Light Scalar Fields
and
de Sitter Swampland Conjecture

CTPU Welcome Workshop

2018 Oct. 11

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Light Scalar Fields

- String theory : Enormous landscape + huge energy scale
  → hard to test directly

- String theories and extra dimension theories frequently leave their remnants such as new light particles.
- New scalar fields describing fluctuations of the shape or size of extra dimensions.

  (For other remnants, see [J. Halverson, P. Langacker 1801.03503])
- Not motivated by shortcomings of the SM.
- Thus checking the existence of those remnants is important.

- Do we live in the swampland?

- General Lagrangian including a New Scalar Field, ϕ.

(without derivative couplings and the θ term.)

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + |D_\mu H|^2 + \bar{\psi} i \not{D}\psi - \frac{1}{4g_a^2(\phi)}F^{a\mu\nu}F^a_{\mu\nu} - (y_\psi(\phi)H\bar{\psi}_L\psi_R + h.c.) - \lambda(\phi)|H|^4 + m_H^2(\phi)|H|^2 - V_b(\phi)$$

- At low energy $\mu_{eff} < m_c$,

$$\mathcal{L}_\phi(\mu_{\text{eff}}) \ni -d_g \frac{\beta_s}{2g_s}\frac{\phi}{M_{\text{Pl}}}G^{a\mu\nu}G^a_{\mu\nu} - \sum_{q=u,d,s}(d_q + \gamma_m d_g)m_q \frac{\phi}{M_{\text{Pl}}}\bar{q}q$$

- ϕ − Atom − Atom interaction,

$$\alpha_A = \frac{1}{m_A}\frac{\partial m_A(\phi)}{\partial\phi} \simeq d_g + f(\#N, \#P)(d_q - d_g)$$

Composition-Independent Composition-Dependent

$$V = -G\frac{m_S m_A}{r_{SA}}\left(1 + \alpha_S \alpha_A e^{-m_\phi r_{SA}}\right)$$

Source S Atom A

Observable Effects of ϕ

- Deviation from $\frac{1}{r^2}$ Force (for $m_\phi \sim r_{SA}^{-1}$)

$$V = -G\frac{m_S m_A}{r_{SA}}\left(1 + \alpha_S \alpha_A e^{-m_\phi r_{SA}}\right)$$

- Violation of the Weak Equivalence Principle (for $m_\phi \ll r_{SA}^{-1}$)

Difference of accelerations of two different atoms toward a source $\propto (\alpha_A - \alpha_B)$

$$\alpha_A = \frac{1}{m_A}\frac{\partial m_A(\phi)}{\partial \phi} \simeq d_g + f(\#N, \#P)(d_q - d_g)$$

- When $d_g = d_q$, a post-Newtonian paramter $\gamma = (1 - 2d_g^2)/(1 + 2d_g^2)$

Time dilation due to the Sun's gravity to the signal from Cassini spacecraft

$$ds_J^2 \simeq -\left(1 - \frac{2GM}{r}\right)dt^2 + \left(1 + \gamma\frac{2GM}{r}\right)\left(dr^2 + r^2 d\Omega^2\right)$$

- DM abundance and Oscillation of ϕ (for $m_\phi \gg H_0$)

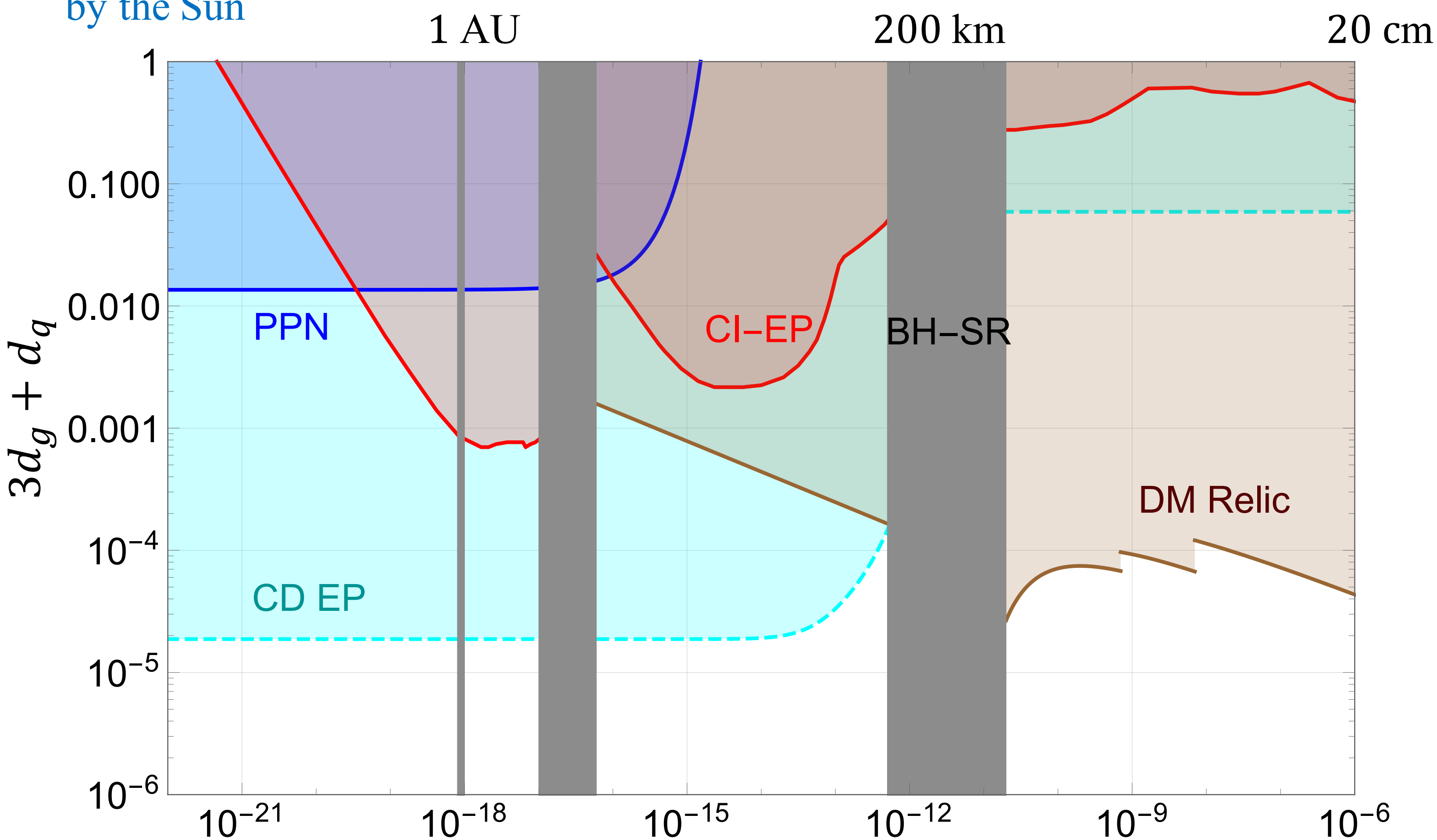
$$V(\phi, T) = -\frac{\pi^2}{90}g_*(T)T^4 + \frac{(6 + N_f)g_s^2(\phi)T^4}{18} + \sum_{m_q < T}\frac{T^2}{4}\left(m_q^2(\phi) + \frac{g_s^2(\phi)T^2}{6}\right)$$

$$\frac{\Delta\phi}{M_{\rm Pl}} \simeq \frac{\partial_\phi V}{M_{\rm Pl}H^2}$$

• Constraints on ϕGG and $\phi \bar{q} q$ couplings ($1 = 2\ \text{km}\ 10^{-10}\ \text{eV}$)

PPN: gravitational time dilation
by the Sun

CI-EP: deviation from $\frac{1}{r^2}$ force



CD-EP: difference of acceleration
of two different atoms toward a source

[K. Choi, **DC**, C.S. Shin, **1809.01475**]

- The de Sitter Swampland Conjecture

$$|\nabla V'_{tot}| = \sqrt{G^{ij}\partial_{\phi_i} V_{tot} \partial_{\phi_j} V_{tot}} > c\, V_{tot} \quad \text{and} \quad c = O(1)$$

for any field point. [G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa 1806.08362]

- Local minimum with positive vacuum energy is forbidden.

