PERTURBATIVE QCD

AT THE LHC

STEFANO FORTE
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INFN Istituto Nazionale di Fisica Nucleare

LHCP 2015 — ST. PETERSBURG, SEPT. 4, 2015

QCD
IN THE HIGGS ERA

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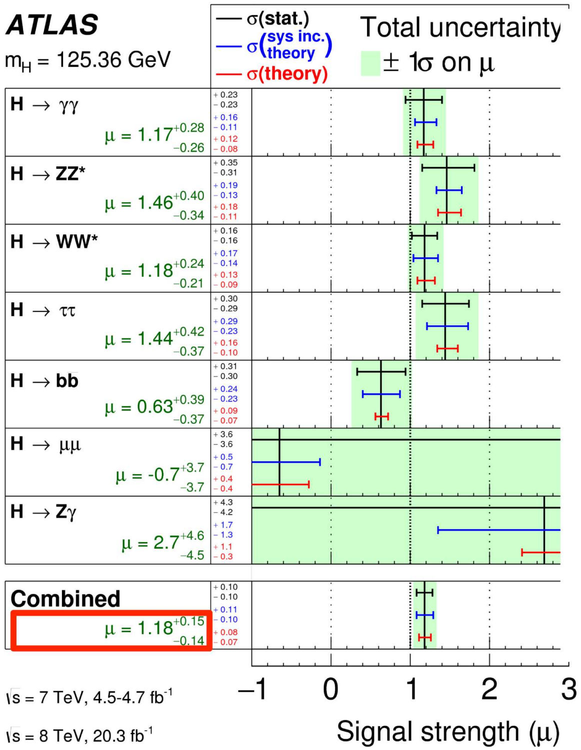
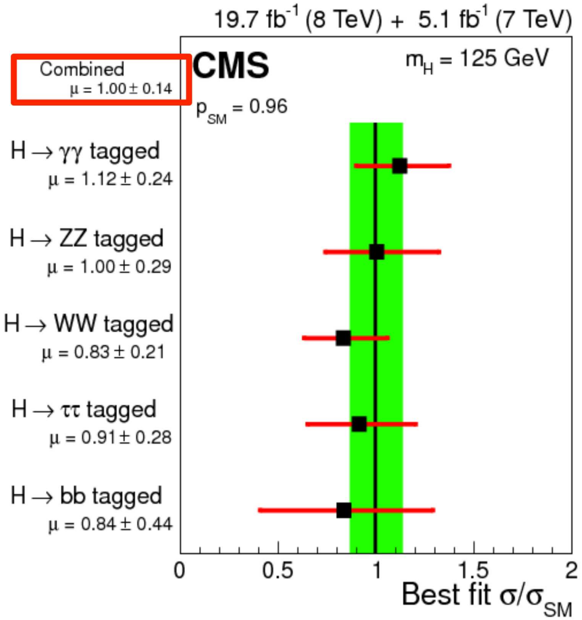
THE CHALLENGE

Higgs signal strength

Signal Strength for Decay Modes

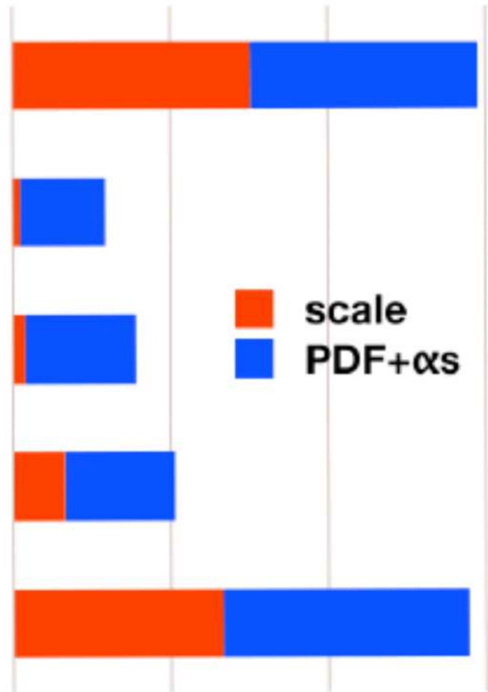




ATLAS: individual μ values from combination of channels
CMS: individual μ values from tagged analyses

THE BOTTLENECK

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



(J. Campbell, HCP2012)

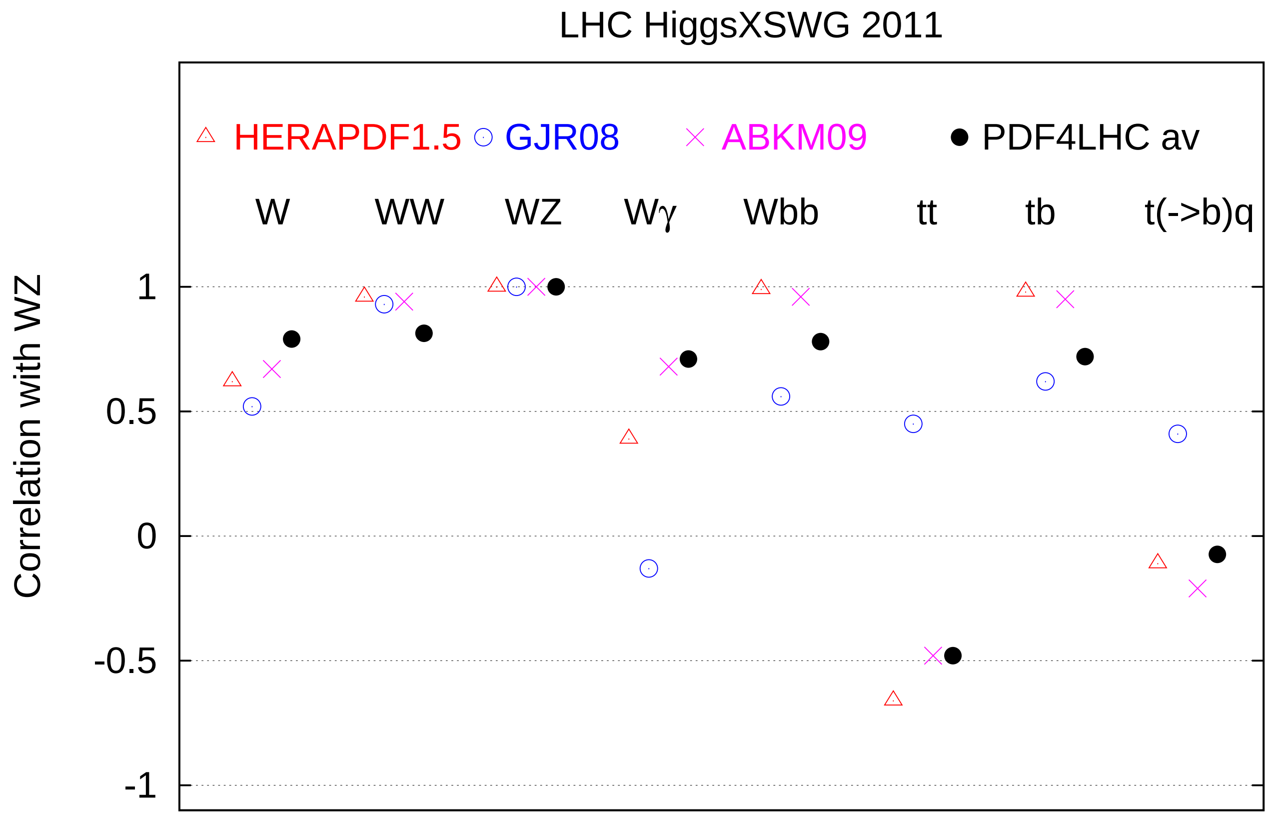
- QCD, PERTURBATIVE & NONPERTURBATIVE, IS THE DOMINANT SOURCE OF UNCERTAINTY
- MANY UNCERTAINTIES IMPROVING (OR ABOUT TO IMPROVE)

INTERLOCKED KNOWLEDGE

- QCD TALKS TO THE REST OF THE SM!
- CORRELATED UNCERTAINTIES BETWEEN SM PROCESSES

CORRELN. OF PDF UNCERTAINTIES

HIGGS BACKGROUND PROCESSES



(Higgs XSWG YR2, 2012)

AN EXAMPLE
GAUGE BOSON PAIR PAIR PRODUCTION

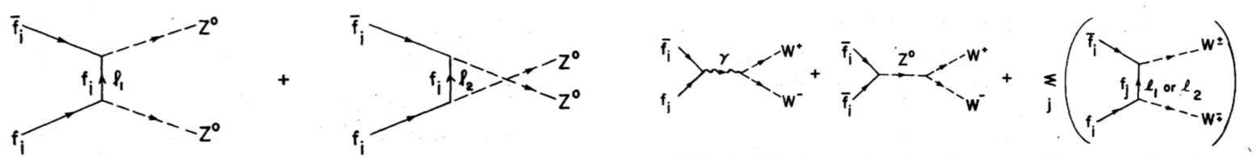

19 W^+W^- AND Z^0Z^0 PAIR PRODUCTION IN e^+e^-, $\bar{p}p$, AND... 925

FIG. 3. The lowest-order Feynman diagrams for $f_i + \bar{f}_i \to Z^0 + Z^0$.

FIG. 4. The lowest-order Feynman diagrams for $f_i + \bar{f}_i \to W^+ + W^-$.

