Soft-gluon resummation for pseudoscalar Higgs boson production at hadron colliders

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José Francisco Zurita

[1]Departamento de Física - FCEyN - Universidad de Buenos Aires

Seminar at Fermilab (June 12 2008)

Work done in collaboration with Daniel de Florian

QCD corrections, at next-to-next-to-leading logarithmic accuracy, to production cross section of a pseudoscalar Higgs boson, in the heavy top mass limit, at proton-proton or proton anti-proton collider.

Outline

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Outline

Starting point

- New Physics $\rightarrow$ QCD for both signal and background
- UV and IR divergences
- Regularization introduces μ_R and μ_F scales
- Predictions became scale dependent !!!

IR singularities

They come from

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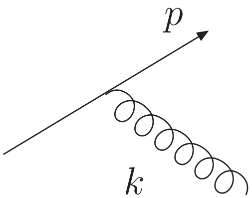

$$\frac{1}{(p+k)^2} = \frac{1}{2E_q E_g(1-\cos\theta)}$$

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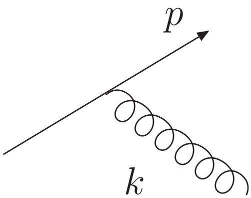

$$\frac{1}{(p+k)^2} = \frac{1}{2E_q E_g (1 - \cos\theta)}$$

Two kind of divergences

- Soft: $E_g \to 0$ *Soft gluon*
- Collinear: $cos\, \theta = 1$ *Mass singularity*

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When fixed order fails

Perturbative expansion reads

$$\sigma = \sigma^{(0)} + \alpha_S \sigma^{(1)} + \alpha_S \sigma^{(2)} + \dots$$

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In processes with several scales, last condition might not hold

$$\sigma^{(i)} \sim Log^j(y) \equiv L^j; \qquad L \to \infty \text{ when } y \to 0$$

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Where do these Logs appear? Two examples:

- Z production with q_t: $y = \frac{q_T^2}{M_Z^2}$
- Higgs production: $y = 1 - \frac{M_H^2}{s x_1 x_2} \to$ soft gluon radiation

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Exponentiation

Soft gluon contributions can be exponentiated. Schematically

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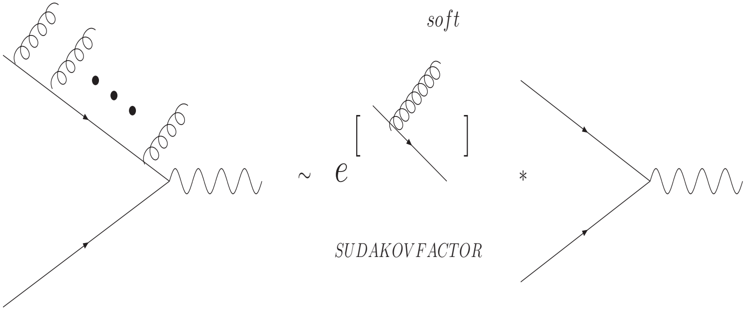

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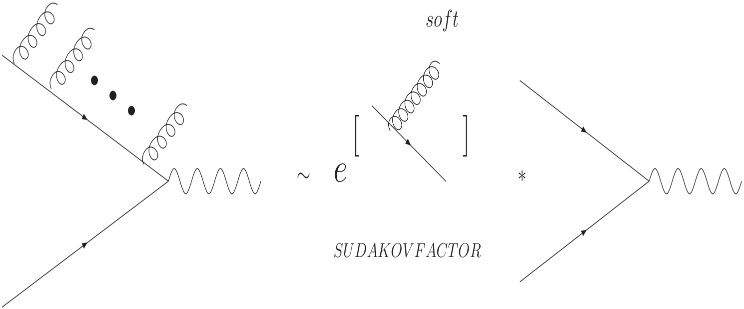

$$\sigma = \sigma^{(0)}\ C_{q\bar{q}}\ Exp[\mathcal{G}] = \sigma^{(0)}\ (1 + \sum_i {\alpha_S}^i C_{q\bar{q}}^{(i)})\ Exp[\mathcal{G}]$$

- $C_{q\bar{q}} \rightarrow$ Hard contribution: Process dependent
- $\mathcal{G} \rightarrow$ Sudakov Factor: Process independent

Structure of resummation

Sudakov factor expansion reads

$$Exp[Lg_1(\alpha_S L) + g_2(\alpha_S L) + \frac{1}{L} g_3(\alpha_S L) + \ldots]$$

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LL

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State of the art: g_4 S.Moch, J.Vermaseren, A.Vogt (2005)

Outline

Introduction

Higgs production at colliders

Results

Conclusions

MSSM Higgs sector

MSSM requires two Higgs doublets
Initially, 8 d.o.f ; after EWSB, only 5 d.o.f left.

