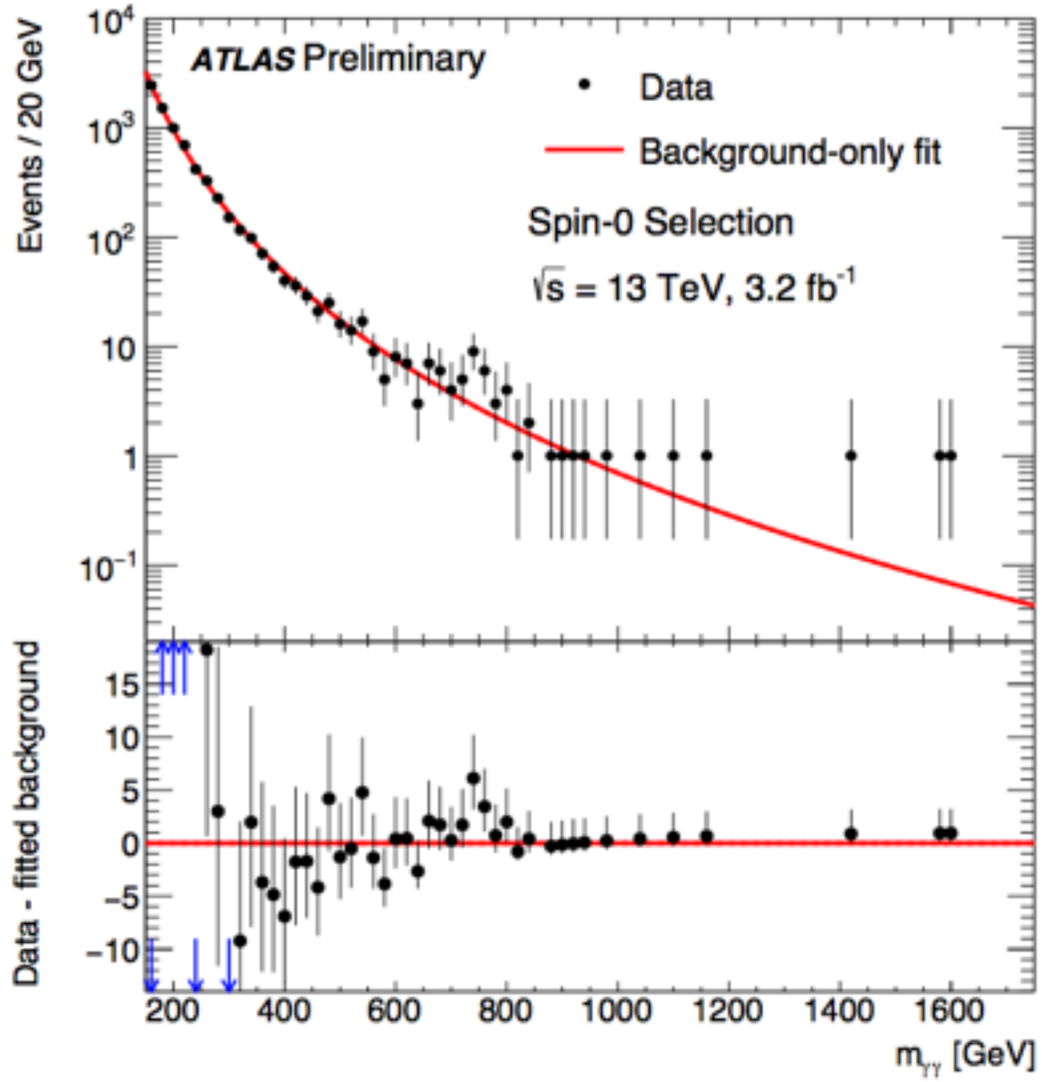
Implications of the 750 GeV Resonance for the ILC

