Probing the origin of 750 GeV diphoton excess
with the precision measurements at the ILC

Keisuke Yanagi
(Univ. of Tokyo)

Probing the **New Physics** diphoton excess

with the precision measurements at the ILC

K. J. Bae, K. Hamaguchi, T. Moroi, K. Y, PLB 759 (2016) 575 [arXiv:1604.08307]

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Precision measurement at the ILC

- The ILC is future electron-positron collider

- Center of Mass energy: $\sqrt{s} =$ **250GeV - 1TeV (3TeV??)**

- Clean environment compared with the LHC

- Even if $m > \sqrt{s}/2$, **new particle affects SM process** via loop correction

We focus on **the differential cross section** of $e^+ e^- \rightarrow f \bar{f}$

Motivations for indirect probe

Powerful method to search new heavy (non-colored) particles with **large EW quantum number** and/or **large multiplicity**

Examples

- Several models for the diphoton excess:
  SM + **singlet** scalar (750GeV) + **charged** scalars/fermions

- WIMP DM models [K. Harigaya et al., arXiv: 1504.03402]
  (Wino/Higgsino DM, Minimal DM…)

- Other BSM particles …

Indirect method is widely applicable!

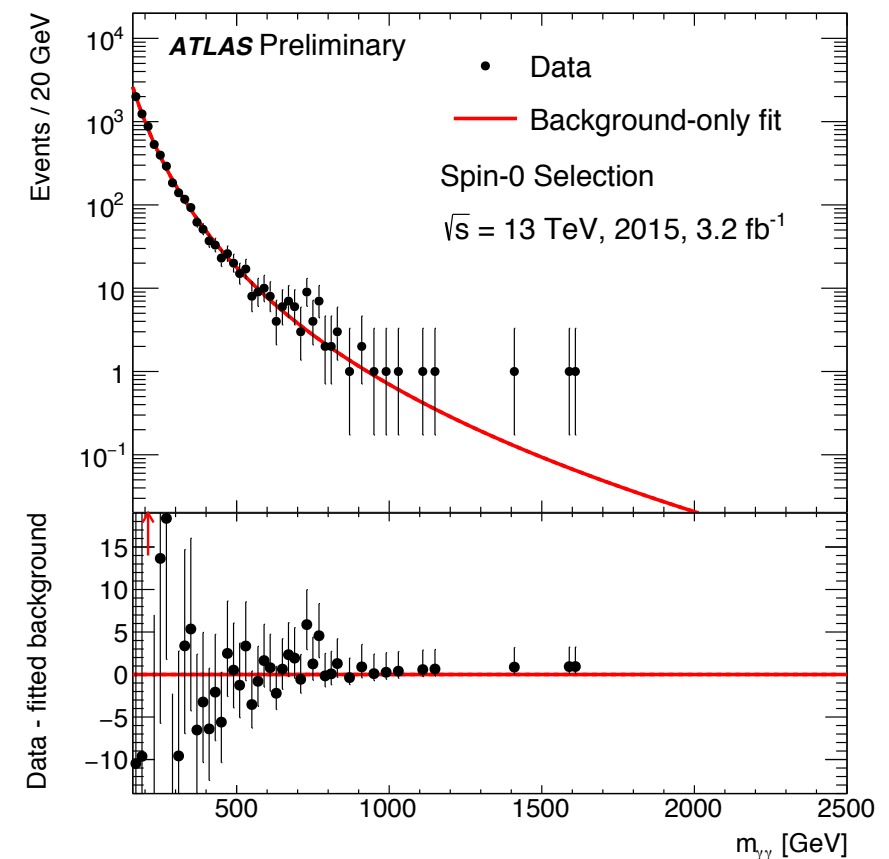(even though the 750 GeV diphoton excess is dead)

Motivations for in...e

Powerful method to search new heav...
with **large EW quantum number** and/...

Events / 20 GeV

ATLAS Preliminary

- Data
— Background-only fit

Spin-0 Selection

$\sqrt{s}$ = 13 TeV, 2015, 3.2 fb^{-1}

Data - fitted background

$m_{\gamma\gamma}$ [GeV]

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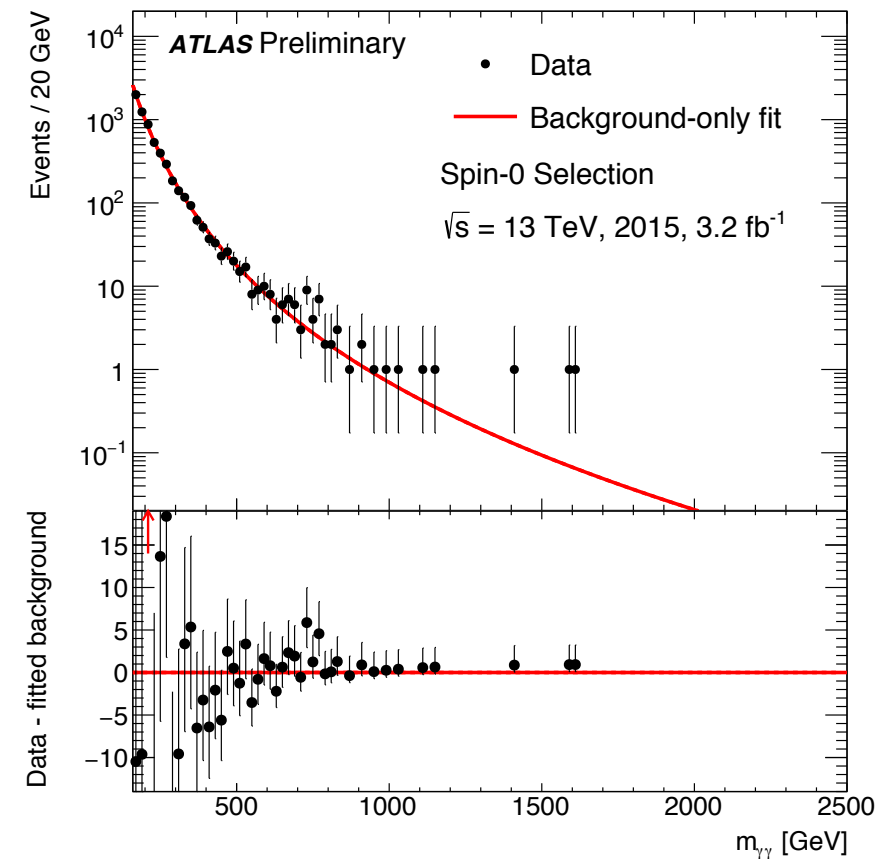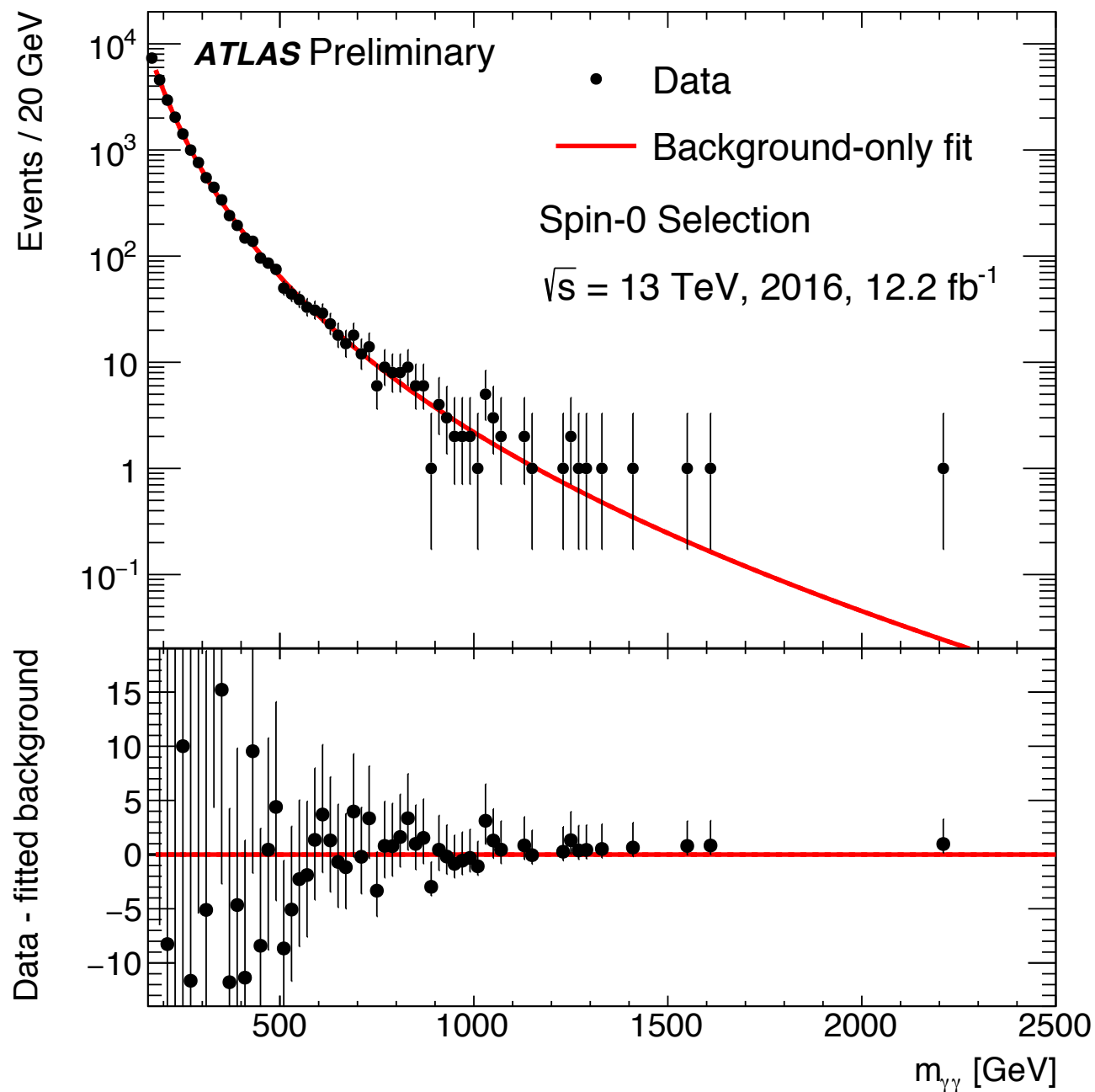 (Wino/Higgsino DM, Minimal DM…)

