Top-quark mass and Yukawa coupling

Y. Sumino
(Tohoku Univ.)

☆Plan of Talk

1. What's top mass(+Yukawa coupling)? [Introduction]

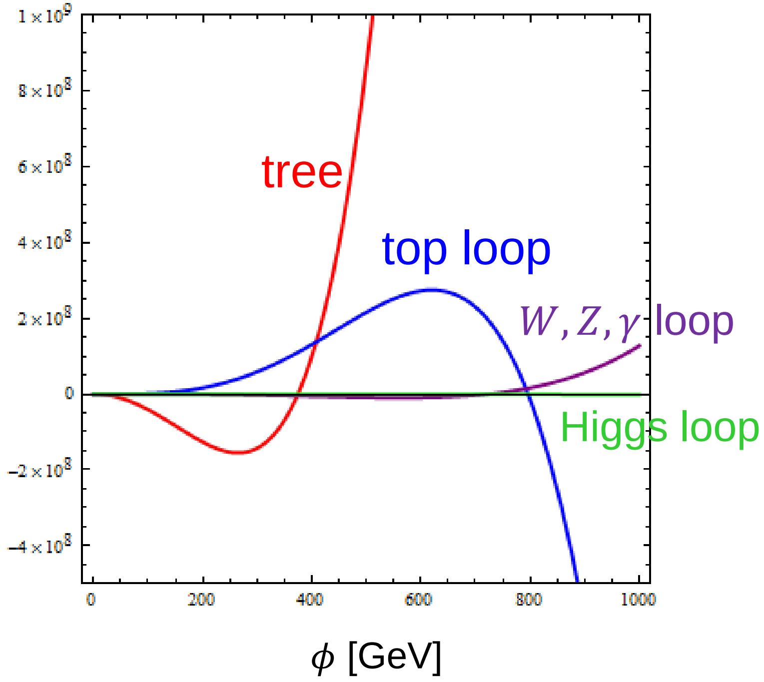
2. Precision top mass determination at ***ILC***

3. Top mass at ***LHC***: status, problems, goals

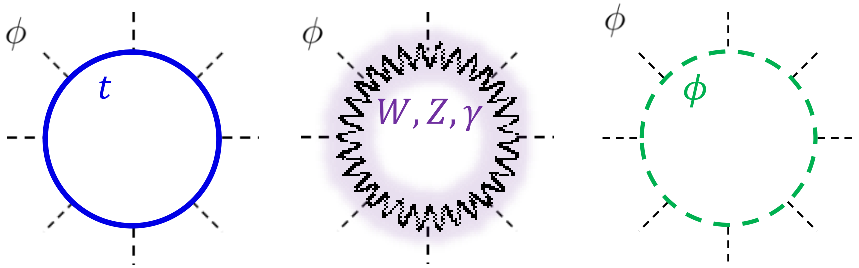
4. Summary and Conclusions

Role of top quark in the SM vacuum structure

Tree+1-loop Higgs potential

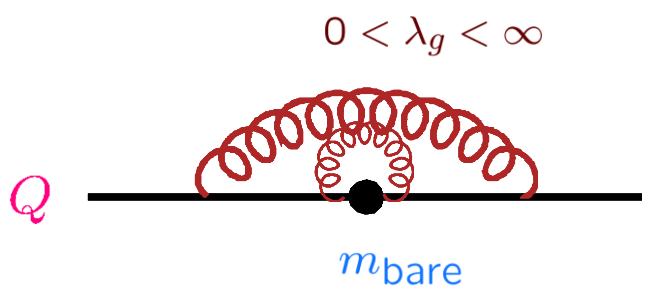


1-loop corrections



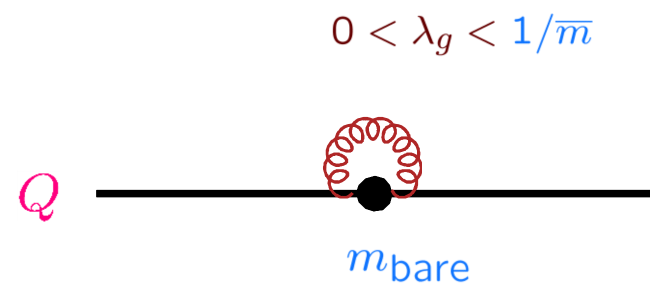
Definitions of top-quark mass in pert. QCD

Pole mass m_{pole}



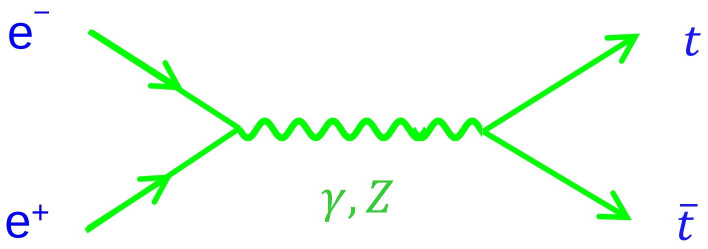
Not defined beyond pert. theory
Perturbative uncertainty
$O(\Lambda_{\text{QCD}}) \lesssim 1$ GeV

$\overline{\text{MS}}$ mass $\overline{m} \equiv m_{\overline{\text{MS}}}(m_{\overline{\text{MS}}})$