→ rolling along a new field direction (Quintessence ϕ with $m_\phi < H_0$)

- When applied on the pion potential maximum $V_{tot} \simeq 2(m_u + m_d)\Lambda^3_{\mathrm{QCD}}$,

$$c < \frac{|\partial_\phi V_{tot}|}{V_{tot}} = |d_q + 3d_g| < 10^{-5} \quad \text{(Comp. dep. Equiv. Principle test)}$$

$$\text{or } 10^{-2} \quad (d_g = \mathrm{d_q})$$

- Even with an additional field χ with $m_\chi > H_0$,

$$c < \frac{\sqrt{(\partial_\phi V)^2 + (\partial_\chi V)^2}}{V} = \sqrt{(d_q + 3d_g)^2 + (d_q^\chi + 3d_g^\chi)^2} < 10^{-5} \text{ or } 10^{-2}$$

Summary

- Light scalar is a hint of Planck scale physics.

- There are many interesting observational and experimental bounds on light scalar bosons.

- The dS swampland conjecture constant is constrained from such bounds by $c < 10^{-5}\ or\ 10^{-2}$.

- The de Sitter swampland conjecture should be modified.

- Standard Model Extension in Higgs Sector

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \lambda_{HS} |H|^2 |S|^2 + |\partial S|^2 - M^2 |S|^2 - \lambda_S |S|^4$$

Radiative EW symmetry breaking (no $|S|^2$ and $|H|^2$ terms)

$V''' = 167\% \, V'''_{SM}$ and $V'''' = 367\% \, V''''_{SM}$

Perturbative to the Planck scale if S has a charge of a hidden gauge.

[**DC**, R. Dermisek, T. H. Jung, and H. D. Kim 1308.0891]

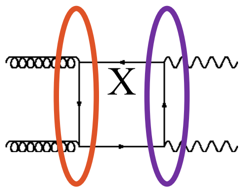
- Large couplings are required for perturbativity to high scale.

  → Two-loop running, two-loop tadpole, two-loop pole mass equation

- Higgs phenomenology (see [Thesis of T. H. Jung])

- Generalized Narrow Width Approximation [**DC**, T. H. Jung, and H. D. Kim 1502.03541]

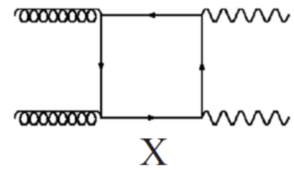
- Any particle carrying EM charge and color mediates $pp \to \gamma\gamma$



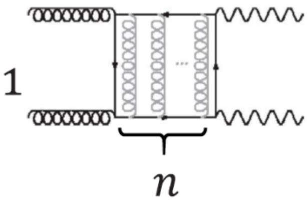
$\propto C_X \equiv N_X T_{R_X} Q_X^2$

SU(3) Dynkin index

Electric charge

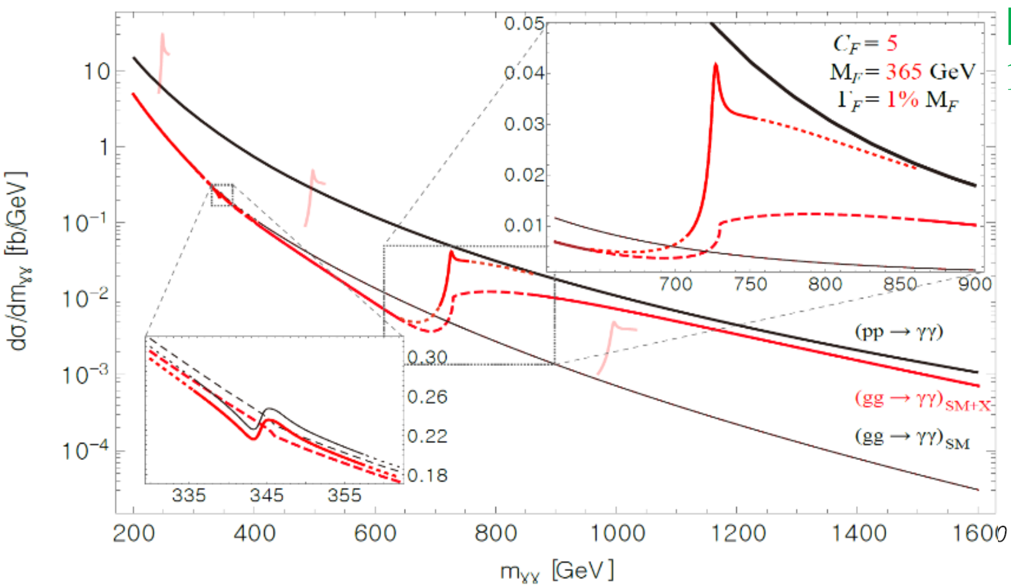


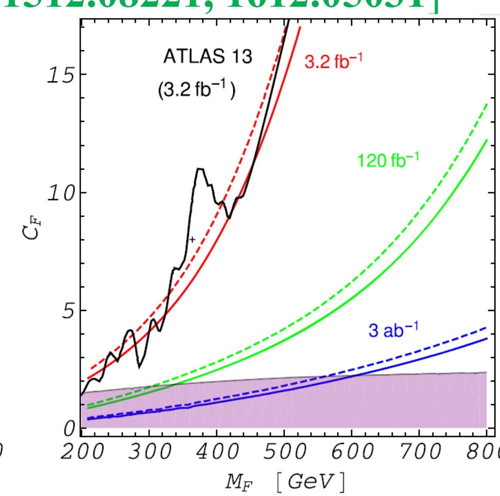
$+ \sum_{n=1}^{\infty}$



- Signal shape (large width $\Gamma_X/m_X \sim 1\%$) and Constraints on new particles

[**DC**, R. Dermisek, T. H. Jung, and H. D. Kim, **1512.08221, 1612.05031**]





Backup Slides

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + |D_\mu H|^2 + \bar{\psi}i\not{D}\psi - \frac{1}{4g_a^2(\phi)}F^{a\mu\nu}F^a_{\mu\nu}$$
$$-(y_\psi(\phi)H\bar{\psi}_L\psi_R + h.c.) - \lambda(\phi)|H|^4 + m_H^2(\phi)|H|^2 - V_b(\phi)$$

