

**NLO QCD corrections to  
(pseudo-)scalar Higgs production  
in association with heavy-quark pairs**

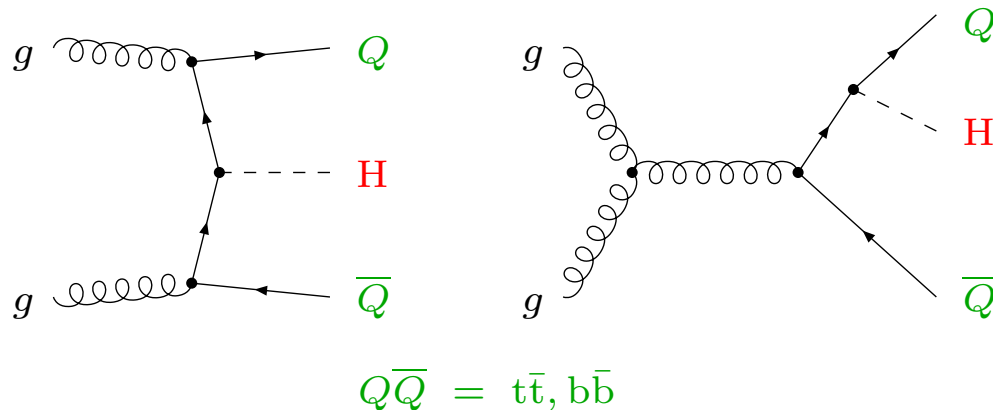
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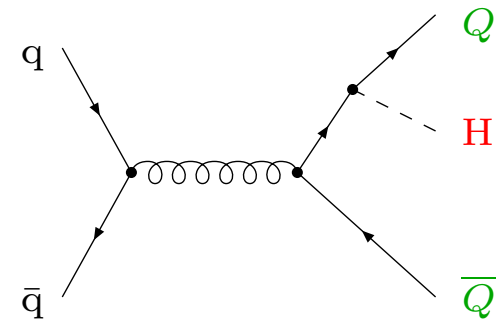
# Higgs production with $t\bar{t}$ or $b\bar{b}$ pairs

## Typical LO diagrams

... for  $gg$  fusion:



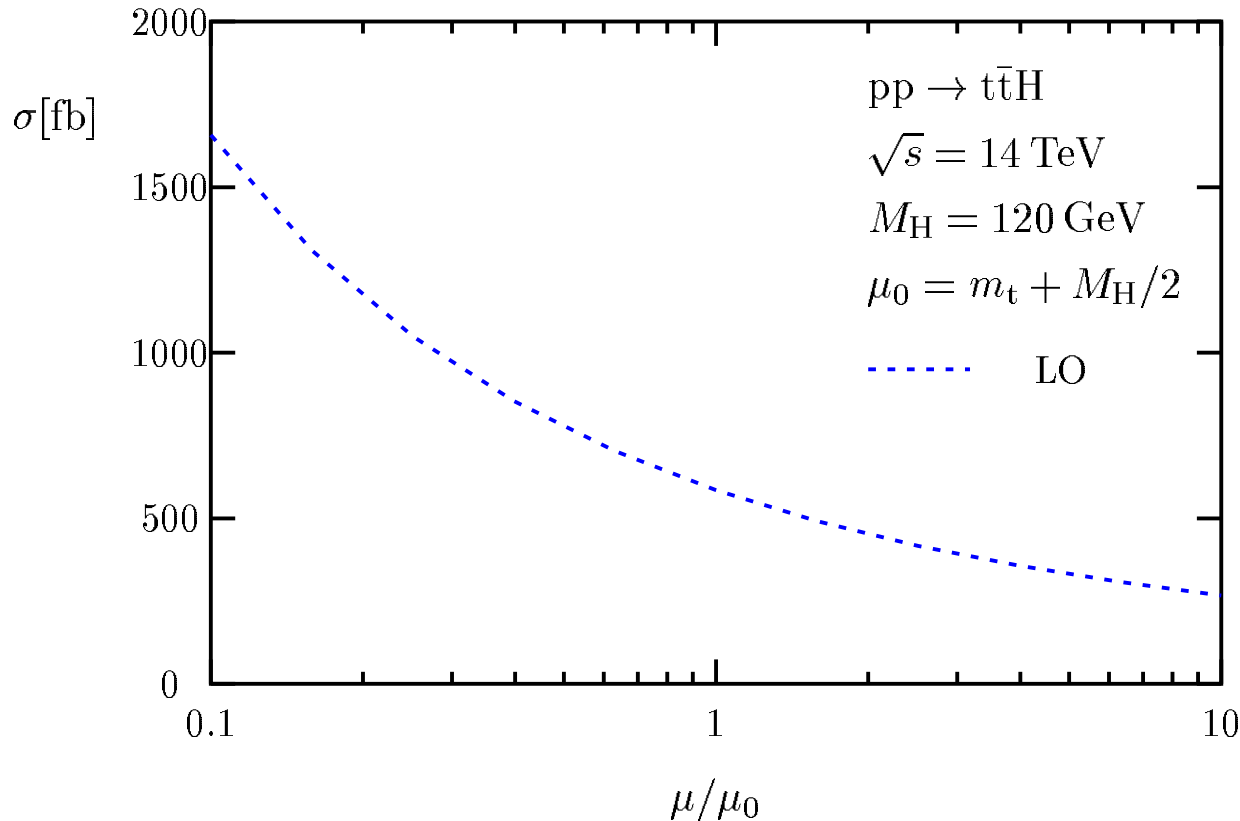
... for  $q\bar{q}$  annihilation:



