

# ***Composite Higgs models and phase shift measurements***

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In collaboration with  
Shinya Kanemura, Naoki Machida and Tetsuo Shindou

Reference  
arXiv:1410.8413

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## ***OUTLINE***

1. Introduction
2. Phase shift measurements at LHC and the ILC
3. Fingerprinting of minimal composite Higgs models
4. Summary

## *1. Introduction*

Observed Higgs boson mass  $m_h \sim 125 \text{ GeV}$  again reminds us *naturalness problem...*

***Why is the Higgs boson mass around 125 GeV against large quantum corrections?***

candidates of a new paradigm

Supersymmetry?

Strong dynamics?

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### **Why is the Higgs boson mass around 125 GeV against large quantum corrections?**

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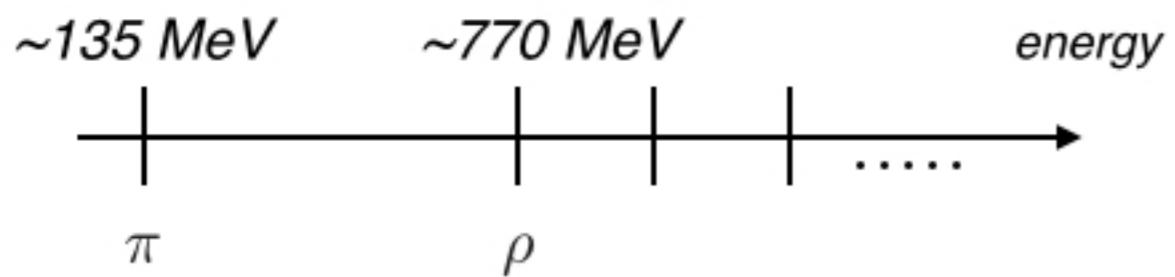
Supersymmetry?

Strong dynamics?

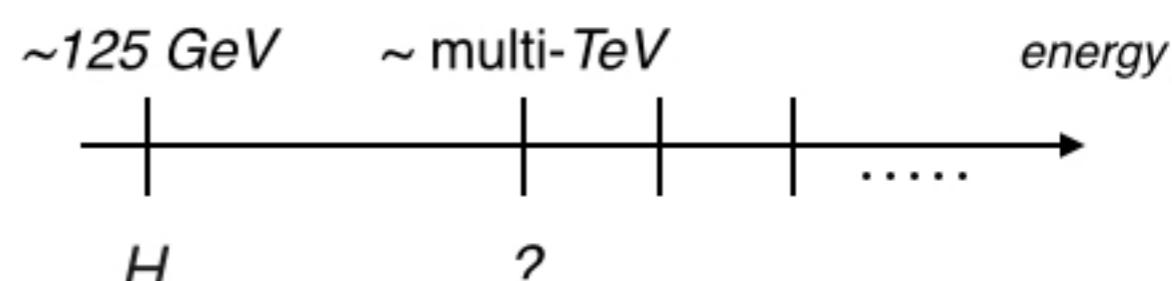
→ Higgs boson = composite state

Analogy

QCD



Composite Higgs



- Pion is the lightest scalar boson in QCD sector.
- Because it is a pseudo Nambu-Goldstone boson.

- Higgs boson is the lightest scalar in EW sector.
- It can be expect that Higgs boson would be a pseudo Nambu-Goldstone boson.

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## Why is the Higgs boson mass around 125 GeV against large quantum corrections?

candidates of a new paradigm

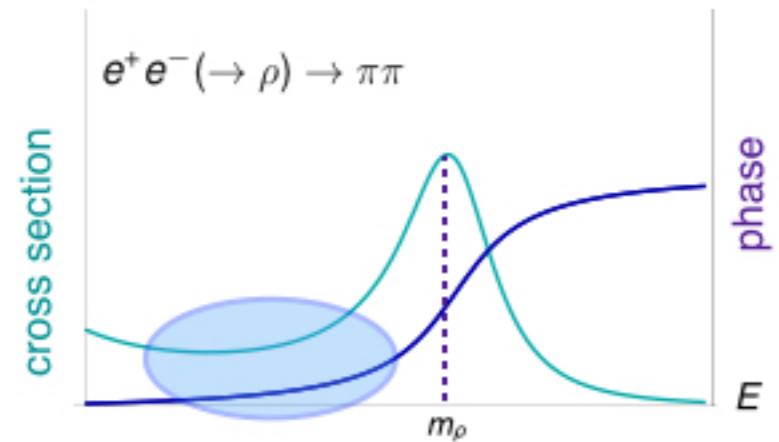
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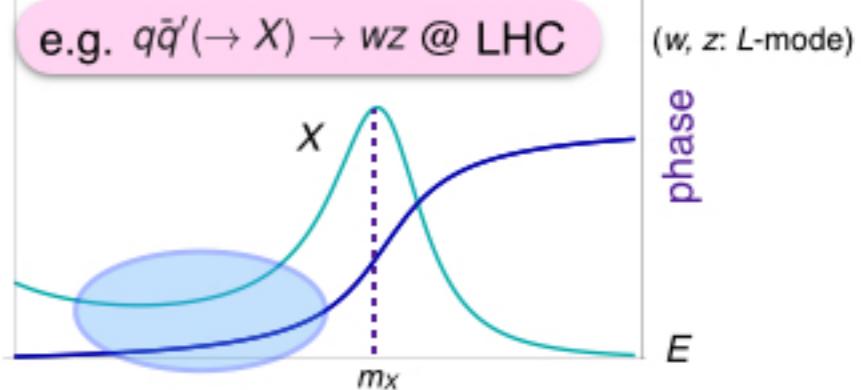
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Analogy

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Composite Higgs



- Pion is the lightest scalar boson in QCD sector.
- Because it is a pseudo Nambu-Goldstone boson.
- The second resonance is rho meson having the large width  $\Gamma_\rho/m_\rho \sim 0.2$ . (c.f.  $\Gamma_Z/M_Z \sim 0.03$ )
- The sizable tail of the cross section appears.
- Hence, phase shifts can be observed in the tail region even if we could not reach the peak.

- Higgs boson is the lightest scalar in EW sector.
- It can be expect that Higgs boson would be a pseudo Nambu-Goldstone boson.
- If the second resonance “X” is broad;  $\Gamma_X/m_X \sim O(0.1)$ , phase shift measurements are important to probe the new resonance.

## ***2. Phase shift measurements at LHC and the ILC***

## **$\delta$ measurement at LHC**

Murayama, et al. (1401.3761)

$$pp \rightarrow W^+ Z \rightarrow l^+ \nu l^+ l^-$$

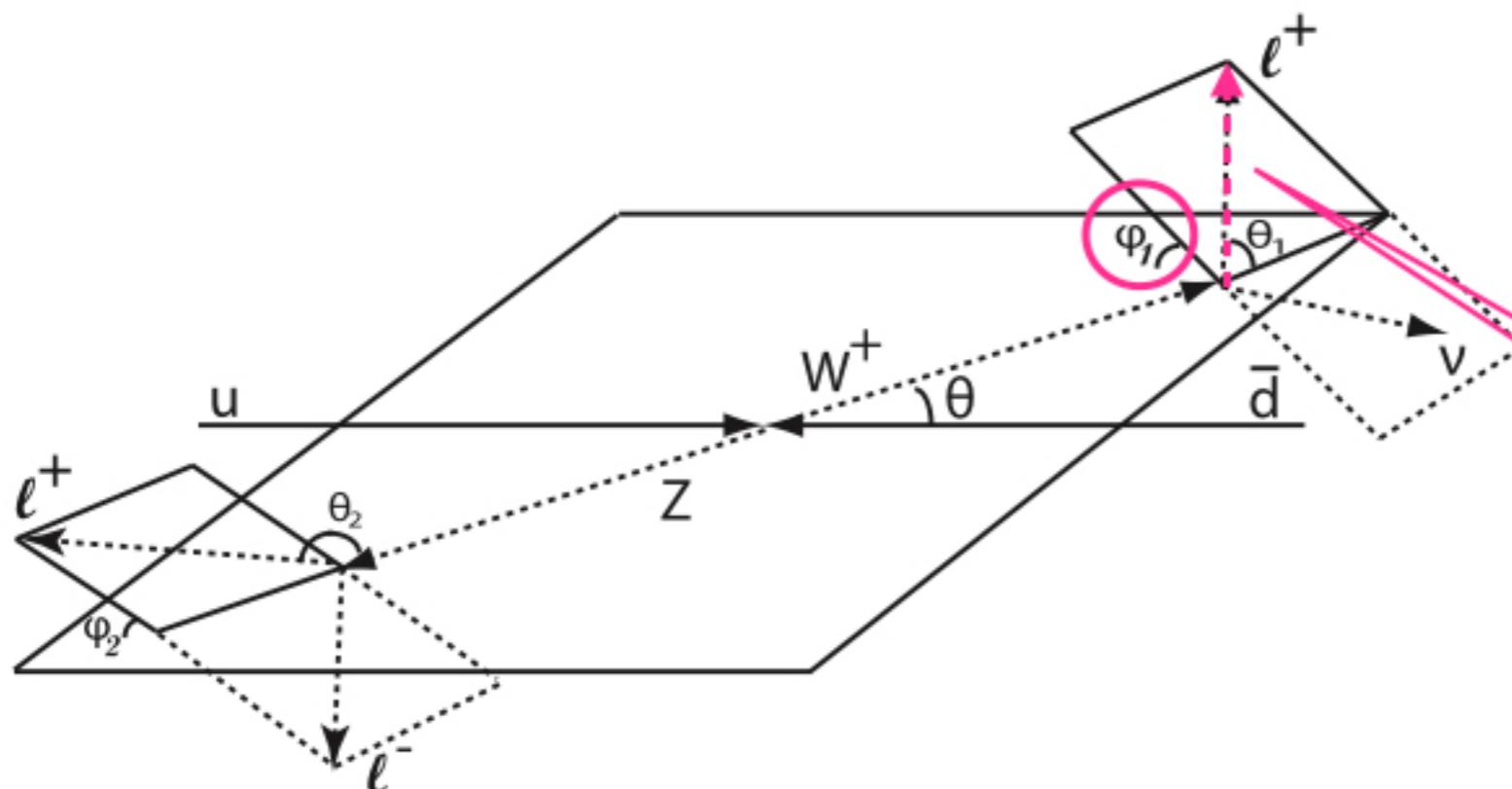
Phase shift can be extracted by azimuthal angle dependence of a final state lepton.

$$|\text{Amp.}|^2 \propto \left| \sum_{\lambda_W, \lambda_Z} \mathcal{M}_{\text{Prod}}^{u\bar{d} \rightarrow W^+ Z}(\theta; \lambda_W, \lambda_Z) \mathcal{M}_{\text{Decay}}^{W^+ \rightarrow l^+ \nu}(\theta_1, \phi_1; \lambda_W) \mathcal{M}_{\text{Decay}}^{Z \rightarrow l^+ l^-}(\theta_2, \phi_2; \lambda_Z) \right|^2$$