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402]

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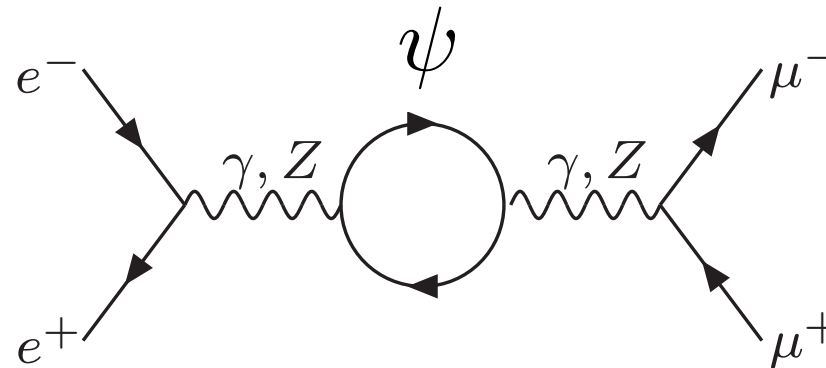 (Wino/Higgsino DM, Minimal DM…)

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Setup

- SM + **N** vector-like fermions ψ of mass **m**, and rep. (**1**, **n**, **Y**)

- $e^+ e^- \to \mu^+ \mu^-$ process

- Define

$$\Delta \chi^2 = \sum_{i:\,\mathrm{bins}} \frac{(N_i^{\mathrm{SM}+\psi} - N_i^{\mathrm{SM}})^2}{N_i^{\mathrm{SM}} + (\epsilon N_i^{\mathrm{SM}})^2}$$

- Bins: 10 uniform intervals for the scattering angle cosθ ∈ [-1, 1]

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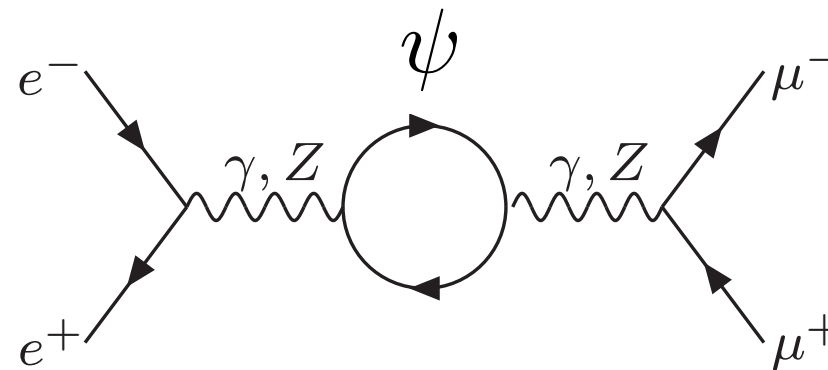**#events in i-th bin**

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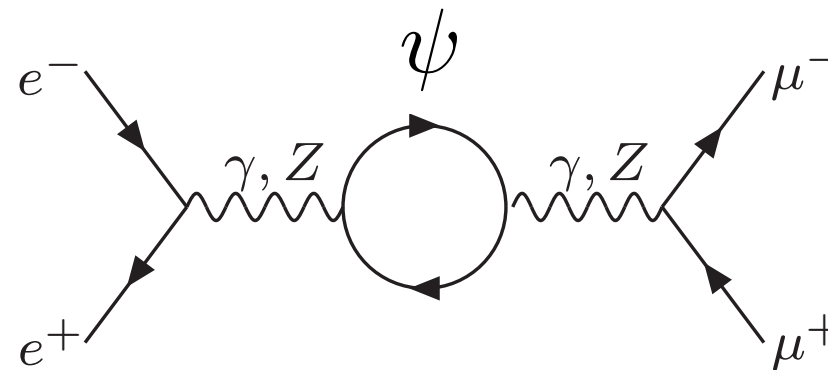$$\Delta \chi^2 = \sum_{i:\,\text{bins}} \frac{(N_i^{\text{SM}+\psi} - N_i^{\text{SM}})^2}{N_i^{\text{SM}} + (\epsilon N_i^{\text{SM}})^2}$$

Systematic uncertainty

- Bins: 10 uniform intervals for the scattering angle cosθ ∈ [-1, 1]

Mass reach

- Expected mass reach (95% C.L.)

- New particle: SU(2) triplet (**n=3**), **Y=0**

- $\sqrt{s} = 1\,\text{TeV}$

- $m > \sqrt{s}/2$ can be probed!

- (Shaded region is favored by the diphoton excess)

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$e^-e^+ \rightarrow \mu^-\mu^+ \quad \sqrt{s} = 1000.0$ GeV $\quad L = 1.0$ ab^{-1} $\quad R_{21} = \infty$

Legend:
- ILCstat only
- ILCsys0.1%
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- ILCsys0.5%
- ILC1%
- y=0.1
- y=0.3
- y=1

Axes: m[GeV] vs $\mathrm{tr}Q^2$

N

How about quantum number of SU(2)ʟ×U(1)ʏ?

