Top quark precision with diphotons at the LHC

Energy Frontier in Particle Physics:
LHC and Future Colliders, NTU, Taipei
2017. 9. 30

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

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arXiv:1710.yyyyy

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

Shaposhnikov

Moriond, March 29 2017 – p. 2

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

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

For $\mathbf{125}$ 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

Shaposhnikov

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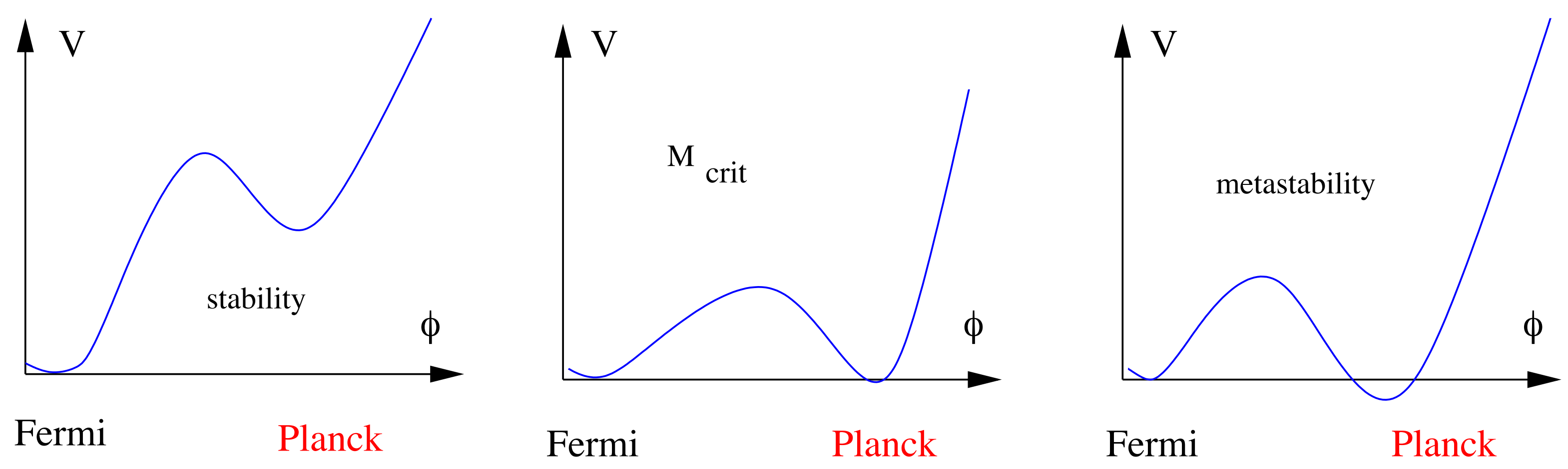
- Marginal evidence (less than 2σ) for the SM vacuum metastability given uncertainties in relation between Monte-Carlo top mass and the top quark Yukawa coupling



Shaposhnikov

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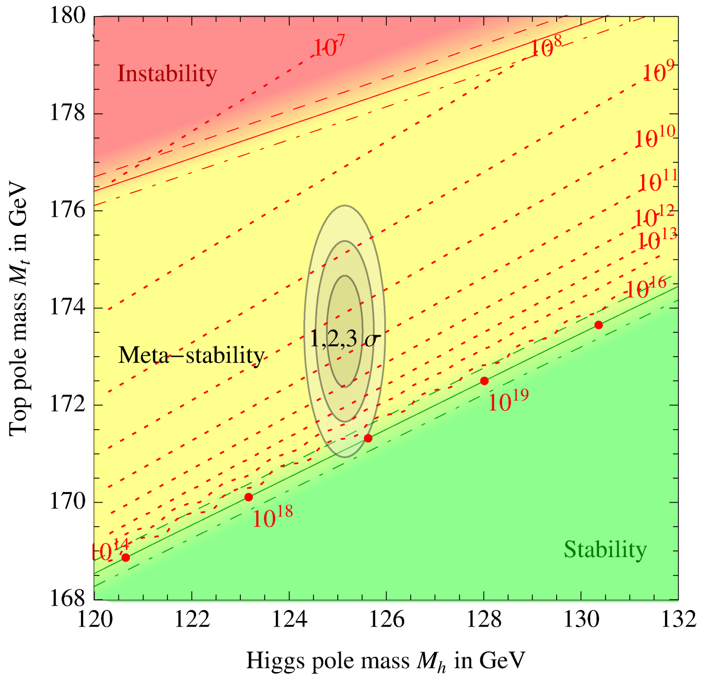
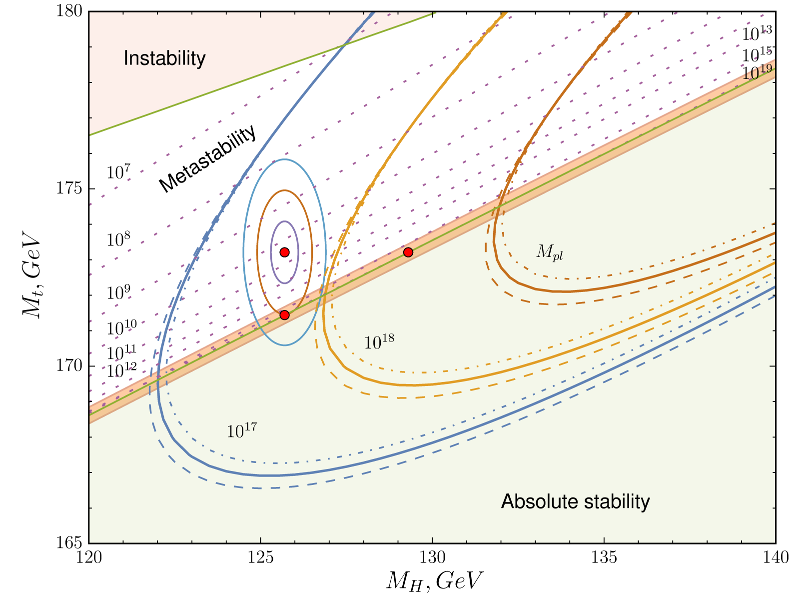




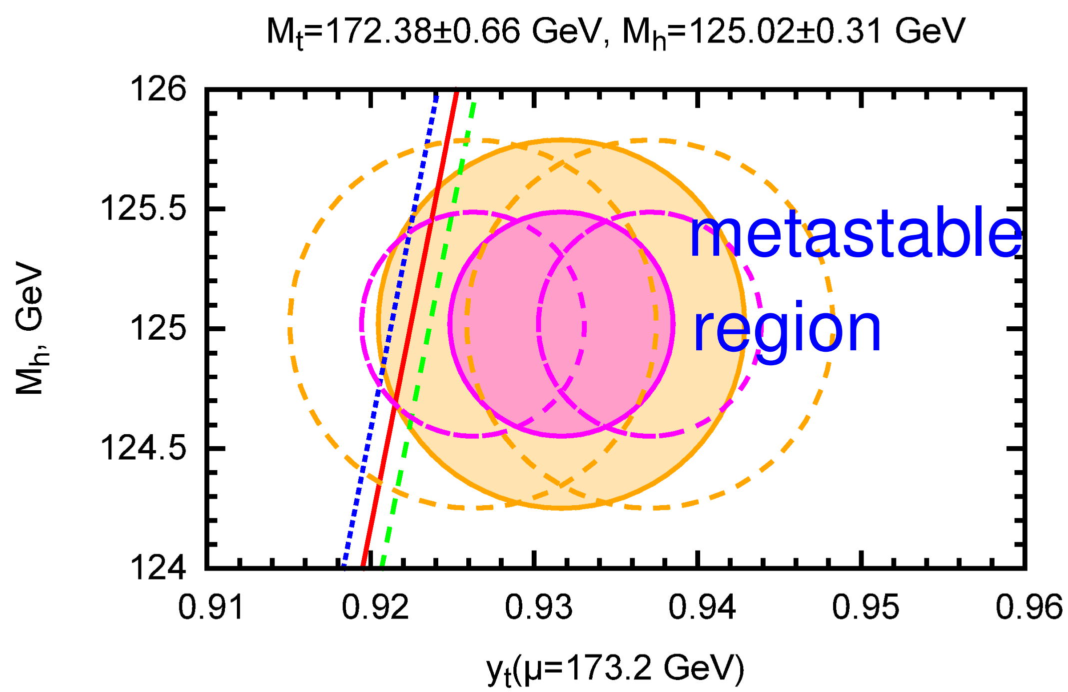
Buttazzo et al, ’13, ’14:

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 ± 1 GeV in M_{top}. Alekhin et al, Frixione et al.

Shaposhnikov

Moriond, March 29 2017 – p. 5

Top quark mass

Monte Carlo mass

bias ~ 1 GeV

Pole mass

renormalon ~ 1 GeV

MSbar mass

Top quark Yukawa coupling

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.

$$gg \to \gamma\gamma$$

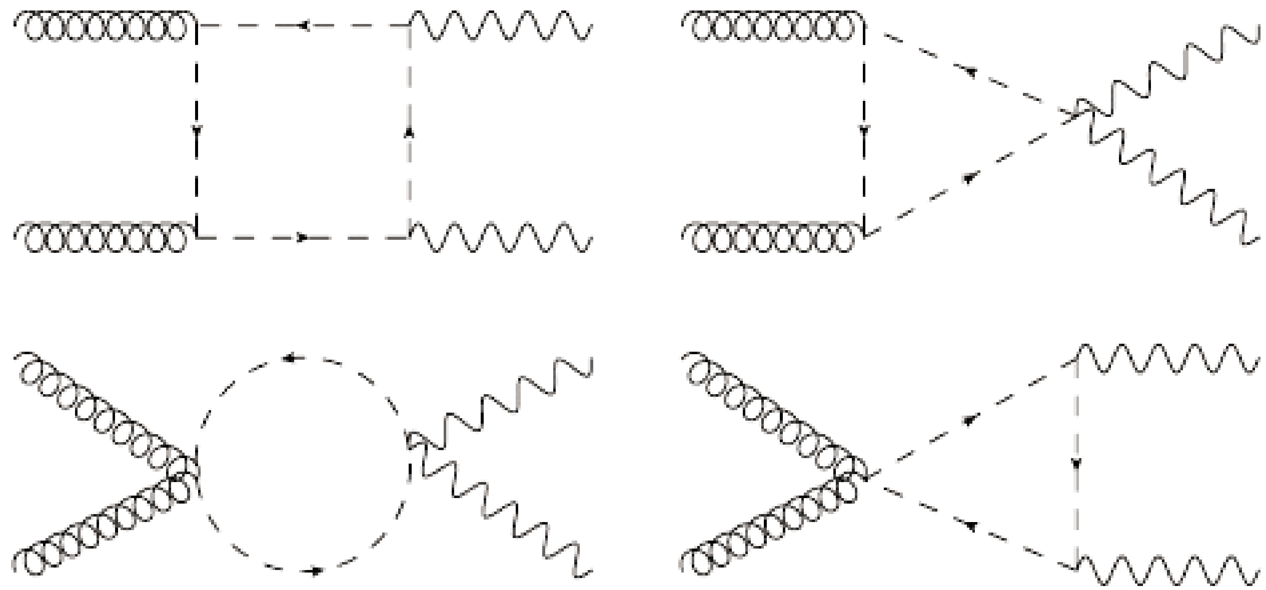
There is no tree level vertex in the Standard Model

$q\bar{q} \to \gamma\gamma$ 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