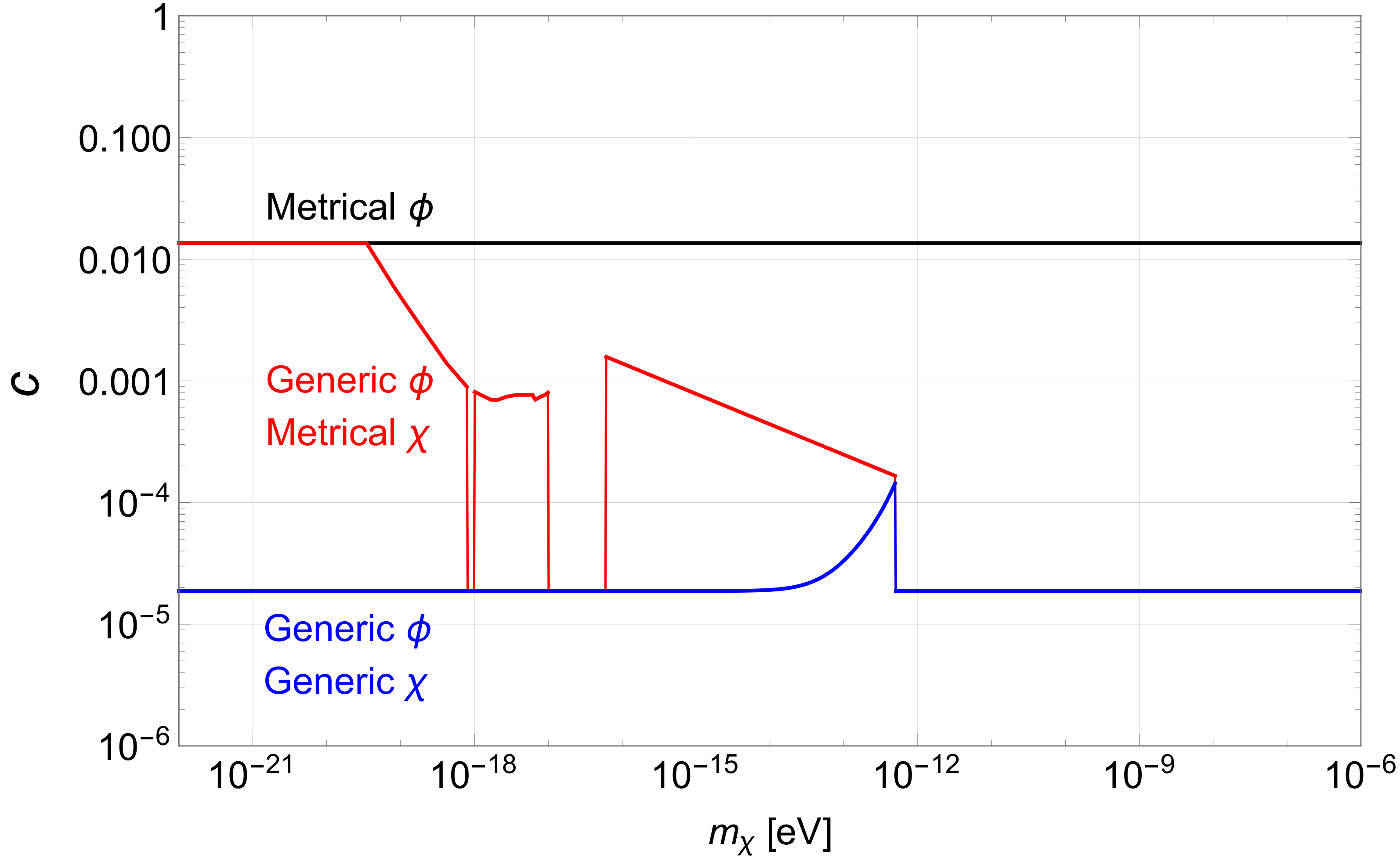
$$\mathcal{L}_\phi(\mu_{\rm eff}) \ni -d_g\frac{\beta_s}{2g_s}\frac{\phi}{M_{\rm Pl}}G^{a\mu\nu}G^a_{\mu\nu} - \sum_{q=u,d,s}(d_q + \gamma_m d_g)m_q\frac{\phi}{M_{\rm Pl}}\bar{q}q$$

$$d_g = \frac{\partial\Lambda_{\rm QCD}}{\partial\phi}\,, \quad d_q = \frac{\partial m_q(\Lambda_{\rm QCD})}{\partial\phi}$$

$$V = -G\frac{m_S m_A}{r_{SA}}\left(1 + \alpha_S\alpha_A e^{-m_\phi r_{SA}}\right)$$

$$\alpha_A = \frac{1}{m_A}\frac{\partial m_A(\phi)}{\partial\phi} \simeq d_g + f(\#N, \#P)(d_q - d_g)$$

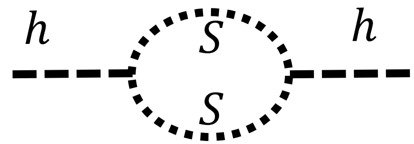
$$ds_J^2 \simeq -\left(1 - \frac{2GM}{r}\right)dt^2 + \left(1 + \gamma\frac{2GM}{r}\right)\left(dr^2 + r^2 d\Omega^2\right)$$



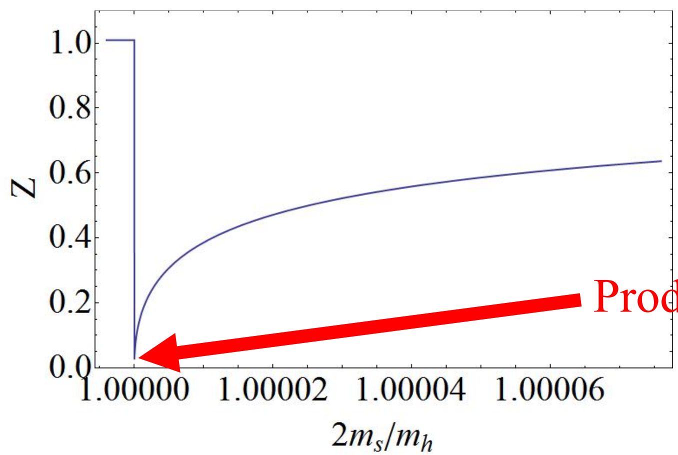
1
0.100
0.010
0.001
10^−4
10^−5
10^−6
c
Metrical ϕ
Generic ϕ
Metrical χ
Generic ϕ
Generic χ
10^−21
10^−18
10^−15
10^−12
10^−9
10^−6
m_χ [eV]

- Wave Function Renormalization Factor, Z

$$Z^{-1} \equiv \frac{\partial}{\partial p^2}\,\mathrm{Re}\left[p^2 - m^2 + \Pi(p^2)\right]\Big|_{p^2 = m^2_{\mathrm{ph}}}$$



$$\Pi(p^2) \sim m_h \Gamma(h \to SS) \propto \sqrt{1 - \frac{(2m_S)^2}{p^2}}$$



$$Z^{-1} \sim \frac{\lambda^2_{HS}}{\sqrt{\left|1 - \frac{4m_S^2}{m_h^2}\right|}} = \frac{\lambda^2_{HS}}{\beta}$$

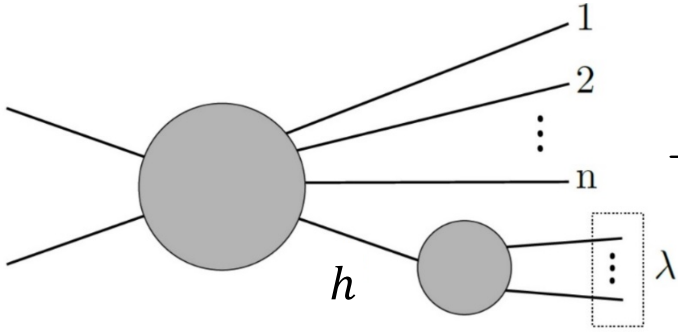
Production cross section shuts down?

$$\sigma_h \to 0\,, \qquad \Gamma_{h\to b\bar{b}} \to 0$$

- LSZ Reduction and Unstable Particle

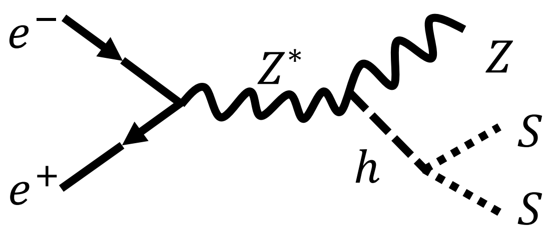
Breit-Wigner Shape ⇒ Narrow Width Approximation ⇒ LSZ like

- Total cross section



$$\to \int dp^2 d\Phi_p d\Phi_d \left|\mathcal{M}_{\rm prod}\right|^2 \left|G_h(p^2)\right|^2 \left|\mathcal{M}_{\rm decay}\right|^2$$

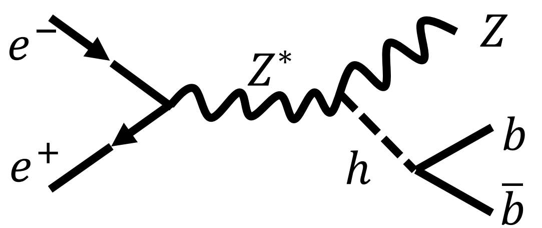
- Narrow width approximation (NWA)



$$\left|\frac{1}{p^2-m_h^2+im_h\Gamma_h}\right|^2 \simeq \frac{\pi}{m_h\Gamma_h}\delta\left(p^2-m_h^2\right)$$

$$\sigma_{\rm NWA} = \sigma_{\rm prod}\frac{\Gamma(h\to SS)}{\Gamma_h}$$ fails as $2m_S \to m_h$

[D. Berdine, N. Kauer, D. Rainwater (2007)]



$$\left|\frac{1}{p^2-m_h^2+\Pi(p^2)}\right|^2 \simeq \left|\frac{1}{Z^{-1}\left(p^2-m_h^2\right)+im_h\Gamma_h}\right|^2$$

$$\sigma_{\rm NWA} = \sigma_{\rm prod} Z \frac{Z\Gamma(h\to b\bar{b})}{Z\Gamma_h}$$ fails as $2m_S \to m_h$

[**DC**, T. H. Jung, H. D. Kim, **JKPS(2016)**]

$$Z^{-1} \sim \frac{\lambda_{HS}^2}{\sqrt{\left|1-\frac{4m_S^2}{m_h^2}\right|}}$$

Signal Shapes near Production Threshold of Intermediate Particles

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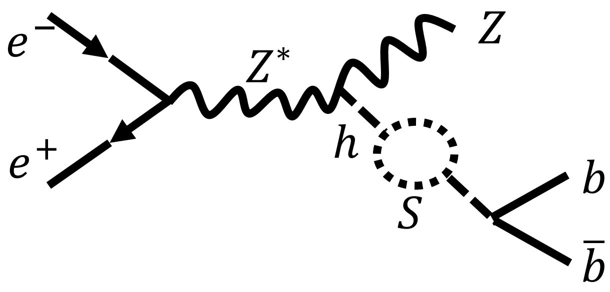
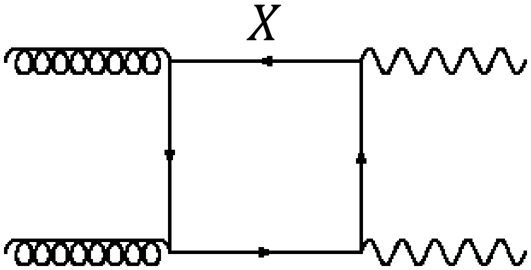
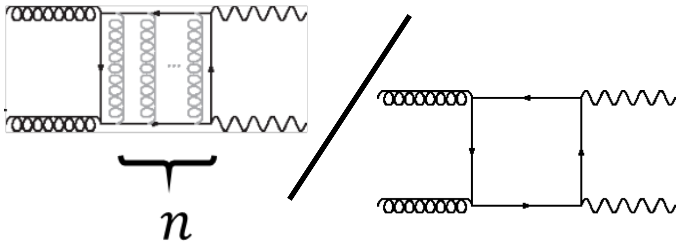




When $E \sim m_{\text{intermediate}}$, interesting shapes can arise.

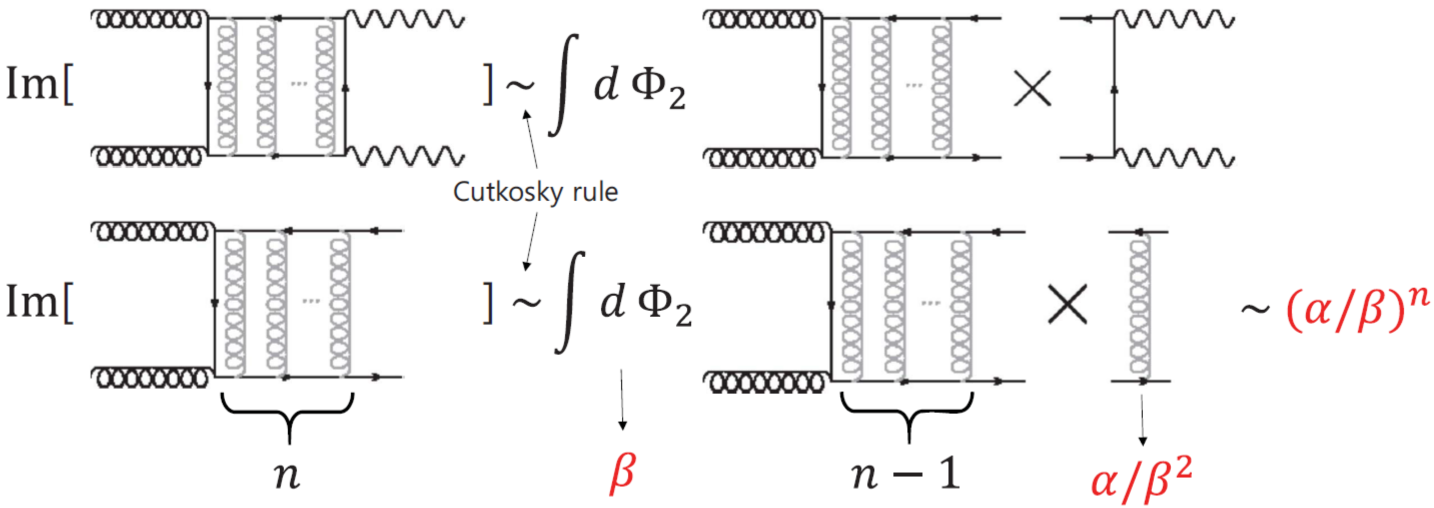
Information on the intermediate particles can be obtained without producing them in the final states.

- Coulomb Singularity [T. Appelquist, H. D. Politzer (1975)]

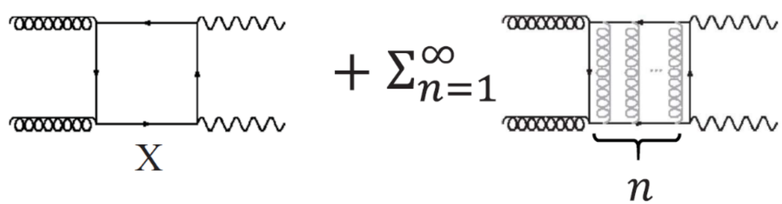


$\sim \left(\frac{\alpha_s}{\beta}\right)^n$

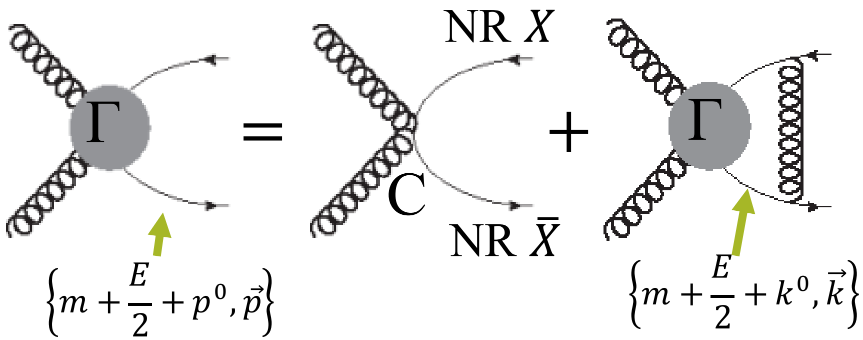
- Cutkosky rule



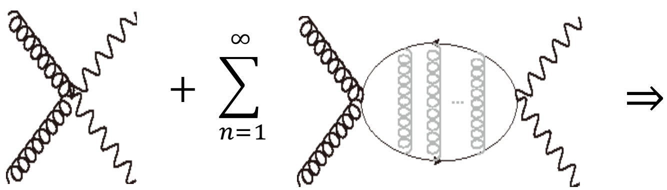
- Resummation

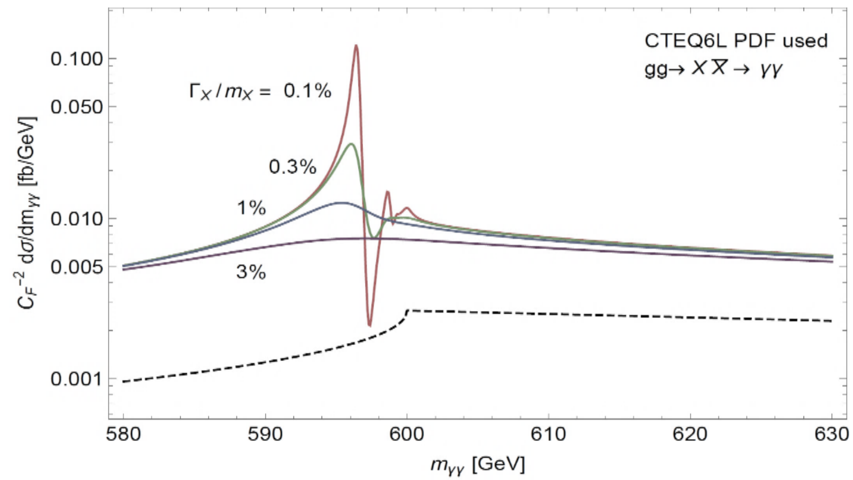


- Non-Relativistic Effective Theory [W. E. Caswell, G. P. Lepage (1986)]
- Unstable particle production Amplitude [V. S. Fadin, V. A. Khoze (1986)]
- Annihilation Amplitude [K. Melnikov, M. Spira, O. I. Yakovlev (1994)]



⇒ Green's Function satisfying Schrödinger Equation with Coulomb Potential





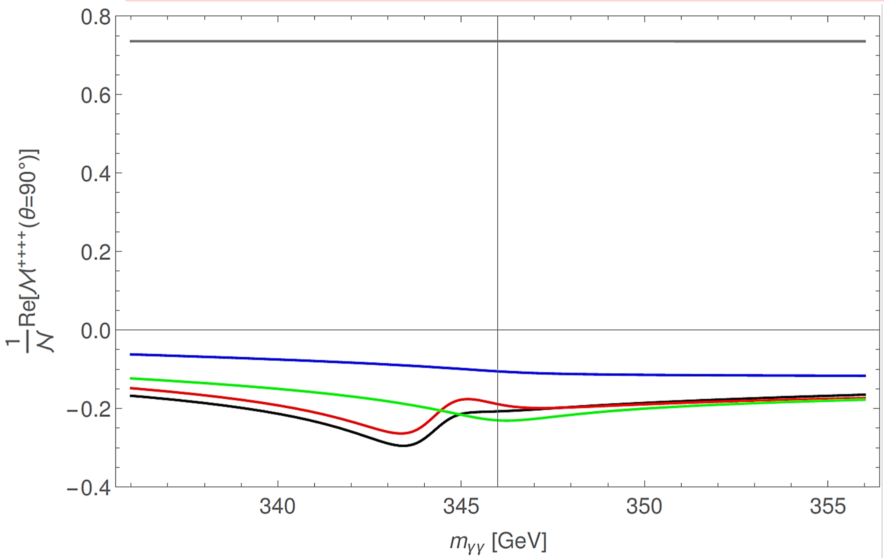
[**DC**, R. Dermisek, T. H. Jung, and H. D. Kim, **PRD(2017)**]

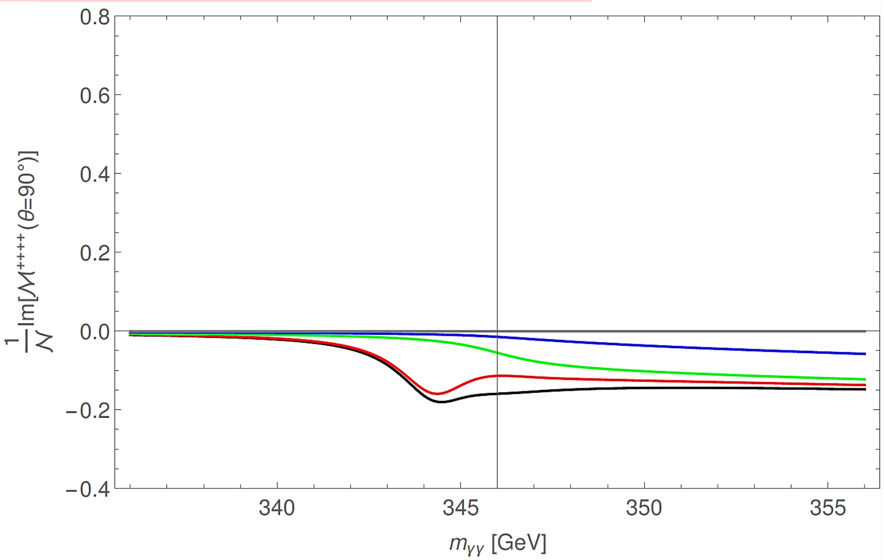
- Top quark mass measurement
  - Well defined mass (1S mass)

RG evolution

n=1 Bound State

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





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

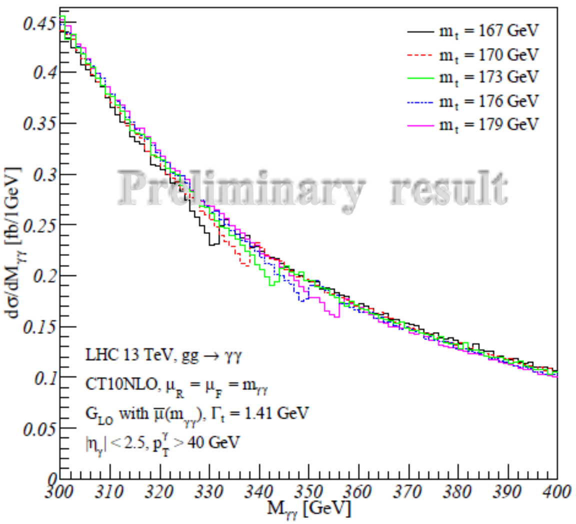
- Top quark mass measurement
  - Well defined mass (1S mass)
  - Free from jet uncertainty

  - Small number of event
  - (Pile up)

- Ballpark estimation on Δm_t^{1S}

  $\pm$1 GeV at 2 ab^{-1} 13 TeV LHC

  $\pm$100 MeV at 2 ab^{-1} 100 TeV HC



(same value is obtained if the S/B ratio is assumed to be 40% in [S.Kawabata, H. Yokoya (2017)])

Conclusion

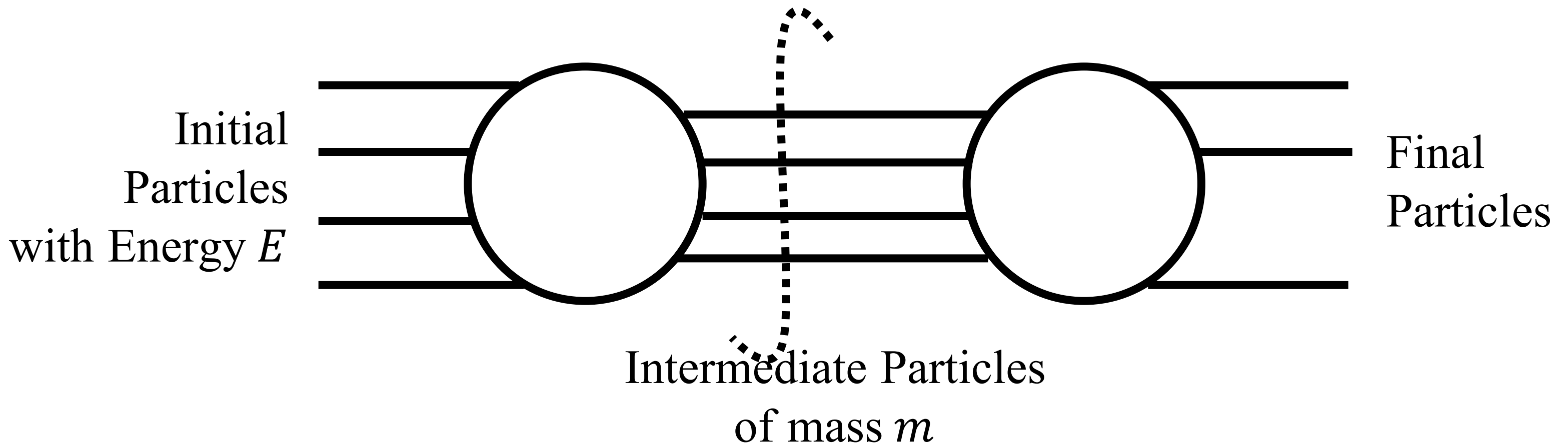
- Existence of new particle affects signal shape of SM processes and requires a generalized NWA for $2m_{daughter} \simeq m_{mother}$.

- Constraints were obtained for color representation and charge of new particles from diphoton invariant mass spectrum.

- Diphoton spectrum near top quark production threshold was obtained.

- Measuring top quark properties using the diphoton spectrum is possible.

Signal Shapes near Production Threshold of Intermediate Particles



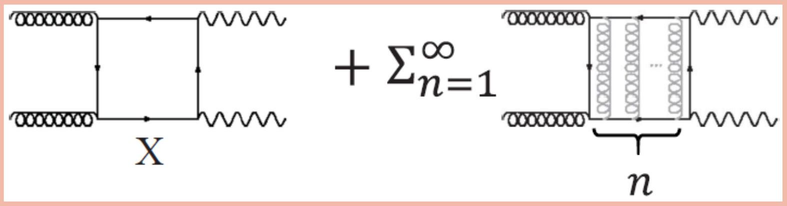
$$\mathcal{A}\left(\frac{E}{m}\right) \xrightarrow[\frac{E}{m}\to 0 \text{ or } \infty]{} \text{Constant}$$

When $E \sim m$, interesting shapes can arise.

Information on the intermediate particles can be obtained without producing them in the final states.

For a general particle charged under $SU(3)_C$ and $U(1)_{EM}$, we obtained amplitudes.

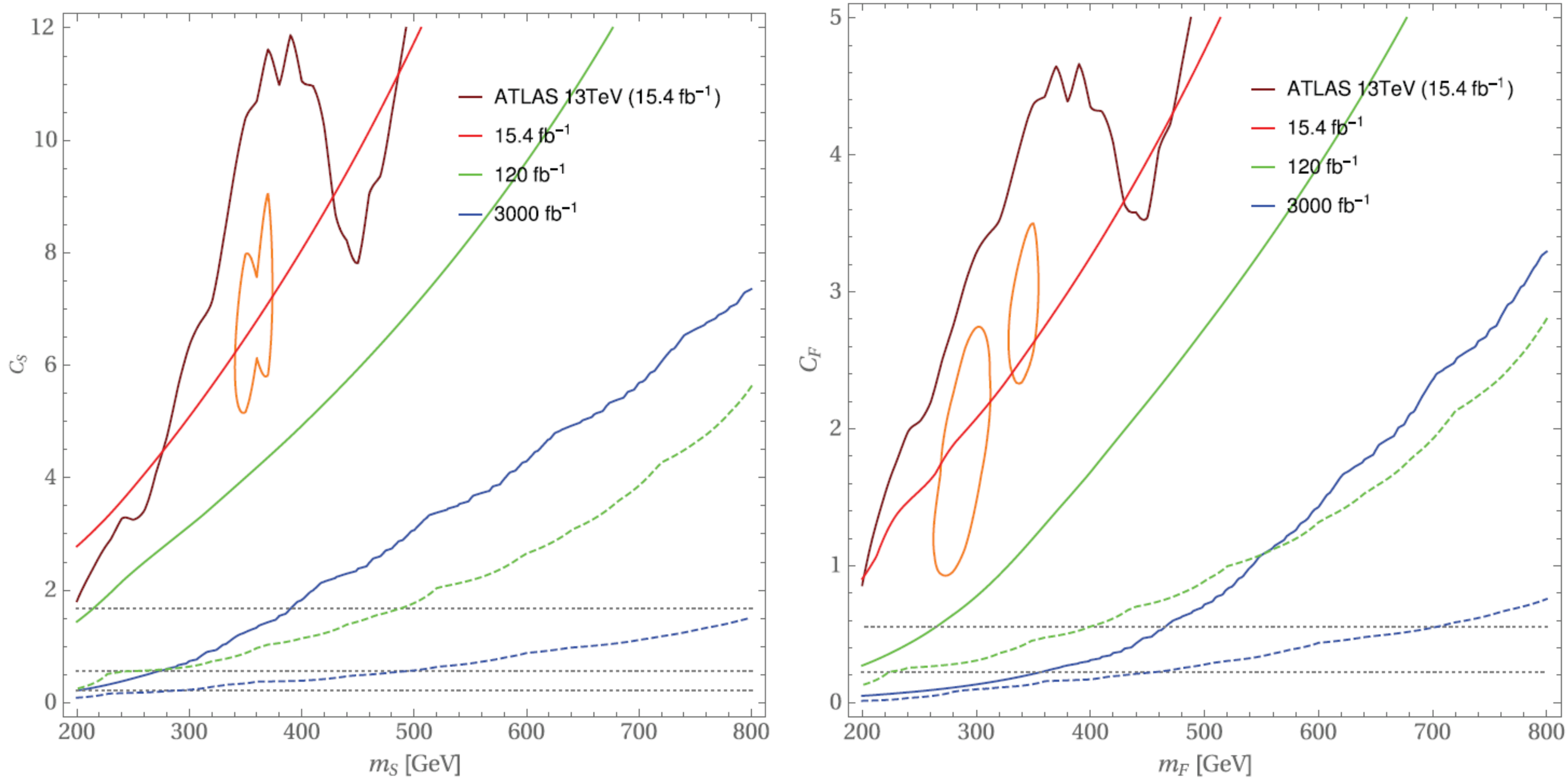
arXiv:1512.08221 (PRL, 117, 061801) and arXiv:1612.05031 (PRD, 95, 115004)



$$N_X T_{R_X} Q_X^2 \alpha \alpha_s \Big(1 + \beta + \alpha_s + \alpha_s\beta + \frac{\alpha_s^2}{\beta} + \alpha_s^2 + \alpha_s^2\beta + \frac{\alpha_s^3}{\beta^2} + \frac{\alpha_s^3}{\beta} + \alpha_s^3 + \alpha_s^3\beta + \frac{\alpha_s^4}{\beta^3} + \frac{\alpha_s^4}{\beta^2} + \frac{\alpha_s^4}{\beta} + \alpha_s^4 + \alpha_s^4\beta + \cdots\Big)$$

Constraints on Charges of New Particles

[**DC**, R. Dermisek, T. H. Jung, and H. D. Kim, **PRD(2017)**]



(a) scalar

(b) fermion

- Top quark mass measurement

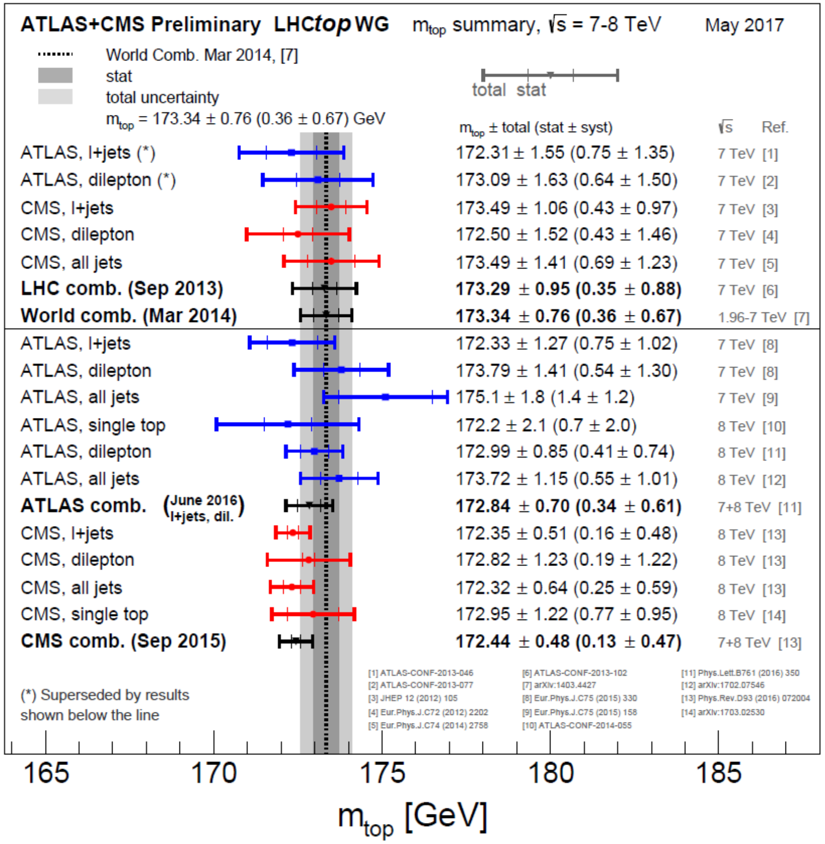
(pp $\rightarrow t + X \rightarrow$ *leptons + jets + missing energy*)

- Conventional method using 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



- Top quark mass measurement

(pp → $t + X$ → $leptons + jets + missing\ energy$)

- Alternative methods:

Cross sections $\sigma_{t\bar{t}}$ and $\sigma_{t\bar{t}+1\ jet}$

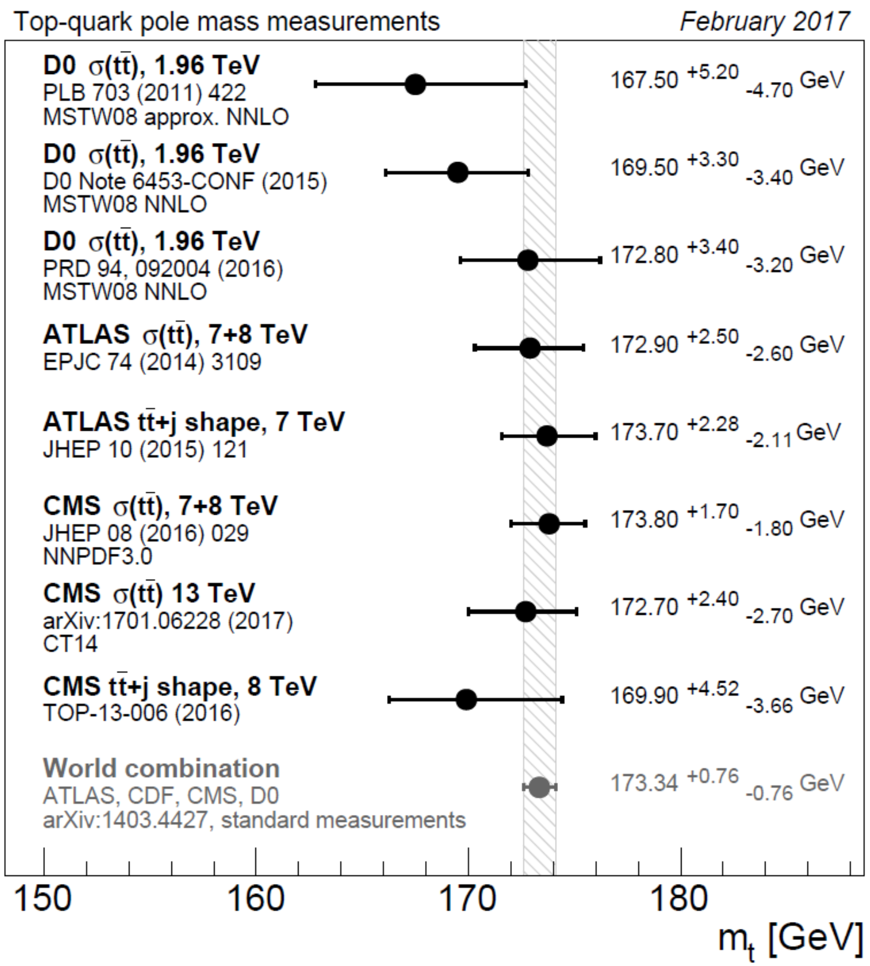
The J/ψ method

The endpoint of $m_{l+b\ jet}$

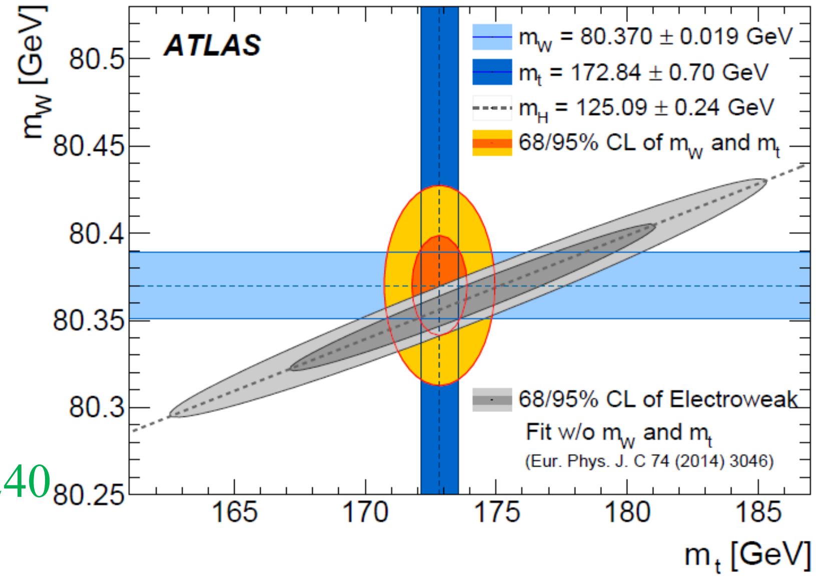
The B decay length L_{xy} method

Boost invariant energy peak

Leptonic observable methods

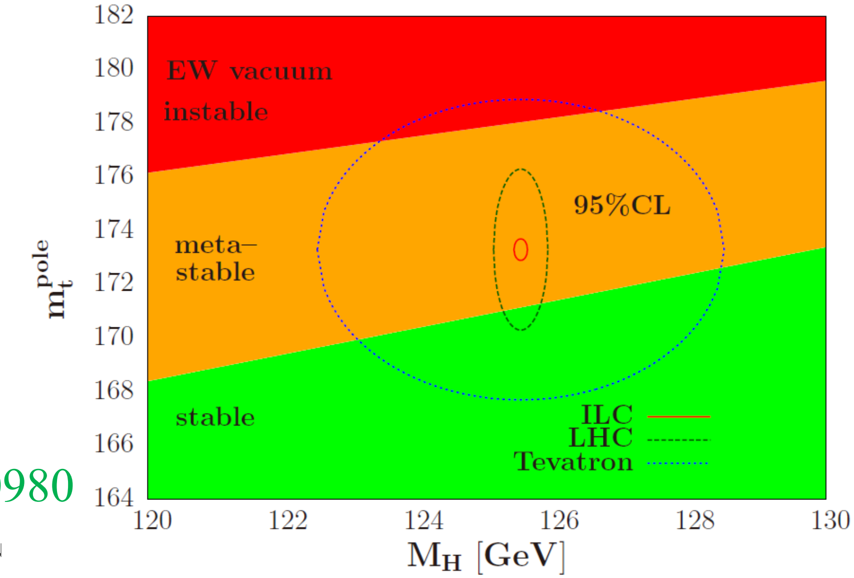


- **Top quark mass**
  - A fundamental parameter of the Standard Model Lagrangian
  - Validity of SM



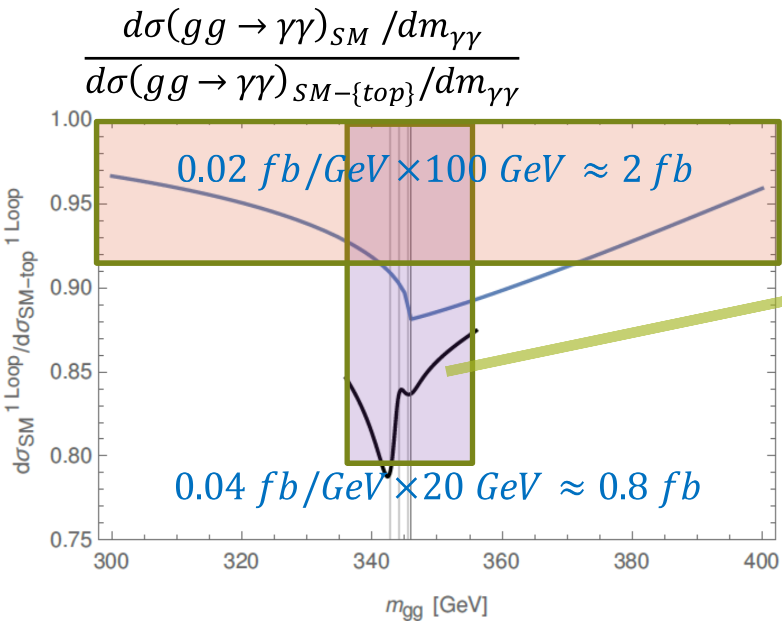
ArXiv:1701.07240

  - EW vacuum stability

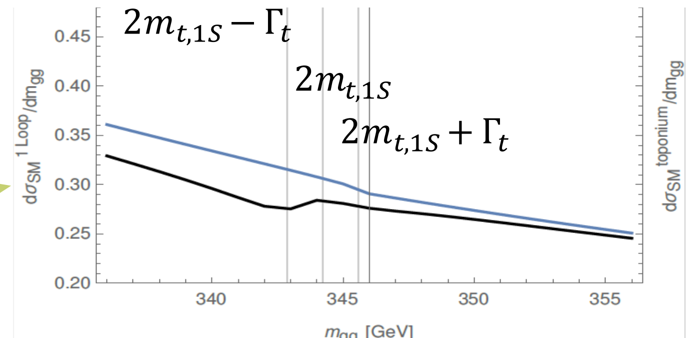


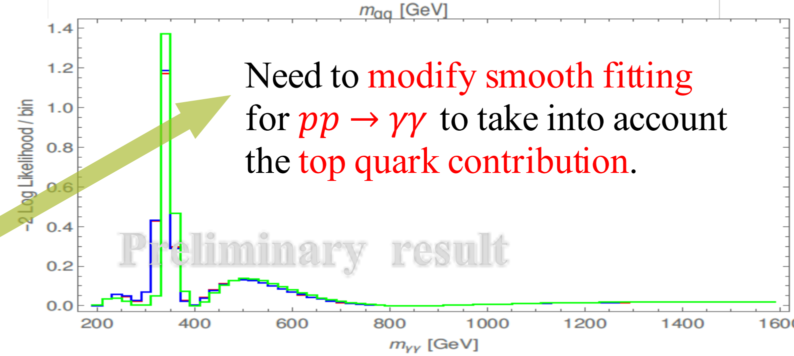
ArXiv:1207.0980

Observing Top Quark with Diphoton



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

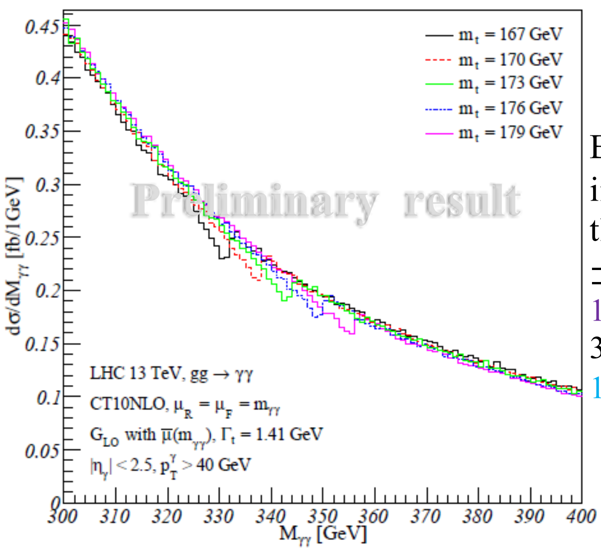




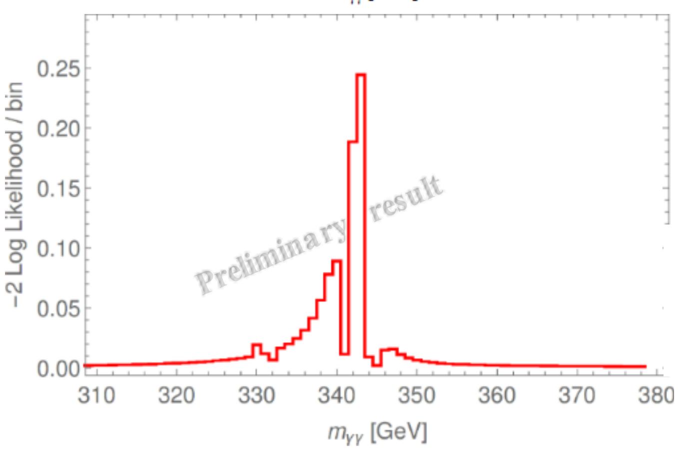
Need to modify smooth fitting for $pp \to \gamma\gamma$ to take into account the top quark contribution.

$$\frac{S}{\sqrt{B}} = 2\ or\ 5 \quad \to 100\ fb^{-1}\ or\ 600\ fb^{-1}$$

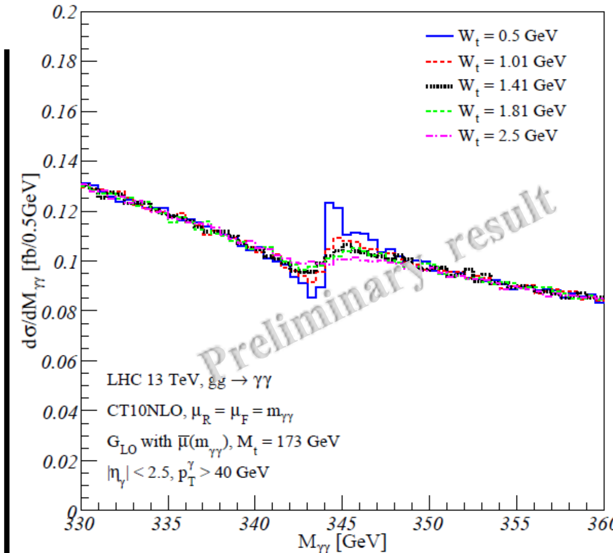
Top mass (and width) measurement



Ballpark estimate on the required integrated luminosity to obtain the top mass with $\pm$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}).



172 v.s. 173
Log likelihood from each bin



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