Bound-state effects on gluino-pair production

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in collaboration with Kaoru Hagiwara (KEK)

JHEP0910,049 [arXiv:0909.3204]

IPMU-KEK Theory Center joint Focus week,
“QCD inconnection with BSM study at LHC”, 11/11 (2009), IPMU

Introduction :

- Exploring the physics beyond the SM at the LHC :

  new particles at TeV scale,

  colored particles have large cross-section at Hadron Colliders

- Sparticle productions at the LHC

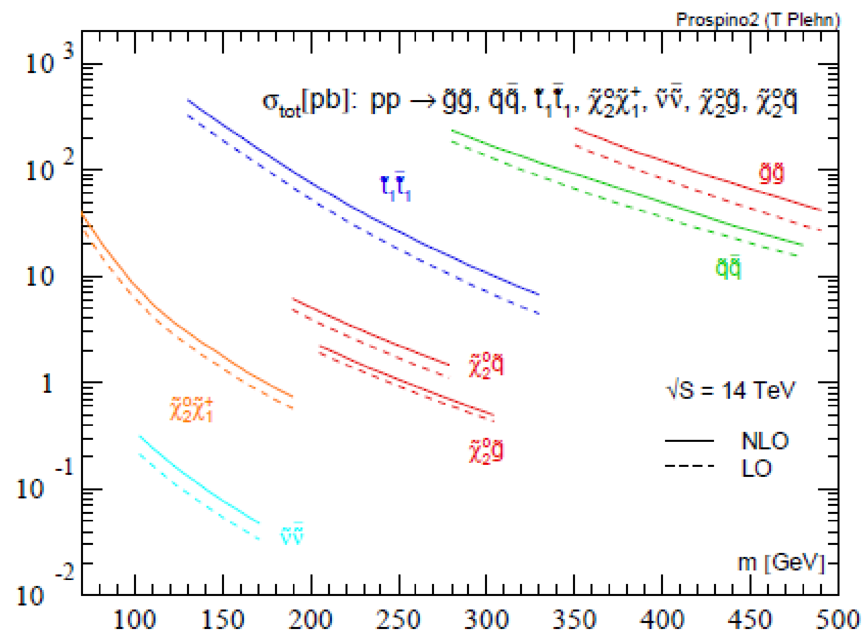
  SUSY-QCD NLO

  Beenakker,Hopker,Spira,Zerwas('96)
  Beenakker,Kramer,Plehn,Spira,Zerwas ('98)

  EW NLO

  Hollik,Kollar,Trenkel('07)
  Hollik,Mirabella('08)
  Hollik,Mirabella,Trenkel('08)
  Mirabella('08)
  Germer,Hollik,Mirabella,Trenkel('09)

  ,,,



Plehn, PROSPINO2

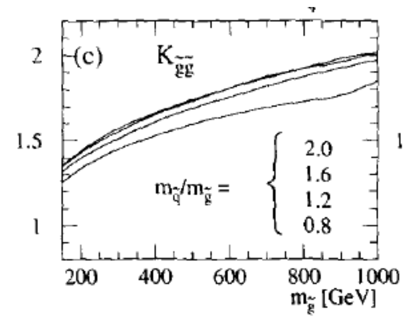
Gluino-pair production

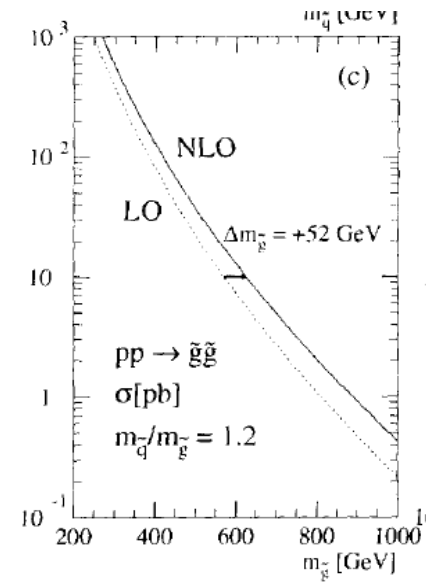
- Gluino pair-production at hadron colliders

  SUSY-QCD NLO :

  Beenakker,Hopker,Spira,Zerwas ('97)

  PROSPINO2, T.Plehn





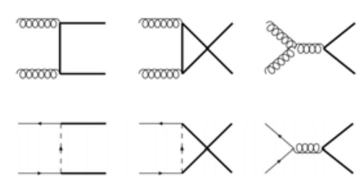
- Beyond the NLO in QCD correction

  Kulesza,Motyka('08,09)

  Resummations of threshold logs & Coulomb singularities

  \+ Bound-state effect

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



- What is different from the top-quark pair production :

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

Color structure and Bound-state spectroscopy

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

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

attractive force ($\mathbf{1}$, $\mathbf{8_S}$, $\mathbf{8_A}$)

absent in Born-level ($\mathbf{10} \oplus \overline{\mathbf{10}}$)

repulsive force ($\mathbf{27}$)

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

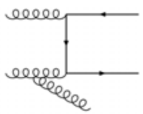
only even S+L — odd S+L — due to the Majorana nature

NLO corrections near the threshold

- NLO correction near partonic threshold : $\hat{s} \sim 4m_{\tilde{g}}^2,\ \beta \to 0$

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

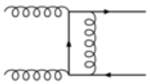
Threshold logs: emission of soft and/or collinear gluon in initial-state and final-state



→ Threshold resummation

NLL; Kulesza,Motyka('08,09)

Coulomb singularity: Coulomb gluon exchange between final-state



Hard correction: process dependent

Our focus is here : Hagiwara,HY('09)

Top-quark case : Fadin,Khoze,Sjostrand('90)
Catani,Mangano,Nason,Trentadue('96)
Hagiwara,Sumino,HY('08)
Kiyo,Kuhn,Moch,Steinhauser('09)

- Factorization of each contributions

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

Coulomb part diagonalizes in the color irreducible representation

Threshold Log vs. Coulomb corrections :

