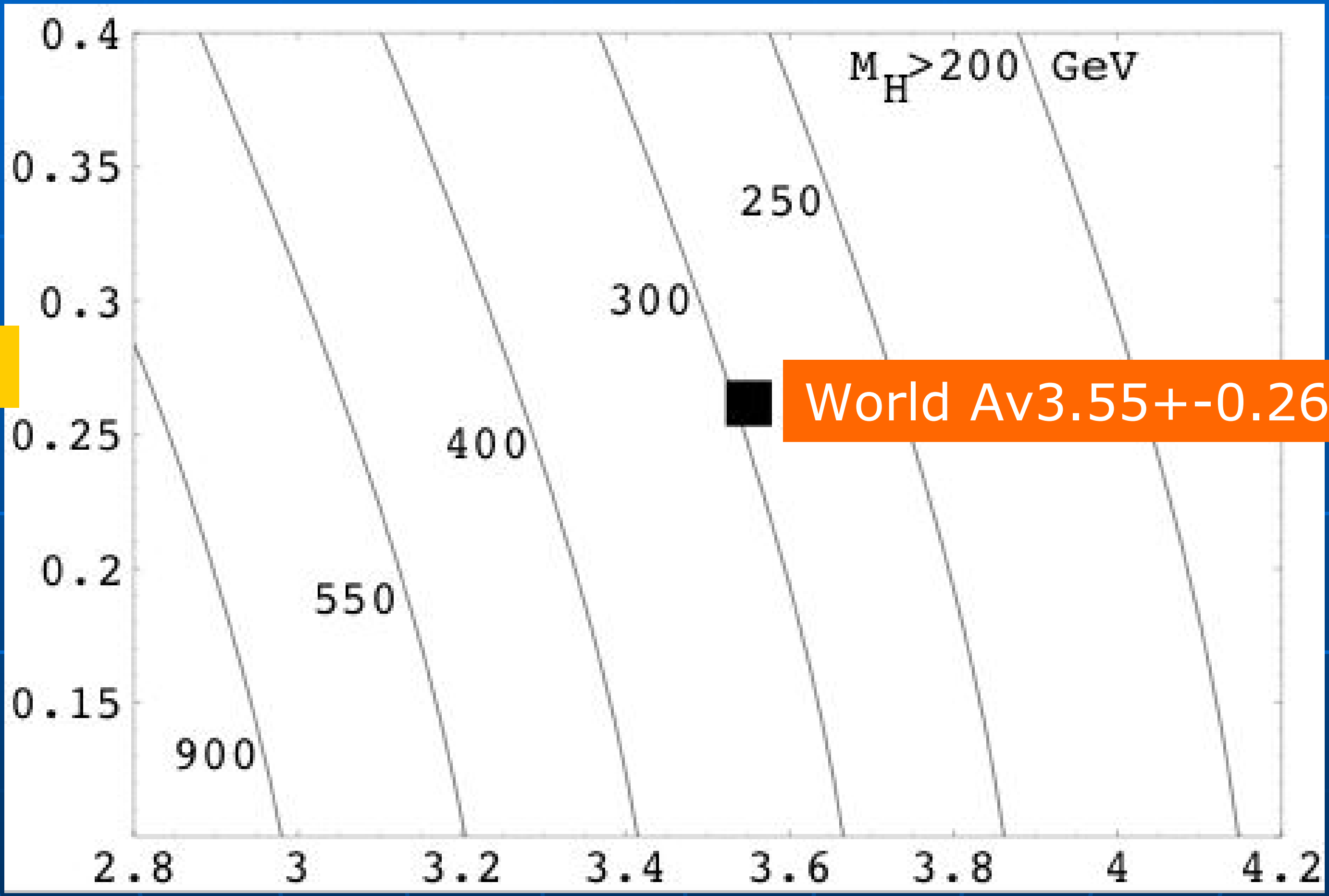
Summary of *B*→ *Xs* g Branching Fraction Measurements



	B ± stat ± syst ± theo / 10
BaBar inc.	$3.94 \pm 0.31 \pm 0.36 \pm 0.21$
BaBar semi.	$3.29 \pm 0.18^{+0.62+0.07}_{-0.40-0.08}$
CLEO	$3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10}$
BELLE	$3.55 \pm 0.32^{+0.30+0.11}_{-0.31-0.07}$
ALEPH	$3.11 \pm 0.80 \pm 0.72$
World Av.	3.55 ± 0.26

Theory is NNLO prediction (2006) $B(B \to X_s\gamma) = 3.15 \pm 0.23 \times 10^{-4}$

B(B-X$_s\gamma$) constraints many models



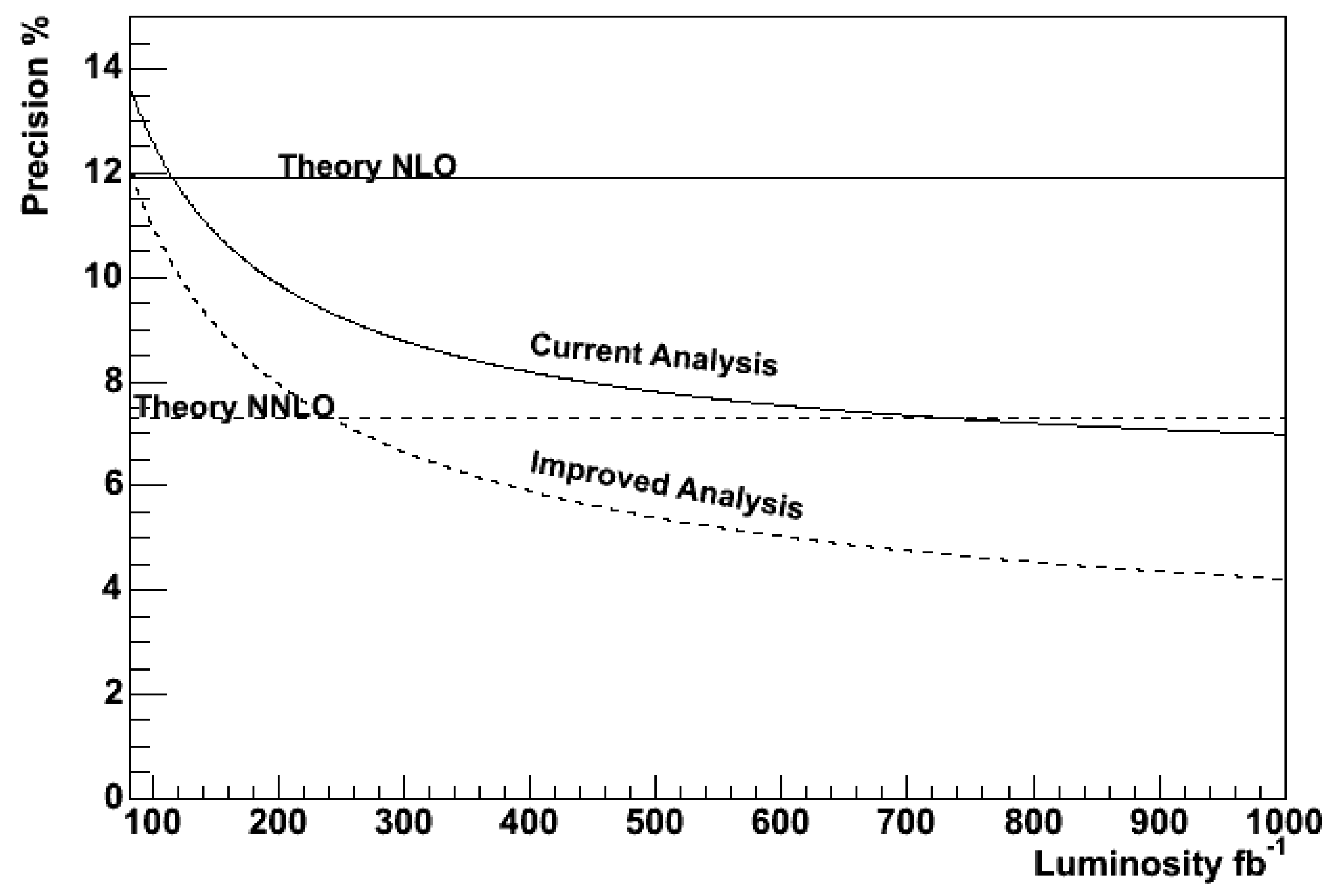
Error x 10^{-4}

World Av3.55+-0.26 x 10^{-4}

B(B->X$_s\gamma$) x 10^{-4}

Example: Two Higgs doublet model M_{H+}>300 GeV cf. direct search > 79.3 Ge

Future Precision of B(B->X$_s\gamma$)



