Precise top mass determination using lepton distribution at LHC

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Phys. Lett. B 741 (2015) 232-238

Problem in m_t measurements

Tevatron+LHC m_t combination arXiv:1403.4427

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

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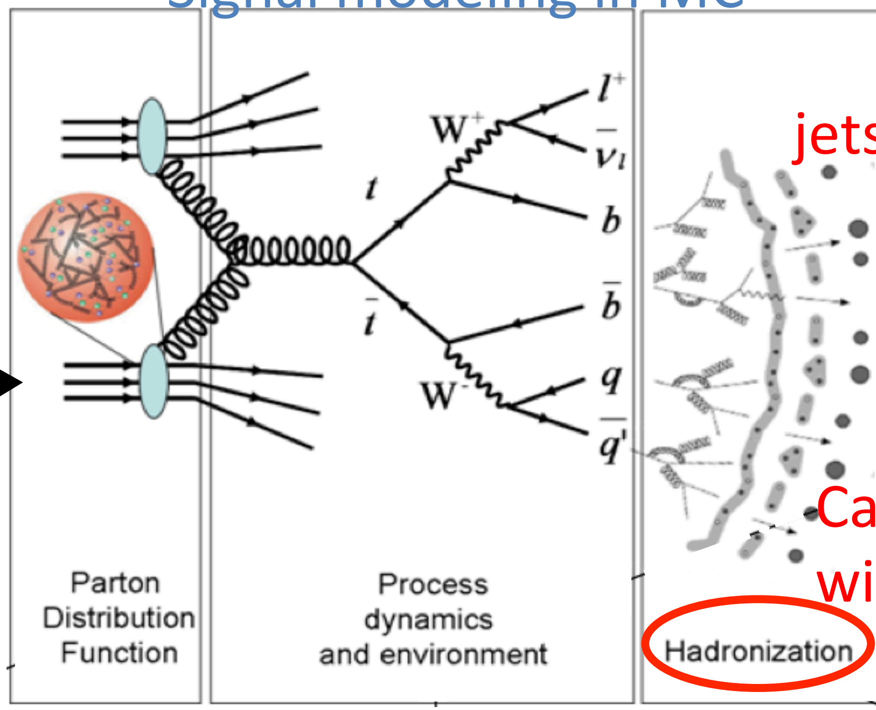
What kind of mass? $\neq m_t^{pole}, m_t^{\overline{MS}}$

Signal modeling in MC

Experiment

m_t measurement

Theory (MC)



jets

Cannot be treated within pert. QCD

Aim of this study

Determine a theoretically well-defined m_t
accurately at the LHC

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

We propose a new method
which uses lepton energy distribution

"Weight function method"

By a simulation analysis,
we show that this method works well.

Weight function method

SK, Y.Shimizu, Y.Sumino, H.Yokoya, PLB 710, 658 (2012)
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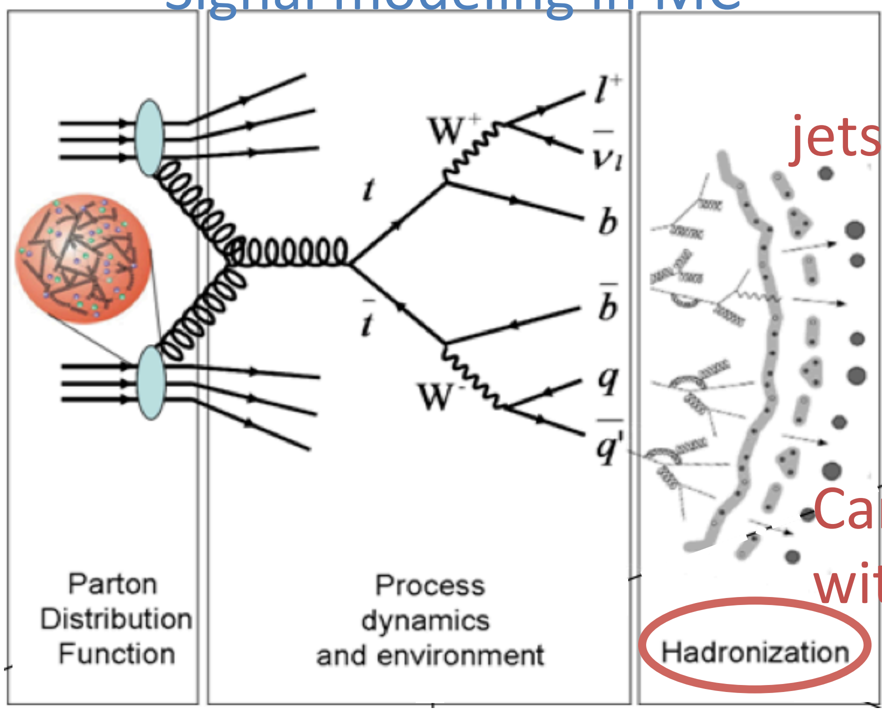
New method for parent particle's mass reconstruction

