Precise top-quark mass at hadron colliders

Sayaka Kawabata
(SeoulTech)

Based on

- SK and H. Yokoya, arXiv:1607.00990
- SK, Y. Shimizu, Y. Sumino and H. Yokoya, PLB741 (2015) 232-238

Outline

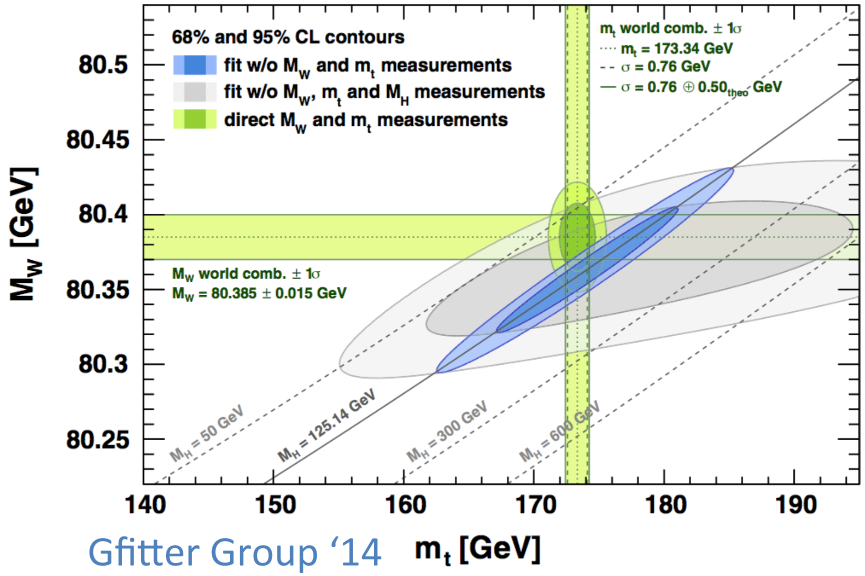
1. Introduction to m_t determination
2. Diphoton mass spectrum を用いる方法
3. Lepton energy distribution を用いる方法
4. Summary

1. Introduction

Motivation to measure m_t

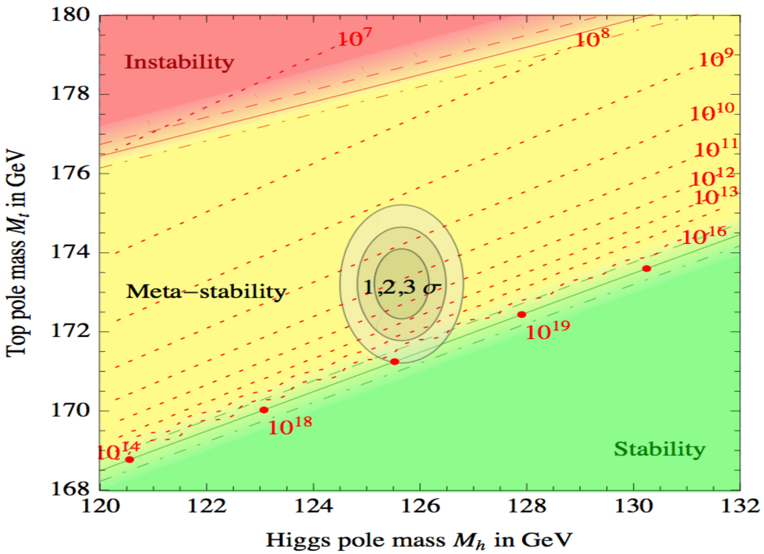
- One of the fundamental parameters of the SM
- Important input to various physics

★ EW precision tests for SM



Gfitter Group '14

★ SM vacuum stability



Buttazzo et al. '13

★ Beyond SM

Current status at hadron colliders

Tevatron+LHC m_t combination arXiv:1403.4427

$m_t = 173.34 \pm 0.76$ GeV 0.4 % precision !

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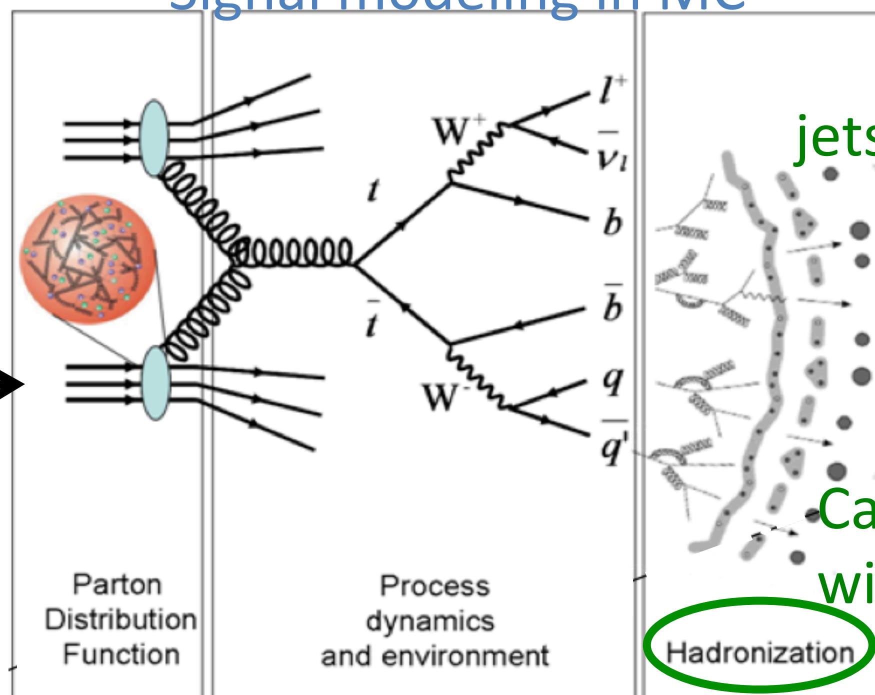
What kind of mass? $\neq m_t^{pole}, m_t^{\overline{MS}}$ "Monte-Carlo mass"