## Physics issues:

- $t\bar{t}H$  yields important contribution to **Higgs signal** for small  $M_H$   
↔ few events but with distinctive signature
- determination of  $t$  **Yukawa coupling**
- MSSM:  $b\bar{b}h/H/A$  production is important reaction for Higgs search at large  $\tan\beta$

## Scale dependence of LO cross section for $pp \rightarrow t\bar{t}H + X$ :

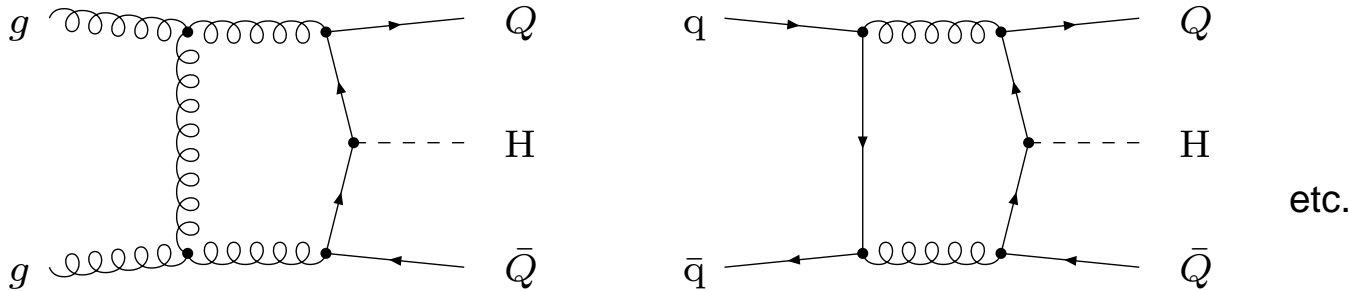


large scale uncertainty  
 $\Rightarrow$  NLO correction important

### Status of theory:

- LO prediction Kunszt '84; Dicus, Willenbrock '89; Gunion '91; Marciano, Paige '91
- NLO prediction:
  - ◇ for total cross section Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01  
Dawson, Orr, Reina, Wackerath '02
  - ◇ for differential cross sections Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '02

## Complications in the virtual corrections – pentagon diagrams:



→ 5-point integrals:

$$E^{\mu\nu\dots} = \frac{(2\pi\mu)^{4-D}}{i\pi^2} \int d^D q \frac{q^\mu q^\nu \dots}{[(q+p_0)^2 - m_0^2] \dots [(q+p_4)^2 - m_4^2]}$$

**Problems:**

- **numerical instabilities** in Passarino–Veltman reduction of tensors  $E_{\mu\nu\dots}$ :  
(vanishing Gram determinants at phase-space boundary)

- ◇ numerical extrapolation in problematic regions, or
- ◇ new method without inverse Gram determinants  
↳ **drastic improvement in stability**

