Bound-State Effects on Top-Quark/Gluino Production at the LHC

Hiroshi Yokoya (CERN-Japan Fellow)

Theory Group Retreat, 4-6/11/09, Les Houches

Summary as an Introduction

Top–quark pair-production at Hadron Colliders

- Top-quark will be produced copiously at the LHC (8M per 10fb^{-1})
- At the LHC, gluon-fusion process dominates, and the ttbar pair can be color-singlet (while color-octet at the Tevatron).
- Color-singlet ttbar is known to form a broad resonance, due to the attractive force by Coulomb-gluon exchange.

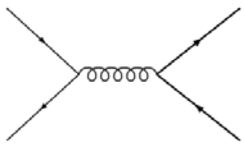
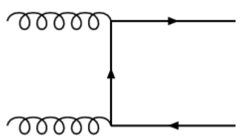
→ Study of Bound-state effect at Hadron colliders

Hagiwara,Sumino,HY ('08)

- Application to the gluino-pair production — Hagiwara,HY ('09)
  (and also the squark-pair production) — Beneke,Falgari,Schwinn ('09)

Top-Quark pair-production at Hadron Colliders

- Partonic Subprocess

			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%

Hadronic cross-section ~8pb, ~900pb

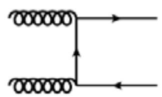
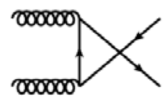
~450pb (10TeV)

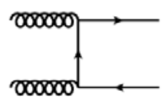
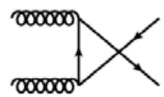
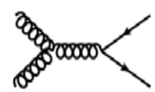
Warming-up; tree-level amplitudes

- Gluon Fusion process :

$$\mathcal{M}_{gg\to t\bar{t}} = g_s^2 \left[\frac{1}{2}\left\{T^a, T^b\right\}_{k\ell} \cdot M_{gg} + \frac{1}{2}\left[T^a, T^b\right]_{k\ell} \cdot N_{gg}\right]$$

$$\begin{cases} M_{gg}(\lambda,\lambda,\sigma,\sigma) = \frac{2m_t}{E}\frac{1}{1-\beta^2\cos^2\theta}(\lambda+\sigma\beta) \\ M_{gg}(\lambda,\lambda,\sigma,-\sigma) = 0 \\ M_{gg}(\lambda,-\lambda,\sigma,\sigma) = -\sigma\frac{2m_t}{E}\frac{\beta\sin^2\theta}{1-\beta^2\cos^2\theta} \\ M_{gg}(\lambda,-\lambda,\sigma,-\sigma) = -2\frac{\beta\sin\theta}{1-\beta^2\cos^2\theta}(\lambda\sigma+\cos\theta) \end{cases}$$

$M_{gg} =$  + 

$N_{gg} =$  -  + 2 

simple relation for any helicities :

$$N_{gg} = \beta_t \cos\theta \cdot M_{gg}$$ (Is this a consequence of any symmetry?)

- Color decomposition :

$$\frac{1}{2}\left\{T^a, T^b\right\}_{k\ell} = \frac{1}{2N}\delta^{ab}\delta_{k\ell} + \frac{1}{2}d^{abc}T^c_{k\ell}$$ singlet + octet

$$\frac{1}{2}\left[T^a, T^b\right]_{k\ell} = \frac{1}{2}if^{abc}T^c_{k\ell}$$ octet

Latest analysis on the total cross-sections :

- Moch,Uwer; arXiv:0804.1476
- Cacciari,Frixione,Mangano,Nason, Ridolfi; arXiv:0804.2800
- Kidonakis,Vogt; arXiv:0805.3844

NLO+NLL (update mass, PDF and resummation)

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

~9% (NLL) >7% (TeV)
~12%(NLO) >4% (LHC)

Moch&Uwer vs Cacciari et al: TeV

$m_{top} = 171$ GeV

CTEQ6.5

M&U $\sigma = 7.93\,^{+0.06(1.0\%)}_{-0.28(3.5\%)}$ (scales) $^{+0.44(5.5\%)}_{-0.45(5.5\%)}$ (PDFs) pb

C&al $\sigma = 7.61\,^{+0.38(5.1\%)}_{-0.80(10.9\%)}$ (scales) $^{+0.49(6.6\%)}_{-0.34(4.6\%)}$ (PDFs) pb

MRSTW-06

M&U $\sigma = 8.23\,^{+0.08(1.0\%)}_{-0.33(4.0\%)}$ (scales) $^{+0.21(2.6\%)}_{-0.23(2.8\%)}$ (PDFs) pb

C&al $\sigma = 7.93\,^{+0.34(4.3\%)}_{-0.56(7.1\%)}$ (scales) $^{+0.24(3.1\%)}_{-0.20(2.5\%)}$ (PDFs) pb.

Moch&Uwer vs Cacciari et al: LHC

$m_{top} = 171$ GeV

CTEQ6.5

M&U $\sigma = 918\,^{-9(1.0\%)}_{-39(4.2\%)}$ (scales) $^{+30(3.3\%)}_{-30(3.3\%)}$ (PDFs) pb

C&al $\sigma = 908\,^{+82(9.0\%)}_{-85(9.3\%)}$ (scales) $^{+30(3.3\%)}_{-29(3.2\%)}$ (PDFs) pb

MRSTW-06

M&U $\sigma = 969\,^{-13(1.3\%)}_{-39(4.0\%)}$ (scales) $^{+11(1.1\%)}_{-11(1.1\%)}$ (PDFs) pb

C&al $\sigma = 961\,^{+89(9.2\%)}_{-91(9.4\%)}$ (scales) $^{+11(1.1\%)}_{-12(1.2\%)}$ (PDFs) pb

- Central values within 1%
- PDF uncertainty results agree, and confirm that δ_{PDF} is underestimated
- NNLL scale uncertainty smaller than NLL?