Keisuke Fujii (KEK)
on behalf of the LCC physics WG

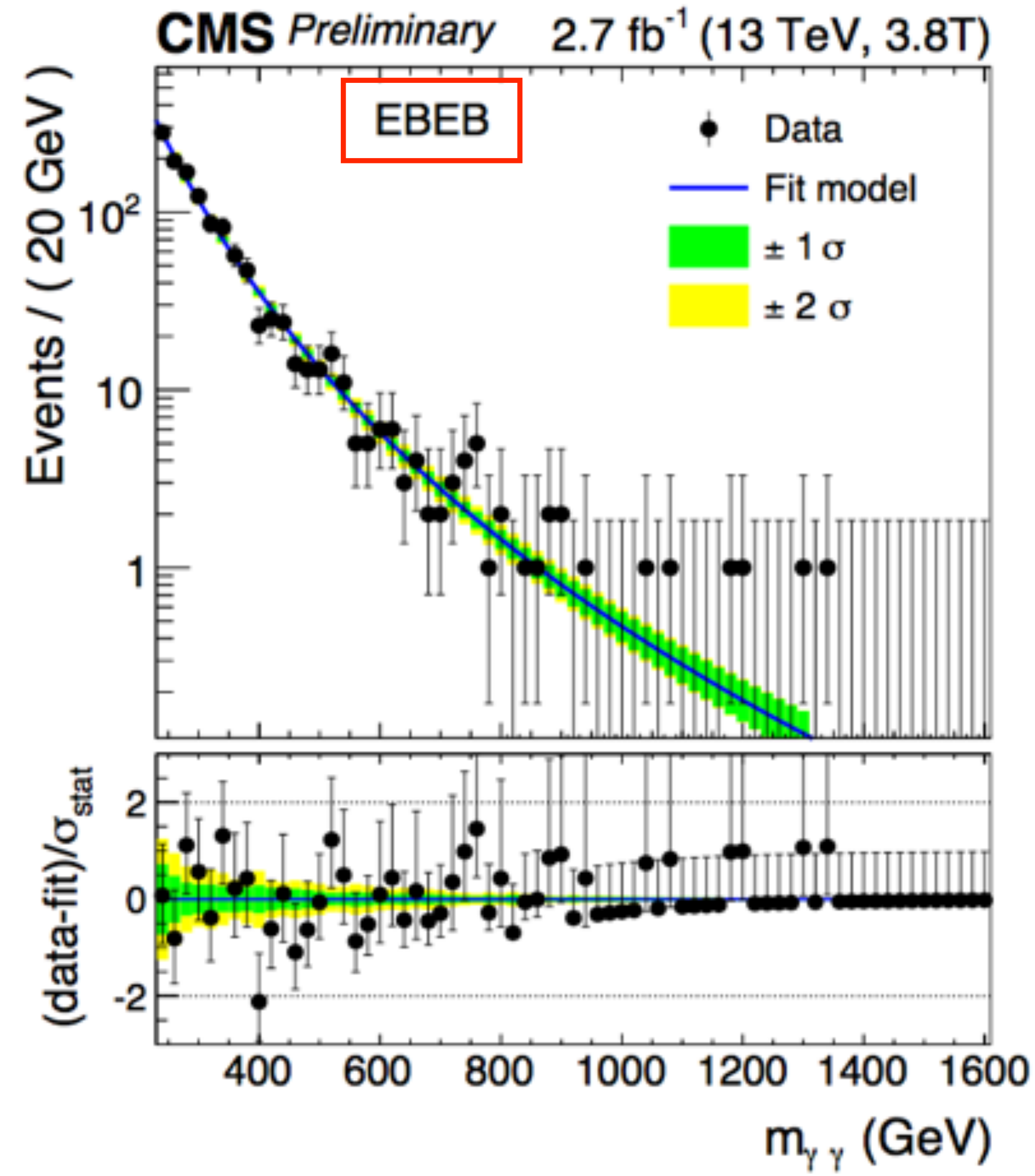
ECFA LCWS 2016, Jun.3, 2016

What ATLAS and CMS have seen

ATLAS-CONF-2016-018



CMS PAS EXO-16-018



J=0 hypothesis

With B=0 data and 8TeV data

Local significance : 3.9σ

global significance : 2σ

Local significance : 3.4σ

global significance : 1.6σ

consistent within 1.2σ with 8TeV data

Our Attitudes towards X750

1. It's too early to get excited,
2. but if it is real, it is ***a good example of case 3*** in the ICFA letter to MEXT's ILC Advisory Panel:
   case 3: LHC discovers relatively heavy new particles *(which cannot be directly produced at the 500 GeV ILC)*
3. Since the MEXT Panel recommended to ***closely monitor, analyze, and examine the development of LHC experiments***, this is ***a good opportunity to do exercise for case 3***. → motivation for this note
4. In LCC's letter to the panel, it is stated that "***While performing precision studies of the Higgs boson and the top quark, we will prepare for the energy upgrade of the ILC*** *taking advantage of energy expandability enabled by its linear shape."*
5. *The note is intended to show*
   1. ***The 500 GeV ILC has a lot to say about X750*** ***through precision measurements*** *plus* ***possible discovery of NPs associated with X750***. → this talk
   2. ***Possible energy upgrade with PLC option will open up even greater opportunities*** ***to uncover the new physics operating behind X750 together with LHC***. → *next talk by Francois Richard*

Preview

Implications of the 750 GeV Resonance for the International Linear Collider

LCC Physics Working Group

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ABSTRACT

If the $\gamma\gamma$ resonance at 750 GeV suggested by 2015 LHC data turns out to be a real effect, what are the implications for the physics case and upgrade path of the International Linear Collider? In this note, we answer this question, with two points: (1) All models proposed for the new 750 GeV particle require additional new particles with electroweak couplings. The key elements of the 500 GeV ILC physics program—precision measurements of the Higgs boson, the top quark, and 4-fermon interactions—will powerfully discriminate among these models. This information will be important in conjunction with new LHC data, or alone, if the new particles accompanying the 750 GeV resonance are beyond the mass reach of the LHC. (2) Over a longer term, the energy upgrade of the ILC to 1 TeV already discussed in the ILC TDR will enable experiments in $\gamma\gamma$ and e^+e^- collisions to directly produce and study the 750 GeV particle.

In this note X750 is called Φ

Questions addressed in the note

1. If Φ (=X750) is real, what would the implications be for the program of the ILC?
2. Will the ILC be able to shed light on this resonance or on accompanying new physics?

Caution

*It might turn out that **the Φ is a relatively minor player** in a new sector of physics that the LHC will begin to uncover in the next few years*.

For this reason, ***it is premature to discuss a new accelerator intended specifically to target the Φ*** or any other new particle that turns up in the early 13 TeV LHC data.

The Powerful Tools

The precision measurement of the couplings of the ***Higgs*** boson and the electroweak couplings of the ***top*** quark and the measurement of possible ***4-fermion*** contact interactions.

These three tools would allow ***the first discovery of physics beyond the Standard Model, if that discovery has not already been made at the LHC***.

