フレーバー物理の展望
B, K, n

後田　裕 (KEK)

June 25th, 2011

高エネルギー物理学将来計画検討小委員会タウンミーティング

『10年先を俯瞰した高エネルギー物理学の将来展望』

Baryogenesis

Evidences that SM is incomplete

Neutrino mass

Dark matter

Grand unification

Mass hierarchy

There must be New Physics @ TeV scale !!

But

Super-symmetry ? $\psi \leftrightarrow \tilde{\psi}$

Extra-dimension ? $D > 4$

Composite Higgs ? $h = \bar{\psi}\psi$

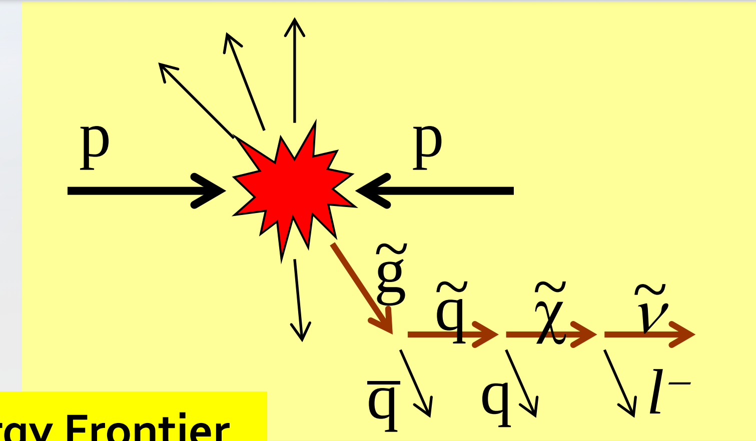
, or else ?

Flavor physics : key to identify the correct theory for NP

B | D | K | n | τ | μ | …

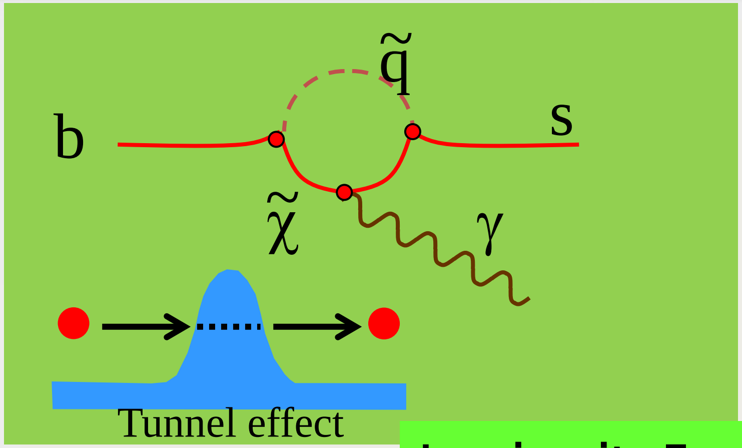
Energy Frontier and Luminosity Frontier

Direct Production by High Energy Coll.



Energy Frontier

Virtual Production via Quantum Eff.



Luminosity Frontier

Diagonal terms

Off-diagonal terms

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

衝突エネルギーを上げて、高いエネルギースケールに感度を得る
陽子コライダの場合、データを増やせば高いエネルギーでの衝突事象数はある程度増える

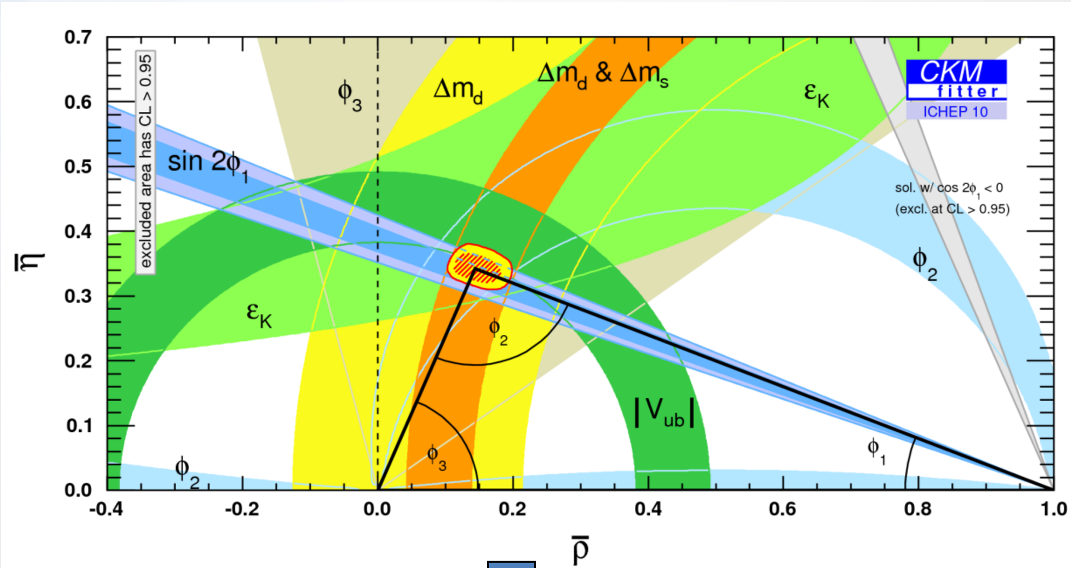
衝突エネルギー（~10GeV）は変えずに、データをためることで、より高いエネルギースケール（~TeV）に感度を得る

フレーバー実験の目指すものと特徴

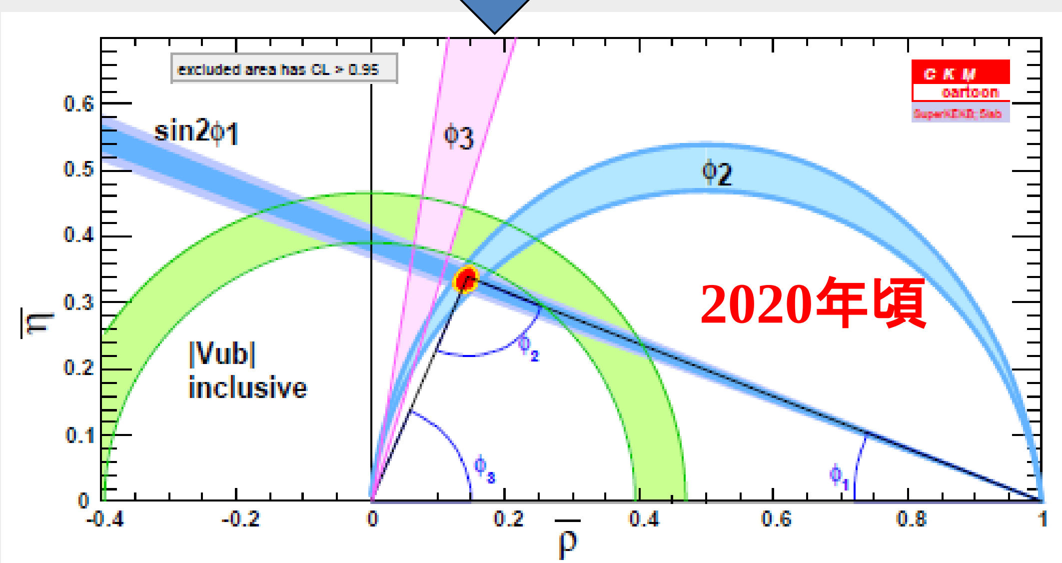
- NP発見を狙う
  ① ダイアグラムの内線への寄与
  ② A) 標準理論"バックグラウンド"がない（禁止／抑制）か、或いは、理論的・実験的に精度よく決められるプロセスを選ぶ
  B) 既になんらかの兆候が見えているものを追求する
  →稀な事象の精密測定
  →高ルミノシティ、大強度
  （エネルギーは高くないので加速器／測定器の規模は比較的小さい）

- 発見は始まりでしかない
  – NPの性質理解のために、相互作用などを測定
  → NPの模型特定・パラメータ決定へ
  →多種多様な測定が必要
  (B, K, n, ...)

CKM unitarity triangle



Still room for O(0.1) NP

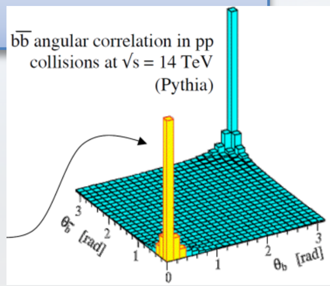


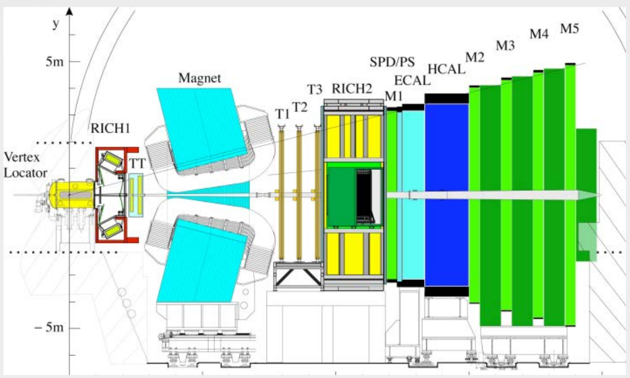
Outline

- フレーバー物理とプレシジョン・フロンティア
- 新物理の探索
  - n
  - 荷電Higgs探索
  - B
  - T-violationの探索
  - 新しいCPV位相探索
  - K
  - 右巻き相互作用探索
- 将来展望
- まとめ

CERN
運転中

pp衝突 bb production: 一山~230μb
46k bb pair/s @ 2×10³²/cm²/s
Dirty environment

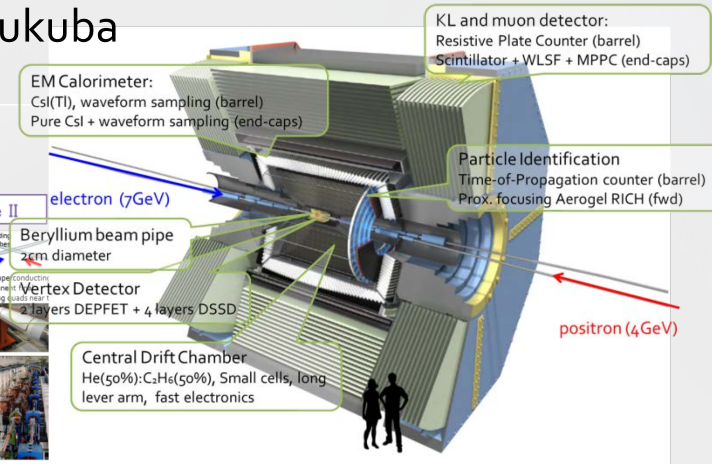


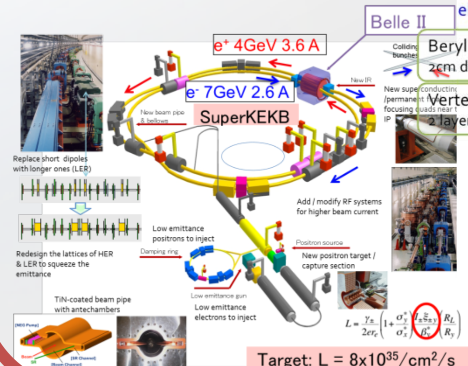


$1.9 < \eta < 4.9$ or
$15 < \theta < 300$ mrad

VELO: Vertex Locator (around interaction point)
TT, T1, T2, T3: Tracking stations
RICH1-2: Ring Imaging Cherenkov detectors
ECAL, HCAL: Calorimeters
M1–M5: Muon stations

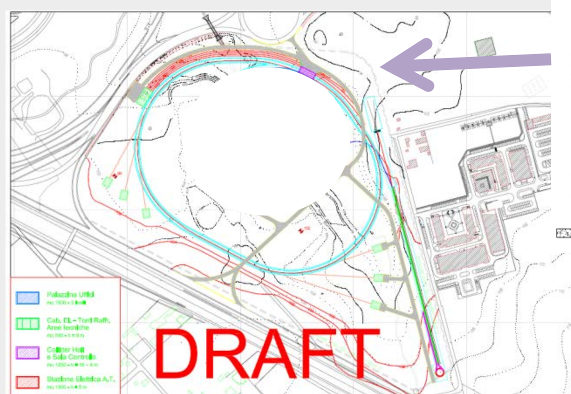
KEK, Tsukuba
建設中

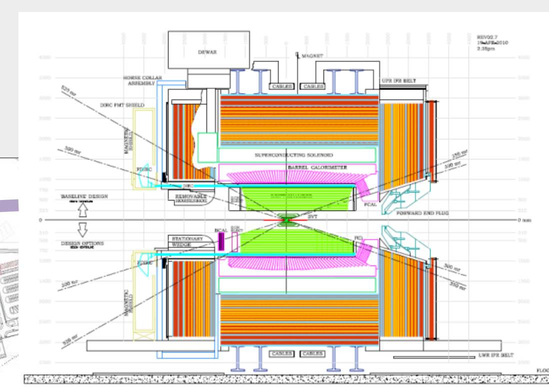




$e^+e^- \rightarrow Y(4S) \rightarrow BB$: ~1nb
1k BB pair/s @ 1×10³⁶/cm²/s
Clean environment

Tor Vergata
建設許可

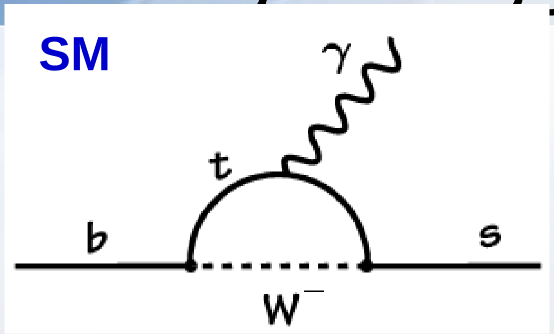


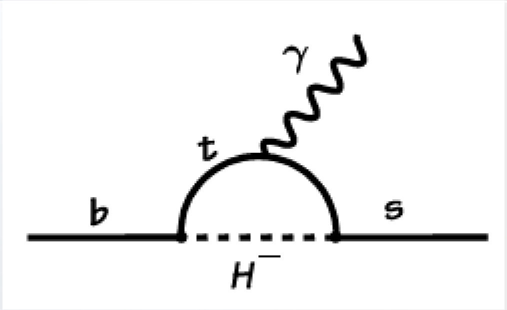


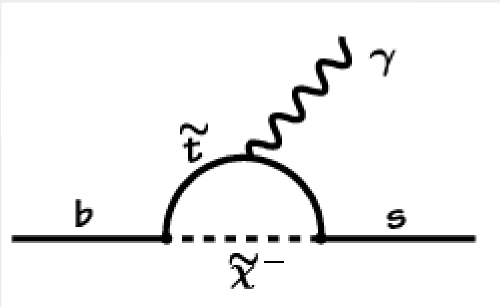
年表

会議などでの数字を勝手に並べた物
SuperBは公式スケジュールを明言せず
LHCbはよくわからない

Charged Higgs hunting 1: inclusive b → s γ



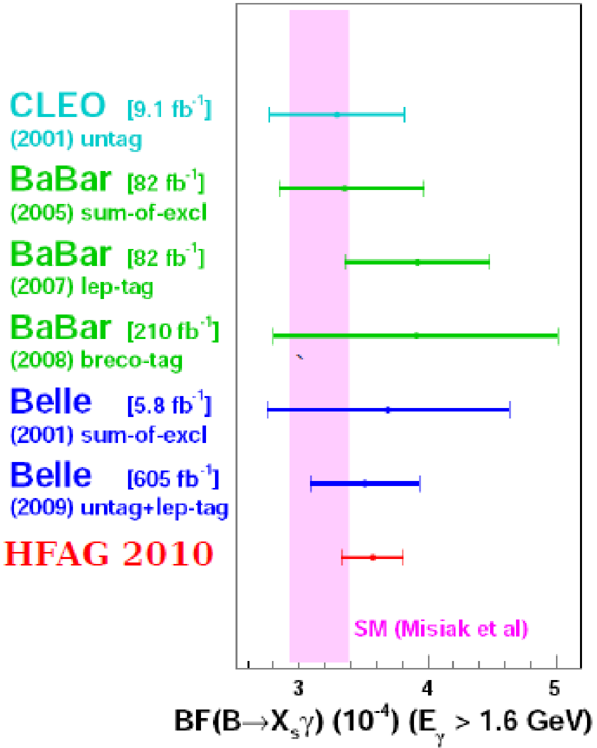




$$\text{HFAG 2010:}\ \ \mathcal{B}(B\to X_s\gamma) = (3.55 \pm 0.26)\times 10^{-4}\ \ (\text{for } E_\gamma > 1.6\ \text{GeV})$$

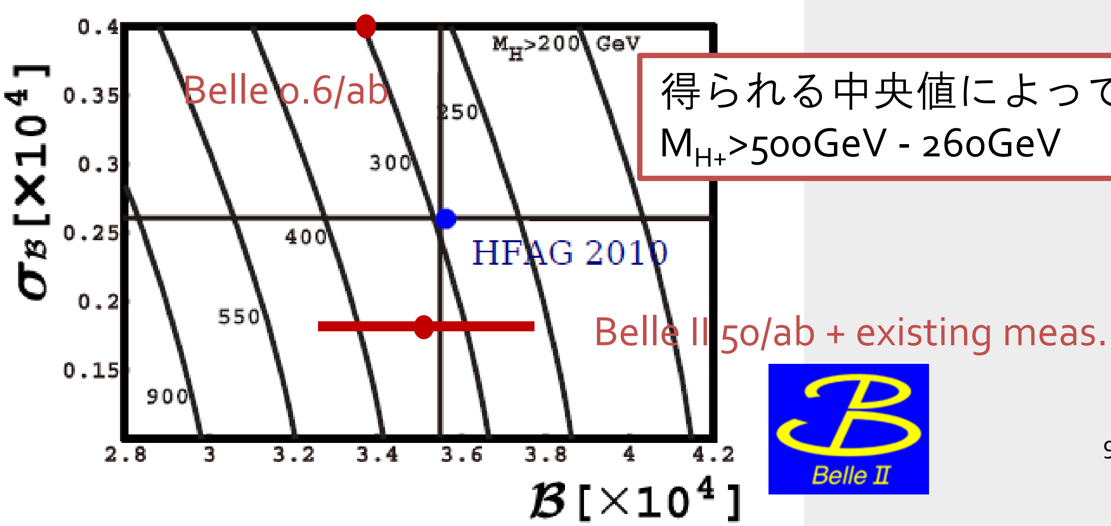
vs

$$\text{SM:}\ \ \mathcal{B}(B\to X_s\gamma) = (3.15 \pm 0.23)\times 10^{-4}\ \ (\text{for } E_\gamma > 1.6\ \text{GeV})$$



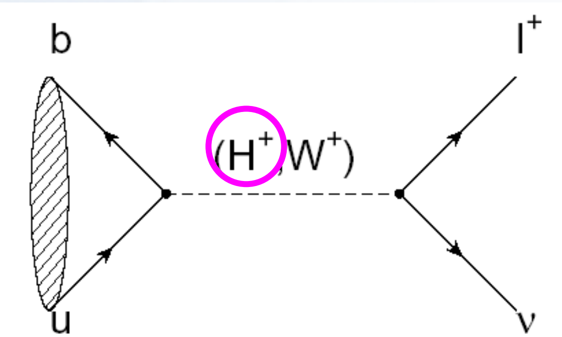
Charged Higss bound (2HDM TypeII)

