Probing Top Quark with Diphoton at Hadron Colliders

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- Top quark mass
  - A fundamental parameter of the Standard Model Lagrangian
 - Validity of SM
  - EW vacuum stability

- Top quark mass measurement ($pp \rightarrow t + X \rightarrow leptons + jets + missing\ energy$)
  - Kinematical reconstruction of top decay
    e.g., CMS (2015) $m_{t,MonteCarlo} = 172.44 \pm 0.48$ GeV
    MC mass is not a well defined mass in any renormalization scheme
  - Alternative methods: cross sections $\sigma_{t\bar{t}}$ and $\sigma_{t\bar{t}+1\ jet}$, the J/ψ method,
    the endpoint of $m_{l+b\ jet}$, the L_{xy} method, boost invariant energy peak,
    and leptonic observable methods

Ultimate
Uncertainty
$\Lambda_{QCD} \sim 200$ MeV
CMS-PAS-FTR-13-017

- Lepton Colliders Threshold scan $\delta m_{t,1S} \approx O(20\sim50)$ MeV
- Hadron Colliders using $t\bar{t}$ annihilation to diphoton ($t\bar{t} \rightarrow \gamma\gamma$)
  - Advantage : no jet, 1S mass   - Disadvantage : small number of events

Continuum Study

u, d, s, c, b, top
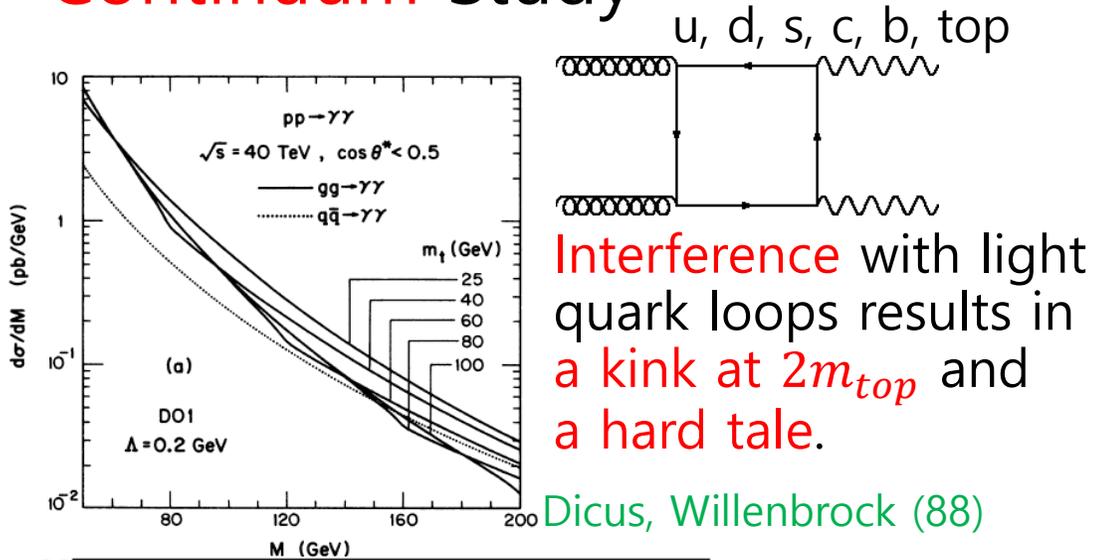
Interference with light quark loops results in a kink at $2m_{top}$ and a hard tale.

Dicus, Willenbrock (88)

$\sigma_{gg}(m_t+5l_f)/\sigma_{gg}(5l_f)$

$6l_f$ (dashed)
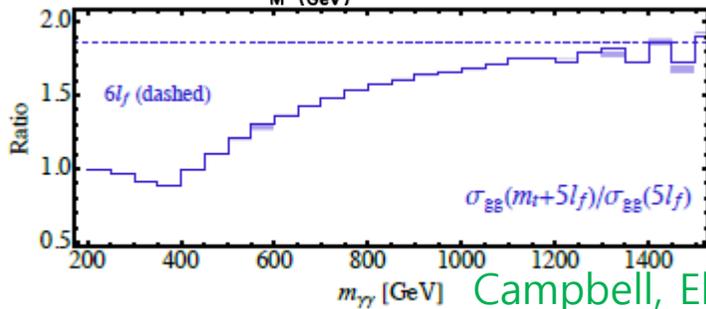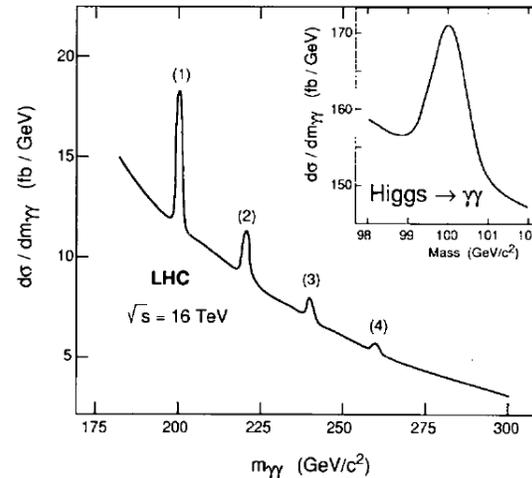
Campbell, Ellis, Li, Williams (16)

