New CP phase in $b \to s$ transition

Chuan-Hung Chen

Department of Physics,
National Cheng-Kung U.,
Tainan, Taiwan

- Inspired & motivated by CDF & D0 experiments

- Z-mediated effects in vector-like quark model

- Summary

cooperate with
C.Q. Geng & Lin Li

- **What is m_{T2} and what is it for ?**

Foreword

- Definitely, SM is an effective model at electroweak scale. Our universe should exist other unknown stuff

  Hints: masses of neutrinos, matter-antimatter asymmetry, dark matter, dark energy,… etc.

  It is interesting to investigate the physics beyond the SM

- Where can we find the new physics (NP) ?

  1. Rare decays :

     • Loop induced processes, such as $b \to s\gamma$, ***CP in B_s-$B_s$bar mixing***

     • tree processes but suppressed by CKM matrix elements

  2. Precision measurements at high energy colliders :

Hereafter, we pay attention to ~~CP~~ in B_s system

■ In the SM, the CP violating source comes from CKM matrix that appears associated with charged currents

Weak states:

$$H_C = J_\mu^C W^\mu = \left(\bar{u}, \bar{c}, \bar{t}\right)\gamma_\mu P_L \begin{pmatrix} d \\ s \\ b \end{pmatrix} W^\mu = \bar{U}_L \gamma_\mu D_L W^\mu$$

After spontaneous symmetry breaking,

$$u_L = V_U^L U_L, \quad d_L = V_D^L D_L$$

Flavor mixing matrices

$$J_\mu^C W^\mu \rightarrow \bar{u}_L \gamma_\mu \underbrace{V_U^L V_D^{L\dagger}}_{\equiv V_{CKM}} d_L W^\mu$$

theoretical constraint : $V_{CKM} V_{CKM}^\dagger = 1$

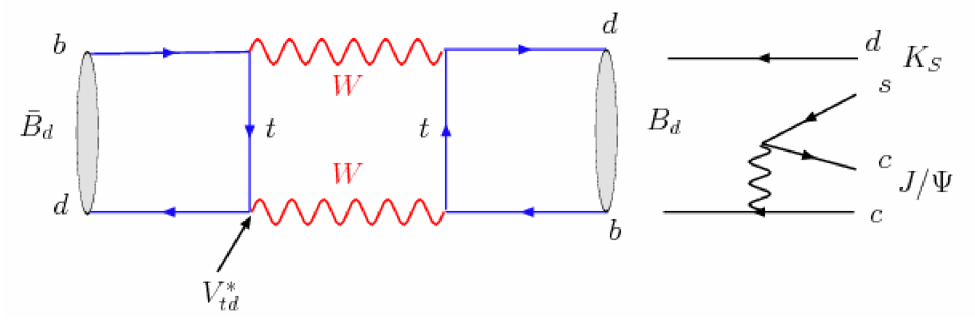
● There is one physical phase (KM phase) in the SM

by Wolfenstein parametrization

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3\left(\rho - i\eta\right) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left(1-\rho-i\eta\right) & -A\lambda^2 & 1 \end{pmatrix} + O\left(\lambda^4\right) = \begin{pmatrix} & & \left|V_{ub}\right| e^{-i\gamma} \\ & & V_{cb} \\ \left|V_{td}\right| e^{-i\beta} & V_{ts} & \end{pmatrix}$$

- the phase of V_{td} could be determined through time-dependent CP asymmetry of B_d-barB_d mixing

e.g.



mixing **decay amp**

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

$$|B_1\rangle = p|B_0\rangle + q|\bar{B}_0\rangle$$

$$|B_2\rangle = p|B_0\rangle - q|\bar{B}_0\rangle$$

$$\left(\frac{q}{p}\right)^2 = \frac{\mathbf{M}^*_{12} - (i/2)\mathbf{\Gamma}^*_{12}}{\mathbf{M}_{12} - (i/2)\mathbf{\Gamma}_{12}}$$

$$\Gamma_{12} << M_{12}$$

$$\left(\frac{q}{p}\right) \simeq \sqrt{\frac{M^*_{12}}{M_{12}}} = \exp(i\phi_d)$$

$$A_{f_{CP}} = \frac{\Gamma(\bar{B} \to f_{CP}) - \Gamma(B \to f_{CP})}{\Gamma(\bar{B} \to f_{CP}) + \Gamma(B \to f_{CP})}$$

$$\mathcal{A}_f(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t),$$

$$S_f \equiv \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2}, \quad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2},$$

Mixing-induced CPX

Direct CPX

$$\sin 2\beta = 0.668 \pm 0.026$$

world average in $B \to J/\psi K_0$ decay

■ How is the ~~CP~~ in B_s system?

● Some observations in B_s mixing

➢ ***mixing of B_s , Δm_s***

$$\Delta m_s = 2\,|M_{12}| = 2\left|\left\langle B_s \middle| H\left(\Delta B = 2\right) \middle| \bar{B}_s \right\rangle\right|$$

In 2006, CDF first observed the mixing effect
Now, the results of CDF and D0 via **$B_s \to J/\psi\ \phi$ decay** are

$$\Delta m_s = \begin{cases} 17.77 \pm 0.10 \pm 0.07\ \text{ps}^{-1} & (\text{CDF}) \\ 18.56 \pm 0.87\ \text{ps}^{-1} & (\text{D0}) \end{cases}$$

➢ ***BR & Direct CP violation***

$$B\left(B_s \to K^- \pi^+\right) = \left(5.00 \pm 1.25\right) 10^{-6}$$

$$A_{CP}\left(B_s \to K^- \pi^+\right) = 0.39 \pm 0.17$$

It will be interesting if the BR (CPA) is really so small (large)

- Time-dependent CP asymmetry in B_s
  - According previous introduction, the $A_{CP}(t)$ is given by