Production:  $\mathcal{M}_{\text{Prod}}^{u\bar{d} \rightarrow W^+ Z}(\theta; 0, 0) \rightarrow \mathcal{M}_{\text{Prod}}^{u\bar{d} \rightarrow W^+ Z}(\theta; 0, 0) e^{i\delta}$  (just a parametrization of “ $\delta$ ”)

Decay:  $\mathcal{M}_{\text{Decay}}^{W^+ \rightarrow l^+ \nu}(\theta_1, \phi_1; \lambda_W) \propto e^{i\lambda_W \phi_1}$  and  $\mathcal{M}_{\text{Decay}}^{Z \rightarrow l^+ l^-}(\theta_2, \phi_2; \lambda_Z) \propto e^{-i\lambda_Z \phi_2}$

$$\sim |A e^{i\delta} + B e^{i(\lambda_W \phi_1 - \lambda_Z \phi_2)}|^2 \propto \cos(\delta + \lambda_W \phi_1 - \lambda_Z \phi_2) \supset \sin(\delta) \sin(\lambda_W \phi_1 - \lambda_Z \phi_2)$$



Due to the interference term, “ $\delta$ ” induces “ $\phi_1$ ” dependence of final state leptons even when  $(\lambda_W, \lambda_Z) \neq (0, 0)$

Let us use

$$A_{\pm} \equiv \frac{|\sigma_+ - \sigma_-|}{\sigma_+ + \sigma_-}, \quad \sigma_{\pm} \equiv \sigma(\sin \phi_1 \gtrless 0)$$

(other phase space is integrated for  $0 < \cos \theta < 1$ )

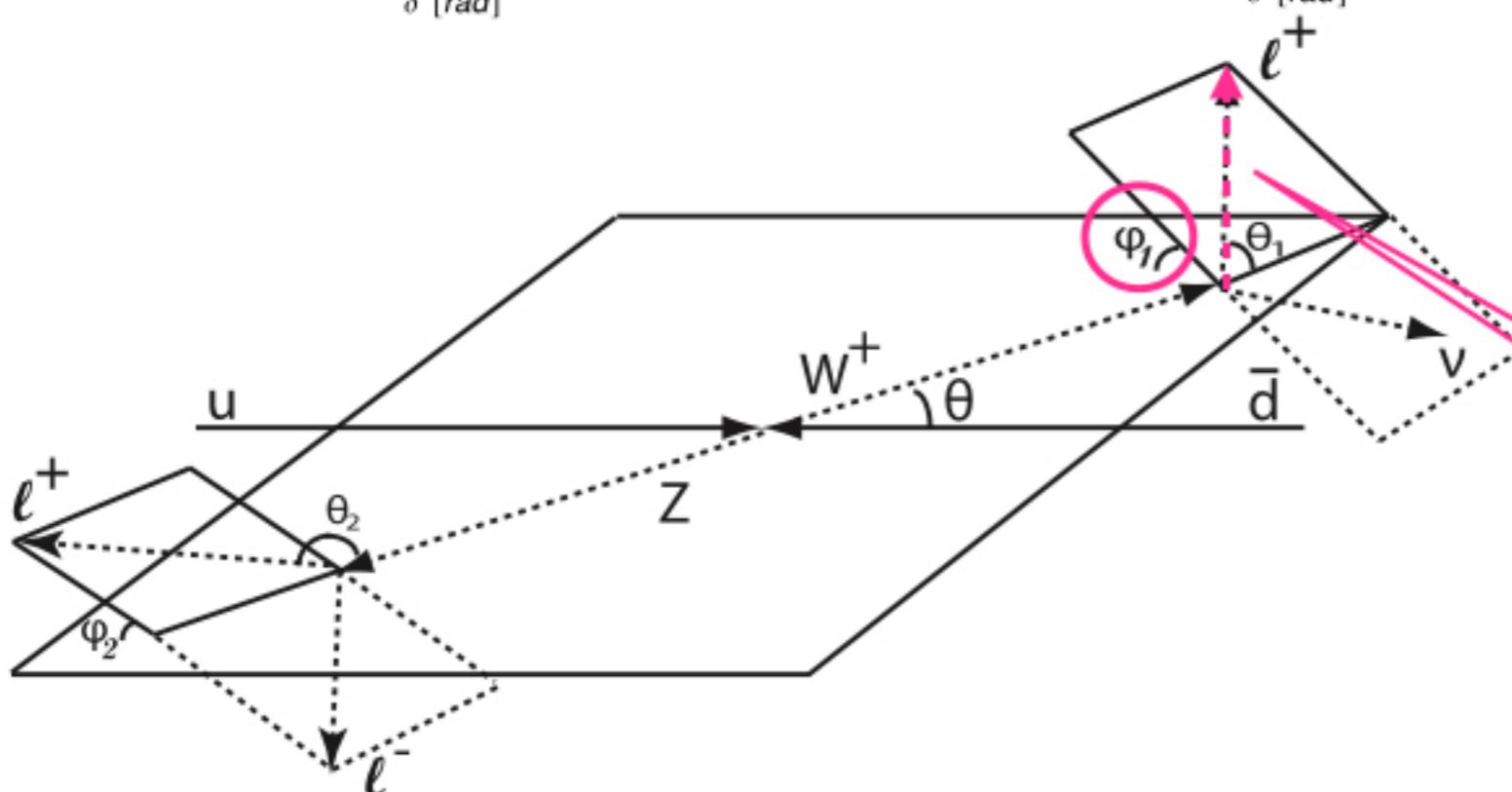
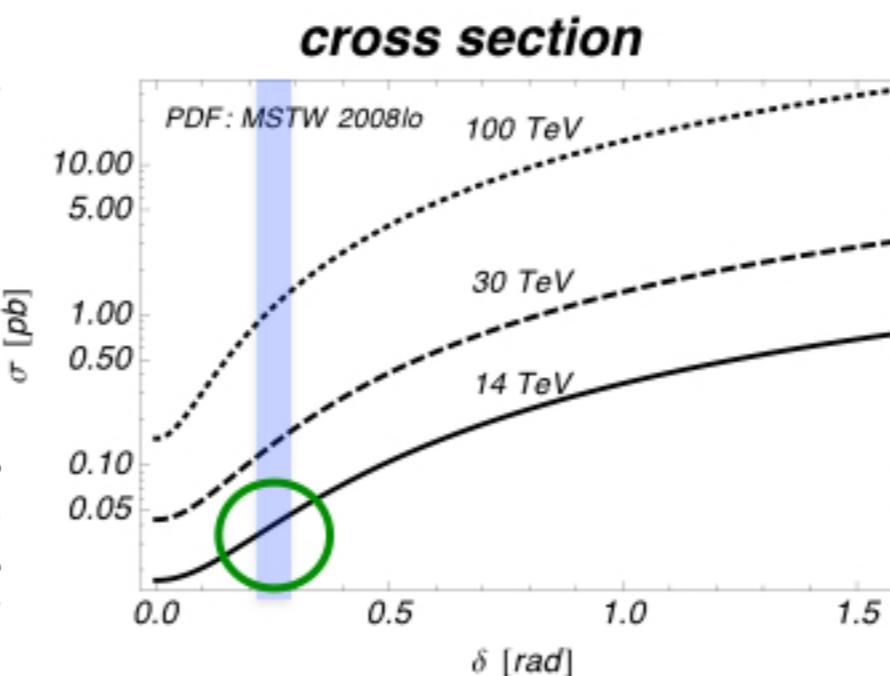
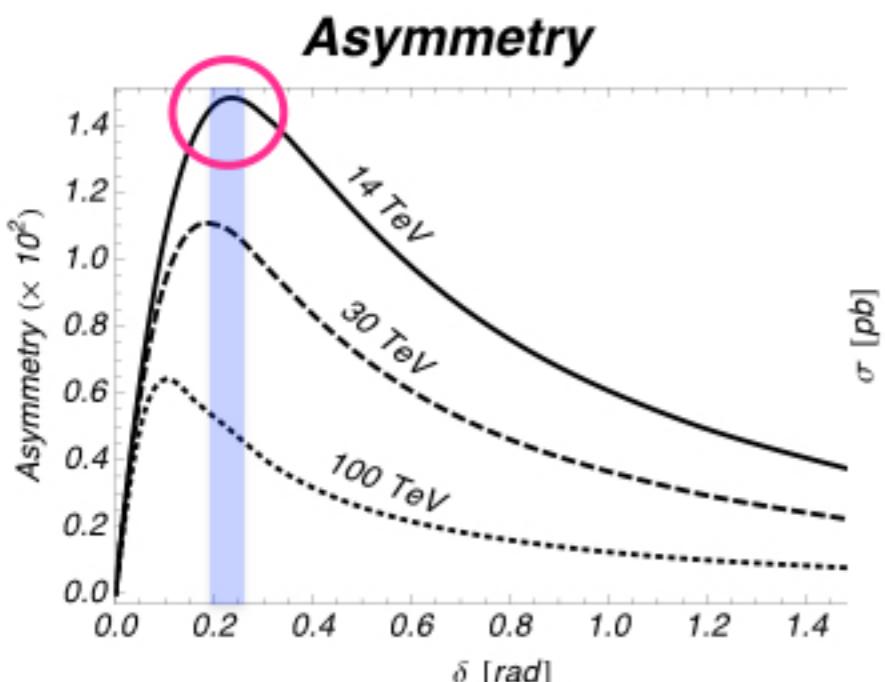
{  $\sigma_+$  :  $l^+$  goes to “above” the production plane  
 {  $\sigma_-$  :  $l^+$  goes to “below” the production plane

## $\delta$ measurement at LHC

Murayama, et al. (1401.3761)

$$pp \rightarrow W^+ Z \rightarrow l^+ \nu l^+ l^-$$

Phase shift can be extracted by azimuthal angle dependence of a final state lepton.