Coulomb singularity, α_s/β, at the threshold should be taken into account.

Bound State Study (Toponium)

Pancheri, Revol, Rubbia (92)

$$\sigma(pp \to \eta_t \to \gamma\gamma) = PDF_{gg}\,\sigma(gg \to \eta_t)\frac{\Gamma(\eta_t \to \gamma\gamma)}{\Gamma_{\eta_t}}$$

Large $m_{top} \Rightarrow$ Large $\Gamma_{\eta_t} \sim 2\Gamma_t \Rightarrow$ Small signal

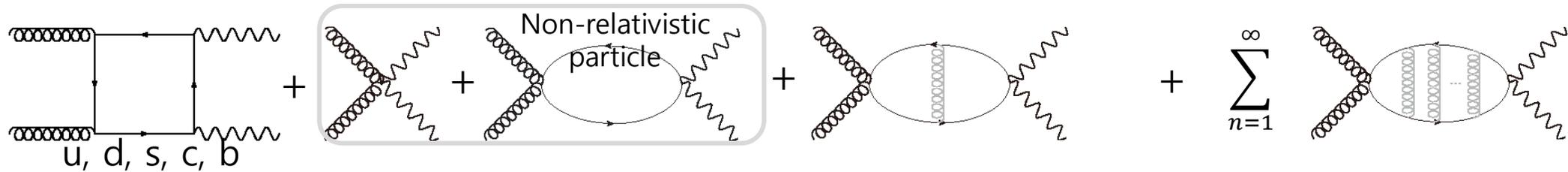Is m_{top}=173 GeV too heavy to see the B.S. shape?

Large width or small charge
$\Rightarrow$ interference is important and NWA fails
$\Rightarrow$ need to know amplitude of bound state

For a general particle charged under $SU(3)_C$ and $U(1)_{EM}$, we obtained amplitudes.
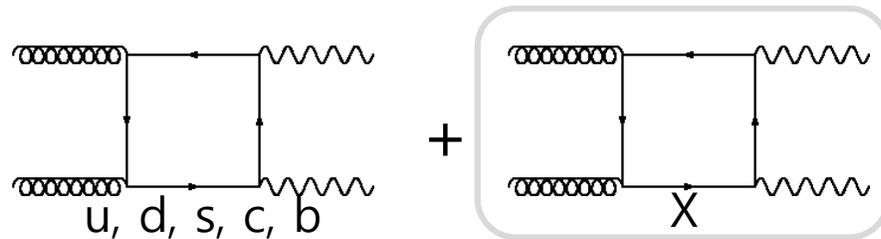arXiv:1512.08221 (Published in PRL) and arXiv:1612.05031 (Submitted to PRD)

Near the threshold $2m_X + E$, using NR EFT, for each polarization $\Lambda = (\lambda_{g1}, \lambda_{g2}, \lambda_{\gamma1}, \lambda_{\gamma2})$,
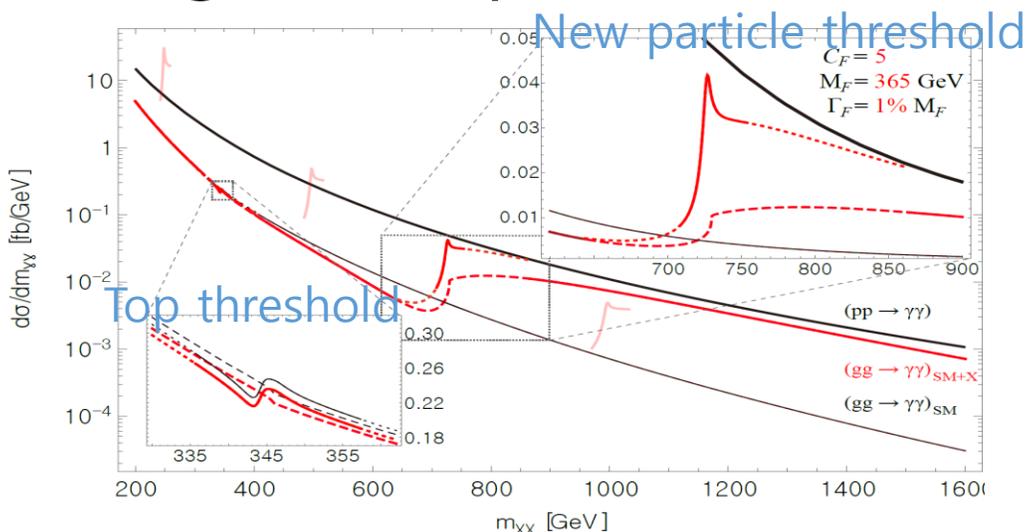

Non-relativistic particle

u, d, s, c, b

$$\mathcal{M}^{\Lambda}_{u,d,s,c,b} + A^{\Lambda}(\mu) + B^{\Lambda}\left(\sqrt{\frac{-E}{m_X}} - C\alpha_S(\mu)\ln\left(\frac{\mu}{\sqrt{-m_X E}}\right) - \frac{2}{\sqrt{m_X}}\sum_{n=1}^{\infty}\frac{E_n}{\sqrt{-E} - Sign(C)\sqrt{E_n}}\right).$$

Obtained by integrating out the relativistic part of the loop particle.
Real. Counterterm. Not Euler-Heisenberg form. Melnikov, Spira, Yakovlev (94)

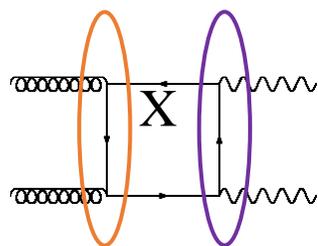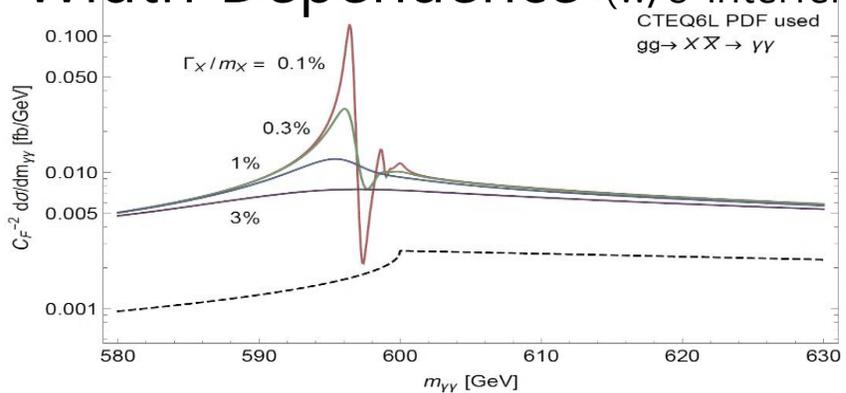Far from the threshold,