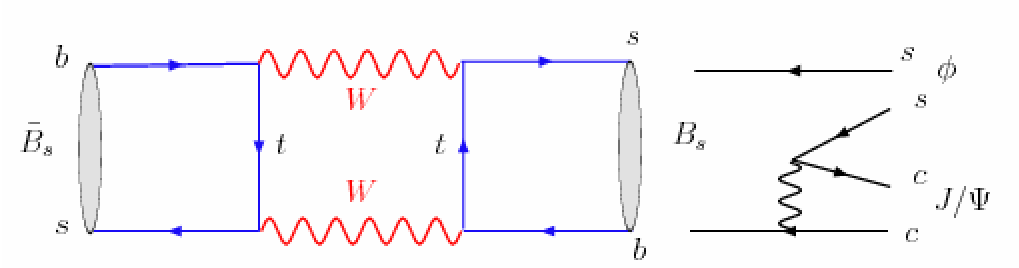
$$\mathcal{A}_f(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t),$$

$$S_f \equiv \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2}, \quad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2},$$

$$|B_1\rangle = p|B_0\rangle + q|\bar{B}_0\rangle$$
$$|B_2\rangle = p|B_0\rangle - q|\bar{B}_0\rangle$$

$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f} \qquad \left(\frac{q}{p}\right) \simeq \sqrt{\frac{M_{12}^*}{M_{12}}}$$

$$f = J/\Psi\phi \qquad \lambda_{J/\Psi\phi} = \frac{q}{p} \simeq \sqrt{\frac{M_{12}^*}{M_{12}}} = \exp[i\phi_s]$$



V_{ts}^*

$$M_{12}^s \propto \left(V_{ts}^*\right)^2$$

➢ How large is the $S_{J/\psi\phi}$ in the SM ?

$$S_{J/\Psi\phi} = \frac{2\,\mathrm{Im}\,\lambda_{J/\Psi\phi}}{1+\left|\lambda_{J/\Psi\phi}\right|^2} \qquad \lambda_{J/\Psi\phi} = \frac{q}{p} \simeq \frac{V_{ts}}{V_{ts}^*} = \exp\left[i\phi_s\right] \qquad S_{J/\Psi\phi} = \sin\phi_s$$

- with $V_{ts} = -A\lambda^2$, $\phi_s=0$

- However, by including higher power of λ where

$$V_{tb} = 1 - A^2\lambda^4/2,\quad V_{ts} = -A\lambda^2 + A\lambda^4\left(1-2\left(\rho+i\eta\right)\right)/2$$

$$V_{cb} = A\lambda^4,\quad V_{cs} = 1-\lambda^2/2-\lambda^4\left(1+4A^2\right)/8$$

Buras, hep-ph/0505175

$$V_{ts} = -A\lambda^2 \exp[i\beta_s],\quad \beta_s \approx \lambda^2\eta$$

With $\eta=0.359$ and $\lambda=0.2272$

$$\Rightarrow \begin{cases} \beta_s \approx \lambda^2\eta \approx 0.019 \\ \phi_s = 2\beta_s \approx 0.038 \end{cases}$$

Very small CPA in the SM

➢ preliminary results of CDF & D0

• to include the possible new physics effects, we write

$$M_{12}^s = A_{12}^{\rm SM} e^{-2i\beta_s} + A_{12}^{\rm NP} e^{2i(\theta_s^{\rm NP}-\beta_s)}$$

$$-S_{J/\Psi\phi} \simeq \mathrm{Im}\left(\sqrt{\frac{M_{12}^{s*}}{M_{12}^s}}\right) = \sin(2\beta_s - \phi_s^{\rm NP}),$$

$$\phi_s^{NP} = \arctan\left(\frac{r\sin 2\theta_s^{\rm NP}}{1 - r\cos 2\theta_s^{\rm NP}}\right) \qquad r = A_{12}^{NP}/A_{12}^{\rm SM}$$

$$\phi_s = 2\beta_s - \phi_s^{NP} = \begin{cases} [0.24,\ 1.36] \cup [1.78,\ 2.82] & \text{(CDF)} \\ 0.57^{+0.30+0.02}_{-0.24-0.07} & \text{(DØ)} \end{cases}$$

at 68% C.L.

In addition, D0 also gives the result at 90% C.L. to be

$$\phi_s \in [-0.06,\ 1.20]$$

- By combining other data of B_s decays, UTfit Collaboration finds that the **non-vanished phase** is more than 3σ from the SM prediction

FIRST EVIDENCE OF NEW PHYSICS IN b ↔ s TRANSITIONS

(UT*fit* Collaboration)

M. Bona,[1] M. Ciuchini,[2] E. Franco,[3] V. Lubicz,[2,4] G. Martinelli,[3,5] F. Parodi,[6] M. Pierini,[1] P. Roudeau,[7] C. Schiavi,[6] L. Silvestrini,[3] V. Sordini,[7] A. Stocchi,[7] and V. Vagnoni[8]

We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than 3σ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.

- - - Don't take this too serious

$$C_{B_s} e^{2i\phi_{B_s}} = \frac{A_s^{\rm SM} e^{-2i\beta_s} + A_s^{\rm NP} e^{2i(\phi_s^{\rm NP} - \beta_s)}}{A_s^{\rm SM} e^{-2i\beta_s}} = \frac{\langle B_s | H_{\rm eff}^{\rm full} | \bar{B}_s \rangle}{\langle B_s | H_{\rm eff}^{\rm SM} | \bar{B}_s \rangle},$$

