Top quark precision physics with di-photons at the LHC

IBS-KIAS High1-2017, Feb. 9th

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with Dongjin Chway, Radovan Dermisek, Tae Hyun Jung

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arXiv:1612.05031
arXiv:1702.yyyyy (including W Cho and D S Lee)

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

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

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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

$$gg \to \gamma\gamma$$

There is no tree level vertex in the Standard Model

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

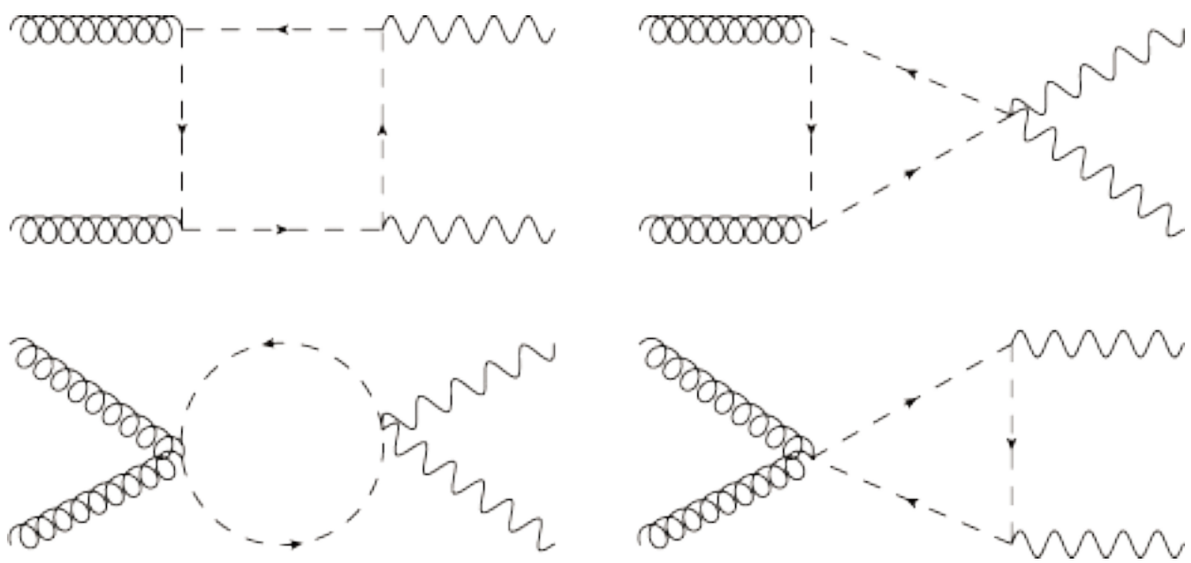
We've discovered Higgs boson with this channel

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

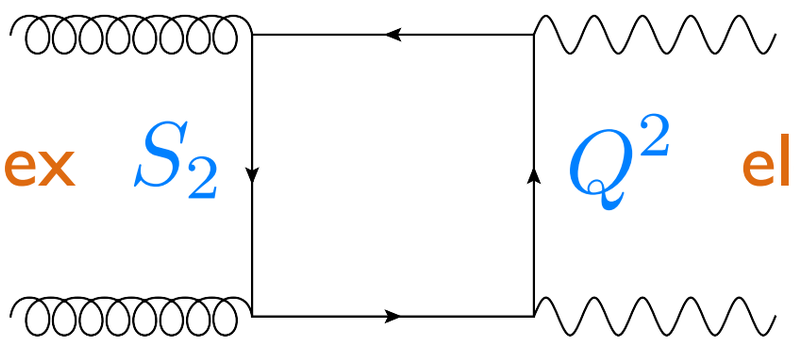
Is it the only possibility?

$gg \to \gamma\gamma$

Scalar



Fermion

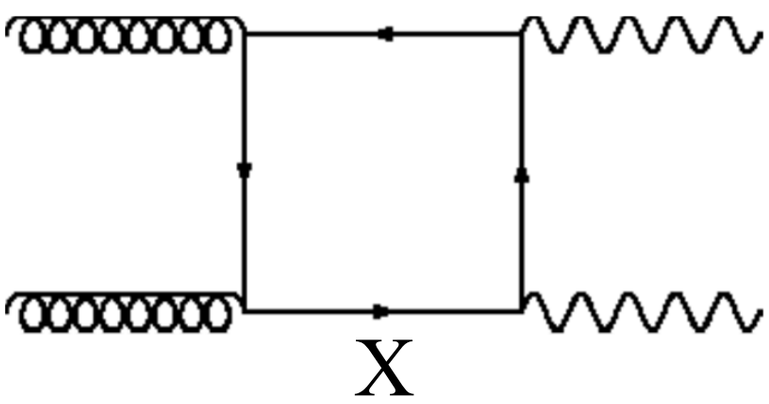


SU(3) Dynkin index S_2 Q^2 electric change

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

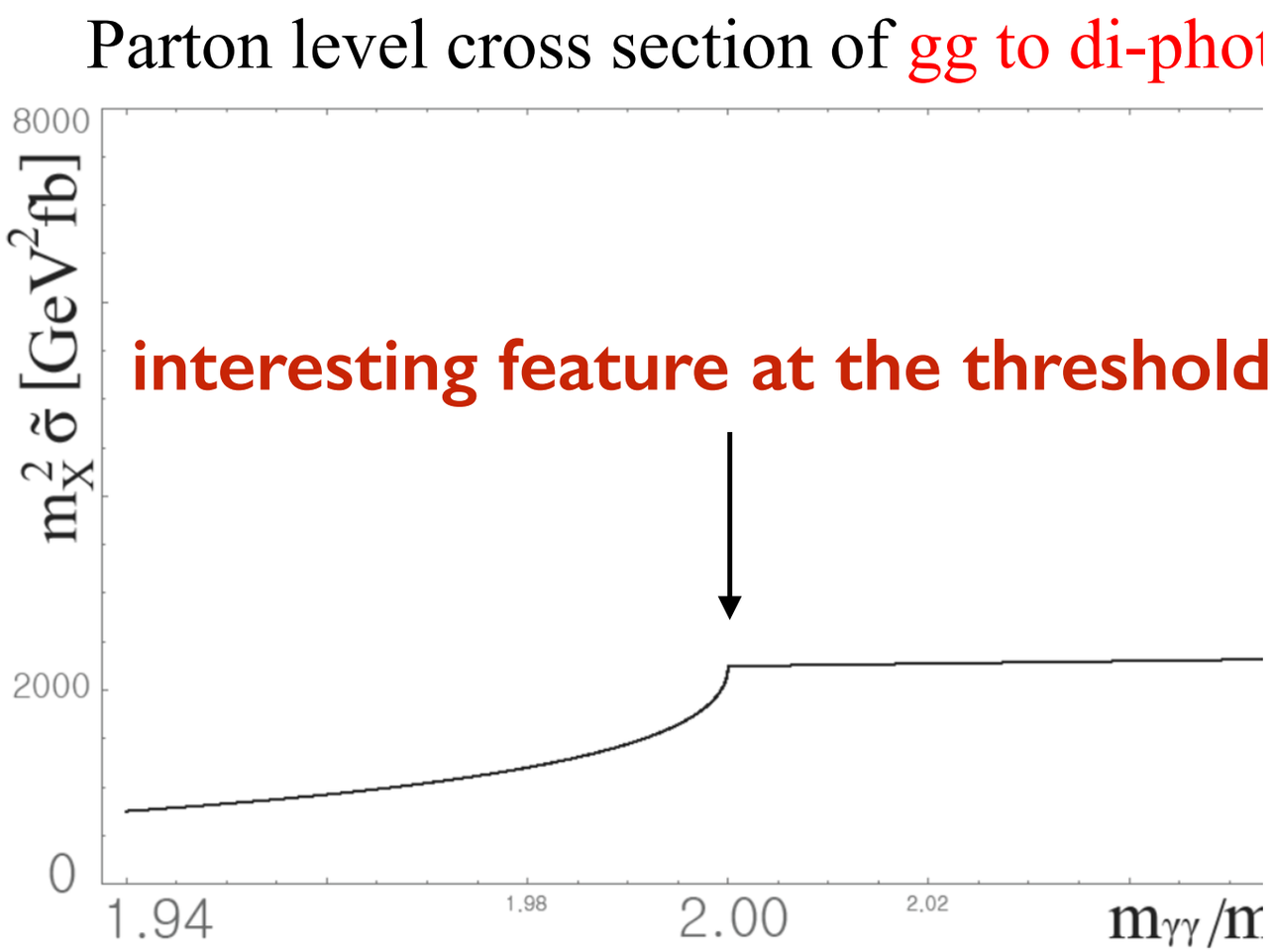
Any new colored/charged particle will contribute to the loop of $gg \to \gamma\gamma$

One Loop

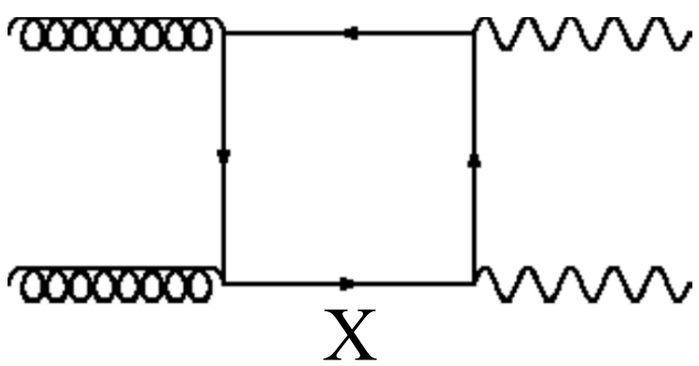


$$\propto C_X \equiv N_X T_{R_X} Q_X^2$$

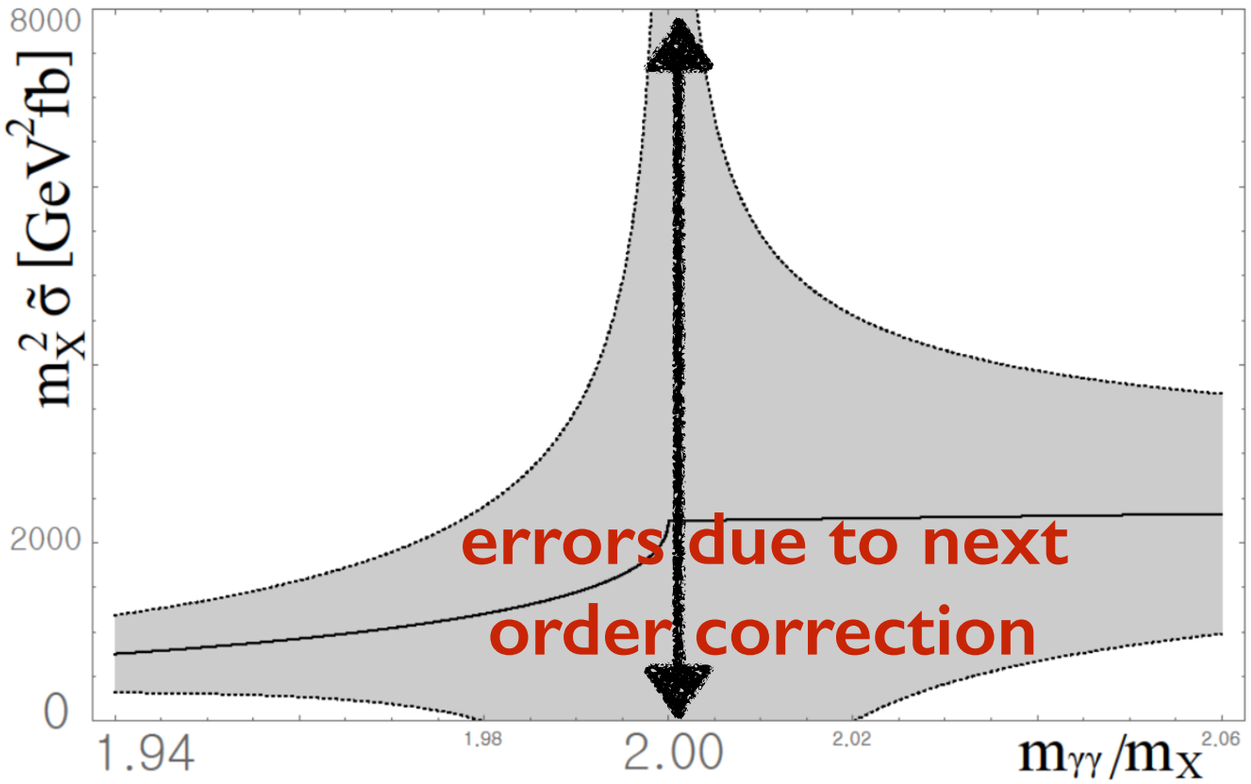
Number of copies SU(3) Dynkin index Electric charge e.g. $C_{top} = 2/9$