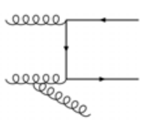
slide by Michelangelo

NLO corrections near the threshold

- NLO correction near partnic threshold : $\hat{s} \sim 4m_t^2,\ \beta \to 0$

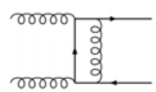
$$\hat{\sigma}_i^{(c),\mathrm{NLO}} \sim \hat{\sigma}_i^{(c),\mathrm{LO}} \left[1 + \frac{\alpha_s}{\pi} \left\{ A_i \ln^2 (8\beta^2) + B_i^{(c)} \ln (8\beta^2) + C_i^{(c)} \frac{\pi^2}{\beta} + D_i^{(c)} + \mathcal{O}(\beta) \right\} \right]$$

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



→ Threshold resummation

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



Hard correction: process dependent

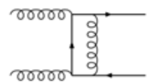
Our focus is here : Hagiwara,Sumino,HY('08)

other literatures : Fadin,Khoze,Sjostrand('90)
Catani,Mangano,Nason,Trentadue('96)
Kiyo,Kuhn,Moch,Steinhauser('09)

- Factorization of each contributions M.Beneke,P.Falgari,C.Schwinn ('09)

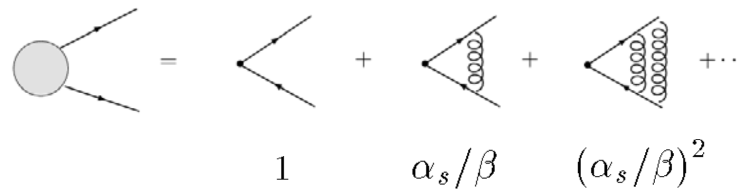
diagonalize in color irreducible representations (singlet,octet,,,)

Coulomb corrections to all-orders

- $\mathcal{O}(\alpha_s) \;\propto C^{(c)}\frac{\alpha_s}{\beta}$  $\mathcal{O}(1)$ for $\beta \simeq \alpha_s$

- Summation of ladder diagrams = Sommerfeld factor   In QED, Sommerfeld,Sakharov,

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



- Non-relativistic treatment near threshold

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

Schrodinger's Equation : 

$$\left[(E+i\Gamma_t) - \left\{-\frac{\nabla^2}{m_t} + V^{(c)}_{QCD}(r)\right\}\right] G^{(c)}(\vec{x}, E+i\Gamma_t) = \delta^3(\vec{x})$$

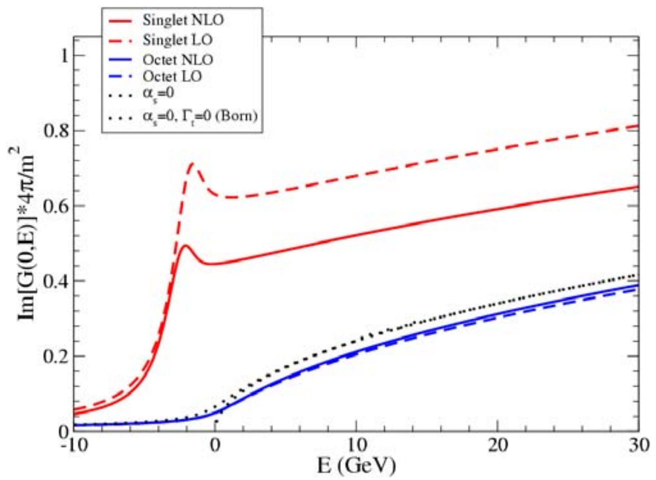
include finite width effects = off-shellness of the constituents

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

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

Coulomb-type with Color-Factors :

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



- Scales : $m_t \gg \mu_B > E_B \simeq \Gamma_t$
  - Bohr radius : $\mu_B \simeq m_t \alpha_s \simeq 20\mathrm{GeV}$ — typical momentum of Coulomb gluon
  - Binding energy : $E_B \simeq m_t \alpha_s^2 \simeq 2\mathrm{GeV}$ — If $\Gamma_t > E_B$, top-quark decays before bound-state formation

Initial-state/Final-state radiation

- ttbar invariant-mass distribution :

$$\sigma_{B,i}^{(c)} = \sigma_{0,i}^{(c)} \cdot \mathrm{Im}[G^{(c)}(\vec{0}, E + i\Gamma_t)]$$

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

$$\tau_0 = m_{tt}^2/s$$

$\mathcal{L}$: partonic luminosity

- Convolution with Initial-state/Final-state radiation

O(α_s) and soft-collinear approximation

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

cf. exact result & Resummation, Kiyo,Keuhn,Moch,Steinhauser('09)

(Near the threshold, O(a_s) is enough, but resummation effect is large for high m_{tt})

- Color-dependent hard-gluon correction : $K_i^{(c)}$

extracted from the NLO Quarkonium production

confirmed by analytical NLO calc. by Czakon,Mitov('08)

Petrelli,Cacciari,Greco,Maltoni,Mangano ('98) + Non-decoupling term HSY('08)