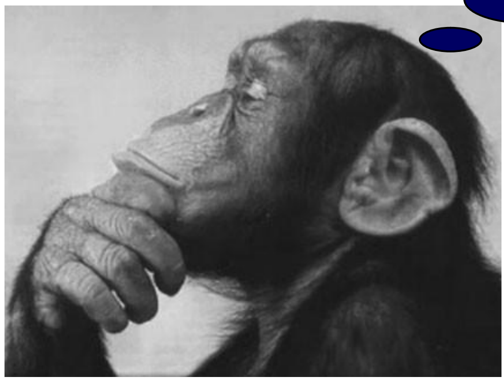
Observable	68% Prob.	95% Prob.
$\phi_{B_s}[^\circ]$	-19.9 ± 5.6	[-30.45,-9.29]
	-68.2 ± 4.9	[-78.45,-58.2]
C_{B_s}	1.07 ± 0.29	[0.62,1.93]
$\phi_s^{\rm NP}[^\circ]$	-51 ± 11	[-69,-27]
	-79 ± 3	[-84,-71]
$A_s^{\rm NP}/A_s^{\rm SM}$	0.73 ± 0.35	[0.24,1.38]
	1.87 ± 0.06	[1.50,2.47]
Im $A_s^{\rm NP}/A_s^{\rm SM}$	-0.74 ± 0.26	[-1.54,-0.30]
Re $A_s^{\rm NP}/A_s^{\rm SM}$	-0.13 ± 0.31	[-0.61,0.78]
	-1.82 ± 0.28	[-2.68,-1.36]

- more than 30 citations since the paper is put on the arXiv

First Evidence of New Physics in b <---> s Transitions.
By UTfit Collaboration (M. Bona *et al.*). Mar 2008. 5pp.
e-Print: **arXiv:0803.0659** [hep-ph]
References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Cited 35 times

- Inspired by the results of CDF& D0 and UTfit collaboration,

If $b \to s$ transition involves new CP phase, can we uncover it in other process? and what is it?



■ Physical quantities related to CP violating phase

- **CP-odd physical quantity**: consider particle B decay, the decay amplitude is written as

θ_W: CPV phase
δ : CPC phase

$$A(B) = a + be^{-i\theta_W} e^{i\delta}$$

accordingly, the decay amplitude for its antiparticle is

$$\bar{A}(\bar{B}) = a + be^{i\theta_W} e^{i\delta}$$

- A CP-odd quantity could be defined by

$$A_{CP-odd} = \frac{\left|\bar{A}(\bar{B})\right|^2 - \left|A(B)\right|^2}{\left|\bar{A}(\bar{B})\right|^2 + \left|A(B)\right|^2} \qquad \frac{\left|\bar{A}(\bar{B})\right|^2 - \left|A(B)\right|^2}{\left|\bar{A}(\bar{B})\right|^2 + \left|A(B)\right|^2} \xrightarrow{CP} \frac{\left|A(B)\right|^2 - \left|\bar{A}(\bar{B})\right|^2}{\left|A(B)\right|^2 + \left|\bar{A}(\bar{B})\right|^2}$$

$$A_{CP-odd} \xrightarrow{CP} -A_{CP-odd}$$

- Such kind of physical quantities need CP violating and conserving phases at the same time

- The quantity is also called direct CP violation

- $\hat{\mathrm{T}}$-odd physical quantity: $t \xrightarrow{\hat{\mathrm{T}}} -t$
  - ✓ Triple-product spin-momentum correlation in 3-body decay

$$\vec{s}_B \cdot \left(\vec{p}_C \times \vec{p}_D\right) \xrightarrow{\hat{T}} -\vec{s}_B \cdot \left(\vec{p}_C \times \vec{p}_D\right)$$

A→BCD

➡ $$\varepsilon_{\mu\nu\rho\sigma} s_B^\mu p_C^\nu p_D^\rho p_A^\sigma$$

➡ $$d\sigma \propto \mathrm{Im}\left(M_\lambda M_{\lambda'}^\dagger\right) \begin{cases} 1.\ \text{CPV phase} \\ 2.\ \text{CPC phase} \end{cases}$$

  - ✓ Triple-product momentum correlation in 4-body decay

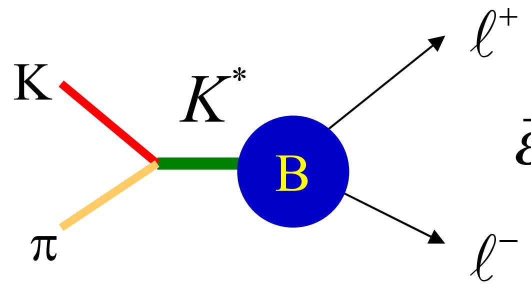
$$\vec{p}_B \cdot \left(\vec{p}_C \times \vec{p}_D\right) \xrightarrow{\hat{T}} -\vec{p}_B \cdot \left(\vec{p}_C \times \vec{p}_D\right)$$

A→BCDE

➡ $$\varepsilon_{\mu\nu\rho\sigma} p_B^\mu p_C^\nu p_D^\rho p_A^\sigma$$

- semileptonic B decays might be a good environment to probe the new phase in b→s transition

e.g. $b \to s\ell^+\ell^-; B \to K^*\ell^+\ell^-$



$\vec{\varepsilon}_{K^*} \cdot \left(\vec{p}_{\ell^+} \times \vec{p}_K\right)$ **T-odd**

$$\frac{d\Gamma}{d\cos\theta_K d\cos\theta_\ell d\phi dq^2} = \frac{3\alpha^2 G_F^2 |\lambda_t|^2 |\vec{p}|}{2^{14}\pi^6 m_B^2}$$
$$\times\{4\cos^2\theta_K \sin^2\theta_\ell \sum_{i=1,2} |\mathcal{M}_i^0|^2 + \sin^2\theta_K(1+\cos^2\theta_\ell)$$
$$\sum_{i=1,2} \left(|\mathcal{M}_i^+|^2 + |\mathcal{M}_i^-|^2\right) - \sin 2\theta_K \sin 2\theta_\ell \sin\phi$$
$$\sum_{i=1,2} Im\left(\mathcal{M}_i^+ - \mathcal{M}_i^-\right)\mathcal{M}_i^{0*} - 2\sin^2\theta_K \sin^2\theta_\ell \sin 2\phi$$
$$\sum_{i=1,2} Im\left(\mathcal{M}_i^+ \mathcal{M}_i^{-*}\right) + \underline{2\sin 2\theta_K \sin\theta_\ell \sin\phi (Im\mathcal{M}_1^0}$$
$$\underline{(\mathcal{M}_2^{+*} + \mathcal{M}_2^{-*}) - Im(\mathcal{M}_1^+ + \mathcal{M}_1^-)\mathcal{M}_2^{0*})} + \cdots]\},$$