NLL threshold resummation and
Coulomb summation by Sommerfeld factor

Kulesza,Motyka ('09)

$$K_X - 1 = \sigma_X/\sigma_{NLO} - 1$$

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

gluino-pair squark-pair

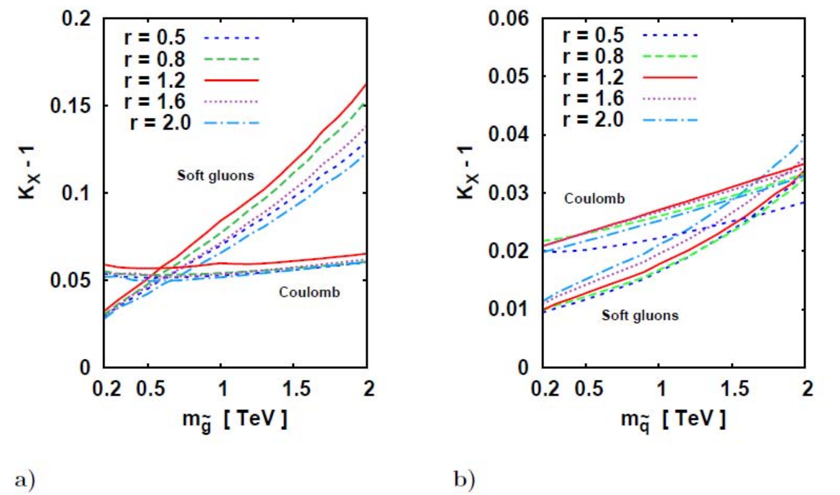
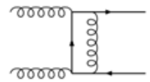


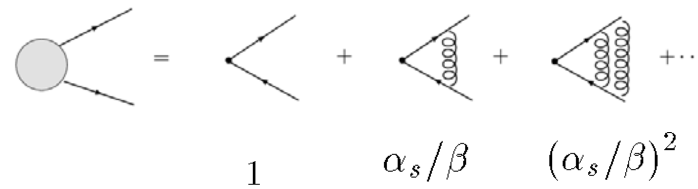
Figure 7: *The relative corrections, $K_{\rm NLL} - 1$ and $K_{\rm Coul} - 1$, to the NLO cross sections for the $\tilde{g}\tilde{g}$ (a) and the $\tilde{q}\bar{\tilde{q}}$ (b) production at the LHC as a function of gluino and squark mass, respectively; $r = m_{\tilde{g}}/m_{\tilde{q}}$.*

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 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 : 

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

include finite width effects = off-shellness of the constituents $\leftarrow \Gamma_{\tilde{g}}$

- Scales involved :

  - Bohr radius : $1/r_B \simeq C\alpha_s m_{\tilde{g}}/2$ typical momentum of Coulomb gluon
  - Binding energy : $E_B \simeq -(C\alpha_s)^2 m_{\tilde{g}}/4$ $\alpha_s \to \alpha_s(1/r_B)$
  - Annihilation decay-width : $\Gamma_{gg} \simeq (C\alpha_s)^5 m_{\tilde{g}}/4$
  - Decay width : $\Gamma_{\tilde{g}}$

- Perturbative QCD potential, since the deep binding energy and IR-cut

$$V_{\rm QCD}^{(c)}(r) = C^{(c)}\frac{\alpha_s(\mu_B)}{r} \times \left[1 + \frac{\alpha_s}{\pi} v_1^{(c)}(r) + \cdots\right] \quad \text{with } C_i = \left\{-C_A, -\frac{C_A}{2}, -\frac{C_A}{2}, 0, 1\right\}$$

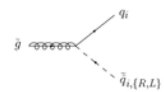
NLO

Gluino decay-width

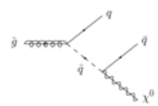
- Physics crucially depends on the decay-width

Estimate the decay width into Bino or Wino through the squarks Barnett,Gunion,Haber('88),,,

$m_{\tilde{g}} > m_{\tilde{q}}$ $\Gamma_{\tilde{g}} \simeq \mathcal{O}(10^{0-1})$ GeV

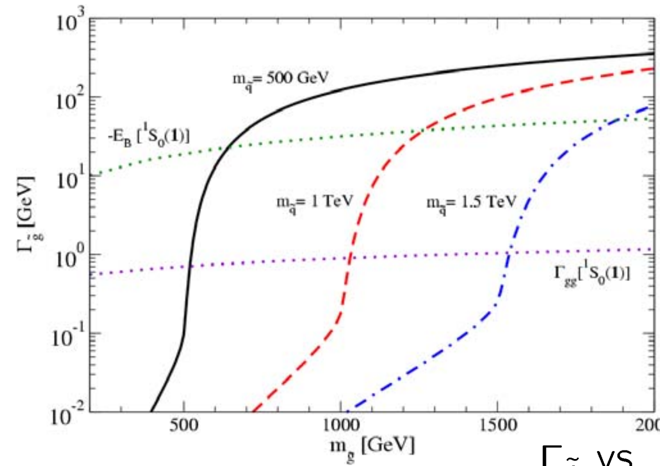


$m_{\tilde{g}} < m_{\tilde{q}}$ $\Gamma_{\tilde{g}} < \mathcal{O}(10^{-1})$ GeV



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

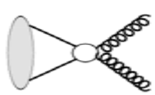
Decay into top and stop are neglected.



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

and relation with the other two scales :

- Binding energy : $|E_B| \simeq C_A^2 m_{\tilde{g}} \alpha_s^2/4$
- Annihilation decay-width : $\Gamma_{gg} \propto C_A^2 \alpha_s^2 |\psi(0)|^2 / m_{\tilde{g}}^2$ with $|\psi(0)|^2 \propto \alpha_s^3 m_{\tilde{g}}^3$



hidden gluino → no cascade decay

Gluino decay-width (2)

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

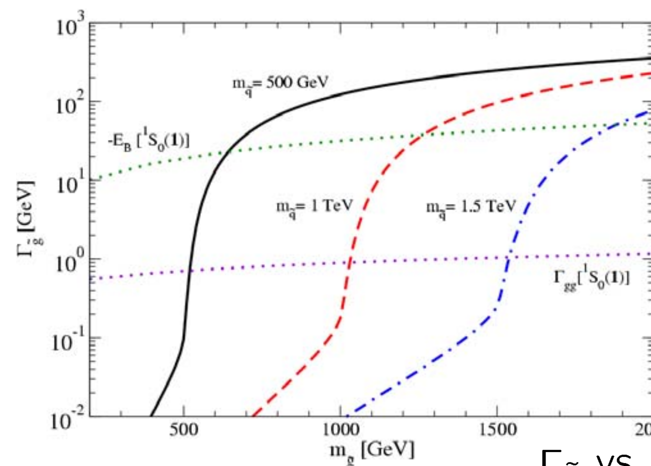
$B : |E_B| > \Gamma_{\tilde{g}} \gg \Gamma_{gg}$: a broad resonance enhancement, similar to the top-quark case.

