Bound-State Effects on Top-Quark Pair Production at the LHC

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K.Hagiwara,Y.Sumino,HY,Phys.Lett.B666,71(2008)
Y.Sumino,HY,JHEP09,034(2010)
[K.Hagiwara,HY,JHEP10,049(2009)]

NCTS(Hsinchu) HEP Jounal Club 2011.3.29

Outline :

1. Introduction : Top-Quark at hadron colliders
2. Bound-state effects on ttbar production at hadron colliders
3. Differential cross-section / Event Generation
4. Summary

1. Introduction

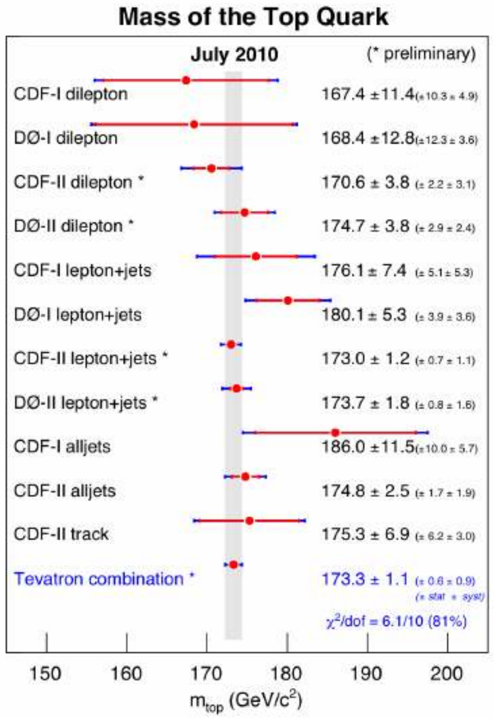
1. Introduction

☐ Properties of the top-quark

- Mass : (CDF and D0 combined, arXiv:0903.2503)

$$m_t = 173.1 \pm 0.6(\text{stat.}) \pm 1.1(\text{syst.})\ [\text{GeV}]$$

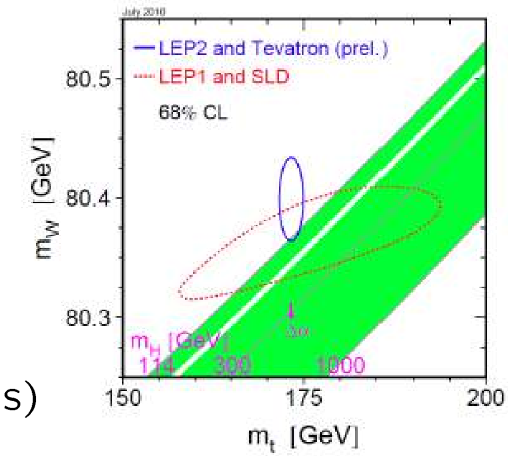
  - Heaviest fundamental particle ever found
  - Important input for EW precision test
  - $y_t \sim 1 \Rightarrow$ may be related to the BSM physics



- Width : SM prediction; $\Gamma_t \simeq \dfrac{G_F m_t^3}{8\sqrt{2}\pi}|V_{tb}|^2 \sim 1.5\,[\text{GeV}]$

  D0 measurement ('10); $\Gamma_t = 1.99^{+0.69}_{-0.55}$ GeV

  - decay before hadronization, $\Gamma_t \gg \Lambda_{QCD}$ $(\tau \sim 10^{-25}\text{s})$
    thus spin information is preserved in decay products



m_H < 158 GeV @ 95% CL

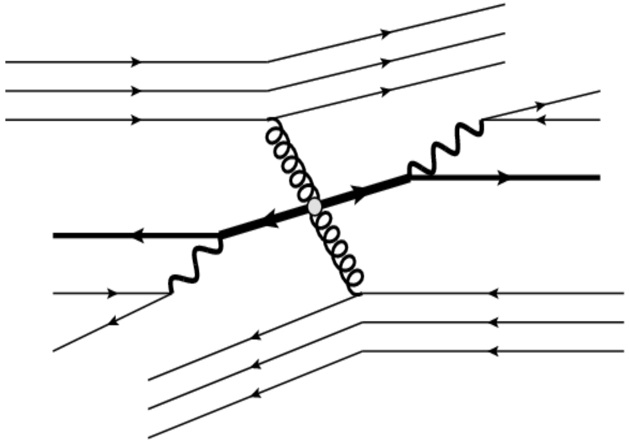
1. Introduction

- Top-quark production at Hadron Colliders

$$\sigma_{t\bar{t}}(s) = \sum_i \int d\tau \frac{dL_i}{d\tau}(\tau)\hat{\sigma}_i(\hat{s} = \tau s)$$

partonic cross-section

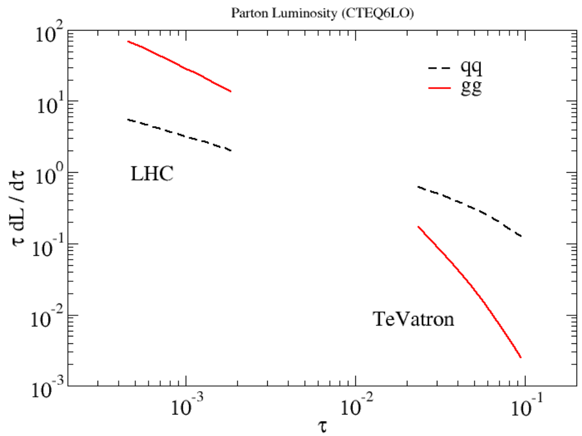
partonic luminosity



- We can calculate the partonic cross-section perturbatively.

- Partonic luminosity is a convolution of the parton distribution functions (PDFs) of the two protons, which are measured by experiments.

$$\frac{dL_i}{d\tau}(\tau, \mu_F) = \int dx_1 dx_2 \delta(\tau - x_1 x_2) f_a(x_1, \mu_F) f_b(x_2, \mu_F)$$

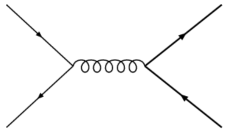


1. Introduction

- Partonic subprocess at Hadron Colliders

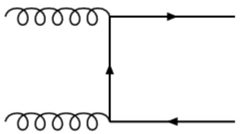
	Tevatron	LHC
$q\bar{q} \to t\bar{t}$ — Color: Octet, |J|=1	85%	10%
	..	..
$gg \to t\bar{t}$ — Color: Singlet, Octet, |J|=0,1,2,,,	15%	90%

$q\bar{q} \to t\bar{t}$



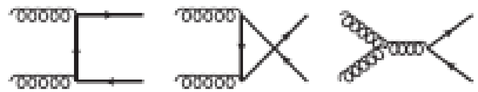
Color: Octet
|J|=1

$gg \to t\bar{t}$



Color: Singlet, Octet
|J|=0,1,2,,,

- Color decomposition in gg process is obtained from the color-matrix in the amplitude



$$\mathcal{M}_{gg\to t\bar{t}} = (T^aT^b)_{ij}\mathcal{M}_1 + (T^bT^a)_{ij}\mathcal{M}_2$$
$$= \frac{1}{2}\{T^a, T^b\}_{ij}\mathcal{M}_S + \frac{1}{2}[T^a, T^b]_{ij}\mathcal{M}_A$$

$$\frac{1}{2}\{T^a, T^b\} = \underline{\frac{1}{2N_c}\delta^{ab}}\delta_{ij} + \frac{1}{2}d^{abc}T^c_{ij}$$

color-singlet

$$\left|\frac{1}{2N_c}\delta_{ab}\delta_{ij}\right|^2 / \left|\frac{1}{2}d^{abc}T^c_{ij}\right|^2 = \frac{2}{N_c^2 - 4}$$

~20-30% of ttbar are color-singlet in gg

1. Introduction

- Perturbative calculations for the partonic cross-section :

$$\hat{\sigma}_i(\hat{s}) = \hat{\sigma}_i^{(0)}(\hat{s}) + \frac{\alpha_s}{\pi}\hat{\sigma}_{ij}^{(1)}(\hat{s};\mu) + \left(\frac{\alpha_s}{\pi}\right)^2 \hat{\sigma}_i^{(2)}(\hat{s};\mu) + \cdots$$

Fixed-Order Calculation :

- NLO : Dawson,Ellis,Nason('88), Beenakker etal.('90)

  (Analytic): Cazkon,Mitov('08)
- Building blocks for full NNLO correction :

  Korner etal.('06),Dittmaier etal.('07),Cazkon etal.('07),,,
- (appx.) NNLO : Kidonakis,Vogt('08),,
- 1-loop electroweak correction : Bernreuther,Fuecker,Si('06), Kuhn,Scharf,Uwer('06),Moretti,Nolten,Ross('06)

Resummation :