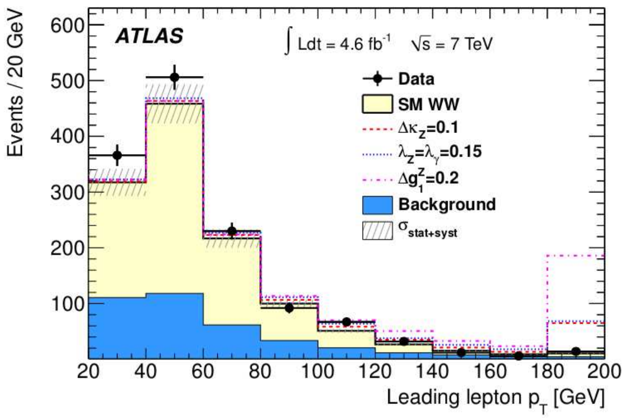
Brown & Mikaelian, 1979

- SENSITIVE TO TRIPLE-GAUGE COUPLINGS & UNITARITY VIOLATION
- IMPORTANT BACKGROUND TO HIGGS PRODUCTION
- CAN BE USED TO BOUND THE HIGGS WIDTH FROM INTERFEROMETRY/OFF-SHELL MEASUREMENTS
- W^+W^- HAS LARGEST RATE, MORE CHALLENGING FINAL STATE
- NLO QCD CORRECTIONS LONG KNOWN
- NLO ELECTROWEAK CORRECTIONS DETERMINED
- VERY RECENT PROGRESS ON HIGHER ORDER CORRECTIONS & RESUMMATION

W PAIR PRODUCTION

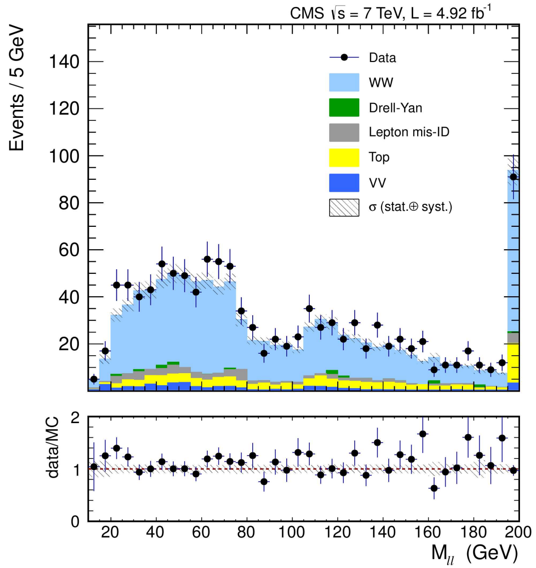
THE DATA

LEADING LEPTON p_T



ATLAS 2013

INVARIANT MASS DISNT.



CMS 2013

- TOTAL CROSS-SECTION MEASURED BY ATLAS & CMS
- SLIGHT EXCESS OVER SM:

51.9 ± 2.0STAT. ± 3.9SYST. ± 2.0LUM. (ATLAS)

52.4 ± 2.0STAT. ± 4.5SYST. ± 2.0LUM. (CMS)

VS. 47.0 ± 2.0MC ± 4.5SCALE ± 3.0PDF PB (CAMPBELL, ELLIS, WILLIAMS, 2012)

PDFs

W PAIR PRODUCTION
PDF UNCERTAINTIES

- UNCERTAINTY ON THE TH PREDICTION QUOTED BY ATLAS IS OBTAINED USING MSTW08
- PDF UNCERTAINTY USED IN THE ANALYSIS FROM MSTW08, WITH MSTW08-CT10 DIFFERENCE ADDED

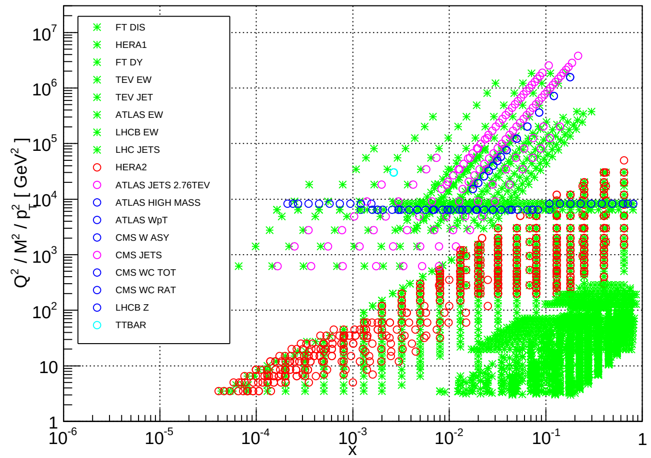
PDF PROGRESS:

MORE FEATURES

	NNPDF3.0	MMHT14	CT14
No. of fitted PDFs	7	7	6
Parametrization	neural nets	$x^a(1-x)^b$ $\times$ Chebyschev	$x^a(1-x)^b$ $\times$ Bernstein
Free parameters	259	37	30-35
Uncertainties	Replicas	Hessian	Hessian
Tolerance	None	Dynamical	Dynamical
Closure test	✔	✗	✗
Reweighting	replicas	eigenvectors	eigenvectors

MORE DATA

NNPDF3.0 NLO dataset

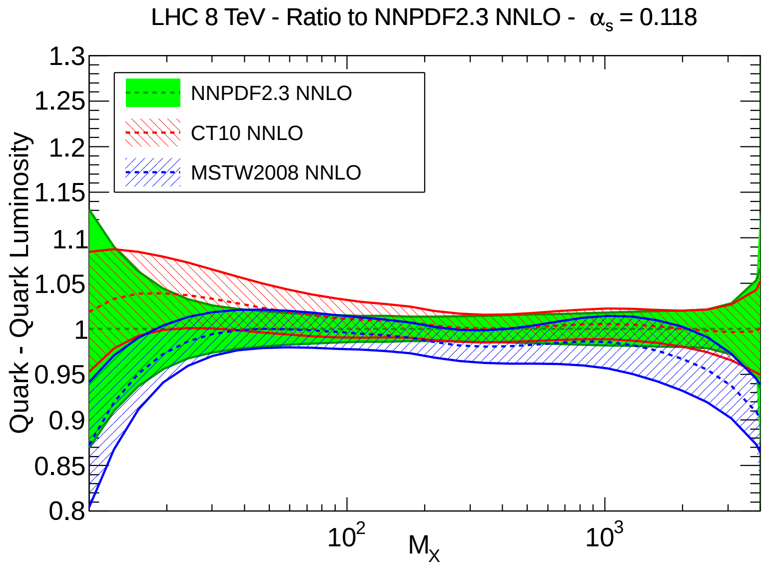


PDFs: RECENT PROGRESS

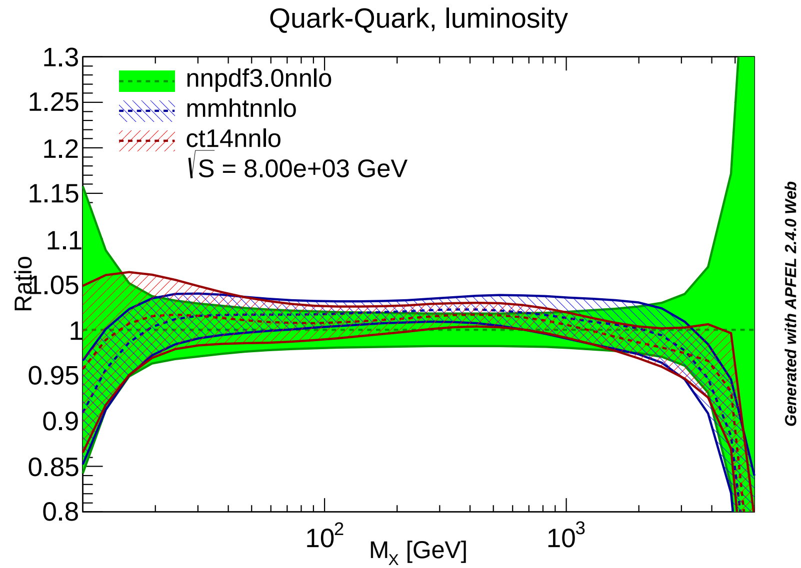
PARTON LUMINOSITIES

QUARK-QUARK

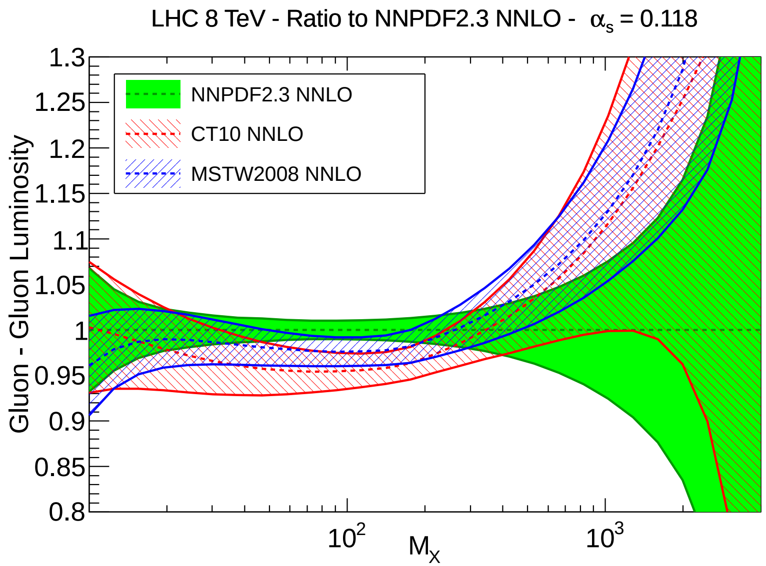
2012

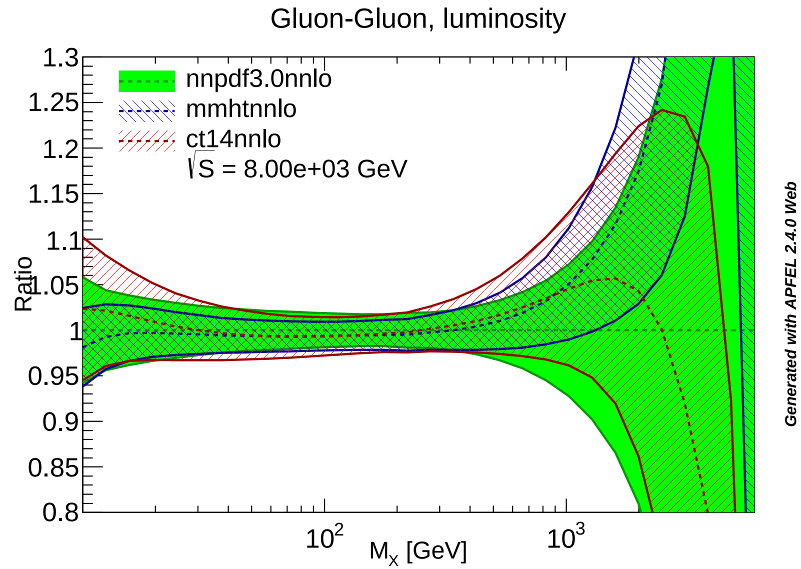


2015



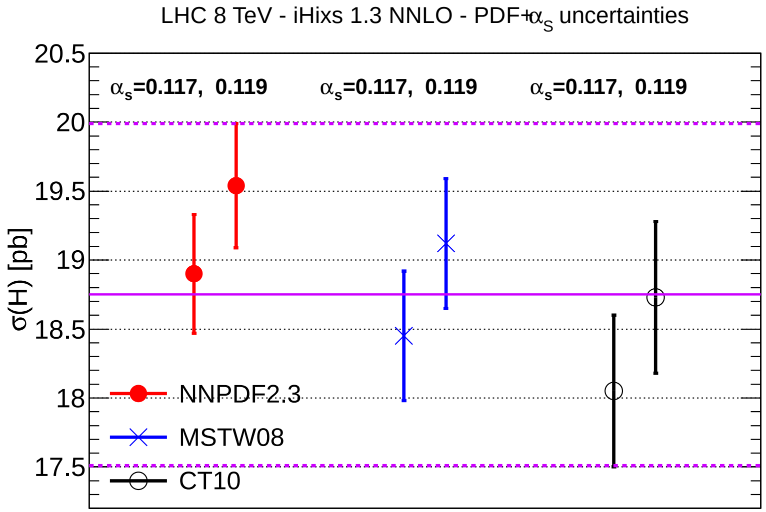
GLUON-GLUON



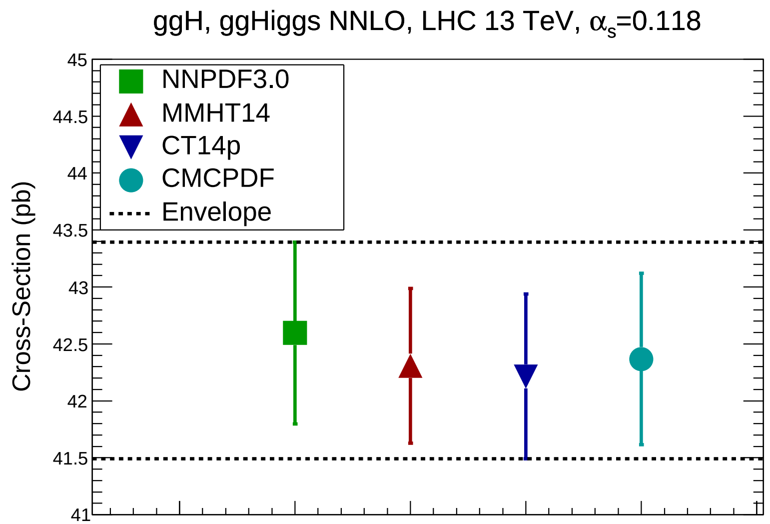


PDFs: RECENT PROGRESS
HIGGS IN GLUON FUSION

2012



2015

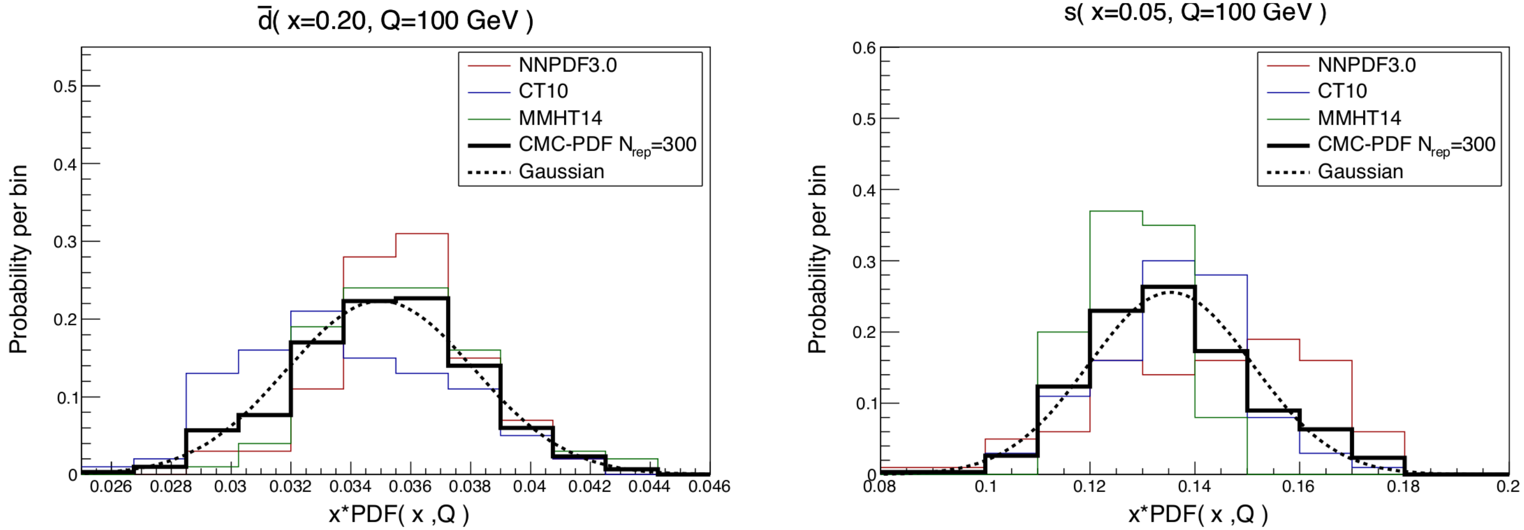


- PDF4LHC prescription 2012: envelope, PDF uncertainty $\sim 6\%$
- PDF4LHC prescription 2015: statistical combination, PDF uncertainty $\sim 2\%$

THE NEW PDF4LHC PRESCRIPTION

- CONVERT ALL SETS INTO MONTE CARLO
- HESSIAN SETS CAN BE CONVERTED BY PERFORMING MONTE CARLO IN PARAMETER SPACE (Watt, Thorne, 2012)
- COMBINE MONTE CARLO REPLICAS INTO SINGLE SET

COMBINED MC SETS FOR ANTIDOWN & STRANGE



- COMBINED SET CONVERTED INTO MANAGEABLE FORMATS:
  - COMPRESSED MONTE CARLO: MC100

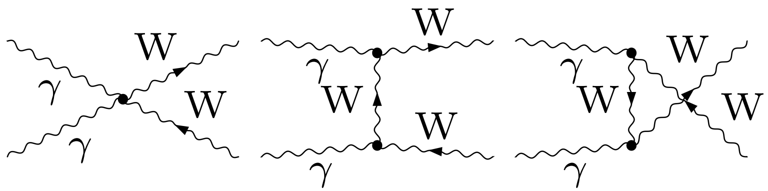
(Carrazza, Latorre, Rojo, Watt, 2015)

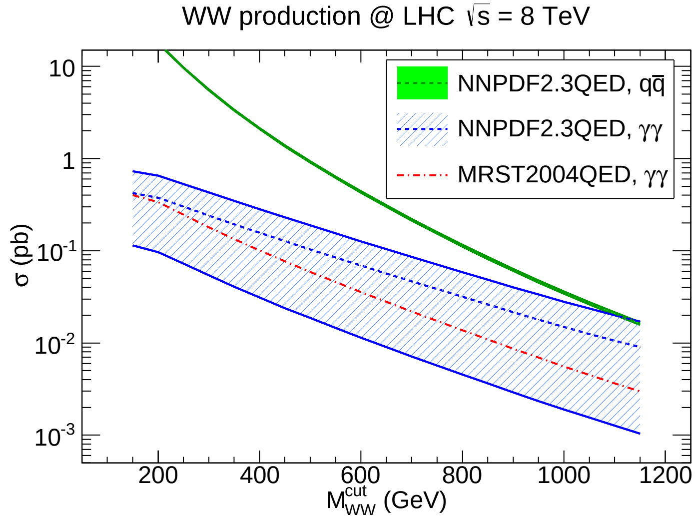
  - ULTRAFAST OR ULTRAPRECISE HESSIAN: H30 & H100

(Gao, Nadolsky, 2014; Carrazza, SF, Kassabov, Latorre, Rojo, 2015)