$M_{H^+} > 300$ GeV



得られる中央値によって、
M_{H+}>500GeV - 260GeV

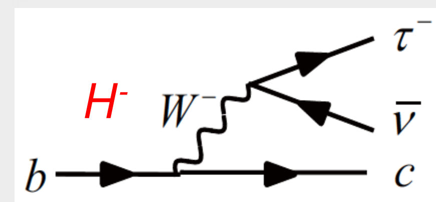
Charged Higgs hunting 2: $B^+ \to \tau^+ \nu_\tau$

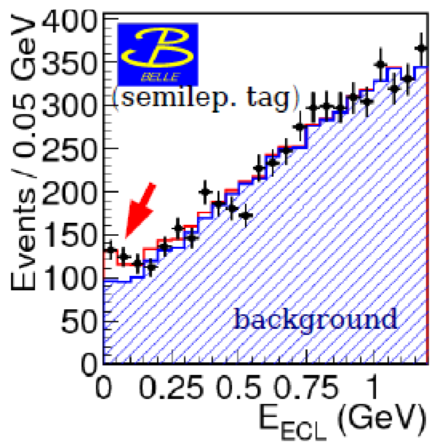


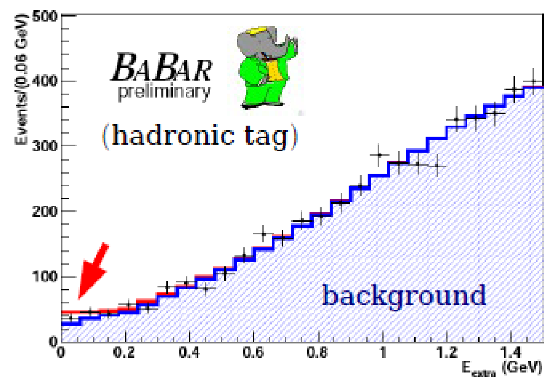
内線の荷電カレントなのでH⁺と置き換え可能

$$\mathcal{B}(B^- \to \tau^- \nu) = \mathcal{B}_{\rm SM}(B^- \to \tau^- \nu)\left[1 - \frac{m_B^2}{m_{H^\pm}^2}\tan^2\beta\right]^2$$

Similar constraints from B → D τν

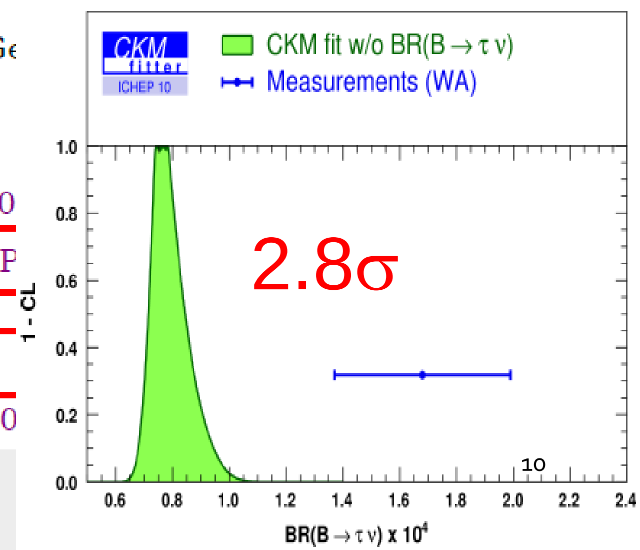






Extra calorimeter energy : $E_{ECL/extra}$ (Ge

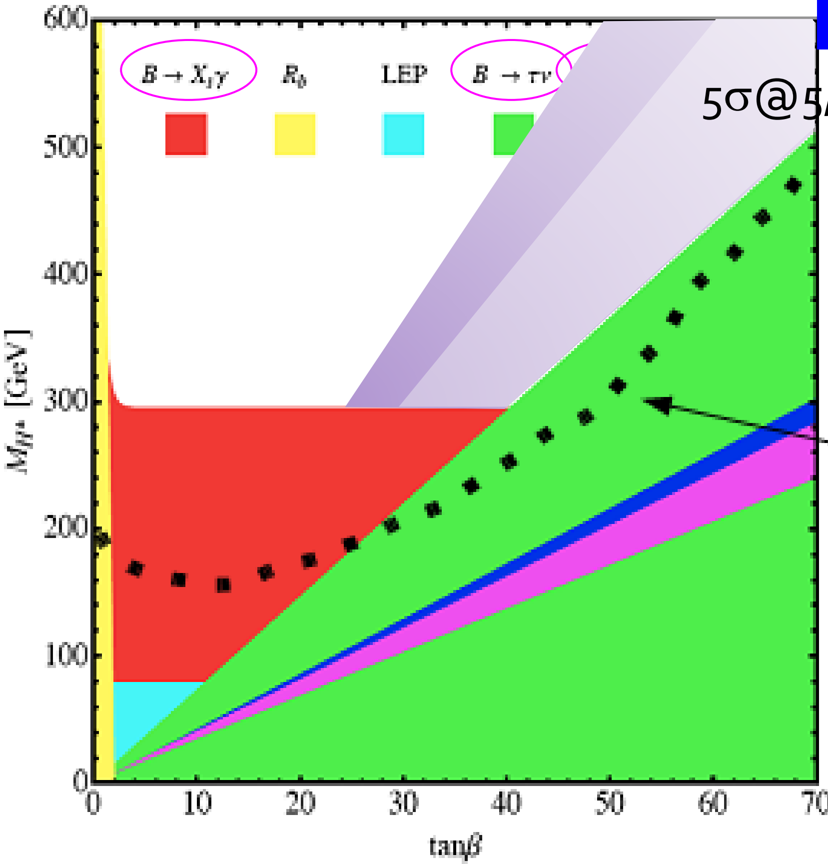
Belle	$N_{B\bar{B}}$	$\boldsymbol{B}\,(10^{-4})$	$\Sigma\,(\sigma)$	
Hadronic tag	(449 M)	$(1.79^{+0.56+0.46}_{-0.49-0.51})$	3.5	PRL97, 251802 (20
⇒ Semilep. tag	(657 M)	$(1.54^{+0.38+0.29}_{-0.37-0.31})$	3.6	arXiv:1006.4201, P
BaBar				
⇒ Hadronic tag	(468 M)	$(1.80^{+0.57}_{-0.54}\pm 0.26)$	3.6	preliminary
Semilep. tag	(459 M)	$(1.7\pm 0.8\pm 0.2)$	2.3	PRD81, 051101 (20



Current constraints and Prospects

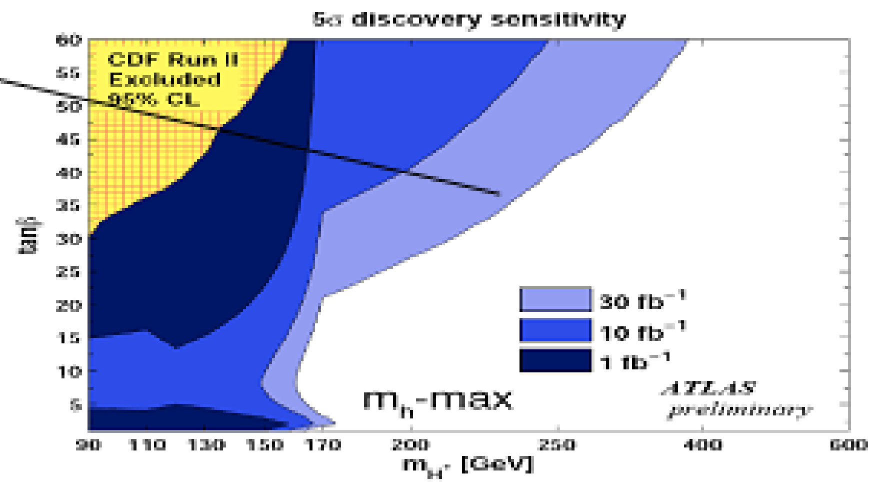
5σ@50/ab

5σ@5/ab



U. Haisch, hep-ph/0805.2141;
ATLAS curve added by *Steve Robertson*

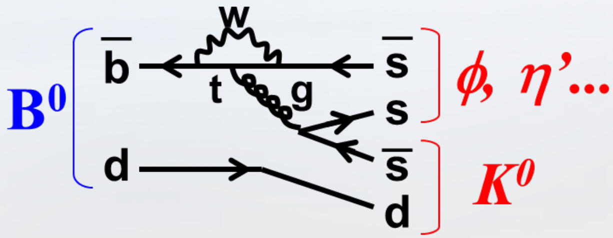
ATLAS 30/fbで発見(5σ)可能な領域は、Flavor Physics により既に棄却(95%)されている。
Belle IIでデータを貯めると、薄紫の領域なら5σで発見可能。



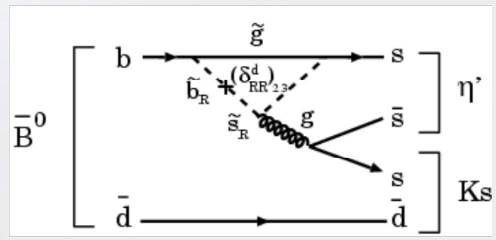
フレーバーの実験が
非常にパワフル

[New CPV phase] TCPV in b to $s q\bar{q}$

$b \to s q \bar{q}$ penguin

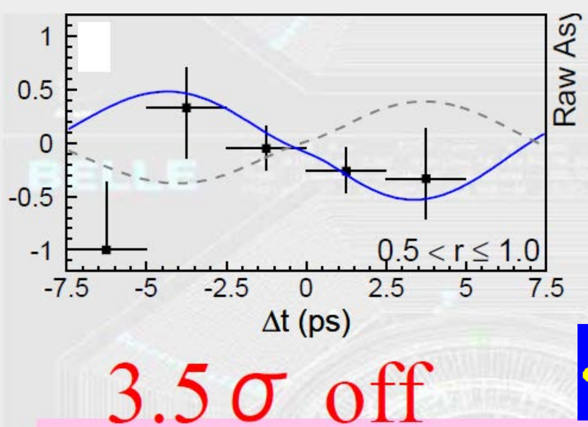


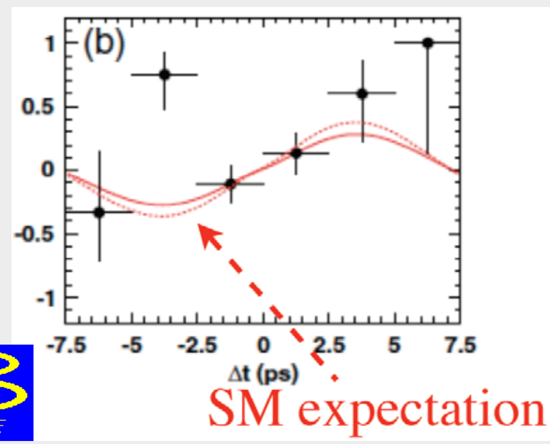
+

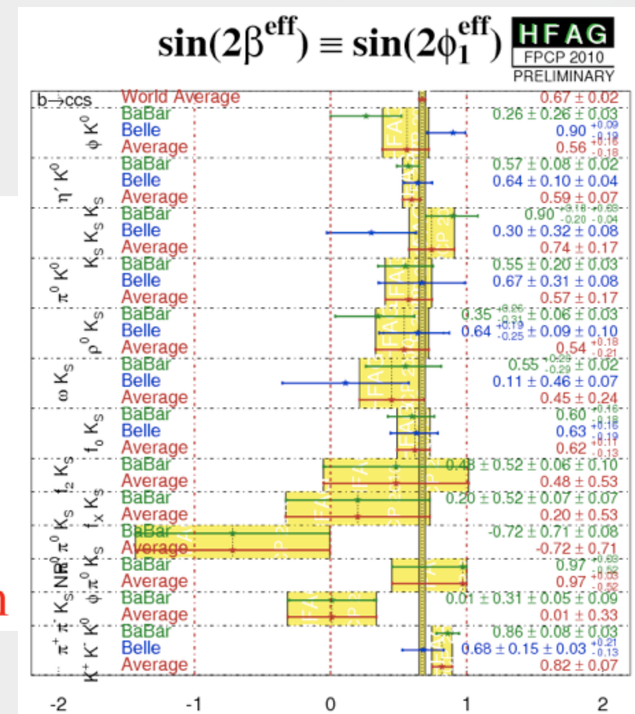


$$A \approx 0$$
$$S \approx -\xi_f \sin 2\varphi_1$$

SMでは、基本的にTCPはJ/ψK⁰と同じで$\sin 2\phi_1$になる
新しい複素位相が加わると値がずれる
SMの値は精密に測れるので比較が容易







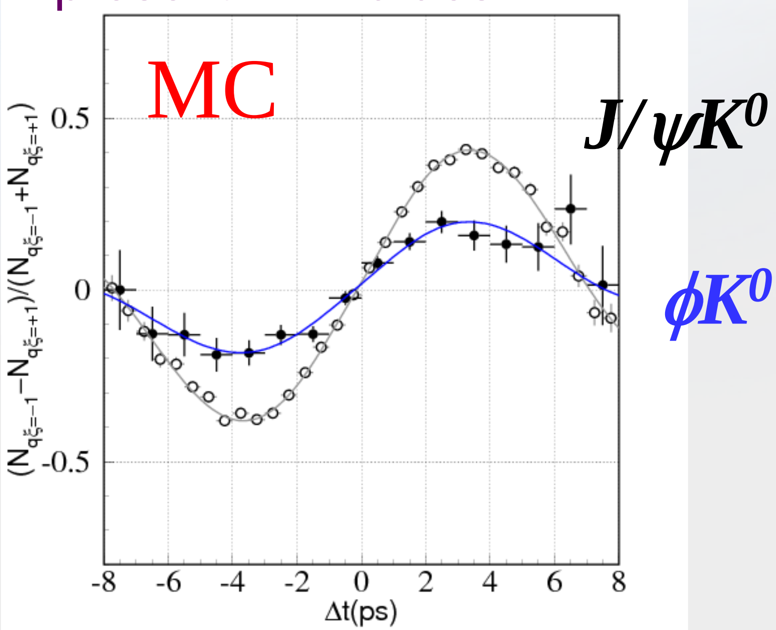
Phys. Rev. Lett. 91, 261602 (2003) 140fb⁻¹

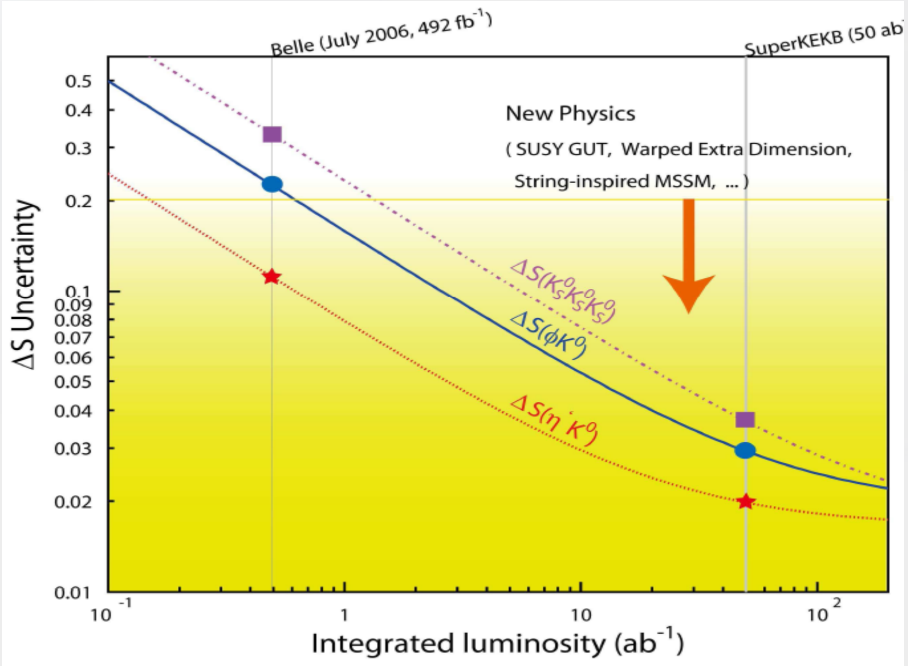
PRD 82, 073011 (2010) 657MBB

QCDF

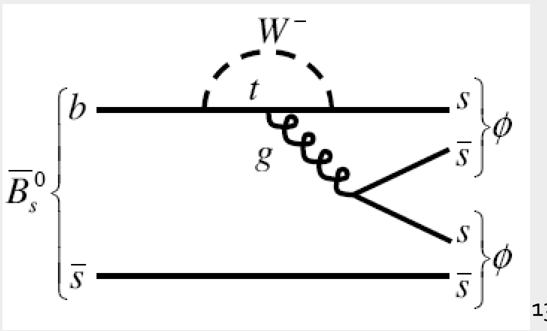
Prospect

$B \to \phi K^0$ at 50/ab with ~present WA values



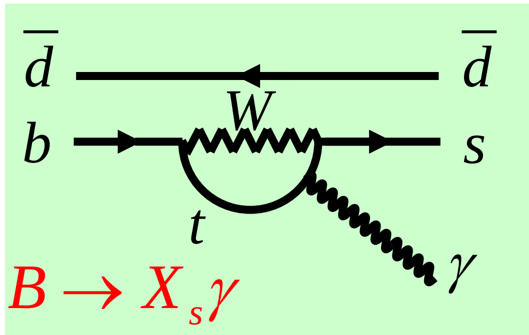


Belle II 5/ab:	$\delta\Delta S_{\phi Ko} = 0.073$
Belle II 50/ab:	$\delta\Delta S_{\phi Ko} = 0.029$
LHCb 10/fb:	$\delta\Delta S_{\phi KS} = 0.14$
LHCb 10/fb:	$\delta\Delta S_{Bs\to\phi\phi} = 0.042$



$B \to K^* (\to K_S \pi^0)\gamma$ TCPV [right-handed current]

