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

Hiroshi Yokoya (University of Toyama)

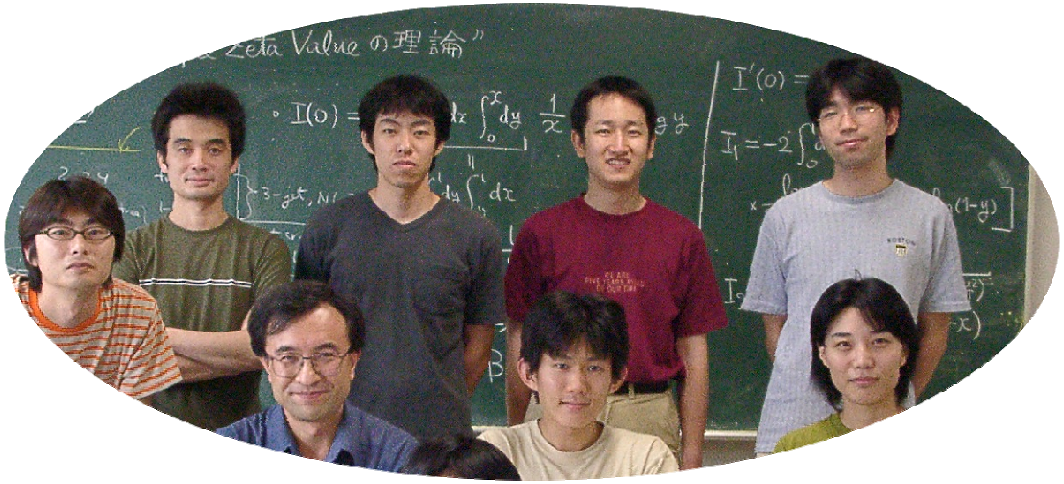
based on the papers done with Kaoru Hagiwara, Yukinari Sumino, etc.

KAERU Conf., IPMU, Kashiwa, March 25-26, 20155

# Collider School on 2001.7.2-7 at KEK



My collaboration with Kaoru began from a collider school he gave to grad. students and posdocs, when I was in a second year of master course at Hiroshima Univ.



**Lecturers**: **Kaoru Hagiwawa**, Y. Sumino, J. Kanzaki ,,,

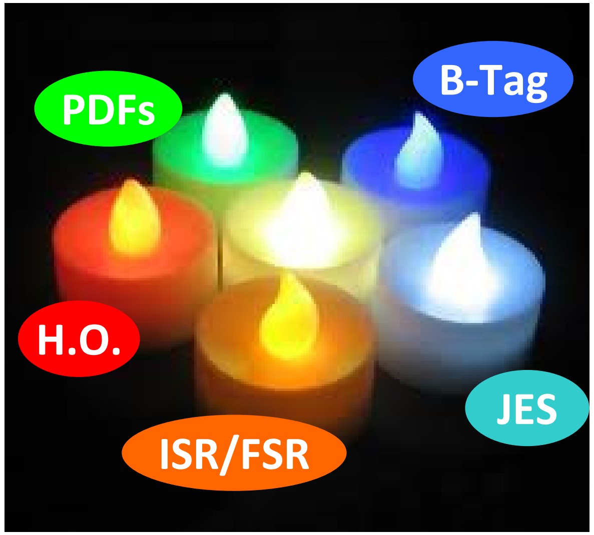
**Students**: M. Aoki, E. Asakawa, K. Hamaguchi, R. Kitano,
K. Mawatari, D. Nomura, N. Okamura, T. Yamashita, H.Y. ,,,

Since then till now, I learned many things on particle physics, colliders, etc.

In addition, it has been my great pleasure to work with Kaoru on tau polarization (w/ K. Mawatari, M. Aoki), T-odd asymmetry (w/ K. Hikasa, K. Mawatari, R. Frederix, T. Yamada), ttbar bound-state (w/ Y. Sumino), etc.

I thank Kaoru very much!

