日本物理学会　2004年秋季大会
素粒子実験シンポジウム
“2009年 日本の素粒子実験”

Super−B での物理

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2004年9月28日　於 高知大学

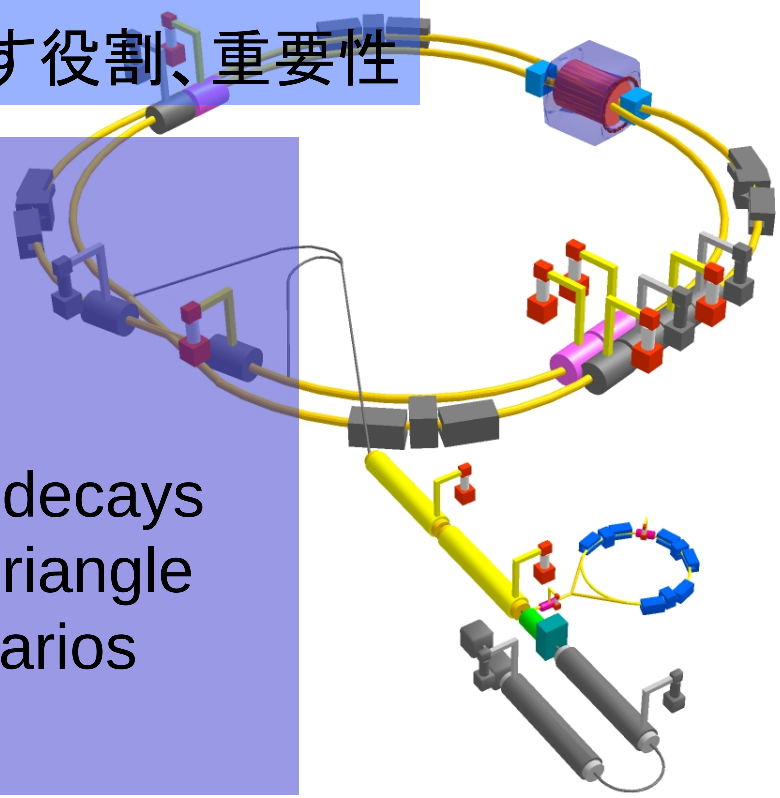
トークの内容

Super-KEKB target luminosity = $5\times10^{35}cm^{-2}s^{-1}$

$5ab^{-1}$, ~ 5×10^{9} BB & $\tau^{+}\tau^{-}$ / year !!

これで何がいつ頃できるか？
今後10年の素粒子研究に果たす役割、重要性

- Introduction
- New CPV phase in b→sqq
- b→sγ, b→sll
- Higgs Search in B→τX
- Lepton Flavor Violation in τ decays
- Precision Test of Unitarity Triangle
- Study of New Physics Scenarios
- Summary



Letter-of-Intent submitted to LCPAC’04 (KEK Report 04-4)

“我々の夢(目標)”

新しい素粒子世界の
発見と構築

Discovery ⇒ Investigation
Contents ⇒ Structure

発見だけでは道半ば。。。

LHC開始後の計画では
この観点が重要。

“New Standard Model”の確立へ

SUSY

- Well motivated by NP at O(1) TeV
  Hierarchy problem, fine-tuning…/Explain EWSB…/Explain GUT…/Provide Dark matter candidate…etc.
- May explain baryon asymmetry
  (SM CPV is too small)…

1 st target = Discovery
LHC ? ILC?
Super-B ?

GUT 10^{15} GeV

$\mathcal{L}_{MSSM} + \mathcal{L}_{soft}$ 1 TeV

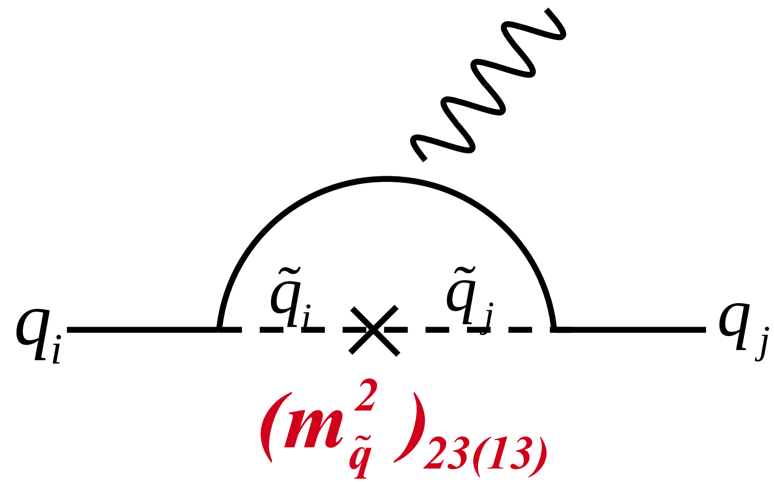
SM 100 GeV

2 nd target = Identification of SUSY breaking mechanism (investigation)
Constraint from Flavor Physics
(already strong)

Investigating SUSY

- MSSM parameters > 100 ! Mass+mixing angle+phase
- The squark/slepton mass matrix
  - Sensitive to SUSY breaking mechanism.
  - New sources of flavor mixing ⟹ **Baryon asymmetry ?**

$$\left(m^2_{\tilde{q}}\right)_{ij} = \begin{pmatrix} m^2_{11} & m^2_{12} & m^2_{13} \\ m^2_{21} & m^2_{22} & m^2_{23} \\ m^2_{31} & m^2_{32} & m^2_{33} \end{pmatrix}$$

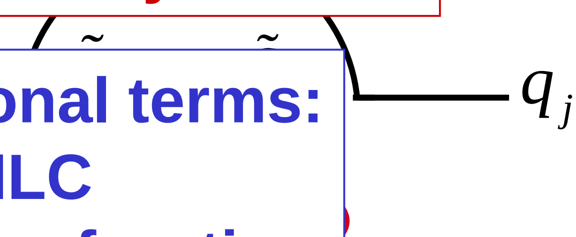


Investigating SUSY

- MSSM parameters > 100 ! Mass+mixing angle+phase
- The squark/slepton mass matrix
  - Sensitive to SUSY breaking mechanism.
  - New sources of flavor mixing → **Baryon asymmetry ?**

$$\left(m_{\tilde{q}}^2\right)_{ij} = \begin{pmatrix} m_{11}^2 & m_{12}^2 & m_{13}^2 \\ m_{21}^2 & m_{22}^2 & m_{23}^2 \\ m_{31}^2 & m_{32}^2 & m_{33}^2 \end{pmatrix}$$

Off-diagonal terms
Flavor Physics
Luminosity frontier



Diagonal terms:
LHC/ILC
Energy frontier

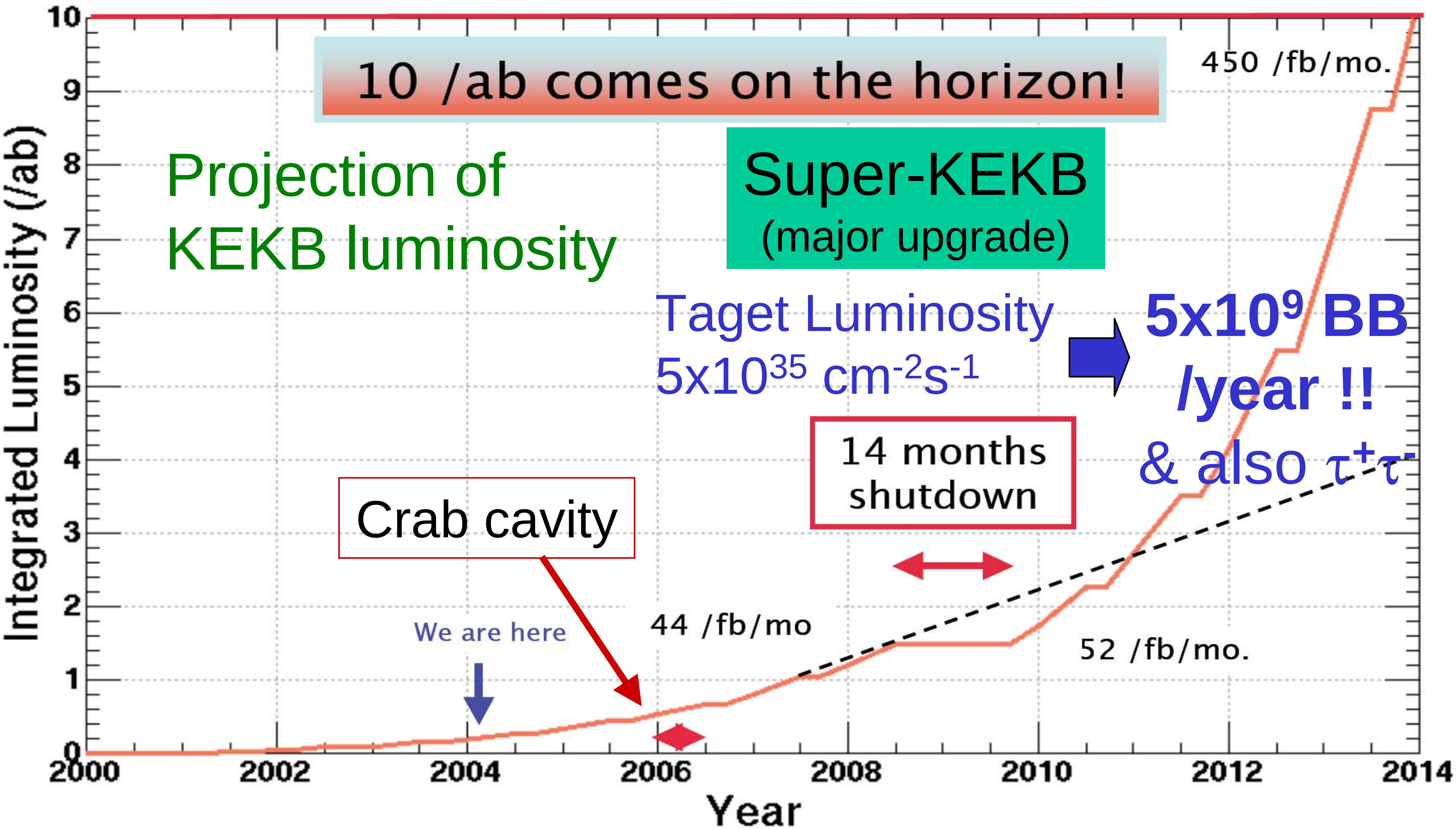
Physics at Super-B = SUSY Flavor Physics

Its importance is independent of LHC results.

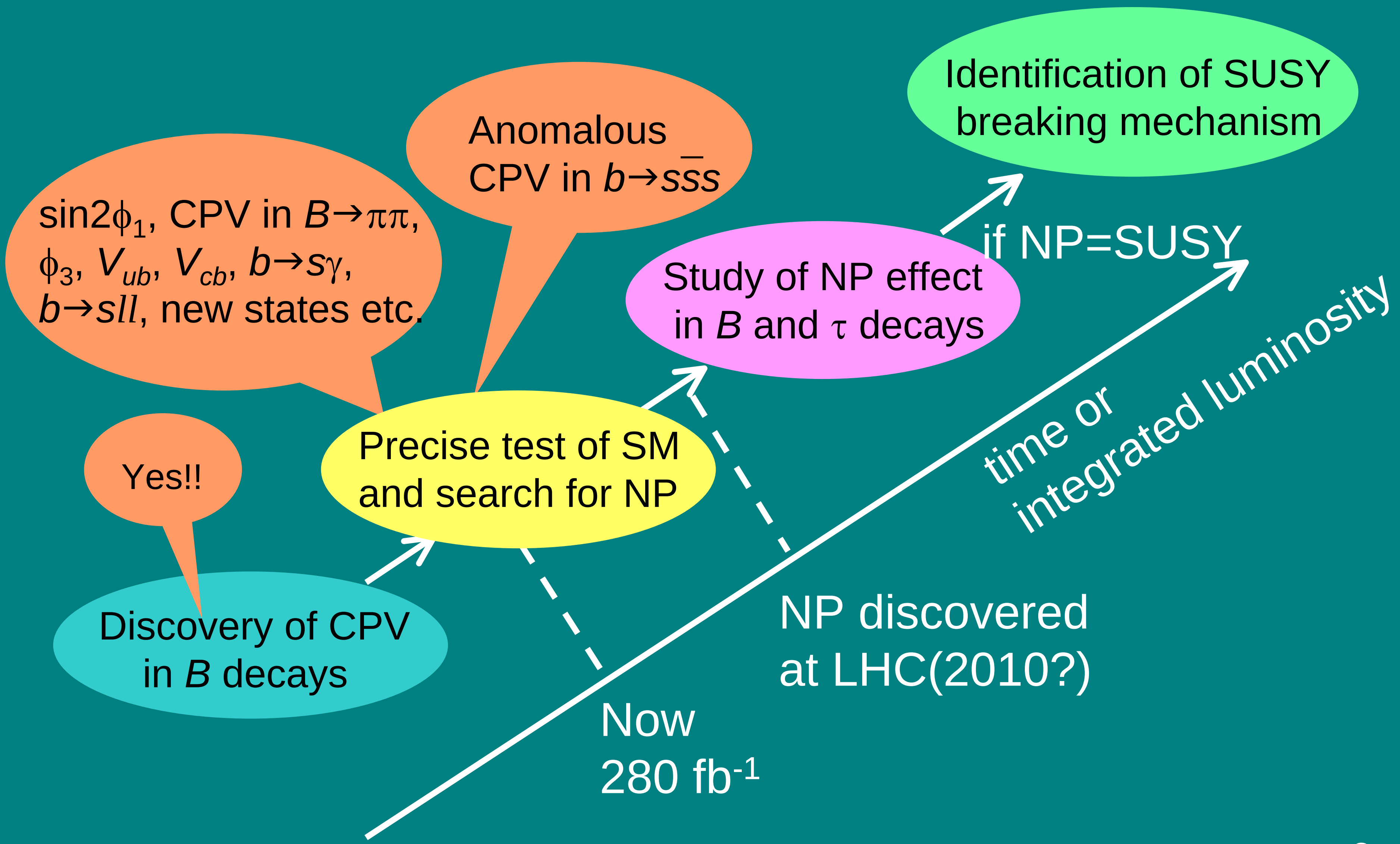
(V_{CKM} could not be pin down only with energy frontier)

Super-KEKB

L_{peak} ($cm^{-2}s^{-1}$)	1.4×10^{34}	5×10^{34}	5×10^{35}
L_{int}	280 fb^{-1}	1 ab^{-1}	10 ab^{-1}



Road Map of Super-B



Physics Program at Super-B

New CPV phase

$B \to \phi K^0, \eta' K^0, \ldots$

$B \to K^* \gamma, X_S \gamma$

FCNC decays

$B \to X_s \gamma$

$B \to K^{(*)} \ell\ell, X_s \ell\ell$

Precision CKM

$\sin 2\phi_1 \ (B \to J/\psi K^0)$

$\sin 2\phi_2 \ (B \to \pi\pi, \rho\pi, \rho\rho)$

$\phi_3 \ (B \to DK)$

$|V_{ub(cb)}| \ (B \to X_{u(c)} \ell \nu)$

LFV decays

$\tau \to \ell \gamma$

$\tau \to \ell\ell\ell, \ell \eta$

Higgs Search

$B \to \tau \nu$

$B \to D^{(*)} \tau \nu$

Global Analysis of B Physics

(Study of New Physics Scenario)

SUSY Models

squark $\left(m^2_{\tilde{d}_R}\right)_{23}$ ⟺ slepton $\left(m^2_{\tilde{l}_L}\right)_{23}$

- **mSUGRA**
  - $\mathfrak{L}$soft is flavor blind
  - KM mixings → mixing in $\tilde{q}_L$

- **SUSY SU(5) w/ ν_R**
  - Large mixing in ν → mixing in $\tilde{d}_R, \tilde{l}_L$
  - KM mixings → mixing in $\tilde{q}_L$

  New CP phase

  Mass of ν_R

  Degenerate — small 2-3 mixing in $\tilde{d}_R$

  Non-degenerate — large 2-3 mixing in $\tilde{d}_R$

- **U(2) flavor symmetry**
  - 1,2 gen. (u,d,c,s,e,μ) — U(2) doblet
  - 3rd gen. (t,b,τ) — U(2) singlet

  → O(λ^2) 2-3 mixing in $\tilde{q}_L$

New CPV phases in $b \to s\bar{q}q$

- CPV in $B \to J/\psi K^0$

$$\sin 2\phi_1 = 0.726 \pm 0.037$$ 2004 W.A. for $b \to ccs$

Not enough to explain the matter-anti-matter asymmetry.

- $b \to s$ loop is the ideal place to look for new CPV phases.

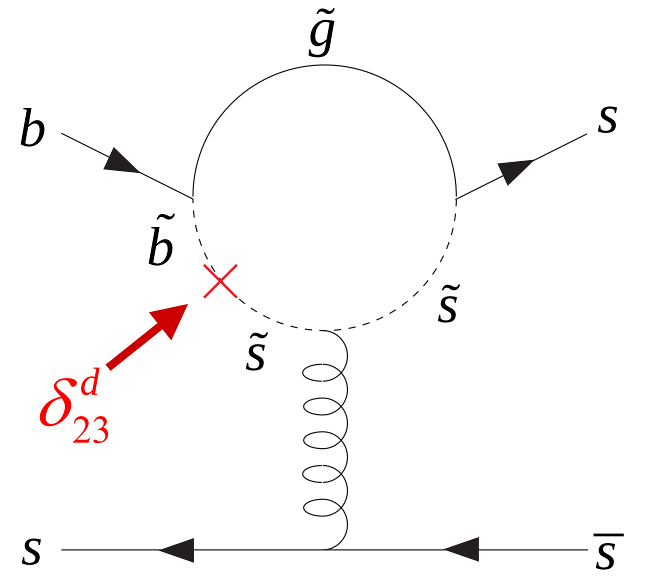
$$B^0 \to \phi K^0, \eta' K^0, K^+ K^- K^0, \ldots$$

  – SM ⇒ no CPV phase in the loop.

$$\sin 2\phi_1 (b \to s\bar{s}s) = \sin 2\phi_1 (b \to c\bar{c}s)$$

  – SUSY ⇒ new CPV phase may appear.

$$\sin 2\phi_1 (b \to s\bar{s}s) \neq \sin 2\phi_1 (b \to c\bar{c}s)$$

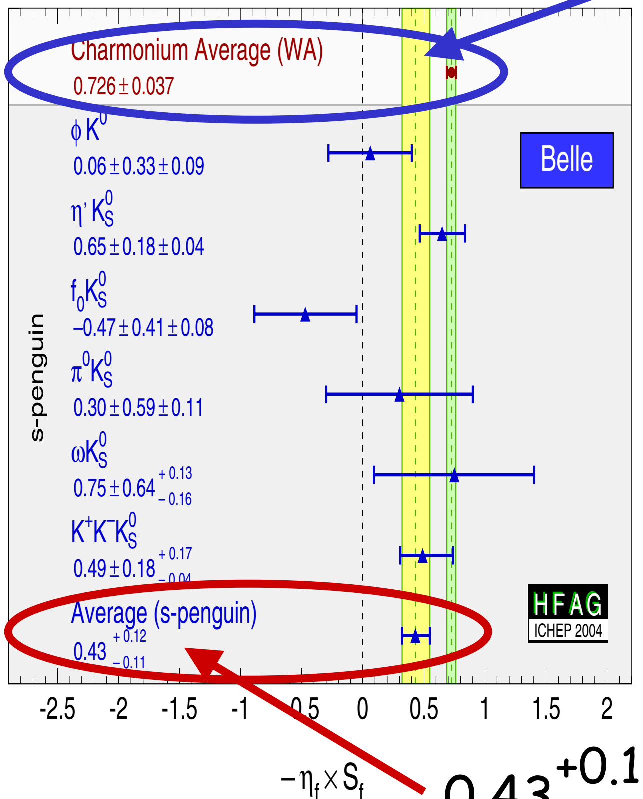


$$A_{CP}(t) \propto \sin 2(\phi_1 + \phi_{NP}) \times \sin(\Delta m_d t)$$

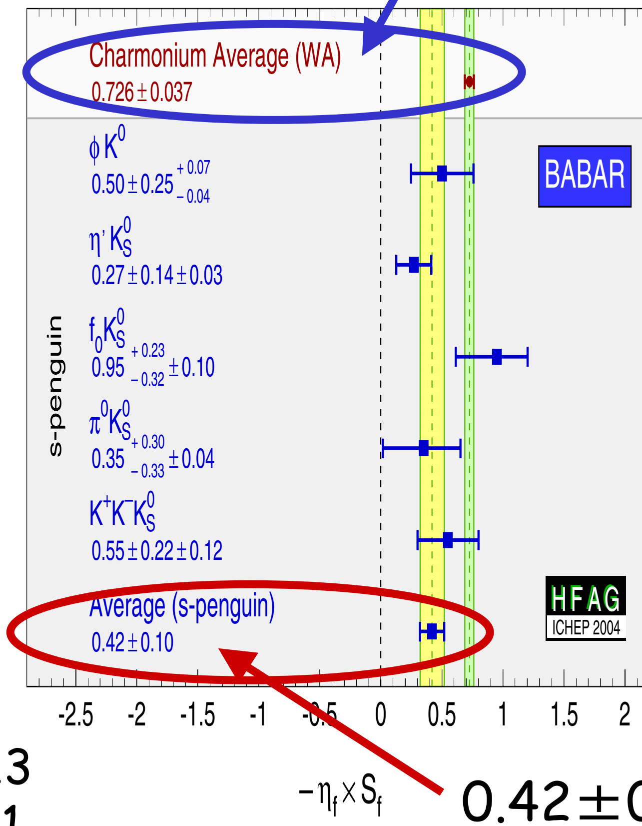
Present Status

Charmonium Average
0.726±0.037

Belle



BaBar



$0.43^{+0.13}_{-0.11}$

0.42 ± 0.10

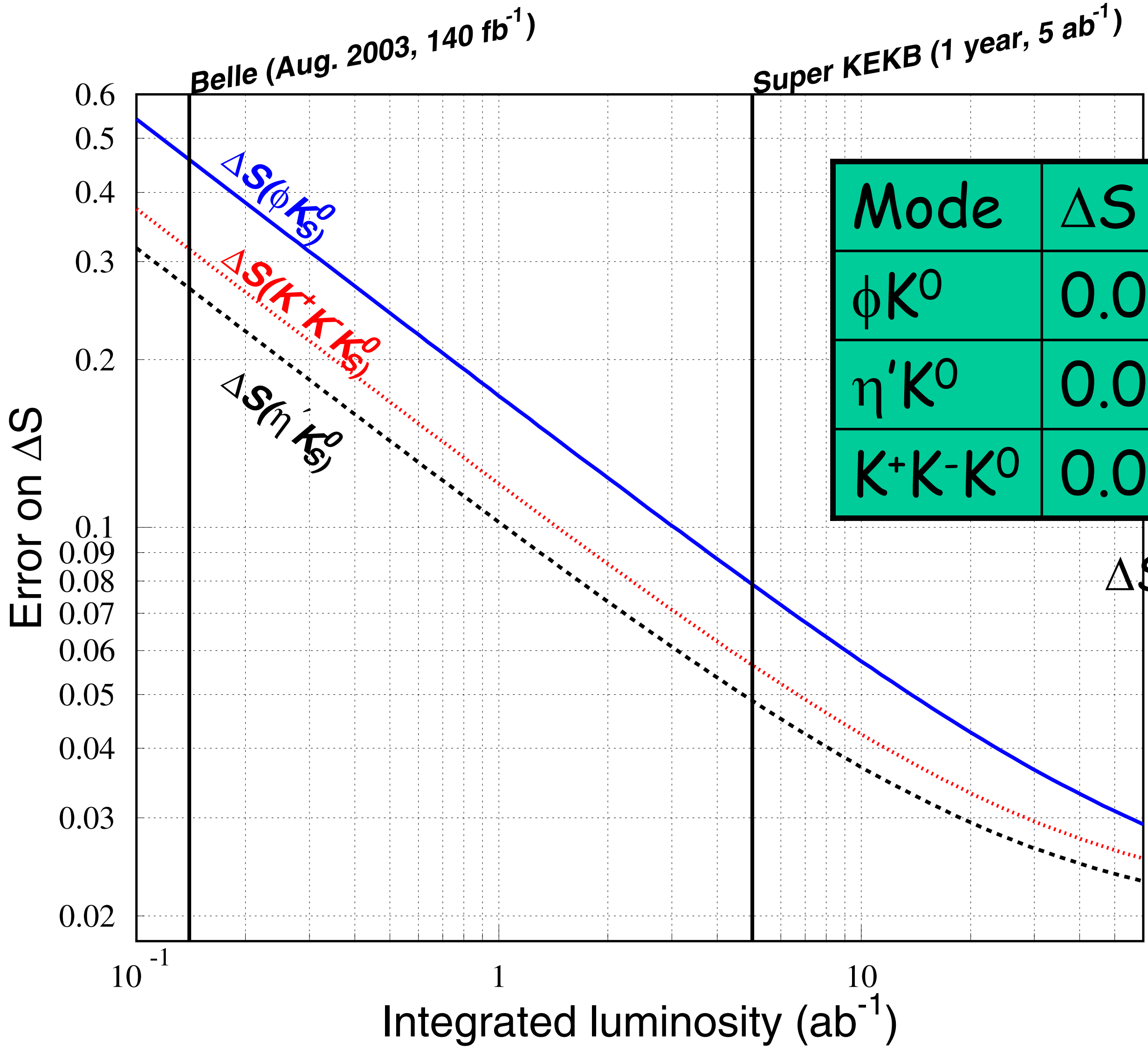
ϕK^0	$+0.34\pm0.20$
$\eta' K^0$	$+0.41\pm0.11$
f^0K^0	$+0.39\pm0.26$
π^0K^0	$+0.34^{+0.27}_{-0.29}$
$K^+K^-K^0$	$+0.53\pm0.17$
$b\rightarrow s$ avg.	$+0.43\pm0.08$

$\langle$charmonium$\rangle$ − $\langle b\rightarrow s$ penguin$\rangle$ = 0.30 ± 0.088

3.6σ deviation !!

Expected Precision

Statistical significance w/ the present central value



Mode	ΔS error	Signif.
ϕK^0	0.079	4.9
$\eta' K^0$	0.049	6.4
$K^+K^-K^0$	0.056	3.5

ΔS theory error

ϕK^0: ~0.05

$h' K^0$: ~0.10

Expected Precision

Statistical significance w/ the present central value

(Aug. 2003, 140 fb^{-1})

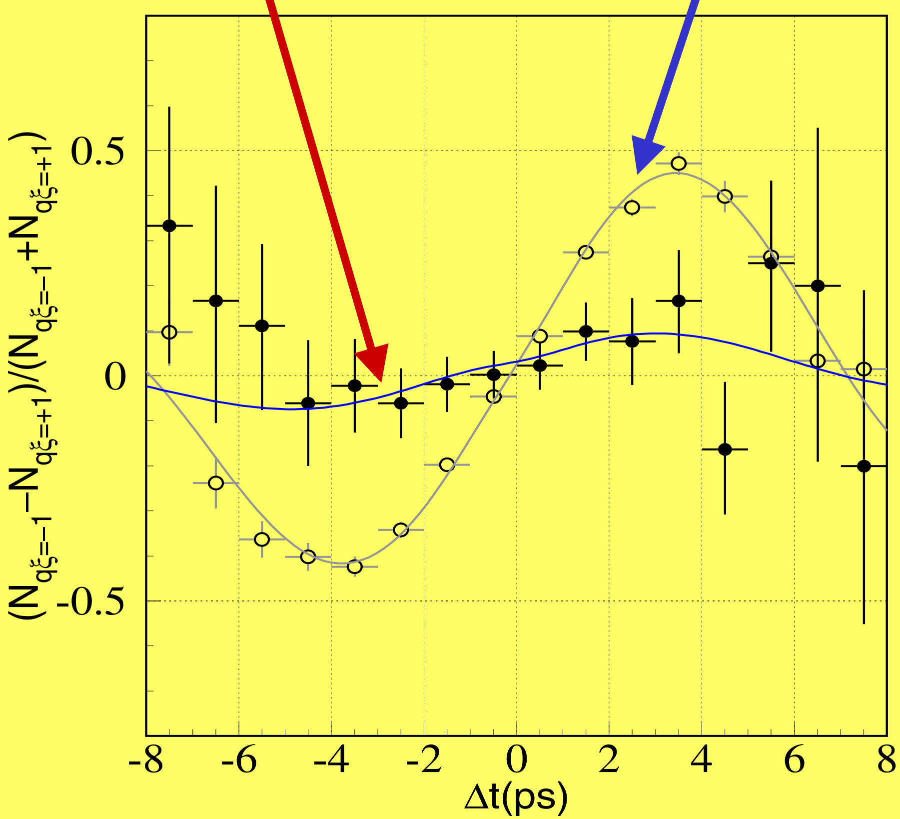
KEKB (1 year, 5 ab^{-1})

Error on ΔS

Expectation at 5ab^{-1}

ϕK^0 (input S=+0.24)

$J/\psi\ K_S^0$



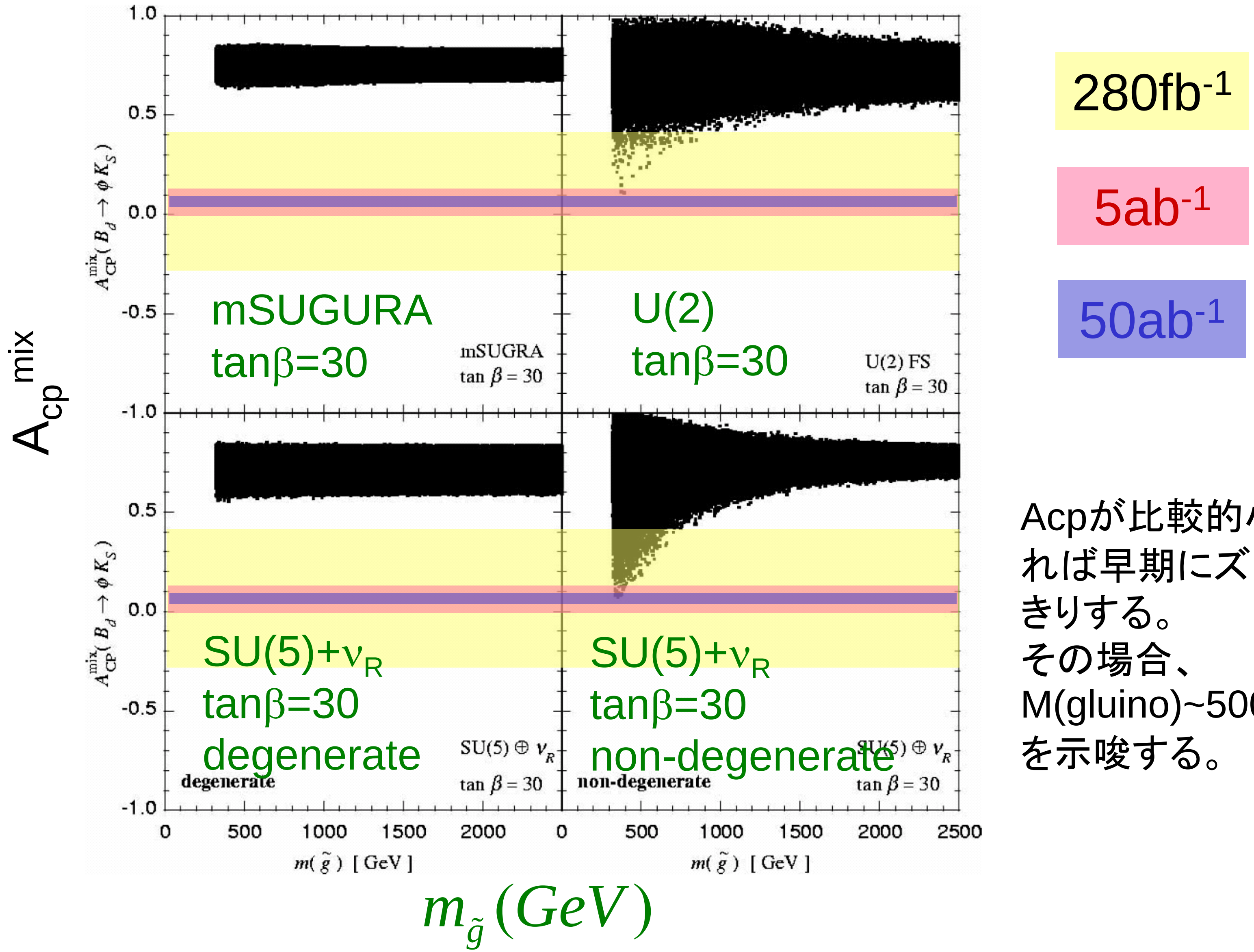
Signif.
4.9
6.4
3.5

...y error

...K^0: ~0.05

...'K^0: ~0.10

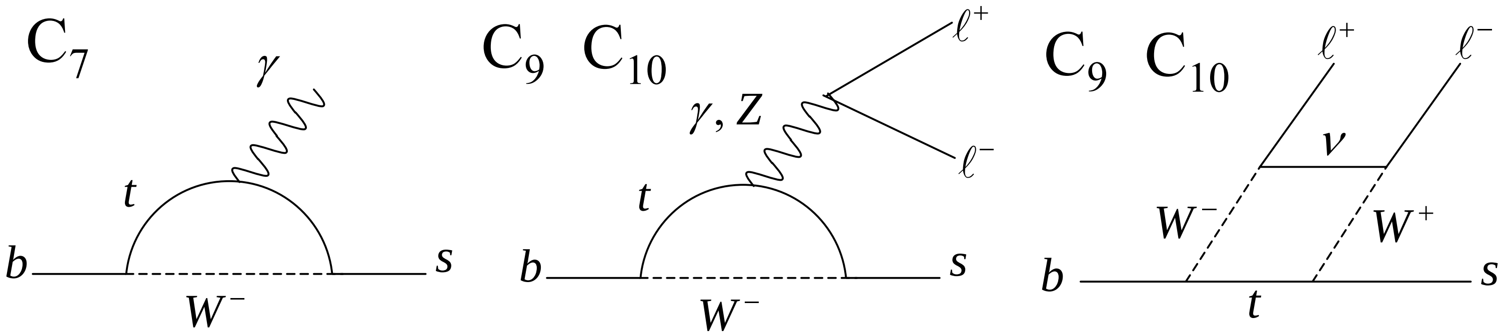
$A_{cp}(B \to \phi K_s)$ vs SUSY models



Acpが比較的小さければ早期にズレははっきりする。
その場合、
M(gluino)~500GeV
を示唆する。

$b \to s\gamma/sl^+l^-$

- Possible to search for NP in theoretically clean way.



Effective Hamiltonian for b→s $$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O(\mu)$$

- Many observables;
  - Branching fractions → M(H^+) > 350 GeV already in TYPE II 2HDM
  - Mixing indcued CPV
  - Direct CPV
  - Forward-backward asym.
  - Ratio of exclusive modes

$b \to s\gamma$

	Present Belle (stat./syst.)	5ab^{-1}	50ab^{-1}
Branching fraction $Br(B \to X_s\gamma)$ → C_7	9% / 9% (E_γ^{th} =1.8 GeV)	5% (E_γ^{th} =1.5 GeV)	still 5%?
Isospin asymmetry $\Delta_{0+}(B \to K^*\gamma)$ → C_7 sign	0.045 / 0.018	0.02	Still 0.02?
Mixing CPV $A_{cp}^{mix}(B \to K^*\gamma, K^* \to K_s\pi^0)$	—	0.14	0.04
Direct CPV $A_{cp}^{dir}(B \to K^*\gamma)$	0.044 / 0.008	0.006	0.002
$A_{cp}^{dir}(B \to X_s\gamma)$	0.051 / 0.038	0.011	0.005

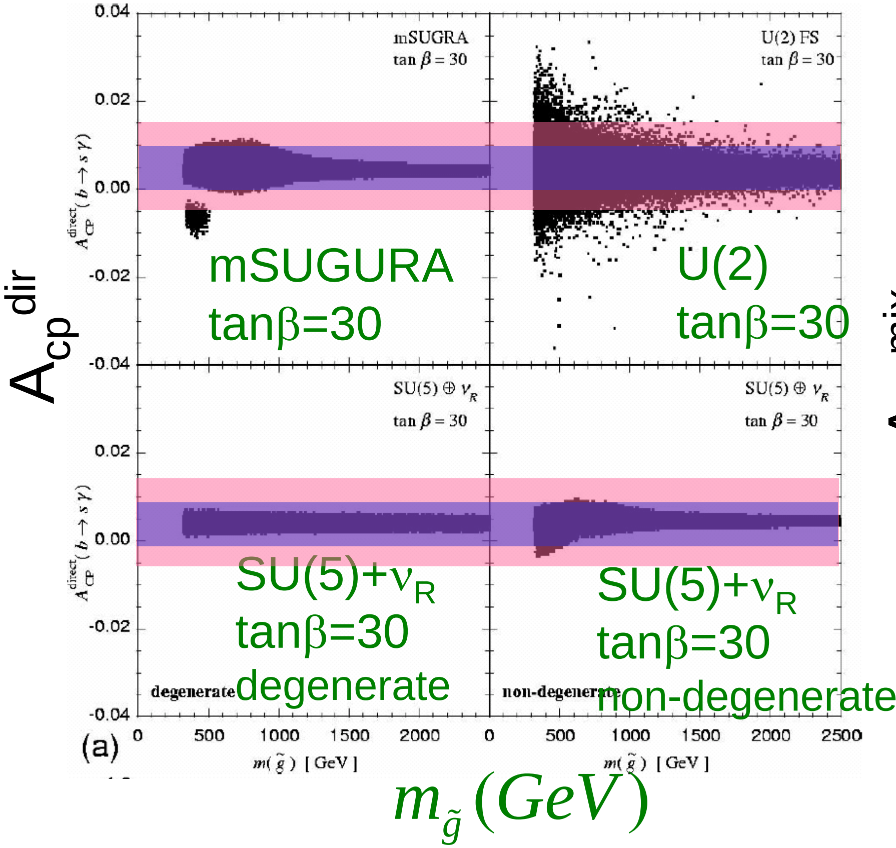
どこまでγのthreshold を減らせるか? Bkg.とのかねあい。

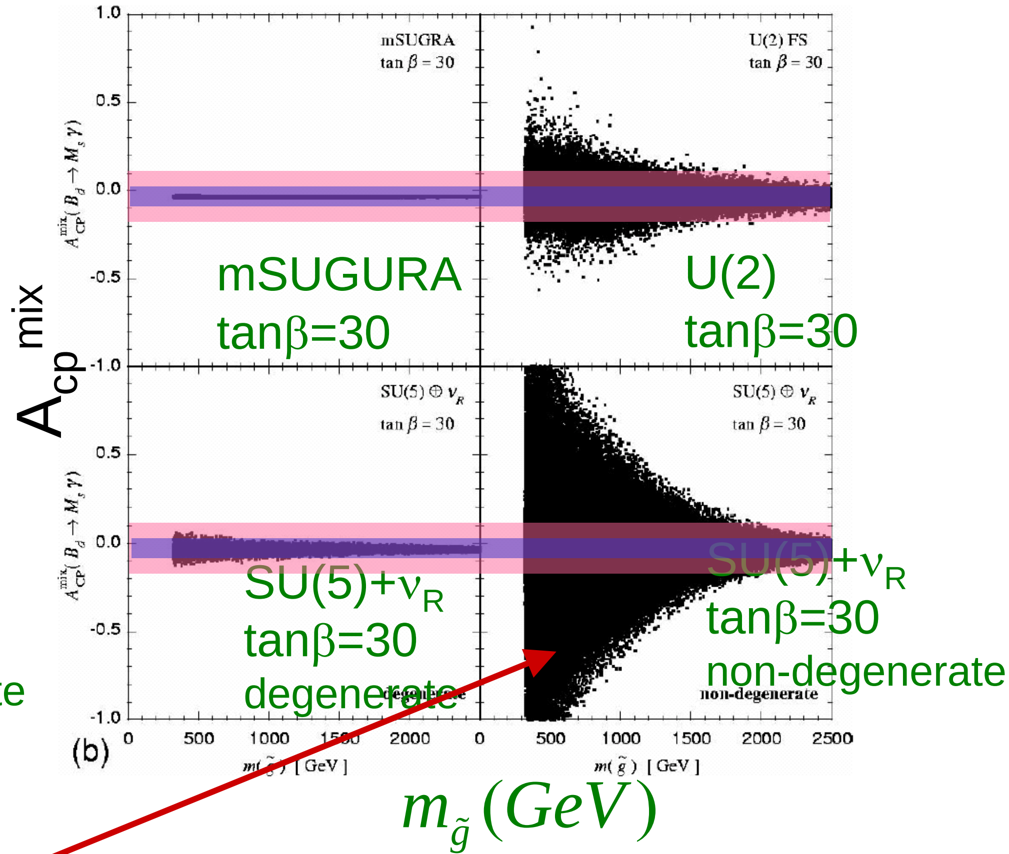
Ks のvertexing 重要

b→sss 同様、NPに敏感。
SMでは殆ど0　non−0 なら即NP

$A_{cp}(B \to X_s\gamma)$ vs SUSY models

5ab-1 50ab-1





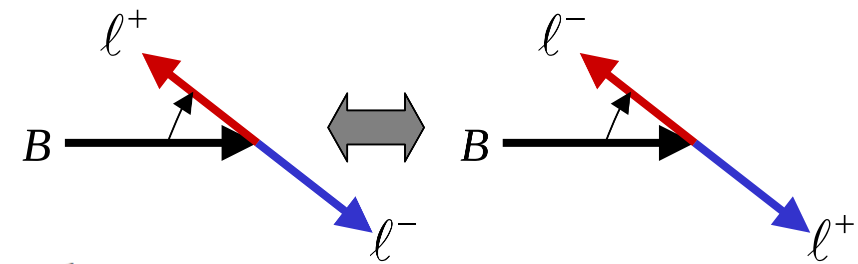
5ab-1 ではM(gluino)=1TeV, 50ab-1では2TeVまで攻める。

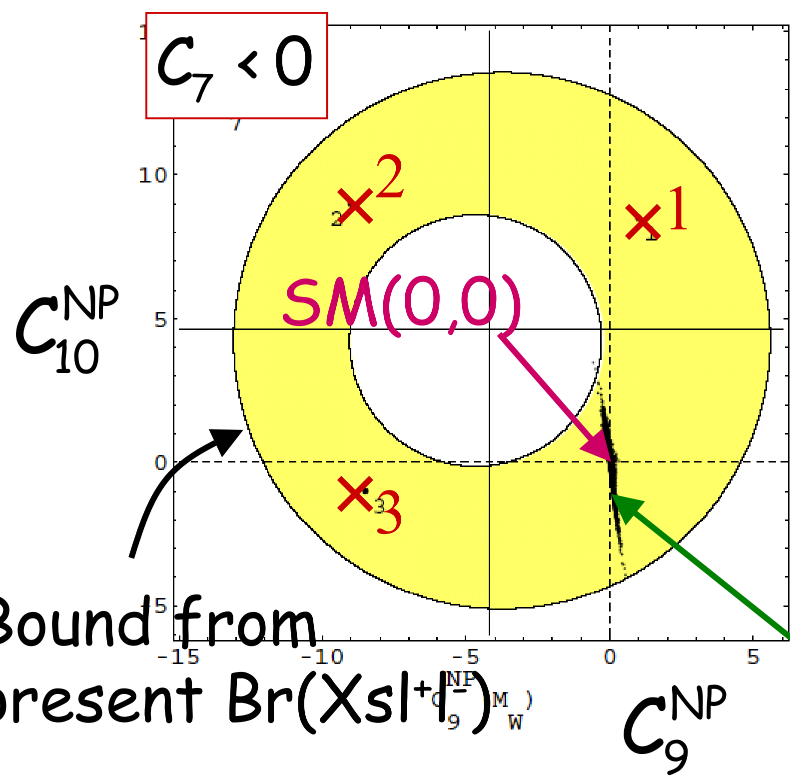
FB asymmetry in b→sl⁺l⁻

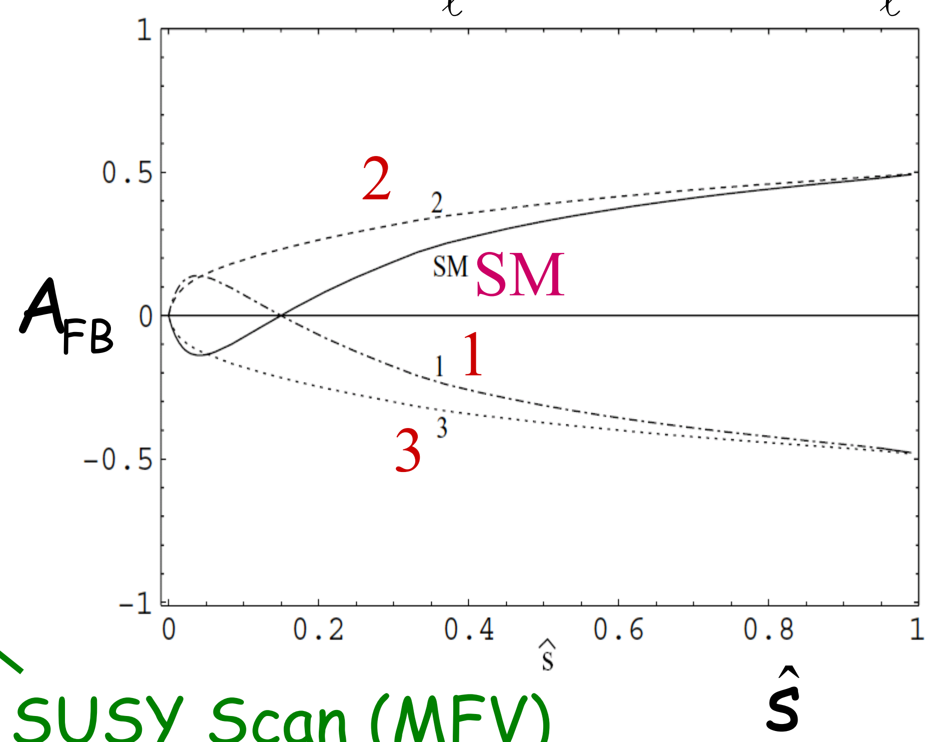
- Sensitive probe for NP (theoretically clean)

$$A_{FB} \propto \Re\left[C_{10}^{*}\left(sC_{9}^{eff}(s)+r(s)C_{7}\right)\right]$$

Br(B→Xsγ), Δ_{0+}(B→K*γ)

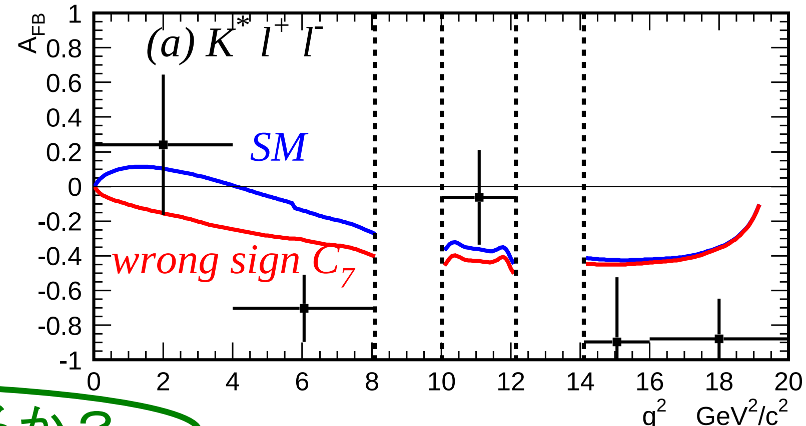






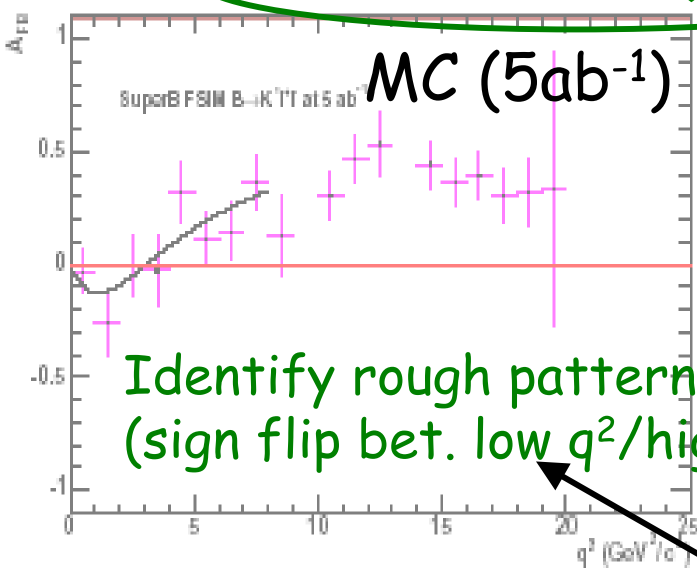
FB asymmetry in b→sl⁺l⁻ (cont'd)

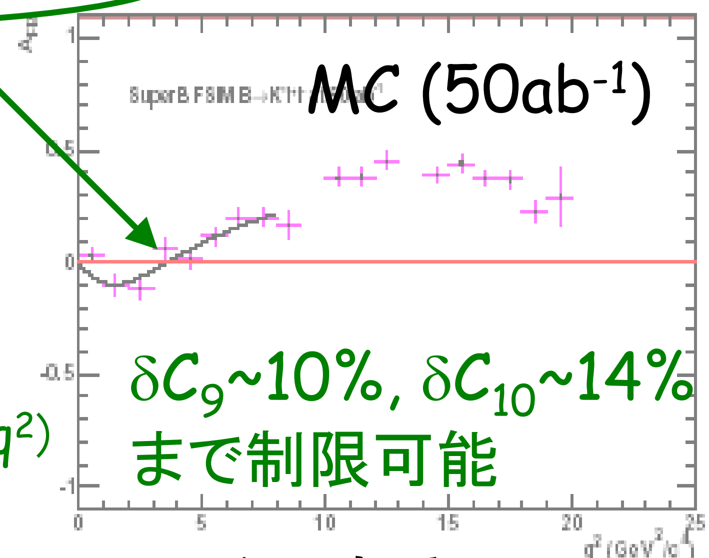
- Present status (250fb^{-1})



- At Super-B

どこで Zero-cross するか？



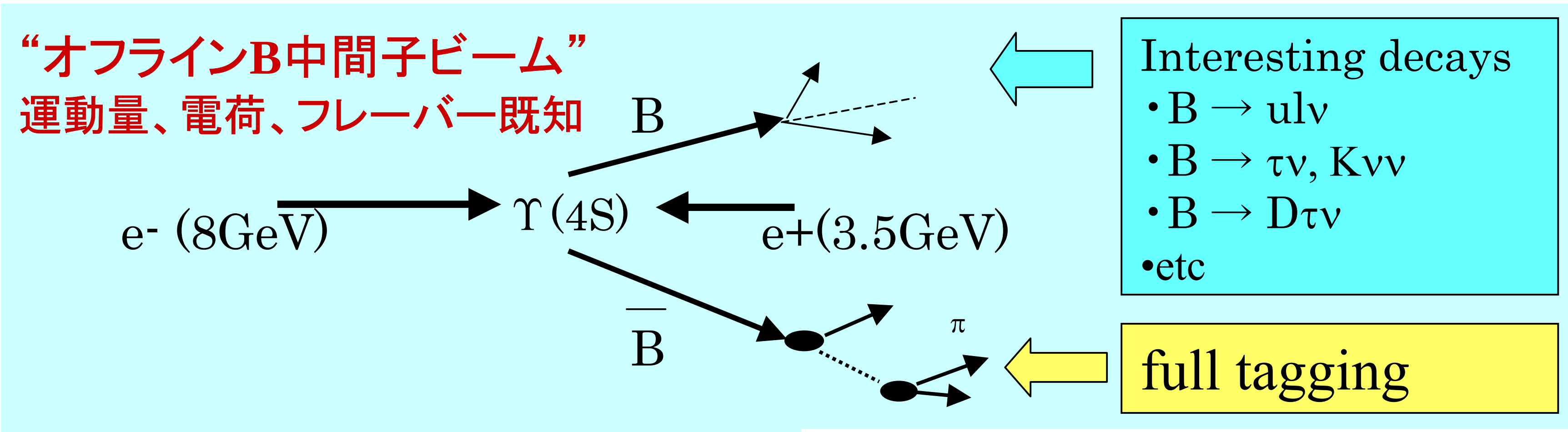


PID（μ/π ）も重要。

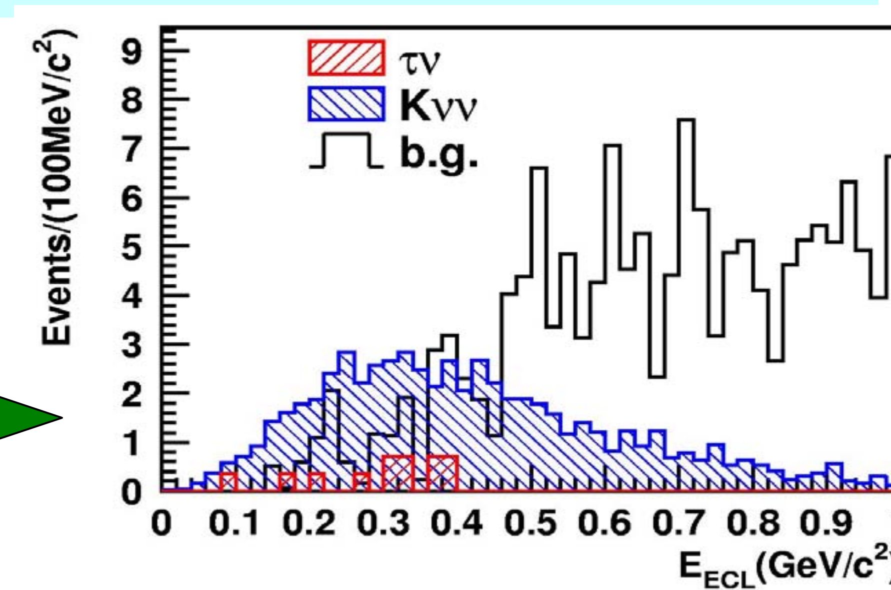
Branching fraction のdilepton mass 分布の測定も有効。

Full reconstruction

- 片側のB中間子を完全再構成して反対側のB崩壊をtagする。
- 特に、ν, τ を含む崩壊の精密測定や探索に威力。e+e- B factory でのみ可能。



- B→ Dτν: 12 σ observation at 5 ab^{-1}.
- B→Kνν: 5 σ observation at 50ab^{-1}.

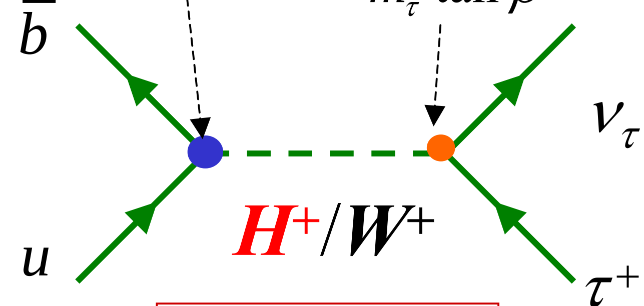


Charged Higgs 探索

- B→τν (leptonic decay)

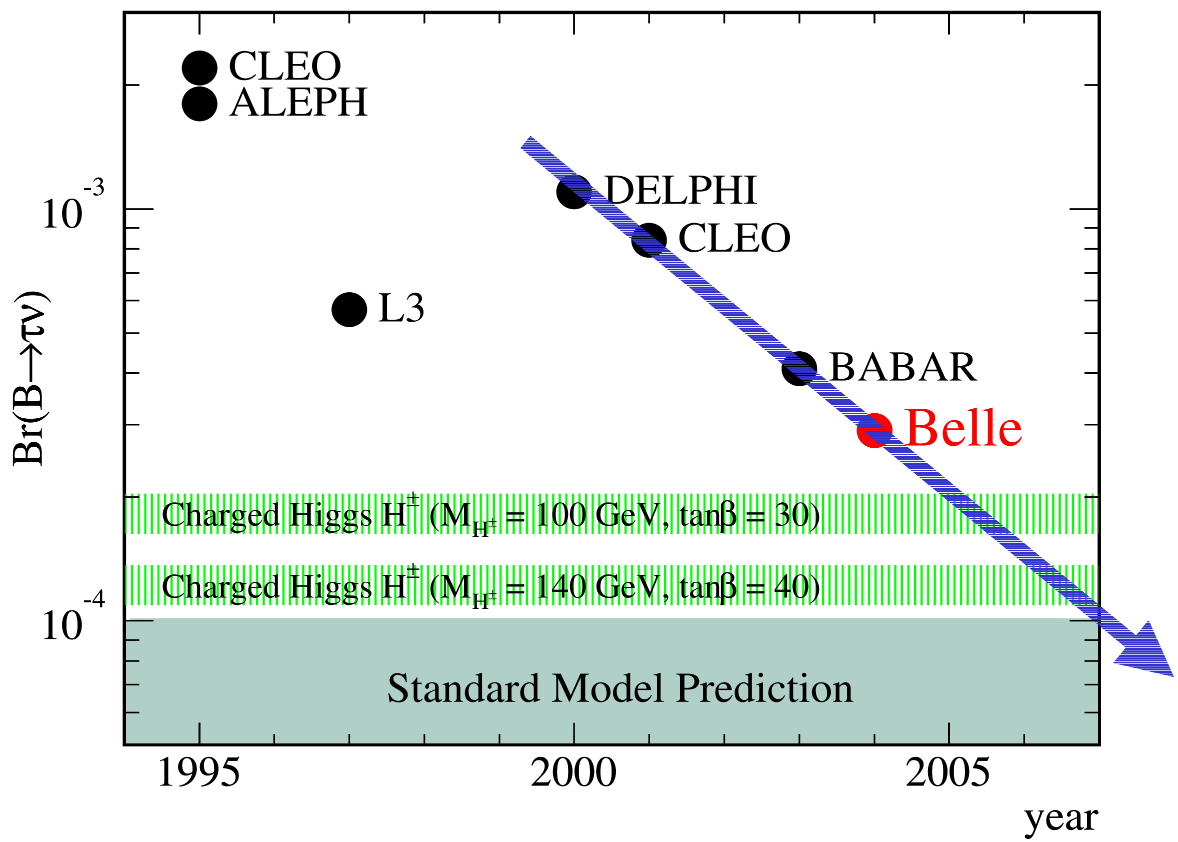
$$\Gamma(B \to \ell \nu) = \frac{G_F^2 m_B m_\ell^2 f_B^2}{8\pi} |V_{ub}|^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right) \times r_H$$

$$r_H = 1 - \tan^2 \beta \frac{m_B^2}{m_{H^\pm}^2}$$



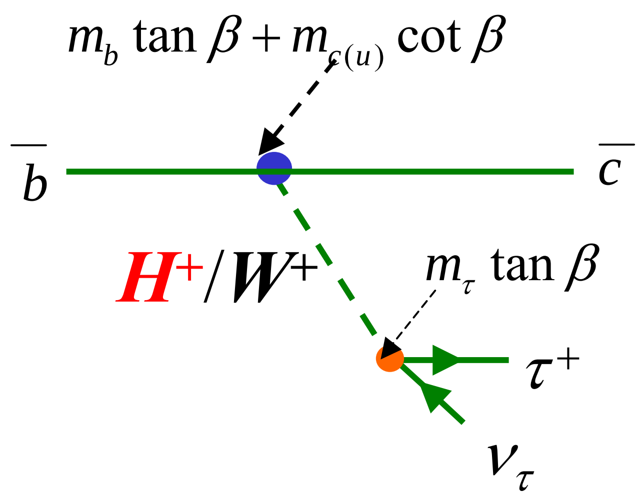
$M \propto m_\tau \tan^2 \beta$

Present status

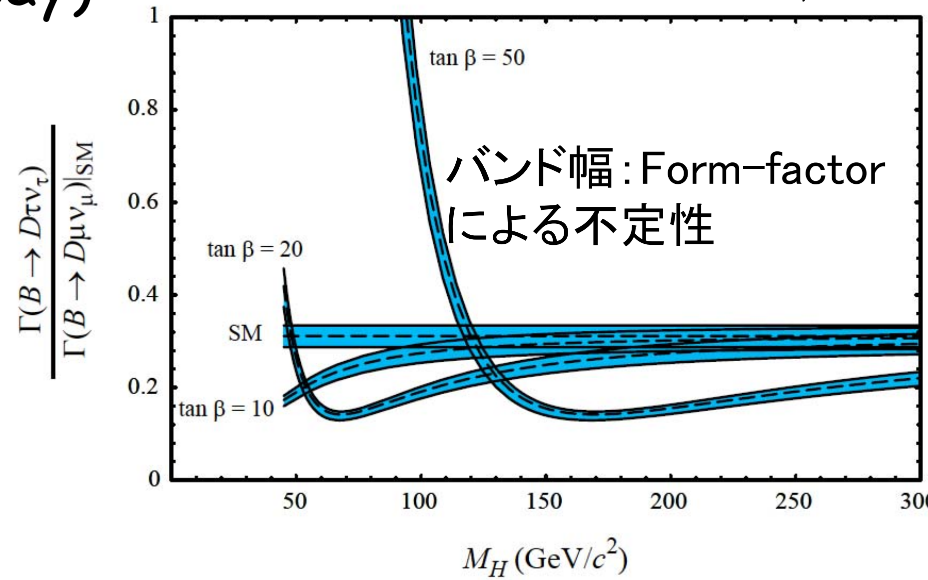


Charged Higgs 探索

- B→Dτν (semileptonic decay)

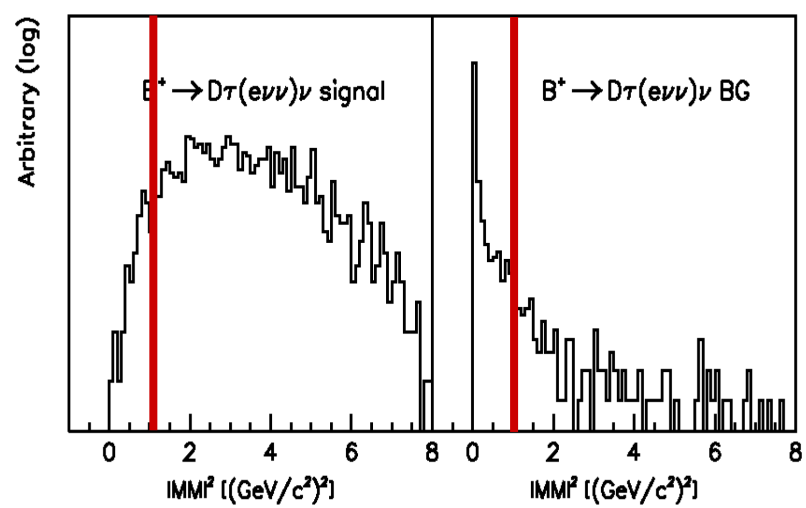


$$B = \frac{\Gamma(B \to \bar{D}\tau\nu_\tau)}{\Gamma(B \to \bar{D}\mu\nu_\mu)}$$



- Signal → large missing mass
- Expected at 5ab^{-1}

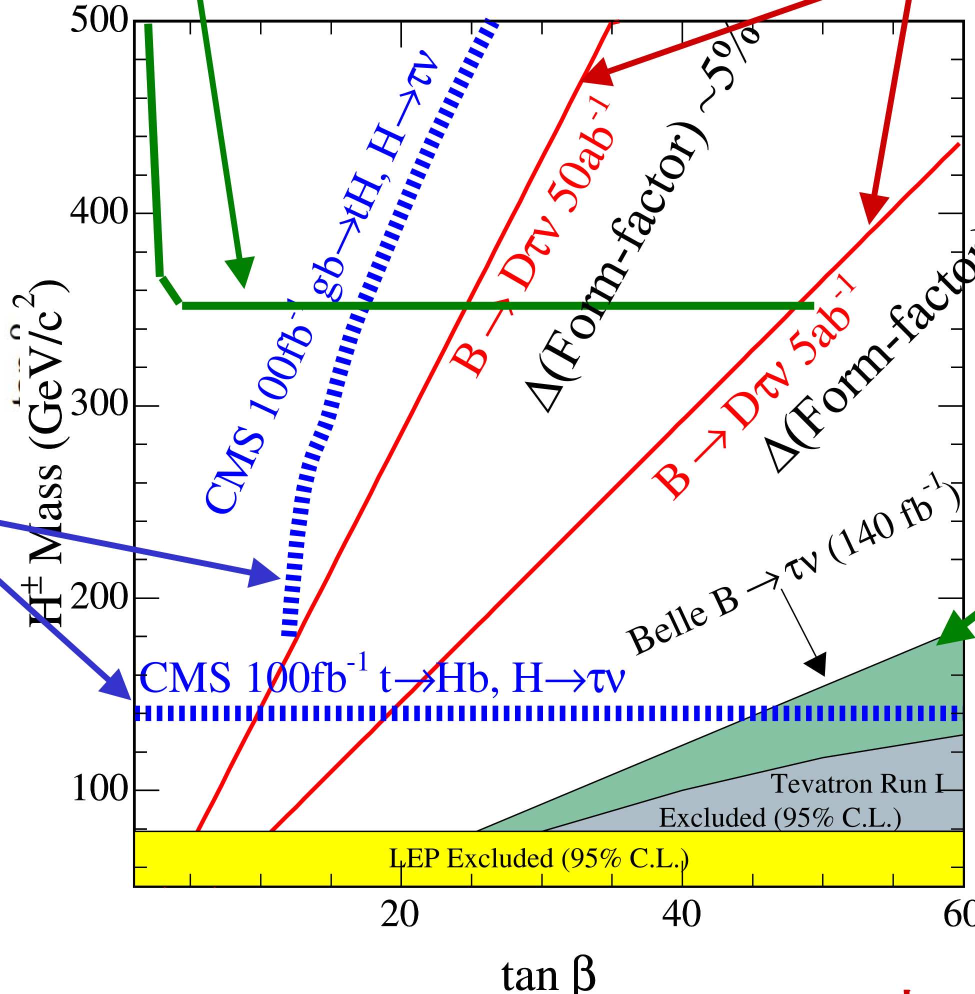
Mode	Nsig	Nbkg	dB/B
$D^0\tau^+(\ell^+\bar{\nu}_\tau\nu_\ell)\nu_\tau$	280	550	7.9%
$D^0\tau^+(h^+\bar{\nu}_\tau)\nu_\tau$	620	3600	



Sensitivity for charged Higgs

B→Xs γ による制限

B→Dτν



LHC
100fb⁻¹

現在のB→τν
による制限

Δ(form-factor)は
現在のB→Dμν
データで測定可能

LHCとの先陣争い。

Lepton Flavor Violation

LFV in neutrino sector already seen (at maximal mixing).

⇒LFV in charged leptons ?

Tau lepton

- The heaviest lepton → Enhancement in the rate
  ex.) $Br(\tau \to \mu\gamma) \sim 10^{4-5} \times Br(\mu \to e\gamma)$
- 3^{rd} generation → Both $3 \to 2(\mu)/3 \to 1(e)$ transition can be explored ⇒slepton flavor structure.

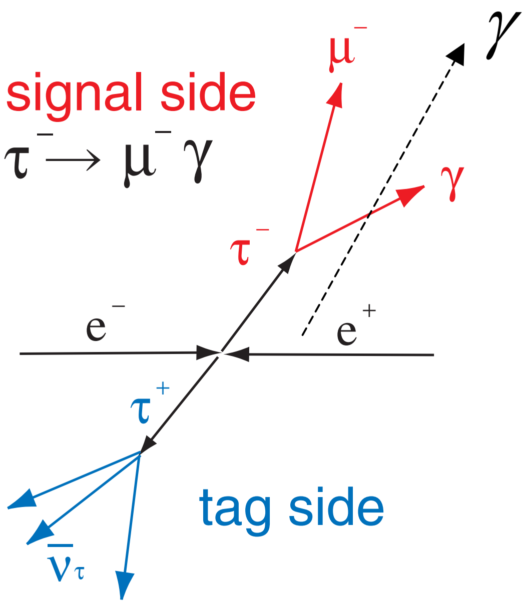
B-factory = "Tau-factory"

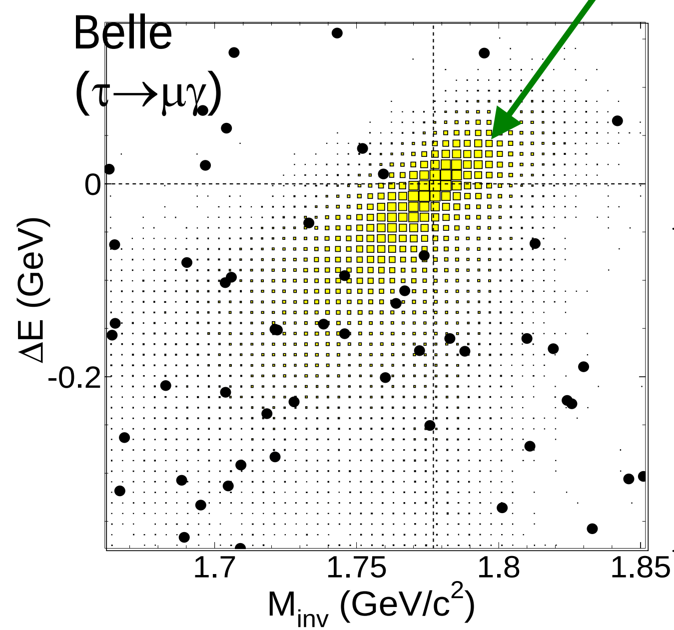
- $\sigma(\tau\tau) \sim \sigma(BB)$
- 5×10^{9} τ pairs at $5ab^{-1}$

→ Rare decay sensitivity at $O(10^{-9})$

τ→μγ measurements

- Present Belle results ($86fb^{-1}$, 7.9×10^{7} τ-pairs)
  - Br(τ→μγ) < 3.1×10^{-7} (90%CL)
  - Br(τ→eγ) < 3.8×10^{-7} (90%CL)





Expected signal distribution

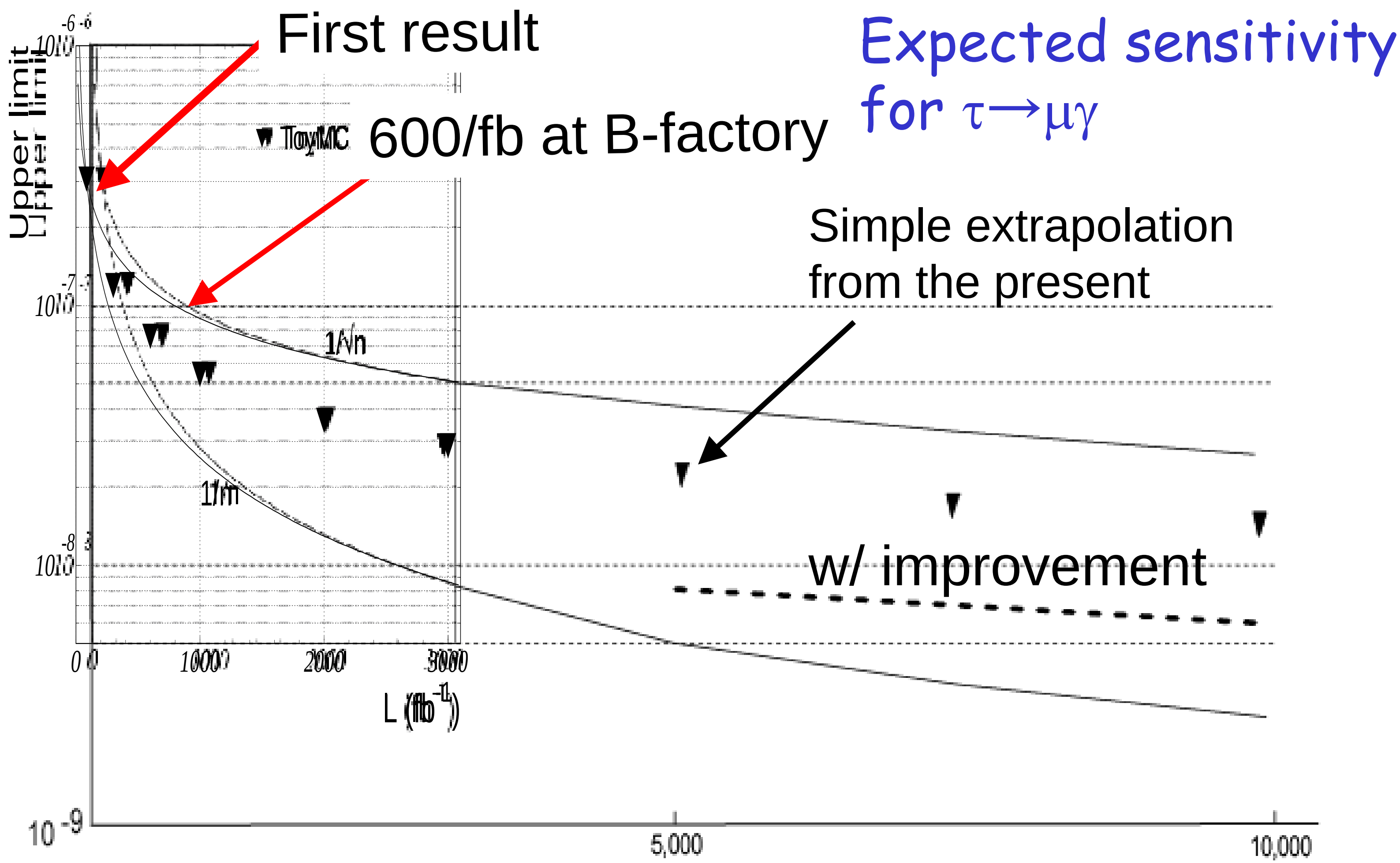
Background

- μμγ
- Mis-id (μ→π)
- ττγ generic
- Escape from missing mass cut

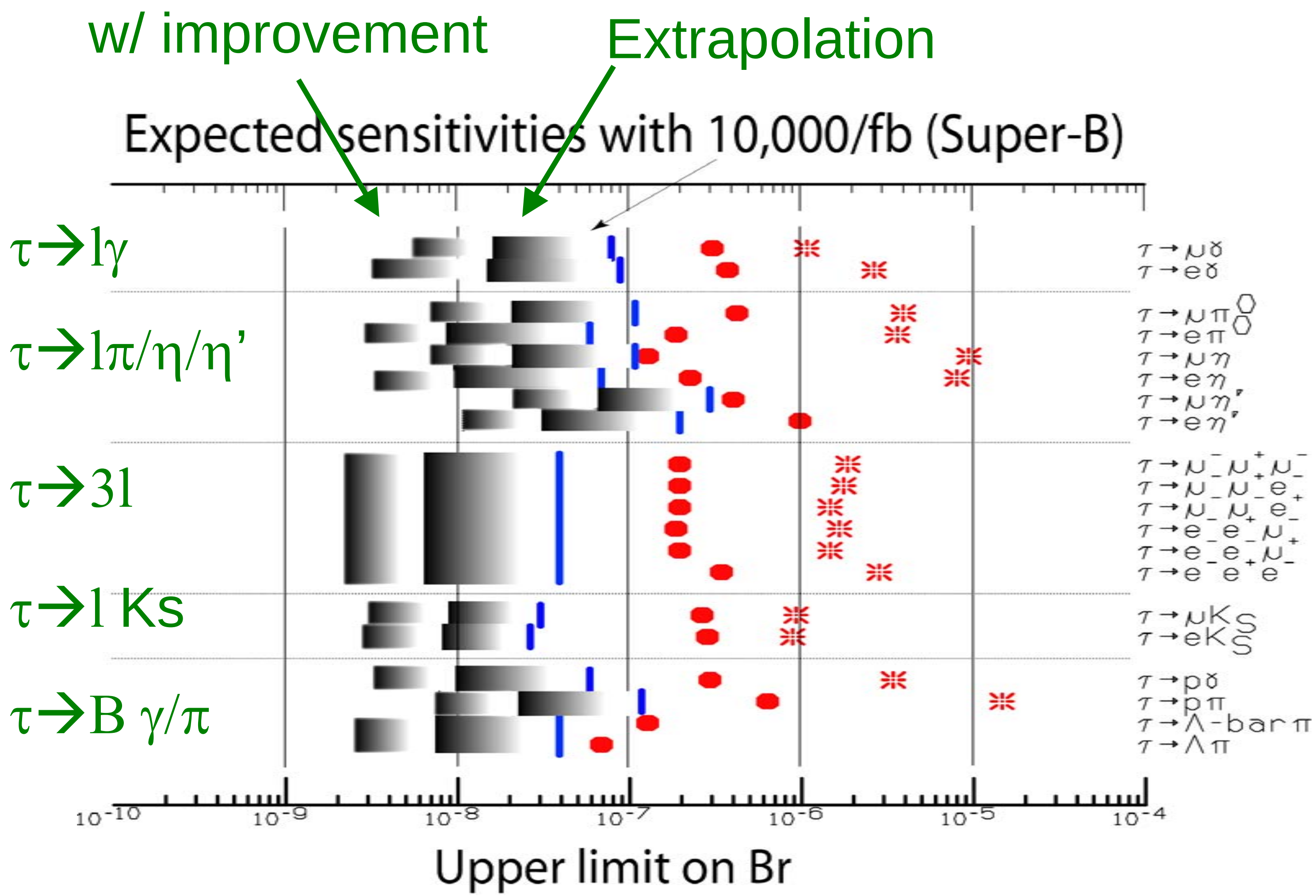
Improvement

- Analysis (selection criteria, cut analysis →likelihood analysis)
- Particle ID (better rejection of μ→π fake)
- γ energy resolution

Tau LFV search (past→future)



Tau LFV search (past→future)

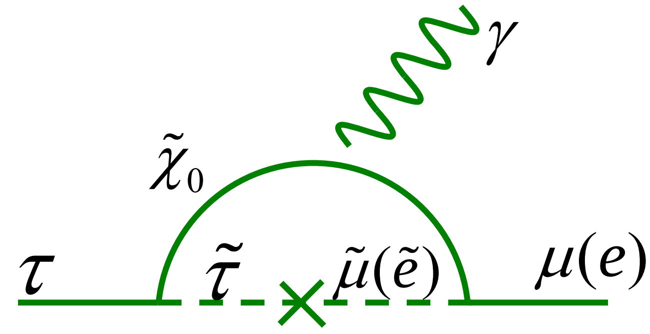


Search region enters into O(10^{-8}→10^{-9})

$\tau \rightarrow \mu\gamma / e\gamma$

- SUSY + Seasaw
  - Flavor violation by ν-Yukawa coupling.
  - Large LFV   Br(τ→μγ)=O(10^{-7~9})

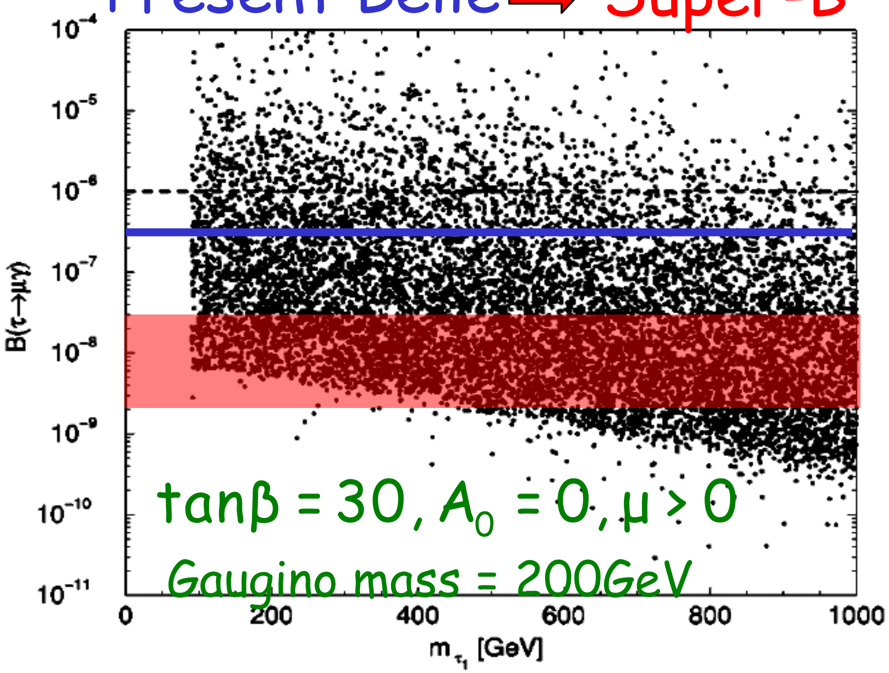
$$Br(\tau \to \mu\gamma) \sim 10^{-6} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\bar{m}^2_{\tilde{L}}} \right) \left(\frac{1\,TeV}{m_{SUSY}} \right)^4 \tan^2\beta$$



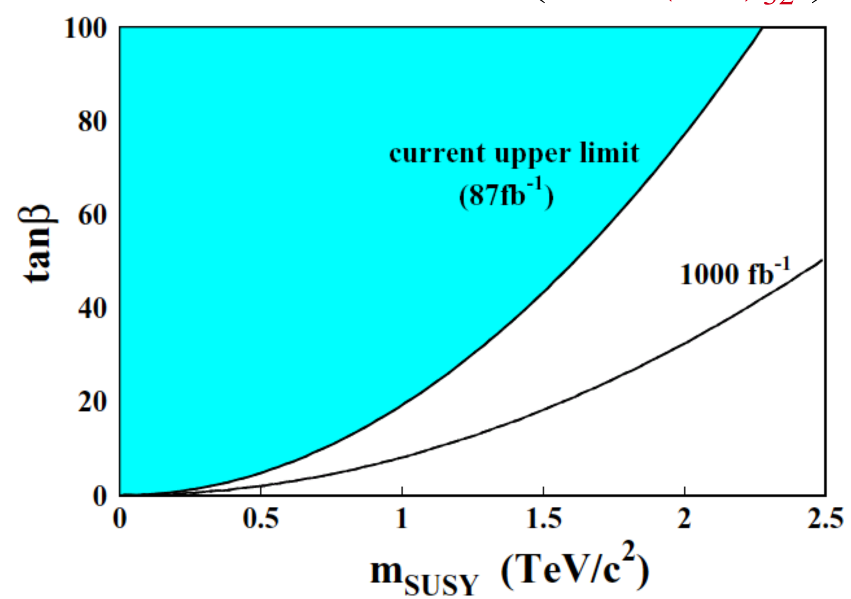
$(m^2_{\tilde{l}})_{23(13)}$

Similar for eγ case

Present Belle ➡ Super-B



探索可能な領域 (max. $(m^2_{\tilde{L}})_{32}$)



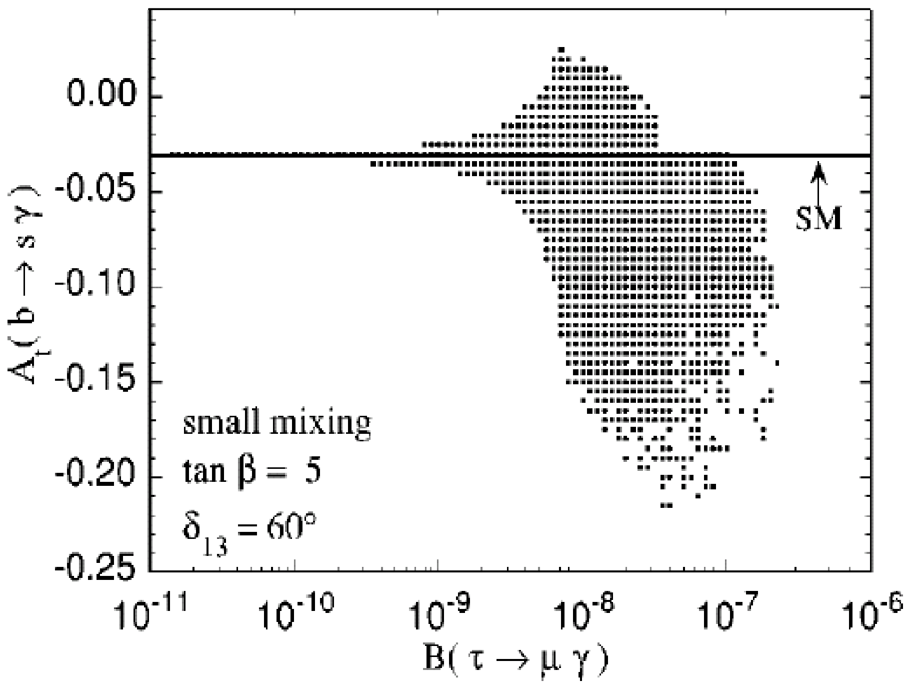
τ→μγ in SUSY GUT

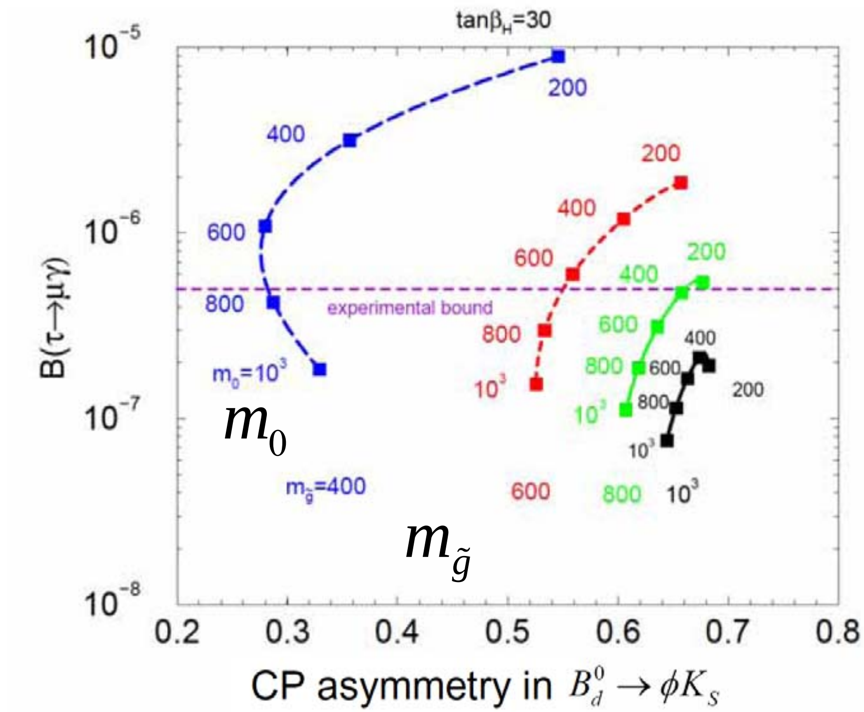
SU(5) GUT+ν_R

Squark/slepton mass matrix relation

$$\left(m^2_{\tilde{d}_R}\right)_{23} \approx \left(m^2_{\tilde{l}_L}\right)_{23} e^{i(\varphi_2-\varphi_3)}$$

➡ Correlation to $A_{cp}^{mix}(B \to X_s\gamma)$ and $A_{cp}^{mix}(B \to \phi K_s)$

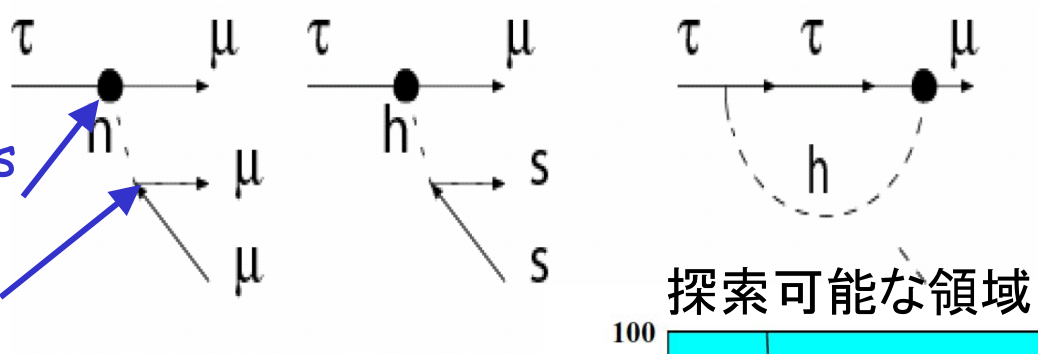




These correlations provides non-trivial test of SUSY GUT

$\tau \rightarrow 3l$, $l\eta$

- Neutral Higgs mediated decays.
- Not suppressed by power of slepton masses.
  - Important decays when the slepton is much heavier than EW scale.



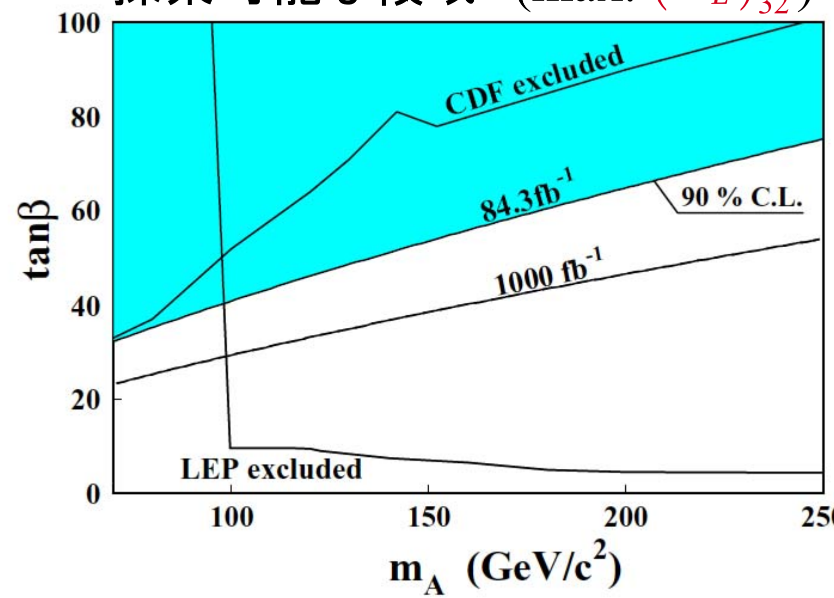
Higgs anomalous coupling ($\tan^2\beta$)

$\tan\beta$

$$Br(\tau \rightarrow 3\mu) = 4\times10^{-7}\times\left(\frac{\left(m^2_{\tilde{L}}\right)_{32}}{\bar{m}^2_{\tilde{L}}}\right)\left(\frac{\tan\beta}{60}\right)^6\left(\frac{100GeV}{m_A}\right)^4$$

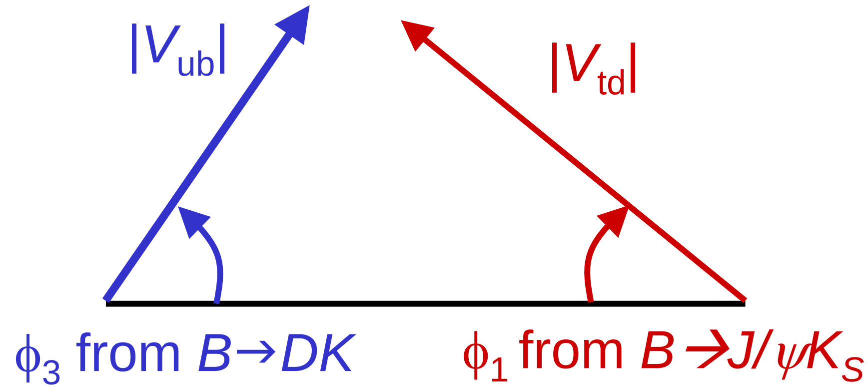
$$Br(\tau \rightarrow \mu\eta) : Br(\tau \rightarrow 3\mu) : Br(\tau \rightarrow \mu\gamma) = 5:1:0.5$$

探索可能な領域 (max. $\left(m^2_{\tilde{L}}\right)_{32}$)



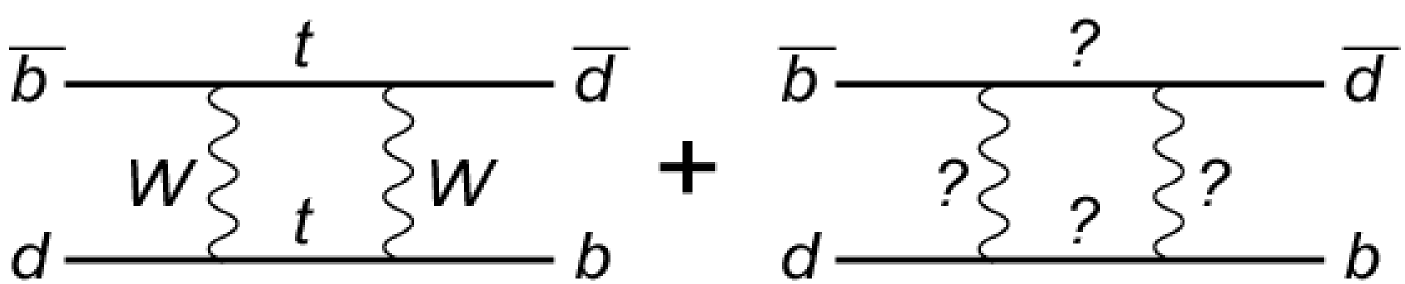
CKM fit

- Determine (ρ,η) only by tree processes (SM dominant).
  - $|V_{ub}|$ from $b\rightarrow ul\nu$
  - ϕ_3 from $B\rightarrow DK$



- Compare it with (ρ,η) determined through
  - $|V_{td}|$ from BB mixing, i.e. ΔM_d
  - ϕ_1 from $B\rightarrow J/\psi K_S$

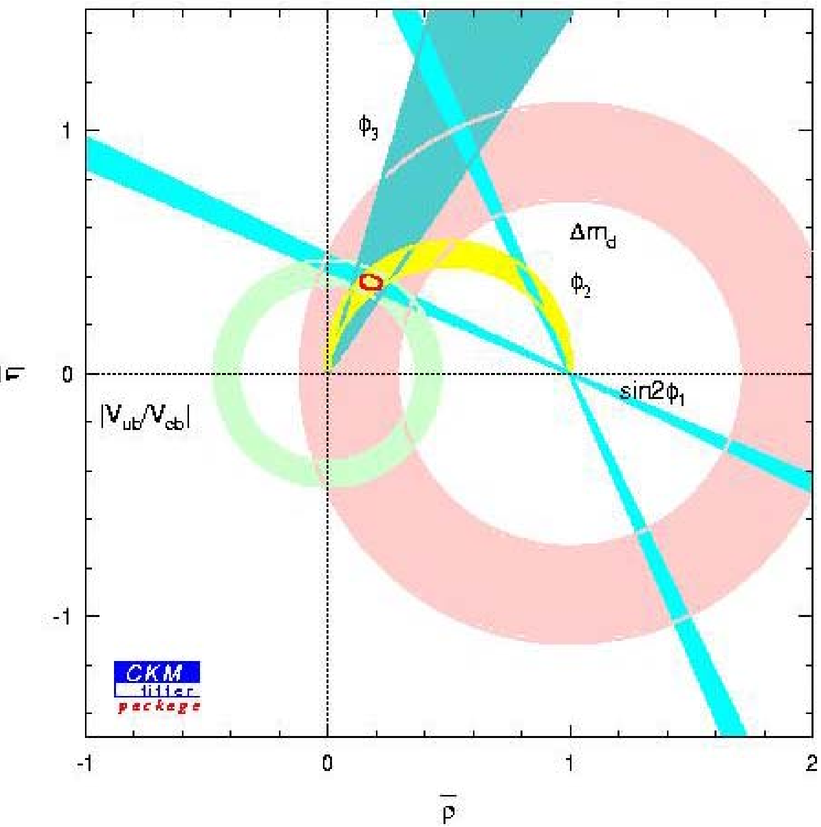
- This gives $M_{12}=M_{12}^{SM}+M_{12}^{NP}$



UT at Super-B

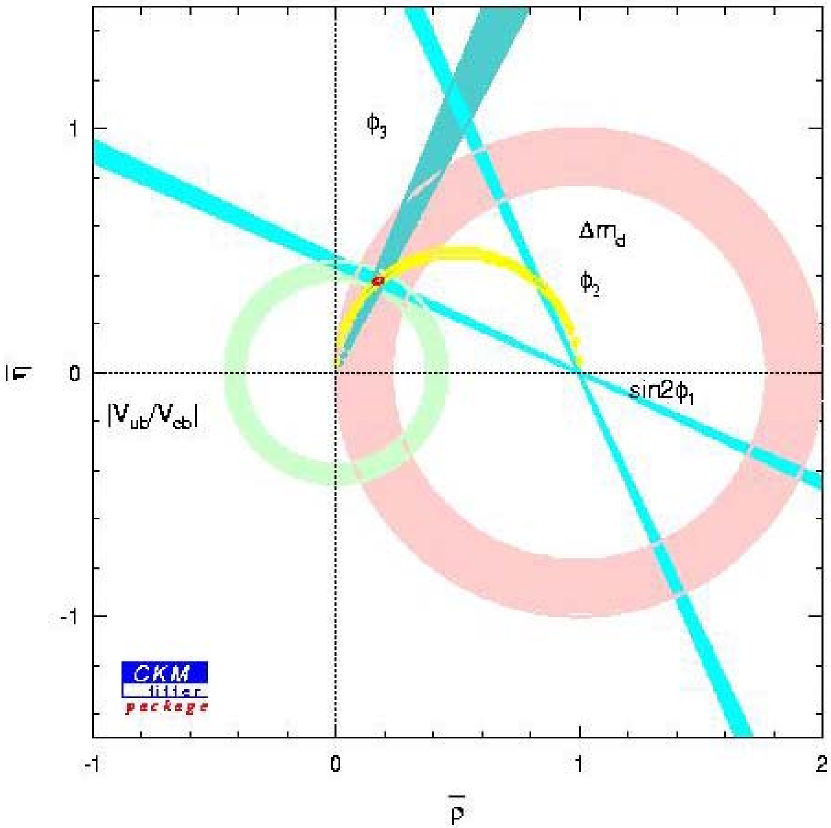
5 ab^{-1}

$$\Delta \sin 2\phi_1 = 0.019$$
$$\Delta(f_B\sqrt{B_d}) = 0.011 \pm 0.026$$
$$\Delta |V_{ub}| = 5.8\%$$
$$\Delta\phi_3 = 4^\circ$$



50 ab^{-1}

$$\Delta \sin 2\phi_1 = 0.014$$
$$\Delta(f_B\sqrt{B_d}) = 0.005 \pm 0.015$$
$$\Delta |V_{ub}| = 4.4\%$$
$$\Delta\phi_3 = 1.2^\circ$$



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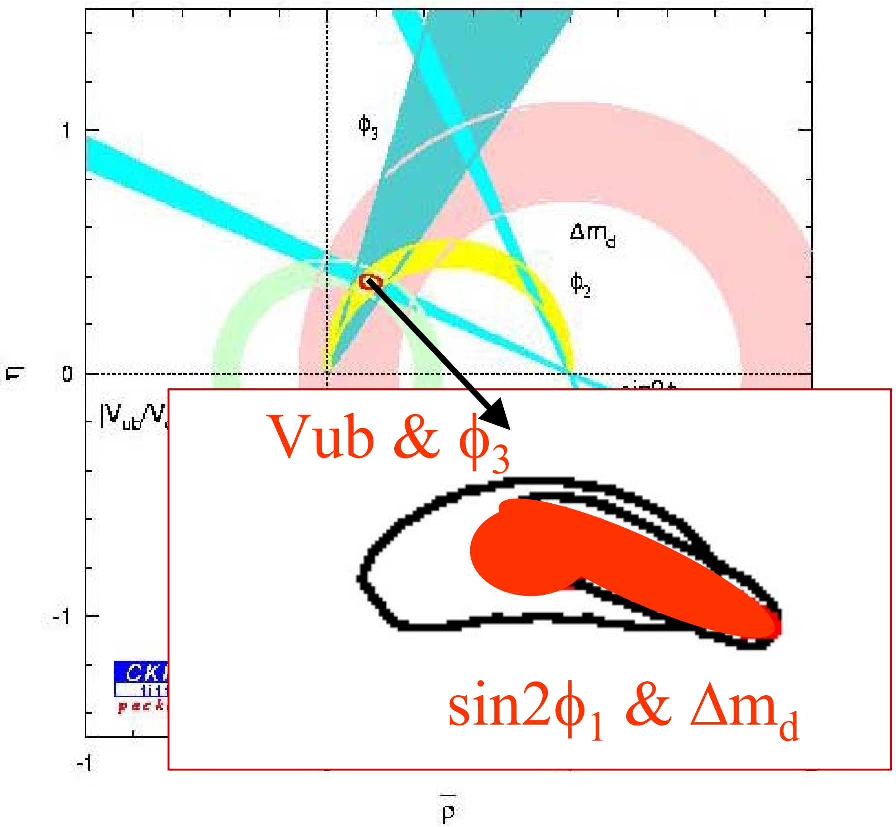
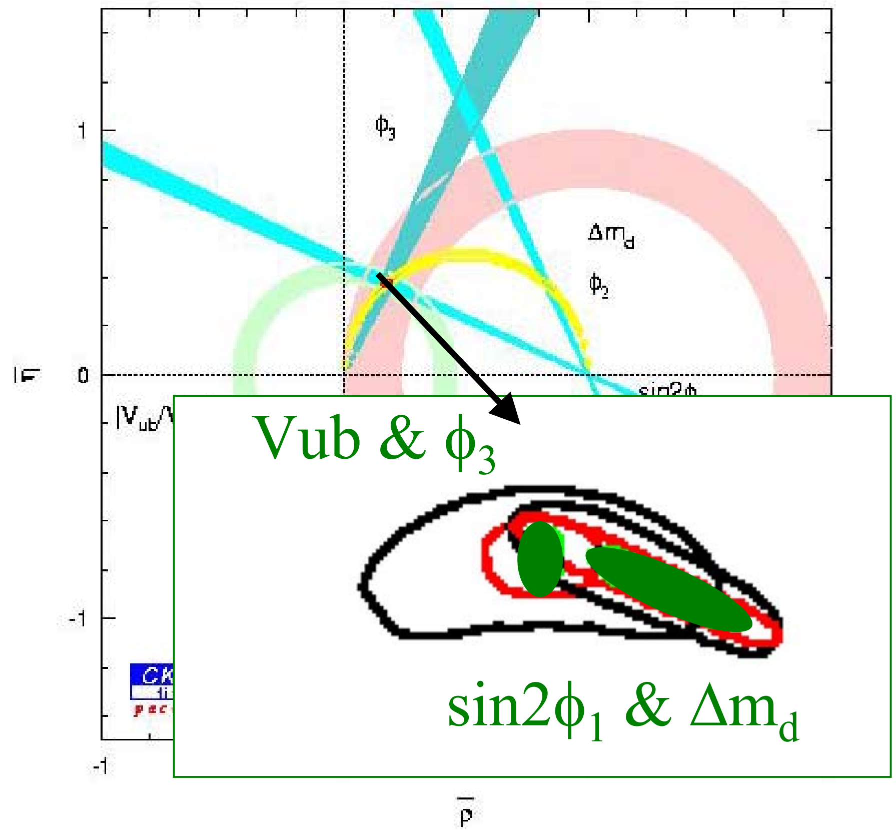
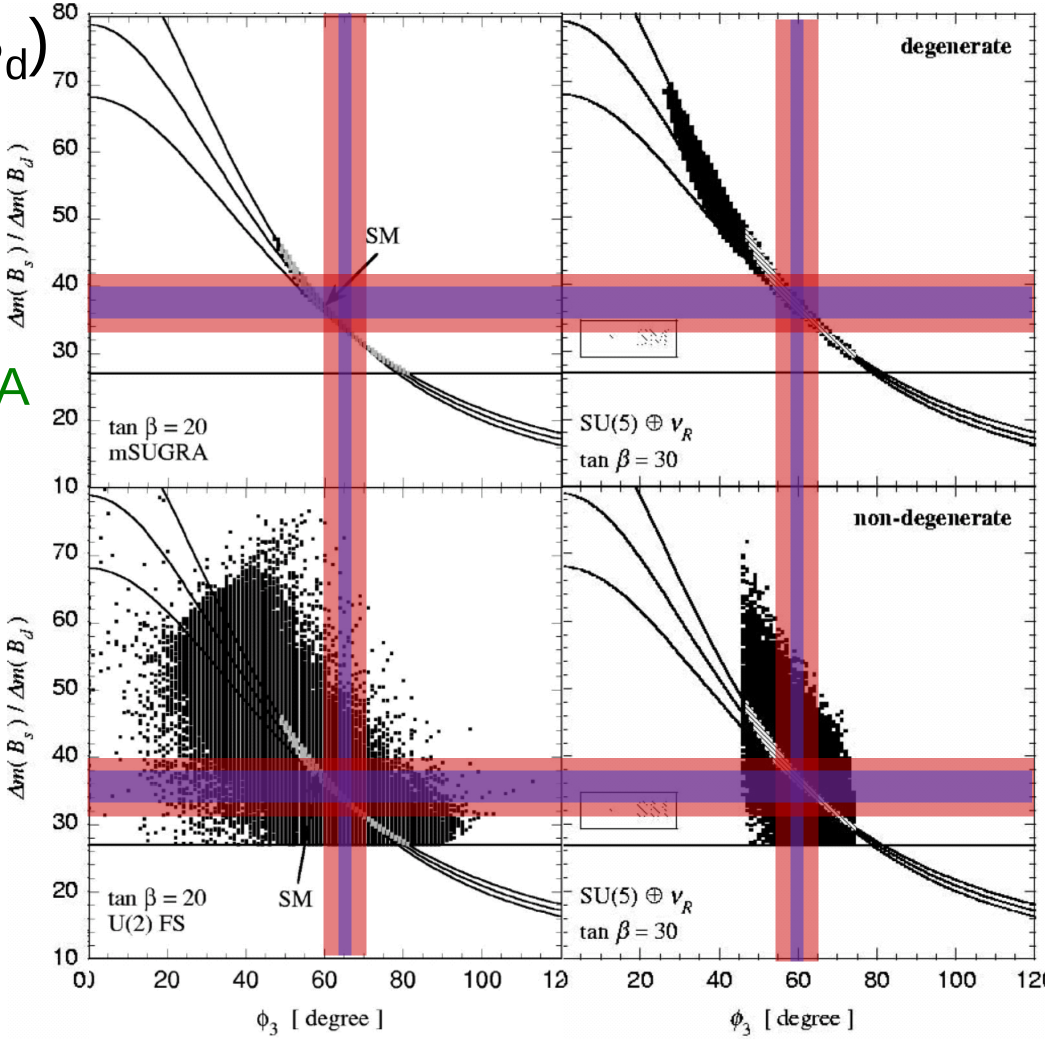




UT vs SUSY models

$\Delta m(B_s)/\Delta m(B_d)$



5ab^{-1}

50ab^{-1}

mSUGRA
tanβ=30

SU(5)+ν_R
tanβ=30
degenerate

U(2)
tanβ=30

SU(5)+ν_R
tanβ=30
non-degenerate

ϕ_3 (degree)

Pattern of the deviation from the SM prediction

Y.Okada

Unitarity triangle | Rare decay

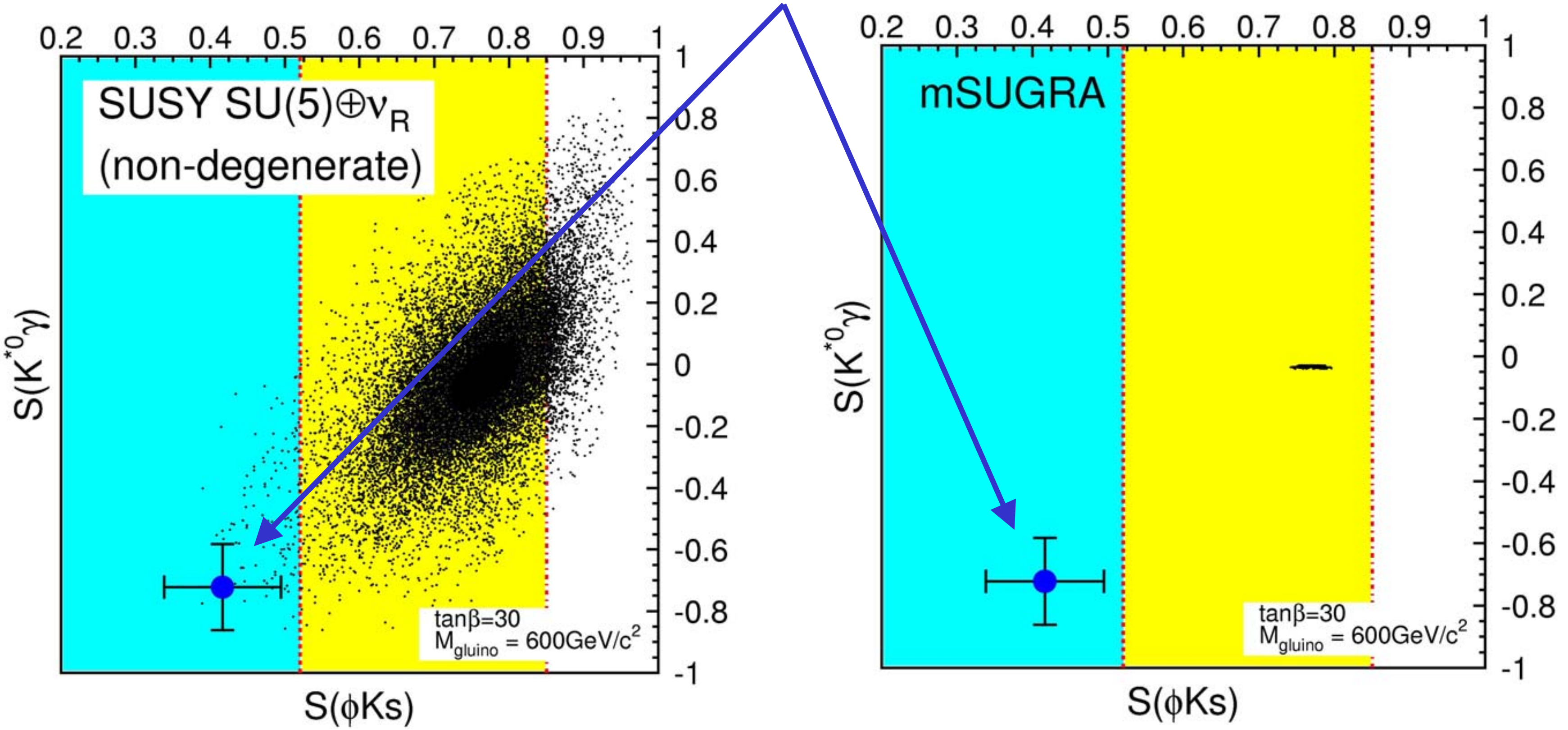
	Bd-unitarity	ε	$\Delta m(B_s)$	$B \to \phi K_s$	$B \to M_s\gamma$ indirect CP	$b \to s\gamma$ direct CP
mSUGRA	-	-	-	-	-	+
SU(5)SUSY GUT + ν_R (degenerate)	-	+	+	-	+	-
SU(5)SUSY GUT + ν_R (non-degenerate)	-	-	+	++	++	+
U(2) Flavor symmetry	+	+	+	++	++	++

++: Large, +: sizable, -: small

Study of NP Scenario-1

- $A_{cp}^{mix}(\phi Ks)$, $A_{cp}^{mix}(K^{*0}\gamma)$の相関からSUSYのモデルを見分けることが可能。

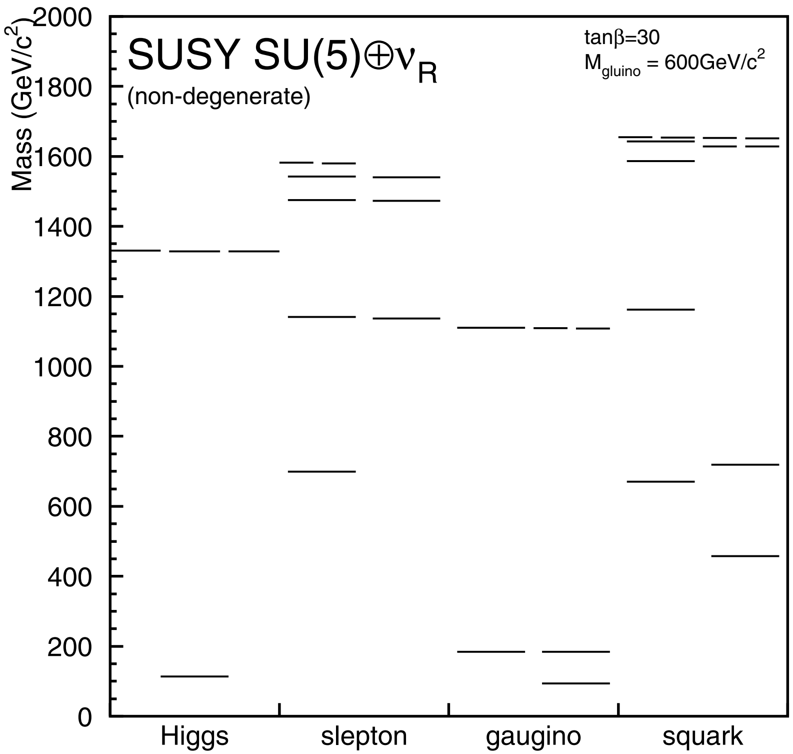
5ab^{-1} で予想される測定精度

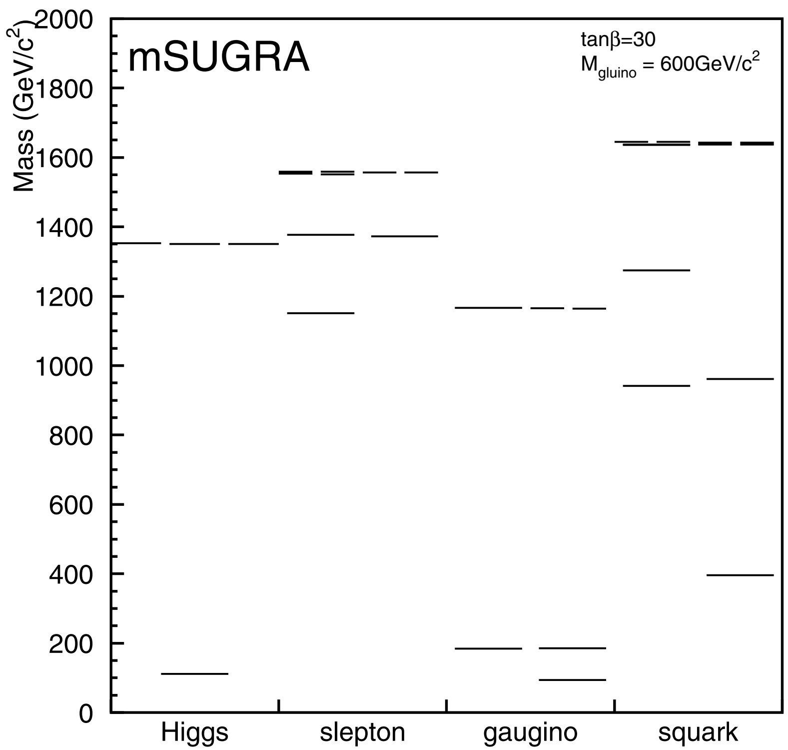


Study of NP Scenario-2

- SUSY粒子の mass spectrum のみでは見分けにくい。

前頁と同じパラメーターでの SUSY mass spectrum





Super-BでのFlavor changing process の測定が重要な情報を与える。

Study of NP Scenario-3

- 有用な崩壊は$A_{cp}^{mix}(\phi K_s)$, $A_{cp}^{mix}(K^{*0}\gamma)$だけではない。
  - $A_{cp}^{dir}(X_s\gamma)$, $Br(X_s\gamma)$, $A_{FB}(X_s ll)$
  - $Br(\tau \rightarrow \mu\gamma)$

- ユニタリティー三角形の精密測定も有用。

GLOBAL ANALYSIS OF B PHYSICS

Stu

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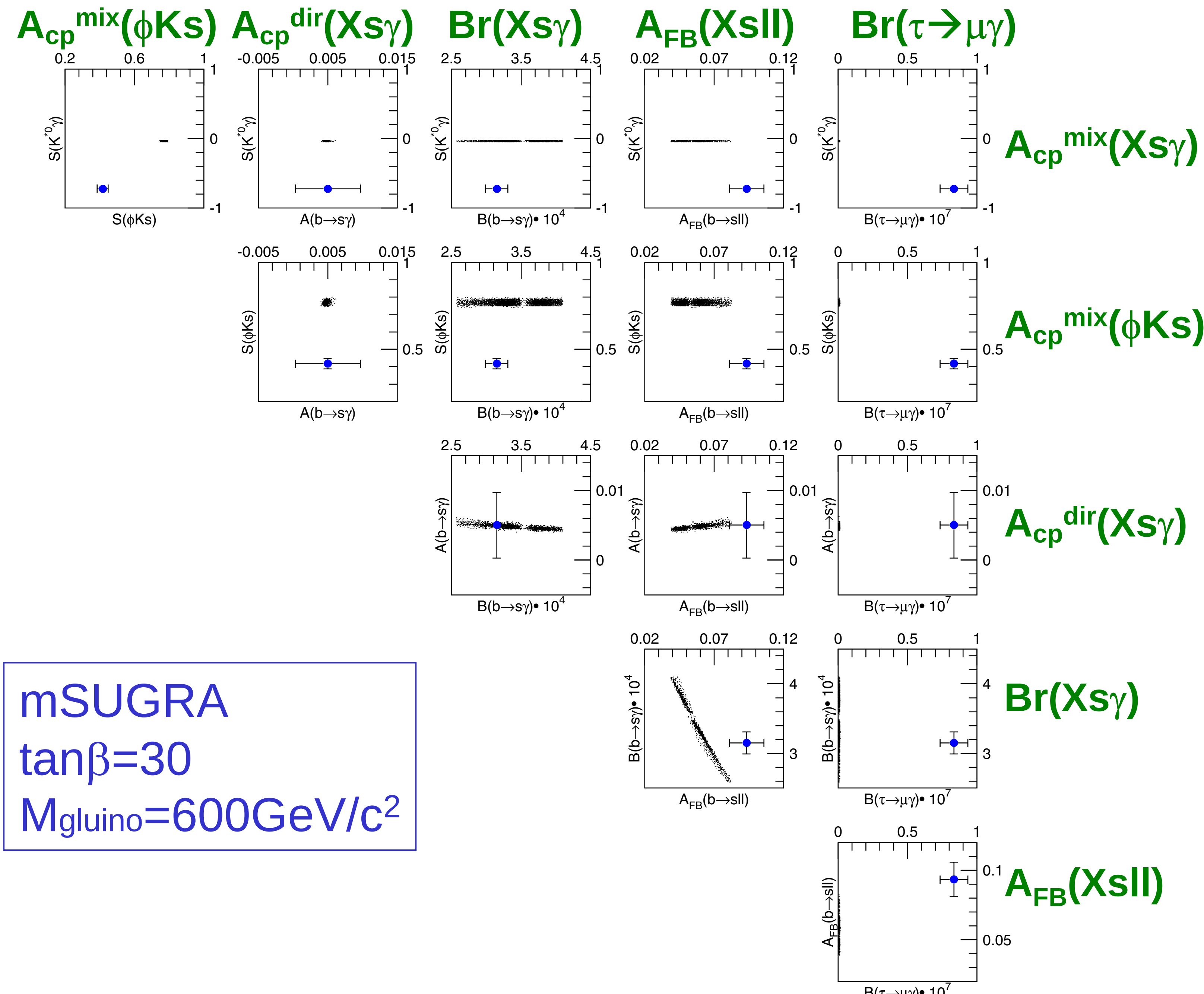
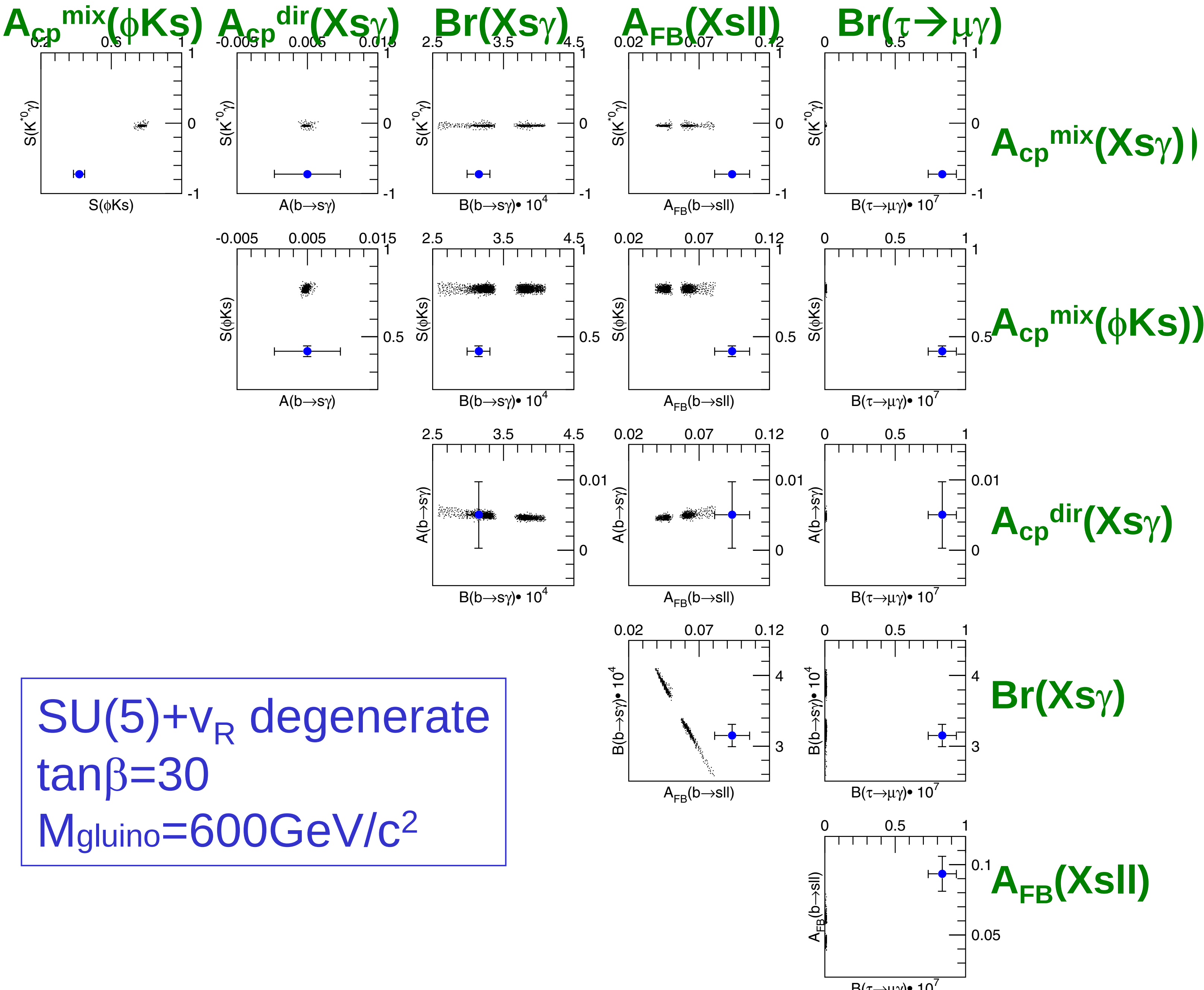
  - –
  - –
- ユ



mSUGRA
tanβ=30
M_{gluino}=600GeV/c²

St

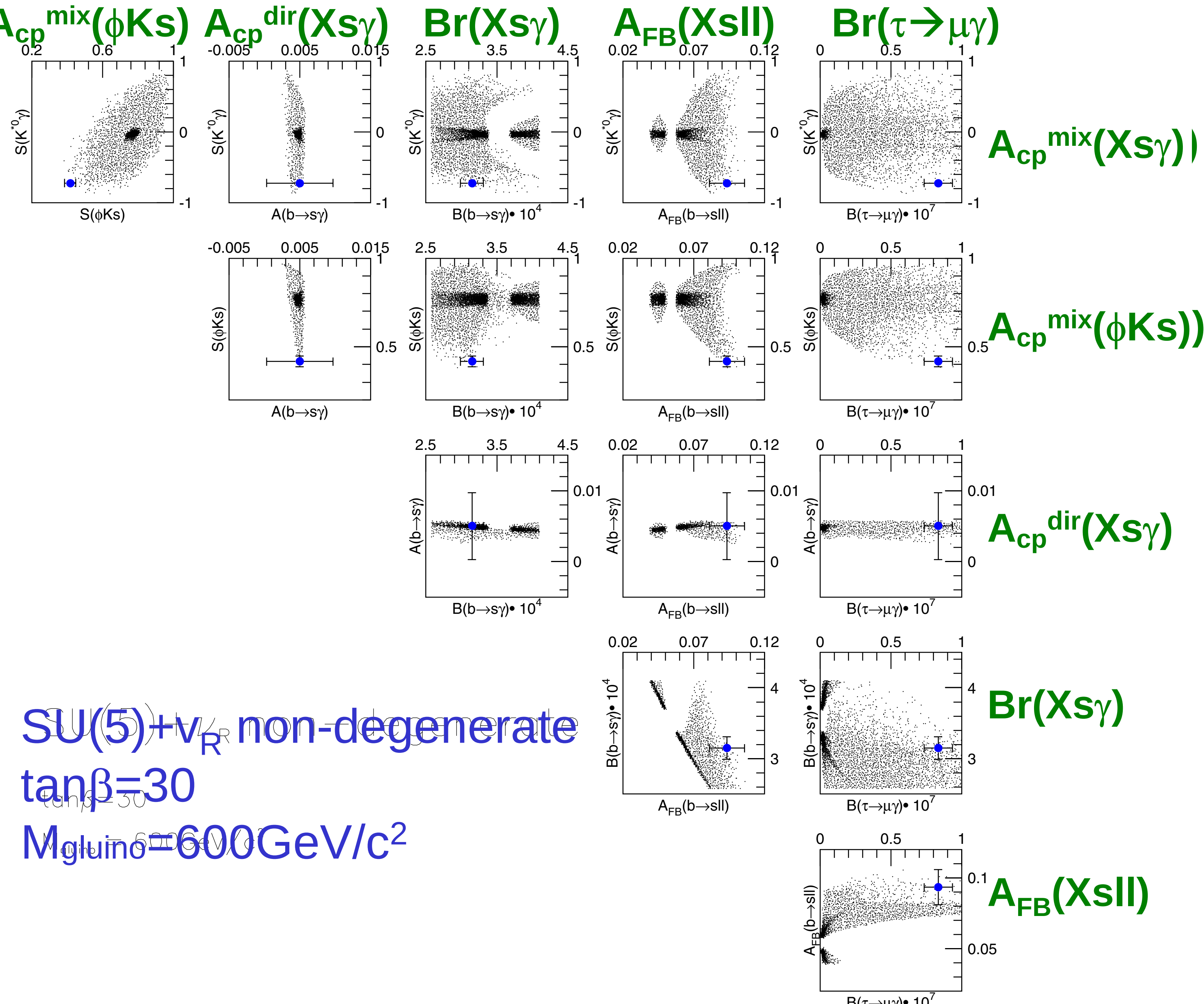


SU(5)+ν_R degenerate

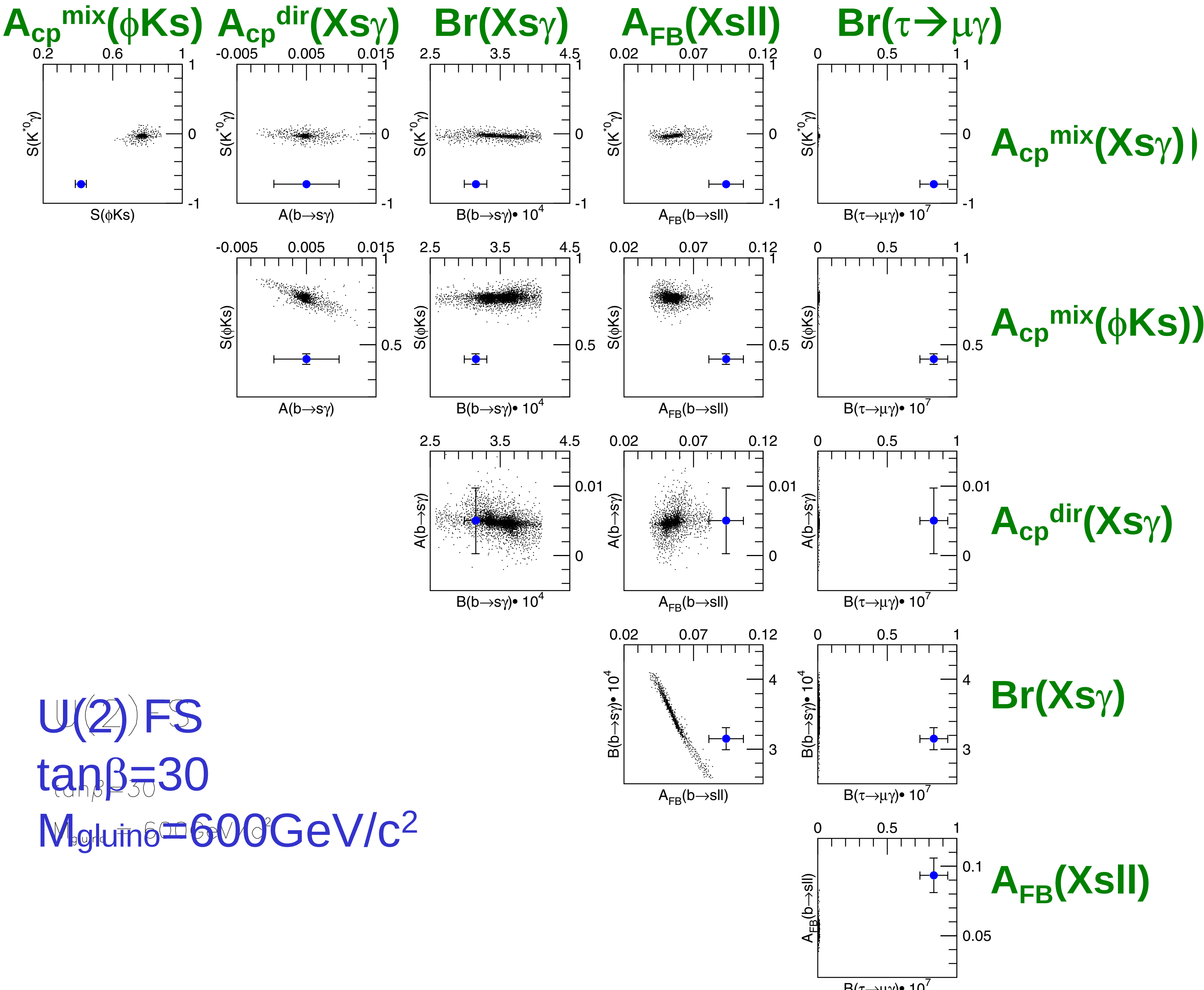
tanβ=30

M_{gluino}=600GeV/c^2

St


$A_{cp}^{mix}(\phi Ks)$
$A_{cp}^{dir}(Xs\gamma)$
$Br(Xs\gamma)$
$A_{FB}(Xsll)$
$Br(\tau \to \mu\gamma)$
$A_{cp}^{mix}(Xs\gamma)$
$A_{cp}^{mix}(\phi Ks)$
$A_{cp}^{dir}(Xs\gamma)$
$Br(Xs\gamma)$
$A_{FB}(Xsll)$
S(φKs)
A(b→sγ)
B(b→sγ)• 10^4
A_{FB}(b→sll)
B(τ→μγ)• 10^7
S(K*0γ)
SU(5)+ν_R non-degenerate
tanβ=30
M_{gluino}=600GeV/c^2

St

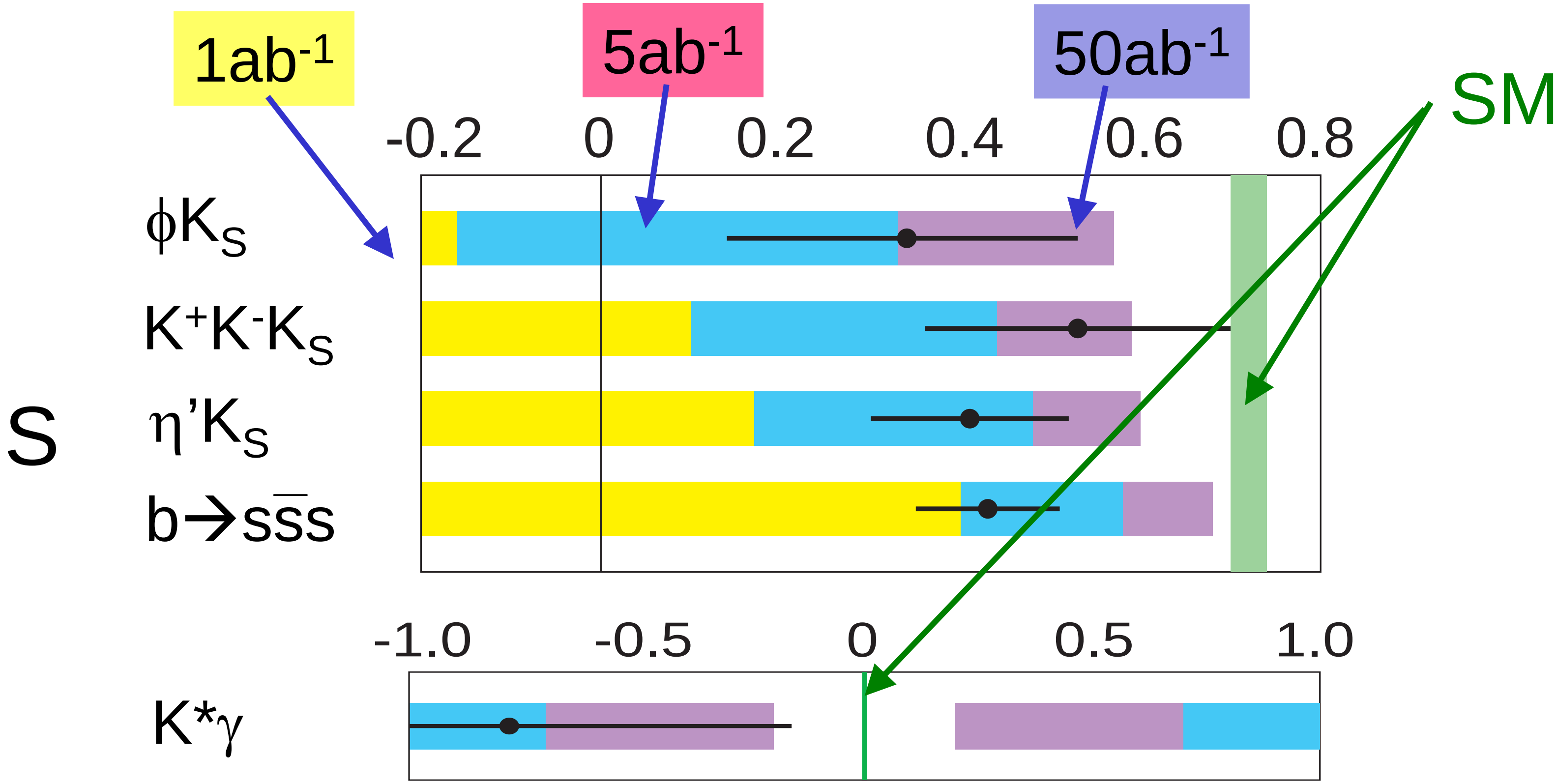


Acpmix(φKs)
Acpdir(Xsγ)
Br(Xsγ)
AFB(Xsll)
Br(τ→μγ)
Acpmix(Xsγ)
Acpmix(φKs)
Acpdir(Xsγ)
Br(Xsγ)
AFB(Xsll)
S(φKs)
A(b→sγ)
B(b→sγ)• 10^4
AFB(b→sll)
B(τ→μγ)• 10^7
S(K*0γ)
U(2) FS
tanβ=30
Mgluino=600GeV/c2

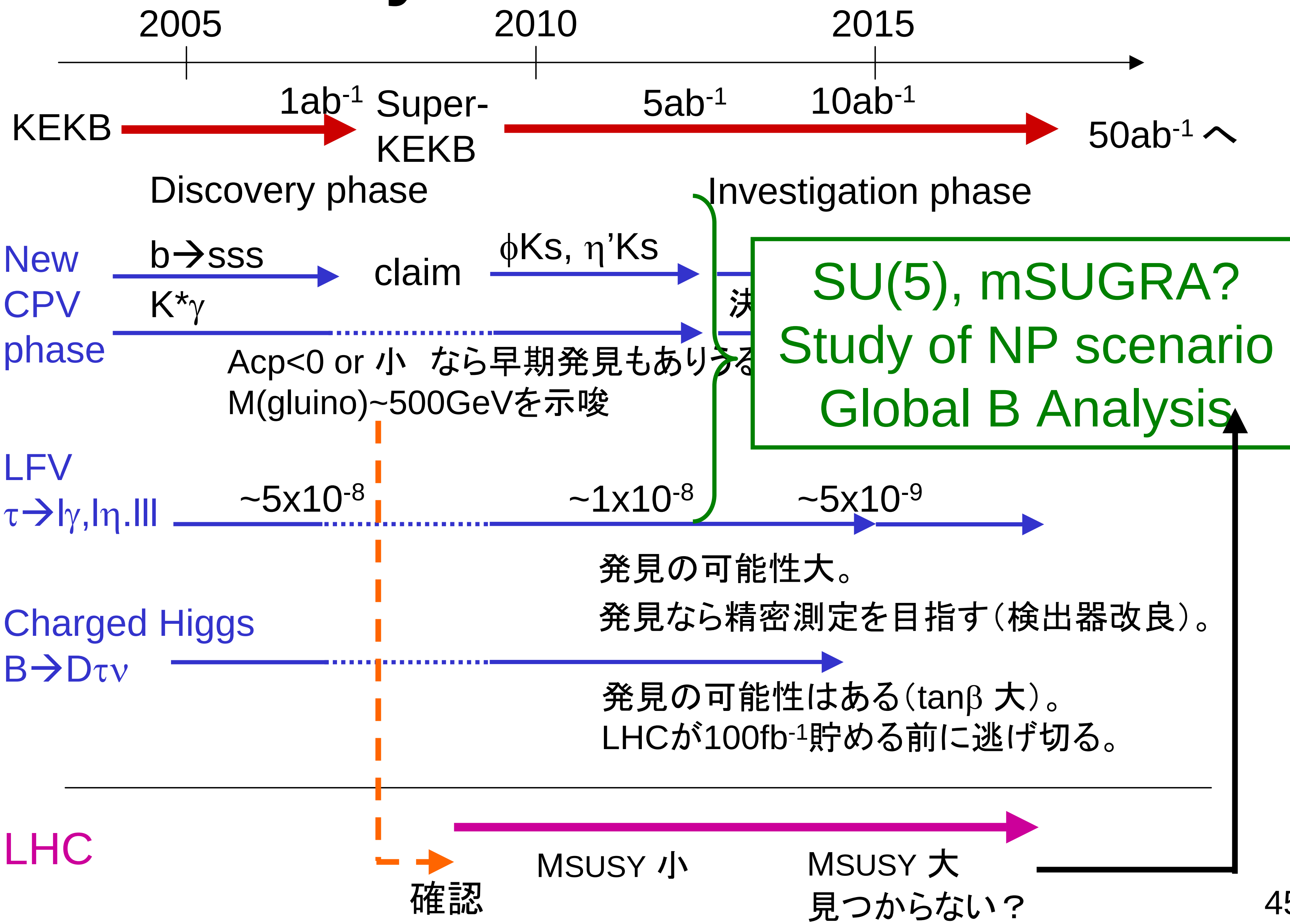
Summary-1

- New CPV phase の発見可能性
  - 中心値による
  - 5ab^{-1} で可能（2012年頃？）
  - B→s$\bar{s}$s 平均については1ab^{-1}でも可（2007年）

“ずれ”>5σとなる領域



Summary-2



2005
2010
2015
KEKB
1ab-1
Super-KEKB
5ab-1
10ab-1
50ab-1 へ
Discovery phase
Investigation phase
New CPV phase
b→sss
claim
φKs, η'Ks
K*γ
決
Acp<0 or 小 なら早期発見もありうる
M(gluino)~500GeVを示唆
SU(5), mSUGRA?
Study of NP scenario
Global B Analysis
LFV
τ→lγ,lη.lll
~5x10-8
~1x10-8
~5x10-9
発見の可能性大。
発見なら精密測定を目指す（検出器改良）。
Charged Higgs
B→Dτν
発見の可能性はある（tanβ 大）。
LHCが100fb-1貯める前に逃げ切る。
LHC
確認
MSUSY 小
MSUSY 大
見つからない？

結論

Discovery:

Super-B は、ループ効果による新粒子探索のフロンティア
New Physics の間接発見をできる可能性は十分にある。

Investigation:

Super-B で、種々のフレーバー遷移過程を測定することによって、New Physics scenario の検証が可能。

2009年前後に Super-B へのアップグレードを行えば、上記のような研究をLHC実験と同時期にできる。

Super-Bの物理の重要性はLHC/ILCと補完的。LHCでSUSYが見つからない（或いは重い）場合、Super-Bの物理はさらに重要。

FCNC＋LFV