Denner, Dittmaier '02

- **complicated singularity structure** in integrals (IR and collinear)

needed: evaluation in  $D$  dimensions

known: decomposition of  $E_0$  in 4-point functions for  $D = 4$  Melrose '65

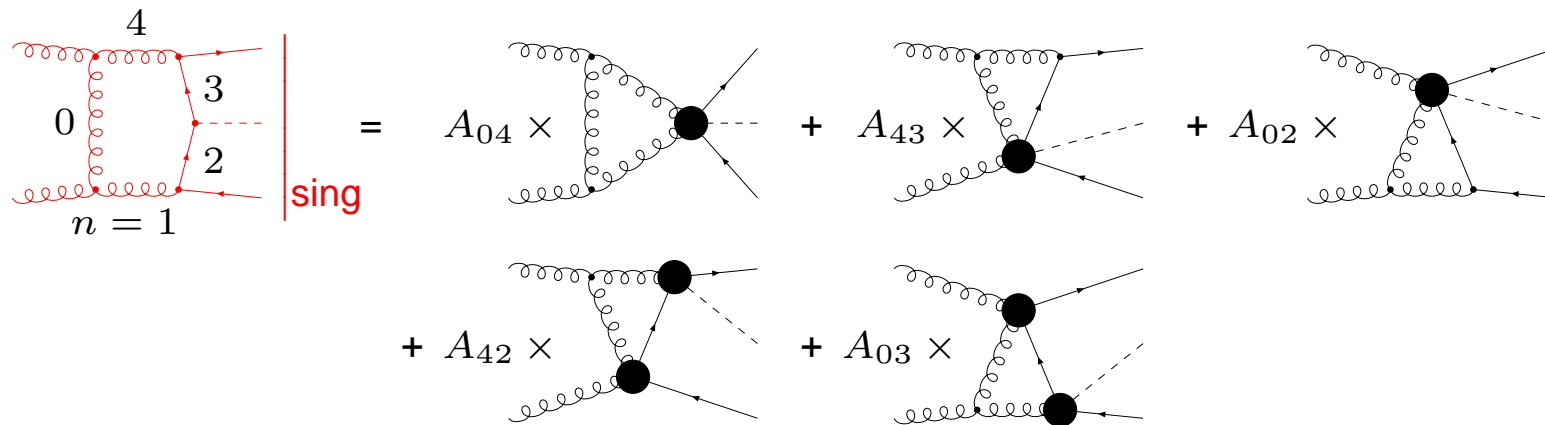
↳ **trick: translate  $E_0$  in regularization with masses; then take  $D = 4$**

calculate  $E_{\dots}^{(D)}$  in  $D = 4 - 2\epsilon$  dimensions  
 from **singular part** and **finite difference**:

$$E_{\dots}^{(D)} = E_{\dots, \text{sing}}^{(D)} + \left[ E_{\dots}^{(D=4, \lambda)} - E_{\dots, \text{sing}}^{(D=4, \lambda)} \right] \Big|_{\lambda \rightarrow 0} + \mathcal{O}(\epsilon)$$

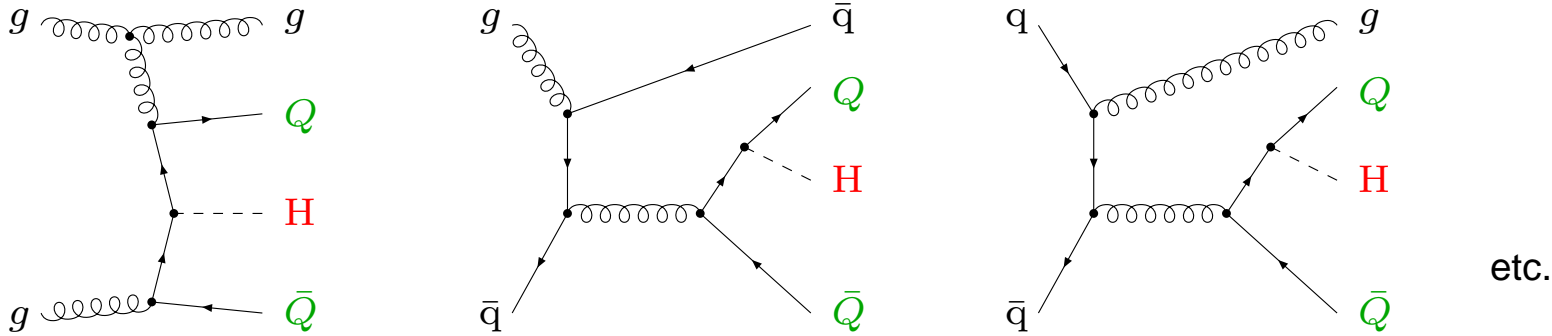
= combination of 3-point and 4-point integrals

determination of **singular part** von  $E_{\dots}^{(D, \lambda)}$



# Real corrections

Typical diagrams:



## Problems:

- evaluation of complicated matrix elements  
↳ application of conventional trace techniques or use of program package **Madgraph**

Stelzer, Long '94

- **soft and collinear divergences** and factorization

- ↳ application of generalized **dipole subtraction formalism**

Catani, Seymour '96

Catani, Dittmaier, Seymour, Trócsányi '02

Phaf, Weinzierl '01

## Dipol subtraction formalism for real corrections

→ process-independent treatment of singularities in real NLO corrections

worked out for

- QCD with massless partons (Catani, Seymour '96)
  - $\gamma$  radiation off massive fermions (Dittmaier '99)
- } QCD with massive quarks  
Phaf, Weinzierl '01  
Catani, Dittmaier, Seymour, Trócsányi '02

Idea: NLO correction to process with  $m$  partons

$$\sigma^{\text{NLO}} = \underbrace{\int_{m+1} \left[ d\sigma^{\text{real}} - d\sigma^{\text{sub}} \right]}_{\text{finite}} + \underbrace{\int_m \left[ d\sigma^{\text{virtual}} + d\bar{\sigma}_1^{\text{sub}} \right]}_{\text{finite}} + \int_0^1 dx \underbrace{\int_m \left[ d\sigma^{\text{fact}}(x) + \left( d\bar{\sigma}^{\text{sub}}(x) \right)_+ \right]}_{\text{finite}}$$

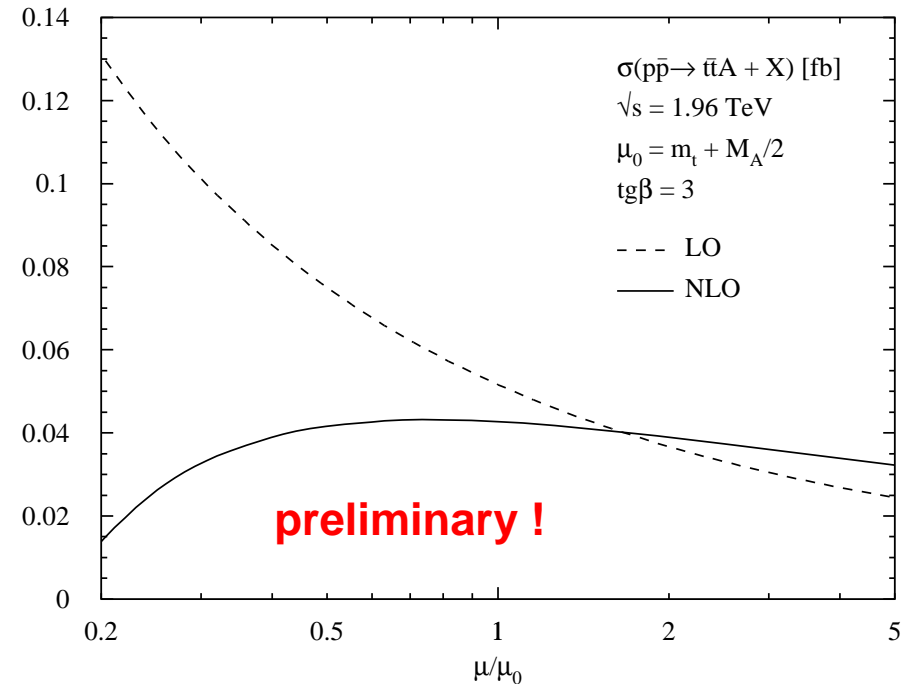
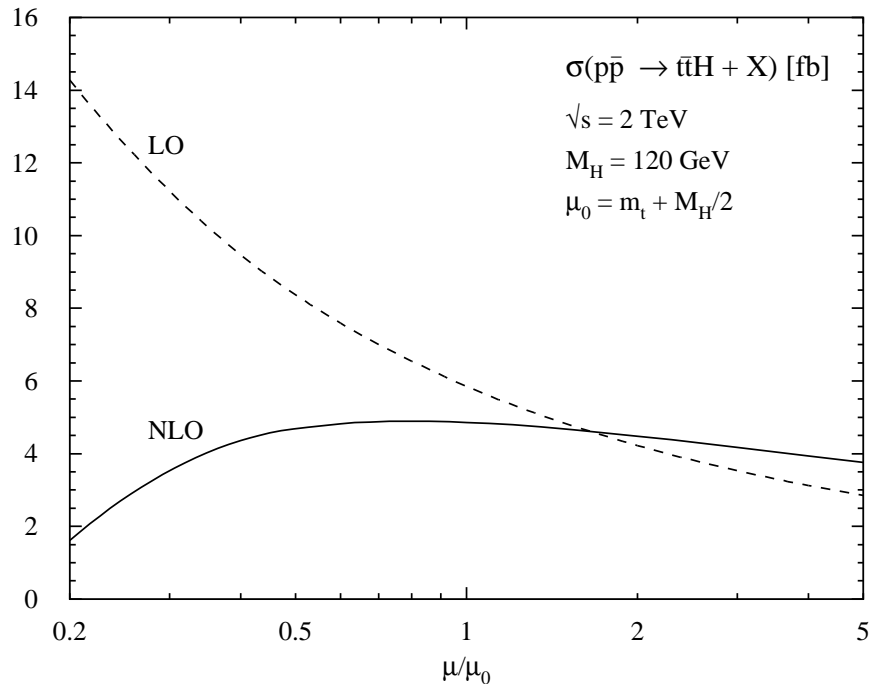
Constraints on  $d\sigma^{\text{sub}}$ :