SMの予言



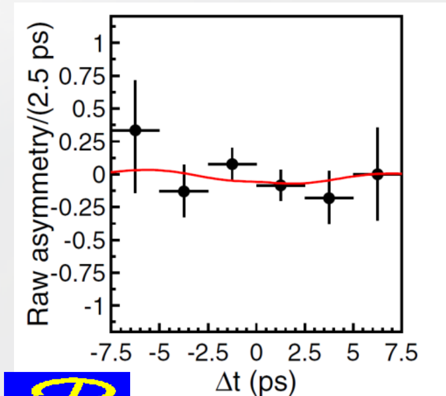
崩壊には弱位相を持たない（J/ψK_Sと同じ）
Wのせいで、γは偏極している。

$$b \to s\gamma_L$$
$$\bar{b} \to \bar{s}\gamma_R$$

$$|S| \sim \frac{2m_s}{m_b} \sin 2\varphi_1 \sim 0.04$$

偏極が解ける度合い＋ハドロン化の際の不定性

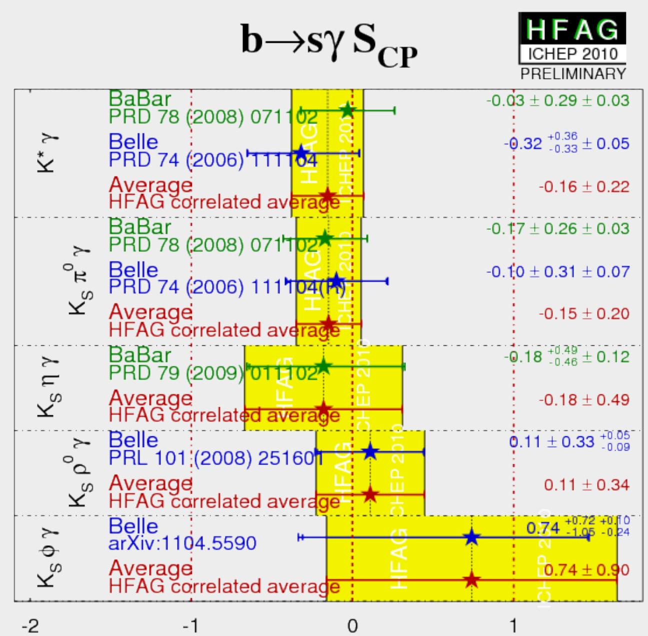
標準理論の予言がほぼ０(Null test)



zero consistent

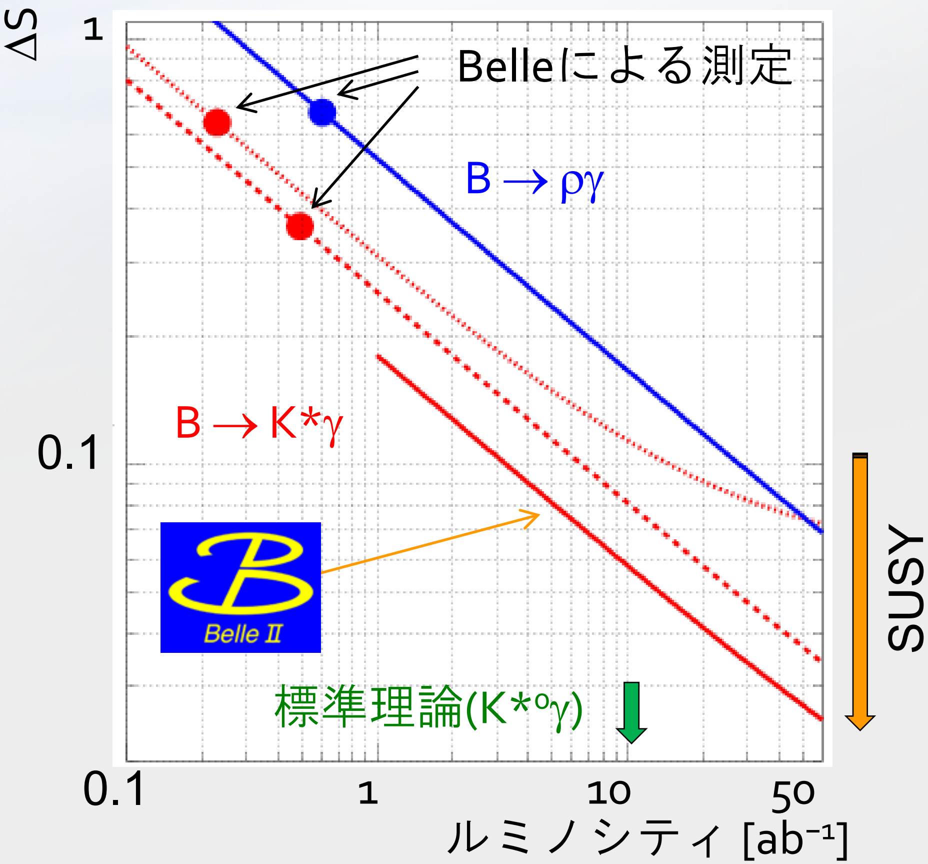
Belle 535MBB (2006)

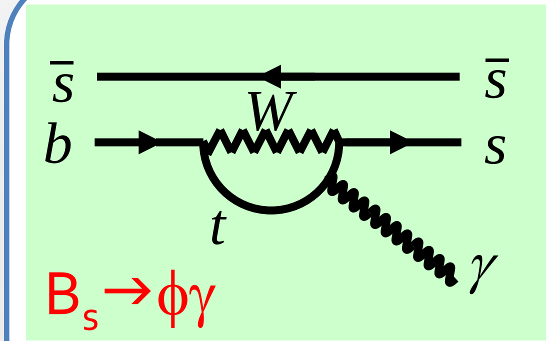
$$S_{K^*\gamma} = -0.32^{+0.36}_{-0.33} \pm 0.05$$



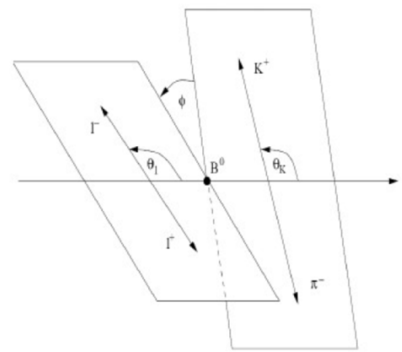
New Physics
O(1): L-R symmetric model
O(0.1): SUSY SU(5)

Prospect





LHCb 2/fb:
$\delta(\sin 2\psi)$=0.2



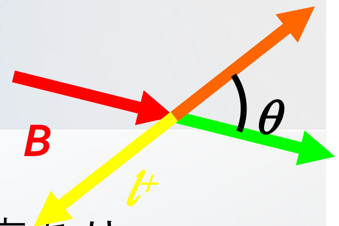
$B_d \to K^* e^+ e^-$
very low q^2

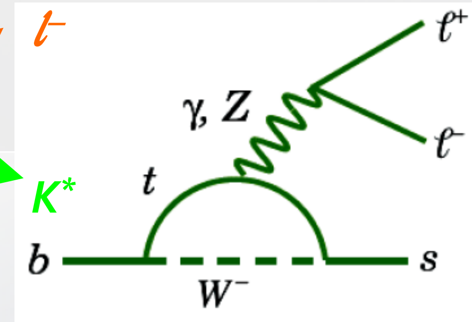
LHCb 2/fb:
$\delta(A_R/AL)$=0.12

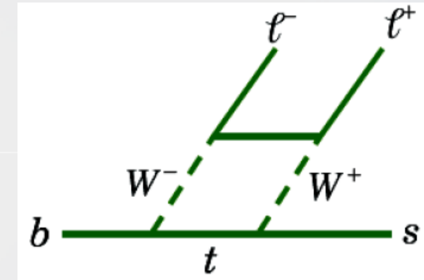
SMの領域近くに迫る

Belle II 50/ab: $\delta S_{K^*\gamma}$ = 0.027
$\delta S_{\rho 0\gamma}$ = 0.075

$B \to K^{(*)} \ell^+ \ell^-$

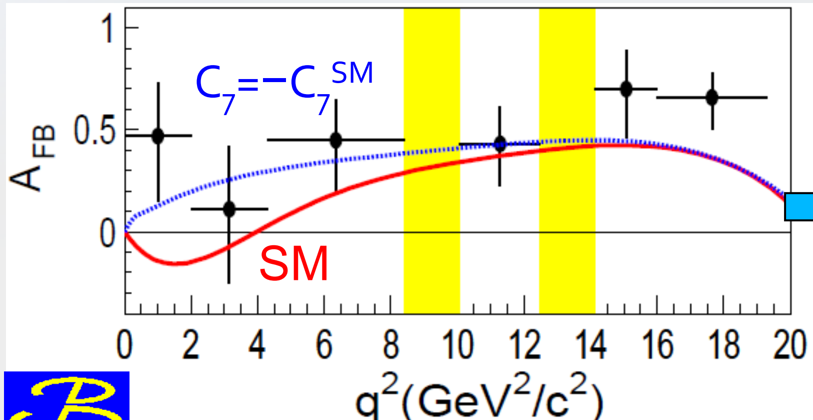




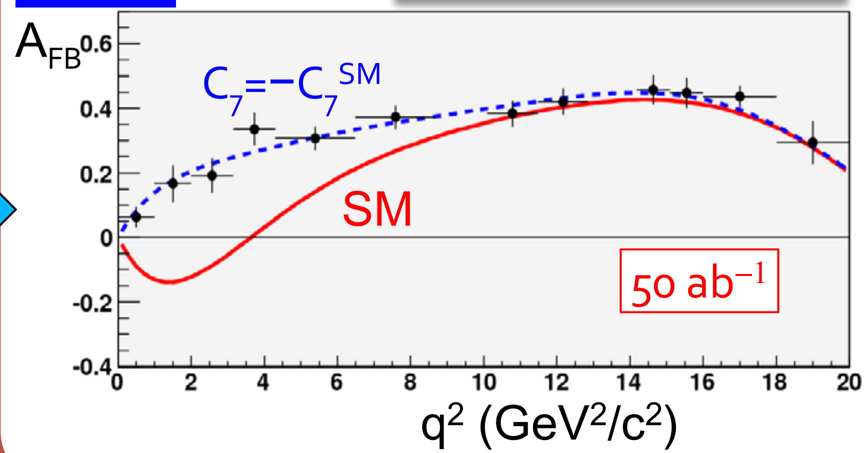


- C_7, C_9, C_{10} Wilson 係数に感度あり。
- 多くの観測量： 分岐比, A_{FB}, μ/e 比

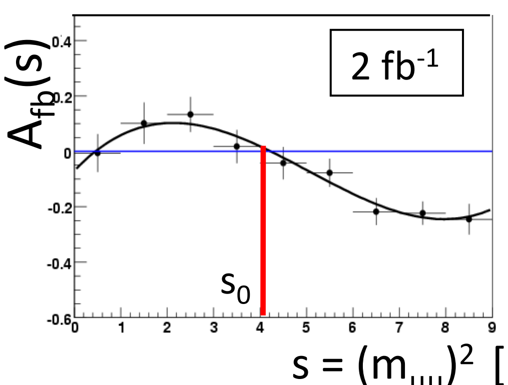
前後方非対称性 (A_{FB})



Belle 2009（新物理のヒント？）



μμのみ



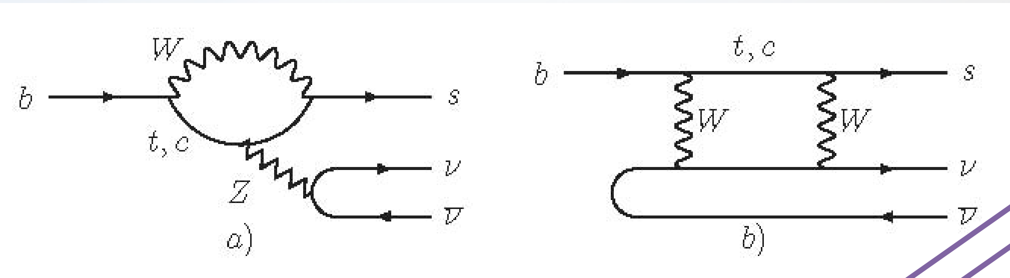
$\sigma(s_0)/s_0$ = 11%@2/fb, 7%@10/fb

Decay	2 fb^{-1} yield	B_{bb}/S
$B^+ \to K^+\mu\mu$	3.8k	~1
$B^+ \to K^+ee$	1.9k	~5

$B \to K^{(*)}\nu\nu$

+Tag手法の改善

Theoretically very clean, experimentally challenging



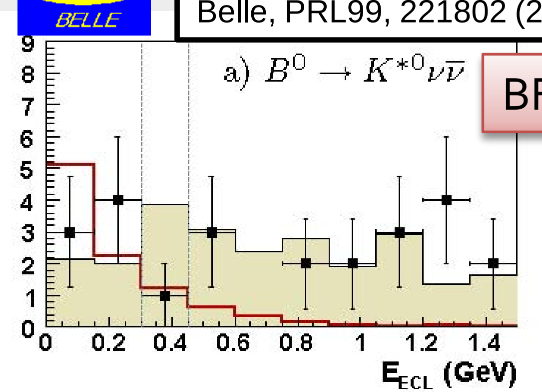
3σ evidence w/ Belle II 50/ab
if BF=0.68×10^{-5} (SM)

右巻き相互作用の
強さと位相を厳しく制限できる

$Br(B \to K^{*0}\nu\nu) < 3.4 \times 10^{-4}$ @90% C.L.

Belle, PRL99, 221802 (2007), 490 fb^{-1}

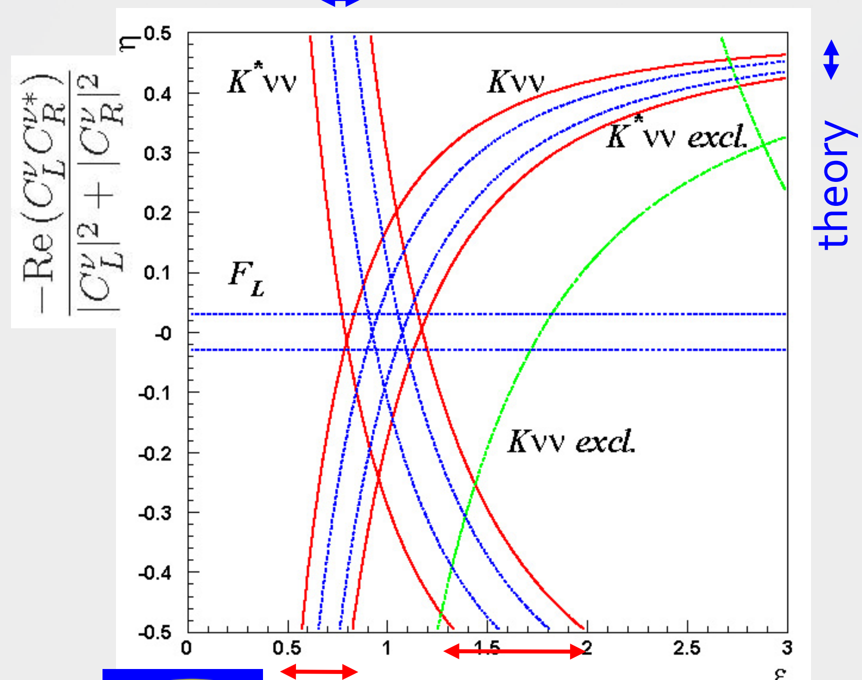
BF=0.68×10^{-5} (SM)



-- exp. signal (20xBr)

exp. bkg. (scaled to sideband)

theory

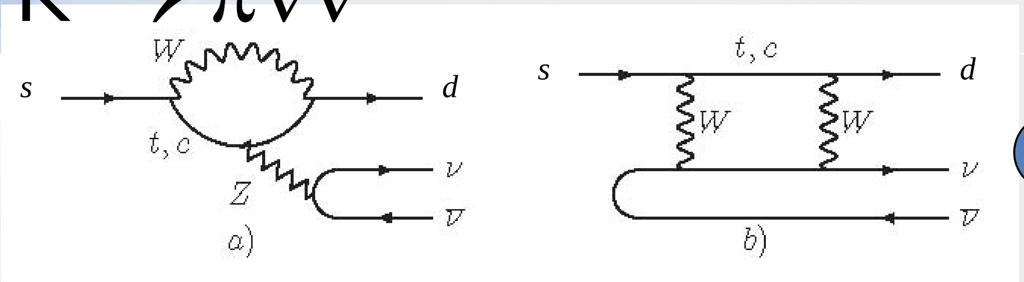


50 ab^{-1}

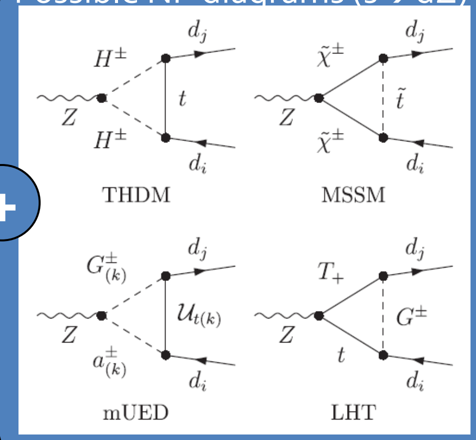
$$\frac{\sqrt{|C_L^\nu|^2+|C_R^\nu|^2}}{|(C_L^\nu)^{SM}|}$$

adopted from W. Altmannshofer et al., JHEP 0904, 022 (2009)

[s→d] K → πνν



Possible NP diagrams (s→dZ)



PRD76.074027

ハドロン部分の不定性はよく測られたBF($K^+\to\pi^0 e^+\nu$)で規格化
理論的には$B\to K^{(*)}\nu\nu$よりもクリーン

$K^+\to\pi^+\nu\nu$

振幅 = A

top + charm contribution (→理論誤差)

$$B(K^+\to\pi^+\nu\bar{\nu}) = \kappa_+(1+\Delta_{EM})\left|\frac{V_{ts}{}^*V_{td}X_t}{\lambda^5}+\frac{V_{cs}{}^*V_{cd}(P_c+\delta P_{c,u})}{\lambda}\right|^2$$

$$BR_{SM} = (7.81^{+0.80}_{-0.71}\pm 0.29)\times 10^{-11}$$

$BR=1.73(^{+1.15}_{-1.05})\times 10^{-10}$

(BNL-E787/949; PRL 101, 191802 (2008))

$K_L\to\pi^0\nu\nu$

$K_L \sim (K^0-\bar{K}^0)/\mathrm{sqrt}(2)$

振幅としてAの虚部がとり出される(2iη)

Charm の寄与がキャンセル(更にクリーン)

$$B(K_L\to\pi^0\nu\bar{\nu}) = \kappa_L\left(\frac{Im.(V_{ts}{}^*V_{td})X_t}{\lambda^5}\right)^2$$

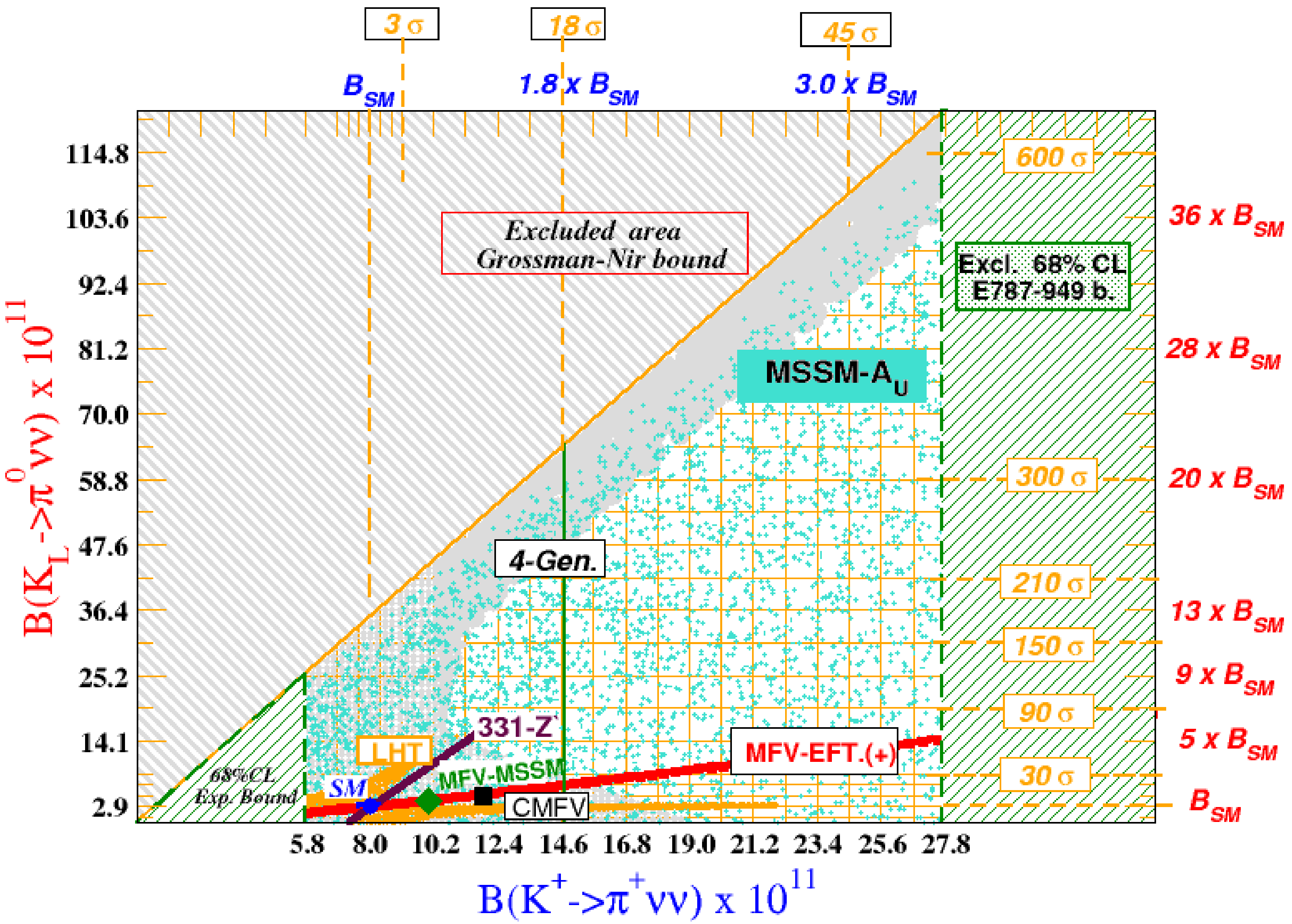
$$BR_{SM} = (2.43^{+0.40}_{-0.37}\pm 0.06)\times 10^{-11}$$