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

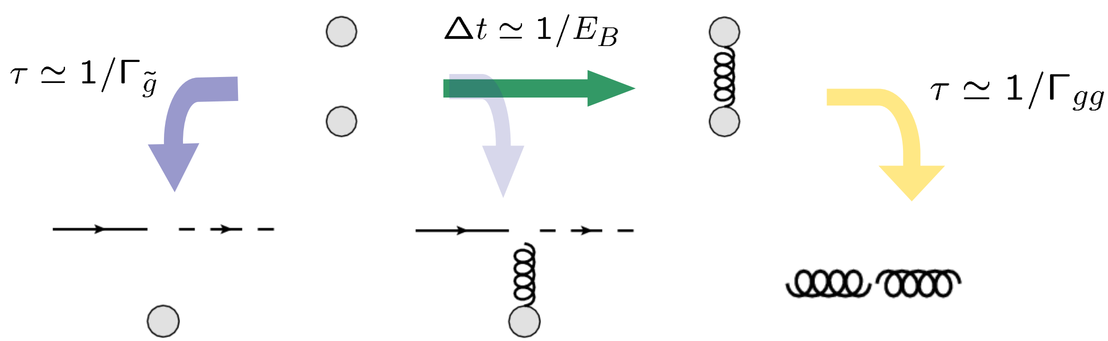
$D : \Gamma_{\tilde{g}} < \Gamma_{gg}$: dominantly decays into jets, but not in cascade. If $\Gamma_{\tilde{g}} < \Lambda_{QCD}$, it hadronizes.

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. $m_{\tilde{g}}$



Gluino decay-width (3)

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

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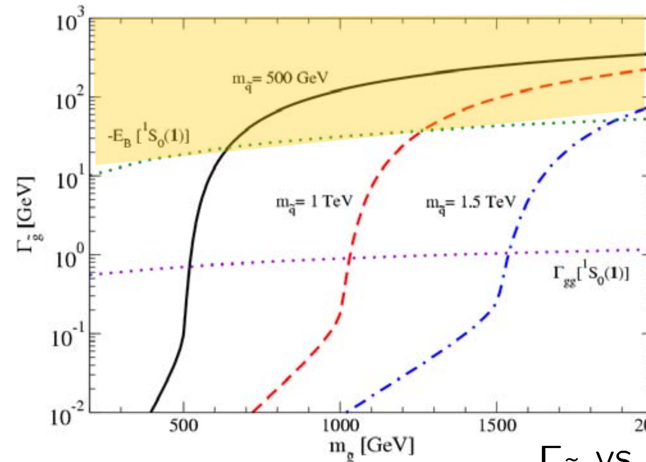
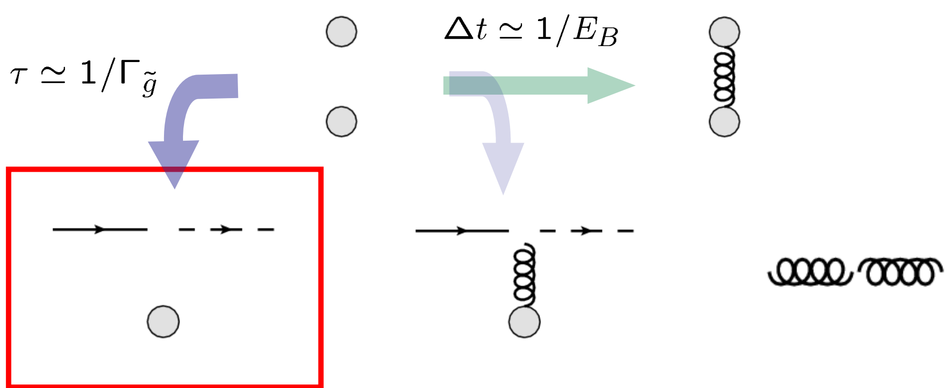


$\Gamma_{\tilde{g}}$ vs. $m_{\tilde{g}}$



Gluino decay-width (4)

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

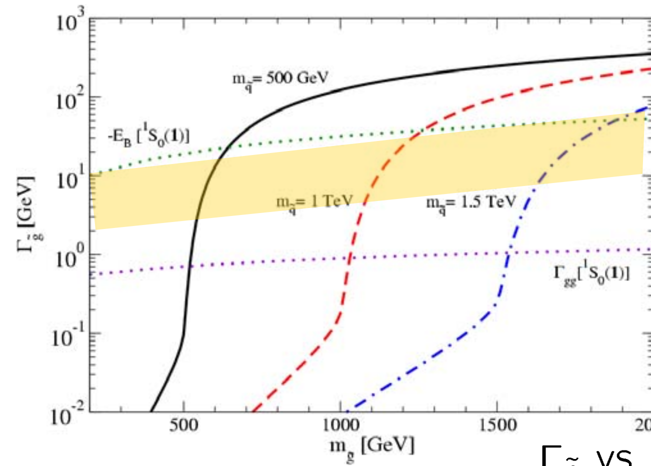
$B : |E_B| > \Gamma_{\tilde{g}} \gg \Gamma_{gg}$: a broad resonance enhancement, similar to the top-quark case.