Dominant effect

$$\mathcal{M}_a^0 = \sqrt{q^2}\left(\frac{E_V}{m_V} f_2 + 2\sqrt{q^2}\frac{|\vec{p}_V|^2}{m_V} f_3\right),$$
$$\mathcal{M}_a^\pm = \sqrt{q^2}\left(\pm 2|\vec{p}_V|\sqrt{q^2} f_1 + f_2\right),$$

$$h_1 = \frac{C_9^{\rm eff} V}{m_B + m_V} + \frac{2m_b}{q^2} C_7 T_1,$$
$$h_2 = -\frac{1}{2}(m_B + m_V) C_9^{\rm eff} A_1 - \frac{1}{2}\frac{2m_b}{q^2} P\cdot q C_7 T_2,$$
$$h_3 = \frac{C_9^{\rm eff} A_2}{m_B + m_V} + \frac{2m_b}{q^2} C_7\left(T_2(q^2) + \frac{q^2}{P\cdot q} T_3\right),$$
$$g_i = h_i|_{C_9^{\rm eff}\to C_{10}, C_7=0}, \quad (i = 1,2,3).$$

- To explore the effects, we examine the T-odd observable, defined by

$$\langle \mathcal{O}_T \rangle = \int \mathcal{O}_T d\Gamma$$

$$\mathcal{O}_T = \frac{\vec{p}_B \cdot \vec{p}_K}{|\vec{p}_B|\,|\vec{p}_K|} \frac{\vec{p}_B \cdot (\vec{p}_K \times \vec{p}_{\ell^+})}{|\vec{p}_B|\,|\vec{p}_K|\,\omega_{\ell^+}} \qquad \mathcal{O}_T = \cos\theta_K \sin\theta_K \sin\theta_\ell \sin\phi.$$

The statistical significance is given by

$$\varepsilon_T(q^2) = \frac{\int \mathcal{O}_T d\Gamma}{\sqrt{(\int d\Gamma)(\int \mathcal{O}_T^2 d\Gamma)}}\,.$$

$$\varepsilon_T(q^2) \simeq \frac{0.76}{\sqrt{\mathcal{D}_1\mathcal{D}_2}}[Im\mathcal{M}_1^0(\mathcal{M}_2^{+*} + \mathcal{M}_2^{-*}) - Im(\mathcal{M}_1^+ + \mathcal{M}_1^-)\mathcal{M}_2^{0*}]\,,$$

$$\mathcal{D}_a = \sum_{i=1,2}\left[|\mathcal{M}_i^0|^2 + \frac{1}{a}\left(|\mathcal{M}_i^+|^2 + |\mathcal{M}_i^-|^2\right)\right].$$

- Since β_s is small, to obtain large phase in b→s, we need to consider the extension of the SM

■ We consider the so-called vector-like quark model (VQM)

VQM: add a pair of L and R gauge singlet quarks to the SM

$$(D_L, D_R);(U_L, U_R) \longleftarrow \text{SU(2)}_L \text{ singlet}$$

- Since the new particles are $SU(2)_L$ singlet, they don't couple to charged W-boson, but they couple to Z-boson

For W-coupling

$$H_C = J^C_\mu W^\mu = (\bar{u}, \bar{c}, \bar{t}, U)\gamma_\mu S P_L \begin{pmatrix} d \\ s \\ b \\ D \end{pmatrix} W^\mu \qquad S = \begin{pmatrix} 1_{3\times3} & 0 \\ 0 & 0 \end{pmatrix}_{4\times4} \qquad \underbrace{V_U^L S V_D^{L\dagger}}_{\equiv V_{CKM}}$$

⟶ New 4 ×4 CKM is not an unitary matrix

For Z-coupling

$$\mathcal{L}_Z = -\frac{g c_L^f}{2\cos\theta_W} \bar{F}\gamma^\mu \left(V_F^L X_F V_F^{L\dagger}\right) P_L F Z_\mu ,$$

$$c_L^f = c_V^f + c_A^f$$

$$c_V^f = T_f^3 - 2\sin^2\theta_W Q_f , \quad c_A^f = T_f^3$$

$$\xi_f = -2\sin^2\theta_W Q_f / c_L^f$$

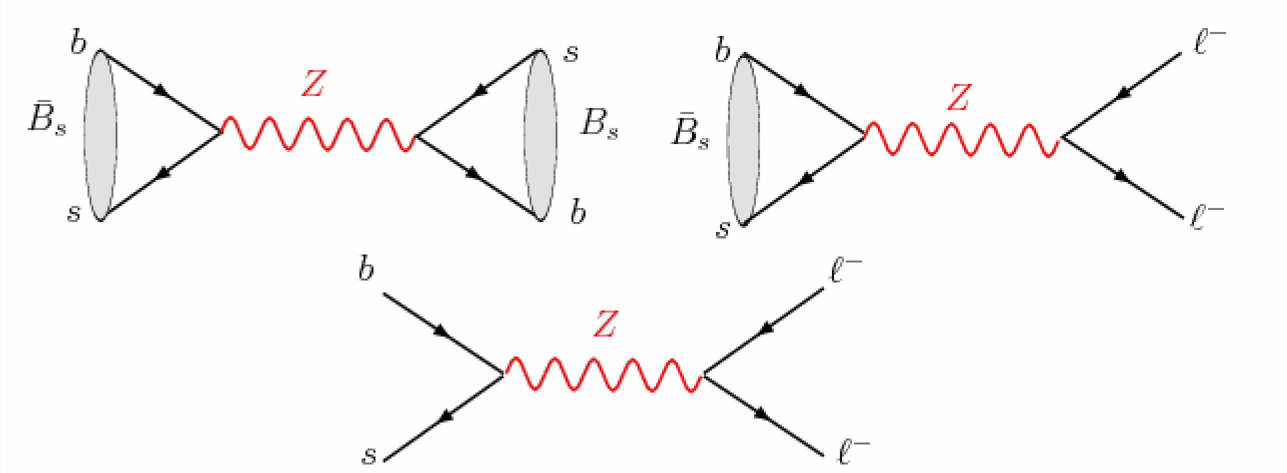
$$X_Q = \left[\begin{array}{c|c} \mathbb{1}_{3\times3} & 0_{3\times1} \\ \hline 0_{1\times3} & \xi_Q \end{array}\right], \quad X_\ell = \mathbb{1}_{3\times3} ,$$