$BR<2.6\times 10^{-8}$

(KEK-E391a; PRD 81, 072004 (2010)

Grossman-Nir limit ($K_L\to\pi^0\nu\nu$の分岐比は$K^+\to\pi^+\nu\nu$の分岐比の
ファクター倍より大きくなれない)

NP possibility in K→πνν

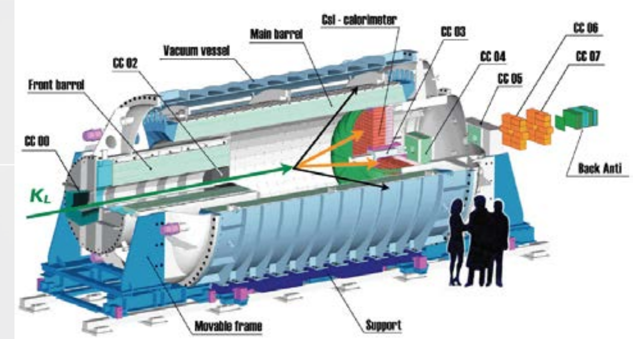


FlaviAnet http://www.lnf.infn.it/wg/vus/

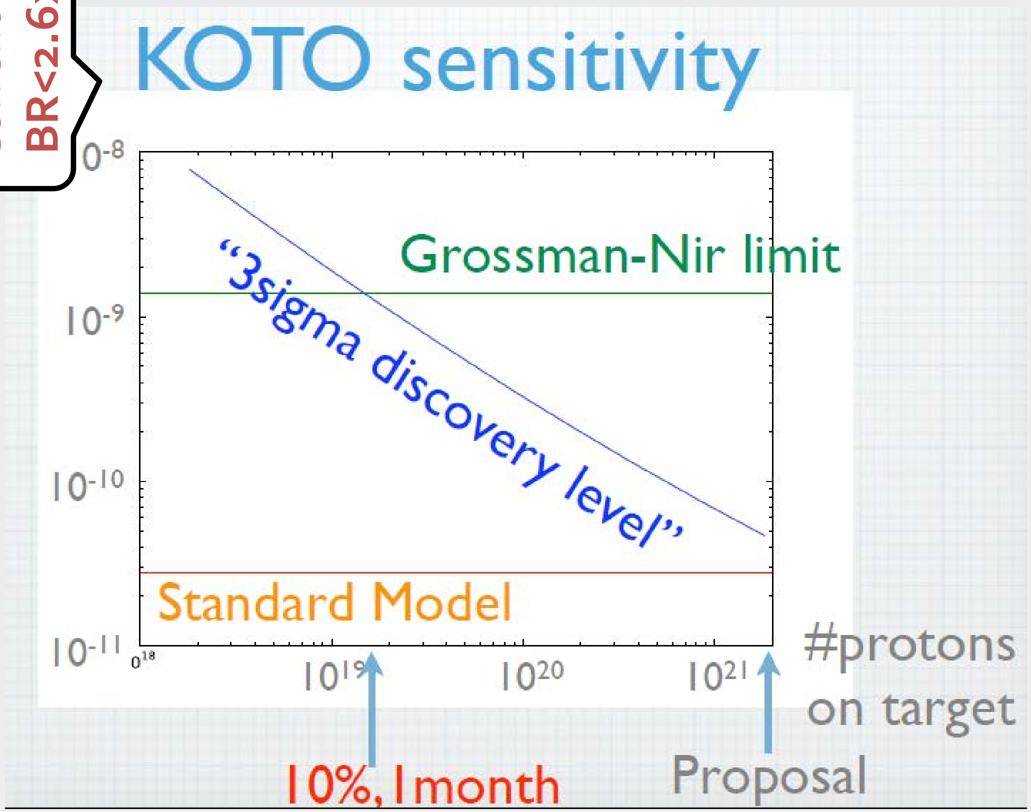
$K_L \rightarrow \pi^0 \nu\nu$実験

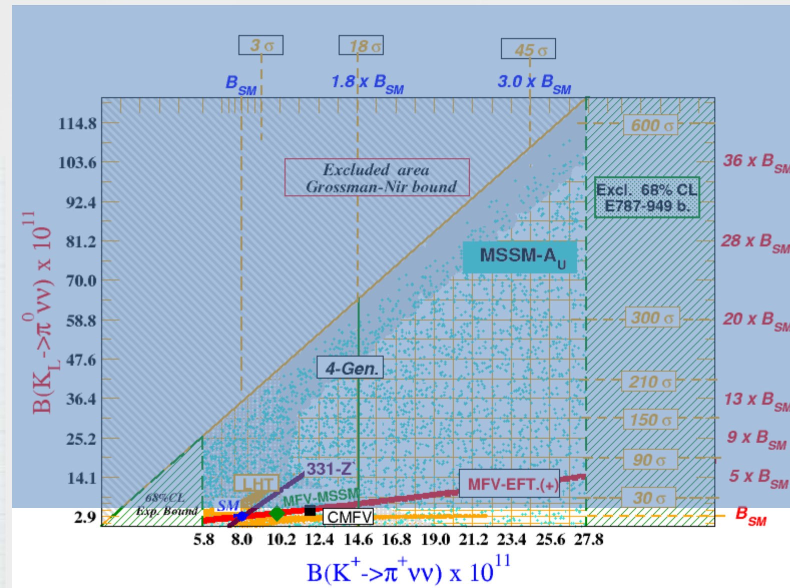
KOTO=K⁰ at Tokai

- KL Beam line newly built at J-PARC/hadron hall
- KEK-E391a detector + upgrade of key components
  - Longer CsI crystals from KTeV, etc…



Current limit:
BR<2.6x10^{-8}



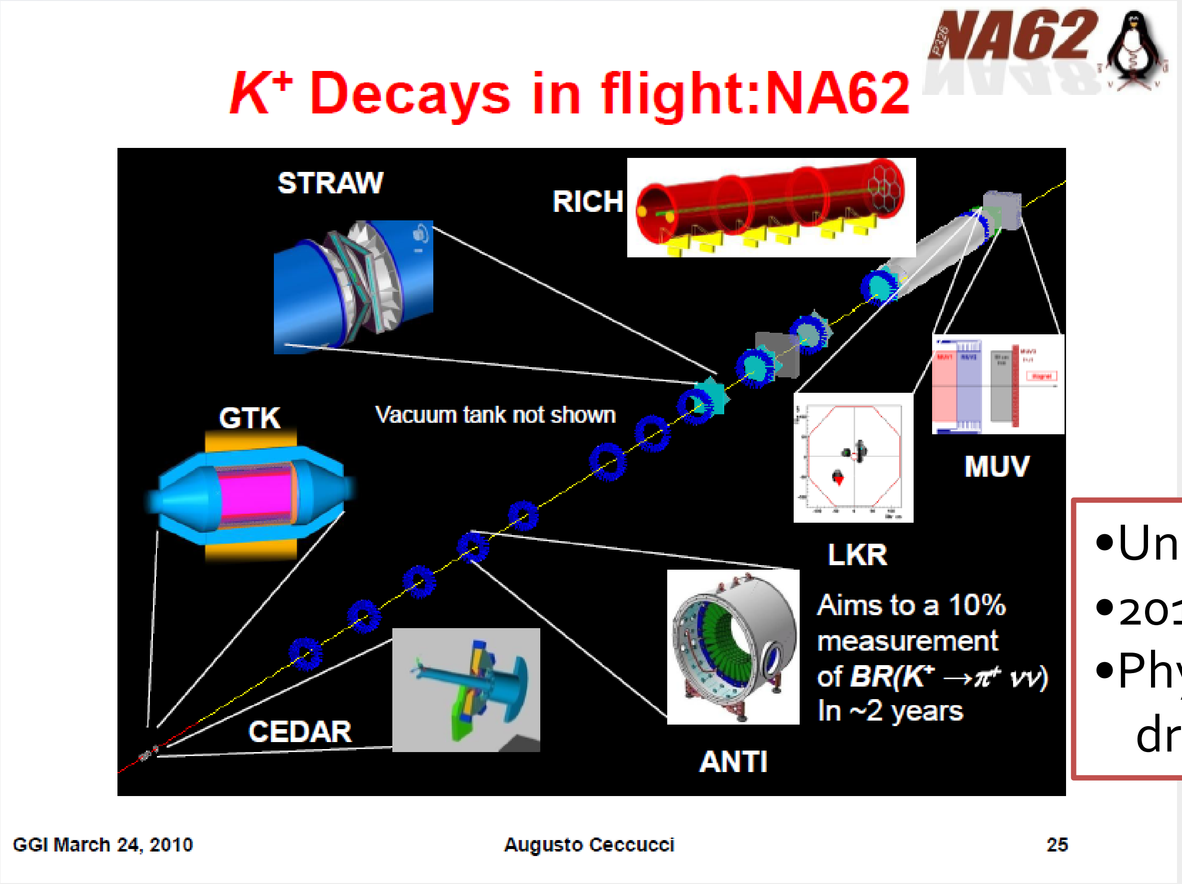


2012秋~ 物理ラン
SX power ~10kW
2013夏 G-N limit
2014秋~
SX power >100kW
~2017 KOTO goal

•SX power増強やbeam time割当てに依存
•SXスピル構造の改善が実験の質の鍵

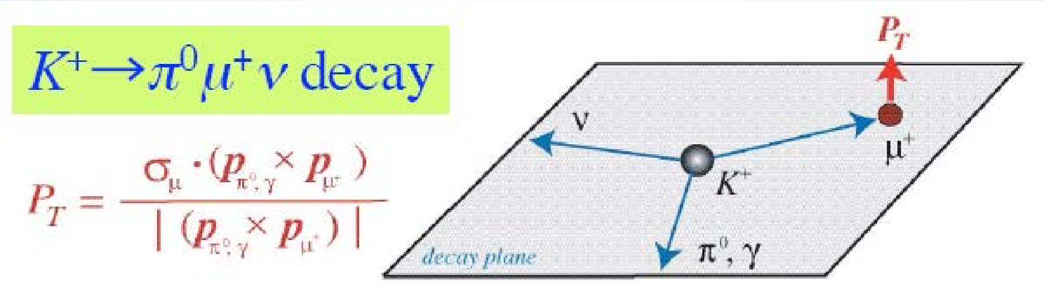
$K^+ \to \pi^+ \nu\nu$

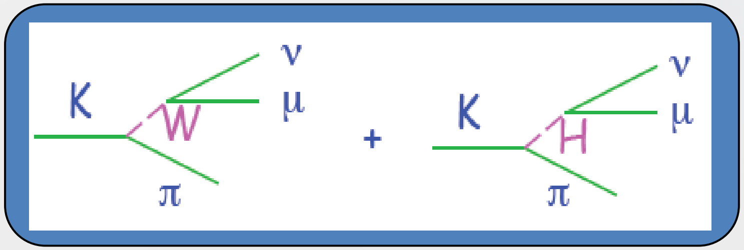
- CERN NA62
  - 100 SM events with S/N = 10 in 2 years run
  - Decay in flight ⇔ stopped in BNL exp't



- Under construction
- 2012夏: 1st technical run
- Physics run driven by CERN acc. schedule

K中間子を用いたT violation探索



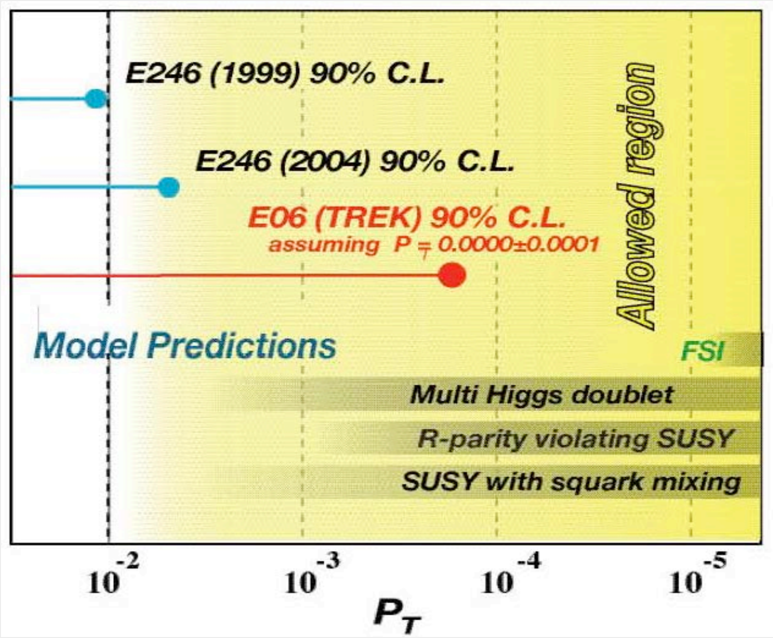


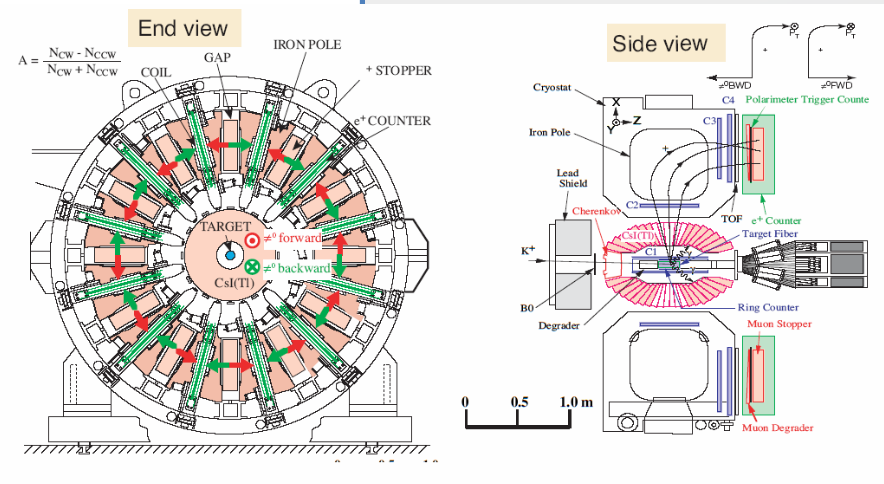
Non-zero PT (transverse polarization)があればT-violation

SM prediction: ~10^{-7}, FSI< ~10^{-5}なので、それより大きければNP

Current value: (-1.7+/-2.3+/-1.1)x10^{-3} (KEK E246)

→ δP_T~10^{-4} を目指す　(TREK)





- Stage 1 approval
- KEK-E246 detector + upgrade
- 270kW x 1year data taking for T violation exp.
- 30kW x 50 days data taking for lepton universality exp.

(staging of TREK experiment)

Electric Dipole Moment

$\mathbf{d}=d\boldsymbol{\sigma}$

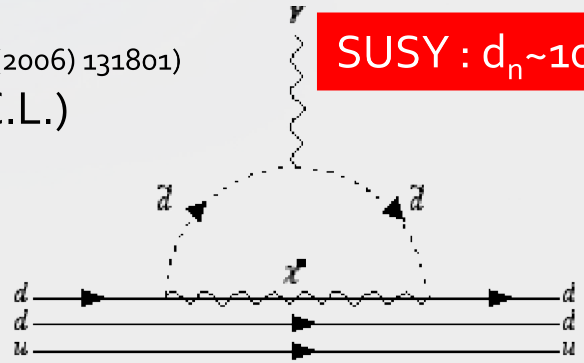
- EDMは、存在すればT及びP反転対称性を破るプロセスであり、CPT定理を仮定するとCP対称性も破る。

CP
電・空間反転

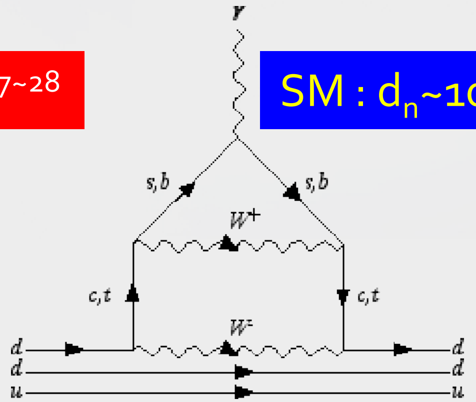
- 現在の測定感度は標準理論を超える理論の予言値に迫ってきている。
  - ✓ 現在の上限値(Baker et al., PRL97 (2006) 131801)
    $|d_n| < 2.9\times10^{-26}$ e cm (90% C.L.)