- Threshold Resummation

  NLL : Bonciani etal.('98),,, ; NNLL : Moch,Uwer('08),
- **Coulomb Summation** : Catani,Mangano,Nason,Trentadue('96), Hagiwara,Sumino,HY('08), Kiyo etal('08), Sumino,HY('10)

1. Introduction

- Total cross-section and its uncertainties :

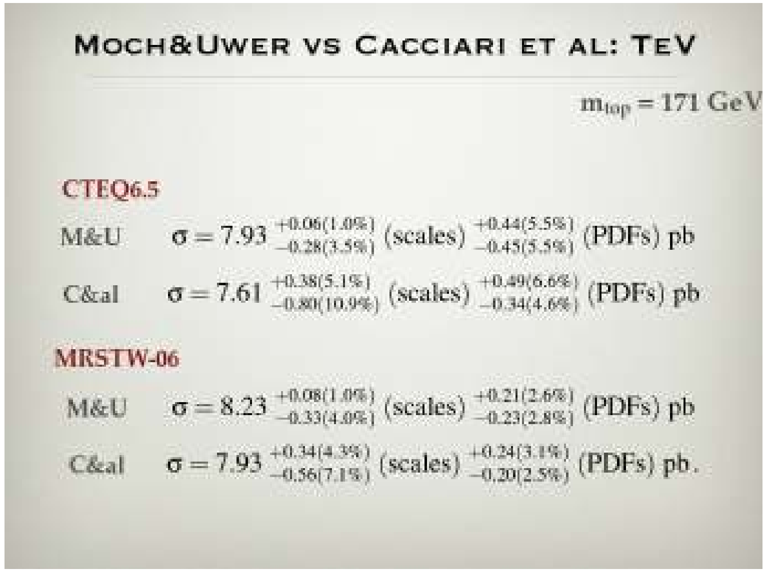
$\sigma_{t\bar{t}}(\text{TeV}) \sim 8$ [pb]

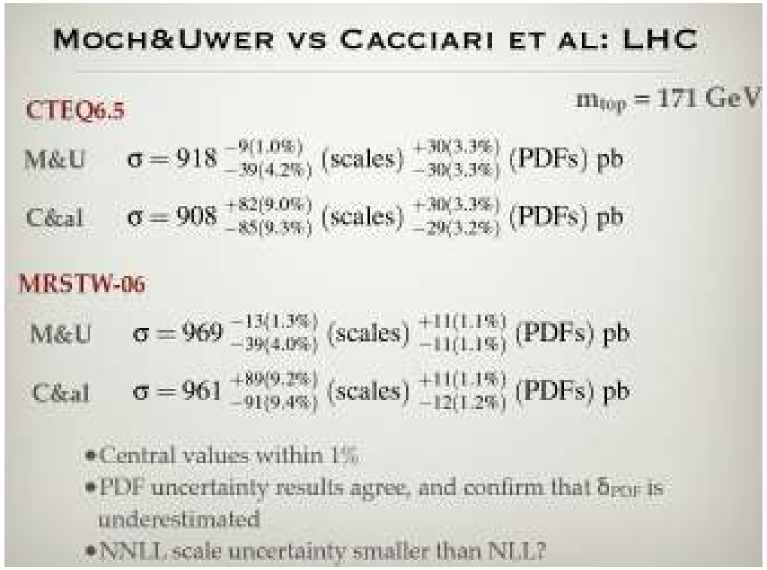
$\sigma_{t\bar{t}}(\text{LHC 7TeV}) \sim 150$ [pb] $\quad \sigma_{t\bar{t}}(\text{LHC 14TeV}) \sim 900$ [pb]

Theoretical uncertainties = (Ren & Fac scales) + (PDF)

~10% (Ren & Fac scales)

~5% (TeV)
~3% (LHC) (PDF)