$\delta \sim 0.24$ , for example,  
 $A_{\pm} \sim 1.5\% (@ 14 \text{ TeV LHC})$

cross section  $\sim 3.7 \text{ fb}$

stat. error:  $1/\sqrt{N} \sim 3\% (300 \text{ fb}^{-1})$   
 $\lesssim 1\% (3000 \text{ fb}^{-1})$

It would be possible to observe the phase shift @ HL-LHC, but it seems not so significant.  
(not so changed even if the efficiency  $\sim 70\%$ )

Let us use

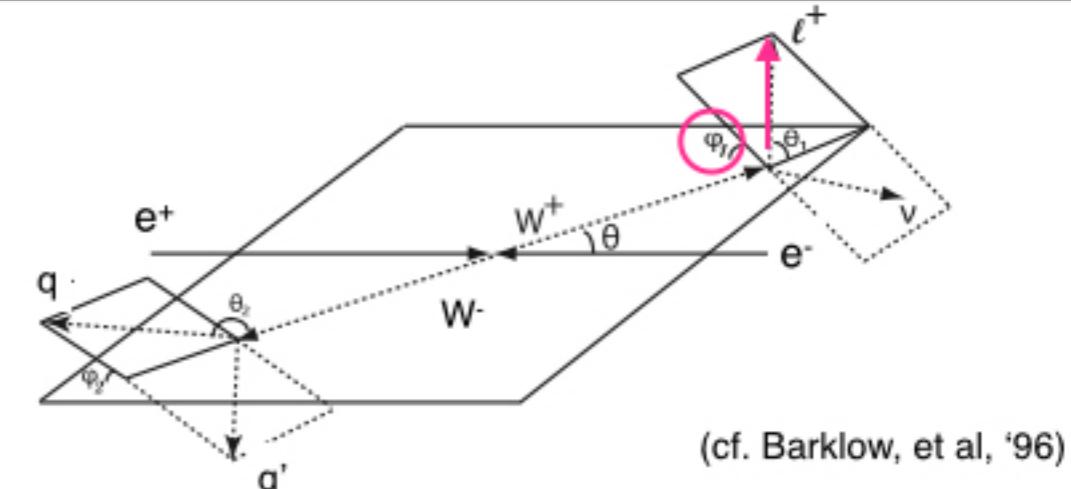
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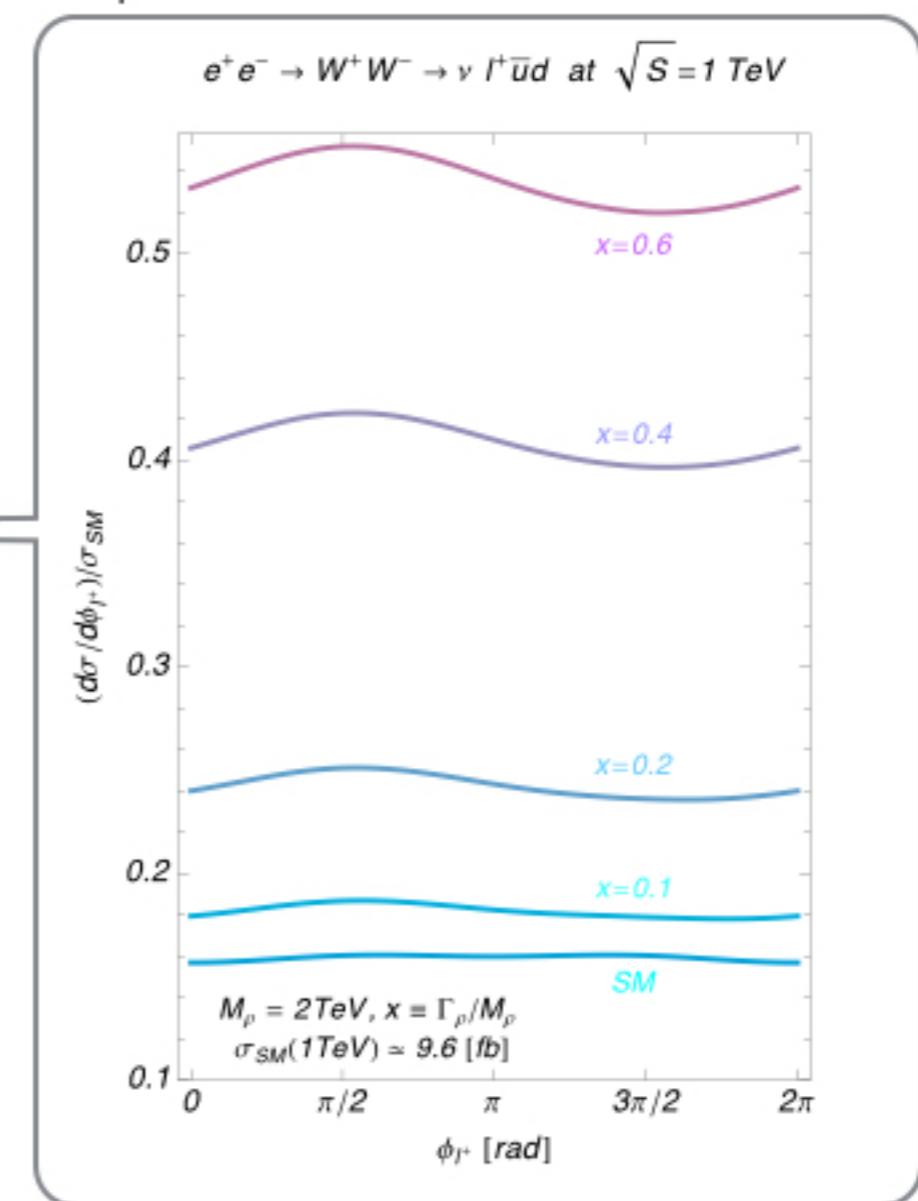
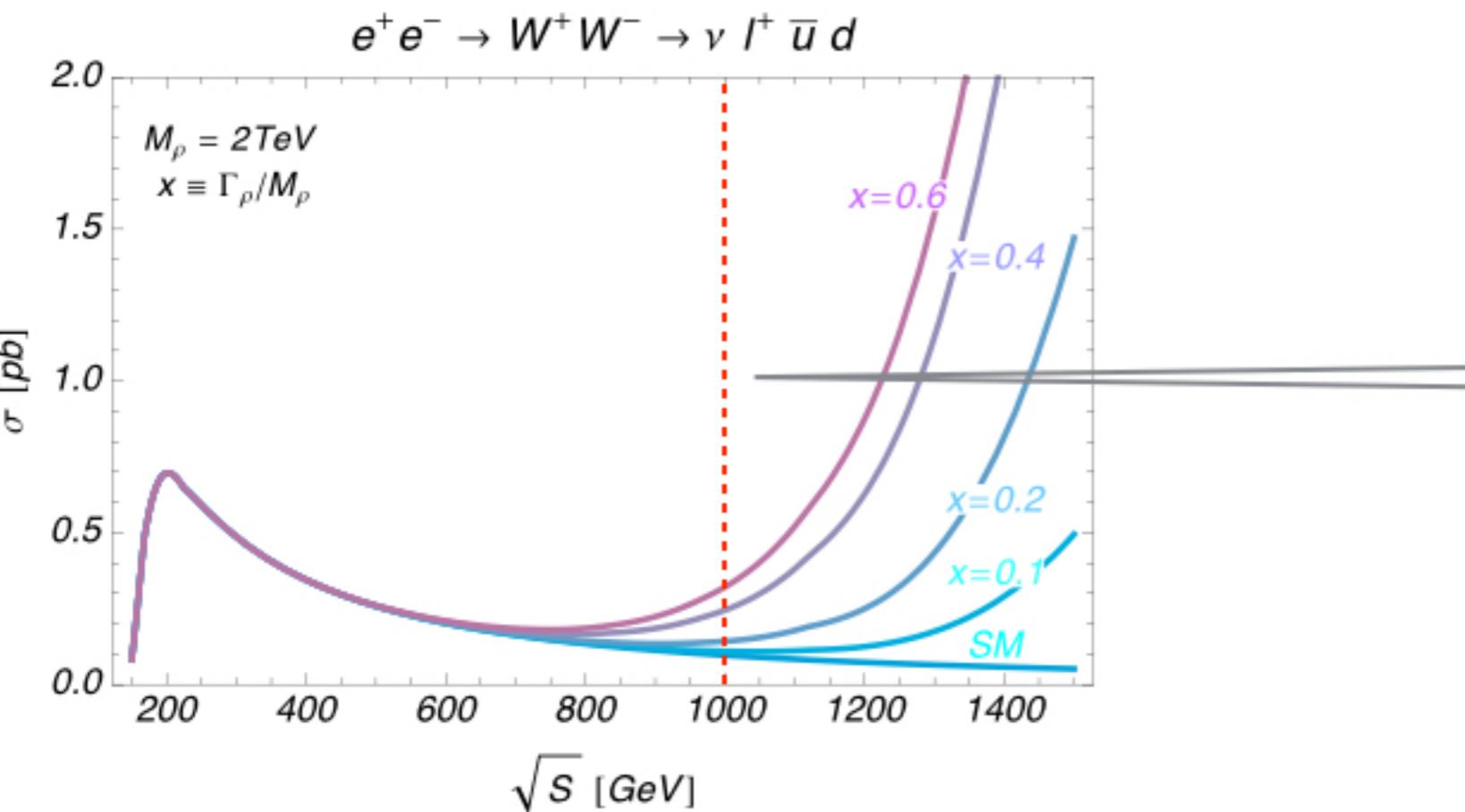
$\left\{ \begin{array}{l} \sigma_+ : l^+ \text{ goes to "above" the production plane} \\ \sigma_- : l^+ \text{ goes to "below" the production plane} \end{array} \right.$

## **$\delta$ measurement at the ILC (preliminary)**

$$e^+ e^- \rightarrow W^+ W^- \rightarrow l \nu q \bar{q}'$$



Phase shift can be extracted by azimuthal angle dependence of a final state lepton as in the case of LHC.



There is a possibility to observe the phase shift if the cross section and the angular distribution can be measured with  $O(1)\%$  level. (detailed BG estimation is necessary)

## Anticipating new resonance scales from $\delta$

e.g.) MCHM<sub>4</sub>

- In minimal composite Higgs models (MCHMs), Higgs interactions are deviated from the SM, which are characterized by  $\xi \equiv v^2/f^2$ .  
( $f$  is the breaking scale of  $SO(5) \rightarrow SO(4)$ )

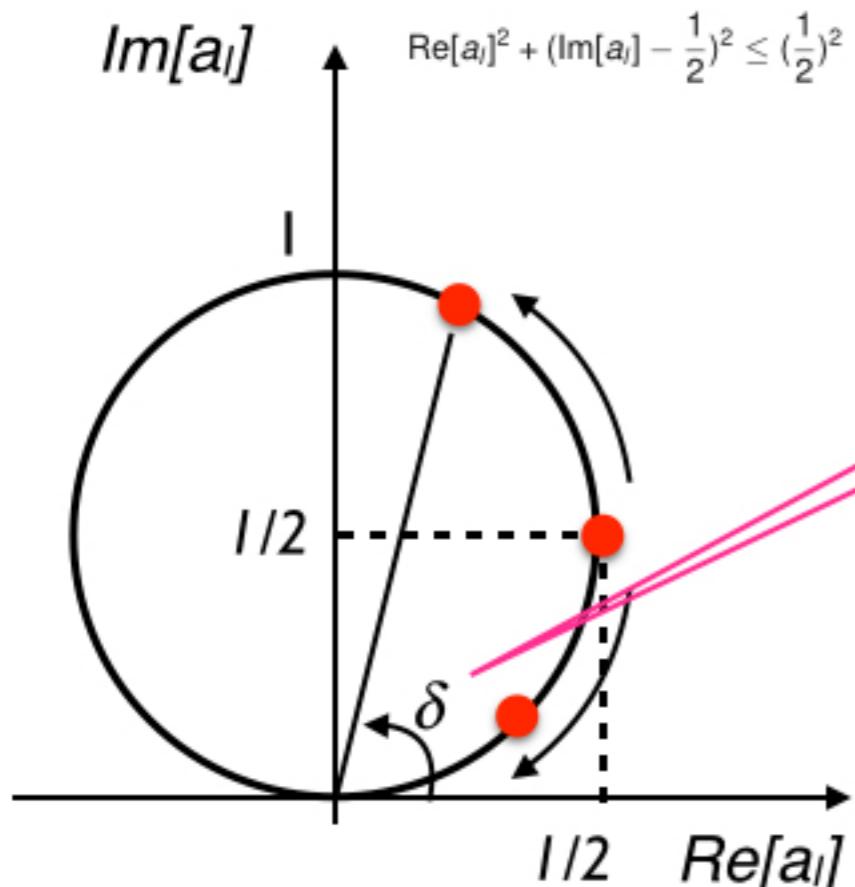
$$= g_{hVV}^{\text{SM}} \sqrt{1 - \xi}$$

- Due to the deviation of h-V-V coupling, perturbative unitarity is violated in high energy scales.

$$a_0 \simeq \frac{G_F \xi}{16\sqrt{2}\pi} S$$

- New resonances would appear below the unitarity violation scales, and (partly) cure the unitarity of the amplitude.