PDF EXOTICA

QED PDFs

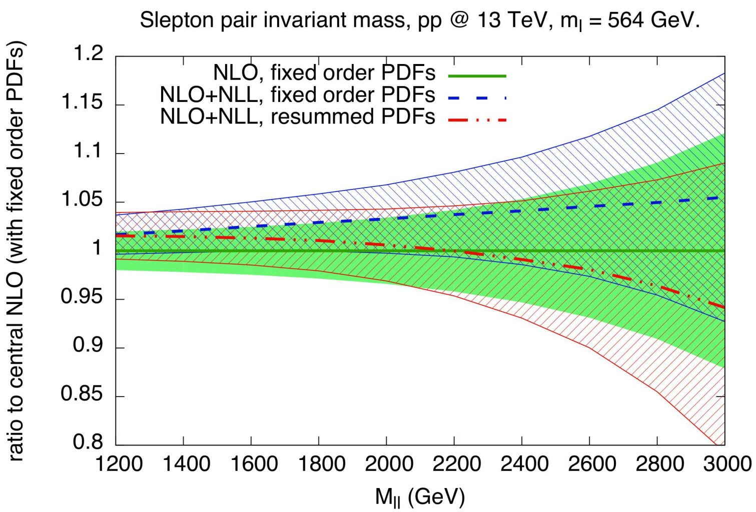




- PHOTON COUPLES DIRECTLY TO W
- PHOTON-INDUCED W PAIR PRODUCTION COMPARABLE TO QUARK-INDUCED FOR LARGE INVARIANT MASS

NNPDF2.3QED, Carrazza et al. 2013

RESUMMED PDFs

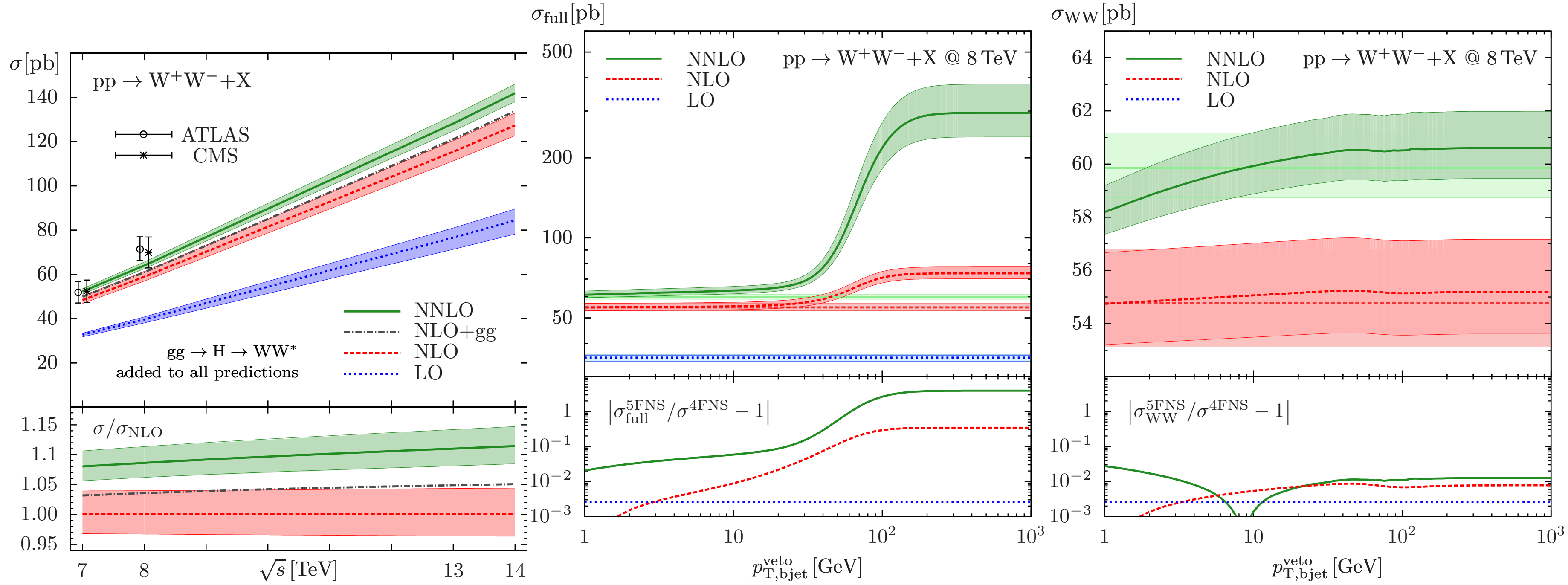


- THRESHOLD RESUMMATION AFFECTS LARGE x PDFs $\Rightarrow$ HEAVY FINAL STATES
- CORRECTION COMPARABLE IN SIZE TO THAT ON MATRIX ELEMENT
- COMPENSATION BETWEEN CORRN TO PDF & ME

Bonvini, Marzani, Rojo, Rottoli, Ubiali et al., 2015

NNLO & HEAVY QUARKS

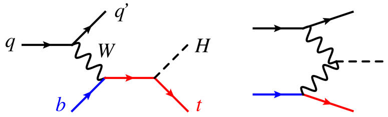
W PAIR PRODUCTION
NNLO QCD CORRECTIONS

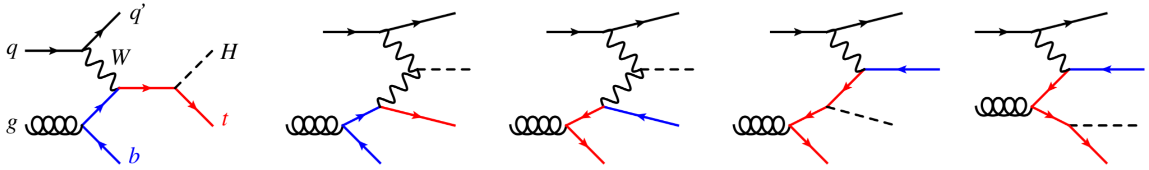


(Gehrmann, Grazzini, Kallweit, Maierhöfer, von Mantteuffel, Pozzorini, Rathlev, Tancredi, 2014)

- NLO QCD, NNLO GLUON CHANNEL, NLO EW CORRNS KNOWN, NNLO COMPUTED RECENTLY: $\sim 10\%$ ENHANCEMENT W.R. TO NLO, UNDERESTIMATED BY SCALE VARIATION (NEW PARTONIC SUBCHANNELS)
- 5-FLAVOR VS 4 FLAVOR SCHEME: IN 5FS, HUGE RESONANT $pp \to Wt \to WWb$
- CANNOT JUST REJECT B WITH $p_T^b < p_{T,\,veto}^b \Rightarrow \ln p_T/m_b$ DEPENDENCE, AMBIGUITY
- SUBTRACT RESONANT USING DEPENDENCE ON WIDTH Γ_t

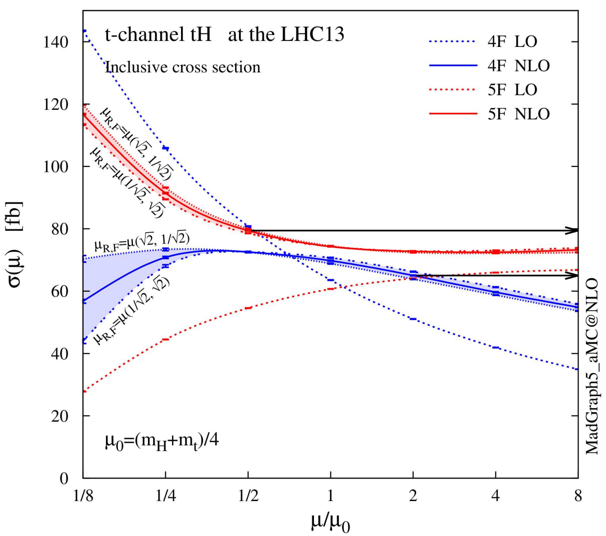
5FS vs 4FS
Higgs+single top

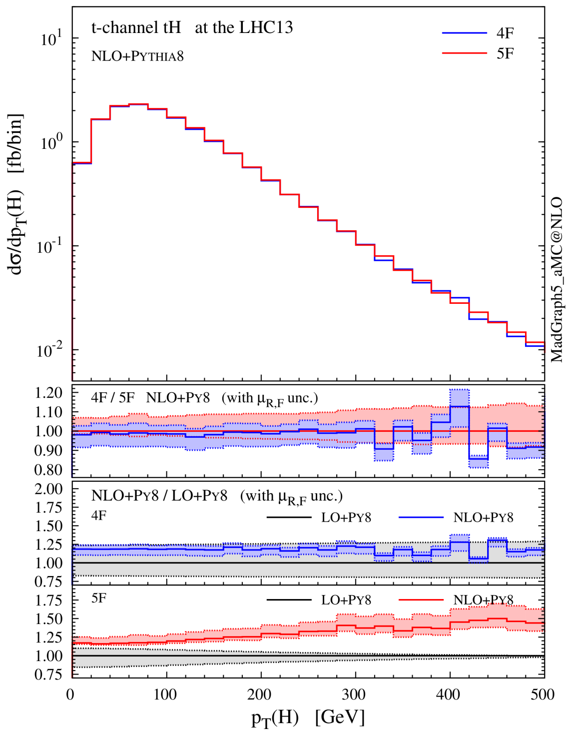
5F: 

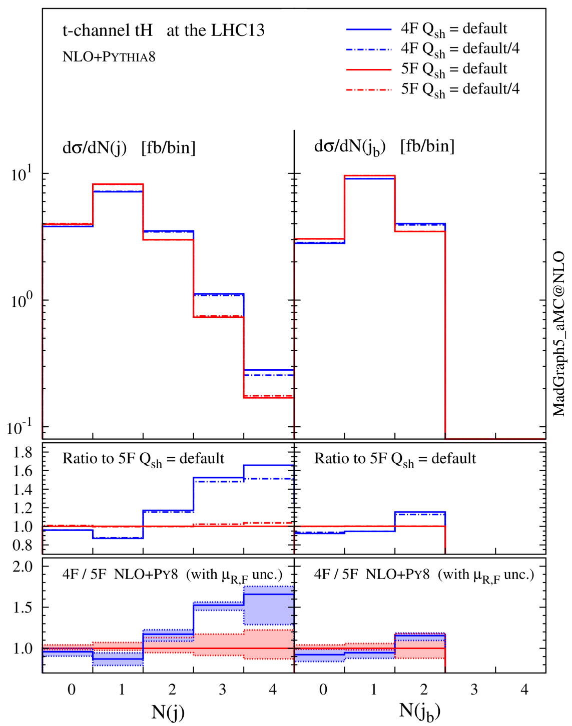
; 4F: 

(Demartin, Maltoni, Mawatari, Zaro, 2014)

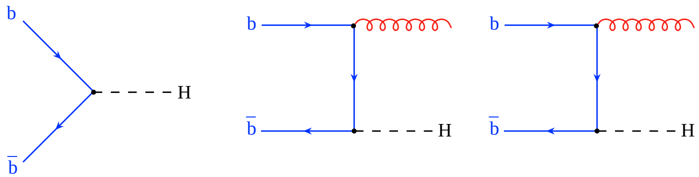
- 5FS easier at higher orders, but 4FS more realistic final state
- good agreement for inclusive observables already at NLO
- agreement for single distributions, 5FS more accurate for multiparticle FS

