# Top precision with diphotons at the LHC

SNU BRL workshop
2017. 6. 17

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with D Chway, R Dermisek, T H Jung (+W Cho, D Lee)

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The LHC has discovered something quite unexpected : the Higgs boson and nothing else, confirming the Standard Model.

Moriond, March 29 2017 – p. 2

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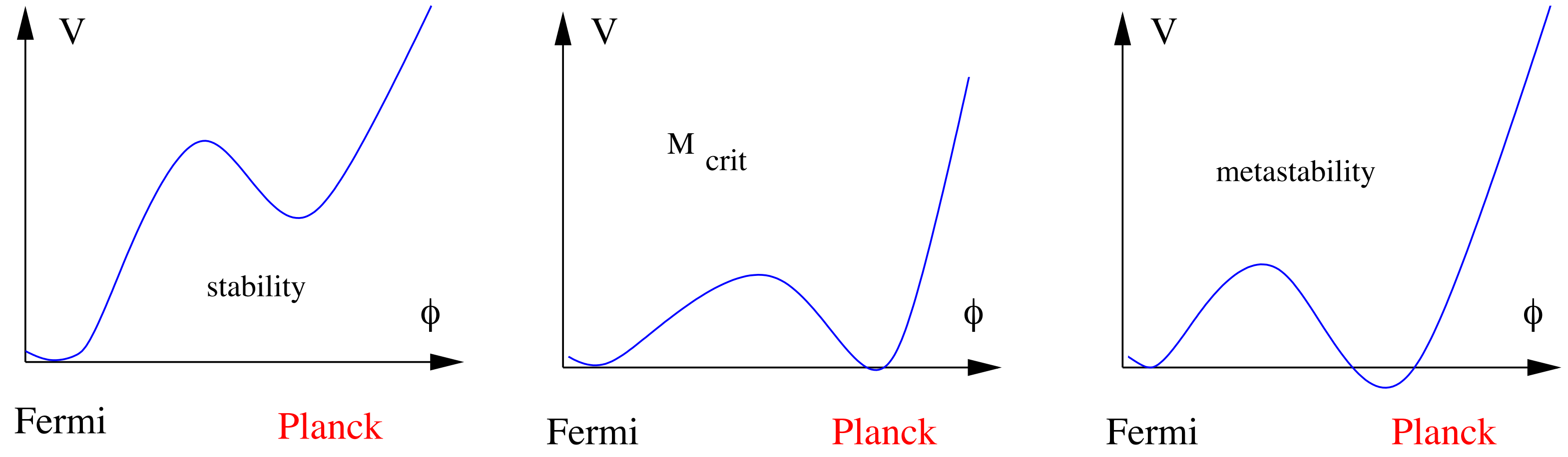
No low energy SUSY, no large extra dimensions, no new strong interactions.

For $125$ GeV Higgs mass the Standard Model is a self-consistent weakly coupled effective field theory for all energies up to the quantum gravity scale $M_P \sim 10^{19}$ GeV

Moriond, March 29 2017 – p. 2

- Marginal evidence (less than $2\sigma$) for the SM vacuum metastability given uncertainties in relation between Monte-Carlo top mass and the top quark Yukawa coupling

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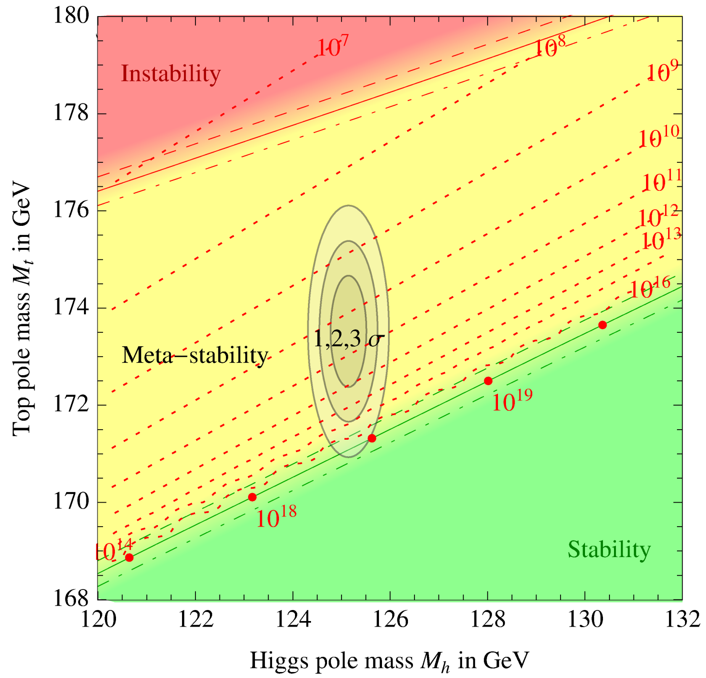
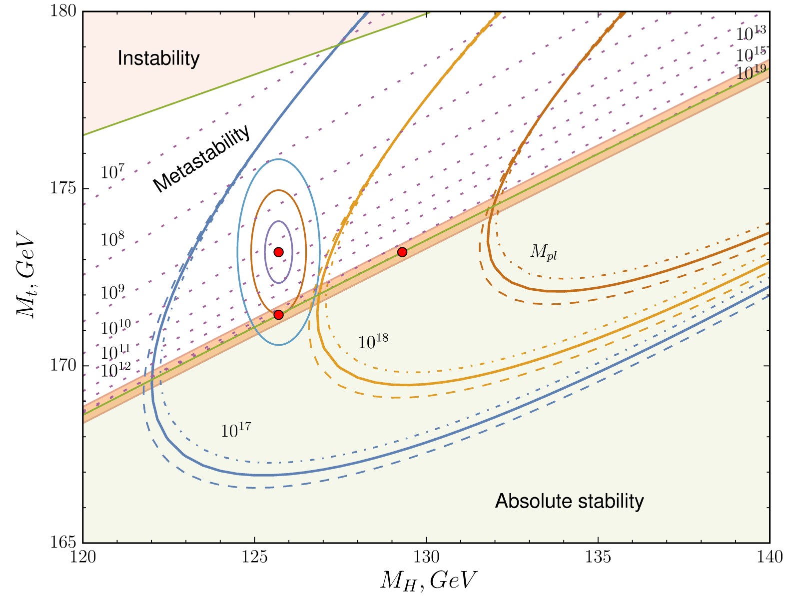


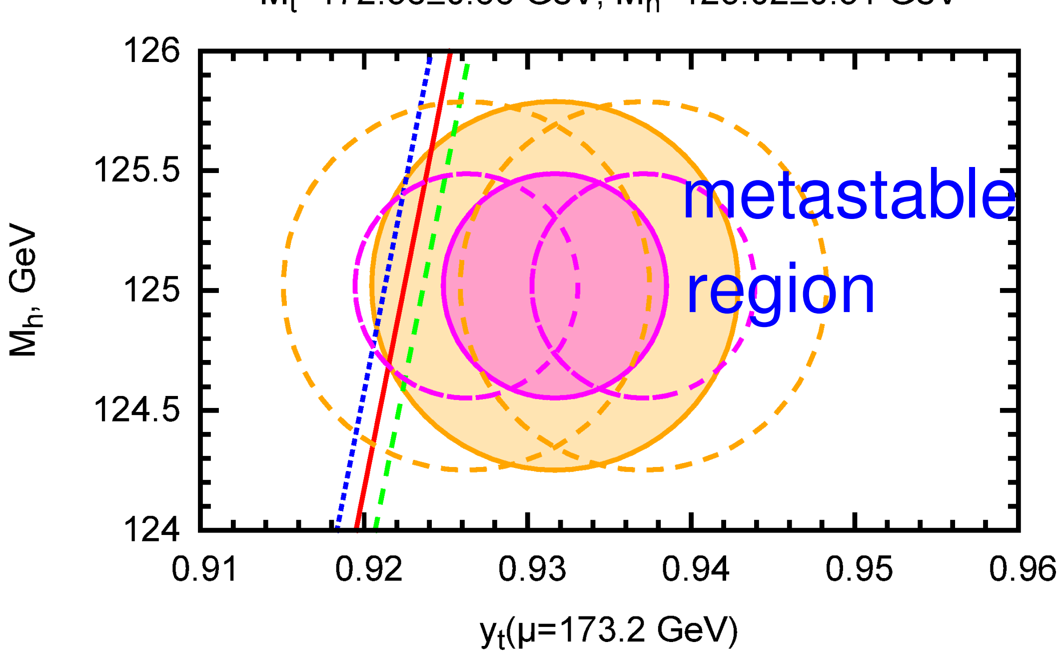

Buttazzo et al, ’13, ’14:

vacuum is unstable at $\mathbf{2.8\sigma}$

Bednyakov et al, ’15:

vacuum is unstable at $\mathbf{1.3\sigma}$

Bezrukov, MS updated




Main uncertainty: top Yukawa coupling, relation between the MC mass and the top Yukawa coupling allows for $\pm 1$ GeV in $M_{top}$. Alekhin et al, Frixione et al.

# Glue to light signal of a new particle

PRL **117,** 061801 (2016) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2016

## Gluons to Diphotons via New Particles with Half the Signal's Invariant Mass

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(Received 1 May 2016; published 5 August 2016)

Any new particle charged under $SU(3)_C$ and carrying an electric charge will leave an imprint in the diphoton invariant mass spectrum, as it can mediate the $gg \to \gamma\gamma$ process through loops. The combination of properties of loop functions, threshold resummation, and gluon parton distribution functions can result in a peaklike feature in the diphoton invariant mass around twice the mass of a given particle even if the particle is short lived, and thus it does not form a narrow bound state. Using a recent ATLAS analysis, we set upper limits on the combined $SU(3)_C$ and electric charge of new particles and indicate future prospects. We also discuss the possibility that the excess of events in the diphoton invariant mass spectrum around 750 GeV originates from loops of a particle with a mass of around 375 GeV.

DOI: 10.1103/PhysRevLett.117.061801

Model independent search strategy
for colored and charged (new) particles in diphoton channel at LHC.

## Pros and Cons : Signal of New Physics?

Pro

: Diphoton channel is very clean
: Repetition of Higgs discovery
: Both in ATLAS and CMS

Con

: Excess is close to the event tail
: Not in ttbar, jj, ll
: So many 2 sigma bumps in CMS
: Strong coupling is necessary
(cross section*Br is too big)
: No motivated BSM can explain it

We have to wait till summer or the end of the year

Independently of the result, it would be a great opportunity for postdocs and students

It can also stimulate some ideas

# Physics of ambulance chasing


One success in 2012 Dec.
: precursor of Higgs discovery

Many other failures
: Many B physics anomalies
Tevatron W+dijet,
dimuon charge asymmetry,
top A_FB,
DAMA/LIBRA,
CoGeNT,
PAMELA,
140 GeV Higgs (WW*)
BICEP2

$$gg \to \gamma\gamma$$

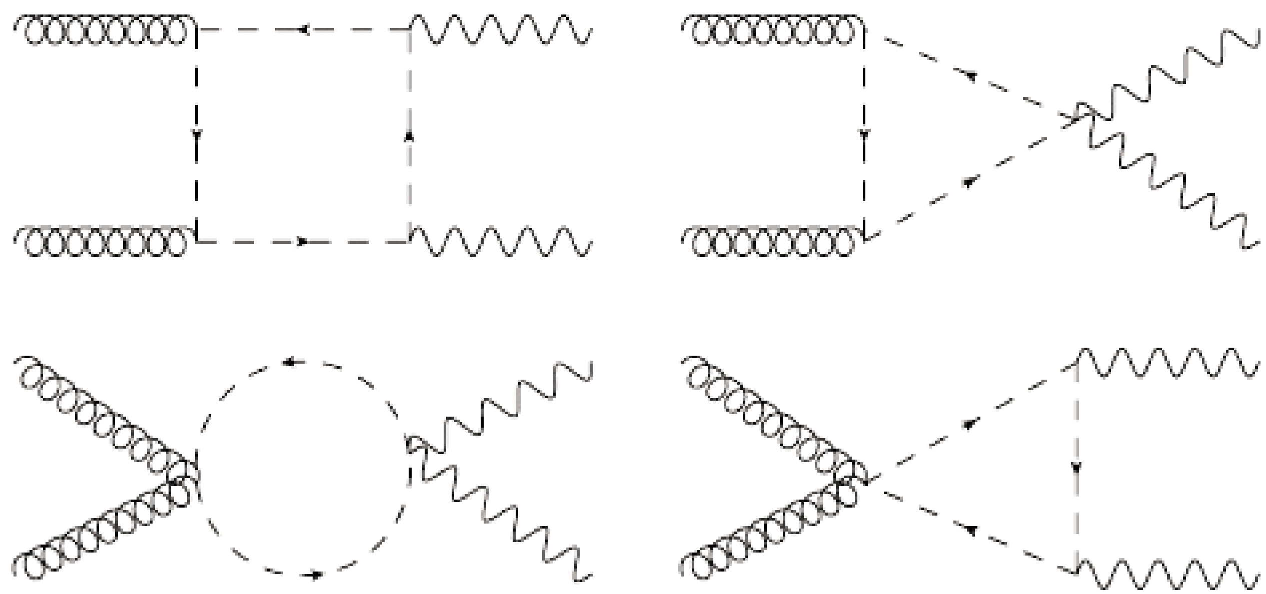
There is no tree level vertex in the Standard Model

$q\bar{q} \to \gamma\gamma$ is the leading background for di-photon events

Any new particle which is produced from gluon fusion
and decays into di-photons will be discovered easily
from the invariant mass of the di-photon spectrum

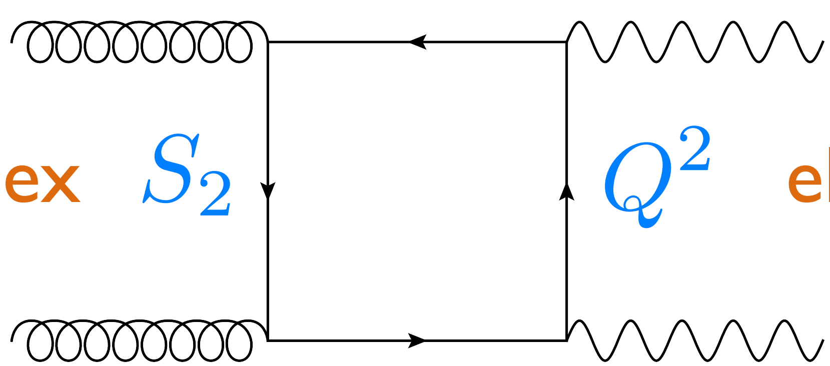
# $gg \to \gamma\gamma$

## Scalar



## Fermion

SU(3) Dynkin index $S_2$



$Q^2$ electric change

$C = N S_2 Q^2$ for N copies of the particles

Any new colored/charged particle will contribute to the loop of $gg \to \gamma\gamma$

Near threshold

Positronium

Hydrogen atom

Coulomb potential
(no running of couplings)
+IR free & frozen coupling

J/psi

Hydrogen atom?

Confining potential
(linear potential model)
+Coulomb in UV

Any quantitative approach possible?

Any quantitative approach possible?

If $m \gg mv \gg mv^2 \gg \Lambda_{\mathrm{QCD}}$

we can discuss quarkonium system perturbatively

Top quark and heavier

# Non-Relativistic(NR) QCD

Caswell and Lepage (1986)
Bodwin Braaten Lepage (1995)

$$m \gg mv \gg mv^2 \gg \Lambda_{\rm QCD}$$

Below m, heavy quark is integrated out

UV divergence comes from UV theory

no scale separation of m, mv, mv^2

the appearance of log v

$$
\begin{aligned}
&\text{hard} &:& \quad (k^0, \mathbf{k}) \sim (m, m)\,, \\
&\text{soft} &:& \quad (k^0, \mathbf{k}) \sim (mv, mv)\,, \\
&\text{potential} &:& \quad (k^0, \mathbf{k}) \sim (mv^2, mv)\,, \\
&\text{ultrasoft} &:& \quad (k^0, \mathbf{k}) \sim (mv^2, mv^2)
\end{aligned}
$$

e.g., scaling in v : $d^4k \sim \underset{\text{hard}}{v^0}, \ \underset{\text{soft}}{v^4}, \ \underset{\text{potential}}{v^5}, \ \underset{\text{ultrasoft}}{v^8}$

potential NRQCD
(pNRQCD)

Pineda Soto (1998)

$$\mathcal{L}_{\rm QCD} \qquad\qquad (\mu > m)$$
$$\Downarrow$$
$$\mathcal{L}_{\rm NRQCD} \qquad\qquad (m > \mu > mv)$$
$$\Downarrow$$
$$\mathcal{L}_{\rm pNRQCD} \qquad\qquad (mv > \mu > mv^2)$$

Integrated out at m and mv : two step

velocity NRQCD
(vNRQCD)

Luke Manohar Rothstein (2000)

matching at m

$$\mu_{\mathrm{U}} = \frac{\mu_{\mathrm{S}}^2}{m}$$

summing log (m/mv)
log (m/mv^2)
log (mv/mv^2)
at the same time

E,p,m

Take the velocity v as the running parameter

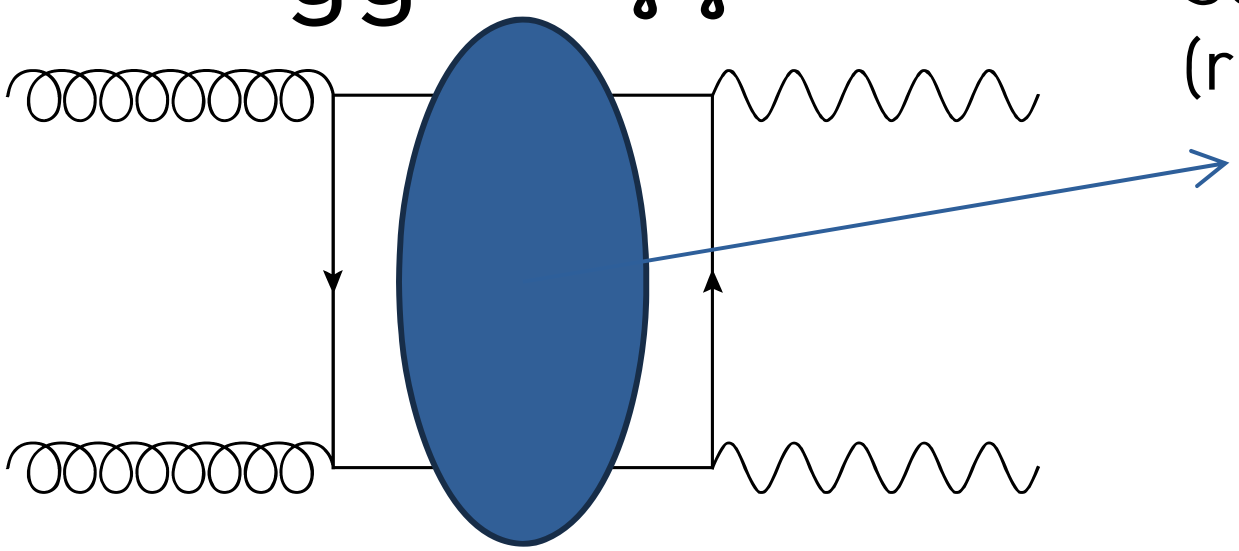
works only for $m \gg mv \gg mv^2 \gg \Lambda_{\mathrm{QCD}}$