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

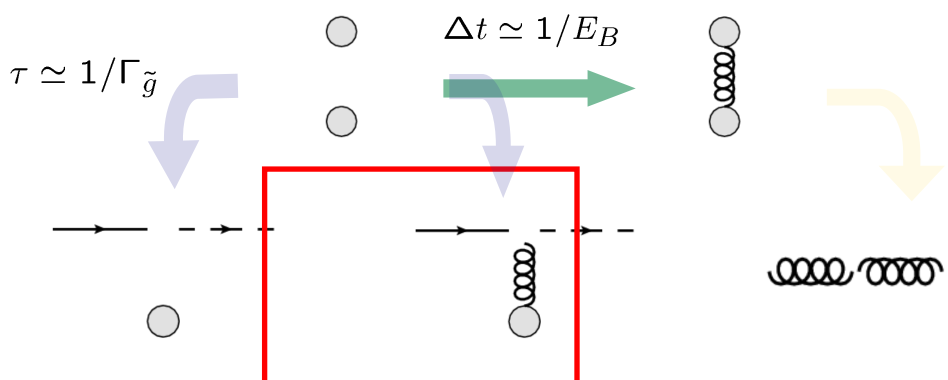
$D : \Gamma_{\tilde{g}} < \Gamma_{gg}$: dominantly decays into jets, but not in cascade. If $\Gamma_{\tilde{g}} < \Lambda_{QCD}$, it hadronizes.

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. $m_{\tilde{g}}$



Gluino decay-width (5)

$A : \Gamma_{\tilde{g}} \gtrsim |E_B|$: 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 $\Gamma_{\tilde{g}} < \Lambda_{QCD}$, it hadronizes.

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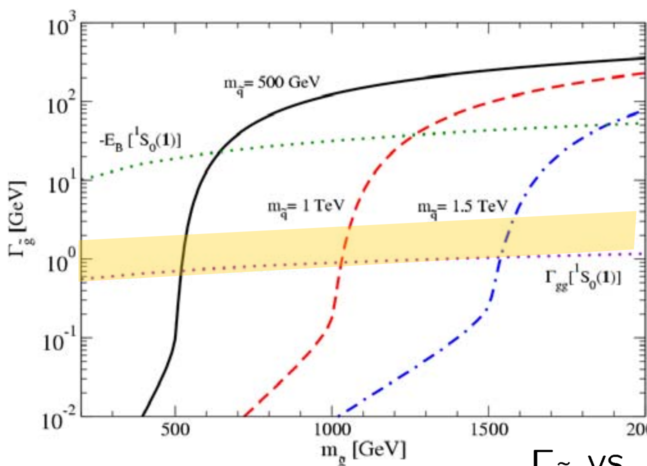
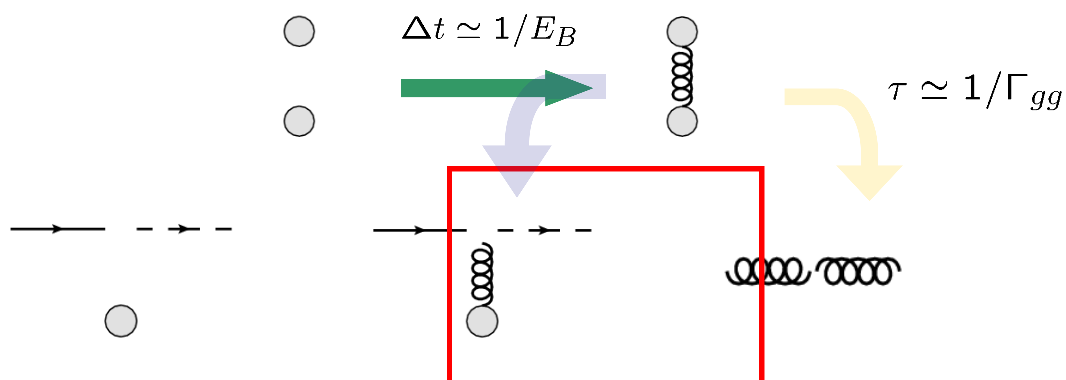
Decay into top and stop are neglected.



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



Gluino decay-width (6)

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

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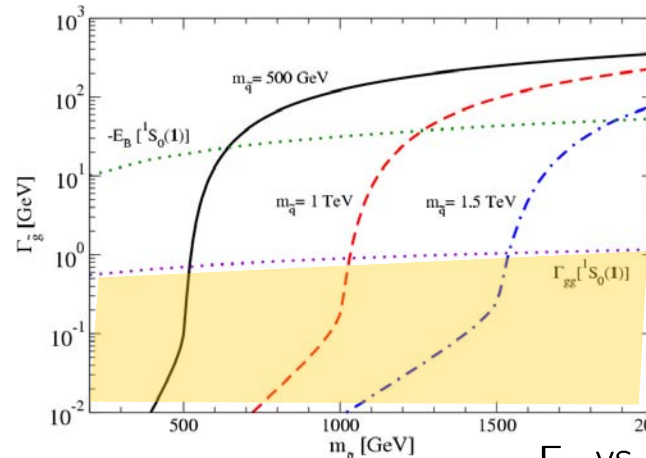
$C : |E_B| \gg \Gamma_{\tilde{g}} > \Gamma_{gg}$: few narrow resonances can be formed, while the decay is dominated by the constituent gluino's decay.

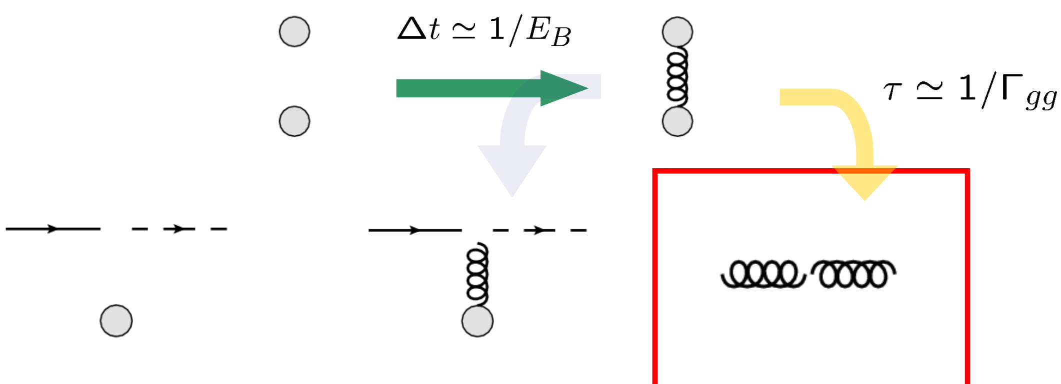
$D : \Gamma_{\tilde{g}} < \Gamma_{gg}$: dominantly decays into jets, but not in cascade. If $\Gamma_{\tilde{g}} < \Lambda_{QCD}$, it hadronizes.