Signal modeling in MC

Experiment

m_t measurement

Theory (MC)



jets

Cannot be treated within pert. QCD

Current status at hadron colliders

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What kind of mass? $\neq m_t^{pole}, m_t^{\overline{MS}}$ "Monte-Carlo mass"

m_t^{pole}, $m_t^{\overline{MS}}$ measurements

- $m_t^{pole} = 173.8 \pm 2$ GeV

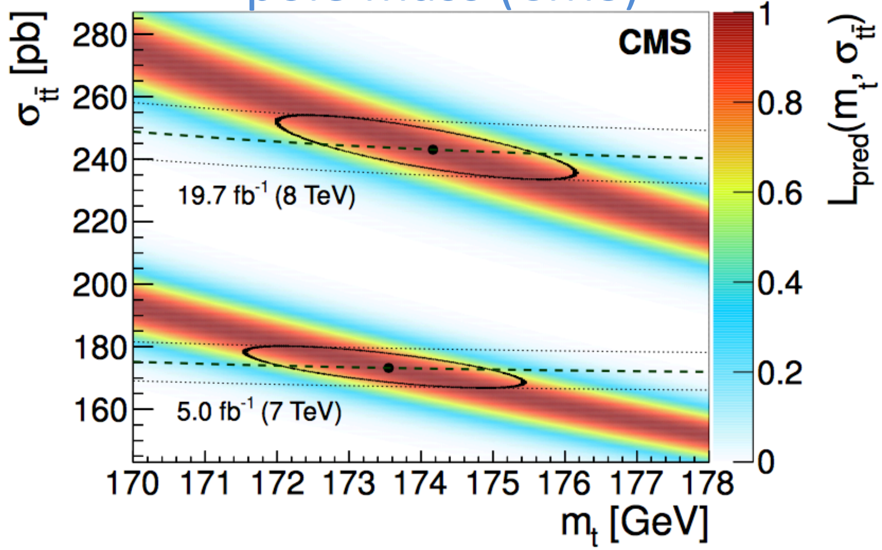
  CMS, JHEP 08 (2016) 029

- $m_t^{\overline{MS}} = 160.0\,^{+5.1}_{-4.5}$ GeV

  D0, PLB 703 (2011) 422

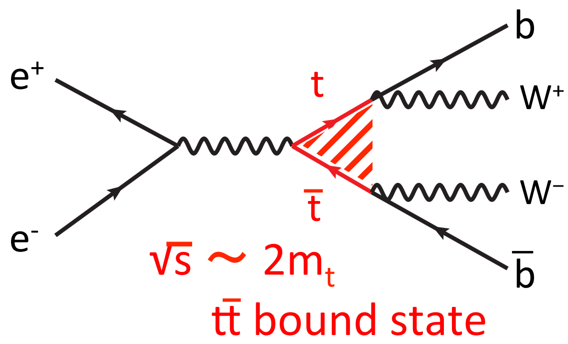
The errors are still large.

pole mass (CMS)

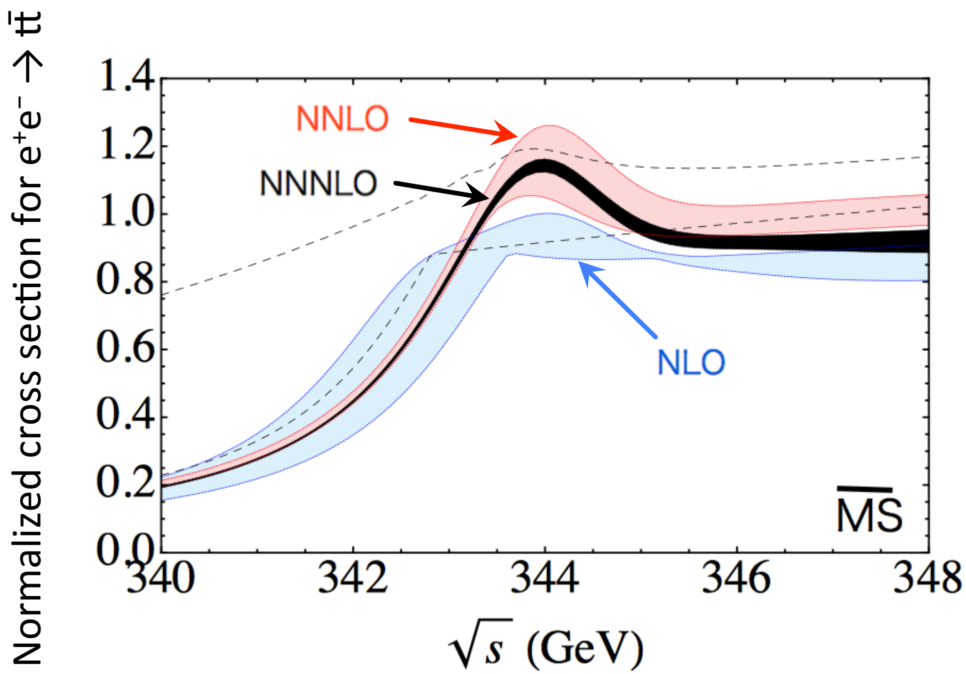


m_t measurement at future e^+e^- colliders

Threshold scan of $t\bar{t}$ production



- N^3LO: Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser, PRL 115 (2015)192001
- ILC study: Horiguchi, Ishikawa, Suehara, Fujii, Sumino, Kiyo, Yamamoto, arXiv:1303.3758
- CLIC study: Seidel, Simon, Tesar, Poss, Eur.Phys.J.C73 (2013)2530