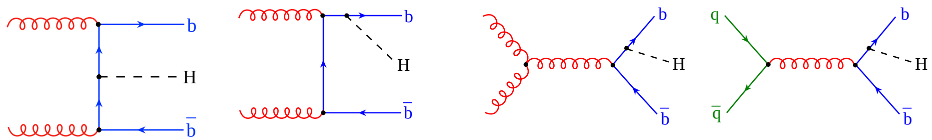




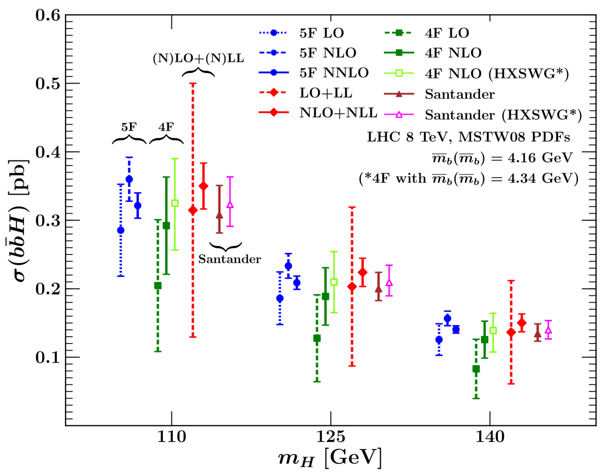


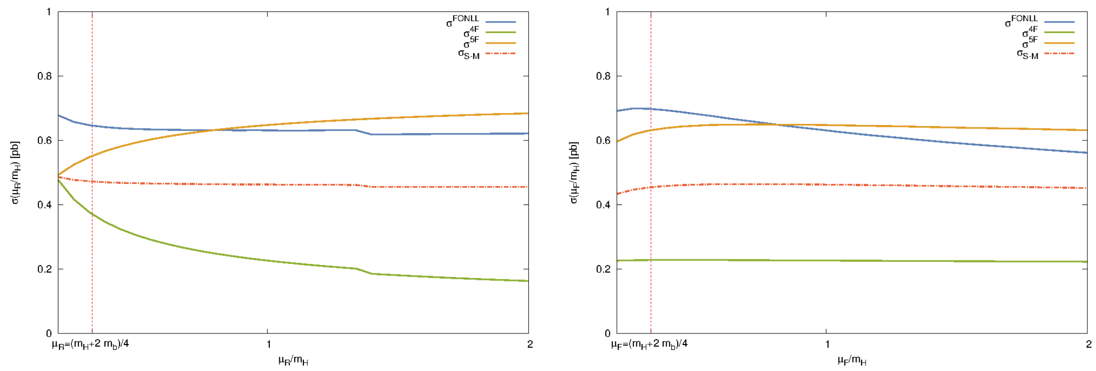
5FS vs 4FS
$b\bar{b}$ Higgs

5F: 

; 4F: 

- Large differences between 4FS & 5FS, alleviated by low scale choice & higher order in the 4FS computation
- Matched result available in FONLL (4FS LO+ 5FS NNLL) & SCET (4FS NLO+ 5FS NLL) approach: differ by subleading terms, FONLL allows for any combination of orders
- FONLL shows that pure mass corrections to massless NNLL $\sim 10\%$, but affected by large scale dependence
- naive 'Santander' matching not very reliable



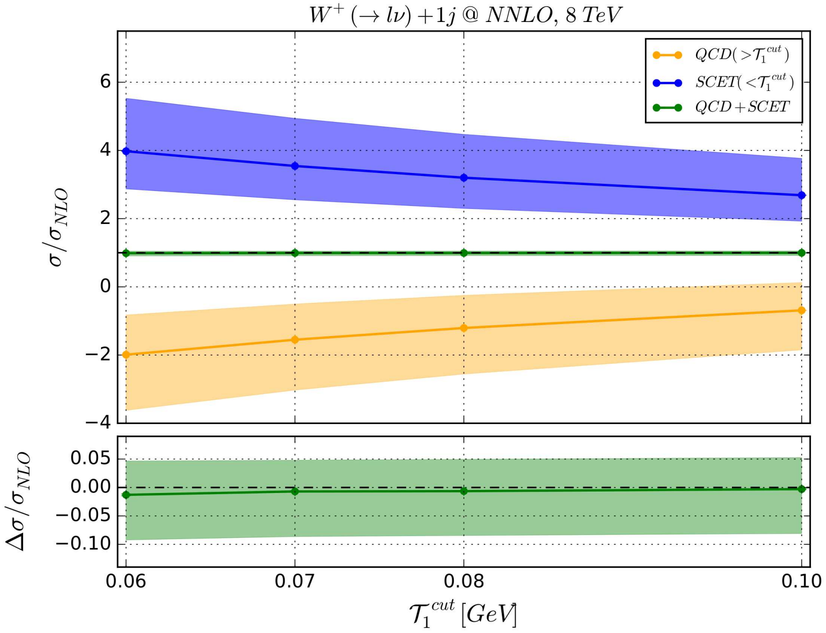


(Bonvini, Papanastasiou, Tackmann, 2015); (SF, Napoletano, Ubiali, 2015)

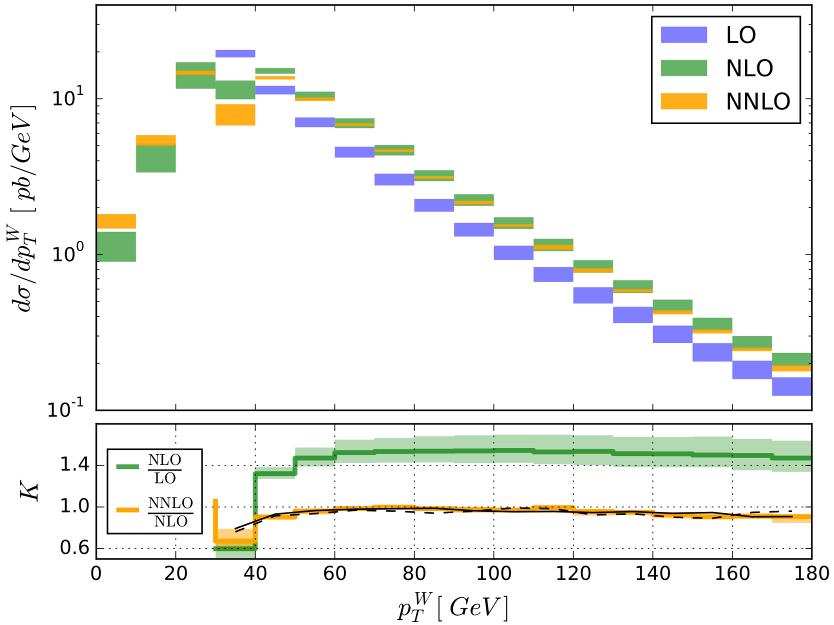
NNLO PROGRESS
W+JET; W p_T: JETTINESS SUBTRACTION

- CATANI-GRAZZINI-LIKE SUBTRACTION FOR COLORED FINAL STATES
- CANCEL INFRARED DIVERGENCE USING UNIVERSAL BEHAVIOUR OF RESUMMED RESULT:
  N-JETTINESS $\mathcal{T}_N$ AS RESUMMED OBSERVABLE
  - FOR $\mathcal{T}_N > \mathcal{T}_N^{\rm cut}$, NNLO=NLO+ONE JET
  - FOR $\mathcal{T}_N < \mathcal{T}_N^{\rm cut}$ EXPAND OUT RESUMMED RESULT

CUT DEPENDENCE CANCELLATION



W p_T DISTN.



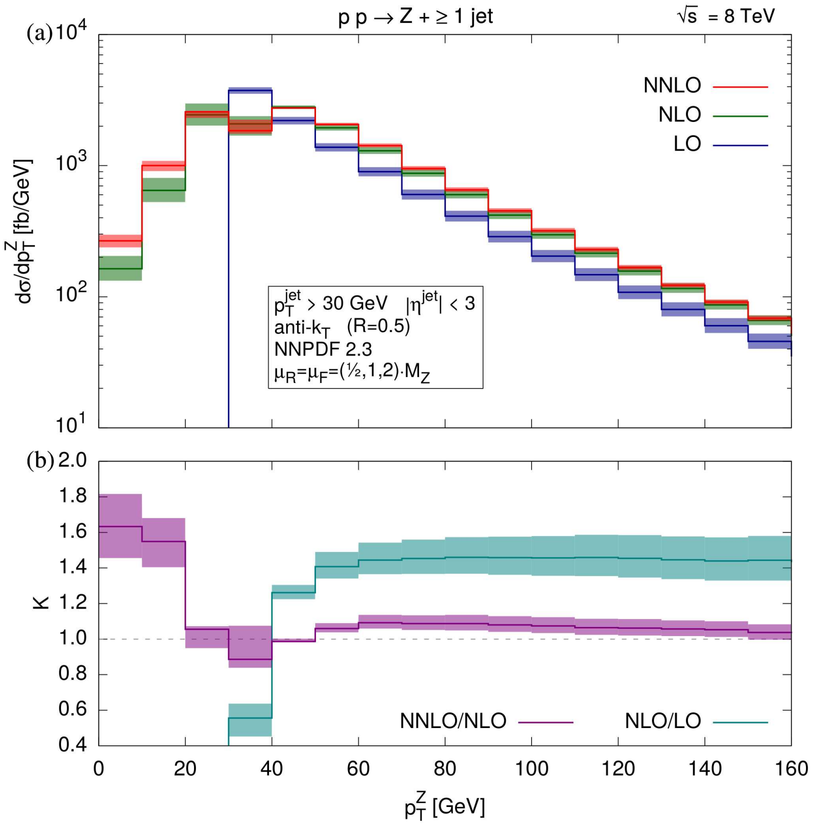
(Boughezal, Focke, Giele, Liu, Petriello, 2015)

- NNLO CORRECTIONS TO W p_T COMPUTED: MODERATE
- METHOD ALSO APPLIED TO HIGGS+JET: ALL-CHANNEL NNLO

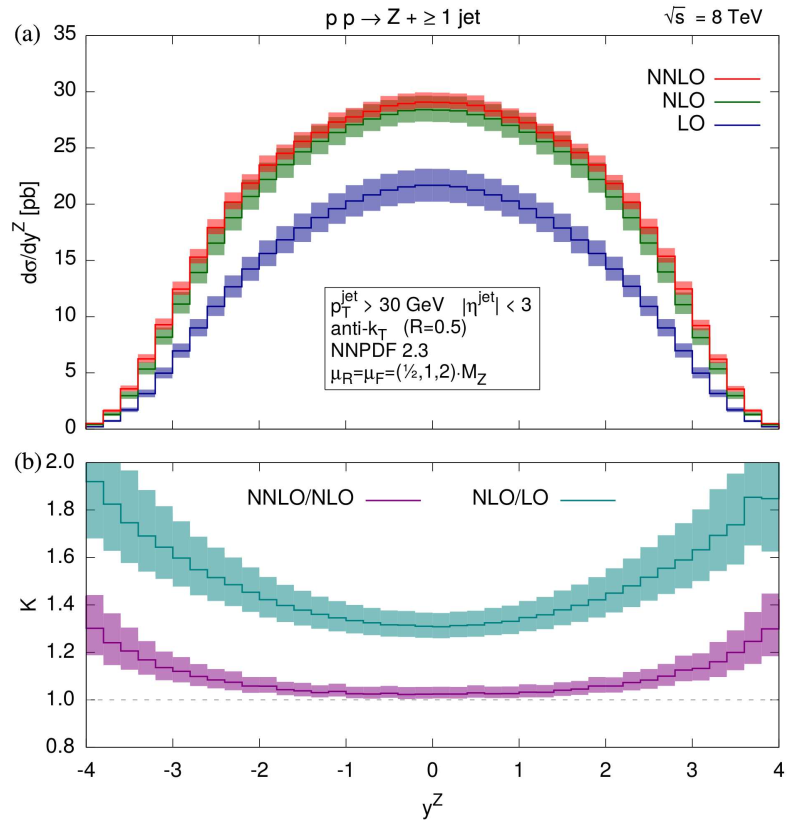
NNLO PROGRESS
Z+JET

- IMPORTANT FOR PDF DETERMINATION: SIZE OF THE GLUON
- COMPUTED USING ANTENNA SUBTRACTION ⇒ DIFFERENTIAL DISTRIBUTIONS

Z p_T DISTN.



Z RAP. DISTN.



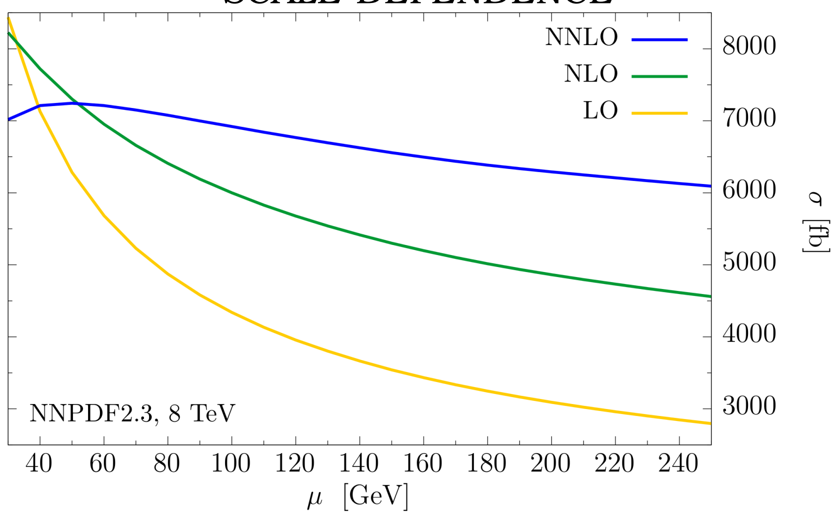
(Gehrmann-de Ridder, Gehrmann, Glover, Huss, Morgan, 2015)

- MODERATE NNLO CORRECTIONS
- CORRECTIONS IN DIFFERENTIAL DISTRIBUTIONS NON UNIFORM ⇒ CANNOT JUST GIVE K-FACTOR

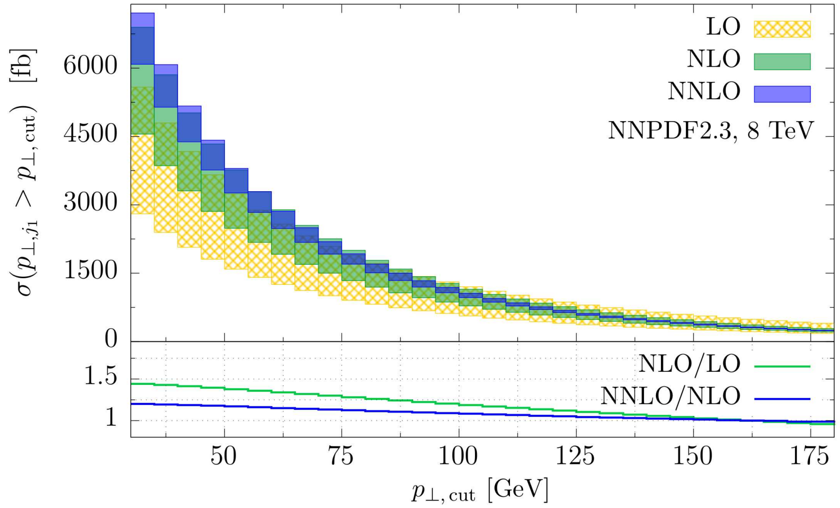
NNLO PROGRESS
HIGGS+JET: FULL COMPUTATION

- FULLY DIFFERENTIAL, ALL-CHANNEL ANALYTIC RESULT
- MAIN DIFFICULTY:
  - DIFFERENT MULTIPLICITIES CANNOT BE COMBINED ⇒ PHASE-SPACES DIFFERENT
  - FULLY ANALYTIC ⇒ NO INTEGRATION OVER HIGHER MULTIPLICITIES
- SOLUTION: SECTOR IMPROVED RESIDUE SUBTRACTION FOR PHASE-SPACE PARAMETRIZATION (Czakon 2010; Boughezal, Melnikov, Petriello 2012)

SCALE DEPENDENCE



DEPENDENCE ON JET p_T CUT



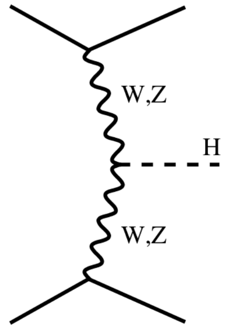
(Boughezal, Caola, Melnikov, Petriello, Schulze, 2015)

- SIZABLE NNLO CORRECTIONS
- SIZE OF CORRNS DEPENDS STRONGLY ON MINIMUM p_T OF THE JET
- FIDUCIAL RESULTS (INCLUDING HIGGS DECAY) NOW AVAILABLE (Caola, Melnikov, Schulze, 2015)

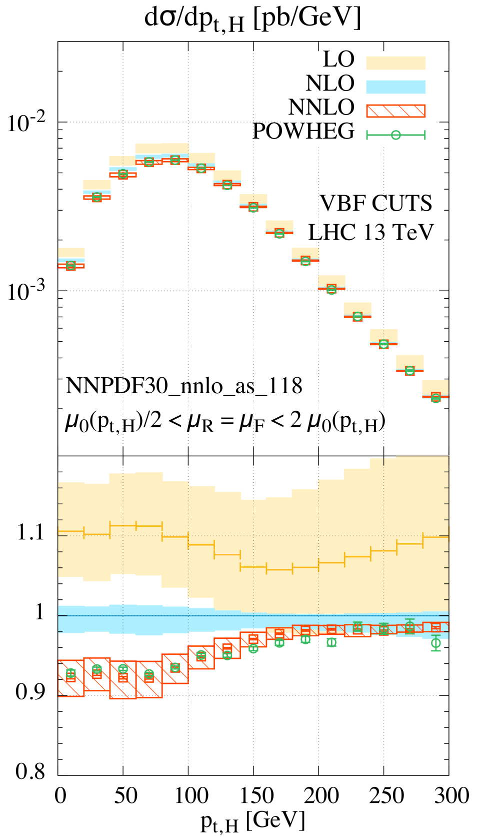
NNLO PROGRESS

FULLY DIFFERENTIAL HIGGS IN W FUSION

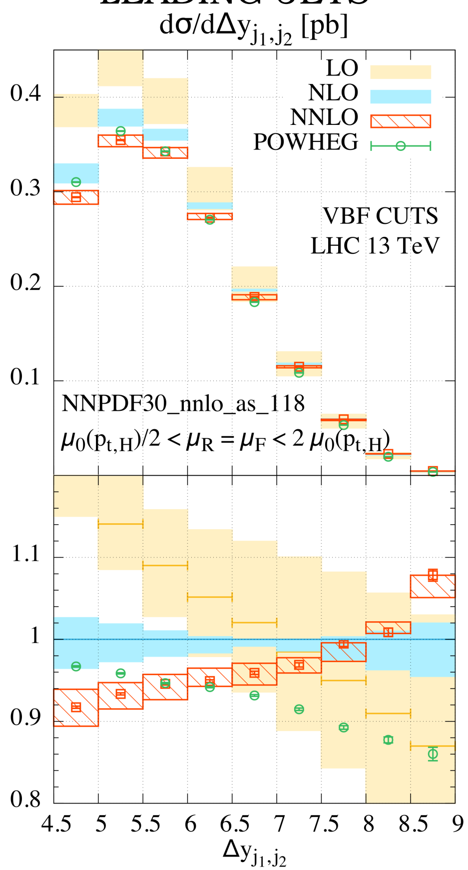
(Cacciari, Dreyer, Karlberg, Salam, Zanderighi, 2015)