Is it possible to **discriminate different BSM particles?**

Angular distribution

- The deviation of the differential cross section from SM

- $e^+ e^- \rightarrow \mu^+ \mu^-$ process

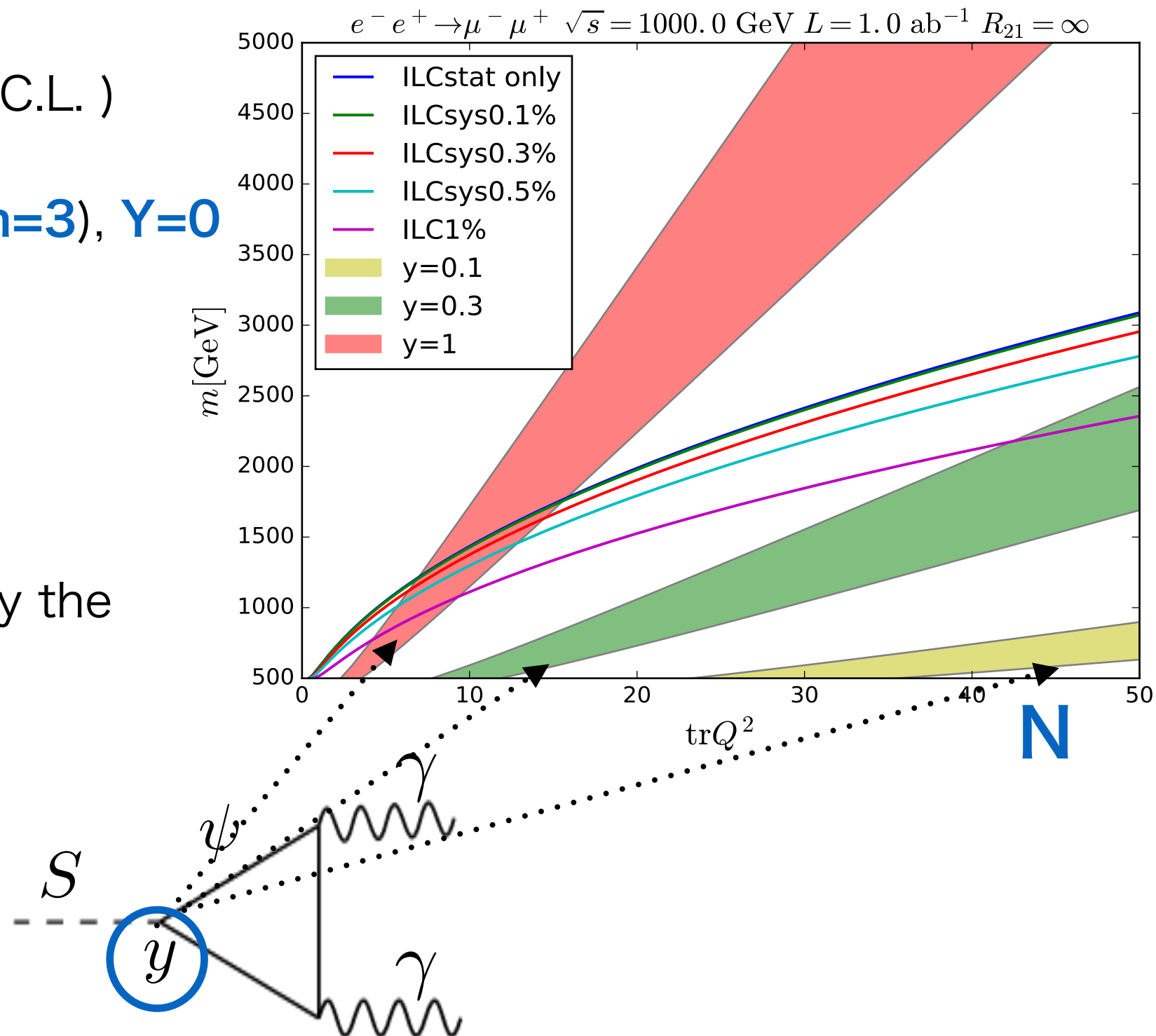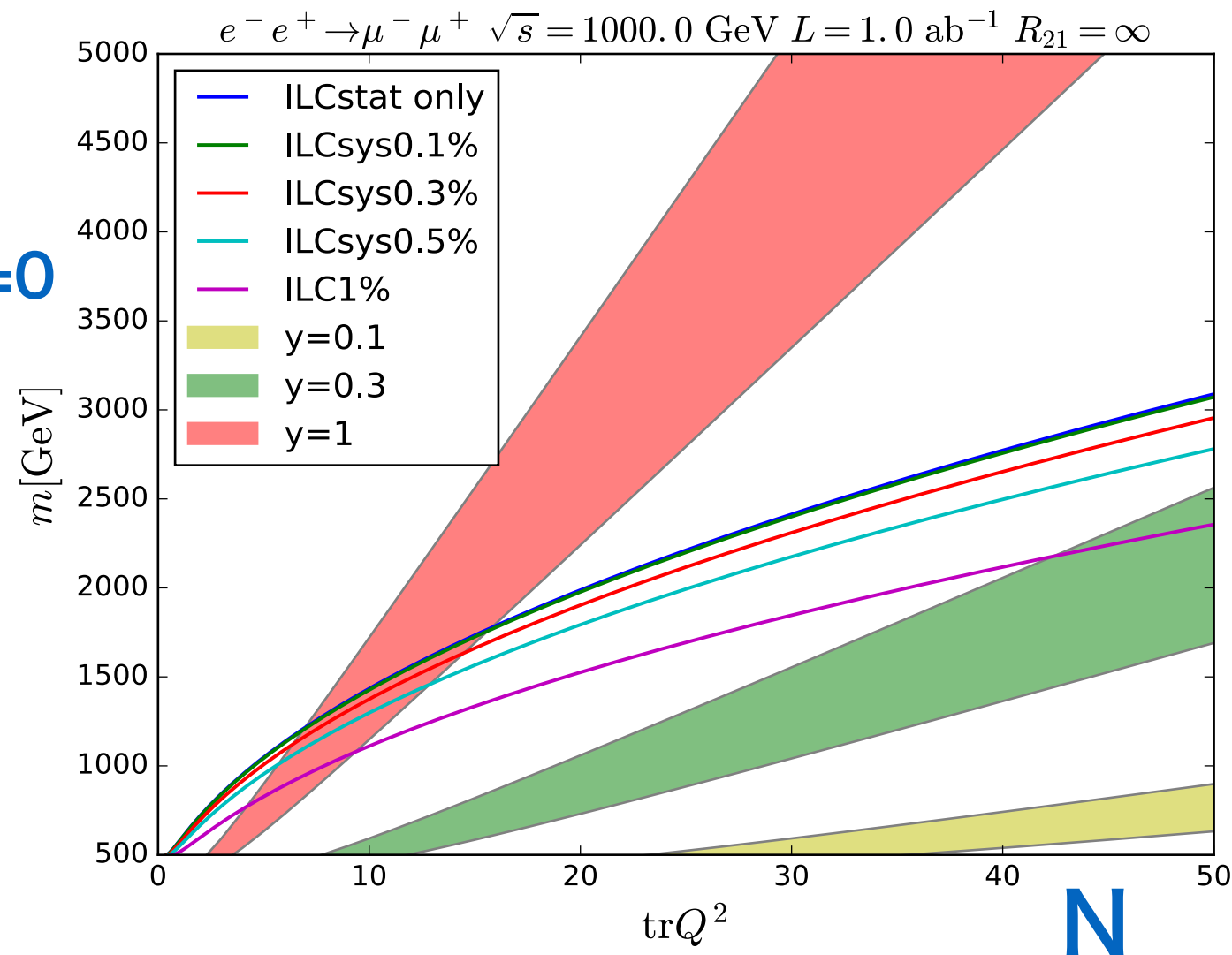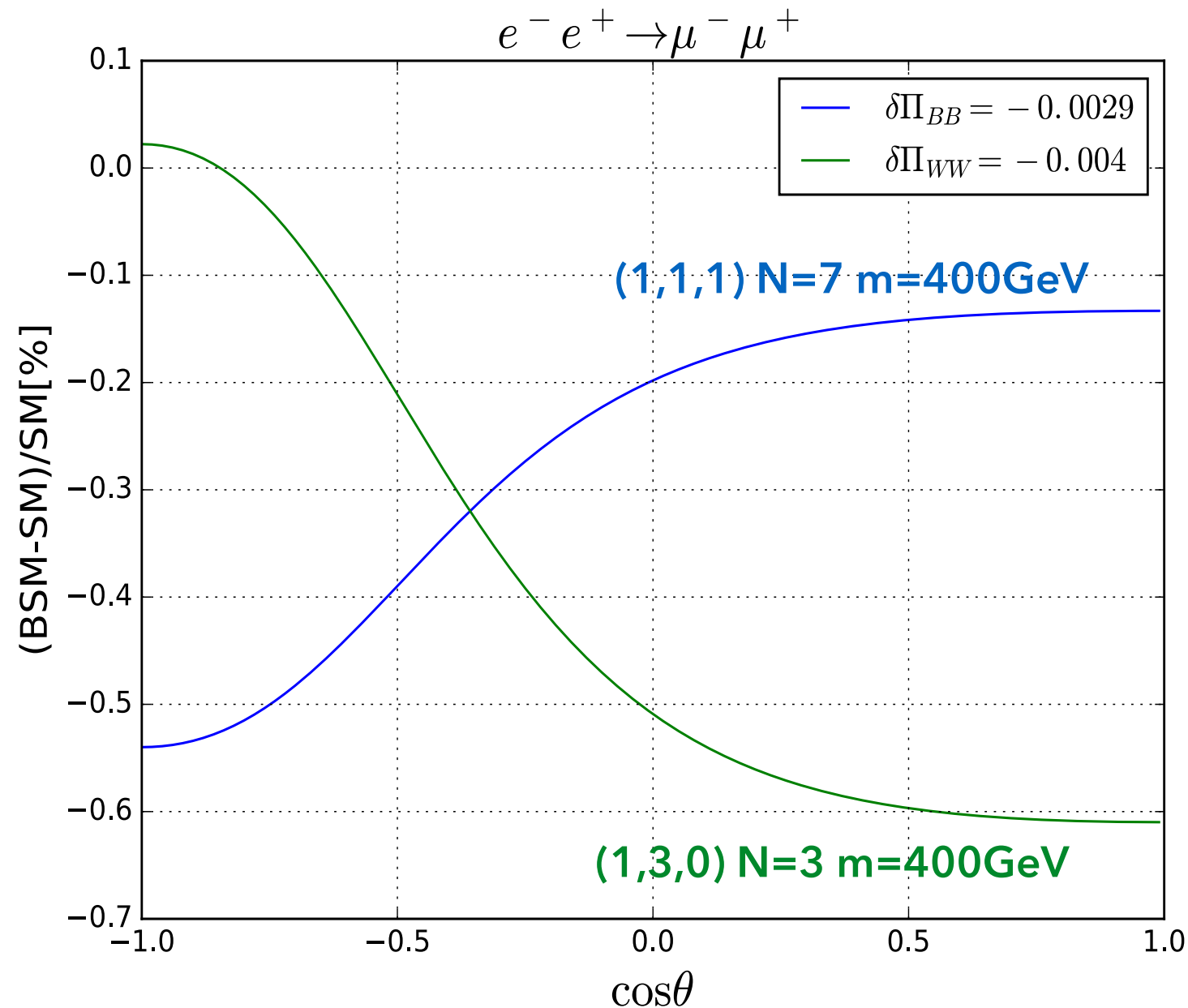- **Angular distribution is different** for different quantum number