Results : ttbar invariant-mass distribution

m_t=173 GeV, CTEQ6M

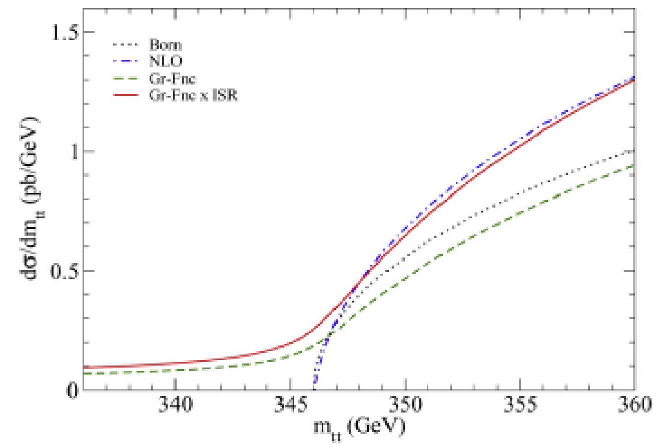
Black : Born

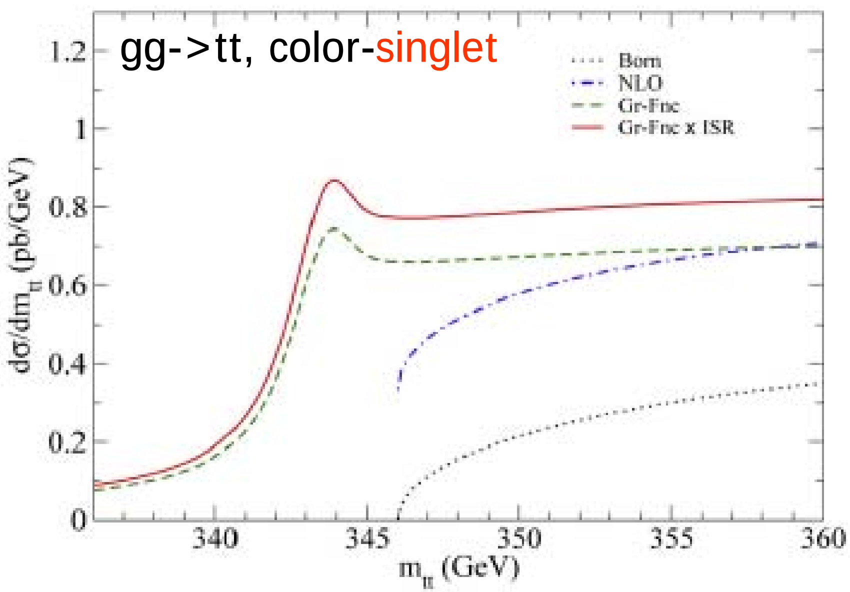
Blue : NLO (soft-collinear approx.)

Green : Gr-Fnc. without ISR

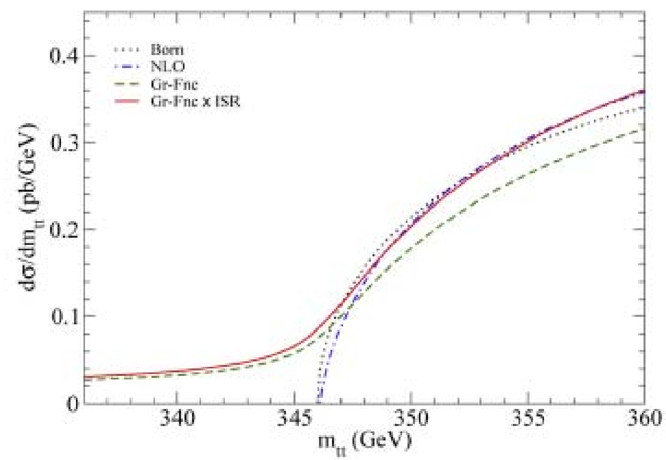
Red : Gr-Fnc. with ISR

gg->tt, color-octet



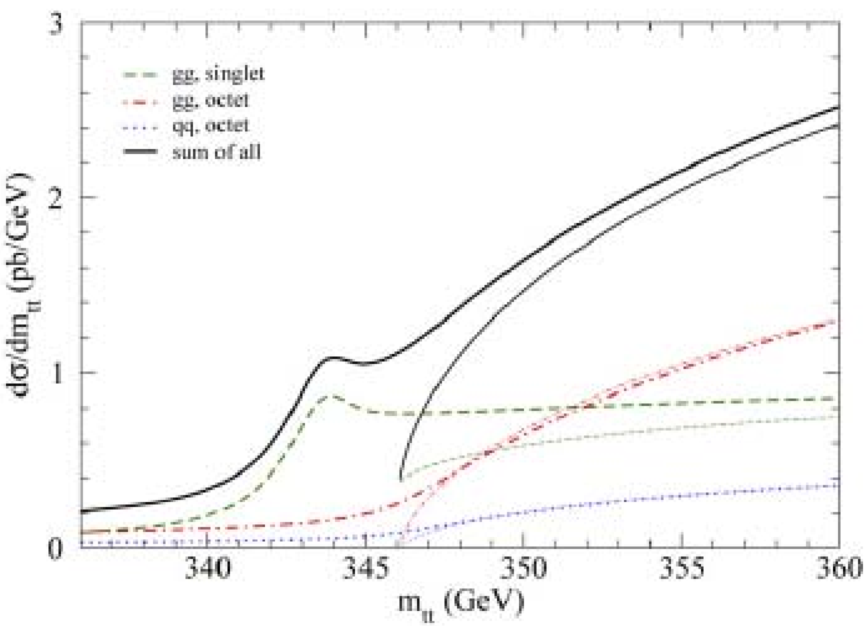


qq->tt, color-octet



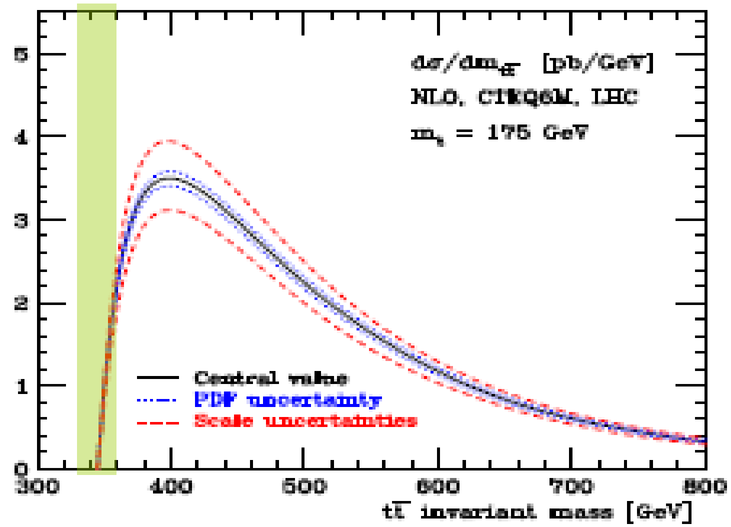
In total at the LHC :

- Resonance peak at $m_{tt} = 2m_t$ - (E_B=2GeV) (observable in principal)
- Deformation of the invariant-mass distribution.