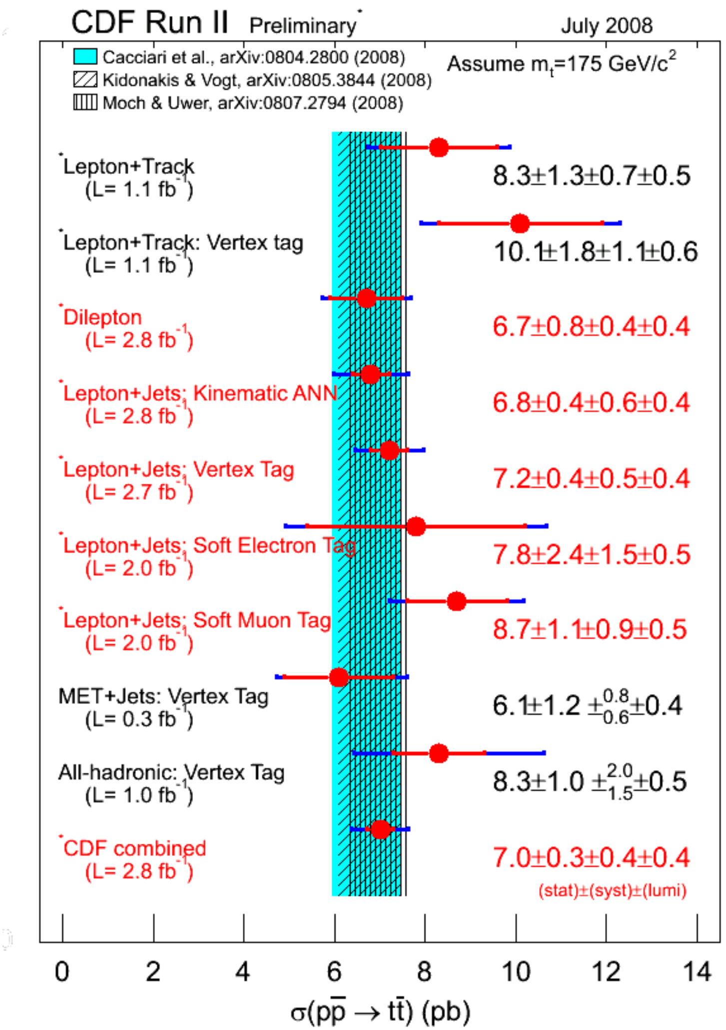


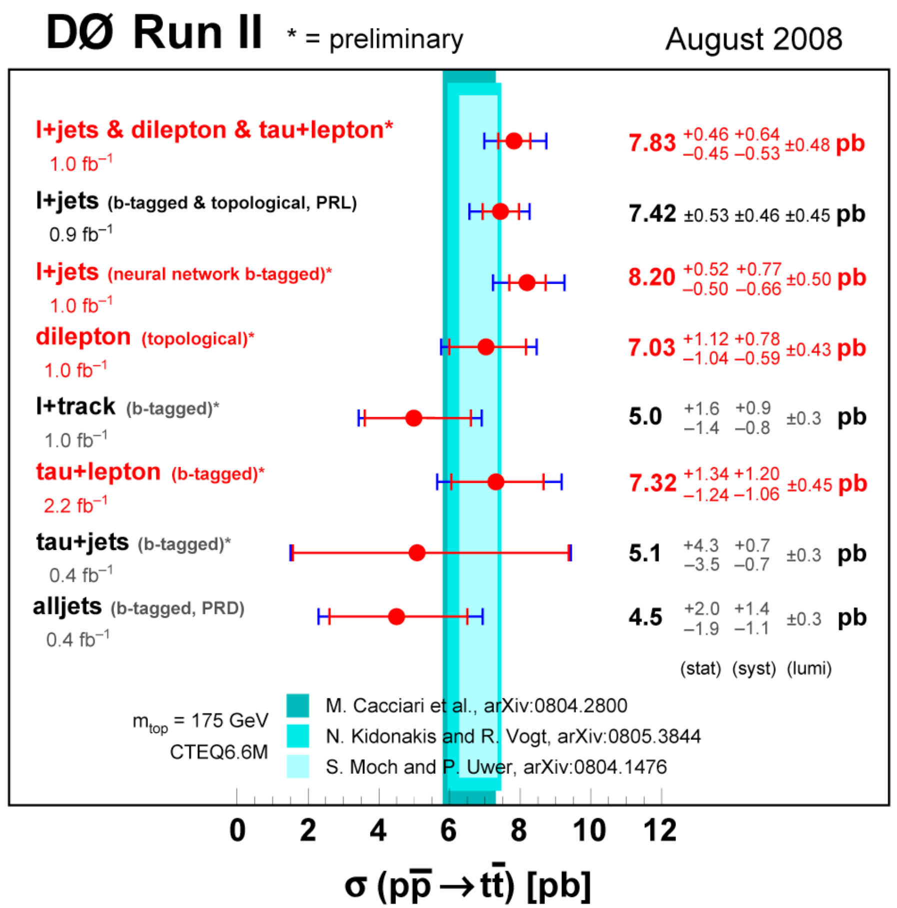


slide by M.Mangano

1. Introduction

Cross-Section Measurements at CDF and D0





1. Introduction

LHC has already found Top-Quarks

CERN-PH-EP/2010-039
2010/11/12

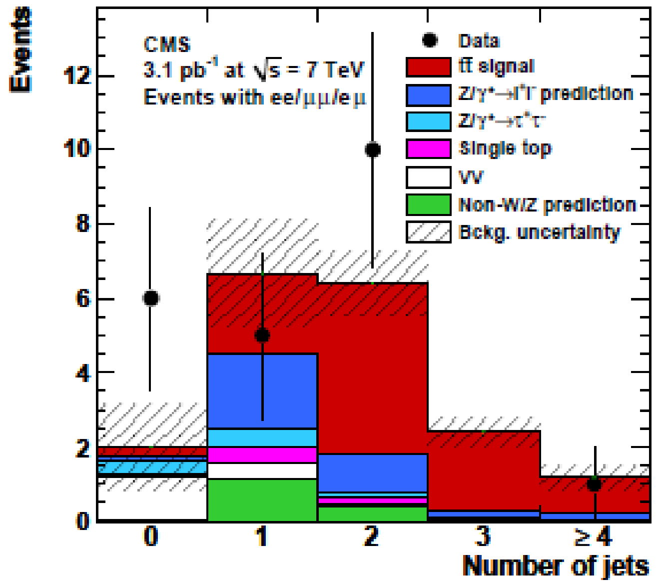
CMS-TOP-10-001

First Measurement of the Cross Section for Top-Quark Pair Production in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

The first measurement of the cross section for top-quark pair production in pp collisions at the LHC at center-of-mass energy $\sqrt{s} = 7$ TeV has been performed using 3.1 ± 0.3 pb^{-1} of data recorded by the CMS detector. This result utilizes the final state with two isolated, highly energetic charged leptons, large missing transverse energy, and two or more jets. Backgrounds from Drell-Yan and non-W/Z boson production are estimated from data. Eleven events are observed in the data with 2.1 ± 1.0 events expected from background. The measured cross section is $194 \pm 72(\text{stat.}) \pm 24(\text{syst.}) \pm 21(\text{lumi.})$ pb, consistent with next-to-leading order predictions.



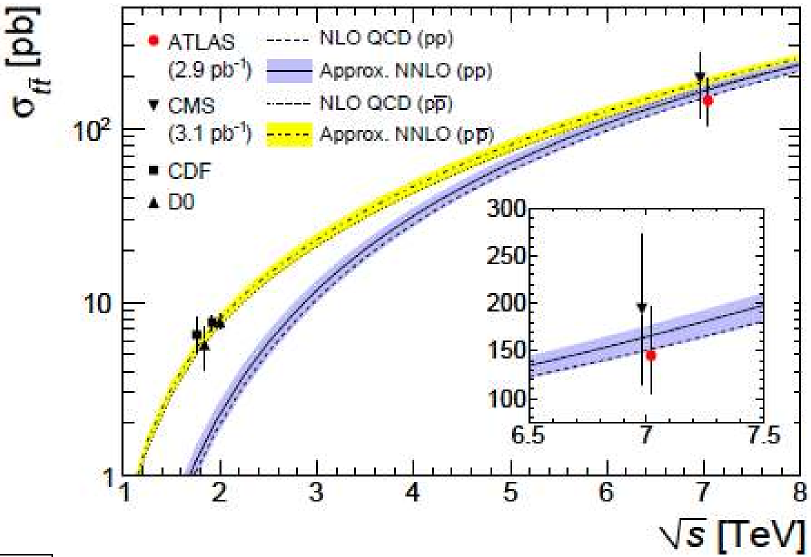
1. Introduction

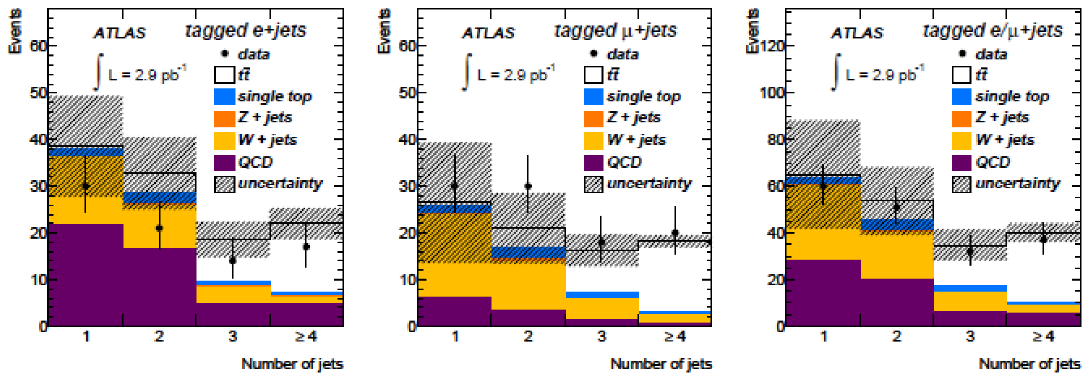
CERN-PH-EP-2010-064
(Submitted to EPJC)

December 8, 2010

Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration

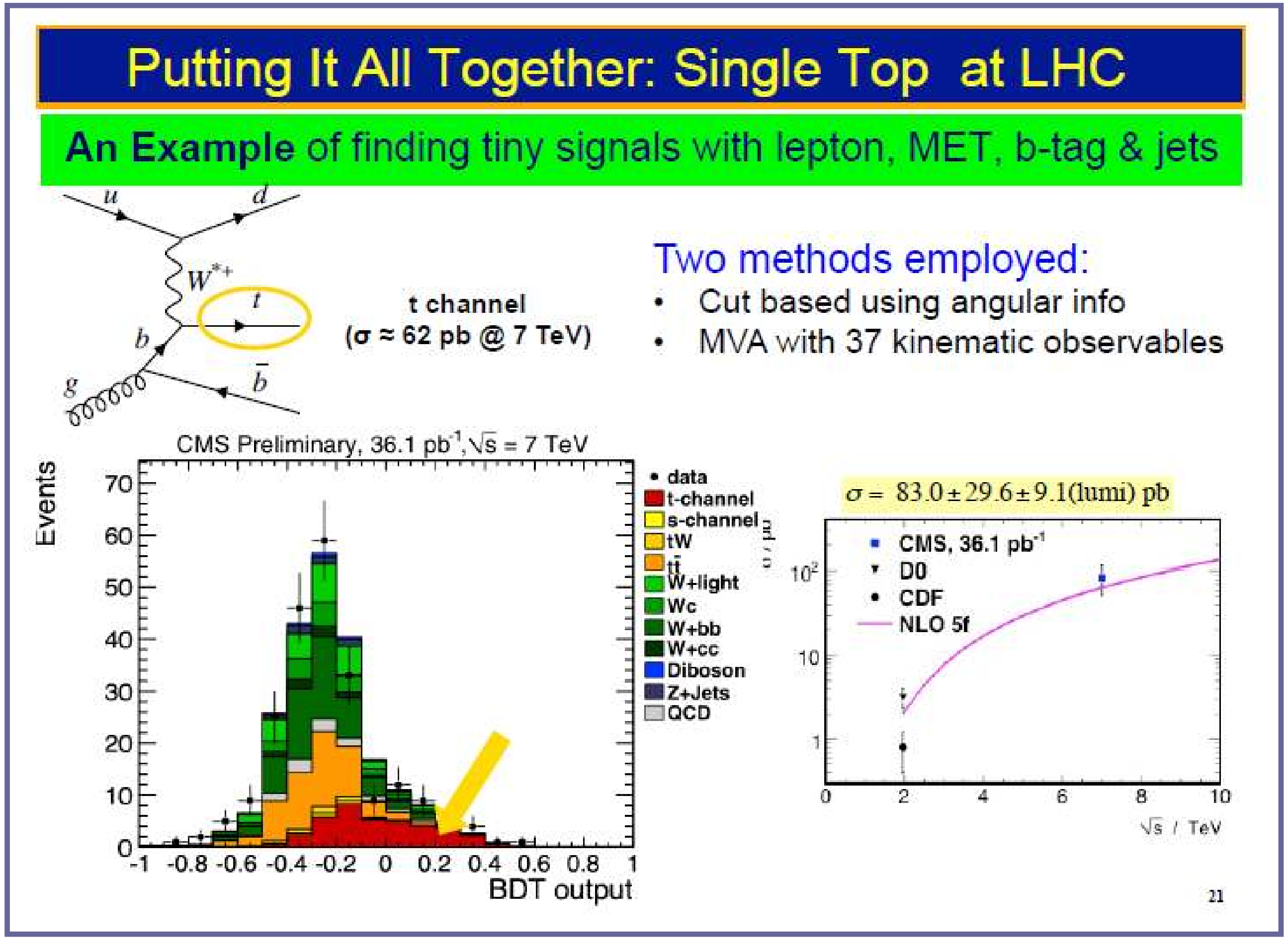




(d) (e) (f)

1. Introduction

Single Top event is also rediscovered.