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$e^- e^+ \rightarrow \mu^- \mu^+$

$\delta\Pi_{BB} = -0.0029$
$\delta\Pi_{WW} = -0.004$

(1,1,1) N=7 m=400GeV

(1,3,0) N=3 m=400GeV

(BSM-SM)/SM[%]

$\cos\theta$

$P_+ = +30\ \%\ \ P_- = -80\ \%$ (Beam polarization)

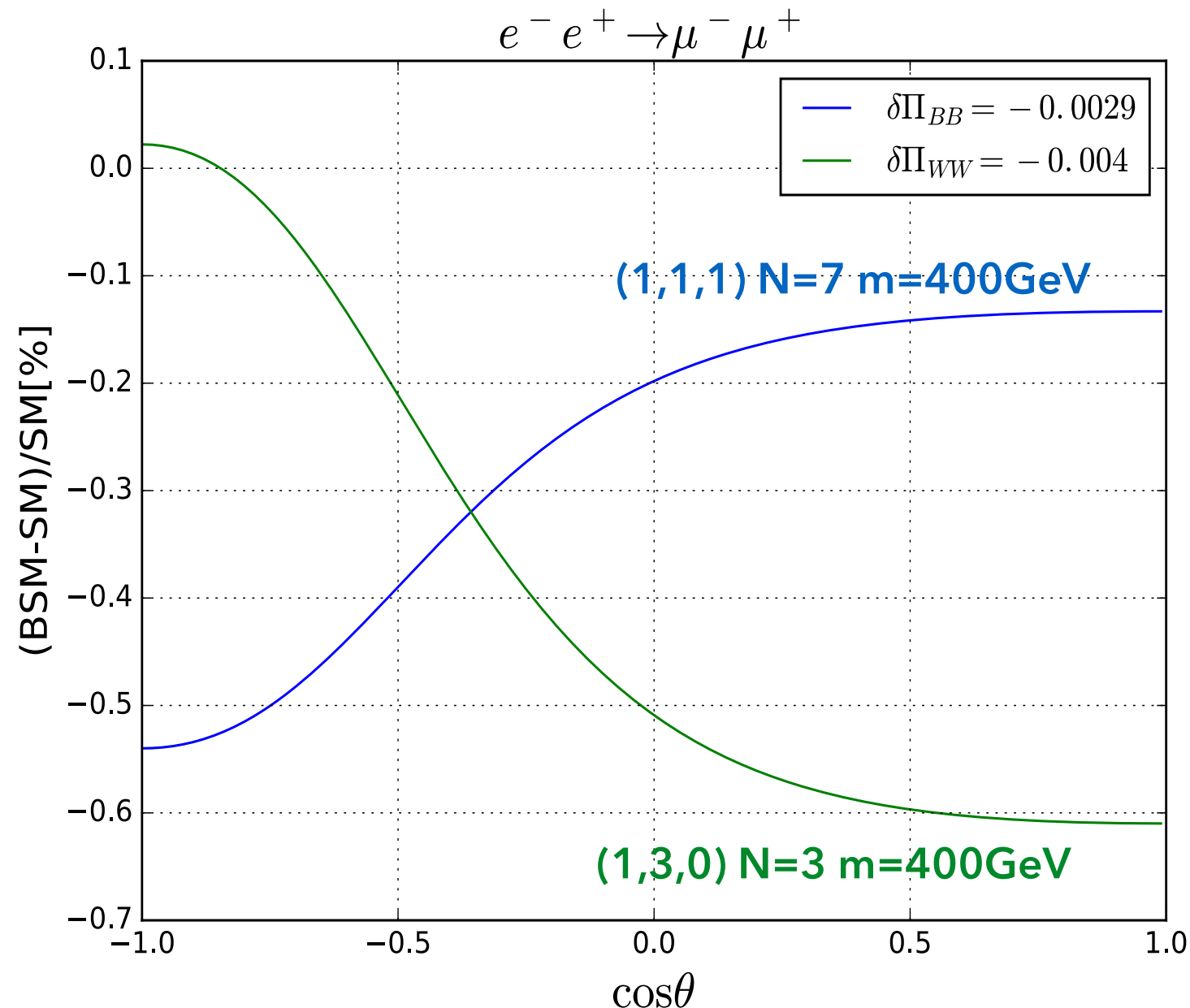$\sqrt{s} = 500\ \text{GeV}$ (Beam energy)

Angular distribution

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y-axis: (BSM-SM)/SM[%]

x-axis: $\cos\theta$
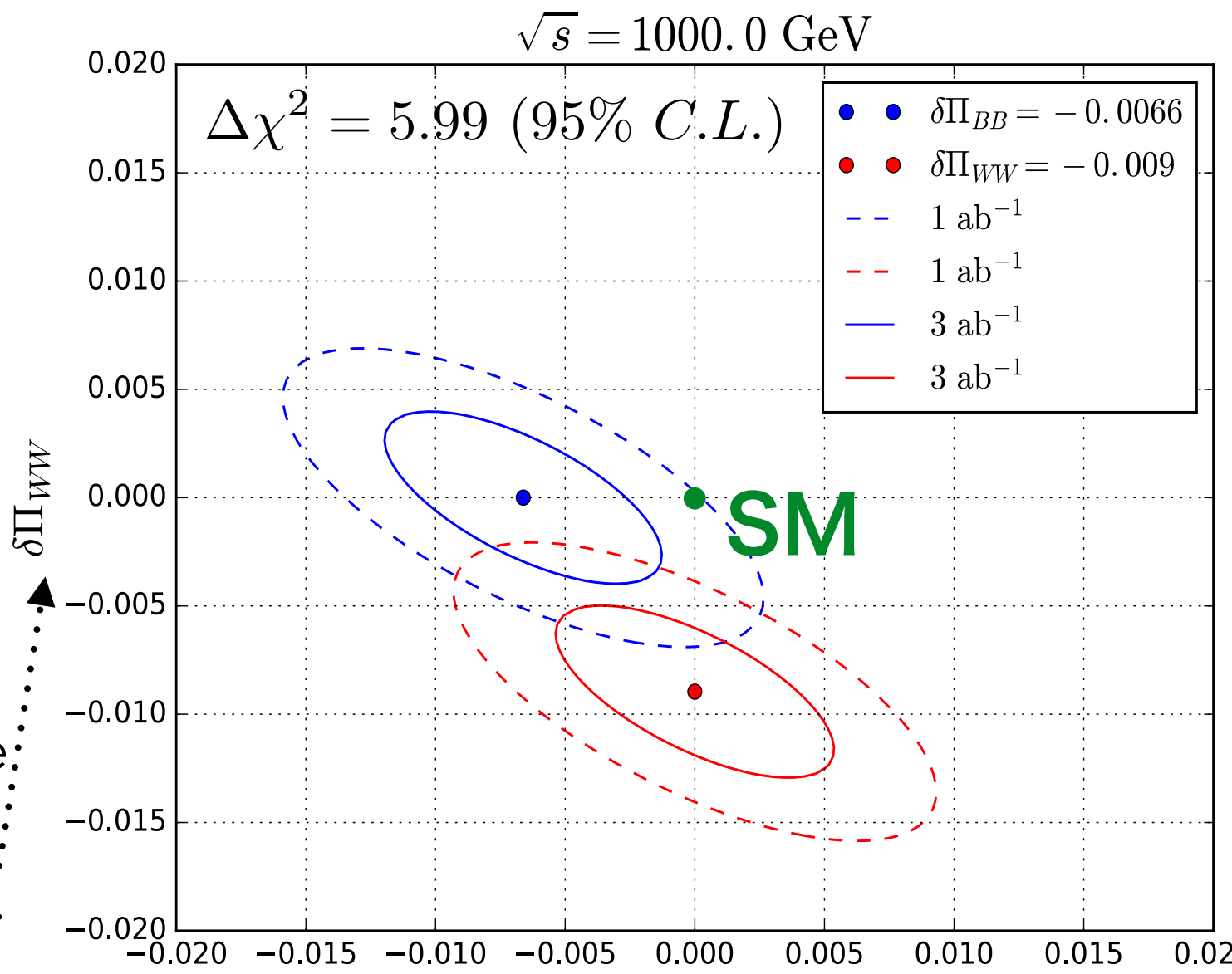
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SU(2)$_L$ vs. U(1)$_Y$

- $\delta\Pi_{WW}$, $\delta\Pi_{BB}$ are the vacuum polarizations of new particles

- Each point corresponds to a new physics model

- Integrated luminosity **1 ab^{-1}** and **3 ab^{-1}** are considered

- **SM+U(1)$_Y$** or **SM+SU(2)$_L$** can be distinguished from **models outside the contour** at 95 % C.L.

$\sqrt{s} = 1000.0$ GeV

$\Delta\chi^2 = 5.99 \ (95\% \ C.L.)$

Legend:
- $\delta\Pi_{BB} = -0.0066$
- $\delta\Pi_{WW} = -0.009$
- 1 ab^{-1}
- 1 ab^{-1}
- 3 ab^{-1}
- 3 ab^{-1}

SM

$\delta\Pi_{WW}$

$\delta\Pi_{BB}$

$$\delta\Pi_{WW} = \quad W \quad \psi \quad W$$

$$\delta\Pi_{BB} = \quad B \quad \psi \quad B$$

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(1,1,1) N=7 m=600GeV

SM+U(1)$_Y$

SM

$\delta\Pi_{WW}$

$\delta\Pi_{BB}$

ψ

$\delta\Pi_{WW} = \ W \quad W$
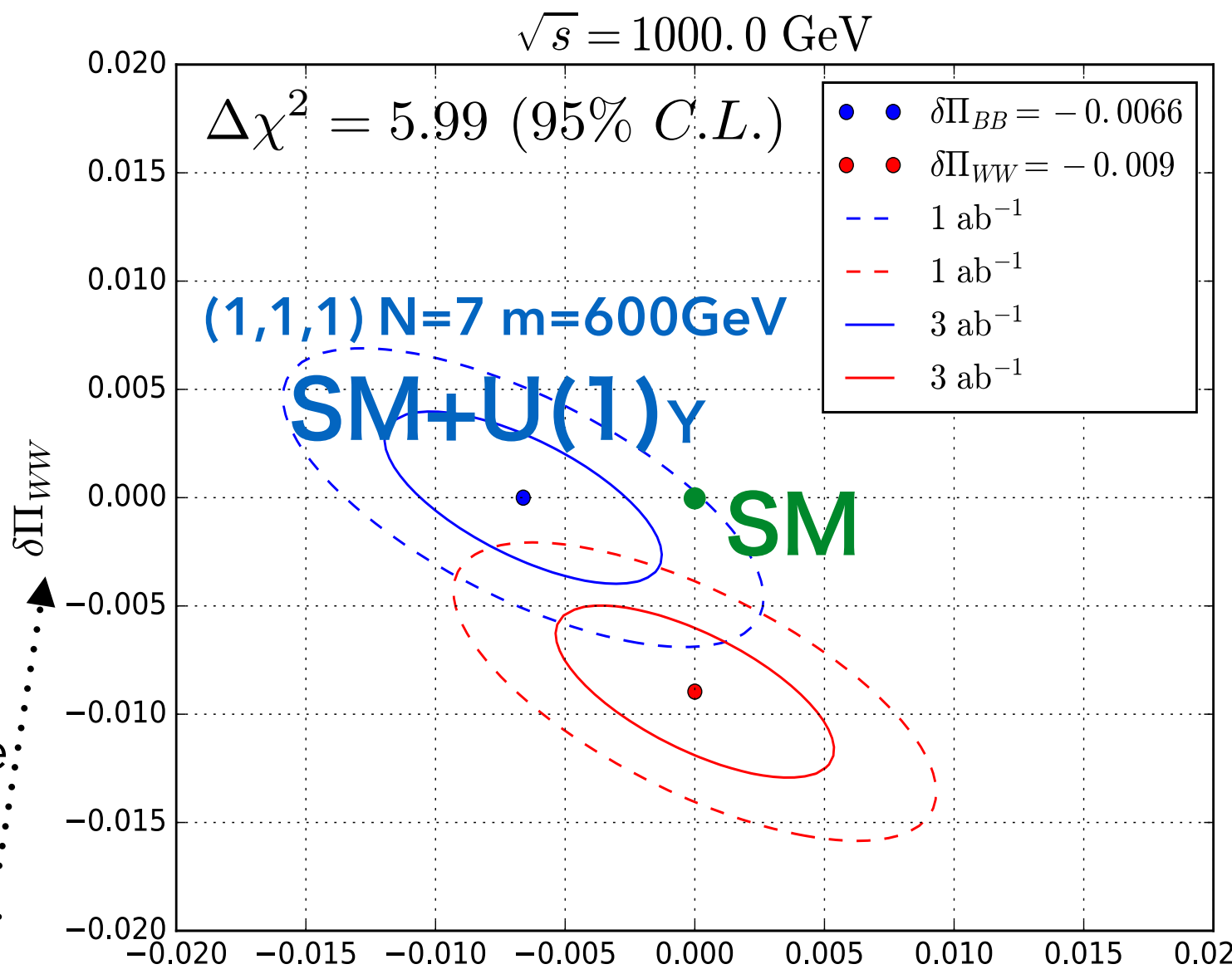
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SM

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$\delta\Pi_{WW}$
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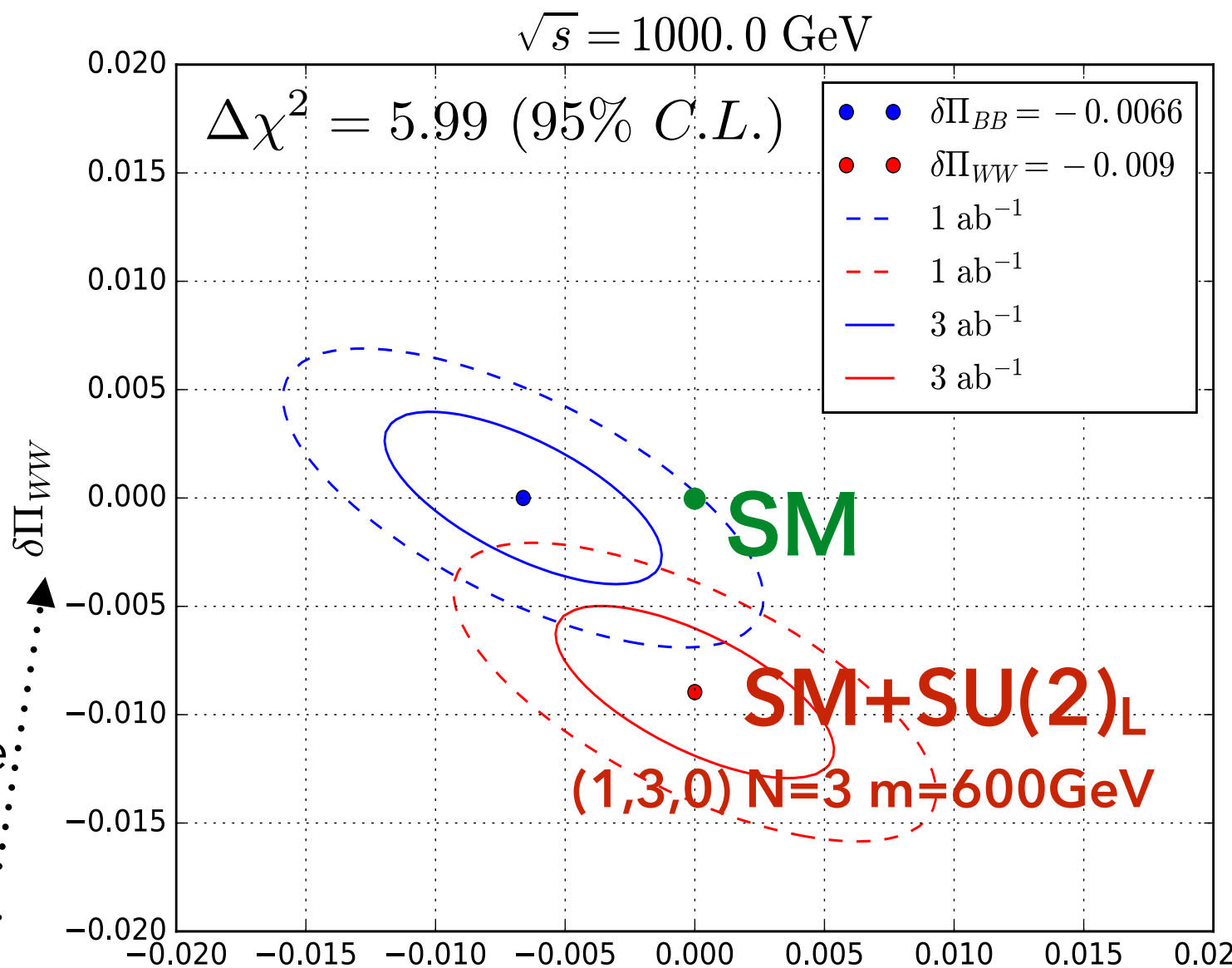$\delta\Pi_{BB} = \quad B \qquad \psi \qquad B$

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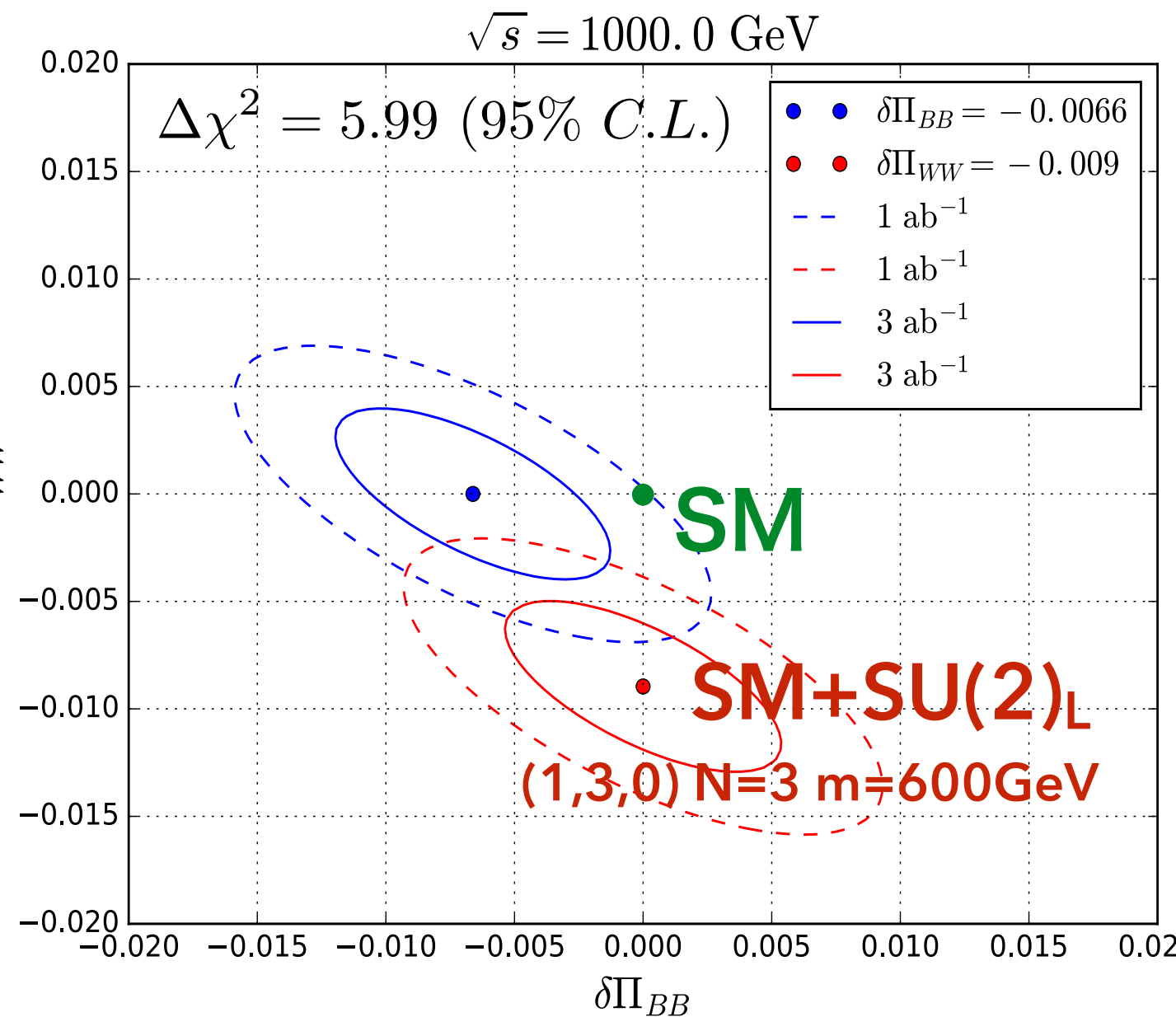- **SM+U(1)$_Y$** or **SM+SU(2)$_L$** can be distinguished from **models outside the contour** at 95 % C.L.

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$\delta\Pi_{WW}$

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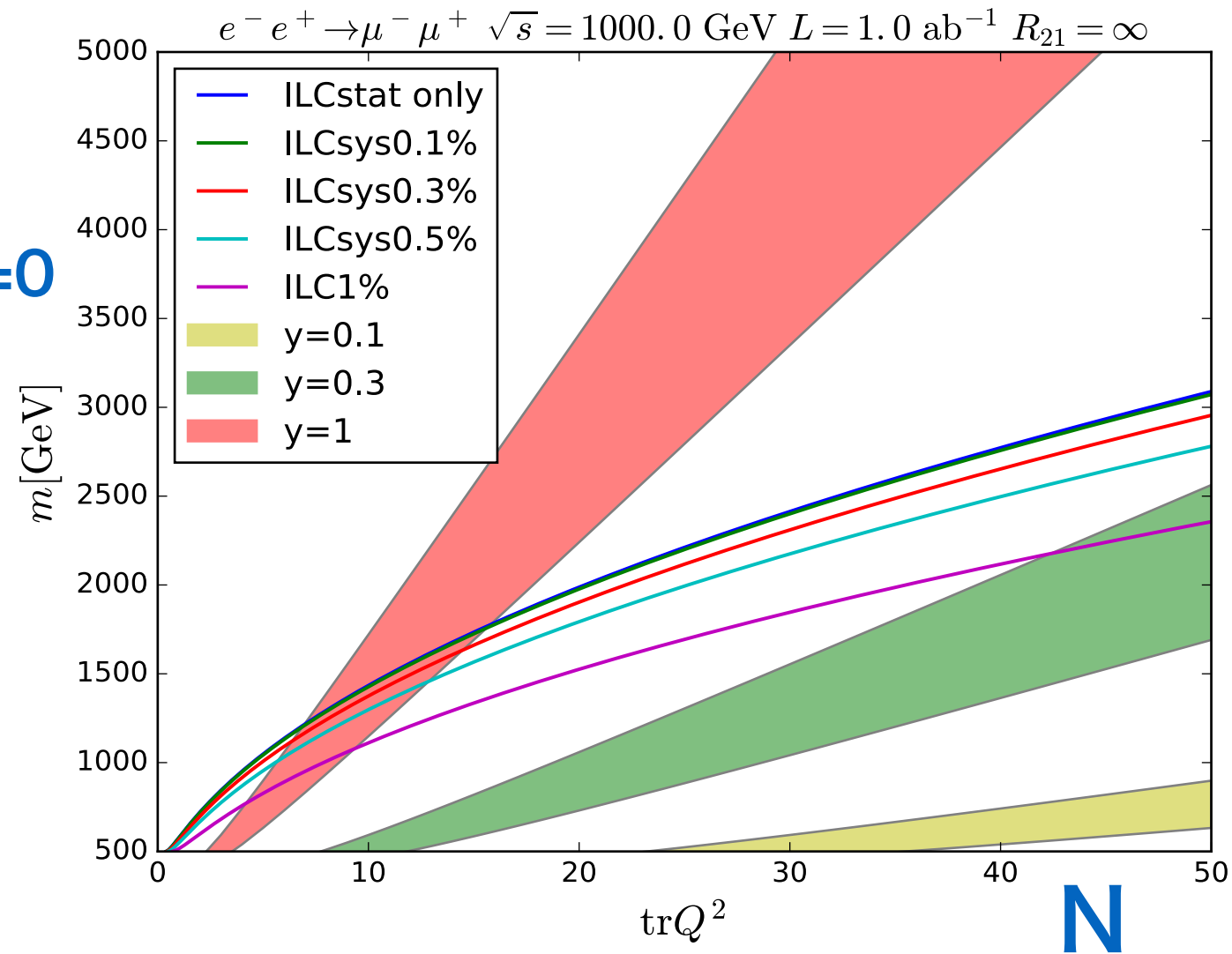It is possible to **discriminate SU(2)$_L$×U(1)$_Y$ quantum number!**