Kiyo, Top WS@Valencia 2015

Peak position

∼ 1S resonance mass

$\overline{\mathrm{MS}}$ mass

$\Delta m_t^{\overline{\mathrm{MS}}} \sim$ 30 MeV in principle

Kiyo, Mishima, Sumino, JHEP11 (2015) 084

Aim of this study

e^+e^- collider と違って、hadron collider で
摂動QCD における定義の明確な top mass を
高精度で決定することは困難

↓

この困難を克服する2つの方法を提案する

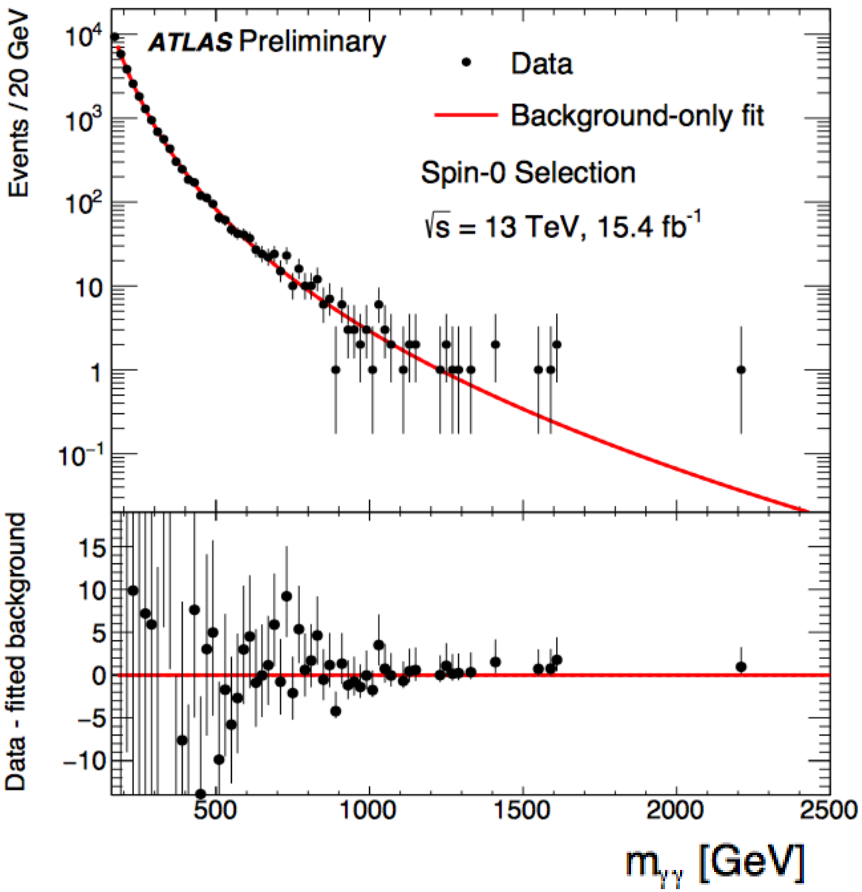
- Diphoton mass spectrum を用いる方法
  SK and H. Yokoya, arXiv:1607.00990
- Lepton energy distribution を用いる方法
  SK, Y. Shimizu, Y. Sumino and H. Yokoya, PLB741 (2015) 232-238