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

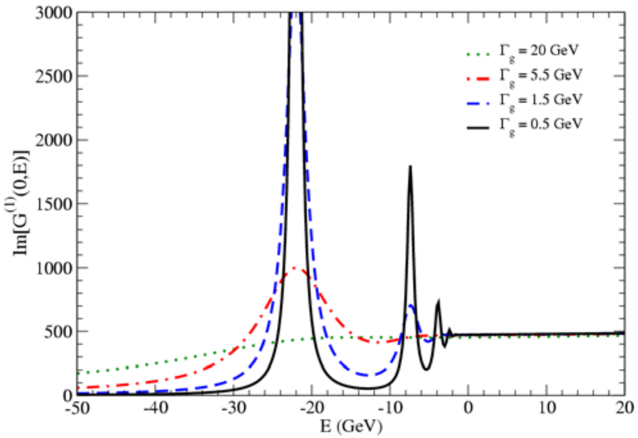
Decay into top and stop are neglected.



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



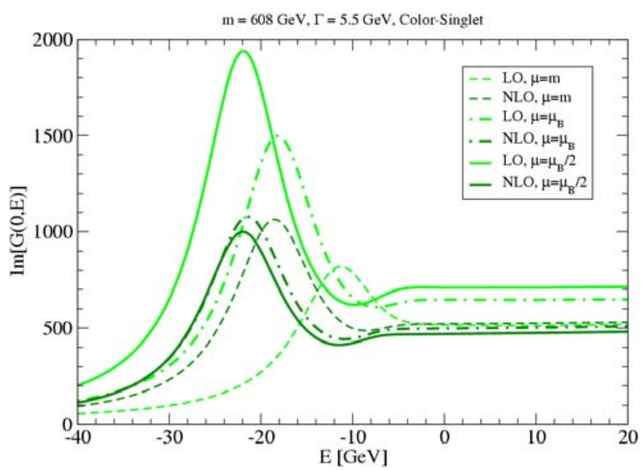
- Green's function (color-singlet)



- Width dependence

E.g. $m_{\tilde{g}} = 608$ GeV

Above the threshold,
small dependence on the width
= Sommerfeld correction



- **LO** vs. **NLO** & scale dependence

Dashed : $\mu = m_{\tilde{g}}$
Dot-dashed : $\mu = 1/r_B$
Solid : $\mu = \mu_B \equiv 1/2r_B$

Initial-state/Final-state radiation

- Gluino-pair invariant-mass distribution :

$$M^2 = (p_{\tilde{g}_1} + p_{\tilde{g}_2})^2$$

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

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

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

$\mathcal{L}$: partonic luminosity

- Convolution with Initial-state/Final-state radiation

O(α_s) and soft-collinear approximation

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

- Hard-gluon correction : $K_i^{(c)} = 1 + \frac{\alpha_s}{\pi} h_{i,1}^{(c)}$

Matching with the NLO calc. at threshold

- Color dependence is neglected, but the averaged one is obtained

Gluino-pair invariant-mass distribution

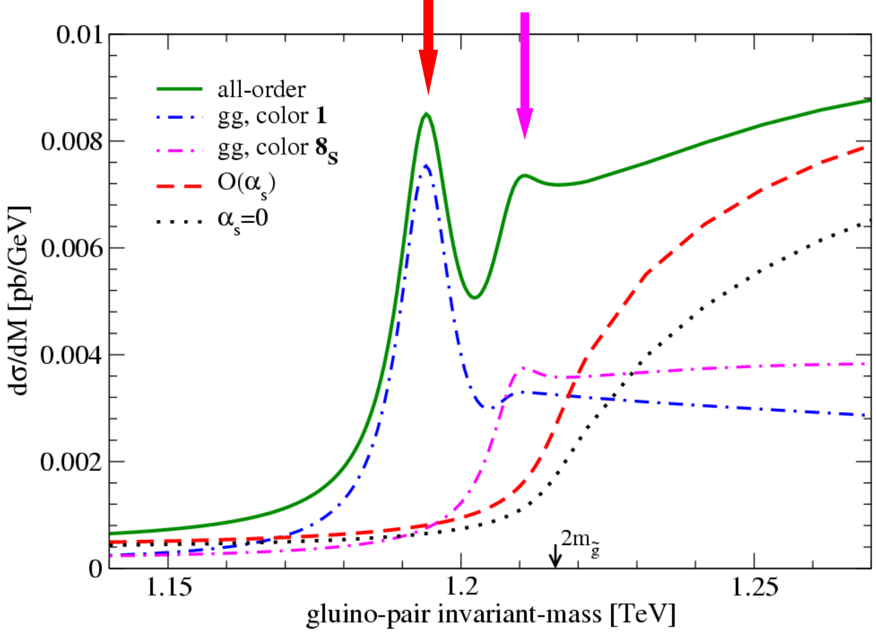
Example : SPS1a $m_{\tilde{g}} = 608$ GeV and $\Gamma_{\tilde{g}} = 5.5$ GeV ($m_{\tilde{q}} \simeq 547$ GeV)