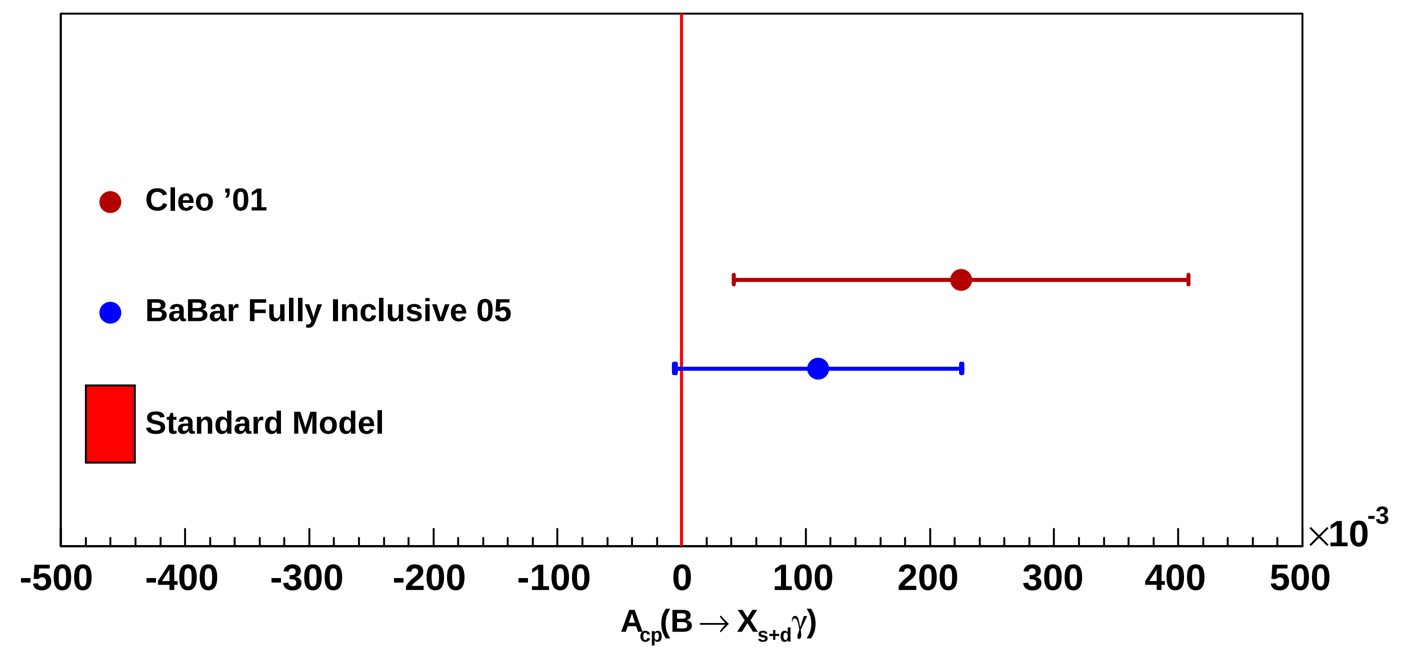
Expect 5% precision from full dataset

Direct CP asymmetry is sensitive to non MFV SUSY

$$A_{cp}(B \to X_{s+d}\gamma) = \frac{\Gamma(\bar{B} \to X_{s+d}\gamma) - \Gamma(B \to X_{s+d}\gamma)}{\Gamma(\bar{B} \to X_{s+d}\gamma) + \Gamma(B \to X_{s+d}\gamma)}$$

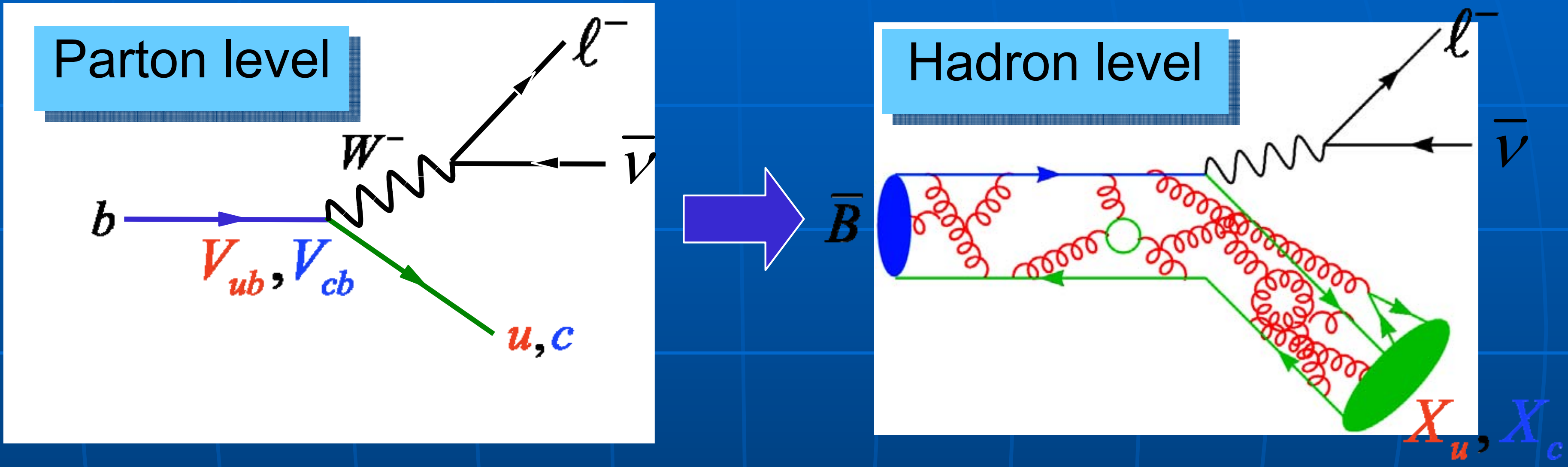
Fully-Inclusive: Lepton charge tags flavor. Dilution from mixing.

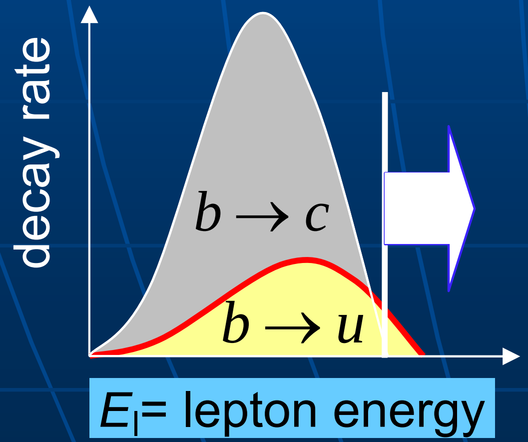
$$A_{cp}(B \to X_{s+d}\gamma) = -0.110 \pm 0.115(stat) \pm 0.017(sys)$$