2. Diphoton mass spectrum を用いる方法

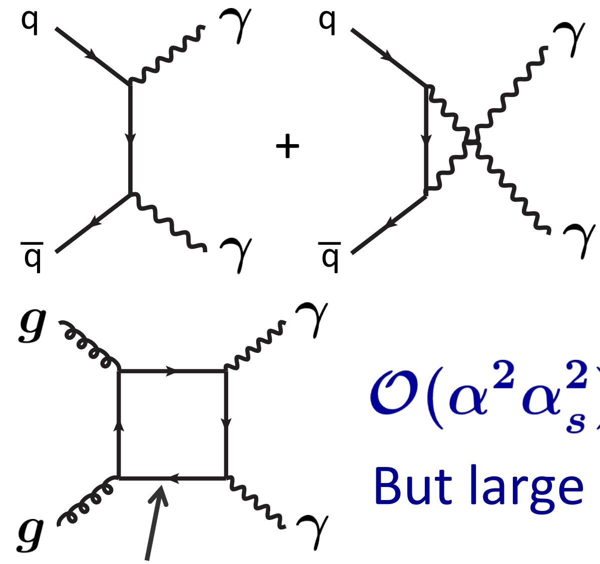
SK and H. Yokoya, arXiv:1607.00990

Diphoton mass spectrum

- $H \to \gamma\gamma$
- New resonance search



$$pp \to \gamma\gamma$$



$\mathcal{O}(\alpha^2)$

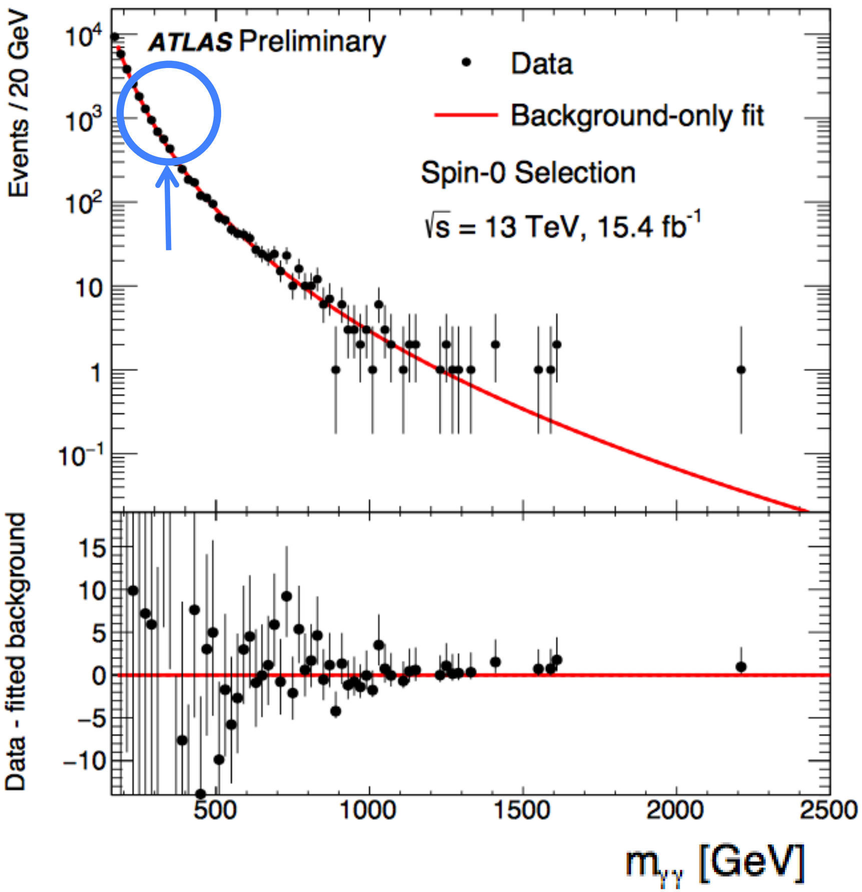
$\mathcal{O}(\alpha^2 \alpha_s^2)$

But large gluon PDF

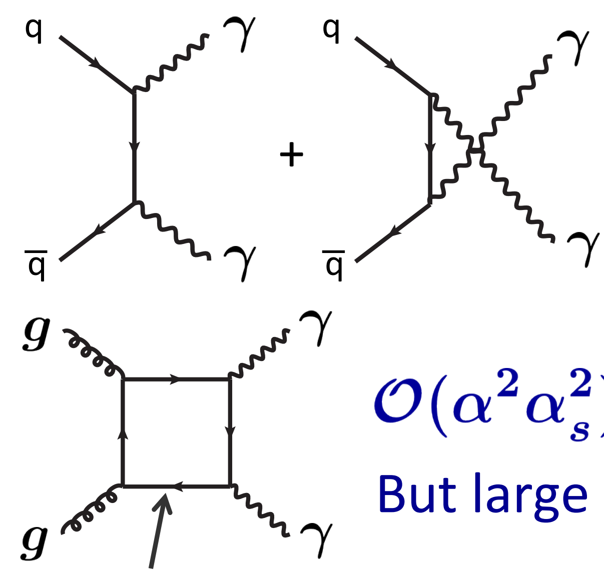
$q = u,\ d,\ s,\ c,\ b,\ t$

Diphoton mass spectrum

- $H \to \gamma\gamma$
- New resonance search



$pp \to \gamma\gamma$



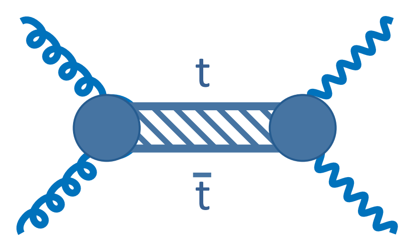
$\mathcal{O}(\alpha^2)$

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

But large gluon PDF

$q = u,\ d,\ s,\ c,\ b,\ t$

$m_{\gamma\gamma} \sim 2\ m_t$



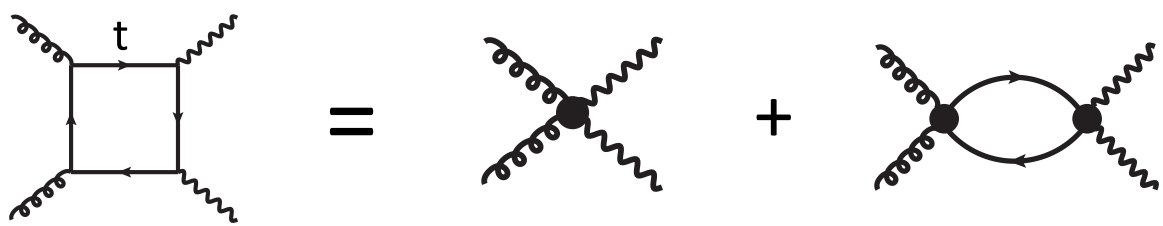
Bound-state effects

gg → γγ amplitude

- Two-loop amplitude for massless-quark loop — Bern, De Freitas, Dixon, JHEP0109 (2001) 037
- One-loop amplitude for 5 massless-quark + top-quark loop — Dicus, Willenbrock, PRD37 (1988) 1801; Campbell, Ellis, Li, Williams, arXiv:1603.02663

Bound-state effectsを含める (this work)

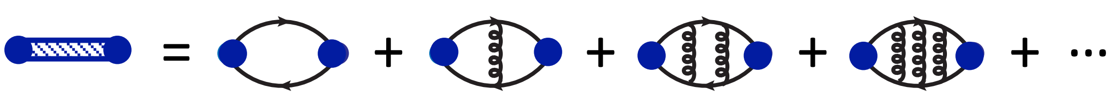
Near $t\bar{t}$ threshold $v = \sqrt{1 - 4m_t^2/m_{\gamma\gamma}^2}$で展開



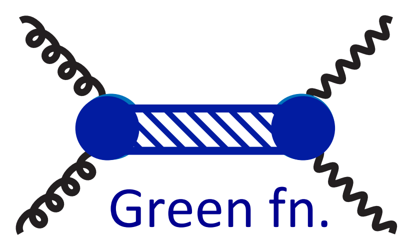
$+ \ \mathcal{O}(v^2)$

Schrodinger eq.

$$\left[\left\{-\frac{\nabla^2}{m_t} + V_{\rm QCD}(r)\right\} - \mathcal{E}\right] G(\vec{r};\mathcal{E}) = \delta^3(\vec{r})$$