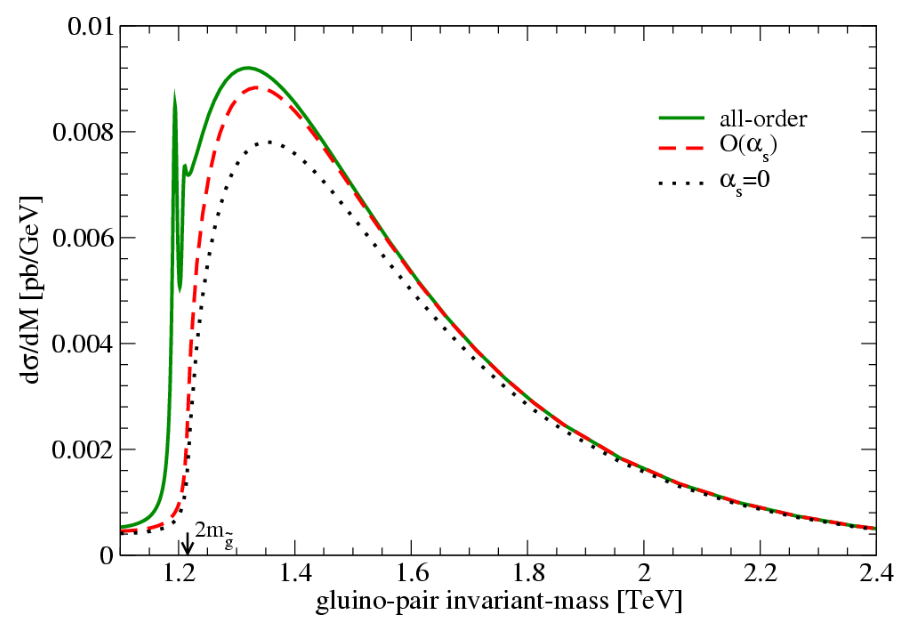
Gluino-pair inv.-mass dist. in threshold region

- Enhancement only near the threshold
- Above the threshold is independent of $\Gamma_{\tilde{g}}$ (= Sommerfeld correction), Klesza,Motyka

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

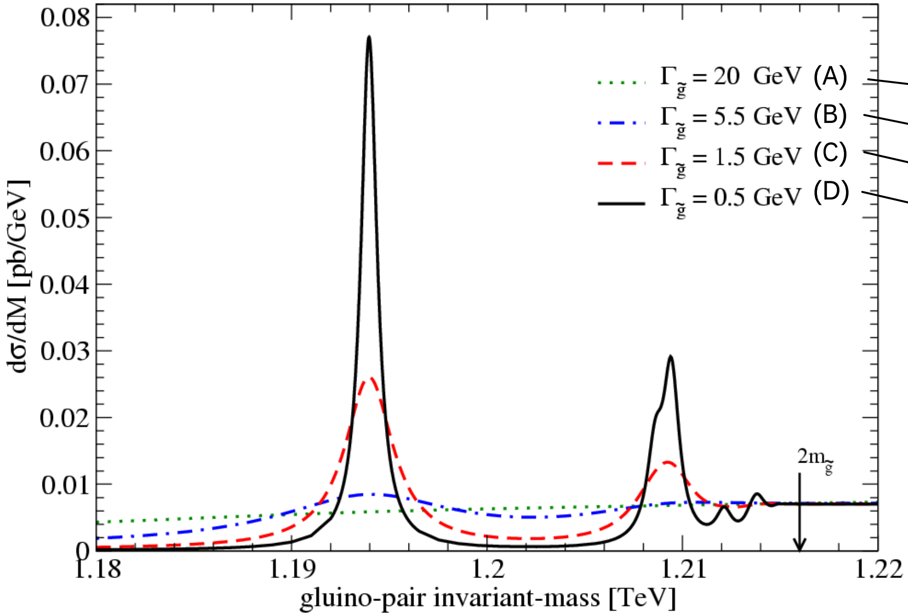
$E_{1S}[\mathbf{8_s}] \sim E_{2S}[\mathbf{1}] \sim -7$GeV



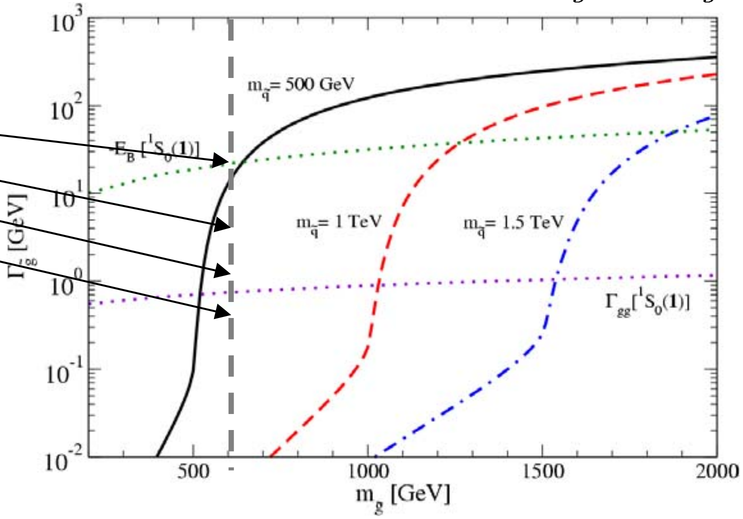


Gluino-pair invariant-mass distribution

- 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;

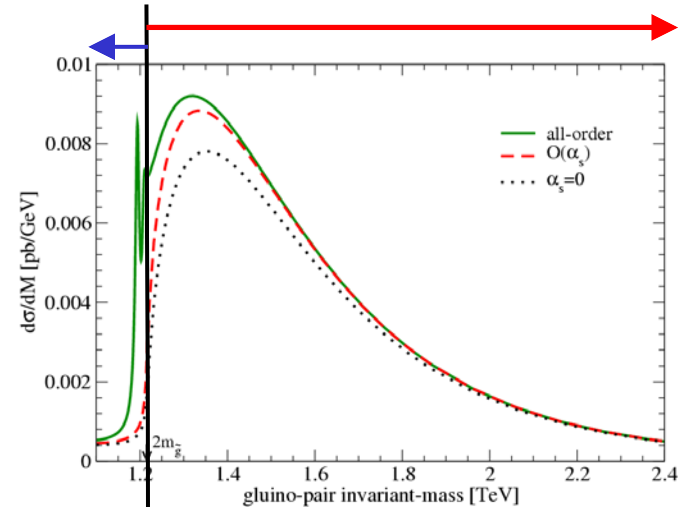
$$B((\tilde{g}\tilde{g}) \to gg) \simeq \Gamma_{gg}/(2\Gamma_{\tilde{g}} + \Gamma_{gg})$$

Effect to the Total Cross-section

Above threshold : described by Sommerfeld correction.
independent of $\Gamma_{\tilde{g}}$

Below threshold : Resonances + smearing.