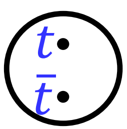


Conceptually close to
Yukawa coupling at scale $\mu \sim \overline{m}$

Top quarks in collider experiments



$t\bar{t}$ threshold at ILC

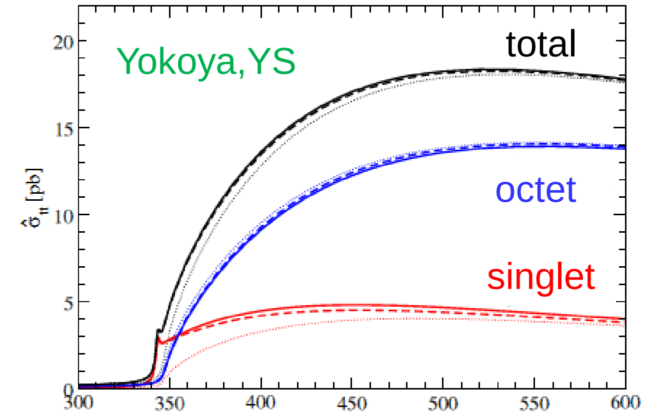


$R \sim 10^{-2} \times \Lambda_{\rm QCD}^{-1}$

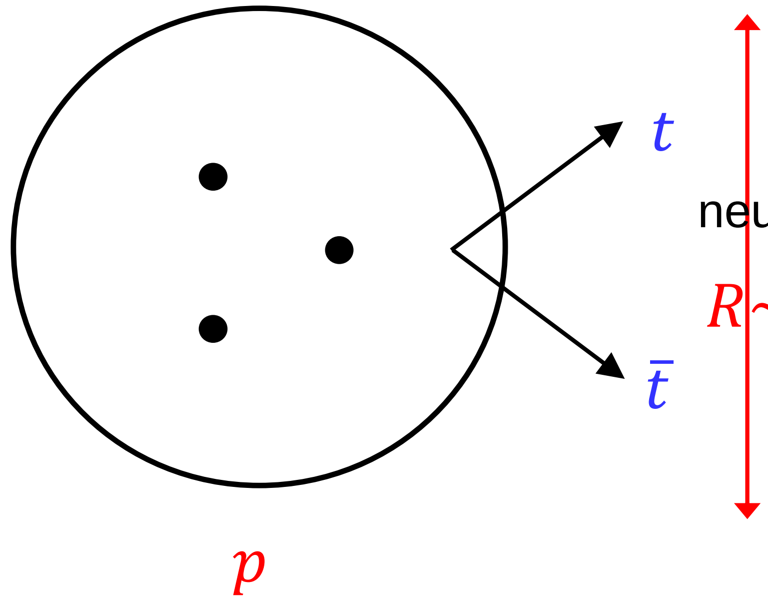
color-singlet resonance

LHC

$t\bar{t}$ prod. cross section



$t\bar{t}$ inv. mass

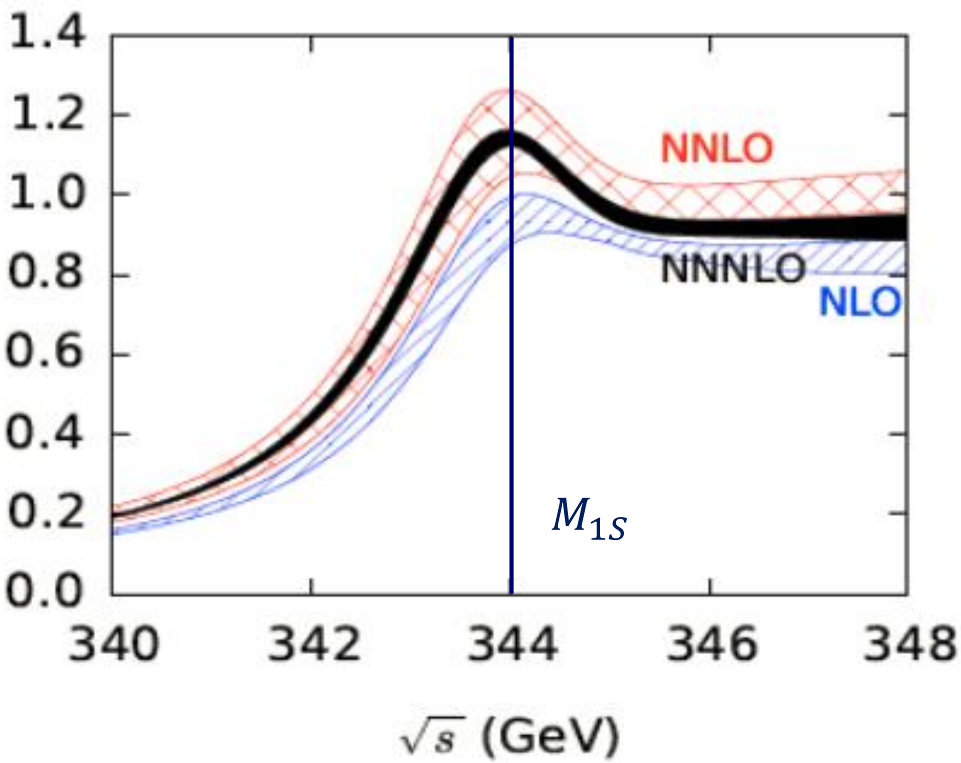


neutralize at

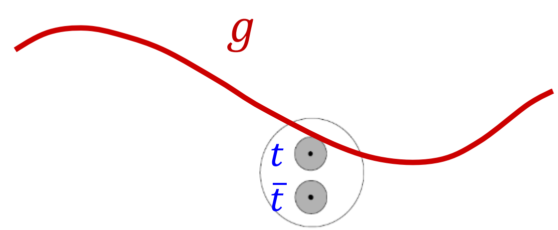
$R \sim \Lambda_{\rm QCD}^{-1}$

Precise m_t determination near $t\bar{t}$ threshold at e^+e^- collider

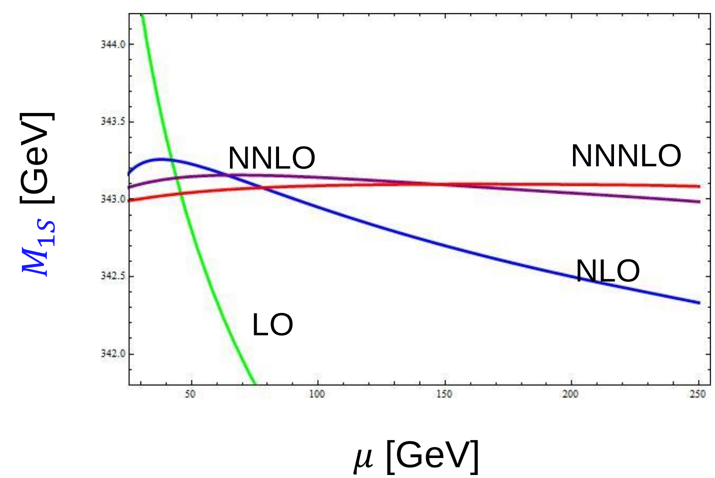
After decades of endeavor, $e^+e^- \to t\bar{t}$ cross section near threshold was computed.



Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser



color-singlet
1S resonance



Our estimate: $\Delta m_t^{\overline{\text{MS}}} = 20\text{-}30$ MeV

Kiyo, Mishima, YS

Relative acc. order 10^{-4}

Particle Data Group 2018

t $\qquad I(J^P) = 0(\tfrac{1}{2}^+)$

Charge $= \frac{2}{3}\, e$ $\qquad$ Top $= +1$

t-Quark Mass (Direct Measurements)

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
173.0 ± 0.4 OUR AVERAGE				Error includes scale factor of 1.3. See the ideogram below.
$172.95 \pm 0.77 {}^{+0.97}_{-0.93}$	[1] SIRUNYAN	17L	CMS	t-channel single top production
$172.84 \pm 0.34 \pm 0.61$	[2] AABOUD	16T	ATLS	combination of ATLAS
$172.44 \pm 0.13 \pm 0.47$	[3] KHACHATRY...	16AK	CMS	combination of CMS
$174.30 \pm 0.35 \pm 0.54$	[4] TEVEWWG	16	TEVA	Tevatron combination
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$173.72 \pm 0.55 \pm 1.01$	[5] AABOUD	17AH	ATLS	≥ 5 jets ($2b$)
$174.95 \pm 0.40 \pm 0.64$	[6] ABAZOV	17B	D0	$\ell +$ jets and dilepton channels
170.8 ± 9.0	[7] SIRUNYAN	17N	CMS	jet mass in highly-boosted $t\bar{t}$

t-Quark Mass from Cross-Section Measurements

The top quark $\overline{\rm MS}$ or pole mass can be extracted from a measurement of $\sigma(t\bar{t})$ by using theory calculations. We quote below the $\overline{\rm MS}$ mass. See the review "The Top Quark" and references therein for more information.

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t-Quark Pole Mass from Cross-Section Measurements

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
173.1±0.9 OUR AVERAGE				
$173.2 \pm 0.9 \pm 0.8 \pm 1.2$	[1] AABOUD	17BC	ATLS	$e + \mu + \geq 1b$ jets
170.6 ± 2.7	[2] SIRUNYAN	17W	CMS	$\ell + \geq 1$j
$172.8 \pm 1.1 {}^{+3.3}_{-3.1}$	[3] ABAZOV	16F	D0	$\ell\ell$, ℓ+jets channels
$173.8^{+1.7}_{-1.8}$	[4] KHACHATRY...	16AW	CMS	$e + \mu + \not{E}_T + \geq 0$j
$173.7^{+2.3}_{-2.1}$	[5] AAD	15BW	ATLS	$\ell + \not{E}_T + \geq 5$j ($2b$-tag)
$172.9^{+2.5}_{-2.6}$	[6] AAD	14AY	ATLS	pp at $\sqrt{s} = 7$, 8 TeV

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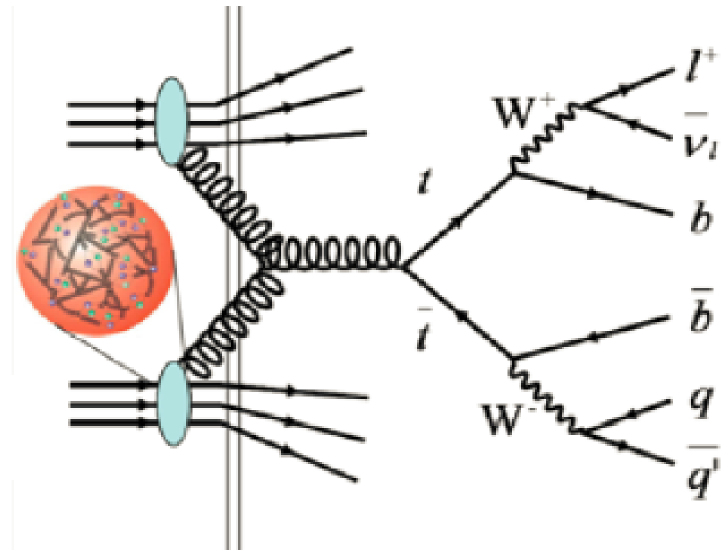

- PDF
- hadronization

All masses measured in hadron collider exp.

Particle Data Group 2018

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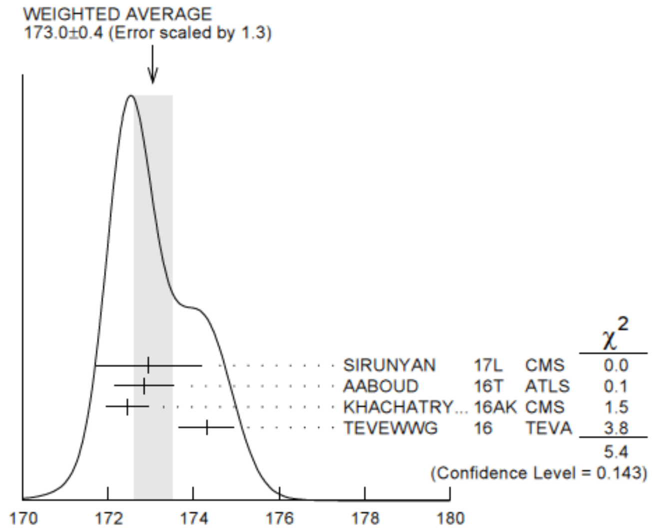