- sum rule:  $-\int_{m+1} d\sigma^{\text{sub}} + \int_m d\bar{\sigma}_1^{\text{sub}} + \int_0^1 dx \int_m \left( d\bar{\sigma}^{\text{sub}}(x) \right)_+ = 0$
- asymptotics:  $\sigma^{\text{sub}} \sim \sigma^{\text{real}}$  in all singular regions

# NLO cross sections for Tevatron – scale dependence

...for SM  $t\bar{t}H$  production: Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01

...for MSSM  $t\bar{t}A$  production: Dittmaier, Krämer, Spira '05



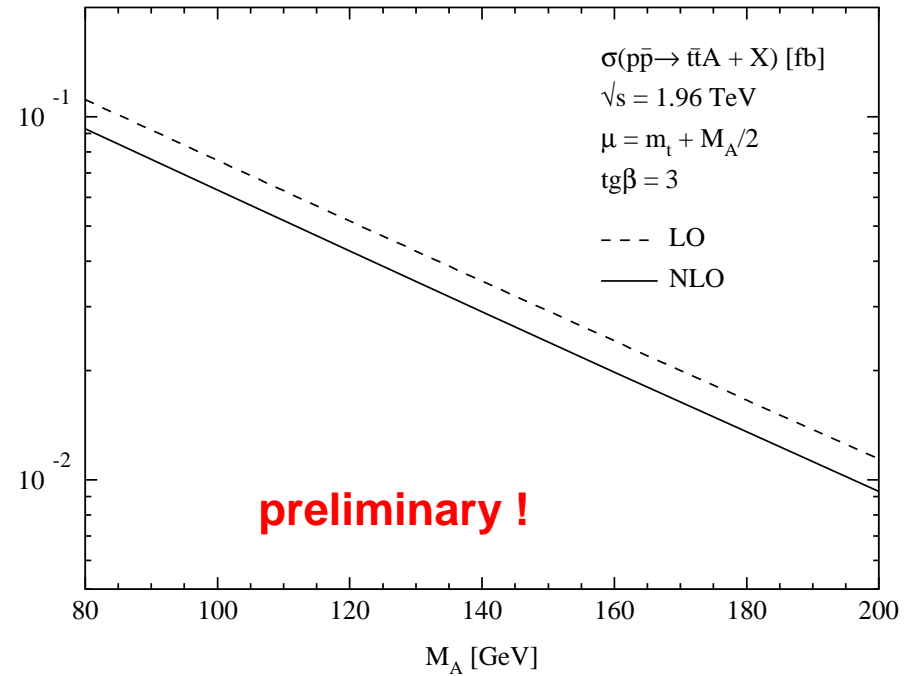
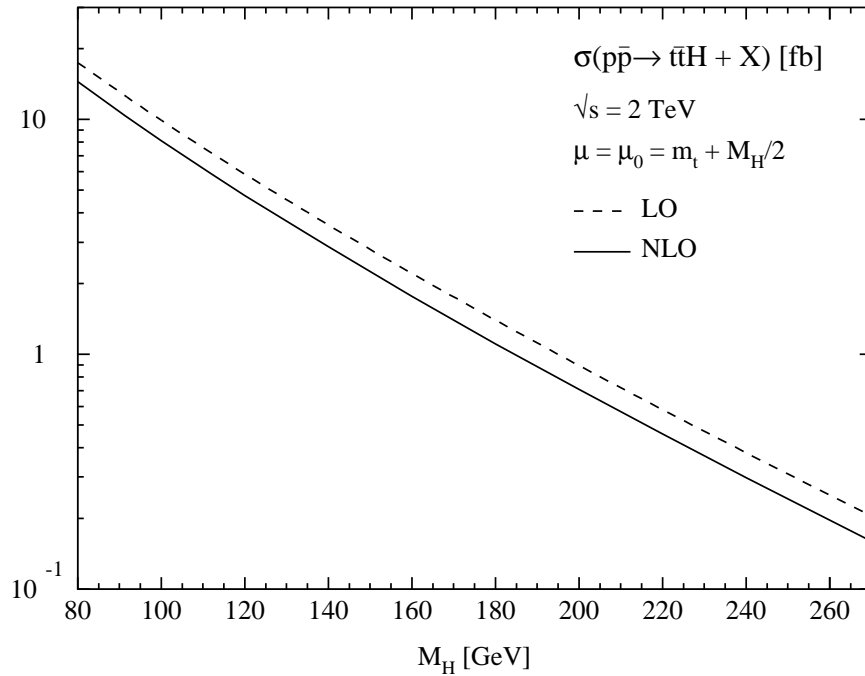
- drastic reduction of scale uncertainty
- scale dependence of NLO QCD correction to MSSM  $t\bar{t}A$  production almost identical to SM  $t\bar{t}H$  production