= New resonances keep the amplitude within the unitarity circle.

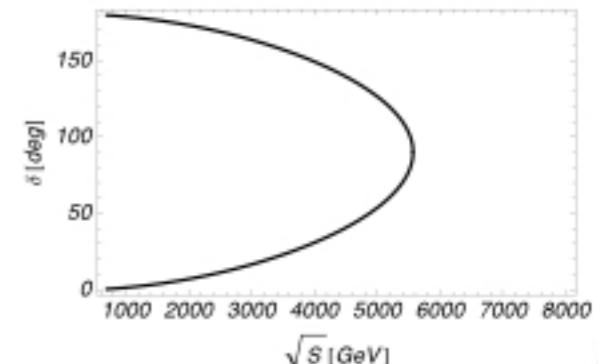


$$\delta = \tan^{-1} (\text{Im}[a_I]/\text{Re}[a_I])$$

> We consider s-wave elastic scattering case.  
(on the unitarity circle)

$$\delta = \tan^{-1} \left[ 1/(2\text{Re}[a_0]) \pm \sqrt{1/(4\text{Re}[a_0]^2) - 1} \right]$$

$$= \delta(\xi, S)$$

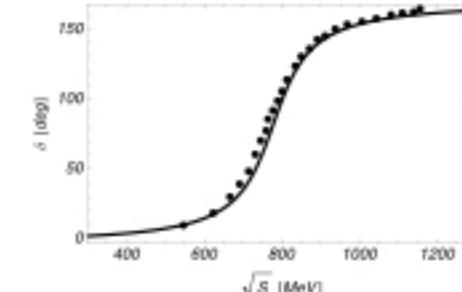


- In the  $\pi$ - $\pi$  scattering, phase shift has been experimentally observed.
- The data can be fitted by

$$\delta = \begin{cases} \tan^{-1} \left[ (\Gamma_\rho/m_\rho)S/(m_\rho^2 + \Gamma_\rho^2 - S) \right] & \text{for } S < m_\rho^2 + \Gamma_\rho^2 \\ \tan^{-1} \left[ (\Gamma_\rho/m_\rho)S/(m_\rho^2 + \Gamma_\rho^2 - S) \right] + \pi & \text{for } S \geq m_\rho^2 + \Gamma_\rho^2 \end{cases}$$

$$= \delta(m_\rho, \Gamma_\rho, S)$$

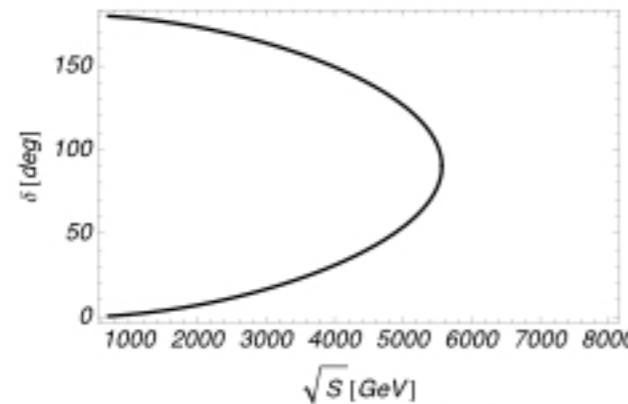
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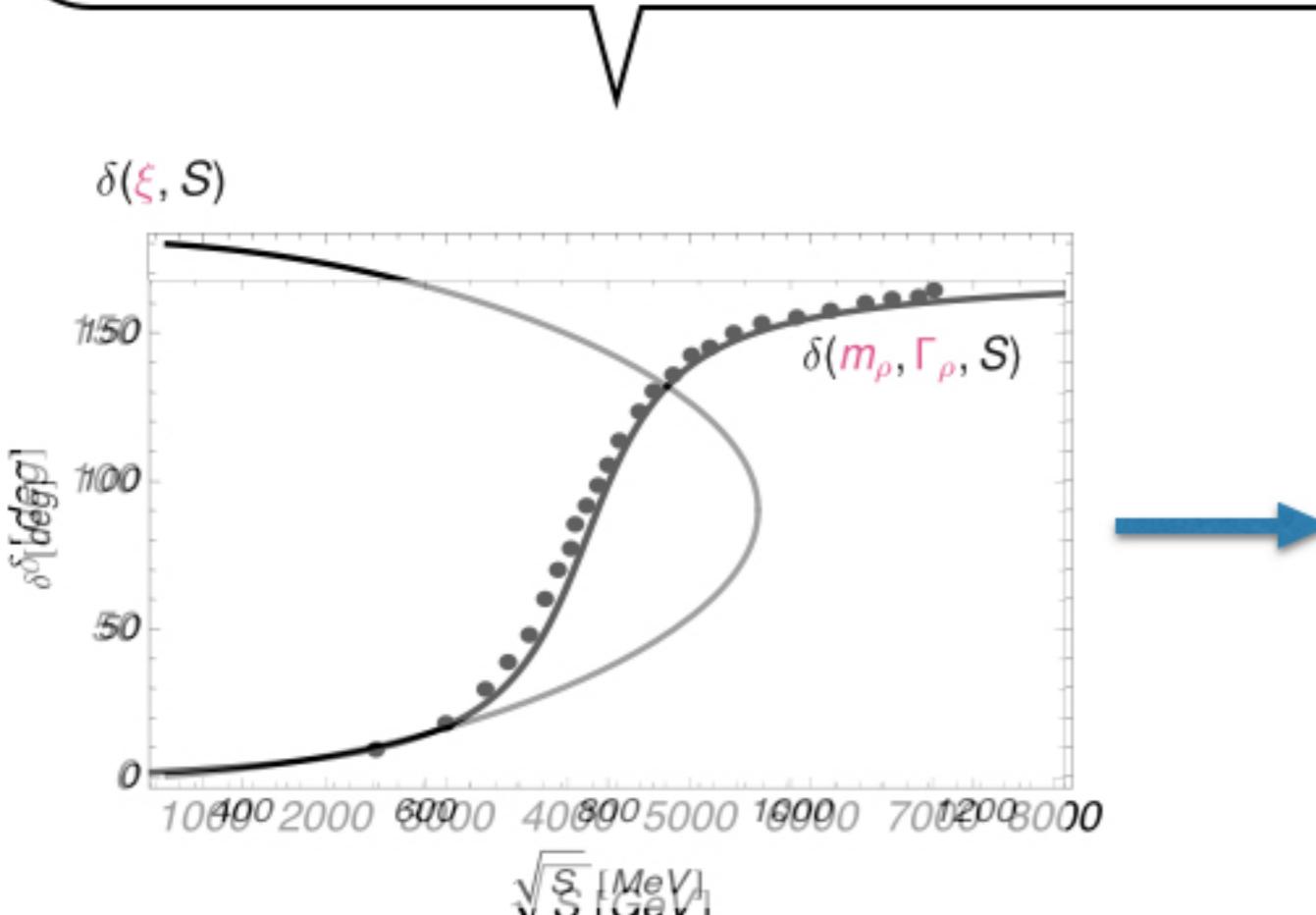
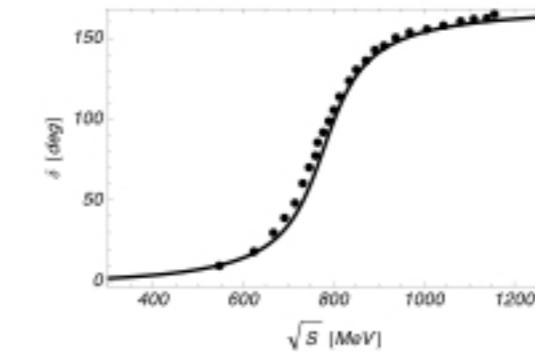
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**Ansatz**

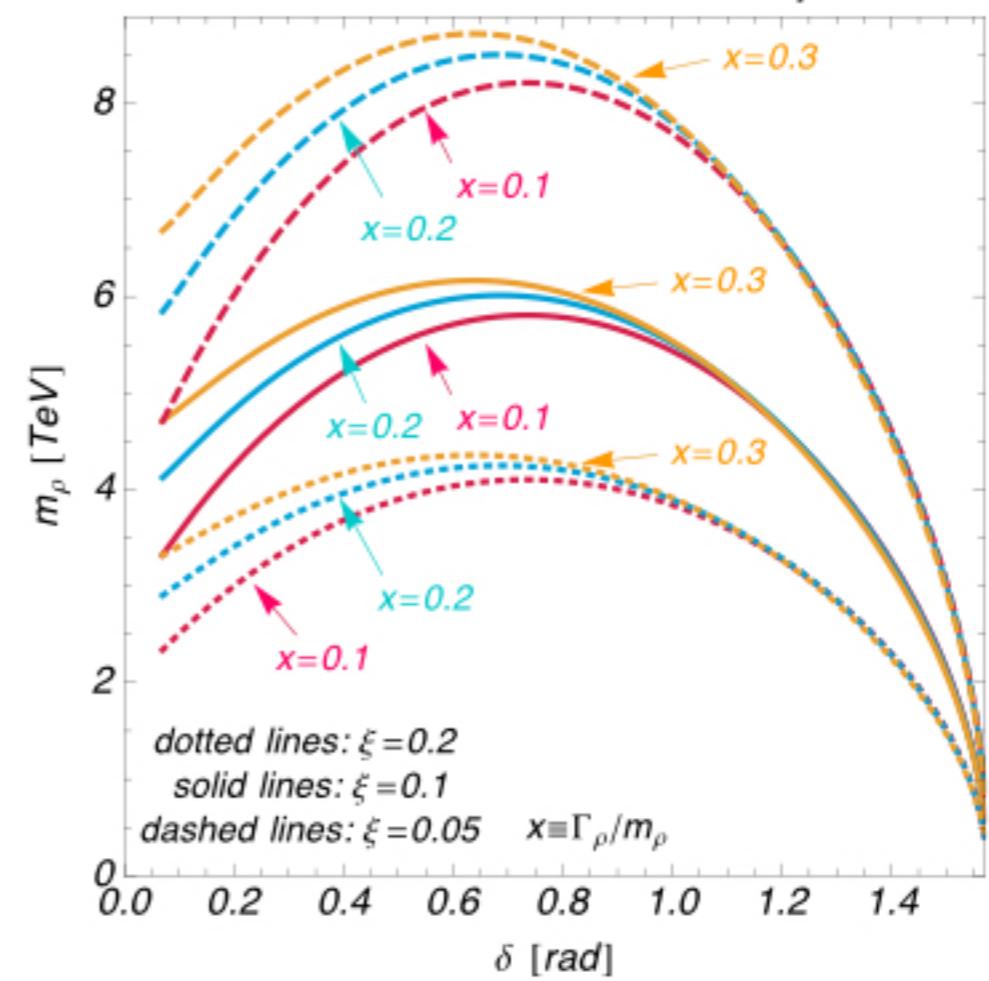
$$\delta = \tan^{-1} \left[ 1/(2\text{Re}[a_0]) \pm \sqrt{1/(4\text{Re}[a_0]^2) - 1} \right] = \delta(\xi, S)$$



$$\delta = \begin{cases} \tan^{-1} \left[ (\Gamma_\rho/m_\rho)S/(m_\rho^2 + \Gamma_\rho^2 - S) \right] & \text{for } S < m_\rho^2 + \Gamma_\rho^2 \\ \tan^{-1} \left[ (\Gamma_\rho/m_\rho)S/(m_\rho^2 + \Gamma_\rho^2 - S) \right] + \pi & \text{for } S \geq m_\rho^2 + \Gamma_\rho^2 \end{cases} = \delta(m_\rho, \Gamma_\rho, S)$$



**relation between  $\delta$  and  $m_\rho$**



**" $\delta$ " has important information about the resonance scales!**

### ***3. Fingerprinting of minimal composite Higgs models***

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➤ Since MCHMs have many varieties according to Yukawa interactions, we need to discriminate them.