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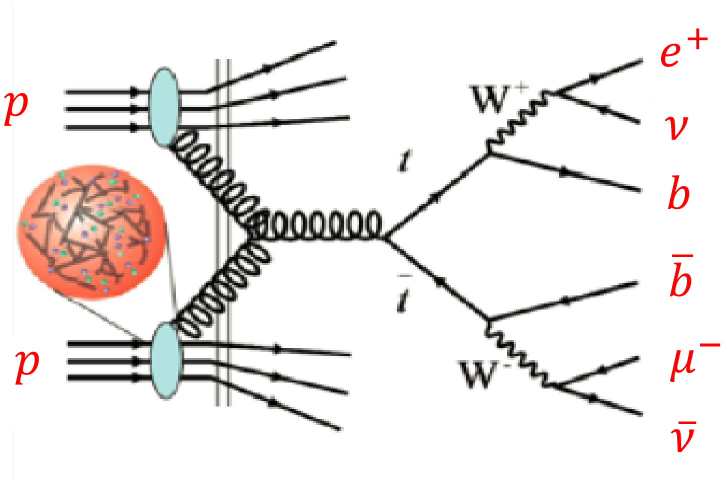
m_t^{pole} determination at LHC using lepton distributions in dilepton channel



$\sqrt{s}$ = 8 TeV

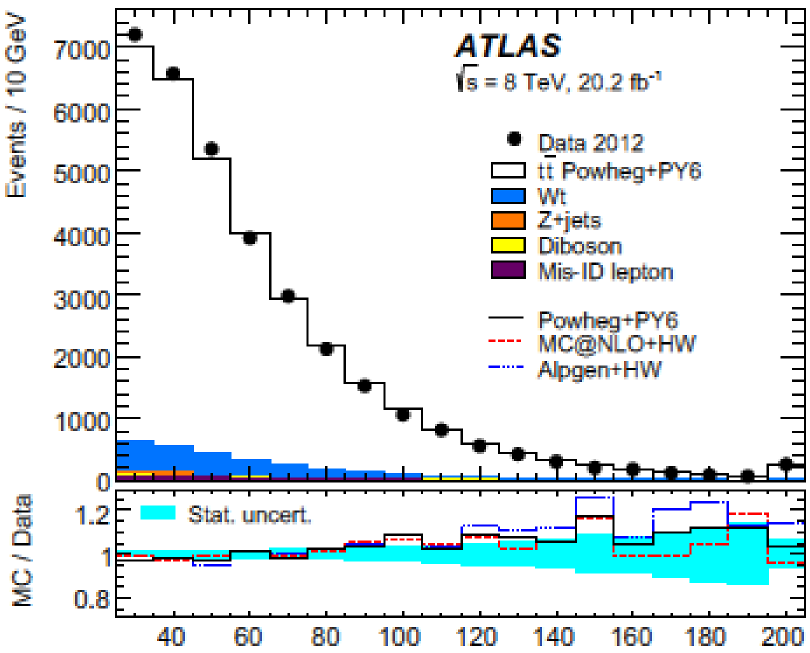
m_t^{pole} = 173.2$\pm 0.9 \pm 0.8 \pm 1.2$ GeV

= 173.2$\pm$1.6 GeV

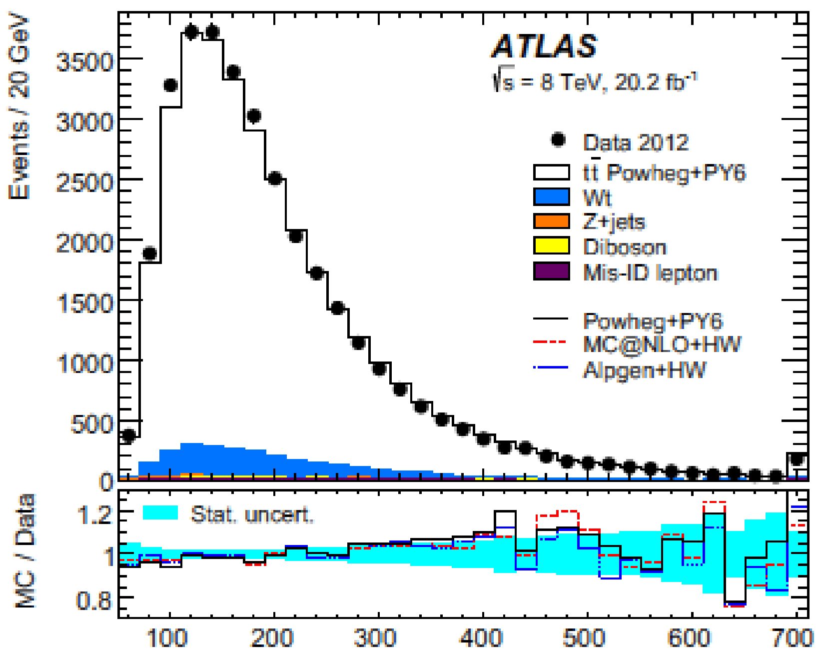
The pole mass is extracted from a fit of NLO predictions to 8 lepton differential distributions in dileptonic $t\bar{t}$ events, while simultaneously constraining uncertainties due to PDFs and QCD scales.

Largely indep. of jet profiles
(e.g. Missing p_T cut is not used)

Leptonic observables vs. MC predictions



Muon p_T [GeV]



Dilepton $E^e + E^\mu$ [GeV]

MC input $m_t = 172.5$ GeV

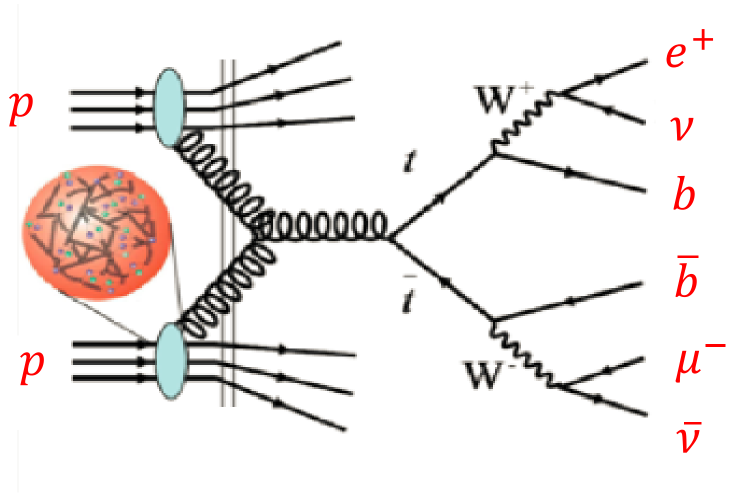
Pert. QCD prediction for $t\bar{t}$ cross sections at LHC

NNLO+NNLL predictions

Czakon, Heymes, Mitov (prod)

Gao, Papanastasiou (prod+decay)

More to come soon.