# Near threshold

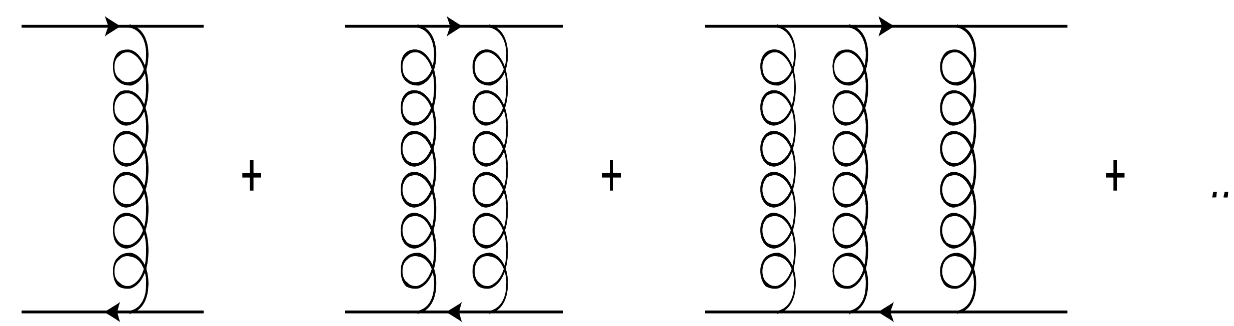
$$\frac{\alpha_s}{v} \qquad (\frac{\alpha_s}{v})^2 \qquad \cdots \qquad (\frac{\alpha_s}{v})^n$$

should be resummed

$gg \to \gamma\gamma$

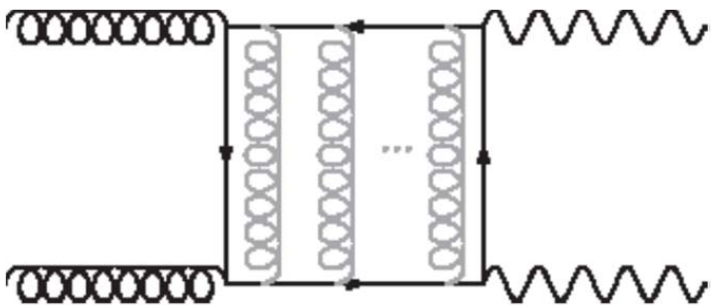
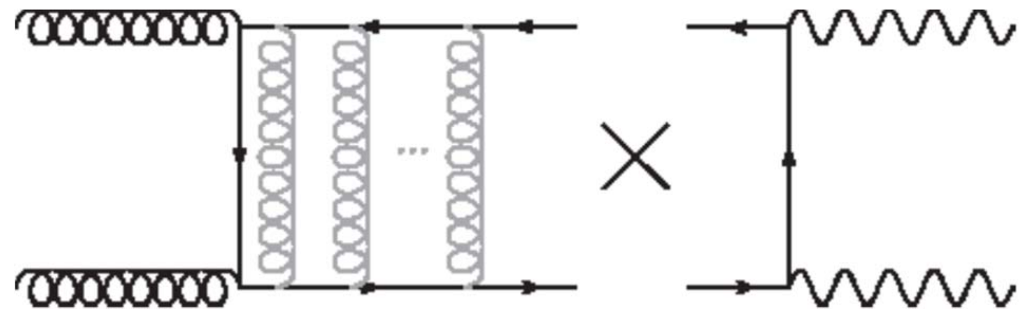


Sommerfeld enhancement near $m_{\gamma\gamma} = 2m_X$
(resummation of ladder diagrams)

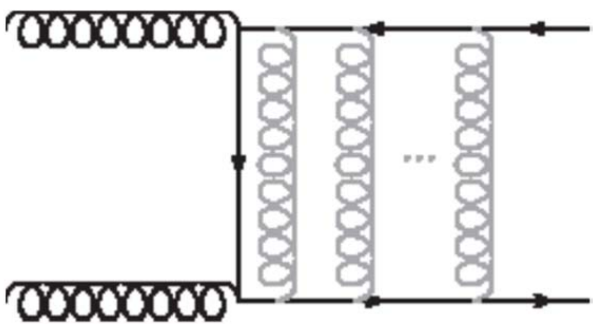
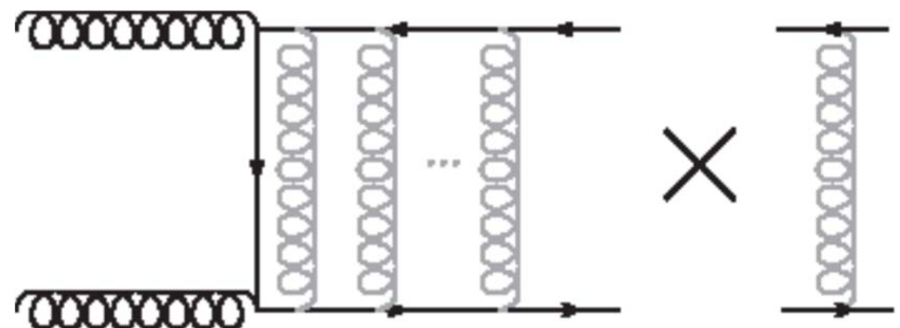


$$v_{\min} = \sqrt{\frac{\Gamma_X}{M_X}}$$ acts as a regulator if X has a finite width

# Higher loop

Im[  ] $\sim \int d\,\Phi_2$ 

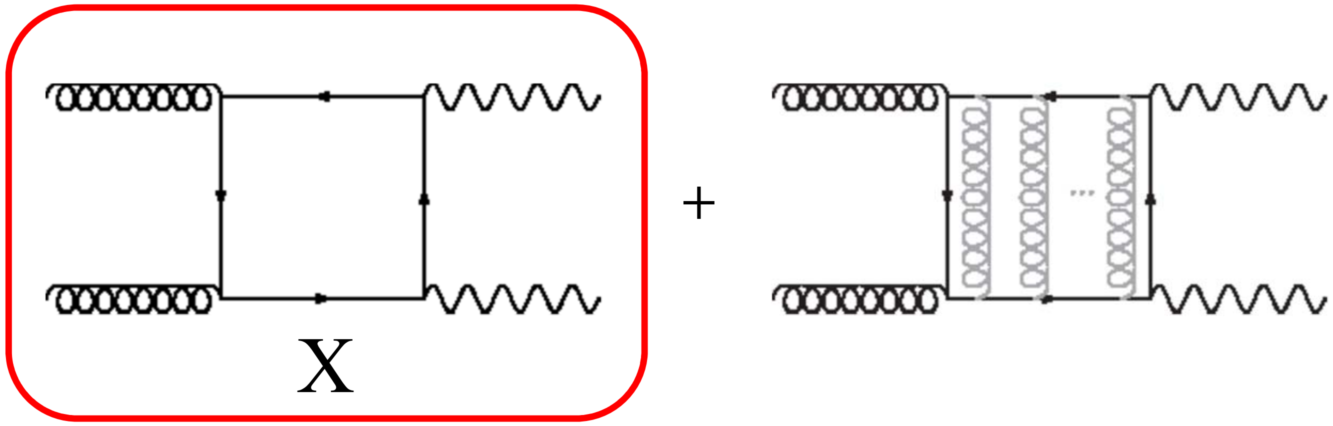
Cutkosky rule

Im[  ] $\sim \int d\,\Phi_2$  $\sim (\alpha/\beta)^n$

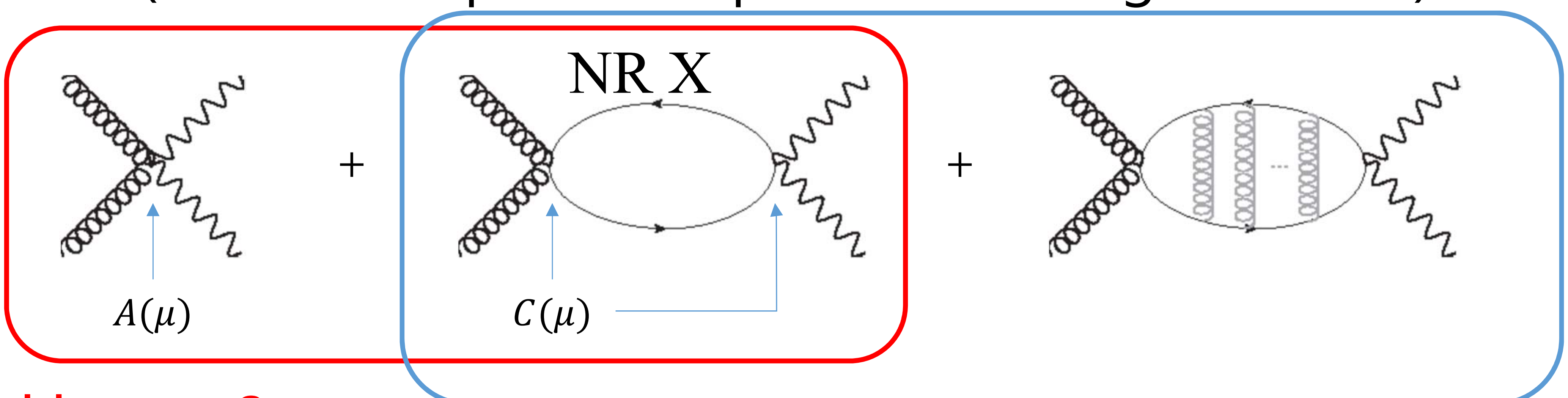
$n$ $\quad \beta \quad$ $n-1$ $\quad \alpha/\beta^2$

$\beta$ : Velocity of the loop particle

# Threshold Resummation




EFT (Relativistic part of X particle is integrated out)




Up to $\beta$

Self-consistency equation leads to
Schroedinger equation of Coulomb potential

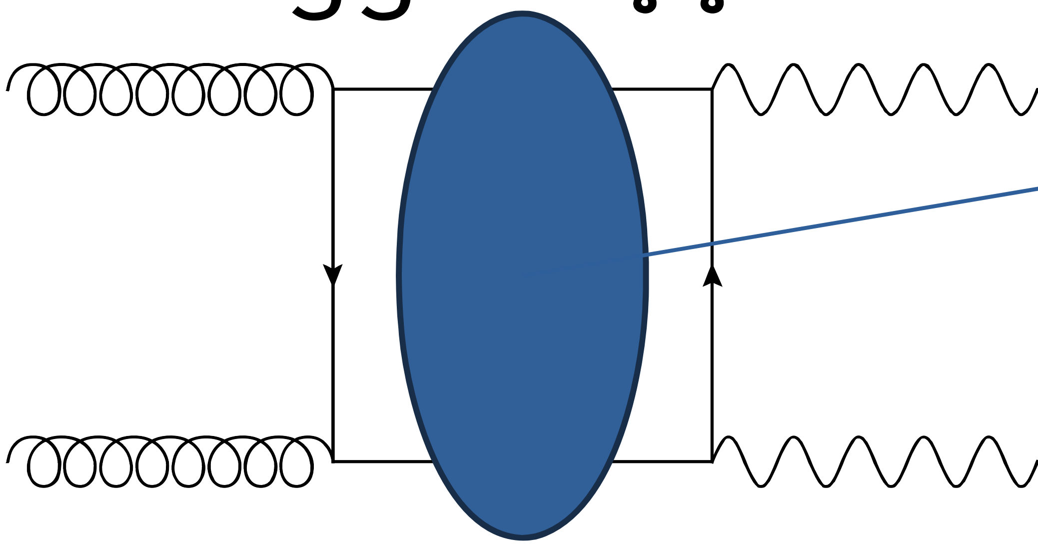
Strassler, Peskin (91)

## Near threshold

$$\frac{\alpha_s}{v} \qquad (\frac{\alpha_s}{v})^2 \qquad \cdots \qquad (\frac{\alpha_s}{v})^n$$

should be resummed

$gg \longrightarrow \gamma\gamma$



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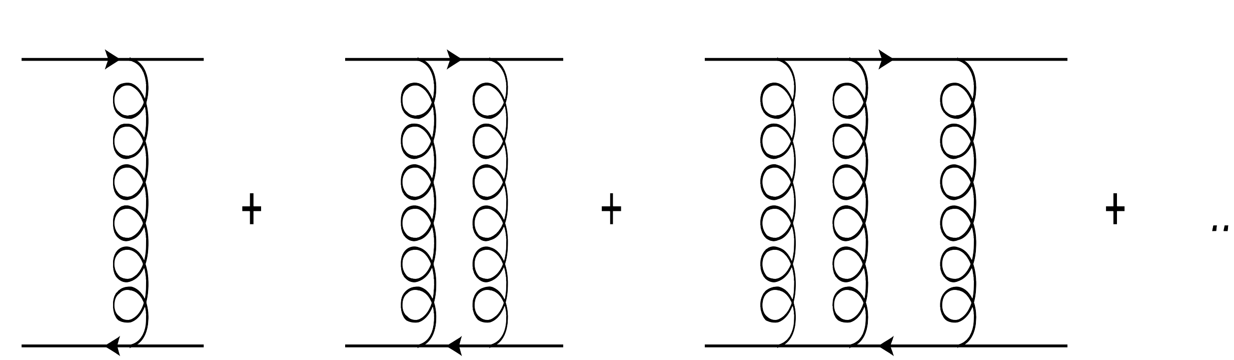



$$v_{\min} = \sqrt{\frac{\Gamma_X}{M_X}}$$ acts as a regulator if X has a finite width

## quarkonium physics

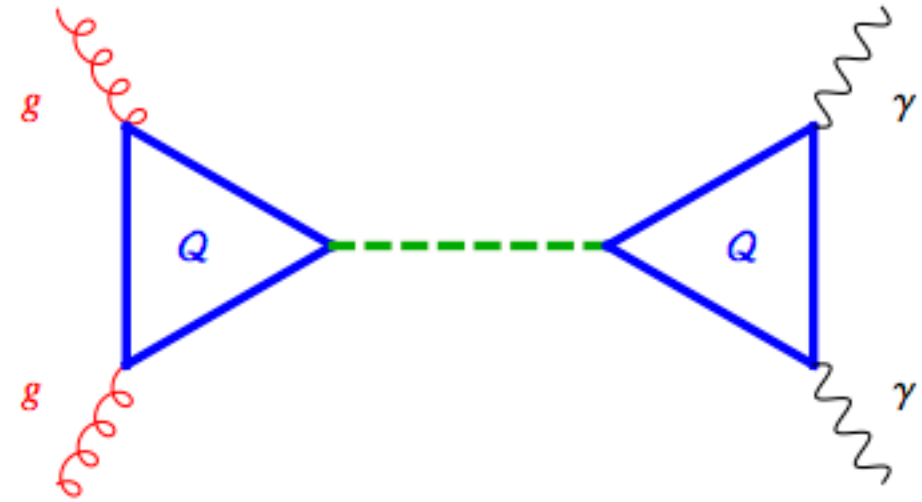
$$v = C_F \alpha_s$$

quadratic Casimir

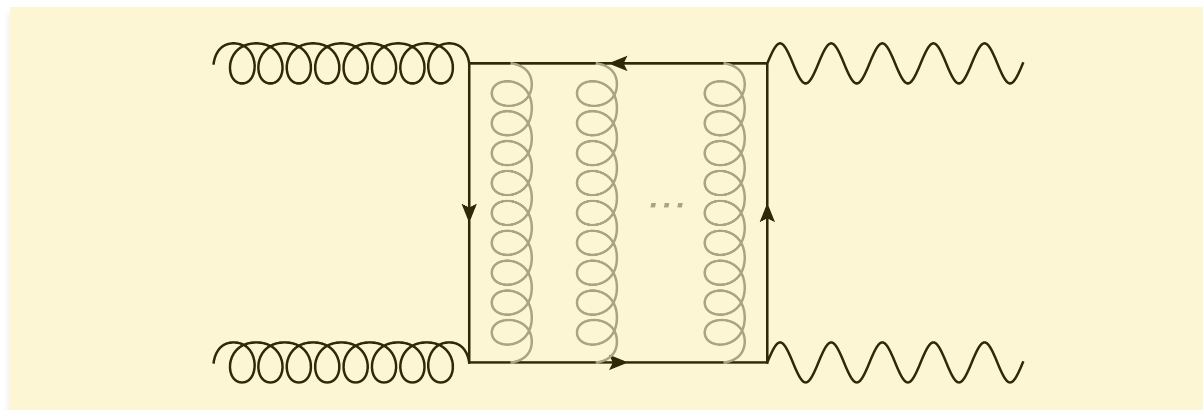
$$r = \frac{2}{m_q C_F \alpha_s}$$

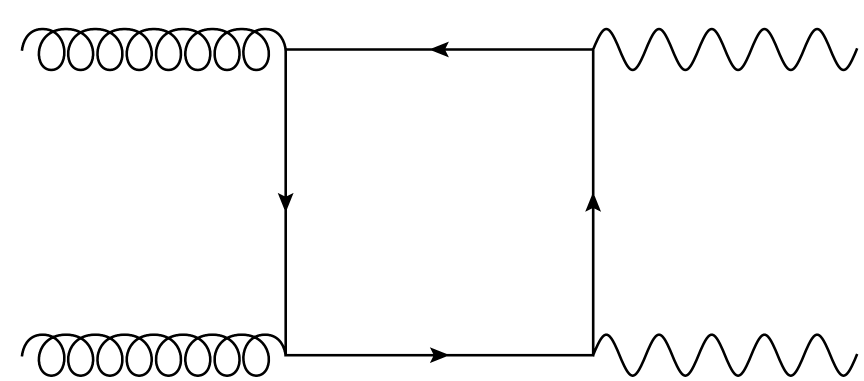
$$E_b = \frac{1}{2}\frac{m_q}{2} C_F^2 \alpha_s^2$$