1. Introduction

LHC = Top Factory

So top-quark physics can be more precisely at the LHC

- Cross-Section at the LHC (14 TeV):
  - Pair production cross-section ~ 900pb
  - Single production cross-section ~ 300pb (t-ch. > tW > s-ch.)
- QCD physics (standard candle process):

  Luminosity monitor, PDF monitor, Jet energy scale, B-tagging,,,
- Electroweak physics :

  Decay (width, distribution, V_{tb},,), Interaction with Long. weak-bosons,,,

$$\Gamma_t = \Gamma_L + \Gamma_T$$

70% 30%

- And Beyond Standard Model physics :

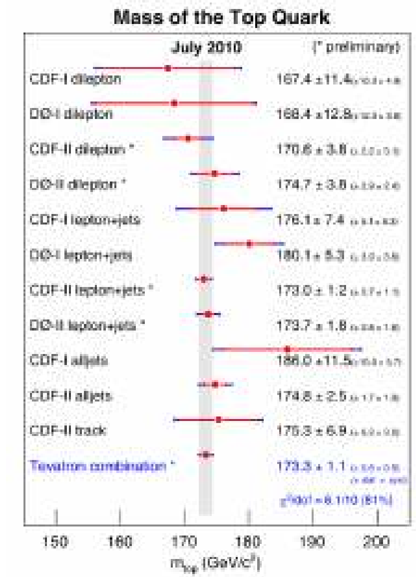
1. Introduction

- Precise mass (and width) determination :

  What is the top-quark mass observed so far?

  pole mass? a parameter in the Monte Carlo?

Fact : Pole mass is not a well-defined.
Theoretical prediction using pole mass has bad pert. convergency



Important : definition of the mass in an IR-safe manner
(short-distance mass)

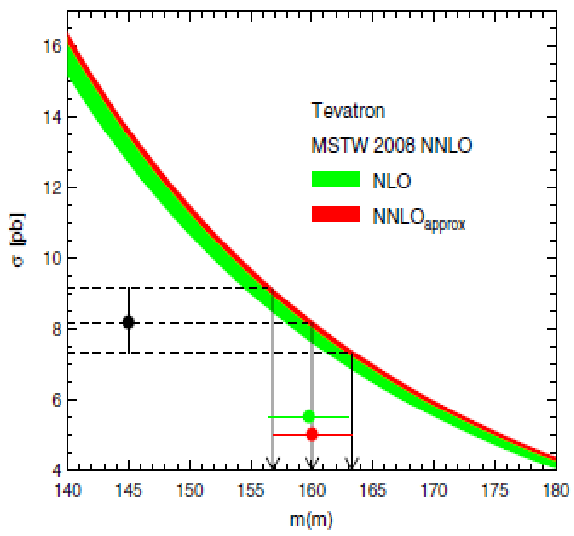
Langenfeld,Moch,Uwer('09) determination of the $\overline{\rm MS}$ mass from the total cross-section at Tevatron.

$$\bar{m}(\bar{m}) \;=\; 160.0^{+3.3}_{-3.2}\,[\mathrm{GeV}] \qquad \text{(NNLO)}$$

$$\rightarrow \text{pole mass } m_t = 168.9 \pm 3.5 \text{ GeV}$$

Another choice may be the "threshold mass".

PHYSICAL REVIEW D 80, 054009 (2009)

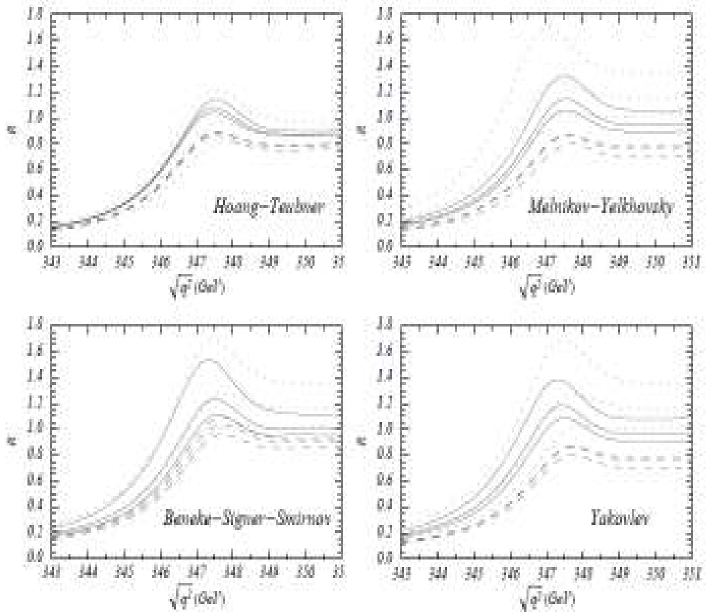


(b)

1. Introduction

- At e^+e^- colliders, "Threshold Scan" can be performed

hep-ph/0001286



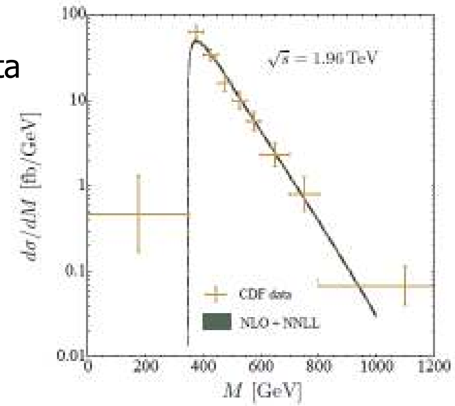
precise determinations of the top-quark mass,
width and strong coupling constant are possible

$\delta m_t \sim 100\,[\mathrm{MeV}] \quad \delta\Gamma_t/\Gamma_t \sim 20\,[\%]$

- Peak of the 1S resonance ⇔ Threshold mass
  (1S mass, PS mass,,,)

Relation between the threshold mass, $\overline{\mathrm{MS}}$ mass and
pole mass is well-known to higher-orders

CDF data



- However, at hadron colliders, (partonic) collision energy
  is not fixed, so one has to reconstruct top-pair invariant mass.

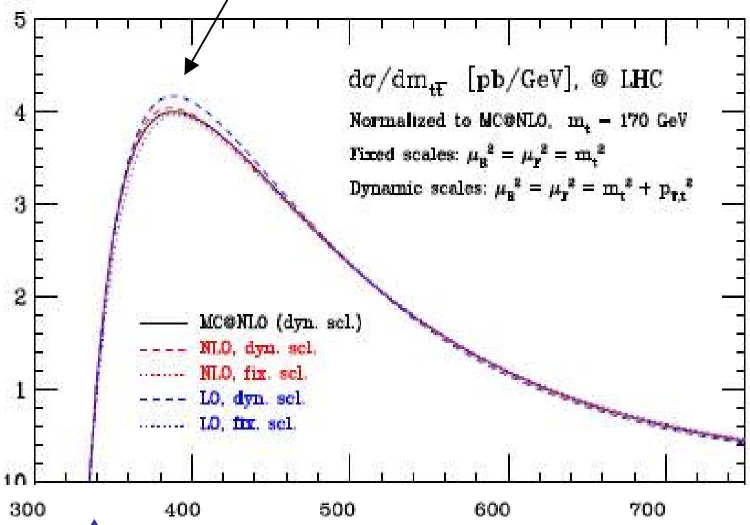
It would be a very challenging task to have good precision

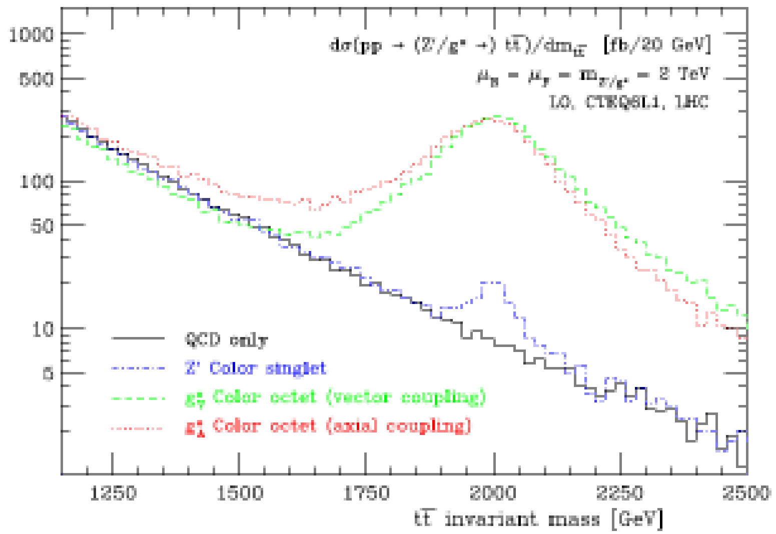
1. Introduction

- ttbar Invariant-mass distribution : $m_{tt} = (p_t + p_{\bar{t}})^2$

peak region $\beta \sim 0.5$

Frederix,Maltoni('07)





threshold region $\beta \lesssim 0.3$ (m_{tt} < 360 GeV)