One of gluinos is in off-shell.



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

4～6％ from resonances + smearing by finite-width effect

$m_{\tilde{g}}$	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

[Bigi,Fadin,Khoze(92)]
M.Beneke,P.Falgari,C.Schwinn ('09)

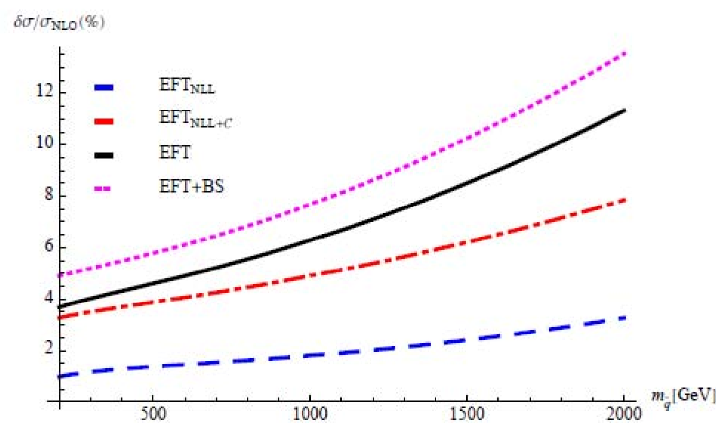
Squark-antisquark resummed cross section

Beneke, PF, Schwinn, PRELIMINARY

- $\mathbf{EFT}_{\mathbf{NLL}}$: NLL soft resummation, no Coulomb resummation
- $\mathbf{EFT}_{\mathbf{NLL+C}}$: 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
- $m_{\tilde{g}} = 1.25 m_{\tilde{q}}$
- $\mu_f = m_{\tilde{q}}$



BS effect 1~2%

interference between soft/1st Coulomb

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

Pietro Falgari (IPPP) RADCOR 2009 12 / 15

slide by P.Falgari (RADCOR 2009)

Summary :

- Sparticles production at the LHC → Heavy, colored particles
  → anticipate sizable QCD corrections beyond NLO

- Summations of soft/collinear gluon & Coulomb gluon corrections :

  Coulomb gluon → Bound-state effects below the threshold

  - 4~6% for gluino pair
  - 1~2% for squark pair
  - (1% for top-quark pair)

- Deform the pair invariant-mass distribution :

  Resonances structure, enhancement around the threshold, smearing by the finite-width

  crucially depend on the gluino decay-width

Kauth,Kuhn,Marquard,Steinhauser, arXiv:0910.2612

for stable gluinos; $\Gamma_{\tilde{g}} \to 0$ cf. Split-SUSY

- Gluinonia using NNLO potential

pole mass scheme with →

$$\mu_S = m_{\tilde{g}} C_A \alpha_s(\mu_S)$$

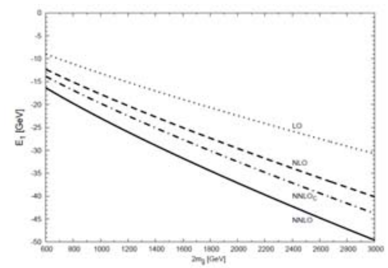


Figure 3: Ground state energy E_1 in the pole mass scheme as function of twice the constituent mass.

Potential Subtracted scheme

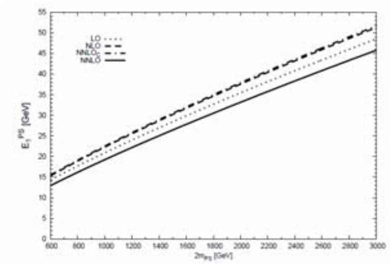


Figure 4: Ground state energy E_1 in the potential subtracted mass scheme as function of twice the potential subtracted mass. The curves have been obtained using the pole mass as input and evaluating both the potential subtracted mass (using Eq. (7)) and E_1^{PS} to a given order in α_s. Note that the dash-dotted and dashed curves are almost on top of each other.

also corrections to the wave-function at the origin

$\mu = 2m_{\tilde{g}}$

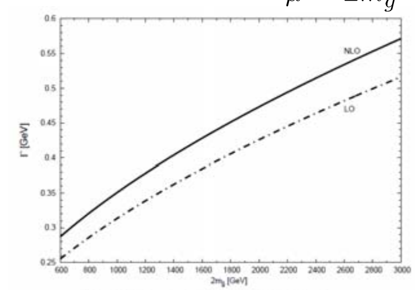


Figure 9: Decay rate of the 1S state into gluons.