How to ideally compare with pert. QCD**?**

Model dependences should be largely eliminated.

hadronization, PDF

- Hadronic inclusive obs. $\sum |had.\rangle\langle had.| = \sum |q,g\rangle\langle q,g| = \mathbf{1}$

  (More accurately, OPE formulation desirable.) ⇨ Leptonic obs.

- Uncertainty due to PDF can be eliminated (in principle).

  ⇨ Weight fn. method Kawabata, Shimizu, YS, Yokoya

- Roles of MC simulation needs to be reconsidered.

OPE formulation (idea)

$$\frac{1}{\sigma}\frac{d\sigma(pp\to t\bar{t}\to l\nu X)}{d\Phi(l)} = \frac{1}{\sigma}\int d\Phi(had)\,\langle pp|l\nu X\rangle\langle l\nu X|pp\rangle$$

$$= \frac{1}{\sigma}\int d\Phi(had)\,H^{\mu\nu}L_{\mu\nu}$$

$\int d\Phi(had)\ H^{\mu\nu}(pp\to X) =$ Identify OPE in terms of EFT by integr.-by-region method

Similar to DIS in ep collision

- Precise treatment of IR contributions
- Simplification by EFT and inclusive calc.

Summary and Conclusions

- Accurate view on current status of top mass determination is important.
  def./assumptions w.r.t. pert. QCD
- $\overline{\mathrm{MS}}$ mass determination at $e^+e^- \to t\bar{t}$ near threshold is ideal. $O(10^{-4})$ acc.
- At LHC Δm_t much below 1 GeV is currently challenging.
  Color charge distribution around octet $t\bar{t}$ introduces unsuppressed/uncontrolled IR physics.
- For determination of well-defined top mass at LHC, use of leptonic obs. combined with NNLO prediction analysis is optimal.
  PDF indep. property can be exploited in addition. (Weight fn. method)
  OPE is desirable to control IR contributions precisely.
  ⇨ Model indep. analysis

Kawabata, Shimizu, YS, Yokoya

Slides from S. Kawabata's talks
TopWG@CERN2014,TopWS2015

Weight functions and the weighted integrals

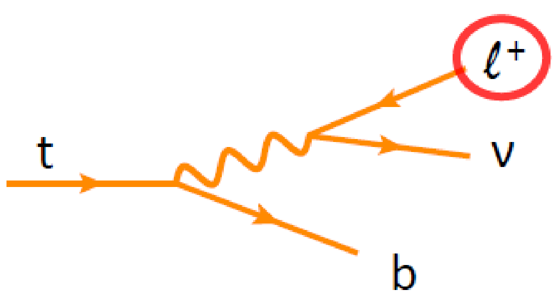
Weight function

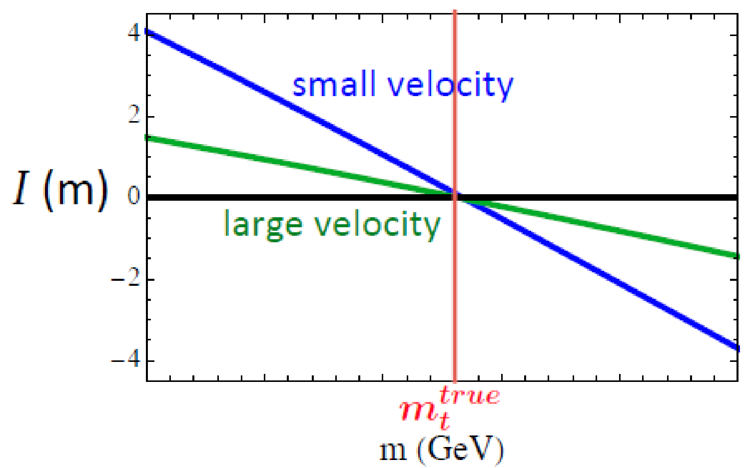
$$I(m) \equiv \int dE_l \, D(E_l) \, W(E_l, m)$$

Lepton energy distribution in the lab. frame

There exist an infinite number of weight functions which satisfy

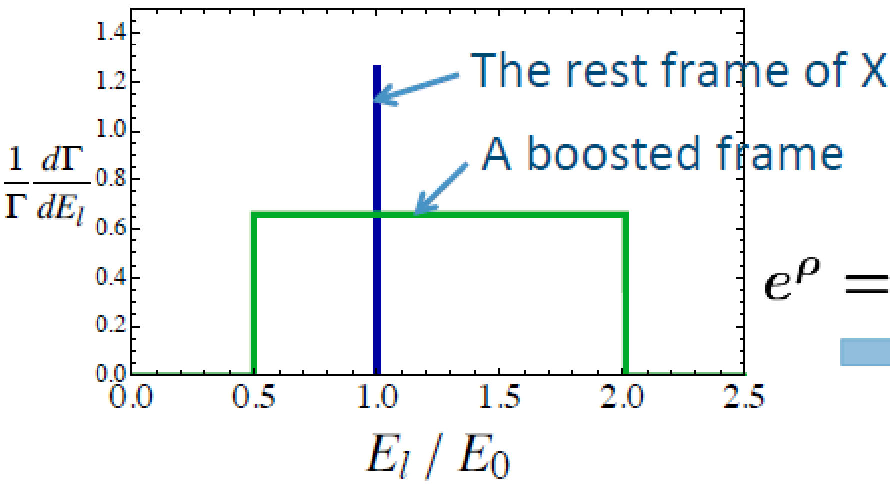
$I(m = m_t^{true}) = 0$ for an arbitrary velocity distribution of top quarks