HIGGS p_T DISTRIBUTION



RAPIDITY SEP. LEADING JETS



- STRUCTURE FUNCTION APPROX: SQUARE OF DIS
- NNLO DIS KNOWN AT INCLUSIVE LEVEL: DIFFERENTIAL INFO LOST
- PROJECTION TO BORN:
  - INCLUSIVE 2 LOOP HAS BORN KINEMATICS!
  - DOUBLE REAL & PROJECTED ONE-LOOP SINGLE REAL IN BORN KINEMATICS
  - EXCLUSIVE PART FROM VBF H+3J AT NLO (Figy, Hankele, Jäger, Schissler, Zeppenfeld 2008-2014)

RESULTS

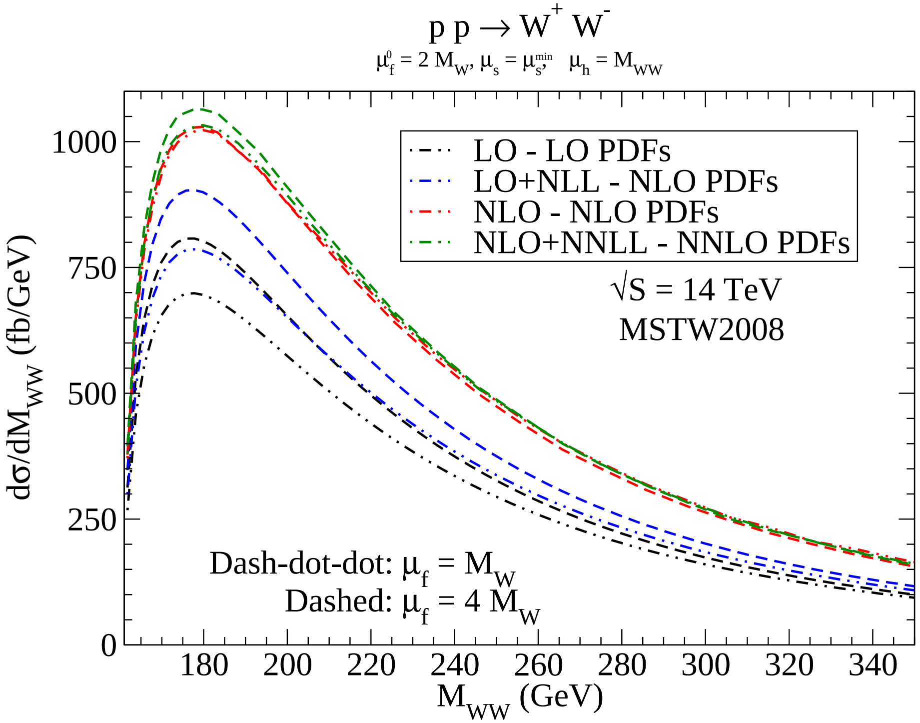
- LARGE NNLO CORRNS: NLO FIRST ORDER AT WHICH NON-INCLUSIVENESS MATTERS
- CAPTURED BY PARTON SHOWERING FOR p_T DISN, NOT FOR RAPIDITY SEPARATION

SOFT GLUON RESUMMATION

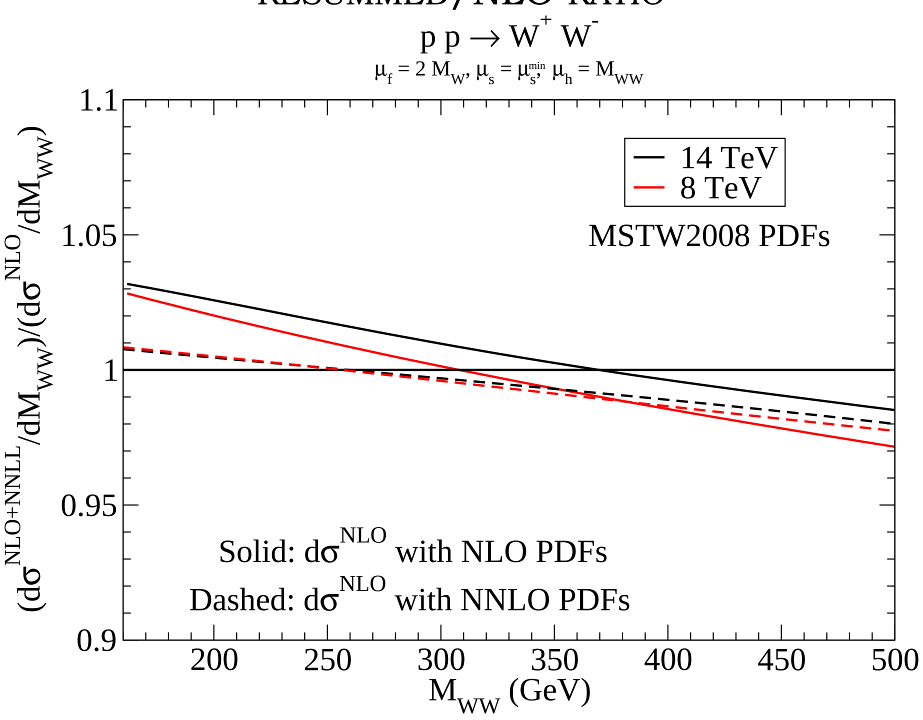
W PAIR PRODUCTION
SOFT GLUON RESUMMATION

WW INV. MASS DISTN.

RESUMMED VS NLO



RESUMMED/NLO RATIO



(Dawson, Lewis, Zeng, 2015)

- RESUMMATION PERFORMED IN SCET AT NNLL (CORRESP. TO $NN^{1/2}LL$)
- 3-4% ENHANCEMENT AT THE PEAK, $\lesssim 1\%$ ENHANCEMENT OF TOTAL XSECT.
- MOST OF THE EFFECT DUE TO USE OF NNLO PDFs ⇒ APPROXIMATE NNLO

Q: WHEN IS RESUMMATION USEFUL?

- PARTONIC CROSS SECTIONS $\hat{\sigma}(z, \alpha_s)$ ARE DISTRIBUTIONS, $0 \leq z = \frac{M_h^2}{s} \leq 1$, CONVOLUTED WITH LUMINOSIITY TO GIVE HADRONIC CROSS-SECTION
- THEIR MELLIN TRANSFORMS $\hat{\sigma}(N, \alpha_s)$ ARE ORDINARY FUNCTIONS
- FOR GIVEN m_H^2 AND s ONLY ONE "SADDLE" N VALUE CONTRIBUTES; POSITION OF SADDLE DETERMINED ESSENTIALLY BY PDF
$\Rightarrow$ PDF TELLS YOU WHICH FRACTION OF HADRON MOMENTUM GOES INTO PARTONIC PROCESS

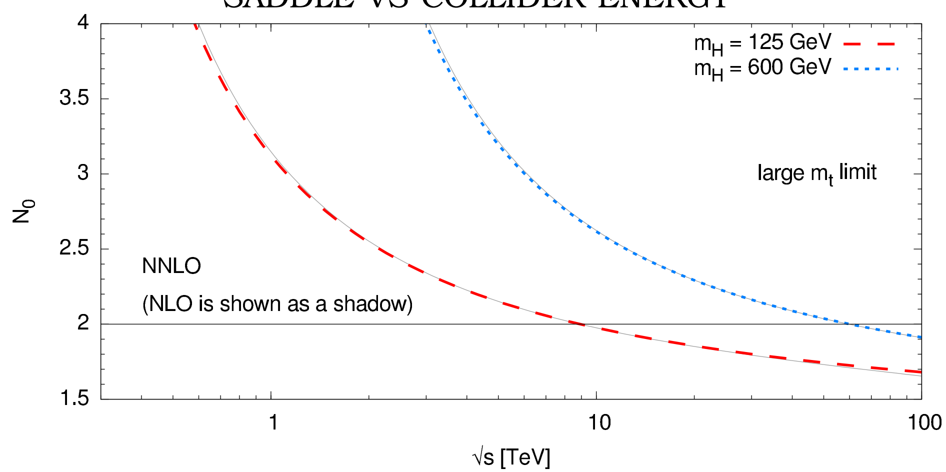
A: WHEN SADDLE N IS LARGE!

- SOFT RESUMMATION INCLUDES TO ALL ORDERS $\alpha_s \ln(1-z)$, $z = \frac{M_X^2}{s} \Leftrightarrow \alpha_s \ln N$
- SOFT $\leftrightarrow z \to 1 \leftrightarrow N \to \infty$.

EXAMPLE: HIGGS IN GLUON FUSION

- RESUMMATION CURRENTLY INCLUDED IN HXSWG RECOMMENATION: NNLO+NNLL
- BUT $N_{\text{saddle}} \sim 2$, $\Rightarrow$ RESUMMATION SUMS UP $\beta_0 \alpha_s \ln 2 \approx 0.04 \ll 1$

SADDLE VS COLLIDER ENERGY



(Bonvini, SF, Ridolfi, 2012)

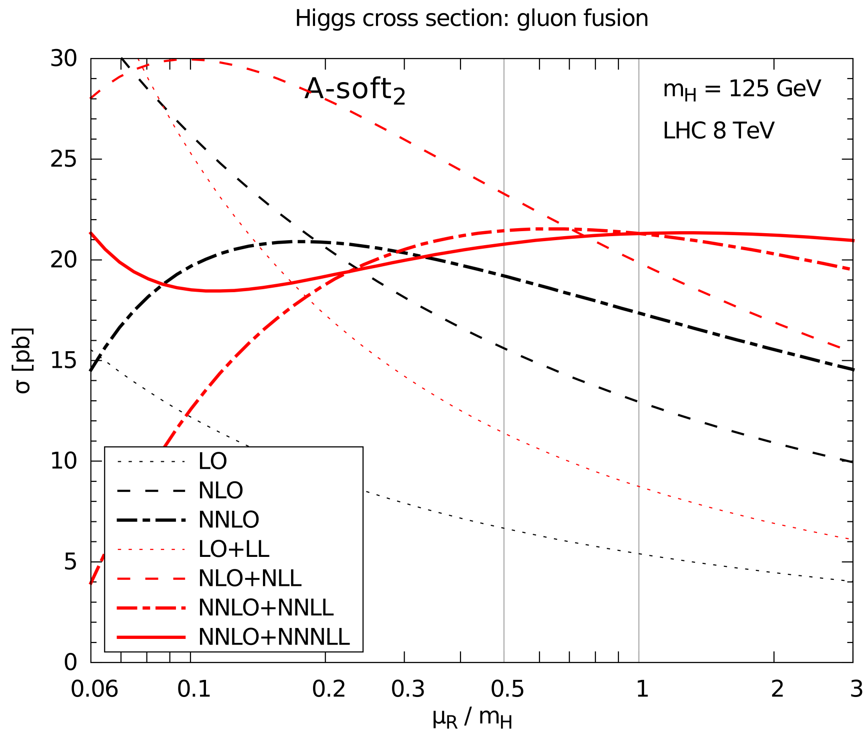
HIGGS IN GLUON FUSION: DOES RESUMMATION HELP?