Quarkonium : narrow width approximation




formalism developed here works
for small and large width
at the same time





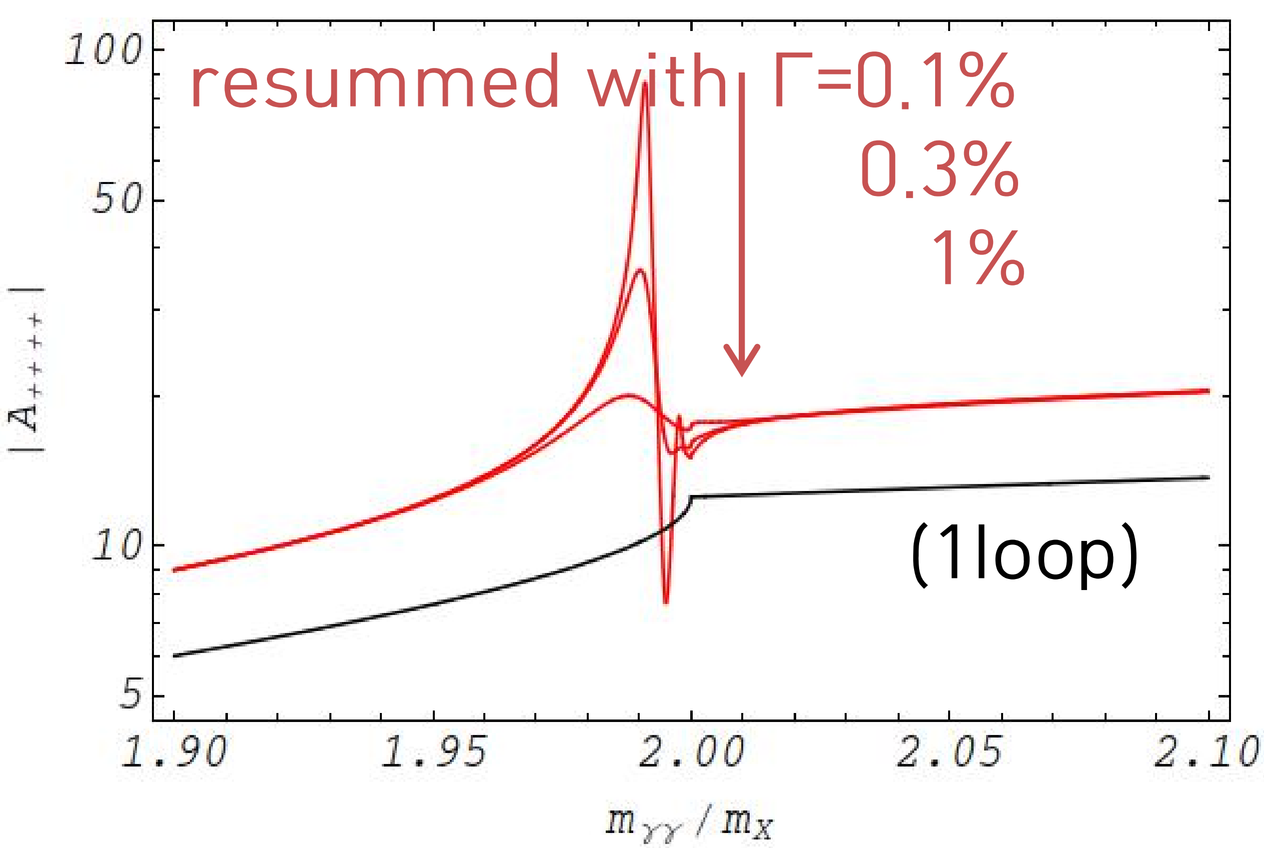
1 loop : breaks down at the threshold

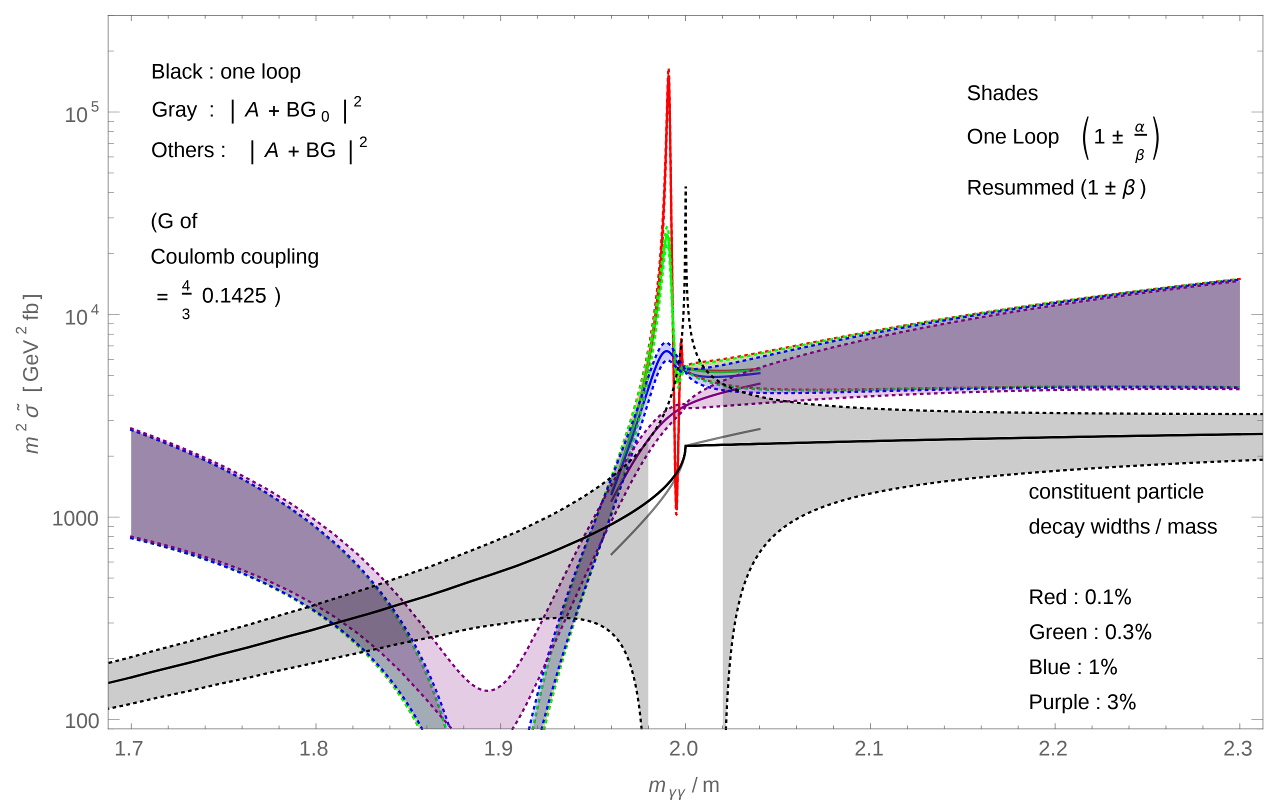
$$\left(\frac{\nabla^2}{m} + V(r) - E\right) G(\mathbf{r}, \mathbf{r}'; E) = \delta(\mathbf{r} - \mathbf{r}').$$

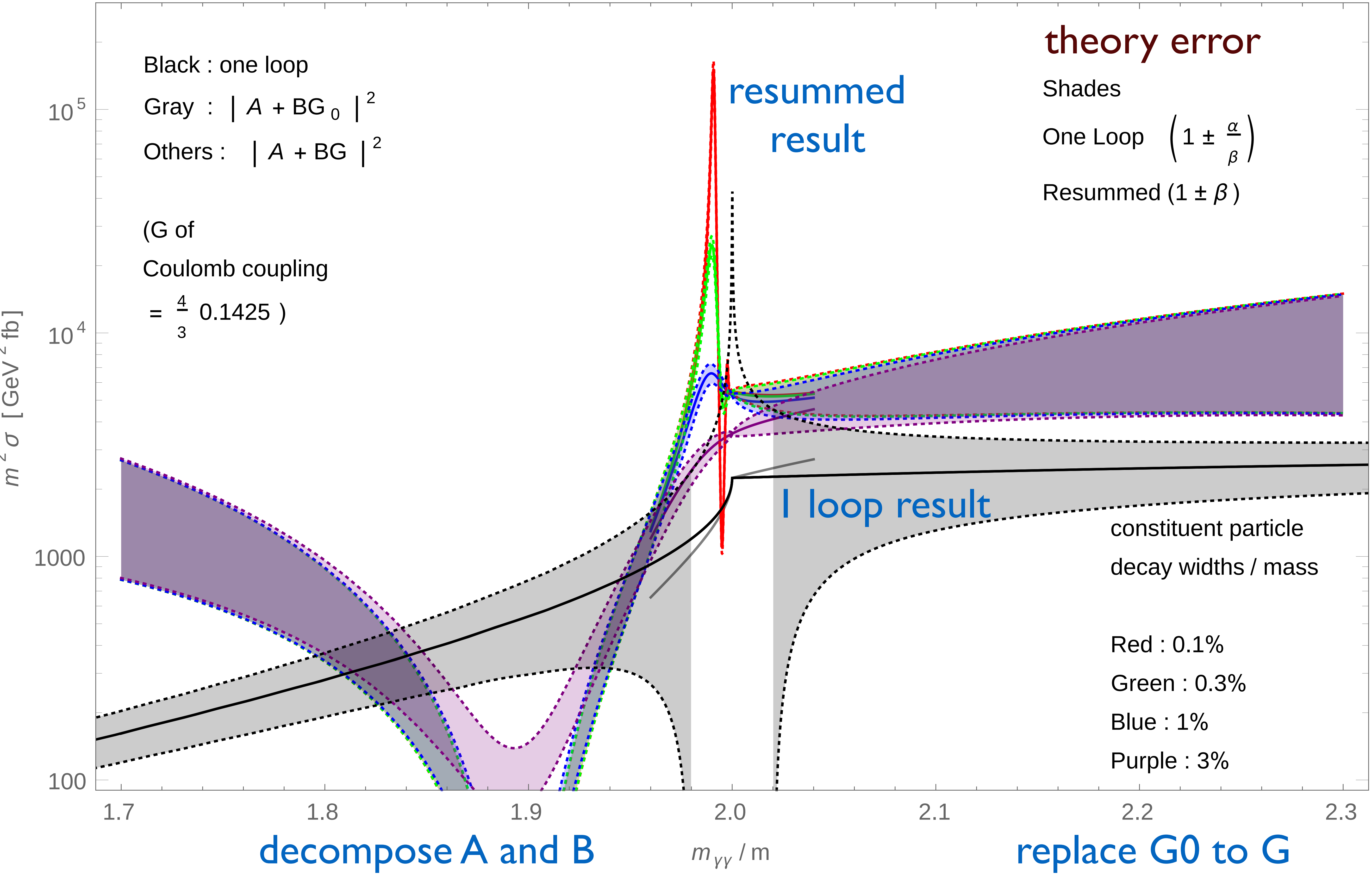
$$V(r) = -Y C_2(X) \frac{\alpha_S(\bar{\mu})}{r}$$ (Y > 1 from QED resummation)

free Green's function before resummation

$$G(0,0;E) = \frac{m_X^2}{4\pi}\left(\sqrt{-\frac{E}{m_X} - i\epsilon} - Y C_2(X)\alpha_S \ln\left(\frac{|Y C_2(X)|\alpha_S}{2}\sqrt{-\frac{m_X}{E} + i\epsilon}\right) - \frac{2}{\sqrt{m_X}} \sum_{n=1}^{\infty} \frac{E_n}{\sqrt{(-E - i\epsilon)} - \mathrm{sigr}}\right.$$






decompose A and B

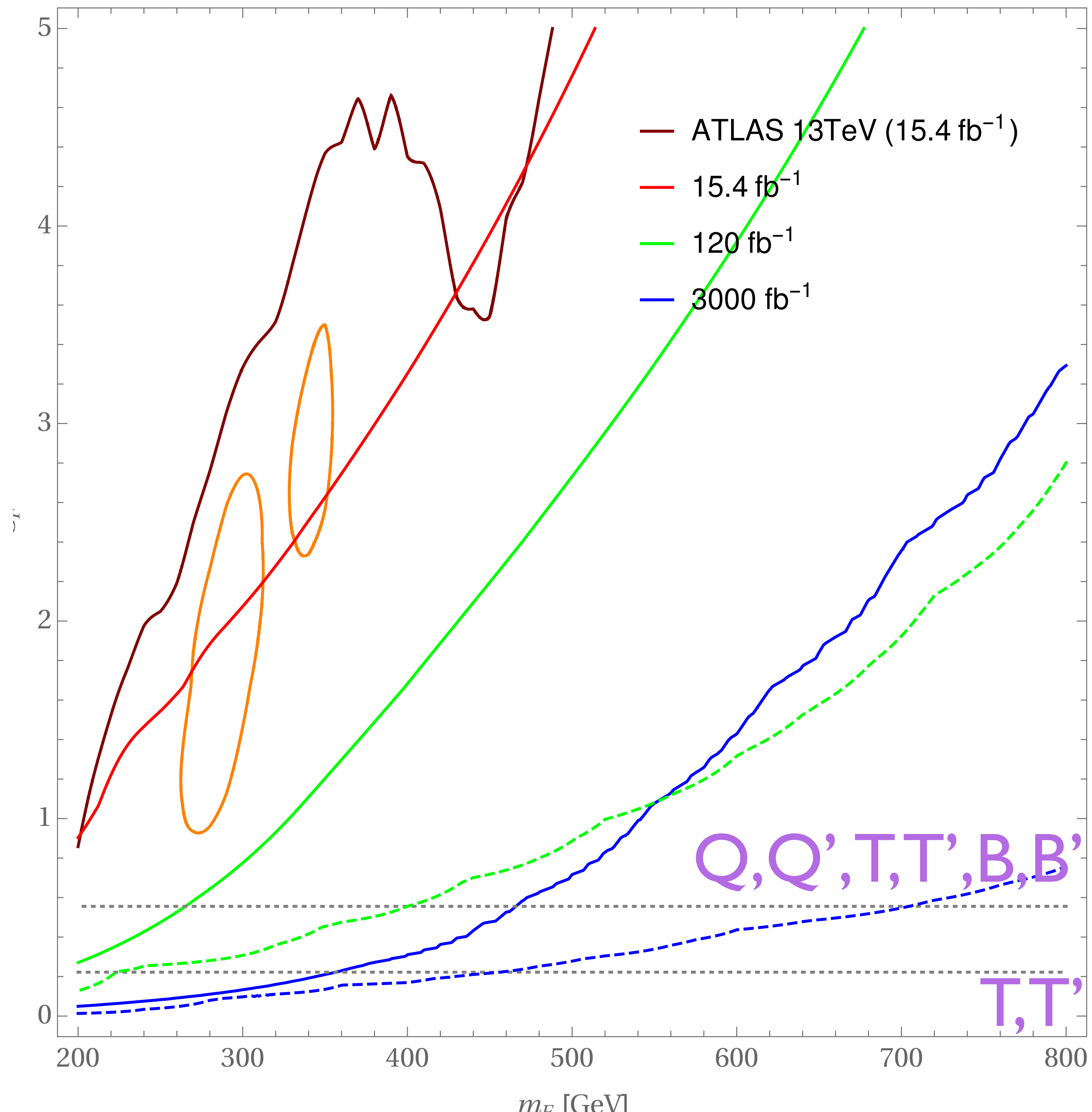
replace G0 to G

$$\mathcal{M} \simeq \mathcal{A} + \mathcal{B} \cdot G^{(0)}(\vec{0}, E + i\epsilon) \to \mathcal{A} + \mathcal{B} \cdot G(\vec{0}, E + i\Gamma_t)$$

