Top-Quark Mass from Diphoton Mass Spectrum

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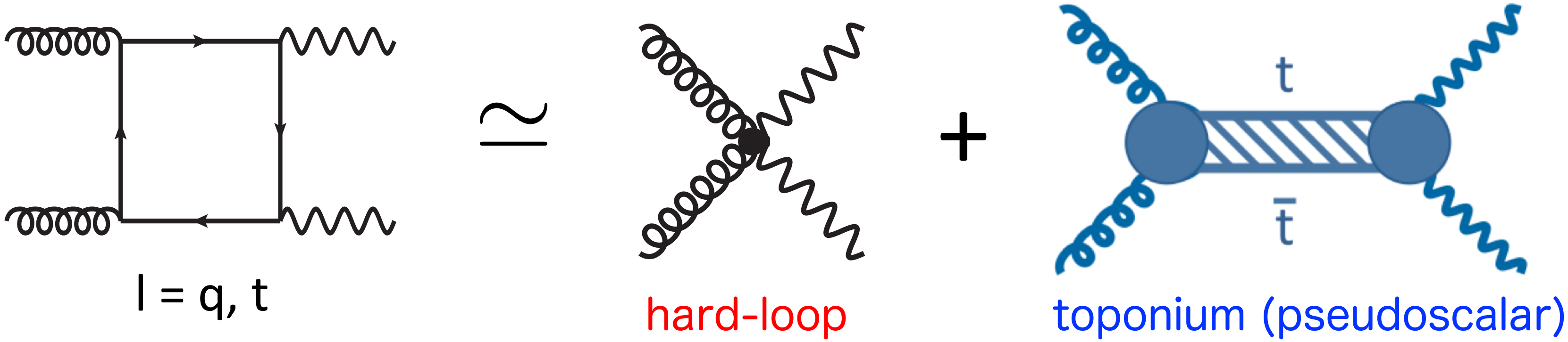
NRQCD amplitudes

- NRQCD amplitudes for gg→γγ near top-quark loop threshold



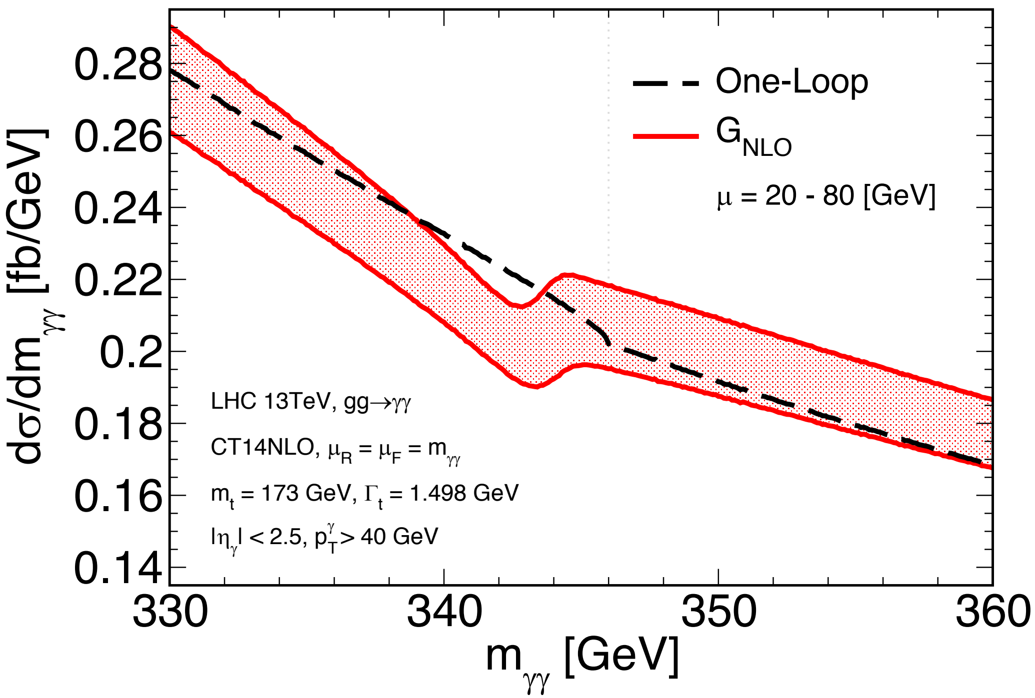
$$\mathcal{M}_t^{\mathrm{NR}} = \mathcal{A}_t(\theta) + \mathcal{B}_t \cdot G(\vec{0}, \mathcal{E}) + \mathcal{O}(v^2)$$

