

Machine Learning • PDFs • QCD

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PRECISION STANDARD MODEL PHYSICS AT THE LHC

STEFANO FORTE
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UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA



MASS 2018

ODENSE, MAY 31, 2018

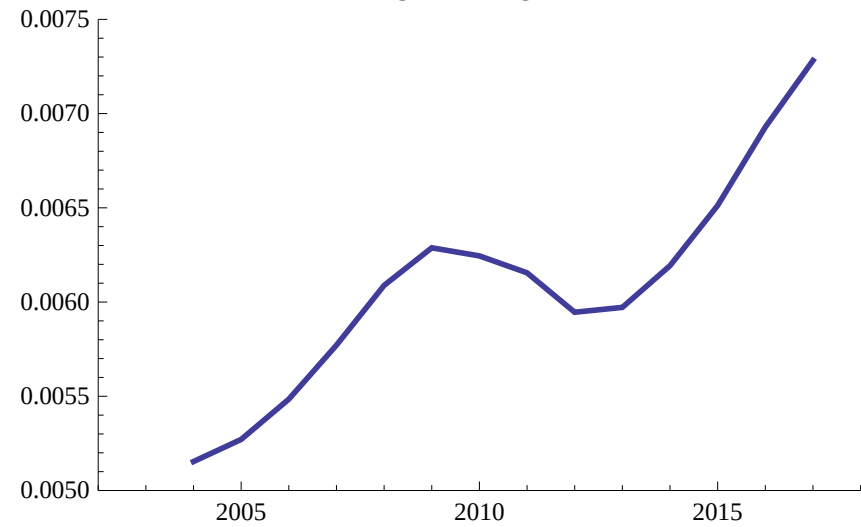
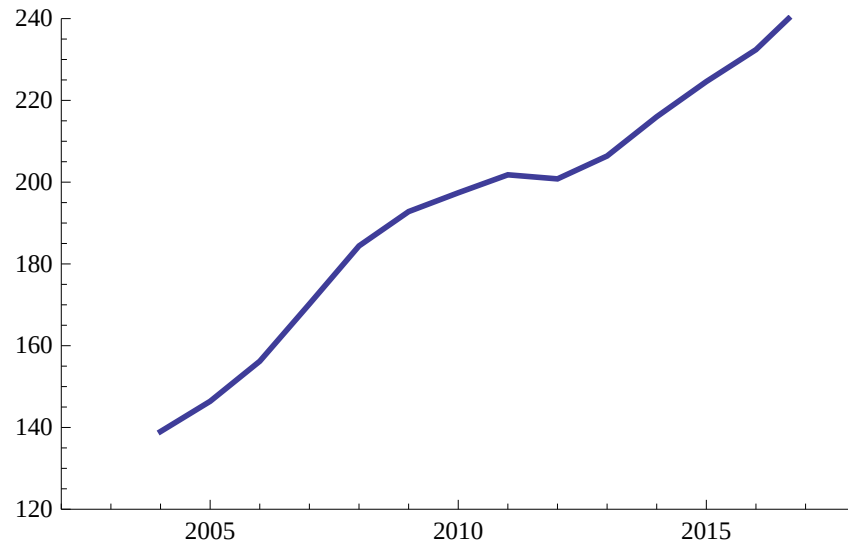
PROLOGUE: PRECISION?

PRECISION

PAPERS WITH "PRECISION" IN TITLE

NUMBER

PERCENTAGE

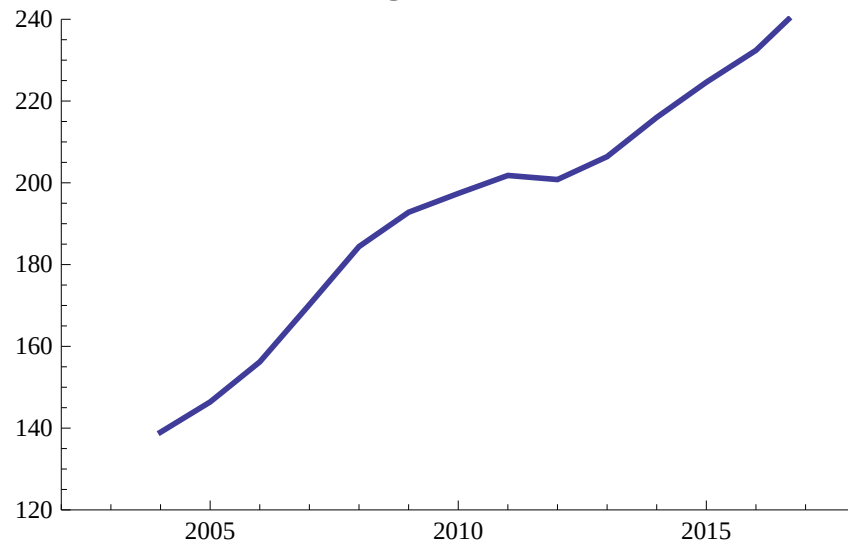


INSPIRE, 5 YR MOVING AVERAGE

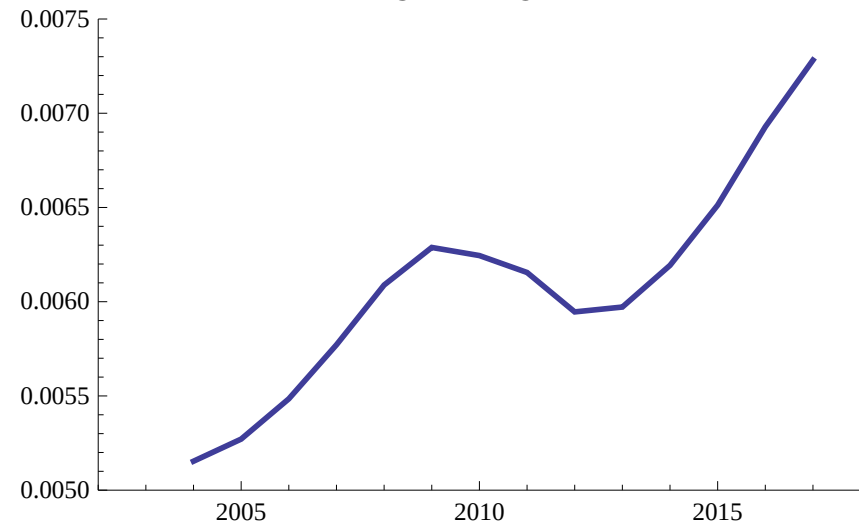
PRECISION

PAPERS WITH "PRECISION" IN TITLE

NUMBER



PERCENTAGE



INSPIRE, 5 YR MOVING AVERAGE

YES, SOMETIMES THEY REALLY MEAN ACCURACY

THE MOST PRECISE (ACCURATE) CALCULATION

HIGGS IN GLUON FUSION: TOTAL CROSS-SECTION

Higgs Cross Section Working Group, YR4 (Nov 2016-Apr 2017)

(APPR) N³LO+N³LL QCD (EFT); NLO PURE EW; NLO EXACT HQ;
NNLO APPROX TOP; NNLO PDFs

$$\sigma(\text{LHC13}, m_H = 125 \text{ GeV}) = 48.58 \text{ pb} \pm 2.2^{\text{TH}} (4.5\%) \pm 1.6^{\text{PDF}+\alpha_s} (3.2\%)$$

THEORY UNCERTAINTIES

- MISSING HIGHER ORDERS **HO**
 - TRUNC. OF SOFT EXPANSION FOR N³LO $\pm 0.18 \text{ pb}$ (0.4%)
 - N⁴LO & BEYOND $\pm 1.4 \text{ pb}$ (3%)
- MIXED NLO QCD-ELECTROWEAK CORRNS. **EW** $\pm 1.2 \text{ pb}$ (2.5%)
- HEAVY QUARK MASS EFFECTS **HQ**
 - NNLO B(C)/T INTERFERENCE: $\pm 0.5 \text{ pb}$ (1%)
 - $1/m_t$ ON N³LO: $\pm 0.7 \text{ pb}$ (1.5%)
- MISSING N³LO PDFs **PDF-TH** $\pm 0.6 \text{ pb}$ (1.2%)

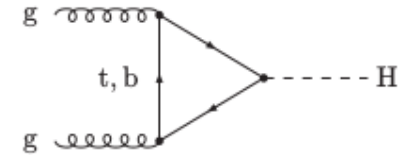
PDF+ α_s

- **PDF** $\pm 0.9 \text{ pb}$ (1.9%)
- α_s $\pm 1.3 \text{ pb}$ (2.6%)

QCD: HIGHER ORDERS AND RESUMMATION

HIGGS AT N³LO

(Mistlberger, 2018)

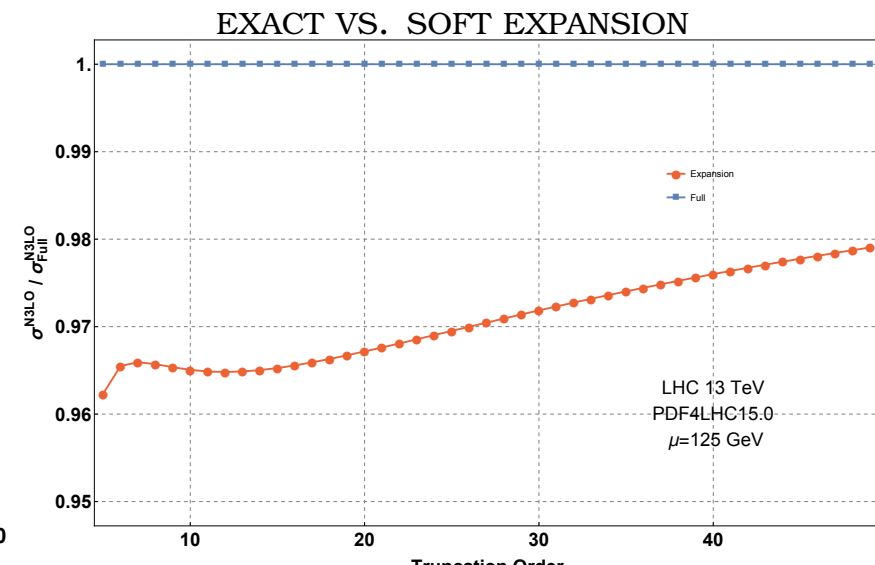
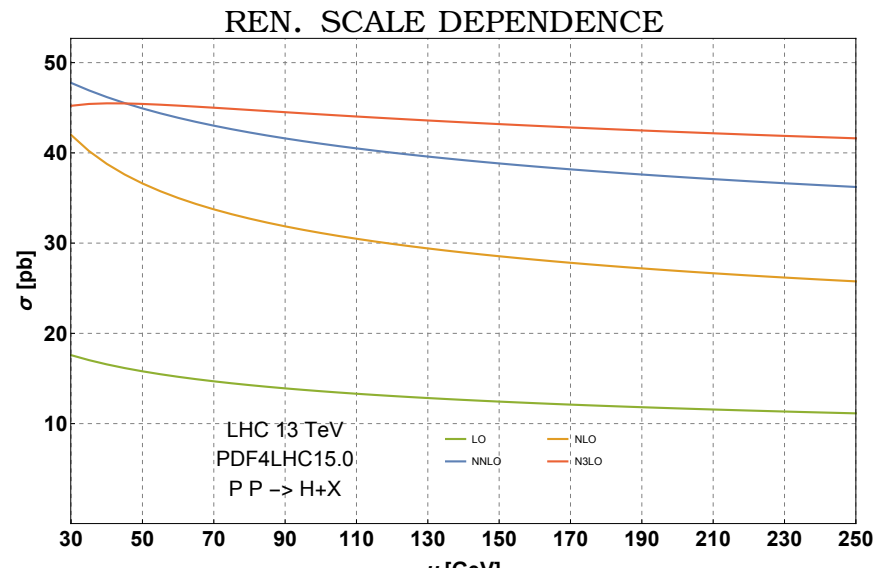


HIGGS IN GLUON FUSION: **LOOP INDUCED**

EXACT N³LO QCD CORRECTIONS NOW INCLUDED:

$$\sigma(\text{LHC13}, m_H = 125 \text{ GeV}) = 48.69 \text{ pb}$$

- HISTORIC, FIRST EXACT N³LO HADRONIC PROCESS
- RESULTS OF **SOFT EXPANSION** BY AND LARGE **CONFIRMED** (Anastasiou et al., 2016)
- **SLOWLY CONVERGENT** PERTURBATIVE EXPANSIONS, **STABILIZES** AT N³LO
- DIFFERENCE TO SOFT EXPANSION (30 ORDERS) +0.11 pb (0.2%)
⇒ **0.4% ESTIMATED UNCERTAINTY REMOVED**



THE TIP OF THE ICEBERG

THE LES HOUCHES WISHLIST

- NLO **WISHLIST DISCONTINUED** IN 2011 DUE TO AUTOMATION → TENTATIVE NNLO WISHLIST
- 2013: **PRECISION WISHLIST** “EXTREMELY AMBITIOUS”
- HIGGS, GAUGE BOSON, TOP+JET TABLES

JET+HQ WISHLIST

2013

Process	State of the Art	Desired
$t\bar{t}$	σ_{tot} (stable tops) @ NNLO QCD $d\sigma$ (top decays) @ NLO QCD $d\sigma$ (stable tops) @ NLO EW	$d\sigma$ (top decays) @ NNLO QCD + NLO EW
$t\bar{t} + j(j)$	$d\sigma$ (NWA top decays) @ NLO QCD	$d\sigma$ (NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t} + Z$	$d\sigma$ (stable tops) @ NLO QCD	$d\sigma$ (top decays) @ NLO QC + NLO EW
single-top	$d\sigma$ (NWA top decays) @ NLO QCD	$d\sigma$ (NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO

Table 2: Wishlist part 2 – Jets and Heavy Quarks

2017

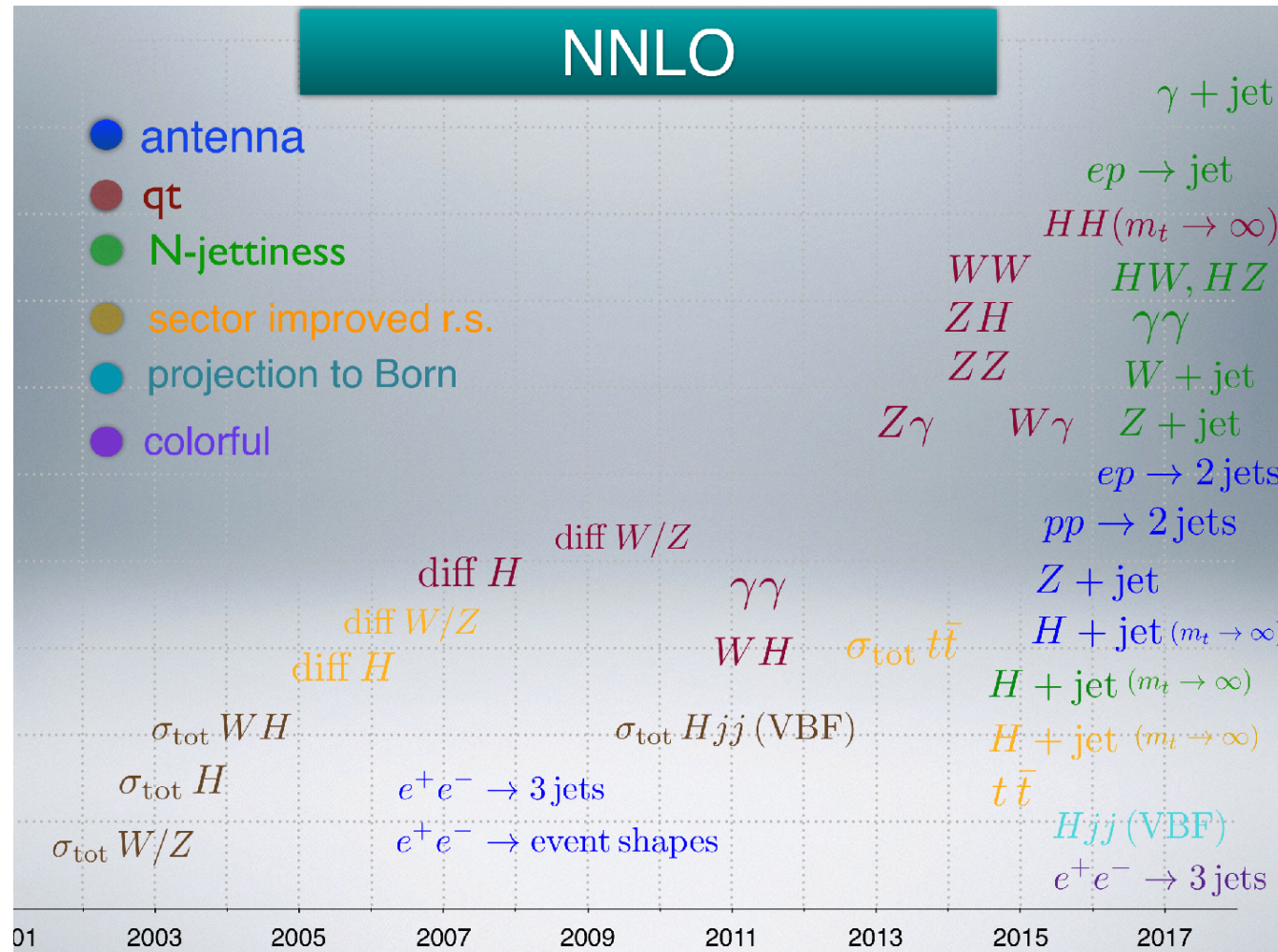
process	known	desired
$pp \rightarrow t\bar{t}$	$N^2\text{LO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ NLO_{QCD} (w/ decays, off-shell effects) NLO_{EW} (w/ decays, off-shell effects)	$N^2\text{LO}_{\text{QCD}}$ (w/ decays)
$pp \rightarrow t\bar{t} + j$	NLO_{QCD} (w/ decays) NLO_{EW}	$N^2\text{LO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (w/ decays)
$pp \rightarrow t\bar{t} + 2j$	NLO_{QCD} (w/ decays)	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (w/ decays)
$pp \rightarrow t\bar{t} + Z$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (w/ decays)	
$pp \rightarrow t\bar{t} + W$	NLO_{QCD} NLO_{EW}	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (w/ decays)
$pp \rightarrow t/\bar{t}$	$N^2\text{LO}_{\text{QCD}}^*$ (w/ decays)	$N^2\text{LO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (w/ decays)

Table I.4: Precision wish list: top quark final states. $N^2\text{LO}_{\text{QCD}}^*$ means a calculation using the structure function approximation.

- **LARGELY DONE!**

THE NNLO REVOLUTION

NNLO



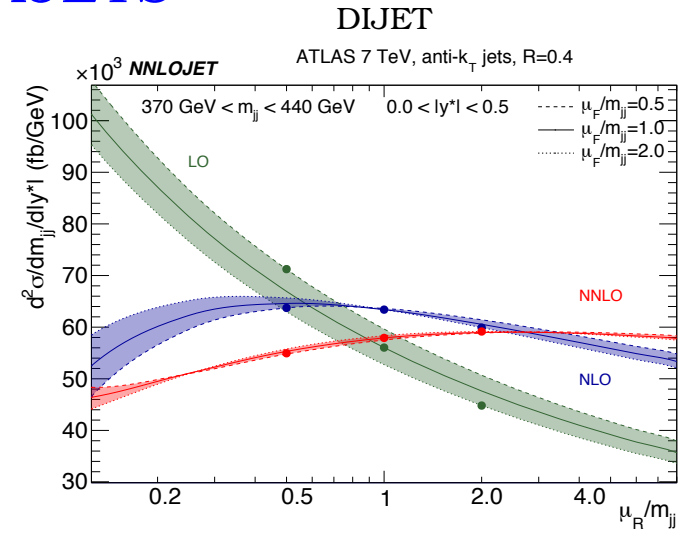
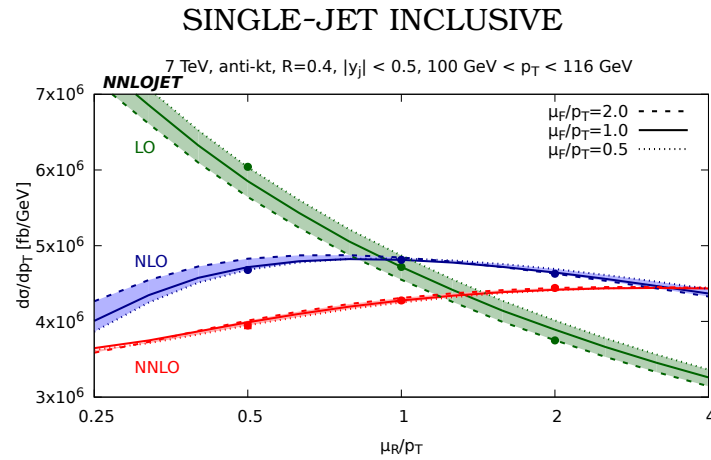
(G.Heinrich, LHCP2017)

- TWO CLASSIC CLASSES OF METHODS FOR SING. CANCELLATION: SLICING & SUBTRACTION
- NEW VARIANTS SUGGESTED: JETTINESS (Petriello, 2015) ANALOGOUS TO q_T (Catani, 2007); GEOMETRIC SUBTRACTION (Herzog, 2018)

NNLO HIGHLIGHTS: 2017-2018

- **SINGLE-JET INCLUSIVE AND DIJET** (Catani, Cieri, de Florian, Ferrera, Grazzini, 2018)
- **PROMPT PHOTON** (Campbell, Ellis, Williams, 2017)
- **HIGGS VBF: FULLY DIFFERENTIAL** (Cruz-Martinez, Gehrmann, Glover, Huss, 2018)
- **HIGGS: ASSOCIATE WITH W FULLY DIFFERENTIAL INCLUDING HIGGS DECAY** (Somogy, Ferrera, Tramontano, 2017; Caola, Luisoni, Melnikov, Rötsch, 2018)
- **SEVERAL CROSS-CHECKS: DIPHOTON, DRELL-YAN AND HIGGS p_T DISTRIBUTIONS, ASSOCIATE HIGGS+ W , HIGGS VBF+2JETS, ZZ**

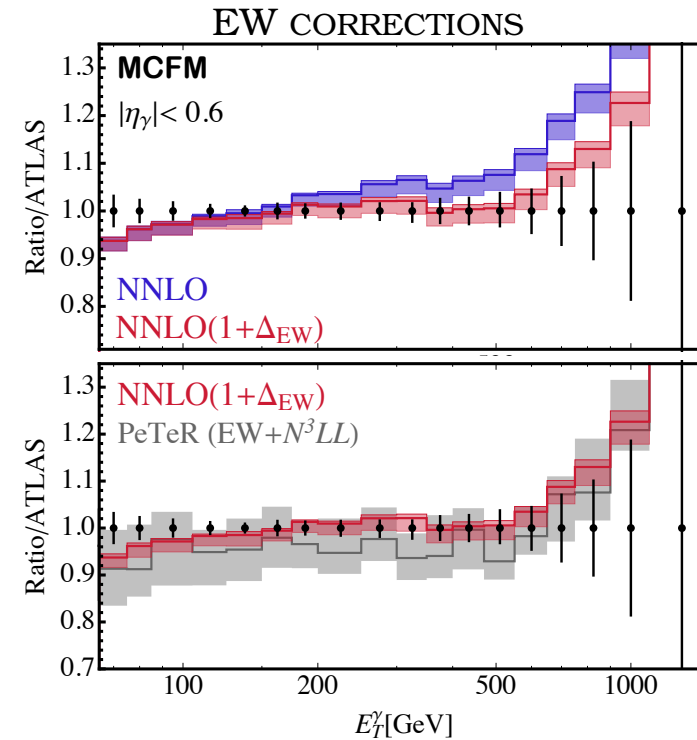
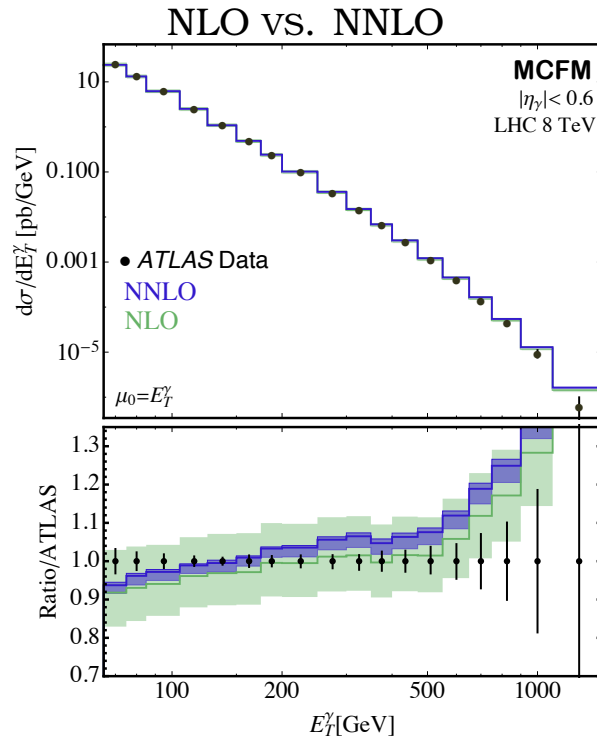
JETS AND DIJETS



- SINGLE-JET INCLUSIVE:
 - NO OPTIMAL SCALE CHOICE: p_T VS. p_t^1 DIFFER SIGNIFICANTLY
 - NO CLEAR PERTURBATIVE CONVERGENCE
- DIJET:
 - OPTIMAL SCALE CHOICE: DIJET MASS
 - GOOD PERTURBATIVE CONVERGENCE

PROMPT PHOTONS

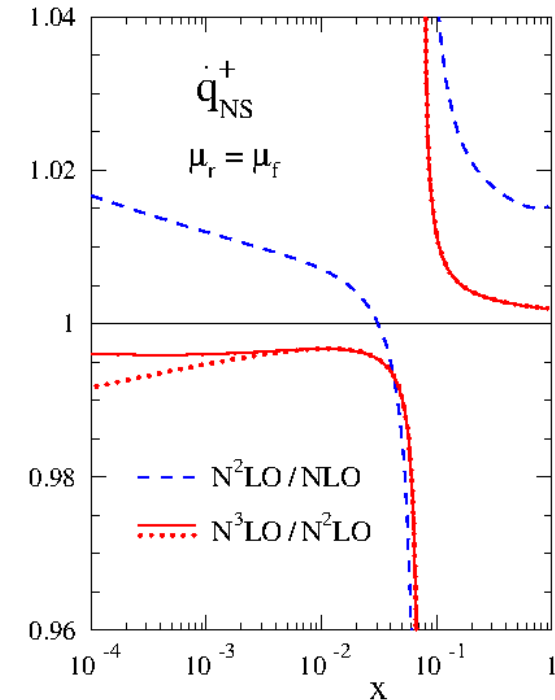
- JET-LIKE PROCESS, DONE THANKS TO JETINESS SUBTRACTION
- MODERATE CORRECTIONS & GOOD CONVERGENCE



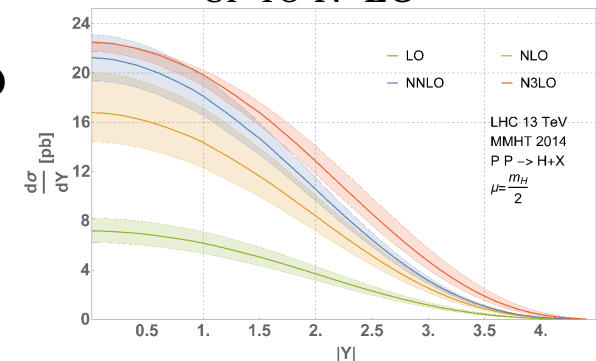
N³LO RESULTS TOWARDS A WISHLIST

- DEEP-INELASTIC JET PRODUCTION (PROJECTION TO BORN) (Cruz-Martinez, Gehrmann, Glover, 2018)
- NONSINGLET ANOMALOUS DIMENSIONS (PLANAR LIMIT) (Moch, Ruijl, Ueda, Vermaseren, Vogt, 2018)
 - LARGE NUMBER OF MELLIN MOMENTS KNOWN IN PLANAR LIMIT (NONSINGLET ONLY)
 - N³LO CORRECTION MODERATE
 - RESIDUAL AMBIGUITY ON N³LO NOT NEGLIGIBLE, BUT IMPACT SMALL
- HIGGS DIFFERENTIAL (SOFT EXPANSION) (Dulat, Mistlberger, Pelloni, 2018)
 - ONLY FIRST TWO TERMS OF SOFT EXPANSION KNOWN
 - CONVERGENCE OF SOFT EXPANSION FAST FOR RAPIDITY DISTRIBUTION, SLOW FOR p_T SPECTRUM
 - NOT YET COMPETITIVE FOR PHENO BUT FIRST EVER N³LO DIFFERENTIAL HADRONIC PROCESS

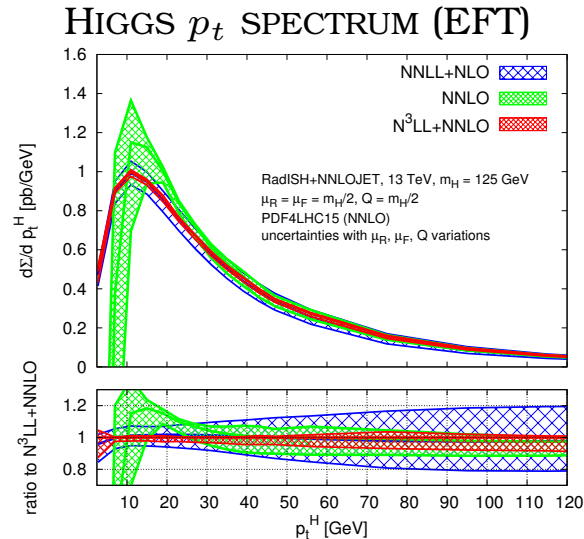
NS QUARK EVOLUTION
UP TO N³LO



HIGGS RAPIDITY DISTRIBUTION
UP TO N³LO



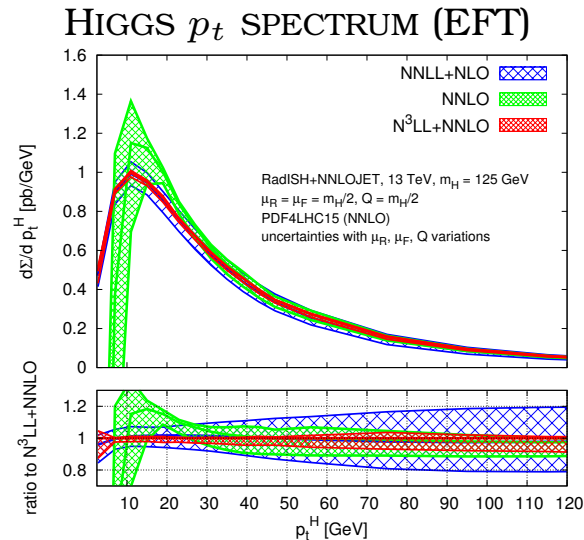
RESUMMATION



(Bizon, Chen, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrielli, 2018)

- **THRESHOLD RESUMMATION** $\Rightarrow$ ROUTINELY INCLUDED, **IMPROVE FIXED ORDER** (TYPICALLY SMALL IMPACT)
- MATCHING OF p_t RESUMMATION TO FIXED ORDER STANDARD FOR p_T SPECTRA
- **TOWARDS RESUMMED PDFs** (BOTH THRESHOLD & BFKL), ALSO THANKS TO **PUBLIC CODES**: E.G. xFitter/APFEL (Bertone, 2016-2017), TROLL, HELL (Bonvini, 2016-2018), TOP++ (Czakon, Mitov, 2016-2018)
- CONSIDERABLE **THEORY PROGRESS**: NEXT-TO-LEADING POWER, MOMENTUM-SPACE RESUMMATION, NON-GLOBAL, DIVERGENT...

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- **CONSIDERABLE THEORY PROGRESS**: NEXT-TO-LEADING POWER, MOMENTUM-SPACE RESUMMATION, NON-GLOBAL, DIVERGENT...

STAY TUNED FOR LUND

PSR18 Parton Showers, Event Generators and Resummation 2018
 NINTH INTERNATIONAL WORKSHOP ON PARTON SHOWERS AND RESUMMATION
 4 - 6 JUNE 2018
 LUND, SWEDEN

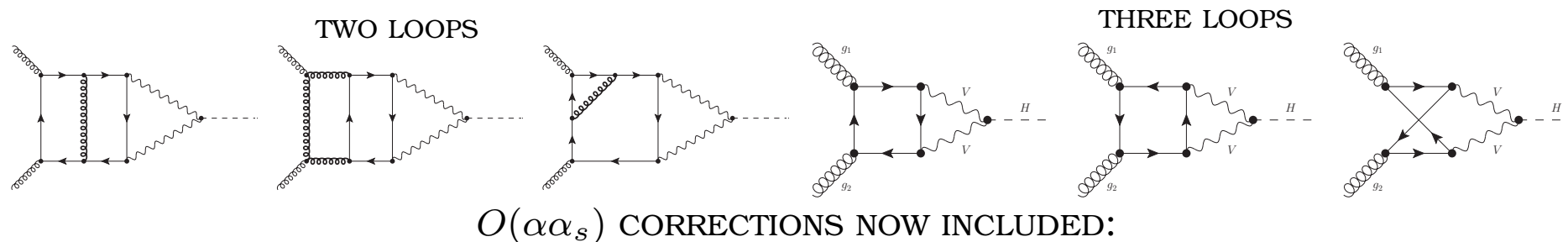
4-6 June 2018
 Department of Theoretical Physics and Astronomy, Lund University
 Europe/Stockholm timezone

Search...

ELECTROWEAK EFFECTS

HIGGS IN GLUON FUSION

(Bonetti, Melnikov, Tancredi, 2017-2018)



$$\sigma(\text{LHC13}, m_H = 125 \text{ GeV}) = 47.93 \text{ pb}$$

- THREE-LOOP VIRTUAL CORRECTIONS COMPUTED
- TWO LOOP VIRTUAL CORRECTIONS COMBINED WITH APPROXIMATE REAL EMISSION
 $\Rightarrow$ EXTREMELY ACCURATE APPROX. RESULT
- SIZE OF MIXED $O(\alpha\alpha_s)$: $\Delta\sigma(\text{LHC13}, m_H = 125 \text{ GeV}) = 1.75 \text{ pb (3.6\%)}$
- AGREES WELL WITH COMPLETE FACTORIZATION W.R. TO NLO,
 DIFFERENCE TO YR (COMPLETE FACTORIZATION W.R. TO NNLO) -0.65 pb
- 2.5% UNCERTAINTY REMOVED OR AT LEAST REDUCED BELOW THE PERCENT LEVEL

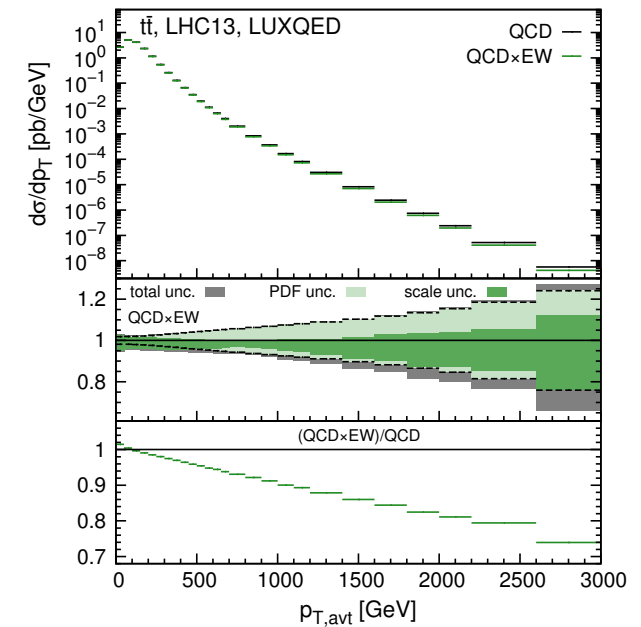
EW CORRECTIONS

- **POWER COUNTING**: TYPICAL LHC PROCESSES $\alpha_s \sim \frac{1}{10}$, $\alpha \sim \frac{1}{100}$
 $\Rightarrow$ **NNLO QCD** $\sim$ **NLO EW**
- **INTERFERENCE**
- **RESONANT TOP OR VB CONTRIBUTIONS**
- **PHOTON-INDUCED CONTRIBUTIONS**
- **DOUBLE SUDAKOV LOGS** AT LARGE $p_T \Leftrightarrow$ HIGH ENERGY

HIGHLIGHTS: 2017-2018

- **NLO** [$O(\alpha)$] CORRECTIONS FOR **DIJET**, **DRELL-YAN**, **TOP** IN **MCFM** (Campbell, Wackerth, Zhou, 2017)
- **NLO QCD+EW** [$O(\alpha\alpha_s)$] FOR **DIBOSON** PRODUCTION (Kallweit, Lindert, Pozzorini, Schönherr, 2017)
- **NLO QCD+EW** [$O(\alpha\alpha_s)$] FOR **TOP** (Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro, 2017)
- **NLO QCD+EW** [$O(\alpha\alpha_s)$] FOR **HV** AND **HV+JET** (Granata, Lindert, Oleari, Pozzorini, 2017)
- **NLO EW** [$O(\alpha)$] FOR $\gamma\gamma$ +**JET** (Chiesa, Greiner, Schönherr, Tramontano 2018)

AVERAGE p_t OF $t\bar{t}$ PAIR



(Czakon, Heymes, Mitov,
Pagani, Tsinikos, Zaro,
2017)

THE PHOTON PDF BREAKTHROUGH

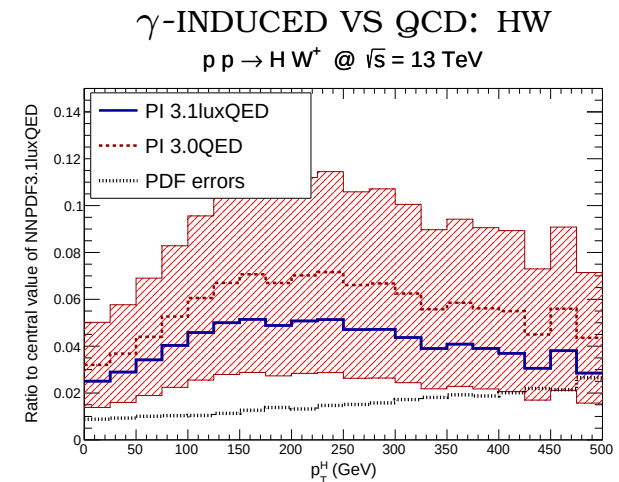
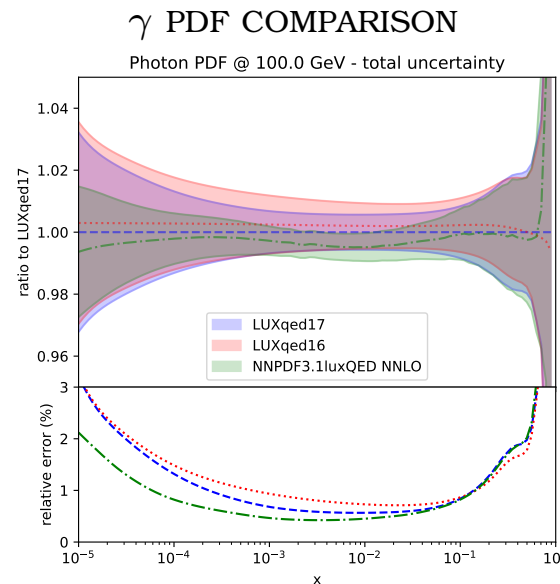
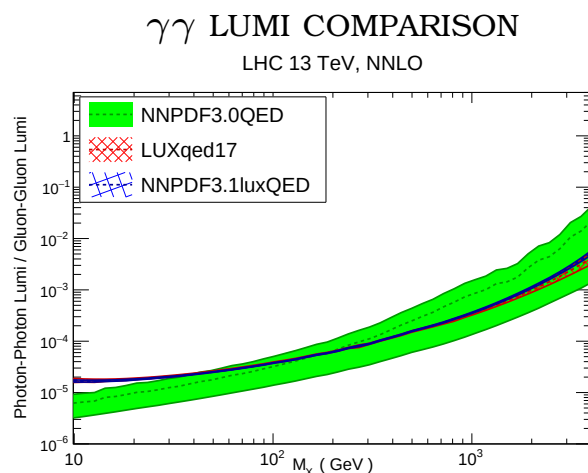
(Manohar, Nason, Salam, Zanderighi, 2016)

- **QED IS PERTURBATIVE** DOWN TO LOW SCALES $\Rightarrow$ THE **PHOTON PDF** MUST BE **COMPUTABLE** IF THE INPUT QUARK SUBSTRUCTURE IS KNOWN
- $\Rightarrow$ **PDF EXPRESSED IN TERMS OF THE STRUCTURE FUNCTION INTEGRATED OVER ALL SCALES**
- LUX16/LUX17 SETS CONSTRUCTED FROM PDF4LHC15 $\Rightarrow$ **AGREE WELL WITH NNPDF3.0 QED, MUCH SMALLER UNCERTAINTY**

THE LUXQED PHOTON PDF

(Carrazza et al., 2017)

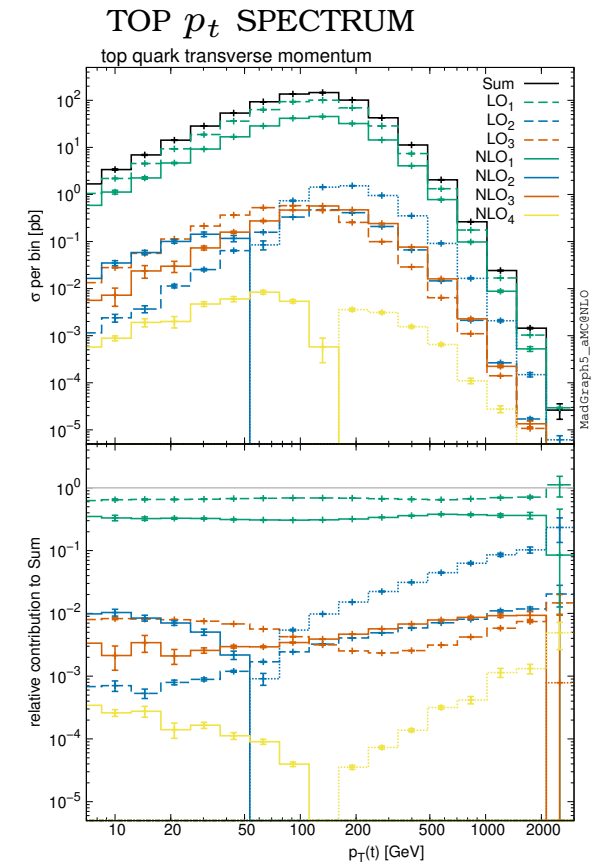
- FIRST PDF SET BASED ON **CONSISTENT FIT WITH LUX CONSTRAINT: NNPDF3.0LUXQED**
- **NNPDF3.1LUXQED** VS LUX17: GOOD AGREEMENT BUT **SMALLER UNCERTAINTIES**
- **SIZABLE IMPACT** ON PRECISION PHYSICS: EG **ASSOCIATE HIGGS** PROD. WITH W



THE NLO EW AUTOMATION BREAKTHROUGH

(Frederix, Frixione, Hirschi, Pagani, Shao, Zaro, 2017)

- FULL AUTOMATION & IMPLEMENTATION
IN MadGraph5_aMC@NLO
- MIXED CORRECTIONS FULLY INCLUDED UP TO NLO:
E.G. TOP
LO₁: $O(\alpha_s^2)$, LO₂: $O(\alpha_s\alpha)$, LO₃: $O(\alpha^2)$
NLO₁: $O(\alpha_s^3)$, NLO₂: $O(\alpha_s^2\alpha)$, NLO₃: $O(\alpha_s\alpha^2)$, NLO₄: $O(\alpha^3)$

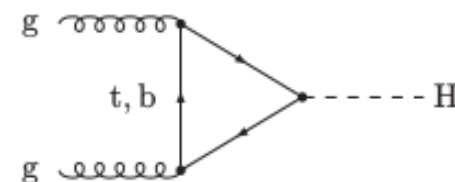


HEAVY QUARK MASSES

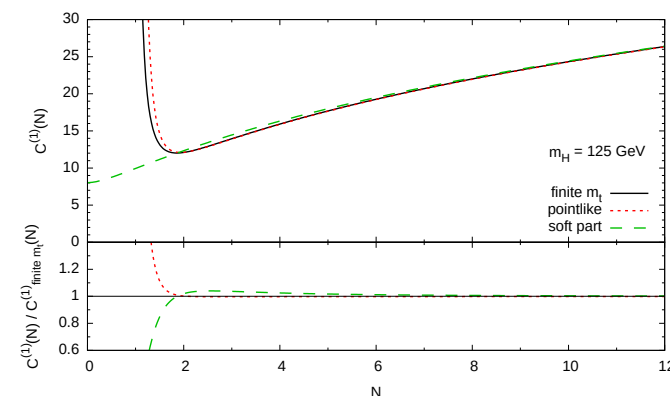
HIGGS IN GLUON FUSION (TOTAL XSECT)

THE PROBLEM?: MULTISCALE!

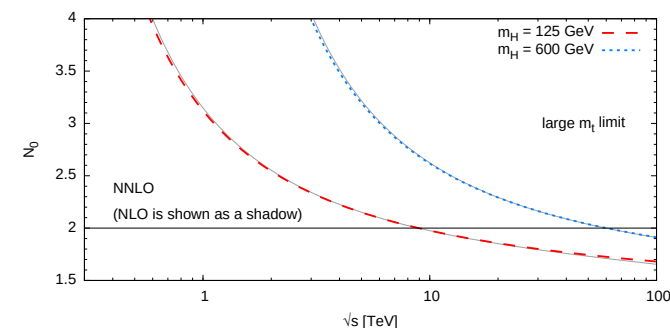
- EXACT RESULT ONLY KNOWN UP TO NLO
- HIGH ENERGY LIMIT IN EFT $\neq$ EXACT
- MASS DEPENDENCE KNOWN TO ALL ORDERS IN HIGH ENERGY LIMIT
- TOP DEPENDENCE KNOWN AT NNLO AS EXPANSION IN $\frac{1}{m_t}$ MATCHED TO HIGH ENERGY LIMIT
- AT LHC 13
- SMALL TOP MASS CORRECTIONS AT N³LO ESTIMATED (MATCHED HIGH ENERGY LIM.) $\Rightarrow$ 0.1 PB (0.2%)
- NOT SMALL B-T INTERFERENCE AT NNLO? $\sim$ 0.7 PB (1.5%) (NLO SCHEME DEPENDENCE)



NLO N -SPACE PARTONIC XSECT
EFT VS EXACT BEHAVIOUR



SADDLE POINT VS COLL. ENERGY



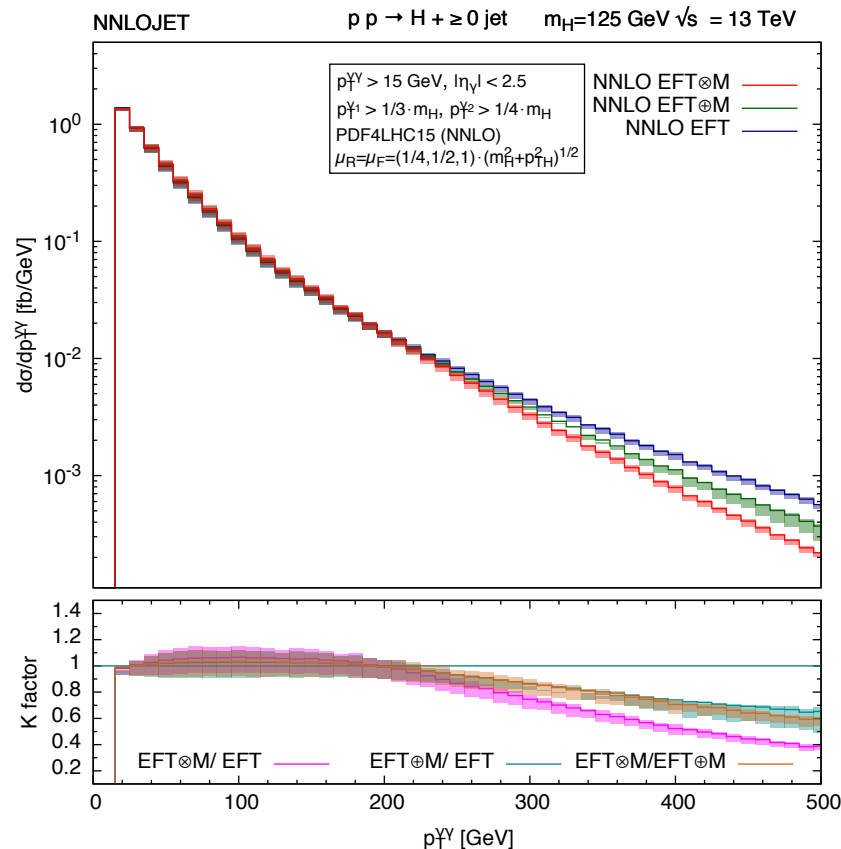
	$\overline{\text{MS}}$	OS	$\delta\sigma^{sc}$
$\sigma_{ex;t}^{LO}$	16.00 pb	16.04 pb	0.25%
$\sigma_{ex;t+b}^{LO}$	14.94 pb	14.24 pb	-4.8%
$\sigma_{ex;t+b+c}^{LO}$	14.83 pb	13.81 pb	-6.9%
$\sigma_{ex;t}^{NLO}$	36.60 pb	36.63 pb	0.08%
$\sigma_{ex;t+b}^{NLO}$	34.96 pb	34.49 pb	-1.3%
$\sigma_{ex;t+b+c}^{NLO}$	34.77 pb	34.04 pb	-2.1%

HIGGS IN GLUON FUSION (p_T SPECTRUM)

WHAT'S THE PROBLEM WITH THE TOP MASS

- UNTIL 2017: MASS DEPENDENCE KNOWN EXACTLY ONLY AT LO
- INCLUSION BEYOND LO SUBJECT TO LARGE UNCERTAINTIES?

MASS DEPENDENCE: MULTIPLICATIVE VS. ADDITIVE



(Chen, Cruz-Martinez,
Gehrmann, Glover, Jacquier, 2016)

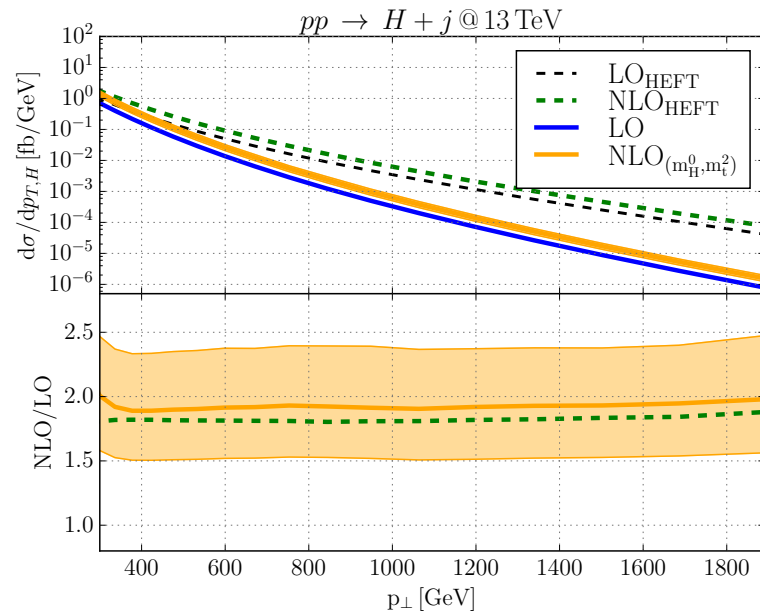
- $R^{LO}(p_T) = \left(\frac{d\sigma_{LO}^{m_t, m_b, m_c}}{dp_T} / \frac{d\sigma_{LO}^{EFT}}{dp_T} \right)$
- EFT $\otimes$ M: $\frac{d\sigma}{dp_T} = R^{LO}(p_T) \frac{d\sigma_{NNLO}^{EFT}}{dp_T}$ (MULTIPLICATIVE)
- EFT $\oplus$ M: $\frac{d\sigma}{dp_T} = \frac{d\sigma_{NNLO}^{EFT}}{dp_T} + \left(R^{LO}(p_T) - 1 \right) \frac{d\sigma_{LO}^{EFT}}{dp_T}$ (ADDITIVE)
- ADDITIVE DROPS LESS THAN MULTIPLICATIVE

- ELUCIDATED BY HIGH-ENERGY LIMIT
- LEADING POWER BEHAVIOUR DIFFERS BETWEEN EFT AND WITH MASS DEPENDENCE, BUT IS SAME TO ALL ORDERS

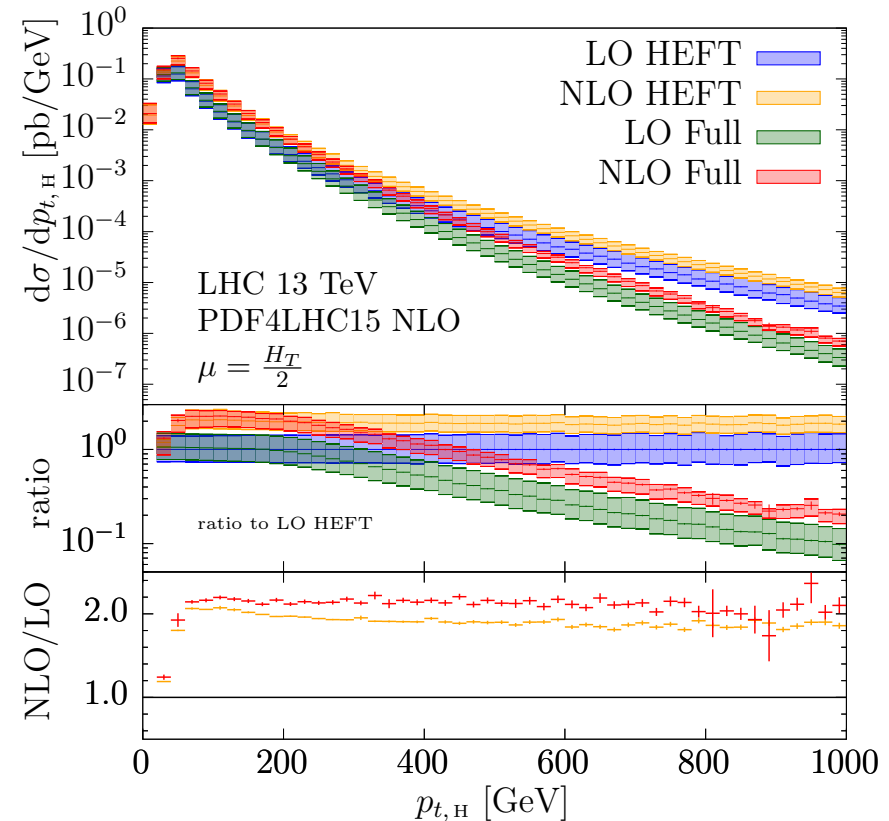
HIGGS IN GLUON FUSION (p_T SPECTRUM)

NLO: PROBLEM SOLVED

- **NLO** RESULT WITH **FULL** m_t DEPENDENCE PUBLISHED BY TWO GROUPS
- Lindert et al.: TWO LOOP COMPUTED BY EXPANDING IN p_t/m_t
- Jones et al.: TWO LOOP COMPUTED NUMERICALLY BY BRUTE FORCE BY INTEGRATING OVER FEYNMAN PARAMS FOR FIXED KINEMATICS, THEN INTERPOLATED



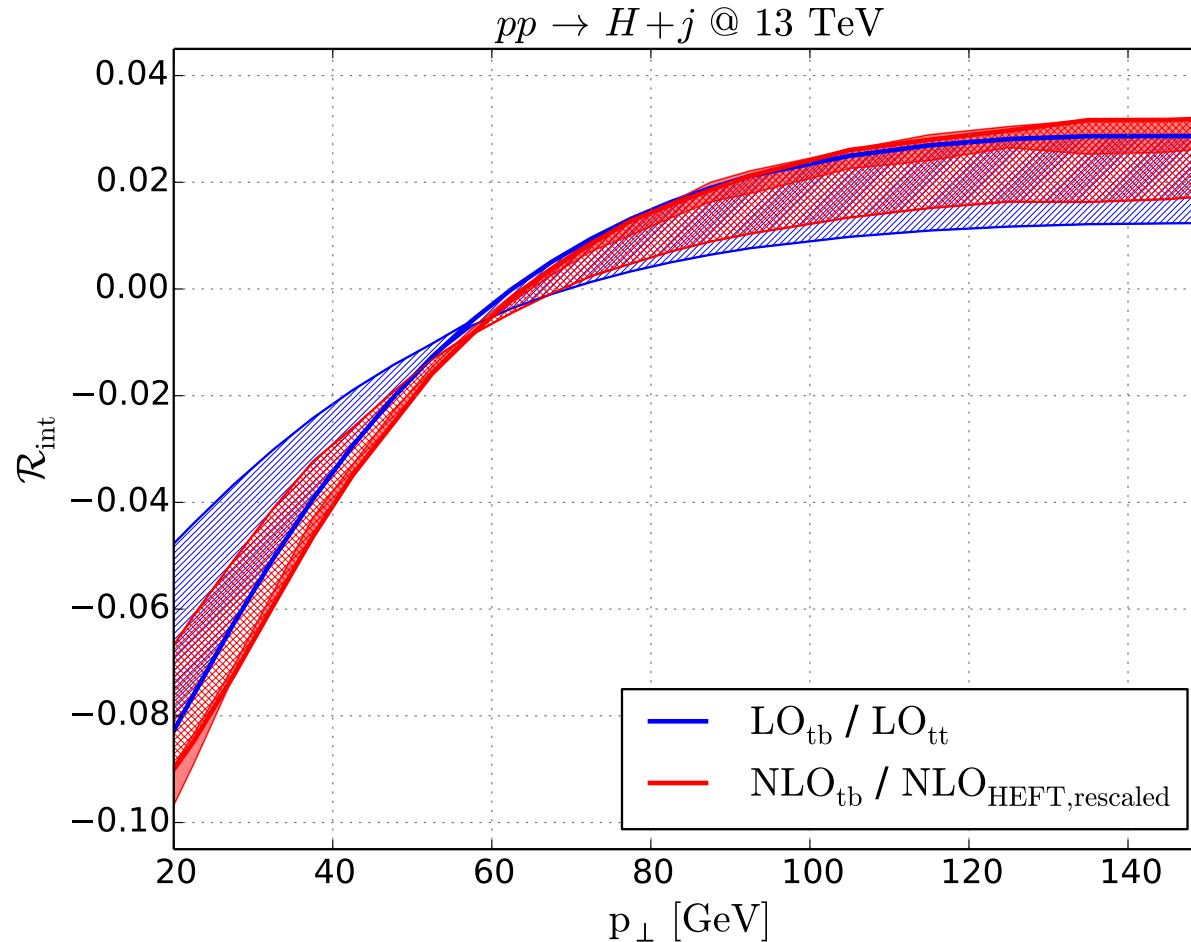
(Lindert, Kudashin, Melnikov, Wever, 2018)



(Jones, Kerner, Luisoni, 2018)

HIGGS IN GLUON FUSION (p_T SPECTRUM)

WHAT'S THE PROBLEM WITH THE B MASS



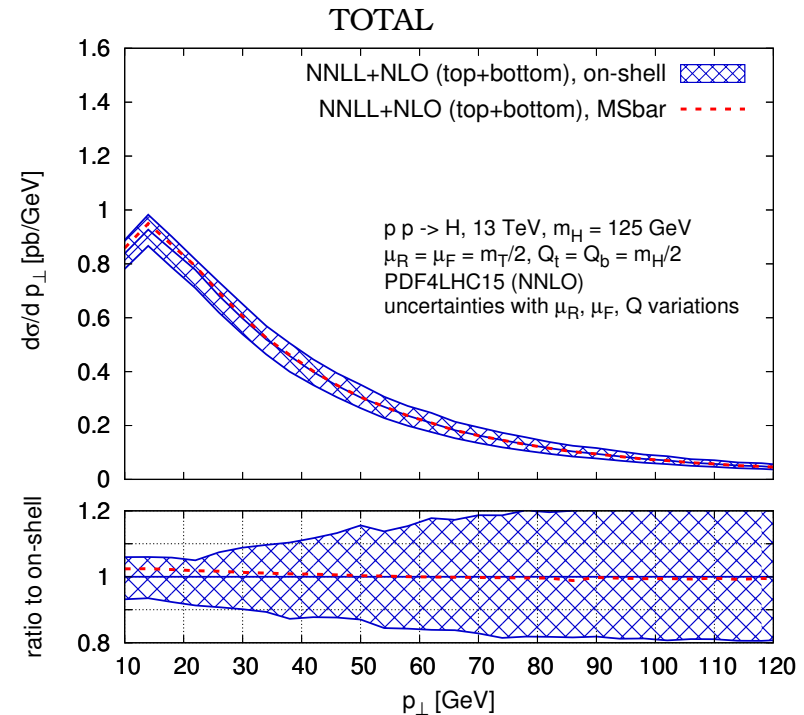
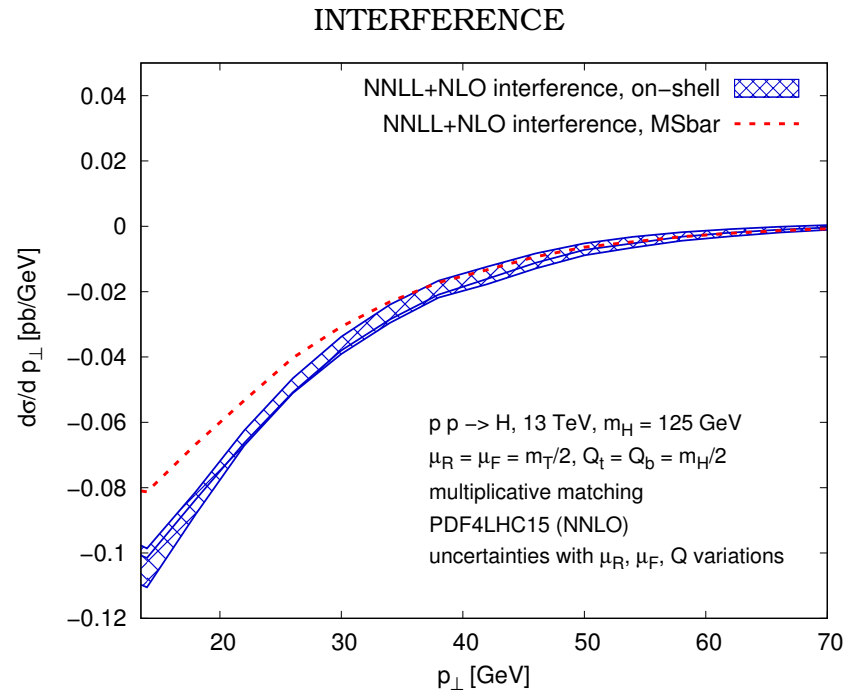
- $A_{gg \rightarrow Hg}^b \sim m_b^2 / m_H^2 \ln^2(p_T^2 / m_b^2) \Rightarrow$ SUDAKOV-LIKE **NON-SUDAKOV DOUBLE LOGS** FROM BOTTOM LOOPS, **RESUMMED** TO ALL ORDERS IN ABELIAN LIMIT (Melnikov, Penin, 2016)
- LARGE tb INTERFERENCE, MUST **EXTRACT NON-ANALYTIC TERM** WHEN EXPANDING IN m_b
- **CORRECTION** AS **LARGE** AS 10% FOR $p_T \sim 20 \text{ GeV}$ (Lindert, Melnikov, Tancredi, Wever, 2017)

HIGGS IN GLUON FUSION (p_T SPECTRUM)

NLO: TOWARDS A SOLUTION

(Caola, Lindert, Melnikov, Monni, Tancredi, Wever, 2017)

- NLO t-b MATCHED TO RESUMMATION
- LARGE SCHEME DEPENDENCE $O(20\%)$ OF INTERFERENCE CONTRIBUTION: NEED NNLO; PERHAPS RESUMMATION OF $\ln m_b/p_t$
- INTERFERENCE $O(5\%)$ OF TOTAL $\Rightarrow$ STABLE MATCHED RESULT



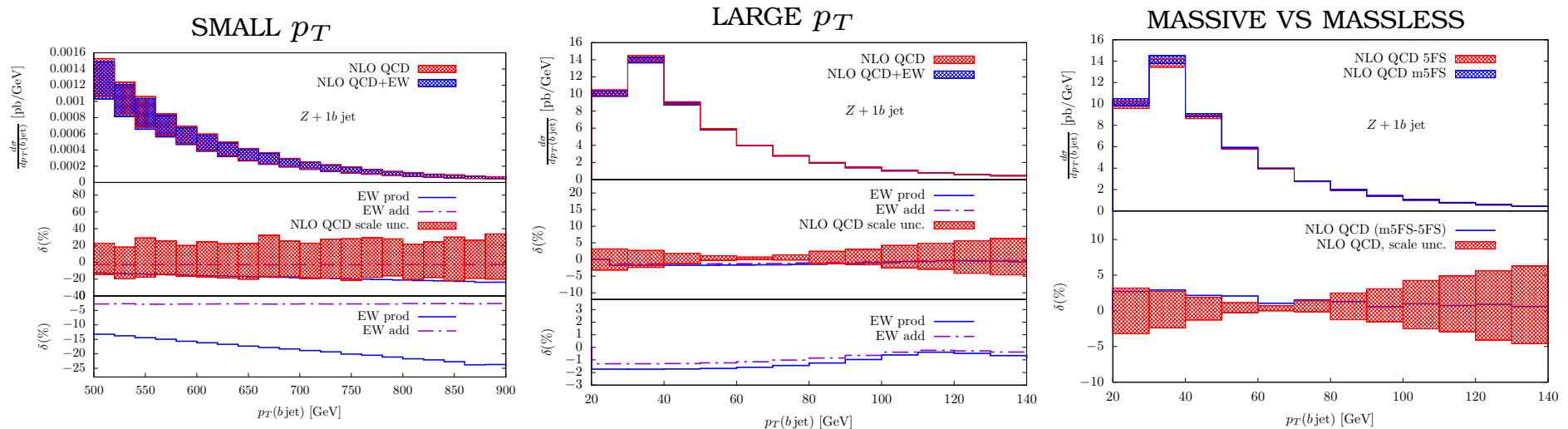
MASSIVE EVOLUTION

THE MASSIVE 5FS

- b MASS INCLUDED IN **MATCHED SCHEMES**:
4FS (MASSIVE, UNRESUMMED B)+5FS (MASSLESS, RESUMMED B) (FONLL)
⇒ **CUMBERSOME** TO IMPLEMENT, AVAILABLE FOR A HANDFUL OF INTEGRATED CROSS-SECTIONS
- MASSIVE FIVE-FLAVOR SCHEME: **MASS** INCLUDED IN **SPLITTING KERNELS** (Krauss, Napoletano, 2018)
 - +: CAN BE **IMPLEMENTED IN PS** (SHERPA AVAILABLE)
 - +: MASSIVE **CORRECTIONS EXPONENTIATED**
 - -: ONLY (UNIVERSAL) **SUBSET OF FONLL TERMS INCLUDED**
- FIRST APPLICATION TO $Z + b$ PRODUCTION: Figueroa et al, 2018

$Z+b$: p_T SPECTRUM OF B JET

(Figueroa, Honeywell, Quackenbuch, Reina, Reuschle, Wackerroth, 2018)

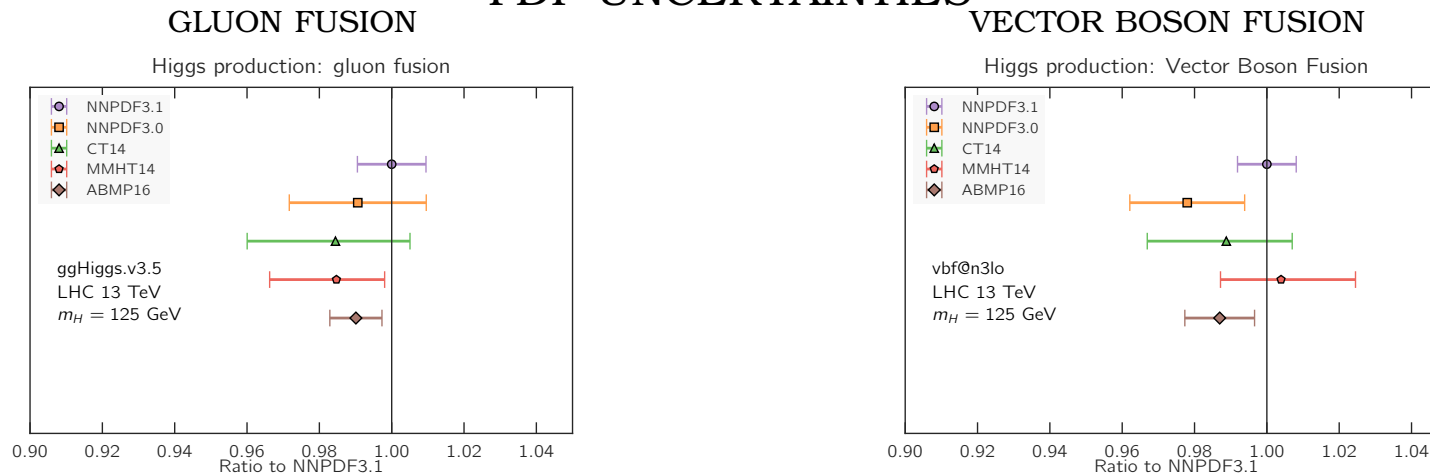


PDFS AND α_s

PDF PROGRESS

- CURRENTLY **PDF4LHC15** SET RECOMMENDED FOR PRECISION PHENO
- **STATISTICAL COMBINATION** OF CT14, NNPDF3.0, NNPDF3.0 $\Rightarrow$ 2014 **DATA, MOSTLY PRE-LHC**
- **NNPDF3.1** AVAILABLE (2017) $\Rightarrow$ SIZABLE IMPACT OF **RUN I LHC DATA** $\Rightarrow$ **METHODOLOGICAL IMPROVEMENTS**

THE HIGGS PRODUCTION CROSS SECTION PDF UNCERTAINTIES

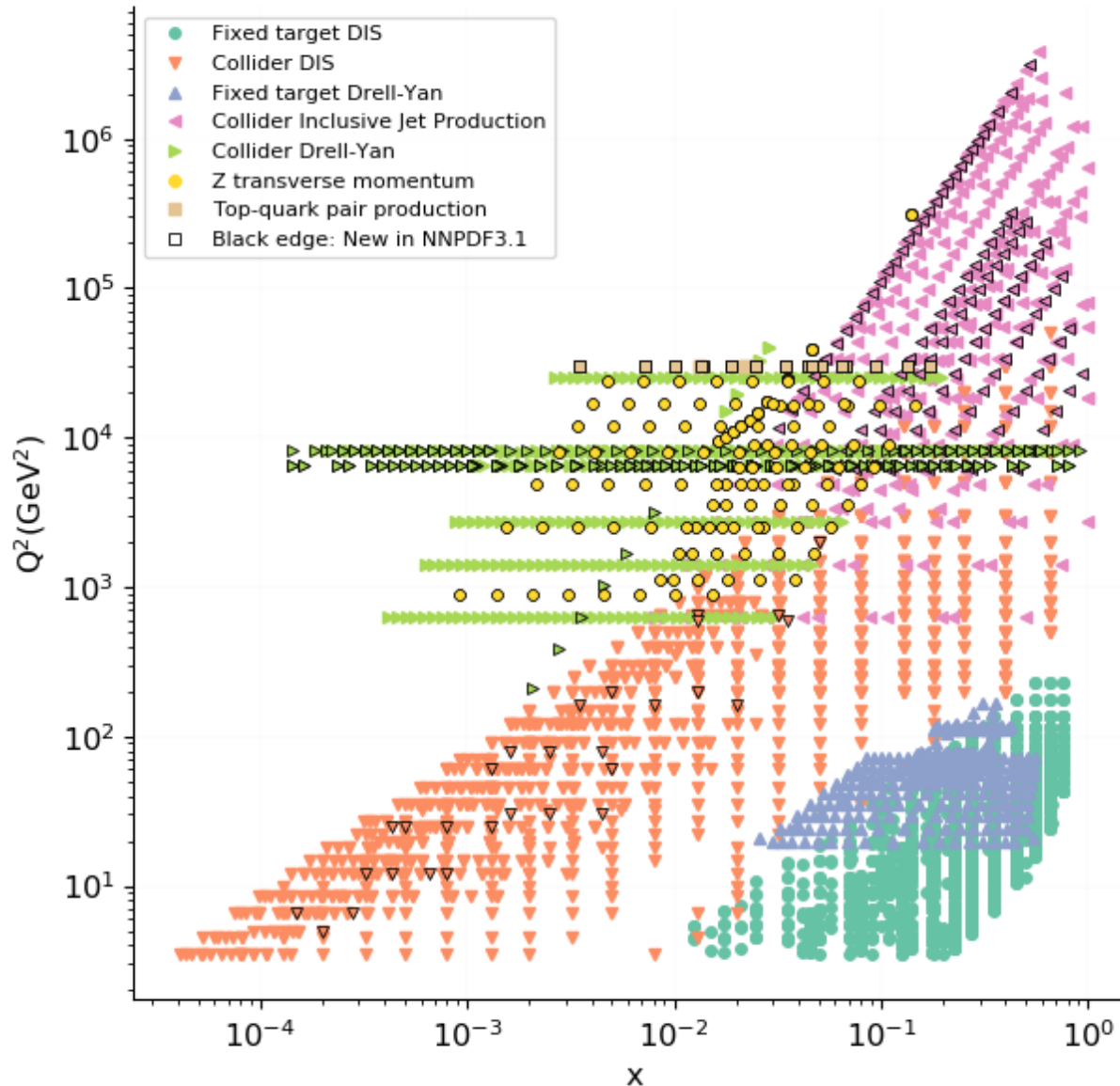


$$\Delta_{\text{ggF}}^{\text{PDF}} \sigma \approx 0.5 \text{ pb (1\%)} [\text{WAS } 0.9 \text{ pb (1.9\%)}]; \quad \Delta_{\text{ggF}}^{\text{PDF}+\alpha_s} \sigma \approx 1.4 \text{ pb (2.8\%)} [\text{WAS } 1.6 \text{ pb (3.2\%)}]$$

IF NO CHANGE IN α_s UNCERTAINTY

WHY THE IMPROVEMENT? LHC DATA!: NNPDF3.0 vs NNPDF3.1

Kinematic coverage



NEW DATA: (BLACK EDGE)

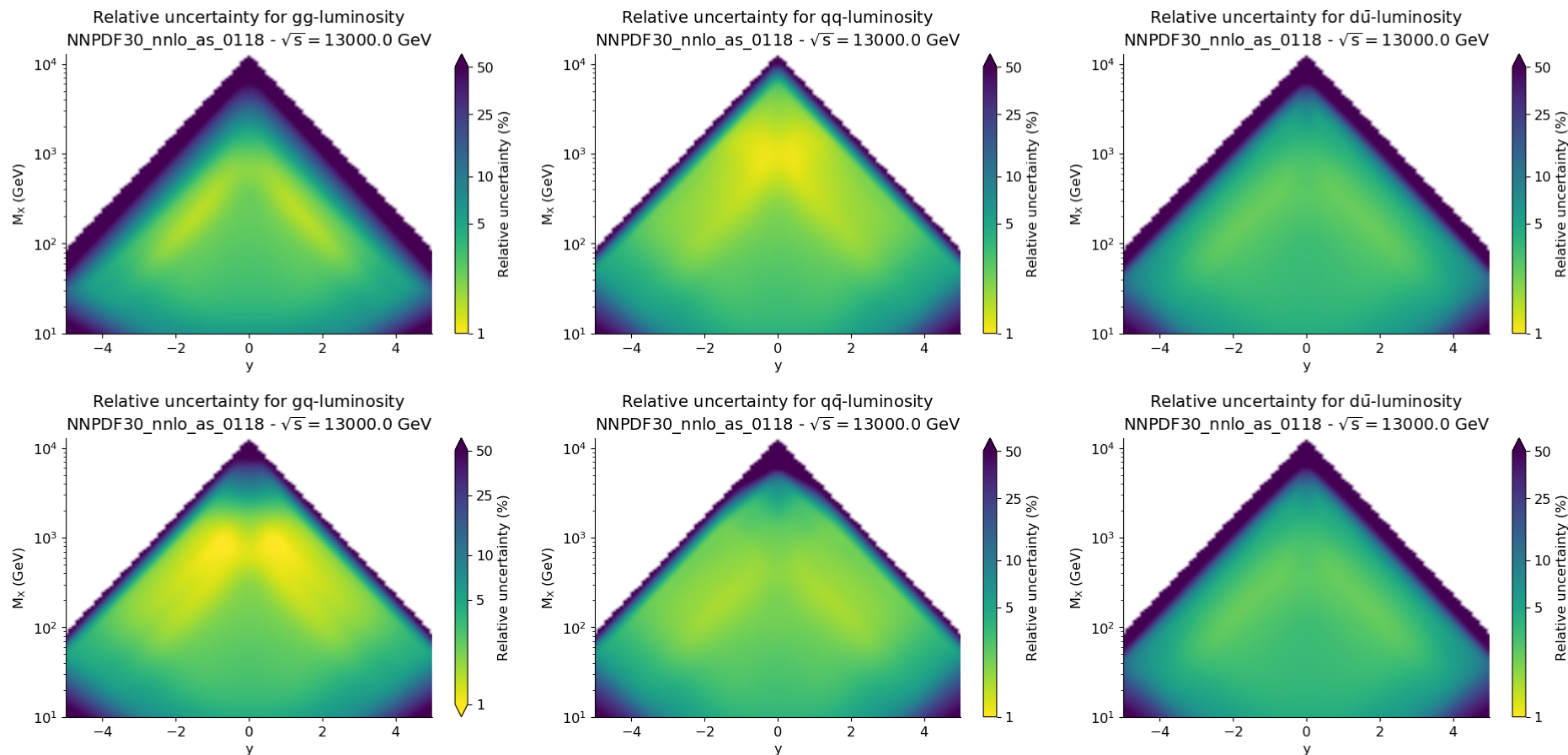
- HERA COMBINED F_2^b
- D0 W LEPTON ASYMMETRY
- ATLAS W, Z 2011, HIGH & LOW MASS DY 2011;
CMS $W^\pm$ RAPIDITY 8TeV
LHCb W, Z 7TeV & 8TeV
- ATLAS 7TeV JETS 2011, CMS 2.76TeV JETS
- ATLAS & CMS TOP DIFFERENTIAL RAPIDITY
- ATLAS $Z p_T$ DIFFERENTIAL RAPIDITY & INVARIANT MASS 8TeV,
CMS $Z p_T$ DIFFERENTIAL RAPIDITY 8TeV

THE IMPACT OF LHC DATA NNPDF3.0 (2014) PDF UNCERTAINTIES (NNLO)

GLUON

SINGLET

FLAVORS



- TYPICAL UNCERTAINTIES IN DATA REGION $\sim 3 - 5\%$

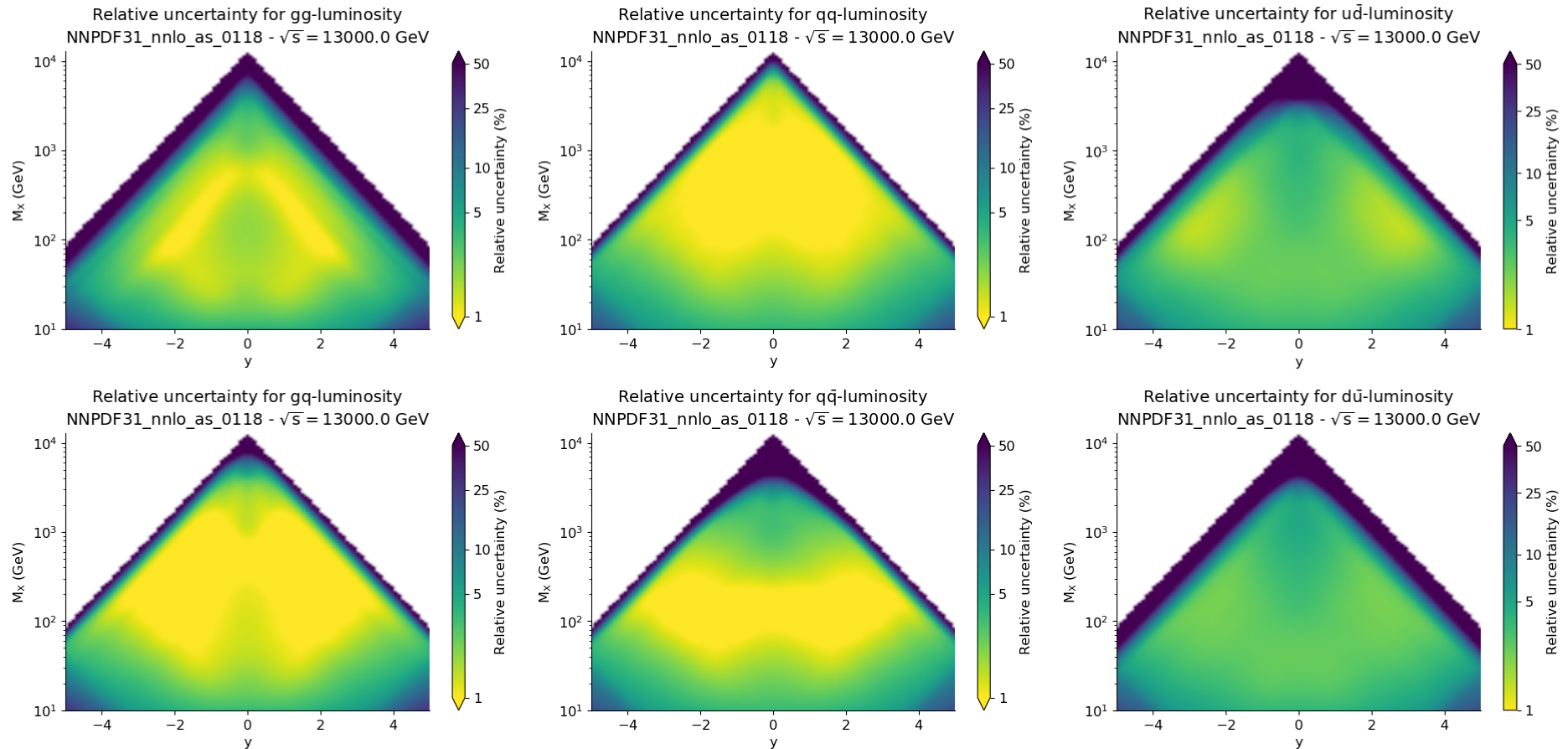
- .

THE IMPACT OF LHC DATA NNPDF3.1 (2017) PDF UNCERTAINTIES (NNLO)

GLUON

SINGLET

FLAVORS



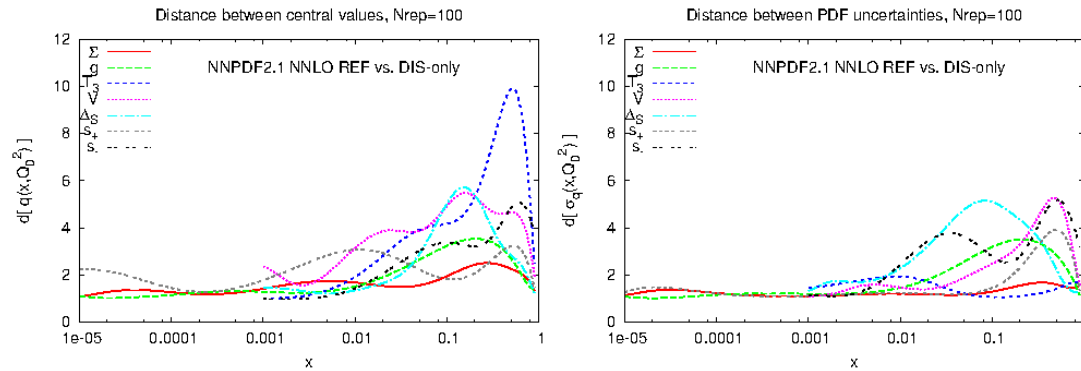
- TYPICAL UNCERTAINTIES IN DATA REGION $\sim 1 - 3\%$
- NEW LHC DATA $\Rightarrow$ SIZABLE REDUCTION IN UNCERTAINTIES

THE IMPACT OF LHC DATA

BEFORE LHC: PDFs **MOSTLY DETERMINED BY DIS DATA**

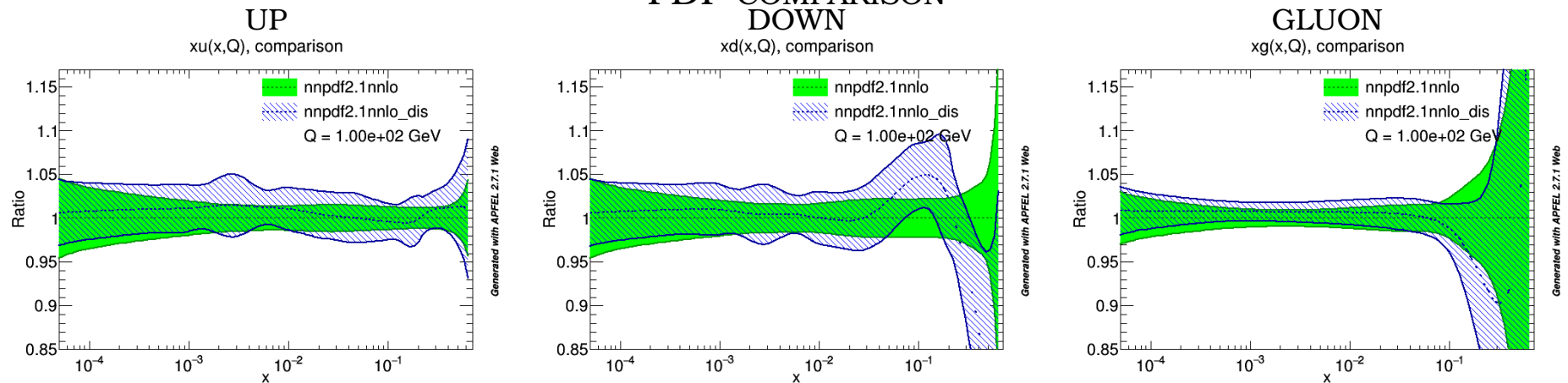
NNPDF2.1 vs NNPDF2.1 DIS ONLY

DISTANCES (difference in units of st. dev.)



$d = 10 \Leftrightarrow$ one sigma difference

PDF COMPARISON



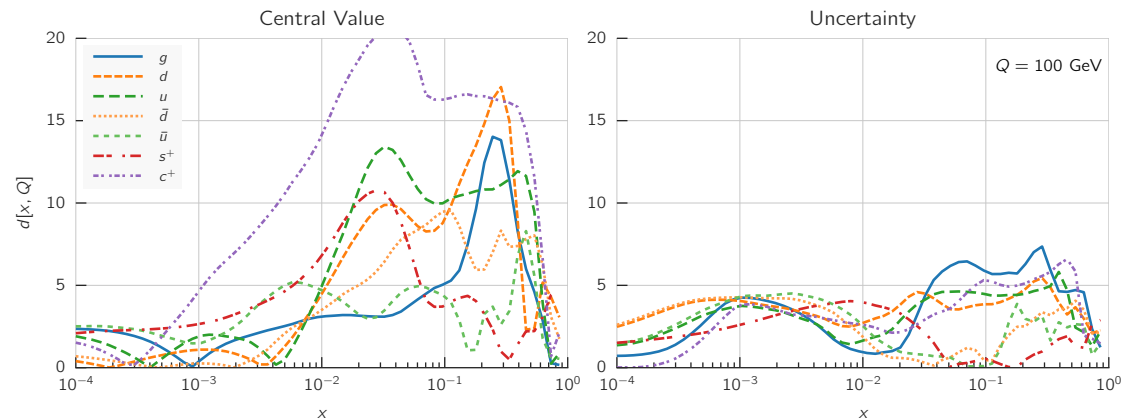
- ALL DIFFERENCES **BELOW ONE SIGMA**
- ONLY **UP-DOWN SEPARATION** SIGNIFICANTLY AFFECTED

THE IMPACT OF LHC DATA

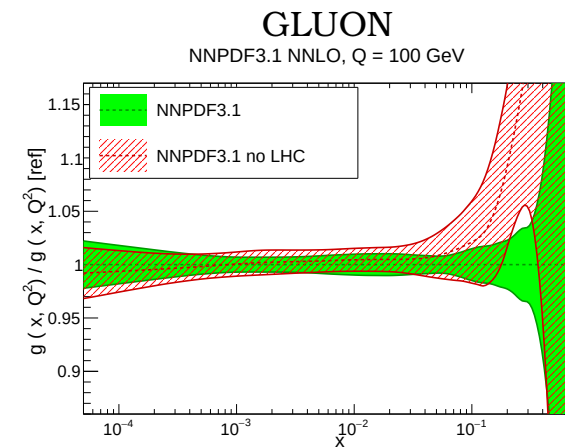
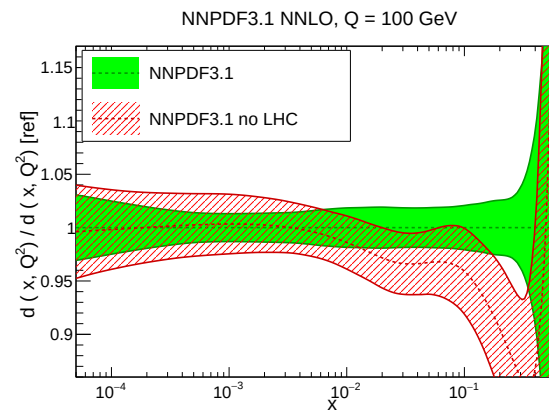
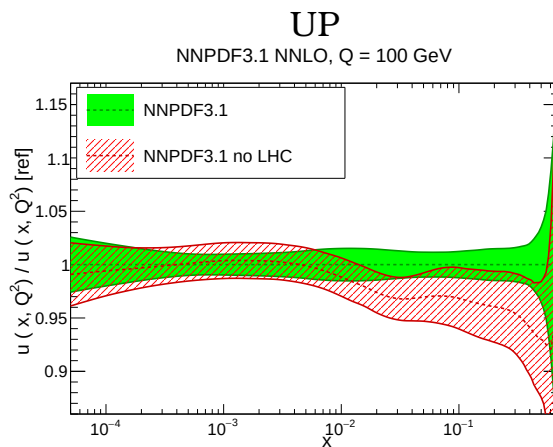
NOW: PDFs **LARGELY DETERMINED BY LHC DATA**

NNPDF3.1 vs NNPDF3.1 no LHC DISTANCES (difference in units of st. dev.)

NNPDF3.1 NNLO, Impact of LHC data



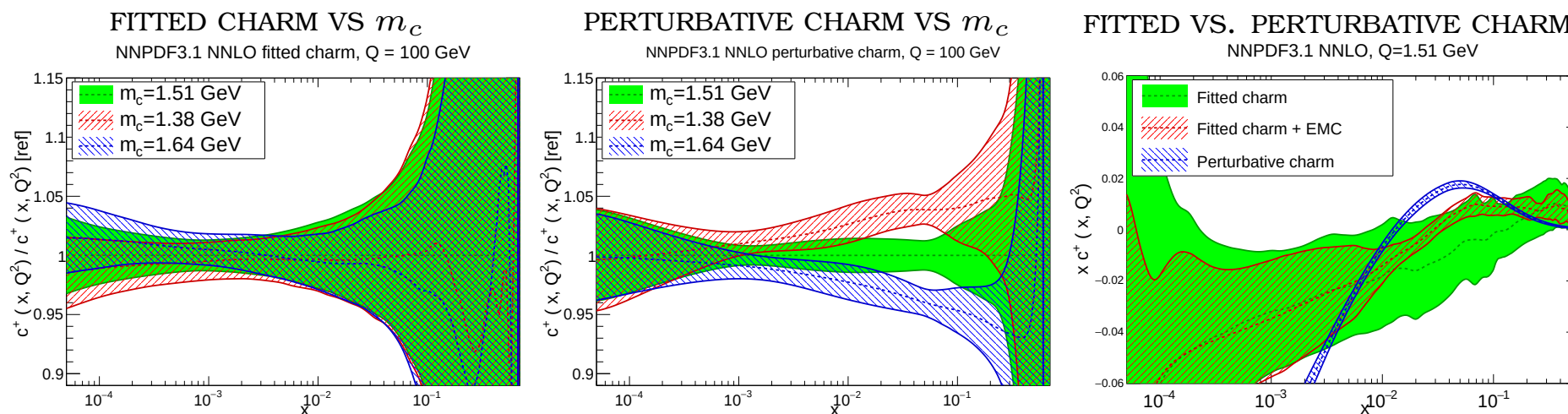
$d = 10 \Leftrightarrow$ one sigma difference
PDF COMPARISON
DOWN



- MANY PDFs CHANGE BY MORE THAN ONE SIGMA
- BOTH FLAVOR SEPARATION & GLUON SIGNIFICANTLY AFFECTED

METHODOLOGICAL PROGRESS: CHARM FROM DATA

- CHARM **SHOULD NOT DEPEND** STRONGLY **CHARM MASS**



- ITS **SHAPE SHOULD NOT** BE DETERMINED BY **FIRST-ORDER MATCHING**
(NO HIGHER NONTRIVIAL ORDERS KNOWN)
- MIGHT EVEN HAVE A NONPERTURBATIVE COMPONENT

FITTED VS. LO PERTURBATIVE:

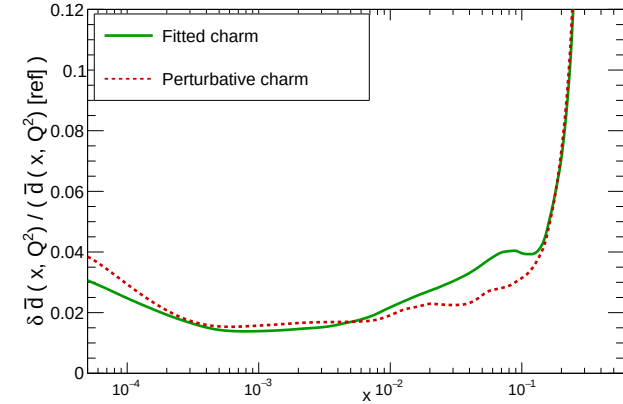
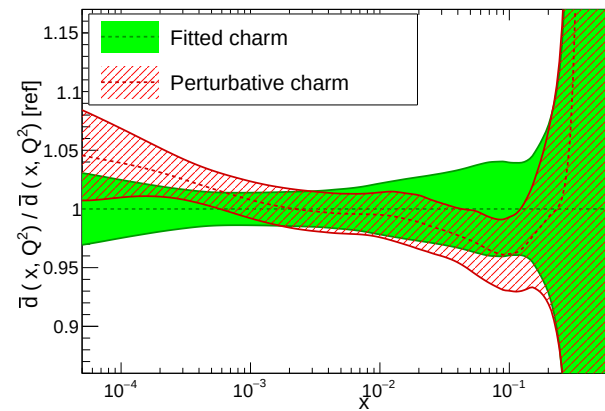
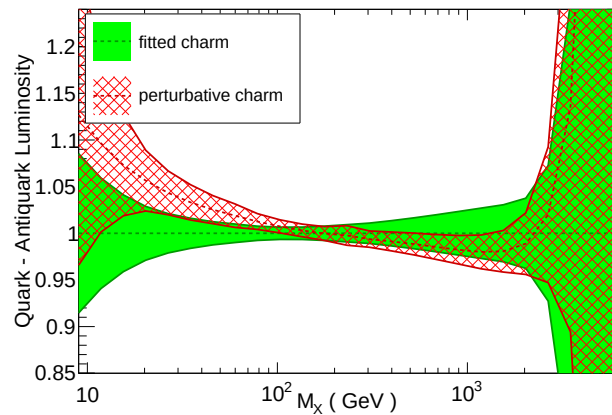
SUPPRESSED AT MEDIUM-SMALL x , ENHANCED AT VERY SMALL, VERY LARGE x

THE CHARM PDF FROM DATA IMPACT ON LIGHT QUARK PDFS

FITTED VS. PERTURBATIVE CHARM
ANTIDOWN PDF

ANTIDOWN PDF UNCERTAINTY
NNPDF3.1 NNLO, $Q = 100$ GeV

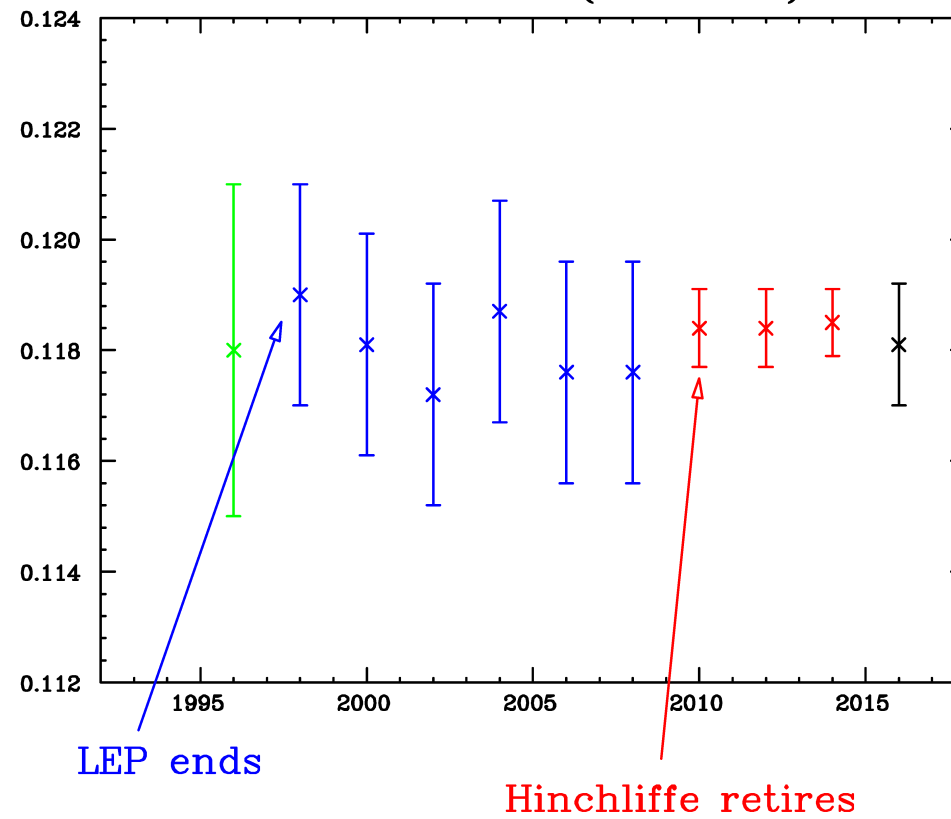
QQBAR LUMI
LHC 13 TeV, NNLO



- QUARK (ESPECIALLY QUARK-ANTIQUARK) LUMI AFFECTED BECAUSE OF CHARM SUPPRESSION AT MEDIUM- x
- FLAVOR DECOMPOSITION ALTERED
- UNCERTAINTIES ON LIGHT QUARKS NOT SIGNIFICANTLY INCREASED
- AGREEMENT OF 13TeV W,Z PREDICTED CROSS-SECTIONS IMPROVES!

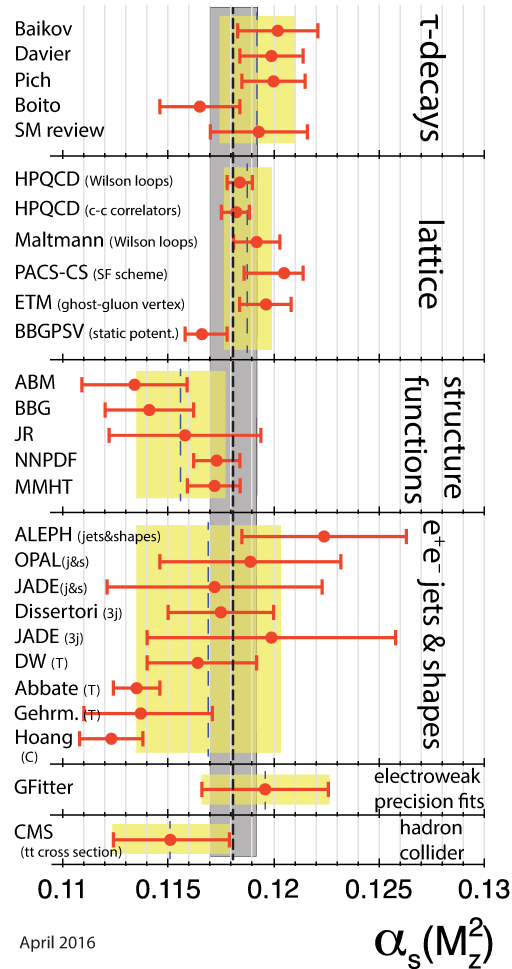
THE PROBLEM OF α_s

THE PDG VALUE (VS.TIME)



WHERE DOES THE PDF AVERAGE COME FROM?

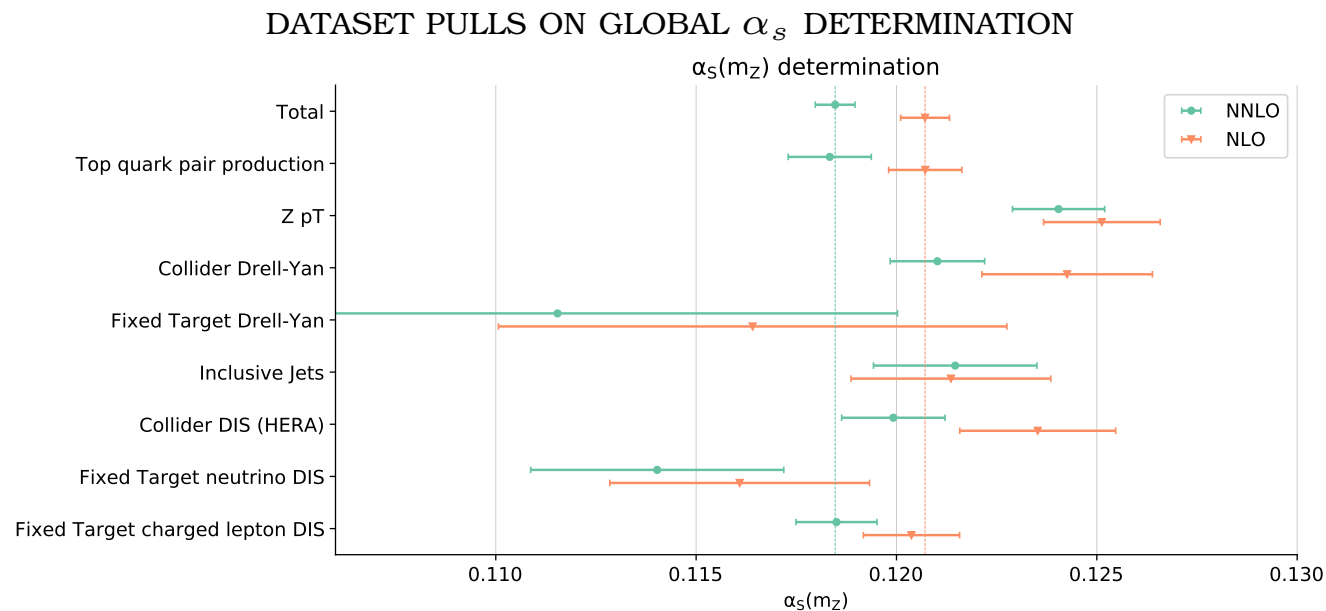
PDG PRE-AVERAGES



- PDG AVERAGE: χ^2 -AVERAGING OF SIX PRE-AVERAGES, CHOSEN TO BE MAXIMALLY UNCORRELATED
- χ^2 AVERAGING $\Rightarrow$ UNCERTAINTIES INFLATED OR CORRELATED UNTIL $\chi^2/dof = 1$
- EACH PRE-AVERAGE IS THE SIMPLE (UNWEIGHTED) AVERAGE OF ITS COMPONENTS, UNCERTAINTY $\leftrightarrow$ AVERAGE OF UNCERTAINTIES (OR STANDARD DEVIATION OF VALUES IF LARGER)

WHAT'S THE PROBLEM?

- GLOBAL EW FIT THEORETICALLY SAFE, BUT NOT VERY PRECISE
- τ QUITE PRECISE, BUT LOW SCALE $\Rightarrow$ PERTURBATIVE ACCURACY?
- LATTICE: VERY PRECISE, BUT WHAT IS THE ACCURACY OF THE TRUNCATION?
- ANY PROCESS WITH HADRONS IN THE FINAL STATE: DEPENDENCE ON THE PDF



(NNPDF, 2018)

PULLS DO NOT ADD TO ZERO $\Leftrightarrow$ BEST FIT PDF FOR DATASET IS NOT GLOBAL BEST FIT α_s USING EXTERNAL PDF SET POTENTIALLY BIASED DUE TO α_s -PDF CORRELATION

THE FINAL STATE

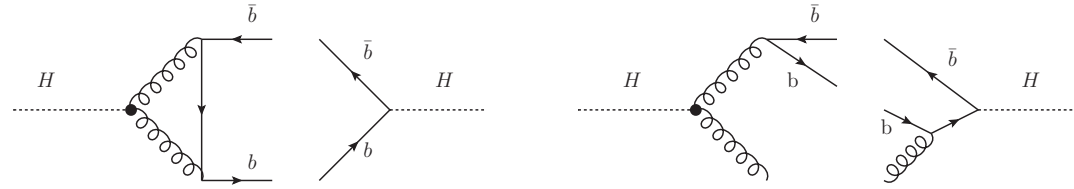
FULLY EXCLUSIVE FINAL STATES WITH DECAY PROGRESS...

- FULLY DIFFERENTIAL NNLO HIGGS IN GLUON FUSION (Dulat, Lionetti, Mistlberger, Pelloni, Specchia, 2017)
- NNLO FULLY DIFFERENTIAL FIDUCIAL ASSOCIATE WH, ZH (Grazzini, Kallweit, Rathlev, Wieseemann, 2017)
- FULLY DIFFERENTIAL NNLO AUTOMATION: MATRIX (Grazzini, Kallweit, Wieseemann, 2017) :
 - $2 \rightarrow 1$ AND $2 \rightarrow 2$ WITH FINAL STATE VB & HIGGS
 - AMPLITUDES FROM OPENLOOPS; q_t SUBTR.
 - ALL DECAY CHANNELS INCLUDED, ALSO WITH RESONANT & NON-RESONANT

SUBTLETIES: AN EXAMPLE

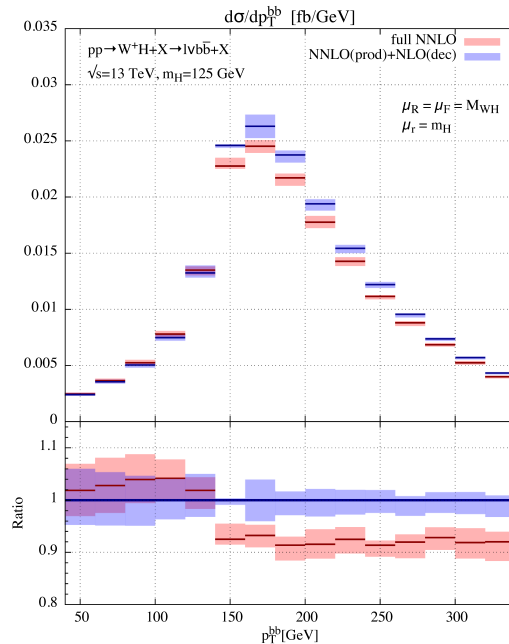
ASSOCIATE WH WITH $H \rightarrow \bar{b}b$ DECAY

- TWO COMPUTATIONS AVAILABLE
- LARGE DECAY CORRECTIONS WITH CUTS

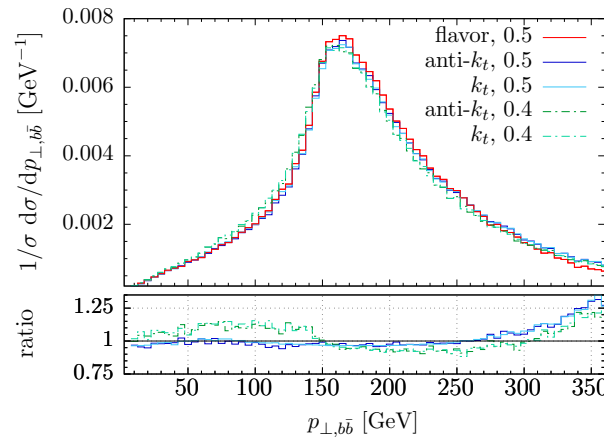


- INTERFERENCE (NOT INCLUDED)
- PARTON SHOWER
- JET DEFINITION

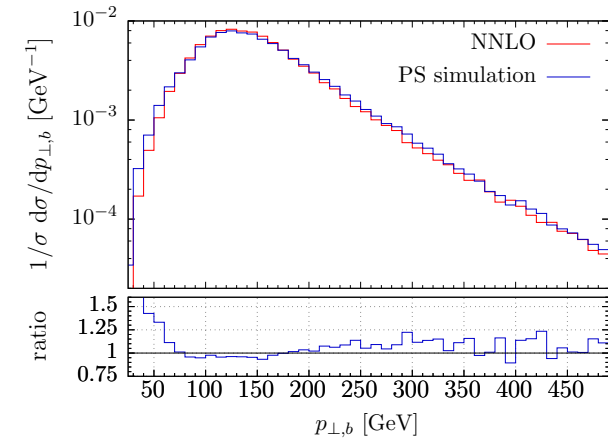
IMPACT OF NNLO DECAY



IMPACT OF PS



IMPACT OF JET DEF.



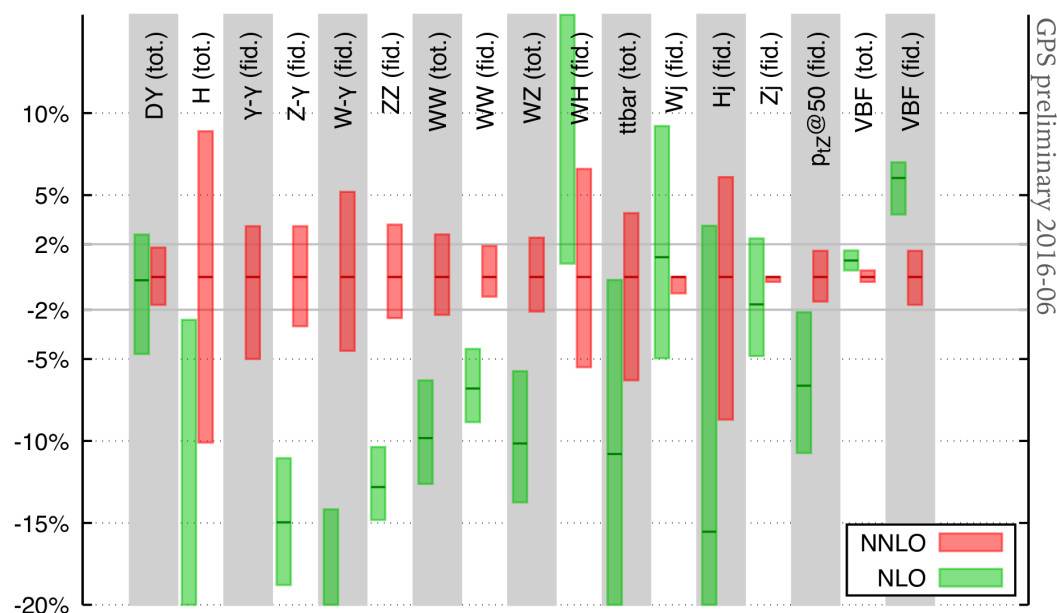
(Caola, Luisoni, Melnikov, Rönsch, 2018)

(Ferrera, Somogyi, Tramontano, 2017)

WHAT IS THE UNCERTAINTY,
ANYWAY

WHAT IS A THEORY UNCERTAINTY?

NLO SCALE VARIATION VS ACTUAL NNLO CORRECTION



(G. Salam, 2016)

- **SCALE VARIATION** FREQUENTLY FAILS
SOMETIMES **OBVIOUS** (NEW PARTON SUBCHANNELS) OR **LESS OBVIOUS** (NEW STRUCTURES IN DIAGRAMS)
- BAYESIAN METHODS DIFFICULT WHEN ONLY FEW ORDERS KNOWN
- SERIES ACCELERATION (PADÉ ETC) INCONCLUSIVE
- **RESUMMATION** SOMETIMES **HELPS** $\Rightarrow$ PARTIAL INFO ON MHO
- **CONSERVATIVE ESTIMATE** $\Rightarrow$ NNLO UNCERTAINTY **BASED** ON NLO-NNLO **SHIFT**
- NOTE **TH UNCERTAINTIES** SOMETIMES **NEGLECTED**: E.G. **ON PDFs**

EPILOGUE:
SO, THE HIGGS?

THE MOST PRECISE (ACCURATE) CALCULATION

HIGGS IN GLUON FUSION: TOTAL CROSS-SECTION

THEORY UNCERTAINTIES

- MISSING HIGHER ORDERS **HO**
 - ~~TRUNC. OF SOFT EXPANSION FOR N³LO ± 0.18 pb (0.4%)~~
 - N⁴LO & BEYOND ± 1.4 pb (3%)
- ~~MIXED QCD-ELECTROWEAK CORRNS.~~ **EW** ± 1.2 pb (2.5%)
- HEAVY QUARK MASS EFFECTS **HQ**
 - NNLO B(C)/T INTERFERENCE: ± 0.5 pb (1%)
 - ~~$1/m_t$ ON N³LO: ± 0.7 pb (1.5%)~~
- MISSING N³LO PDFs **PDF-TH** ± 0.6 pb (1.2%)

PDF+ α_s

- **PDF** ~~± 0.9 pb (1.9%)~~ ± 0.5 pb (1%)
- **α_s** ± 1.3 pb (2.6%)

(APPR) N³LO+N³LL QCD (EFT); NLO PURE EW; NLO EXACT HQ;
NNLO APPROX TOP; NNLO PDFs

$$\sigma(\text{LHC13}, m_H = 125 \text{ GeV}) = 48.58 \text{ pb} \pm 2.2^{\text{TH}} (4.5\%) \pm 1.6^{\text{PDF}+\alpha_s} (3.2\%)$$

$$\sigma(\text{LHC13}, m_H = 125 \text{ GeV}) = 48.58 \text{ pb} \pm 1.6^{\text{TH}} (3.3\%) \pm 1.4^{\text{PDF}+\alpha_s} (2.8\%)$$

SUBSTANTIAL PROGRESS ON

- $N^3\text{LO}$
- ELECTROWEAK
- MULTISCALE
- PDFs
- FINAL STATES

AND ALSO SHAMELESSLY NEGLECTED IN THIS TALK

- SM PARAMETERS (M_w , M_t)
- PARTON SHOWERING AND MONTE CARLO MATCHING
- JET SUBSTRUCTURE

LITTLE PROGRESS ON

- α_s
- THEORY UNCERTAINTIES

PRECISION OK,
ACCURACY NOW NEEDED