Frederix,Maltoni('08)

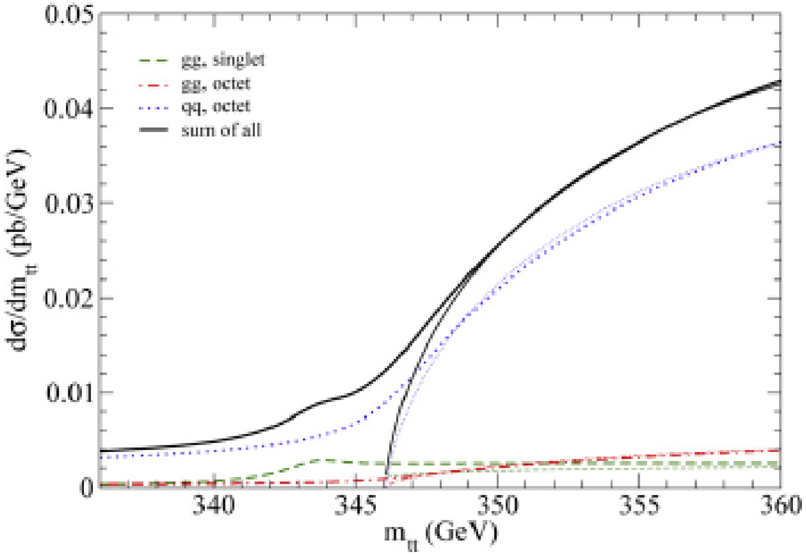
NLO dist. using MCFM (Campbell,Ellis)

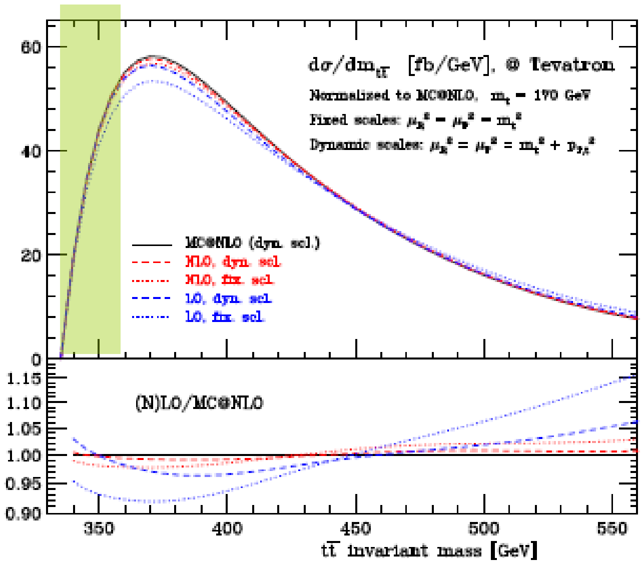


~ 6pb for m_{tt}=336-346 GeV

just 1% of the total ttbar events, but still $6*10^4$ events in $10fb^{-1}$.

At the Tevatron:





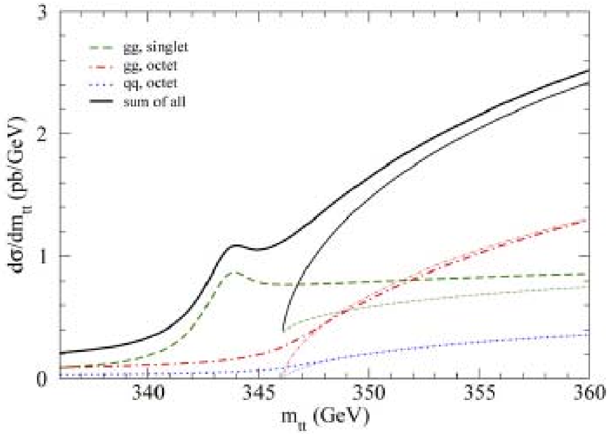
Summary

- Top-quark will be produced copiously at the LHC (8M per 10fb^{-1})
- At the LHC, gluon-fusion process dominates, and the ttbar pair can be color-singlet (while color-octet at the Tevatron).
- Due to the attractive force by Coulomb-gluon exchange, color-singlet ttbar form a broad resonance below the threshold.

✓ Resonance peak at m_{tt} = 2m_t - (E_B=2GeV) (observable in principal)

✓ Deformation of the invariant-mass distribution

✓ ~6pb for m_{tt}=336-346 GeV (1% of total ttb)



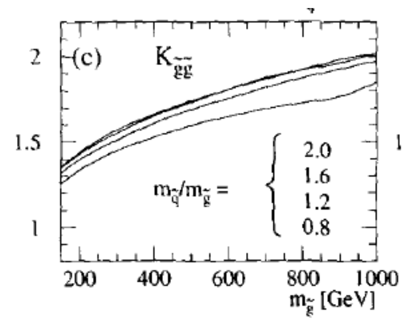
- Application to the gluino-pair production Hagiwara,HY ('09)
  (and also the squark-pair production) Beneke,Falgari,Schwinn ('09)

