PRECISE PREDICTIONS FOR HIGGS PRODUCTION VIA GLUON FUSION IN BSM SCENARIOS

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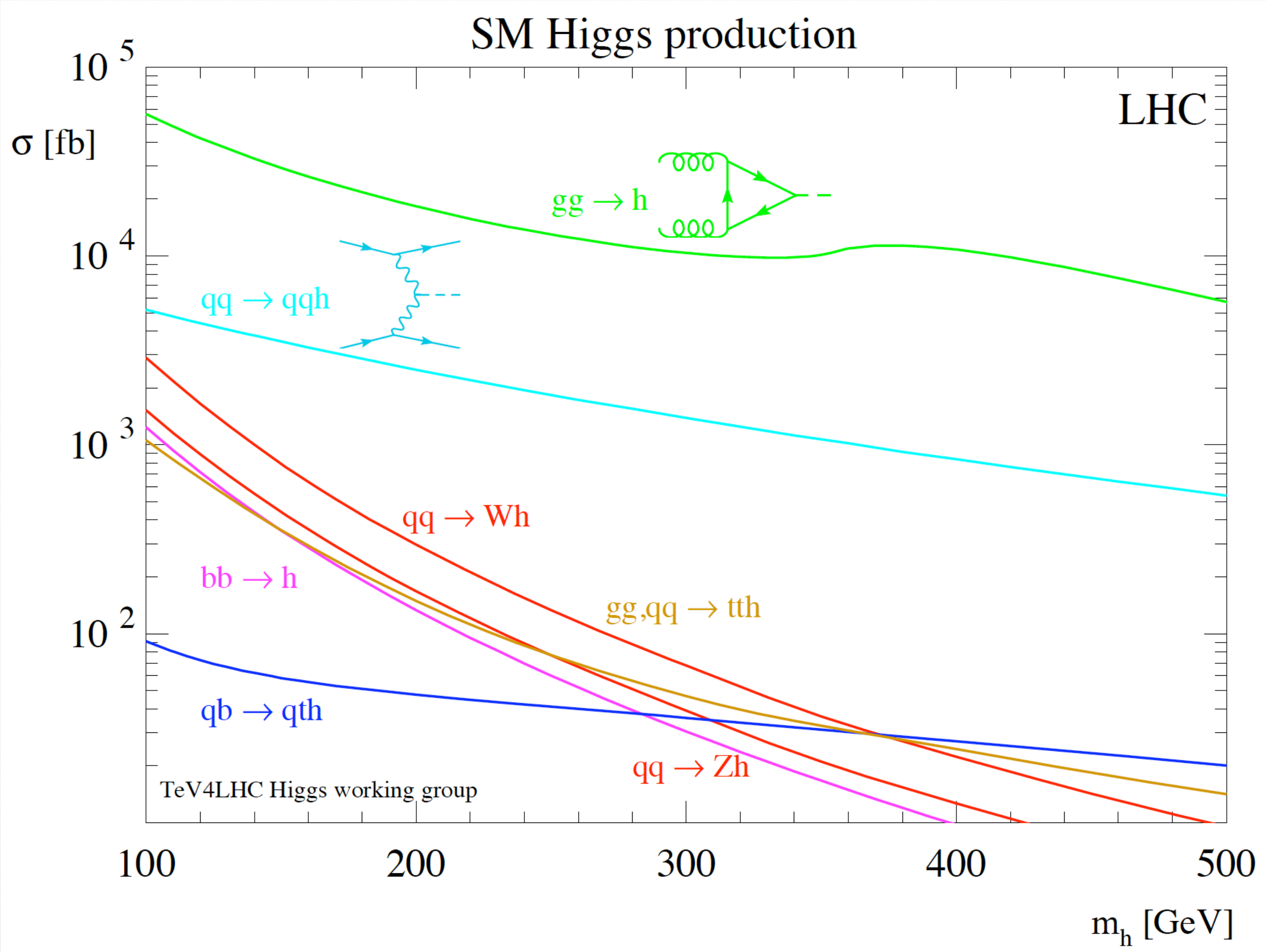
BNL

HEAVY PARTICLES WORKSHOP

JAN 7TH, 2011

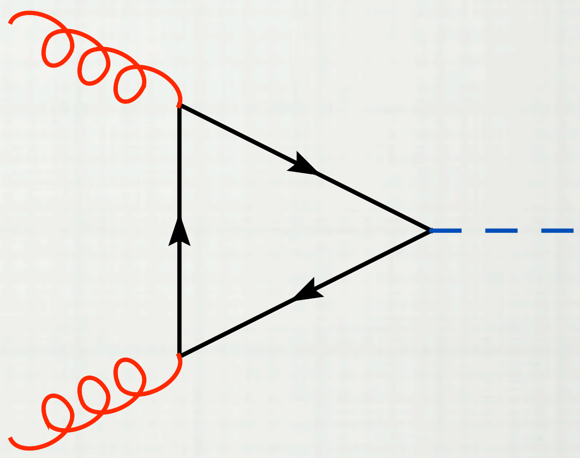
MOTIVATION

- GLUON FUSION IS THE MAIN MECHANISM FOR HIGGS PRODUCTION AT HADRON COLLIDERS



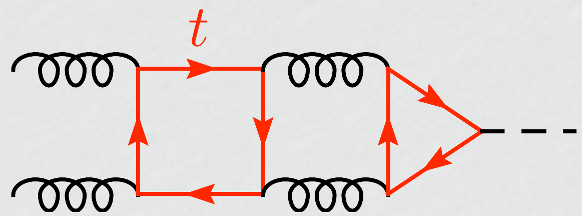
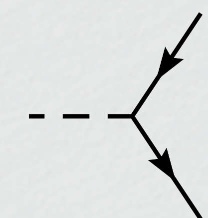
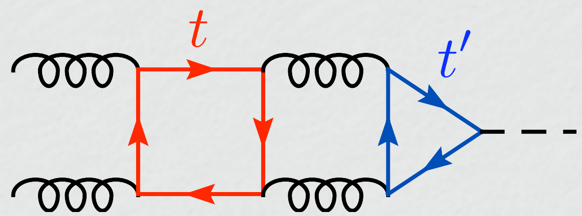
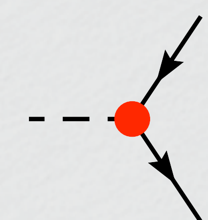
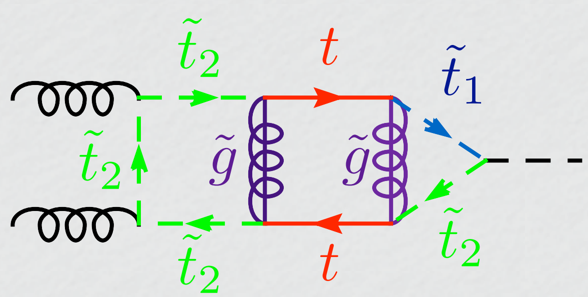
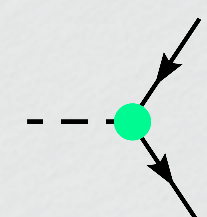
MOTIVATION

- HIGGS PRODUCTION VIA GLUON FUSION IS SENSITIVE TO ANY COLOURED PARTICLE THAT COUPLES TO THE HIGGS, E.G. THE TOP



- THE HIGGS SECTOR IS UNTESTED
- THE DESCRIPTION OF ELECTROWEAK SYMMETRY BREAKING SECTOR PROVIDED BY THE STANDARD MODEL NEEDS TO BE EXTENDED
- EXTENSIONS OF THE SM INTRODUCE NEW PARTICLES WHICH MAY CONTRIBUTE TO GLUON FUSION

MOTIVATION

particles in different representations of the Lorentz group	particles of different mass in the loops	particles in different colour representations	different structure of the Higgs coupling
quarks		singlets, triplets, octets	 $\sim \bar{\psi}\psi$
squarks		fundamental, adjoint	 $\sim \bar{\psi}\gamma_5\psi$
Majorana fermions		⋮	 $\neq \frac{m}{v}\bar{\psi}\psi$
⋮	⋮		⋮

GLUON FUSION IN THE STANDARD MODEL

- IT IS KNOWN VERY PRECISELY...