# NLO cross sections for Tevatron

...for SM  $t\bar{t}H$  production: Beenakker, Dittmaier, Krämer, Plümer, Spira, Zerwas '01

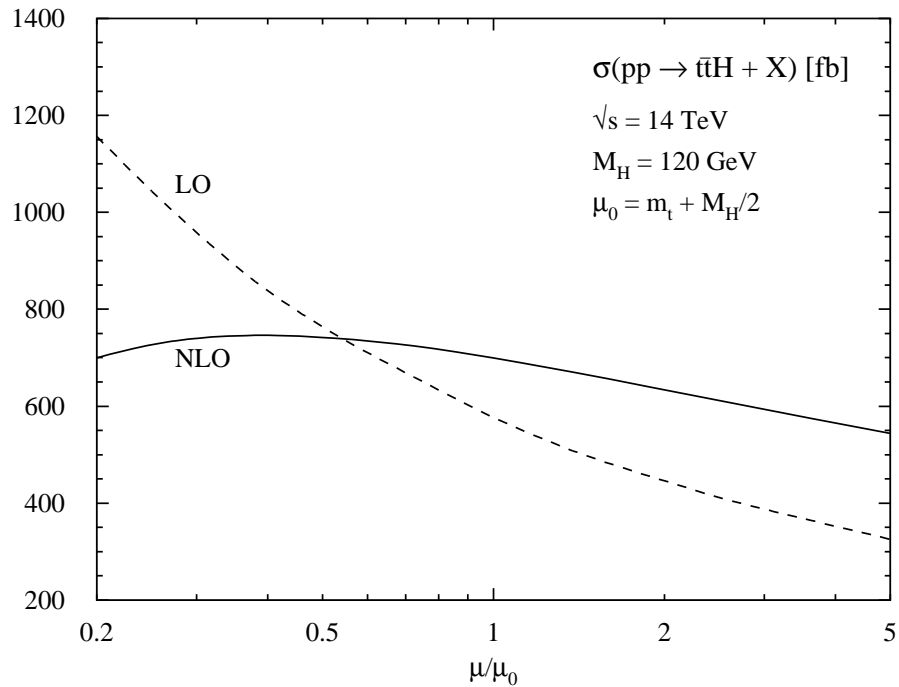
...for MSSM  $t\bar{t}A$  production: Dittmaier, Krämer, Spira '05



# NLO cross sections for the LHC – scale dependence

...for SM  $t\bar{t}H$  production: Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01

...for MSSM  $t\bar{t}A$  production: Dittmaier, Krämer, Spira '05



**Work in progress !**