# Top quark production at colliders



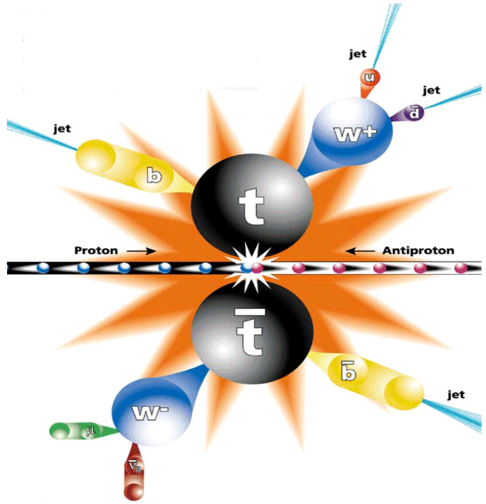

## Top as a standard candle for BSM searches

- Large top quark production rates at the LHC;

$$\boxed{\sigma_{t\bar{t}} \simeq 1 \text{ nb},}\ \sigma_t \simeq 300 \text{ pb},\ \sigma_{t\bar{t}h} \simeq 1 \text{ pb}.$$

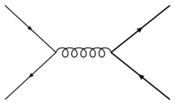
- Regarded as a standard candle process
  [PDFs, ISR/FSR, JES, B-tag, MET, Higher-orders, Spin,,,]

- Or, perhaps, "Top as a window to BSM physics"
  due to its large Yukawa coupling to the Higgs boson.

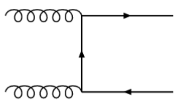



## Pair production at hadron colliders

$$\begin{cases} q\bar{q} \to t\bar{t} \\ gg \to t\bar{t} \end{cases}$$



85% at Tevatron — Color-Octet, J=1



90% at LHC — Color-Singlet or Octet, J=0,1,2,,

# Perturbative QCD calculation

## Factorization theorem:

$$\sigma_{\mathrm{pp}\to \mathrm{t\bar{t}X}}(s) = \sum_{ij} \int dx_1 f_{i/p}(x_1,\mu_F) dx_2 f_{j/p}(x_2,\mu_F) \hat{\sigma}_{ij\to t\bar{t}}(\hat{s},\mu_F)$$

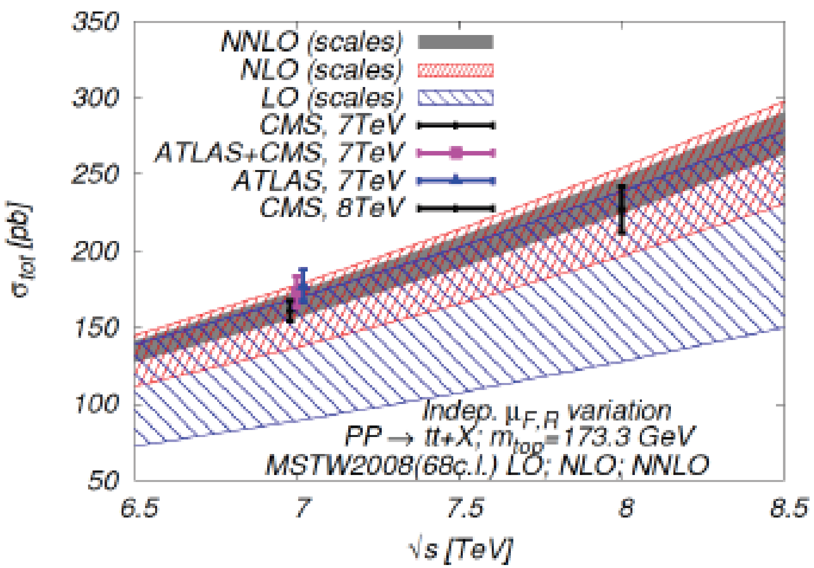
- Fixed order calculation:

LO

NLO : Nason,Dawson,Ellis(88),,,

$$\hat{\sigma}(\hat{s},\mu_F) = \alpha_s^2(\mu_R)\hat{\sigma}^{(0)}(\hat{s}) + \alpha_s^3(\mu_R)\hat{\sigma}^{(1)}(\hat{s},\mu_R,\mu_F) + \alpha_s^4(\mu_R)\hat{\sigma}^{(2)}(\hat{s},\mu_R,\mu_F) + \cdots$$

NNLO : ,,, ; Bernreuther,Czakon,Mitov(12); Czakon,Fieldler,Mitov(13)




**Uncertainties:**

| | |
|---|---|
| Scales | ~ 3% |
| pdf (at 68%cl) | ~ 2-3% |
| $\alpha_s$ (parametric) | ~ 1.5% |
| $m_{top}$ (parametric) | ~ 3% |

c.f. Lumi. uncertainty ~ 3% at LHC8TeV

# QCD Resummation

$$\beta = \sqrt{1 - 4m_t^2/m_{tt}^2}$$

top velocity in the tt c.m. frame.

- Structure of higher order corrections:

$$\begin{cases} \text{NLO:} & \hat{\sigma}_a^{(1)} \simeq \hat{\sigma}_a^{(0)} \times \left[A_a^{(1)} \ln^2\beta + B_a^{(1)} \ln\beta + C_a^{(1)}/\beta + D_a^{(1)}\right] \\ \text{NNLO:} & \hat{\sigma}_a^{(2)} \simeq \hat{\sigma}_a^{(0)} \times \left[\underbrace{A_a^{(2)} \ln^4\beta + A_a^{\prime(2)} \ln^3\beta + \cdots}_{\text{Threshold logs}} + \underbrace{C_a^{(2)}/\beta^2}_{\text{Coulomb singularities}} + \cdots + D_a^{(2)}\right] \end{cases}$$

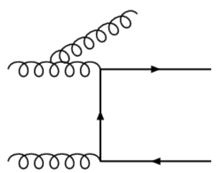
$(a = q\bar{q},\ gg)$

Threshold logs
→ **Threshold resummation**

Coulomb singularities
→ **Coulomb resummation**

Thre. logs: soft/collinear gluon from IS/FS.

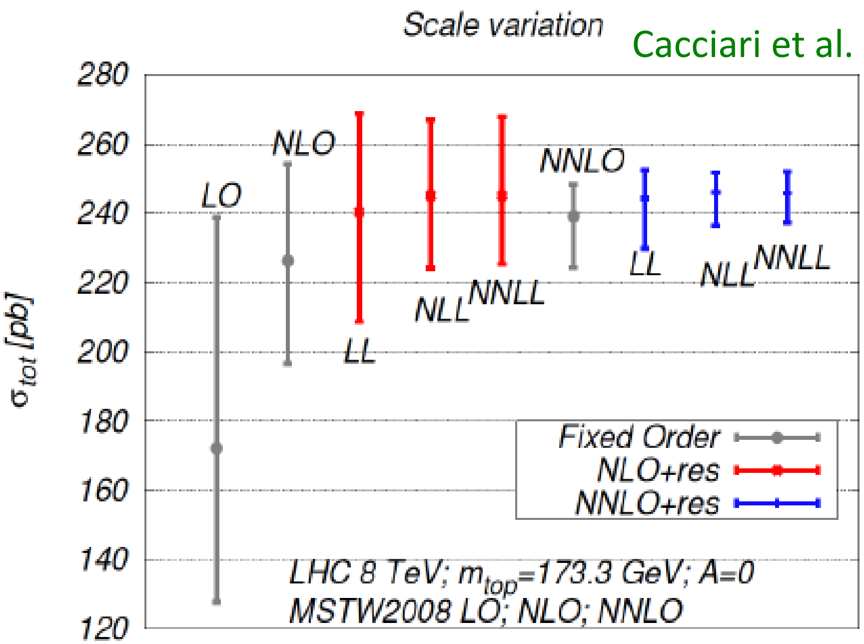
can be resummed to all-order
→ **Sudakov exponent**



$$\sim \exp\left[L(\alpha_s L)^k + (\alpha_s L)^m + \alpha_s(\alpha_s L)^n + \cdots\right]$$