Matching coefficients: A_t (B_t) is known up to LO (NLO)
[one-loop matching for gg→tt, γγ→tt]

S-wave Green function [known up to N^3LO in NRQCD]:

$$G(\vec{0}; E) = i \int d^4x e^{iEt} \langle 0 | T \{ j_p(x) j_p(0) \} | 0 \rangle$$

Dip & bump due to the interference effects



- Shape is stable under scale variation of the (NLO) Green function [δm_{dip} ~ δm_{bump} ~ 0.6 GeV]
- Uncertainties are mostly on the normalization ~ 10%. [Another 20% uncertainty from μ_R and μ_F variations.]

- Top-quark mass (and width) can be determined by observing the shape of the diphoton mass spectrum.
- No top-quark in the final-state, but only photons → good momentum resolution, no FSR, no FSI
- Probing color-singlet resonance → short-distance mass

[similar to the threshold scan method at lepton colliders]

Short-distance mass

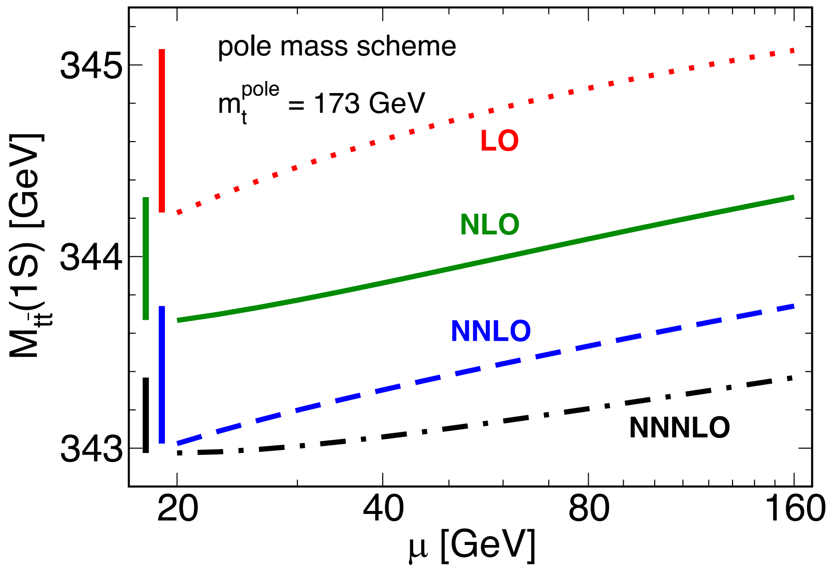
Penin,Steinhauser;Beneke,Kiyo,Schuller; Kiyo,Sumino;Anzai,Kiyo,Sumino;Smirnov, Smirnov,SteinHauser;Marquard;Smirnov, Smirnov,Steinhauser

Dip & bump positions ↔ Green function peak

~ 1S toponium energy-level

↔ top-quark short distance mass (renormalon cancellation)