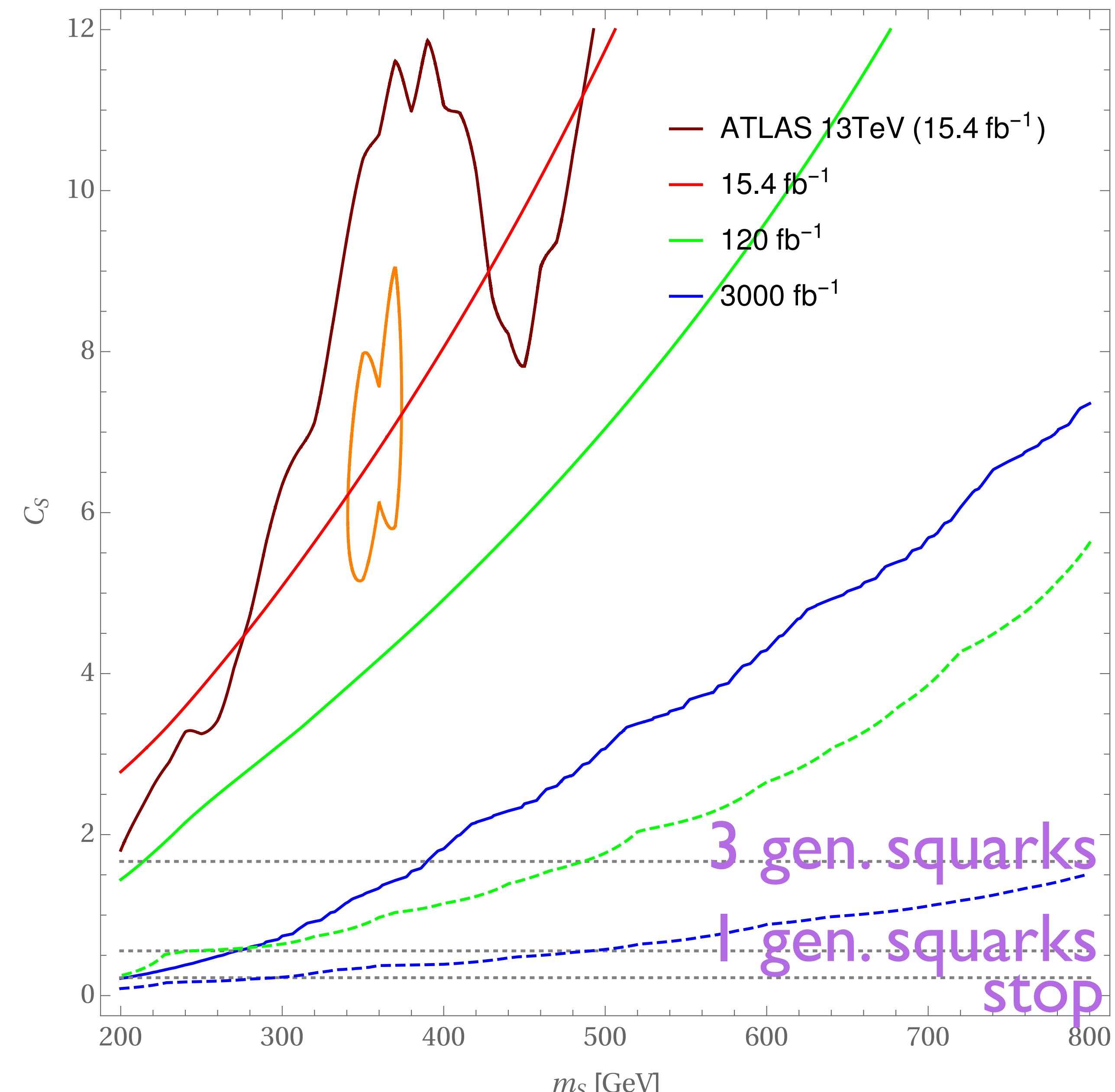
# exclusion or expected exclusion

arXiv:1612.05031

Fermion




Scalar




solid : $\Gamma = 10^{-2} m$

dotted: $\Gamma = 10^{-4} m$

$$C = S_2 Q^2$$

color charge

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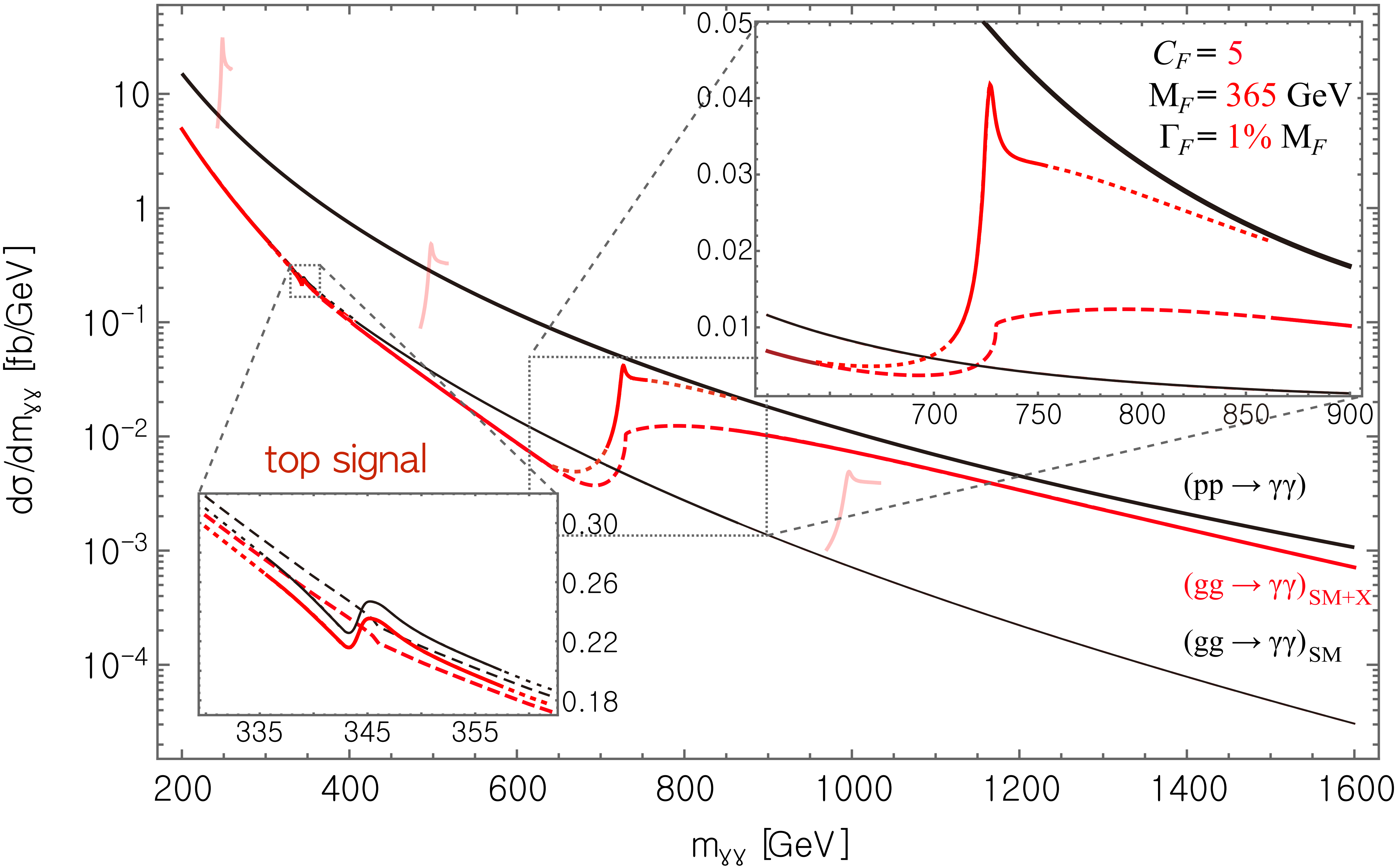


# Precise top mass determination is very important

Top mass precision at LHC : $\Lambda_{\rm QCD}$

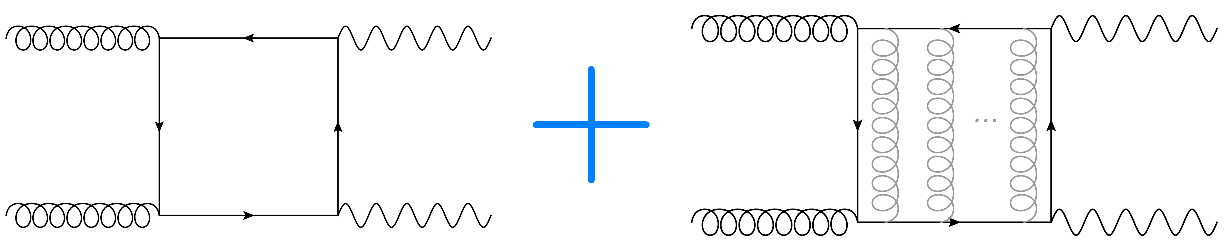
Top mass precision at ILC : 20 MeV

Can we overcome the huddle with diphotons?

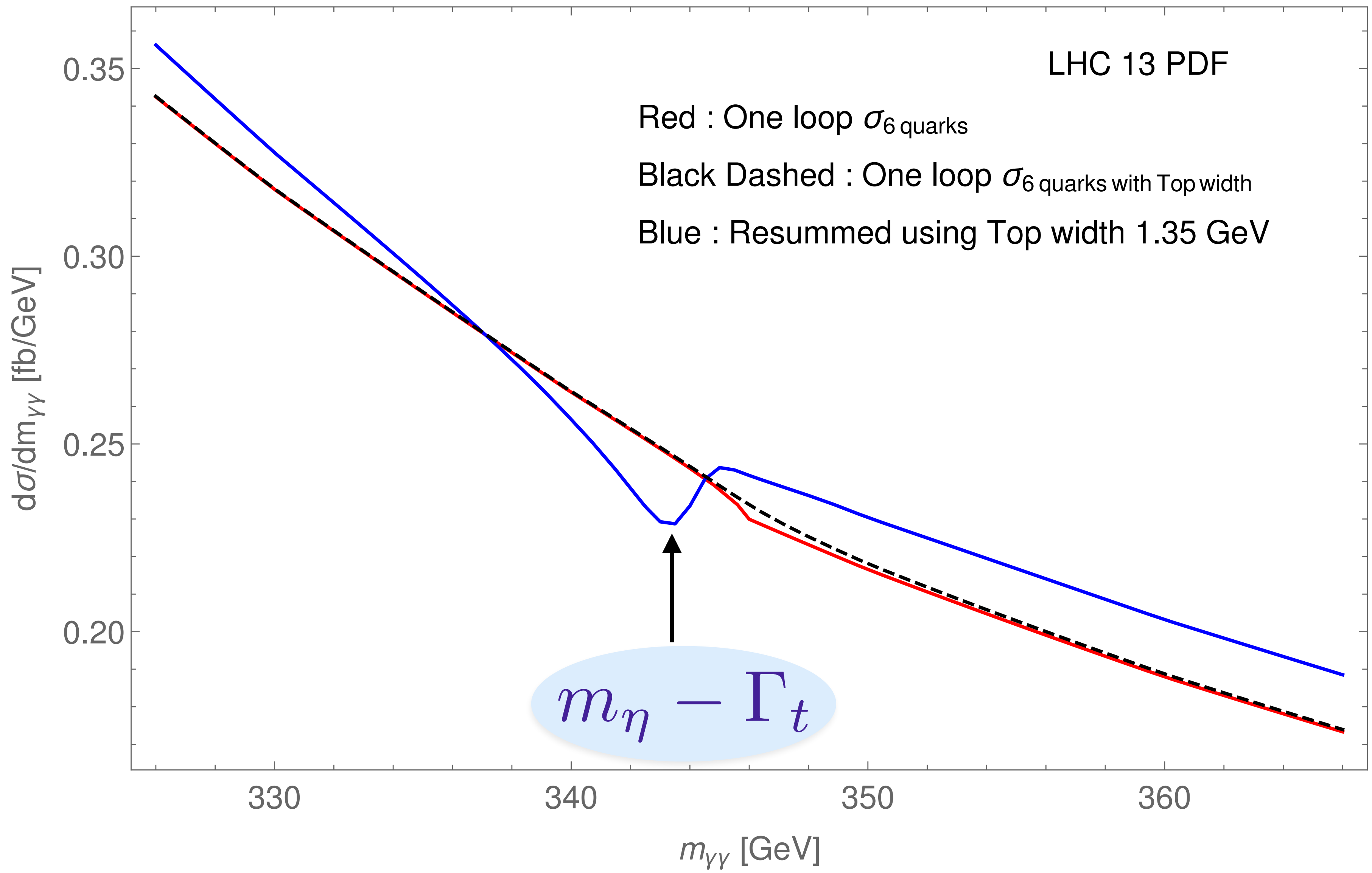
# fat toponium

u,d,s,c,b

top



At LHC, top quark can show 2~3% effects in di-photon invariant mass spectrum from interference with 5 light quarks



# fat toponium

$$\Delta E_b = E_2 - E_1 \leq \Gamma_{\eta_t} = 2\Gamma_t$$

Still we can see 1s state below 2mt

higher states overlap (less than 20%)

we can call it toponium though not a single resonance

# Top quark

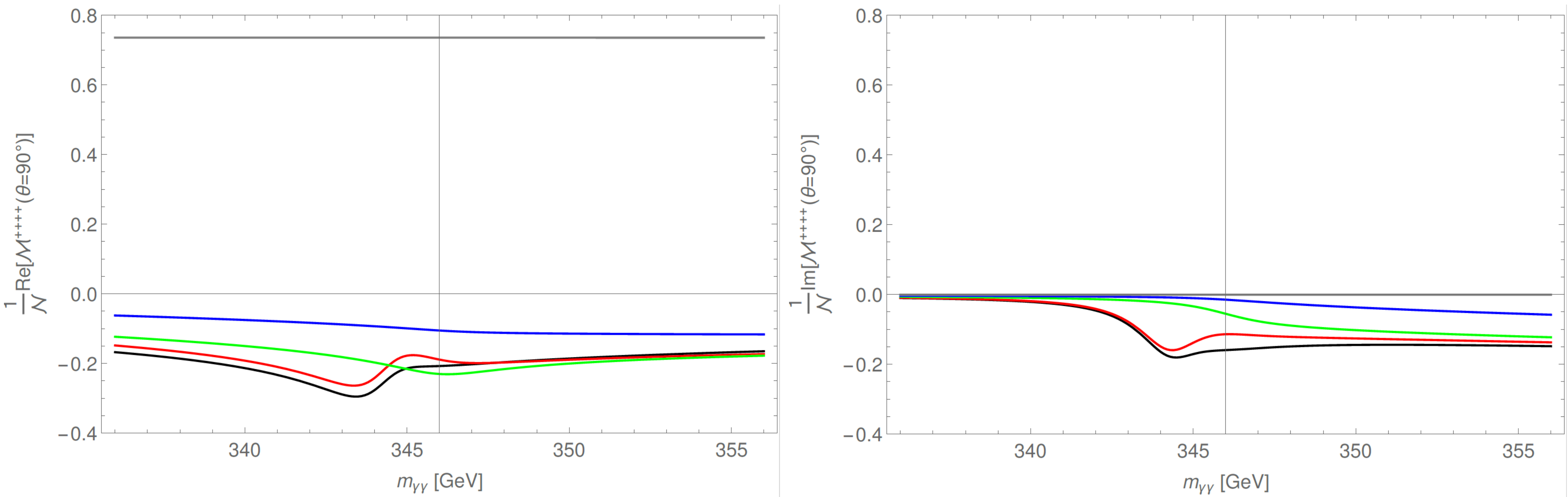
$$\frac{2}{\sqrt{m_X}}\frac{E_1}{\sqrt{-E-i\Gamma}-\sqrt{E_n}} \cong (C^3\alpha_S^3 m_X^2)\frac{1+\sqrt{\frac{-E-i\Gamma}{E_1}}}{p^2-m_\eta^2+im_\eta(2\Gamma)}$$