Leading-Log(LL) NLL NNLL

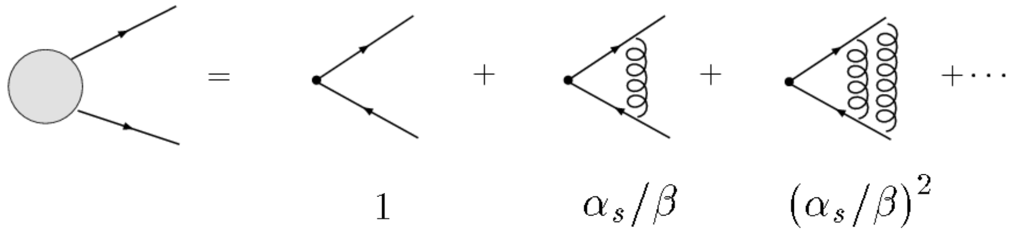
✓ estimation of the corr. in incalculable orders
✓ reduction of scale uncertainties

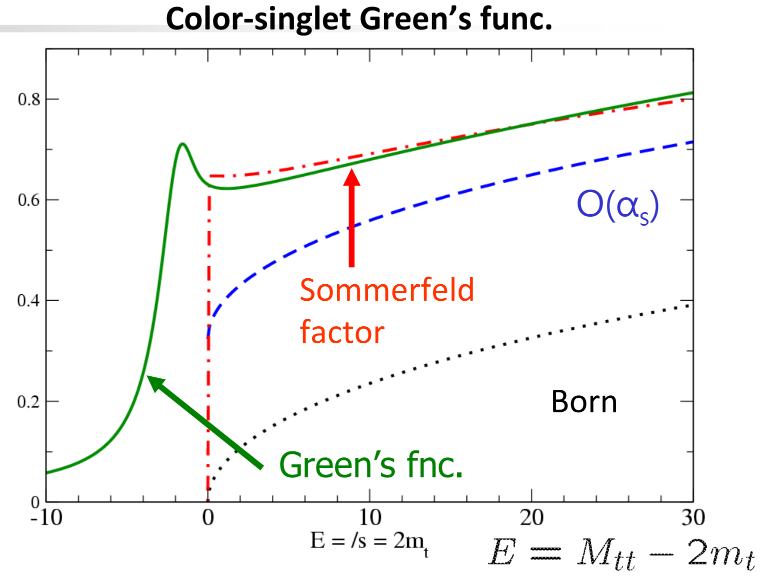



Cacciari et al.

# Coulomb Resummation

- Coulomb summation to all orders:




- Green's function with QCD potential and top finite width.

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

Fadin,Khoze (87) → NRQCD formalism

$$\hat{\sigma}_{\rm tot} \propto {\rm Im}[G(\vec{0}, E+i\Gamma_t)]$$

- **Scales in the system** : $m_t \gg \mu_B > E_B \simeq \Gamma_t \gg \Lambda_{\rm QCD}$ $\left(\begin{array}{l} {}^1S_0 \text{ for } gg \\ {}^3S_1 \text{ for } e^+e^- \end{array}\right)$

Bohr radius : $\mu_B \simeq m_t\alpha_s \simeq 20 - 30\text{GeV}$ (typical momentum of the Coulomb gluon)

Binding energy : $E_B \simeq m_t\alpha_s^2 \simeq 2\text{GeV}$

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

# Coulomb Resummation

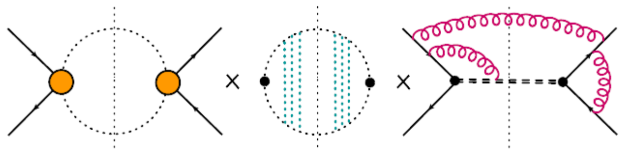


## Bound-state effects at hadron colliders

Hagiwara,Sumino,HY (08);
Kiyo et al. (08),,,

- Factorization formula into three parts: Beneke,Falgari,Schwinn(09)

$$\hat{\sigma}^{(c)}_{i\to t\bar{t}} \simeq K^{(c)}_i \otimes \hat{\sigma}^{(c)}_{i\to t\bar{t}} \otimes F^{(c)}_{\mathrm{ISR},i}$$