Summary

Precision measurement of the process $e^+e^- \to f\bar{f}$ provides a clue for the beyond standard physics.

1. We can probe new charged fermions **even when they are out of kinematical reach** at the ILC.

2. We can **discriminate SU(2)$_L$×U(1)$_Y$** quantum numbers of the new particles by **studying the angular distribution** at the ILC.

Backup

Mass reach

- Expected mass reach (95% C.L.)

- New particle: SU(2) triplet (**n=3**), **Y=0**

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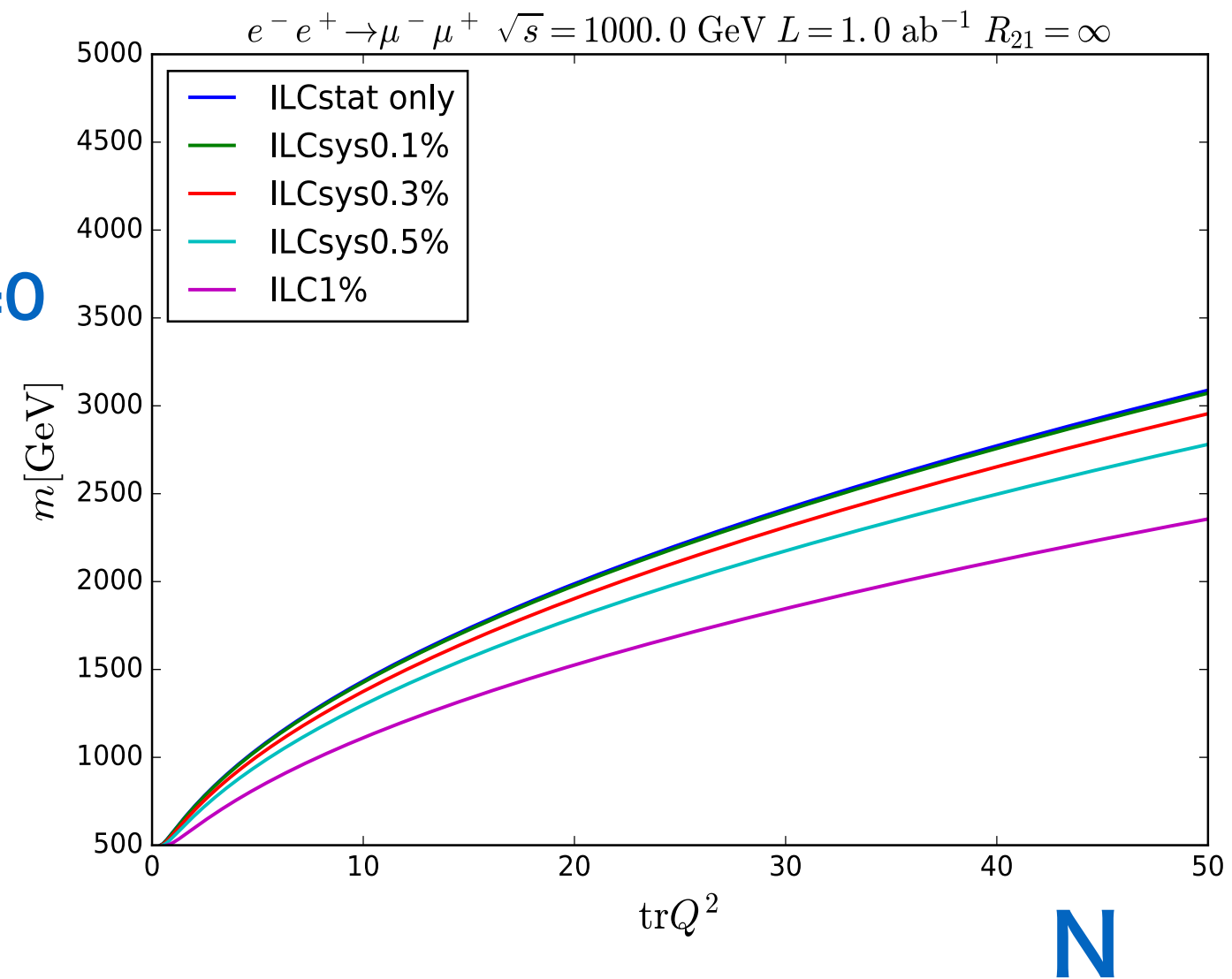- y=0.1
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m[GeV] vs trQ^2

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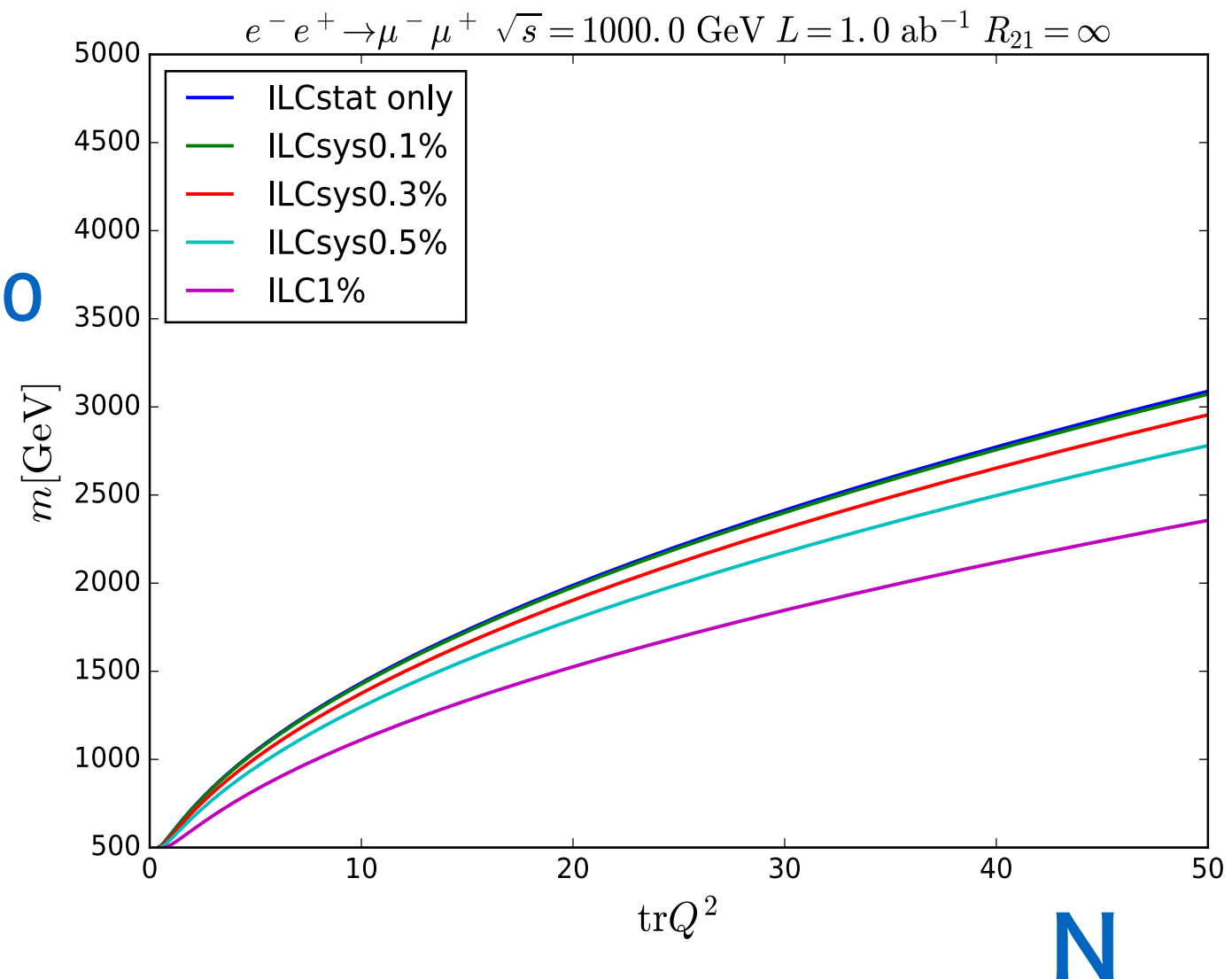
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x-axis: $\text{tr}Q^2$