→1-2桁の精度向上による新物理の探索

SUSY : d_n~$10^{-27\sim-28}$

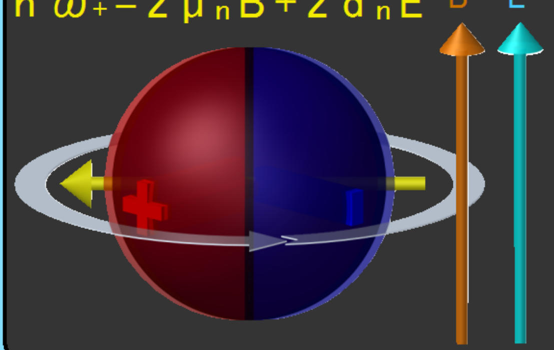


SM : d_n~10^{-31}



- 測定原理
  磁場/電場下での超冷中性子(UCN)の才差運動周波数の精密測定

$\hbar\omega_+=2\mu_n B+2d_n E$



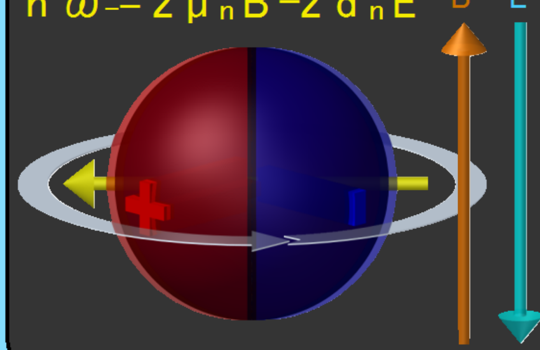
$$\Delta\phi=\int(\omega_+-\omega_-)dt=\frac{2d_n ET}{\hbar}$$

B = 1 μT

E = 10⁴ V/cm

T = 100 s

$\hbar\omega_-=2\mu_n B-2d_n E$

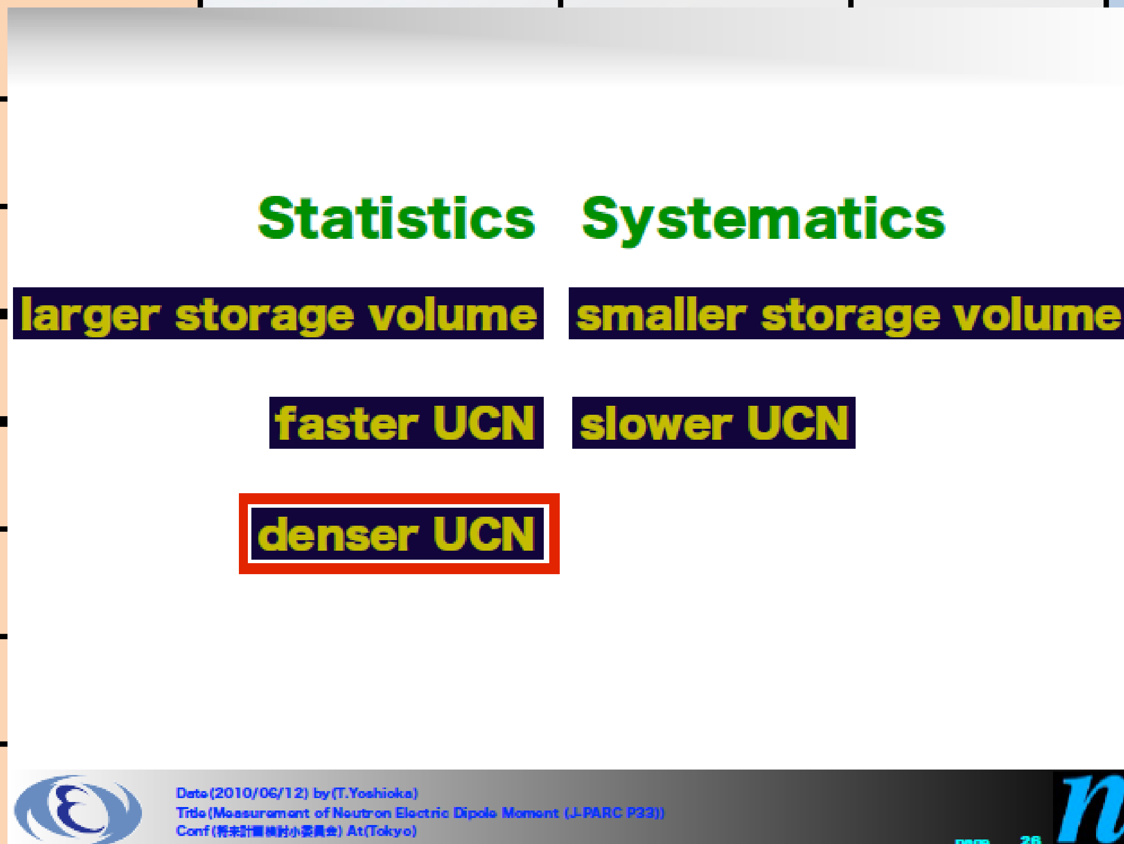


世界の情勢

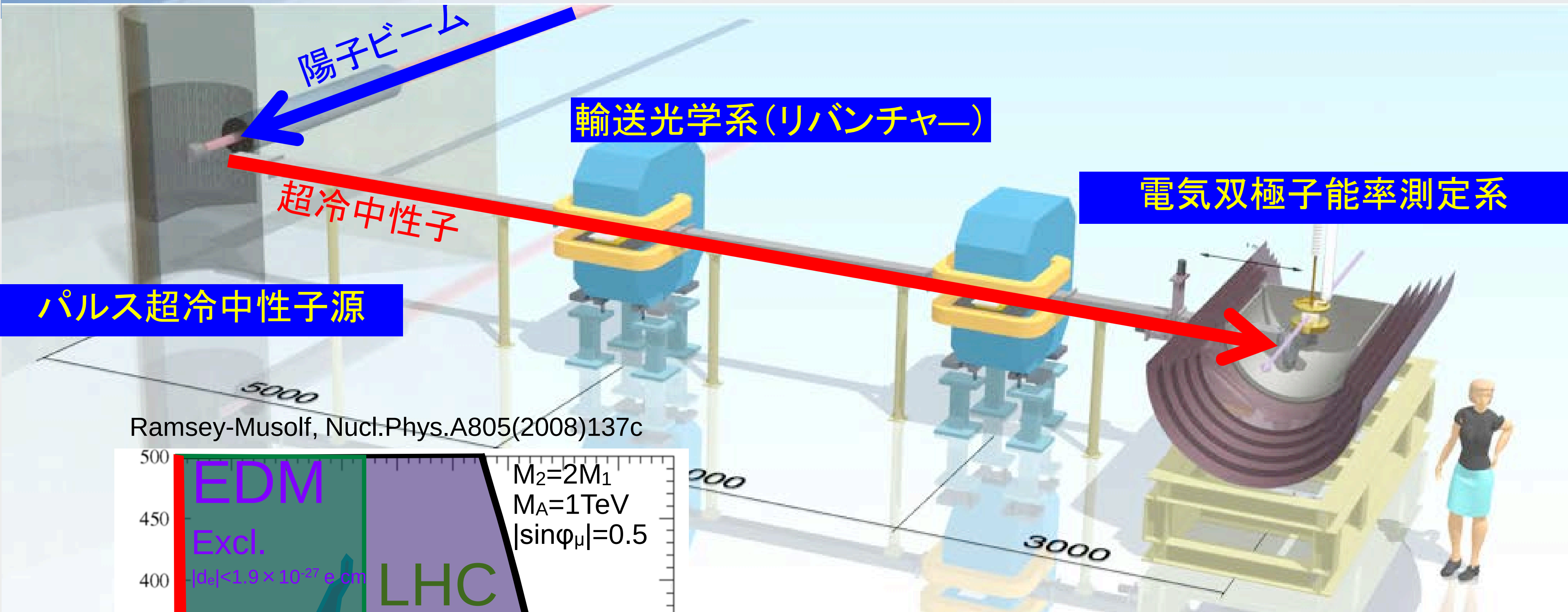
$$\Delta d_n = \frac{\hbar/2}{E(TN)^{1/2}}$$

$$N = \rho_{ph} V_{ph}$$

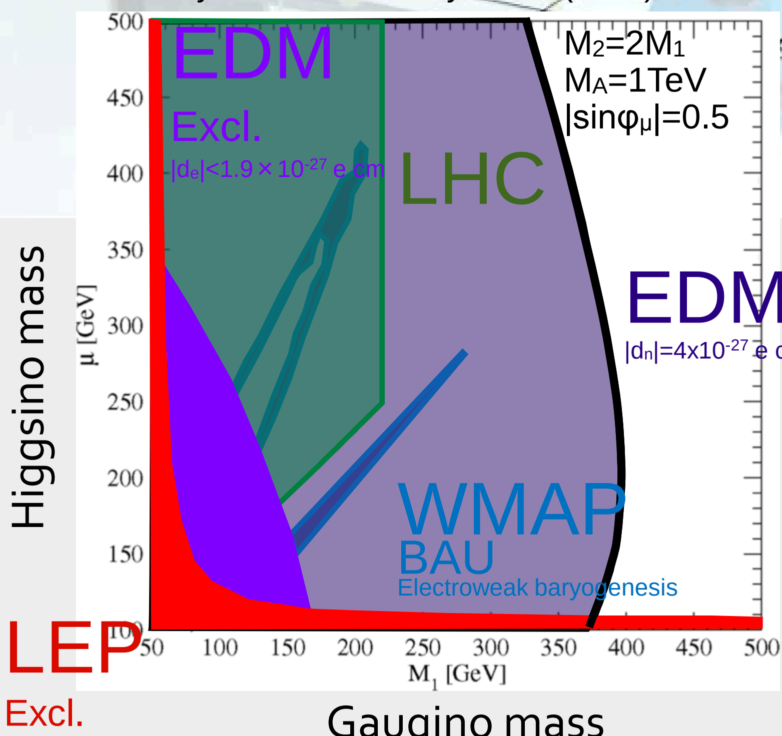
	ILL	PSI	SNS	TRIUMF	J-PARC
ρ_{ph} [$cm^{-3}(m/s)^{-3}$]					1.2 (→≤86)
E [kV/cm]					[13]
T_i [s]					[130]
共磁束計					Hg
一次ビーム					Pulse
最大瞬間強度					20MW
利用する平均強度					2kW
超冷中性子輸送					時間収束 (→位相空間重ね合わせ)
到達感度 [e cm/E_c=90neV]	2.9×10^{-26}	5×10^{-27} →5×10^{-28}	$O(10^{-28})$	$O(10^{-28})$	1×10^{-27} (→2×10^{-28})
物理測定開始	-	2012→2014	2015?	2014-5	2014(→2018?)



J-PARCのn-EDM実験



Ramsey-Musolf, Nucl.Phys.A805(2008)137c



10^{-27} e cm (phase 1; ~2016?)
10^{-28} e cm (phase 2; 2017~18??)

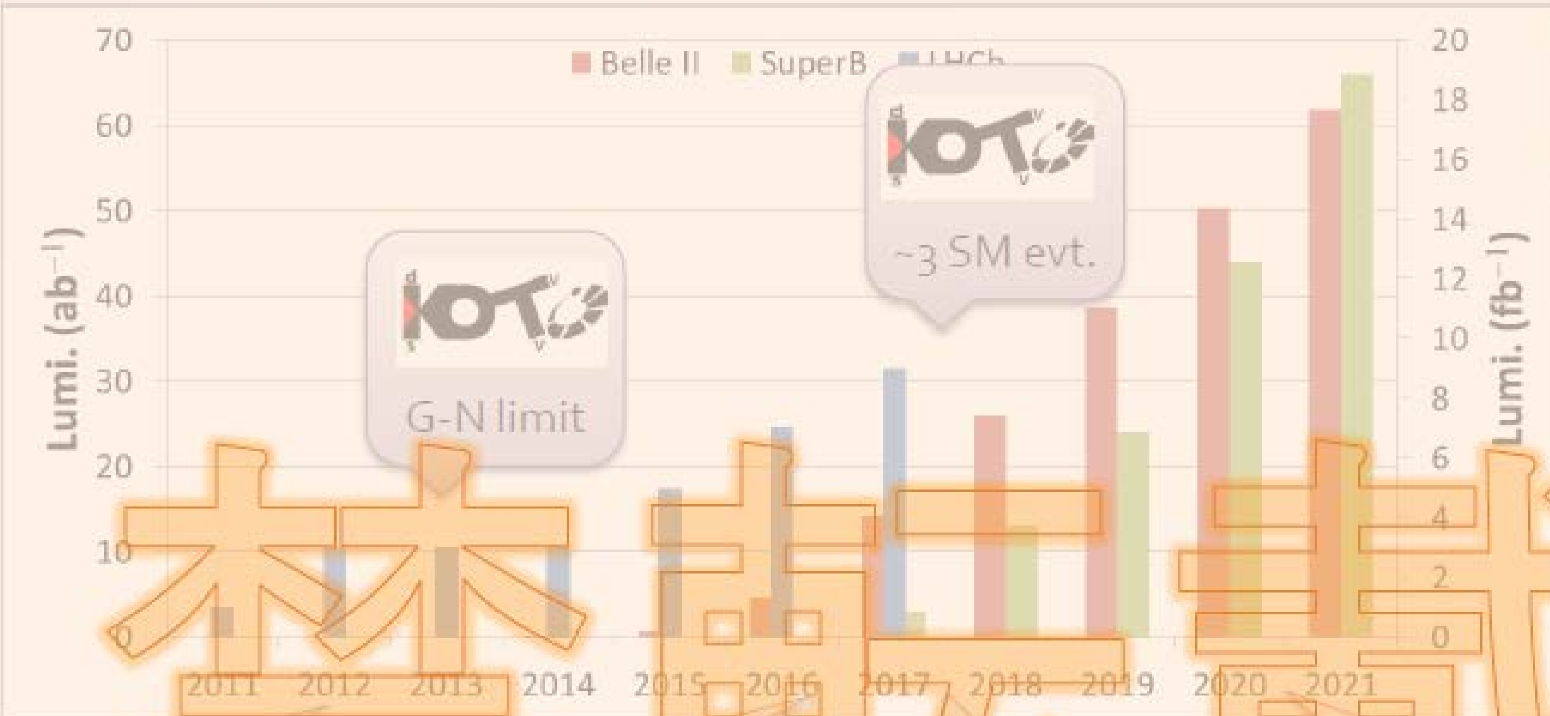
•PAC議論中

$|d_n|$: 4×10^{-27}ecm
covers all the region relevant to Supersymmetric (MSSM) electroweak baryogenesis

【仮定】
•技術開発が順調に進展
•系統誤差を順調に理解
•年間2500時間 など

年表

Prediction is very difficult,
especially about the future.
Niels Bohr (1885-1962)



TREK
$\delta P_T \sim 10^{-4}$

NA62
100 SM evt.

n-EDM
$\sim 10^{-27}, 10^{-28}$
e cm

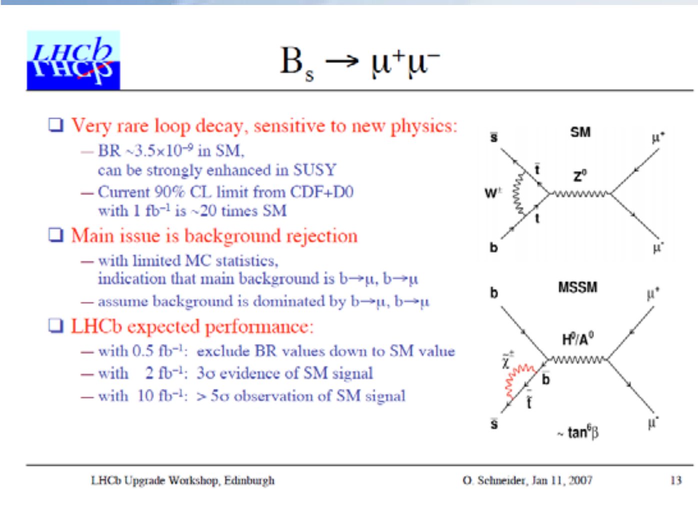
@2fb^{-1}
$\delta \sin 2\phi_1 \sim 0.02$
$\delta\varphi_3 = 4.2^\circ$

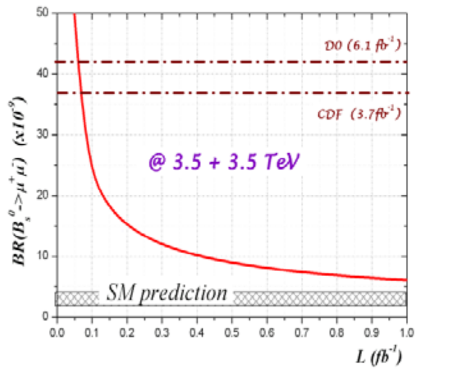
@5ab^{-1}
$\delta \sin 2\phi_1 = 0.016$
$\delta S_{\varphi K^0} = 0.073$
$\delta\varphi_3 = 6^\circ$
$\delta A(K_S^0\pi^0) = 0.072$

@10fb^{-1}
$\delta \sin 2\phi_1 \sim 0.01$
$\delta S_{\varphi\varphi} = 0.042$
$\delta\varphi_3 = 2.4^\circ$
δs0: 7%

@50ab^{-1}
$\delta \sin 2\phi_1 = 0.012$
$\delta S_{\varphi K^0} = 0.029$
$\delta\varphi_3 = 1.5^\circ$
$\delta A(K_S^0\pi^0) = 0.042$
δs0: 5%

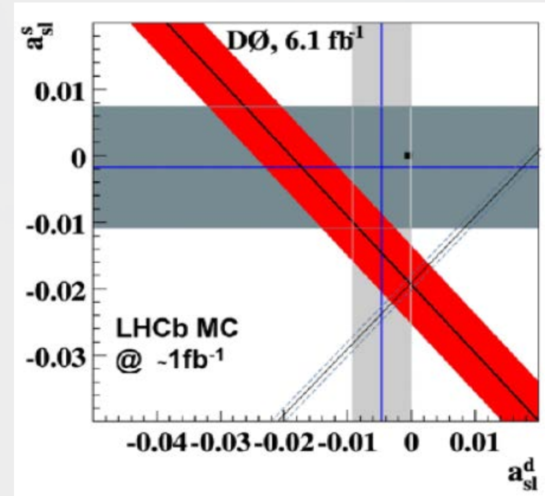
他にもまだまだたくさん

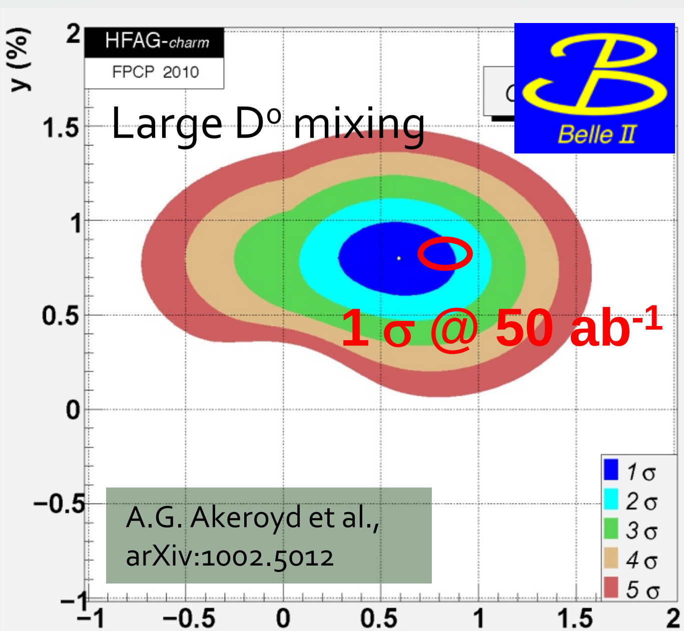




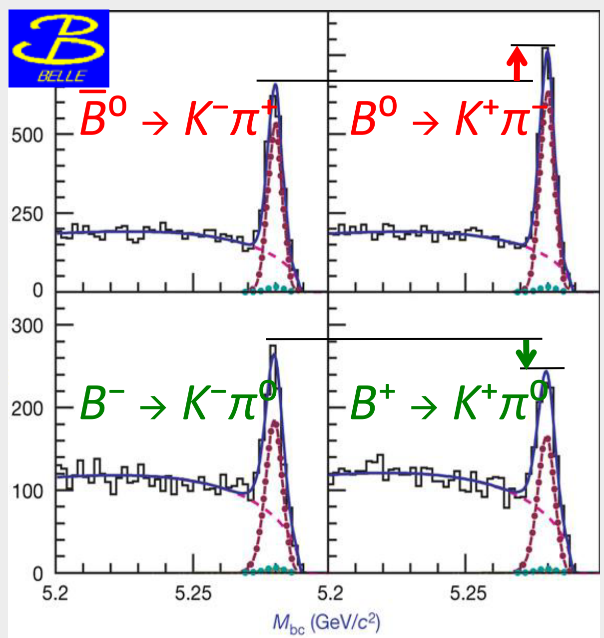
5σ SM@6fb⁻¹

Like-sign dilepton charge asymmetry
Do, arXiv:1005.2757





See ,arXiv:0705.3650
for NP implications

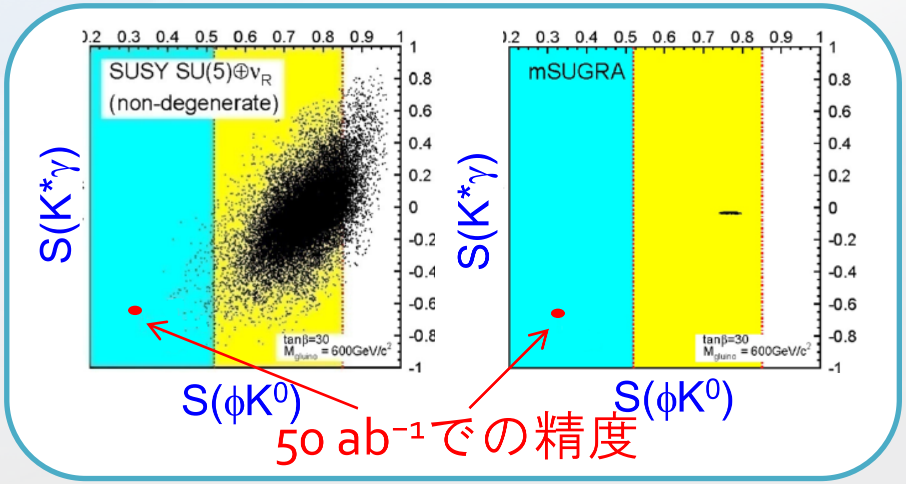


B^0

B^+

Nature **452**, 332 (2008).