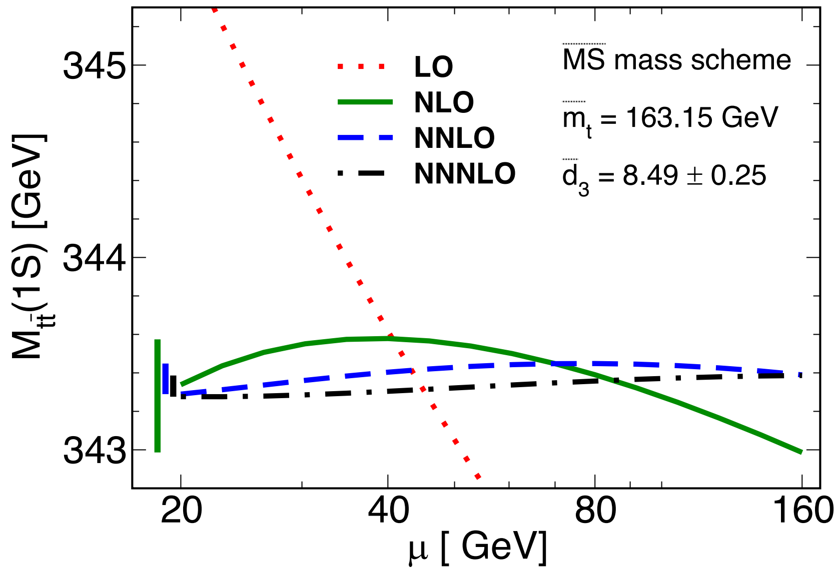
Pole-mass scheme



slow convergence, large uncertainty

$\delta_{N^3LO} \sim 0.4$ GeV

MSbar-mass scheme



faster convergence, small uncertainty

$\delta_{N^3LO} < 0.1$ GeV

Statistical Errors

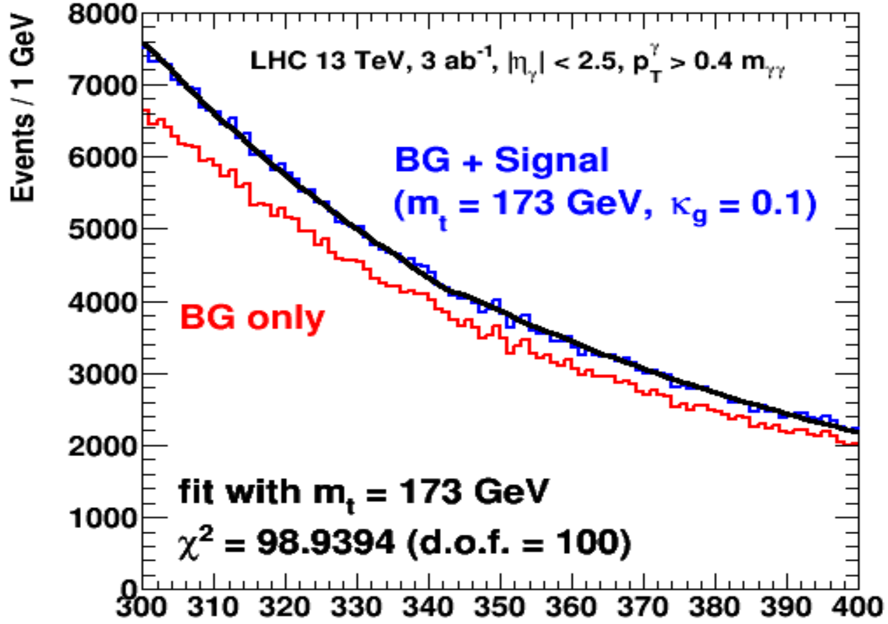
We estimated the mass extraction accuracy by fitting the spectrum with the "signal + continuum" function

- Signal = gg→γγ; calculated by theory for given m_t and Γ_t $\quad f_{\rm sig}(m_{\gamma\gamma}; m_t, \Gamma_t)$
- BG = the others; parameterized by a smooth analytic function

$$f_{\rm bg}(m_{\gamma\gamma}; a) = \left[1 - \left(\frac{m_{\gamma\gamma}}{\sqrt{s}}\right)^{\frac{1}{3}}\right]^a$$

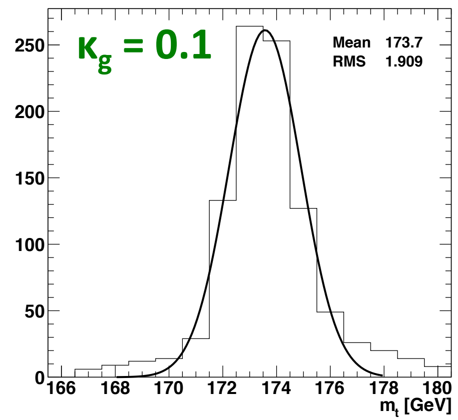
Signal-to-BG ratio is also fitted

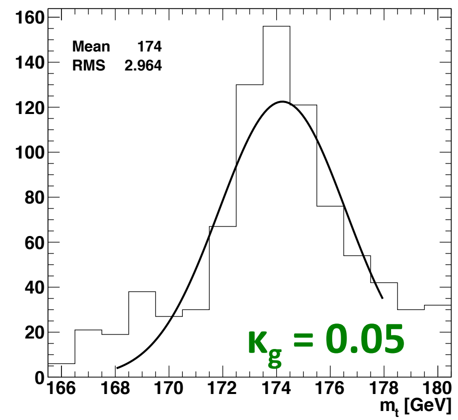
[Event samples are prepared by assuming it to be 5% to 10%]



Best-fit-mass results in our Toy MC simulation

$\delta m_t^{\rm stat.} \sim 2$ GeV $\quad\quad \sim 3$ GeV





Systematic Errors

- Dominant source can be the Photon Energy Scale

  (calibration uncertainty of the EM calorimeter)