  ... BUT IT REQUIRED TOUGH CALCULATIONS

$$\sigma^{(SM)}_{NNLO} = \sigma^{(SM)}_{LO}\,(1 + \underbrace{0.7}_{\text{NLO}} + \underbrace{0.3}_{\text{NNLO}})$$

HARLANDER, KILGORE; ANASTASIOU, MELNIKOV; RAVINDRAN, SMITH, VAN NEERVEN

$$\left(\frac{\Delta\sigma}{\sigma}\right)^{\exp} \sim \pm 10\% \quad , \quad \left(\frac{\Delta\sigma}{\sigma}\right)^{NNLO}_{SM} \sim \pm 10\%$$

  ... AND AN EFFECTIVE-THEORY APPROACH (CHETYRKIN, KNIEHL, STEINHAUSER)

GLUON FUSION IN THE STANDARD MODEL

- ONLY VERY RECENT CALCULATIONS IN SOME BSM SCENARIOS

BOUGHEZAL, PETRIELLO;
ANASTASIOU, BOUGHEZAL, EF;
PAK, STEINHAUSER, ZERF

- WHY?

THE LOW-ENERGY THEORY IS THE SAME AS IN THE STANDARD MODEL, BUT THE MATCHING CALCULATION AT NNLO IS MUCH MORE COMPLICATED:

  - NUMBER OF DIAGRAMS
  - RENORMALIZATION
  - DEPENDENCE ON MULTIPLE MASS SCALES

SEPARATING NEW PHYSICS

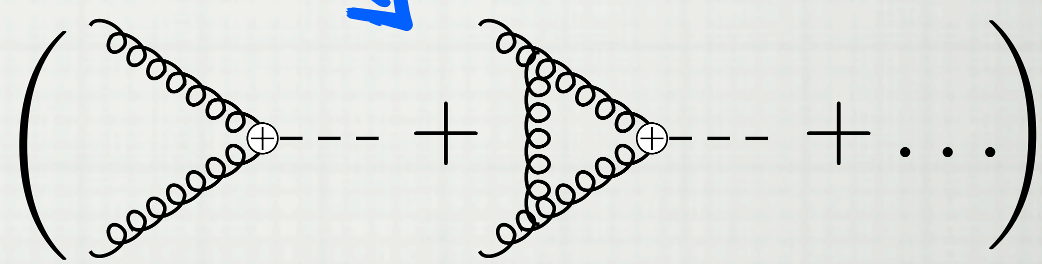
- EXPERIMENTS (LEP, TEVATRON, ..) INDICATE THAT NEW PARTICLES MUST BE HEAVY, WHILE THE HIGGS IS LIGHT

- THIS ALLOWS FOR AN EFFECTIVE-THEORY APPROACH:

$$\mathcal{L}_{eff} = -\frac{\alpha_S}{4v} C \, H G^a_{\mu\nu} G^{a\mu\nu}$$

$$\left(C_0 + \left(\frac{\alpha_s}{\pi}\right) C_1 + \left(\frac{\alpha_s}{\pi}\right)^2 C_2 + \ldots \right)$$

DEPENDS ON THE SPECIFIC MODEL

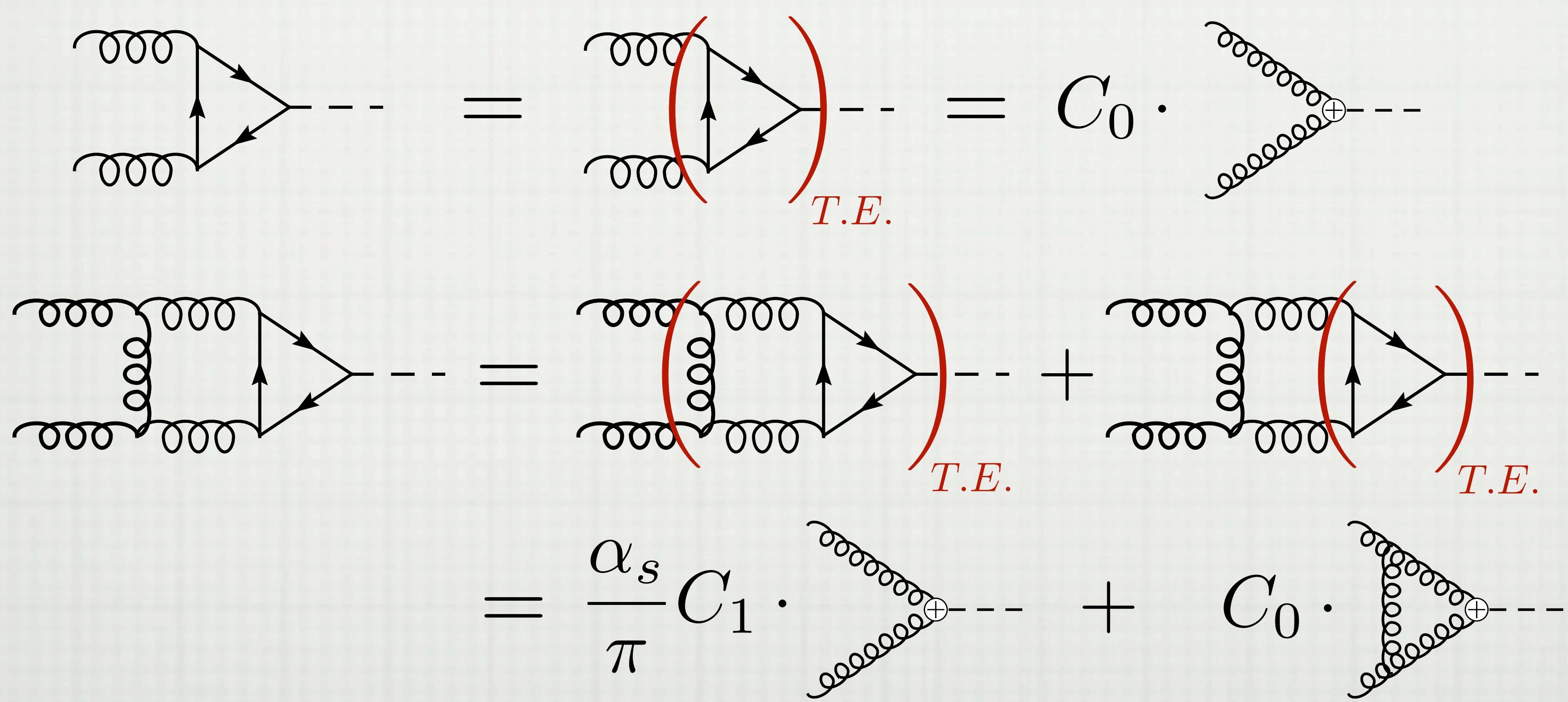


QCD ONLY!

→ FACTORIZATION OF QCD AND NP EFFECTS

METHOD

EXPANSION BY SUBGRAPHS (CHETYRKIN; GORISHNY; V. A. SMIRNOV)
+ SMALL MOMENTUM EXPANSION (FLEISCHER, TARASOV):



TECHNICAL CHALLENGES

- LARGE NUMBER OF FEYNMAN DIAGRAMS

  ~ 500 IN THE SM, ~ 2000 IN FOUR-GENERATION SM, ~ 6000 IN COMPOSITE HIGGS, ...

- APPLY COSTLY DIFFERENTIATIONS FOR TAYLOR EXPANSION

- REDUCE A LARGE NUMBER (~10^5) OF INTEGRALS TO MASTER INTEGRALS

➡ WE WROTE OUR OWN ROUTINES IN

- QGRAF (NOGUEIRA)
- MATHEMATICA
- FORM (VERMASEREN)
- AIR (ANASTASIOU, LAZOPOULOS)

➡ SAME METHODS FOR SM AND BSM WILSON COEFFICIENTS

TECHNICAL CHALLENGES

- ☐ EVALUATE THE MASTER INTEGRALS
  - ➡ MUCH MORE DIFFICULT THAN IN THE STANDARD MODEL (MANY MASS SCALES)
  - ➡ IN MANY CASES, IMPOSSIBLE WITH TRADITIONAL ANALYTIC METHODS ⇨ SECTOR DECOMPOSITION

HEPP; DENNER, ROTH; BINOTH, HEINRICH;
ANASTASIOU, MELNIKOV, PETRIELLO;
ANASTASIOU, BEERLI, DALEO;
LAZOPOULOS, MELNIKOV, PETRIELLO

FOUR-GENERATION STANDARD MODEL

IN COLLABORATION WITH C. ANASTASIOU AND R. BOUGHEZAL

- SIMPLE EXTENSION OF THE STANDARD MODEL

	I	II	III	IV ?		
QUARKS	u	c	b	B	γ	GAUGE BOSONS
	d	s	t	T	G	
LEPTONS	ν_e	ν_μ	ν_τ	ν'_τ	Z	
	e	μ	τ	τ'	W	

FOUR-GENERATION STANDARD MODEL

- TEVATRON COLLABORATIONS CAN PUT ACCURATE EXPERIMENTAL BOUNDS ON THE MASS OF THE HIGGS BOSON IN THIS MODEL

- PREVIOUS ANALYSES ARE BASED ON (ARIK ET AL.)

  - ➡ NLO CALCULATION
  - ➡ INFINITE - MASS APPROXIMATION

  $$\left.\right\} \sigma^{(4,NLO)} = 9\sigma^{(3,NLO)}$$

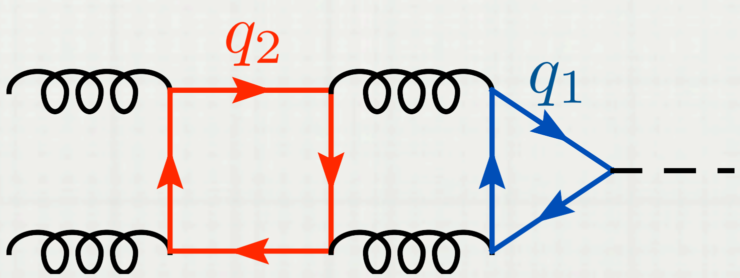
- ALREADY AT LO, FINITE-MASS EFFECTS CAN CHANGE THE ENHANCEMENT FACTOR BY ~20%

- THE THEORY UNCERTAINTY ON THE NLO CROSS SECTION IS MUCH HIGHER THAN THE EXPERIMENTAL UNCERTAINTY

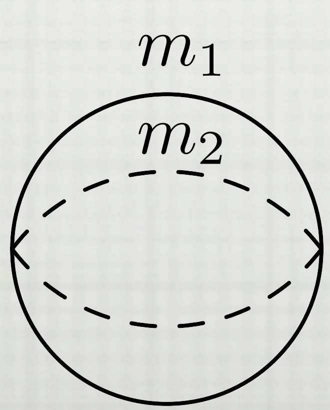
FOUR-GENERATION STANDARD MODEL

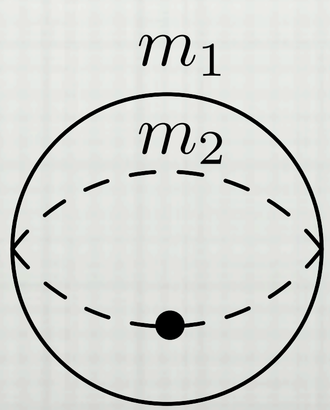
- WE HAVE THE TOOLS TO COMPUTE THE HIGGS PRODUCTION CROSS SECTION VIA GLUON FUSION AT NNLO ACCURACY

- AT NNLO, WE HAVE DIAGRAMS CONTAINING TWO DIFFERENT HEAVY QUARKS



⇨ MASTER INTEGRALS CAN CONTAIN UP TO TWO, DIFFERENT, MASSIVE PROPAGATORS





→ BEKAVAC, GROZIN, SEIDEL, SMIRNOV

HIGGS PRODUCTION CROSS-SECTION

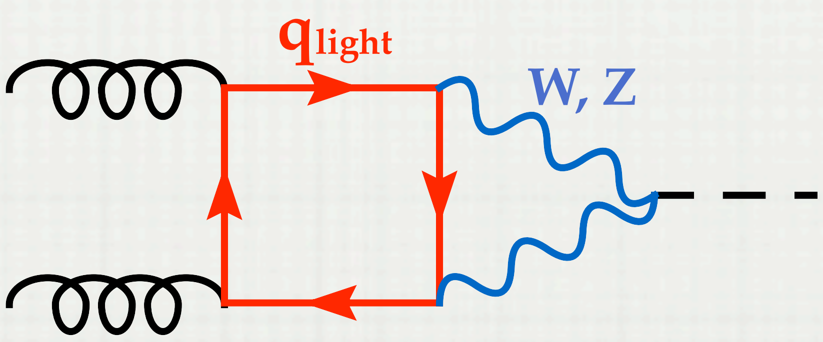
- WE INCLUDE
  - ➡ THE EXACT LO AND NLO AMPLITUDE FOR THE HEAVY QUARKS AND FOR THE BOTTOM QUARK

    WILCZEK; ELLIS ET AL.; GEORGI ET AL.; SPIRA ET AL.; ANASTASIOU ET AL.

  - ➡ OUR NNLO WILSON COEFFICIENT IN THE HEAVY-QUARK APPROXIMATION

HIGGS PRODUCTION CROSS-SECTION

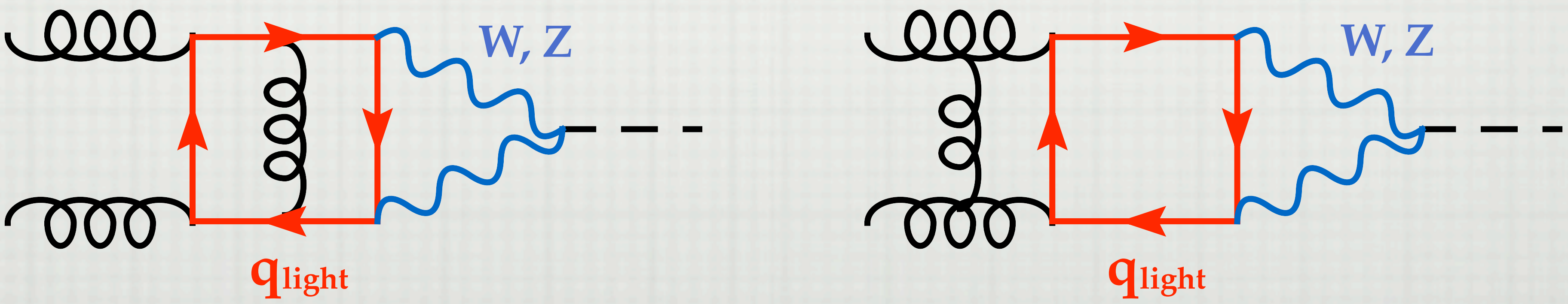
- THE TWO-LOOP ELECTROWEAK CORRECTIONS



AGLIETTI ET AL.

- THE THREE-LOOP MIXED QCD-ELECTROWEAK CORRECTIONS

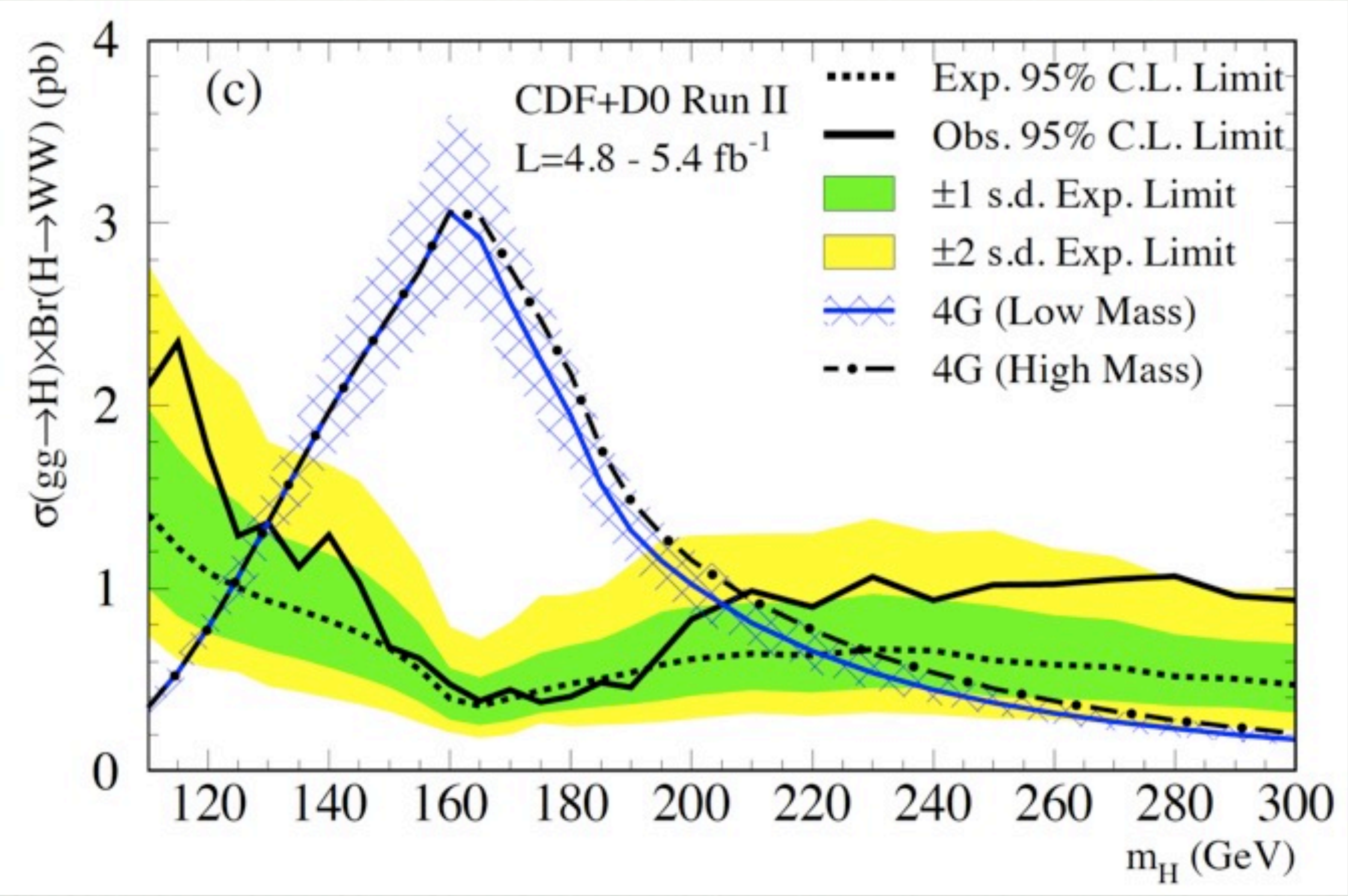
ANASTASIOU ET AL.



FOUR-GENERATION STANDARD MODEL

- THE NNLO CROSS SECTION IS 10-15% HIGHER THAN THE NLO CROSS SECTION
- THE THEORETICAL ERROR DECREASES FROM 20-30% AT NLO TO 10% AT NNLO
- OUR RESULT ALLOWS THE TEVATRON COLLABORATIONS TO PUT ACCURATE CONSTRAINTS ON THE MASS OF THE HIGGS BOSON IN A FOUR-GENERATION STANDARD MODEL

FOUR-GENERATION STANDARD MODEL



CDF & D0

EXCLUDE $131\,\mathrm{GeV} \lesssim m_H \lesssim 204\,\mathrm{GeV}$

COMPOSITE HIGGS MODELS

GEORGI, KAPLAN

- CLASS OF MODELS THAT ADDRESS THE HIERARCHY PROBLEM
- THE COUPLING OF THE HIGGS BOSON ARE REDUCED WITH RESPECT TO THE STANDARD MODEL
- NEW HEAVY QUARKS ARE TYPICALLY INTRODUCED

} how is the Higgs production cross section modified?

COMPOSITE HIGGS MODELS

GEORGI, KAPLAN

- AT LO, EXPECT A SUPPRESSION IN THE HIGGS PRODUCTION VIA GLUON FUSION

FALKOWSKI

- THE SUPPRESSION FACTOR DEPENDS ON THE DETAILS OF THE MODEL

- FOR THE MODEL THAT IS MORE FAVOURED BY CURRENT EXPERIMENTAL BOUNDS

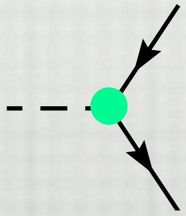
$$\frac{\sigma_{CH}^{LO}}{\sigma_{SM}^{LO}} \sim 35\%$$

- (HOW) DOES THIS RESULT CHANGE AT HIGHER ORDERS?

COMPOSITE HIGGS MODELS

GEORGI, KAPLAN

- WE CONSIDER A MODEL WITH ADDITIONAL MULTIPLETS OF VECTOR-LIKE FERMIONS
  - THREE CHARGE 2/3 QUARKS
  - ONE CHARGE -1/3 QUARK
  - ONE CHARGE 5/3 QUARK
- DIFFERENCE TO THE STANDARD MODEL: HIGGS - QUARK COUPLINGS



$$\frac{m_1}{v} \rightarrow Y_1$$

HIGGS PRODUCTION CROSS SECTION

- ONE MULTIPLET:
  - CONFIRM A 30-35% SUPPRESSION WITH RESPECT TO THE STANDARD MODEL THROUGH NNLO
  - BOTTOM QUARK- AND TWO-LOOP ELECTROWEAK CORRECTIONS ARE MORE IMPORTANT THAN IN THE STANDARD MODEL

	SM	CHM[(1)]
$\frac{\sigma_{tb}^{LO} - \sigma_{t}^{LO}}{\sigma_{t}^{LO}}$	- 7%	- 10%
$\frac{\sigma_{tbew}^{NLO} - \sigma_{tb}^{NLO}}{\sigma_{tb}^{NLO}}$	+ 5%	+ 7%

HIGGS PRODUCTION CROSS SECTION

- TWO MULTIPLETS:
  - CAN GO FROM A ~1% SUPPRESSION WITH RESPECT TO THE STANDARD MODEL TO A FACTOR ~ 3 ENHANCEMENT
  - STRONG SUPPRESSION ⇨ LARGE NLO (~2.5) AND NNLO (~ 3) K-FACTORS

CONCLUSIONS

- THE HIGGS BOSON IS LIKELY TO COME WITH SOME NEW PHYSICS
- MANY VIABLE BSM THEORIES EXIST, AND MANY NEED TO INTRODUCE NEW, COLOURED PARTICLES
- THEY CAN SIGNIFICANTLY AFFECT THE GLUON-FUSION CROSS SECTION
- WE ADOPT AN EFFECTIVE THEORY APPROACH TO DISENTANGLE NEW PHYSICS FROM QCD
- WE HAVE AUTOMATISED THE MATCHING PROCEDURE FOR BSM MODELS THROUGH NNLO
- READY FOR HIGH-PRECISION PREDICTIONS FOR HIGGS BOSON CROSS-SECTION BEYOND THE STANDARD MODEL
  - EXAMPLE: FOUR-GENERATION STANDARD MODEL, COMPOSITE HIGGS MODELS