K: hard vertex correction

$F_{\mathrm{ISR}}$: ISR[FSR] correction kernel

$$\hat{\sigma}_{\mathrm{tot}} \propto \mathrm{Im}[G(\vec{0}, E + i\Gamma_t)]$$

- Effect to the total cross section is ~ 1%,

  but significant in the threshold region!

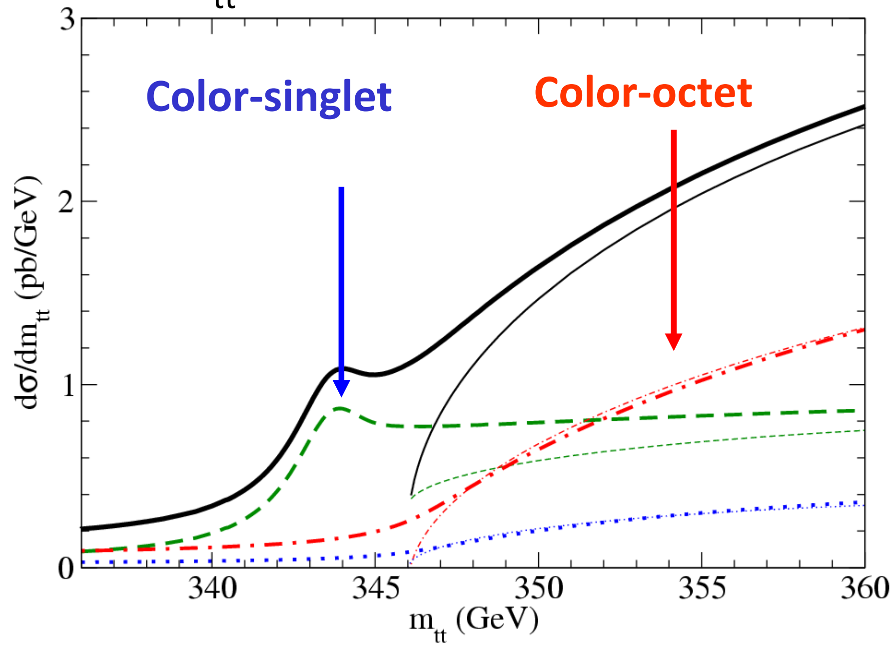
- The pseudo bound-state decays,

  through the decay of top quarks

$$\Gamma_{gg} \simeq m_t \alpha_s^5 \ll 2\Gamma_t$$

→ additional contribution to the usual tt events

$M_{tt}$ dist. near thre. at the LHC



# Differential Distributions

VOLUME 47, NUMBER 1

**Top-quark pair production near threshold**

Y. Sumino
*Department of Physics, University of Tokyo, Tokyo 113, Japan*

K. Fujii
*KEK, Tsukuba, Ibaraki 305, Japan*

K. Hagiwara
*KEK, Tsukuba, Ibaraki 305, Japan*
*and Department of Physics, University of Durham, DH1 3LE, United Kingdom*

H. Murayama
*Department of Physics, Tohoku University, Sendai 980, Japan*

C.-K. Ng
*SLAC, Stanford University, Stanford, California 94309*
(Received 15 April 1992)

- Current status of pQCD calc. and EGs:

  NLO+PS: MC@NLO, POWHEG, MG5_aMC@NLO,,,

  NLO for bWbW final-state  Bevilacqua et al, Denner et al ,,,

  Many efforts toward NNLO accuracy

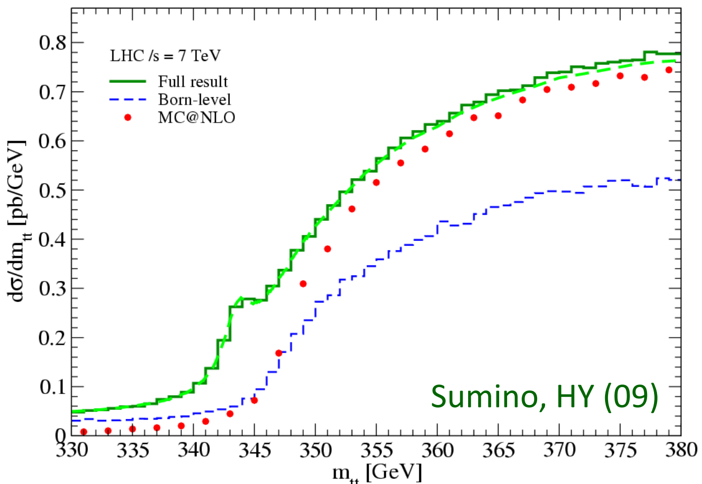
- Coulomb correction at the amplitude level

  → momentum-space Green's func.

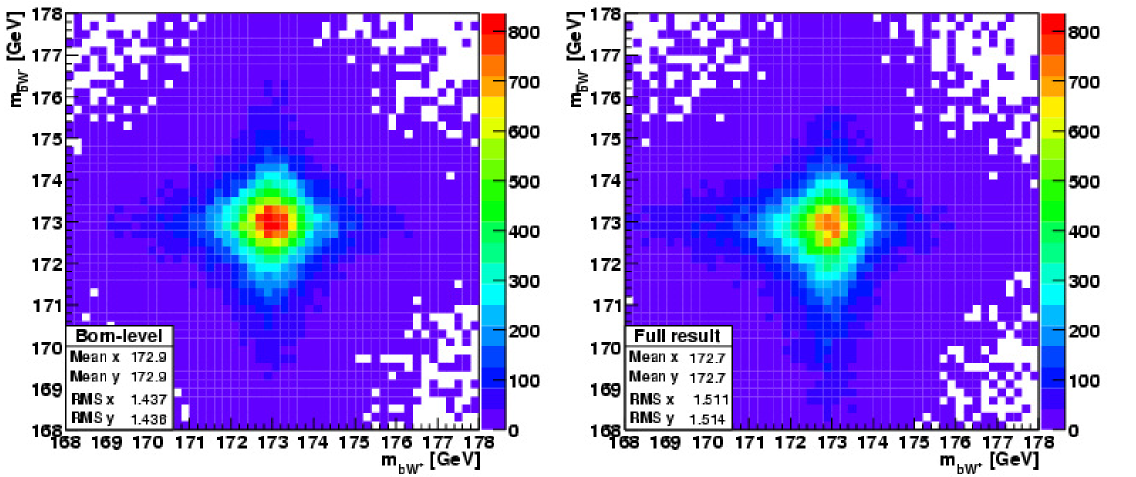
$$\mathcal{M}_{t\bar{t}}^{(c)} \to \mathcal{M}_{t\bar{t}}^{(c)} \times \frac{\tilde{G}^{(c)}(E+i\Gamma_t,\vec{p})}{\tilde{G}_0(E+i\Gamma_t,\vec{p})}$$

Sumino,Fujii,Hagiwara,Murayama,Ng(92) [$e^+e^-$ case] → Sumino, HY (09) [HCs]

- Event Generator with Coulomb effects → Events for unstable BS production




$M_{tt}$ dist.: MC@NLO vs. "LO+Coul."