- Production and decay at NLO

- Decay ratio to ttbar, two photons ~ few percent, 10^{-5}

- Signal-to-Background ratio in dijet decay ~ 0.5 %

Results : ttbar invariant-mass distribution

m_t=173 GeV, CTEQ6M

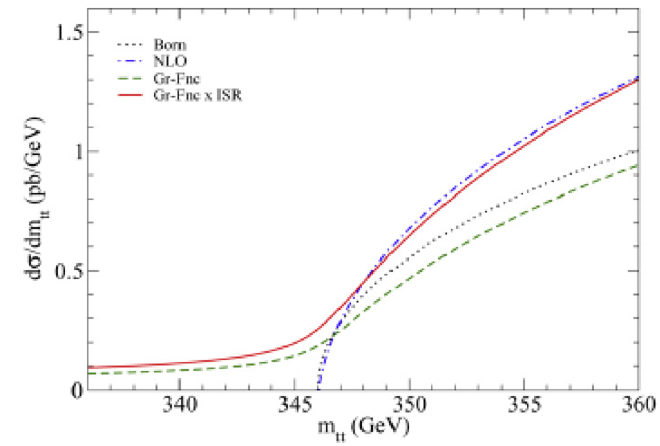
Black : Born

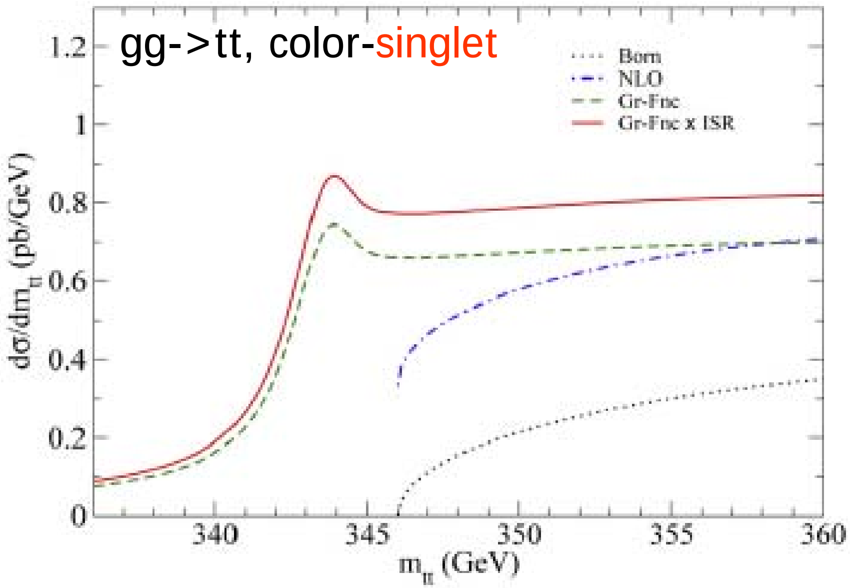
Blue : NLO (soft-collinear approx.)

Green : Gr-Fnc. without ISR

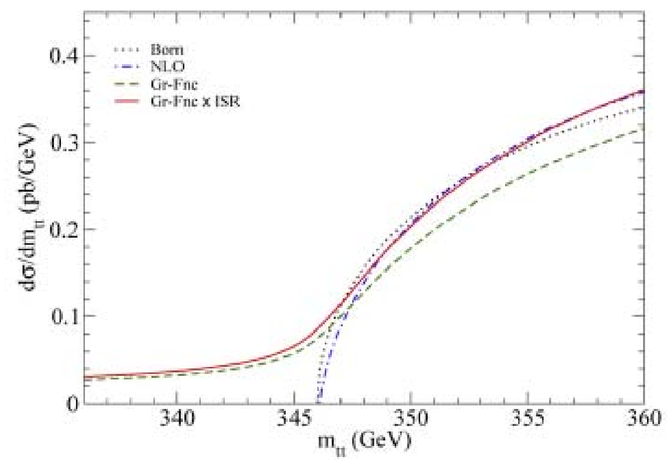
Red : Gr-Fnc. with ISR

gg->tt, color-octet



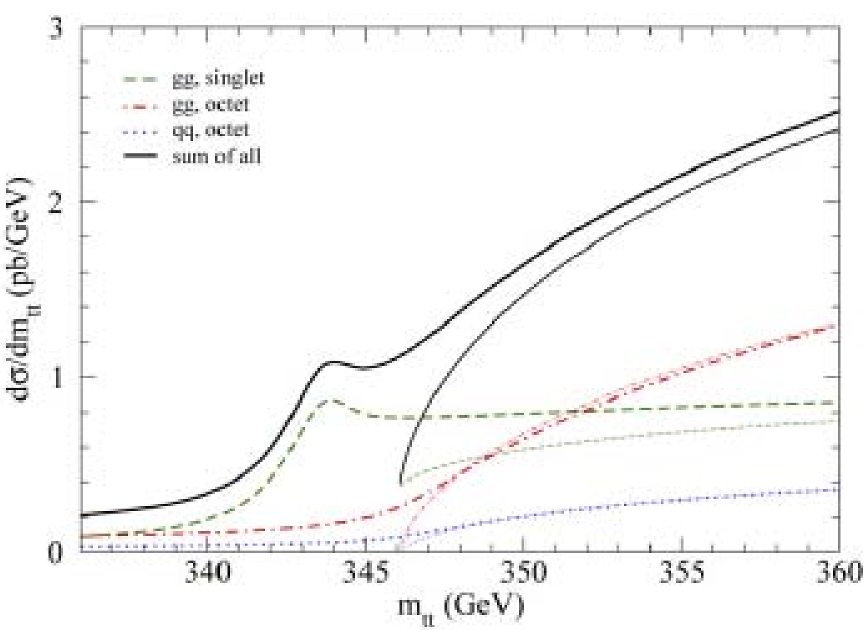


qq->tt, color-octet



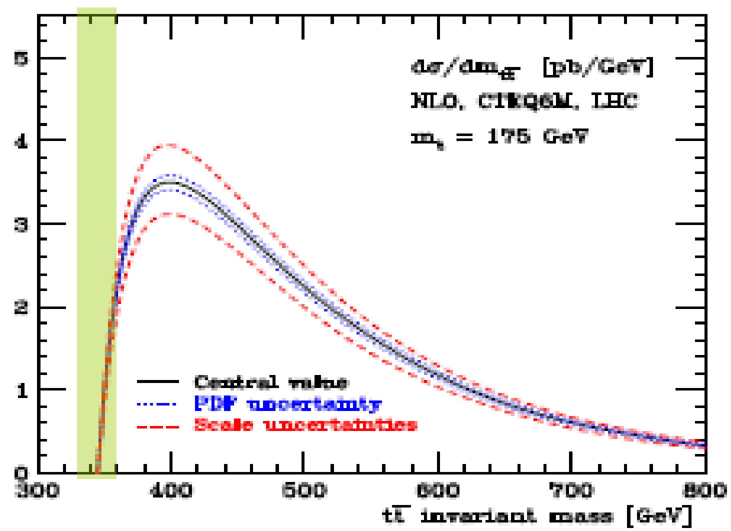
In total at the LHC :

- 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: