PRECISION STANDARD MODEL PHYSICS AT THE LHC

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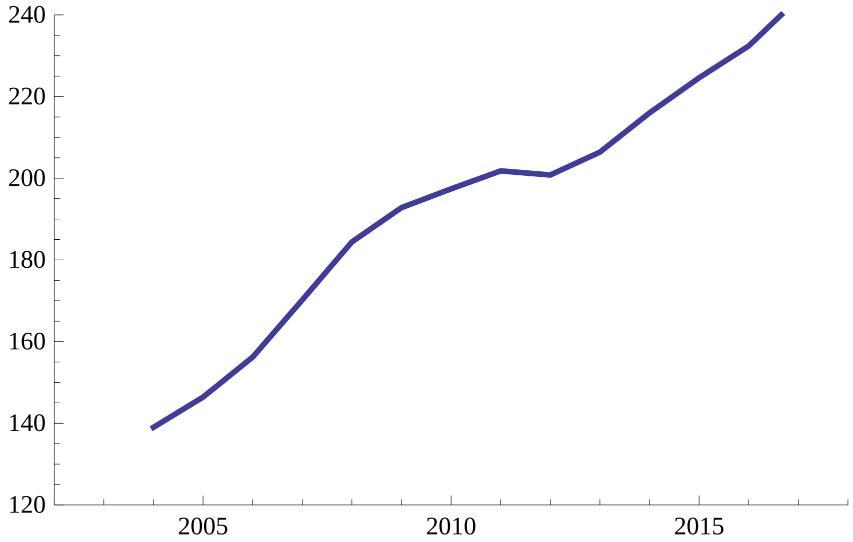
PROLOGUE: PRECISION?

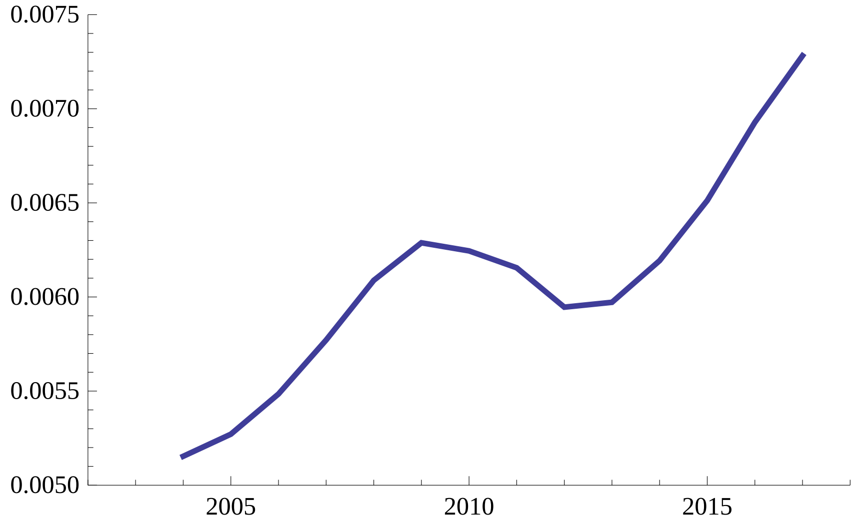
PRECISION

PAPERS WITH “PRECISION” IN TITLE

NUMBER



PERCENTAGE



inSPIRE, 5 yr moving average

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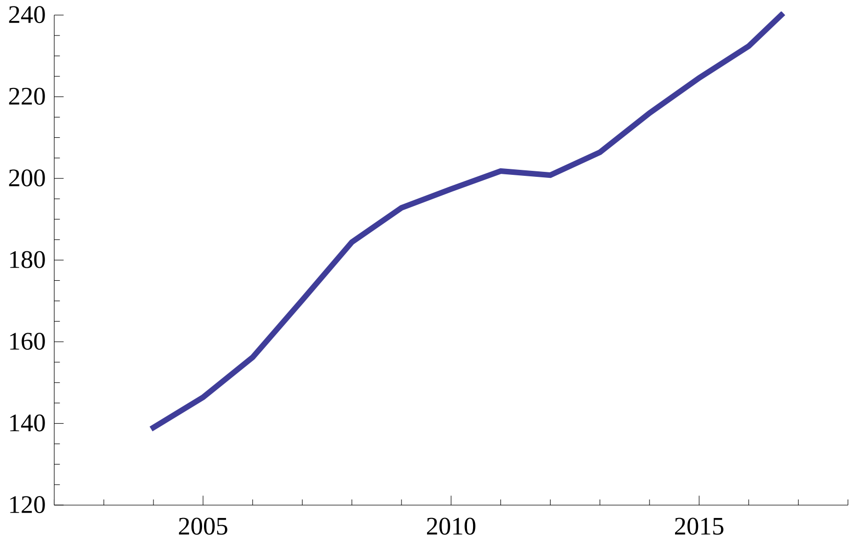

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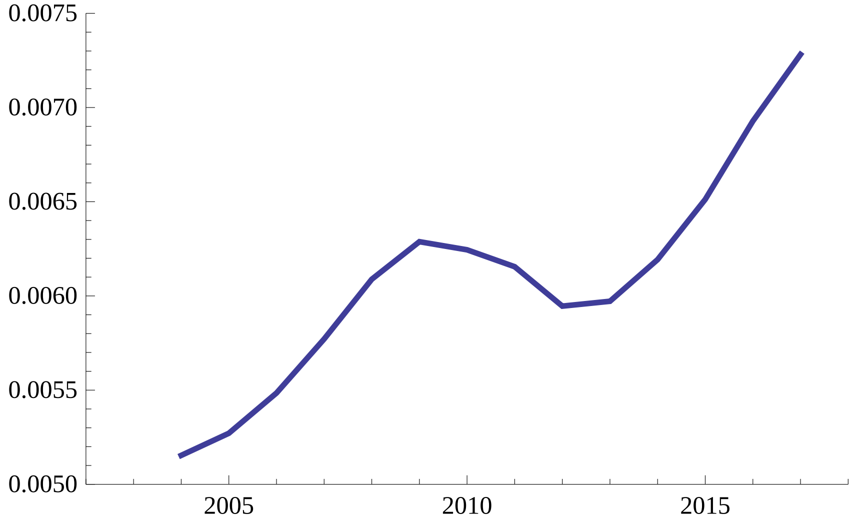


INSPIRE, 5 YR MOVING AVERAGE

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) N^3LO+N^3LL 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 N^3LO ± 0.18 pb (0.4%)
  - N^4LO & BEYOND ± 1.4 pb (3%)
- MIXED NLO 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 N^3LO: ± 0.7 pb (1.5%)
- MISSING N^3LO PDFS PDF-TH ± 0.6 pb (1.2%)

PDF+α_s

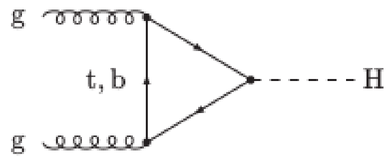
- PDF ± 0.9 pb (1.9%)
- α_s ± 1.3 pb (2.6%)

QCD: HIGHER ORDERS AND RESUMMATION

HIGGS AT N^{3}LO

(Mistlberger, 2018)

HIGGS IN GLUON FUSION: LOOP INDUCED

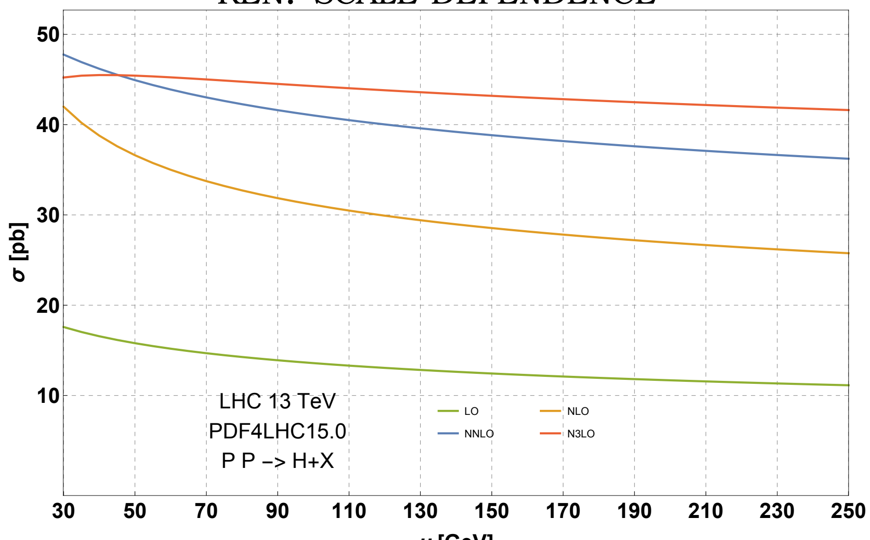


EXACT N^{3}LO QCD CORRECTIONS NOW INCLUDED:

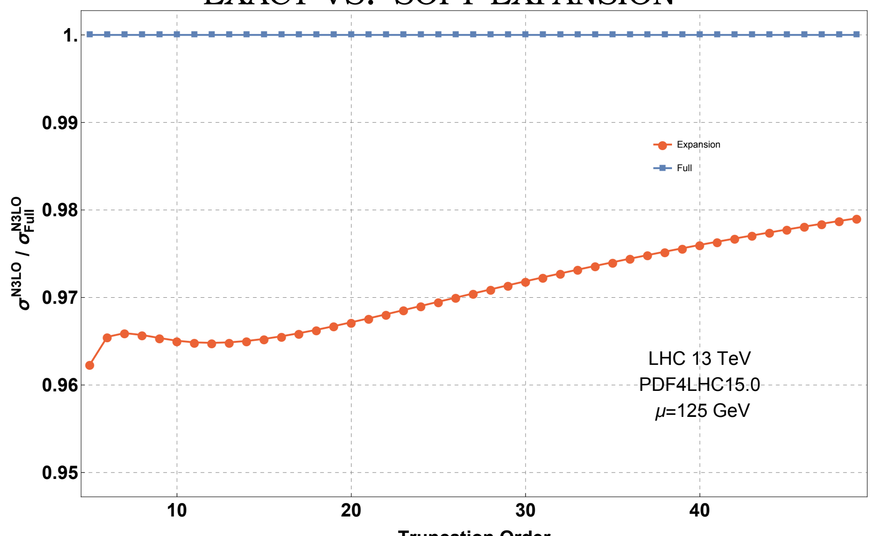
$$\sigma(\text{LHC13},\, m_H = 125\ \text{GeV}) = 48.69\ \text{pb}$$

- HISTORIC, FIRST EXACT N^{3}LO HADRONIC PROCESS
- RESULTS OF SOFT EXPANSION BY AND LARGE CONFIRMED (Anastasiou et al., 2016)
- SLOWLY CONVERGENT PERTURBATIVE EXPANSIONS, STABILIZES AT N^{3}LO
- DIFFERENCE TO SOFT EXPANSION (30 ORDERS) +0.11 pb (0.2%)
  $\Rightarrow$ 0.4% ESTIMATED UNCERTAINTY REMOVED

REN. SCALE DEPENDENCE



EXACT VS. SOFT EXPANSION



THE TIP OF THE ICEBERG
THE LES HOUCHES WISHLIST

- NLO WISHLIST DISCONTINUED IN 2011 DUE TO AUTOMATION $\to$ TENTATIVE NNLO WISHLIST
- 2013: PRECISION WISHLIST "EXTREMELY AMBITIOUS"
- HIGGS, GAUGE BOSON, TOP+JET TABLES

