QCD:

PRECISION PHYSICS IN THE MAKING

STEFANO FORTE
UNIVERSITÀ DI MILANO & INFN

O Captain! My Captain!

Torino, 27 September 2022

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 740006

TURIN UNIVERSITY, EARLY '80s

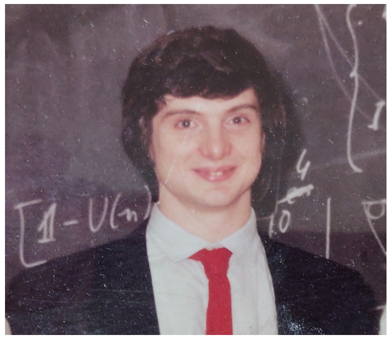
Giampiero(?),

Les Houches 1975

GP: since 1974 junior professor,
assistant professor since 1981
on leave at SLAC and Michigan from 1982

SF, graduation,

July 1984



SF: undergraduate 1980-1984

QCD AT A HADRON COLLIDER CIRCA 1984

THE DISCOVERY OF THE W

THEORETICAL PREDICTION

42 *G. Altarelli et al. / Vector boson production*

TABLE 2
Values (in nb) of the total cross sections for $W^{\pm}$ and Z^0 production

$\sqrt{S}$ (GeV)	$W^+ + W^-$ GHR	$W^+ + W^-$ DO1	$W^+ + W^-$ DO2	Z^0 GHR	Z^0 DO1	Z^0 DO2	$\frac{\sigma(W^+ + W^-)}{\sigma(Z^0)}$ GHR	$\frac{\sigma(W^+ + W^-)}{\sigma(Z^0)}$ DO1	$\frac{\sigma(W^+ + W^-)}{\sigma(Z^0)}$ DO2
540	4.2	4.3	4.1	1.3	1.3	1.2	3.1	3.4	3.5
700	6.2	6.3	6.1	2.0	1.9	1.8	3.1	3.3	3.4
1000	9.5	9.5	9.6	3.1	3.0	2.9	3.1	3.2	3.3
1300	12.5	12.5	12.9	4.0	3.9	3.9	3.1	3.2	3.3
1600	15.5	15.6	16.5	5.0	4.8	5.0	3.1	3.2	3.3

ALTARELLI, ELLIS, GRECO, MARTINELLI, 1984

EXPERIMENTAL DISCOVERY

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/85-108
11 July 1985

W PRODUCTION PROPERTIES AT THE CERN SPS COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen[1] – Amsterdam (NIKHEF)[2] – Annecy (LAPP)[3] – Birmingham[4] – CERN[5] – Harvard[6] – Helsinki[7] – Kiel[8] – London (Imperial College[9] and Queen Mary College[10]) – Padua[11] – Paris (Coll. de France)[12] – Riverside[13] – Rome[14] – Rutherford Appleton Lab.[15] – Saclay (CEN)[16] – Victoria[17] – Vienna[18] – Wisconsin[19] Collaboration

The corresponding experimental result for the 1984 data at $\sqrt{s}$ = 630 GeV is

$$(\sigma \cdot B)_W = 0.63 \pm 0.05\ (\pm 0.09)\ \text{nb}.$$

This is in agreement with the theoretical expectation [14] of $0.47^{+0.14}_{-0.08}$ nb. We note that the 15%

AGREEMENT AND UNCERTAINTIES AT 20% CONSIDERED TO BE SATISFACTORY

QCD AT A HADRON COLLIDER CIRCA 1984

GIAMPIERO'S TAKE

Volume 148B, number 4,5 PHYSICS LETTERS 29 November 1984

PRODUCTION OF LARGE p_T SINGLE JETS IN ASSOCIATION WITH $Z^0 \to \nu\bar{\nu}$ DECAYS IN $p\bar{p}$ COLLISIONS

Alessandro BALLESTRERO and Giampiero PASSARINO
Istituto di Fisica Teorica, Università di Torino, Turin, Italy
and INFN, Sezione di Torino, Turin, Italy

Received 24 July 1984

Motivated by the recently reported single jet events with large missing transverse energy of the UA1 Collaboration, the p_T distribution for a jet produced in the processes $q\bar{q} \to g + (Z^0 \to \nu\bar{\nu})$ and $qg \to q + (Z^0 \to \nu\bar{\nu})$ is examined. Compact analytical expressions are derived, including a detailed discussion of the jet phase space. Numerical results show that there are no appreciable contributions in the interval $35 \leqslant p_T \leqslant 70$ GeV.