Asymmetry consistent with Standard Model and previous measurements

Extracting V_{bc} and V_{bu}





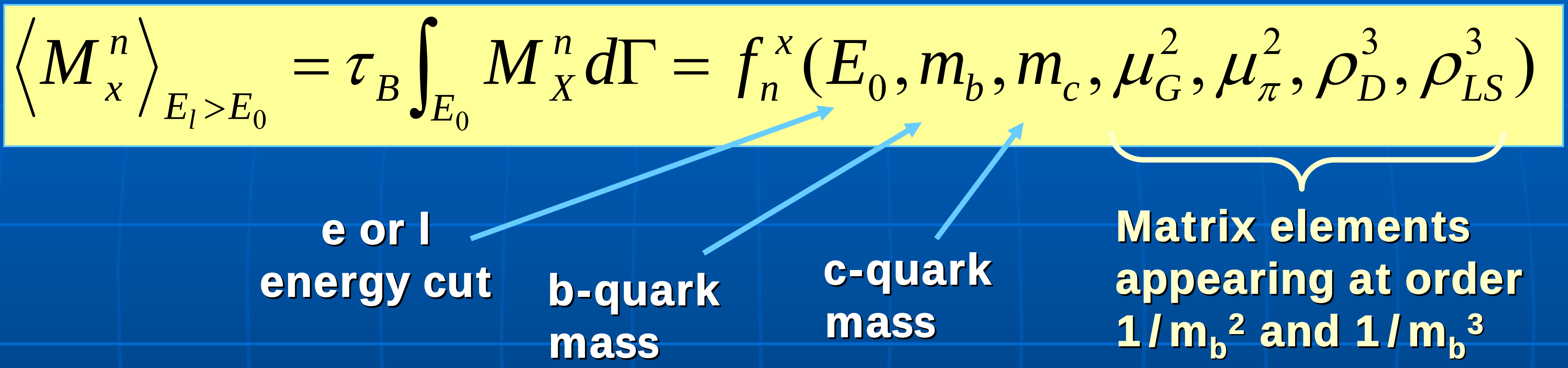
Use inclusive measurements of lepton spectra

Motion of b quark is dominant theoretical Uncertainty

Use B->$X_s\gamma$ to significantly increase precision

Moments

- Fit predicted moments of inclusive processes b→clν and b→sγ for various cuts on kinematic variables in HQE:



$$\left\langle M_x^n \right\rangle_{E_l>E_0} = \tau_B \int_{E_0} M_X^n \, d\Gamma = f_n^x(E_0, m_b, m_c, \mu_G^2, \mu_\pi^2, \rho_D^3, \rho_{LS}^3)$$

e or l energy cut

b-quark mass

c-quark mass

Matrix elements appearing at order $1/m_b^2$ and $1/m_b^3$

- Calculations available in "kinetic" and "1S" renormalization schemes

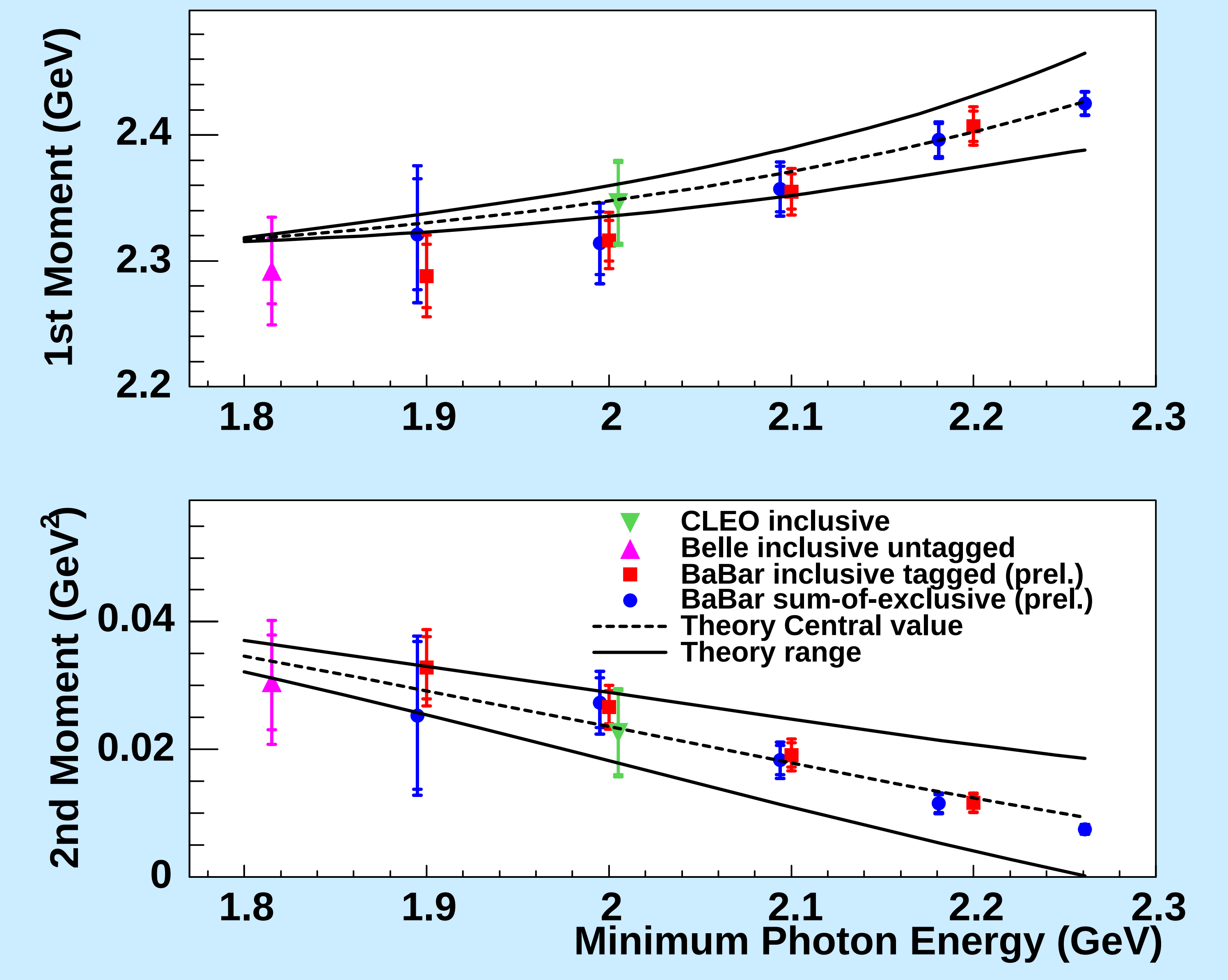
Benson, Bigi, Gambino, Mannel, Uraltsev
(several papers)

Bauer, Ligeti, Luke, Manohar, Trott
PRD 70:094017 (2004)

- 47 measured moments used from DELPHI, CLEO, BABAR, BELLE, CDF (and, of course, the B lifetime)

Results: Spectrum Moments vs E_γ

most precise moments from BaBar fully inclusive



Curves are theory prediction using measured b->Xclv moments

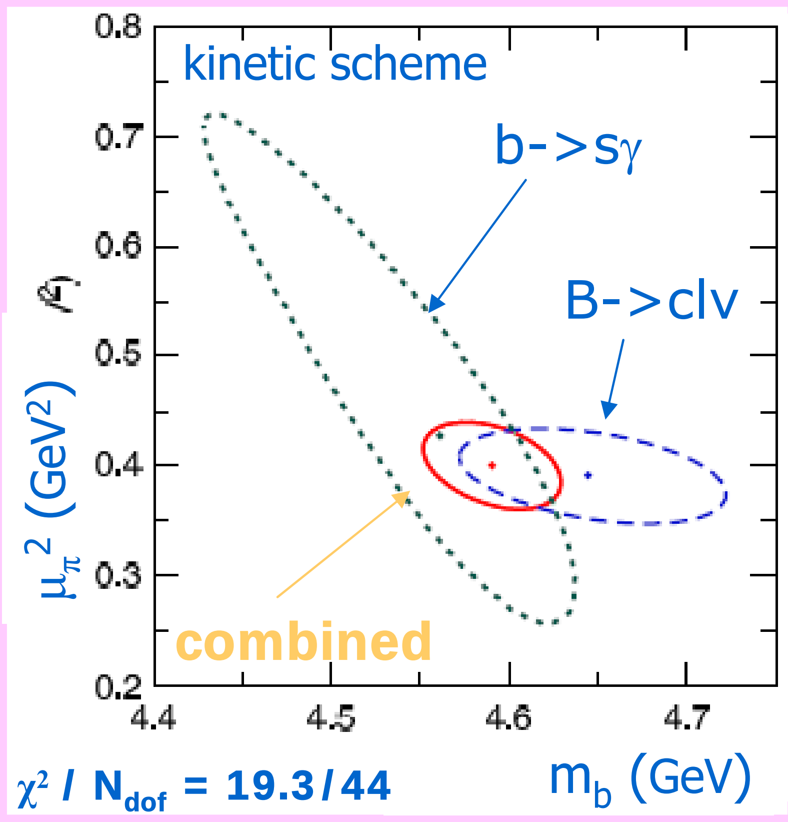
Demonstrates assertion that b quark motion is universal