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

Signal modeling in MC



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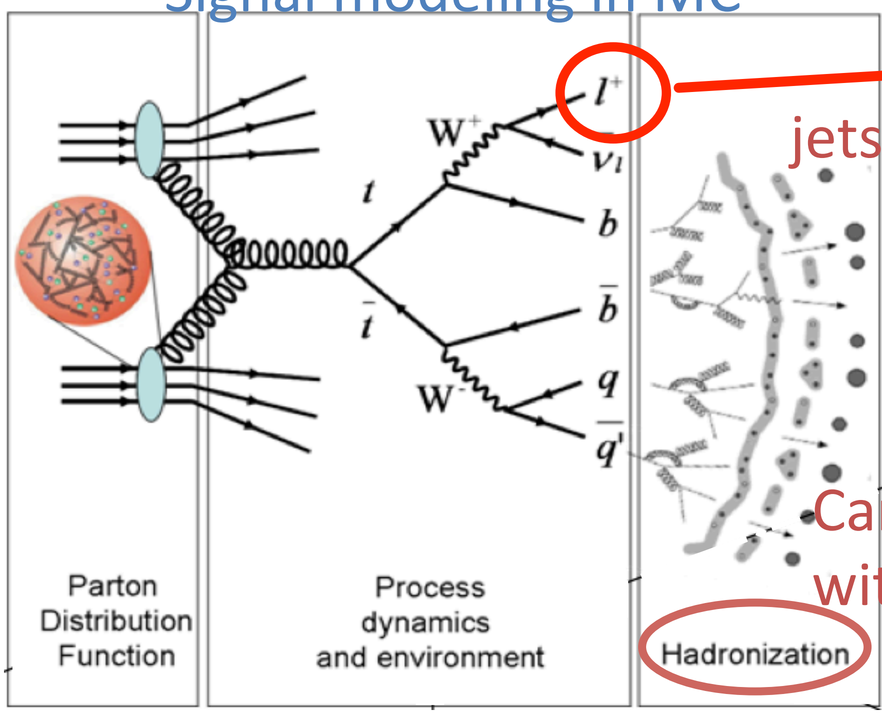


Free from ambiguity of hadronization model

We can determine a theoretically well-defined m_t

Cannot be treated within pert. QCD

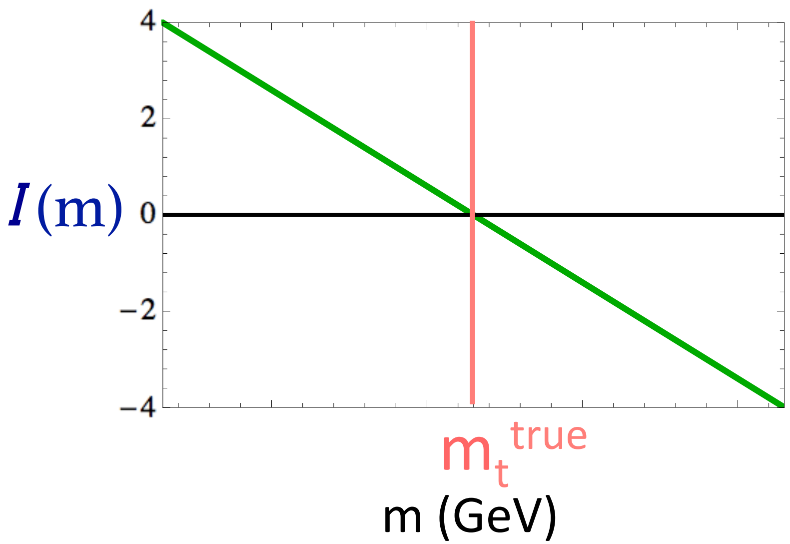
Weight function method

1. Compute a weight function W(E_ℓ,m)

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

Lepton energy dist. in the rest frame of top quark (with mass m), which can be calculated in pert. QCD

2. Use lepton energy distribution measured by experiment as D(E_ℓ)



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

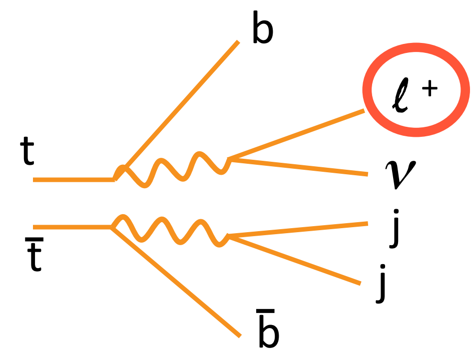
3. Obtain the zero of I(m) as m_t^{true}

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

Simulation analysis

m_t measurement with weight function method at LHC

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



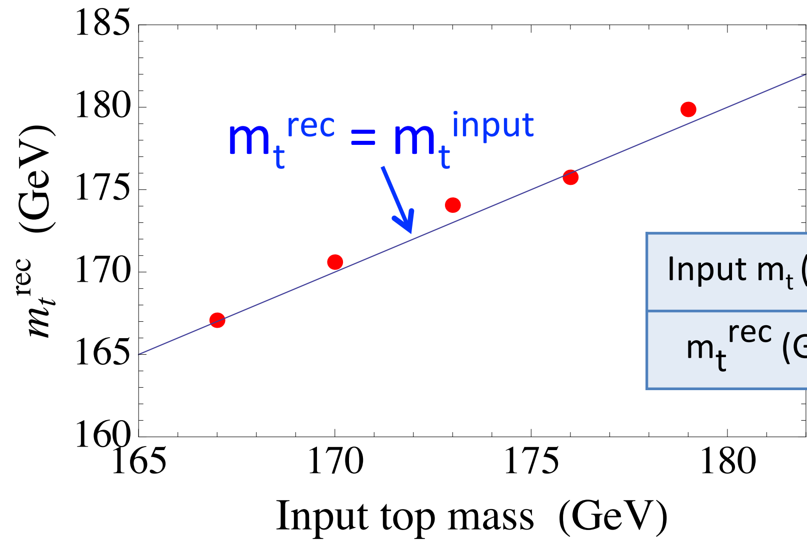
Background

Other $t\bar{t}$ events, W+jets, $Wb\bar{b}$+jets, Single top

Event selection cuts

- 1 muon with p_T > 20GeV, $|\eta|$ < 2.4
- At least 4 jets
- At least 1 b-tag
- $p_T(j_1) > 55$, $p_T(j_2) > 25$, $p_T(j_3) > 15$, $p_T(j_4) > 8$ GeV

Sensitivity of m_t determination (LO)



Input m_t (GeV)	167	170	173	176	179
m_t^{rec} (GeV)	167.1	170.6	174.1	175.7	179.9

Uncertainties [GeV]

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 (Signal stat. error)

← Can be improved by including NLO (μ_F scale)