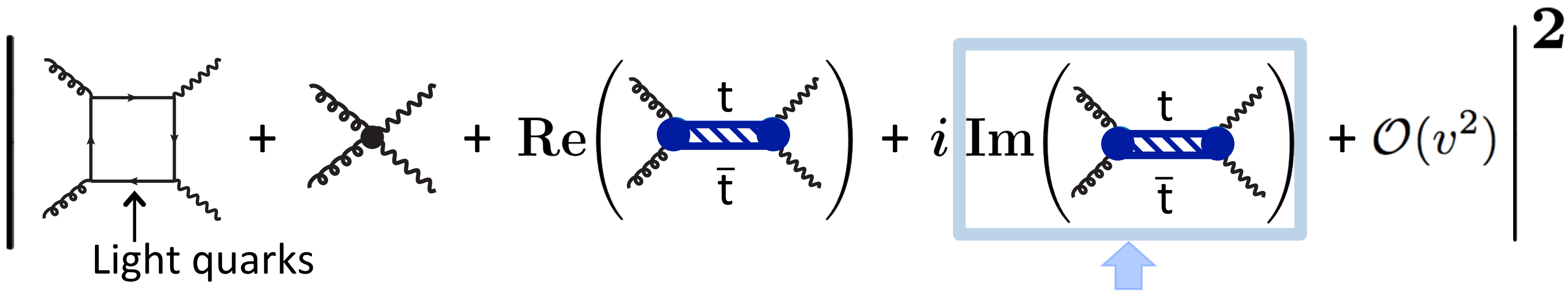


α_s/v $(\alpha_s/v)^2$ $(\alpha_s/v)^3$



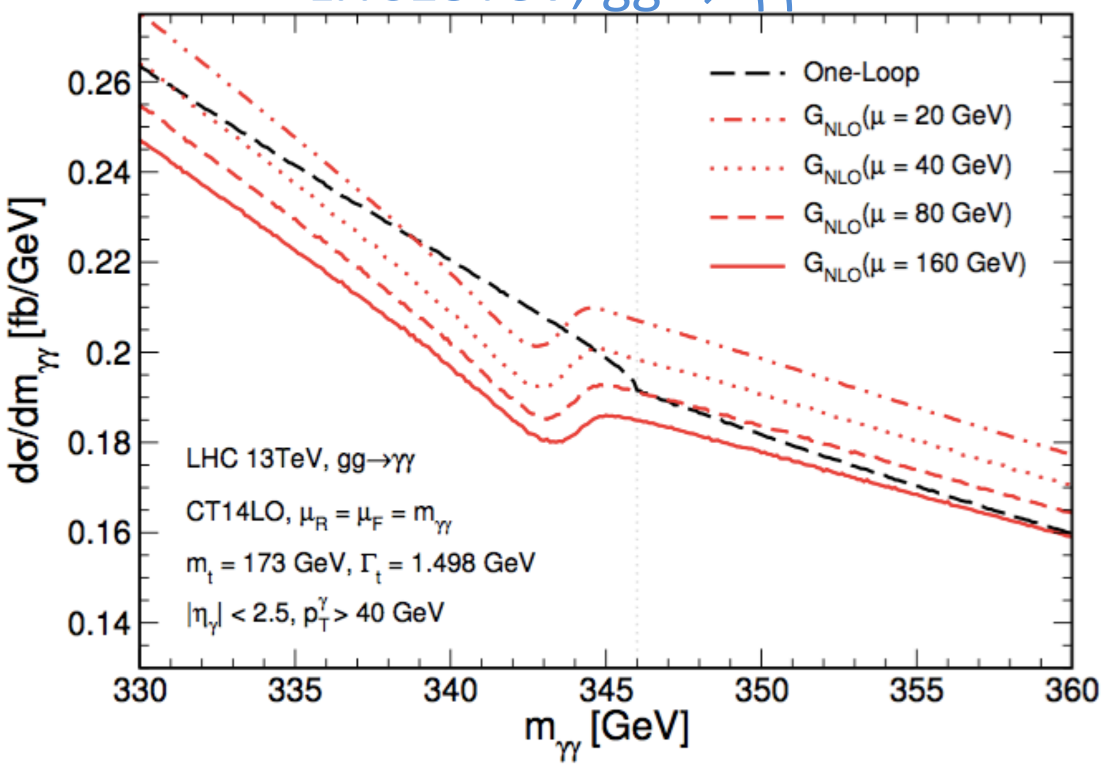
Green fn. in NRQCD

Diphoton mass spectrum near threshold



$e^+e^- \to t\bar{t}$ の場合

LHC13TeV, $gg \to \gamma\gamma$

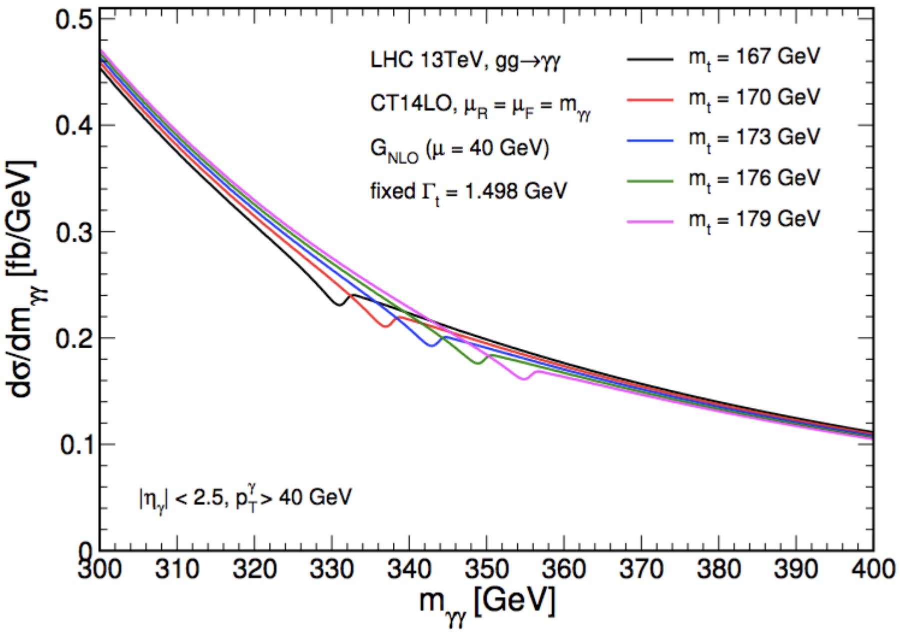


Theoretical uncertainties

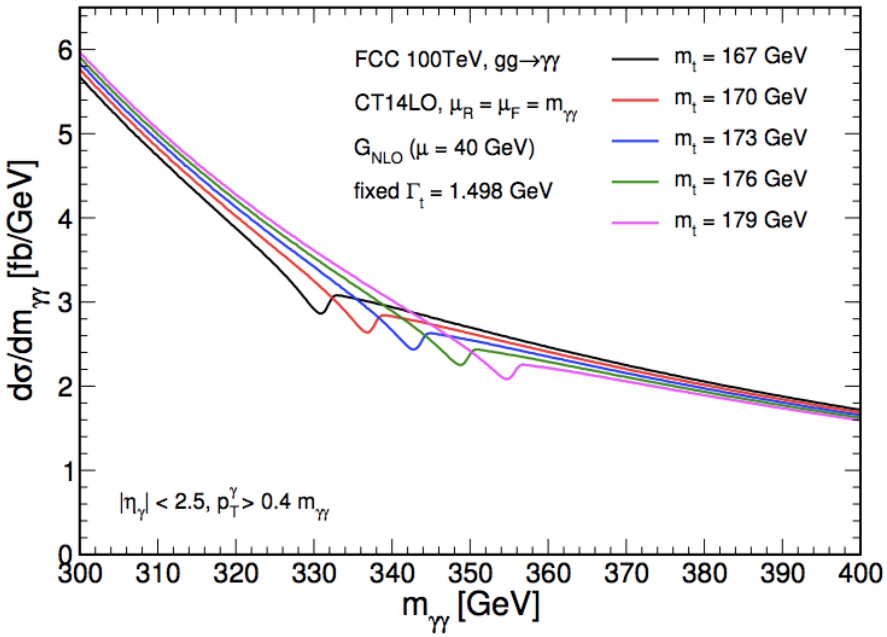
- Green fn. scale
  - Overall normalization ～10 %
  - Positions of dip and bump ～ sub-GeV level
- PDF and α_S scale ～20%

m_t measurement at LHC and FCC

LHC 13TeV



FCC 100TeV



Simulation

- $gg \to \gamma\gamma$ generated according to our calculation
- $q\bar{q} \to \gamma\gamma$
- Fragmentation contributions

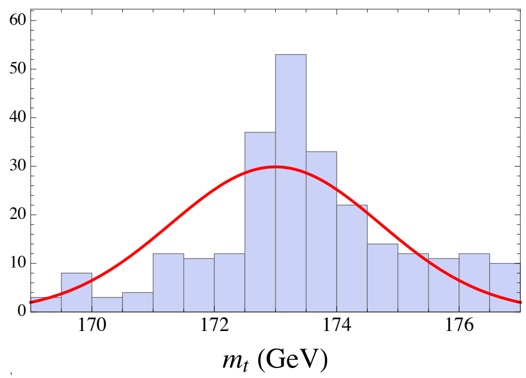
} Diphox (LO)

Fitting fn : (gg prediction) + analytic smooth fn.