Extraction of V_{bc}, m_b, μ_π

$\lvert V_{cb}\rvert$ (10^{-3})	$41.96 \pm 0.23_{exp} \pm 0.35_{HQE} \pm 0.59_{\Gamma SL}$
$m_{b\,[kin]}$ (GeV)	$4.59 \pm 0.025_{exp} \pm 0.030_{HQE}$
$\mu_\pi^2{}_{[kin]}$ (GeV^2)	$0.401 \pm 0.019_{exp} \pm 0.035_{HQE}$

$\lvert V_{cb}\rvert$ determined to <2%

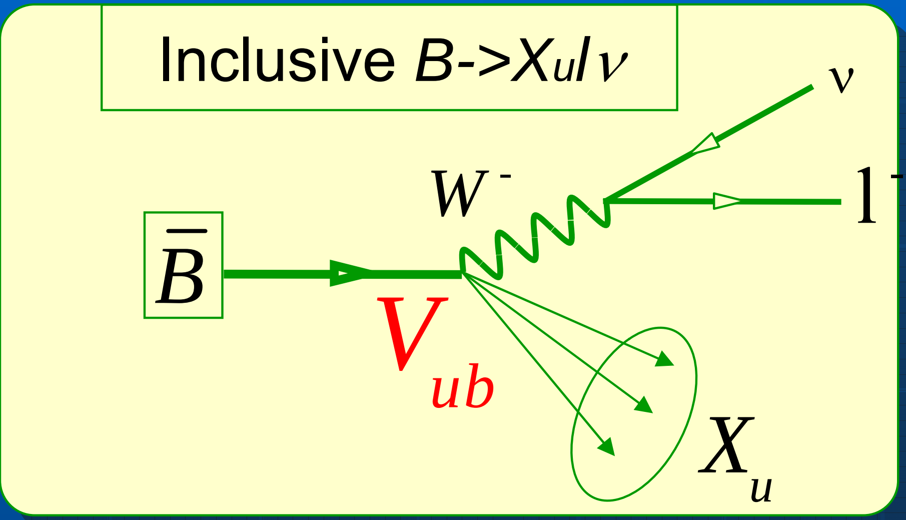
m_b to 1%;
crucial for $\lvert V_{ub}\rvert$



Buchmüller and Flächer, PRD 73: 073008 (2006)

[kin]/[1S] values agree after scheme translation

Extracting V_{ub}



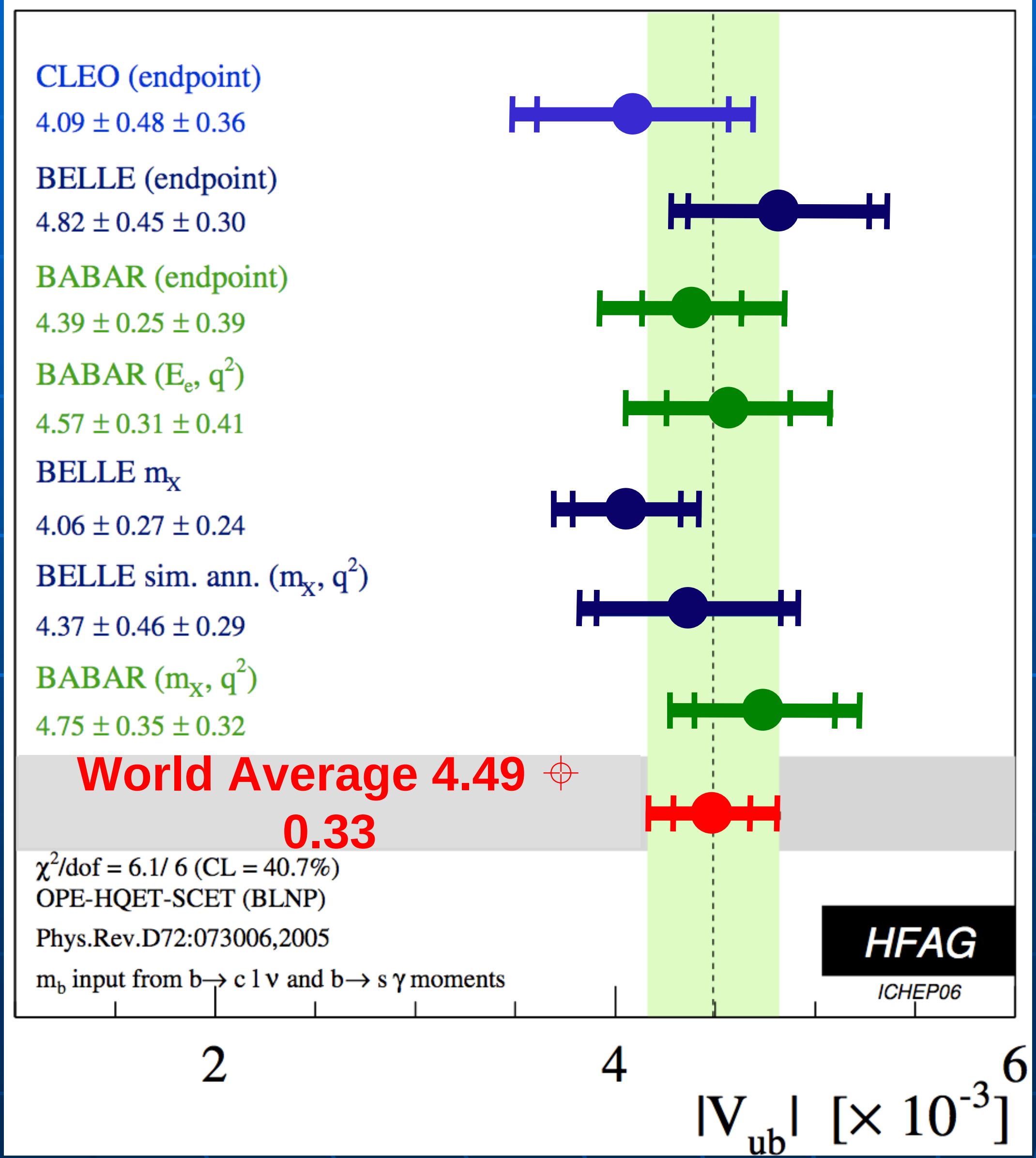
Inclusive $B \to X_u l \nu$

$$\Gamma(B \to X_u l \nu) = \frac{G_F |V_{ub}|^2 m_b^5}{192\pi^3}\left[1 - O\left(\frac{\alpha_s}{\pi}\right) - O\left(\frac{\Lambda_{QCD}^2}{m_b^2}\right) + \ldots\right]$$

m_b enters as m_b^5 so 1% error in m_b gives 2.5% error in V_{ub}

Other HQE parameters estimated from $B \to X_s\gamma$ enter into non-perturbative terms

$|V_{ub}|$ from B->Xlν



Statistical	±2.2%
Expt. syst.	±2.8%
B->Xclν model	±1.9%
B->Xulν model	±1.6%
Theory	±5.9%