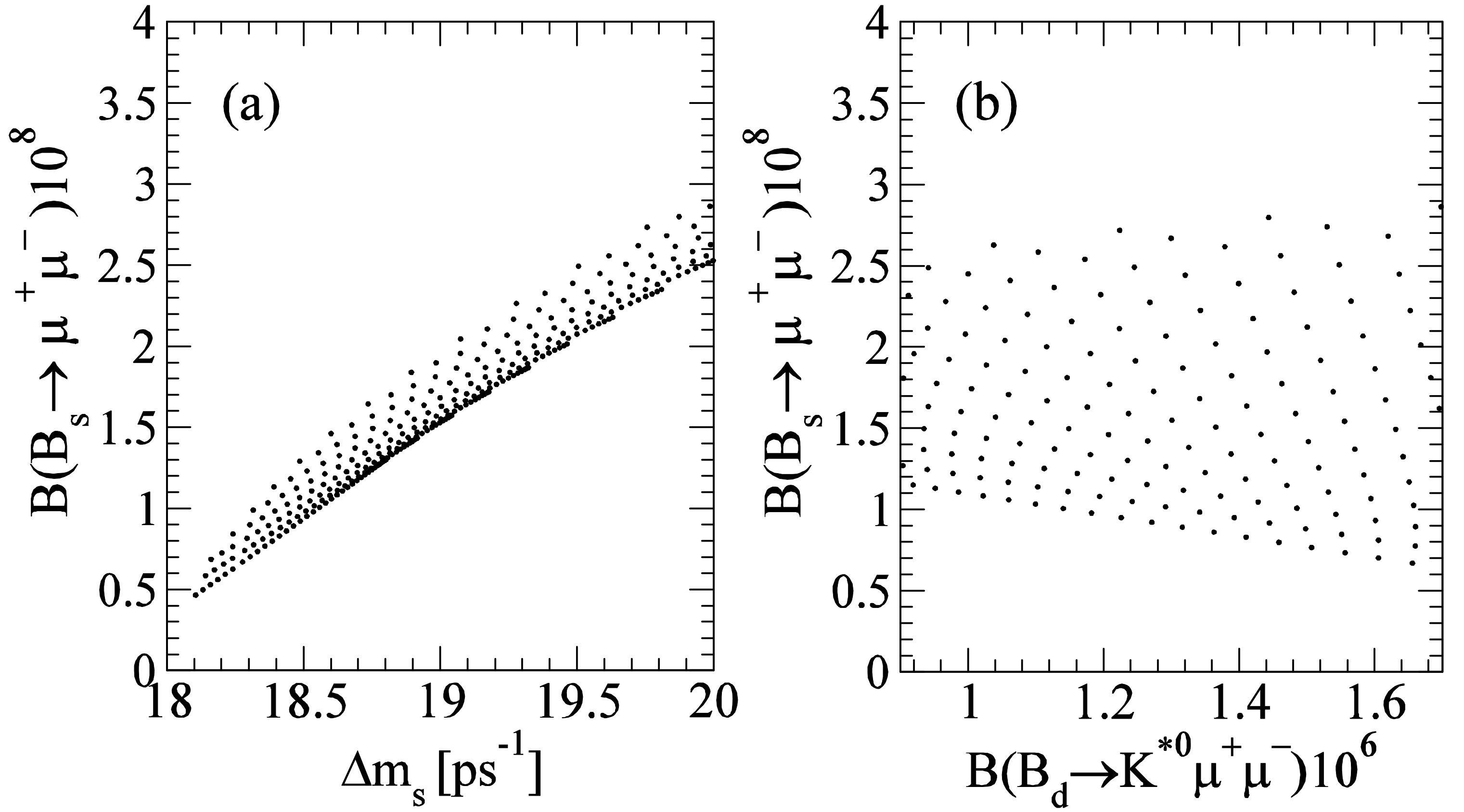
FCNC induced at tree (→ ξ_Q)

- We only pay attention to the Z-mediated FCNC

$$V_D^L X_D V_F^\dagger = I + V_D^L \left(X_D - I \right) V_F^\dagger$$

$$\left(V_D^L X_D V_F^\dagger \right)_{sb} = \left(V_D^L \right)_{24} \left(X_D - I \right)_{44} \left(V_F^\dagger \right)_{43}$$