Identification of NP type



NPのモデルによって
様々な観測量のどこにズレが生じるかが
異なる

SUSY models

Measurements	mSUGRA	MSSM+ν_R degenerate	MSSM+ν_R non-degenerate	SU(5)+ν_R degenerate	SU(5)+ν_R non-degenerate	U(2) FS	…
$A_{CP}(s\gamma)$						✓	
$S(K^*\gamma)$				✓	✓	✓	
$S(\rho\gamma)$				✓	✓	✓	
$S(\phi K_S)$				✓	✓	✓	
$S(B_s \to J/\psi\ \phi)$				✓	✓	✓	
$\mu \to e\gamma$		✓		✓	✓	?	
$\tau \to \mu\gamma$		✓	✓	✓	✓	?	
$\tau \to e\gamma$			✓		✓	?	
⋮							

✓: deviation from SM

[based on T.Goto et.al. PRD77, 095010(2008)]

もっと将来の展望

NPが小さく、happy end にならない場合

- B-factory → Super B-factory →?
  - 高統計のリファレンスモード（とcharm）は系統誤差が気になり始めるが、他はまだまだ統計誤差が主
  - ルミノシティーを更に一桁以上改善するためのアイデア（加速器（と測定器））が必要
- KOTO → KOTO step 2
  - 生成K_L数を稼ぐために小さい生成角度の新ビームラインが必要
  - 崩壊領域長を長くし、カロリメータのサイズを大型化

  現有の実験ホールにとらわれない努力が必要

SM pollutionを抑える努力が必要（理論も）

- T-violation
  - 見つかるまで一桁ずつ感度を改善していく
  - 系統誤差を抑えるアイデア（測定器・ビームライン）が必要

SMはまだ遠い

物理がある
経験もある（日本の得意分野）
施設などの遺産もある
（実験規模は比較的小さい）

あとはアイデア勝負

まとめ

- フレーバーの物理は、数々の物理量の精密測定により、NP発見と模型の同定を目指す
- 次の10年間に、様々な測定が精度よく進められる予定
  - B, K, n, charm; lepton (next talk)も
- 新物理発見？同定？？　新物理の制限？
- そこから先はアイデア勝負
  - さらなる統計量を得るための加速器・測定器
  - 精度良く測定するための測定器・ビーム輸送路など

参考資料

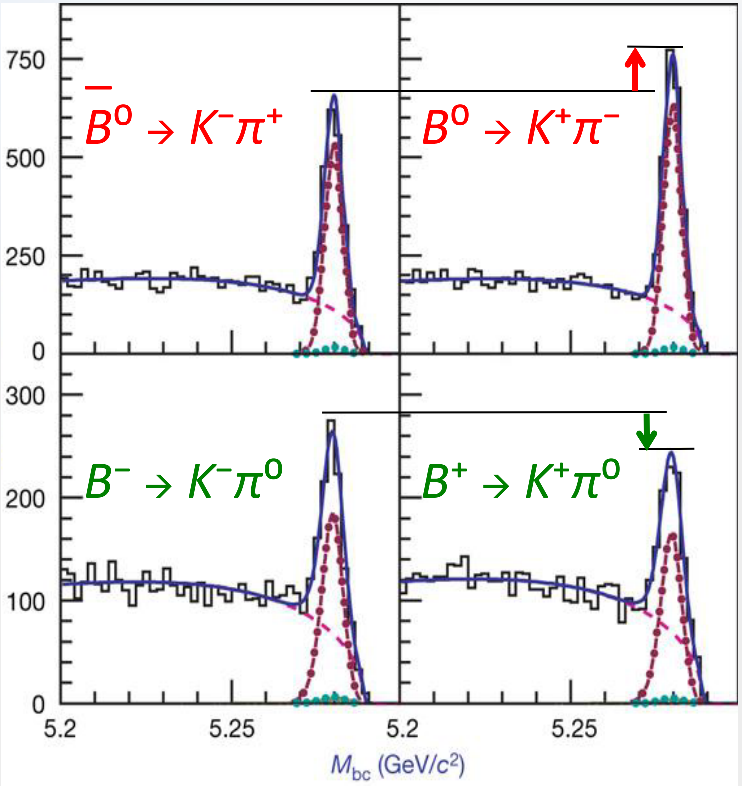
Observable	Belle 2006	SuperKEKB		†LHCb	
	($\sim$0.5 ab^{-1})	(5 ab^{-1})	(50 ab^{-1})	(2 fb^{-1})	(10 fb^{-1})
Hadronic $b \to s$ transitions					
$\Delta S_{\phi K^0}$	0.22	0.073	0.029		0.14
$\Delta S_{\eta' K^0}$	0.11	0.038	0.020		
$\Delta S_{K_S^0 K_S^0 K_S^0}$	0.33	0.105	0.037	-	-
$\Delta \mathcal{A}_{\pi^0 K_S^0}$	0.15	0.072	0.042	-	-
$\mathcal{A}_{\phi\phi K^+}$	0.17	0.05	0.014		
$\phi_1^{eff}(\phi K_S)$ Dalitz		3.3°	1.5°		
Radiative/electroweak $b \to s$ transitions					
$S_{K_S^0 \pi^0 \gamma}$	0.32	0.10	0.03	-	-
$\mathcal{B}(B \to X_s \gamma)$	13%	7%	6%	-	-
$A_{CP}(B \to X_s \gamma)$	0.058	0.01	0.005	-	-
C_9 from $\overline{A}_{FB}(B \to K^* \ell^+ \ell^-)$	-	11%	4%		
C_{10} from $\overline{A}_{FB}(B \to K^* \ell^+ \ell^-)$	-	13%	4%		
C_7/C_9 from $\overline{A}_{FB}(B \to K^* \ell^+ \ell^-)$	-		5%		7%
R_K		0.07	0.02		0.043
$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$	†† $< 3\ \mathcal{B}_{SM}$		30%	-	-
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$	†† $< 40\ \mathcal{B}_{SM}$		35%	-	-
Radiative/electroweak $b \to d$ transitions					
$S_{\rho\gamma}$	-	0.3	0.15		
$\mathcal{B}(B \to X_d \gamma)$	-	24% (syst.)		-	-
Leptonic/semileptonic B decays					
$\mathcal{B}(B^+ \to \tau^+ \nu)$	3.5σ	10%	3%	-	-
$\mathcal{B}(B^+ \to \mu^+ \nu)$	†† $< 2.4 \mathcal{B}_{SM}$	4.3 ab^{-1} for 5σ discovery		-	-
$\mathcal{B}(B^+ \to D \tau \nu)$	-	8%	3%	-	-
$\mathcal{B}(B^0 \to D \tau \nu)$	-	30%	10%	-	-
LFV in τ decays (U.L. at 90% C.L.)					
$\mathcal{B}(\tau \to \mu\gamma)$ [10^{-9}]	45	10	5	-	-
$\mathcal{B}(\tau \to \mu\eta)$ [10^{-9}]	65	5	2	-	-
$\mathcal{B}(\tau \to \mu\mu\mu)$ [10^{-9}]	21	3	1	-	-
Unitarity triangle parameters					
$\sin 2\phi_1$	0.026	0.016	0.012	$\sim$0.02	$\sim$0.01
ϕ_2 ($\pi\pi$)	11°	10°	3°	-	-
ϕ_2 ($\rho\pi$)	$68° < \phi_2 < 95°$	3°	1.5°	10°	4.5°
ϕ_2 ($\rho\rho$)	$62° < \phi_2 < 107°$	3°	1.5°	-	-
ϕ_2 (combined)		2°	$\lesssim 1°$	10°	4.5°
ϕ_3 ($D^{(*)}K^{(*)}$) (Dalitz mod. ind.)	20°	7°	2°	8°	
ϕ_3 ($DK^{(*)}$) (ADS+GLW)	-	16°	5°	5-15°	
ϕ_3 ($D^{(*)}\pi$)	-	18°	6°		
ϕ_3 (combined)		6°	1.5°	4.2°	2.4°
$\lvert V_{ub} \rvert$ (inclusive)	6%	5%	3%	-	-
$\lvert V_{ub} \rvert$ (exclusive)	15%	12% (LQCD)	5% (LQCD)	-	-
†††$\bar{\rho}$	20.0%		3.4%		
†††$\bar{\eta}$	15.7%		1.7%		

Table 5.27: Summary of sensitivity (I). Branching fraction limits in the table are at the 90% confidence level. †Values for LHCb are statistical only and are taken from [415] unless otherwise stated. †† $\mathcal{B}_{SM}$ represents the expected branching fraction in the SM; $\mathcal{B}_{SM} = 5 \times 10^{-6}$ for $\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$, 7×10^{-6} for $B^0 \to K^{*0} \nu\bar{\nu}$ and 7.07×10^{-7} for $\mathcal{B}(B^+ \to \mu\nu)$ are used in this table. †††See the next chapter for details.

Observable	Belle	Belle/SuperKEKB		LHCb†	
				(2 fb^{-1})	(10 fb^{-1})
B_s physics	(25 fb^{-1})	(5 ab^{-1})			
$\mathcal{B}(B_s \to \gamma\gamma)$	$< 8.7 \times 10^{-6}$	0.25×10^{-6}		-	-
$\Delta\Gamma_s^{CP}/\Gamma_s$ ($Br(B_s \to D_s^{(*)} D_s^{(*)})$)	3%	1% (model dependency)		-	-
$\Delta\Gamma_s/\Gamma_s$ ($B_s \to f_{CP}$ t-dependent)	-	1.2%		-	-
ϕ_s (with $B_s \to J/\psi\phi$ etc.)	-	-	-	0.02	0.01
$\mathcal{B}(B_s \to \mu^+\mu^-)$	-			6 fb^{-1} for 5σ discovery	
ϕ_3 ($B_s \to KK$)	-			7-10°	
ϕ_3 ($B_s \to D_s K$)	-			13°	
Υ decays	(3 fb^{-1})	(500 fb^{-1})			
$\mathcal{B}(\Upsilon(1S) \to$ invisible)	$< 2.5 \times 10^{-3}$	$< 2 \times 10^{-4}$			
	($\sim$0.5 ab^{-1})‡	(5 ab^{-1})	(50 ab^{-1})		
Charm physics					
D mixing parameters					
x	0.25%	0.12%	0.09%		0.25%††
y	0.16%	0.10%	0.05%		0.05%††
$\delta_{K\pi}$	10°	6°	4°		
$\lvert q/p \rvert$	0.16	0.1	0.05		
ϕ	0.13 rad	0.08 rad	0.05 rad		
A_D	2.4%	1%	0.3%		
New particles§					
$\gamma\gamma \to Z(3930) \to D\bar{D}^*$		$> 3\sigma$			
$B \to KX(3872)(\to D^0 \bar{D}^{*0})$		400 events			
$B \to KX(3872)(\to J/\psi\pi^+\pi^-)$		1250 events			
$B \to KZ^+(4430)(\to \psi'\pi^+)$		1000 events			
$e^+e^- \to \gamma_{ISR} Y(4260)(\to J/\psi\pi^+\pi^-)$		3000 events			
Electroweak parameters		($\sim$10 ab^{-1})			
$\sin^2\Theta_W$	-	3×10^{-4}			

Table 5.28: Summary of sensitivity studies (II). †Values for LHCb are taken from [415] unless otherwise stated. ‡For D mixing parameters the world average of results from [22] is quoted. ††LHCb sensitivities on x and y are estimated from sensitivities on x'^2, y' and y_{CP} [295] assuming $x = y = 0.80\%$ and $\delta_{K\pi} = 25° \pm 6°$. §Due to a large number of various possible measurements we only list expected signal yields for a few interesting processes.

Direct CPV: $K\pi$ Puzzle in B^0/B^+ *CP* Violation



S.-W. Lin *et al*. (The Belle collaboration), Nature **452**, 332 (2008).

B^0

$$A_{CP}(K^+\pi^-) = -0.094 \pm 0.018 \pm 0.008$$

$$A_{CP}(K^+\pi^0) = +0.07 \pm 0.03 \pm 0.01$$

B^+

Expected to be same

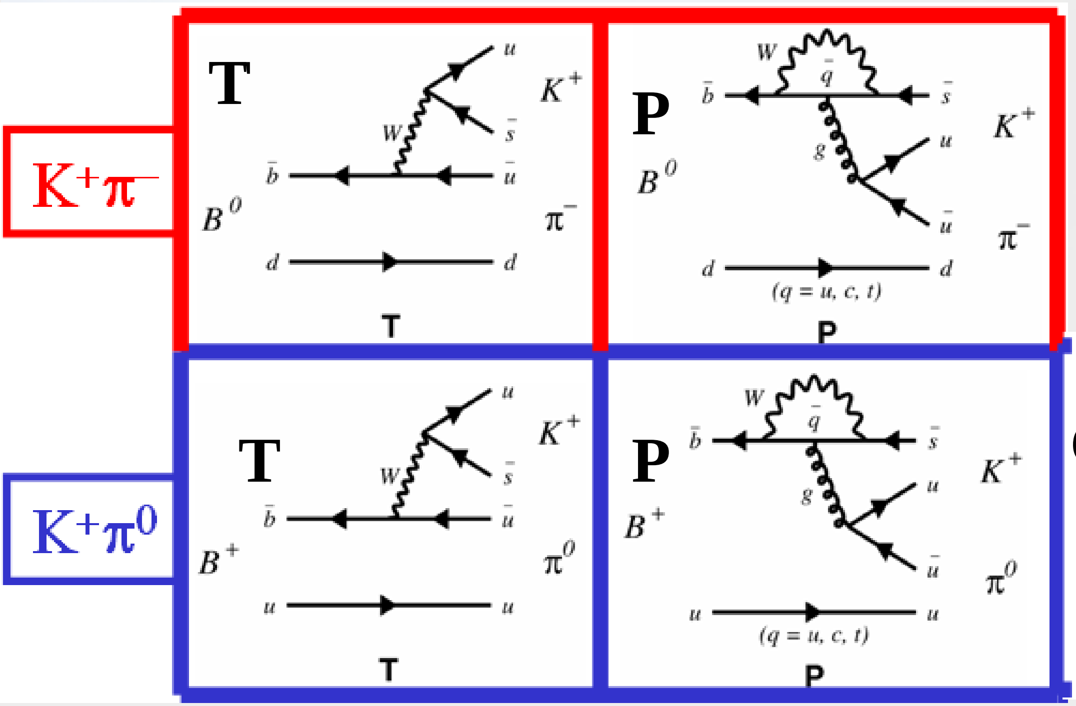
$$\Delta A_{K\pi} = A(K^+\pi^-) - A(K^+\pi^0) = -0.147 \pm 0.028$$

5.3σ deviation

→ Hint of NP ?

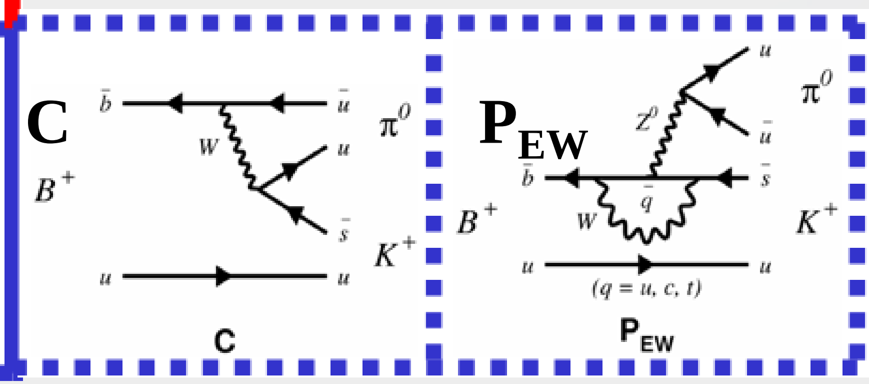
Solutions to the $\Delta A_{K\pi}$ Puzzle

See Nature commentary by Michael Peskin



Expectation from current theory

T & P are dominant $\Rightarrow \Delta A_{K\pi} \sim 0$



- **Enhancement of large C with large strong phase to T $\Rightarrow$ strong inter. !?**

Chiang, Gronau, Rosner & Suprun 2004;
Li, Mishima & Sanda 2005

Enhancement of large P_{EW} $\Rightarrow$ New physics

Yoshikawa 2003; Mishima & Yoshikawa 2004;
Buras et. al. 2004, 2006; Baek & London 2007;
Hou et. al. 2007; Feldmann, Jung & Mannel 2008

Can this issue be resolved in a model-independent way by experiment ?