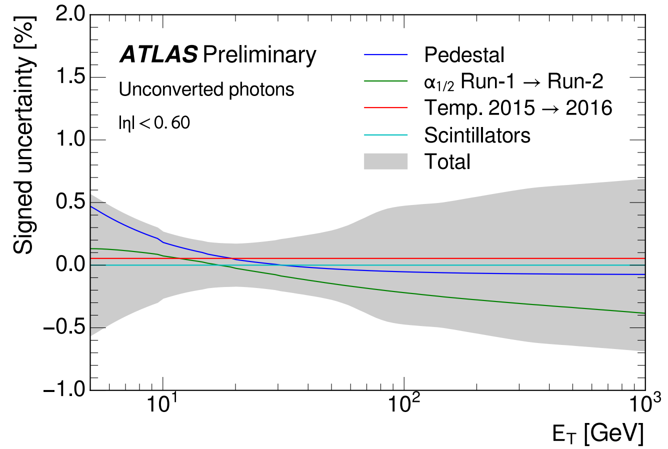
$\delta E_\gamma / E_\gamma$ =
- **~ 0.5% in ATLAS,** ATL-PHYS-PUB-2016-015
- **~ 0.1% - 0.3% in CMS** JINST 10 P08010 (2015)

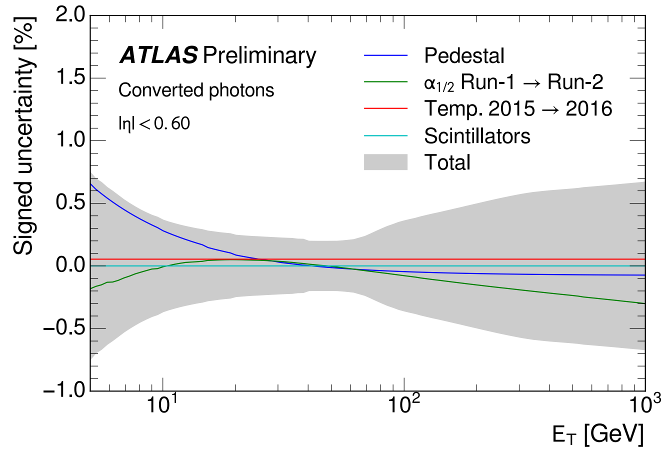
(barrel) (endcap) for $p_T \sim m_Z/2$ [need extrapolation]

$\delta m_t^{sys.}$ ~ 0.9 GeV [ATLAS], (~ 0.5 GeV [CMS])

not serious at the LHC → statistic dominant

could be serious at 100 TeV → systematic dominant





To-do list

Theory:

- Higher-orders corrections for the signal [2-loop amp. & one-gluon emission → **NLO NRQCD prediction**]

Background is known up to NNLO for qqbar

S.Catani,L.Cieri,D.de Florian,G.Ferrera,M.Grazzini

and NLO for fragmentation processes

T.Binoth,J.P.Guillet,E.Pilon,M.Werlen

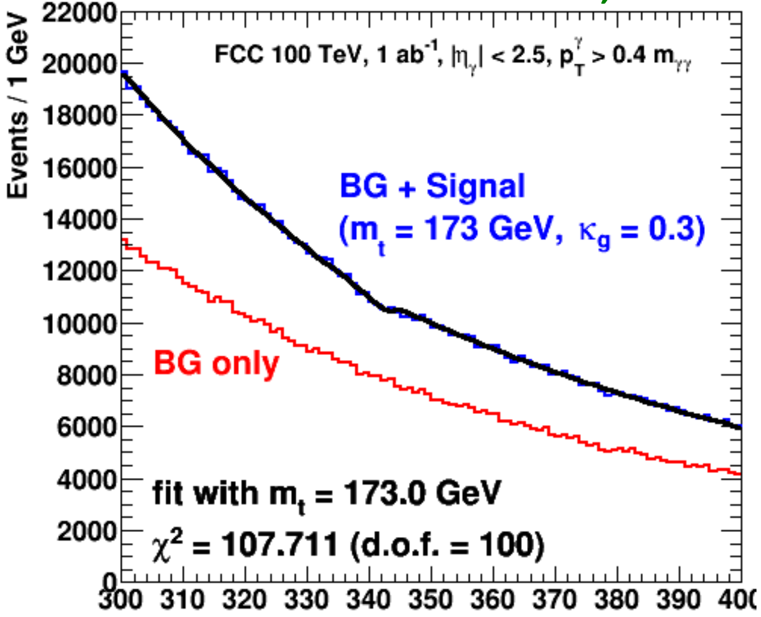
Experiment:

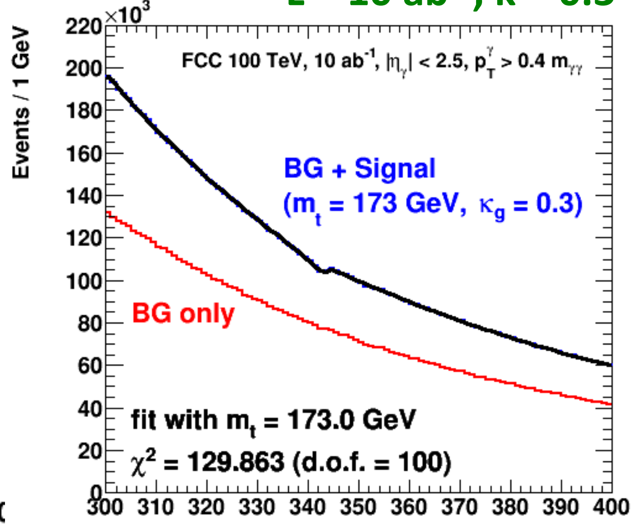
- Realistic simulation study with detector effects
- Better method to extract the dip-bump position from the spectrum
- Systematic error analysis [PES extrapolation to O(100 GeV)]

Simulation study: FCC 100 TeV, 1 or 10 ab^{-1}

Sample $m_{\gamma\gamma}$ histogram in 1-GeV bin

Total # of evt ~ 10^6 / 10^7 for $m_{\gamma\gamma}$ = [300, 400] GeV





Best-fit m_t histogram in ToyMC

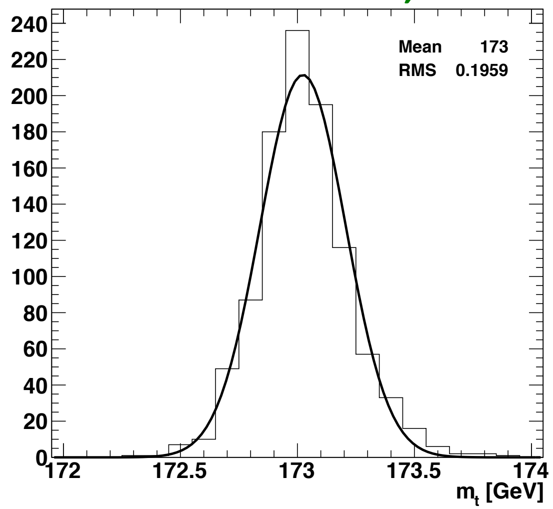
→ behave clear Gaussian

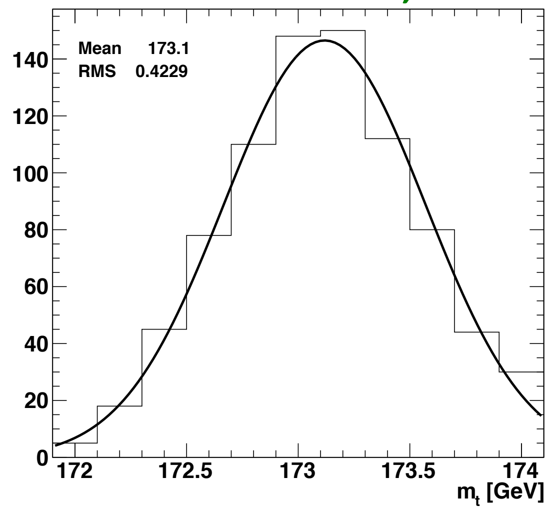
RMS = Gaussian SD

~ 0.2 GeV / 0.06 GeV (κ=0.3)

~ 0.6 GeV / 0.2 GeV (κ=0.1)

L = 1 ab^{-1} / 10 ab^{-1}





Estimation of the accuracy

Fitting the diphoton mass spectrum by "Signal + BG" function

- Signal = gg→γγ; calculated by theory for given m_t and Γ_t $\quad f_{\rm sig}(m_{\gamma\gamma}; m_t, \Gamma_t)$
- BG = the others; parameterized by a smooth analytic function

$$f_{\rm bg}(m_{\gamma\gamma}; a) = \left[1 - \left(\frac{m_{\gamma\gamma}}{\sqrt{s}}\right)^{\frac{1}{3}}\right]^a$$

The Signal-to-BG ratio is taken to be free.