Error dominated by theory (m_b and HQE parameter estimation)

7.2% error down from 15% in 2003. 5% ultimately

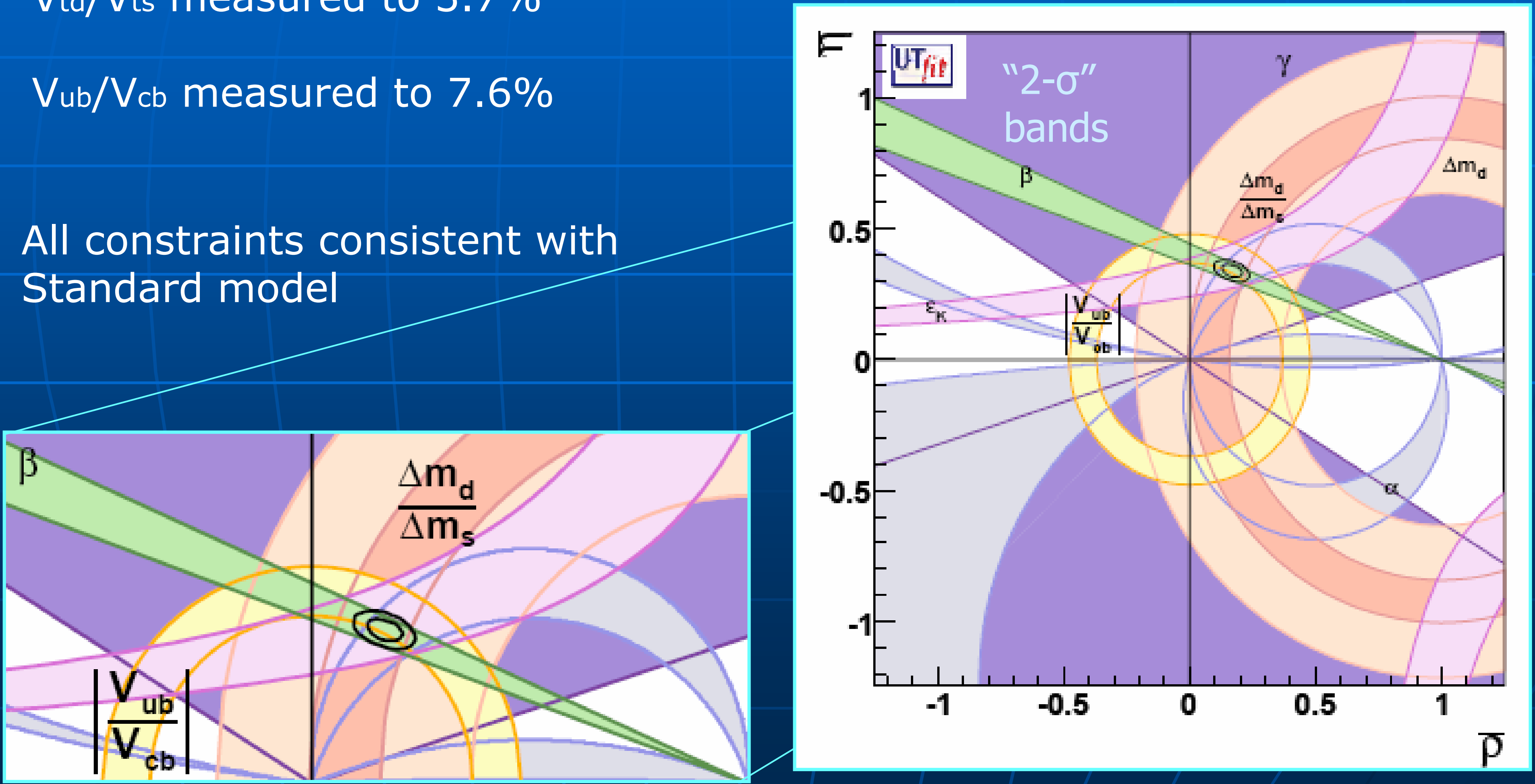
Current status of Unitarity Triangle

sin(2β) measured to 4.7%

V_{td}/V_{ts} measured to 3.7%

V_{ub}/V_{cb} measured to 7.6%

All constraints consistent with Standard model



Summary

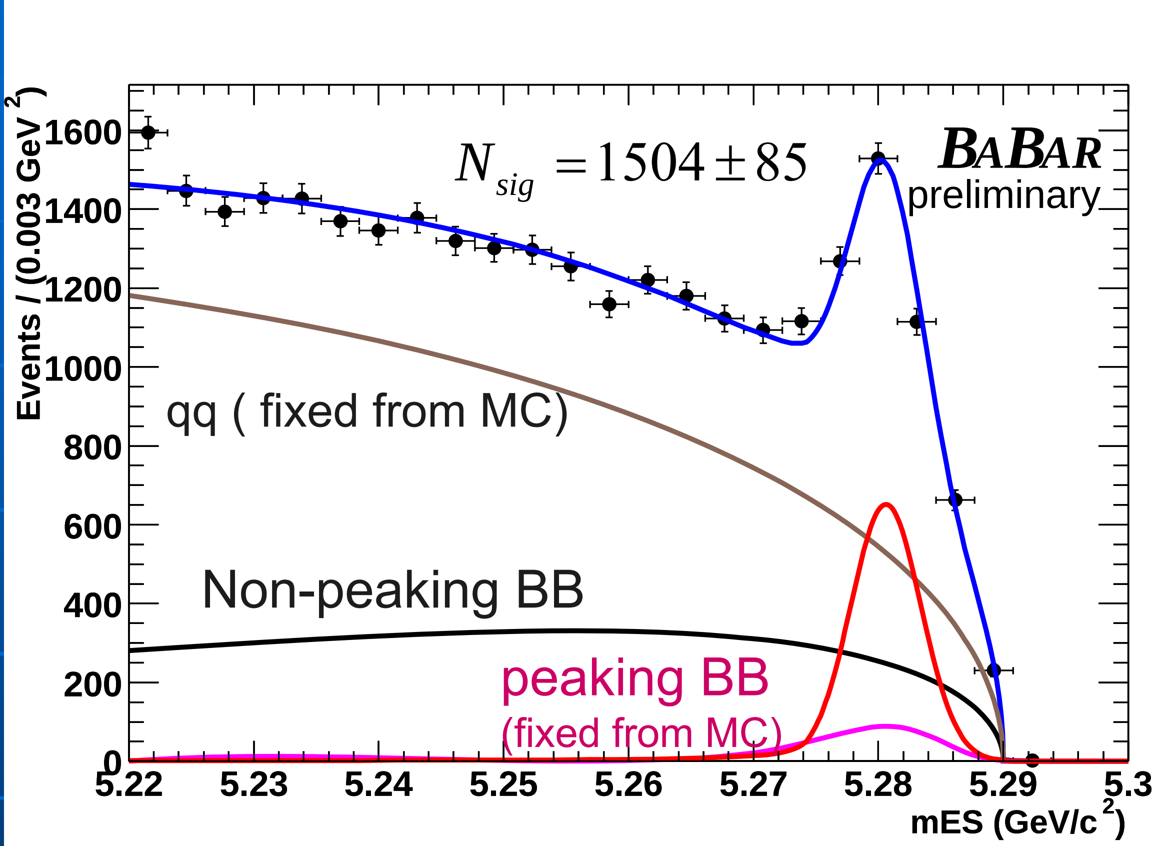
Large datasets have allowed us to catalog the rare penguin decays