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Tree level parameters: M_A and $\tan\beta = \frac{v_2}{v_1}$

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Experimental constraints (LEPII):

- $M_A > 91.9$ GeV
- $0.6 < \tan\beta < 2.4$ excluded

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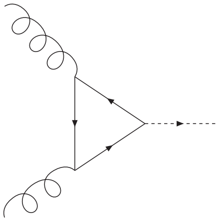
Higgs production

Main channel at hadron collider: *gg* fusion



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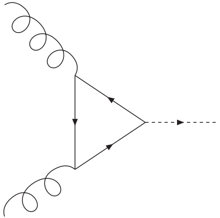

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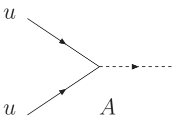
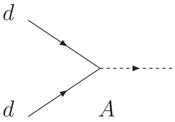
In MSSM, the *A* Yukawa couplings to fermions go as



$\sim m_u \, \gamma_5 \, cot\beta$



$\sim m_d \, \gamma_5 \, tan\beta$

Naively, calculation reliable for $\tan\beta < 6.41$

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Theoretical Status

- LO : known from a long time ago F. Wilczek (1977) ;
  H. Georgi, S. Glashow, M. Machacek, D. Nanopoulos (1978) ;
  J. Ellis, M. Gaillard, D. Nanopoulos, C. Sachrajda (1979) ;
  T. Rizzo (1980)

- NLO (exact) give an increase of almost 100 % !!!
  M. Spira, A. Djouadi, D. Graundenz, P.Zerwas (1995)

- NNLO (heavy M_t limit): moderate numerical impact
  R. Harlander, W.Kilgore (2002); C. Anastasiou, K. Melnikov (2002);
  V. Ravindran, J.Smith, W. L. van Neerven (2003)

- NNLL (h): scale dependence greatly reduced! (10 %)
  S. Catani, D. De Florian, M. Grazzini, P.Nason (2003)

Missing piece: NNLL result for A production.

Large M_t approximation

Effective Lagrangian, valid for $M_A < M_t$

$$\mathcal{L}_{eff} = \frac{1}{4}\left[1 - \frac{\alpha_S}{3\pi}\frac{H}{v}(1+\Delta)\right] Tr(G_{\mu\nu}G^{\mu\nu})$$

J. Ellis, M.K.Gaillard,D.V.Nanopoulos (1976)

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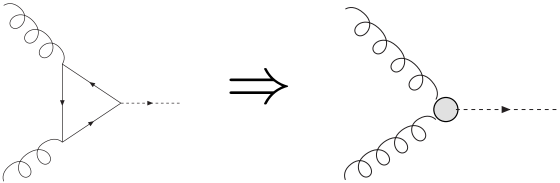
shrinks the loop into an effective vertex



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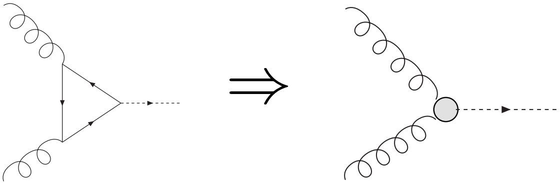

We got rid of the Loop:

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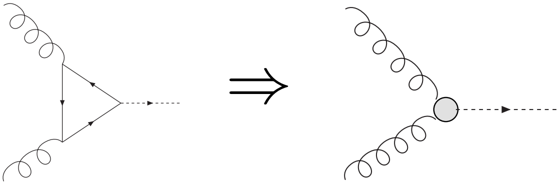

We got rid of the Loop: *trainless Chicago!!!*

Large M_t approximation accuracy

- NLO and NNLO are very well approximated by large M_t limit.
  S.Dawson (1991)

- The bulk of the QCD corrections comes from parton radiation at low transverse momenta: weakly sensitive to the top loop.
  S. Catani, D. de Florian, M. Grazzini (2001)

- Hard effects (most sensitive to heavy quark loop) are about 2% at LHC and 4% at Tevatron (NNLO calculations).