ATLAS-CONF-2016-081

Our set-up for simulation study

Signal : our prediction [m_t=173 GeV and Γ_t=1.5 GeV]

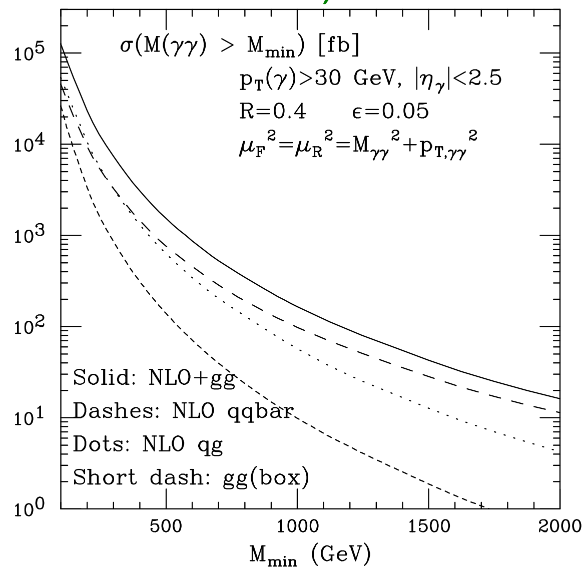
BG : qqbar annihilation, frag.-photon (LO Diphox)

Signal-to-BG ratio (κ): **5%** - **10%** @ LHC
10% - **30%** @ 100TeV

[LO gg]/[NNLO qq] "conservative"

[LO gg]/[LO qq] "optimistic" or [(N)LO gg]/[NNLO qq]

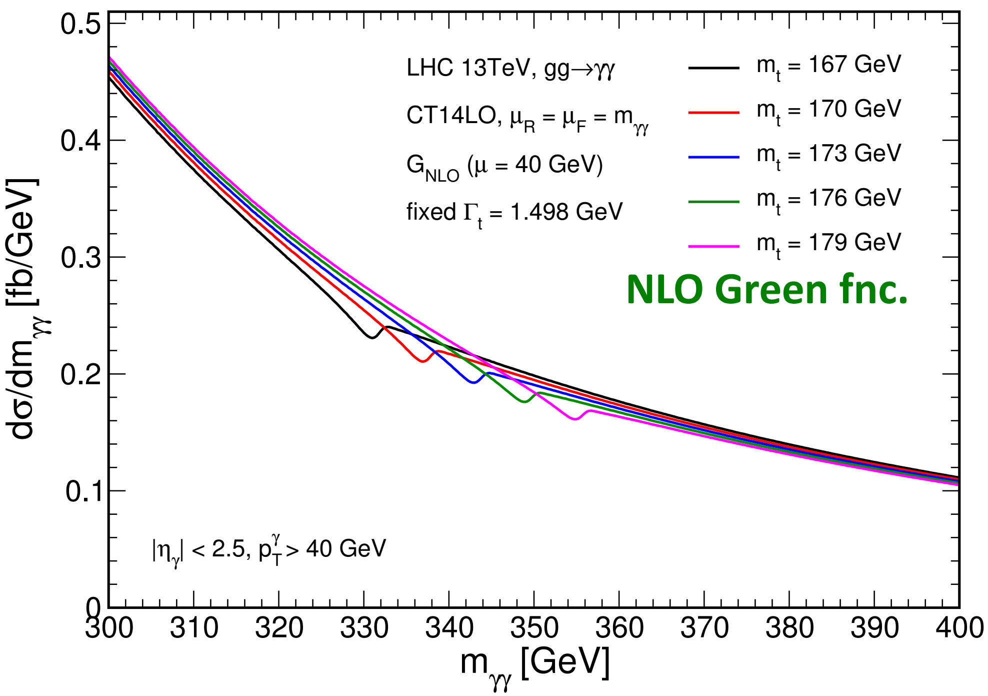
FCC, 1607.01831



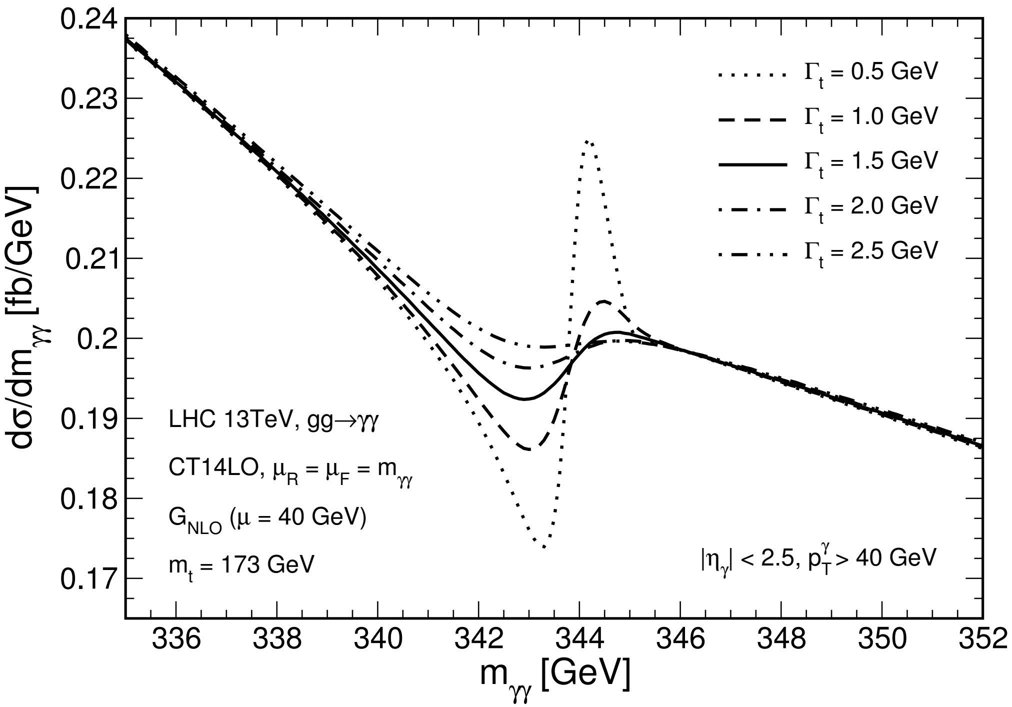
Top-quark mass from the diphoton mass spectrum

Top-quark mass and width can be extracted from the spectrum shape

mass dependence



width dependence



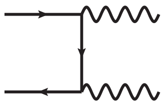
current limit by direct measurement:

$$0.6 \leq \Gamma_t \leq 2.5 \text{ GeV}$$

CMS PAS TOP-16-019

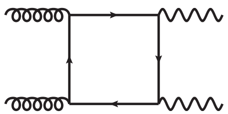
Diphoton production at hadron colliders

Diphoton production in the SM

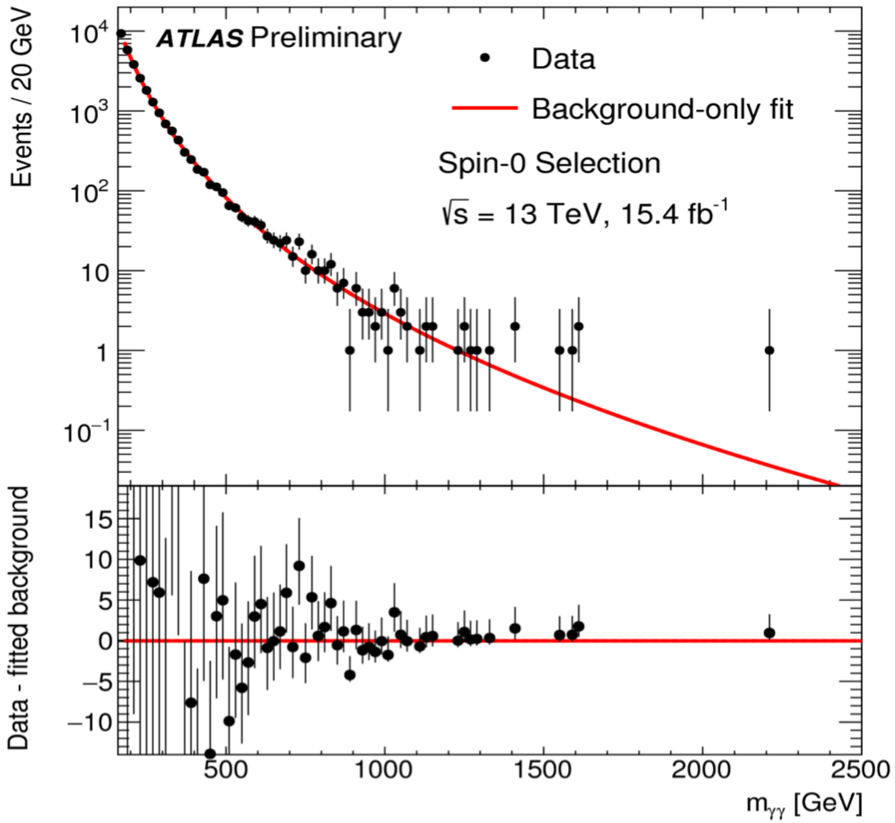
①  qqbar annihilation $\mathcal{O}(\alpha^2)$