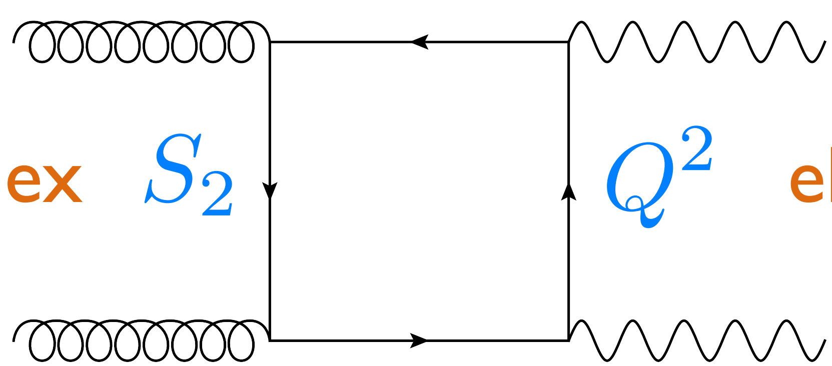
$gg \to \gamma\gamma$

Scalar



Fermion

SU(3) Dynkin index S_2



Q^2 electric change

$C = NS_2Q^2$ for N copies of the particles

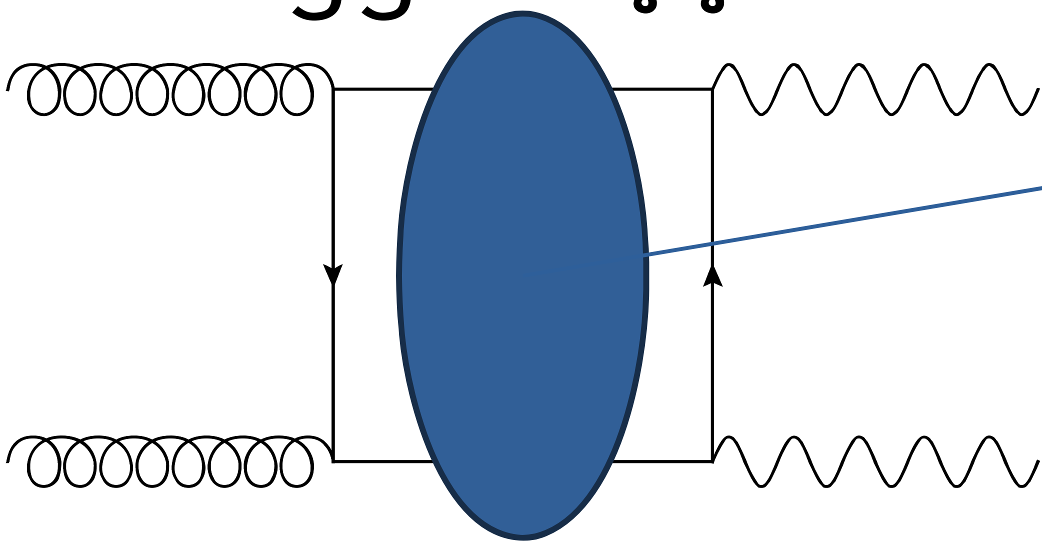
Any new colored/charged particle will contribute to the loop of $gg \to \gamma\gamma$

Near threshold

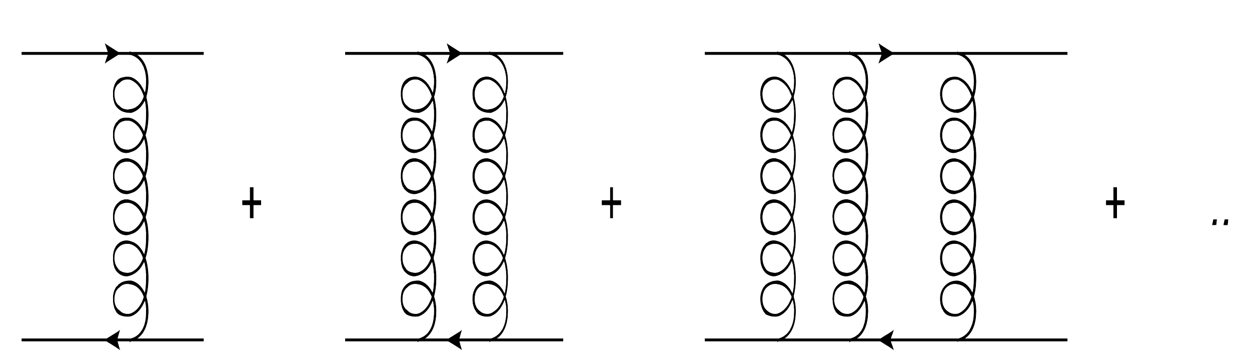
$$\frac{\alpha_s}{v} \qquad \left(\frac{\alpha_s}{v}\right)^2 \qquad \cdots \qquad \left(\frac{\alpha_s}{v}\right)^n$$

should be resummed

gg → γγ



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

quarkonium physics

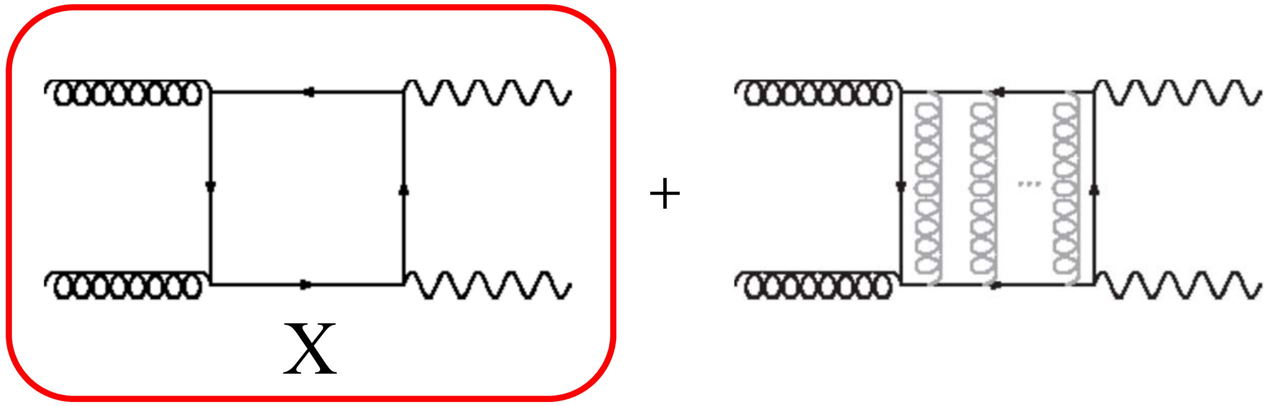
$$v = C_F \alpha_s$$

quadratic Casimir → C_F

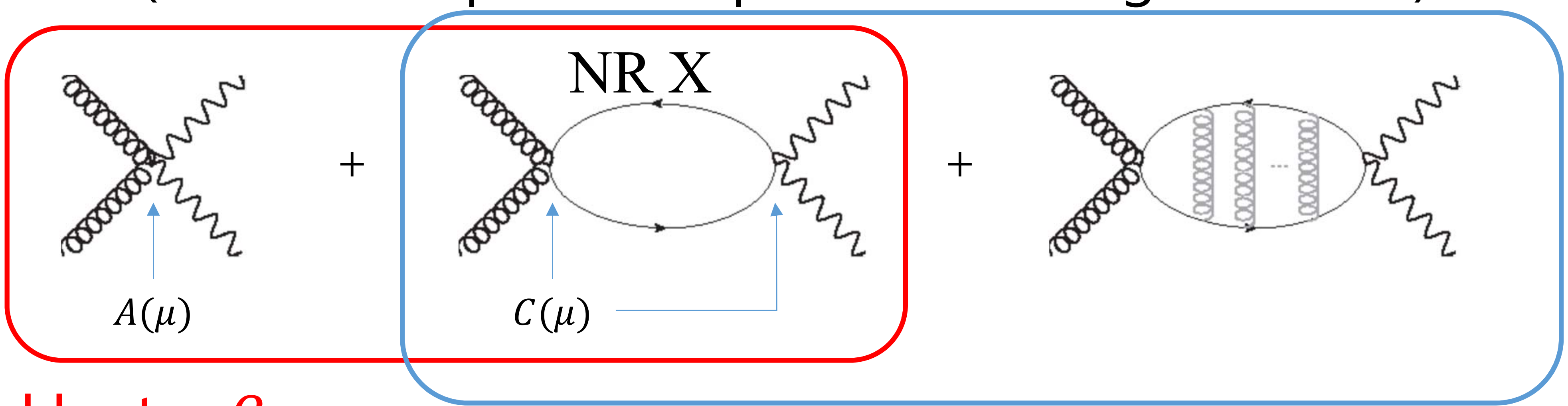
$$r = \frac{2}{m_q C_F \alpha_s}$$

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

Threshold Resummation



EFT (Relativistic part of X particle is integrated out)

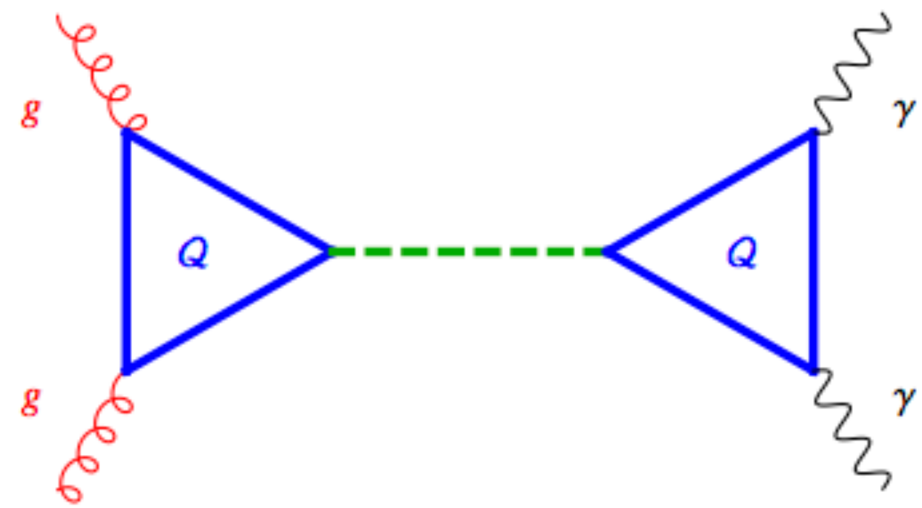


Up to β

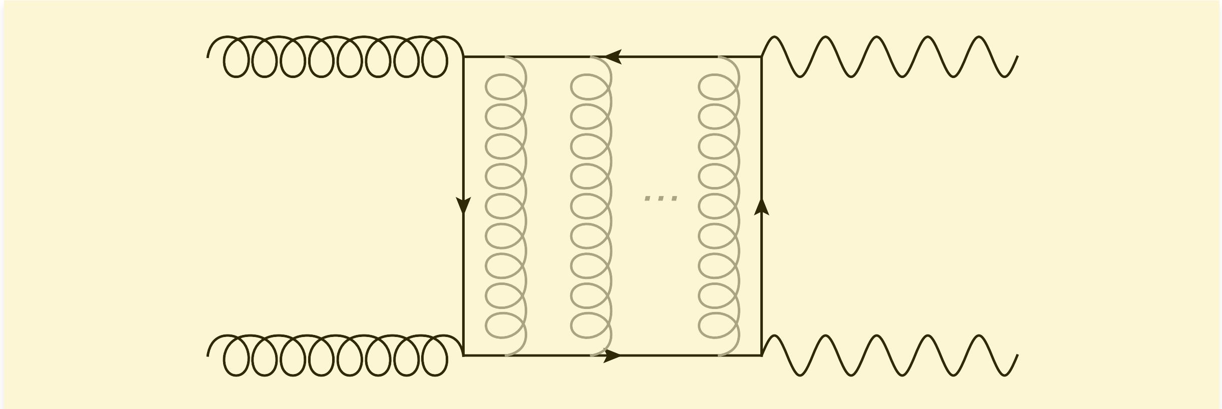
Self-consistency equation leads to
Schroedinger equation of Coulomb potential

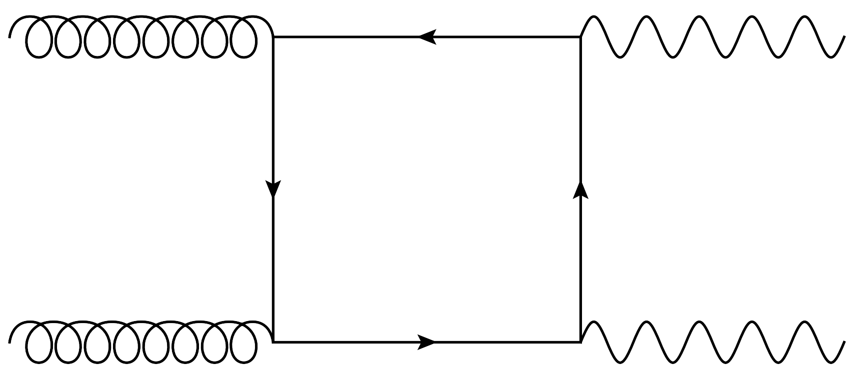
Strassler, Peskin (91)