Volume 148B, number 4,5 PHYSICS LETTERS 29 November 1984

DISTRIBUTIONS FOR $p\bar{p} \to \gamma + (Z^0 \to \nu\bar{\nu})$ AT LARGE $E_T(\gamma)$

Alessandro BALLESTRERO and Giampiero PASSARINO
Istituto di Fisica Teorica, Università di Torino, Turin, Italy
and INFN, Sezione di Torino, Turin, Italy

Received 2 August 1984

Motivated by the recently presented sample of two "photon" events with large missing transverse energy of the UA1 Collaboration, various distributions are investigated for the process $p\bar{p} \to \gamma + (Z^0 \to \nu\bar{\nu})$ in the context of the standard model. There are no appreciable contributions predicted in the interval $40 \leqslant E_T \leqslant 60$ GeV.

QCD AT A HADRON COLLIDER CIRCA 1984

GIAMPIERO'S TAKE

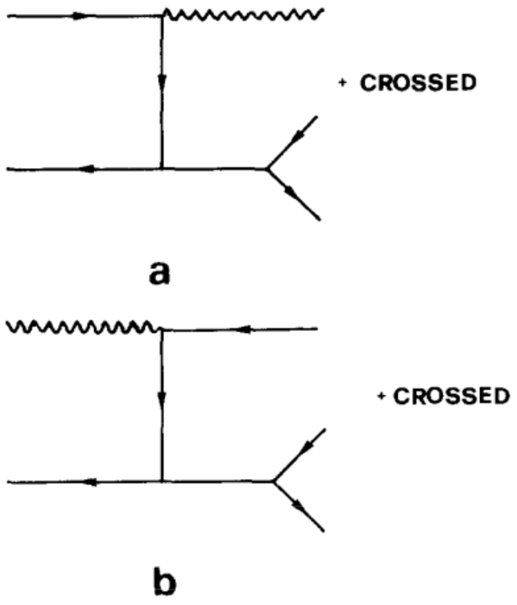


Fig. 1. (a) The process $q\bar{q} \to g + (Z^0 \to \nu\bar{\nu})$. Wavy line denotes the gluon. (b) The process $gq \to q + (Z^0 \to \nu\bar{\nu})$. Wavy line denotes the gluon.

with $u_{\min} = \mathrm{tn}(\theta_{\mathrm{cut}}/2)$, $u_{\max} = \mathrm{ctn}(\theta_{\mathrm{cut}}/2)$. We get that $Q^2(u) \leqslant 0$ whenever $u_- \leqslant u \leqslant u_+$ with $u_\pm$ roots of the equation $x_1\bar{p}_T u^2 - x_1 x_2 u + x_2 \bar{p}_T^2 = 0$. Therefore we obtain

$$u_{\mathrm{inf}} = \max(u_{\min}, u_-), \quad u_{\mathrm{sup}} = \min(u_{\max}, u_+) , \tag{11}$$

with the condition $u_{\mathrm{sup}} \geqslant u_{\mathrm{inf}}$. As a consequence of this result the x_1, x_2 plane is divided into different regions, each of which corresponds to a different choice for the integration limits relative to u. The final result can be cast in the form