Gluino-pair production

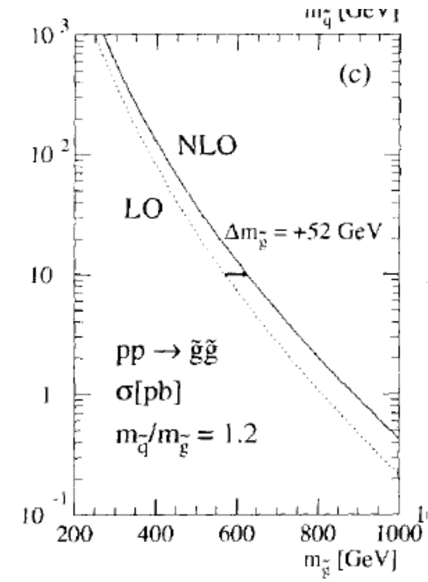
- Gluino pair-production at hadron colliders

NLO : Beenakker,Hopker,Spira,Zerwas ('97)
PROSPINO2, T.Plehn

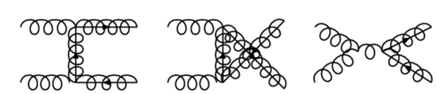
NLL : Kulesza,Motyka ('08,'09)



$$\frac{\sigma_{NLL}}{\sigma_{NLO}} - 1 \sim 0.05 - 0.15$$



- Dominant process is gluion-fusion, up to m_g<1.5 TeV



- What is different from the top-quark :

Majorana Fermion(MSSM), octet color-charge, mass and decay-width

Threshold Log vs. Coulomb corrections :

NLL Threshold resummation and
Coulomb summation by Sommerfeld factor

Kulesza,Motyka ('09)

- Large corrections in gluino production
- Coulomb summation can overtake the threshold resummation

gluino-pair squark-pair

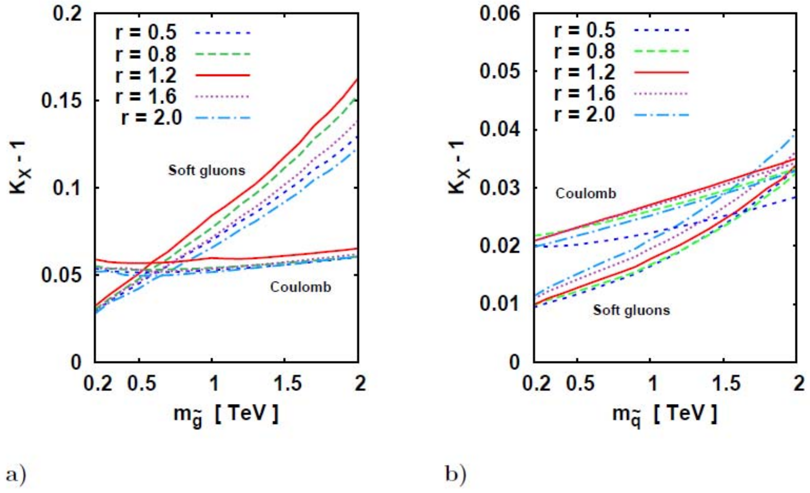


Figure 7: *The relative corrections, $K_{\rm NLL}-1$ and $K_{\rm Coul}-1$, to the NLO cross sections for the $\tilde{g}\tilde{g}$ (a) and the $\tilde{q}\bar{\tilde{q}}$ (b) production at the LHC as a function of gluino and squark mass, respectively; $r = m_{\tilde{g}}/m_{\tilde{q}}$.*

Color structure and Spectroscopy

- Color decomposition (gg→$\tilde{g}\tilde{g}$) :

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{1} \oplus \mathbf{8_S} \oplus \mathbf{8_A} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27}$$

repulsive force

absent in Born-level

attractive force

Color-factor in QCD Potential :

$$V^{(i)}(r) = C_i \frac{\alpha_s}{r}, \quad \text{with} \;\; C_i = \left\{ -C_A, -\frac{C_A}{2}, -\frac{C_A}{2}, 0, 1 \right\}$$

- Gluinonium (Gluinonia) :

Kuhn,Ono(‘84),Goldman,Haber(’85),,,
Kauth,Kuhn,Marquard,Steinhauser, arXiv:0910.2612

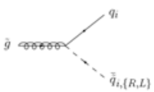
color	symmetric $(\mathbf{1}, \mathbf{8_S}, \mathbf{27})$	anti-symmetric $(\mathbf{8_A})$
$\tilde{g}\tilde{g}$	$^1S_0,\ ^3P_{0,1,2},\ ^1D_2,\ \cdots$	$^3S_1,\ ^1P_1,\ ^3D_{1,2,3},\ \cdots$
$i = gg$	$^1S_0,\ ^3P_{0,\ \ 2},\ ^1D_2,\ \cdots$	$^1P_1,\ ^3D_{1,\ \ 3},\ \cdots$
$i = q\bar{q}$	$^3P_{\ \ 1,2},\ \cdots$	$^3S_1,\ ^3D_{1,2,3},\ \cdots$

only even S+L   odd S+L   due to the Majorana nature

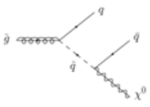
Gluino decay-width

- Physics crucially depends on the decay-width

$m_{\tilde g} > m_{\tilde q}$ $\quad \Gamma_{\tilde g} \simeq \mathcal{O}(10^{0-2})$ GeV



$m_{\tilde g} < m_{\tilde q}$ $\quad \Gamma_{\tilde g} < \mathcal{O}(10^{-1})$ GeV

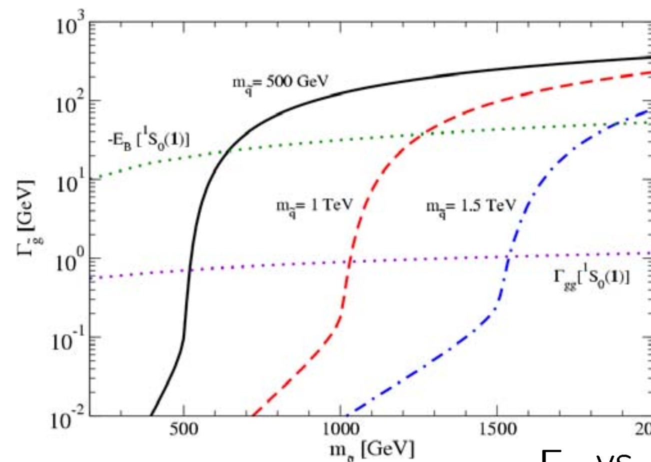


and relation with the other two scales :