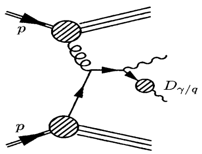
Dominant (after appropriate cuts),
QCD corr. known up to NNLO (K~2-3)

Catani et al. (12), Campbell et al(16)

②  gluon-fusion $\mathcal{O}(\alpha^2\alpha_s^2)$

Same order as NNLO of ①,
phenomenologically large due to the large gluon PDF.



③  Fragmentation photon contributions

known up to NLO; Diphox Binoth,Guillet,Pilon,Werlen ('00)

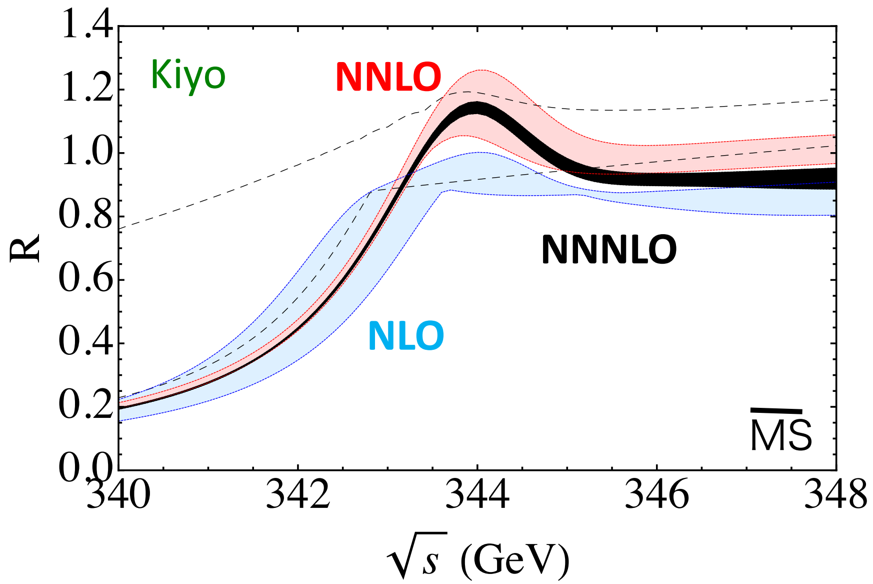
④ Fake photon contributions

hadron jet tagged as photon,,,

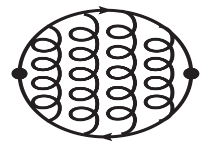
③ & ④ are reducible by appropriate photon isolation cut Frixione (98)

Top-quark mass at future e^+e^- colliders

Short-distance mass can be precisely measured by “threshold scan”
at future e^+e^- colliders [ILC, FCC-ee, CLIC,,,]



$$\sigma_{\rm tot}(s) \propto {\rm Im}\left[G(\vec{0}, \sqrt{s}+i\Gamma_t)\right]$$



Renormalon-free relation between the short distance mass and the (1S) resonance mass

$$M_{1S} = 2m_t + \Delta E$$

- Threshold cross section at N^3LO in NRQCD — Beneke,Kiyo,Marquard,Penin,Piclum,Steinhauser (15)
- 4-loop relation between pole mass and MS mass — Marquard,Smirnov,Smirnov,Steinhauser (15)
- Direct conversion from the peak energy to the MS mass — Kiyo,Mishima,Sumino (15)

$$\delta m_{\rm fit} \sim 30 \text{ MeV}, \delta m_{\rm scl} \sim 20 \text{ MeV}, \ [\delta m_{\alpha_s} \sim 40 \text{ MeV}]_{\delta_{\alpha_s}=0.0006}$$

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