- M_t approximation works with accuracy better than 10% for $M_h \leq 1 TeV$.
  M. Kramer, E.Laenen, M. Spira (1998)

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Framework

By virtue of the factorization theorem, the cross section for $h_a h_b \to A + X$ may be written as a convolution of the partonic cross section $\hat{\sigma}_{ab}$ with the PDFs.

$$\sigma(s, M_A^2) = \sum_{a,b} \int_0^1 dx_1\, dx_2\, f_{a/h_1}(x_1, \mu_F^2)\, f_{b/h_2}(x_2, \mu_F^2)$$

$$\int_0^1 dz\, \delta\left(z - \frac{M_A^2}{s\, x_1 x_2}\right)\, \hat{\sigma}_{ab}(z, \alpha_S(\mu_R^2), M_A^2/\mu_R^2, M_A^2/\mu_F^2)$$

High precision requires a good knowledge of both PDF's and partonic cross sections.

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Mellin transform technique

Convolutions are disentangled with the aid of *Mellin transforms*

$$g_N = \int_0^1 dy\, y^{N-1}\, g(y) \equiv M[g(y)]$$

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$$\sigma_N(M_A^2) = \sum_{a,b} f_{a/h_1,N}(\mu_F^2)\, f_{b/h_2,N}(\mu_F^2)\, \hat{\sigma}_{ab,N}\,(\alpha_S(\mu_R^2), M_A^2/\mu_R^2, M_A^2/\mu_F^2)$$

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and the resummed cross section also factorizes

$$\hat{\sigma}^{res}_{ab,N} = \hat{\sigma}^{(0)}_{ab,N}\, \Delta_{ab,N}$$

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Threshold limit: $z = \frac{{M_A}^2}{s x_1 x_2} \rightarrow 1 \equiv N \rightarrow \infty$

Threshold limit

${\alpha_S}^n Log^m N$ dominate over constants and $\mathcal{O}(1/N)$

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Threshold limit

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Singular contributions at threshold

Soft: $$M\left[[\frac{\ln^k(1-z)}{1-z}]_+\right] = \frac{(-1)^{k+1}}{k+1}\ln^{k+1}N + \mathcal{O}(\ln^k N)$$

Virtual: $$M\left[[\delta(1-z)]_+\right] = 1$$

Collinear: $$M\left[[\ln^k(1-z)]_+\right] = \frac{(-1)^k}{N}\ln^k N + \mathcal{O}\left(\frac{1}{N}\ln^{k-1}N\right)$$

where $\int_0^1 f(w)[g(w)]_+ dw = \int_0^1 (f(w)-f(1))g(w)dw$

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Matching

How can we profit from the fixed order result?

$$\sigma^{f.o} = \sigma^{(0)} + \alpha_S\, \sigma^{(1)} + \alpha_S{}^2 \sigma^{(2)}$$

$$\sigma^{res} = \sum_{i=0}^{\infty} \alpha_S{}^i R^{(i)}$$

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Simply: by writing down

$$\sigma^{matched} = \sigma^{(0)} + \alpha_S \sigma^{(1)} + {\alpha_S}^2 \sigma^{(2)} + \sum_{i=3}^{\infty} {\alpha_S}^i R^{(i)}$$

Match = fixed order + Extra resummed terms

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The matching is performed by computing the $C_{gg}^{(i)}$ coefficients.

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Moreover, we can include the dominant collinear terms by doing

$$C_{gg}^{(1)} \rightarrow C_{gg}^{(1)} + 6\frac{\ln N}{N}$$

THIGRES

FORTRAN code that computes Higgs production cross sections:

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THIGRES

FORTRAN code that computes Higgs production cross sections:

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- cross sections and PDF's written directly in N-space (no need to deal with $+$ distributions)
- PDF in Mellin

  Toy PDF: $f(x) = (1-x)^{\alpha} x^{\beta}$

  Simple expression: $M[f(x)] = \frac{\Gamma(b+1)\Gamma(a+N)}{\Gamma(a+b+N+1)}$

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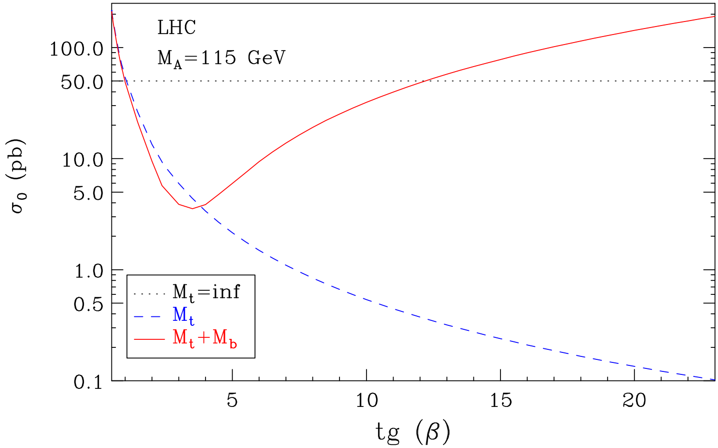
- code available upon request