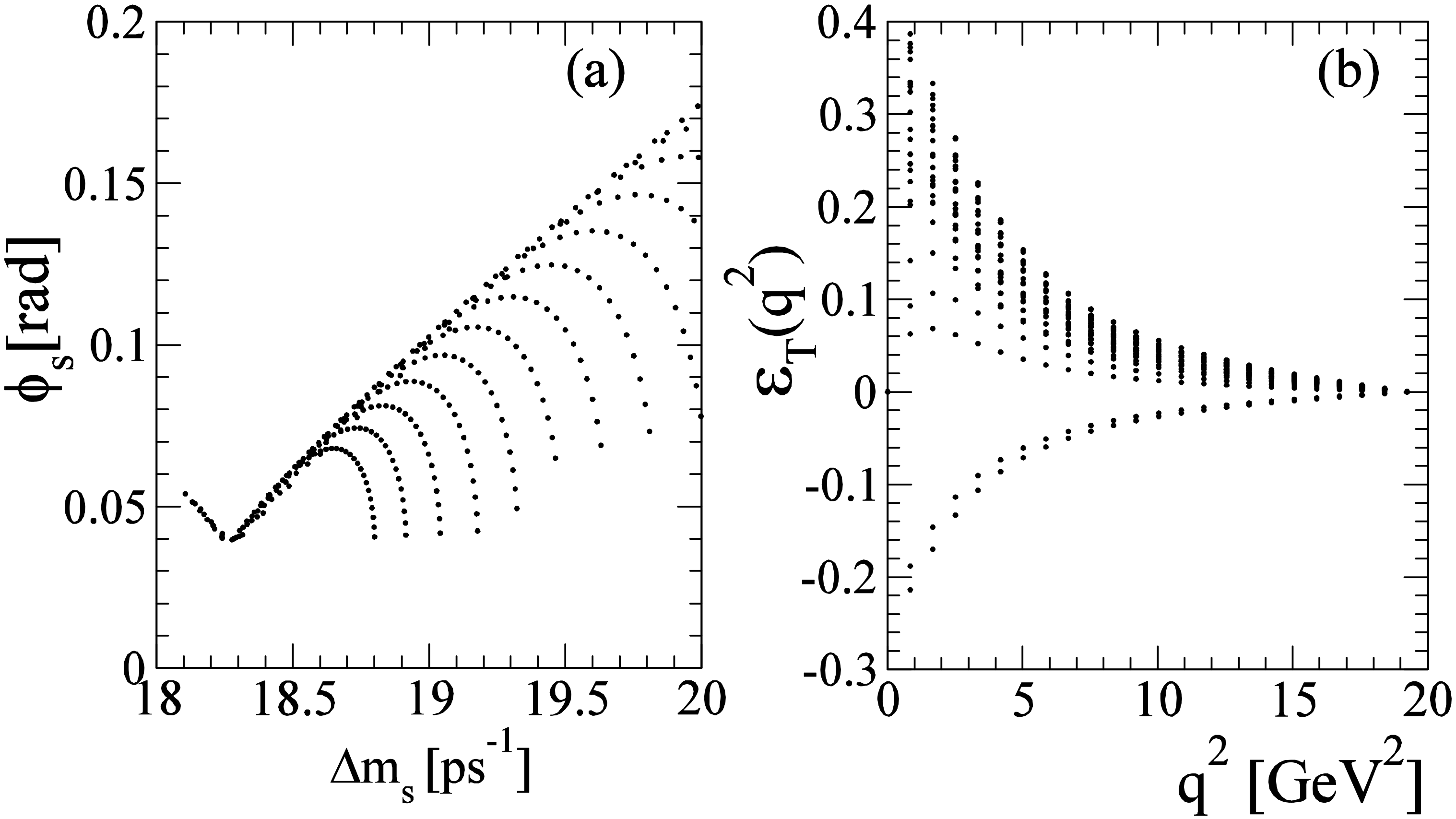


$\Delta m_s = 18.17 \pm 0.86\ \mathrm{ps}^{-1}$

$\mathcal{B}(B_d \to K^{*0}\mu^+\mu^-) = (1.22^{+0.38}_{-0.32}) \times 10^{-6}$

$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM} \approx 0.33 \times 10^{-8}$

Current limit < 4.7×10^{-8} CDF



$$\phi_s = 2\beta_s - \phi_s^{NP} = \begin{cases} [0.24,\ 1.36] \cup [1.78,\ 2.82]\ \text{(CDF)} \\ 0.57^{+0.30+0.02}_{-0.24-0.07} \qquad \text{(DØ)} \end{cases}$$

Summary:

- Although CKM matrix provides a unique phase in the SM, due to the failure to explain the matter-antimatter asymmetry, it is important to find out other new CP violating phase at colliders

- $b \to s$ transition could be the good candidate to look for the new CP phase

- By studying time-dependent CPA of B_s mixing, it helps to know whether there exists a new CP phase in $b \to s$ transition

- T-odd effects of $B_{d(s)} \to K^* (\phi) \ell^+ \ell^-$ decay provide another chance to observe the new phase

A brief introduction to $\mathbf{m_{T2}}$

- The definition:

$$M_{T2}^2 \equiv \min_{\not{p}_1+\not{p}_2=\not{p}_T}\left[\max\left\{m_T^2(\mathbf{p}_{Tl^-},\not{p}_1),\, m_T^2(\mathbf{p}_{Tl^+},\not{p}_2)\right\}\right]$$

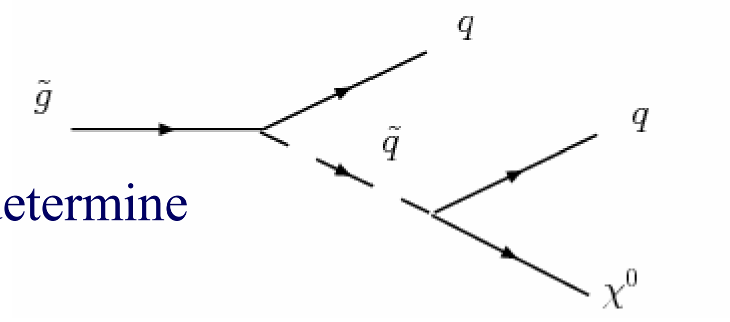
$\not{p}$: missing transverse momentum

p_T : visible transverse momentum

m_T : transverse mass

- A method to determine the mass of unknown particle when invisible particle appears in the final state

for instance:

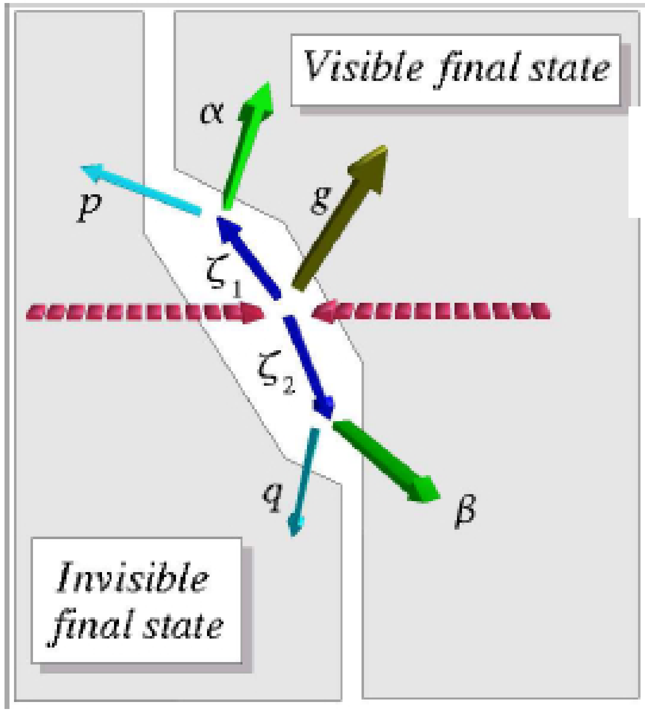


m_{T2} could be used to determine the mass of gluino

- Original question: how to determine the mass of new particle that is produced in pair at collider, where the particle decays to a visible and an invisible particles

Lester & Summers, PLB463 (99)

example:



$$pp \to X + \tilde{l}_R^+ \tilde{l}_R^- \to X + l^+ l^- \tilde{\chi}_1^0 \tilde{\chi}_1^0.$$

Mass of slepton ?

A. Barr, C. Lester, P. Stephens, J. Phys. G29 (2003)

■ To understand m_{T2}, we need to know the definition of transverse mass

- set a particle A decaying to B and C, if B and C are visible

$$P_A^2 = m_A^2 = \left(p_B + p_C\right)^2$$

can be observed

no problem to know the mass of A particle

- Now, if C is an invisible particle and escapes the detection from detector

example: $W \to \ell \nu_\ell$

$$P_W^2 = m_W^2 = \left(p_\ell + p_\nu\right)^2$$

$$= m_\ell^2 + \not{m}^2 + 2\left(E_\ell \not{E} - \vec{p}_\ell \cdot \vec{\not{p}}\right)$$

$$= m_\ell^2 + \not{m}^2 + 2\left(E_{T\ell} \not{E}_T \cosh \Delta\eta - \vec{p}_{T\ell} \cdot \vec{\not{p}}_T\right)$$

$$\geq m_\ell^2 + \not{m}^2 + 2\left(E_{T\ell} \not{E}_T - \vec{p}_{T\ell} \cdot \vec{\not{p}}_T\right) \equiv m_T^2$$

$$E_T = \sqrt{\vec{p}_T + m^2}$$

$$\eta = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

= is satisfied when the rapidity difference vanishes

■ Using the concept of transverse mass, Lester & Summers proposed m_{T2} variable to determine the mass of new particle which is produced in pair at collider

- m_{T2} is a variable that is calculated with event by event

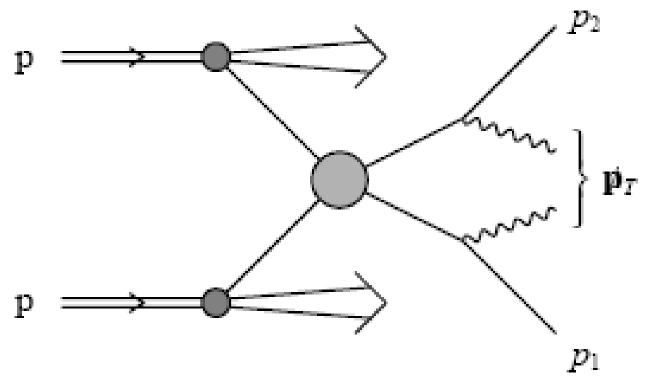
$$pp \to X + \tilde{l}_R^+ \tilde{l}_R^- \to X + l^+ l^- \tilde{\chi}_1^0 \tilde{\chi}_1^0.$$

$$M_{T2}^2 \equiv \min_{\not{\mathbf{p}}_1 + \not{\mathbf{p}}_2 = \not{\mathbf{p}}_T} \left[\max \left\{ m_T^2(\mathbf{p}_{Tl^-}, \not{\mathbf{p}}_1), m_T^2(\mathbf{p}_{Tl^+}, \not{\mathbf{p}}_2) \right\} \right]$$

$$m_T^2 \equiv m_\ell^2 + \not{m}^2 + 2\left(E_{T\ell} \not{E}_T - \vec{p}_{T\ell} \cdot \vec{\not{p}}_T \right)$$