One Loop



Parton level cross section of gg to di-photon



Coulomb singlarity at the threshold

CFT or EFT

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

we can discuss Q\bar{Q} 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

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

on-shell

e.g., scaling in v : $d^4k \sim v^0,\ v^4,\ v^5,\ v^8$

hard soft potential ultrasoft

potential NRQCD (pNRQCD)

Pineda Soto (1998)

$$\mathcal{L}_{\rm QCD} \qquad (\mu > m)$$

$$\Downarrow$$

$$\mathcal{L}_{\rm NRQCD} \qquad (m > \mu > mv)$$

$$\Downarrow$$

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

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

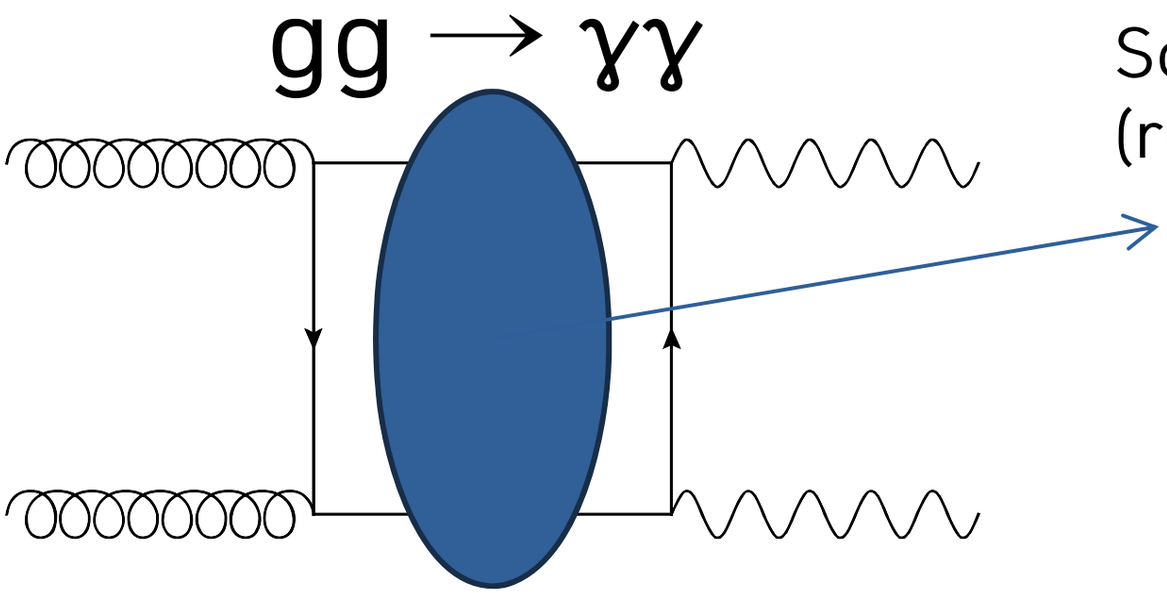
Take the velocity v as the running parameter

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

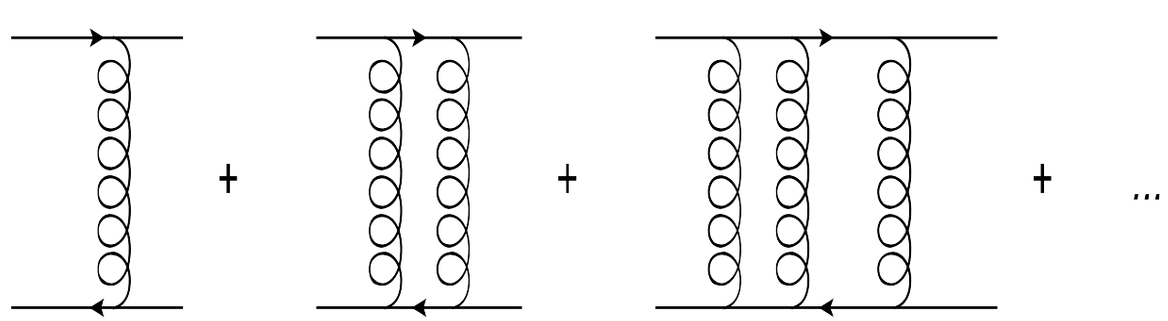
Near threshold

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

should be resummed



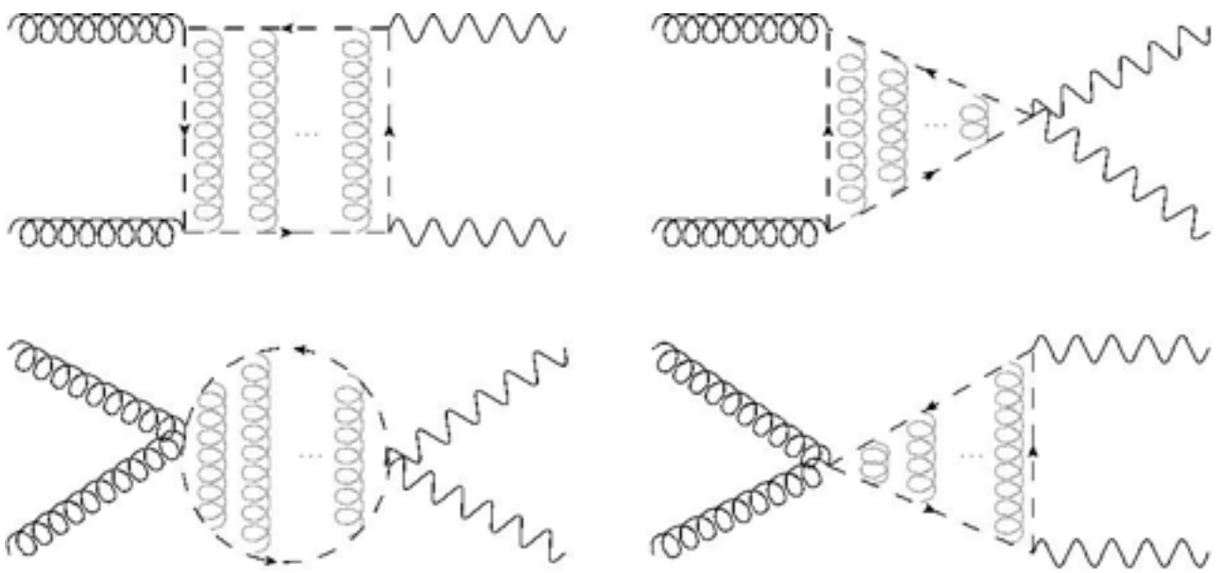
Sommerfeld enhancement near $m_{\gamma\gamma} = 2m_X$
(resummation of ladder diagrams)



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

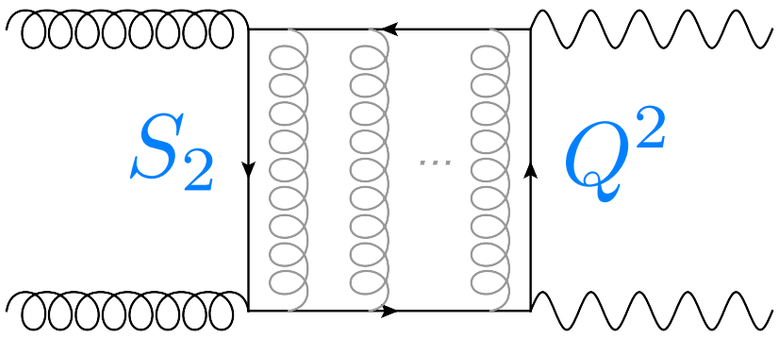
$gg \to \gamma\gamma$

Scalar



Fermion

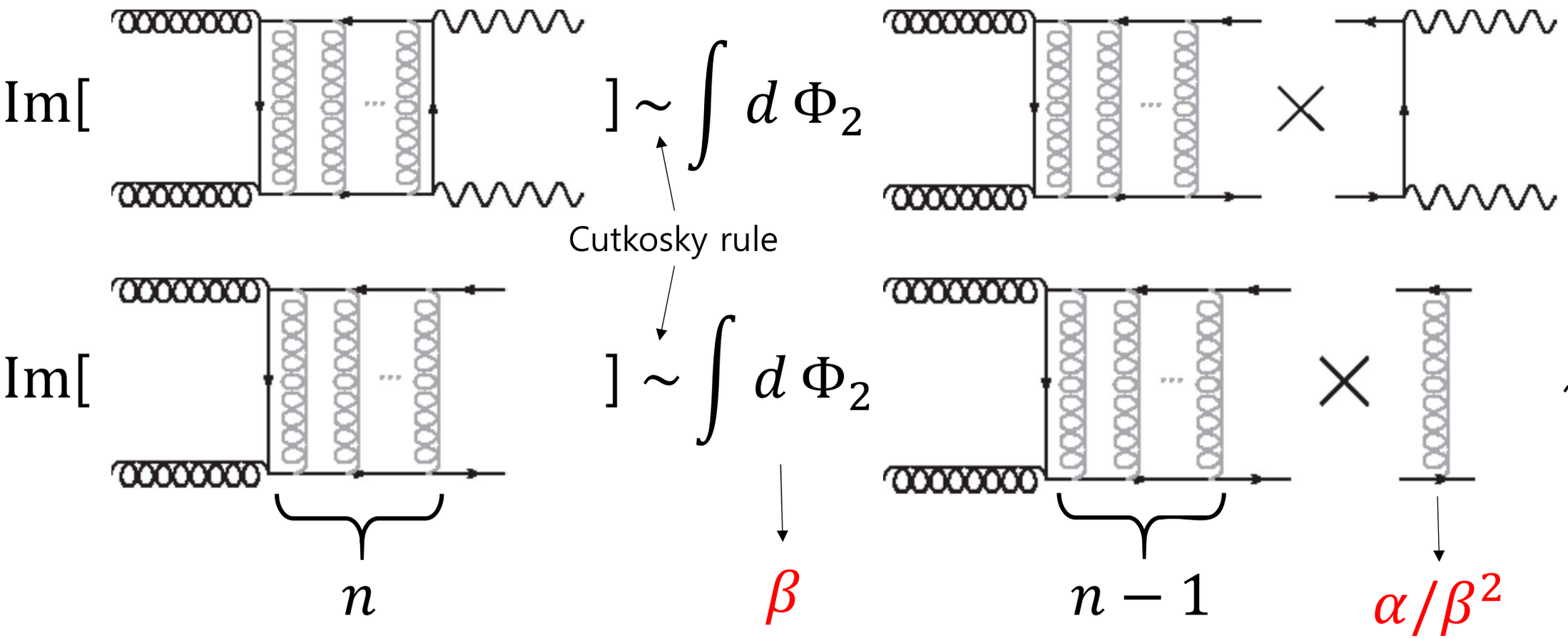
Threshold resummation



$$C = N S_2 Q^2$$

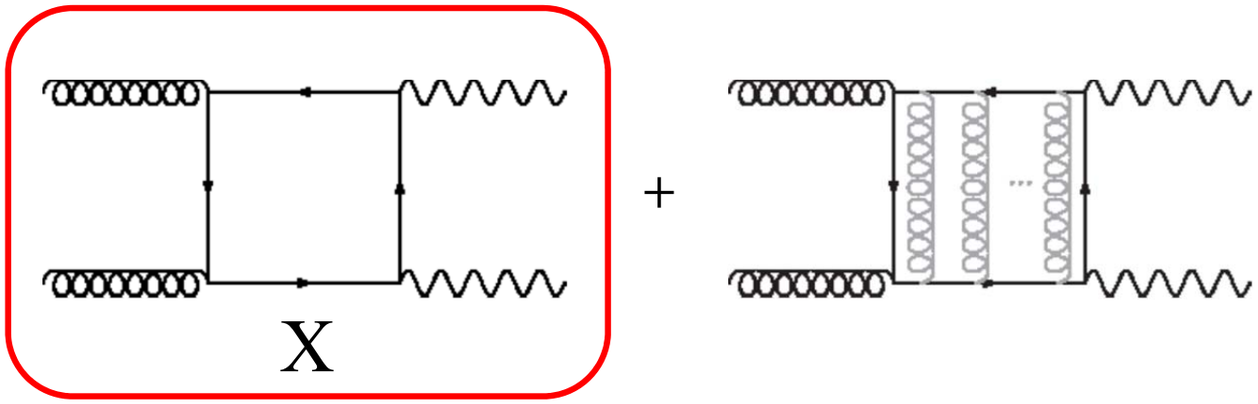
Any new colored/charged particle will contribute to the loop of $gg \to \gamma\gamma$

Higher loop

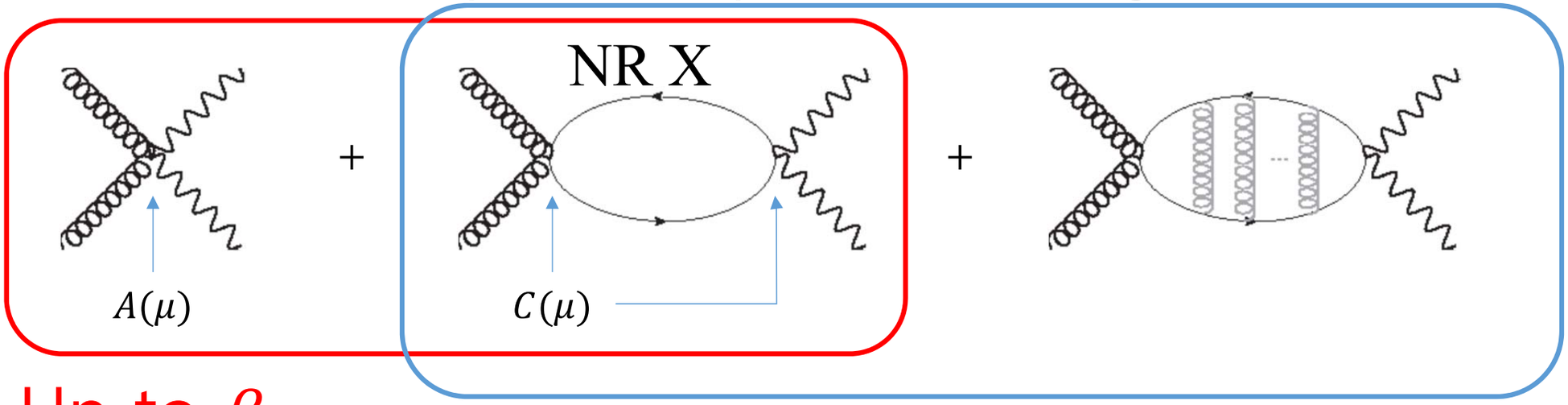


β : Velocity of the loop particle

Threshold Resummation



EFT (Relativistic part of X particle is integrated out)



Up to β

Self-consistency equation leads to
Schroedinger equation of Coulomb potential

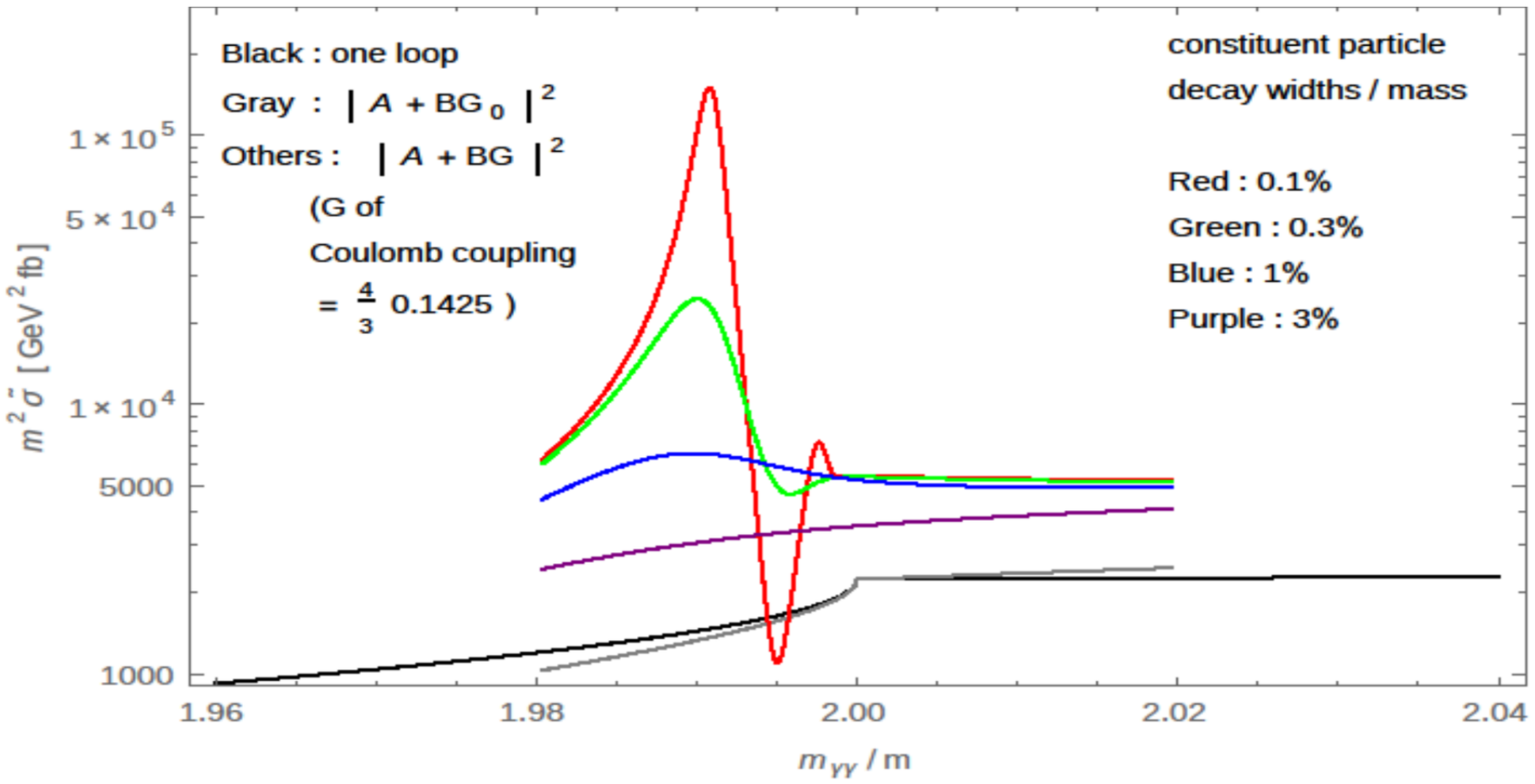
Strassler, Peskin (91)

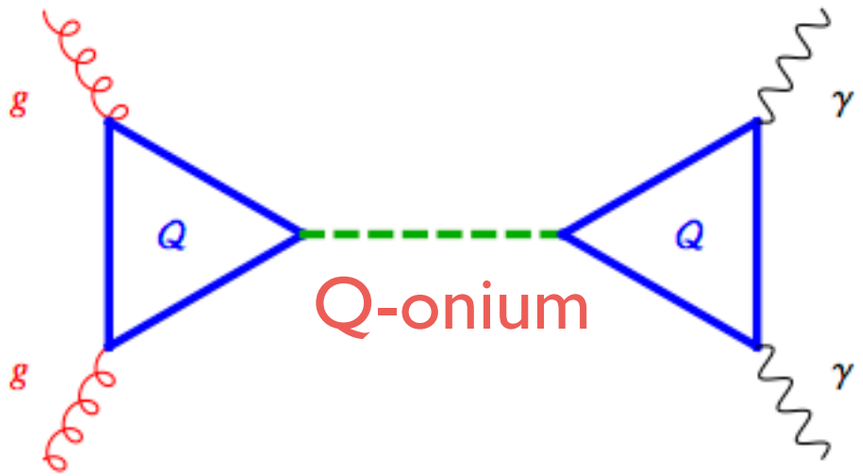
Melnikov, Spira, Yakovlev (94)

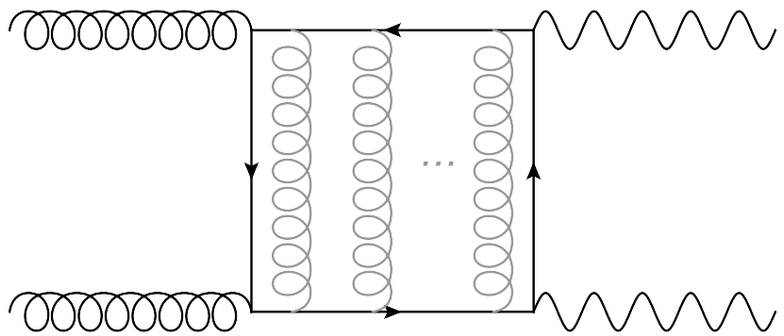
$$\mathcal{M}^{\lambda_1\lambda_2\lambda_3\lambda_4} = \mathcal{M}^{\lambda_1\lambda_2\lambda_3\lambda_4}_{\text{One Loop}} - B^{\lambda_1\lambda_2\lambda_3\lambda_4} G_0 + B^{\lambda_1\lambda_2\lambda_3\lambda_4} G(0, \Delta E + i\Gamma_X)$$

Fadin, Khoze (87)

$$G(0,\Delta E) = \frac{m_X^2}{4\pi}\left(\sqrt{-\frac{\Delta E}{m_X}} - C_2(X)\overline{\alpha_s}\ln\left(\frac{\sqrt{m_X \Delta E}}{\mu}\right) - \frac{2}{\sqrt{m_X}}\Sigma_{n=1}^{\infty}\frac{\mathrm{E_n}}{\sqrt{-\Delta E} - sign\left(C_2(X)\right)\sqrt{E_\mathrm{n}}}\right)$$




g
g
Q
Q
γ
γ
Q-onium


...

In the small width limit of the particle X,
the bound state production and decay applies

$$\Gamma_X < \alpha^3(E_b) M_X$$

life time of X > formation time of the bound state

X should live long enough to form a bound state

Bohr radius

$$r_b = \frac{1}{M_X \alpha_S(E_b)}$$

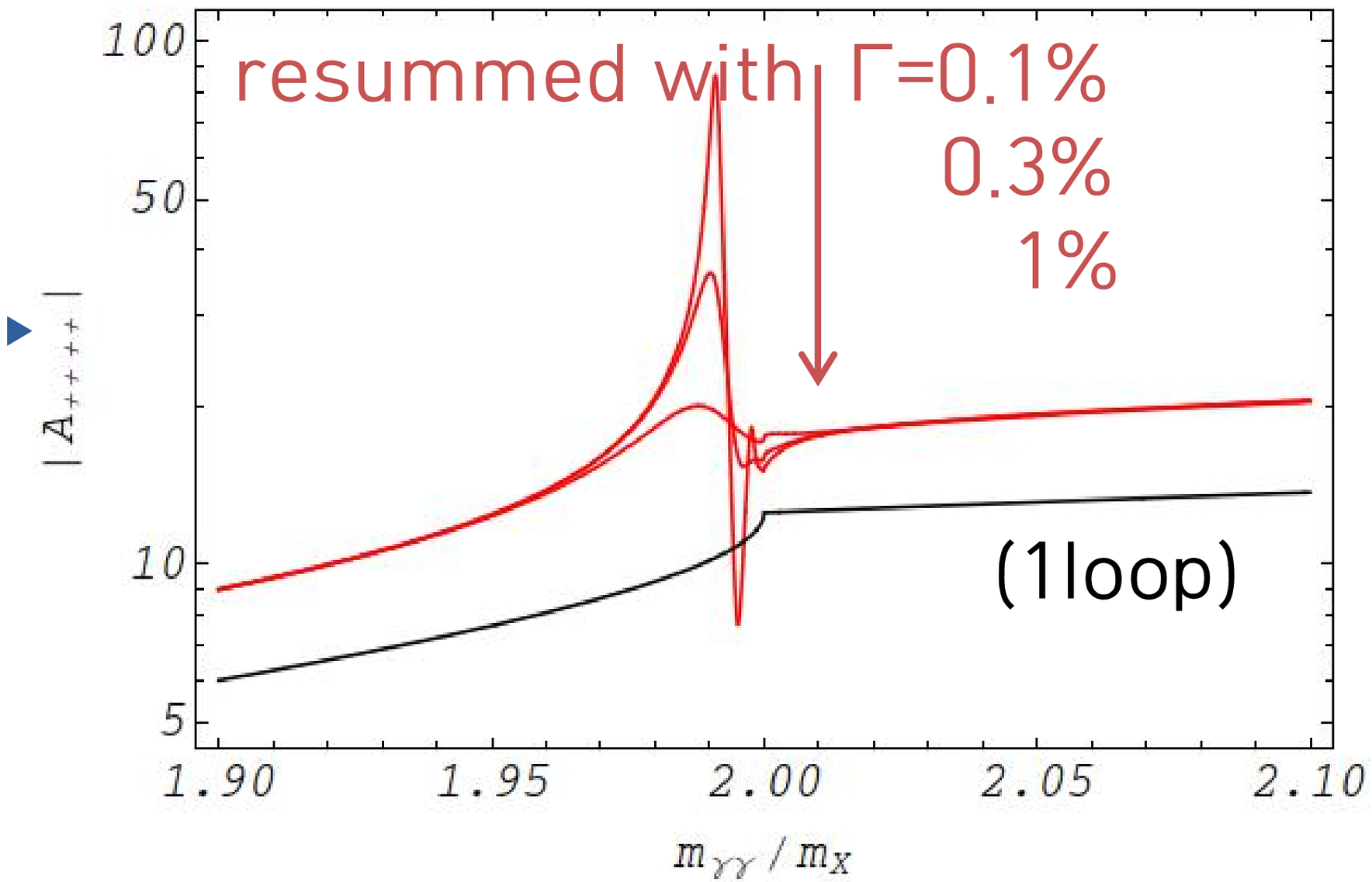
velocity

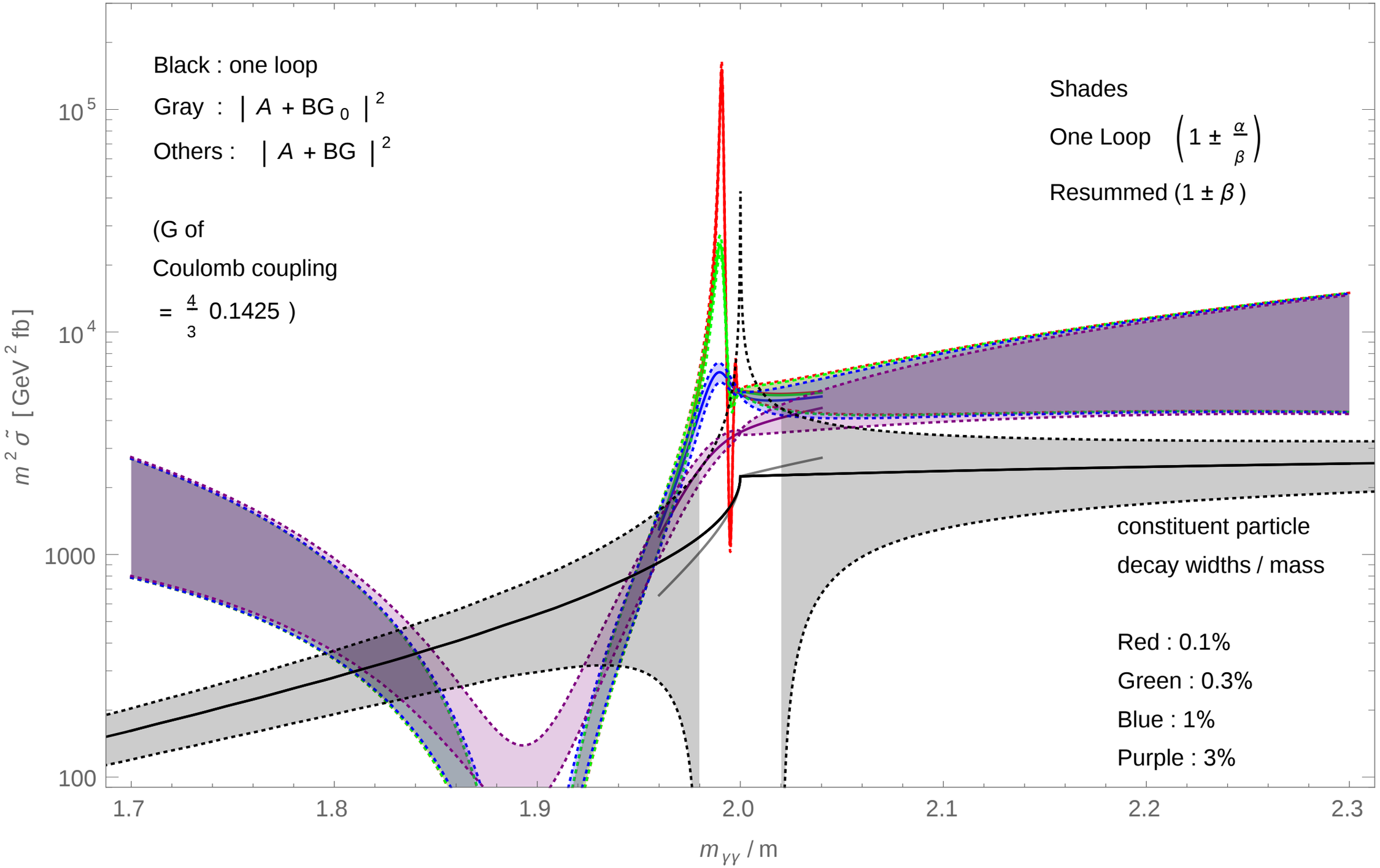
$$v = \alpha_S(E_b)$$

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

$$V(r) = -YC_2(X)\frac{\alpha_S(\bar{\mu})}{r}$$ (Y > 1 from QED resummation)

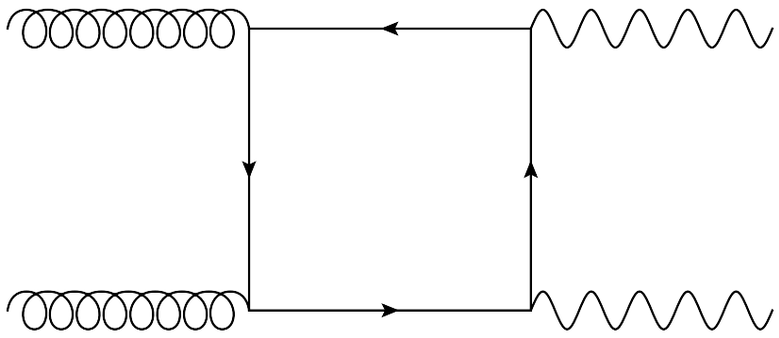
$$G(0,0;E) = \frac{m_X^2}{4\pi}\left(\sqrt{-\frac{E}{m_X} - i\epsilon} - YC_2(X)\alpha_S \ln\left(\frac{|YC_2(X)|\alpha_S}{2}\sqrt{-\frac{m_X}{E} + i\epsilon}\right) - \frac{2}{\sqrt{m_X}}\sum_{n=1}^{\infty}\frac{E_n}{\sqrt{(-E - i\epsilon)} - \text{sign}}\right.$$


resummed with Γ=0.1%
0.3%
1%
(1loop)
100
50
10
5
1.90
1.95
2.00
2.05
2.10
$m_{\gamma\gamma} / m_X$
$|A_{++}|$

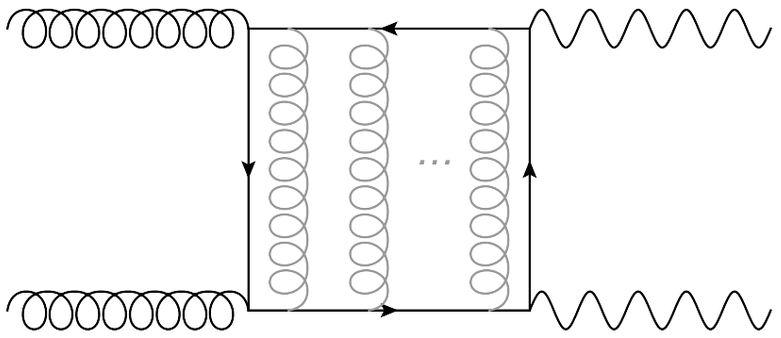

Black : one loop
Gray : | A + BG 0 | 2
Others : | A + BG | 2
(G of
Coulomb coupling
= 4/3 0.1425)
Shades
One Loop (1 ± α/β)
Resummed (1 ± β)
constituent particle
decay widths / mass
Red : 0.1%
Green : 0.3%
Blue : 1%
Purple : 3%
m 2 σ̃ [GeV 2 fb]
m γγ / m
10 5
10 4
1000
100
1.7
1.8
1.9
2.0
2.1
2.2
2.3

Threshold resummation included

u,d,s,c,b

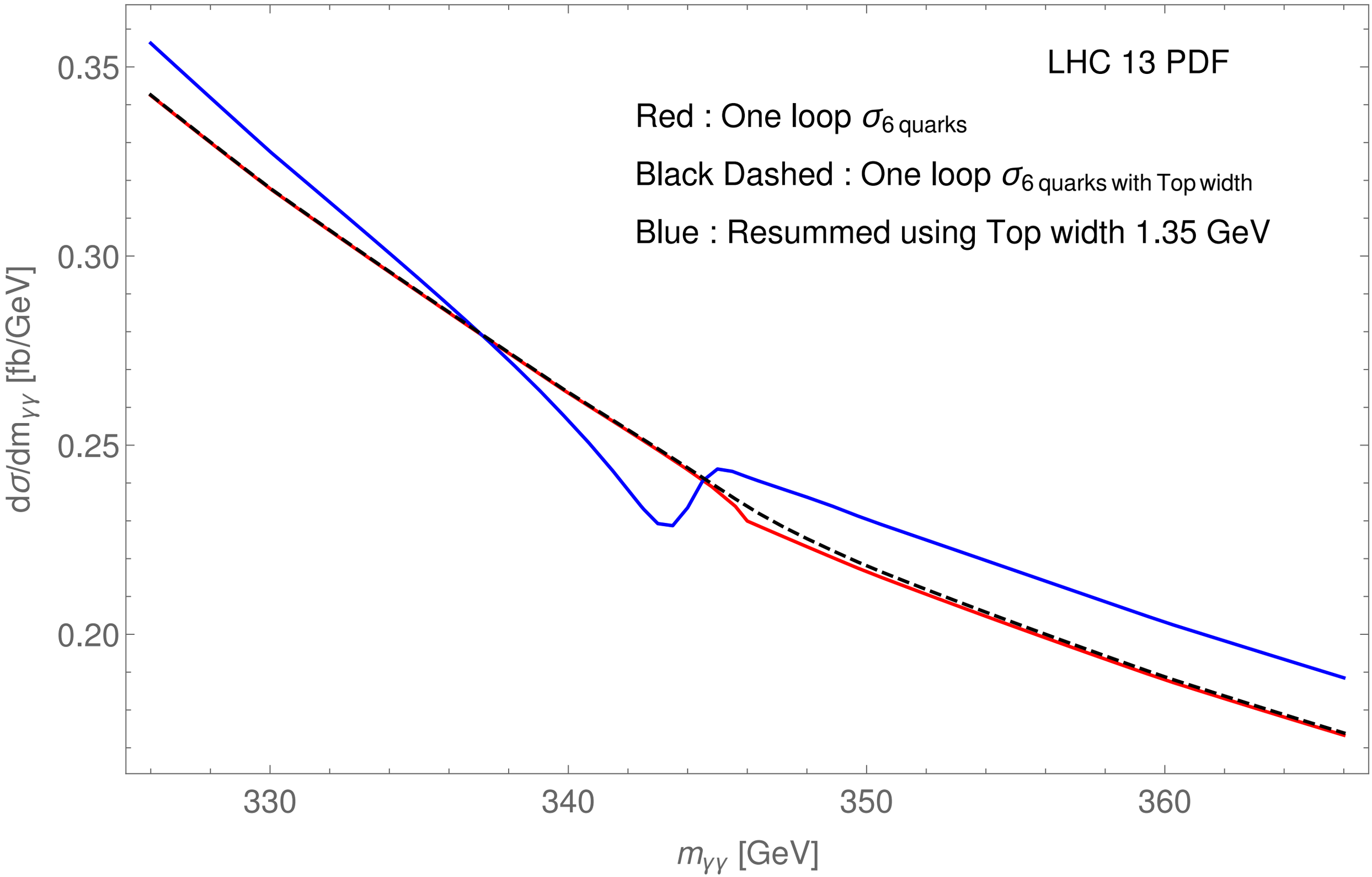


top

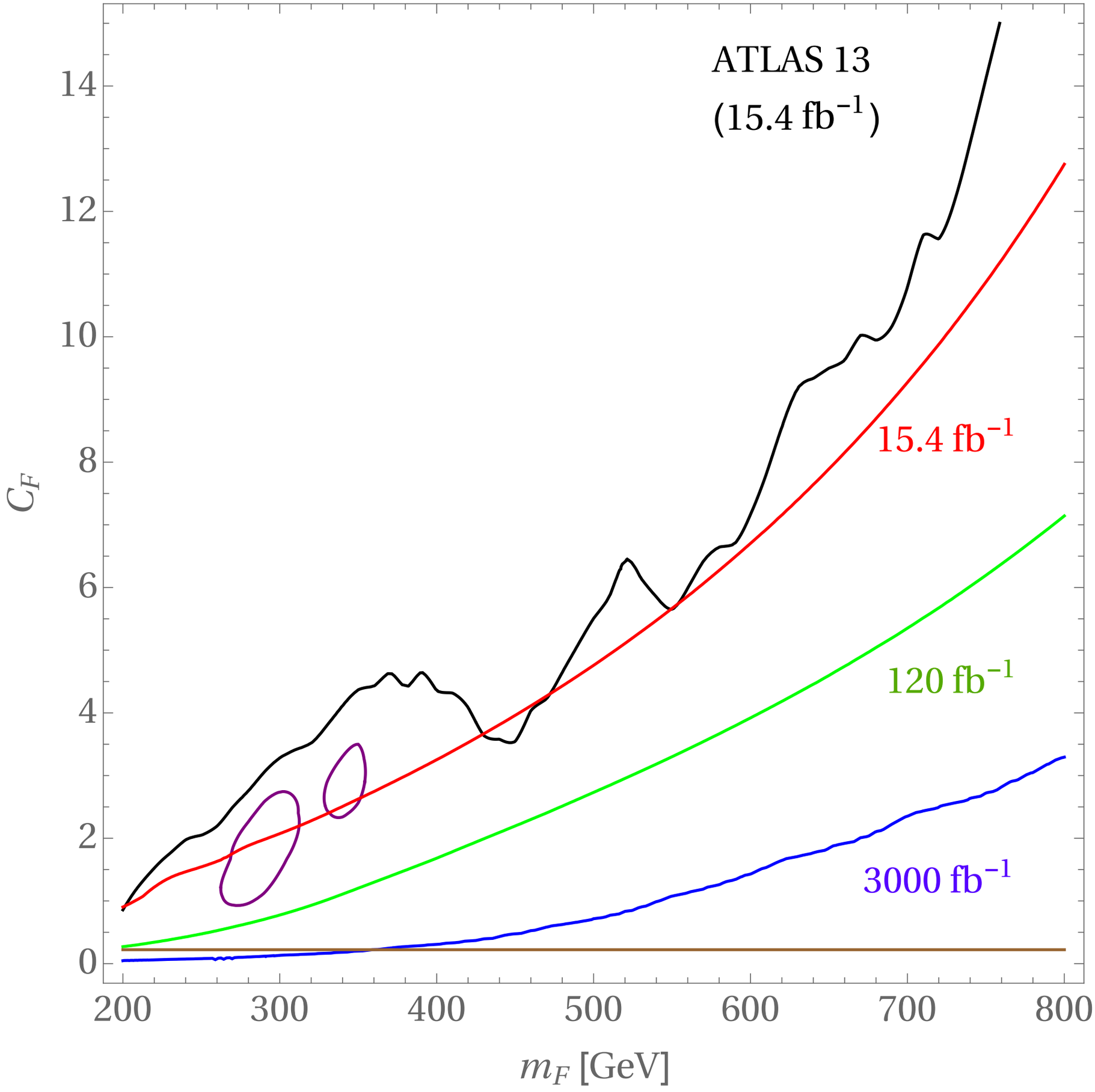


At LHC, top quark can show 2~3% effects
in di-photon invariant mass spectrum
from interference with 5 light quarks

Top threshold from di-photon



Discovery or exclusion


ATLAS 13
(15.4 fb^{-1})
15.4 fb^{-1}
120 fb^{-1}
3000 fb^{-1}
C_F
m_F [GeV]
0
2
4
6
8
10
12
14
200
300
400
500
600
700
800

ATLAS 13
(15.4 fb^{-1})

15.4 fb^{-1}

120 fb^{-1}

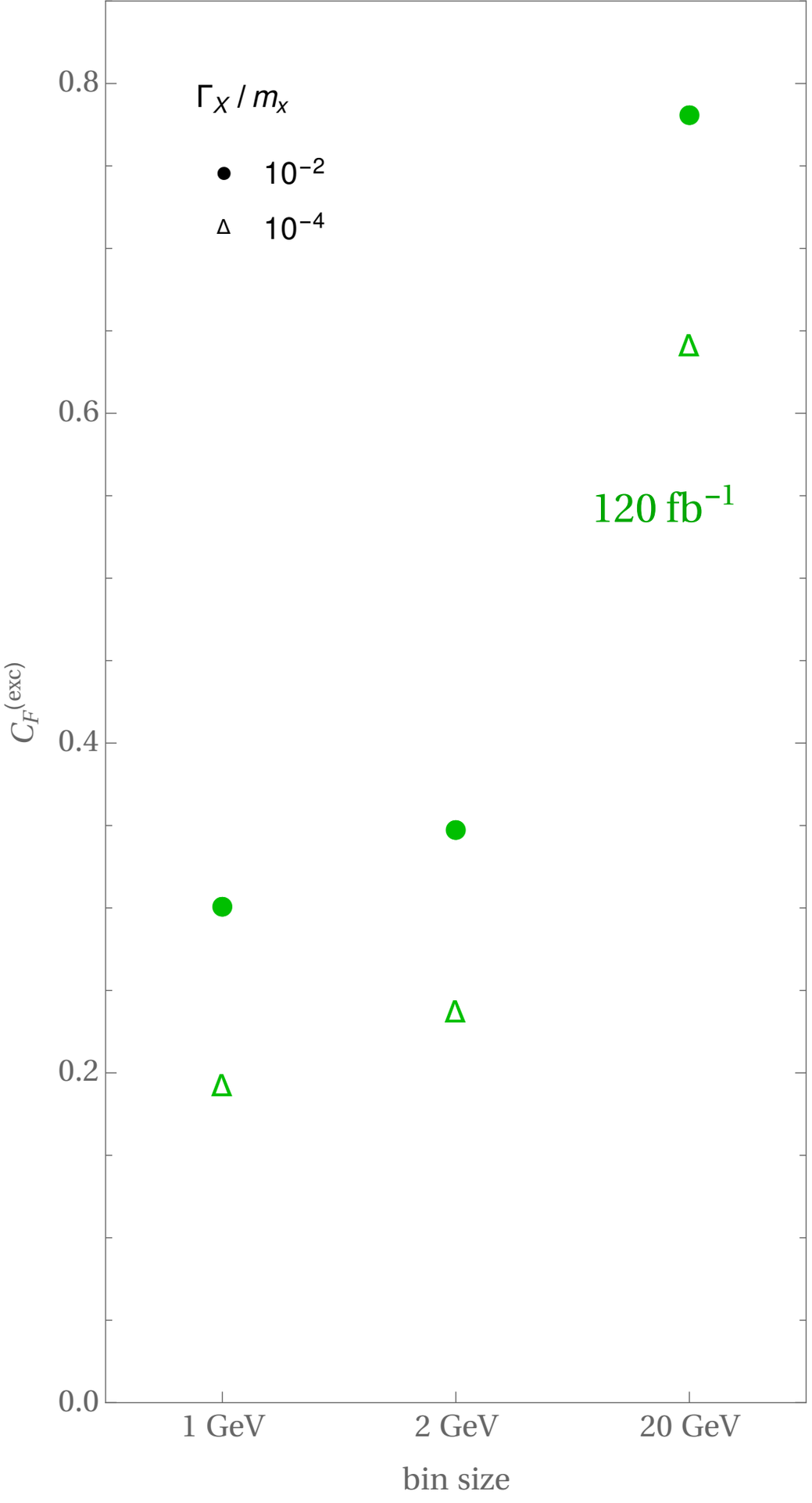
3000 fb^{-1}

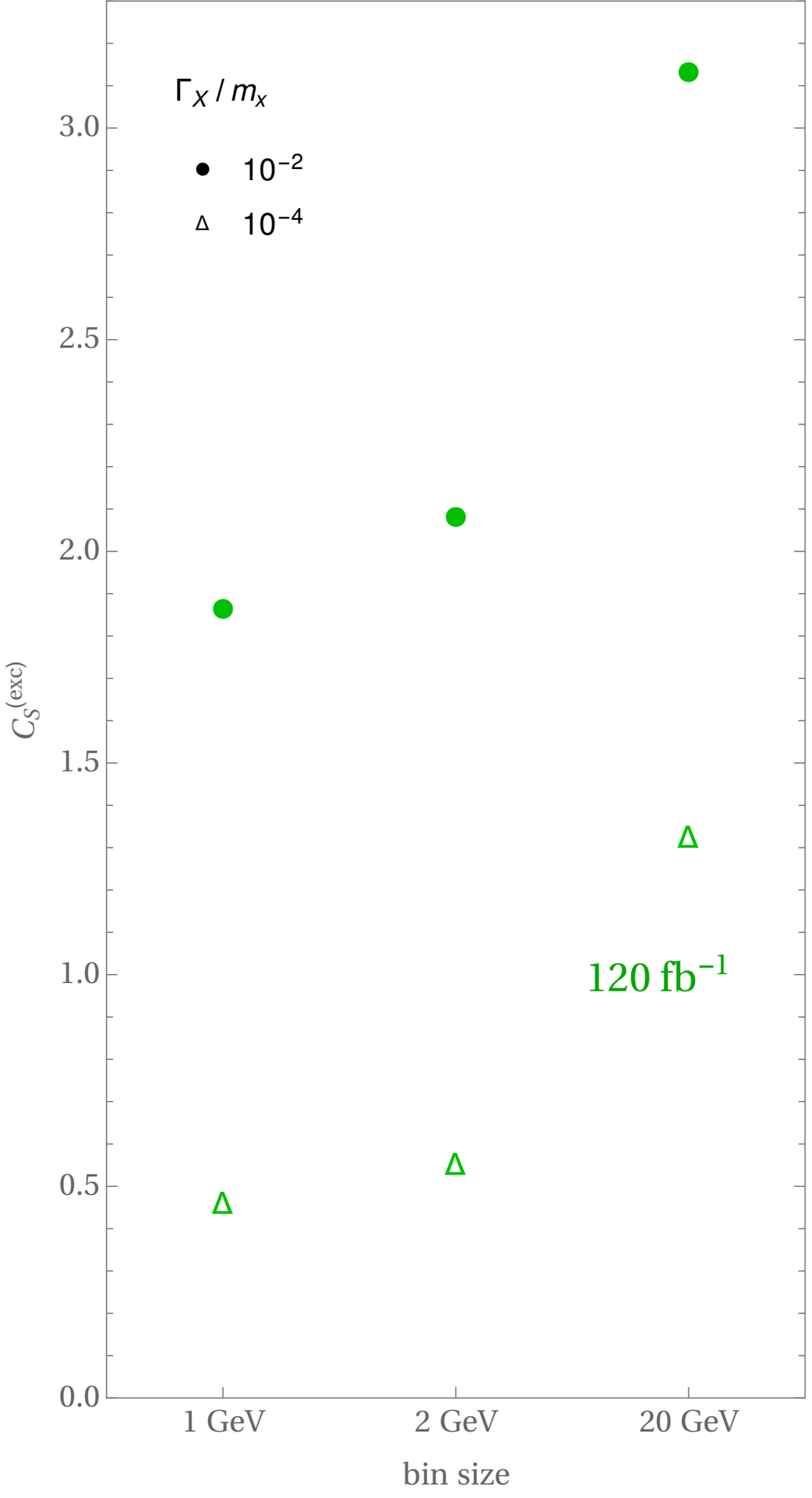
$\mathcal{CS}$

30
25
20
15
10
5
0

200
300
400
500
600
700
800

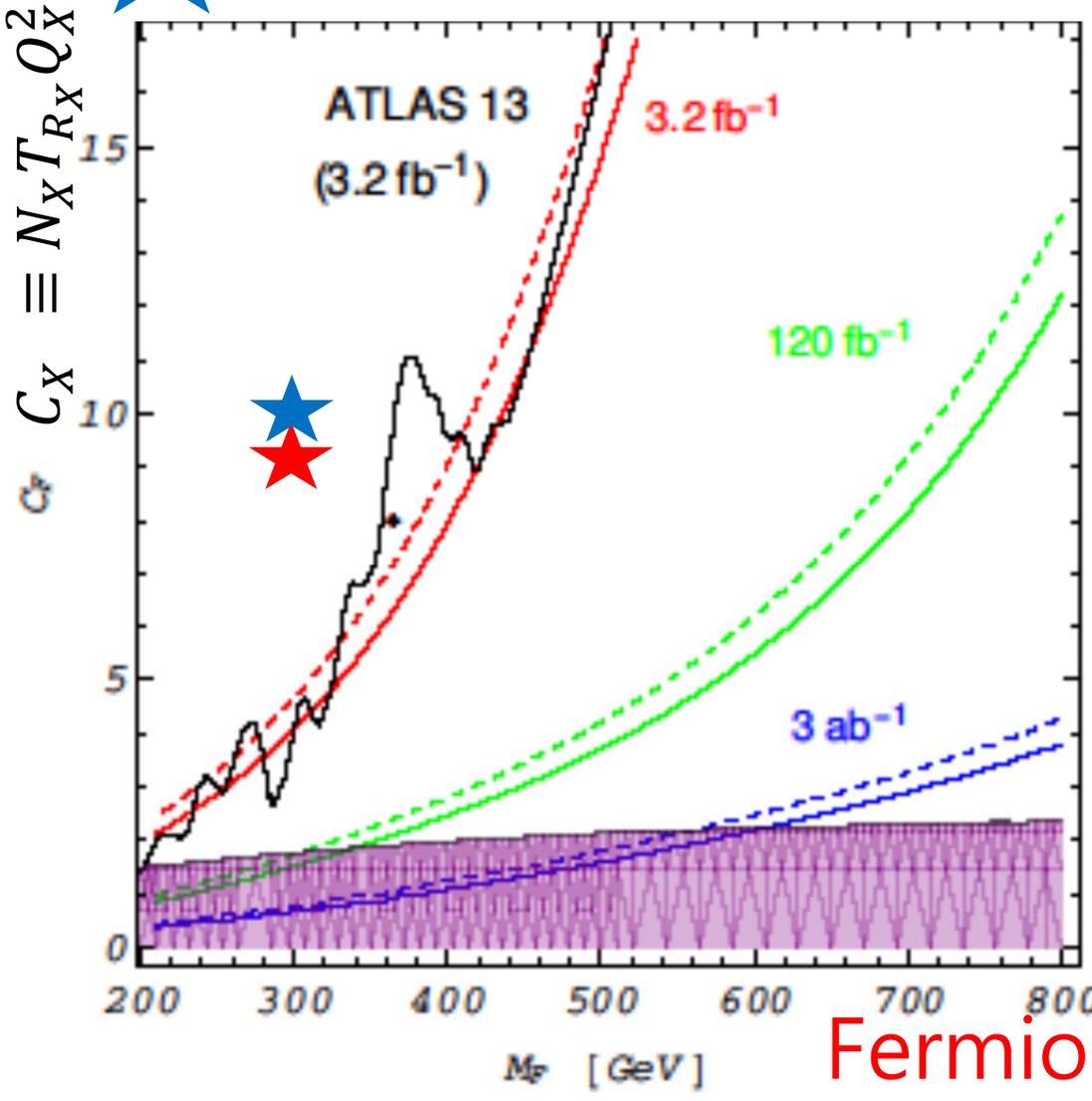
m_S [GeV]


Γ_X / m_x
10^{-2}
10^{-4}
120 fb^{-1}
$C_F^{(\mathrm{exc})}$
0.0
0.2
0.4
0.6
0.8
1 GeV
2 GeV
20 GeV
bin size


Γ_X / m_x
10^{-2}
10^{-4}
120 fb^{-1}
$C_S^{(\mathrm{exc})}$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
1 GeV
2 GeV
20 GeV
bin size

: $N_X = 1, T_{R_X} = 3, Q_X^2 = 3$

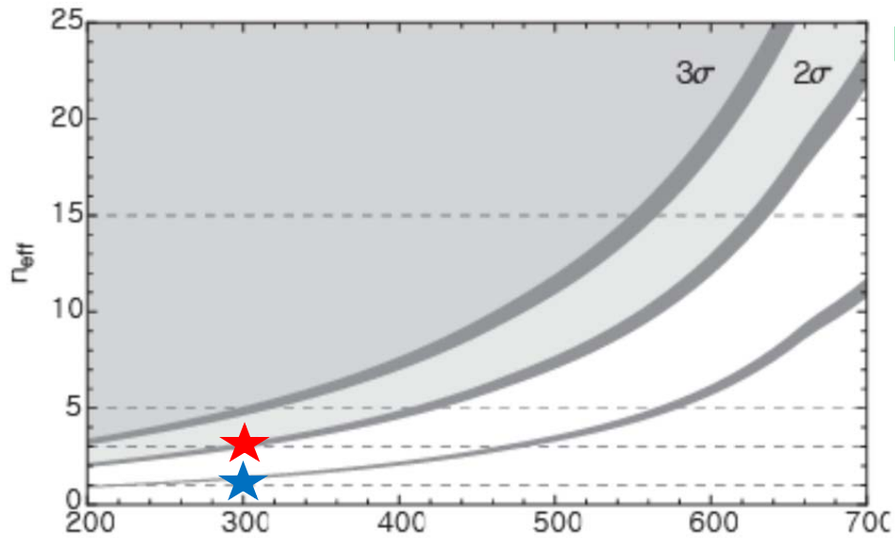
: $N_X = 1, T_{R_X} = 1/2, Q_X^2 = 20$



Fermion

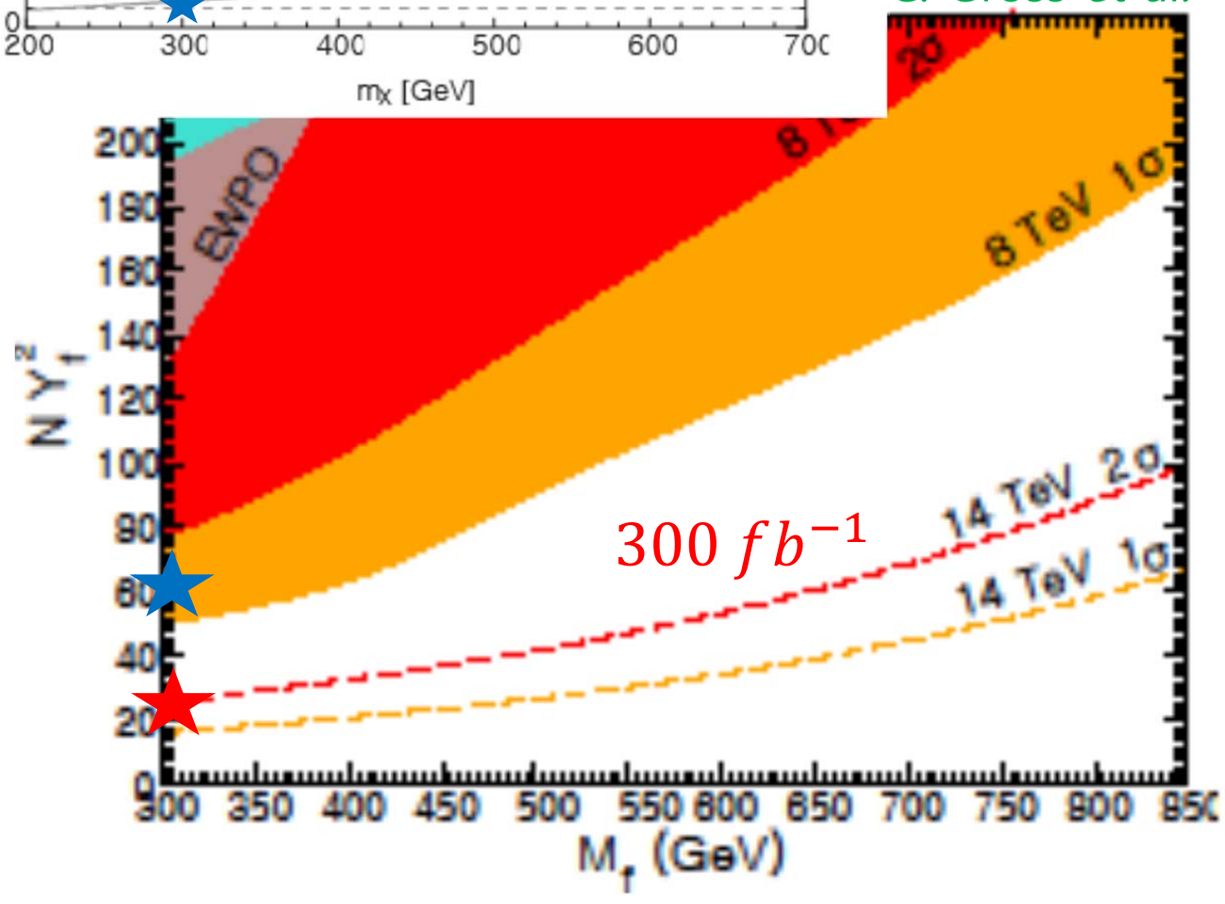
PHYSICAL REVIEW D 91, 015010 (2015)

D. Becciolini *et al.*



arXiv:1602.03877

C. Gross *et al.*



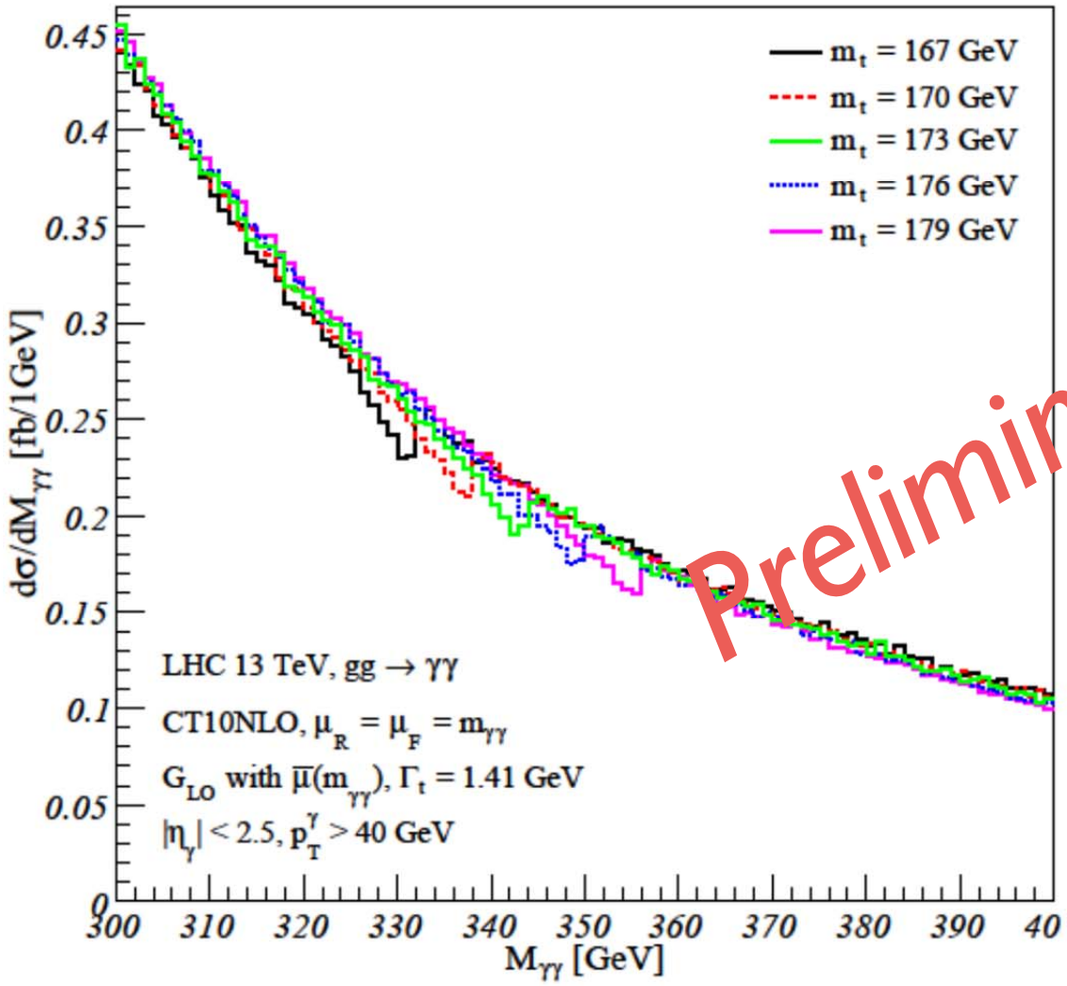
Top quark precision physics

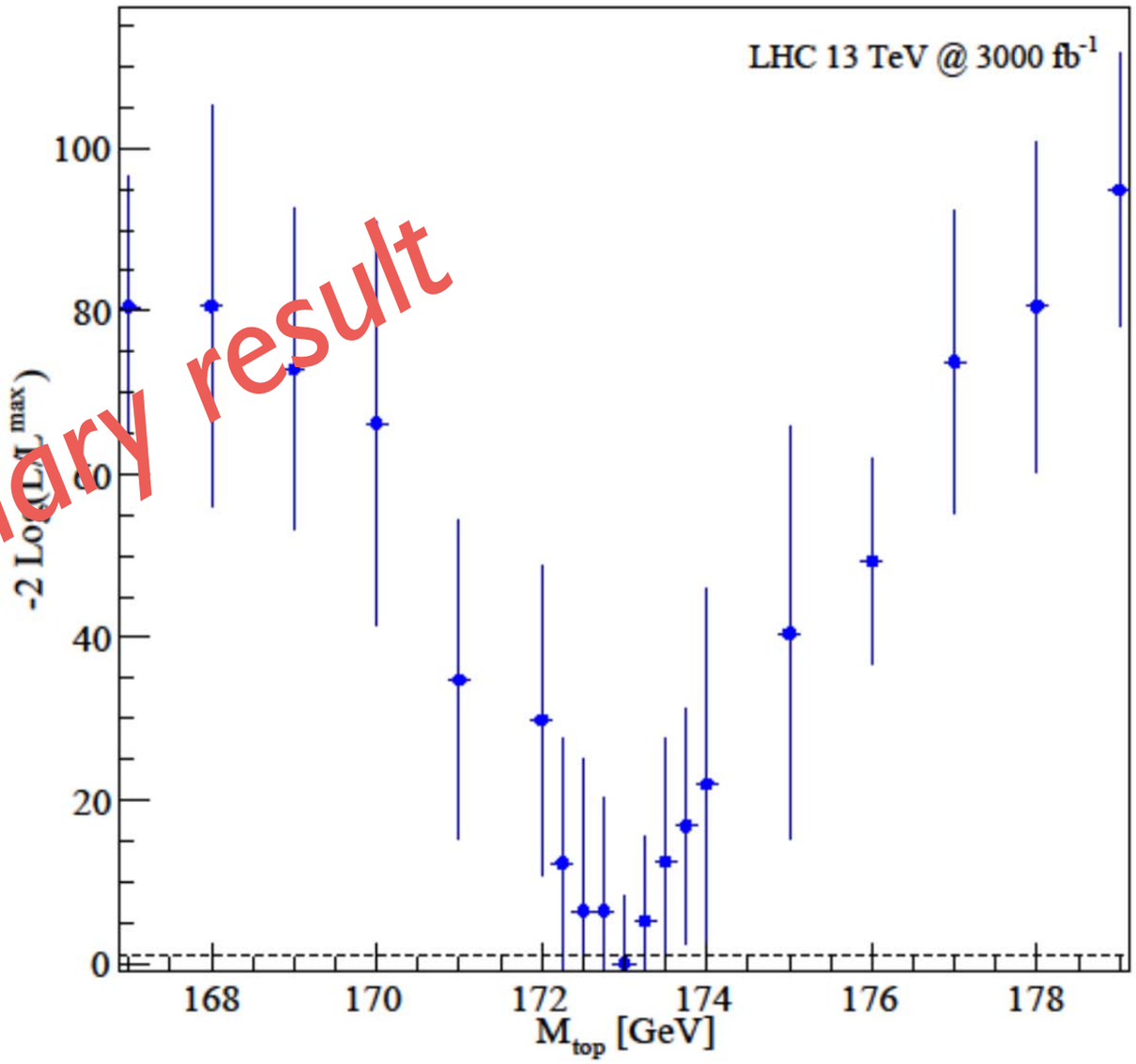
renormalon effects cancel out in the energy

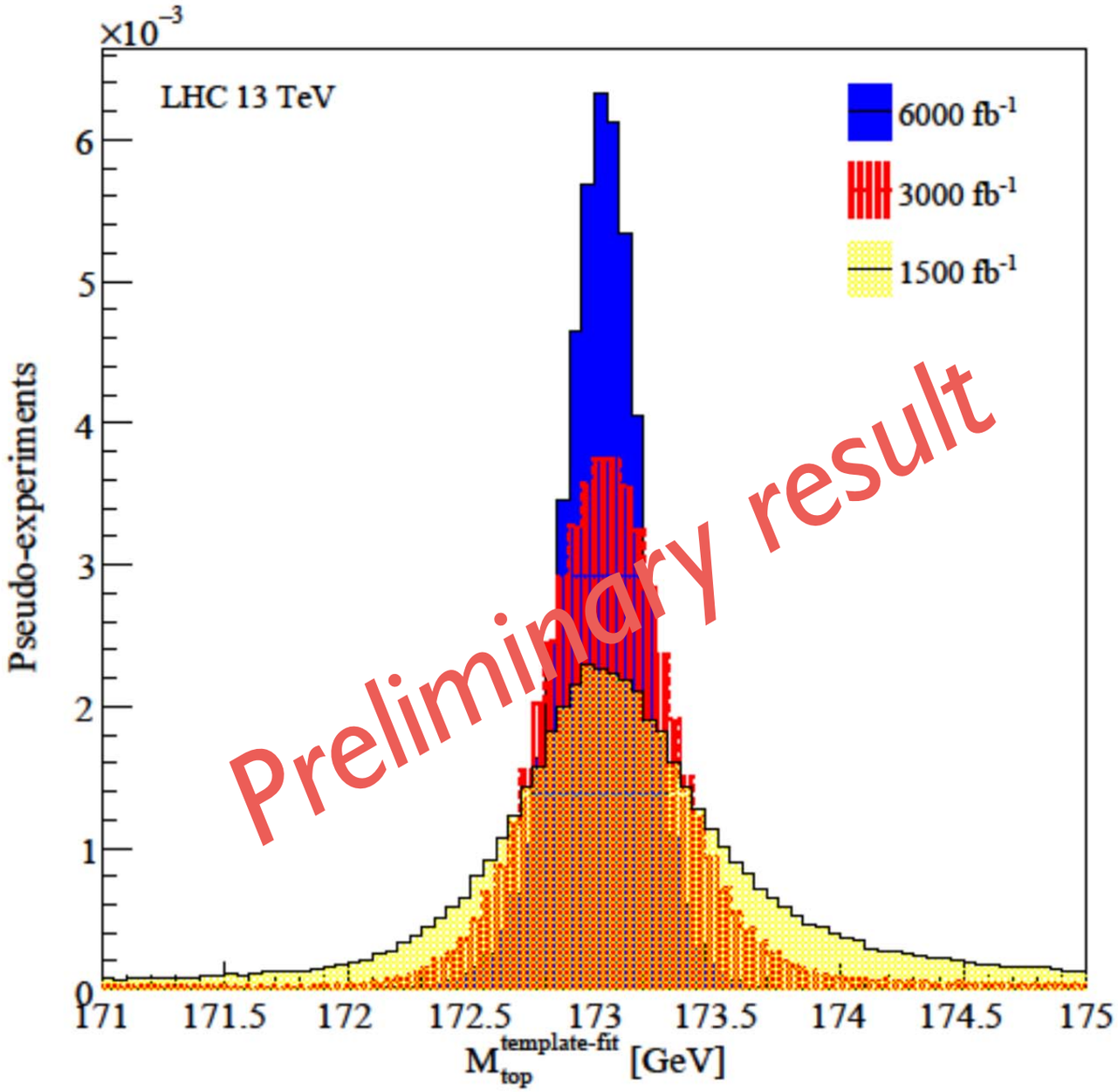
$$E_{\rm stat} = 2m_{\rm pole} + V_{\rm stat}(r)$$

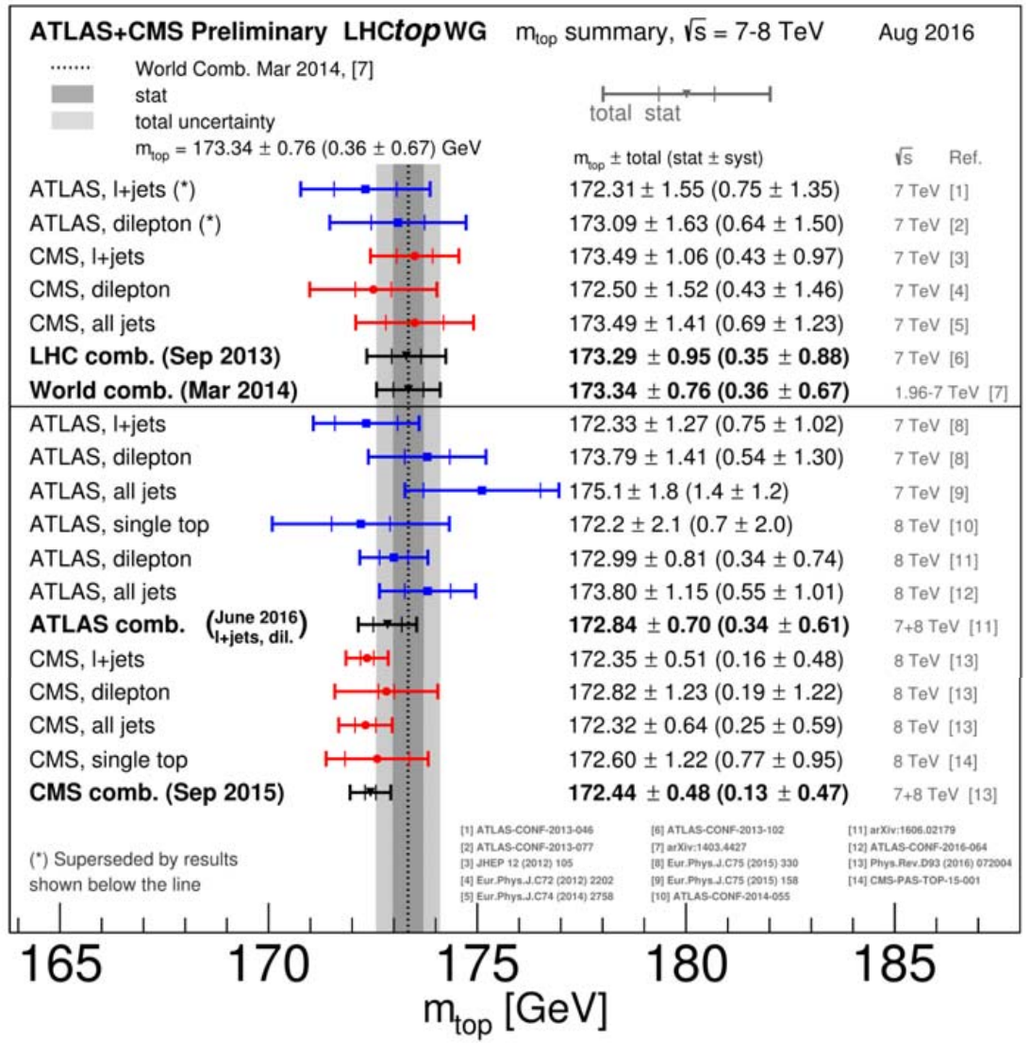
renormalon renormalon

Top search



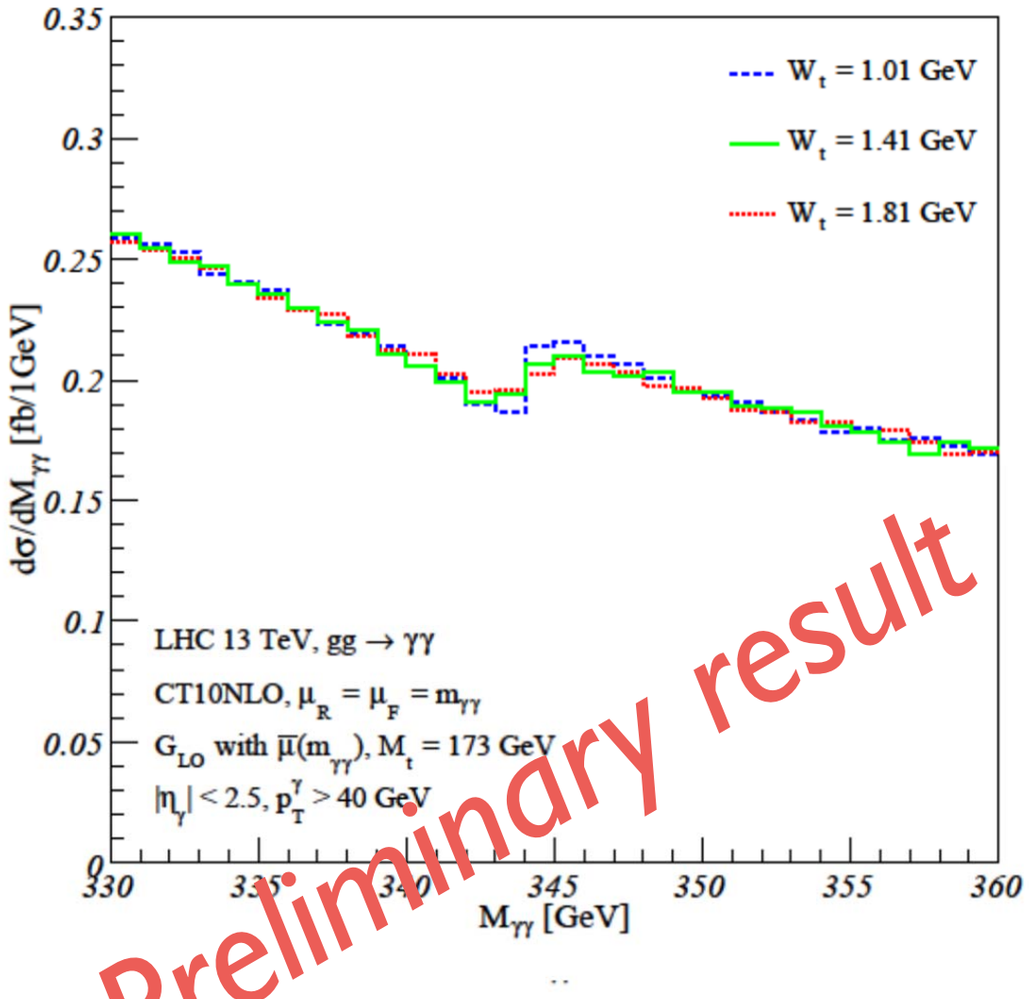






sub GeV precision

Top Width



Preliminary result

Best precision
among direct measurements