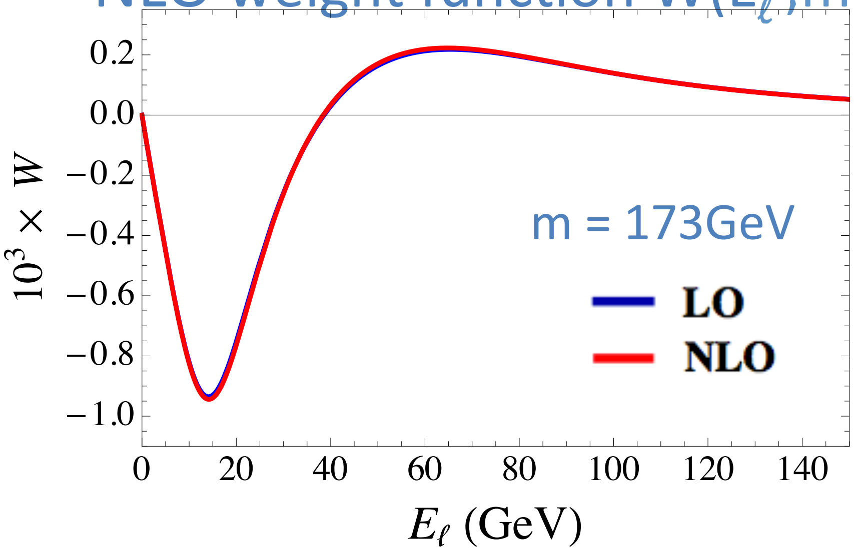
We aim for $\Delta m_t^{pole} < 1$ GeV

NLO analysis (on-shell scheme)

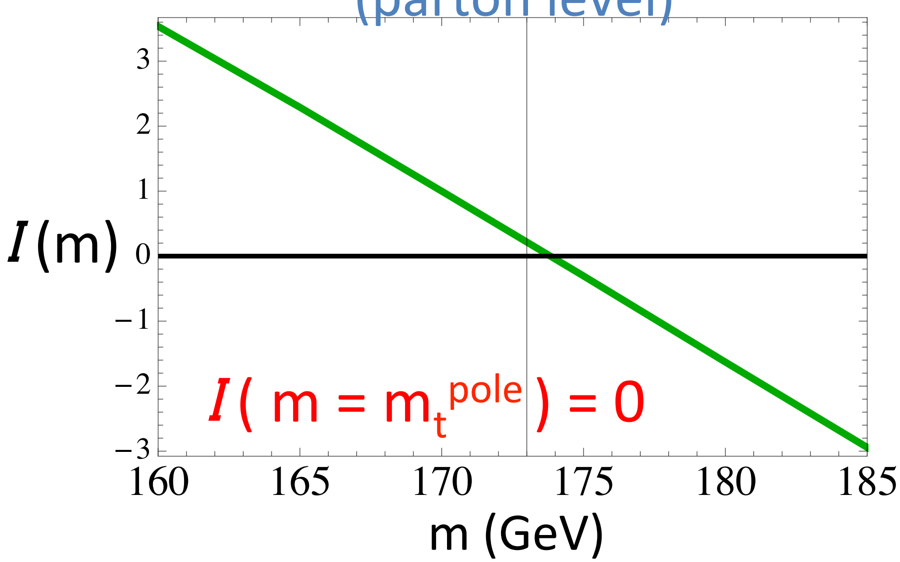
Required NLO correction

- involving only top production ➡ MC simulator
- involving only top decay ➡ MC + weight fn.
- involving both production and decay ➡ Correction

NLO weight function $W(E_\ell, m)$



Preliminary simulation analysis
(parton level)



Summary and future works

- We proposed a new method to measure m_t using lepton energy distribution at LHC.
- Results of simulation analysis at LO show that $\Delta m_t^{pole} < 1\text{GeV}$ is probable with this method.

Ongoing & future works

★ NLO, NNLO ⇨ $\Delta m_t^{pole} < 1\text{GeV}$, $m_t^{\overline{MS}}$

★ Effects of top off-shellness

Backup

Measurements of m_t^{pole} and $m_t^{\overline{MS}}$

From $t\bar{t}$ cross section

- $m_t^{pole} = 172.9\ ^{+2.5}_{-2.6}$ GeV

  ATLAS, Eur.Phys.J. C74, 3109 (2014)

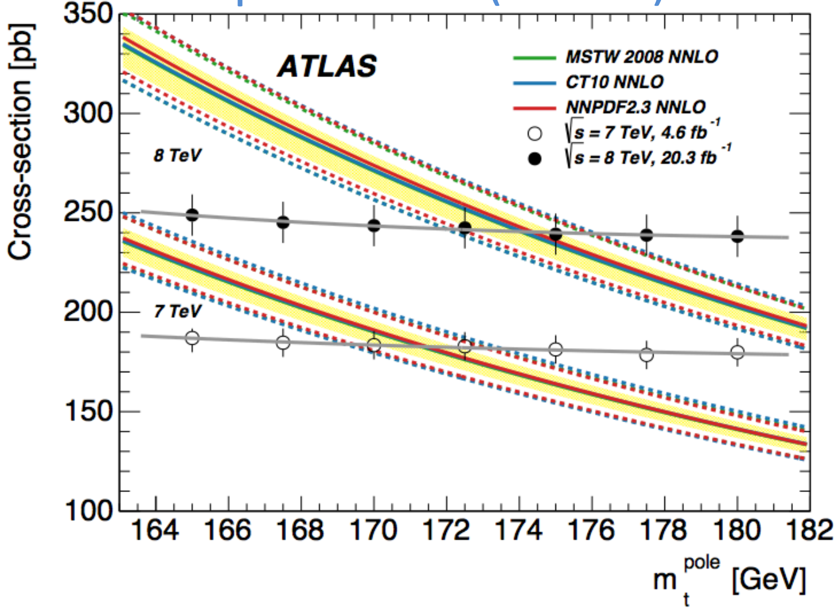
- $m_t^{pole} = 176.7\ ^{+3.0}_{-2.8}$ GeV

  CMS, PLB 728, 496 (2014)

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

  D0, PLB 703, 422 (2011)

pole mass (ATLAS)