MCHM<sub>Q-U-D</sub>

$$\kappa_i \equiv g_i/g_i^{\text{SM}}$$

Label	Model	$\kappa_V$	$c_{hhVV}$	$\kappa_{hhh}$	$c_{hhhh}$	$\kappa_t$	$\kappa_b$	$c_{hhtt}$	$c_{hhbb}$
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### 3. Fingerprinting of minimal composite Higgs models

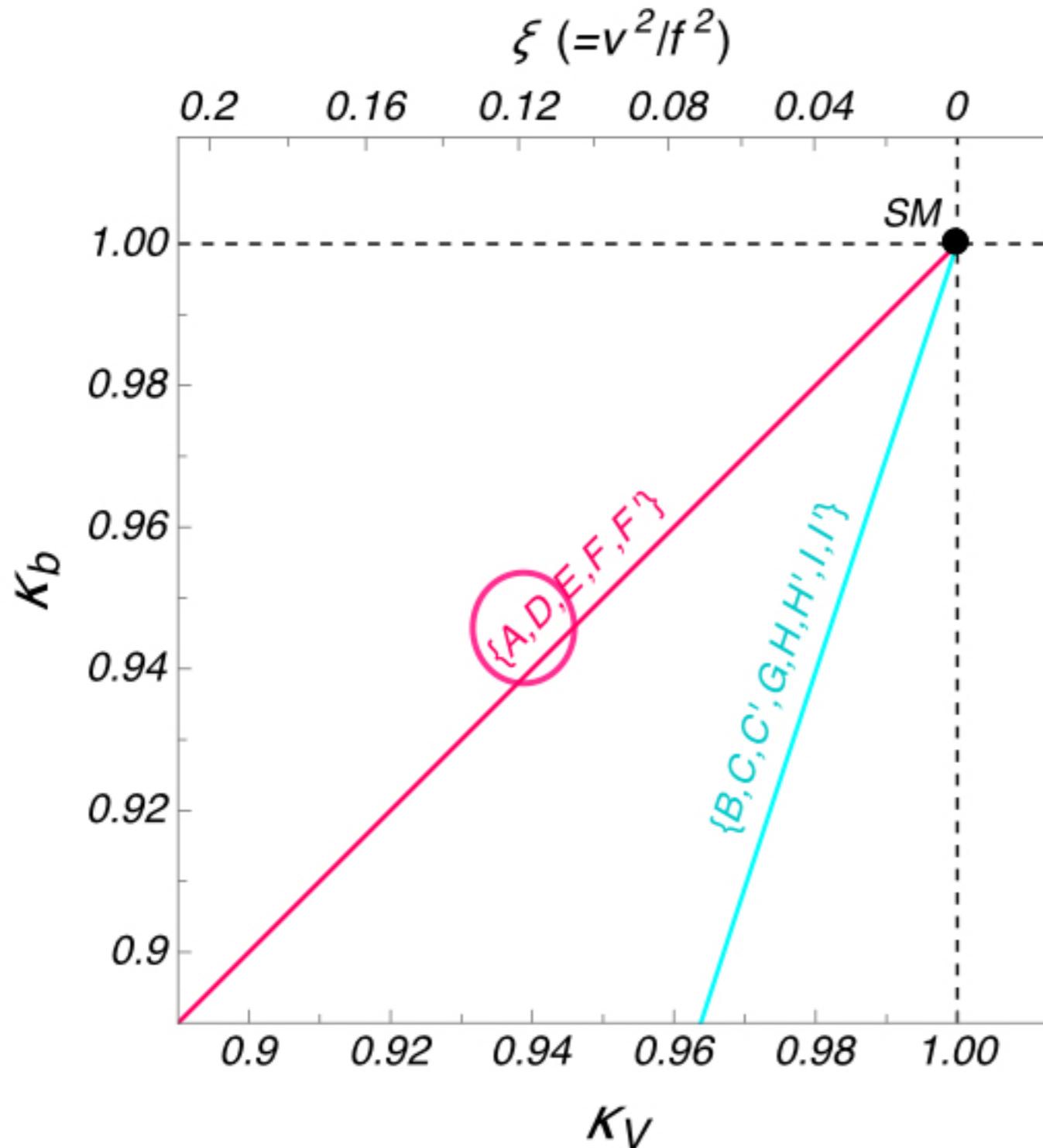
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H, H'	MCHM <sub>14-5-10</sub>	$\sqrt{1-\xi}$	$1-2\xi$	$H_1$	$H_2$	$F_4$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$F_7$	$-4\xi$
B	MCHM <sub>14-10-10</sub>	$\sqrt{1-\xi}$	$1-2\xi$	$H_1$	$H_2$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$-4\xi$	$-4\xi$
I, I'	MCHM <sub>14-14-10</sub>	$\sqrt{1-\xi}$	$1-2\xi$	$H_1$	$H_2$	$F_3$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$F_6$	$-4\xi$

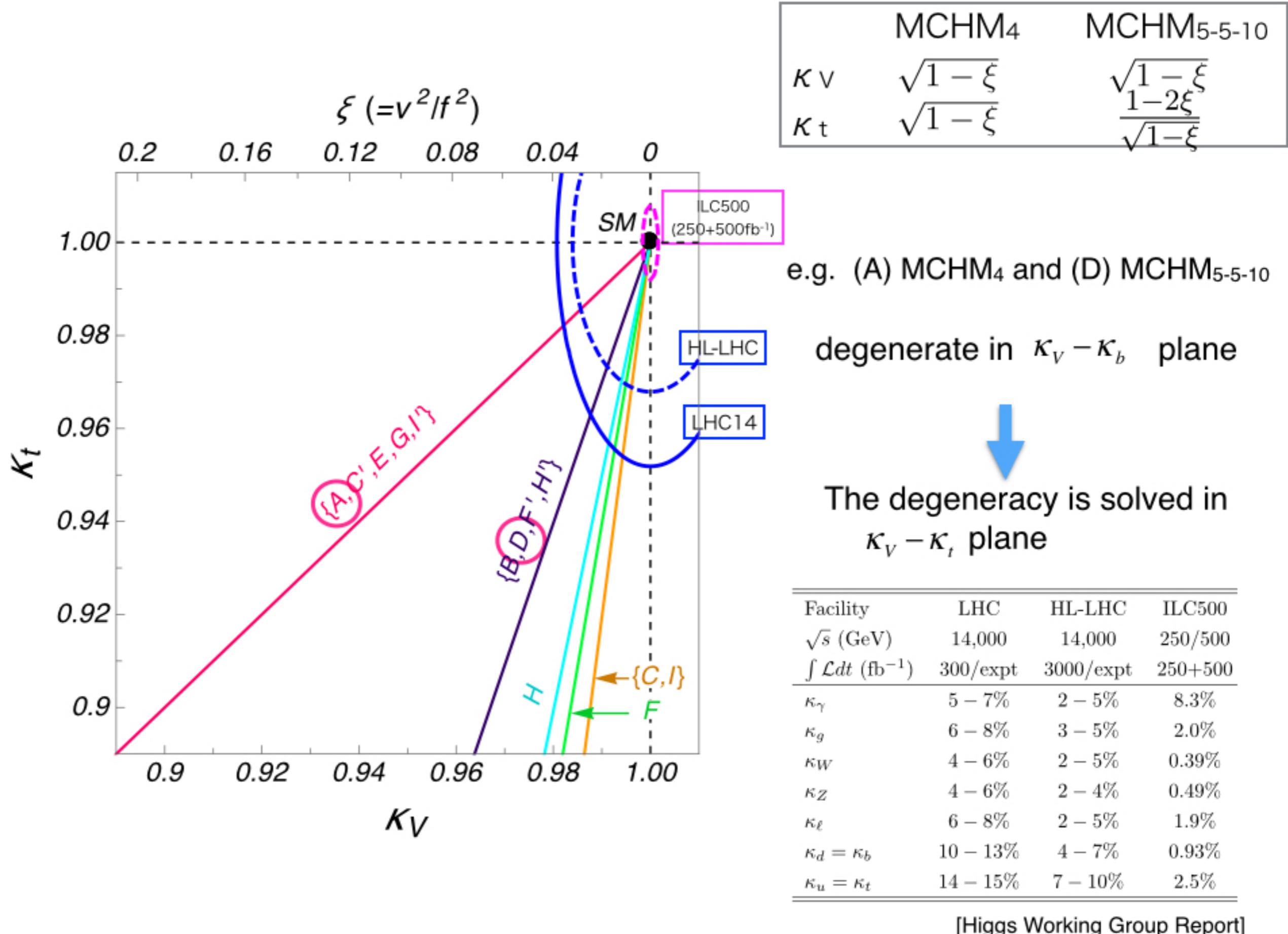


	MCHM <sub>4</sub>	MCHM <sub>5-5-10</sub>
$\kappa_V$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$\kappa_b$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$

e.g. (A) MCHM<sub>4</sub> and (D) MCHM<sub>5-5-10</sub>

degenerate in  $\kappa_V - \kappa_b$  plane

Facility	LHC	HL-LHC	ILC500
$\sqrt{s}$ (GeV)	14,000	14,000	250/500
$\int \mathcal{L} dt$ (fb $^{-1}$ )	300/expt	3000/expt	250+500
$\kappa_\gamma$	5 – 7%	2 – 5%	8.3%
$\kappa_g$	6 – 8%	3 – 5%	2.0%
$\kappa_W$	4 – 6%	2 – 5%	0.39%
$\kappa_Z$	4 – 6%	2 – 4%	0.49%
$\kappa_\ell$	6 – 8%	2 – 5%	1.9%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%



# ***Summary***

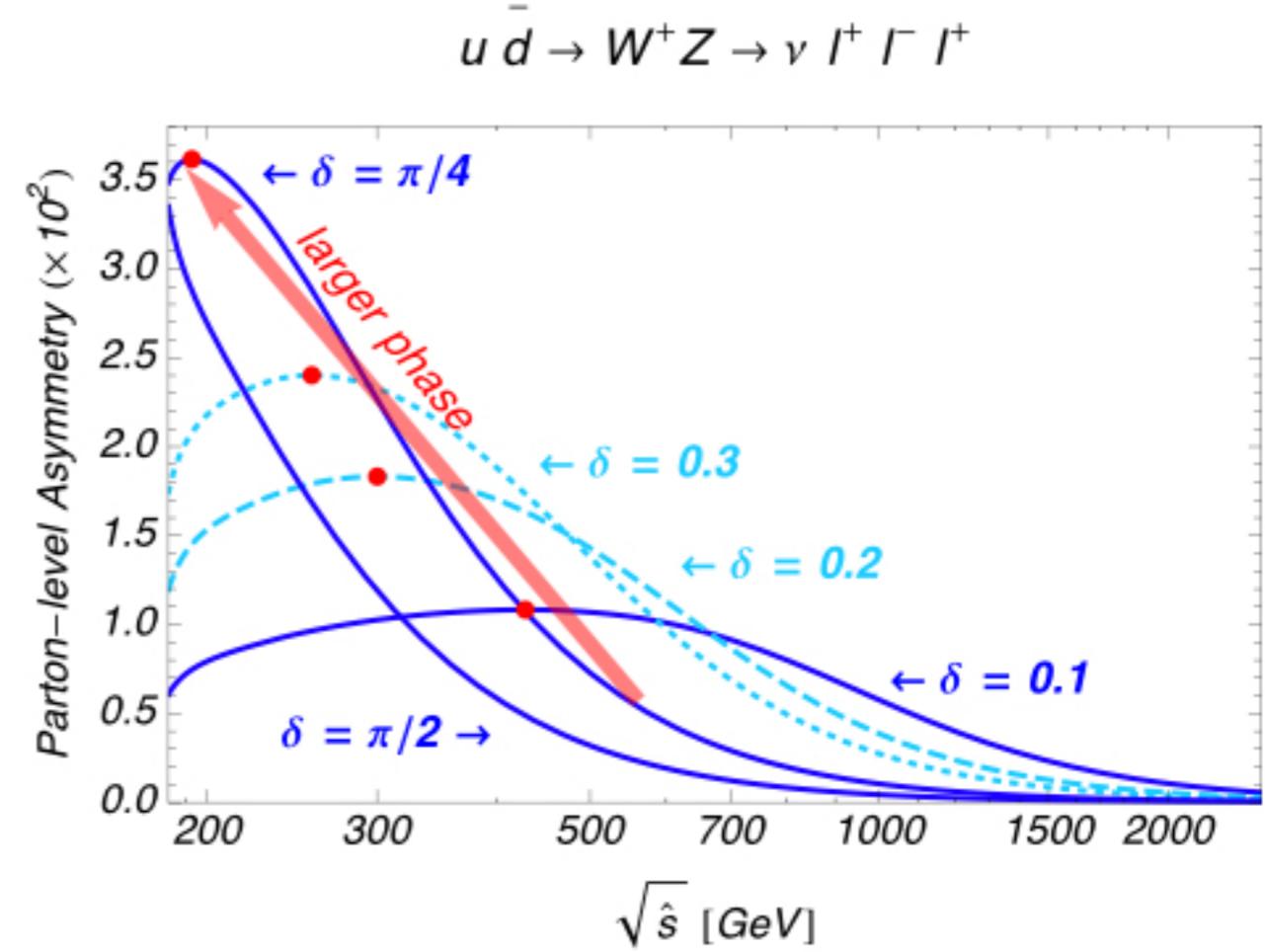
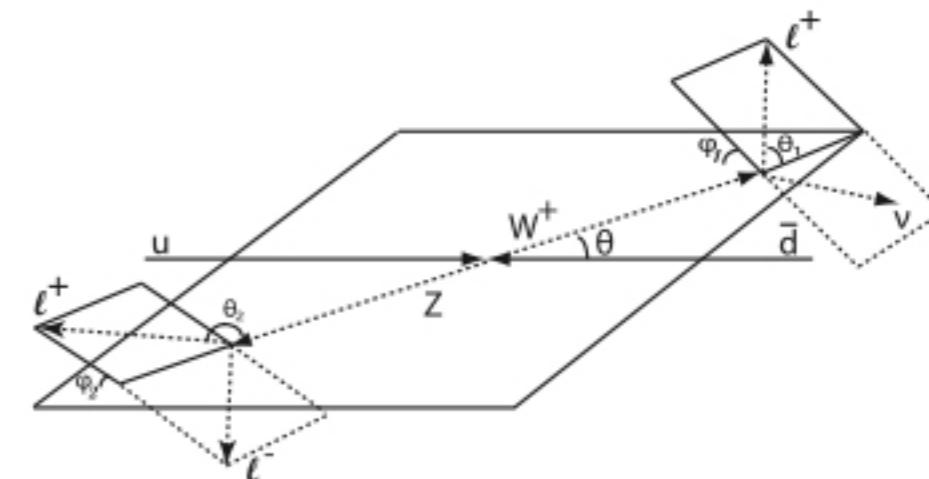
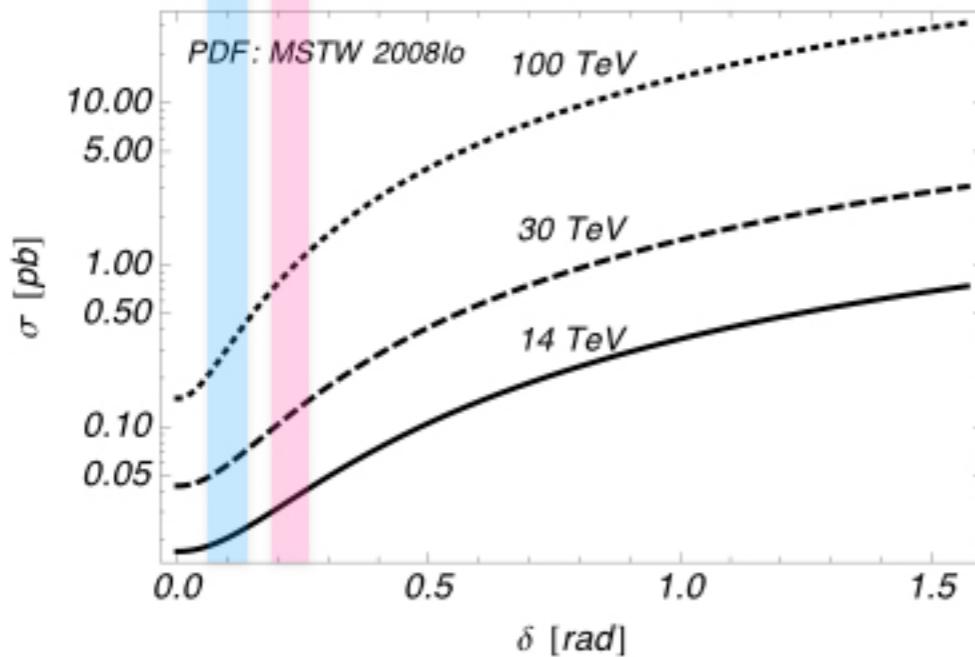
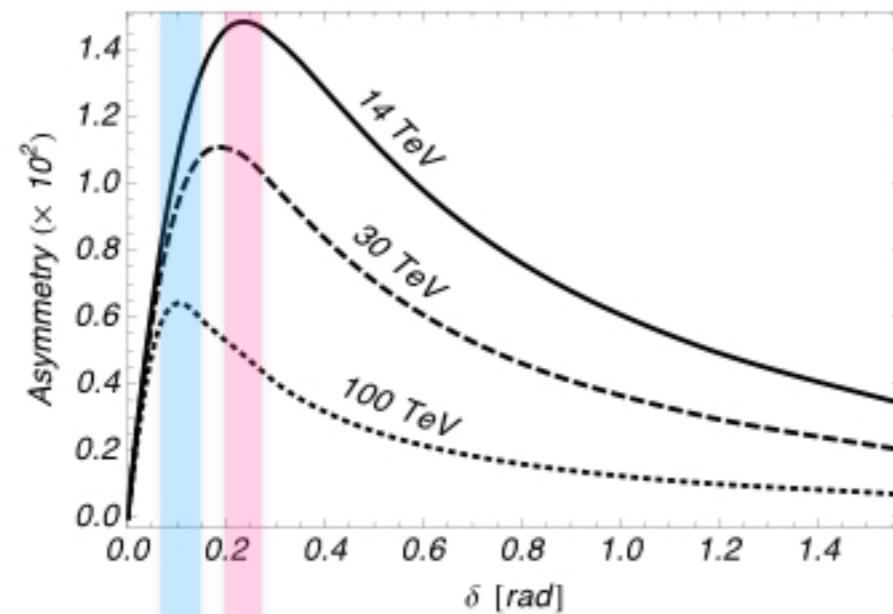
- Composite Higgs scenario is one of new paradigms to explain why Higgs boson mass is around 125 GeV.
- Analogy with pion physics in QCD may help us to search new resonance scales above the EW scale.
- Phase shifts in weak gauge boson scatterings can be a clue to new resonances.
- We have also discussed the relation between “ $\xi$ ” and “ $\delta$ ” by setting an ansatz between unitarity violation and the phase shift of pi-pi scattering amplitude.
- ***Phase shift measurement can be an important method to search new resonance scales at LHC and the ILC.***
- ***Some of MCHMs could be discriminated by the ILC.***

## Backup

\*  $\delta$  measurement at LHC

$$pp \rightarrow W^+ Z \rightarrow l^+ \nu l^+ l^-$$

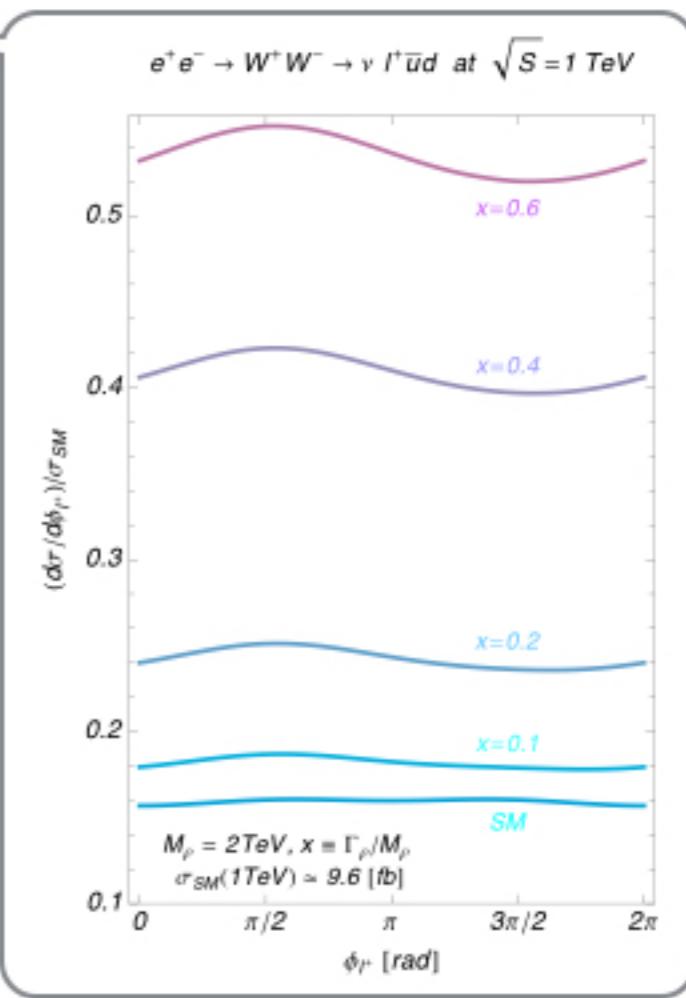
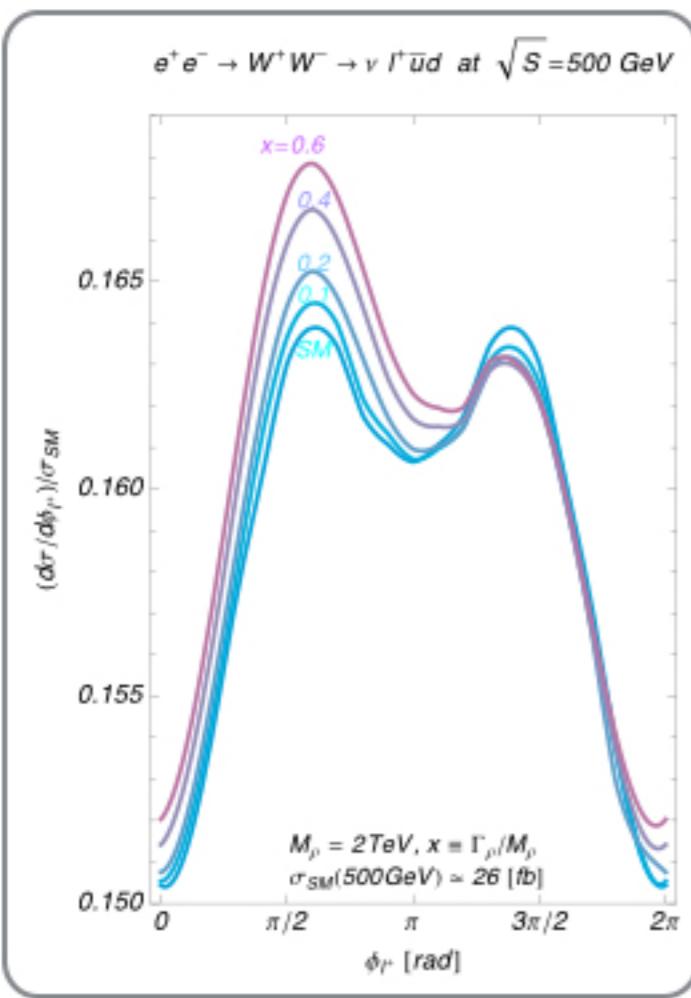
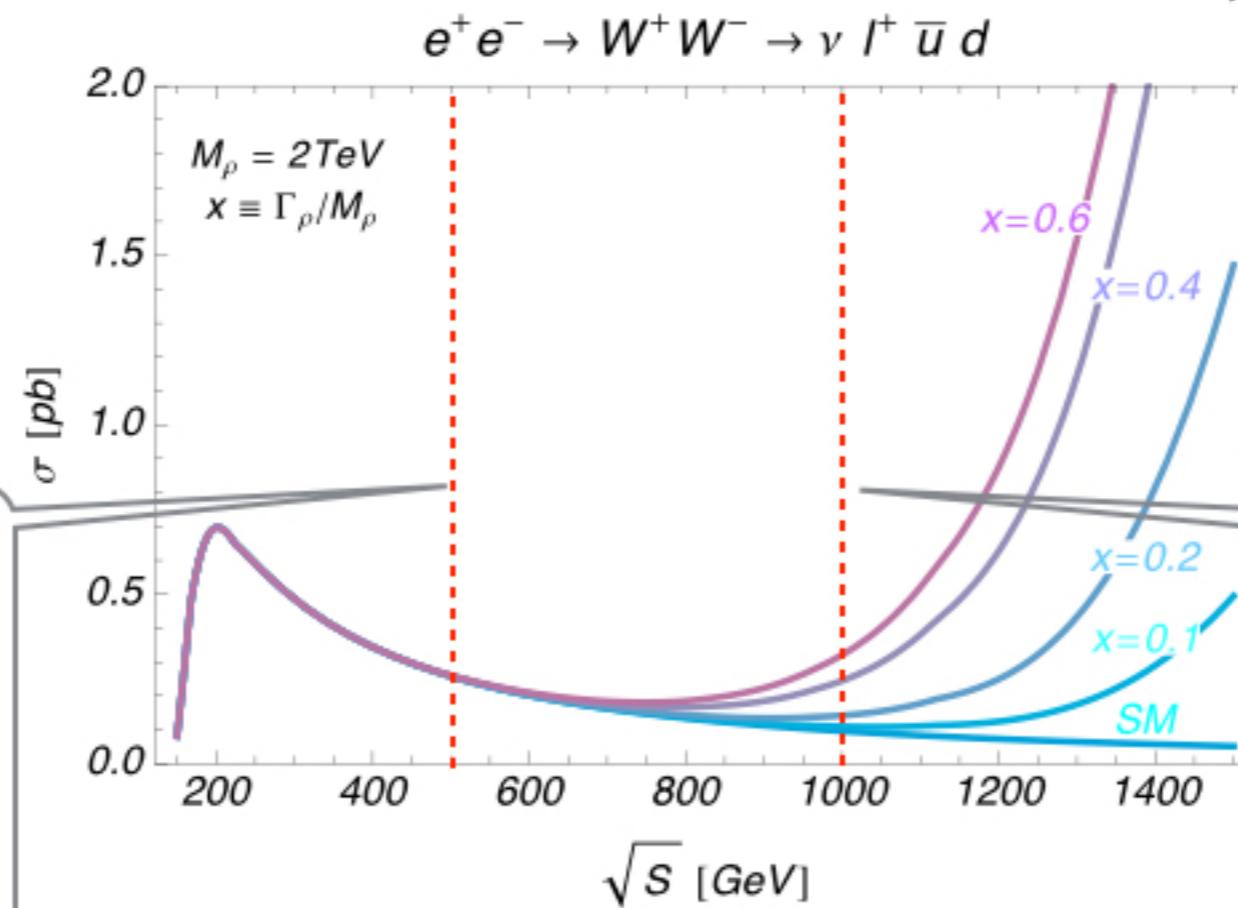
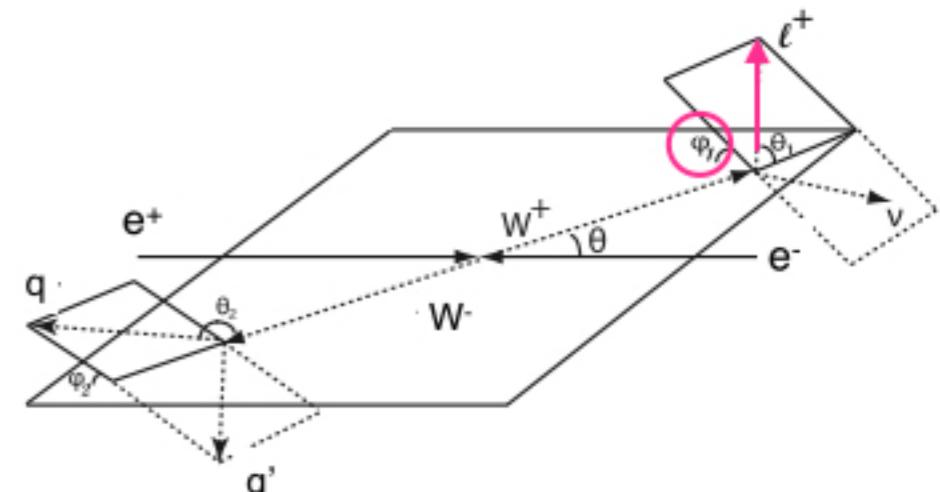
$$A_{\pm} \equiv \frac{|\sigma_+ - \sigma_-|}{\sigma_+ + \sigma_-}, \quad \sigma_{\pm} \equiv \sigma(\sin \phi_1 \gtrless 0)$$



## Backup

\*  $\delta$  measurement at the ILC

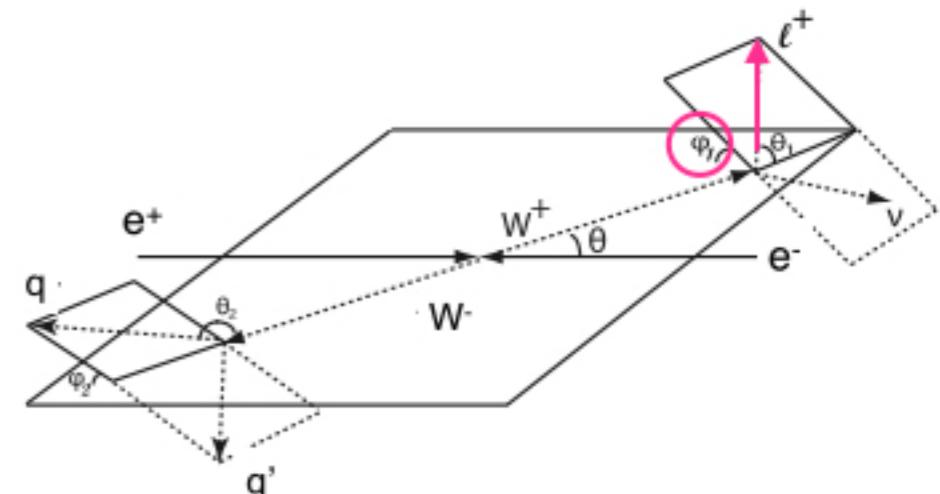
$$e^+ e^- \rightarrow W^+ W^- \rightarrow l \nu q \bar{q}'$$