Quarkonium : narrow width approximation



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





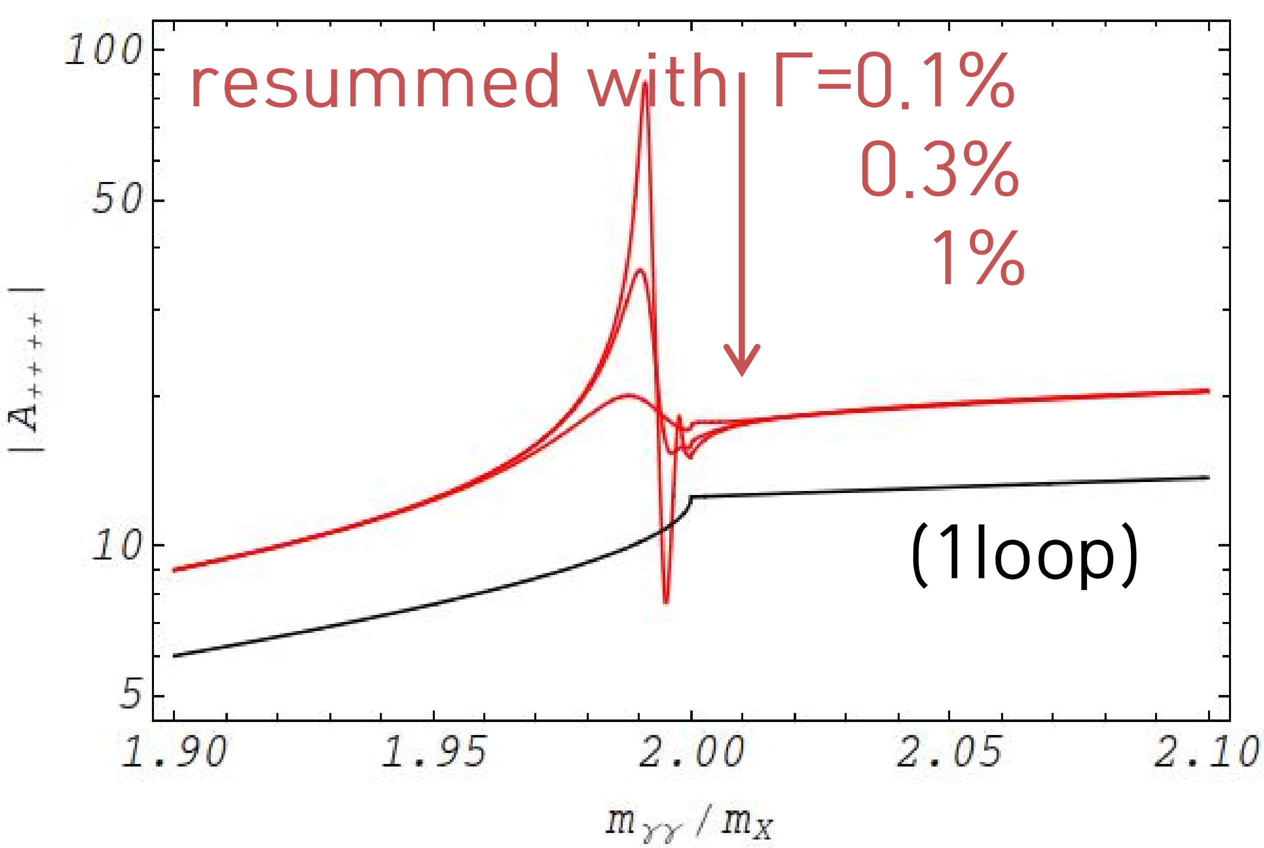
1 loop : breaks down at the threshold

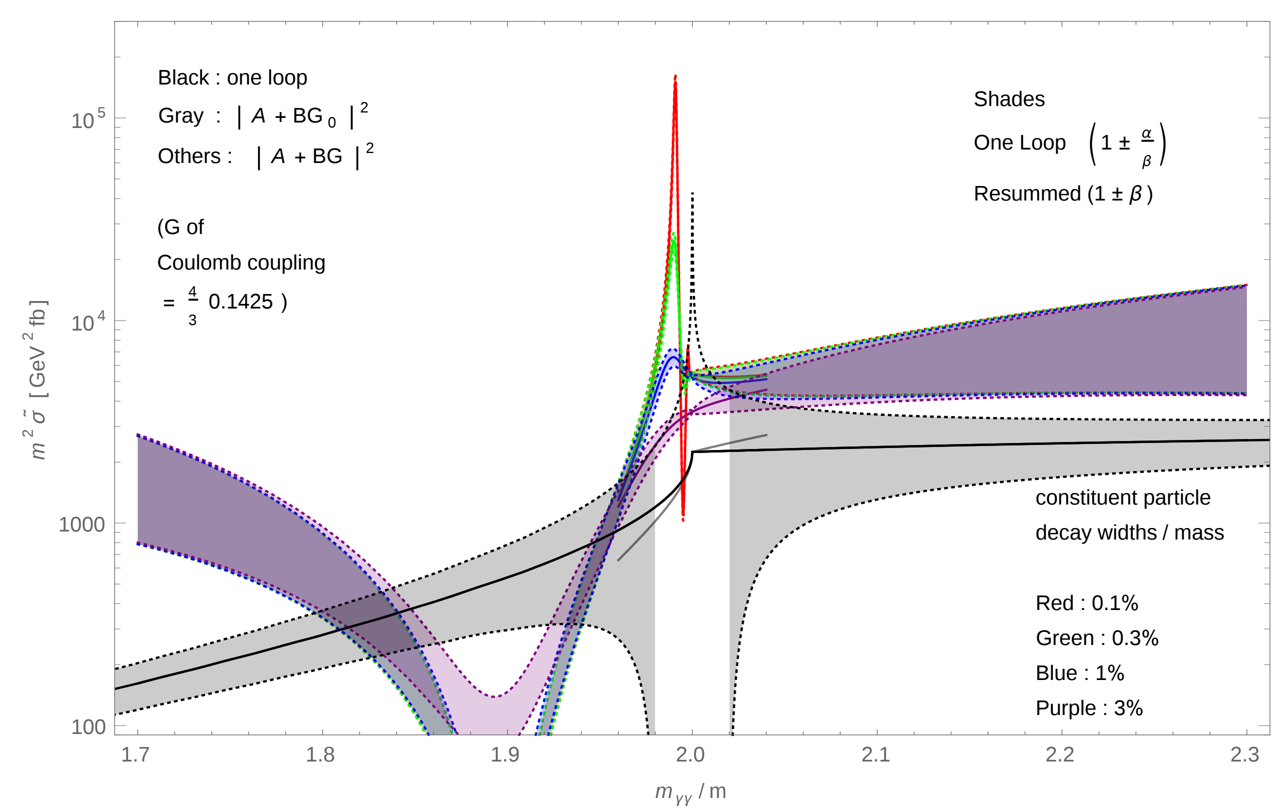
$$\left(\frac{\nabla^2}{m} + V(r) - E\right) G(\mathbf{r}, \mathbf{r}'; E) = \delta(\mathbf{r} - \mathbf{r}').$$

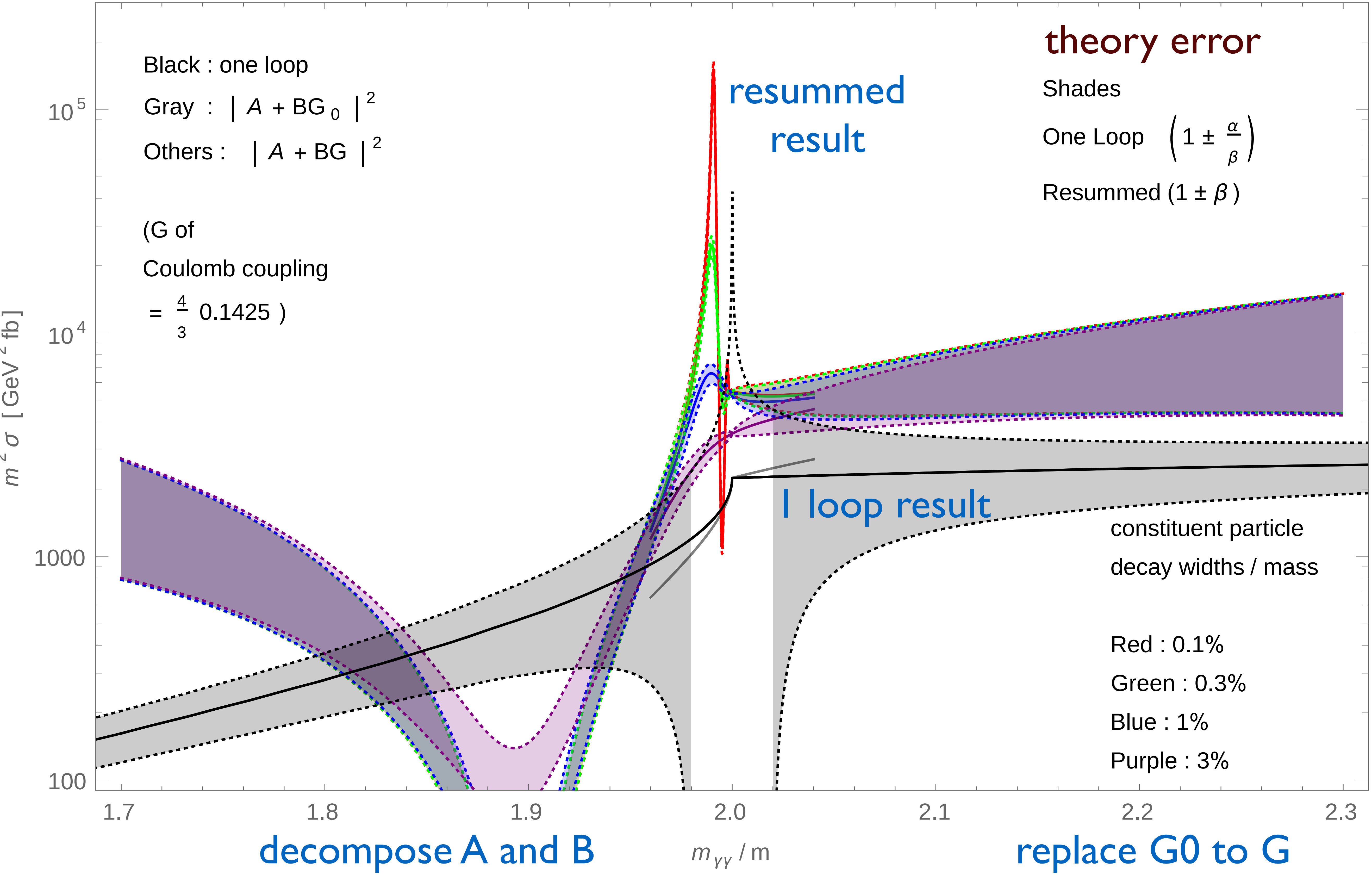
$$V(r) = -Y C_2(X) \frac{\alpha_S(\bar{\mu})}{r}$$ (Y > 1 from QED resummation)