- $\mathcal{M}^\Lambda(gg\to\gamma\gamma)$

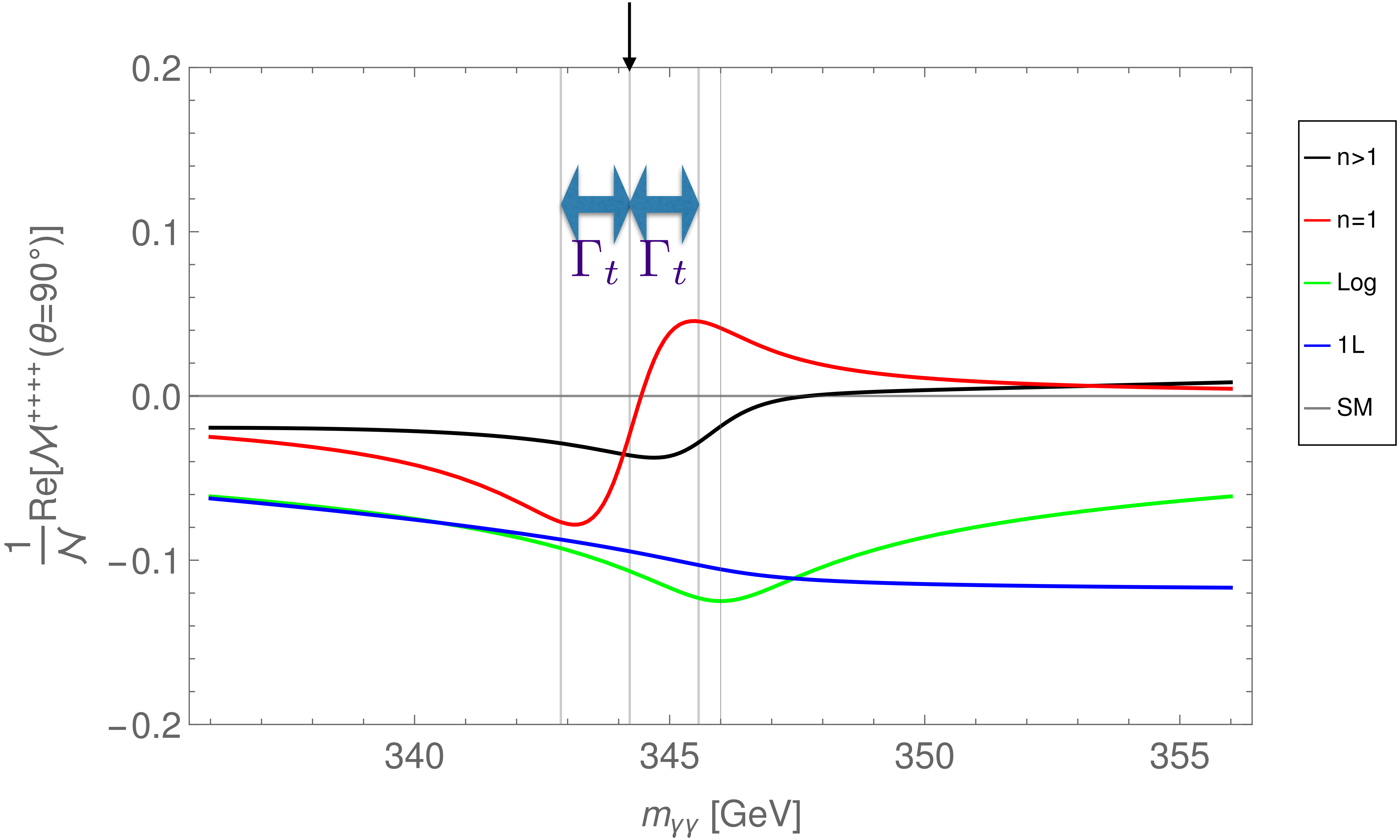
RG evolution

n=1 Bound State

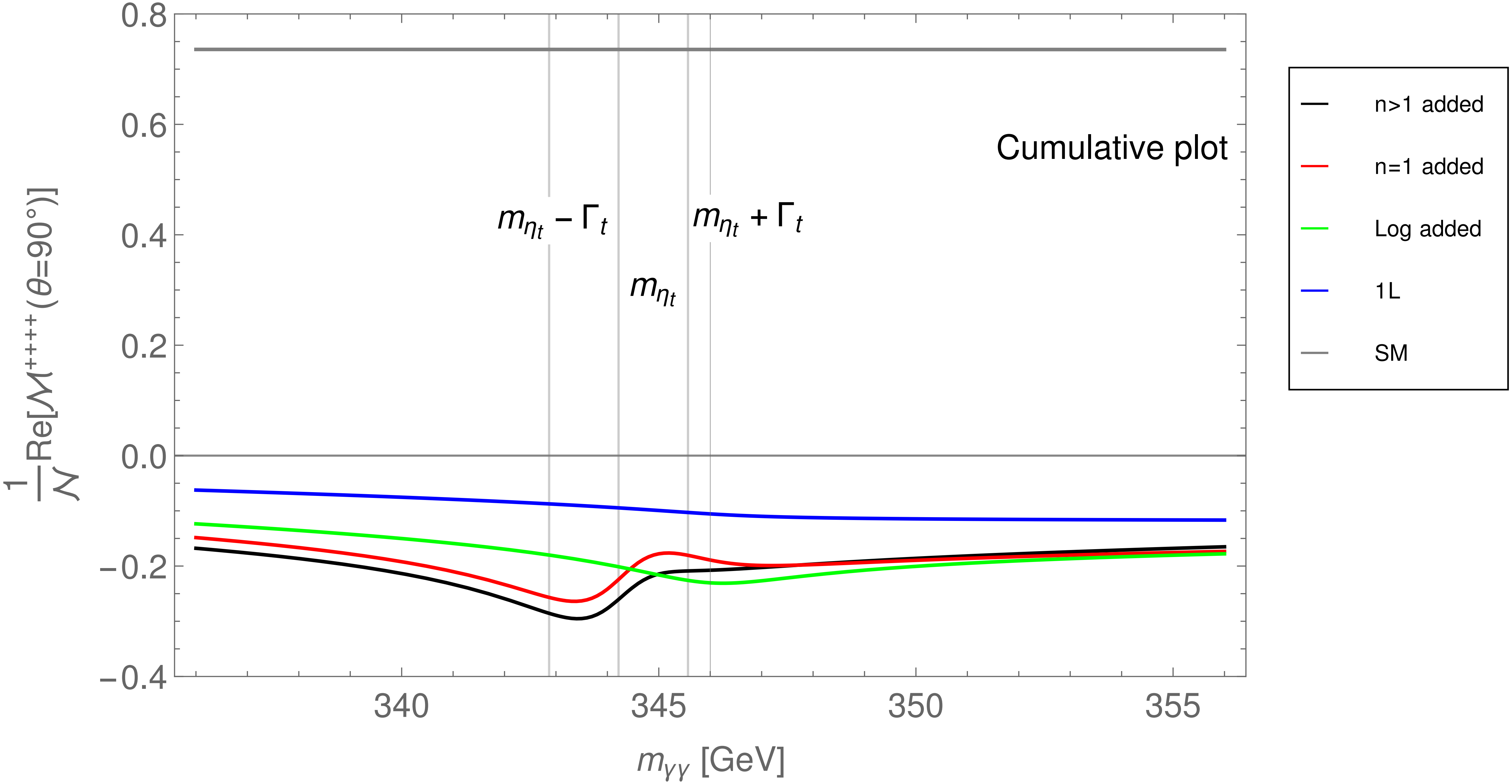
$$=\mathcal{M}^\Lambda_{one\ loop}(s,t,u)+B^\Lambda\left(-C\alpha_S(\mu)\ln\left(\frac{m_X}{\sqrt{-m_X E}}\right)-\frac{2}{\sqrt{m_X}}\sum_{n=1}^{\infty}\frac{E_n}{\sqrt{-E}-Sign(C)\sqrt{E_n}}\right)+\mathcal{M}^\Lambda_{u,d,s,c,b}$$



$$m_\eta = 2m_t - E_b$$

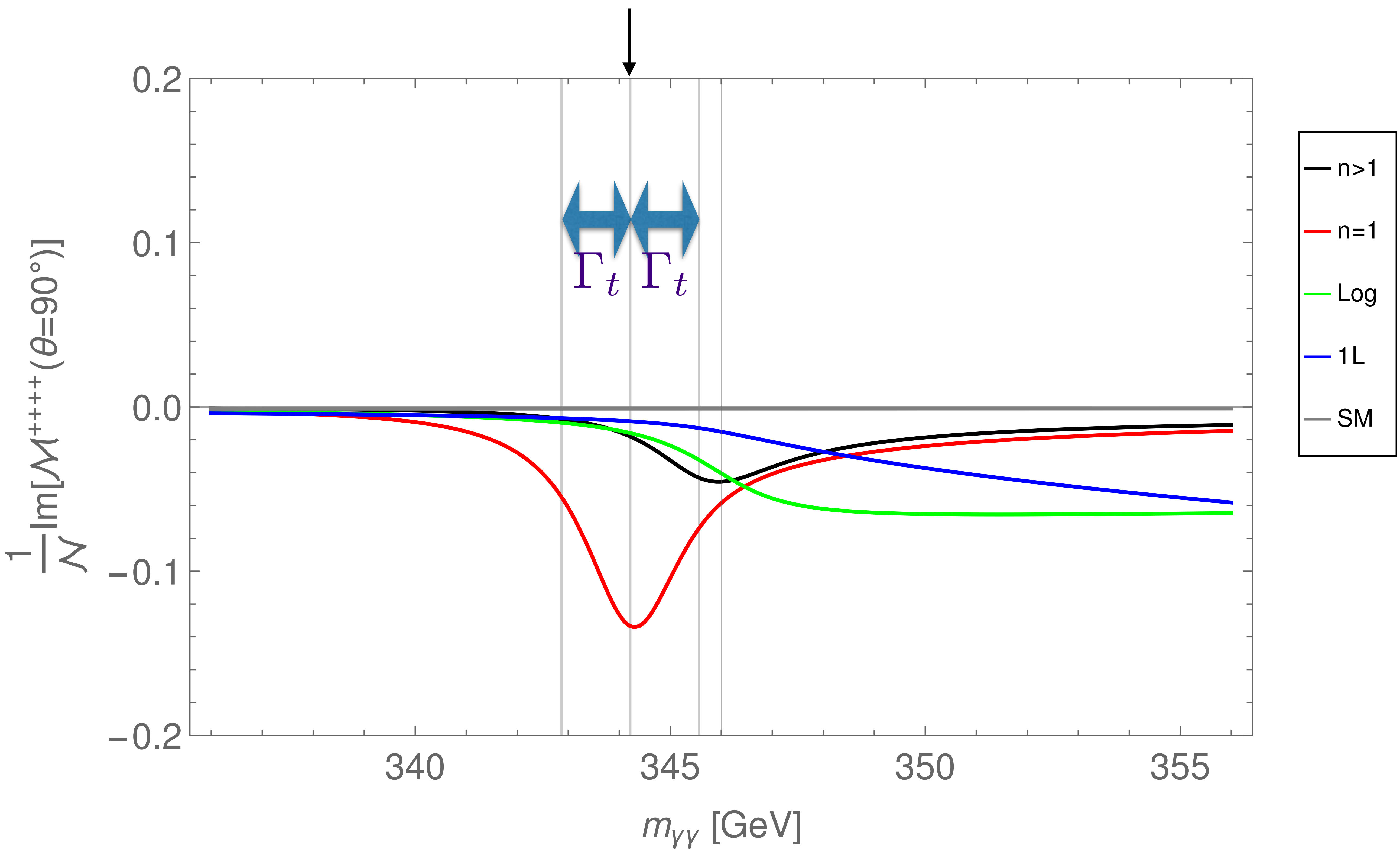


$\Gamma_t$
$\Gamma_t$
0.2
0.1
0.0
−0.1
−0.2
$\frac{1}{\mathcal{N}}\mathrm{Re}[\mathcal{M}^{++++}(\theta=90°)]$
340
345
350
355
$m_{\gamma\gamma}$ [GeV]
n>1
n=1
Log
1L
SM



0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
340
345
350
355
$m_{\gamma\gamma}$ [GeV]
$\frac{1}{\mathcal{N}}\mathrm{Re}[\mathcal{M}^{++++}(\theta=90°)]$
Cumulative plot
$m_{\eta_t} - \Gamma_t$
$m_{\eta_t}$
$m_{\eta_t} + \Gamma_t$
n>1 added
n=1 added
Log added
1L
SM

$$m_\eta = 2m_t - E_b$$



$\Gamma_t$ $\Gamma_t$
0.2
0.1
0.0
−0.1
−0.2
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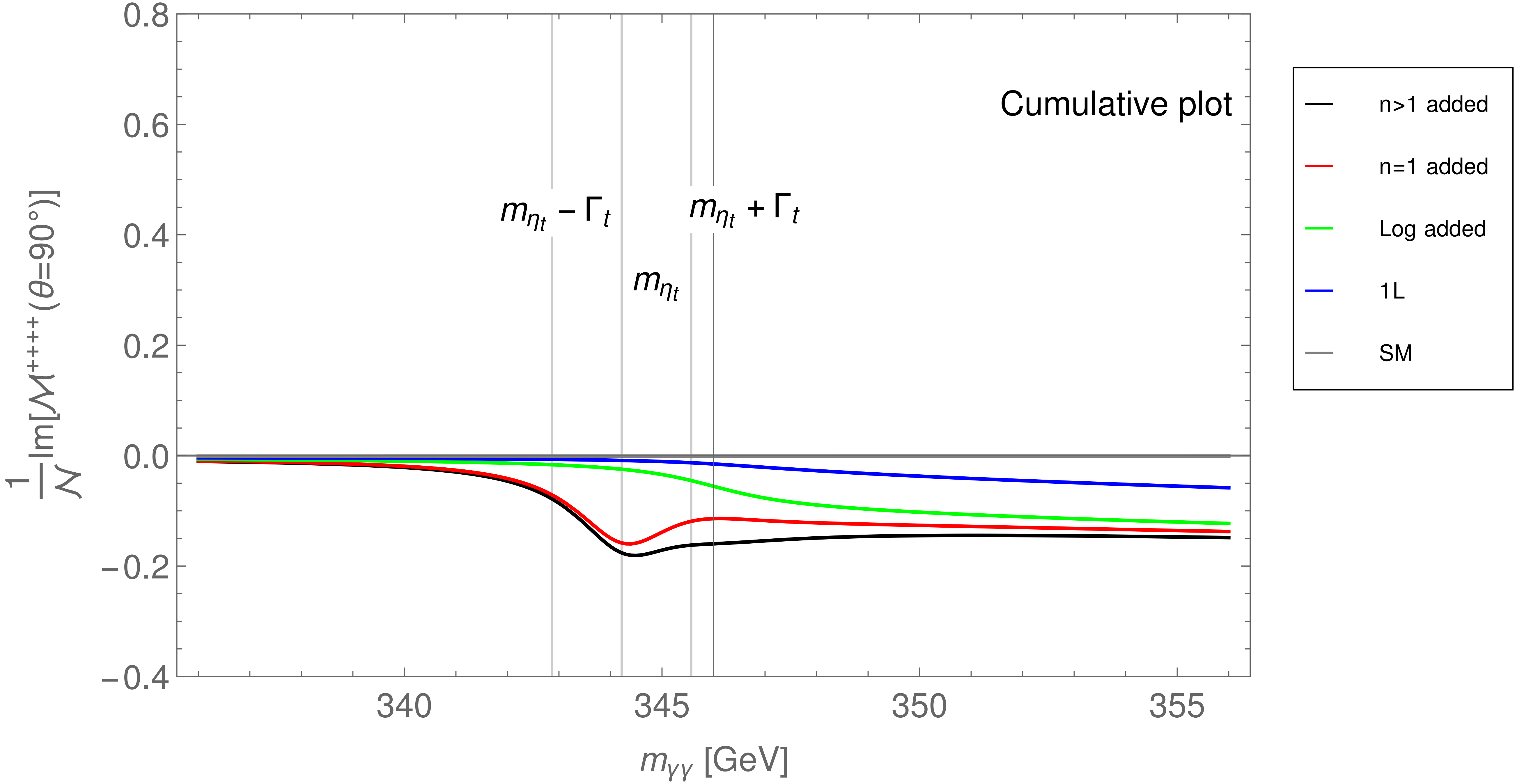
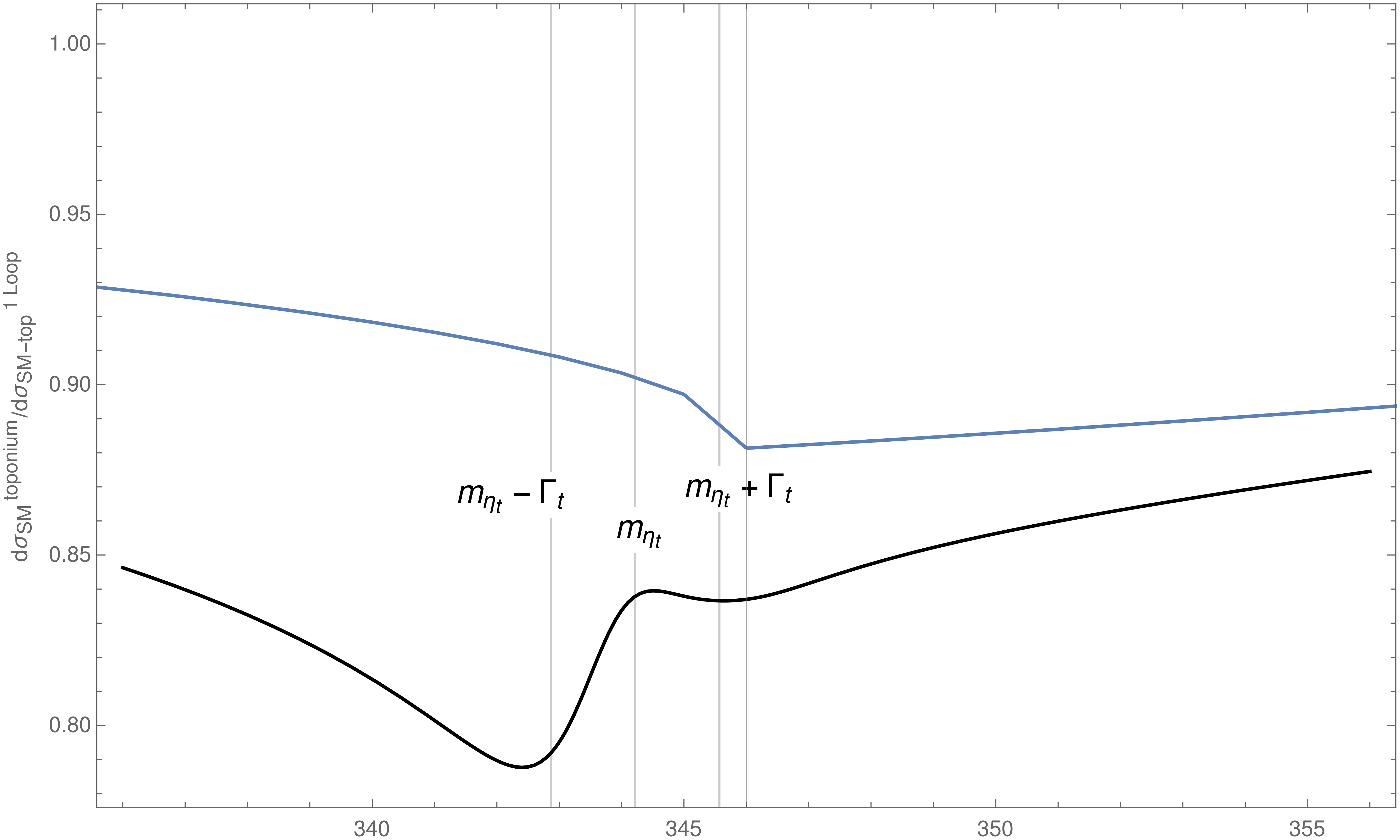


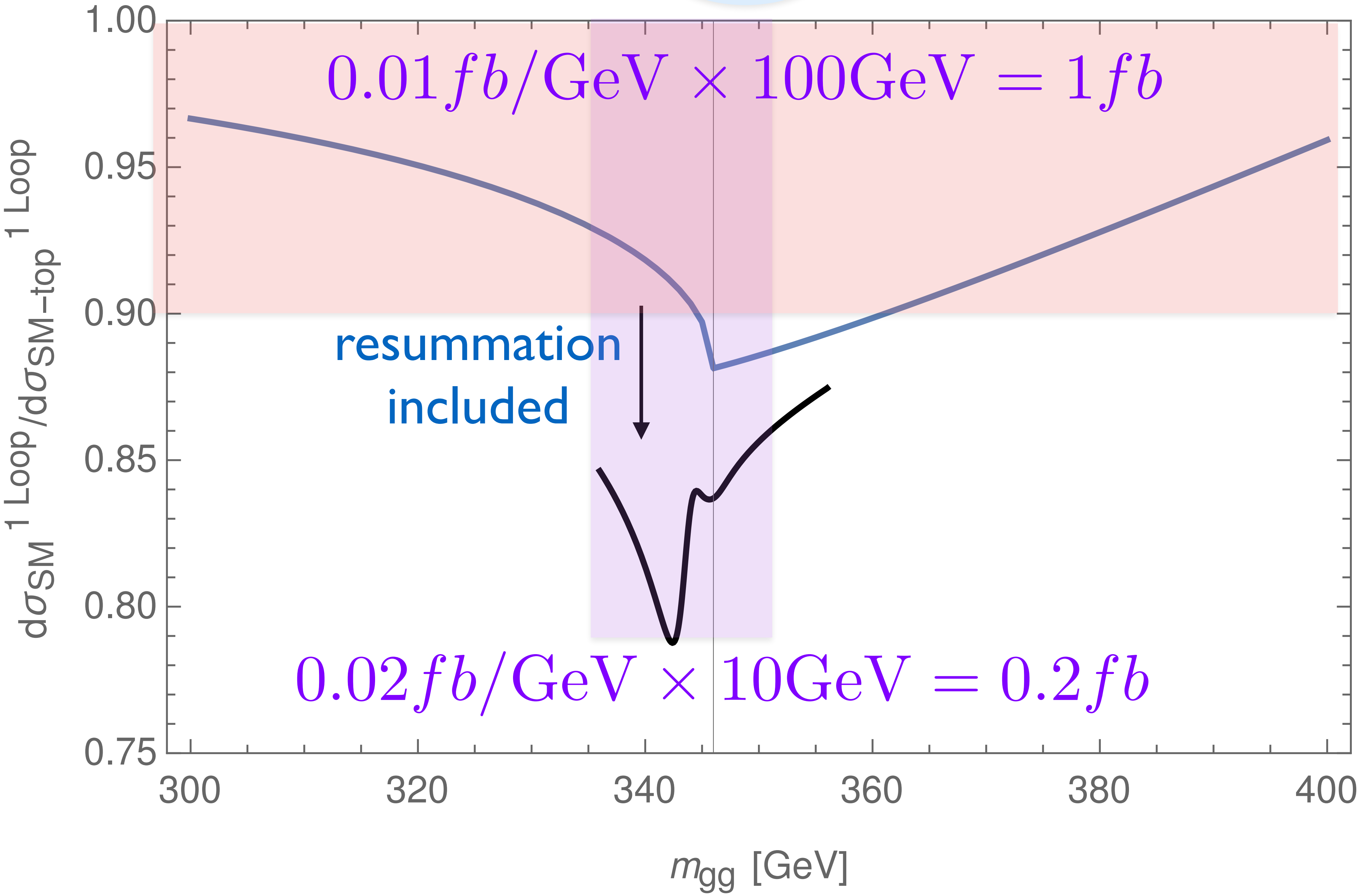
Cumulative plot
$m_{\eta_t} - \Gamma_t$
$m_{\eta_t}$
$m_{\eta_t} + \Gamma_t$
n>1 added
n=1 added
Log added
1L
SM
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
340
345
350
355
$m_{\gamma\gamma}$ [GeV]
$\frac{1}{\mathcal{N}}\mathrm{Im}[\mathcal{M}^{++++}(\theta=90°)]$



1.00
0.95
0.90
0.85
0.80
340
345
350
355
$d\sigma_{SM}^{toponium}/d\sigma_{SM-top}^{1\ Loop}$
$m_{\eta_t} - \Gamma_t$
$m_{\eta_t}$
$m_{\eta_t} + \Gamma_t$

$$E_b = \frac{1}{2}\frac{m_t}{2}C_F^2\alpha_s^2 = 1.5\ \text{GeV} \qquad \Gamma_{t\bar{t}} = 2\Gamma_t = 2.7\ \text{GeV}$$

$1.7 \sim 2\ \text{GeV}$ at NLO




$$\frac{S}{\sqrt{B}} = 5 \rightarrow 600 fb^{-1} \sim 6ab^{-1}$$

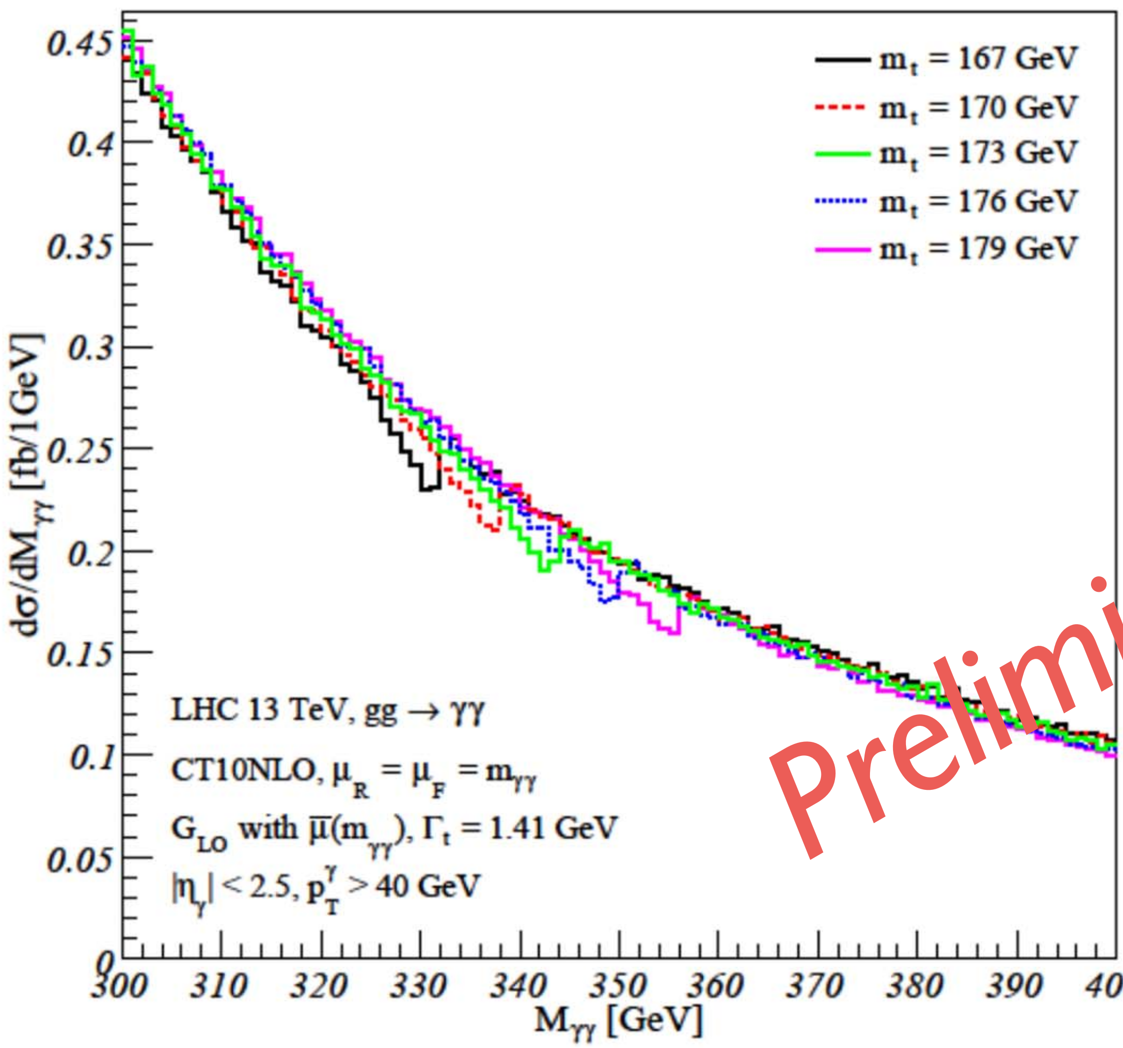
renormalon effects cancel out in the energy

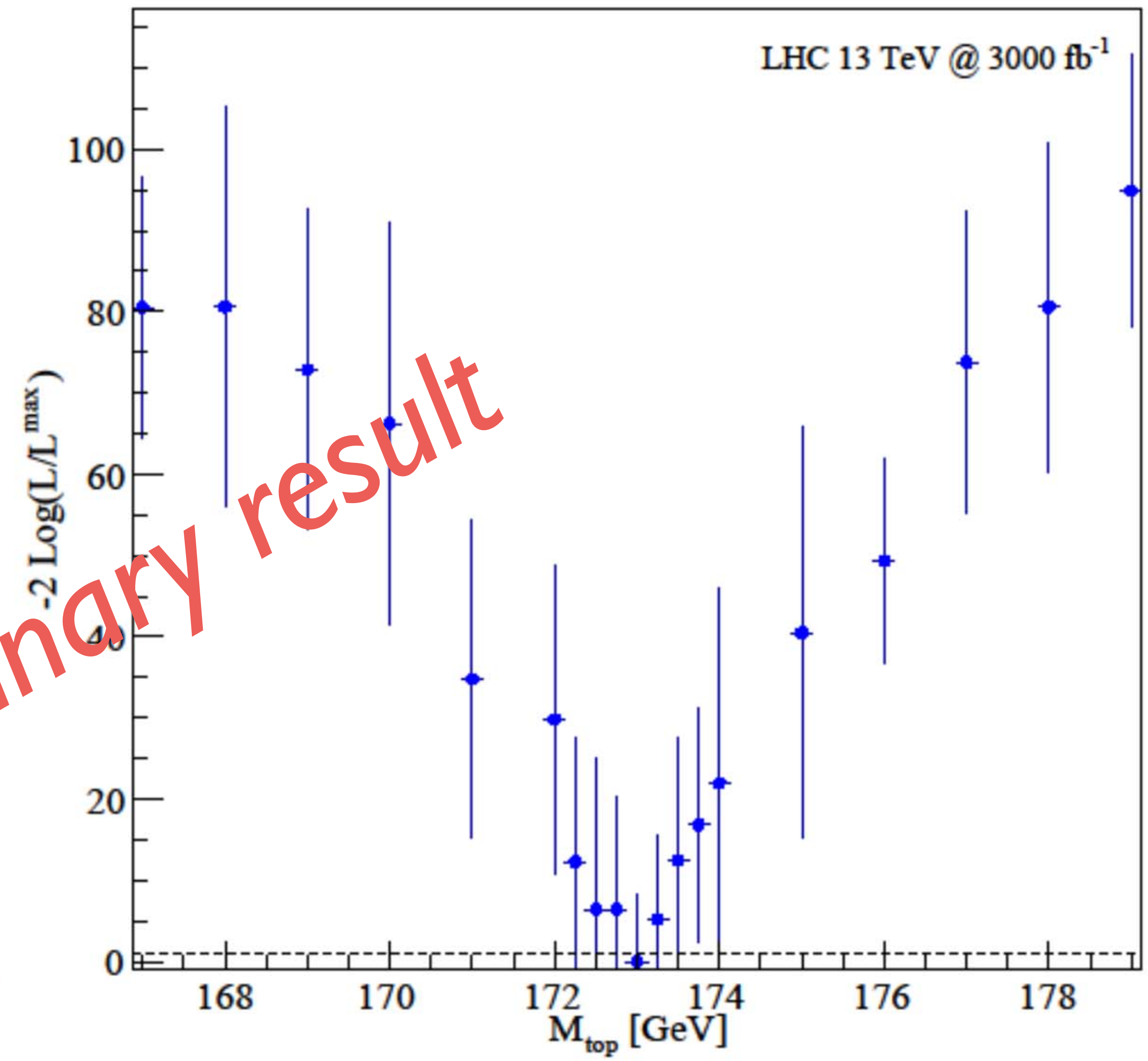
$$E_{\text{stat}} = 2m_{\text{pole}} + V_{\text{stat}}(r)$$

$$m_{1S} = m_{\text{pole}} + \frac{1}{2}V(r)$$

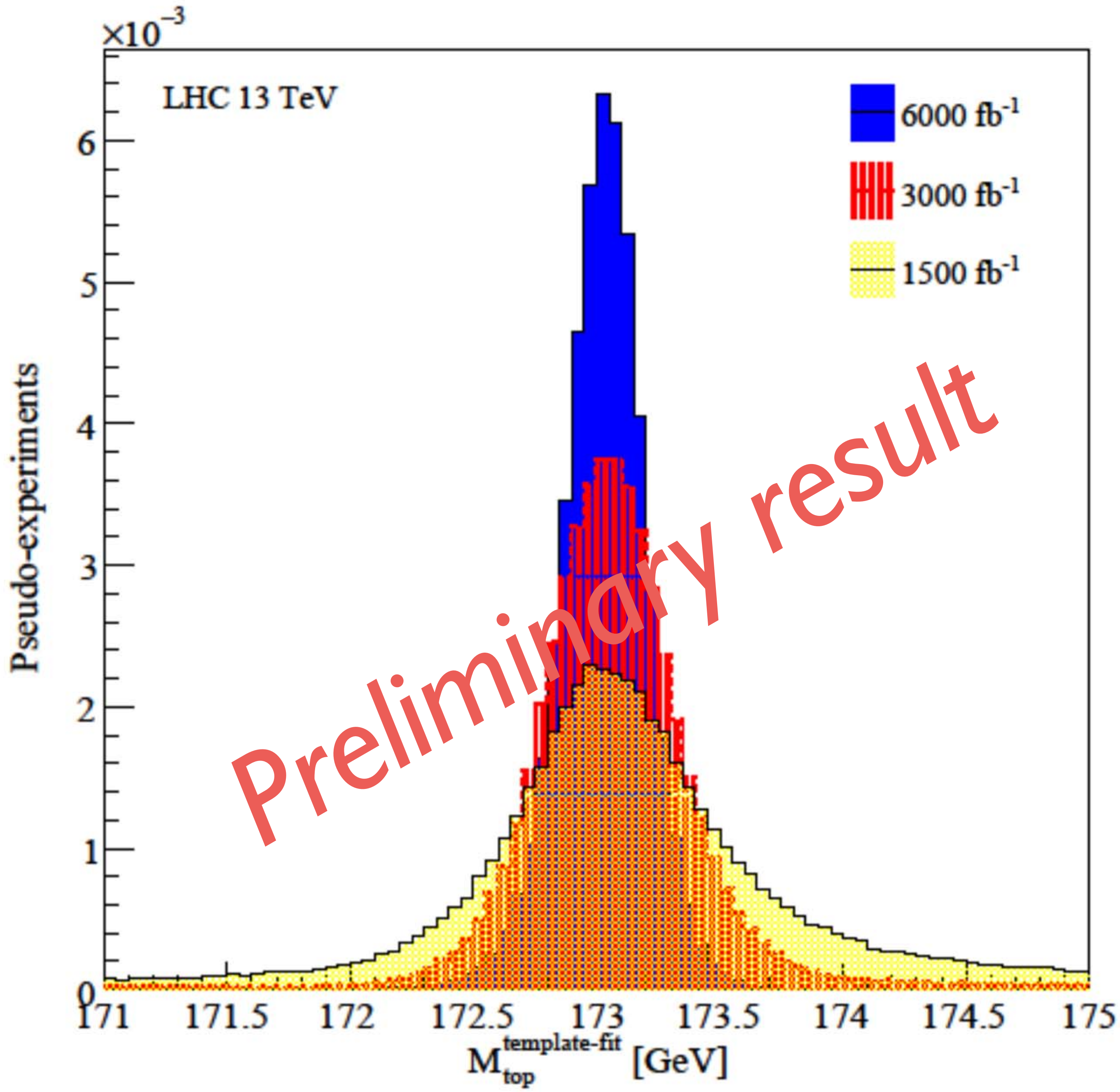
free from $\Lambda_{\text{QCD}}$

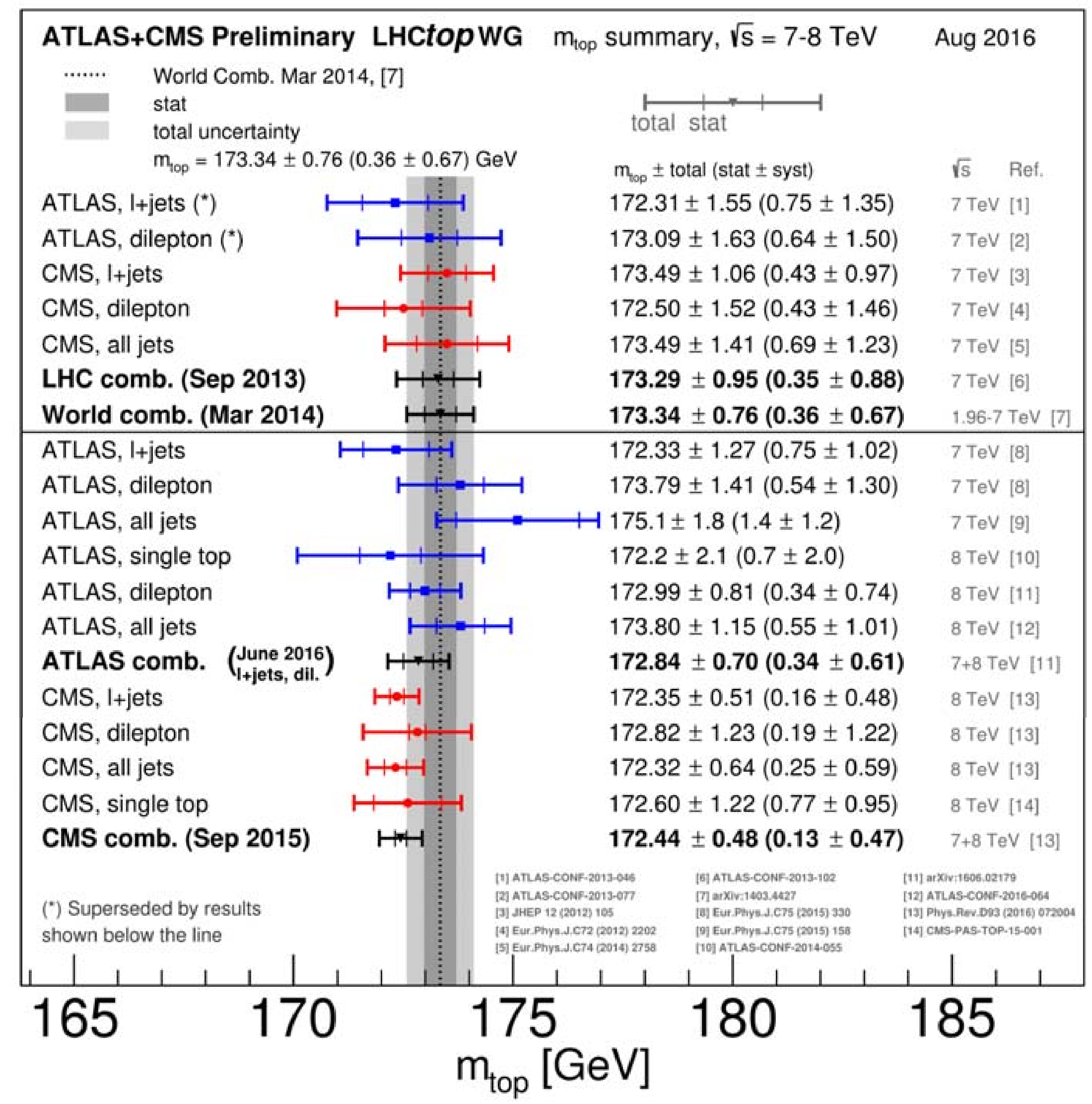
# Top search




Preliminary result




There is a hope for $\Delta m_t < 0.5 \text{ GeV}$ from a single channel measurement