Sensitivity

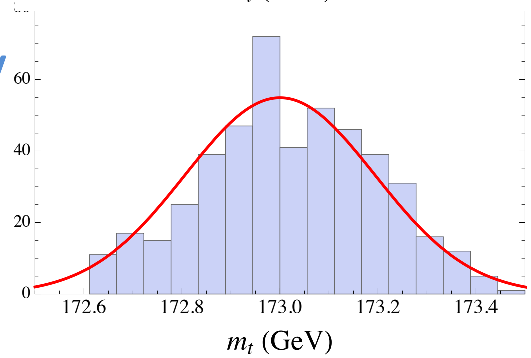
Estimate of statistical error

LHC $\sqrt{s}$ = 13TeV
3 ab^{-1}



$\Delta m_t \sim$ 2 GeV for 3 ab^{-1}

FCC $\sqrt{s}$ = 100TeV
1 ab^{-1}, 10 ab^{-1}



Δm_t = 0.2 GeV for 1 ab^{-1}

Δm_t = 0.06 GeV for 10 ab^{-1}

- At FCC, systematic uncertainties should dominate.
  Photon energy scale, isolation cuts, …
- Higher-order QCD corrections for pp → γγ X would be important.
  NLO $q\bar{q}$, LO and NLO qg, NLO gg

3. Lepton energy distributionを用いる方法

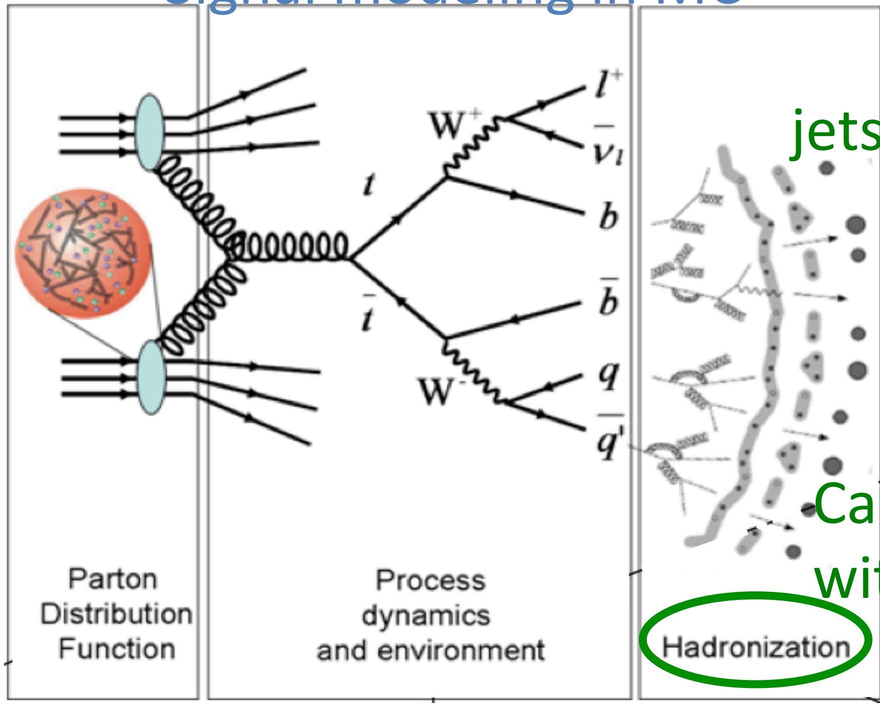
SK, Y. Shimizu, Y. Sumino and H. Yokoya,
PLB741 (2015) 232-238

Weight function method

SK, Y.Shimizu, Y.Sumino, H.Yokoya, PLB 710, 658 (2012)
SK, Y.Shimizu, Y.Sumino, H.Yokoya, JHEP 08, 129 (2013)

- Only lepton energy distribution is needed
- Independent of top-quark velocity distribution

Signal modeling in MC



jets

Cannot be treated within pert. QCD

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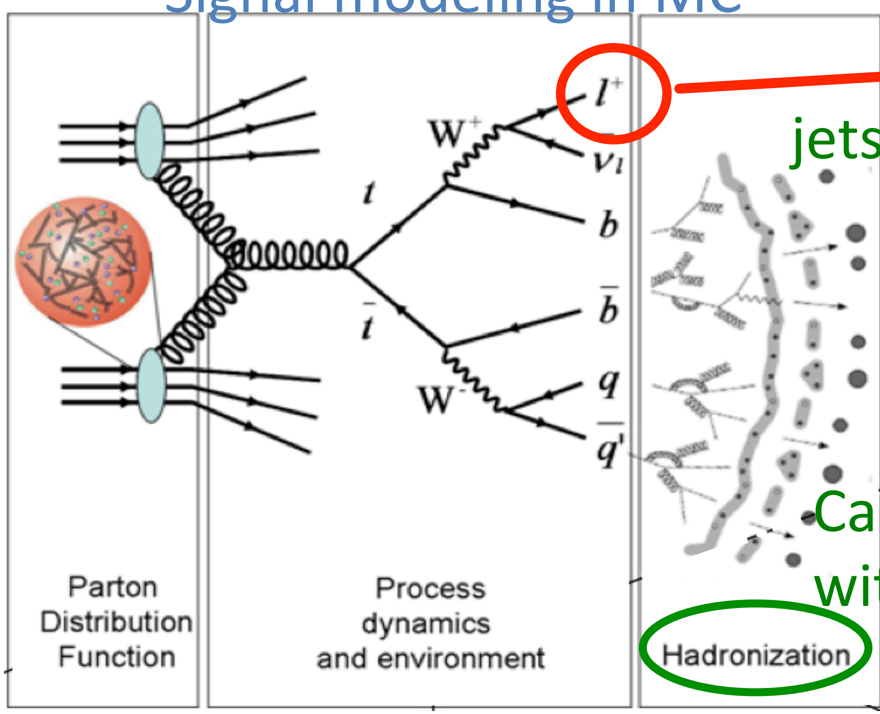