free Green's function before resummation

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







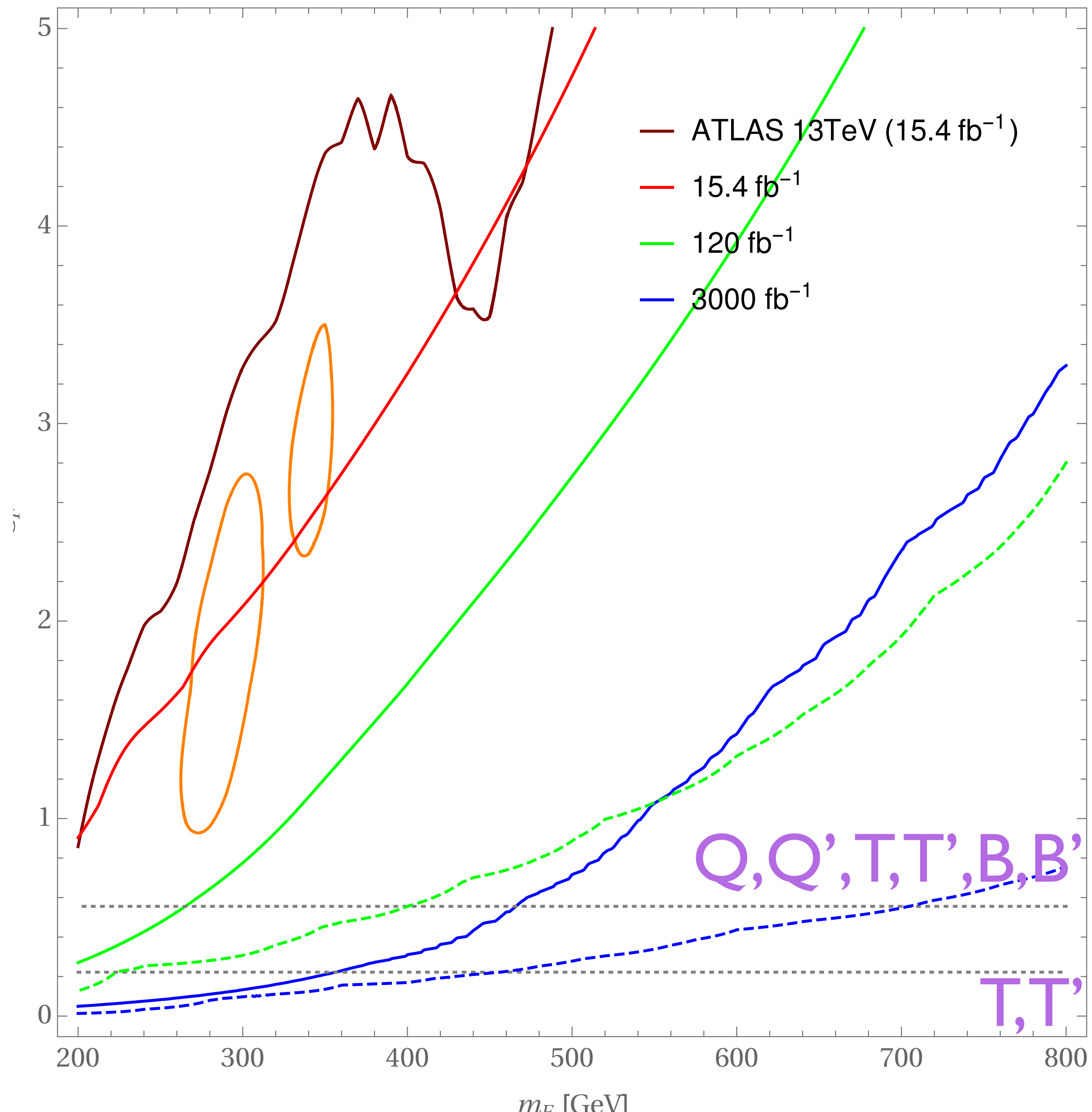
decompose A and B

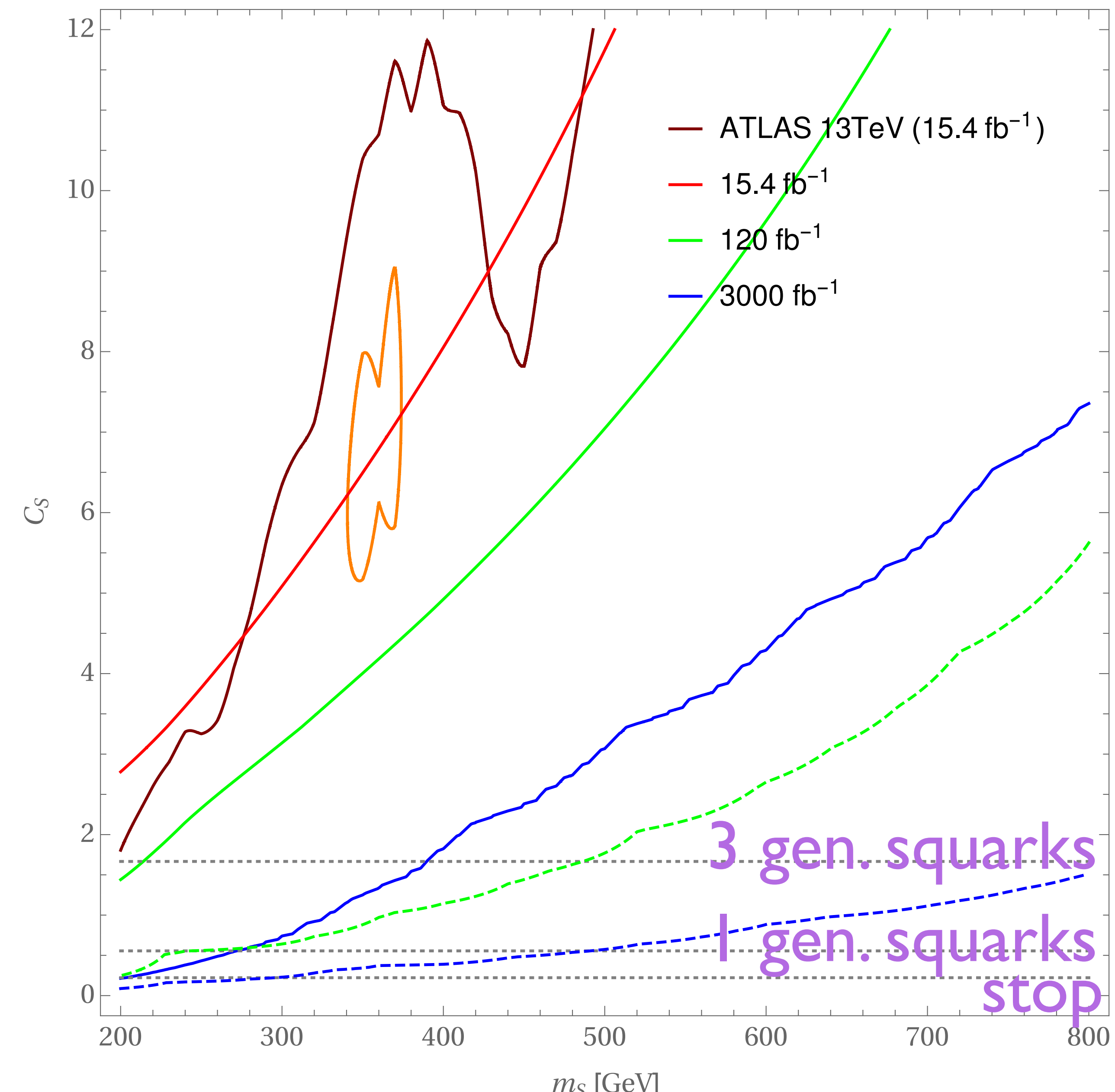
replace G0 to G

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

exclusion or expected exclusion

arXiv: 1612.05031





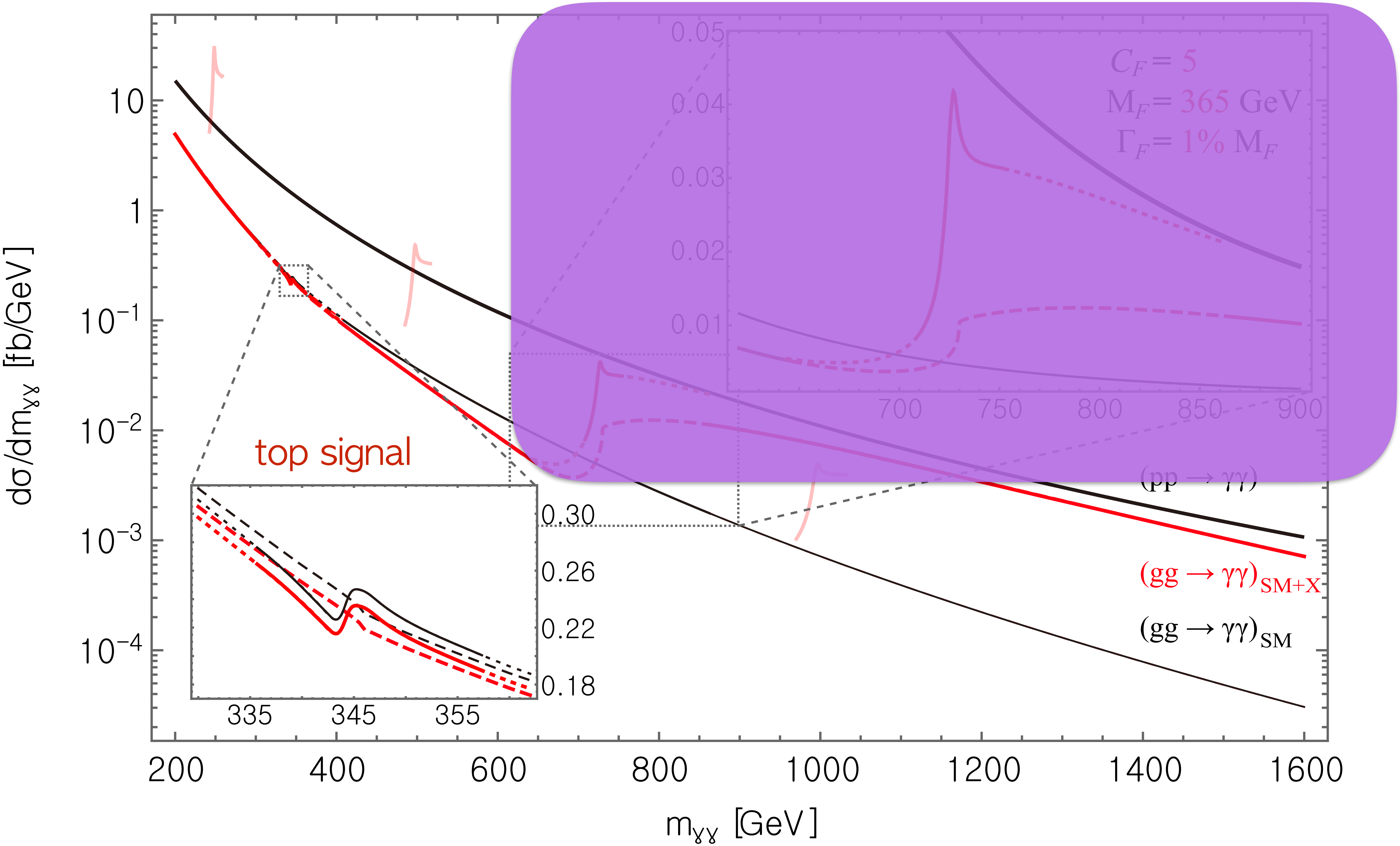
solid : $\Gamma = 10^{-2} m$

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

$C = S_2 Q^2$

color charge

PRL 117 (2016) 061801



Precise top mass determination is very important

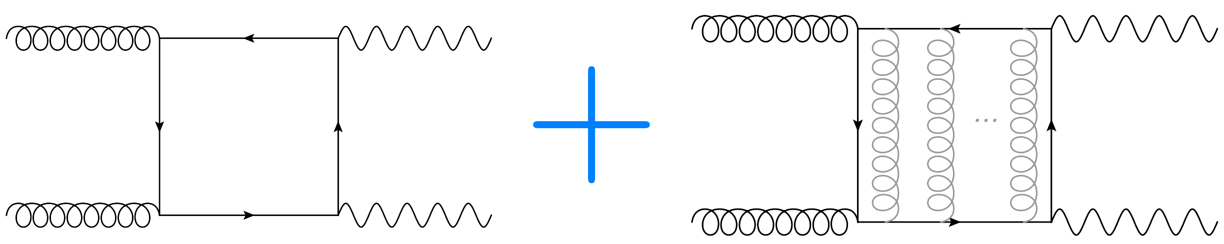
Top mass precision at LHC : Λ_{QCD}

Top mass precision at ILC : 20 MeV

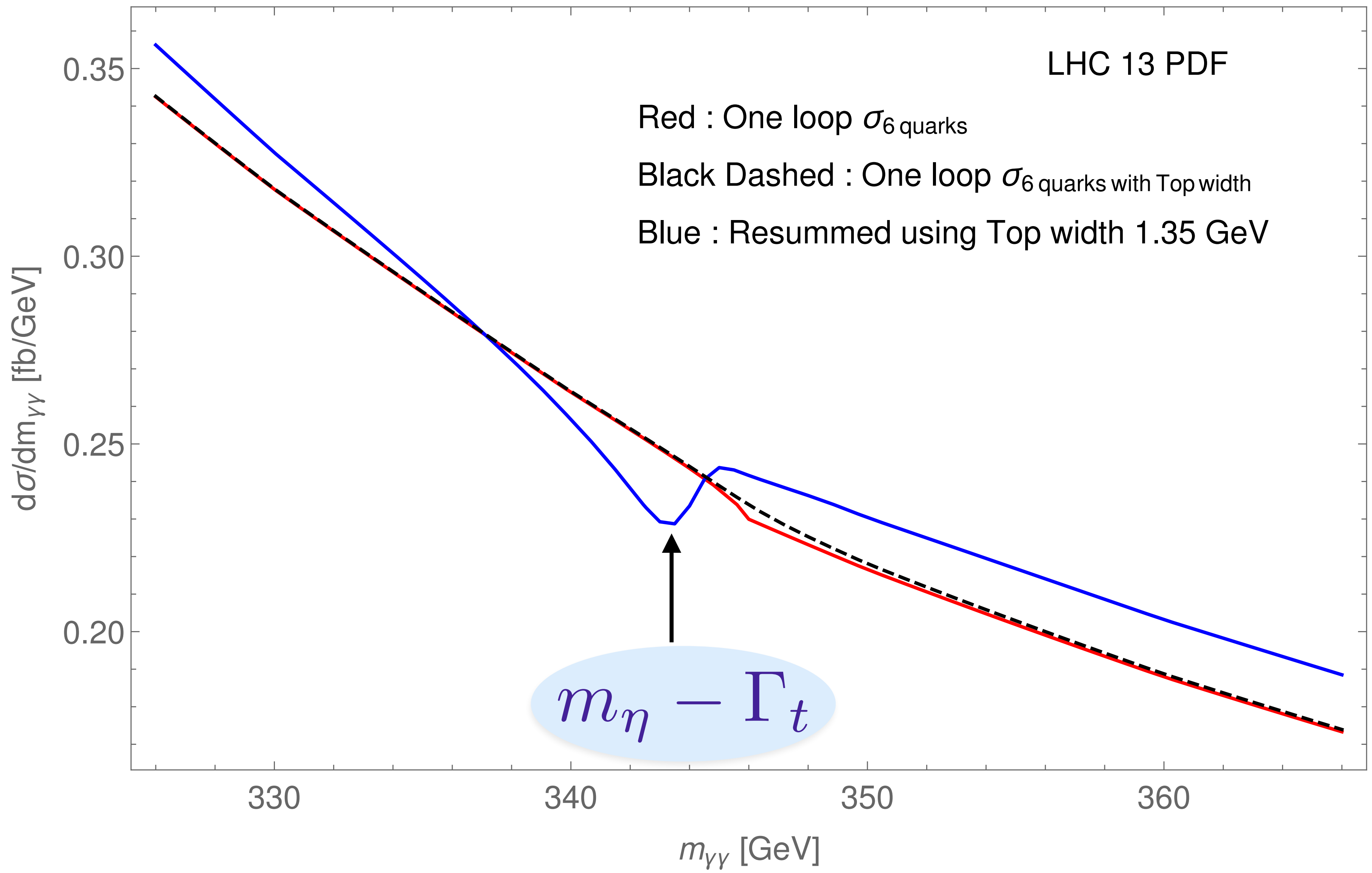
Can we overcome the huddle with diphotons?