Outline

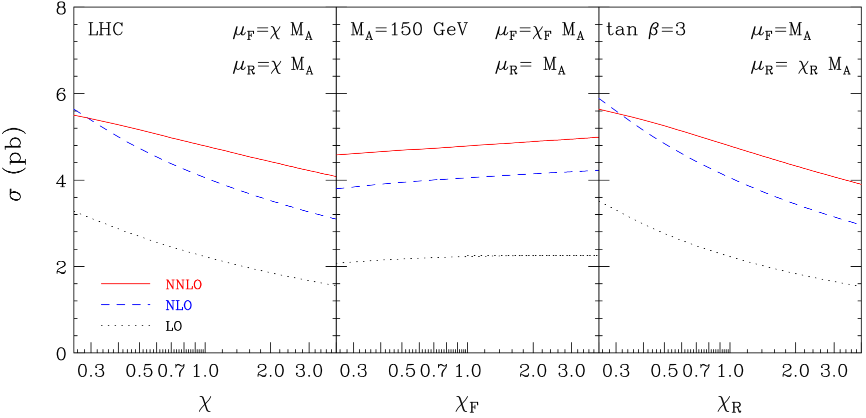
Heavy quark mass effects

One can add finite M_t (and M_b) effects in Born cross section.



+ compare at NLO: exact result (HIGLU) with large M_t limit.

Fixed order σ scale dependence at LHC



$$\mu_F = \chi_F M_A \qquad \mu_R = \chi_R M_A$$

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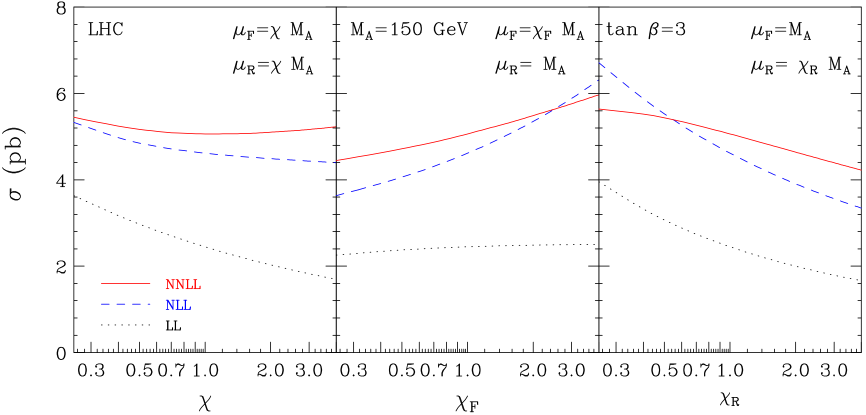
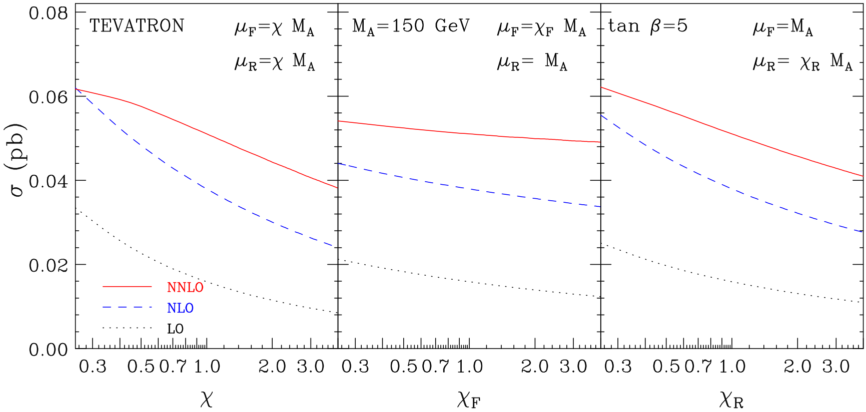
Resummed σ scale dependence at LHC