$M_{t,1}$ vs. $M_{t,2}$ distribution for events with $m_{tt} < 370$ GeV

# Applications:

## Top mass measurement

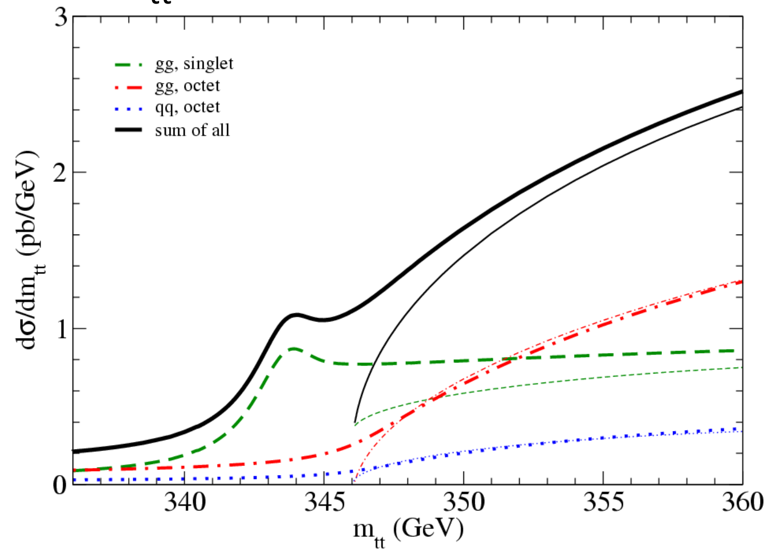
Possibility of measuring short distance mass at the LHC

$$M_{tt}^{\text{peak}} = 2m_t^{\text{pole}} - \Delta E|_{\text{pole}}$$
$$= 2m_t^{\overline{\text{MS}}} - \Delta E|_{\overline{\text{MS}}}$$

**Need many new ideas to measure it at the LHC**

**(At the ILC, $\Delta m_t$ ~ 100MeV !)**

$M_{tt}$ dist. near thre. at the LHC




## Bound-state signal of new particles

Gluinonium [Hagiwara, HY(09),,,],

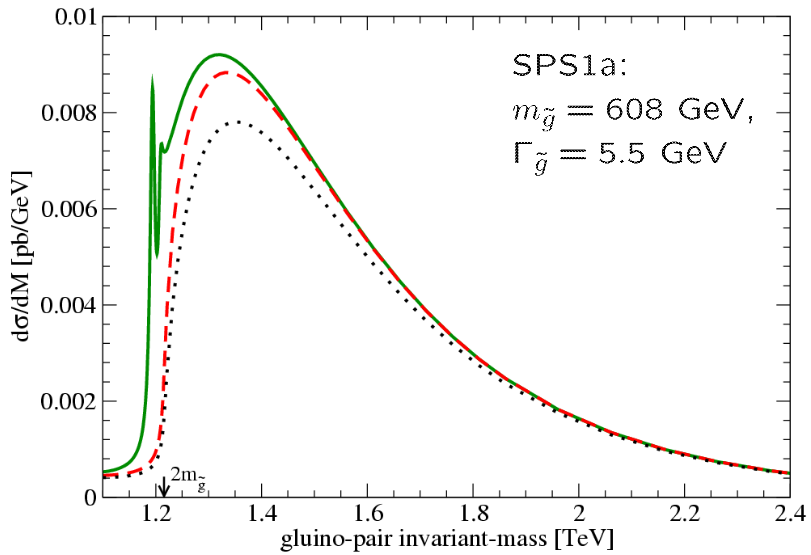
Squarkonium [Beneke, Falgari,Schwin,Wever(08,09),,,],

etc.

Additional contribution to the total cross-section [<10% for heavy gluino],

or new signals by annihilation decay

gluino pair prod. with BS effects



# Summary:

- Collider experiments always lead us toward
  **E**xploring the **R**oad to **U**nification.
- "QCD and Collider Physics" is therefore one of the **K**ey **A**spects
  for particle physicist.
- Top quark as a standard candle [or a window to new physics].
  There are lots of continual and rapid developments:
  NNLO, Threshold and Coulomb summation,
  (N)NLO distributions, off-shell effects, Event Generators,,
- Be prepared for many new measurements which come soon
  from the LHC and from the ILC in future.