But also, in the case that the LHC does discover new particles, these tools have ***the ability to discriminate possible explanations*** and ***to show the presence of further states beyond the reach of the LHC.***

Properties of X750 (hereafter called Φ)

$\Phi \rightarrow \gamma\gamma$ means ***Φ = color singlet*** with ***J ≠ 1***

we assume J = 0

Different models will require it to be a scalar, a pseudo-scalar, or a spin-2 state; we leave this choice open.
It has also been proposed that the Φ enhancement is a kinematic endpoint in the decay of 2 a particle with mass above 1.5 TeV. We will not discuss that option here.

Φ is seen at 13 TeV but is much less apparent at 8 TeV

	gg	$b\bar{b}$	$d\bar{d}$	$u\bar{u}$	$\gamma\gamma$
$r_{p\bar{p}}$	4.8	5.7	2.7	2.6	1.9

Assume production via gg:

$$\sigma(pp \to \Phi \to \gamma\gamma) = 5 \text{ fb} .$$

Cross section

$$\sigma(pp \to \Phi \to \gamma\gamma) = 5 \text{ fb} .$$

Assume production via gg

$$\sigma(gg \to \Phi \to \gamma\gamma) = \frac{\pi^2}{8} \frac{\Gamma(\Phi \to gg)}{m_\Phi} \delta(\hat{s} - m_\Phi^2) \cdot \frac{\Gamma(\Phi \to \gamma\gamma)}{\Gamma(\Phi)}$$

to be integrated over parton distributions. Higher order effects lead to a K-factor for production of 2.8, of which 2.0 is the QCD correction to $\Gamma(\Phi \to gg)$.

$$\sigma = 5 \text{ fb} \quad \Longrightarrow \quad \frac{\Gamma(\Phi \to gg)\Gamma(\Phi \to \gamma\gamma)}{\Gamma(\Phi)} = 0.5 \text{ MeV}$$

$$\Longrightarrow \quad \Gamma(\Phi \to \gamma\gamma) \geq 0.5 \text{ MeV}$$

Effective Lagrangian

Underlying BSM physics must respect SU(3) x SU(2) x U(1)

→ γ must be a mixture of neutral SU(2) and U(1) gauge bosons

$$\boxed{\mathcal{L} = \frac{\alpha_s}{4} A_3 \, \Phi \, G_{\mu\nu} G^{\mu\nu} + \frac{\alpha_w}{4} A_2 \, \Phi \, W_{\mu\nu} W^{\mu\nu} + \frac{\alpha'}{4} A_1 \, \Phi \, B_{\mu\nu} B^{\mu\nu}}$$

For H(125), $A_3 = \frac{1}{3\pi v}$

$$\Gamma(\Phi \to \gamma\gamma) = \frac{\alpha^2}{64\pi} (A_2 + A_1)^2 m_\Phi^3$$

$$\Gamma(\Phi \to \gamma\gamma) \geq 0.5 \text{ MeV} \rightarrow (A_2 + A_1) = 1/(500 \text{ GeV})$$

$$\rightarrow V \approx 250 \text{ GeV}$$

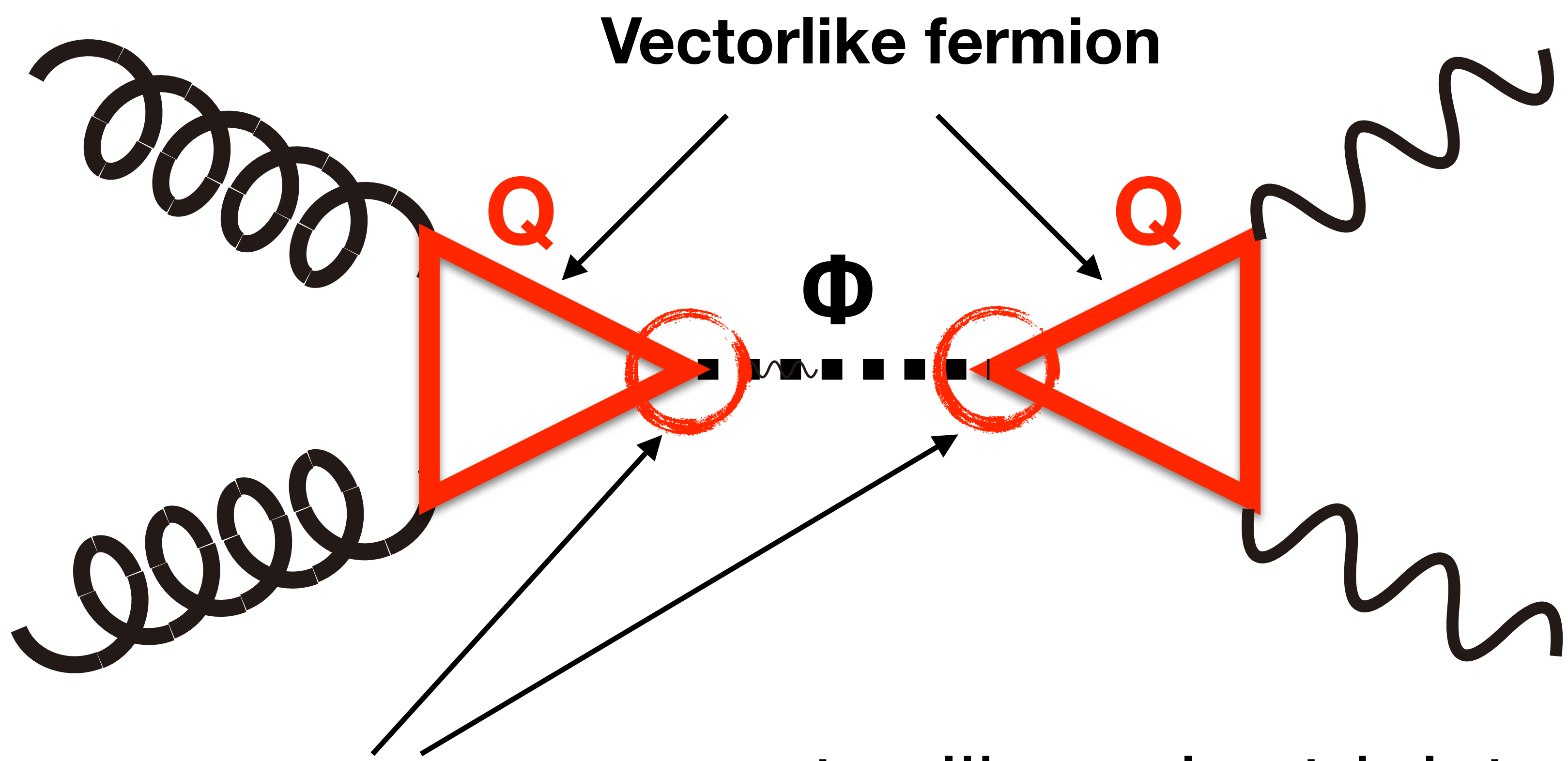
The physics that generates Φ and its counterpart states should be within the reach of the LHC. ***The very fact that the presence of the Φ implies new physics near the TeV scale is a plus for the ILC.***

→ precision measurements

Models

Φ = ***SM singlet*** coupling to ***vectorlike quarks and leptons***

Vectorlike quarks for both production and decay



$$\mathcal{L} \subset (m_\Psi + y\Phi)\overline{Q}Q$$

vector-like color-triplet quark: (I,Y)=(0,2/3)

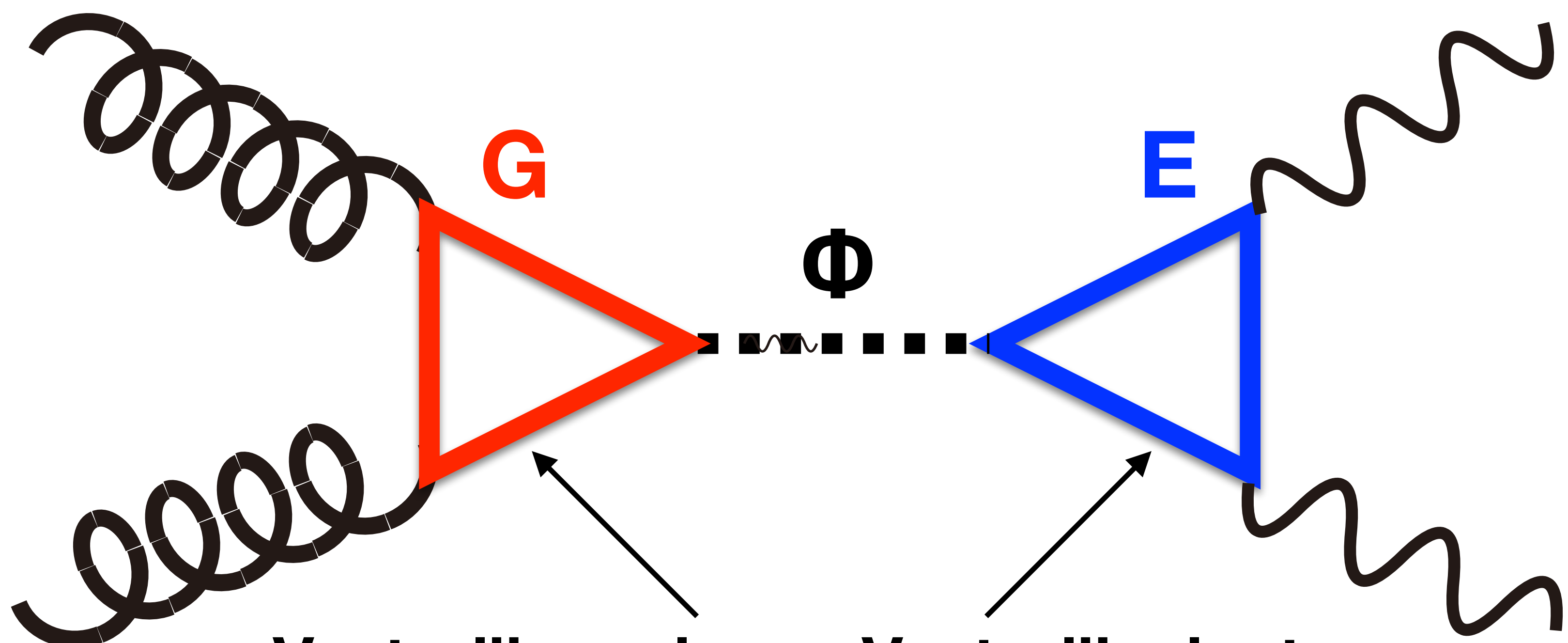
$$A_1 = \frac{8}{9}\frac{y}{\pi m_Q}\,, \quad A_2 = 0\,, \quad A_3 = \frac{1}{3}\frac{y}{\pi m_Q}$$

$m_Q/y \sim 700$GeV   y~1 → Q should have been discovered.

1 < y < 3   y~3 → non-perturbative

Except at y~3, Q will be discovered soon at LHC.

Vectorlike quarks for production and vectorlike leptons for decay



Vectorlike color-octet quark

(I,Y)=(0,0)

Vectorlike lepton

(I,Y)=(0,1)

$$A_1 = \frac{2}{3}\frac{y}{\pi m_E}\,, \quad A_2 = 0\,, \quad A_3 = 2\frac{y}{\pi m_G}$$

$m_E < 500$ GeV

Easy to have $m_G > 3$TeV

G and E are probably beyond the reach of LHC.

Φ mixing with H125 (=h)

To avoid large mixing with H125, we need Z_2 under which Φ is odd and H is even. But the Yukawa coupling:

$$\mathcal{L} \subset \ (m_\Psi + y\Phi)\overline{Q}Q$$

breaks Z_2. → ***shifts in H→γγ/gg couplings by 1 - 10%***

The extra scalar boson may induce a strongly 1st-order electroweak phase transition, opening the possibility of ***electroweak baryogenesis***.

→ ***shifts in h→γγ/gg couplings by 5 - 10%***

Vectorlike quark mixing with top

In ***Little Higgs theories*** and *certain versions of the* ***Randall-Sundrum model***, *vectorlike quarks with charge 2/3—****top quark partners****—*cancel the divergence in the Higgs boson mass coming from top quark loops and thus *are a crucial ingredient in* ***solving the hierarchy problem***.

→ ***Top partners mix with the top***

→ ***deviation in the ttZ couplings.***

Vectorlike leptons mixing with SM leptons

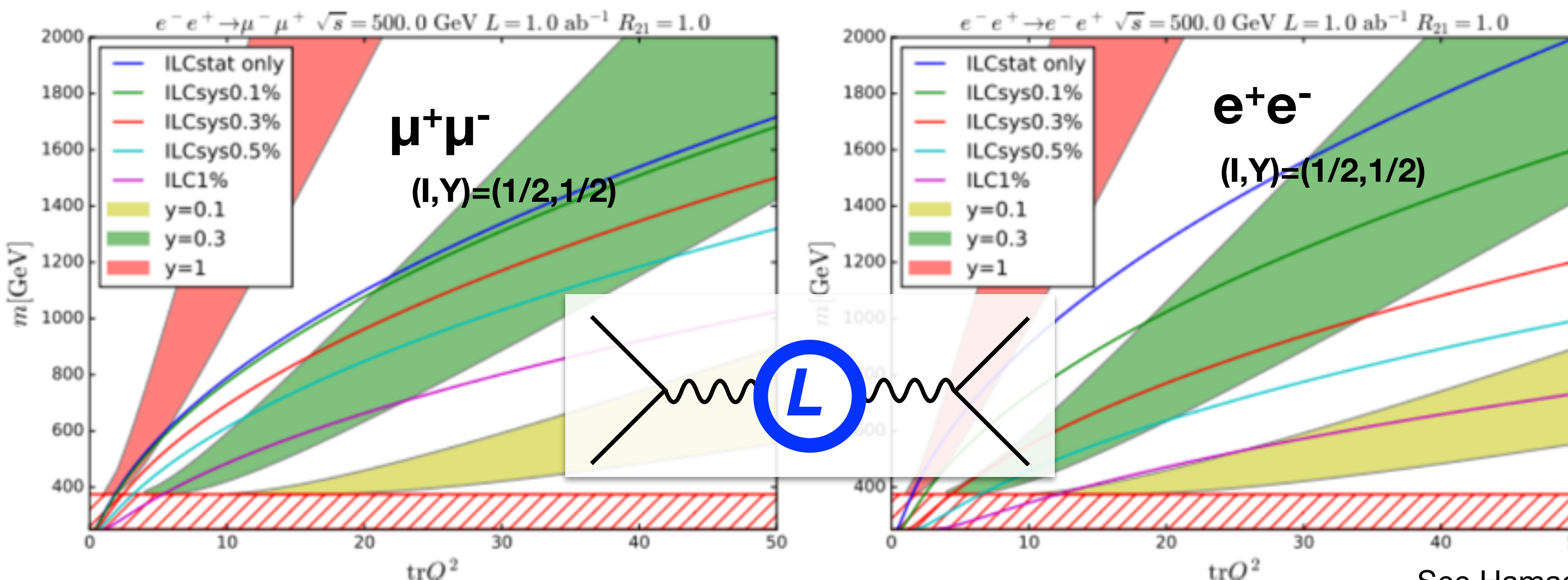
SUSY SU(5) GUT with additional 5=(D,L) and 5bar

$$W = W_{\rm MSSM} + \lambda S \mathbf{5}\overline{\mathbf{5}} + \frac{\mu_s}{2} S^2 + \mu \mathbf{5}\overline{\mathbf{5}}$$

Possible to add 4 extra 5+5 pairs and keep the Standard Model couplings perturbative up to the GUT scale. For 4 (3) pairs, the mass ratio (μ_D/μ_L) becomes 2.5 (1.9), and the parameters needed to give σ=5 fb predict μ_L< 400 GeV.

→ ***4 (3) lepton pairs with m_L < 400 GeV and 4 (3) quark pairs with m_L < 1 TeV. L can mix with SM leptons.*** → ***$e^+e^- \to Z^* \to Ll$.***

→ ***Also deviations in 2-fermion scattering (oblique correction)***



With 0.1% accuracy, ILC can go beyond LHC's reach

See Hamaguchi's talk in the Pheno session.

Models with Extended Higgs Sector

SM + a Singlet Higgs Boson (Φ) + Vector-like fermions

An SU(2) singlet scalar boson has the same quantum numbers, after symmetry breaking, as the Higgs boson and, in general, cannot avoid mixing with the Higgs boson. For a 750 GeV singlet, PEW measurements require

$$sin^2\theta_m < 0.12$$

→ The ***6% decrease in the hWW and hZZ couplings at maximum***.

Neutral heavy vectorlike fermion = DM: 300 GeV < m_ψ < 450 GeV
→ ***Mono-photon search at 1TeV ILC***

SM + a Doublet Higgs Boson (2HDM) + Vector-like fermions (Φ=H or A)

Non-observation of Φ→ττ, tt at LHC → ***tanβ~7***

→ ***LHC "wedge" region where bb→H/A→ττ for $M_{H/A}$>500GeV is difficult to observe. gg→H/A→ττ might also be difficult.***

→ ***shifts in H125 to ττ and bb couplings.***

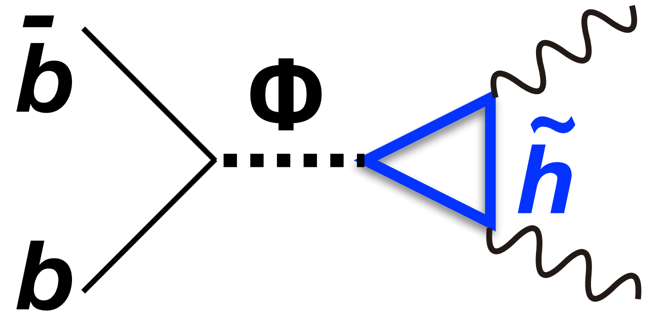
→ ***750GeV H/A well within 5σ reach of ILC (H20)***.

Φ = H+A (double resonances sitting close together)

→ ***PLC option with transverse photon polarizations to separate H/A***.

NMSSM

The LHC ***production is through bb annihilation*** and the ***Higgsinos*** as the ***heavy vectorlike fermions*** to generate a coupling to γγ.



The higgsino mass is typically $m_\Phi/2$, can be as light as 150 GeV.
→ ***can be accessible with 1TeV ILC, maybe even at 500 GeV.***

Φ → aa : decay to very light (~m_π) higgs state can be possible.
then ***H125 → aa decay unavoidable!***

SM + a Doublet Higgs Boson (2HDM) + Vector-like fermions (2nd doublet has no couplings to fermions except through small flavor mixing effects): Φ as the heavy Higgs

The to explain *the suggestion by CMS of* ***a decay H125 → τμ***.
→ ***Higgs flavor violation will be a major task of the 500 GeV ILC.***

Bound State of New Constituents

Φ = a bound state of heavy colored fermions

→ ***continuum production of the constituents should be discovered at the LHC.***

→ radiative corrections produce ***O(5%) shift in the hbb coupling***.

→ ***precision H125 measurement at ILC.***

→ oblique correction of ***O(1%)***.

→ ***deviations in 2-fermion scattering ($e^+e^- \to \mu^+\mu^- / e^+e^-$) at ILC.***

Pion of a New Strong Interaction Sector

Φ = pNGB of ***new strong interactions*** at multi-TeV

→ ***Additional pNGBs are expected in the LHC range.***

Composite Higgs models, models of ***partial compositeness***, ***Little Higgs*** models or even ***Twin Higgs*** models, are all having ***particular patterns of deviations in the Higgs (and also top) couplings***.

DM = the lightest pNGB → might be enhancing the Φ width (Φ→***DM DM)***

→ $m_{DM} < m_\Phi/2$

Thermal relic abundance of dark matter is correct for ***m_{DM} ~300 GeV***. If there are two pNGBs close in mass, so that the relic abundance is set by coannihilation, ***m_{DM} <100 GeV is favored*** (arXiv:1602.07297) → ***within the reach of 500 GeV ILC.***

Radion of Randall-Sundrum models

Φ = radion

The RS model can be considered ***a dual description of a strong-interaction theory above 1 TeV***, with the KK excitations modeling the strong interaction

Three effects

1st Effect: ***Higgs-radion mixing:***

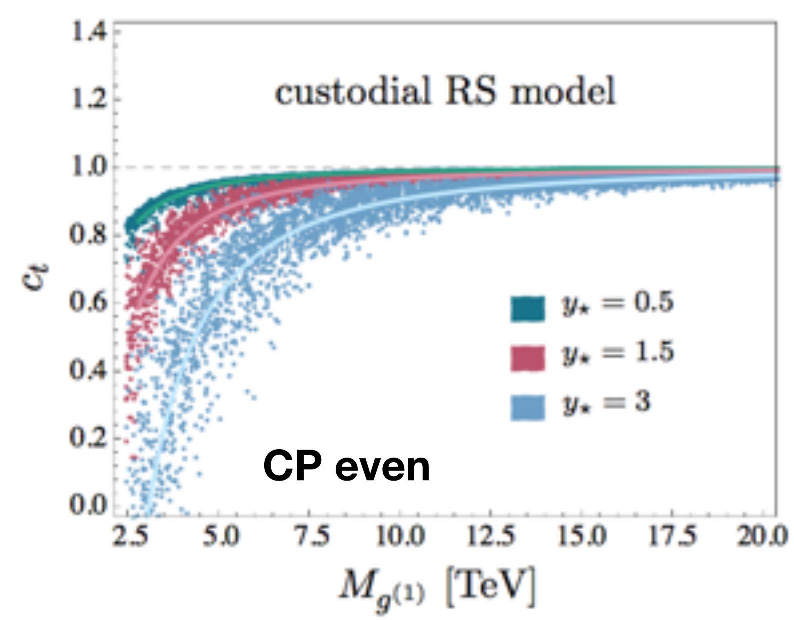
The mixing angle: e.g. $\boldsymbol{\theta_m < m^2_h/6m^2_\Phi < 0.5\%}$, too small to observe in the overall shift of Higgs couplings ($\propto \cos\theta_m$) but ***shifts in H125 to gg and γγ couplings should be observable*** owing to ***large radion to gg and γγ couplings***($\propto \sin\theta_m$).

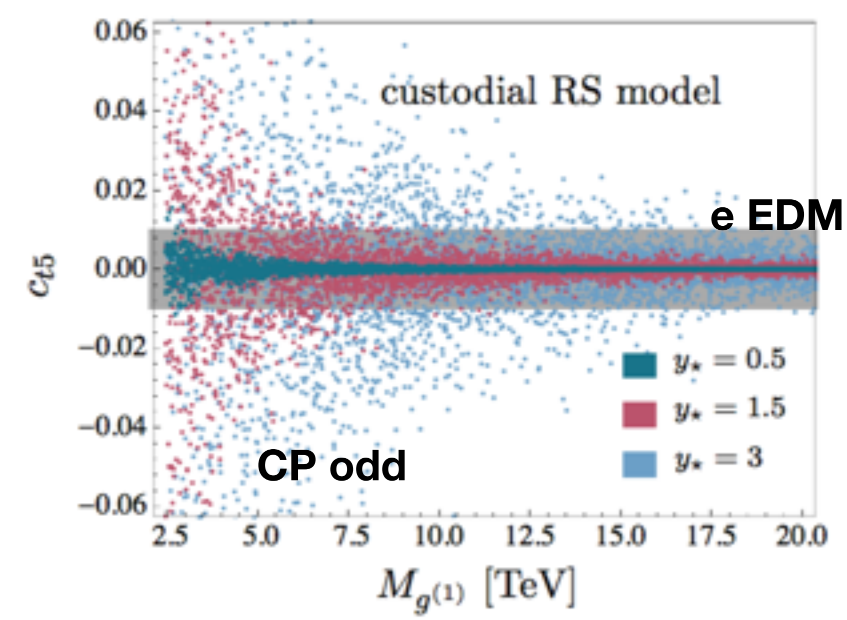
2nd Effect: ***KK loop corrections H125 to W/Z/t:***

$$c_W \approx c_Z \approx 1 - 0.078\left(\frac{5\ \text{TeV}}{M_{g^{(1)}}}\right)^2$$

ILC H20 would be ***sensitive to even a 20 TeV KK gluon*** through ***hWW and hZZ shifts***.

The corrections are in general complex, leading to ***CPV in the htt coupling***





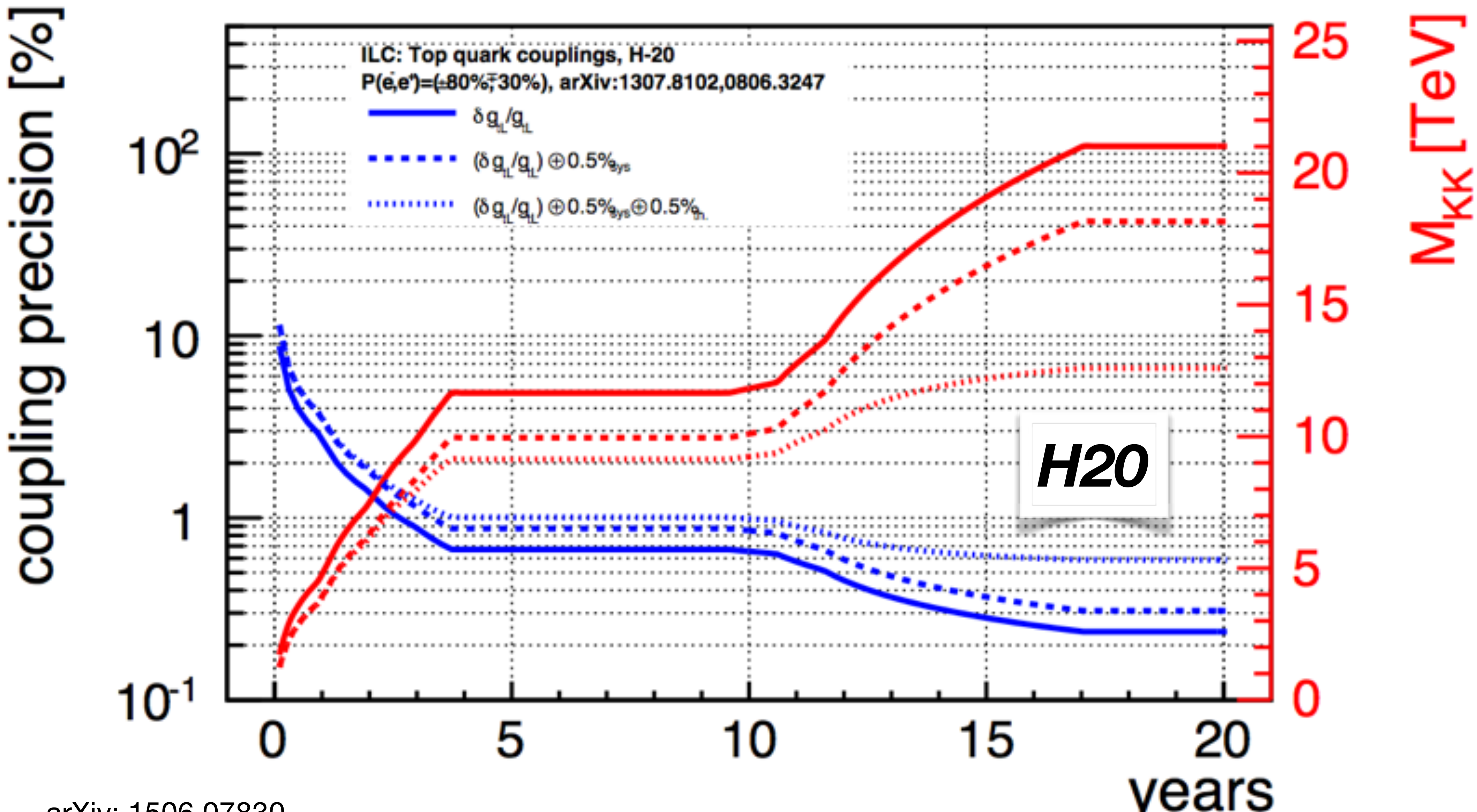
JHEP 1502, 008 (2015)

3rd Effect: ***Modifications of the EW couplings of top***

Large overlap of t_R wave function with the Higgs (to explain $m_t >> m_q$)

→ partial compositeness of the top quark

→ ***shifts in ttZ couplings (with different size for t_L and t_R)***



arXiv: 1506.07830

→ ILC H20 would be ***sensitive to even a 20 TeV KK W/Z bosons***

Φ = KK Graviton: *we assume J = 2 here*

By the introduction of boundary interaction terms, it is possible to realize parameters in which ***the KK graviton is lighter than the RS radion*** excitation. It is also possible to have non-universal couplings of the spin-2 resonance to the SM if one allows ***the SM fields to also propagate in the bulk.***
→ ***Possible to correctly reproduce X750 properties*** seen by LHC.
For ***the RS framework to solve the hierarchy problem***, ***WW, ZZ, hh, and tt decays are expected with a significant BR.***

SM on the IR brane — SM in the bulk

	IR	MIN	MED	MAX	GMAX
Br($X \to \gamma\gamma$) [%]	4.3	8.5	7.0	0.5	2.3
Br($X \to ZZ$) [%]	4.8	7.9	7.8	2.9	12
Br($X \to WW$) [%]	9.5	16	15	5.6	21
Br($X \to Z\gamma$) [%]	0	0	0	0	1.1
Br($X \to hh$) [%]	0.3	0	0.4	1.4	6.9
Br($X \to t\bar{t}$) [%]	5.1	0	8.3	85	56
Br($X \to b\bar{b}$) [%]	6.4	0	5.2	0.4	0.04
Br($X \to jj$) [%]	66	68	61	4.5	0.5
Br($X \to e^+e^-$) [%]	2.1	0	0	0	0
$\Gamma(X \to \gamma\gamma)$[MeV]	0.25	0.15	0.18	2.5	25
$\Gamma(X \to \text{tot})$[MeV]	5.7	1.8	2.6	500	1060
PLC: $\sigma_{eff}(\gamma\gamma \to X)$ [fb]	40	24	29	400	4000
LC: $\sigma(e^+e^- \to X)$ [pb]	0.4	0	0	0	0

arXiv:1602.02793 — arXiv:1603.06980

The J=2 contact interaction effect is too small at 500 GeV.

Φ→e+e- is a key to tell whether SM fields propagate in the bulk or not.

If the LHC were to confirm J=2, and if especially if the ILC provided evidence for the presence of RS excitations above the TeV scale, ***the 1 TeV ILC would be able to make unique measurements of the gravity sector of the RS model.***

This possibility will be covered by the next talk by Francois.

Summary

	hWW hZZ	$hb\bar{b}$ $h\tau\tau$	$h\gamma\gamma$ hgg	$ht\bar{t}$	$h \to$ invis.	$h\tau\mu$	$t\bar{t}Z$	$ee \to$ $ee, \mu\mu$	$ee \to$ $\gamma+$ invis.
Vectorlike fermions		X	X	X			X	X	
2 Higgs doublet	X	X	X	X					
Higgs singlet	X	X		X			X		
NMSSM	X	X	X	X	X				X
Flavored Higgs	X	X	X			X			
NR bound state		X		X				X	
Pion of new forces		X	X	X	X		X	X	X
RS radion	X	X	X	X			X		
RS graviton	X	X		X			X		

Table 2: Anomalies in precision measurements expected to be visible at the ILC for the models of the Φ discussed in this section.

1. *The note is intended to show*
    - ***The 500 GeV ILC has a lot to say about X750 through precision measurements*** *plus* ***possible discovery of NPs associated with X750.***
    - ***Possible energy upgrade with PLC option will open up even greater opportunities to uncover the new physics operating behind X750 together with LHC.***
      → next talk by Francois Richard
2. ***Our strategy stated in the ICFA letter to MEXT's ILC Advisory Panel is intact:***
   While performing precision studies of the Higgs boson and the top quark, we will prepare for the energy upgrade of the ILC *taking advantage of energy expandability enabled by its linear shape.*

Caution

It might turn out that ***the Φ is a relatively minor player*** *in a new sector of physics that the LHC will begin to uncover in the next few years*.

For this reason, ***it is premature to discuss a new accelerator intended specifically to target the Φ*** or any other new particle that turns up in the early 13 TeV LHC data.