JET+HQ WISHLIST

2013

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

Table 2: Wishlist part 2 – Jets and Heavy Quarks

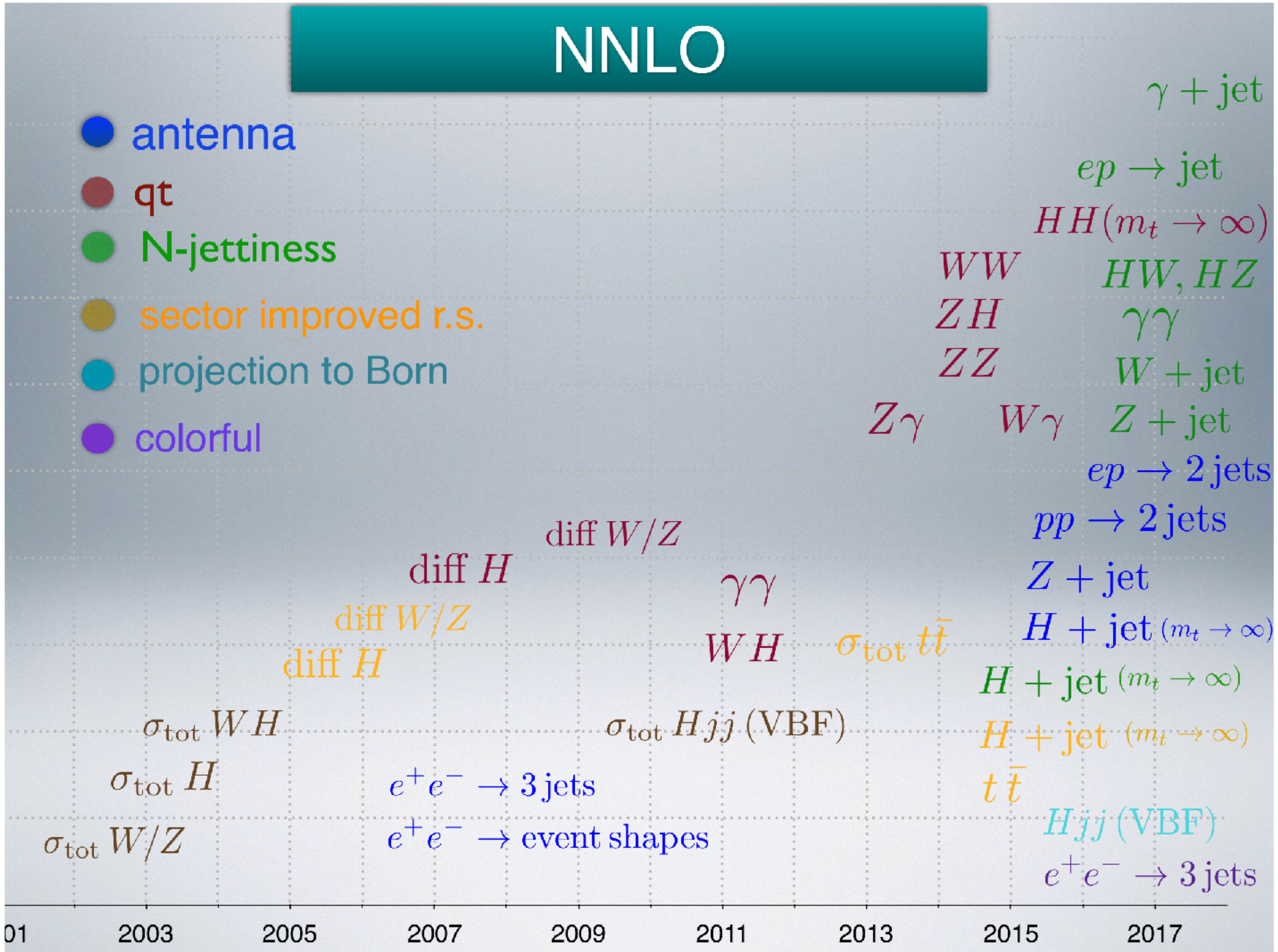
2017

process	known	desired
$pp \to t\bar{t}$	$\mathrm{N^2LO_{QCD}}$+$\mathrm{NLO_{EW}}$ $\mathrm{NLO_{QCD}}$ (w/ decays, off-shell effects) $\mathrm{NLO_{EW}}$ (w/ decays, off-shell effects)	$\mathrm{N^2LO_{QCD}}$ (w/ decays)
$pp \to t\bar{t}+j$	$\mathrm{NLO_{QCD}}$ (w/ decays) $\mathrm{NLO_{EW}}$	$\mathrm{N^2LO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t}+2j$	$\mathrm{NLO_{QCD}}$ (w/ decays)	$\mathrm{NLO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t}+Z$	$\mathrm{NLO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays)	
$pp \to t\bar{t}+W$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NLO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t/\bar{t}$	$\mathrm{N^2LO_{QCD}}$*(w/ decays)	$\mathrm{N^2LO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays)

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

- LARGELY DONE!

THE NNLO REVOLUTION



(G.Heinrich, LHCP2017)

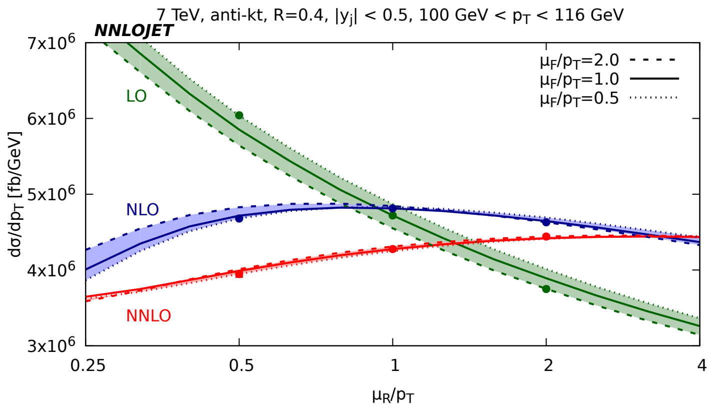
- TWO CLASSIC CLASSES OF METHODS FOR SING. CANCELLATION: SLICING & SUBTRACTION
- NEW VARIANTS SUGGESTED: JETTINESS (Petriello, 2015) ANALOGOUS TO q_T (Catani, 2007); GEOMETRIC SUBTRACTION (Herzog, 2018)

NNLO HIGHLIGHTS: 2017-2018

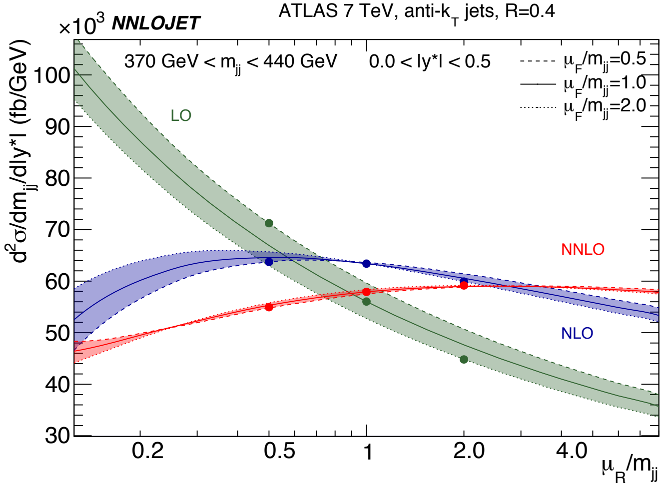
- SINGLE-JET INCLUSIVE AND DIJET (Catani, Cieri, de Florian, Ferrera, Grazzini, 2018)
- PROMPT PHOTON (Campbell, Ellis, Williams, 2017)
- HIGGS VBF: FULLY DIFFERENTIAL (Cruz-Martinez, Gehrmann, Glover, Huss, 2018)
- HIGGS: ASSOCIATE WITH W FULLY DIFFERENTIAL INCLUDING HIGGS DECAY (Somogy, Ferrera, Tramontano, 2017; Caola, Luisoni, Melnikov, Röntsch, 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



DIJET

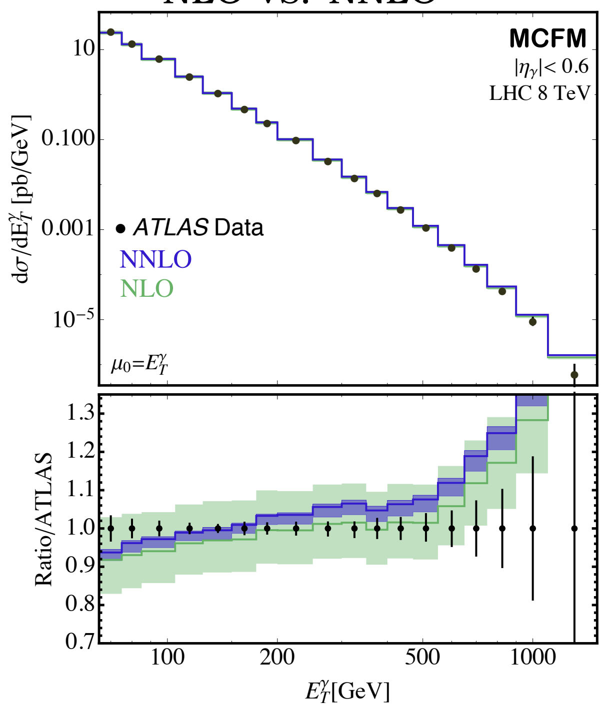


- SINGLE-JET INCLUSIVE:
  - NO OPTIMAL SCALE CHOICE: p_T VS. p_t^1 DIFFER SIGNIFICANTLY
  - NO CLEAR PERTURBATIVE CONVERGENCE
- DIJET:
  - OPTIMAL SCALE CHOICE: DIJET MASS
  - GOOD PERTURBATIVE CONVERGENCE

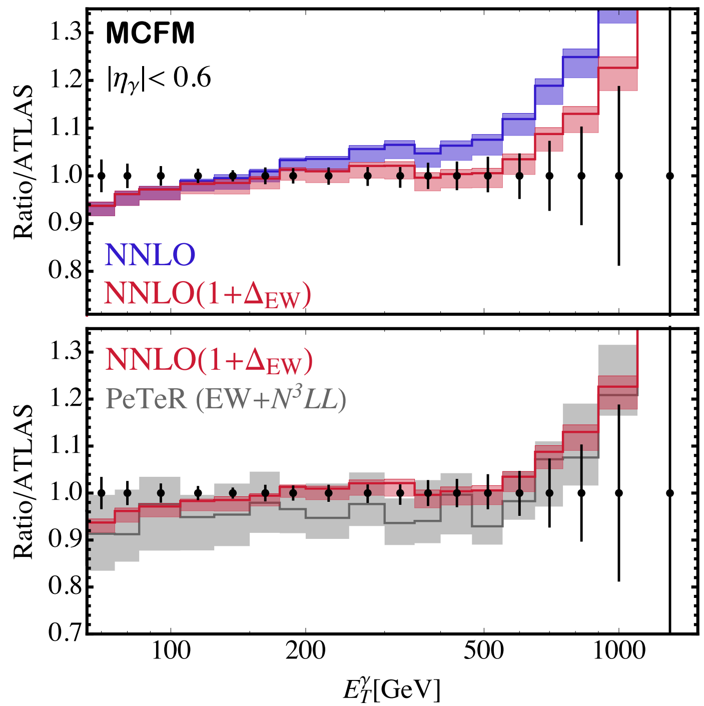
PROMPT PHOTONS

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

NLO VS. NNLO



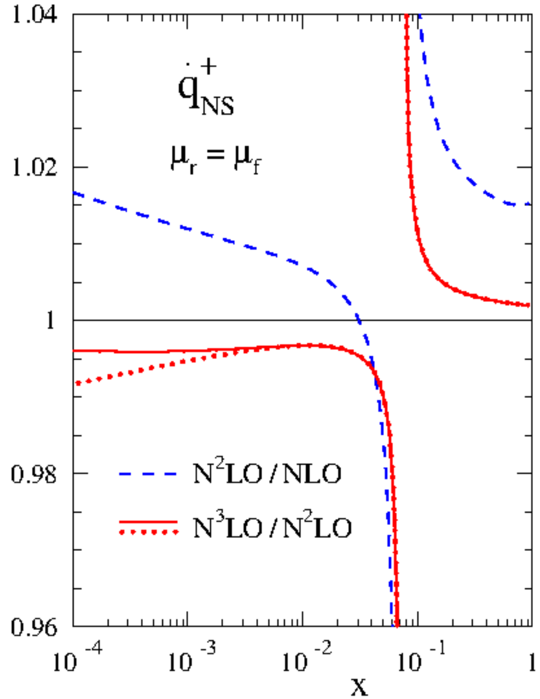
EW CORRECTIONS



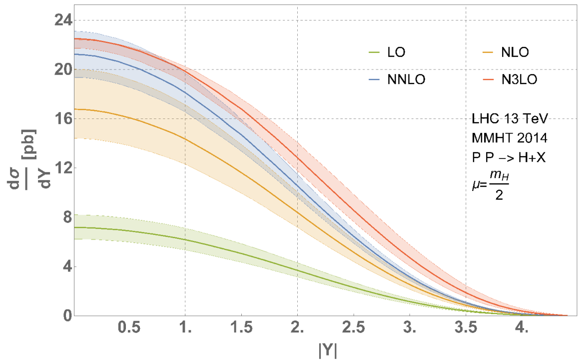
N^3LO RESULTS
TOWARDS A WISHLIST

- 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)
  - N^3LO CORRECTION MODERATE
  - RESIDUAL AMBIGUITY ON N^3LO 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 N^3LO DIFFERENTIAL HADRONIC PROCESS

NS QUARK EVOLUTION UP TO N^3LO

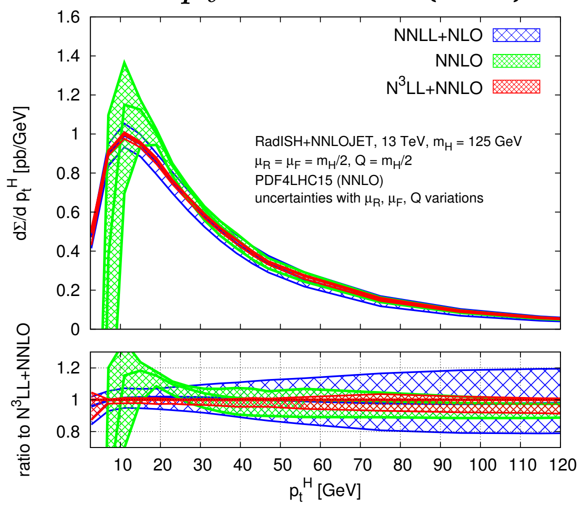


HIGGS RAPIDITY DISTRIBUTION UP TO N^3LO



RESUMMATION

HIGGS p_t SPECTRUM (EFT)



(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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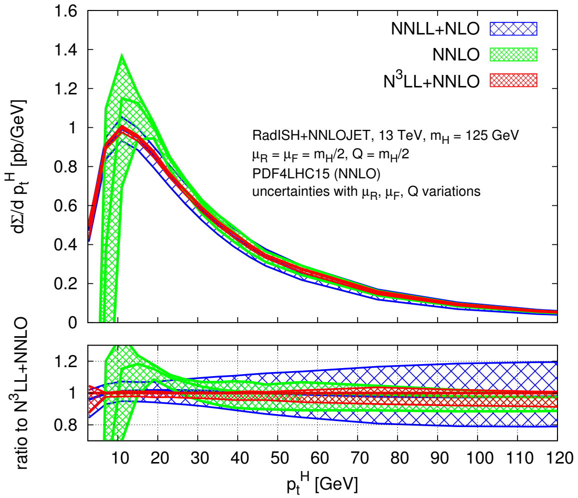

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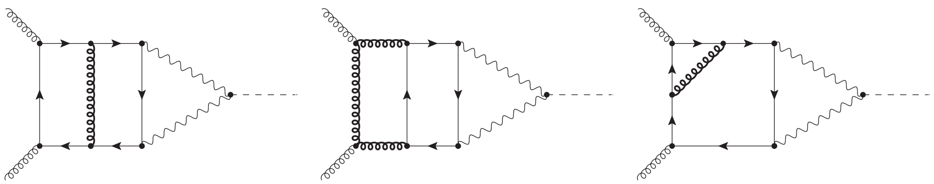
STAY TUNED FOR LUND

ELECTROWEAK EFFECTS

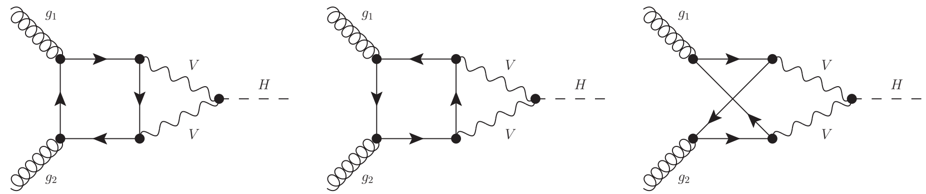
HIGGS IN GLUON FUSION

(Bonetti, Melinikov, Tancredi, 2017-2018)

TWO LOOPS



THREE LOOPS



$O(\alpha\alpha_s)$ CORRECTIONS NOW INCLUDED:

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

- 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) $-0.65\ \text{pb}$
- 2.5% UNCERTAINTY REMOVED OR AT LEAST REDUCED BELOW THE PERCENT LEVEL

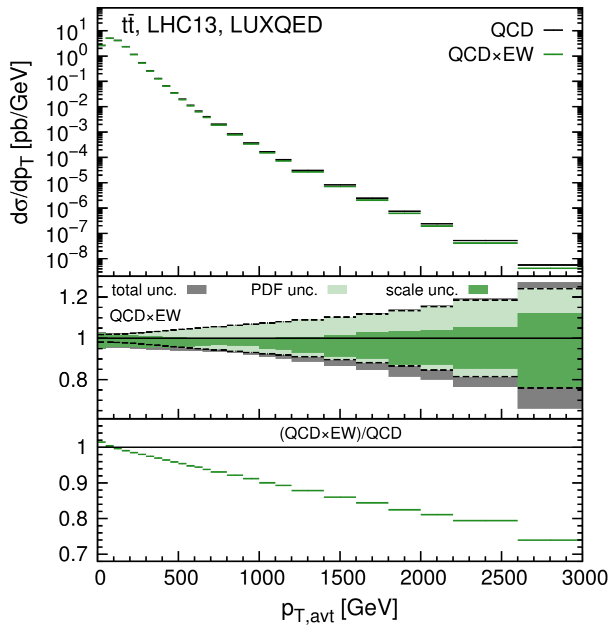
EW CORRECTIONS

- 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, Wackeroth, 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)

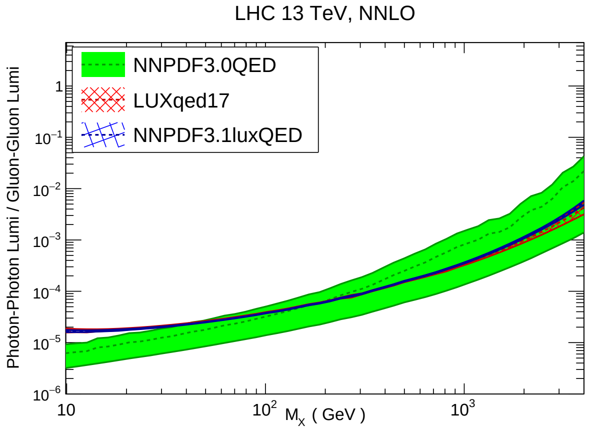
- QED IS PERTURBATIVE DOWN TO LOW SCALES $\Rightarrow$ THE PHOTON PDF MUST BE COMPUTABLE IF THE INPUT QUARK SUBSTRUCTURE IS KNOWN
- $\Rightarrow$ PDF EXPRESSED IN TERMS OF THE STRUCTURE FUNCTION INTEGRATED OVER ALL SCALES
- LUX16/LUX17 SETS CONSTRUCTED FROM PDF4LHC15 $\Rightarrow$ AGREE WELL WITH NNPDF3.0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

THE LUXQED PHOTON PDF

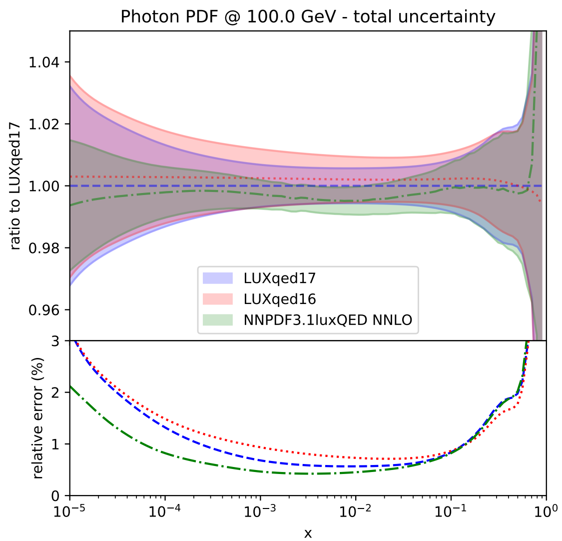
(Carrazza et al., 2017)

- 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

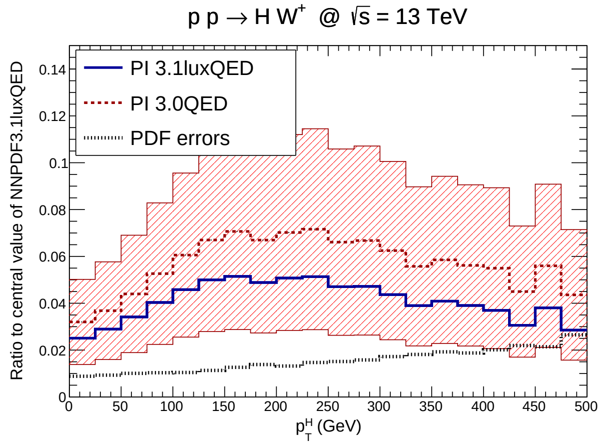
$\gamma\gamma$ LUMI COMPARISON



γ PDF COMPARISON



γ-INDUCED VS QCD: HW

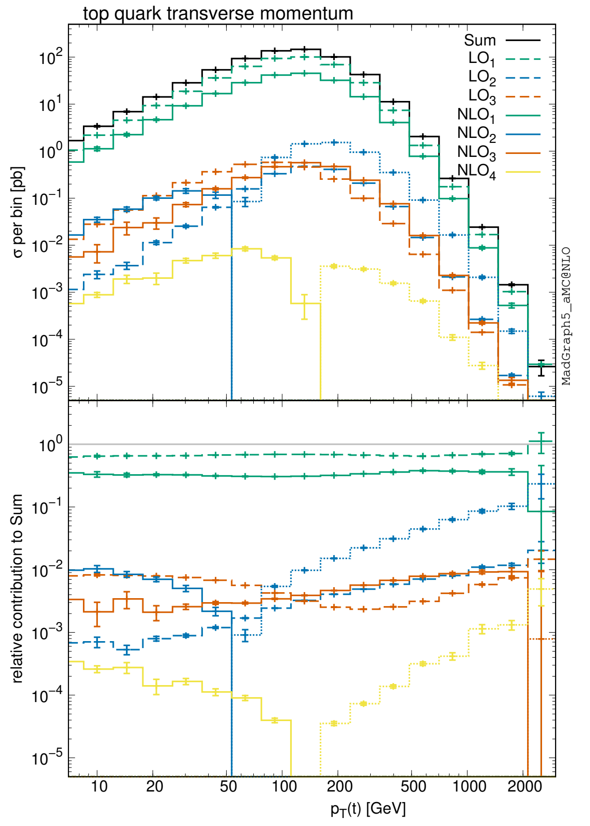


THE NLO EW AUTOMATION BREAKTHROUGH

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

- FULL AUTOMATION & IMPLEMENTATION IN `MadGraph5_aMC@NLO`
- MIXED CORRECTIONS FULLY INCLUDED UP TO NLO:
  E.G. TOP
  LO$_1$: $O(\alpha_s^2)$, LO$_2$: $O(\alpha_s\alpha)$, LO$_3$: $O(\alpha^2)$
  NLO$_1$: $O(\alpha_s^3)$, NLO$_2$: $O(\alpha_s^2\alpha)$, NLO$_3$: $O(\alpha_s\alpha^2)$, NLO$_4$: $O(\alpha^3)$

TOP p_t SPECTRUM

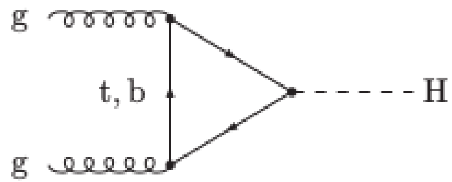


HEAVY QUARK MASSES

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



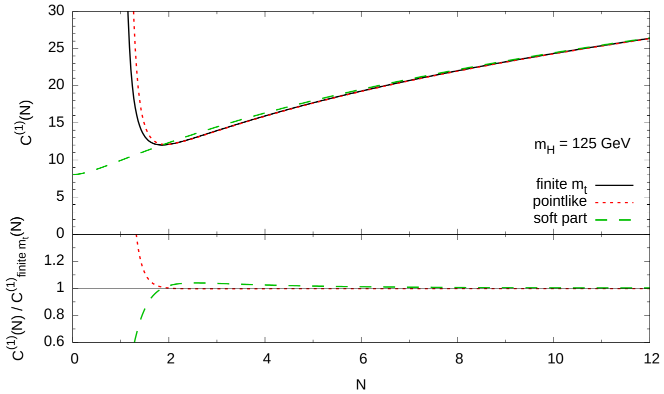
AT LHC 13

- SMALL TOP MASS CORRECTIONS AT N^3LO 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)