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T} = \frac{\alpha^2 \alpha_s \bar{p}_T}{216 s^{3/2}} \sum_i \frac{A_i}{s_\theta^4 c_\theta^4} \times \int \mathrm{d}x_1\, \mathrm{d}x_2 \frac{f_i(x_1, x_2)}{x_1 x_2} [P(u_{\mathrm{sup}}) - P(u_{\mathrm{inf}})] , \tag{12}$$

where f_i are the quark–antiquark distribution functions and $u_{\mathrm{inf}}, u_{\mathrm{sup}}$ are functions of x_1, x_2 as given in eq. (11). For different choices of p_T and θ_{cut} we encounter essentially three different situations which are given respectively in figs. 2a, 2b and 2c. For convenience in discussing the final integrations we have introduced new variables z, y: $z = x_1 x_2$ and $y = x_1$. The three different cases are as follows. In fig. 2a there is only one region, namely $4\bar{p}_T^2 \leqslant z \leqslant 1$ and $z \leqslant y \leqslant 1$ with $u_- \leqslant u \leqslant u_+$. If we fix, for example, $\theta_{\mathrm{cut}} = 10°$, it corresponds to $p_T > 46.9$ GeV. In fig. 2b we have eight different regions. The limits of integration are u_- and $u_{\max}$ for regions 2 and 4, u_- and u_+ for regions 0 and 1, $u_{\min}$ and u_+ for regions 3 and 6, $u_{\min}$ and $u_{\max}$ for regions 5 and 7. For $\theta_{\mathrm{cut}} = 10°$ p_T is restricted to $23.6 \leqslant p_T \leqslant 46.9$ GeV. Finally in fig. 2c we have 9 regions. The limits for u are u_- and u_+ for region 1, u_- and $u_{\max}$ for regions 2.1, 2.2 and 4, $u_{\min}$ and u_+ for regions 3.1, 3.2 and 6, $u_{\min}$ and $u_{\max}$ for regions 5 and

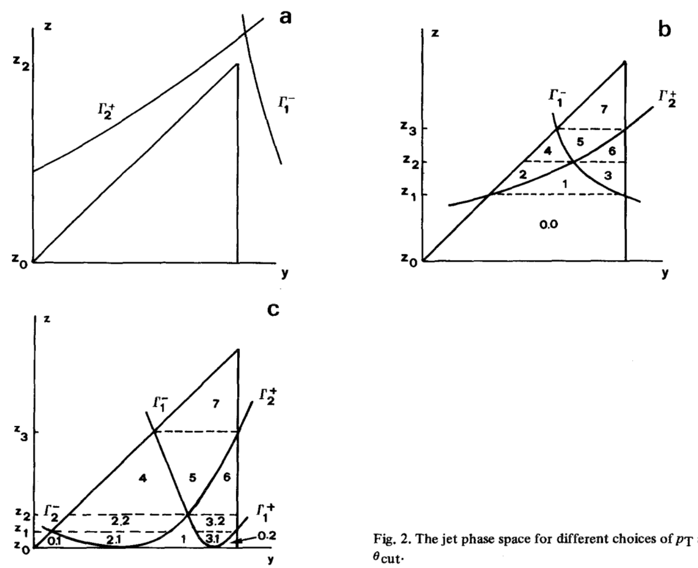


Fig. 2. The jet phase space for different choices of p_T and θ_{cut}.

- $Z\gamma$ & Zj
- CALCULATION INCLUDING Z DECAY
- FIDUCIAL PREDICTIONS

TURIN, 1992

PRECISION EW

ELSEVIER

Physics Letters B
Volume 313, Issues 1–2, 26 August 1993, Pages 213-220

The determination of $\alpha_s(M_Z)$ from the Z^0 lineshape and asymmetry data

Giampiero Passarino [a, b]

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- CORRELATED EXPT. UNCERTAINTIES
- RADIATIVE CORRECTIONS

QUALITATIVE QCD

VOLUME 71, NUMBER 2   PHYSICAL REVIEW LETTERS   12 JULY 1993

Small-Angle Polarization in High-Energy *p-p* Scattering through Nonperturbative Chiral Symmetry Breaking

Mauro Anselmino[(1),(2)] and Stefano Forte[(2)]
[(1)]*Dipartimento di Fisica Teorica, Università di Torino, Torino, Italy*
[(2)]*Istituto Nazionale di Fisica Nucleare, Sezione di Torino, via P. Giuria 1, I-10125 Torino, Italy*
(Received 11 December 1992)