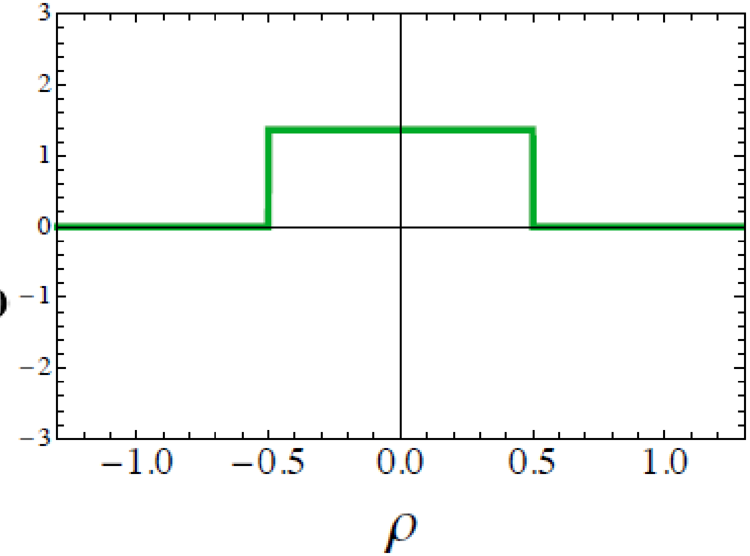
Construction of weight functions

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



Lepton energy distribution

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



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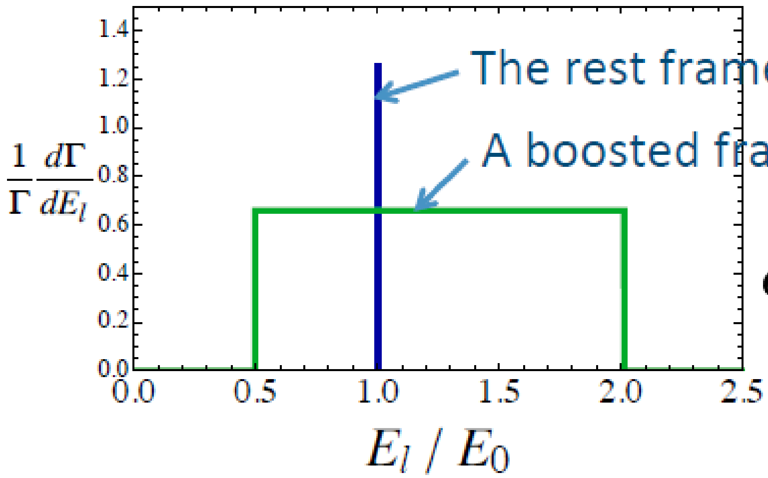

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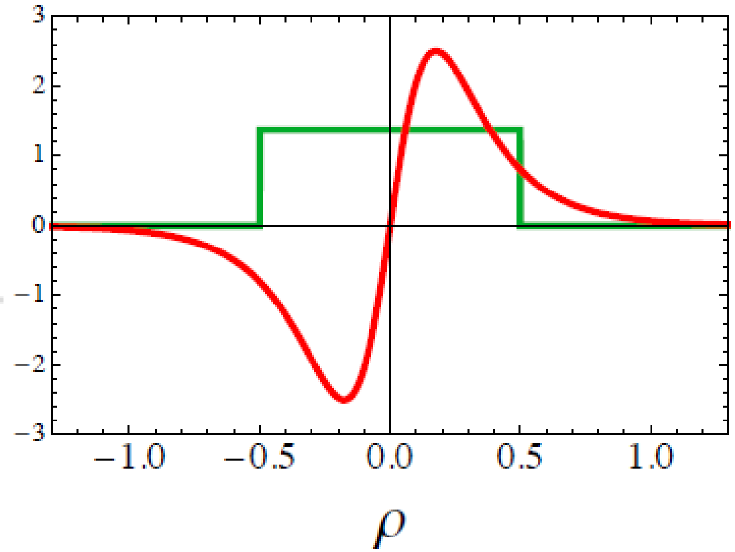


$$\int dE_l\, D(E_l)\, W(E_l, m_X^{true}) \;=\; 0 \;\Longleftrightarrow\; \int d\rho (\text{even func. of } \rho)(\text{odd func. of } \rho) = 0$$

$$d\rho \propto e^{-\rho} dE_l$$

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

Possible OPE formulation (idea)

$$\frac{d\sigma(pp \to t\bar{t} \to l\nu X)}{d\Phi(l)} = \int d\Phi(had)\,\langle pp|l\nu X\rangle\langle l\nu X|pp\rangle$$

$$= \int d\Phi(had)\ H^{\mu\nu}\,L_{\mu\nu}$$

$\int d\Phi(had)\ H^{\mu\nu}(pp \to X) =$ Identify OPE in terms of EFT by integr.-by-region method

similar to DIS in ep collision

☆Plan of Talk

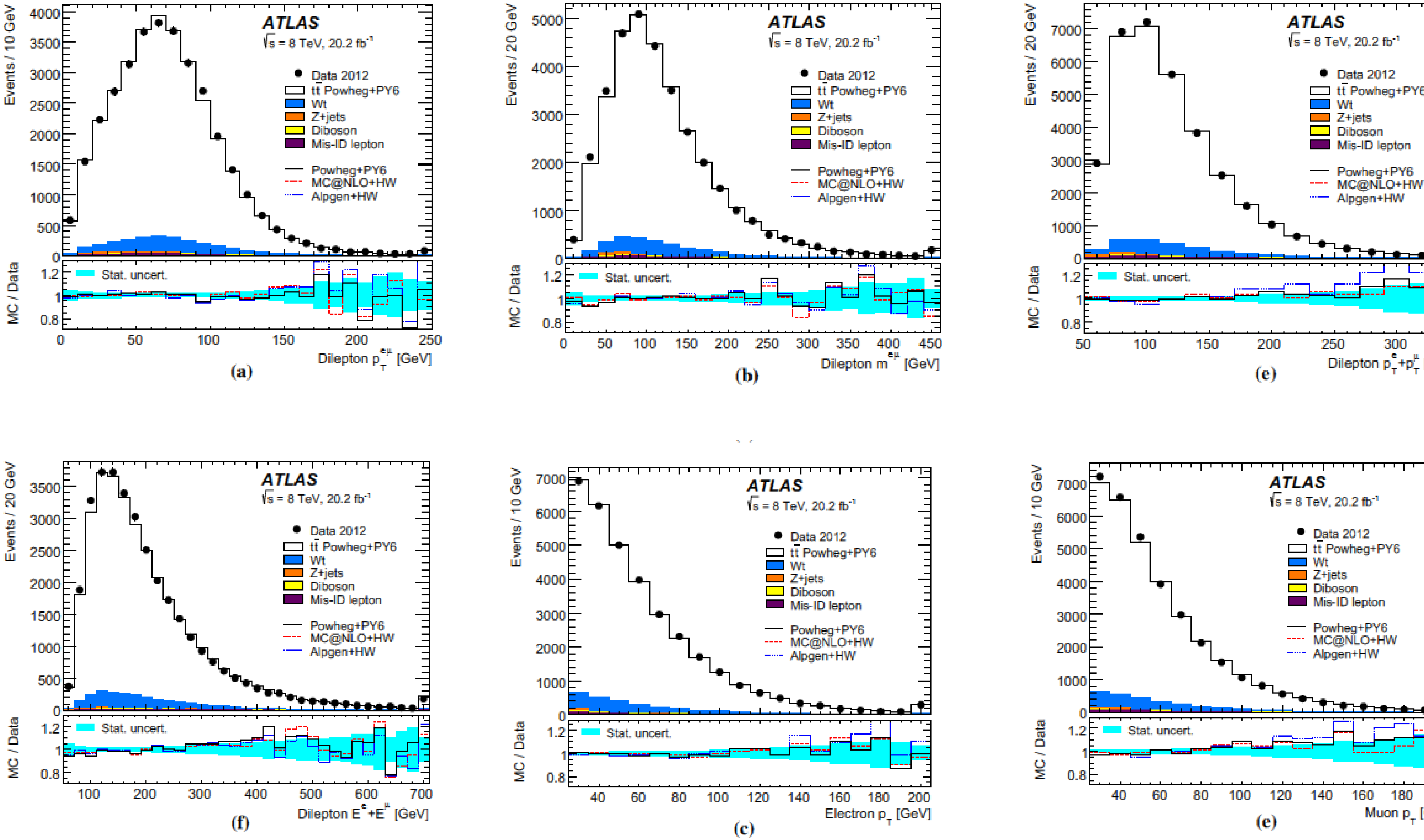
1. Introduction

2. Top mass determination at ILC

3. Top mass determination at LHC: Use of leptonic observables

(4. A future direction for precision QCD)