Free from ambiguity in jets

Theoretically well-defined m_t

Cannot be treated within pert. QCD

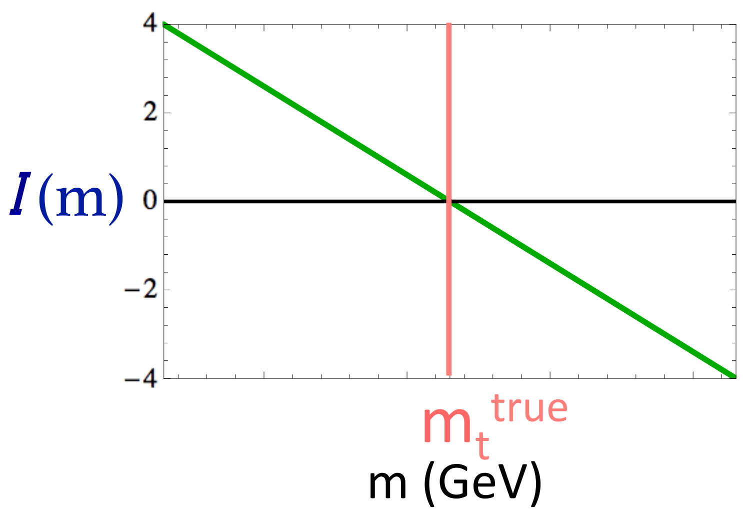
Method

1. Compute a weight function $W(E_\ell, m)$

$$W(E_l, m) = \int dE \, \mathcal{D}_0(E\,;m) \frac{1}{EE_l} (\text{odd func. of } \rho)\Big|_{e^\rho = E_l/E}$$

Lepton energy dist. in the rest frame of top quark (with mass m)

2. Using lepton energy dist. from experiment $D(E_\ell)$,
perform its weighted integration



$$I(m) \equiv \int dE_l D(E_l) W(E_l, m)$$

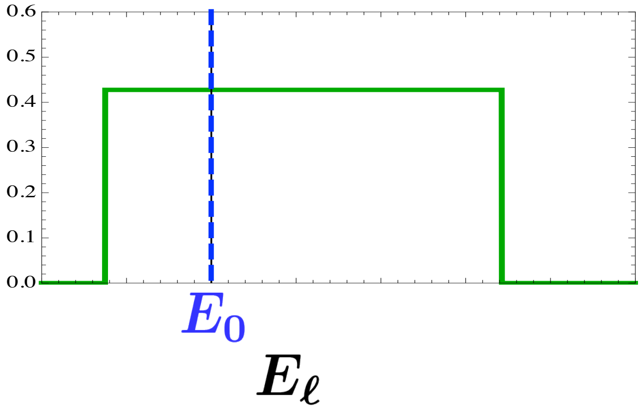
3. Obtain m_t^{true} from

$$I(\,m = m_t^{true}\,) = 0$$

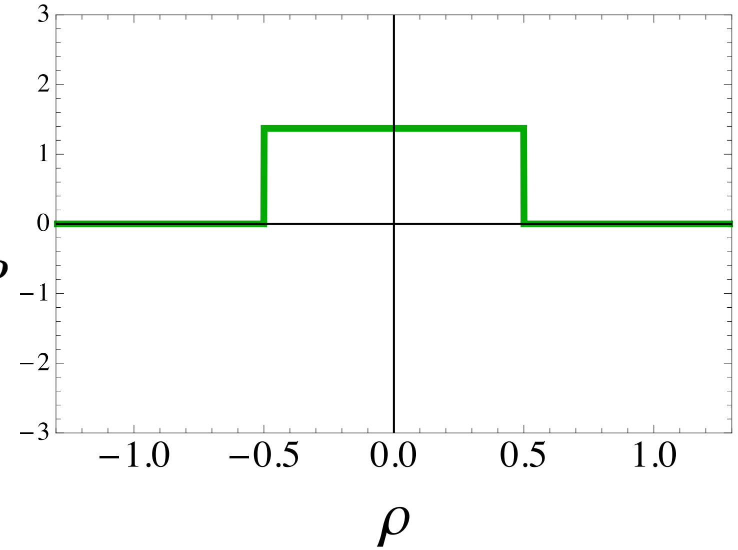
Construction of weight function

For a two-body decay : X $\longrightarrow \ell$ + Y (X is unpolarized)

Lepton energy distribution



$E_\ell / E_0 = e^\rho$



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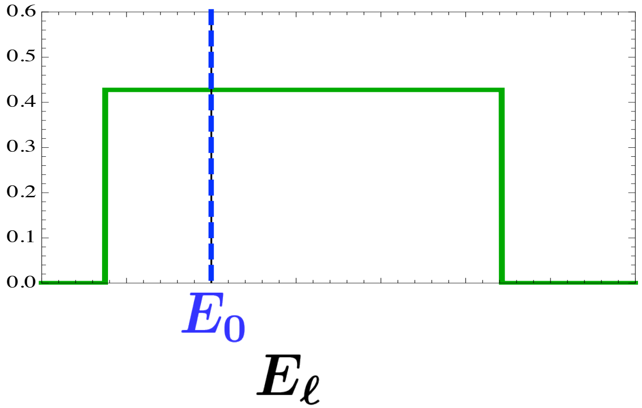
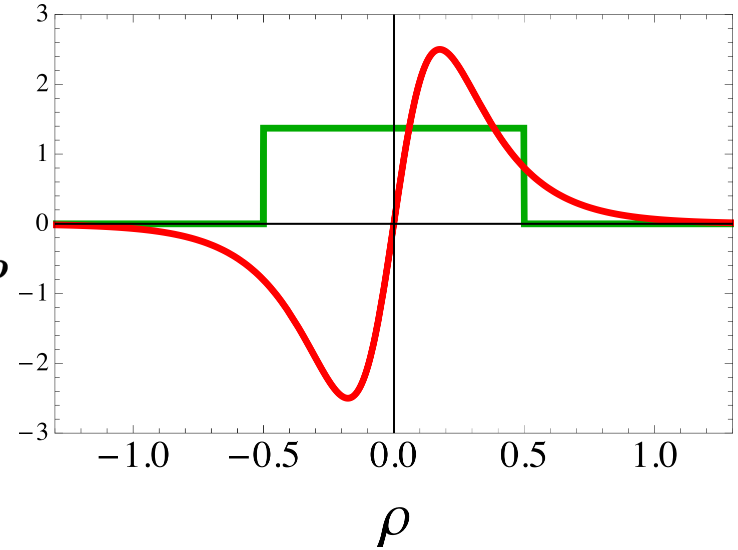