High-energy region $\beta \sim 1$

(Boosted top, resonances,FB asymmetries?,,)

$$\beta = \sqrt{1 - \frac{4m_t^2}{m_{tt}}}$$: velocity of top-quarks in ttbar CM frame

2. Bound-state effects on ttbar production at Hadron Colliders

2. Bound-state effects at Hadron colliders

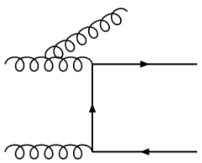
- NLO correction near partonic threshold : $\left(\beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}} \to 0\right)$

velocity of top-quarks in ttbar CM frame

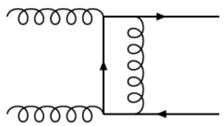
$$\hat{\sigma}_i^{c,(1)} \sim \alpha_s \hat{\sigma}_i^{c,(0)} \left[A_i \ln^2(8\beta^2) + B_i^{(c)} \ln(8\beta^2) + C_i^{(c)} \frac{\pi^2}{\beta} + D_i^{(c)} + \mathcal{O}(\beta) \right]$$

i=qq,gg

Threshold logs: emission of soft and/or collinear gluon in initial-state and final-state



Coulomb singularity: Coulomb gluon exchange between t and t-bar



Hard correction: process dependent

2. Bound-state effects at Hadron colliders

To all orders, we expect,

$$\begin{aligned}\hat{\sigma}_i = \hat{\sigma}_i^0 \quad &\times \quad \left[1 + \alpha_s \ln^2 \beta + \alpha_s \ln \beta + \alpha_s^2 \ln^4 \beta + \cdots\right] \\ &\times \quad \left[1 + \frac{\alpha_s}{\beta} + \frac{\alpha_s^2}{\beta^2} + \cdots\right] \times \left[1 + \alpha_s + \alpha_s^2 + \cdots\right] \\ &+ \quad (\mathrm{non-decoupling\,terms})\end{aligned}$$

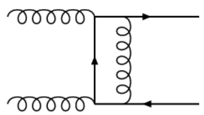
- C.F., factorization of each contribution is shown by

Beneke,Falgari,Schwinn ('09)
Beneke,Czakon,Falgari,Mitov,Schwinn('10)

2. Bound-state effects at Hadron colliders

□ Coulomb corrections to all-orders

- Coulomb singularity $\propto C^{(c)}\dfrac{\alpha_s}{\beta}$ $\qquad \mathcal{O}(1)$ for $\beta \simeq \alpha_s$

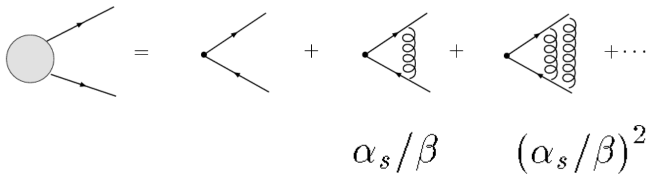


color-factor $\begin{cases} \text{singlet} & C^{(1)} = -C_F \\ \text{octet} & C^{(8)} = C_A/2 - C_F \end{cases}$

- Summation of ladder diagrams = Sommerfeld factor

Sommerfeld,Sakharov (QED)

$$S(z) = \frac{z}{1-\exp[z]}, \quad z = C^{(c)}\pi\alpha_s/\beta$$

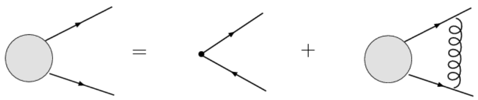


2. Bound-state effects at Hadron colliders

□ Coulomb corrections to all-orders

- Green's function formalism (NRQCD) Fadin,Khoze('87),,,

Schrodinger's Eq. $$\left[(E+i\Gamma_t)-\left\{-\frac{\nabla^2}{m_t}+V_{QCD}^{(c)}(r)\right\}\right]G^{(c)}(E,\vec{x})=\delta^3(\vec{x})$$



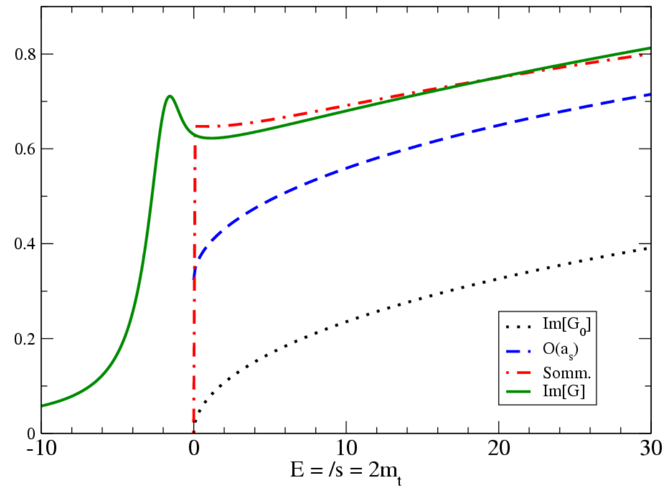
where $E = m_{tt} - 2m_t$

finite width effect is incorporated by complex energy
⇒ Off-shellness of top-quarks

$$G(E,\vec{x})=\sum_n \frac{\Psi_n(\vec{x})\Psi_n^*(0)}{E-E_n+i\Gamma_n/2}+\text{continuum}$$

- Large width smears the multiple resonance structure, but only one broad peak can be seen as a remnant.

color-singlet case



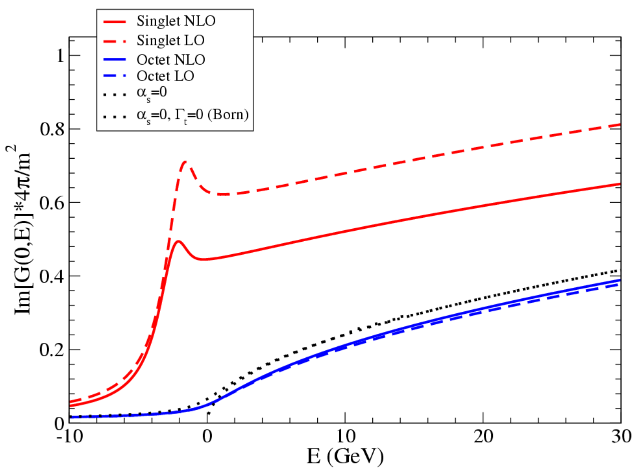
2. Bound-state effects at Hadron colliders

- Perturbative QCD potential (NLO), since an IR cut-off by $r \lesssim \frac{1}{\Gamma_t}$

$$V_{\rm QCD}^{(c)}(r) = C^{(c)} \frac{\alpha_s(\mu_B)}{r} \times \left[1 + \frac{\alpha_s}{\pi} v_1^{(c)}(r) + \cdots\right]$$

$$\begin{cases} \text{singlet} & C^{(1)} = -4/3 \\ \text{octet} & C^{(8)} = 1/6 \end{cases}$$

Singlet is attractive,
but octet is repulsive and small correction.



- Toponium system : $m_t \gg \mu_B > E_B \simeq \Gamma_t \gg \Lambda_{\rm QCD}$
  - Binding energy : $E_B \simeq m_t \alpha_s^2 \simeq 2\text{GeV}$
  - Bohr radius : $\mu_B \simeq m_t \alpha_s \simeq 20 - 30\text{GeV}$

    (typical momentum of the Coulomb gluon)

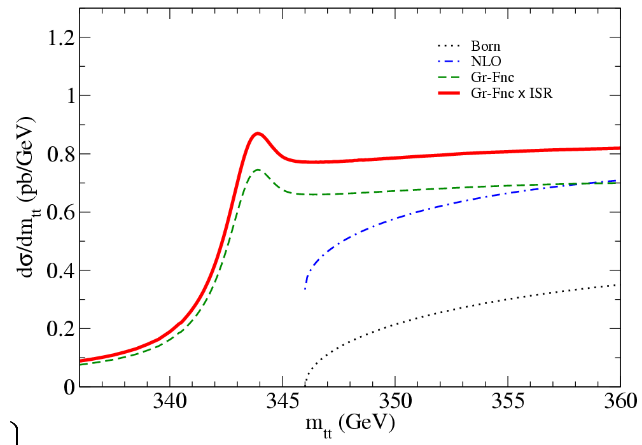
If $\Gamma_t > E_B$, top-quark decays before bound-state formation

2. Bound-state effects at Hadron colliders

- Cross-section is proportional to the Imaginary part of the Green function by Optical theorem.

$$\hat{\sigma}^{(c)}_{tt} \to \hat{\sigma}^{(c)}_{tt,\mathrm{Born}} \cdot \mathrm{Im}[G^{(c)}(E,\vec{0})]$$

gg->tt, color-singlet at the LHC



NLL : Kiyo etal.('08)

- Combining Initial-state/Final-state radiation effects,

$$\frac{d\sigma}{dm_{tt}}(s,m_{tt}^2) = \hat{\sigma}_i^{(c)}(m_{tt}^2) \cdot K_i^{(c)} \int_{\tau_0}^1 \frac{dz}{z} F_i^{(c)}(z) \frac{d\mathcal{L}_i}{d\tau}(\tau_0/z)$$

$$F_i^{(c)}(z) = \delta(1-z) + \frac{\alpha_s}{\pi}\left[A_i\left\{\left(\frac{\ln(1-z)}{1-z}\right)_+ - \left(\frac{1}{1-z}\right)_+ \ln\left(\frac{\mu_F}{2m_t}\right)\right\} + D_{tt}^{(c)}\left(\frac{1}{1-z}\right)_+ + k_i^{(c)}\delta(1-z)\right]$$

- Color-dependent hard correction : $K_i^{(c)} = 1 + \frac{\alpha_s}{\pi} h_i^{(c)}$

 can be extracted from the NLO Quarkonium production

Petrelli,Cacciari,Greco,Maltoni,Mangano ('98)

+Non-decoupling term HSY('08), Czakon,Mitov('08)

$$h_{gg}^{(1)}\left(\frac{\mu_R}{m_t}\right) = C_A\left(1+\frac{\pi^2}{12}\right) + C_F\left(-5+\frac{\pi^2}{4}\right) + \beta_0 \ln\left(\frac{\mu_R}{2m_t}\right),$$

$$h_{gg}^{(8)}\left(\frac{\mu_R}{m_t}\right) = C_A\left(3-\frac{\pi^2}{24}\right) + C_F\left(-5+\frac{\pi^2}{4}\right) + \beta_0 \ln\left(\frac{\mu_R}{2m_t}\right),$$

$$h_{q\bar{q}}^{(8)}\left(\frac{\mu_R}{m_t}\right) = C_A\left(\frac{59}{9}-\frac{\pi^2}{4}+\frac{2\ln 2}{3}\right) + C_F\left(-8+\frac{\pi^2}{3}\right) - \frac{5}{9}n_q - \frac{8}{9} + \beta_0 \ln\left(\frac{\mu_R}{2m_t}\right).$$

2. Bound-state effects at Hadron colliders

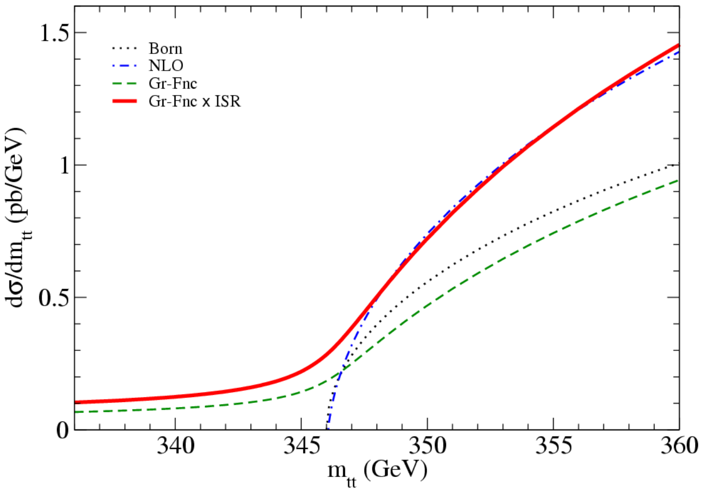
m_t=173 GeV, Γ_t=1.5 GeV, CTEQ6M

ttbar invariant-mass distributions

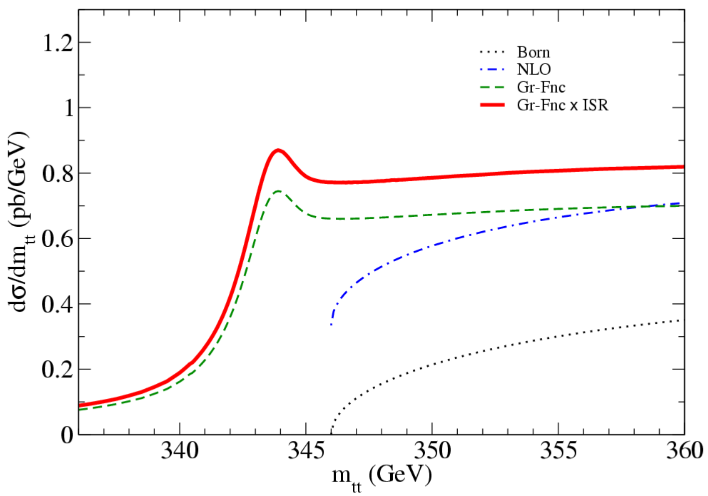
Black	: Born
Blue	: O(as) corr. (NLO)
Green	: Gr-Fnc. without ISR
Red	: Gr-Fnc. with ISR

ISR : up to $O(a_s)$ (soft/collinear)

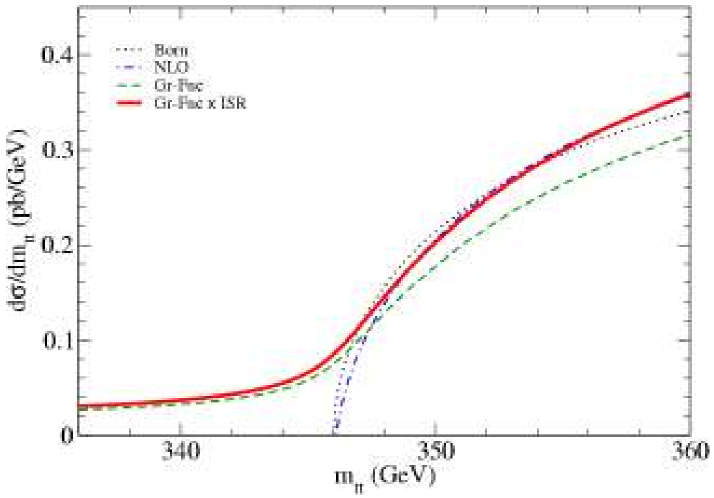
gg->tt, color-octet



gg->tt, color-singlet



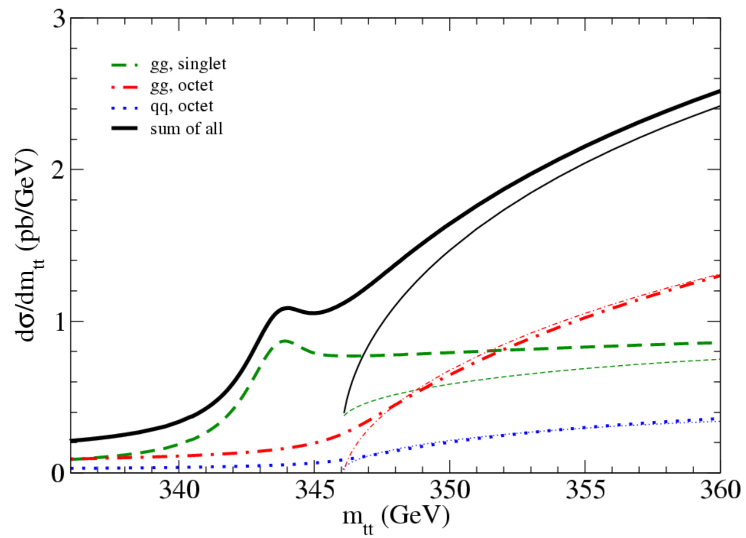
qq->tt, color-octet



2. Bound-state effects at Hadron colliders

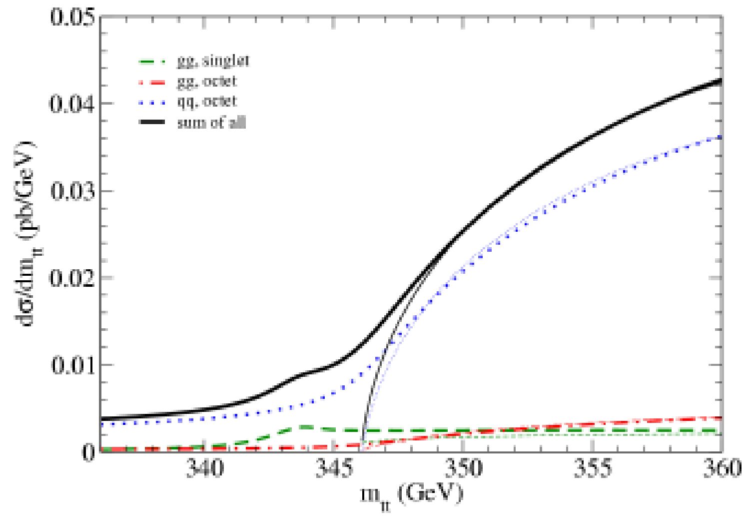
◆ In total at the LHC :

- BS effects deform the invariant-mass distribution near threshold
- Form a broad resonance peak below threshold (observable in principal)
- Enhance the total cross-section by 10 pb ~ O(1%)



◆ On the other hand at the Tevatron :

Resonance can't be seen,
due to the color-octet dominance.