$$\mu_F = \chi_F M_A \qquad \mu_R = \chi_R M_A$$

Fixed order σ scale dependence at Tevatron



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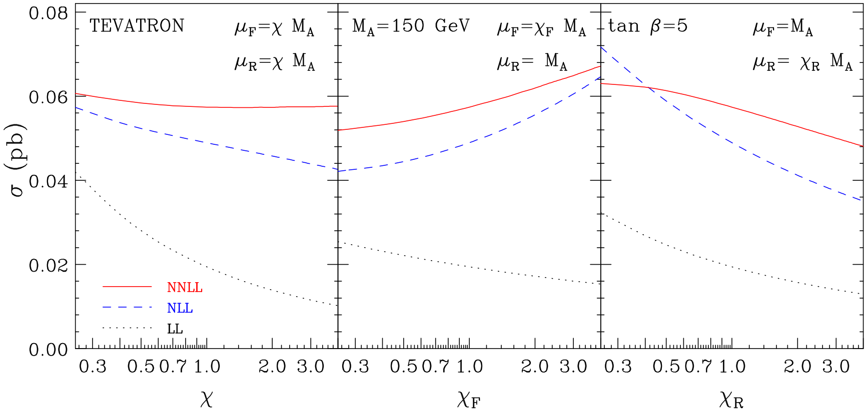

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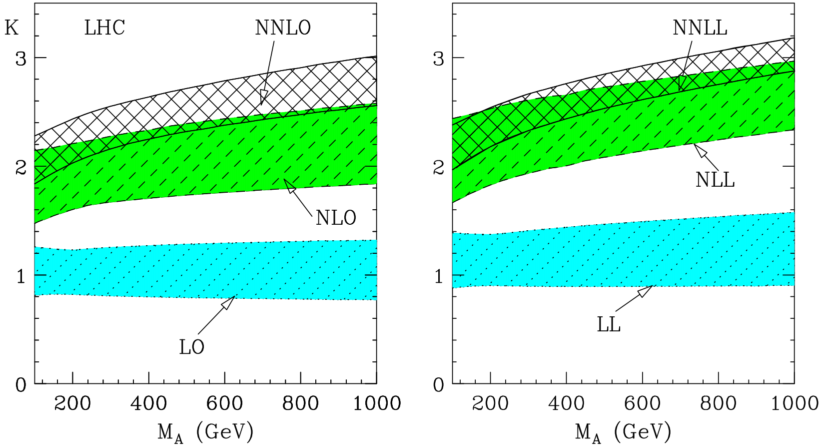
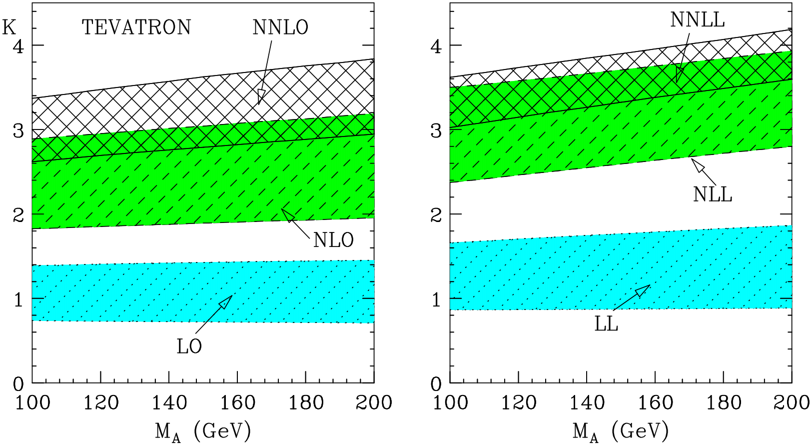
K factors at LHC



$$K_{NLO} = \frac{\sigma_{NLO}}{\sigma_{LO}} \qquad K_{NNLO} = \frac{\sigma_{NNLO}}{\sigma_{LO}}$$

TH Uncertainty: $0.5 \leq \chi_{F,R} \leq 2$ but $0.5 \leq \chi_F/\chi_R \leq 2$

K factors at Tevatron



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Departamento de Física Juan José Giambiagi
Facultad de Ciencias Exactas y Naturales Universidad de Buenos Aires

Outline

Summary

- Gluon-gluon fusion is the dominant production channel for neutral Higgs bosons at hadron colliders.
- Resummation provides not only more accurate predictions, but it also reduces the scale dependence.
- Explicit results for inclusive A production at both Tevatron and LHC were shown.
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- THIGRES Fortran code available upon request.

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Departamento de Física Juan José Giambiagi
Facultad de Ciencias Exactas y Naturales Universidad de Buenos Aires

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Departamento de Fisica Juan José Giambiagi
Facultad de Ciencias Exactas y Naturales Universidad de Buenos Aires

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Departamento de Física Juan José Giambiagi
Facultad de Ciencias Exactas y Naturales Universidad de Buenos Aires

”We haven’t the money, so we’ve got to think”

Ernest Rutherford (1871-1937)

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