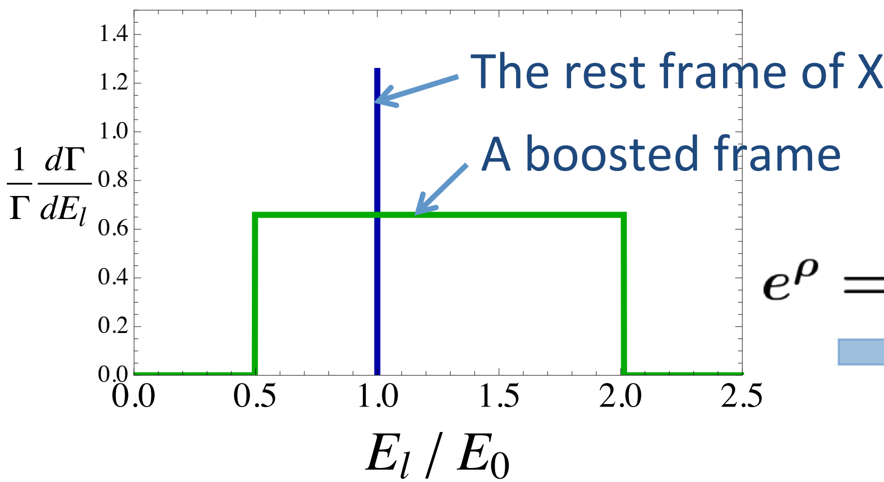


Using $t\bar{t}$+1-jet events

- $m_t^{pole} = 173.7\ ^{+2.3}_{-2.1}$ GeV ATLAS, CERN-PH-EP-2015-100

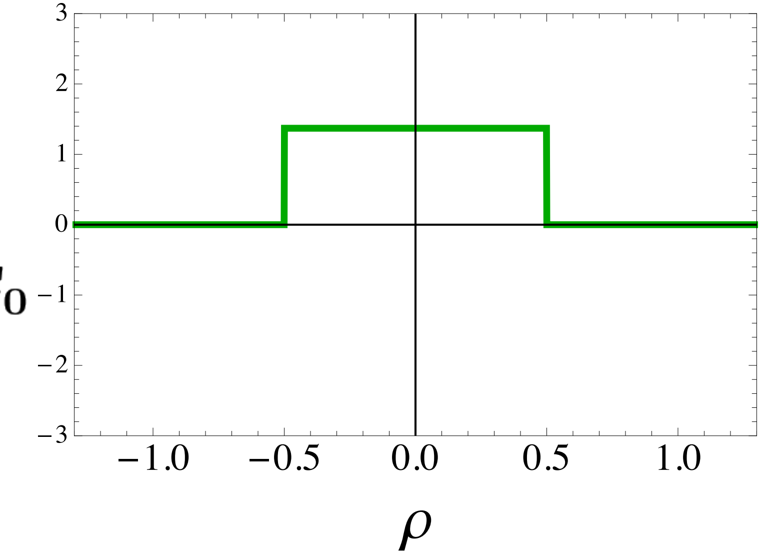
Construction of weight functions

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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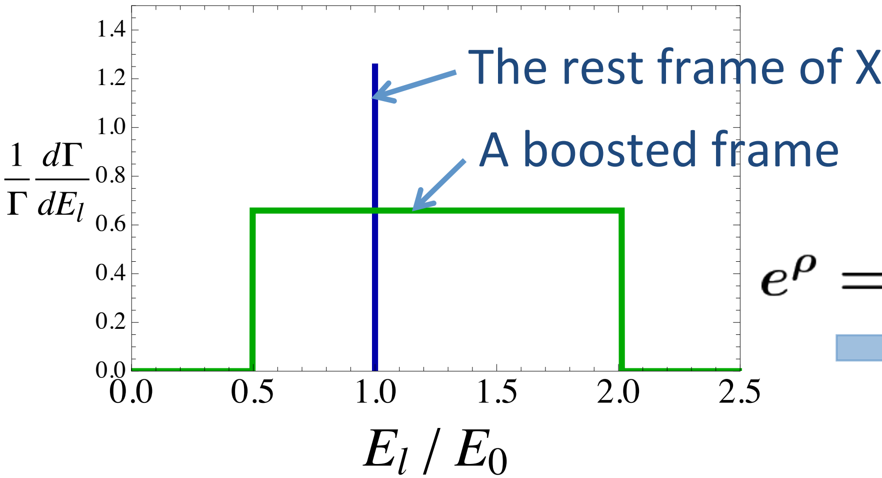

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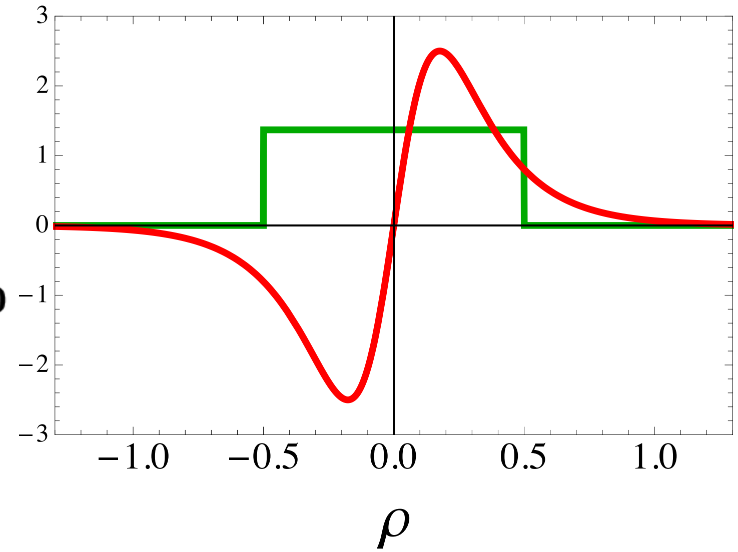


$$\int dE_l\, D(E_l)\, W(E_l, m_X^{true}) = 0 \Longleftrightarrow \int d\rho(\text{even func. of } \rho)(\text{odd func. of } \rho) = 0$$