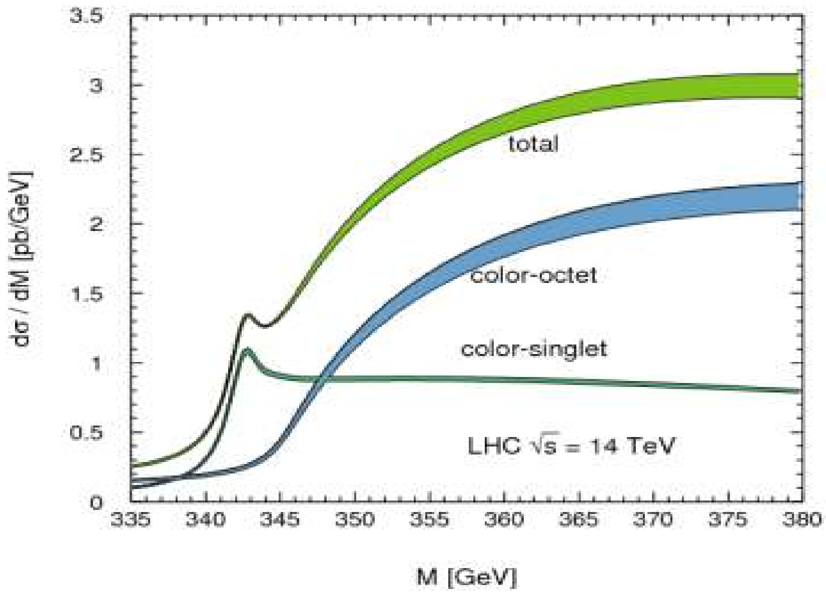


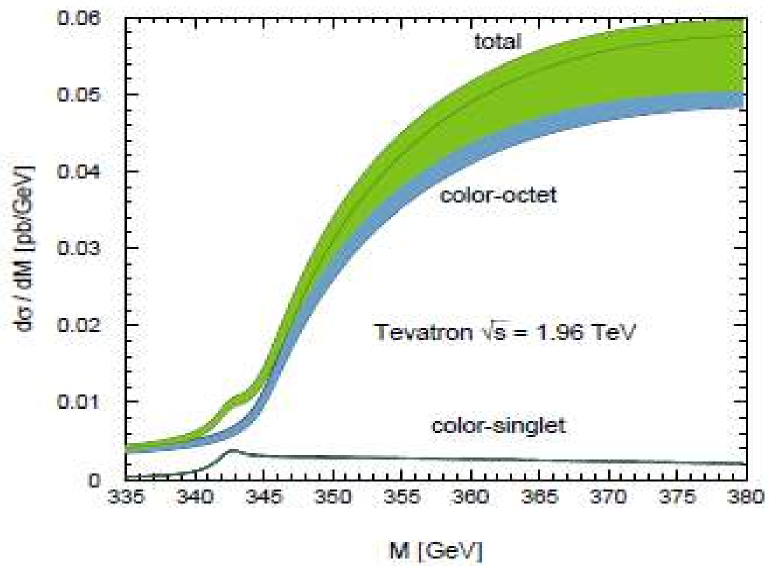
2. Bound-state effects at Hadron colliders

- Kiyo,Kuhn,Moch,Steinhauser,Uwer ('08)

+ full O(a_s) ISR (non-singular term)
+ Resummed ISR (NLL)

Small difference on the overall normalization.
The conclusions agree with each other.





3. Differential Cross-section / Event Generation with BS effects

3. Differential Cross-section

Coulomb correction to differential cross-sections

- Differential distributions are useful for the analysis with kinematical cuts.
- Differential distribution is needed to generate events in MC simulation.
- Method to include BS effects is developed in e^+e^- collider study

Jezabek,Kuhn,Teubner('92)
Sumino,Fujii,Hagiwara,Murayama,Ng('93),,,

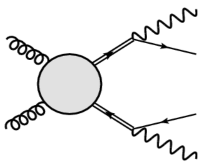
- Take into account the "Leading-order" contribution in both region :
  - Threshold region : $(\alpha_s/\beta)^n$ but not α_s^n, β^n
  - High-energy region : β^n but not α_s^n
  - plus some NLO effects (K-factor, width, QCD potential,,)

note, $\Gamma_t/m_t \sim \alpha_W \sim \alpha_s^2$

3. Differential Cross-section

☐ Coulomb correction in differential cross-section

- gg/qq to bWbW process to take into account the off-shellness of top-quarks
- Divide resonant part and non-resonant part of the amplitude
- Double resonant part of the amplitude :



$$\mathcal{M}_{t\bar{t}} = \bar{D}_{t\to bW} \cdot \frac{i}{\not{p}_t - m_t + i\Gamma_t} \cdot P_{i\to t\bar{t}} \cdot \frac{i}{-\not{p}_{\bar{t}} - m_t + i\Gamma_t} \cdot D_{\bar{t}\to \bar{b}W}$$

Coulomb correction : $P_i \to P_i \times \tilde{G}^{(c)}(E, \vec{p})$

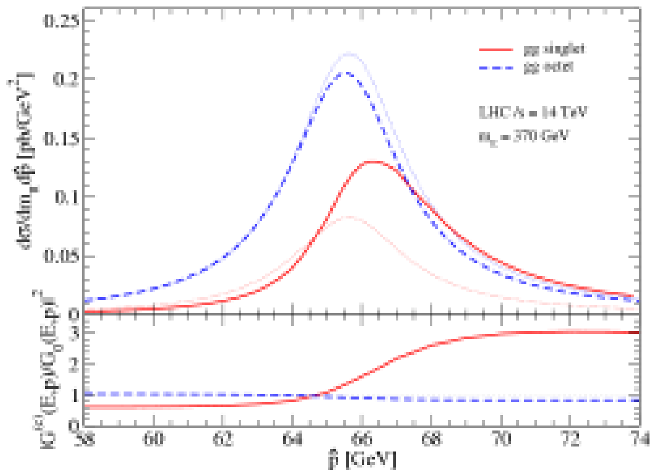
Green function in momentum-space

- Top-quark momentum distribution (of the tt cm frame) is affected by the Coulomb correction.

$$\frac{d\sigma}{d|\vec{p}|} \propto |\tilde{G}(E, \vec{p})|^2$$

color-singlet : $\delta p > 0$

color-octet : $\delta p < 0$



3. Event Generation

Sumino,HY ('10)

http://madgraph.kek.jp/~yokoya/TopBS

☐ Event Generator (LO + all-order Coulomb) :

- Full gg/qq→bWbW plus W-decays Matrix-Elements (6-bodys)
- Color-decomposition in gg→bWbW process
- Bound-state correction to the double-resonant amplitudes
- Color-dependent K-factors to reproduce NLO m_{tt} dist. near threshold

- Difference from General-purpose Monte-Carlo's :

  MadGraph/MadEvent, Sherpa,,, (PYTHIA, HERWIG,,,)

  LO(Tree-level), ○non-resonant effects, off-shell effect,,,

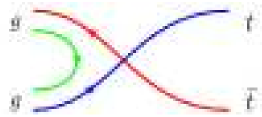
  MCFM, MC@NLO,,,

  NLO (α_s/β term), ×non-resonant effects, Breit-Wigner,,,

3. Event Generation

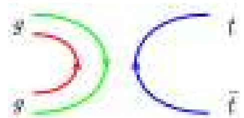
◻ Color-flow assignment

in gluon-fusion process,



$$\mathcal{M}_{gg\to t\bar{t}} = (T^aT^b)_{ij}\mathcal{M}_1 + (T^bT^a)_{ij}\mathcal{M}_2$$
$$= \frac{1}{2}\{T^a, T^b\}_{ij}\mathcal{M}_S + \frac{1}{2}[T^a, T^b]_{ij}\mathcal{M}_A$$

symmetric part : $\frac{1}{2}\{T^a, T^b\} = \underline{\frac{1}{2N_c}\delta^{ab}\delta_{ij}} + \frac{1}{2}d^{abc}T^c_{ij}$



color-singlet

ratio of the amplitudes squared : $\left|\frac{1}{2N_c}\delta_{ab}\delta_{ij}\right|^2 \,/\, \left|\frac{1}{2}d^{abc}T^c_{ij}\right|^2 = \frac{2}{N_c^2 - 4}$