Penguins contributing to precision measurement of the triangle

precision measurements of $b \to s\gamma$ strongly constrains new physics

Backup Slides

Technique 1 – Semi-Inclusive



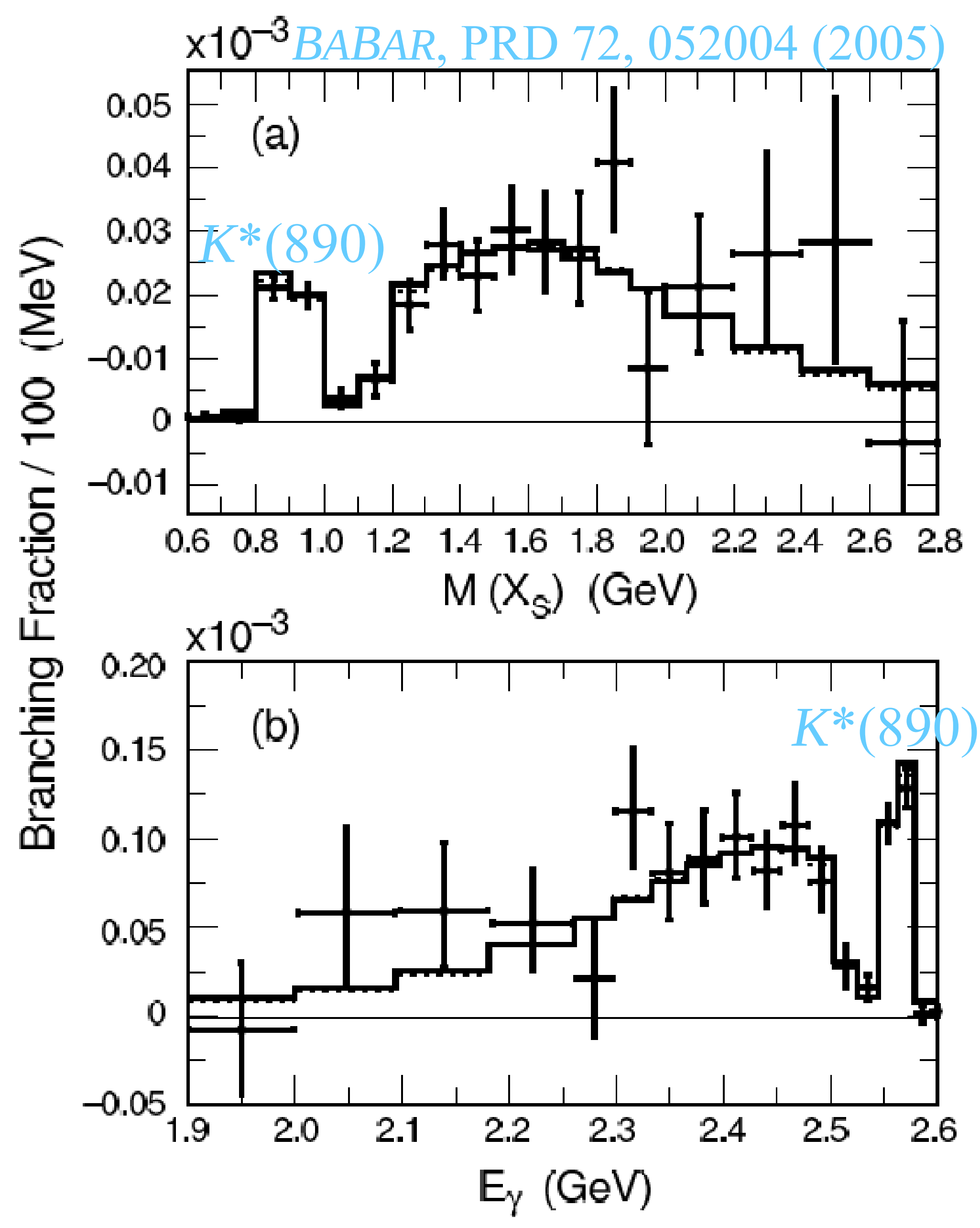
$$E_\gamma = \frac{m_B^2 - m_{Xs}^2}{2m_B}$$

Reconstruct in bins of M_{Xs} and convert to Eγ

Multicomponent fit to extract signal

Dominant systematic is modelling missing final states

BABAR B→ $X_s\,\gamma$ with Sum of Exclusive Final States


BABAR, PRD 72, 052004 (2005)

Energy Range	Branching Fraction (10^{-4})
E_γ >1.9 GeV	$3.27 \pm 0.18^{+0.55+0.04}_{-0.40-0.09}$
E_γ >1.6 GeV (extrapolated)	$3.35 \pm 0.19^{+0.56+0.04}_{-0.41-0.09}$

- averages over two shape-function schemes
- errors: stat, sys, variation of shape fcn params

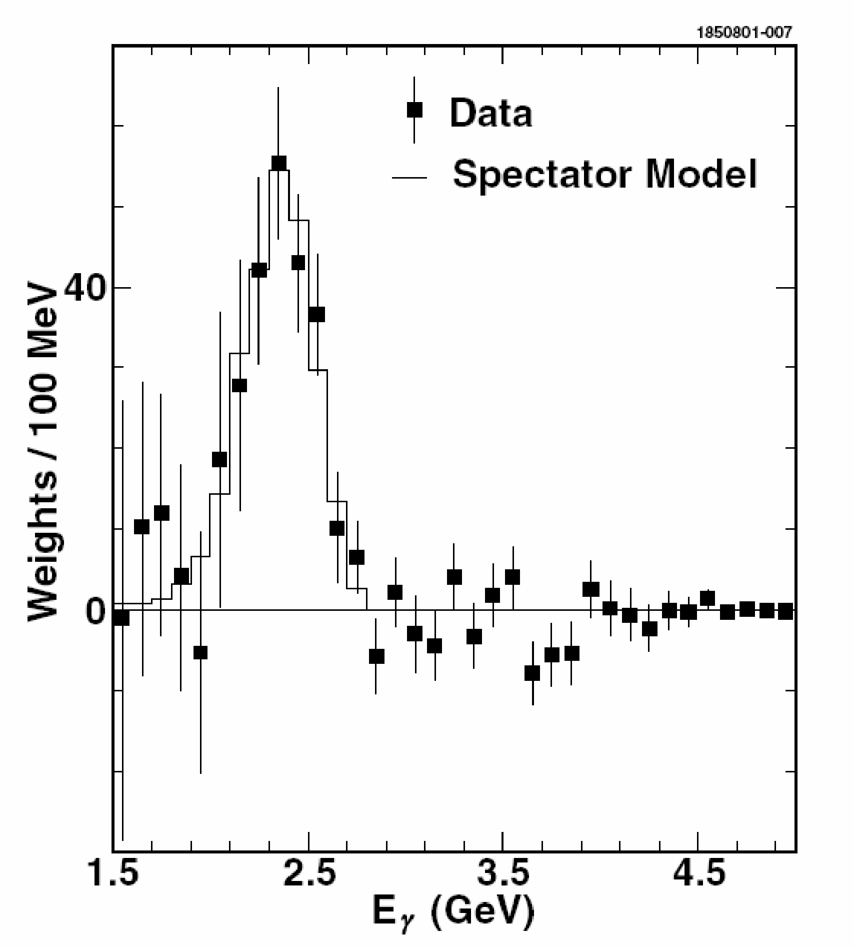
E_γ Moments	Value (GeV or GeV²)
$\left\langle E_\gamma \right\rangle$	$2.321 \pm 0.038^{+0.017}_{-0.038}$
$\left\langle E_\gamma^2 \right\rangle - \left\langle E_\gamma \right\rangle^2$	$0.0253 \pm 0.0101^{+0.0041}_{-0.0028}$