$$E_\ell / E_0 = e^\rho$$



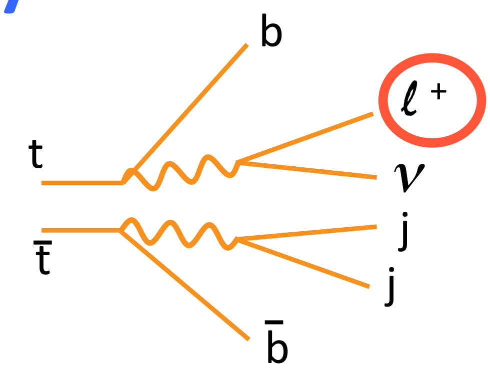
$$\int dE_\ell \, D(E_\ell) W(E_\ell, m_X^{\text{true}}) = 0 \iff \int d\rho \, (\text{even fn. of } \rho)(\text{odd fn. of } \rho) = 0$$

$$dE_\ell \propto d\rho \, e^\rho$$

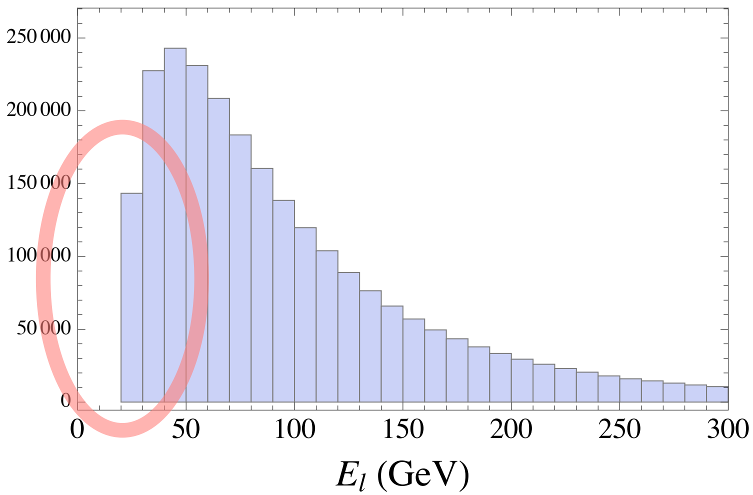
$$W(E_l, m_X^{true}) = \mathrm{e}^{-\rho}(\text{odd func. of } \rho)\Big|_{\mathrm{e}^\rho = E_l/E_0}$$

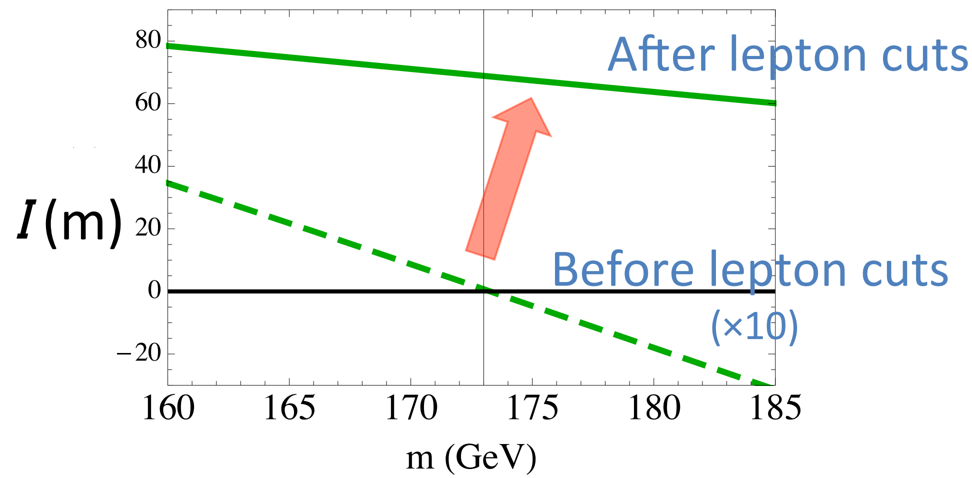
Simulation analysis

- LHC $\sqrt{s}$ = 14 TeV
- $t\bar{t}$ events, Lepton+jets channel



Event selection cuts and background deform lepton distribution.





Parton level の lepton distribution に戻す方針

SK, Y. Shimizu, Y. Sumino and H. Yokoya, PLB741 (2015) 232-238

Sensitivity of m_t determination

Uncertainties [GeV] (LO analysis)

Signal stat. error	0.4
μ_F scale	+1.5/-1.4
PDF	0.6
Jet energy scale	+0.2/-0.0
BG stat. error	0.4

← At 100 fb^{-1}, Lepton+jets channel

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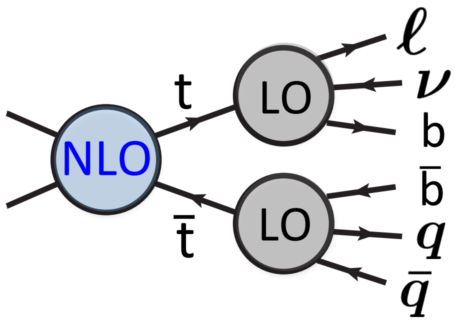
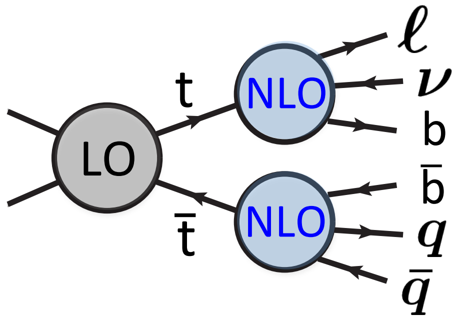
← At 100 fb^{-1}, Lepton+jets channel

← Can be improved by including NLO



Scale uncertainty in NLO top decay

+0.3/-0.2 GeV preliminary



We aim for $\Delta m_t^{pole} < 1$ GeV

4. Summary

- Precise determination of a theoretically well-defined m_t is demanded.

- We proposed two methods for precise m_t measurement at hadron colliders.

  - Diphoton mass spectrum を用いる方法

    $\Delta^{stat}\, m_t = 0.06$ GeV for 10 ab^{-1} at FCC

  - Lepton energy distribution を用いる方法

    $\Delta m_t^{pole} < 1$GeV is probable at LHC