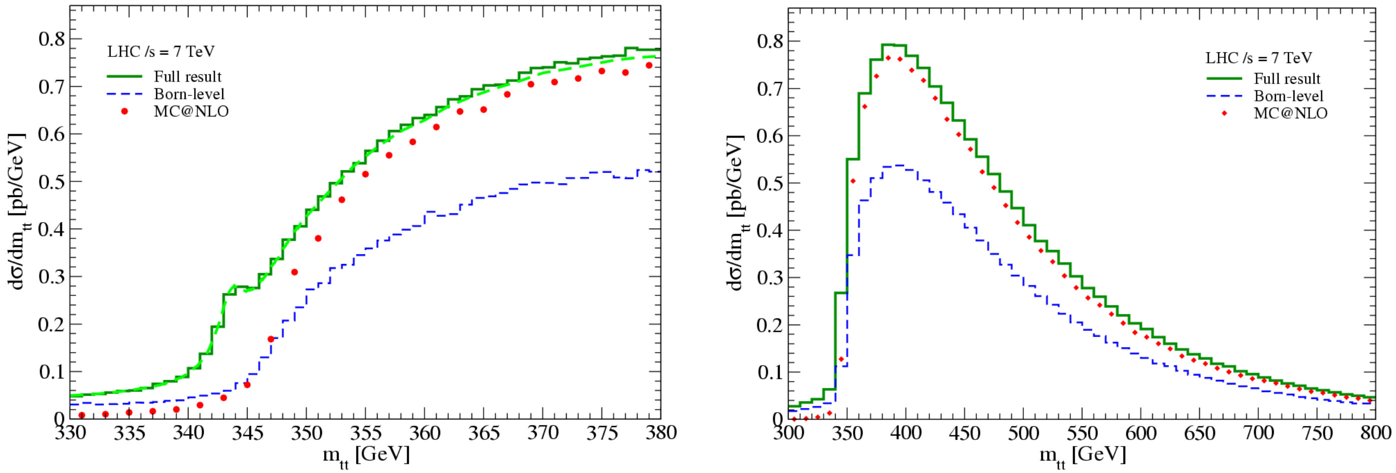
this is zero in large-N limit, but not in QCD

our color-singlet events have correct color-flow assignment in the LHEF record

3. Event Generation

☐ Some Examples (at partonic-level)

(1) ttbrar invariant-mass (m_{tt}) distribution :



- The only generator which describes the threshold enhancement and resonance
- Effectively, well reproduce MC@NLO results at large m_{tt} by taking the scales as

$$\mu = m_t \quad (\mu = \sqrt{m_t^2 + p_T^2} \quad \text{in MC@NLO})$$

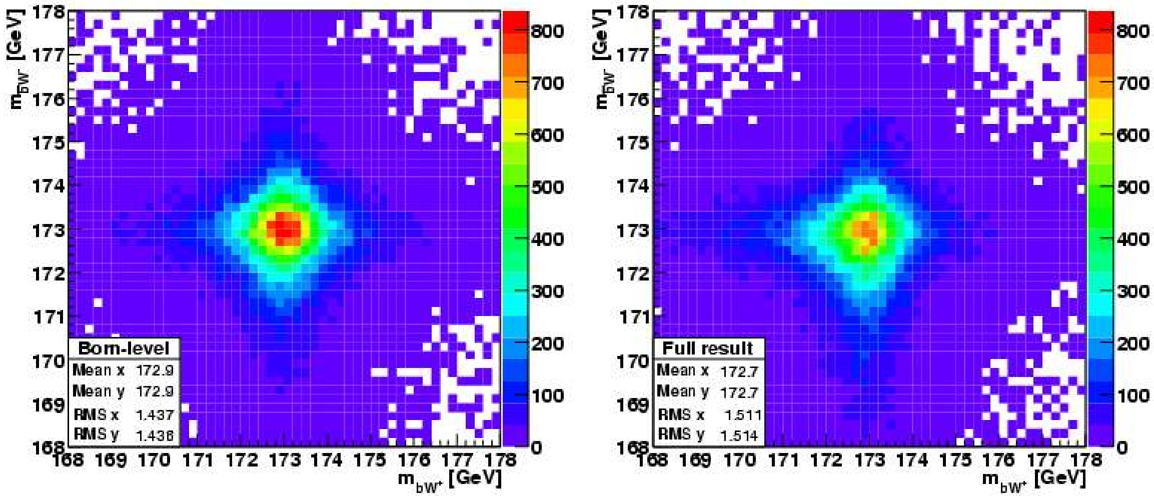
3. Event Generation

☐ Some Examples (at partonic-level)

(2) (bW)-(bW) double invariant-mass distribution of top-quarks ; $m_{bW} = (p_b+p_W)^2$

limiting for the events with m_{tt}<370 GeV (10% of the total event)

Born Coulomb



$\delta m \simeq -200\,[\mathrm{MeV}]$

correlated deviation : one top-quark is still on-shell,
but the other invariant-mass is reduced

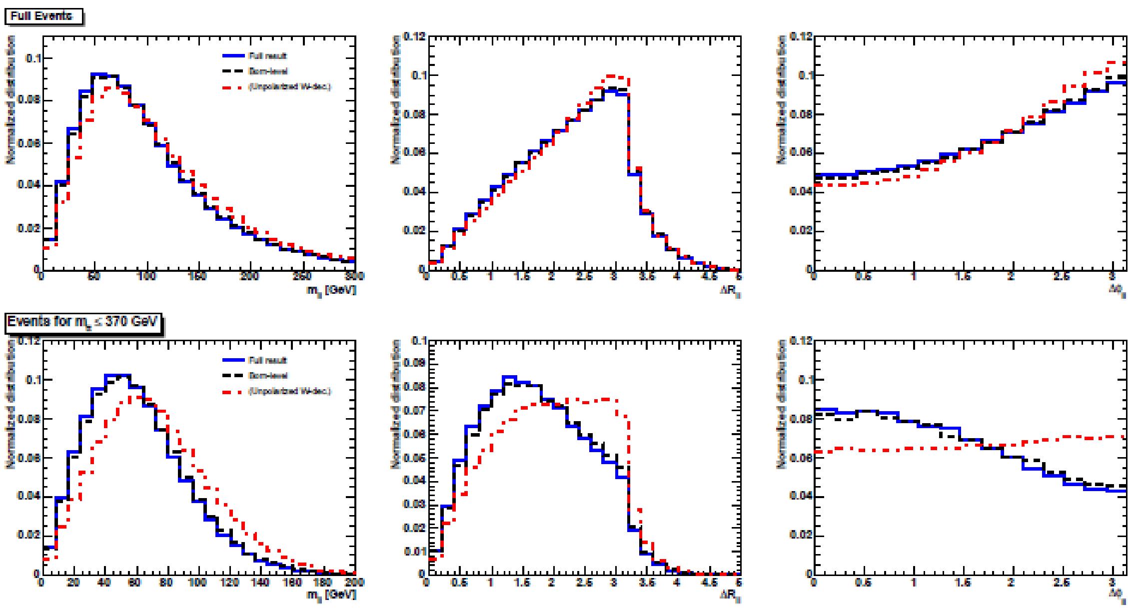
3. Event Generation

Some Examples (at partonic-level)

(3) lepton angular distributions (di-lepton case)

- Unfortunately, small bound-state effects in final lepton angular distributions
- bWbW MEs plus W-decay by parton-shower give wrong distribution (no W polarization)

⇒ use 6-body MEs



4. Summary

We have studied the bound-state effect to the top-quark production at hadron colliders

- At the LHC, gluon-fusion process dominates and substantial amount of ttbar pair is color-singlet.
  - The bound-state effects are calculated for the m_{tt} distribution at Hadron Colliders up to NLO (Green's func., gluon radiation, hard-correction).
  - Large corrections in m_{tt} dist. near threshold is predicted, and there appears a broad resonance below the threshold.
- Differential cross-sections are also calculated including BS effects, non-resonant amp's as well as decays of W's
  - incorporate momentum-space Green functions for color-singlet and octet
  - smooth interpolation to the high-energy region
  - non-resonant diagrams are taken into account

4. Summary

- Event Generator including Bound-state effects
  - MC simulation including BS effects is now possible
  - Deviation from the Breit-Wigner distribution
  - Color-connection between ttbar in color-singlet channel

- Future :
  - Application to the production of heavy colored particles in BSM
    gluino (Hagiwara,HY '09,), squark (Beneke,Falgari,Schwinn '09,'10), KK gluon(Kahawala, Kats '11),,
    Coulomb corrections become relatively important for heavier particles production.
  - Detail phenomenological studies for the LHC measurements :
    how to extract threshold events? useful for the mass/width determination?