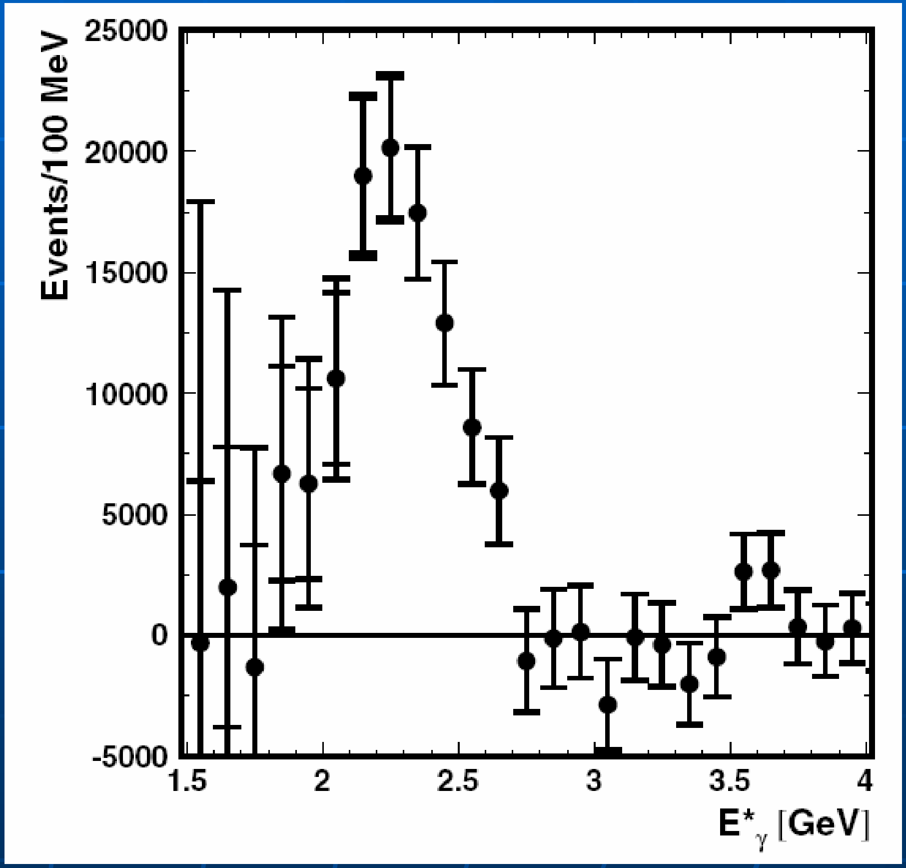
- E_γ (min) = 1.897 GeV

Other Results on Fully inclusive $B \to X_s \gamma$

CLEO, PRL 87, 215807 (2001), 9.1 fb-1

Belle, PRL 87, 061803 (2004), 140 fb^{-1}
Belle, hep-ex/0508005





$$BF = (3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10}) \times 10^{-4}$$

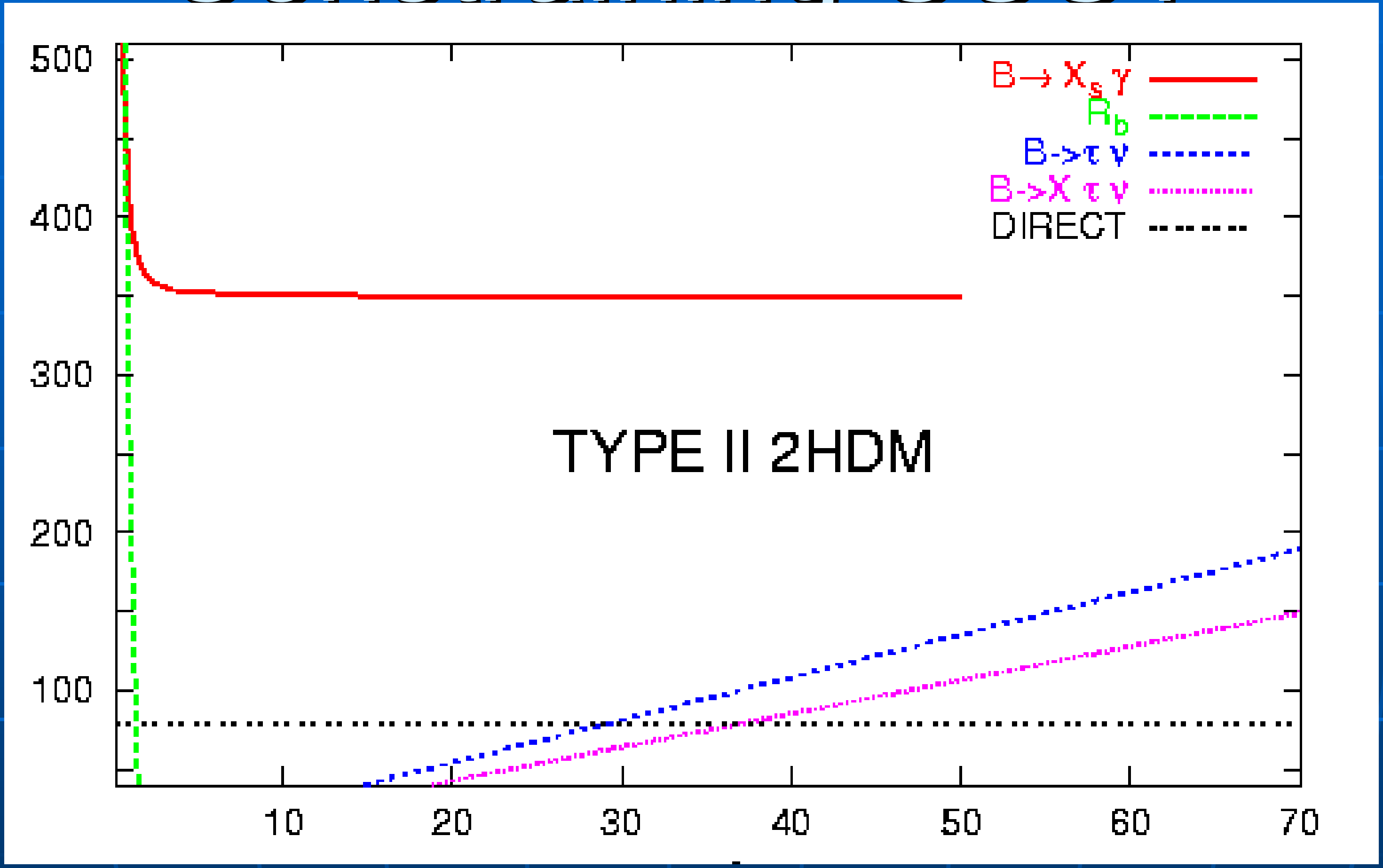
Measure for $E_\gamma > 2.0$; extrap. to $E_\gamma > 0.25$ GeV

$$BF = (3.55 \pm 0.32^{+0.30+0.11}_{-0.31-0.07}) \times 10^{-4}$$

Measure for $E_\gamma > 1.8$ GeV; extrap. to full

Constraining SUSY

M_{H^+}

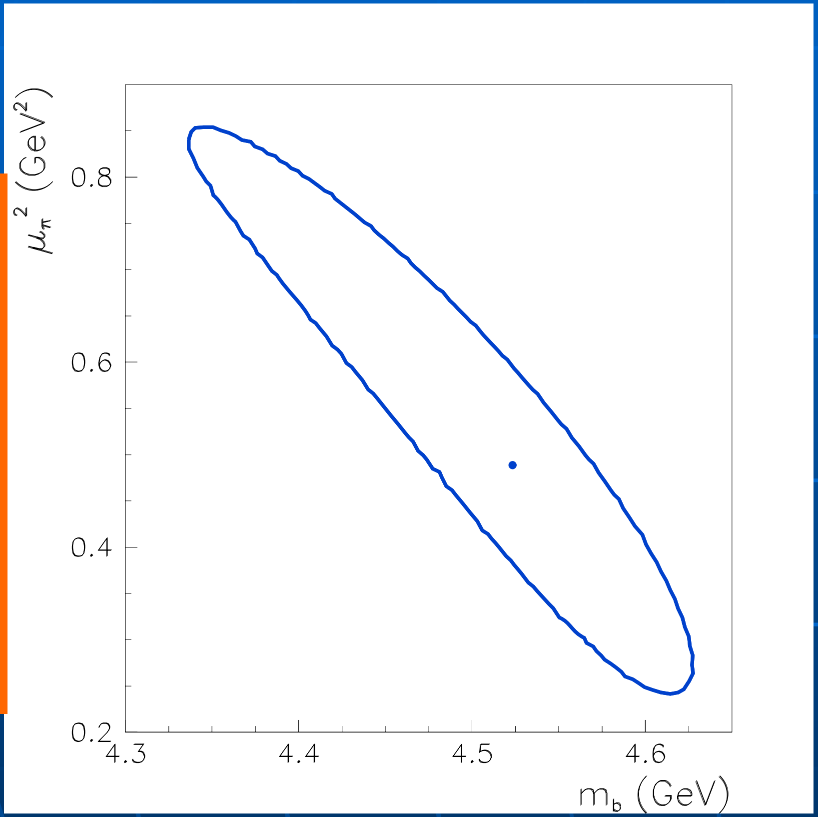


tan(β)