- $|E_B| \sim m_{\tilde g} \alpha_s^2$
- $\Gamma_{gg} \propto \alpha_s^2 |\psi(0)|^2 / m_{\tilde g}^2$ with $|\psi(0)|^2 \propto \alpha_s^3 m_{\tilde g}^3$

Assuming 5-flavor massless quarks and common squark mass, and gaugino mass relation; $m_{\tilde g} : m_{\tilde W} : m_{\tilde B} = 7 : 2 : 1$.

Decay into top and stop are neglected.



$\Gamma_{\tilde g}$ vs. $m_{\tilde g}$

$A : \Gamma_{\tilde g} \gtrsim |E_B|$: gluinos decay before they form a bound-state.

$B : |E_B| > \Gamma_{\tilde g} \gg \Gamma_{gg}$: a broad resonance enhancement, similar to the top-quark case.

$C : |E_B| \gg \Gamma_{\tilde g} > \Gamma_{gg}$: few narrow resonances can be formed,
while the decay is dominated by the constituent gluino's decay.

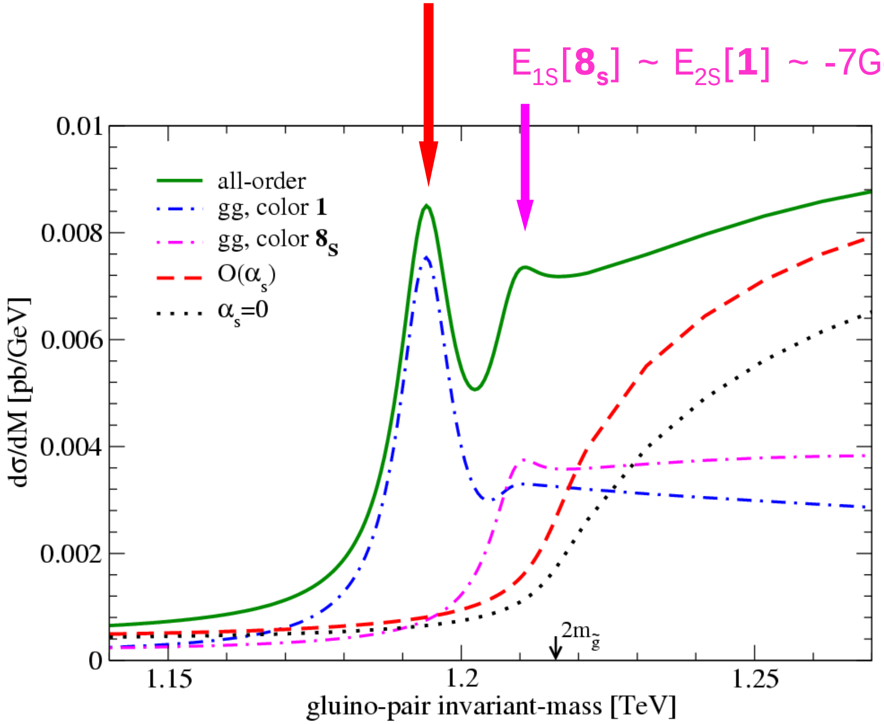
$D : \Gamma_{\tilde g} < \Gamma_{gg}$: dominantly decays into jets, but not in cascade.
If $\Gamma_{\tilde g} < \Lambda_{QCD}$, hadronize and form quite stable bound-states.

Example : SPS1a $m_{\tilde{g}} = 608\ \text{GeV}$ and $\Gamma_{\tilde{g}} = 5.5\ \text{GeV}$ $(m_{\tilde{q}} \simeq 547\ \text{GeV})$