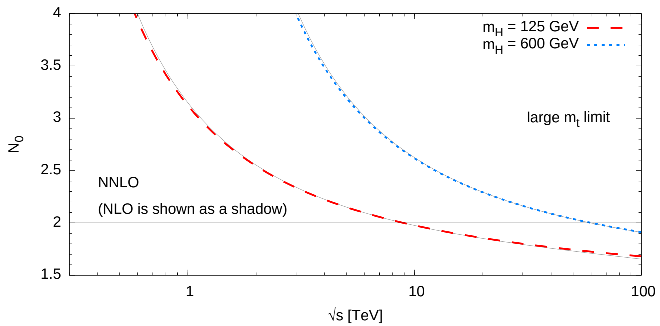
	$\overline{\text{MS}}$	OS	$\delta\sigma^{sc}$
$\sigma^{LO}_{ex;t}$	16.00 pb	16.04 pb	0.25%
$\sigma^{LO}_{ex;t+b}$	14.94 pb	14.24 pb	-4.8%
$\sigma^{LO}_{ex;t+b+c}$	14.83 pb	13.81 pb	-6.9%
$\sigma^{NLO}_{ex;t}$	36.60 pb	36.63 pb	0.08%
$\sigma^{NLO}_{ex;t+b}$	34.96 pb	34.49 pb	-1.3%
$\sigma^{NLO}_{ex;t+b+c}$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

NLO N-SPACE PARTONIC XSECT

EFT VS EXACT BEHAVIOUR



SADDLE POINT VS COLL. ENERGY

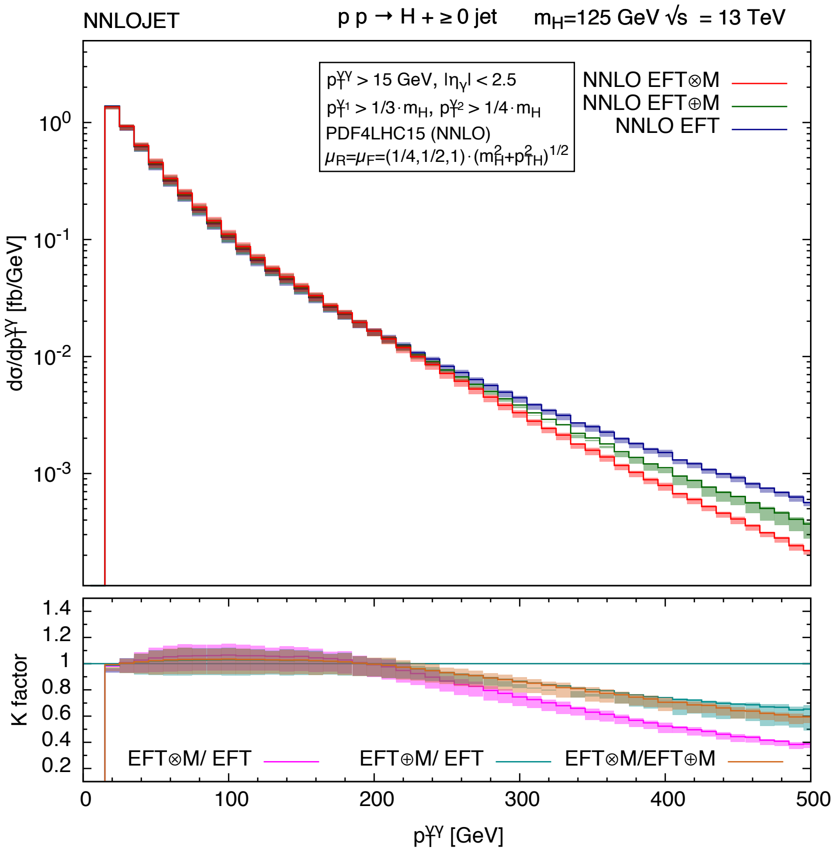


HIGGS IN GLUON FUSION (p_T SPECTRUM)

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



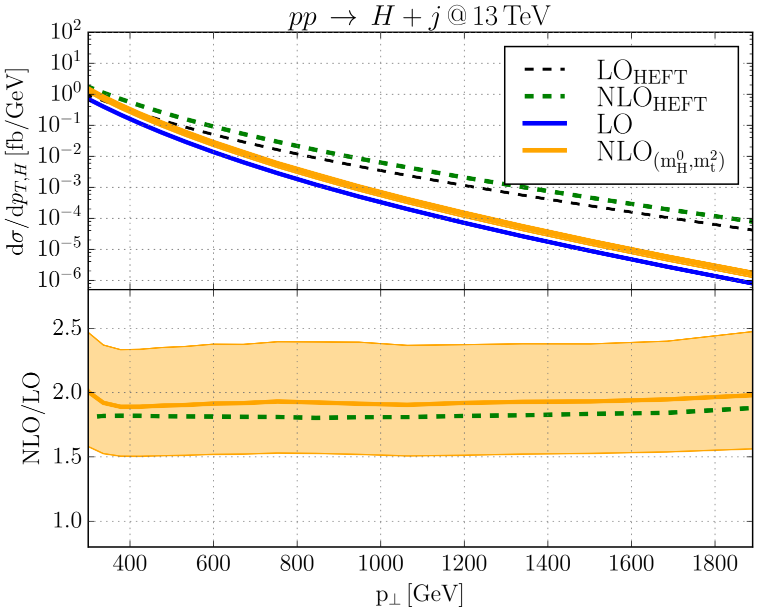
(Chen, Cruz-Martinez, Gehrmann, Glover, Jacquier, 2016)

- $R^{LO}(p_T) = \left(\frac{d\sigma_{LO}^{m_t, m_b, m_c}}{dp_T} \Big/ \frac{d\sigma_{LO}^{EFT}}{dp_T} \right)$
- EFT⊗M: $\frac{d\sigma}{dp_T} = R^{LO}(p_T) \frac{d\sigma_{NNLO}^{EFT}}{dp_T}$ (MULTIPLICATIVE)
- EFT⊕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

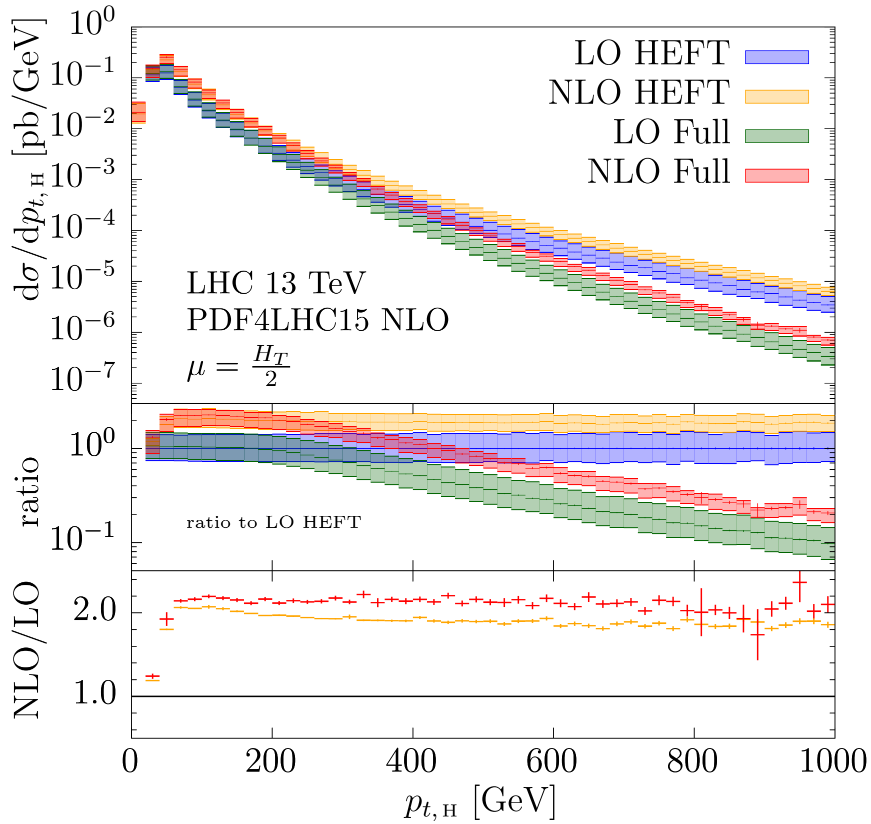
- ELUCIDATED BY HIGH-ENERGY LIMIT
- LEADING POWER BEHAVIOUR DIFFERS BETWEEN EFT AND WITH MASS DEPENDENCE, BUT IS SAME TO ALL ORDERS

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 PARMS FOR FIXED KINEMATICS, THEN INTERPOLATED



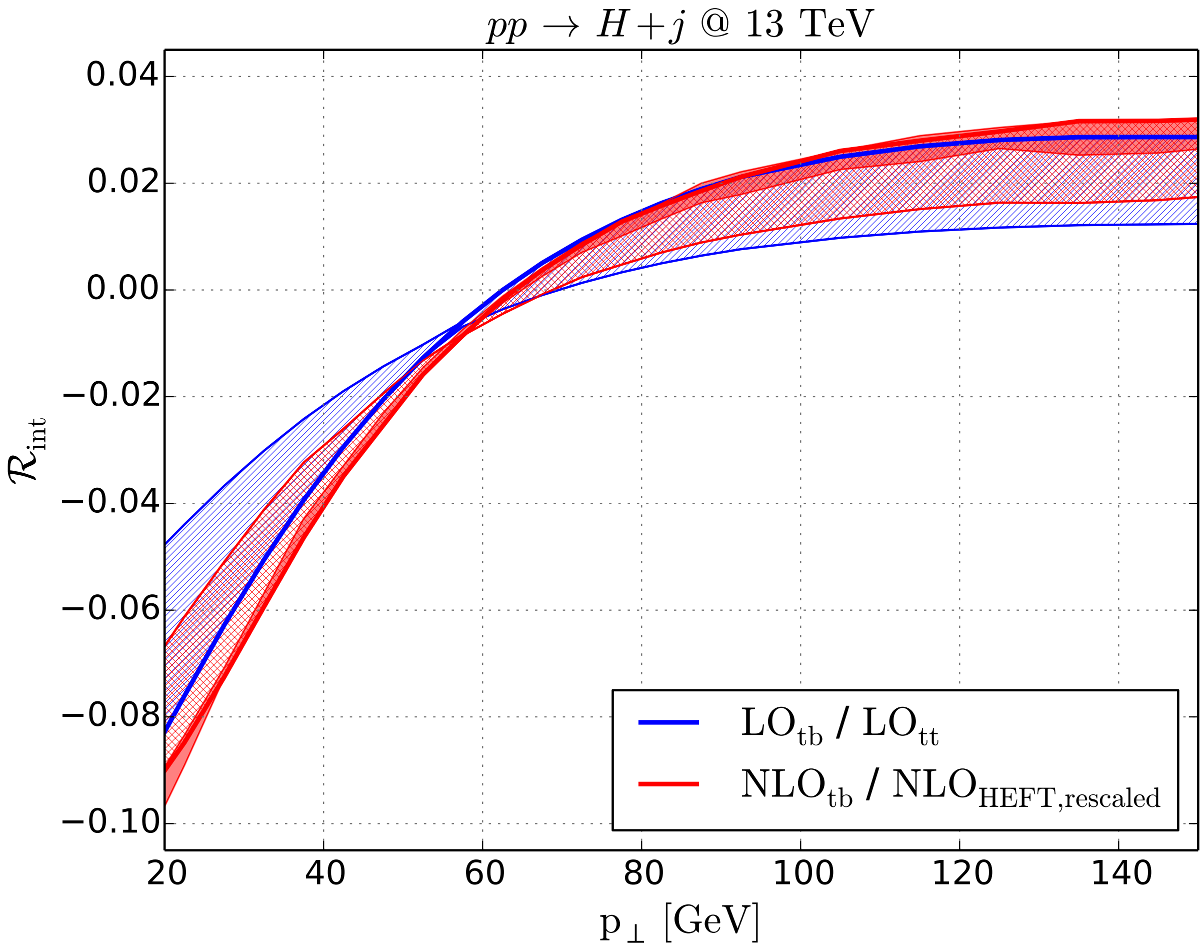
(Lindert, Kudashin, Melnikov, Wever, 2018)



(Jones, Kerner, Luisoni, 2018)

HIGGS IN GLUON FUSION (p_T SPECTRUM)

WHAT'S THE PROBLEM WITH THE B MASS



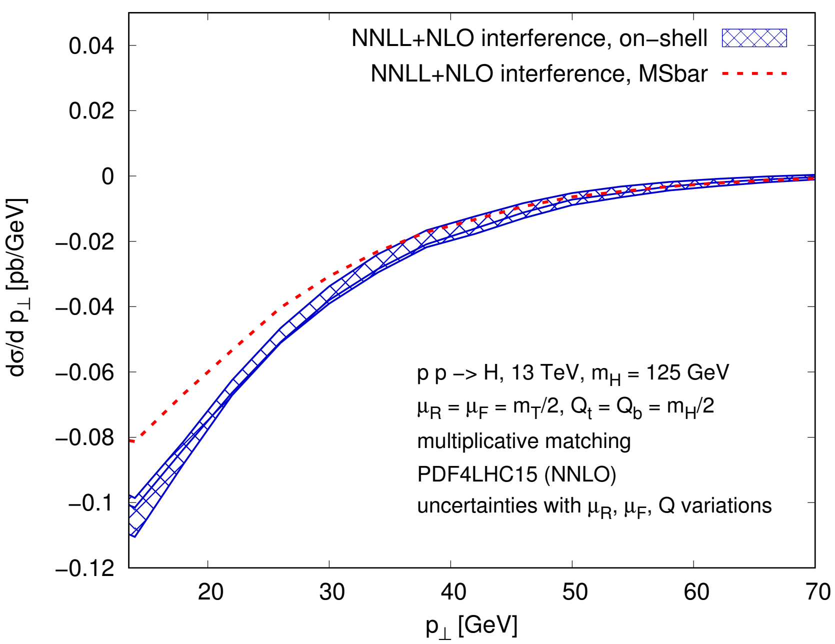
- $A^b_{gg\to Hg} \sim m_b^2/m_H^2 \ln^2(p_T^2/m_b^2) \Rightarrow$ SUDAKOV-LIKE NON-SUDAKOV DOUBLE LOGS FROM BOTTOM LOOPS, RESUMMED TO ALL ORDERS IN ABELIAN LIMIT (Melnikov, Penin, 2016)
- LARGE tb INTERFERENCE, MUST EXTRACT NON-ANALYTIC TERM WHEN EXPANDING IN m_b
- CORRECTION AS LARGE AS 10% FOR $p_T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

HIGGS IN GLUON FUSION (p_T SPECTRUM)
NLO: TOWARDS A SOLUTION

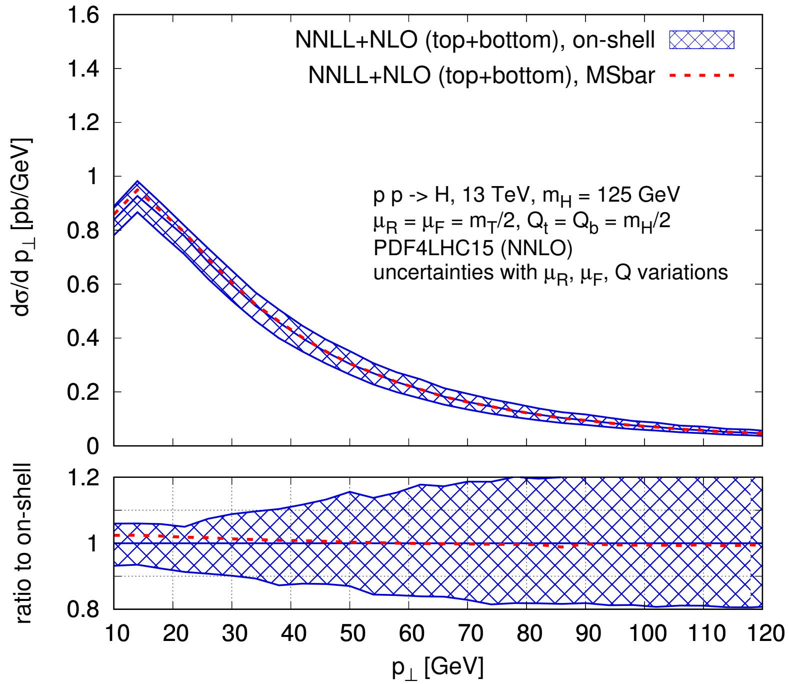
(Caola, Lindert, Melnikov, Monni, Tancredi, Wever, 2017)

- 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

INTERFERENCE



TOTAL



MASSIVE EVOLUTION

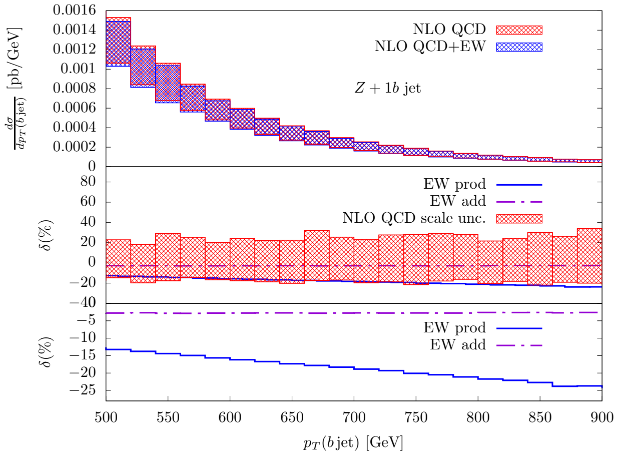
THE MASSIVE 5FS

- 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

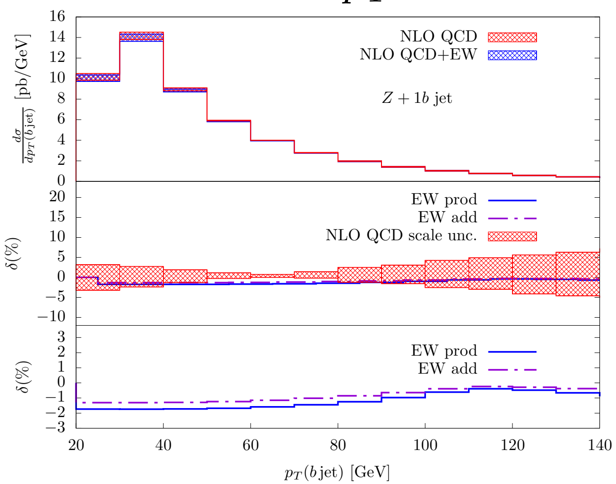
Z+B: p_t SPECTRUM OF B JET

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

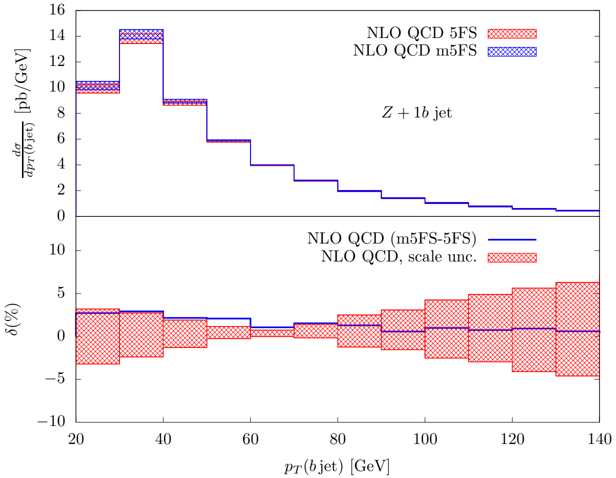
SMALL p_T



LARGE p_T



MASSIVE VS MASSLESS



PDFS AND α_s

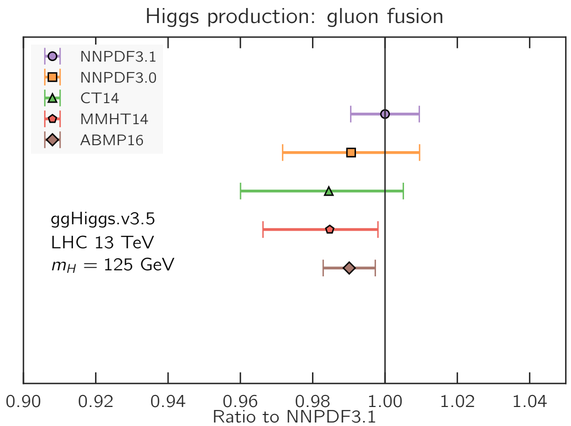
PDF PROGRESS

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

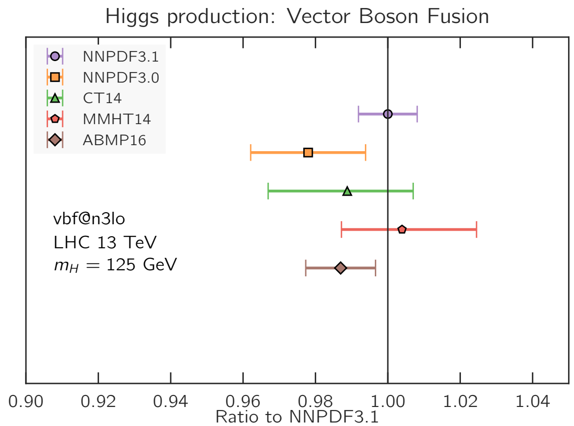
THE HIGGS PRODUCTION CROSS SECTION

PDF UNCERTAINTIES

GLUON FUSION



VECTOR BOSON FUSION

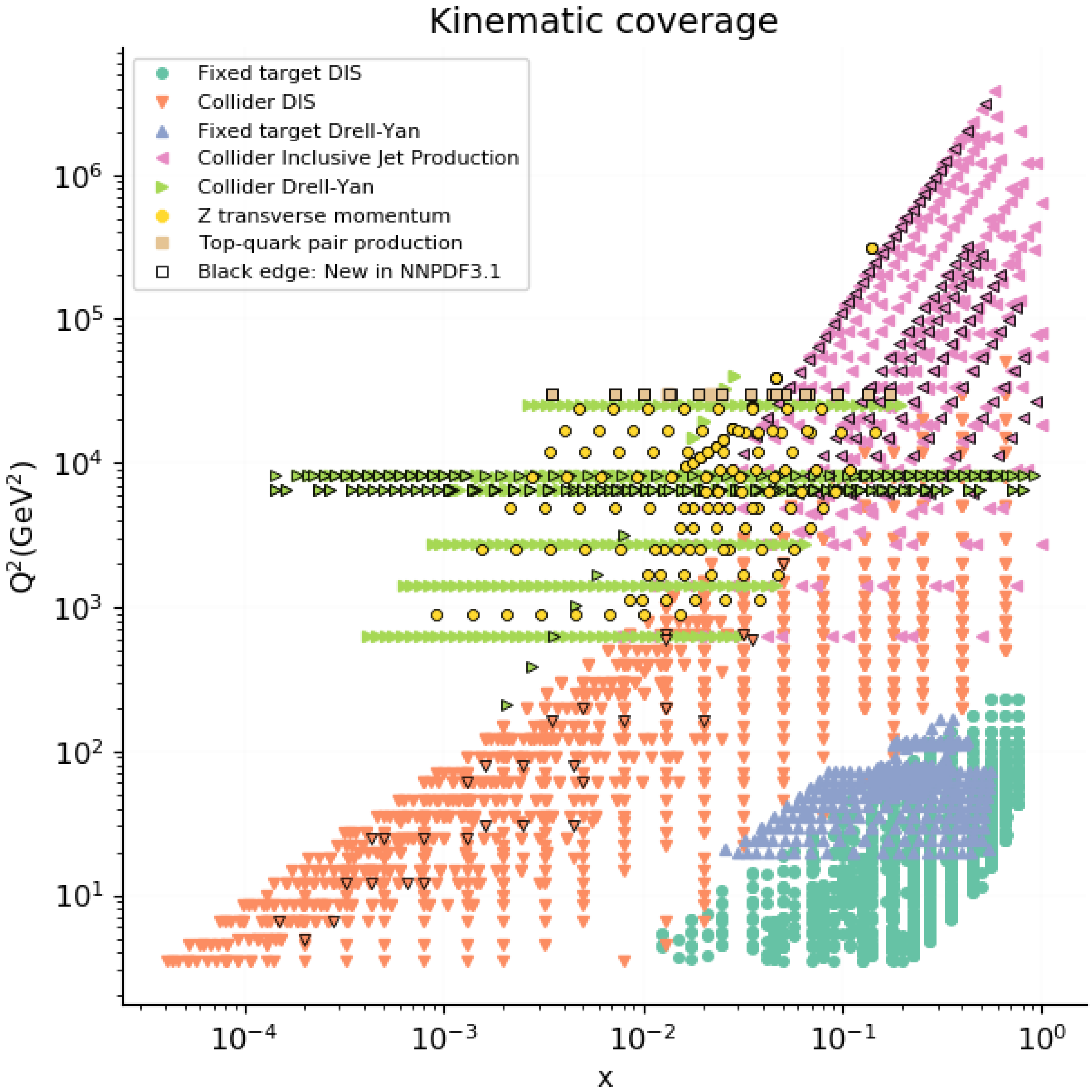


$\Delta^{\rm PDF}_{\rm ggF}\sigma \approx 0.5$ pb (1%) [WAS 0.9 pb (1.9%)]; $\Delta^{{\rm PDF}+\alpha_{\rm s}}_{\rm ggF}\sigma \approx 1.4$ pb (2.8%) [WAS 1.6 pb (3.2%)]

IF NO CHANGE IN α_s UNCERTAINTY

WHY THE IMPROVEMENT?

LHC DATA!: NNPDF3.0 VS NNPDF3.1

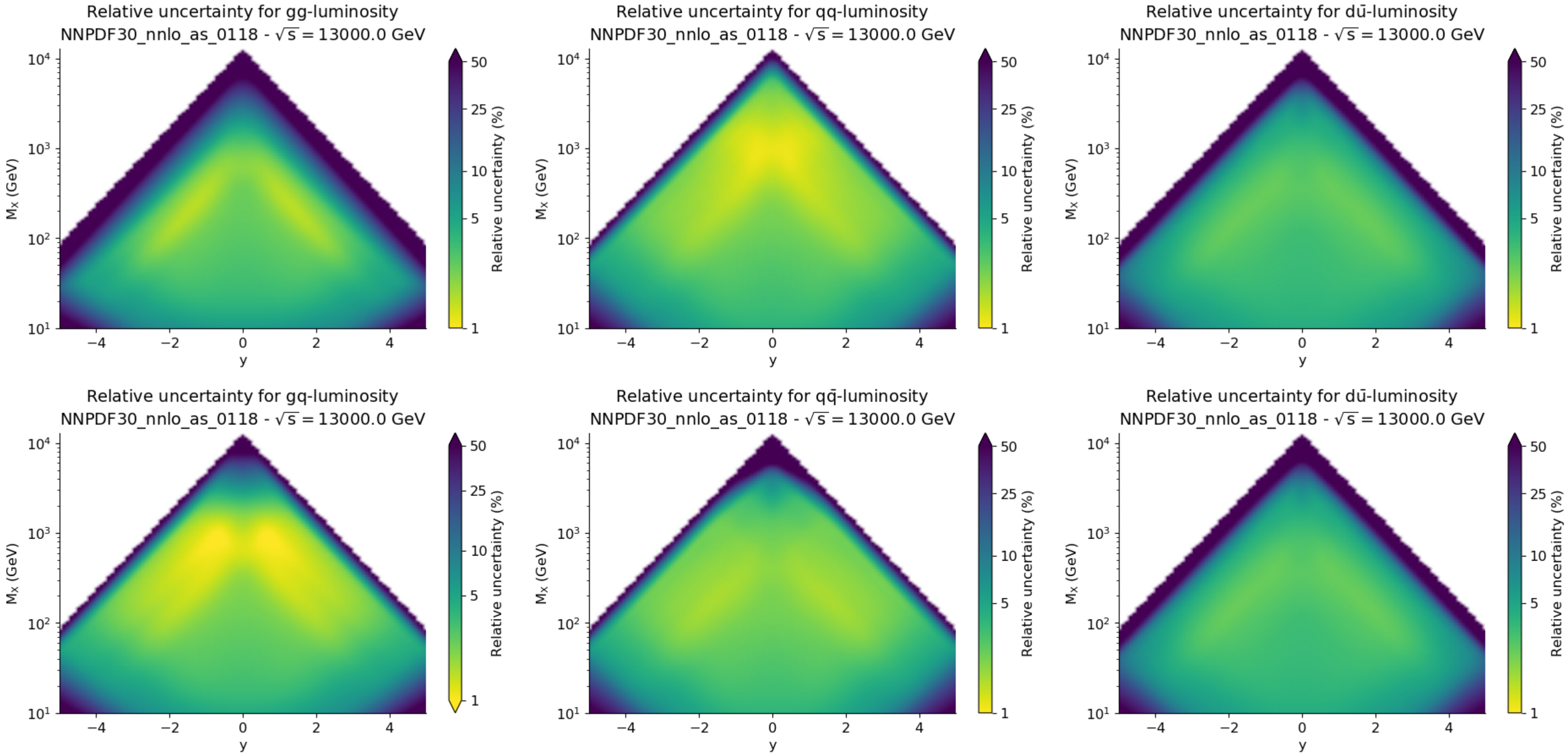


NEW DATA: (BLACK EDGE)

- 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)

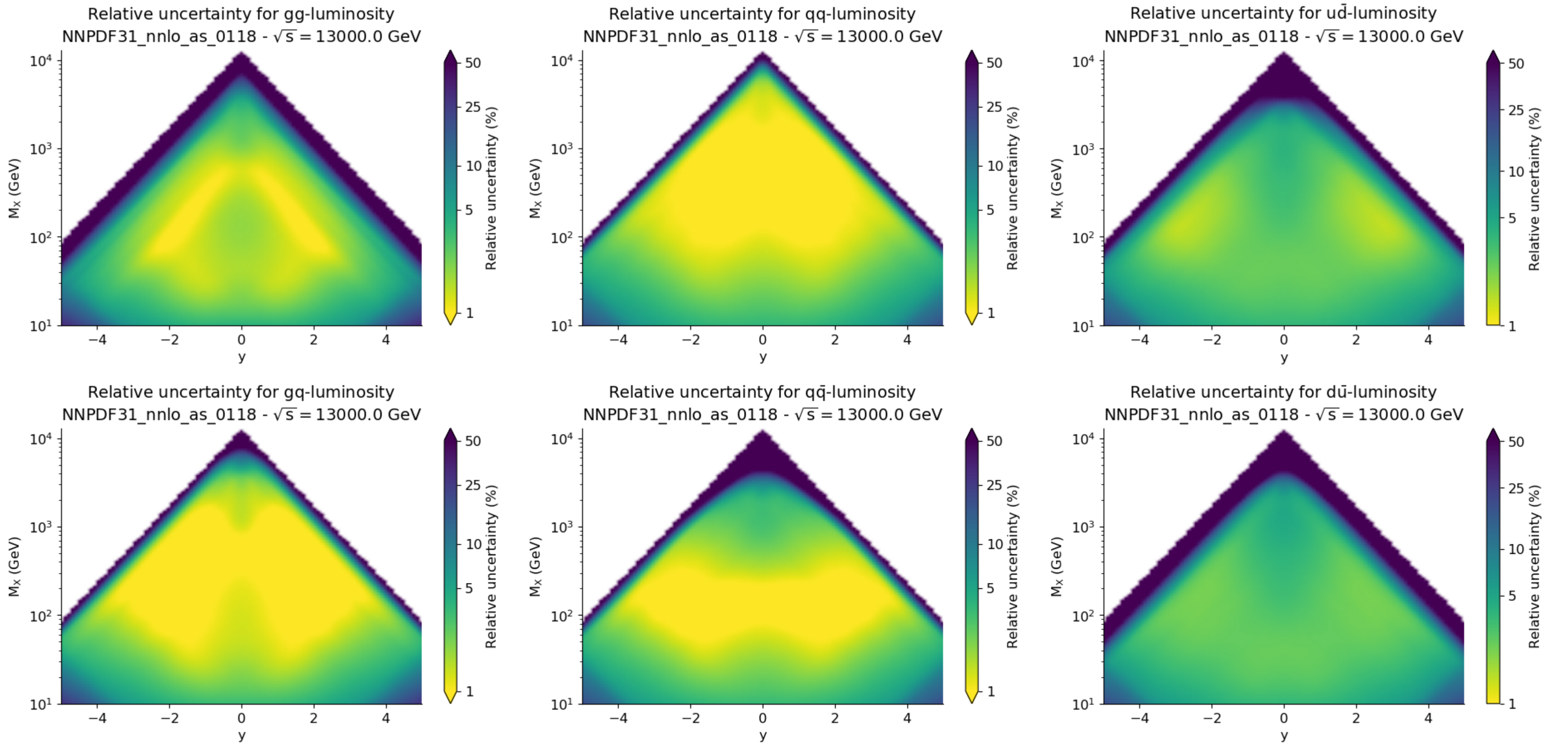
GLUON SINGLET FLAVORS



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

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

GLUON SINGLET FLAVORS



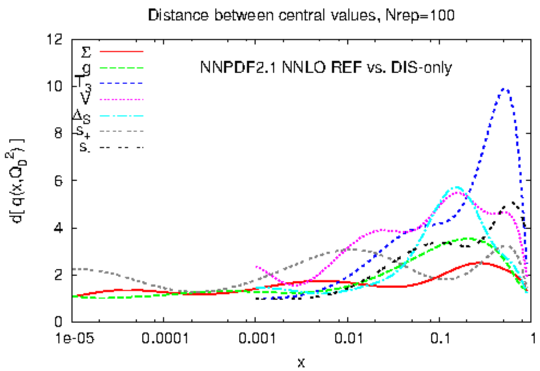
- TYPICAL UNCERTAINTIES IN DATA REGION $\sim 1 - 3\%$
- NEW LHC DATA $\Rightarrow$ SIZABLE REDUCTION IN UNCERTAINTIES

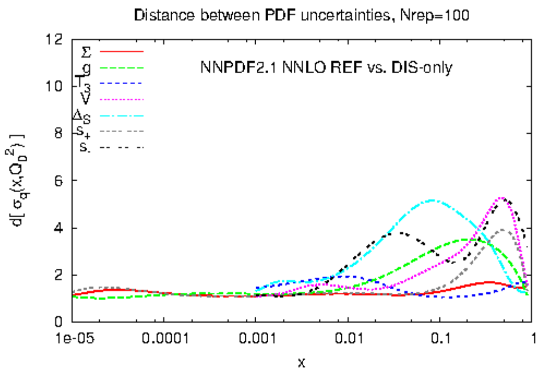
THE IMPACT OF LHC DATA

BEFORE LHC: PDFS MOSTLY DETERMINED BY DIS DATA

NNPDF2.1 VS NNPDF2.1 DIS ONLY

DISTANCES (difference in units of st. dev.)

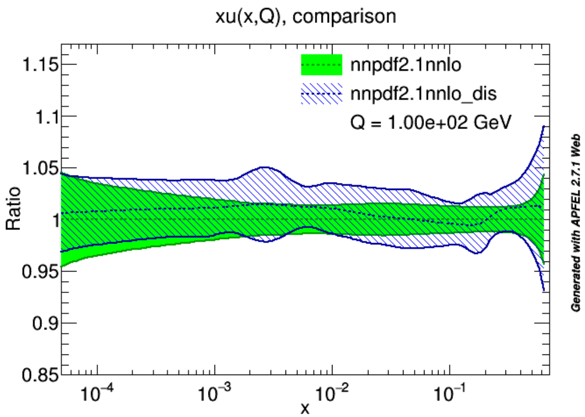




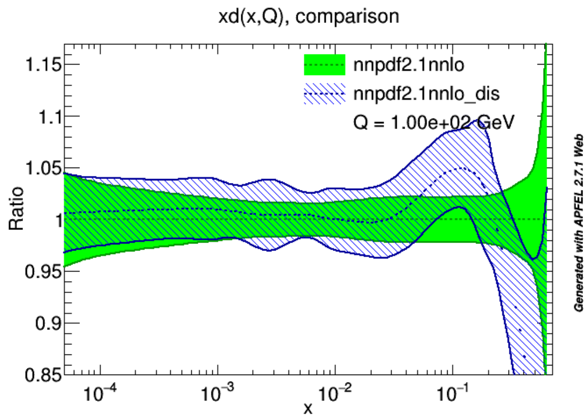
$d = 10 \Leftrightarrow$ one sigma difference

PDF COMPARISON

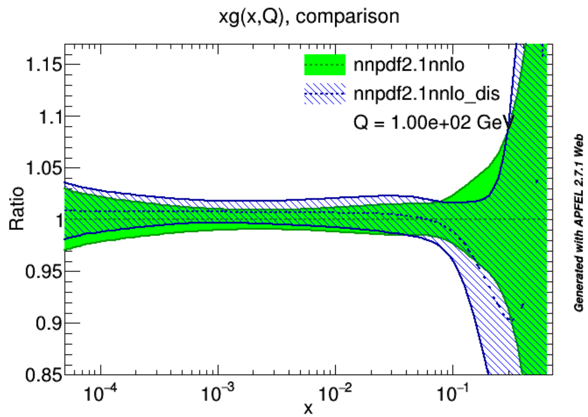
UP



DOWN



GLUON



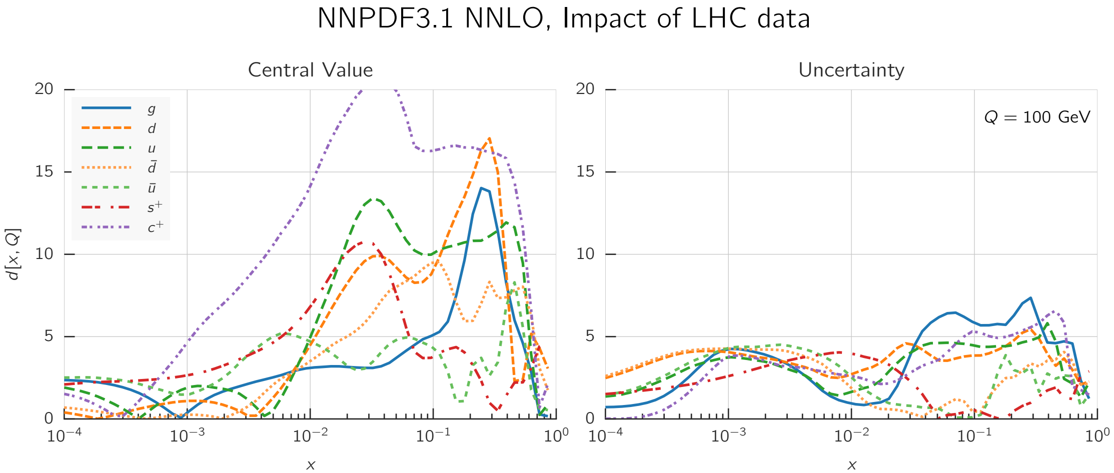
- ALL DIFFERENCES BELOW ONE SIGMA
- ONLY UP-DOWN SEPARATION SIGNIFICANTLY AFFECTED

THE IMPACT OF LHC DATA

NOW: PDFs LARGELY DETERMINED BY LHC DATA

NNPDF3.1 VS NNPDF3.1 NO LHC

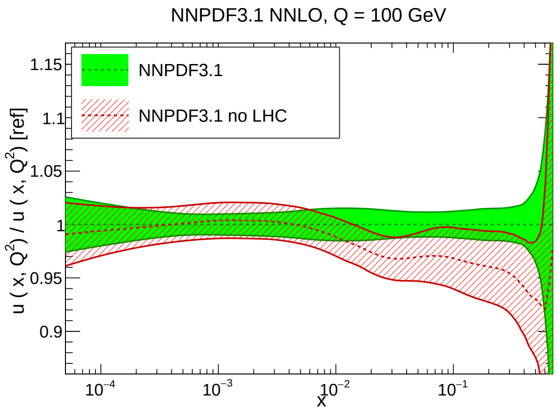
DISTANCES (difference in units of st. dev.)



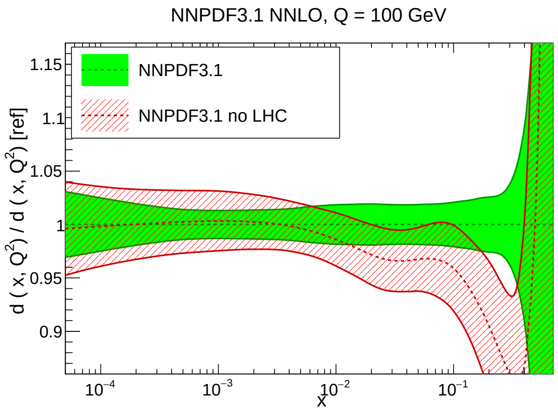
$d = 10 \Leftrightarrow$ one sigma difference

PDF COMPARISON

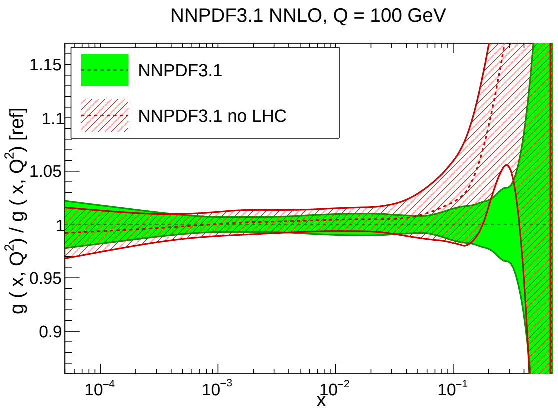
UP



DOWN



GLUON

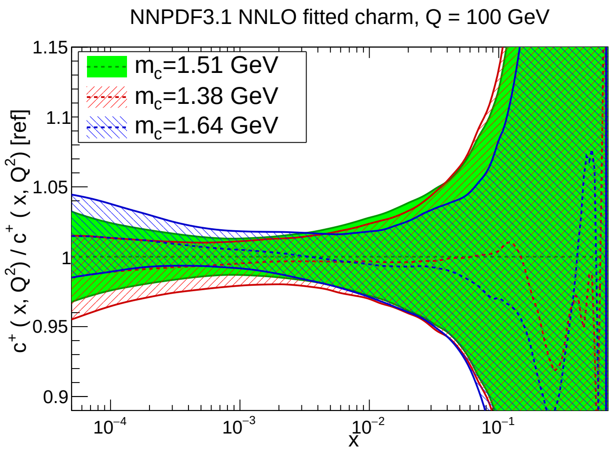


- MANY PDFs CHANGE BY MORE THAN ONE SIGMA
- BOTH FLAVOR SEPARATION & GLUON SIGNIFICANTLY AFFECTED

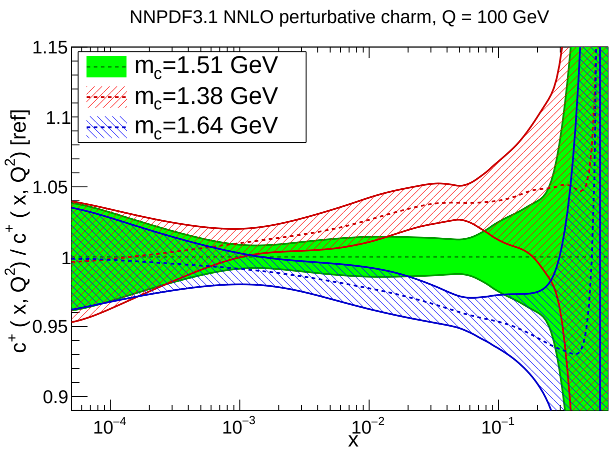
METHODOLOGICAL PROGRESS:
CHARM FROM DATA

- CHARM SHOULD NOT DEPEND STRONGLY CHARM MASS

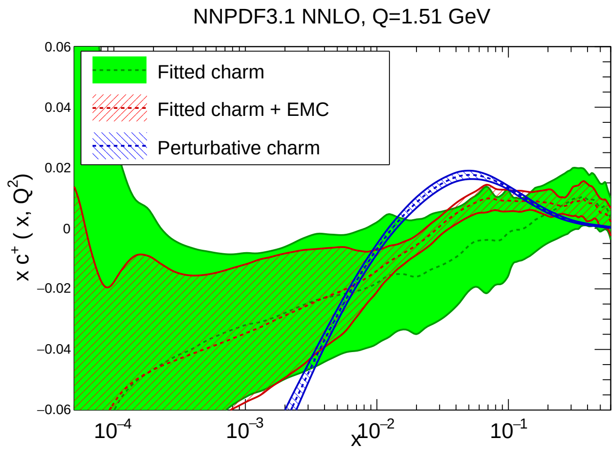
FITTED CHARM VS m_c



PERTURBATIVE CHARM VS m_c



FITTED VS. PERTURBATIVE CHARM



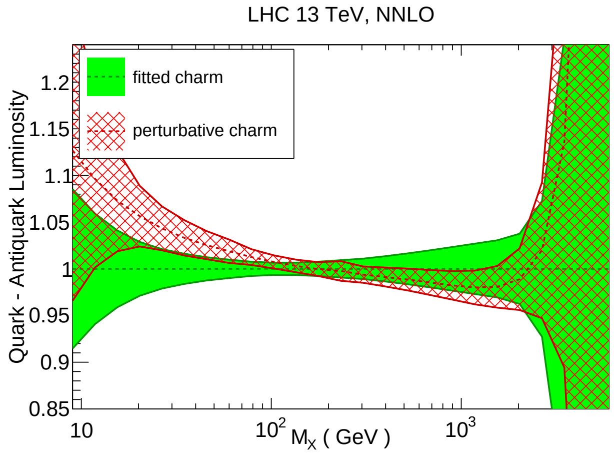
- ITS SHAPE SHOULD NOT BE DETERMINED BY FIRST-ORDER MATCHING (NO HIGHER NONTRIVIAL ORDERS KNOWN)
- MIGHT EVEN HAVE A NONPERTURBATIVE COMPONENT

FITTED VS. LO PERTURBATIVE:
SUPPRESSED AT MEDIUM-SMALL x, ENHANCED AT VERY SMALL, VERY LARGE x

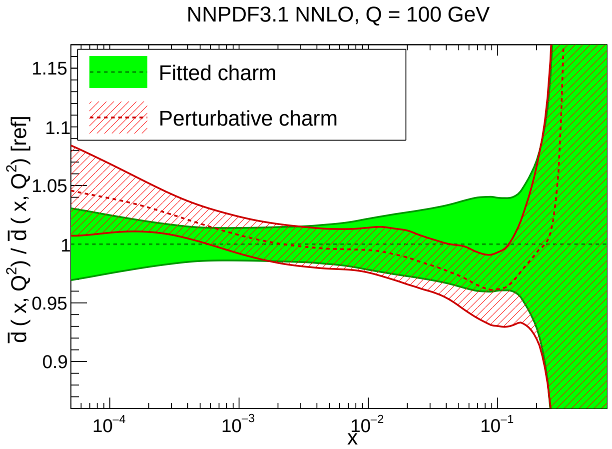
THE CHARM PDF FROM DATA
IMPACT ON LIGHT QUARK PDFS

FITTED VS. PERTURBATIVE CHARM

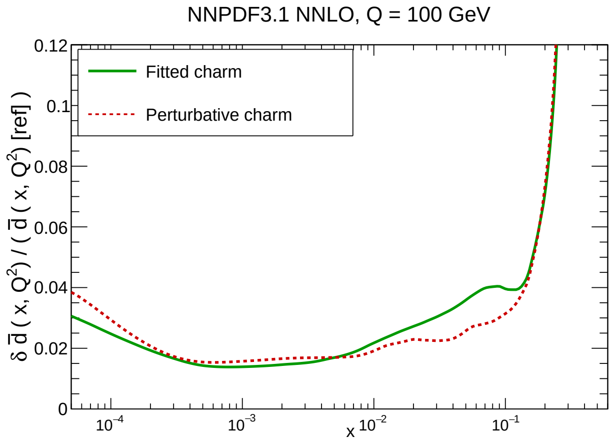
QQBAR LUMI



ANTIDOWN PDF



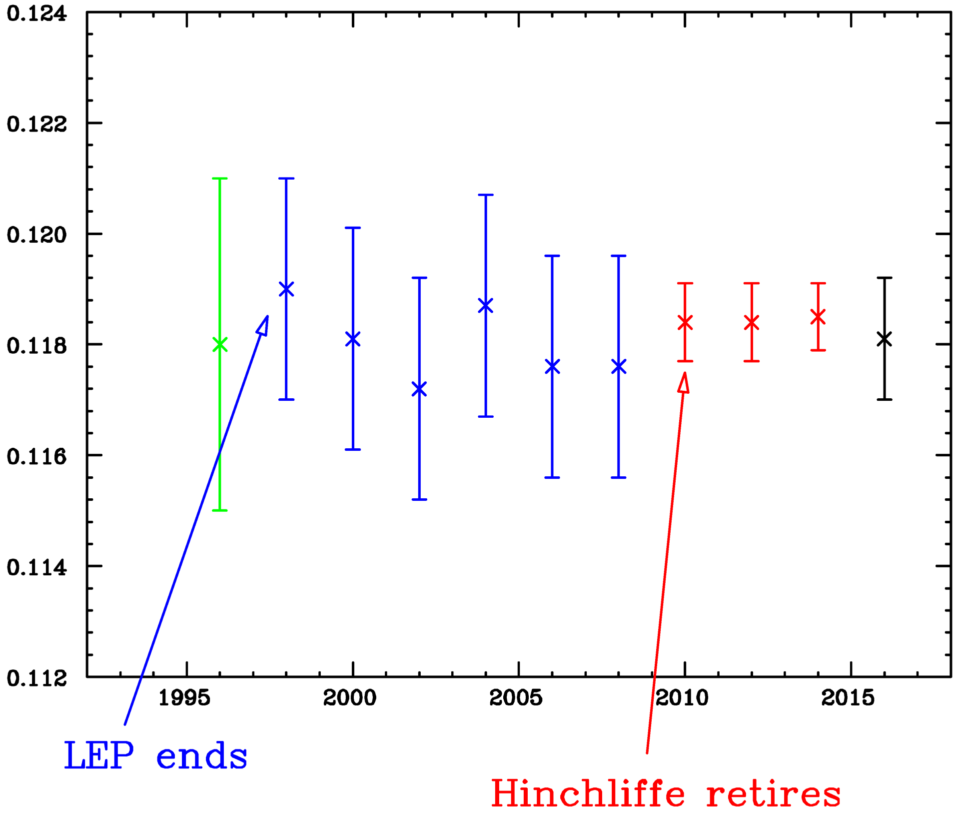
ANTIDOWN PDF UNCERTAINTY



- 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!

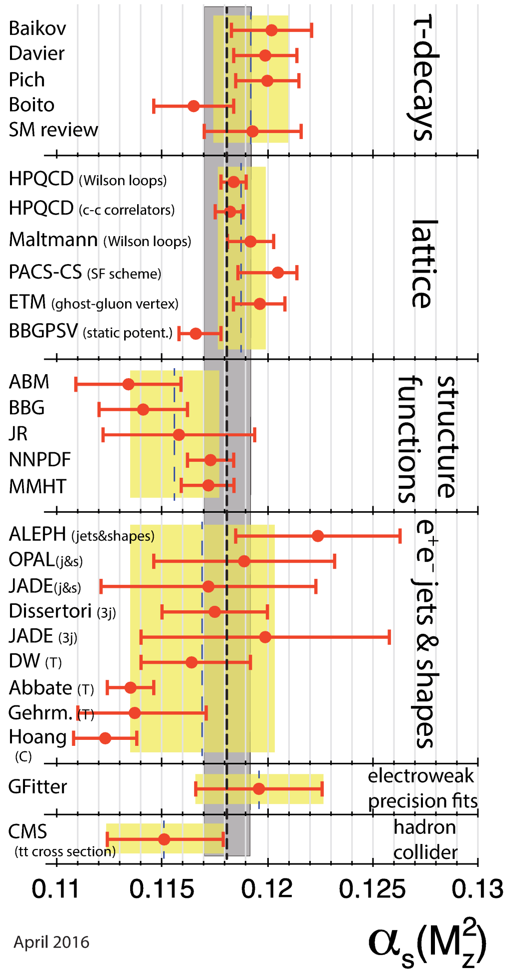
THE PROBLEM OF α_s

THE PDG VALUE (VS.TIME)



WHERE DOES THE PDF AVERAGE COME FROM?

PDG PRE-AVERAGES

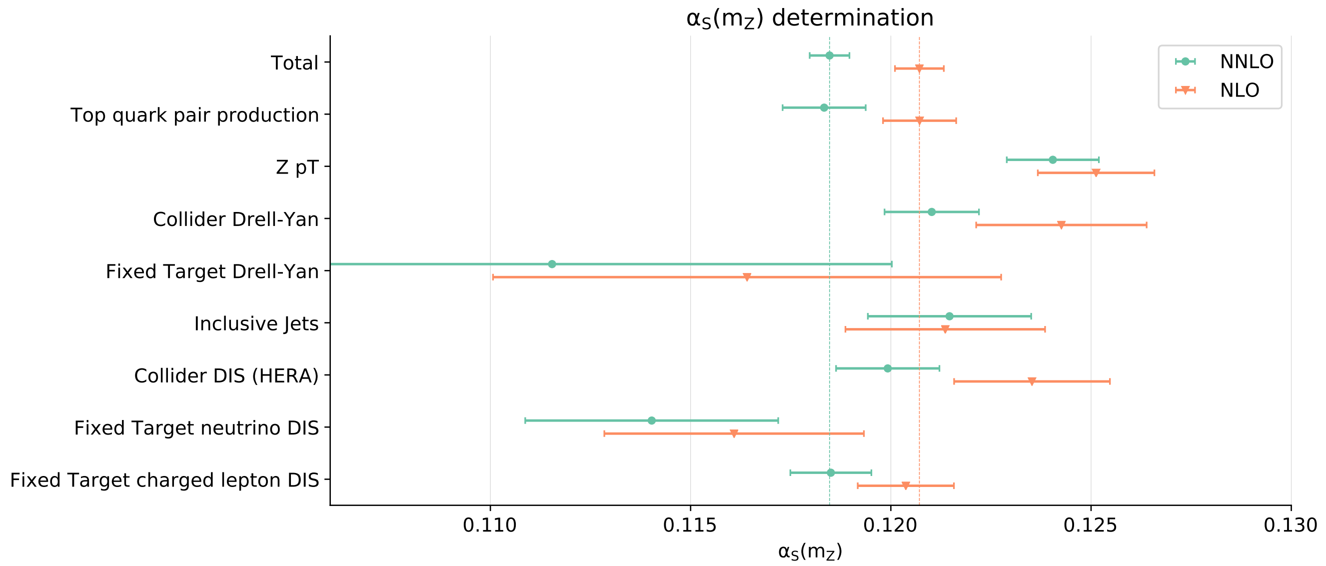


- PDG AVERAGE: χ^2-AVERAGING OF SIX PRE-AVERAGES, CHOSEN TO BE MAXIMALLY UNCORRELATED
- χ^2 AVERAGING $\Rightarrow$ UNCERTAINTIES INFLATED OR CORRELATED UNTIL $\chi^2/dof = 1$
- EACH PRE-AVERAGE IS THE SIMPLE (UNWEIGHTED) AVERAGE OF ITS COMPONENTS, UNCERTAINTY $\leftrightarrow$ AVERAGE OF UNCERTAINTIES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

DATASET PULLS ON GLOBAL α_s DETERMINATION



(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

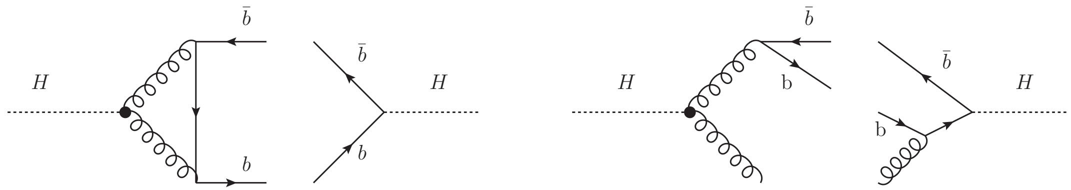
PROGRESS...

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

SUBTLETIES: AN EXAMPLE

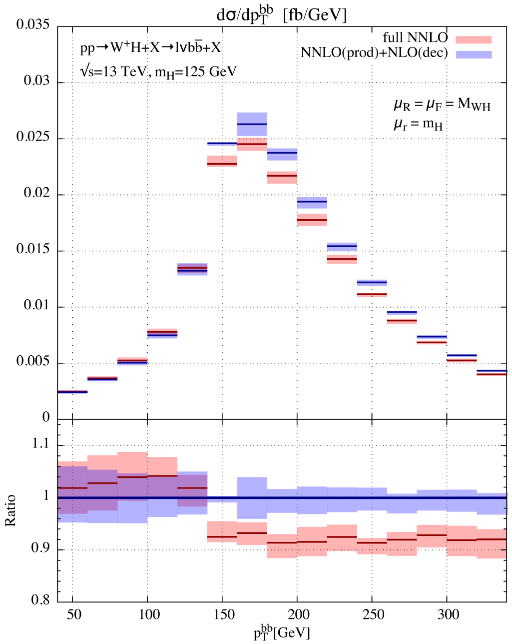
ASSOCIATE WH WITH $H \to b\bar{b}$ DECAY

- TWO COMPUTATIONS AVAILABLE
- LARGE DECAY CORRECTIONS WITH CUTS



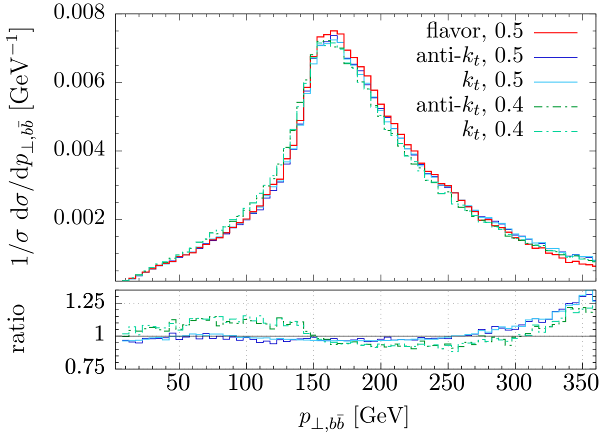
- INTERFERENCE (NOT INCLUDED)
- PARTON SHOWER
- JET DEFINITION

IMPACT OF NNLO DECAY

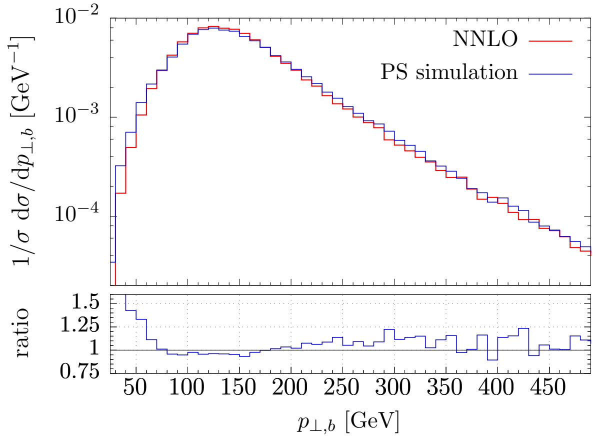


(Ferrera, Somogyi, Tramontano, 2017)

IMPACT OF PS



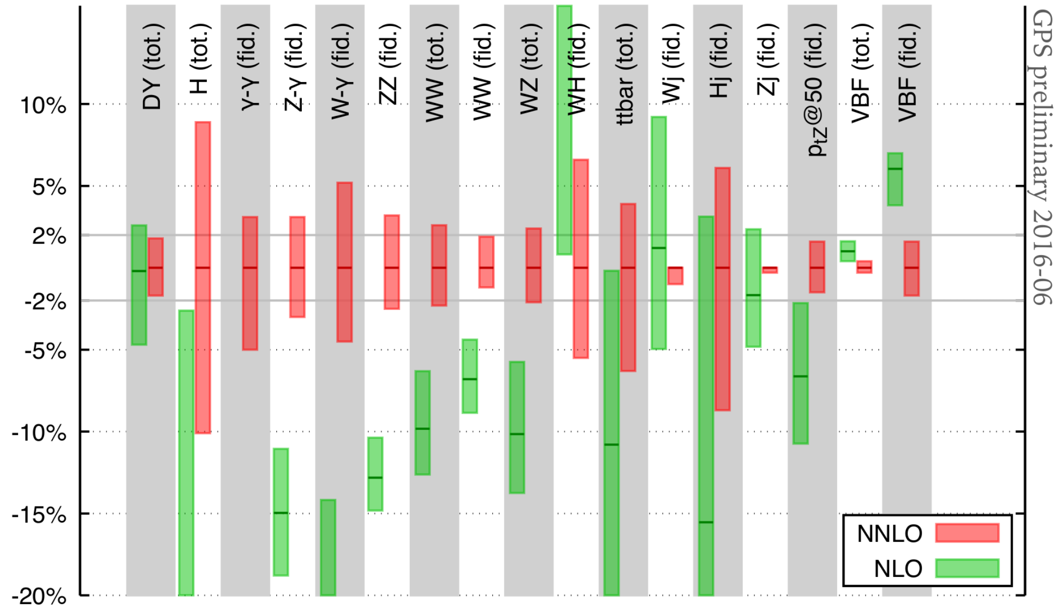
IMPACT OF JET DEF.



(Caola, Luisoni, Melnikov, Röntsch, 2018)

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 ⇒ PARTIAL INFO ON MHO
- CONSERVATIVE ESTIMATE ⇒ 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 N^{3}LO ± 0.18 pb (0.4%)~~
  - N^{4}LO & 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 N^{3}LO: ± 0.7 pb (1.5%)~~
- MISSING N^{3}LO 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)~~ N^{3}LO+N^{3}LL QCD (EFT); NLO ~~PURE~~ EW; NLO EXACT HQ;
NNLO APPROX TOP; NNLO PDFs

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

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

SUBSTANTIAL PROGRESS ON

- N^3LO
- 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