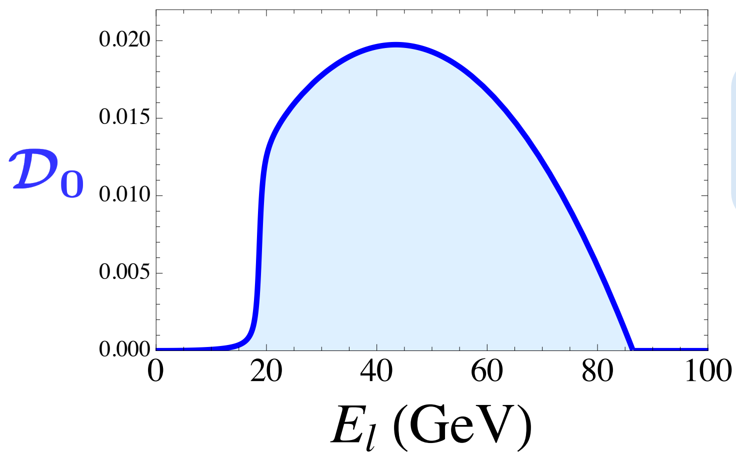
$$d\rho \propto e^{-\rho} dE_l$$

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

Construction of weight functions

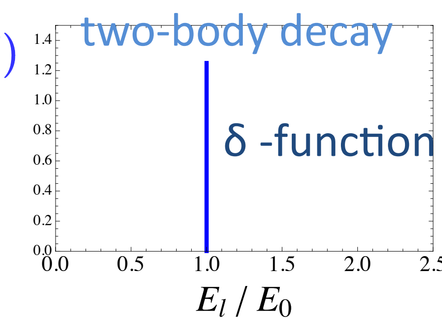
For a many-body decay : X $\longrightarrow \ell$ + anything (X is scalar or unpolarized)

Lepton energy distribution in the rest frame of X



Can be expressed as a superposition of lepton distribution for a two-body decay

$$\mathcal{D}_0(E_l) = \int dE\, \mathcal{D}_0(E)\, \delta(E_l - E)$$



A weight function would be also a superposition of that for a two-body decay

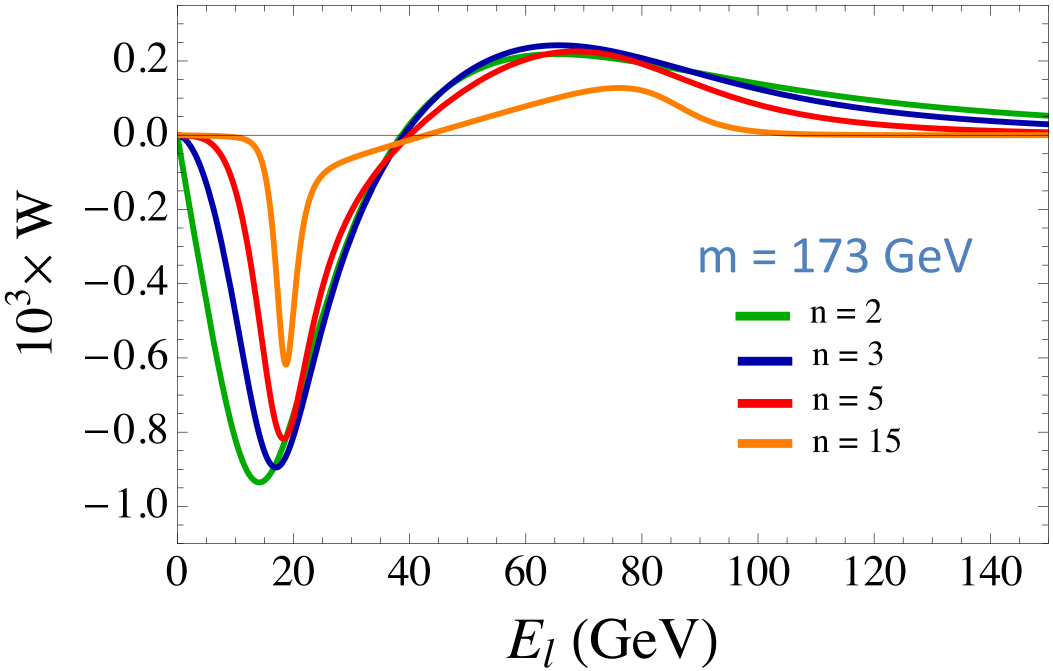
$$W(E_l, m) = \int dE\, \mathcal{D}_0(E\,; m) \frac{1}{E E_l} (\text{odd func. of } \rho) \Big|_{e^\rho = E_l/E}$$

Weight functions

For a top quark decay : t → Wb → ℓ νb

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

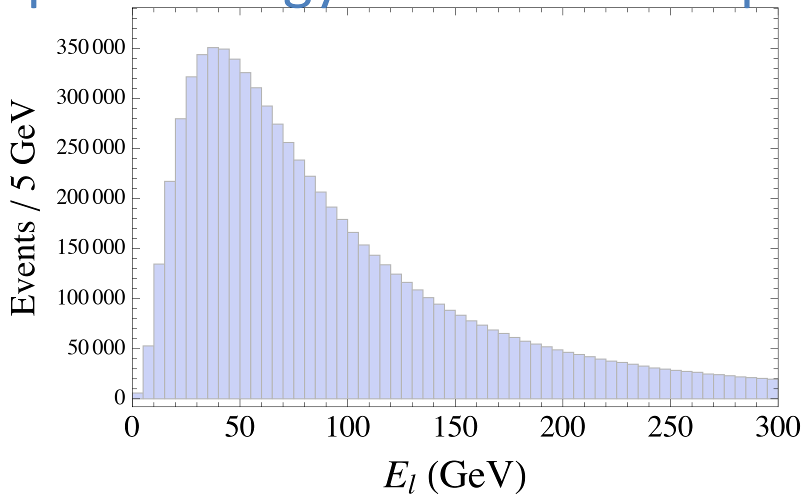
$$(\text{odd func. of } \rho) = \frac{n \tanh(n\rho)}{\cosh(n\rho)}$$