u, d, s, c, b

X

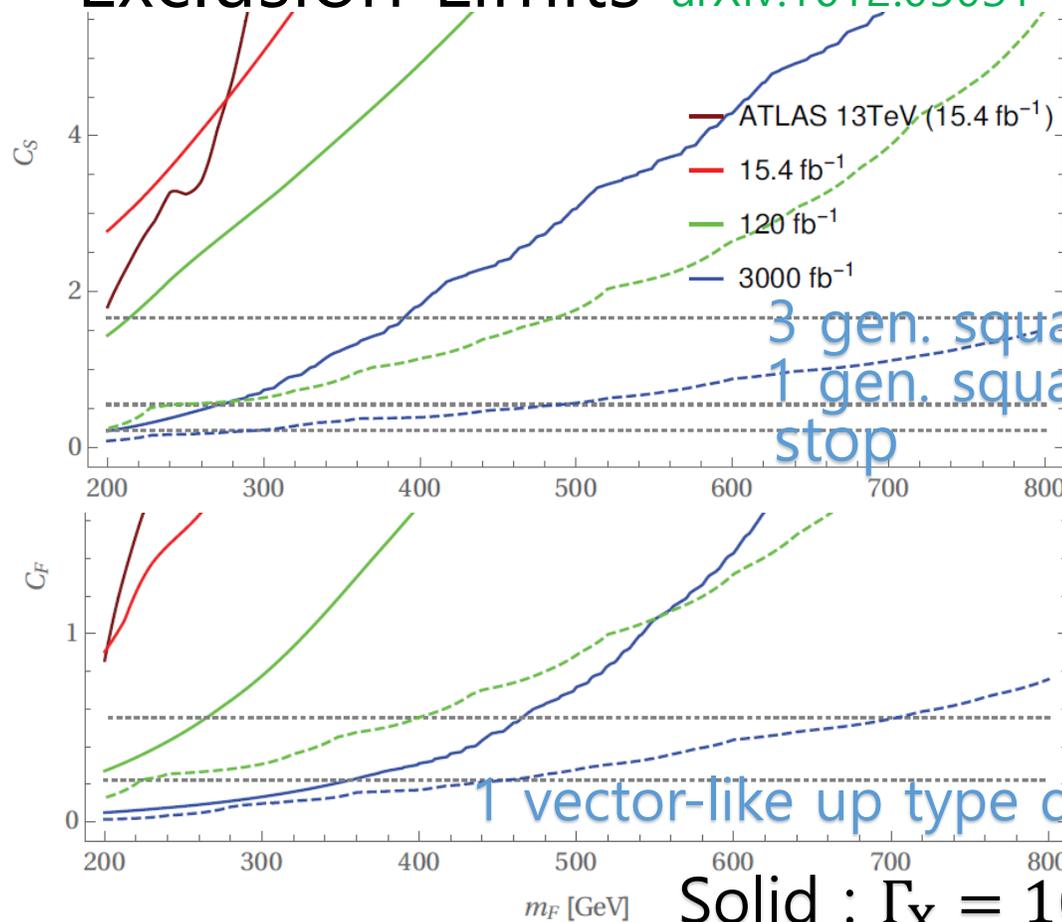Dongjin Chway   Pheno 2017

Signal shapes

New particle threshold

$C_F = 5$
$M_F = 365$ GeV
$\Gamma_F = 1\% \, M_F$

Top threshold

$(pp \to \gamma\gamma)$
$(gg \to \gamma\gamma)_{SM+X}$
$(gg \to \gamma\gamma)_{SM}$

Width Dependence (w/o interference)

CTEQ6L PDF used
$gg \to X\bar{X} \to \gamma\gamma$

$\Gamma_X / m_X = 0.1\%$
0.3%
1%
3%

Exclusion Limits arXiv:1612.05031

Electric charge
SU(3) Dynkin index

$\propto C_X \equiv N_X T_{R_X} Q_X^2$

ATLAS 13TeV (15.4 fb^{-1})
15.4 fb^{-1}
120 fb^{-1}
3000 fb^{-1}

3 gen. squarks
1 gen. squarks
stop

1 vector-like up type quark

Solid : $\Gamma_X = 10^{-2} m_X$
Dashed : $\Gamma_X = 10^{-4} m_X$

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Observing Top Quark with Diphoton

$$\frac{d\sigma(gg \to \gamma\gamma)_{SM} / dm_{\gamma\gamma}}{d\sigma(gg \to \gamma\gamma)_{SM-\{top\}} / dm_{\gamma\gamma}}$$