neutralino

$$m^2 \geq m_T^2$$



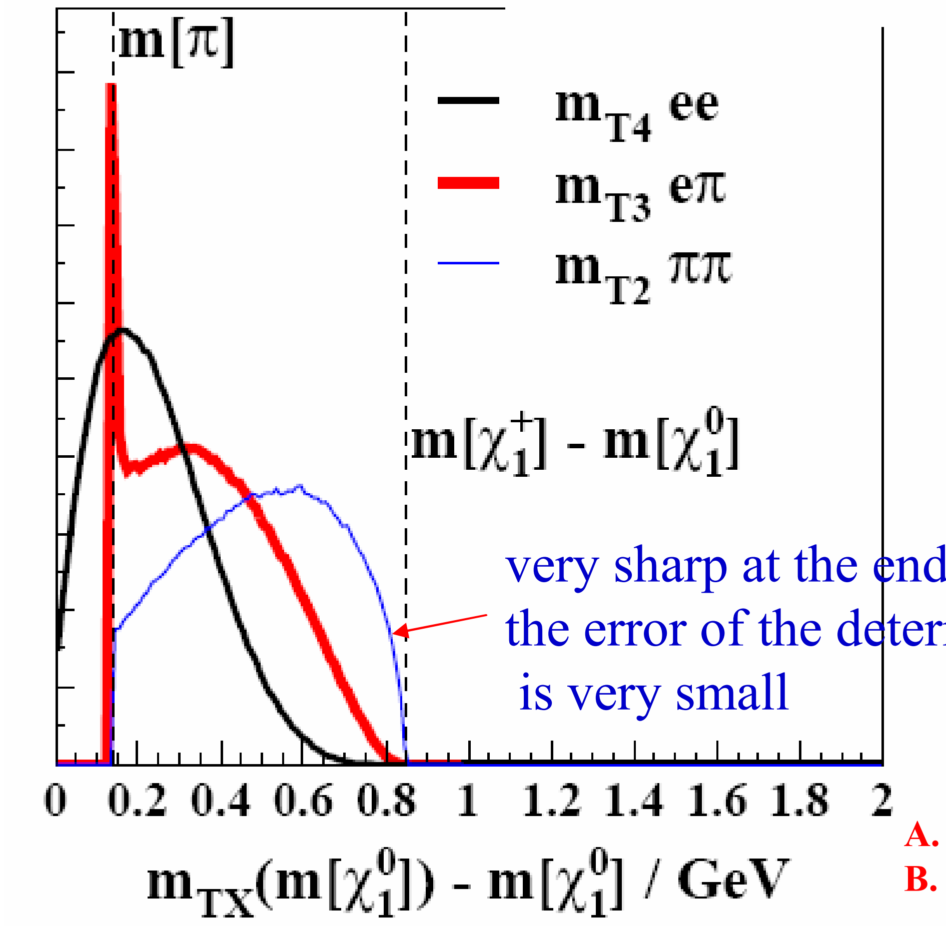
- the total missing momentum is fixed

$$\not{p}_T = \not{p}_1 + \not{p}_2$$

known and fixed

■ How powerful is the m_{T2} ?

$$\chi_1^\pm \chi_1^\pm \to \{\pi^\pm \chi_1^0 \pi^\pm \chi_1^0, \text{ or } e^\pm \nu \chi_1^0 \pi^\pm \chi_1^0, \text{ or } e^\pm \nu \chi_1^0 e^\pm \nu \chi_1^0\} .$$

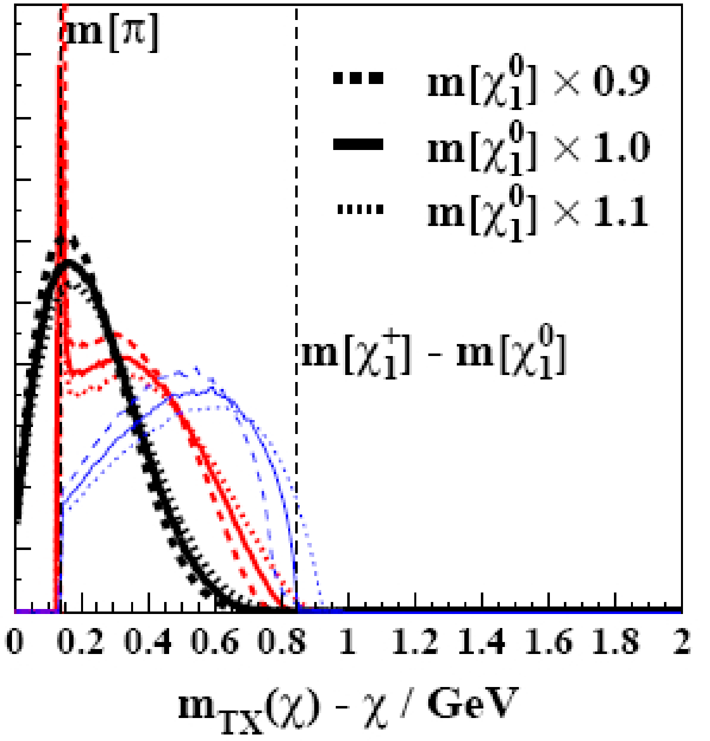


very sharp at the end-point, i.e. the error of the determined mass is very small

A. Barr, C. Lester, P. Stephens,
B. J. Phys. G29 (2003)

• Now, you can see that the 2 in the subscript means the number of missing particles

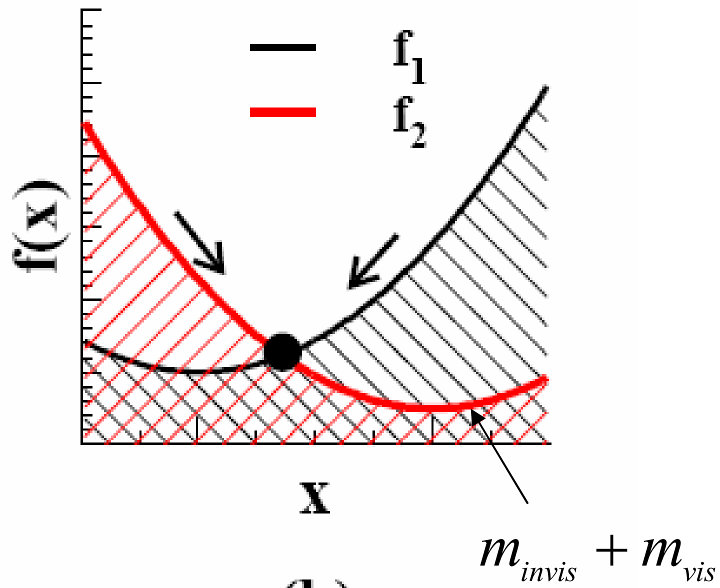
• error of the mass of invisible particle



■ The original m_{T2} variable cannot determine the mass of invisible

■ **How to determine the mass of missing particle by using m_{T2} ?**

W.S. Cho, K. choi, Y.G. Kim, C.B. Park, PRL100:171801,2008



(b)