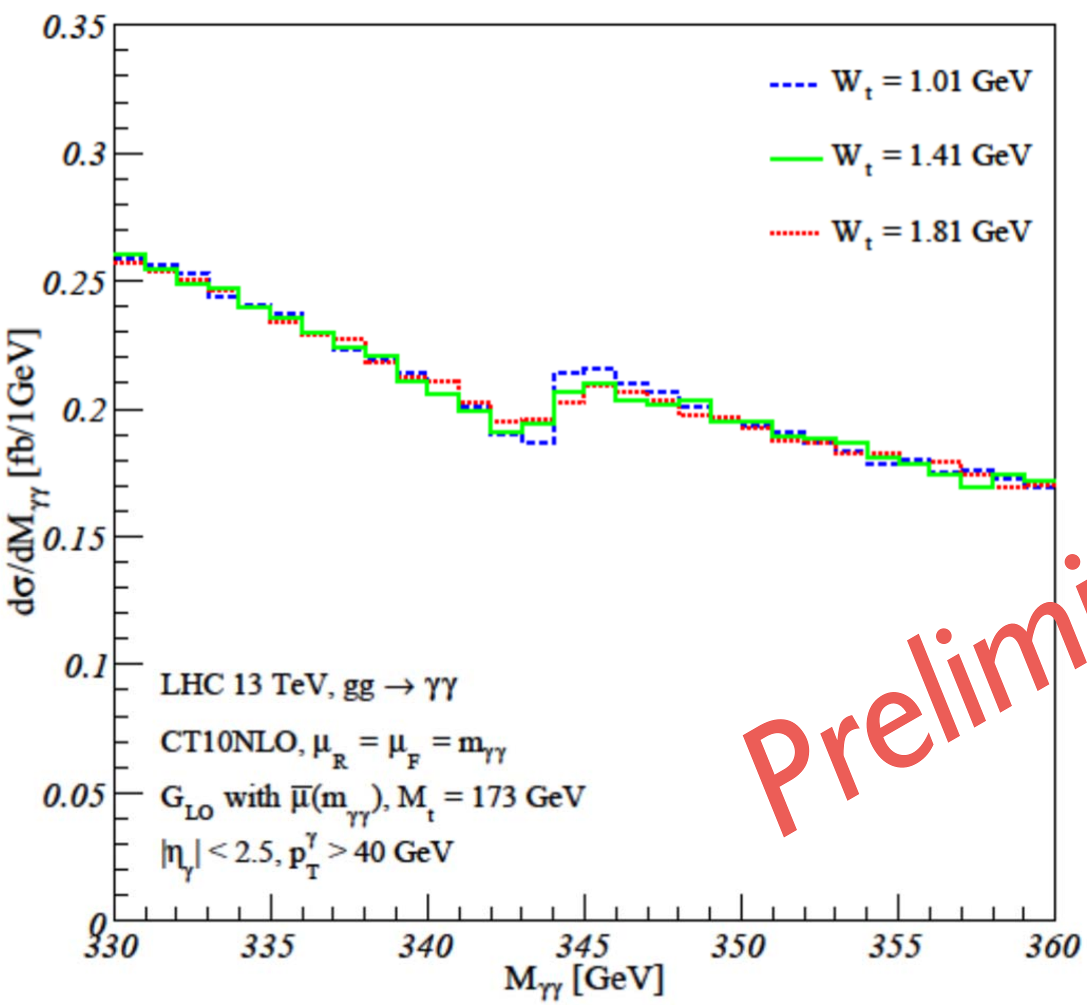
HE-LHC would be better (gluon pdf)

current best limit (direct measurement)

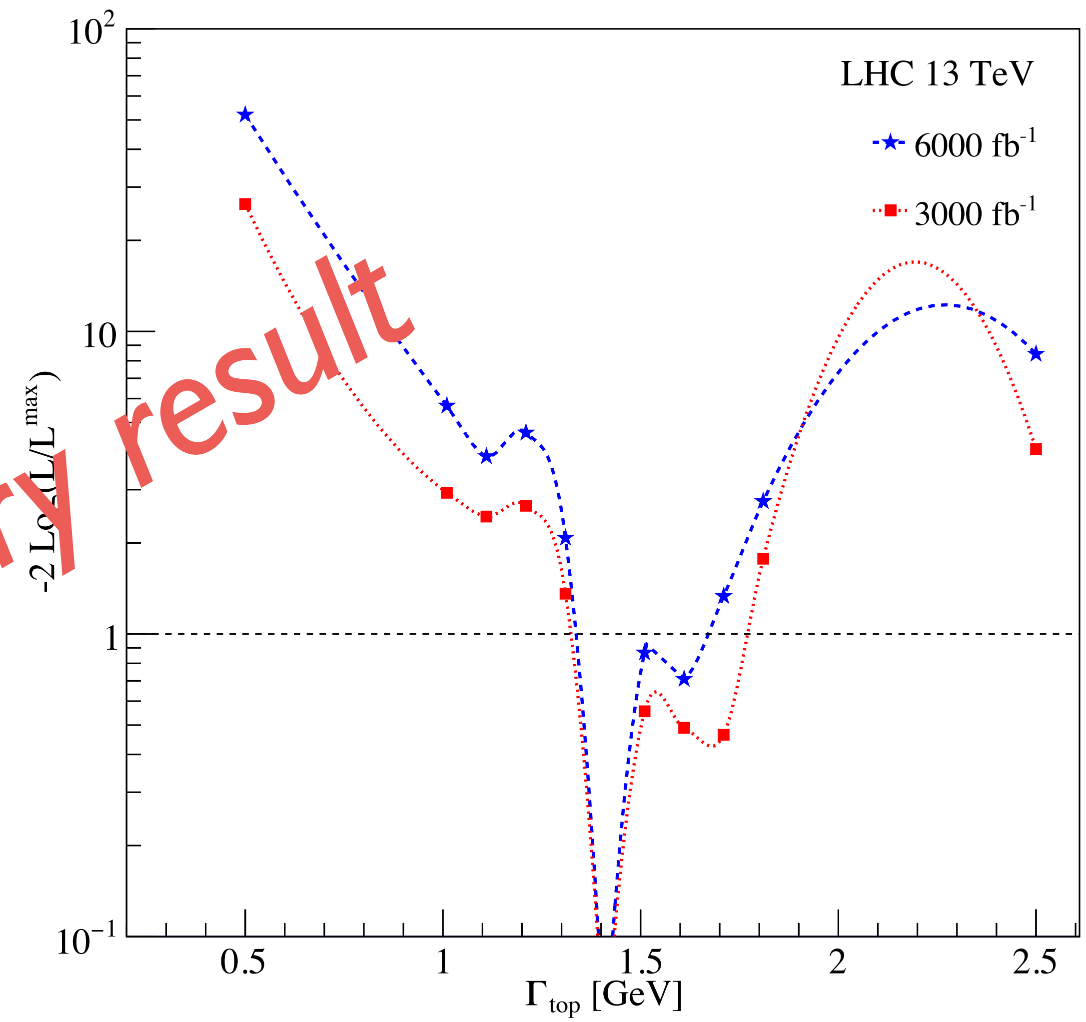
$$1.1\mathrm{GeV} < \Gamma_t < 4.1\mathrm{GeV}$$

(CDF Run II, 68% CL)

# Top Width




Preliminary result




$$1.3\mathrm{GeV} < \Gamma_t < 1.8\mathrm{GeV}$$

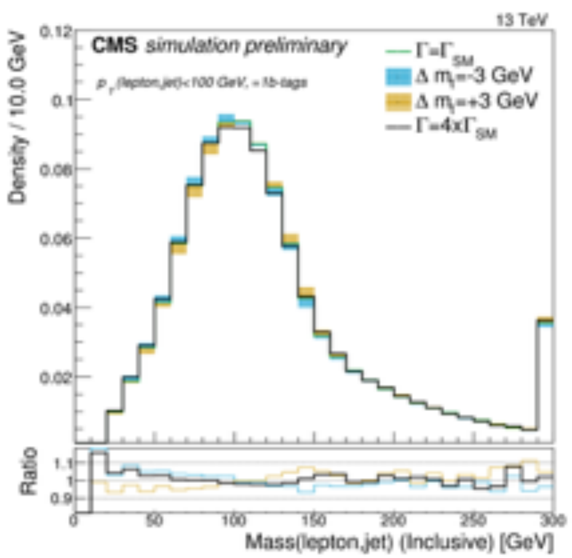
shape is sensitive to the width

## Important property → 1/lifetime

**Sensitive distribution: invariant mass (lepton,b)**

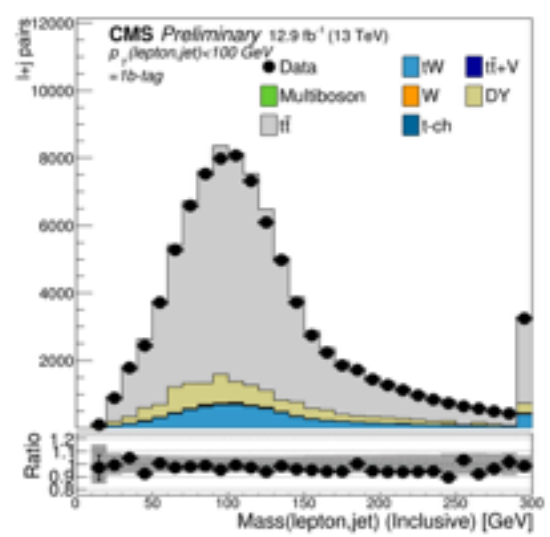
(which for lepton,b correctly matched to parent top drops at $M_{lb} = \sqrt{(m_t^2 - m_W^2)}$

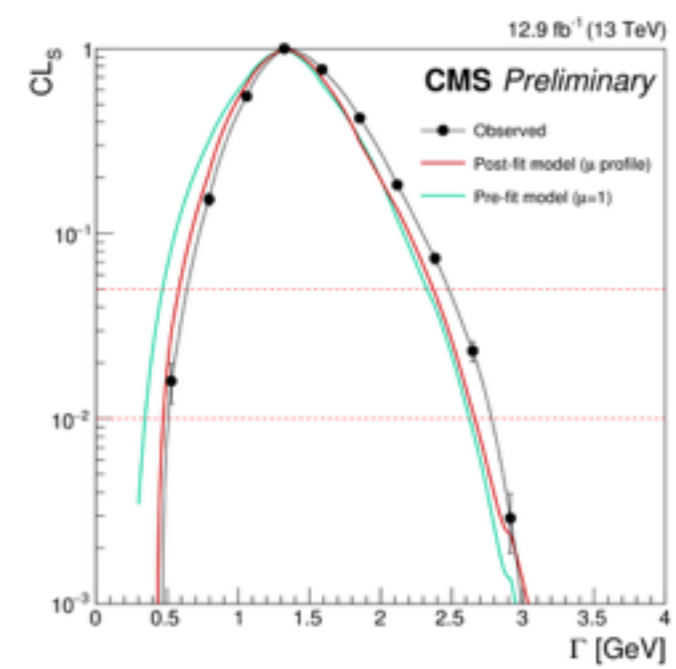
**Hypotheses tested: $\Gamma_{SM}$ and wide top with 4x $\Gamma_{SM}$**




Compare data to templates with

$\Gamma_{SM}$ vs. 4x $\Gamma_{SM}$




**0.6<Γ<2.5 at 95%CL**

**(expected: 0.6<Γ<2.4 GeV for $m_t$ = 172.5 GeV)**

# Summary

Old study focused either on (narrow width) toponium production
or continuum 1 loop computation

1 loop computation fails at the threshold

Toponium production didn't include the **interference** with 5 light quarks

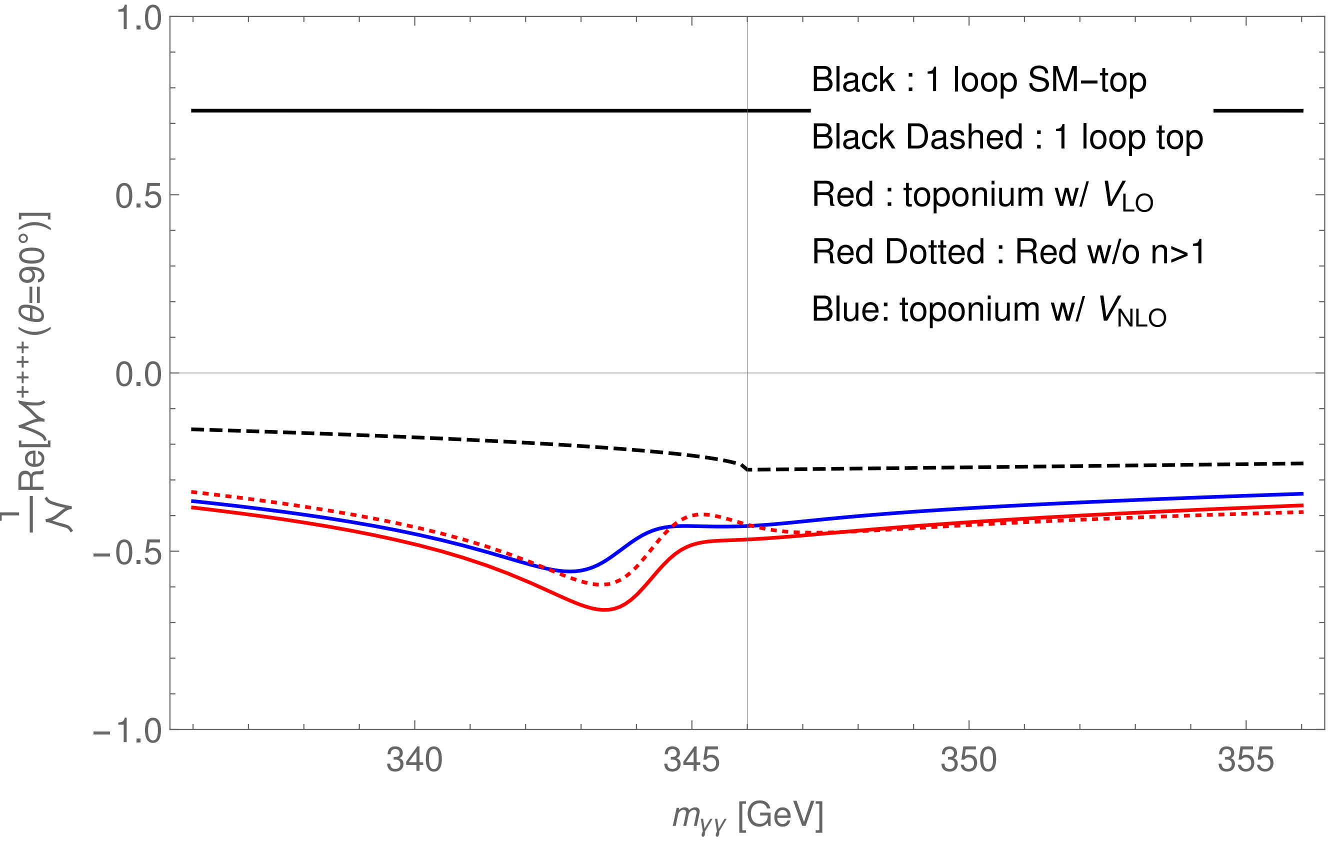
Fat toponium comes from **resummation and matching**