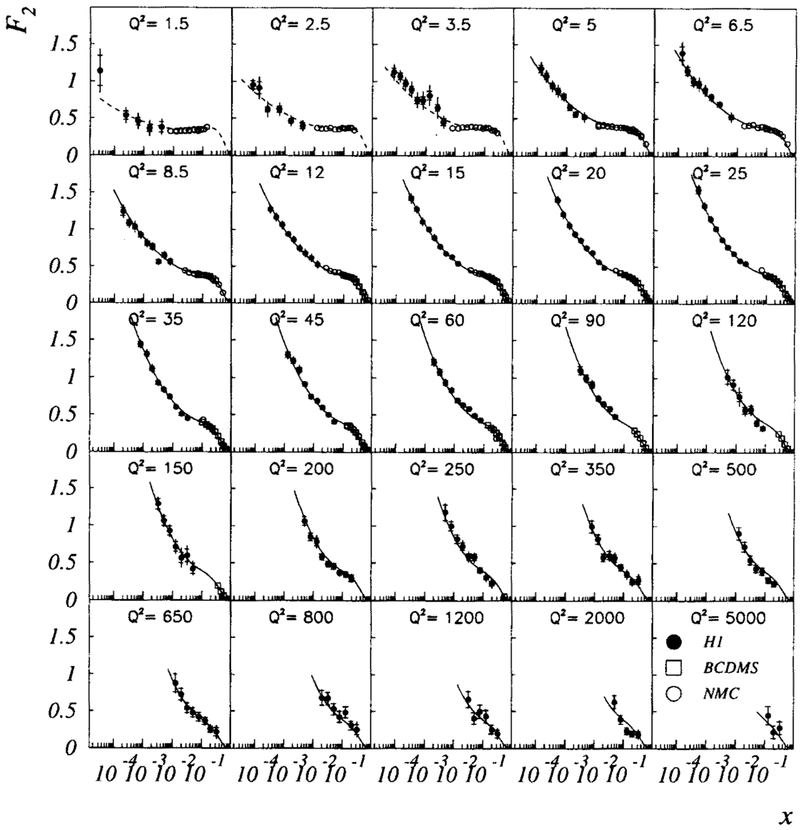
We show that a large anomalous contribution to the axial charge of the proton due to nonperturbative instantonlike gluonic field configurations implies high-energy spin effects in *p-p* elastic scattering. This is the same mechanism which is responsible for anomalous baryon number violation at high energy in the standard model. We compute the proton polarization due to these effects and we show that it is proportional to the center-of-mass scattering angle with a universal (energy independent) slope of order unity.

- INSTANTON-INDUCED χSB
- EXPERIMENTAL SIGNATURE (SINGLE-SPIN POLARIZATION)

QCD IN THE MID 90'S

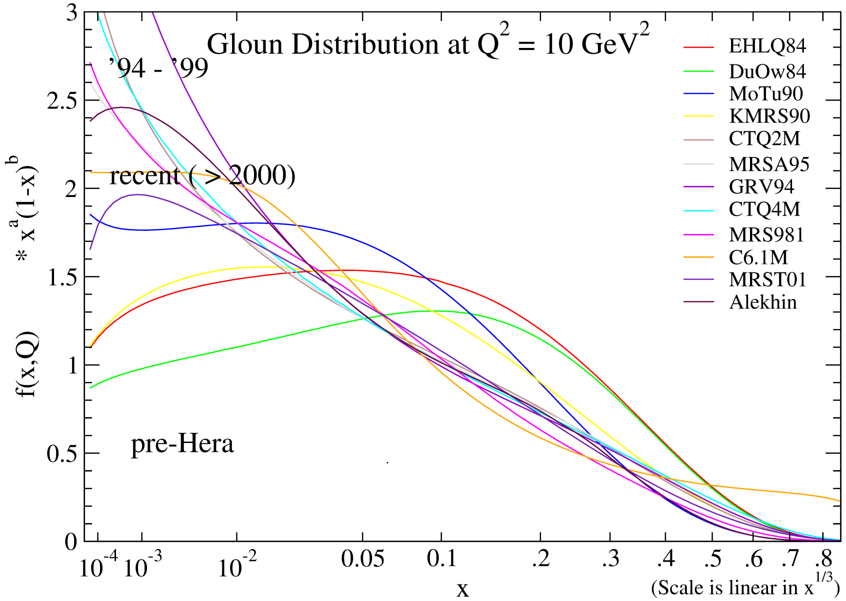
1995: THE RISE OF STRUCTURE FUNCTIONS AT HERA

FIRST HERA DATA VS OLDER DATA



A. de Roeck, Cracow epiphany conf. 1996

HISTORICAL COMPILATION OF GLUON PDFS

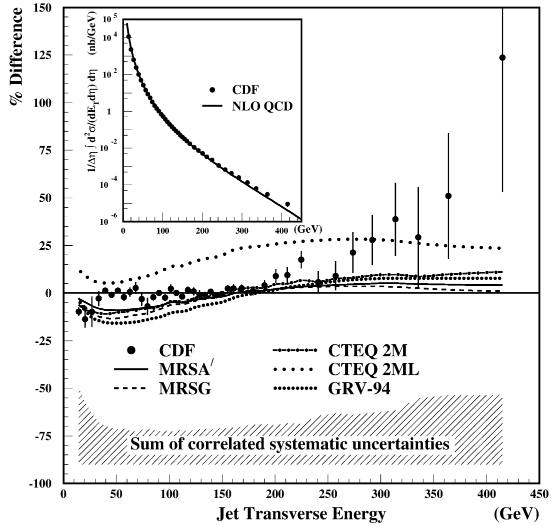


W.K.Tung, DIS 2004

- RISE OF F_2 AT HERA $\Rightarrow$ SURPRIZE
- THEORETICAL BIAS $\Leftrightarrow$ QUALITATIVE UNDERSTANDING

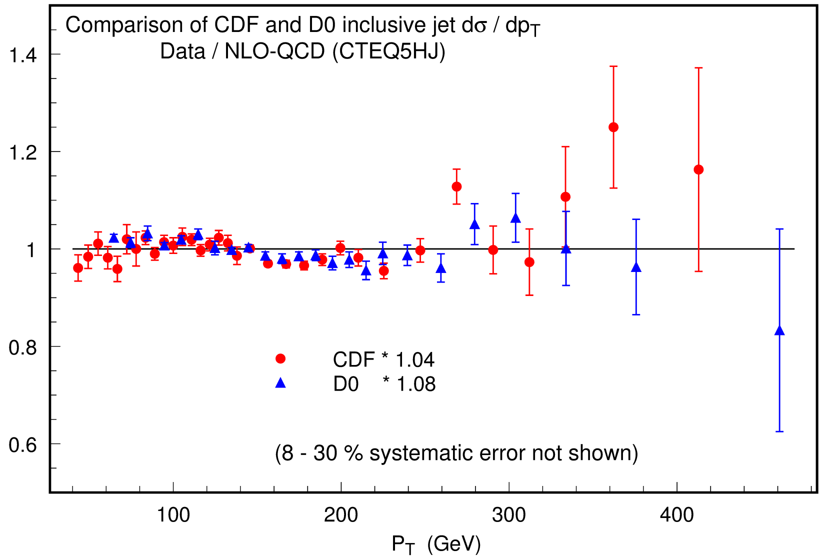
1995: THE “DISCOVERY” OF QUARK COMPOSITENESS

- DISCREPANCY BETWEEN QCD CALCULATION AND CDF JET DATA (1995)
- EVIDENCE FOR QUARK COMPOSITENESS?
- RESULT STRONGLY DEPENDS ON GLUON AT $x \gtrsim 0.1$
- PDF MUST VANISH AT $x = 0$, BUT (THEN) NO DATA FOR $x \gtrsim 0.05$!



DISCREPANCY REMOVED IF JET DATA USED FOR GLUON DETERMINATION

NEW CTEQ GLUON (1998)



1995: TOWARDS PRECISION QCD
THE DETERMINATION OF α_s

ELSEVIER Physics Letters B 331 (1994) 165–170

The ratio R of hadronic and electronic Z widths and the strong coupling constant α_s

Thomas Hebbeker [a], Manel Martinez [b], Giampiero Passarino [c], Günter Quast [d]
[a] CERN, PPE Division, Geneva, Switzerland
[b] Institut de Fisica d'Altes Energies, Barcelona, Spain
[c] Dipartimento di Fisica Teorica, Università di Torino and INFN Sezione di Torino, Torino, Italy
[d] Universität Mainz, Mainz, Germany

Received 15 March 1994
Editor: R. Gatto

Abstract

We review the relation between the ratio of hadronic and electronic Z widths, $R = \Gamma(Z \to q\bar{q})/\Gamma(Z \to e^+e^-)$, and the strong coupling constant at the Z mass, α_s. The theoretical uncertainty of α_s derived from R is estimated to be

$\Delta\alpha_s = \pm 0.002\,(\text{electroweak}) \pm 0.002\,(\text{QCD})\, {}^{+0.004}_{-0.003}\,(m_{\text{top}}, m_{\text{Higgs}})$.

THEORY UNCERTAINTIES:
CAREFUL ANALYSIS

- m_t, m_H
- QCD MHOU
- HADRONIC CONTRIBUTION TO α
- m_b

ELSEVIER Physics Letters B 358 (1995) 365–378

Determination of α_s from F_2^p at HERA

Richard D. Ball [1], Stefano Forte [2]
Theory Division, CERN, CH-1211 Genève 23, Switzerland

Received 6 June 1995
Editor: R. Gatto

Abstract

We compute the proton structure function F_2^p at small x and large Q^2 at next-to-leading order in $\alpha_s(Q^2)$, including summations of all leading and subleading logarithms of Q^2 and $1/x$. We perform a detailed comparison to the 1993 HERA data, and show that they may be used to determine $\alpha_s(M_Z^2) = 0.120 \pm 0.005(\text{exp}) \pm 0.009(\text{th})$. The theoretical error is dominated by the renormalization and factorization scheme ambiguities.

- DEEP-INELASTIC HERA DATA $\Rightarrow$ UNIVERSAL BEHAVIOR
- QCD CORRECTIONS $\Rightarrow \alpha_s$

HERA vs. LEP
EPS 1999

Paper presented at the Int. Europhysics Conf. on High Energy Physics, Tampere, 1999

Tests of the Standard Model at HERA

Stefano Forte[†]

INFN, Sezione di Roma III,
via della Vasca Navale 84, I-00146 Roma, Italy

Abstract

We review how experimental data collected at the HERA lepton-hadron collider have improved our theoretical and phenomenological understanding of the standard model, and specifically of its QCD sector.

1. Factorization

HERA is unique as a lepton-hadron collider. The measurement of lepton-hadron scattering cross sections allows for detailed tests of the standard model thanks to the factorization property of many hard QCD processes. The perturbative computation of the hard elementary process, and in particular

and is thus a crucial ingredient for e.g. LHC physic An accurate determination of QCD backgrounds new physics is also needed. Recent progress involv more accurate determinations of parton distributio (see Sect. 2), and widening the perturbative domai by learning how to treat processes with many larg scales (Sect. 3) and extending factorization theore to less inclusive processes (Sect. 4).

5. Conclusion

HERA has played for QCD a similar role as LEP for the electroweak sector of the standard model. In general, perturbative computations lead to excellent phenomenology; this however seems to happen even beyond the regions were one might expect it.

Acknowledgement: I thank G. Passarino for convening this lively session and for inviting me to put HERA physics in the context of the standard model, and G. Altarelli and R. Ball for useful

THE HIGGS!

2007-2008: TOWARDS DISCOVERY

- LHC: QCD AS PRECISION PHYSICS
- THE DRIVE TO HIGHER PERTURBATIVE ORDERS

Complete two-loop corrections to $H \to \gamma\gamma$ ☆

Giampiero Passarino [a,b,*], Christian Sturm [a,b], Sandro Uccirati [a,b]

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[b] *INFN, Sezione di Torino, Italy*

Received 13 July 2007; received in revised form 30 August 2007; accepted 5 September 2007

Available online 12 September 2007

Editor: G.F. Giudice

Abstract

In this Letter the complete two-loop corrections to the Higgs-boson decay, $H \to \gamma\gamma$, are presented. The evaluations of both QCD and electroweak corrections are based on a numerical approach. The results cover all kinematical regions, including the WW normal-threshold, by introducing complex masses in the relevant (gauge-invariant) parts of the LO and NLO amplitudes.

PACS: 11.15.Bt; 12.38.Bx; 13.85.Lg; 14.80.Bn; 14.80.Cp

Keywords: Feynman diagrams; Multi-loop calculations; Higgs physics

- FULL TWO LOOPS QCD+EW
- CAREFUL TREATMENT
  OF RENORMALIZATION

ELSEVIER

Nuclear Physics B 800 (2008) 127–145

www.elsevier.com/locate/nuclphysb

Higgs production via gluon–gluon fusion with finite top mass beyond next-to-leading order

Simone Marzani [a], Richard D. Ball [b,c], Vittorio Del Duca [c,1], Stefano Forte [d,*], Alessandro Vicini [d]

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[b] *CERN, Physics Department, Theory Division, CH-1211 Genève 23, Switzerland*
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Received 18 January 2008; accepted 17 March 2008

Available online 1 April 2008

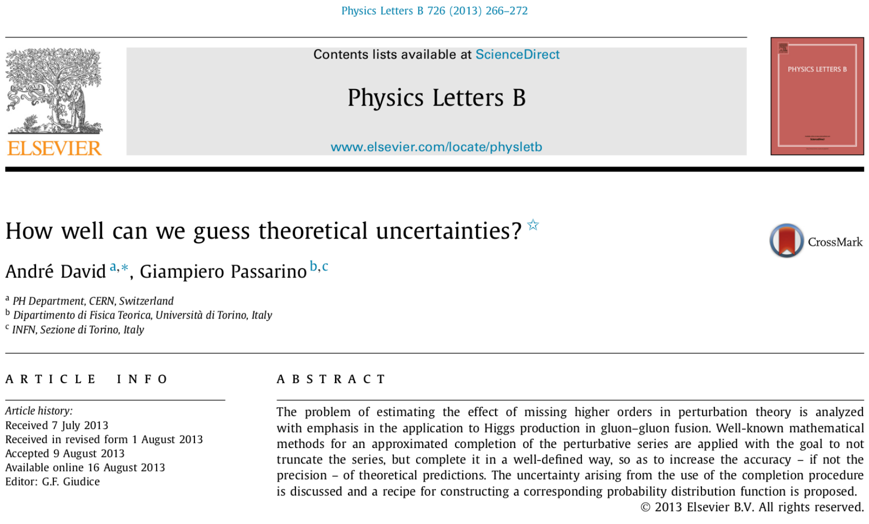
Abstract

We present a computation of the cross section for inclusive Higgs production in gluon–gluon fusion for finite values of the top mass in perturbative QCD to all orders in the limit of high partonic center-of-mass energy. We show that at NLO the high energy contribution accounts for most of the difference between the result found with finite top mass and that obtained in the limit $m_t \to \infty$. We use our result to improve the known NNLO order result obtained at $m_t \to \infty$. We estimate the effect of the high energy NNLO m_t dependence on the K factor to be of the order of a few per cent.

- ALL-ORDER SMALL-x RESUMMATION
- BEYOND POINTLIKE LIMIT AT NNLO

THE PROBLEM OF MHOU

CAN WE DO BETTER THAN SCALE VARIATION?


Physics Letters B 726 (2013) 266–272

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

How well can we guess theoretical uncertainties? ☆

André David [a,*], Giampiero Passarino [b,c]

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ARTICLE INFO

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ABSTRACT

The problem of estimating the effect of missing higher orders in perturbation theory is analyzed with emphasis in the application to Higgs production in gluon–gluon fusion. Well-known mathematical methods for an approximated completion of the perturbative series are applied with the goal to not truncate the series, but complete it in a well-defined way, so as to increase the accuracy – if not the precision – of theoretical predictions. The uncertainty arising from the use of the completion procedure is discussed and a recipe for constructing a corresponding probability distribution function is proposed.
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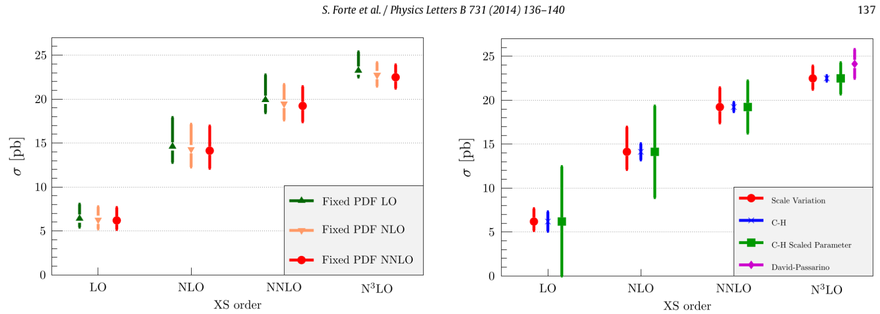

- PERFORM SEQUENCE TRANSFORMATION
- BOREL SUM THE ACCELERATED SERIES

- DEPENDENCE ON PDF PERTURBATIVE ORDER
- COMPARISON OF DIFFERENT MHOU ESTIMATES

THEORY UNCERTAINTIES: 2011: THE HXSWG

HXSWG, YR1

12 Parametric and theoretical uncertainties[23]

12.1 Introduction

In this note we address the following questions: definition of theoretical uncertainties (THU) for LHC predictions, their statistical meaning, inclusion of parametric uncertainties (PU), their combination. For the latter we want to stress that the solution (how to combine) relies on some implicit assumptions; any variation in the assumptions leads to a somehow different solution. In this case intuition may still help to qualitatively guess how the value of the measurement is affected.

12.3 THU, understanding the origin of the problem

In this and the next section we are going to discuss two separate issues [367] that are sometimes mixed:

– What is the optimal choice for QCD scales?
– Can one use scale variation to estimate higher-order corrections?

We begin by addressing the first question. Let us for a moment concentrate on the uncertainty induced by variations of the renormalization scale, μ_R, and of the factorization scale, μ_F. The question

[23] A. Denner, S. Dittmaier, S. Forte and G. Passarino.

THE INFN "WHAT'S NEXT" WORKSHOP:

Eur. Phys. J. C (2015) 75:554
DOI 10.1140/epjc/s10052-015-3759-0

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Special Article - Tools for Experiment and Theory

The Standard Model from LHC to future colliders

S. Forte[1,13,a], **A. Nisati**[2], **G. Passarino**[3,14], **R. Tenchini**[4], **C. M. Carloni Calame**[5], **M. Chiesa**[6], **M. Cobal**[7,15], **G. Corcella**[8], **G. Degrassi**[9,16], **G. Ferrera**[1,13], **L. Magnea**[3,14], **F. Maltoni**[10], **G. Montagna**[5,6], **P. Nason**[17], **O. Nicrosini**[6], **C. Oleari**[11,17], **F. Piccinini**[6], **F. Riva**[12], **A. Vicini**[1,13]

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Received: 9 June 2015 / Accepted: 25 October 2015 / Published online: 25 November 2015

Abstract This review summarizes the results of the activities which have taken place in 2014 within the Standard Model Working Group of the "What Next" Workshop organized by INFN, Italy. We present a framework, general questions, and some indications of possible answers on the main issue for Standard Model physics in the LHC era and in view of possible future accelerators.

Contents

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WHAT'S NEXT?:
ANOMALOUS THRESHOLDS?

Peaks and cusps: anomalous thresholds and LHC physics

Giampiero Passarino[a]

[a]*Dipartimento di Fisica Teorica, Università di Torino, Italy*
INFN, Sezione di Torino, Italy

Abstract

The behavior of scattering amplitudes in the vicinity of a physical-region Landau singularity is considered. The impact on LHC processes is discussed.

Keywords: LHC physics; Feynman diagrams; Landau singularities
PACS: 11.55.Bq, 12.15.Lk, 11.15.Bt

ASK GIAMPIERO!