5. Summary and Conclusions



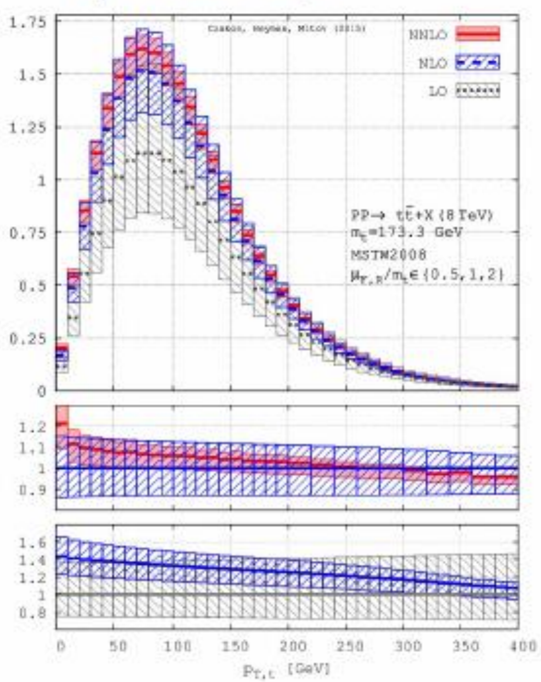
MC input $m_t = 172.5$ GeV

Pert. QCD prediction for $t\bar{t}$ cross sections at LHC

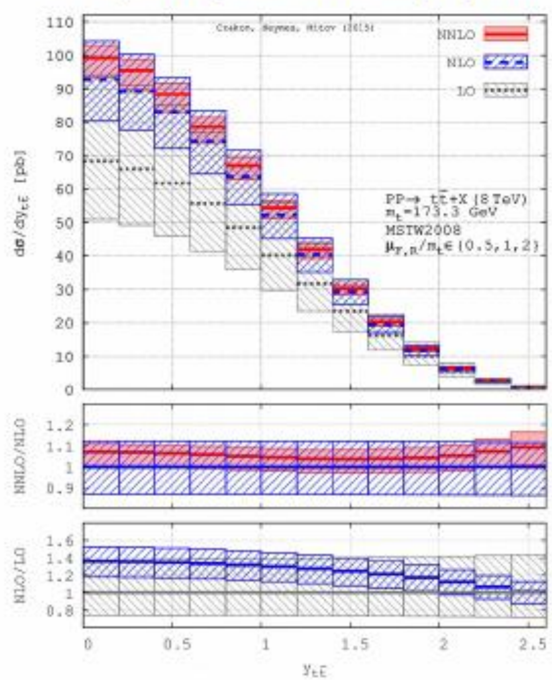
NNLO predictions

Czakon, Heymes, Mitov

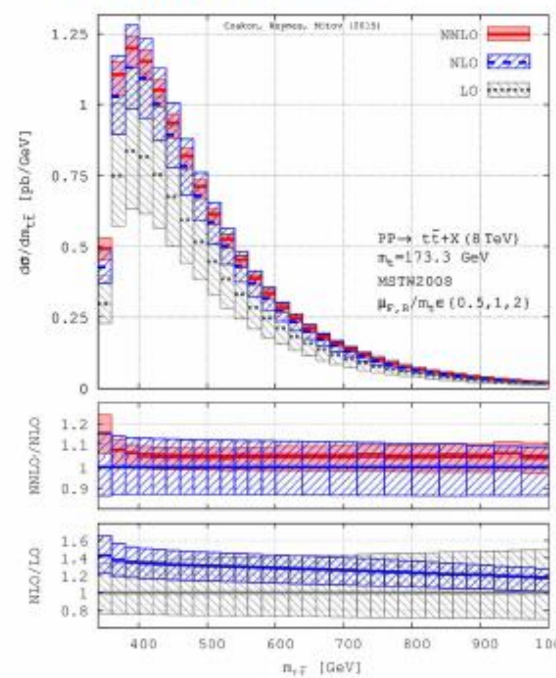
P_T ot the top



Rapidity of the top-pair



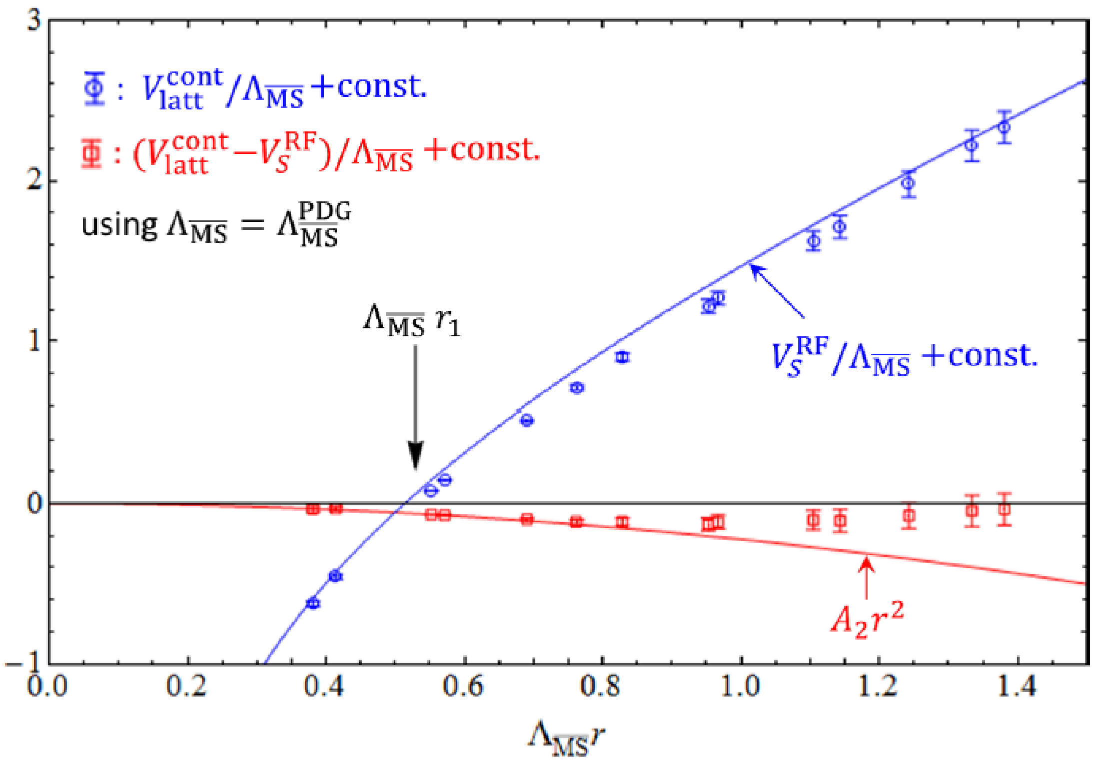
Invariant mass



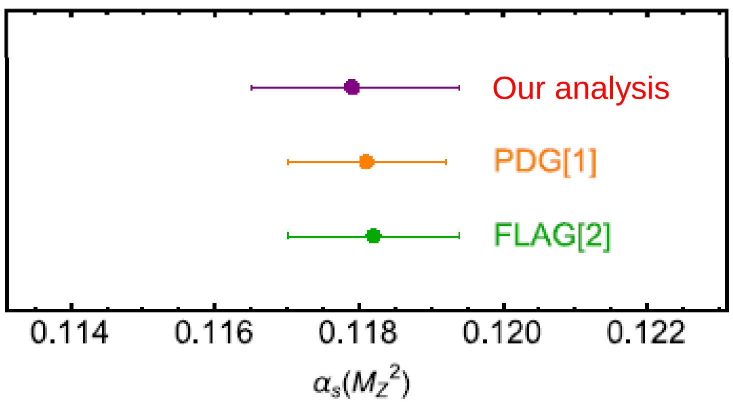
e Direction for Precision QCD: OPE with renormalon subtraction

Consistency check

Takaura, Kaneko, Kiyo, YS



$\alpha_s(M_Z)$ determination



$\boldsymbol{V_{\rm QCD}(r)}$ [JLQCD: $n_f = 3,\ \{64^3{\times}128,\ 48^3{\times}96,\ 32^3{\times}64\}$] consistent with OPE at $r\Lambda_{\overline{\rm MS}} \lesssim 0.8$ after renormalon subtraction.

First time to confirm the OPE structure

$$\boldsymbol{V_{\rm QCD}(r) = V_S^{RF}(r) + \delta E_{US}^{RF}(r)}$$

NNNLL fit fn: $A_0 + A_2 r^2$

Summary and Conclusions

- Need to understand current status of top mass determinations

  def./assumptions

- $\overline{\mathrm{MS}}$ mass determination at $e^+e^- \to t\bar{t}$ near threshold would be ideal.

- At LHC Δm_t much below 1 GeV would be difficult to achieve.

  Color charge distribution around octet $t\bar{t}$ would introduce unsuppressed/uncontrolled IR physics.

- For measurement of well-defined top mass at LHC, use of leptonic observables combined with NNLO prediction + model indep. analysis is ideal.

- Steps taken towards high precision QCD (results in foreseeable future)