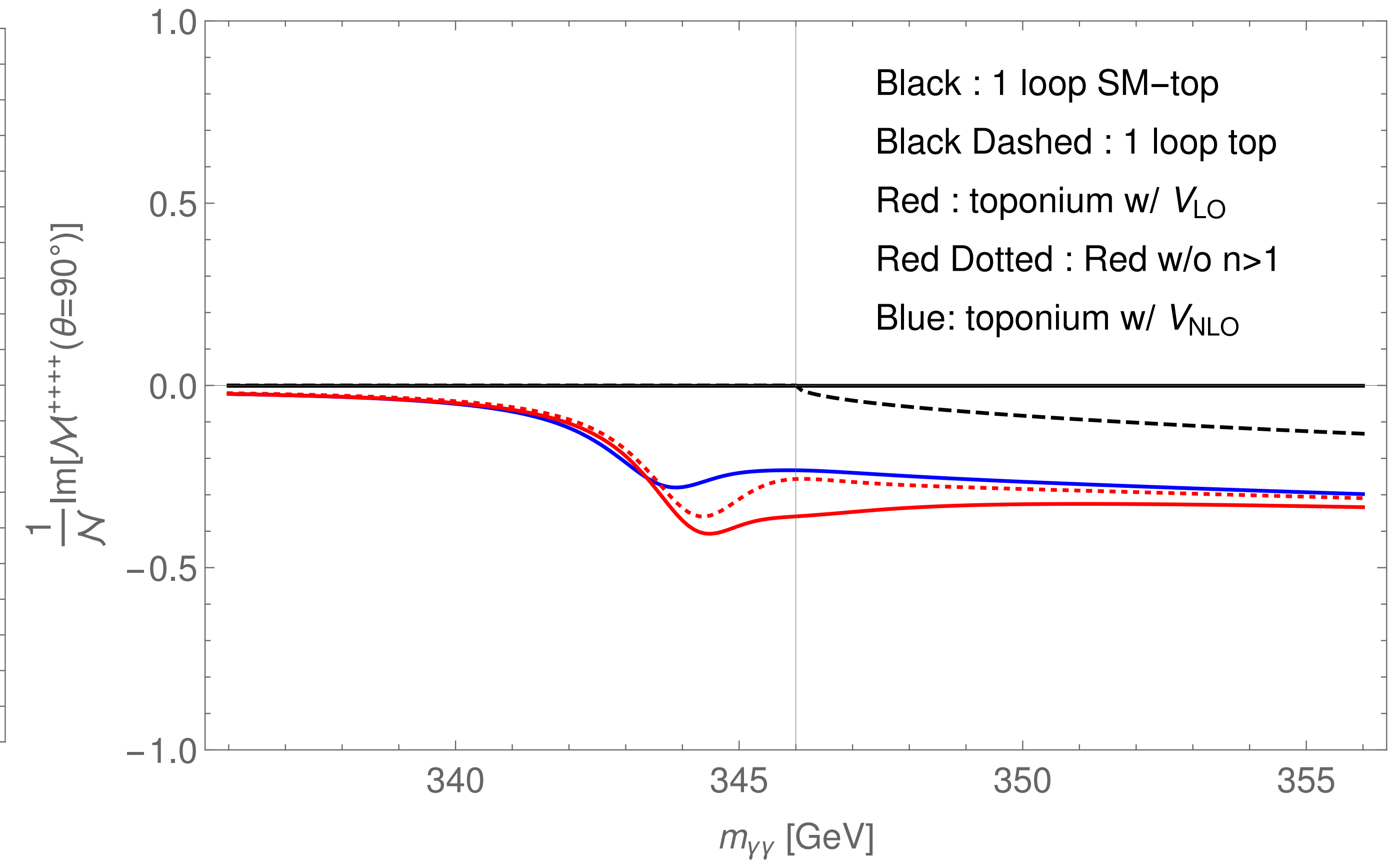
**Top mass and top decay width** can be measured from diphoton spectrum
if we know the signal shape precisely **(dip and peak)**

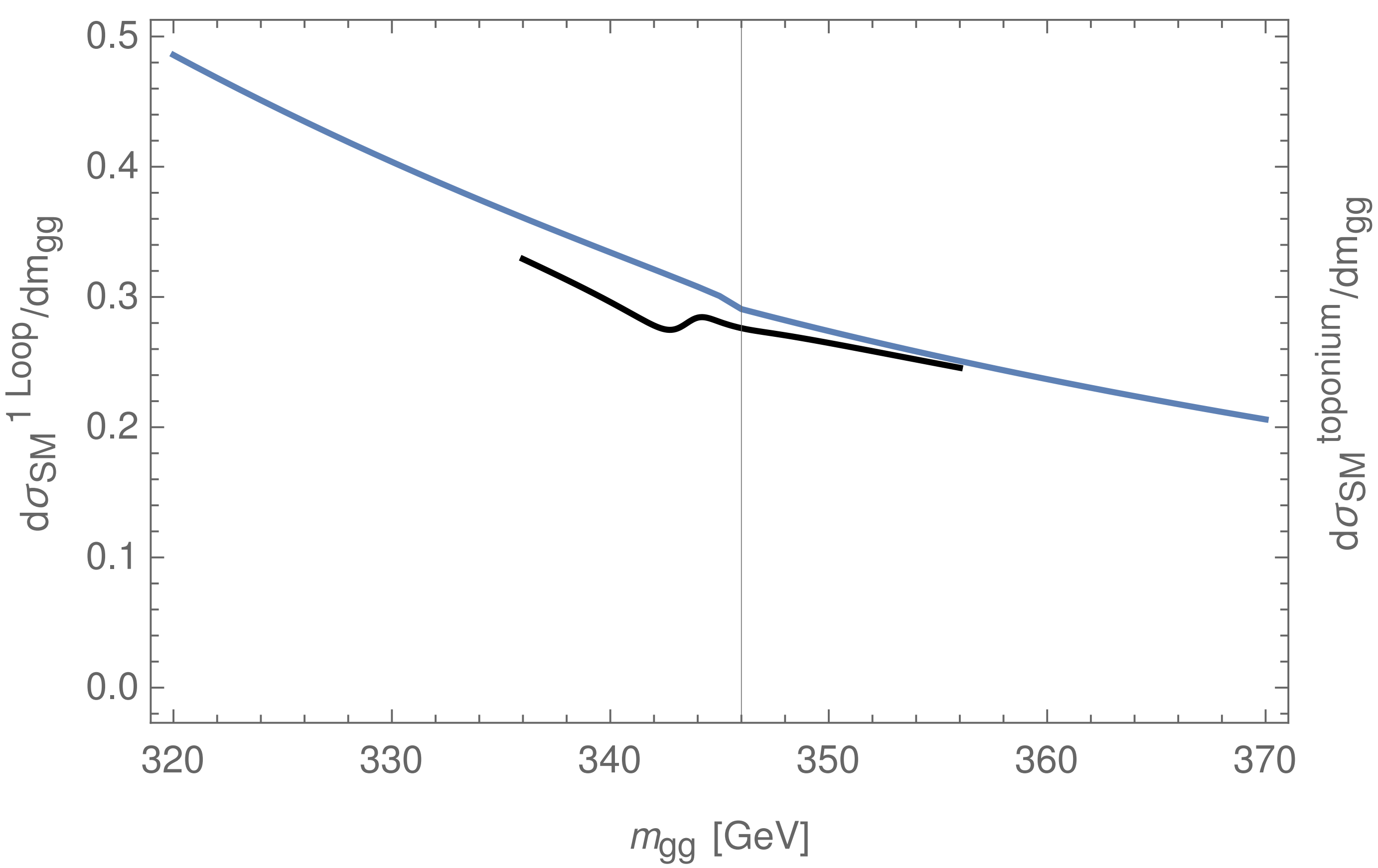
**can be easily hidden if we don't pay attention**

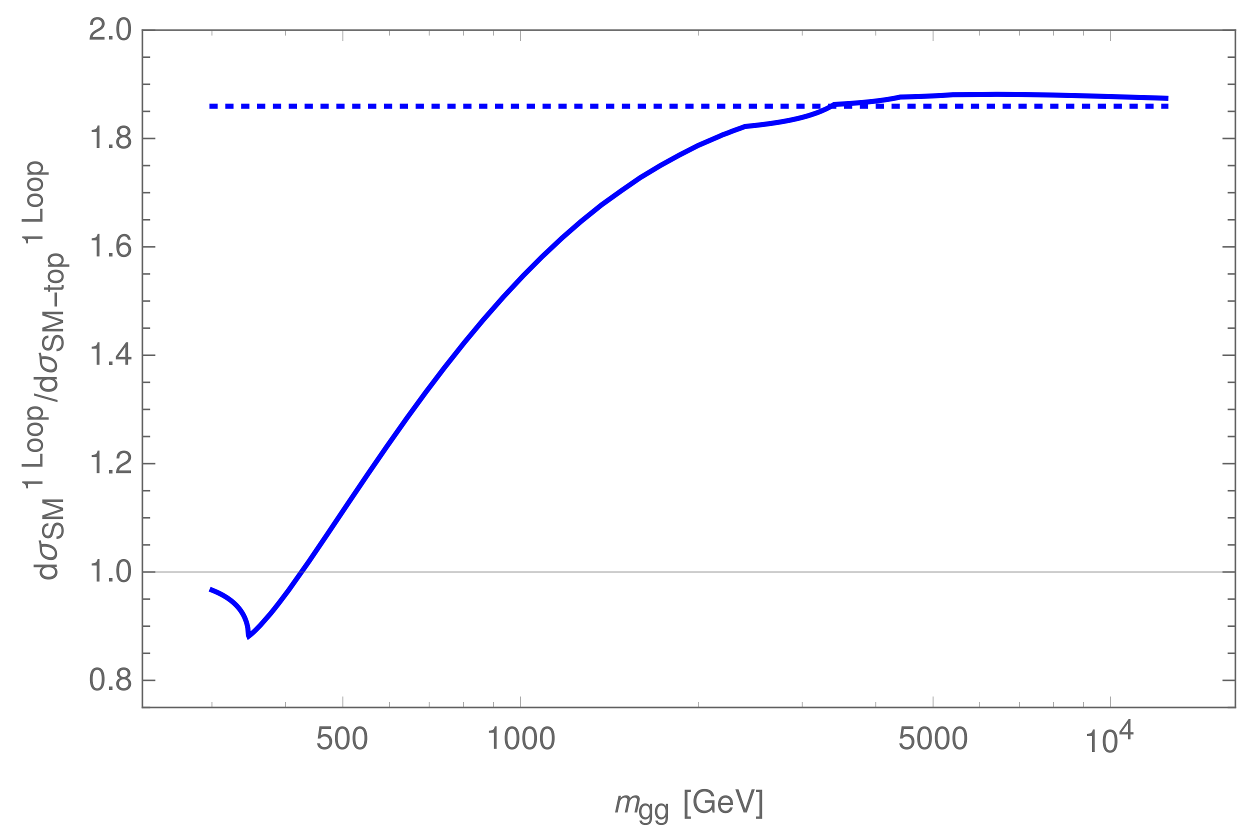
Theory prediction needs to be improved

backup


Black : 1 loop SM−top
Black Dashed : 1 loop top
Red : toponium w/ $V_{LO}$
Red Dotted : Red w/o n>1
Blue: toponium w/ $V_{NLO}$
$\frac{1}{\mathcal{N}}\mathrm{Re}[\mathcal{M}^{++++}(\theta=90°)]$
$m_{\gamma\gamma}$ [GeV]

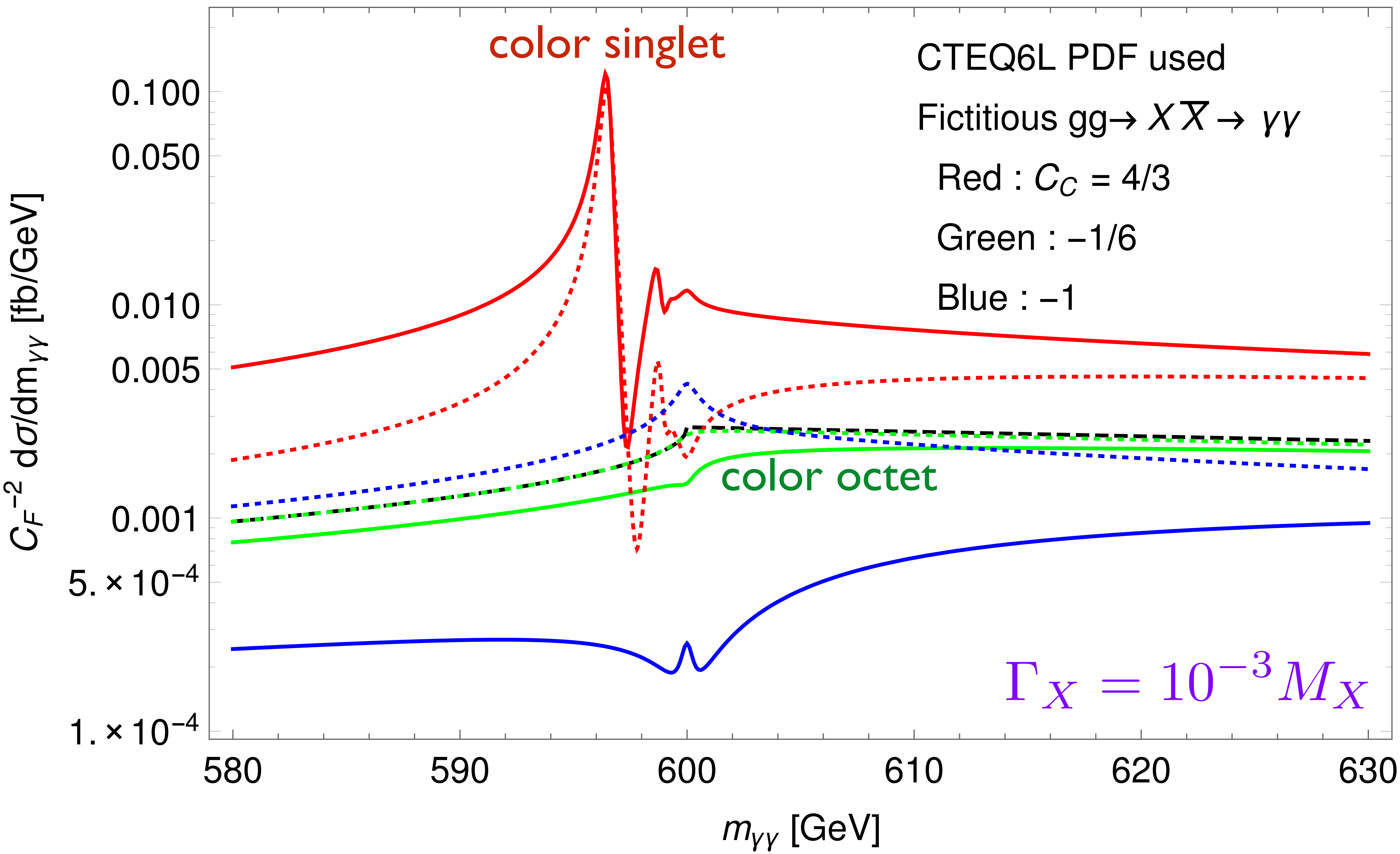

Black : 1 loop SM−top
Black Dashed : 1 loop top
Red : toponium w/ $V_{LO}$
Red Dotted : Red w/o n>1
Blue: toponium w/ $V_{NLO}$
$\frac{1}{\mathcal{N}}\mathrm{Im}[\mathcal{M}^{++++}(\theta=90°)]$
$m_{\gamma\gamma}$ [GeV]

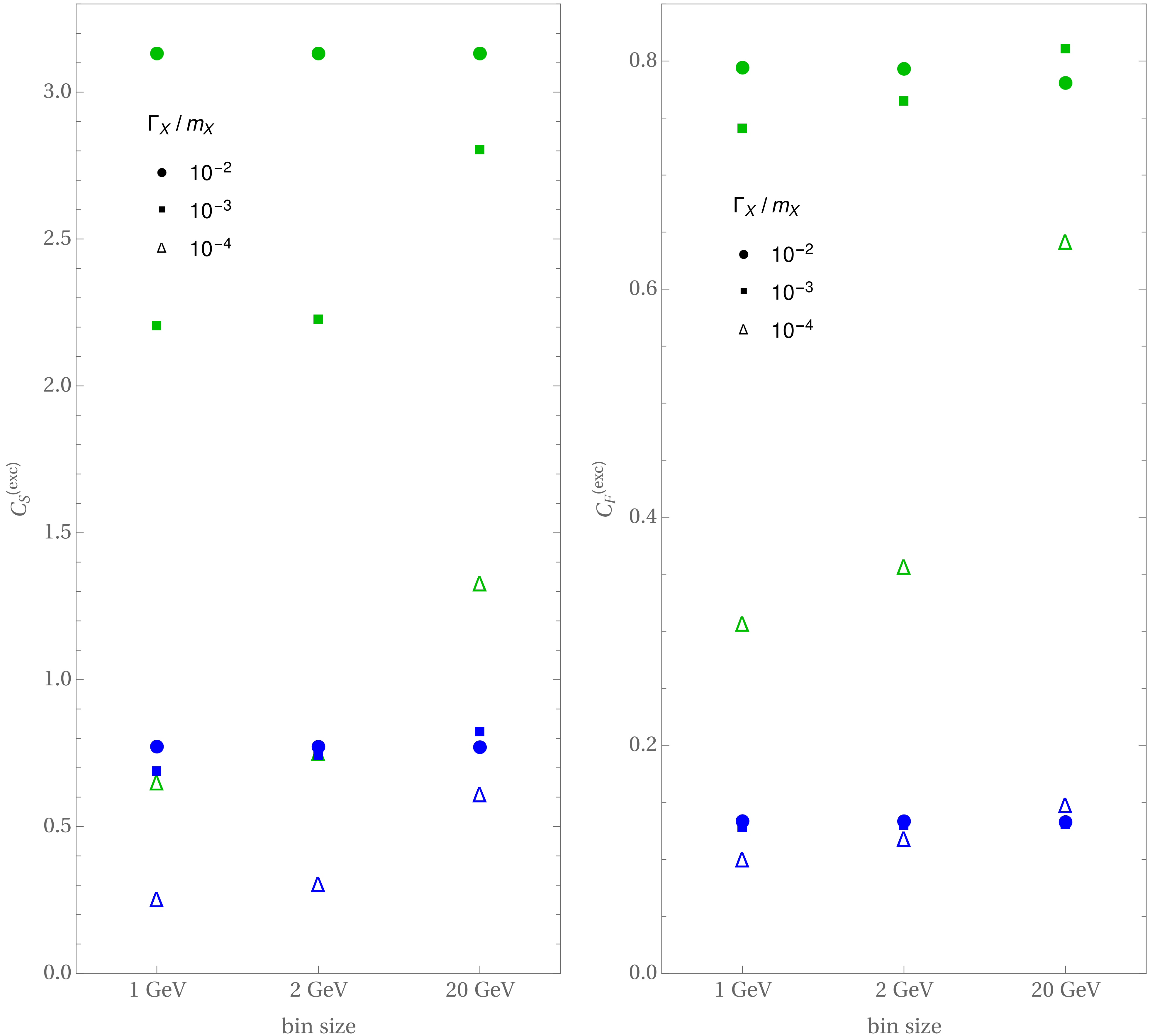

$d\sigma_{SM}{}^{1\ Loop}/dm_{gg}$
$d\sigma_{SM}{}^{toponium}/dm_{gg}$
$m_{gg}$ [GeV]


$d\sigma_{SM}{}^{1\ Loop}/d\sigma_{SM\text{-}top}{}^{1\ Loop}$
$m_{gg}$ [GeV]

## octet contribution? resummation effects are negligible

arXiv: 1612.05031




$\Gamma_X / m_X$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$C_S^{(exc)}$
$C_F^{(exc)}$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.2
0.4
0.6
0.8
1 GeV
2 GeV
20 GeV
bin size