Model-indep. Sum Rule

$$\mathcal{A}_{CP}(K^+\pi^-) + \mathcal{A}_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = \mathcal{A}_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + \mathcal{A}_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

M. Gronau, PLB 627, 82 (2005); D. Atwood & A. Soni, Phys. Rev. D 58, 036005(1998).

$B \rightarrow K\pi$ HFAG, ICHEP08

$A(K^0\pi^+)=0.009 \pm 0.025$

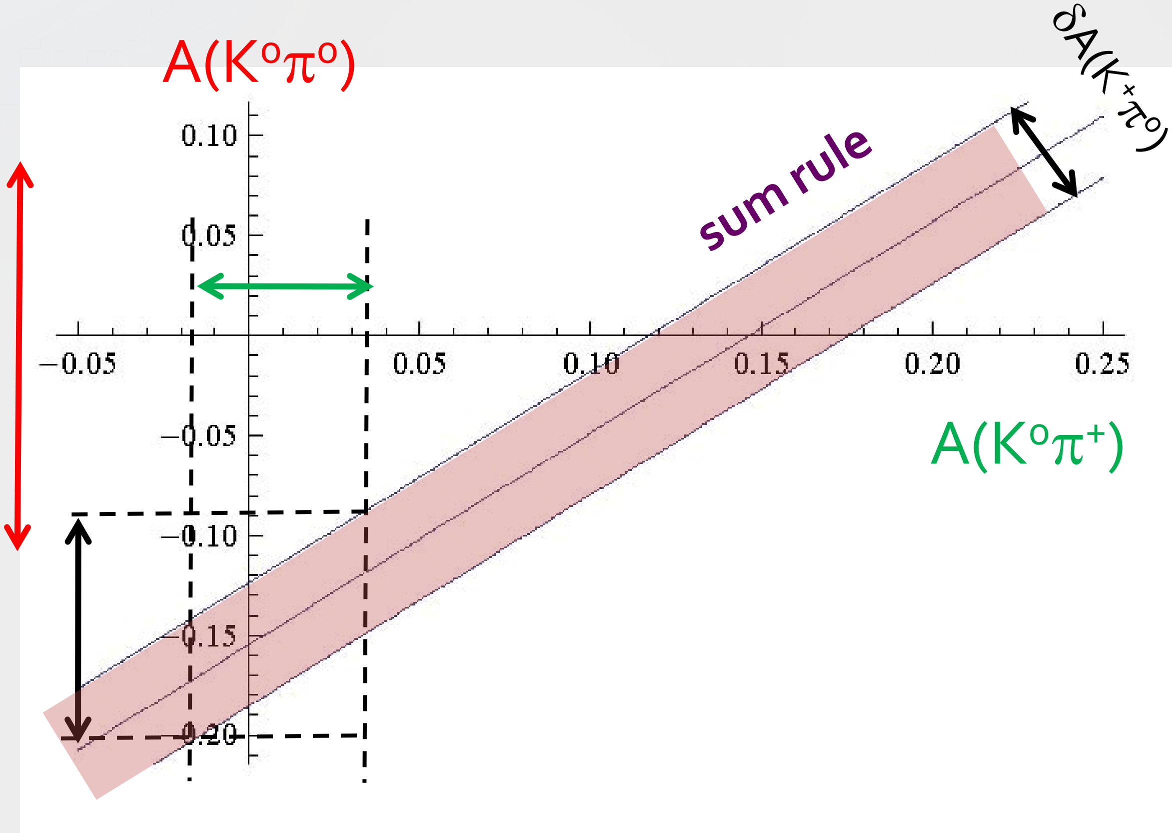
$A(K^+\pi^0)=0.050 \pm 0.025$

$A(K^+\pi^-)=-0.098 \pm 0.012$

$A(K^0\pi^0)=-0.01 \pm 0.10$

measured (HFAG)

expected (sum rule)



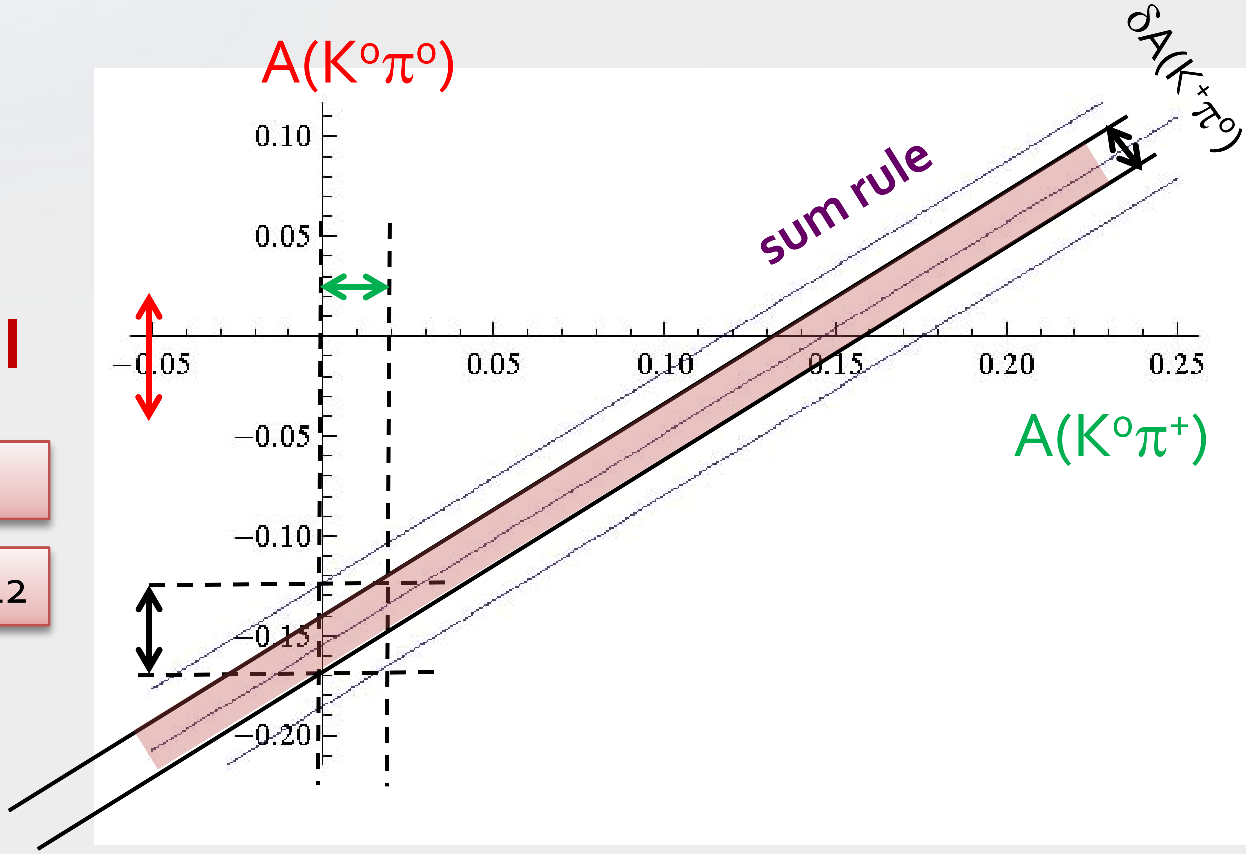
Prospect

Belle II, 50 ab^{-1}

Important to measure $A(K^0\pi^0)$ precisely by Belle II

5/ab: $\delta A_{K0\pi0} = 0.072$

50/ab: $\delta A_{K0\pi0} = 0.042$



$M \to X\nu\nu$まとめ

注：それぞれ独立な量を測定
NPも独立に寄与しうる

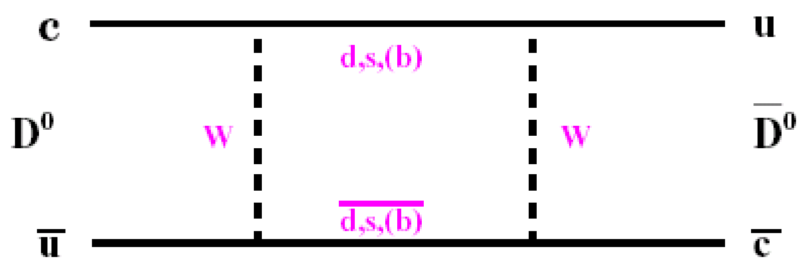
Mode	Current measurement	SM prediction	prospect
$B^0 \to K^{*0}\nu\nu$	$<3.4\times10^{-4}$	6.8×10^{-6} 誤差？	SM 3σ @Belle II $50\mathrm{ab}^{-1}$
$K^+ \to \pi^+\nu\nu$	$1.73(^{+1.15}_{-1.05})\times10^{-10}$	$7.81(^{+0.80}_{-0.71}\pm0.29)\times10^{-11}$	100 SM events, S/N~10 @NA62
$K_L \to \pi^0\nu\nu$	$<2.6\times10^{-8}$	$2.43(^{+0.40}_{-0.37}\pm0.06)\times10^{-11}$	~3 SM events, S/N~2 @KOTO

近い将来の進展が期待される

D^0-$\bar{D}^0$ Mixing

Quark level: Box diagram

(~ B^0-mixing)



SM box: $O(10^{-9})$

+Long distance: $O(10^{-3}\sim10^{-2})$

$x=\Delta m/\Gamma$

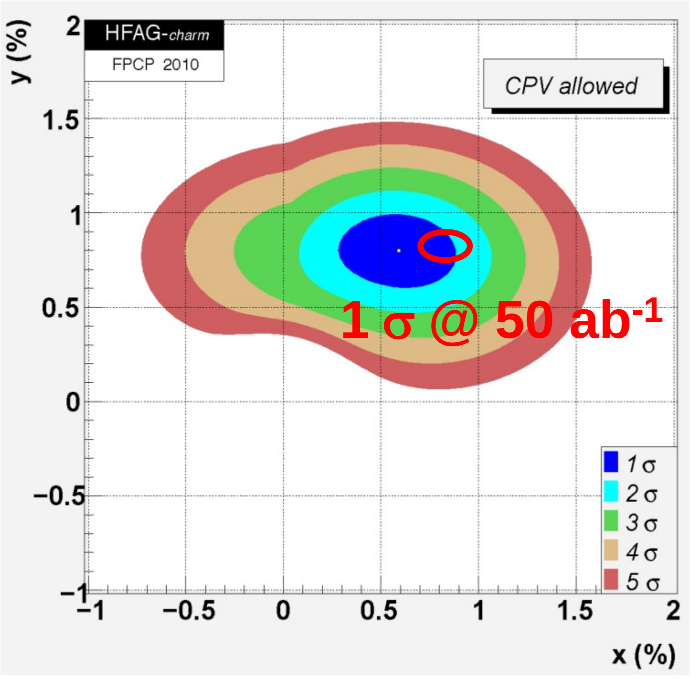
$y=\Delta\Gamma/2\Gamma$

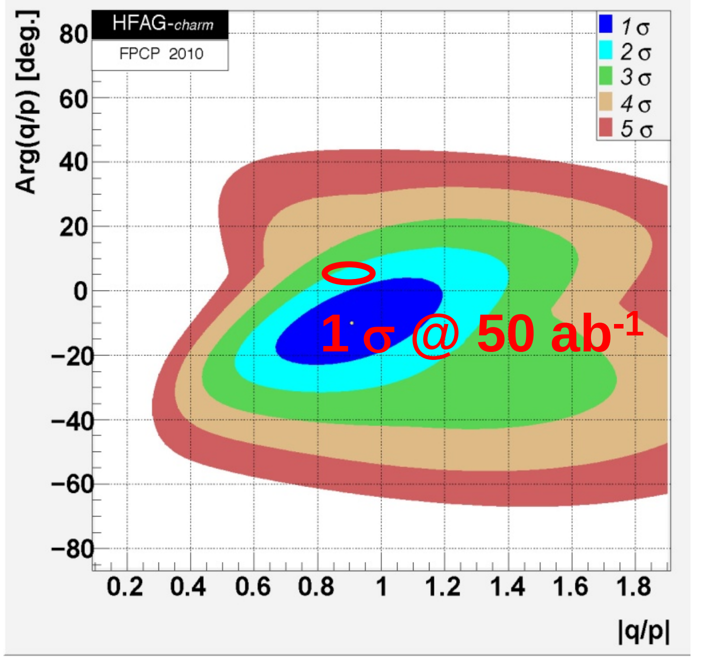
Large mixing, |x|>>|y|, CPV → New Physics !

- Only mixing with up-type quark

complementarity to down-type FCNC

D^0-mixing : prospect





A.G. Akeroyd et al., arXiv:1002.5012

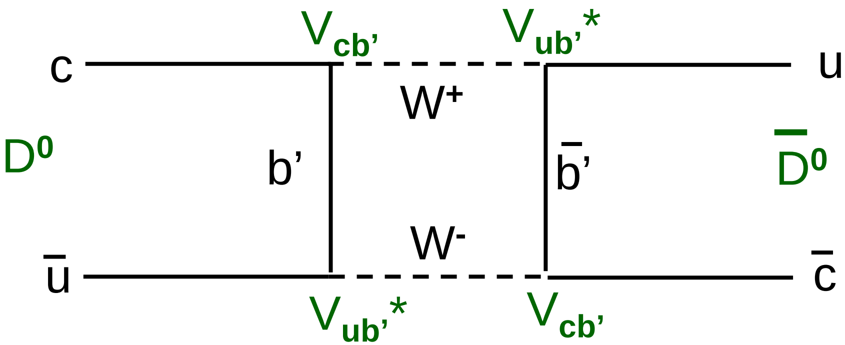
Mixing parameters

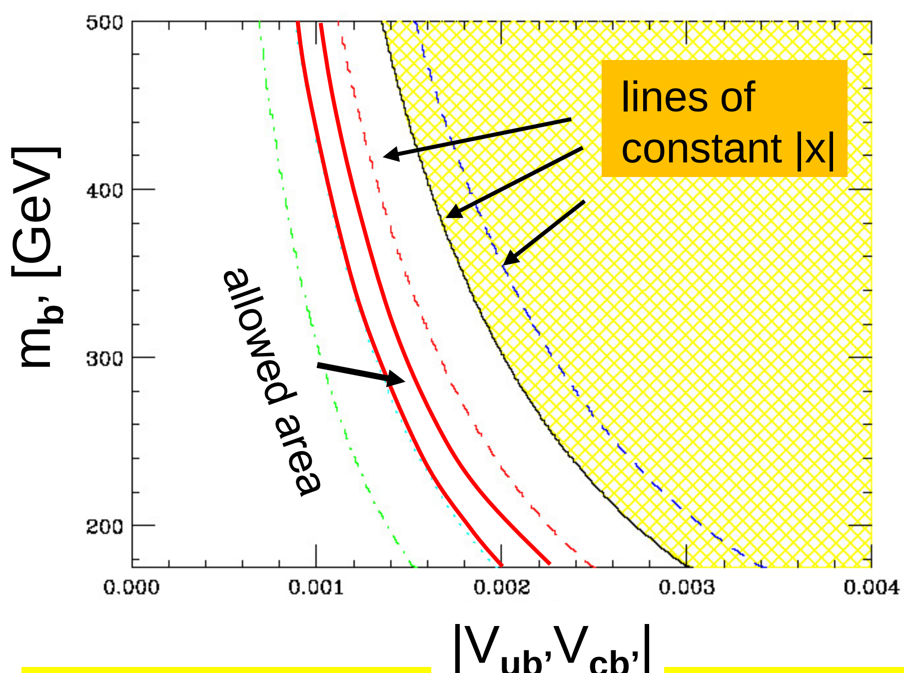
global fit to observables,
only KK/ππ, Kπ and $K_s\pi\pi$
projected sensitivities included
(no external constraints, e.g. $\delta_{K\pi}$)

$$x = (0.832 \pm 0.095)\%$$
$$y = (0.813 \pm 0.064)\%$$
$$\delta_{K\pi} = 24.6^\circ \pm 4.9^\circ$$
$$R_D = (0.336 \pm 0.003)\%$$
$$\frac{|q|}{|p|} = 0.894 \pm 0.054$$
$$\varphi = -0.004 \pm 0.049\ rad$$
$$A_D = (-0.1 \pm 0.8)\%$$

Constraints from D^0-mixing

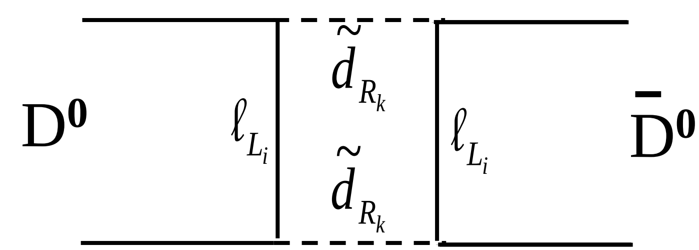
4th generation of fermions

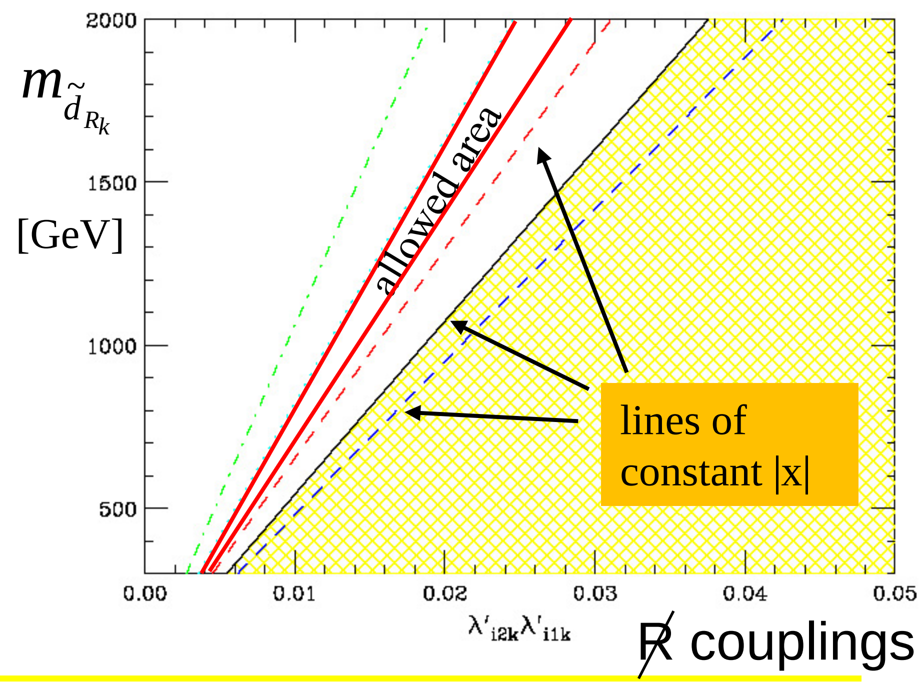




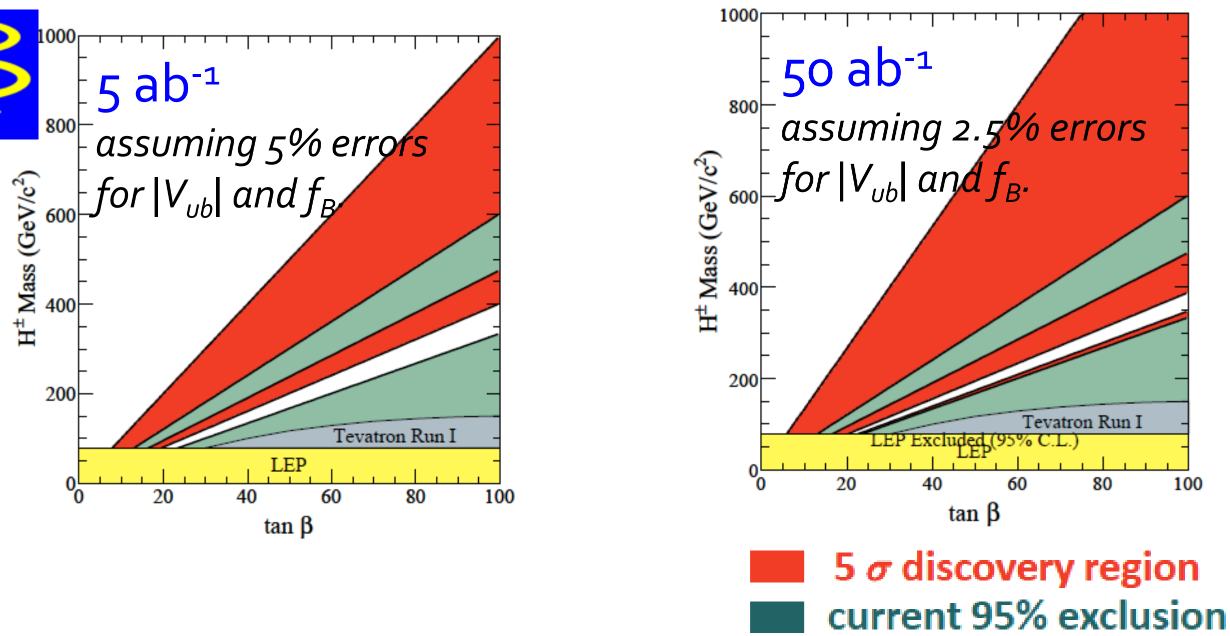
E. Golowich et al., PRD76, 095009 (2007)