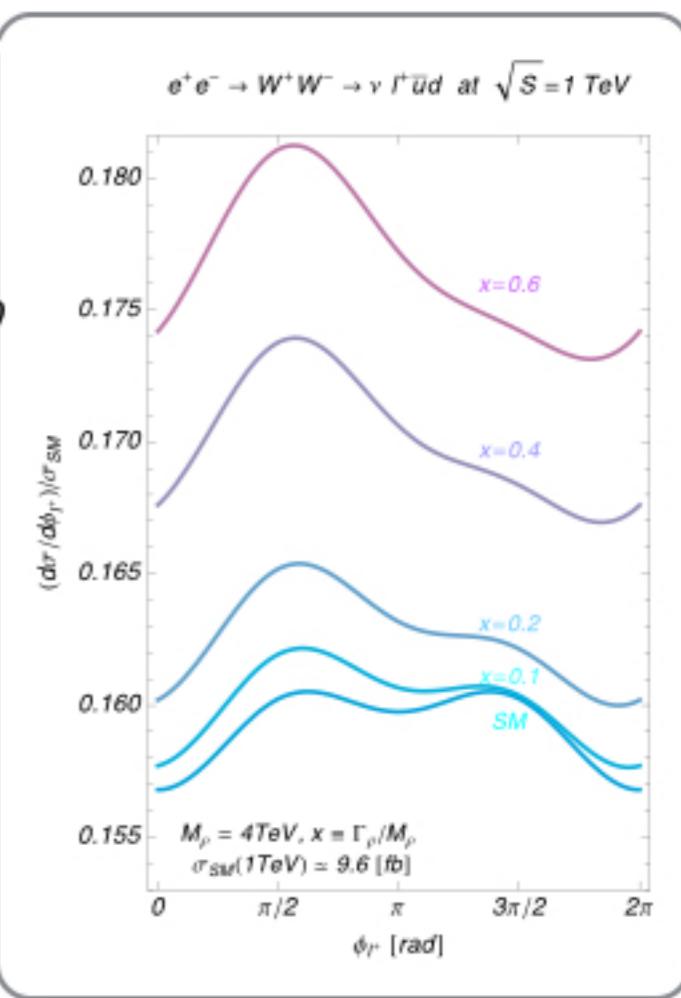
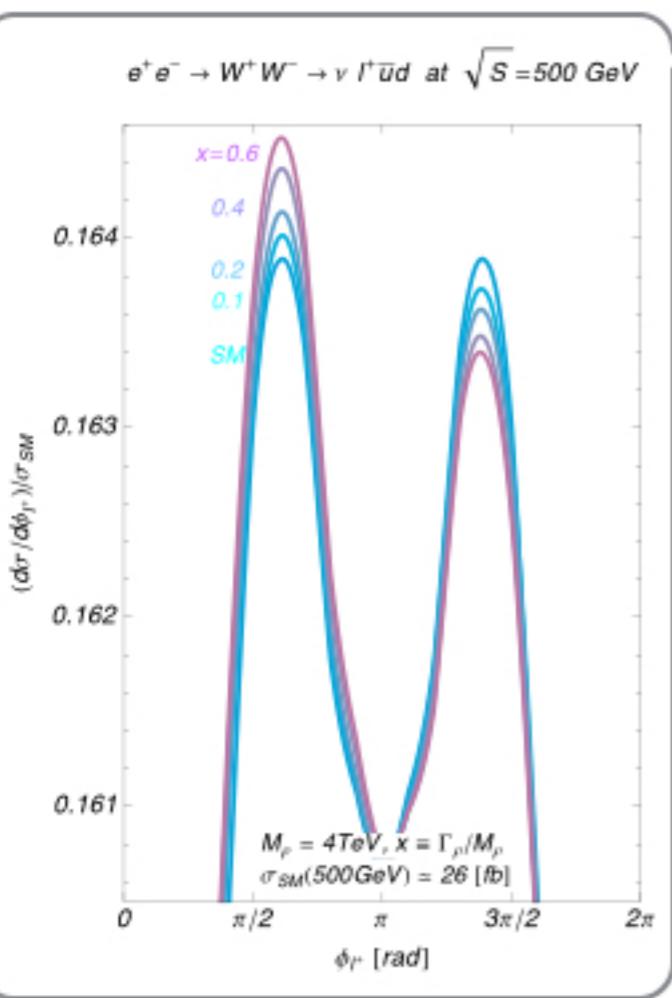
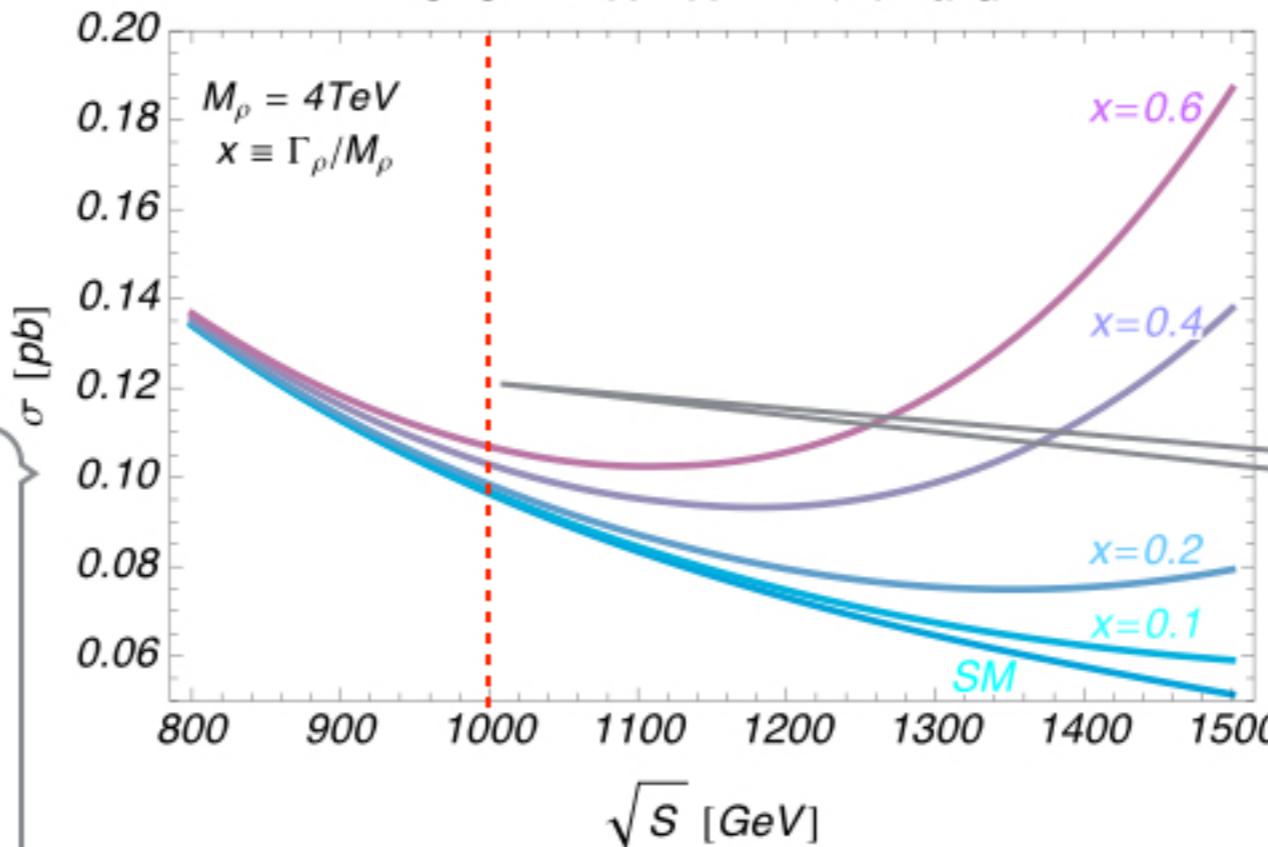
## Backup

\*  $\delta$  measurement at the ILC

$$e^+ e^- \rightarrow W^+ W^- \rightarrow l \nu q \bar{q}'$$



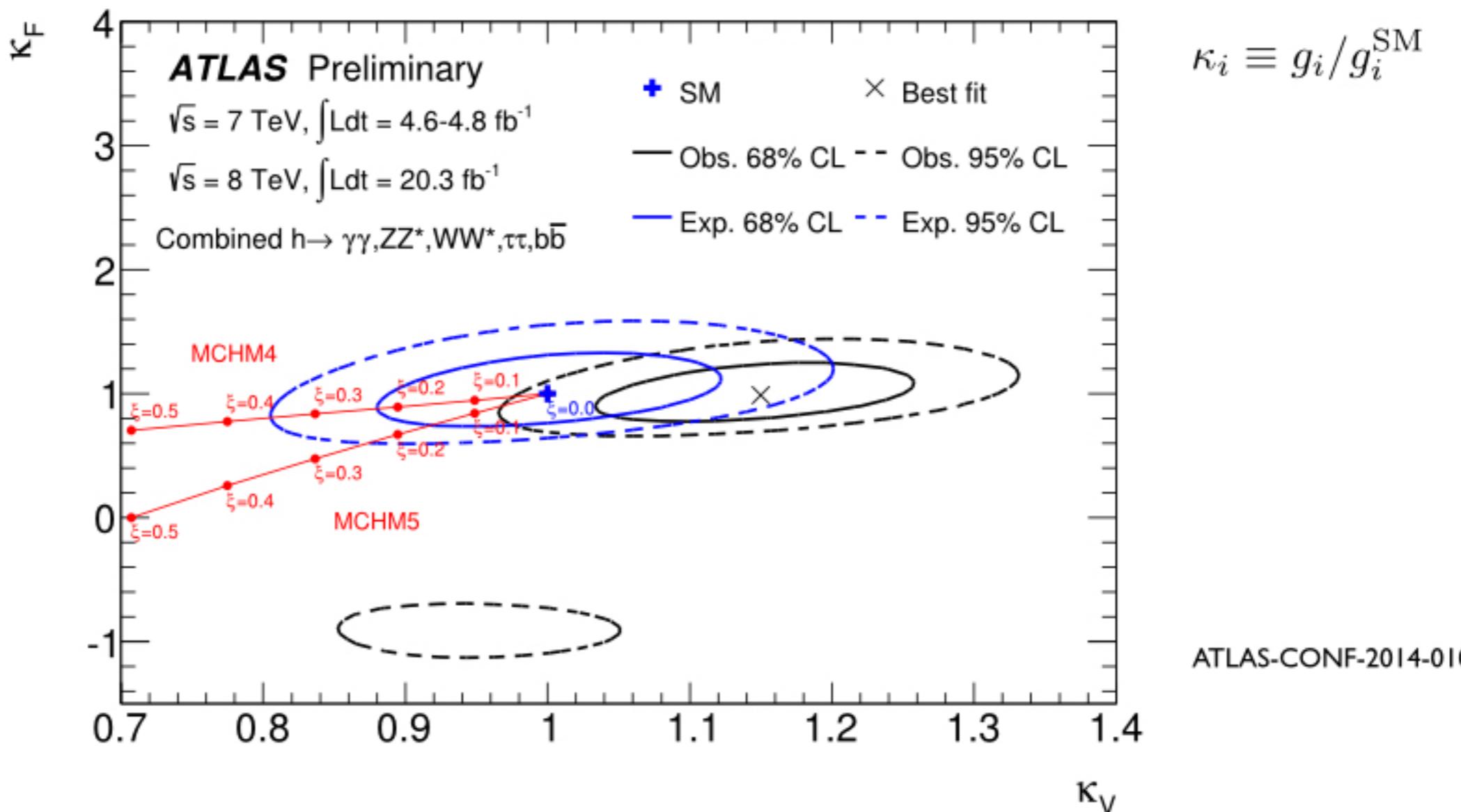
$$e^+ e^- \rightarrow W^+ W^- \rightarrow \nu l^+ \bar{u} d$$



## Backup

- \* examples; MCHM<sub>4</sub>, MCHM<sub>5</sub>

	MCHM <sub>4</sub>	MCHM <sub>5</sub>
$K_V$	$\sqrt{1 - \xi}$	$\sqrt{1 - \xi}$
$K_F$	$\sqrt{1 - \xi}$	$\frac{\sqrt{1 - \xi}}{1 - 2\xi}$



- \*  $\xi < O(0.1)$  is preferred.