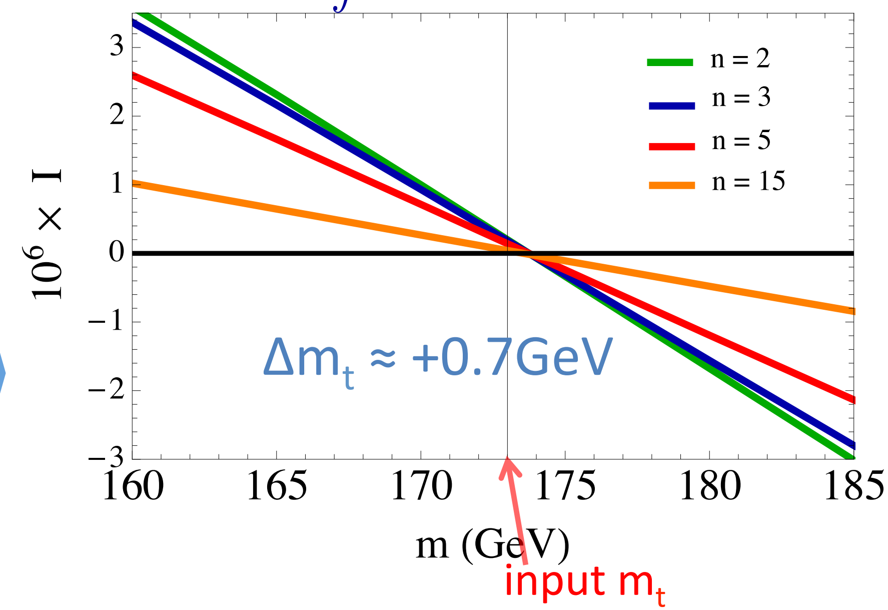
$$W(E_l, m) = \int dE\, \mathcal{D}_0(E; m) \frac{2n E_l^{n-1} E^{n-1} (E_l^{2n} - E^{2n})}{(E_l^{2n} + E^{2n})^2}$$

Parton level analysis (LO)

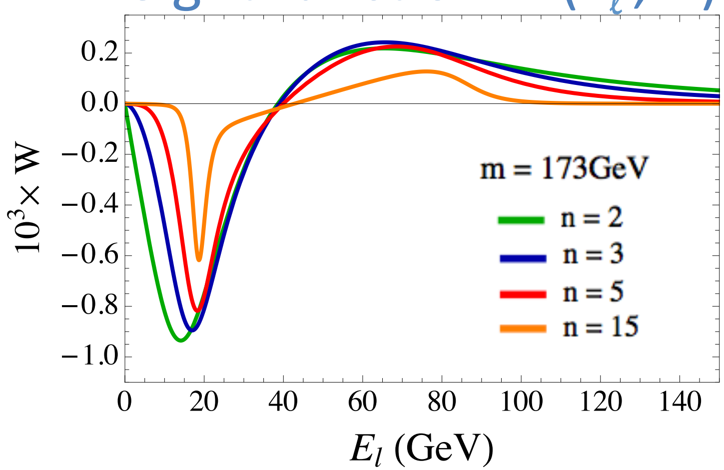
Lepton energy distribution at parton level (signal)