y-axis: $m[\text{GeV}]$

N

How about quantum number of SU(2)×U(1)?

Is it possible to **discriminate different BSM models?**

750 GeV diphoton Excess (1)

SM + **singlet** pseudo-scalar (750GeV) + **charged** scalars/fermions

$$\mathcal{L}_\psi = \sum_i \bar{\psi}_i (i\slashed{D} - m)\psi_i - i \sum_i yS\bar{\psi}_i \gamma_5 \psi_i$$

Narrow width approximation:

$$\sigma(pp \to S \to \gamma\gamma) \simeq \frac{C_{gg}}{s\, m_S} \Gamma(S \to \gamma\gamma)$$

Assuming

$$\sqrt{s} = 13 \text{ TeV} \quad \sigma = 3 - 10 \text{ fb} \quad C_{gg} \simeq 2.1 \times 10^3 \quad m_S = 750 \text{ GeV}$$

Decay width

$$\Gamma(S \to \gamma\gamma) = 0.45 - 1.5 \text{ MeV}$$

is necessary.

750 GeV diphoton excess (2)

Functions

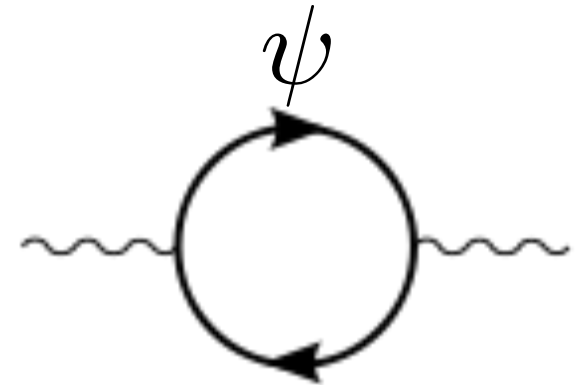$$C_{gg} = (\pi^2/8) \int_0^1 dx_1 \int_0^1 dx_2 \delta(x_1 x_2 - m_S^2/s) g(x_1) g(x_2)$$

$$\Gamma(S \to \gamma\gamma) \simeq \frac{\alpha^2}{256\pi^3} m_S^3 \left[\frac{y}{m} \mathrm{tr} Q^2 L\left(\frac{m_S^2}{4m^2} \right) \right]^2$$

$$L(\tau) = \begin{cases} 2\tau^{-2} \left(\tau + (\tau - 1) \arcsin^2 \sqrt{\tau} \right) & \text{for scalar } S\,, \\ 2\tau^{-1} \arcsin^2 \sqrt{\tau} & \text{for pseudo-scalar } S\,, \end{cases}$$

$$\mathrm{tr} Q^2 = N \left[\frac{n(n-1)(n+1)}{12} + nY^2 \right]$$

Vacuum polarization

$$\delta\Pi_{VV}(q^2, m^2) \equiv \frac{1}{2}g_V^2 C_{VV} I(q^2/m^2)$$

$$C_{WW} = \frac{4}{3}Nn(n-1)(n+1)\,,$$

$$C_{BB} = 16nNY^2\,.$$

$$I(x) \equiv \frac{1}{16\pi^2}\int_0^1 dy\ y(1-y)\ln(1-y(1-y)x) \qquad \text{for fermion}$$

$$I(x) \equiv \frac{1}{16\pi^2}\int_0^1 dy\ (1-2y)^2\ln(1-y(1-y)x) \qquad \text{for scalar}$$

Particle representation

Electromagnetic charge can be written as follows,

$$\mathrm{tr}Q^2 = \frac{1}{16}\left(C_{WW} + C_{BB}\right)$$

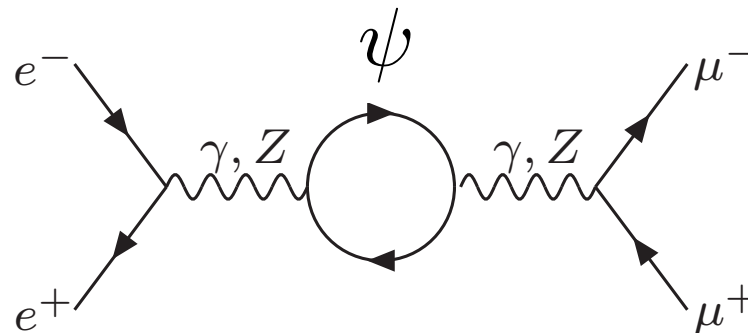We parametrize the ratio of SU(2) and U(1) by

$$R_{21} \equiv C_{WW}/C_{BB} = \frac{n^2 - 1}{12Y^2}$$

Amplitudes (1)

$e^+ e^- \to \mu^+ \mu^-$ matrix element

$$\mathcal{M}^{\mathrm{SM},\psi}(e_h^- e_{\bar{h}}^+ \to \mu_{h'}^- \mu_{\bar{h}'}^+) = \sum_{V,V'=\gamma,Z} C_{e_h V} C_{\mu_{h'} V'} D_{VV'}^{\mathrm{SM},\psi}(s) [\bar{u}_{h'} \gamma^\mu v_{\bar{h}'}][\bar{v}_{\bar{h}} \gamma_\mu u_h]$$

Coupling to gauge boson

$$C_{e_L Z} = C_{\mu_L Z} = g_Z(-1/2 + \sin^2 \theta_W),$$
$$C_{e_R Z} = C_{\mu_R Z} = g_Z \sin^2 \theta_W,$$
$$C_{e_L \gamma} = C_{e_R \gamma} = C_{\mu_L \gamma} = C_{\mu_R \gamma} = -e \qquad g_Z = e/(\sin \theta_W \cos \theta_W)$$

Amplitude (2)

Photon and Z boson propagator

$$D_{VV'}^{\text{SM}}(q^2) = \frac{\delta_{VV'}}{q^2 - m_V^2},$$

$$D_{VV'}^{\psi}(q^2) = \frac{q^2}{(q^2 - m_V^2)(q^2 - m_{V'}^2)} \delta\Pi_{VV'}(q^2, m)$$

where,

$$\delta\Pi_{\gamma\gamma}(q^2, m) = \delta\Pi_{WW}(q^2, m)\sin^2\theta_W + \delta\Pi_{BB}(q^2, m)\cos^2\theta_W,$$

$$\delta\Pi_{ZZ}(q^2, m) = \delta\Pi_{WW}(q^2, m)\cos^2\theta_W + \delta\Pi_{BB}(q^2, m)\sin^2\theta_W,$$

$$\delta\Pi_{\gamma Z}(q^2, m) = \left[\delta\Pi_{WW}(q^2, m) - \delta\Pi_{BB}(q^2, m)\right]\sin\theta_W\cos\theta_W$$