Excludes $M_{H+} < 300$ GeV independent of coupling
(4x range of direct searches)

m_b and μ_π from b->sγ

"Kinetic Scheme" (Benson,Bigi and Uraltsev)



Fermi -momentum

Mass of b quark (GeV)

Fit to moments in kinetic scheme scheme to obtain μ_π and m_b

Ellipse because of correlations between first and second moments

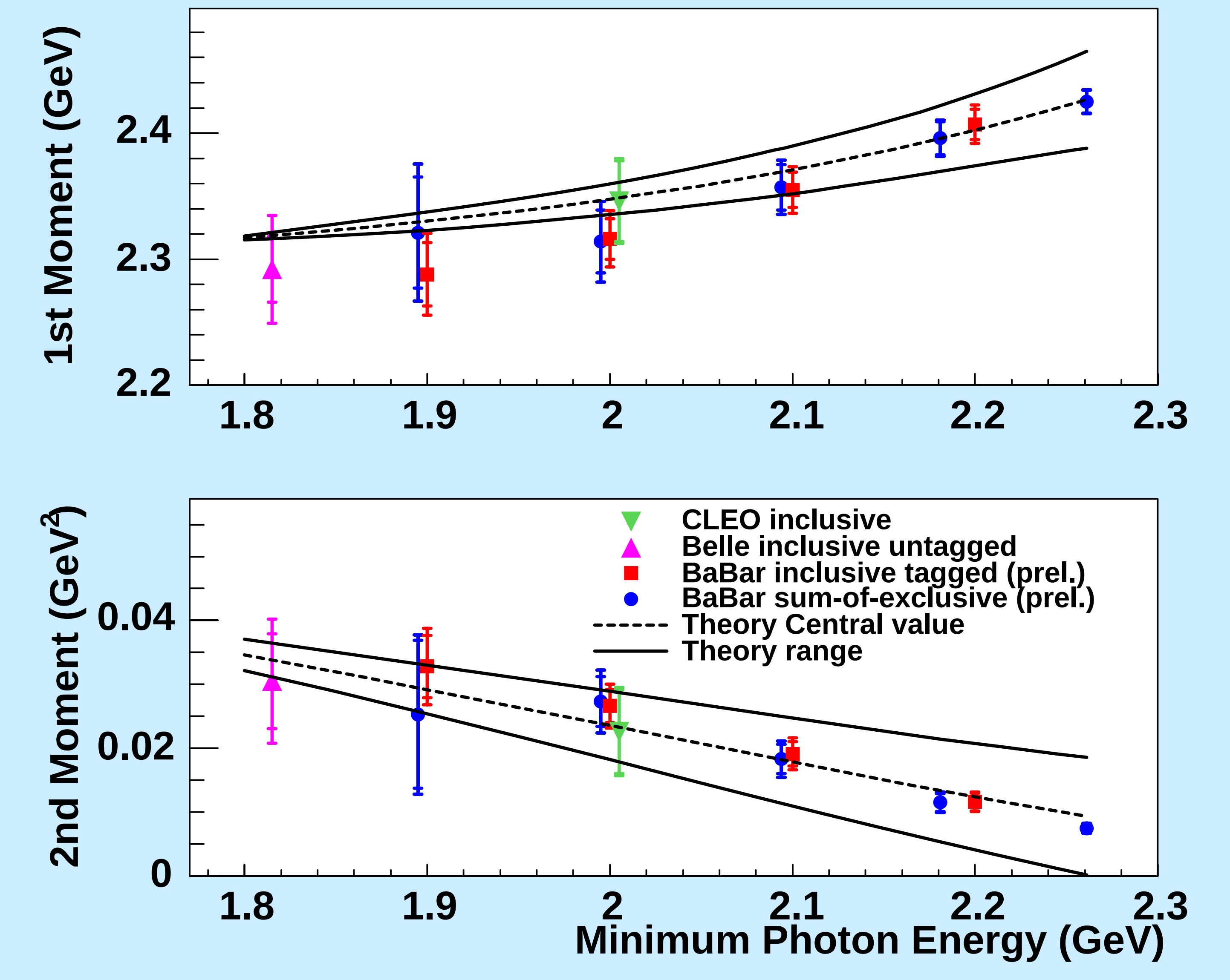
Fit includes theory errors

Results: Moments

$$\left\langle E_\gamma^B \right\rangle \approx \frac{m_b}{2}$$

$$\left\langle E_\gamma^{B2} \right\rangle - \left\langle E_\gamma^B \right\rangle^2 \approx \mu_\pi^2$$

(kinetic energy of b)^2



Theory is Bigi,Benson and Uraltsev (Nucl Phys B 710 371 2005) using BaBar measured B->Xclν moments PRL 93 011803 2004

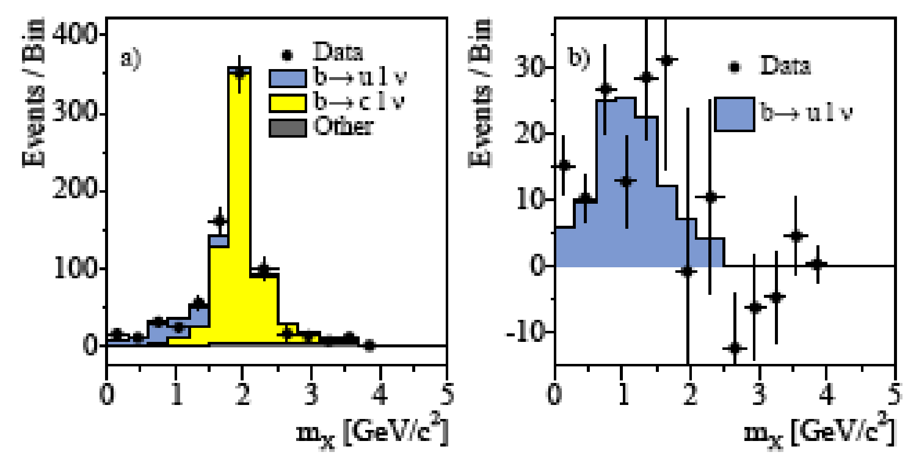
$m_B = 4.6GeV, \mu_\pi^2 = 0.45GeV^2$

Curves are theory prediction using measured b->Xclv moments

b->sγ and V_{ub}

V_{ub} is extracted from inclusive B->$X_u$lv decays. Photon spectrum from b->sγ helps reduce the uncertainty in determination.

e.g. BaBar result: PRL 96:221801 (2006)



Fully reconstruct recoiling B and
Study semileptonic decay Mx in B->$X_u$lv

$$\text{Relate } \int_0^{m_{\max}} \frac{d\Gamma_{b\to u}}{dm_X}\, dm_X \text{ to } \int_{E_{\min}}^{m_B/2} \frac{d\Gamma_{b\to s\gamma}}{dE_\gamma} W(E_\gamma, E_{\min})\, dE_\gamma$$

$|V_{ub}|=(4.43 \pm 0.38(\text{stat.}) \pm 0.25(\text{sys.}) \pm 0.29(\text{theory}) \times 10^{-3}$