$0.02\ fb/GeV \times 100\ GeV \approx 2\ fb$

$0.04\ fb/GeV \times 20\ GeV \approx 0.8\ fb$
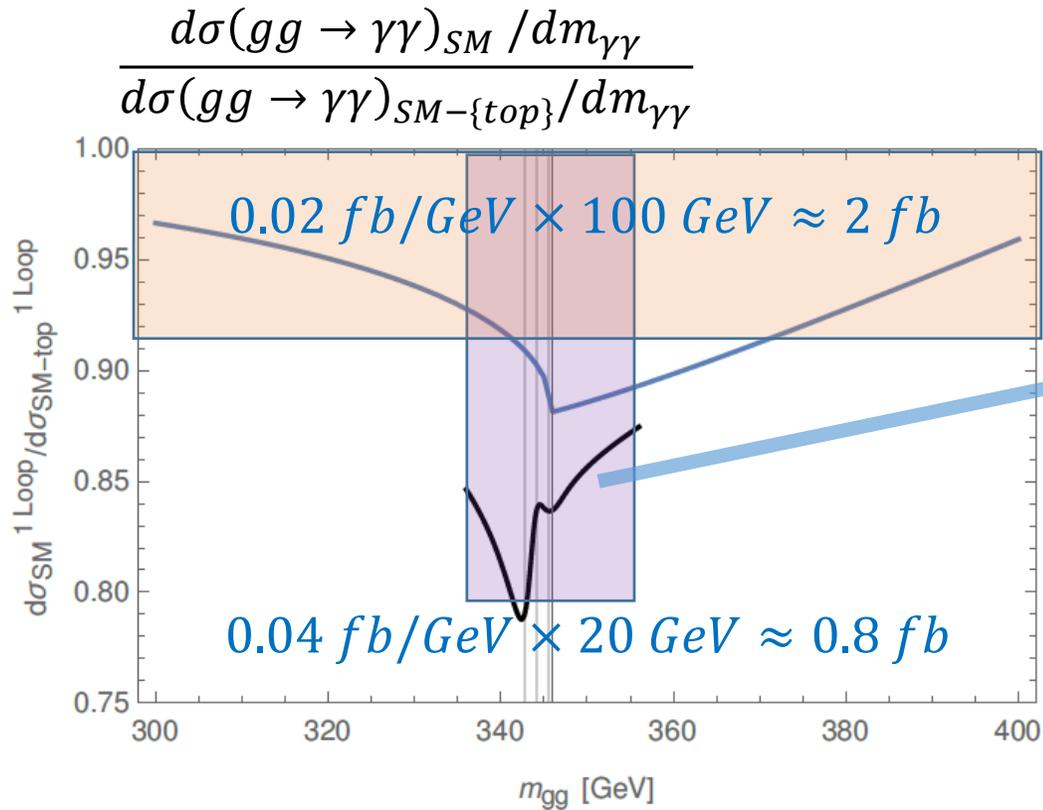
$\frac{S}{\sqrt{B}} = 2\ or\ 5 \ \to 100\ fb^{-1}\ or\ 600\ fb^{-1}$

This structure near the threshold mostly comes from the 1S state.

$2m_{t,1S} - \Gamma_t$

$2m_{t,1S}$

$2m_{t,1S} + \Gamma_t$

Need to modify smooth fitting for $pp \to \gamma\gamma$ to take into account the top quark contribution.

Preliminary result
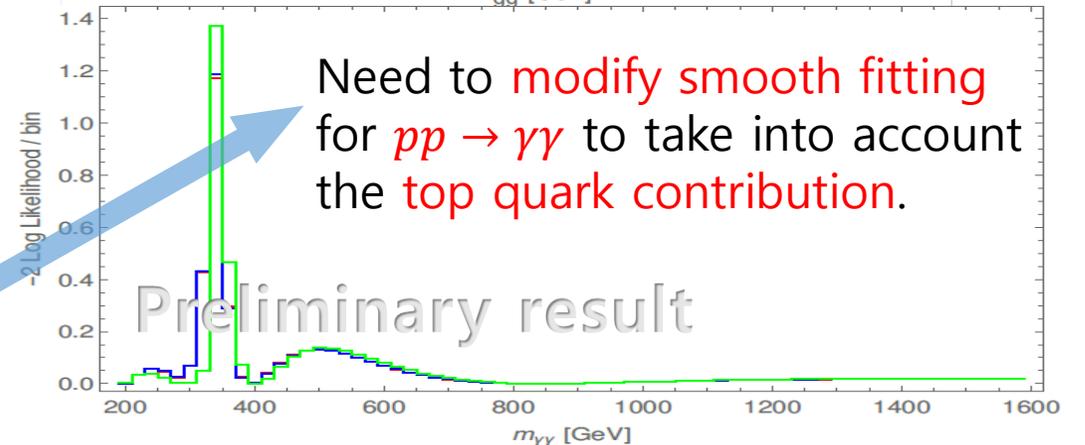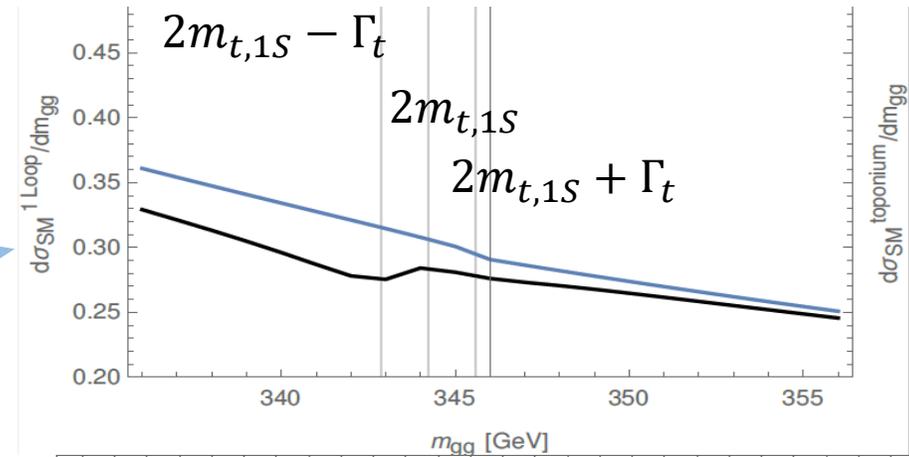
Top mass (and width) measurement

LHC 13 TeV, gg → γγ
CT10NLO, $\mu_R = \mu_F = m_{\gamma\gamma}$
G_{LO} with $\bar{\mu}(m_{\gamma\gamma})$, $\Gamma_t = 1.41$ GeV
$|\eta_\gamma| < 2.5$, $p_T^\gamma > 40$ GeV

Preliminary result
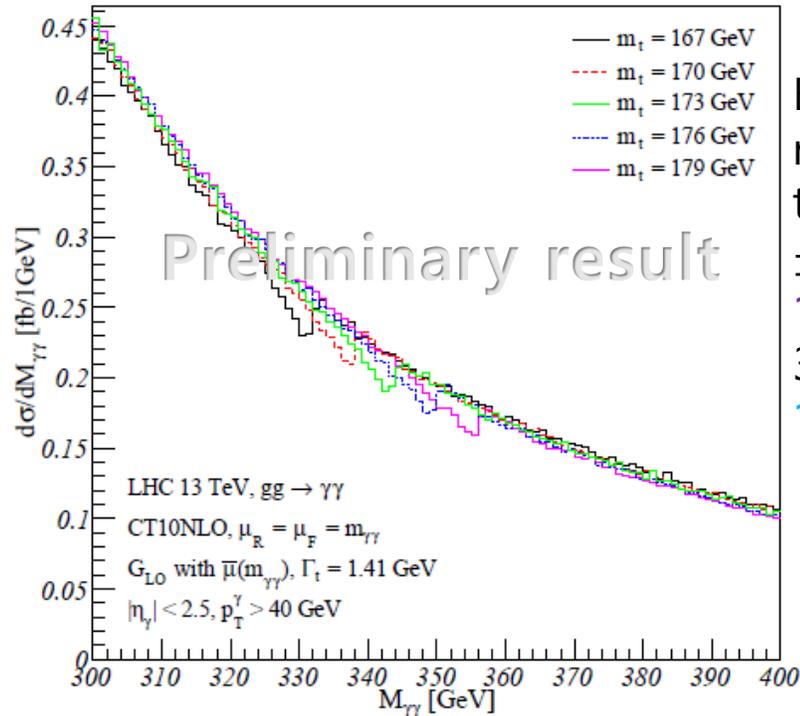
Ballpark estimate on the required integrated luminosity to obtain the top mass with ±1 GeV (100 MeV) precision:
13 TeV LHC 2 ab^{-1} (200 ab^{-1}),
33 TeV HC 250 fb^{-1} (25 ab^{-1}),
100 TeV HC 20 fb^{-1} (2 ab^{-1}).

LHC 13 TeV, gg → γγ
CT10NLO, $\mu_R = \mu_F = m_{\gamma\gamma}$
G_{LO} with $\bar{\mu}(m_{\gamma\gamma})$, $M_t = 173$ GeV
$|\eta_\gamma| < 2.5$, $p_T^\gamma > 40$ GeV

Preliminary result

172 v.s. 173
Log likelihood
from each bin

Preliminary result

Because of the 1S shape, it is also possible to measure the width of the top quark.

Summary

- Old study focused either on (narrow width) toponium production or continuum computation.

- We have studied interference of bound state amplitude in diphton channel.

- Exclusion limits on the $SU(3)_C$ times $U(1)_{EM}$ charge of new particles were obtained.

- Top contribution to diphoton mass spectrum will be visible in near future. (2σ at 100 fb^{-1} and 5σ at 600 fb^{-1})

- Free from jet physics, top mass measurement with precision 1 GeV (100 MeV) will be possible with the integrated luminosity 2 ab^{-1} in LHC (in 100 TeV HC).