Gluino-pair inv.-mass dist. in threshold region

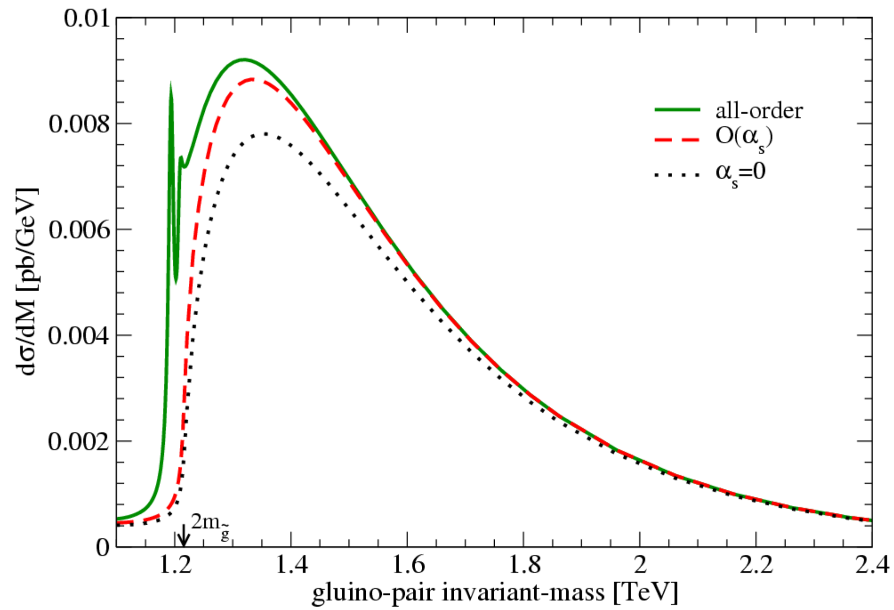
$E_{1S}[\mathbf{1}] \sim -22\text{GeV}$

$E_{1S}[\mathbf{8_s}] \sim E_{2S}[\mathbf{1}] \sim -7\text{GeV}$

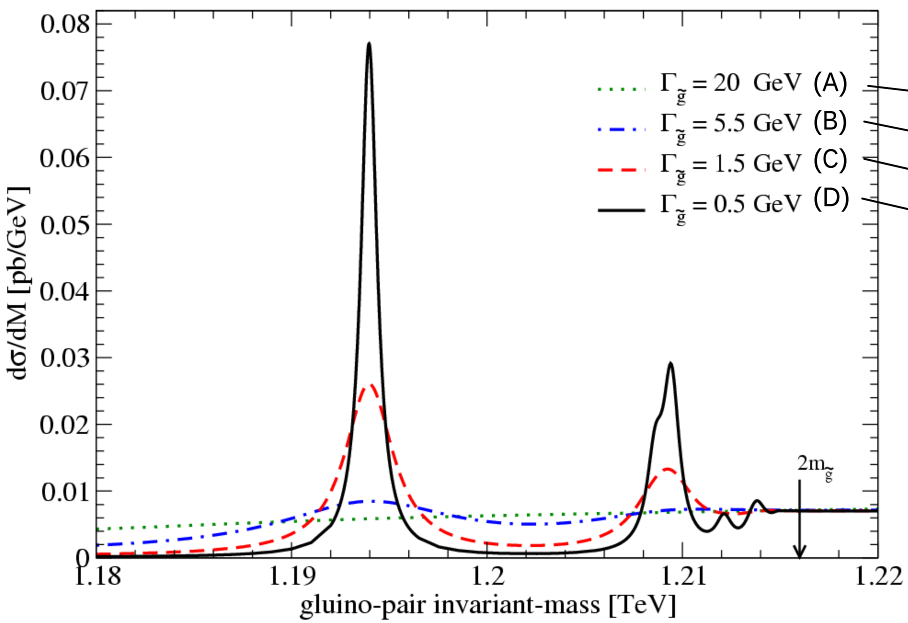


- Enhancement only near the threshold
- Above the threshold is independent of $\Gamma_{\tilde{g}}$

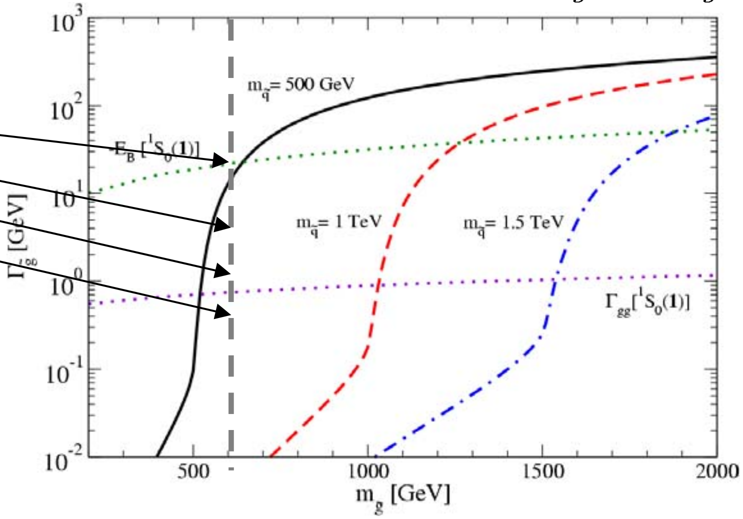
(= Sommerfeld correction), Klesza,Motyka



varying gluino decay-width :



$\Gamma_{\tilde{g}}$ vs. $m_{\tilde{g}}$



$A : \Gamma_{\tilde{g}} \gtrsim |E_B|$

$B : |E_B| > \Gamma_{\tilde{g}} \gg \Gamma_{gg}$

$C : |E_B| \gg \Gamma_{\tilde{g}} > \Gamma_{gg}$

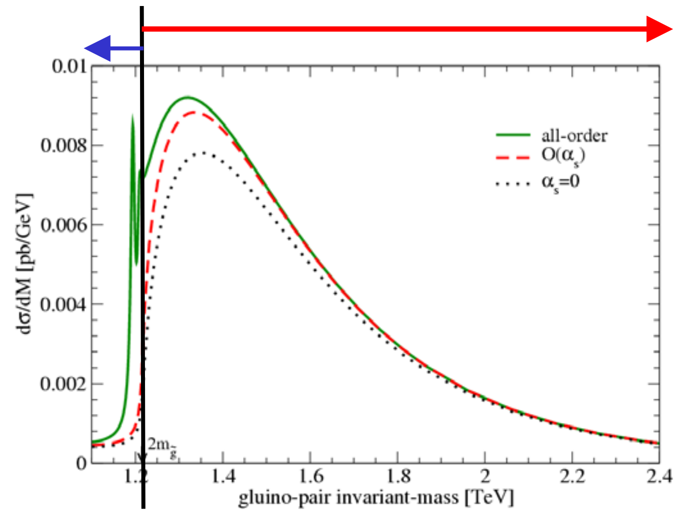
$D : \Gamma_{\tilde{g}} < \Gamma_{gg}$

- More narrower and many resonances for tiny $\Gamma_{\tilde{g}}$.
- For (C)&(D), Non-negligible branching ratio of decay into jets;

$$B((\tilde{g}\tilde{g}) \to gg) \simeq \Gamma_{gg}/(2\Gamma_{\tilde{g}} + \Gamma_{gg})$$

Effect to the Total Cross-section

- How much is the proportion to the total cross-section from below the threshold?



Above threshold : described by Sommerfeld correction.

Below threshold : Resonances + smearing

one of gluinos is off-shell.