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

Binding energy

$$E_b = \frac{1}{2}\frac{m_t}{2}C_F^2\alpha_s^2 = 1.5\ \text{GeV}$$

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

Decay width

$$\Gamma_{t\bar{t}} = 2\Gamma_t = 2.7\ \text{GeV}$$

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

higher states overlap (less than 20%)

we can call it toponium though not a single resonance

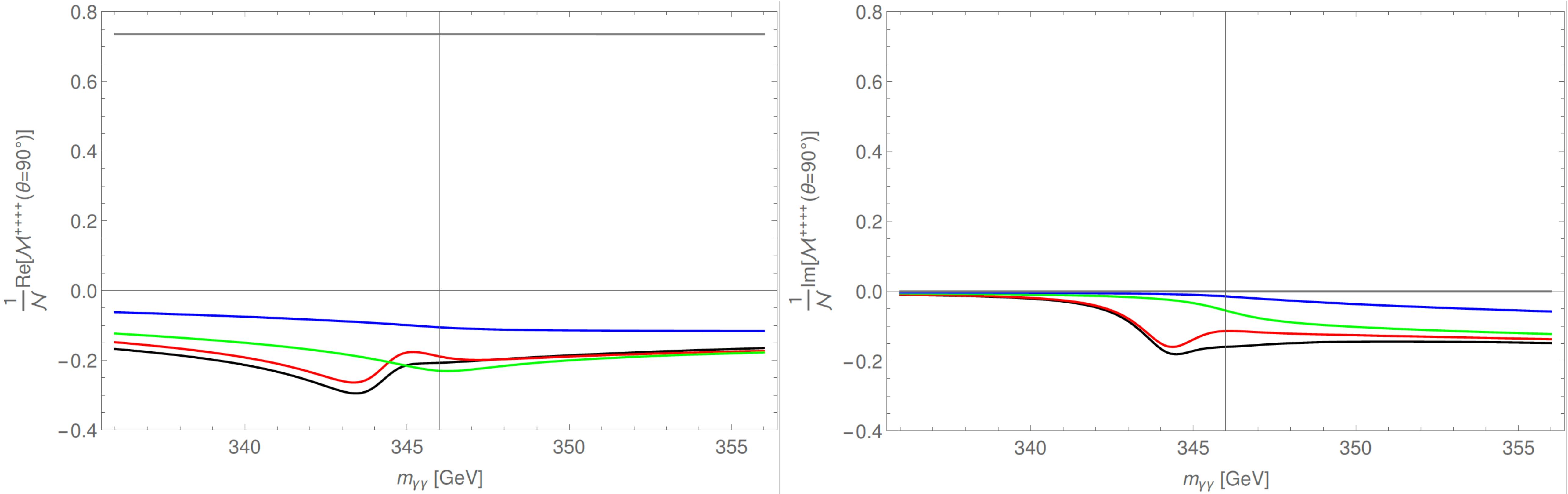
Top quark

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

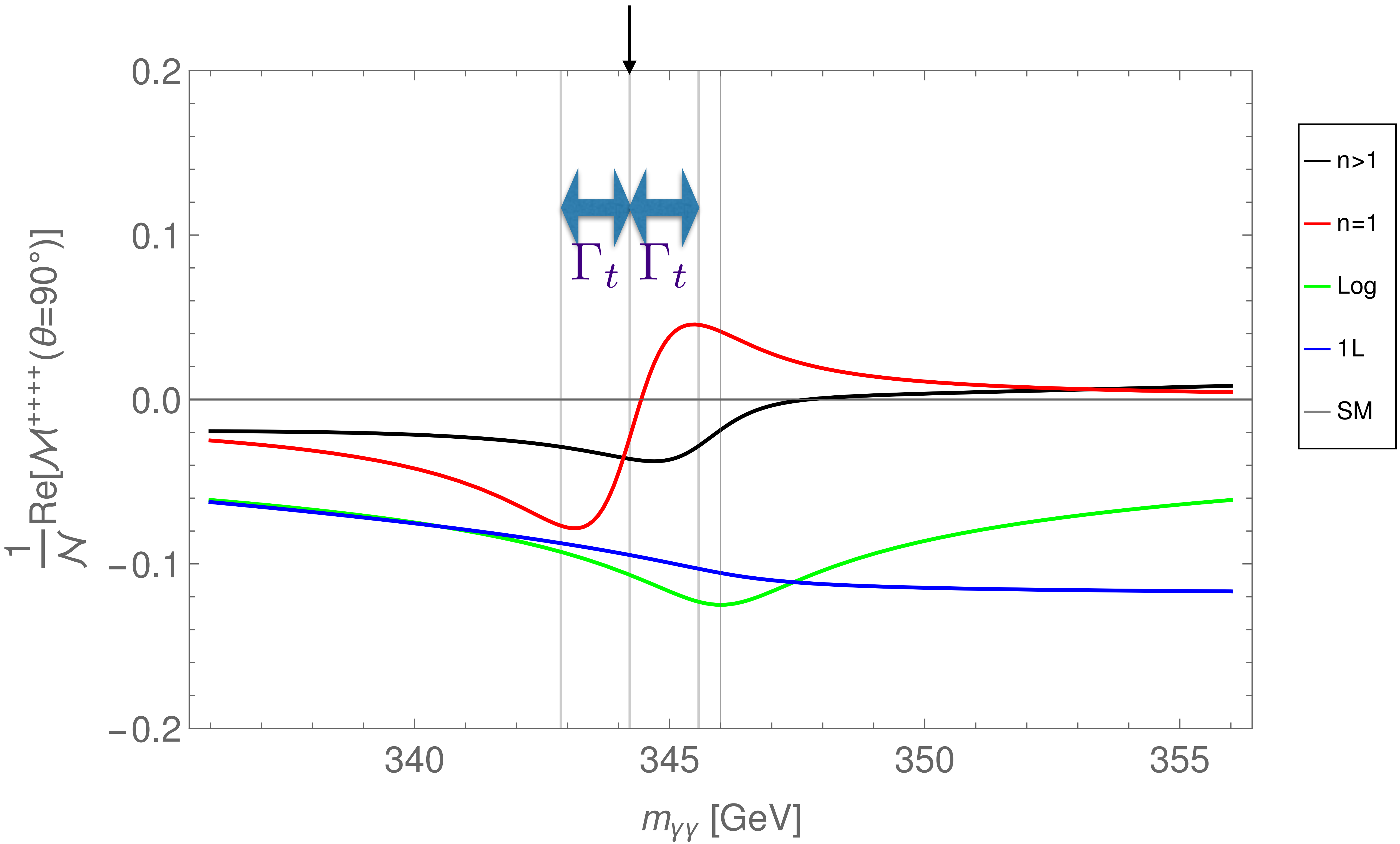
- $\mathcal{M}^\Lambda(gg \to \gamma\gamma)$

RG evolution n=1 Bound State

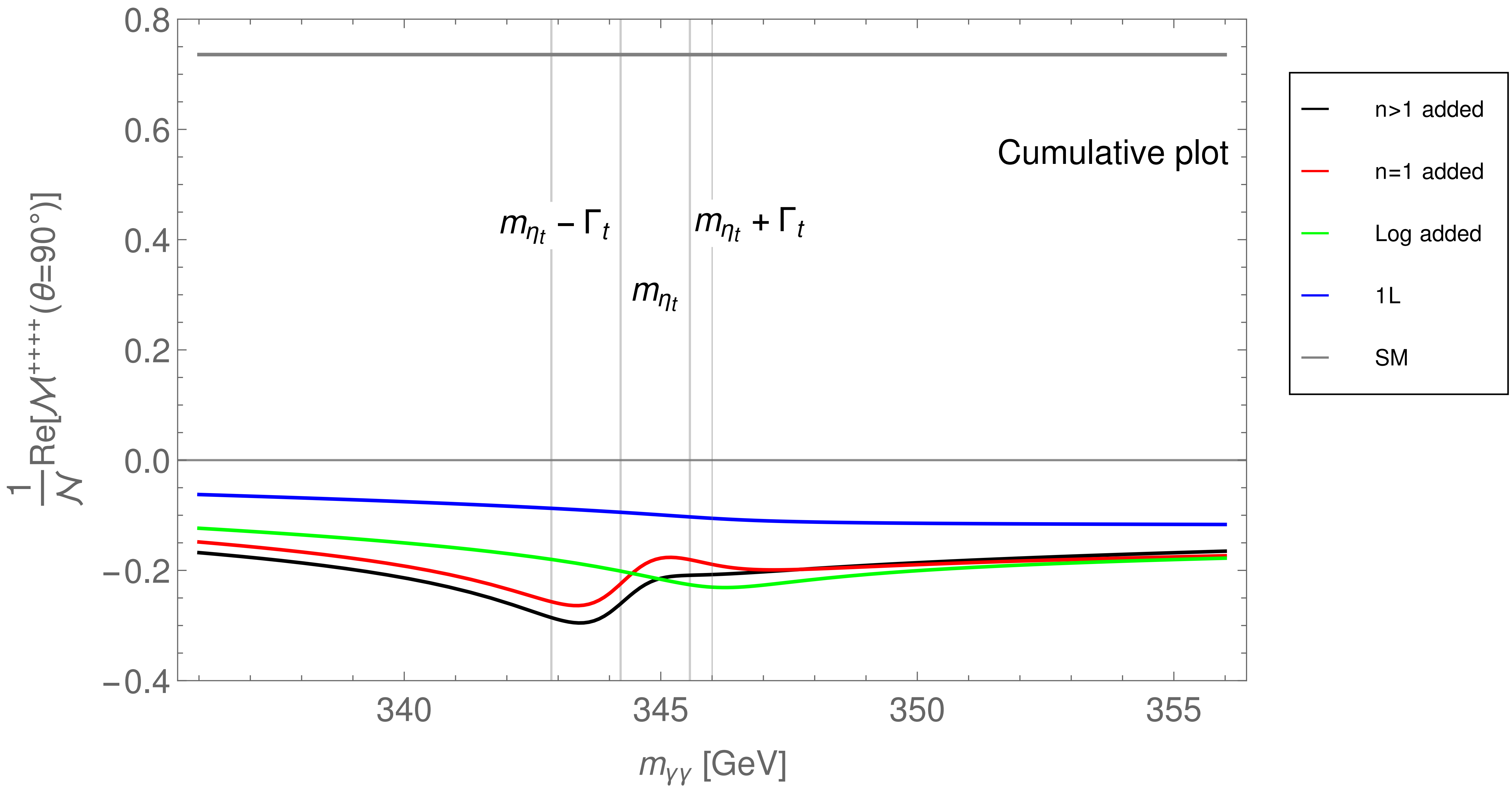
$$= \mathcal{M}^\Lambda_{one\ loop}(s,t,u) + B^\Lambda(-C\alpha_S(\mu)\ln(\frac{m_X}{\sqrt{-m_X E}}) - \frac{2}{\sqrt{m_X}} \sum_{n=1}^{\infty} \frac{E_n}{\sqrt{-E} - Sign(C)\sqrt{E_n}}) + \mathcal{M}^\Lambda_{u,d,s,c,b}$$



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

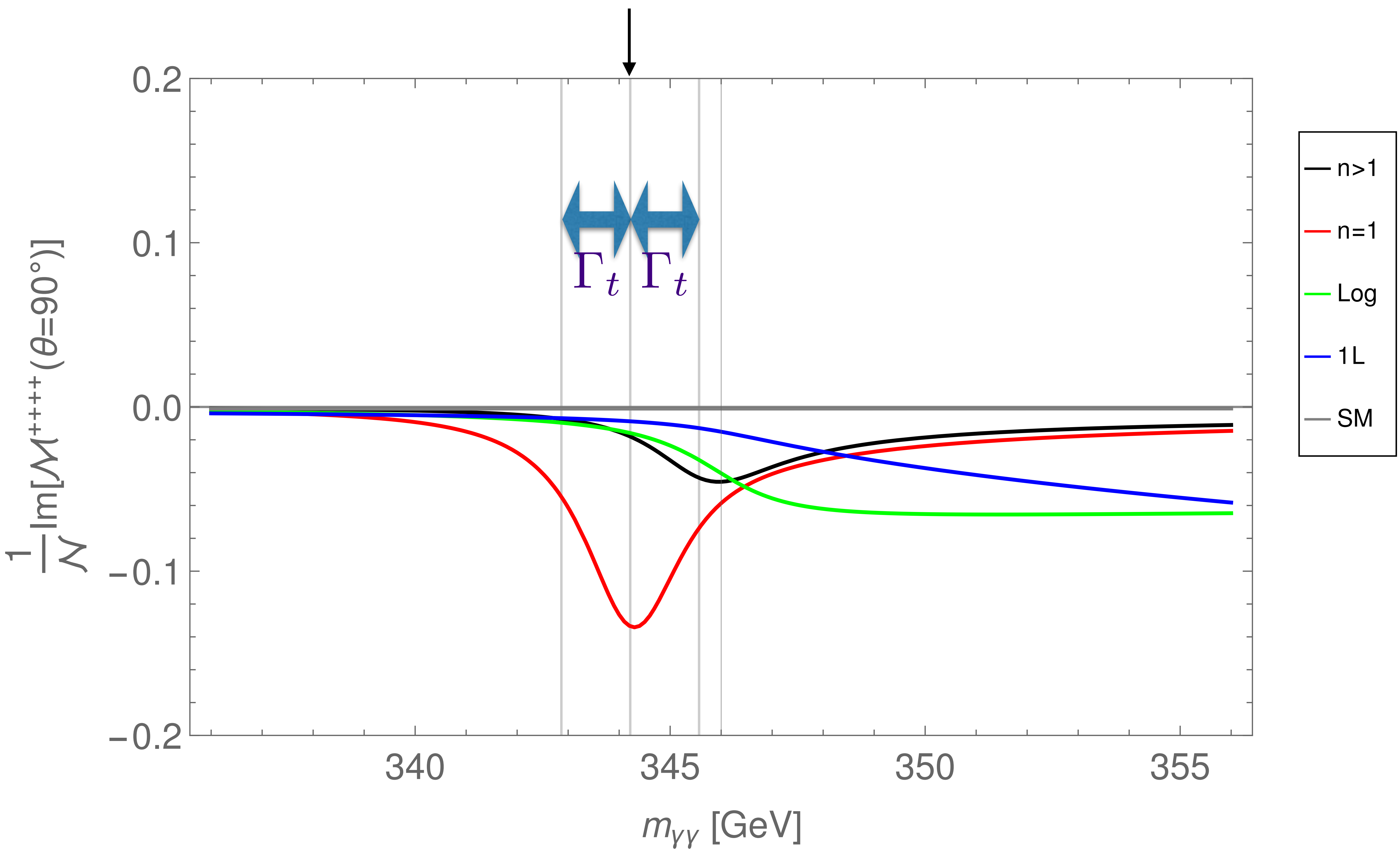


Γ_t
Γ_t
0.2
0.1
0.0
−0.1
−0.2
$\frac{1}{\mathcal{N}}\mathrm{Re}[\mathcal{M}^{++++}(\theta=90°)]$
340
345
350
355
$m_{\gamma\gamma}$ [GeV]
n>1
n=1
Log
1L
SM

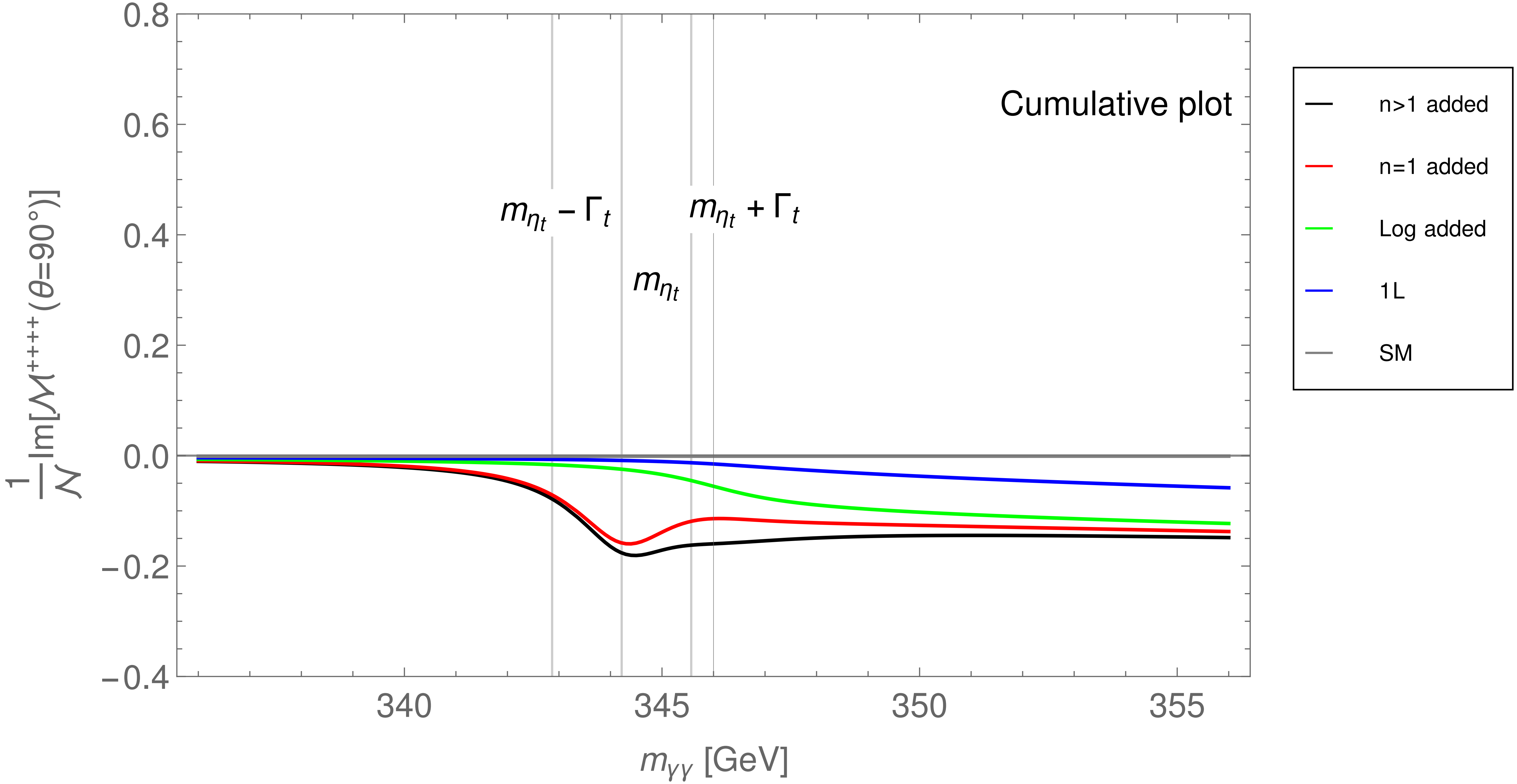


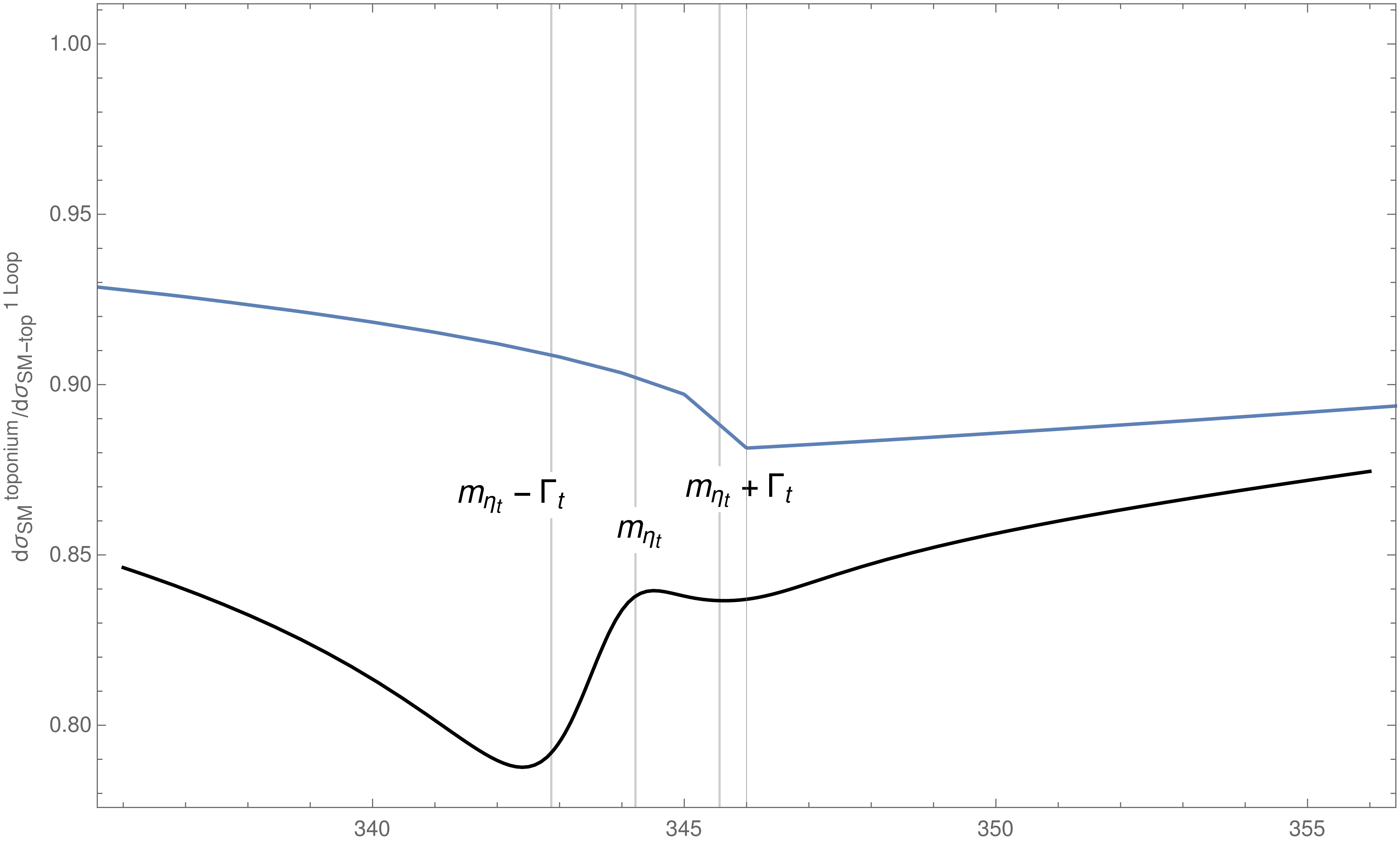
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
340
345
350
355
$m_{\gamma\gamma}$ [GeV]
$\frac{1}{\mathcal{N}}\mathrm{Re}[\mathcal{M}^{++++}(\theta=90°)]$
Cumulative plot
$m_{\eta_t} - \Gamma_t$
m_{η_t}
$m_{\eta_t} + \Gamma_t$
n>1 added
n=1 added
Log added
1L
SM

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

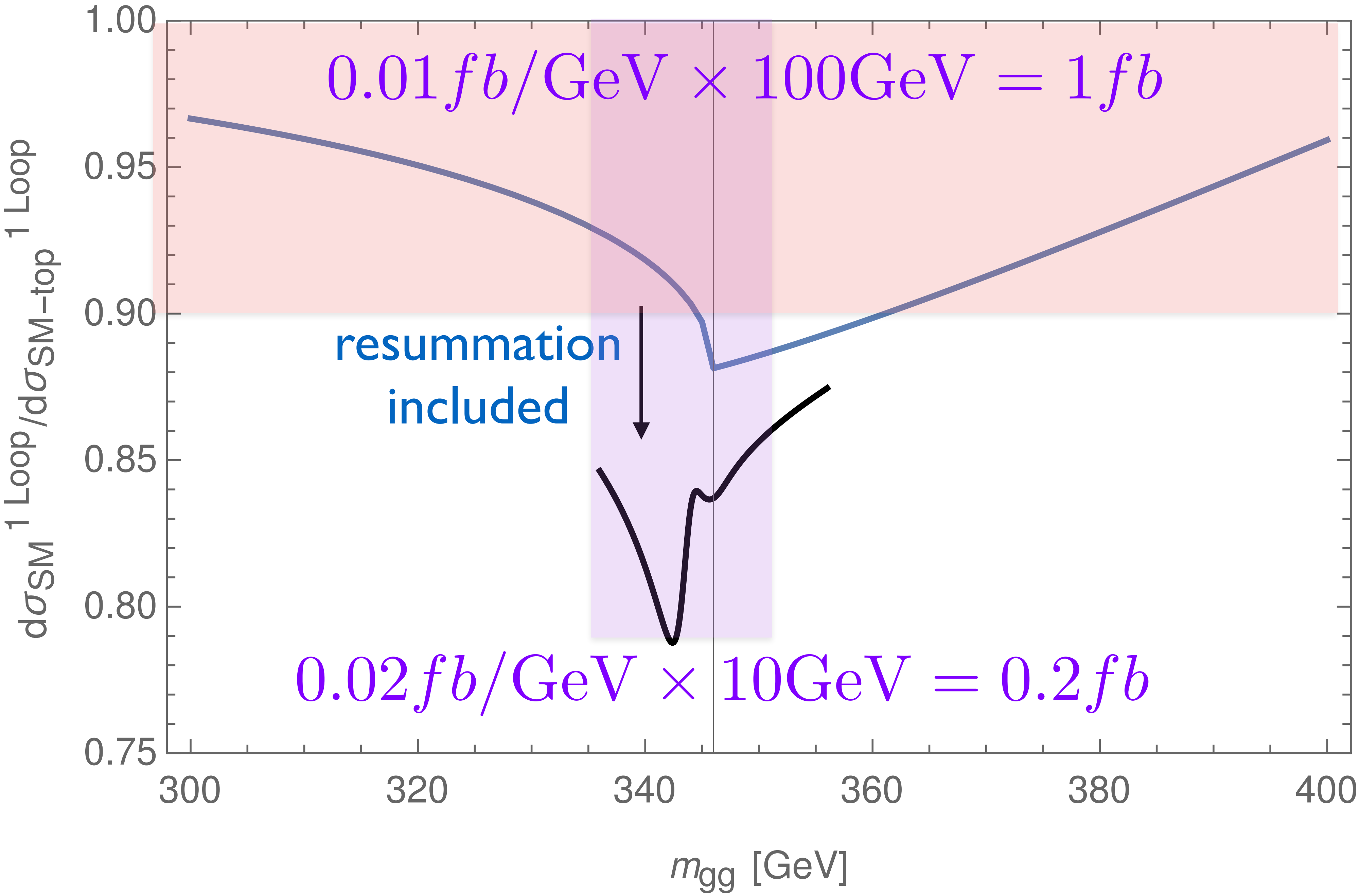


Γ_t Γ_t
0.2
0.1
0.0
−0.1
−0.2
$\frac{1}{\mathcal{N}}\mathrm{Im}[\mathcal{M}^{++++}(\theta=90°)]$
340
345
350
355
$m_{\gamma\gamma}$ [GeV]
n>1
n=1
Log
1L
SM


Cumulative plot
n>1 added
n=1 added
Log added
1L
SM
$m_{\eta_t} - \Gamma_t$
m_{η_t}
$m_{\eta_t} + \Gamma_t$
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_{η_t}
$m_{\eta_t} + \Gamma_t$



1.00
0.95
0.90
0.85
0.80
0.75
300
320
340
360
380
400
m_{gg} [GeV]
$d\sigma_{SM}^{1\,Loop}/d\sigma_{SM-top}^{1\,Loop}$
$0.01fb/\mathrm{GeV} \times 100\mathrm{GeV} = 1fb$
resummation included
$0.02fb/\mathrm{GeV} \times 10\mathrm{GeV} = 0.2fb$

$$\sigma(t\bar{t}) \sim nb$$

$$\sigma(\eta_t \to \gamma\gamma) \sim fb$$

suppression from toponium formation

$$|\Psi(r=0)|^2 \sim \alpha_S^3$$

$$10^{-3}$$

from diphotons

$$\frac{\mathrm{Br}(\eta_t \to \gamma\gamma)}{\mathrm{Br}(\eta_t \to gg)} \sim \frac{\alpha^2}{\alpha_S^2}$$

$$10^{-2}$$

factor 5 enhancement from interference

need a large integrated luminosity

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

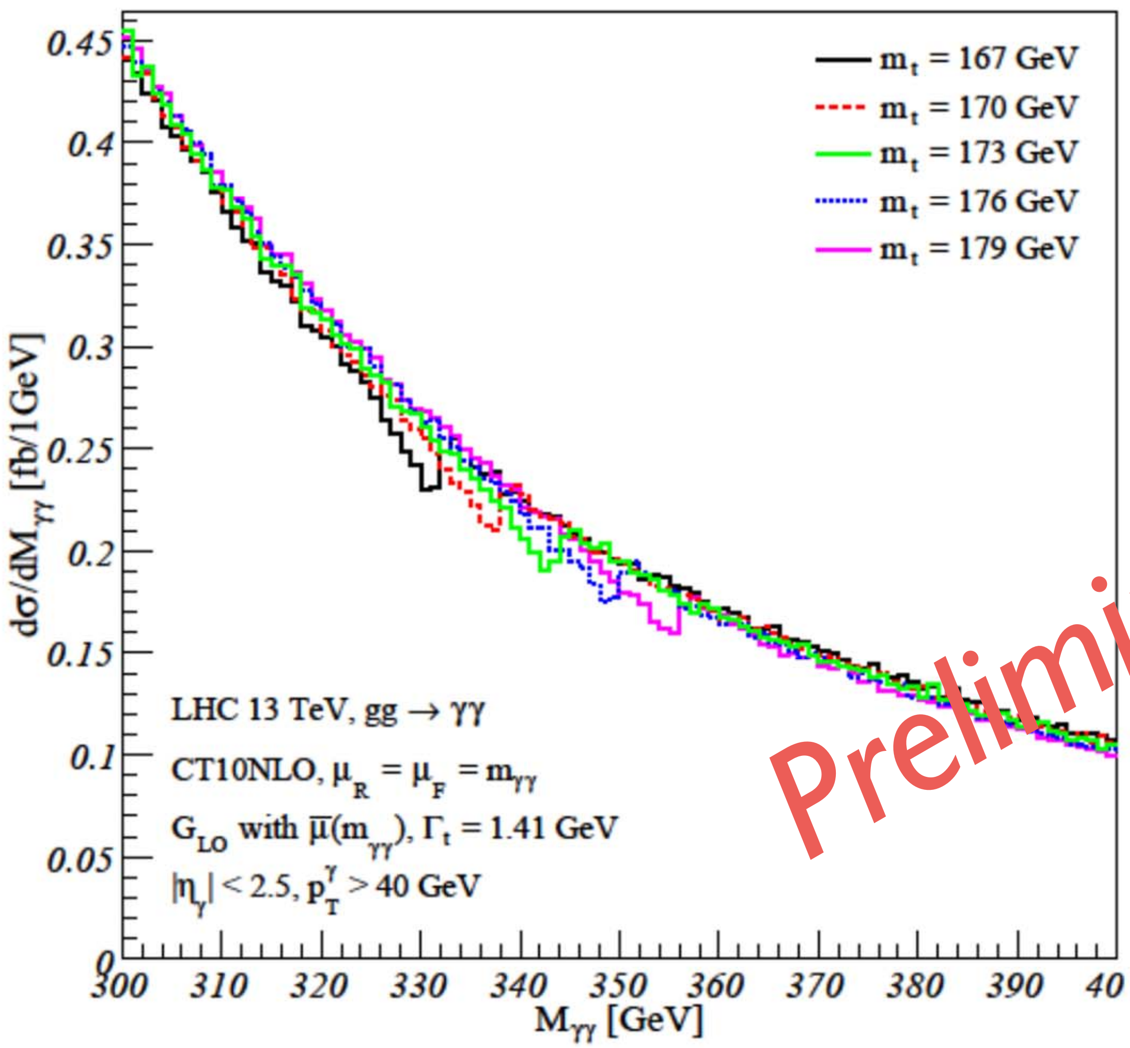
renormalon effects cancel out in the energy

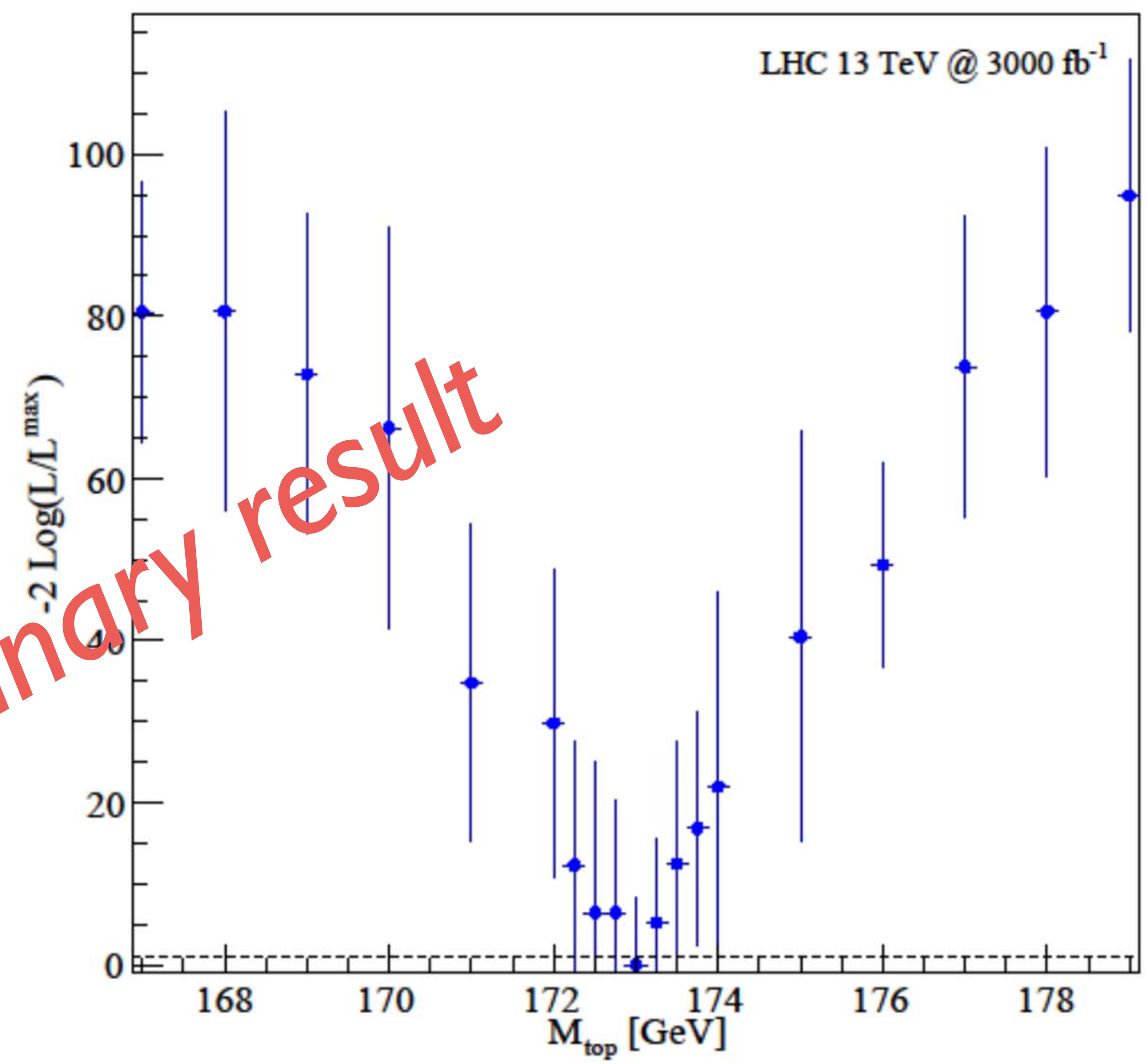
$$E_{\rm stat} = 2m_{\rm pole} + V_{\rm stat}(r)$$

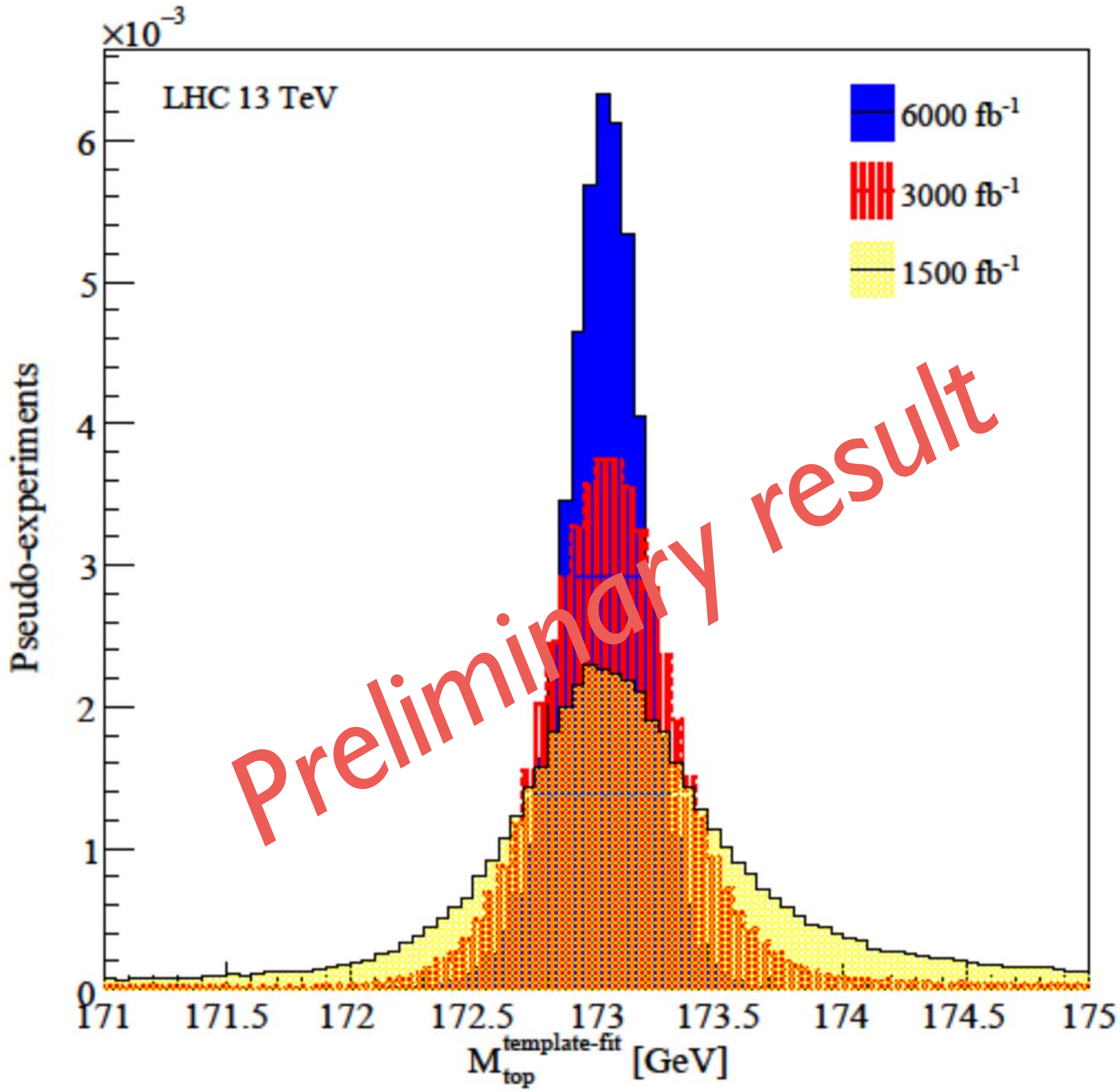
$$m_{1S} = m_{\rm pole} + \frac{1}{2}V(r)$$