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



Weight function $W(E_\ell, m)$



- Effect of Γ_t : +0.34GeV
- MC stat. error : 0.4GeV

➡ Consistent with expectation

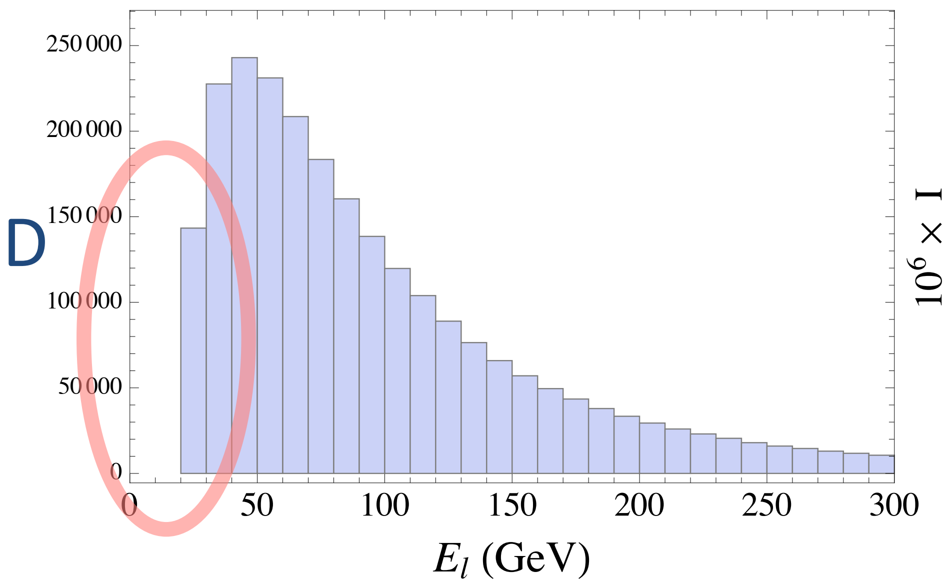
In principle, our method works

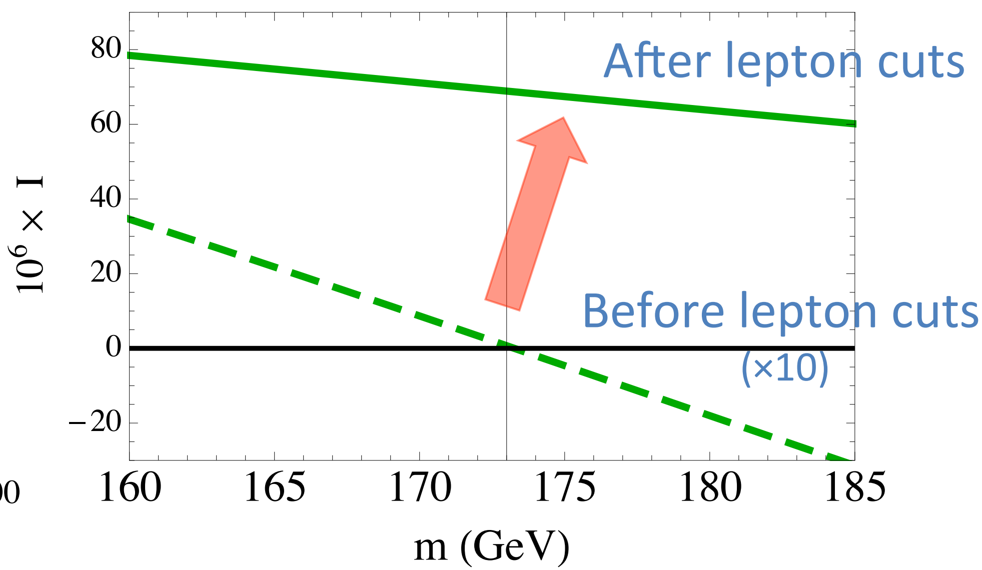
Effect of lepton cuts

The event selection cuts and backgrounds deform the lepton distribution.

The major effect is from the lepton cuts :

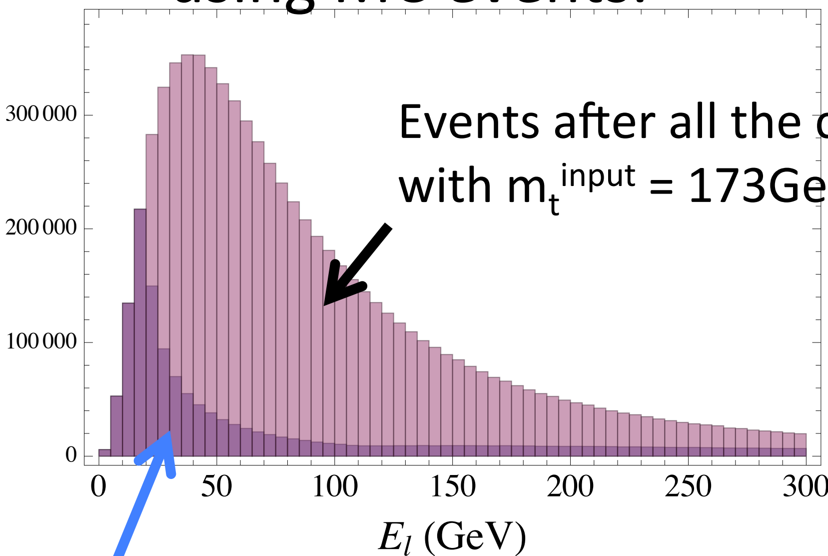
$$p_T(\ell) > 20 \text{ GeV}, \ |\eta(\ell)| < 2.4$$



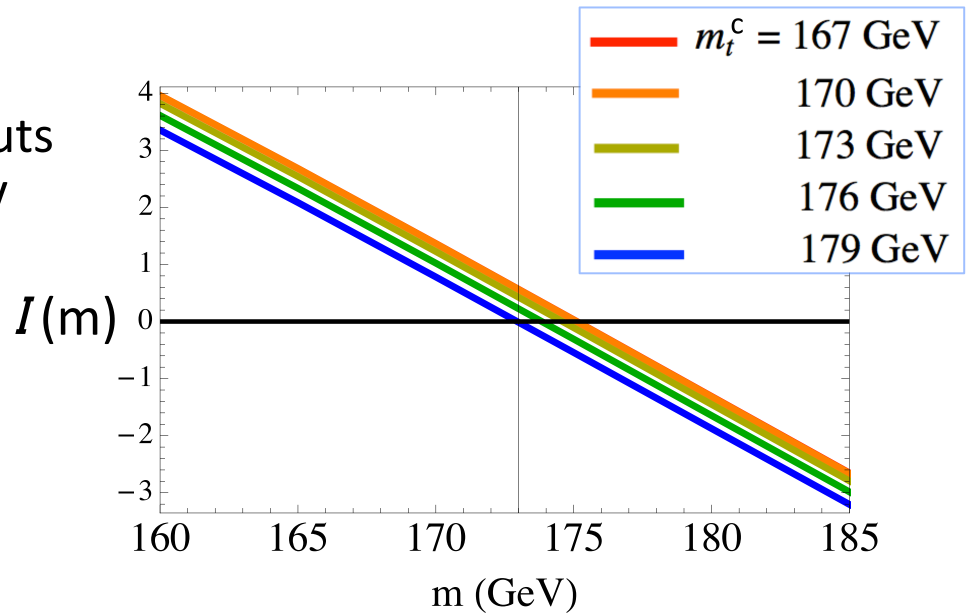


Solution to the problem of lepton cuts

We compensate for the loss caused by lepton cuts using MC events.



Compensated MC events with m_t^c



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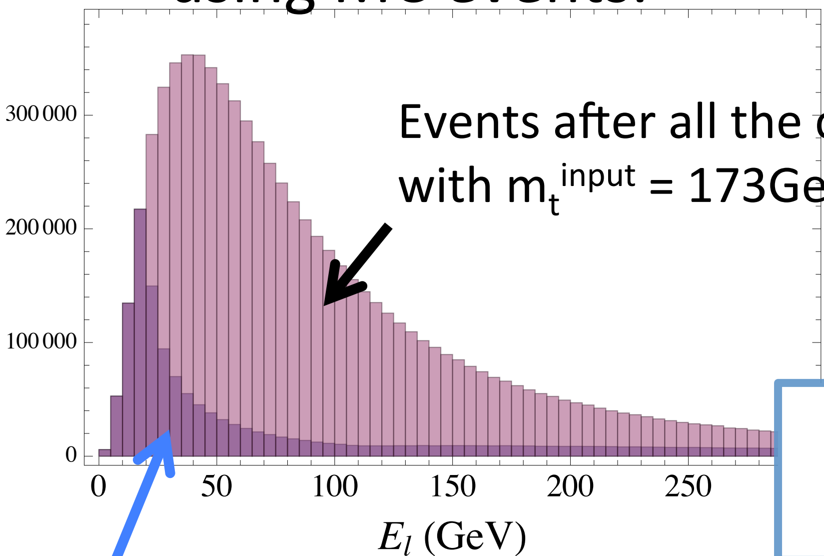