R-parity violating SUSY





E. Golowich et al., PRD76, 095009 (2007)

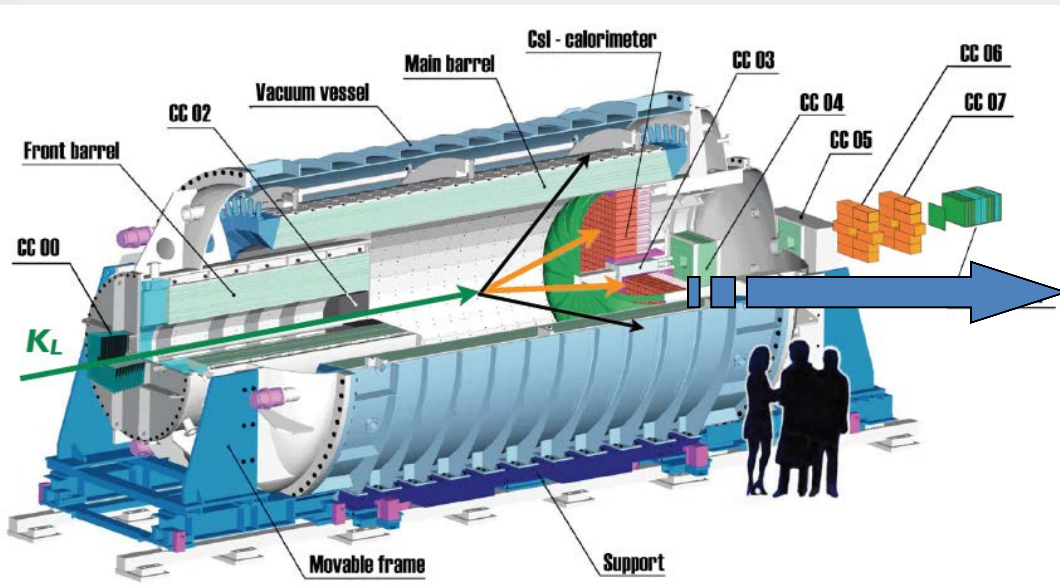

5 ab-1
assuming 5% errors
for |Vub| and fB.
H± Mass (GeV/c2)
tan β
Tevatron Run I
LEP
50 ab-1
assuming 2.5% errors
for |Vub| and fB.
LEP Excluded (95% C.L.)
5 σ discovery region
current 95% exclusion

KOTO: $K_L \rightarrow \pi^0 \nu\nu$実験

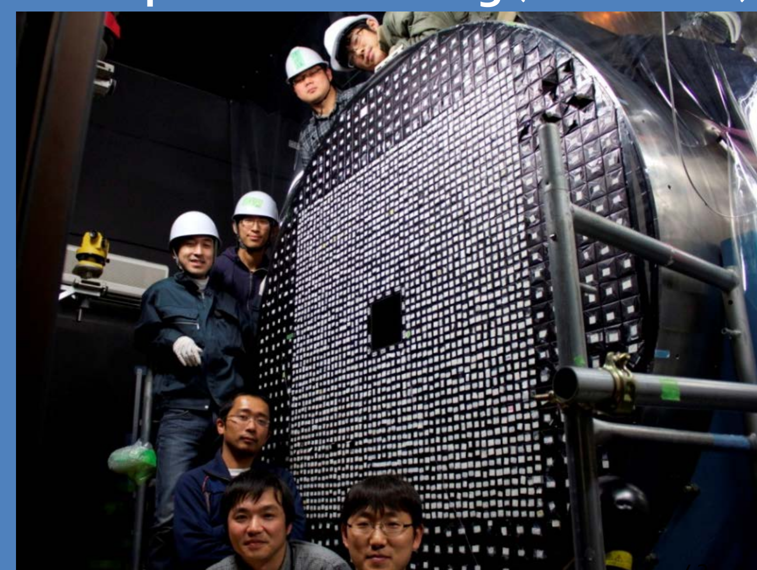
KOTO=K^0 at Tokai

- Sensitivity $O(10^{-11})$
  - ➔ 2~3 SM events (with S/N~2)

- KL Beamline newly built at J-PARC/hadron hall
- KEK-E391a detector + upgrade of key components
  - Longer CsI crystals from KTeV, etc…



Complete CsI stacking (2011.Feb.08)



次世代KOTO ("step 2")計画

- Sensitivity $O(10^{-13})$ ➔ ~100 SM events

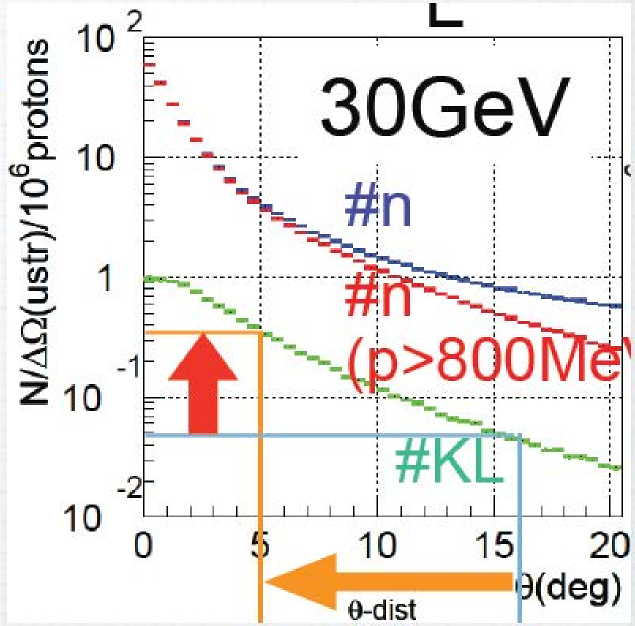
✱ targeting angle: 16→5deg

✱ longer decay volume: 2m→11m

✱ calorimeter: 2mΦ→3mΦ

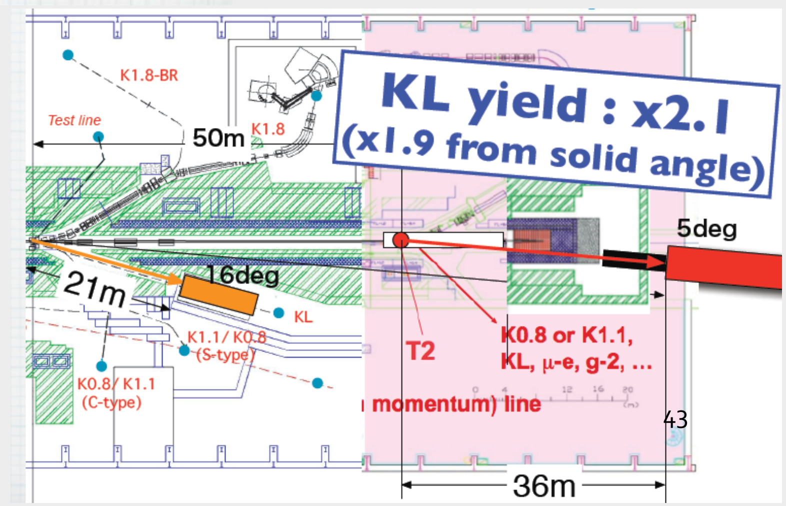
✱ 2E14 → 3E14

✱ 130 events / 3×10^{7} sec



KOTO/E14プロポーザル時のstep 2計画

- 生成KL数をかせぐ
  小さい生成角度の新ビームライン
- 崩壊領域長をかせぐ
  検出器はbrand-new



現ホールの枠にとらわれず、さらに感度をかせぐ努力が必要

R&D進捗

H22年上半期の実績

R&D用UCN源：MLF BL05の冷中性子ビーム→機械的に減速

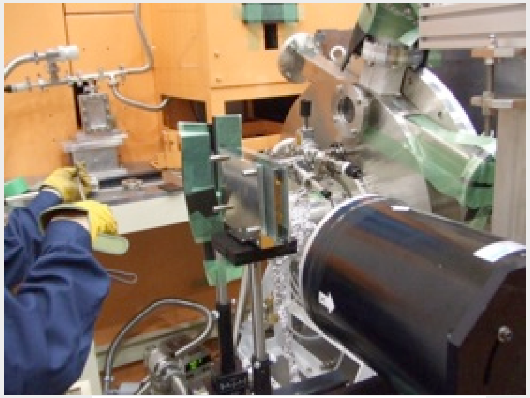
パルス超冷中性子（基盤科研費（東大）にて）大学（京大・東大）とKEKが共同開発

光学系の基礎研究：中性子反射材の研究

学術創成研究「中性子光学による基礎物理」及び中性子S型課題により推進

本年度計画

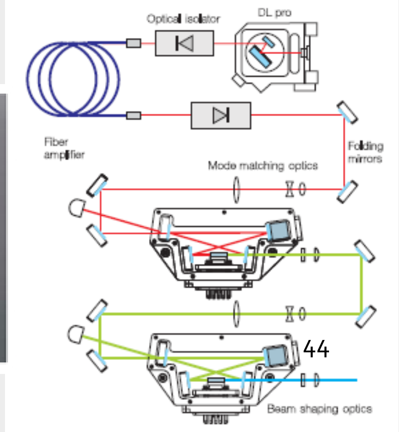
1. 中性子収束「加減速器」の原理実証実験
   - 勾配磁場電磁石・RF共振器・PLL回路の制作及び動作確認(H22年度既製作)
   - ○ H23年度：UCN導管及び上流光学系の改良



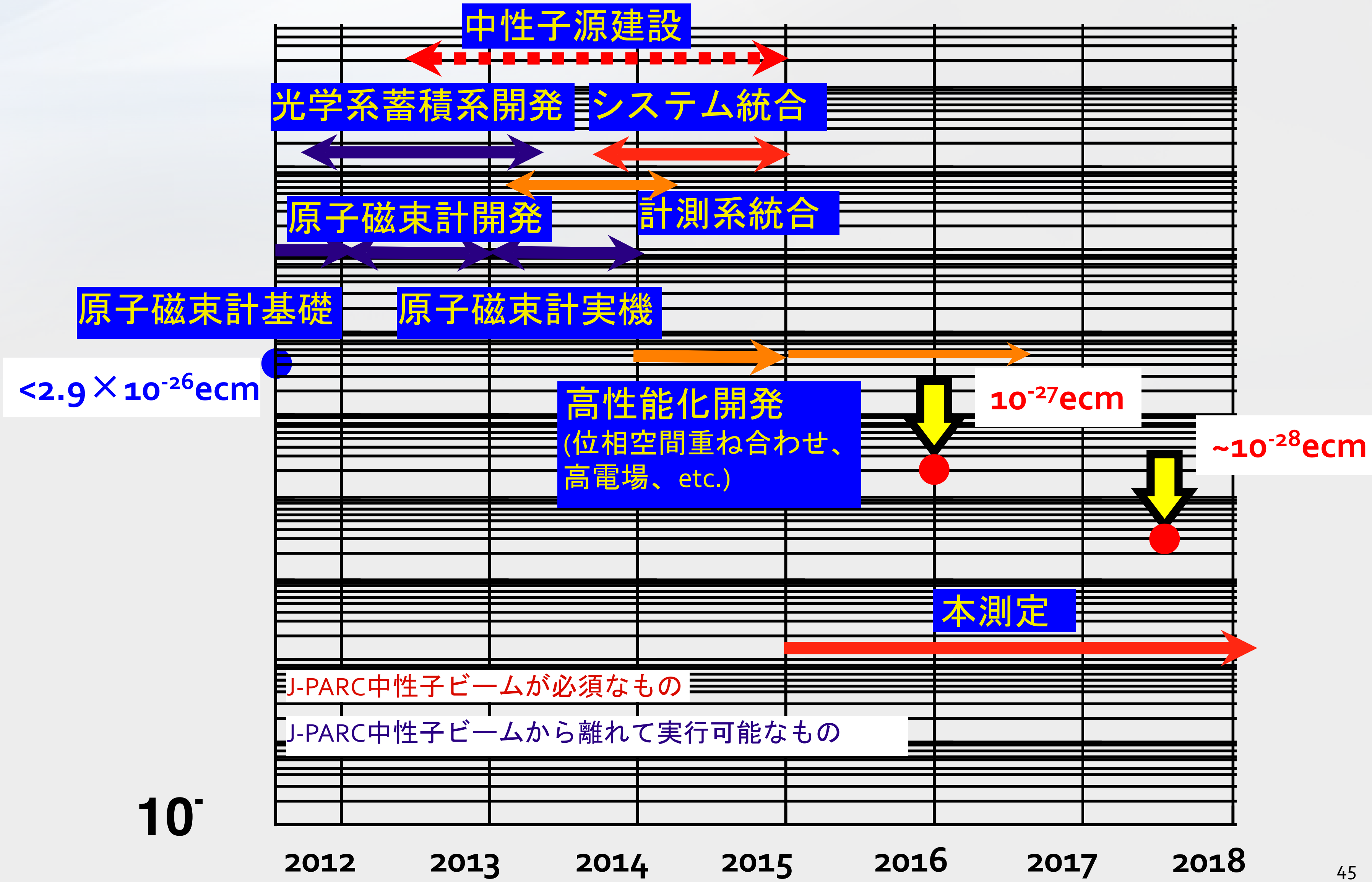
2. UCN導管及び蓄積容器材料選定のための物質表面の研究
   - 測定手法の確立(H22年度既実施)
   - ○ H23年度：材料選定実験

3. 高感度水銀磁束計の開発（H23年度）
   - ○ 濃縮同位体水銀ランプを用いたテストベンチの立ち上げ
   - ○ UVレーザーの導入

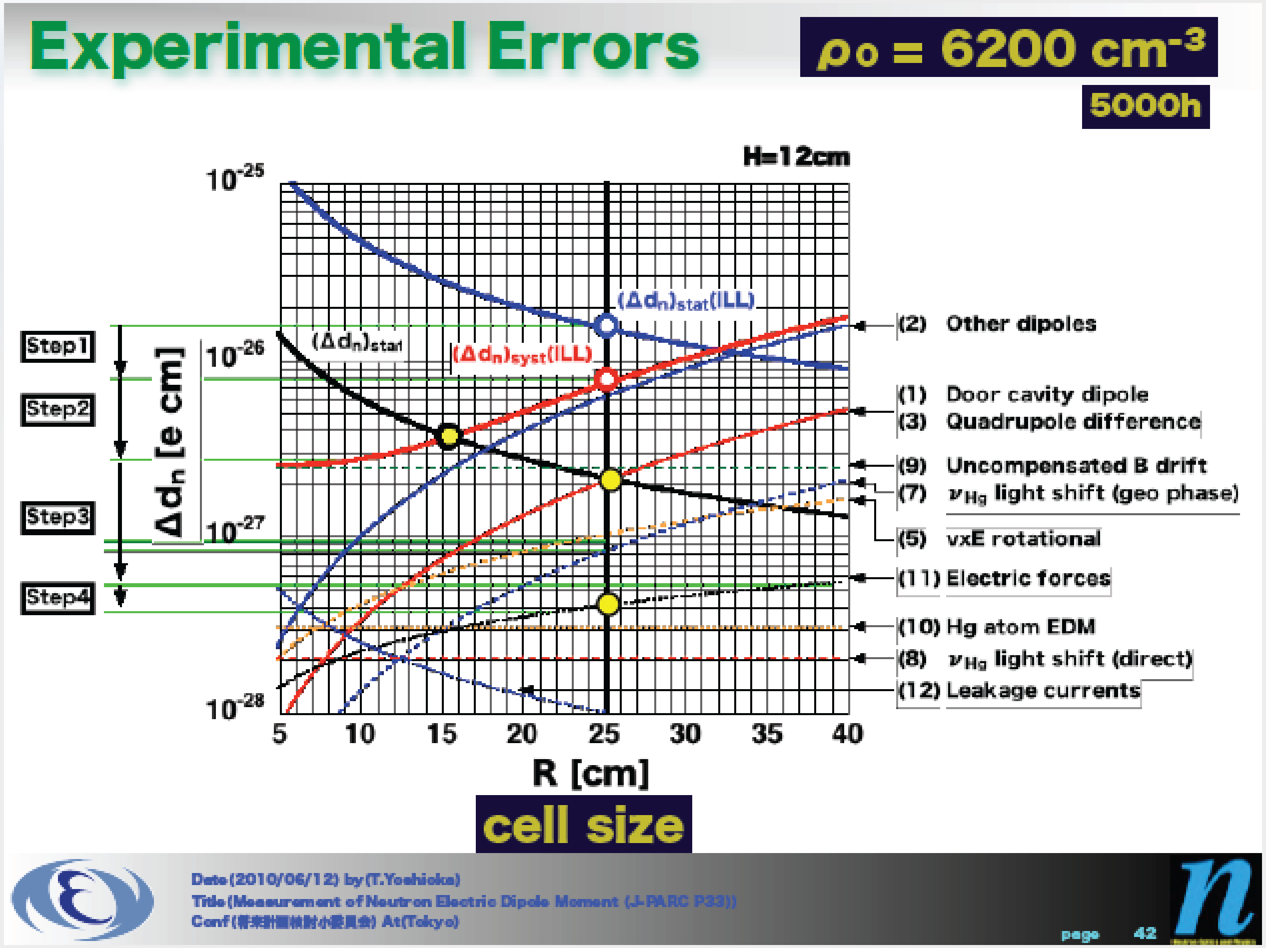
TOPTICA TA-FHG pro



展望



中性子源建設
光学系蓄積系開発
システム統合
原子磁束計開発
計測系統合
原子磁束計基礎
原子磁束計実機
<2.9×10-26ecm
高性能化開発
(位相空間重ね合わせ、
高電場、etc.)
10-27ecm
~10-28ecm
本測定
J-PARC中性子ビームが必須なもの
J-PARC中性子ビームから離れて実行可能なもの
10-
2012
2013
2014
2015
2016
2017
2018



Experimental Errors
ρ_0 = 6200 cm^{-3}
5000h
H=12cm
10^{-25}
10^{-26}
10^{-27}
10^{-28}
Δd_n [e cm]
Step1
Step2
Step3
Step4
(Δd_n)$_{stat}$(ILL)
(Δd_n)$_{stat}$
(Δd_n)$_{syst}$(ILL)
5 10 15 20 25 30 35 40
R [cm]
cell size
(2) Other dipoles
(1) Door cavity dipole
(3) Quadrupole difference
(9) Uncompensated B drift
(7) ν_{Hg} light shift (geo phase)
(5) vxE rotational
(11) Electric forces
(10) Hg atom EDM
(8) ν_{Hg} light shift (direct)
(12) Leakage currents
Date(2010/06/12) by(T.Yoshioka)
Title(Measurement of Neutron Electric Dipole Moment (J-PARC P33))
At(Tokyo)
page 42