4~6% from resonances + $\Gamma_{\tilde{g}}$ smearing

$m_{\tilde{g}}$	A: $\Gamma_{\tilde{g}} = E_B$	B: $\Gamma_{\tilde{g}} = E_B/2$	C: $\Gamma_{\tilde{g}} = 2\Gamma_{gg}$	D: $\Gamma_{\tilde{g}} = \Gamma_{gg}/2$
200 [GeV]	7.5 [4.5]	5.0 [1.8]	4.0 [0.3]	3.9 [0.1]
400 [GeV]	7.1 [4.2]	4.8 [1.7]	3.8 [0.2]	3.8 [0.1]
600 [GeV]	7.2 [4.2]	5.0 [1.7]	3.9 [0.2]	4.2 [0.0]
1 [TeV]	7.9 [4.6]	5.5 [1.8]	4.3 [0.2]	4.4 [0.0]
1.5 [TeV]	9.2 [5.3]	6.3 [2.1]	5.0 [0.2]	5.1 [0.0]
2 [TeV]	10.7 [6.3]	7.4 [2.5]	5.9 [0.2]	5.9 [0.0]

Squark-pair production

M.Beneke,P.Falgari,C.Schwinn ('09)

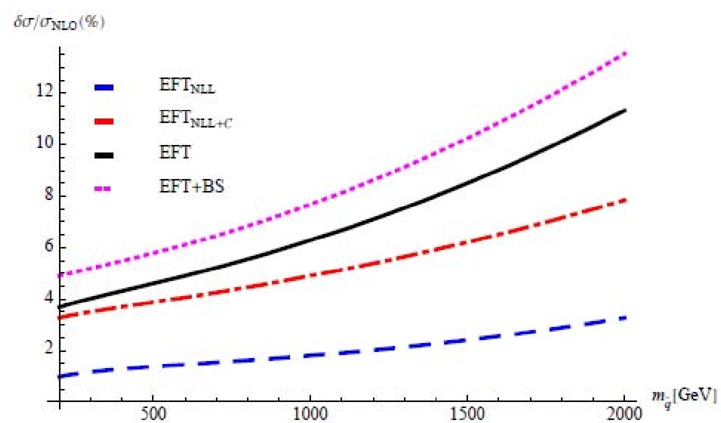
Squark-antisquark resummed cross section

Beneke, PF, Schwinn, PRELIMINARY

- $\mathbf{EFT_{NLL}}$: NLL soft resummation, no Coulomb resummation
- $\mathbf{EFT_{NLL+C}}$: NLL soft resummation **AND** Coulomb resummation (above threshold).
  No soft/Coulomb interference
- **EFT**: NLL soft resummation + Coulomb resummation (above threshold)
  + soft/1st Coulomb interference
- **EFT + BS**: **EFT**+ Bound-state effects

Setup:

- PP@ 14 TeV
- MSTW2008 PDFs
- equal squark masses
- no stops
- $m_{\tilde{g}} = 1.25 m_{\tilde{q}}$
- $\mu_f = m_{\tilde{q}}$



$\mathbf{EFT_{NLL}}$ result agrees well with Kulesza, Motyka '09

slide by P.Falgari (RADCOR 2009)

Differential distributions

- Momentum distribution :

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

modification to the Matrix-Element itself

$$\mathcal{M} \sim \mathcal{M}_0 \cdot \tilde{G}(\vec{p}, E)$$ Green's function in momentum space.

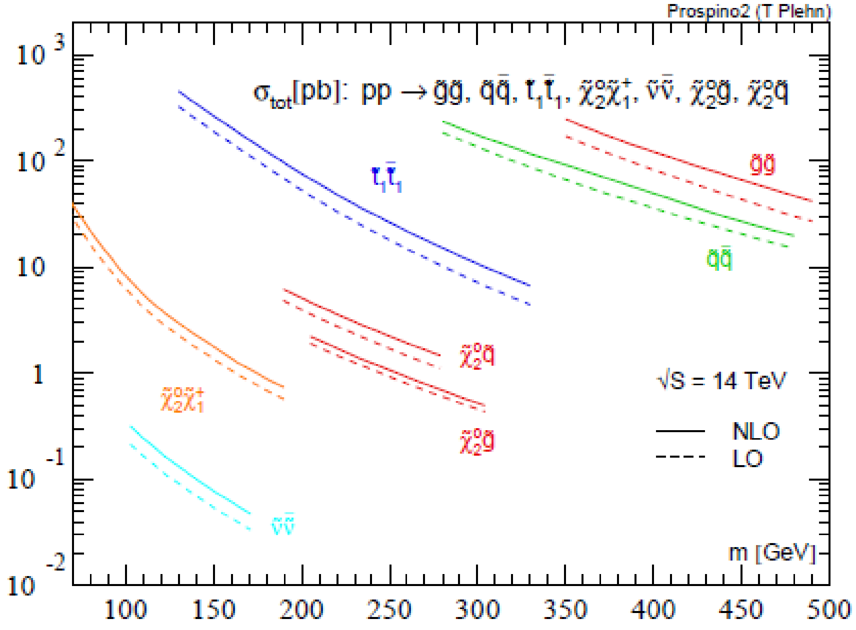
$$\frac{d\sigma}{d^3\vec{p}_t} \propto \left|\tilde{G}(\vec{p}, E)\right|^2 \quad \longleftrightarrow \quad \sigma_{\rm tot} \propto {\rm Im}[G(\vec{0}, E)]$$ (Unitarity of Green's function)

- Toward MC-generation of the resonance events

Off-shell top-quarks → calculate the bWbW production processes

non-resonant diagrams, hard initial-state radiations,,, in progress

- Sparticle productions at the LHC



Plehn, PROSPINO2

Gluino production can be the primary process in sparticle production, even $m_{\tilde{g}} > m_{\tilde{q}}$.

$$\sigma_{\tilde{g}\tilde{g}} > \sigma_{\tilde{q}\tilde{q}}$$