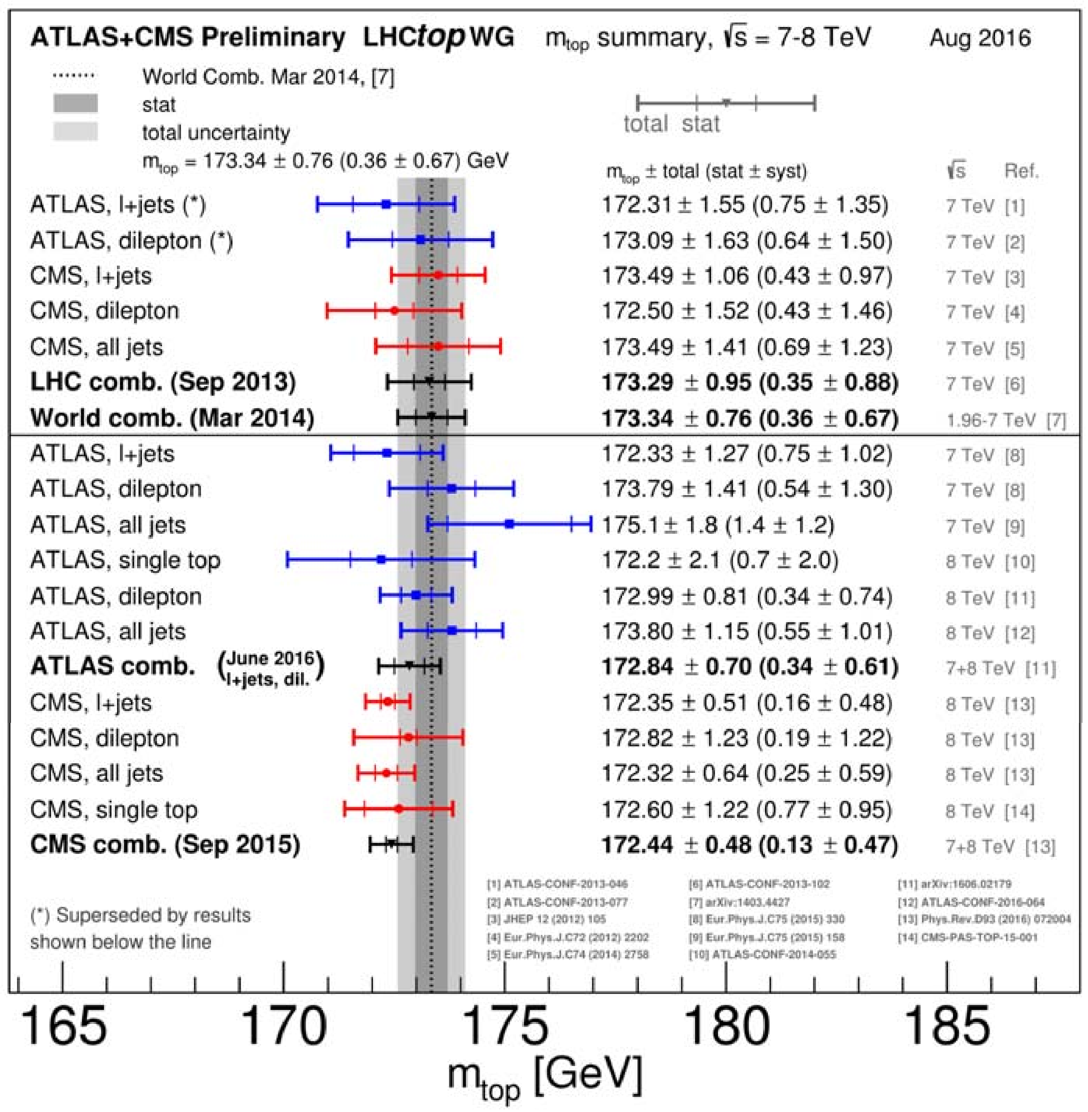
free from $\Lambda_{\rm QCD}$

Top search









There is a hope for $\Delta m_t < 1$ GeV from a single channel measurement

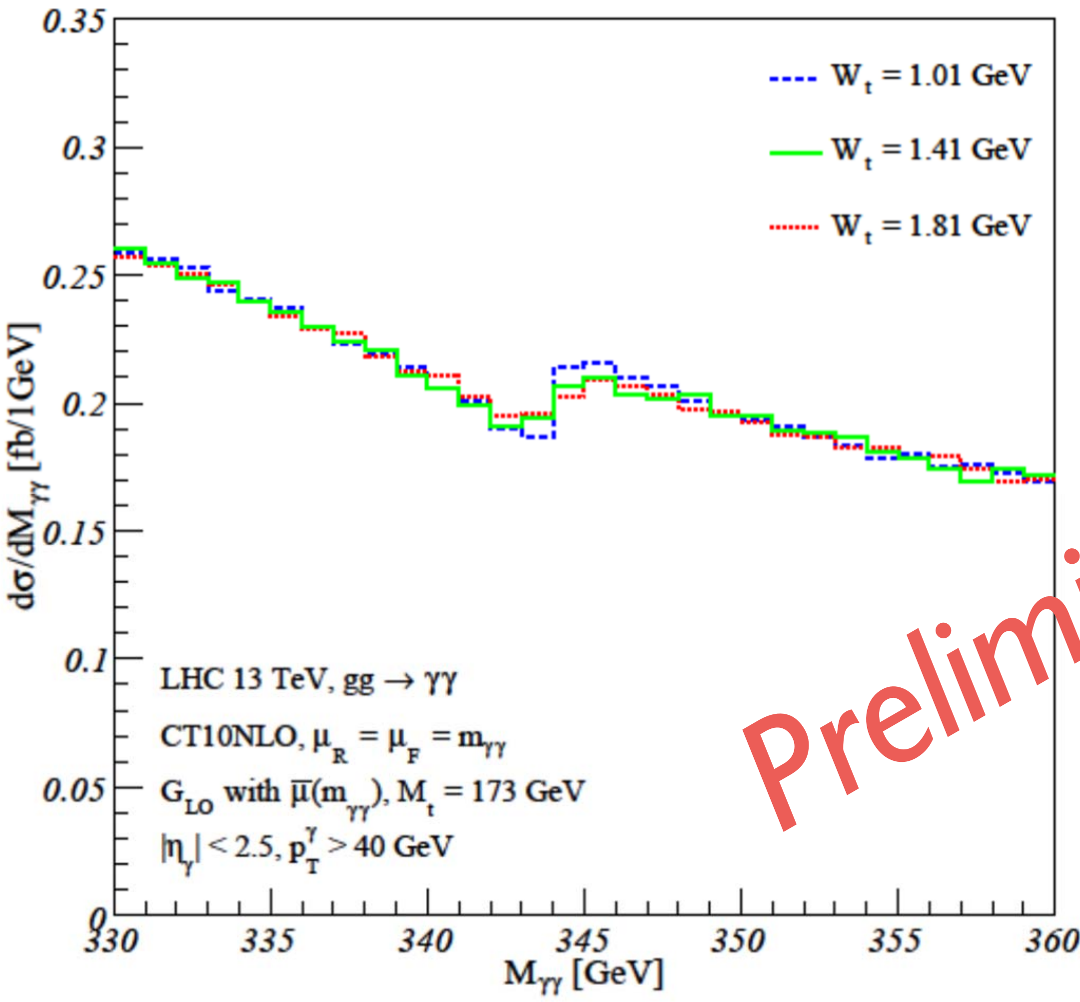
HE-LHC would be better (gluon pdf)

current best limit (direct measurement)

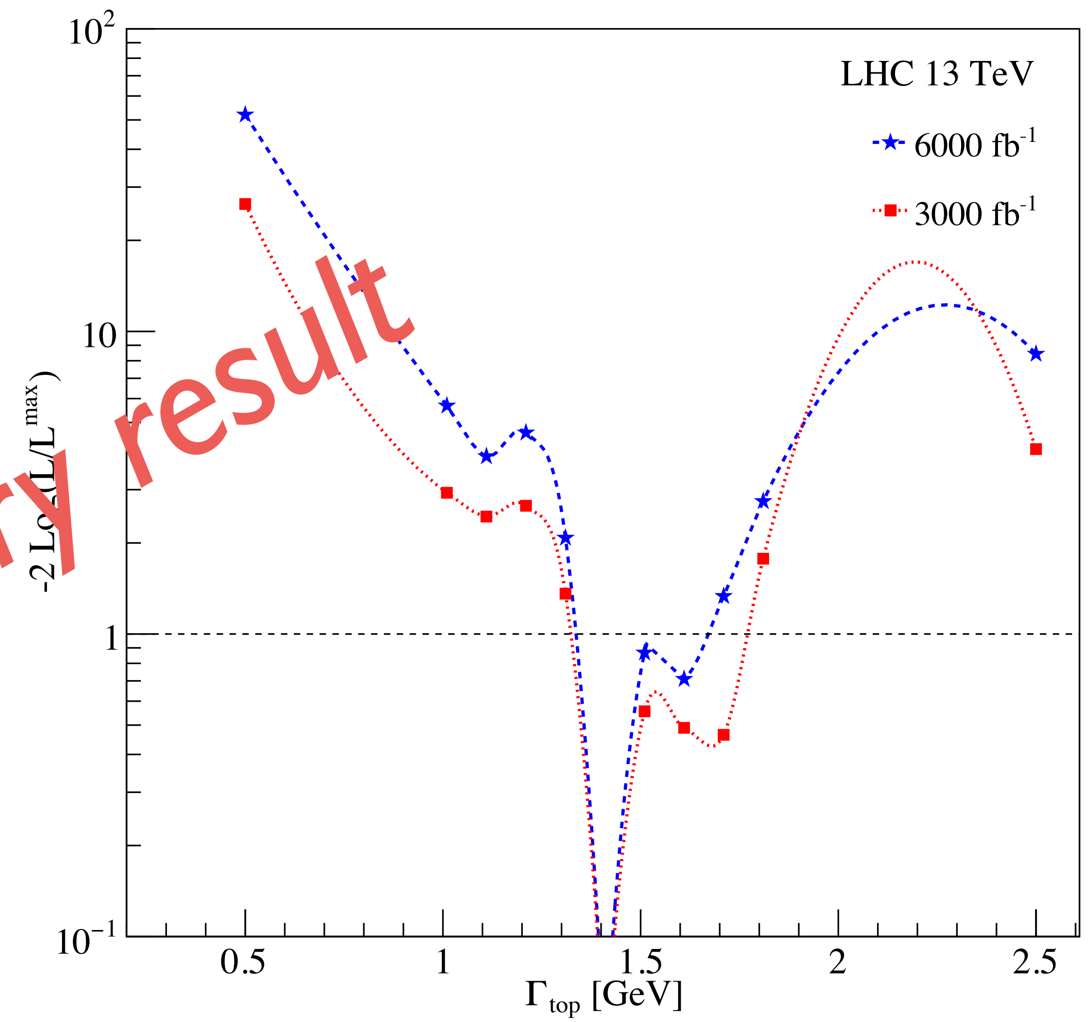
$$1.1\text{GeV} < \Gamma_t < 4.1\text{GeV}$$

(CDF Run II, 68% CL)

Top Width



shape is sensitive to the width



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

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