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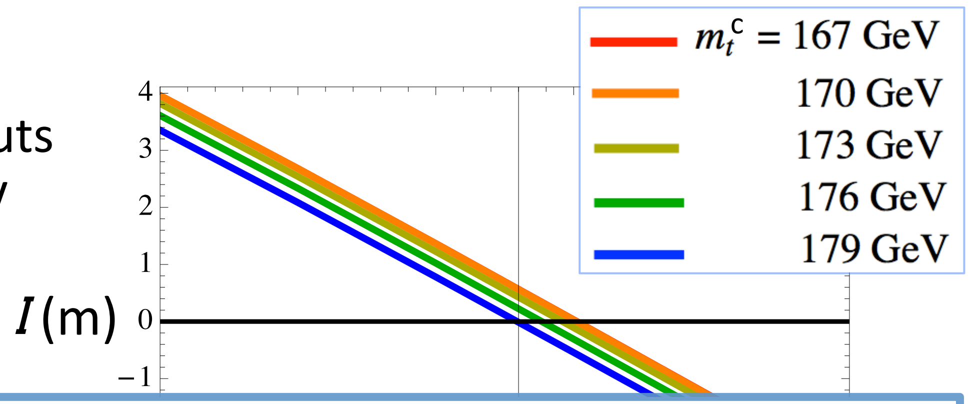
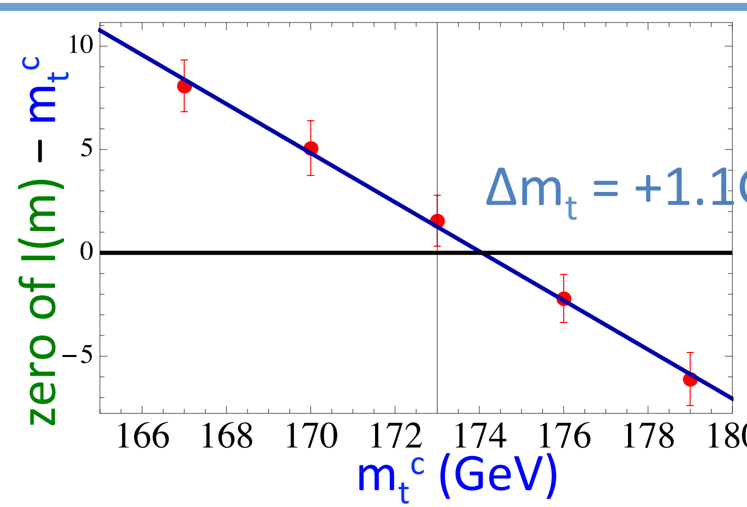


Effect of Γ_t : +0.34GeV
MC stat. error : ~1GeV ⇒ Consistent

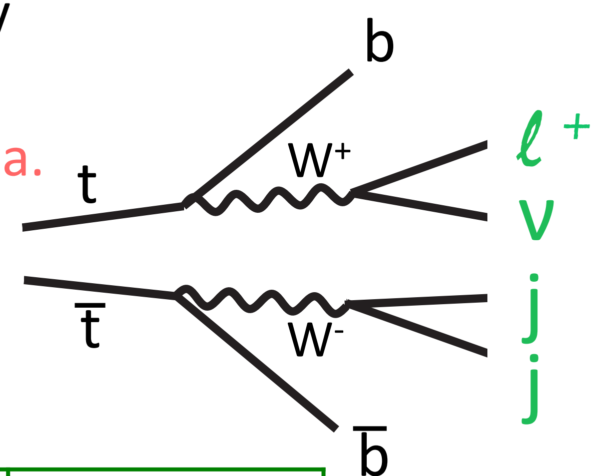
$m_t^c = m_t^{input}$ ⇒ zero of I(m) = m_t^c

$m_t^c \neq m_t^{input}$ ⇒ zero of I(m) ≠ m_t^c (guess)



Event selection cuts

- 1 muon with p_T > 20GeV, $|\eta|$ < 2.4 (lepton cuts)
- At least 4 jets
- At least 1 b-tag with the b-tag efficiency 0.4 independent of p_T and η
- $p_T(j_1) > 55$, $p_T(j_2) > 25$, $p_T(j_3) > 15$, $p_T(j_4) > 8$GeV



We do not use cuts concerning missing momenta.

Cross section after all cuts

Signal (m_t=173GeV)	Other $t\bar{t}$ BG	W+jets BG	$Wb\bar{b}$+jets BG	Single top BG
22.4 pb	5.7 pb	1.8 pb	1.8 pb	1.3 pb

Ongoing & future work

★ NLO, NNLO

- Include NLO, NNLO corrections to the top decay process in weight functions. ⇨ m_t^{pole}, $m_t^{\overline{MS}}$
- Include NLO corrections to the top production process in MC. ⇨ μ_F scale uncertainties can be reduced

★ Finite-width effects

Off-shellness
Single- or non-resonant contributions
Factorizable and non-factorizable corrections

Future work: $\overline{\mathrm{MS}}$ mass

Lepton energy dist. in the top rest frame with $m_t^{\overline{\mathrm{MS}}}$

naïve α_s expansion is not a good approximation
in a part of phase space

➡ But good for the weighted integral I(m) ?

(I(m) is conceptually close to and inclusive quantity, being integrated over lepton energy.)

➡ Use other short-distance masses ?

e.g. PS mass and 1S mass