NO?

YES!

$$
\begin{aligned}
M\left[\eta_{gg}^{(3)}\right](N) \simeq\ & 36\log^6 N && (\to 0.0013\%)\\
&+170.679\ldots\log^5 N && (\to 0.0226\%)\\
&+744.849\ldots\log^4 N && (\to 0.2570\%)\\
&+1405.185\ldots\log^3 N && (\to 1.0707\%)\\
&+2676.129\ldots\log^2 N && (\to 4.0200\%)\\
&+1897.141\ldots\log N && (\to 5.1293\%)\\
&+1783.692\ldots && (\to 8.0336\%)\\
&+108\frac{\log^5 N}{N} && (\to 0.0105\%)\\
&+615.696\ldots\frac{\log^4 N}{N} && (\to 0.1418\%)\\
&+2036.407\ldots\frac{\log^3 N}{N} && (\to 0.9718\%)\\
&+3305.246\ldots\frac{\log^2 N}{N} && (\to 2.9487\%)\\
&+3459.105\ldots\frac{\log N}{N} && (\to 5.2933\%)\\
&+703.037\ldots\frac{1}{N} && (\to 1.7137\%).
\end{aligned}
$$

(Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger, 2014)



Bonvini and Marzani, 2014

- "LEADING" LOGS DO NOT PROVIDE THE DOMINANT CONTRIBUTION
- EXPANSION IN POWERS OF $1/N$ CONVERGES VERY SLOWLY

- RESUMMED EXPANSION CONVERGES FASTER THAN UNRESUMMED ONE
- SCALE DEPENDENCE ALWAYS SMALLER AT RESUMMED LEVEL

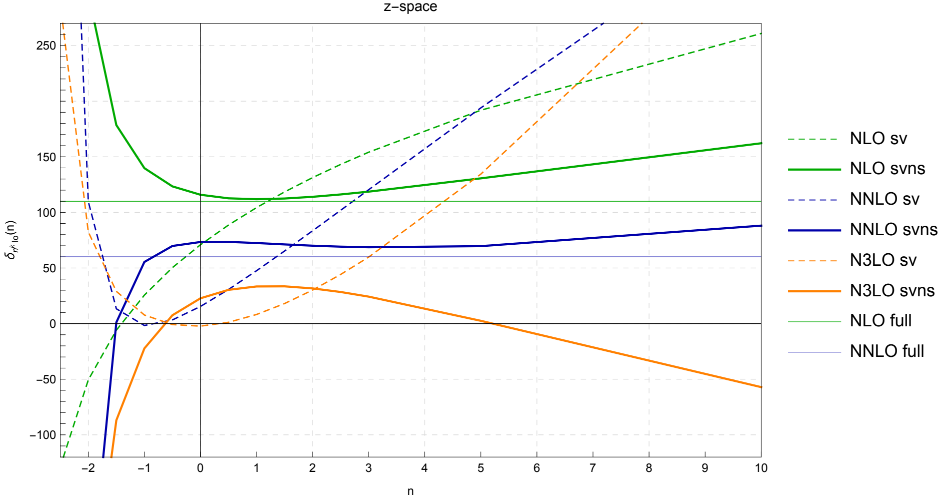
HIGGS IN GLUON FUSION:

APPROXIMATE N^3LO?

IS THERE A PREFERRED WAY OF EXPANDING?

NO?

PERFORM SOFT EXPANSION OF $\frac{\hat{\sigma}(z)}{z^{n+1}}$ & STUDY THE z DEPENDENCE:

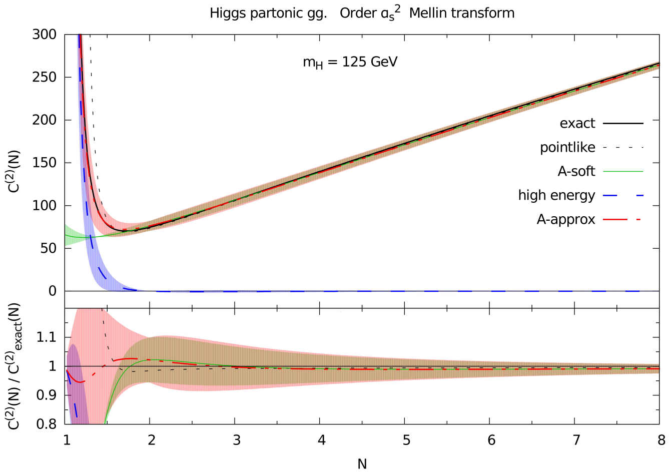


(Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger, 2014)

- SOFT EXPANSION DEPENDS STRONGLY ON WHAT ONE EXPANDS
- NO SIGN OF CONVERGENCE WITHIN THE KNOWN ORDERS

YES!

COMBINE SMALL AND LARGE N SINGULARITIES, ALLOWING FOR UNCERTAINTY DUE TO UNKNOWN ONES:

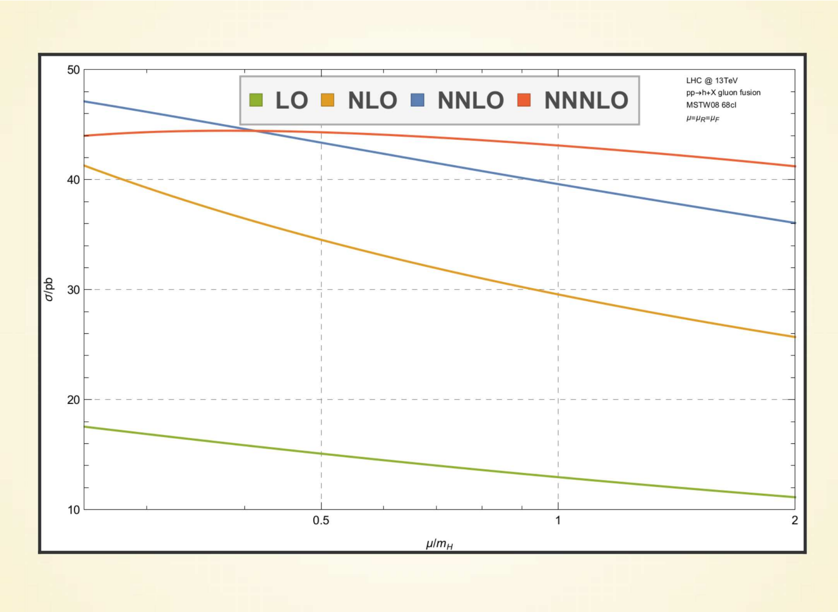


(Ball, Bonvini, SF, Marzani, Ridolfi, 2013)

- ASYMPTOTIC CONSTRAINTS STRONGLY BOUND BEHAVIOUR IN THE MIDDLE
- AT KNOWN ORDERS, EXACT RESULT NICELY BRACKETED

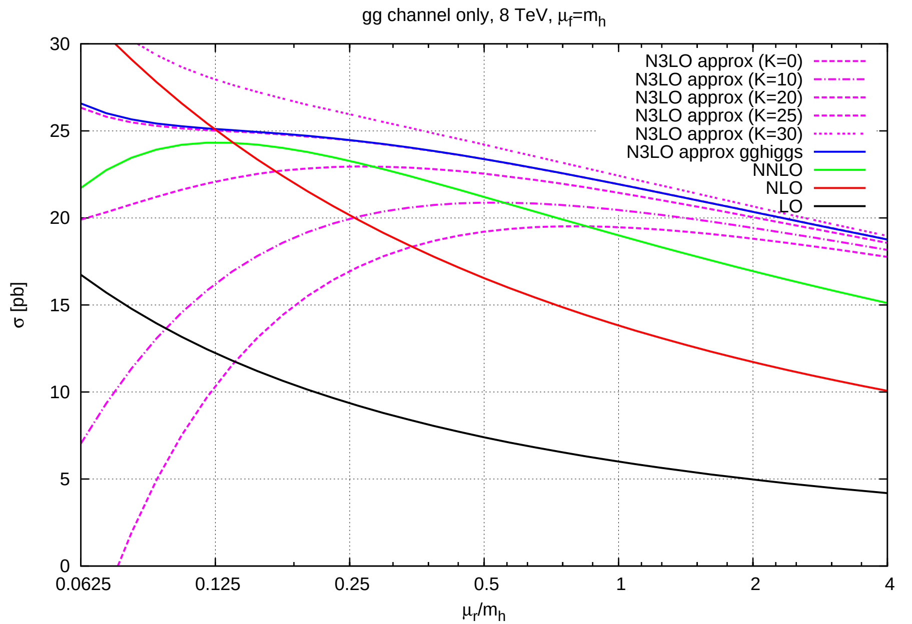
HIGGS IN GLUON FUSION:
EXACT N^{3}LO!

SCALE DEP.
VS PERTURBATIVE ORDER



(Anastasiou, Duhr, Dulat, Herzog, Mistlberger, 2015)

SCALE DEP. OF N3LO VS. SIZE
COMPARED TO APPROX N3LO

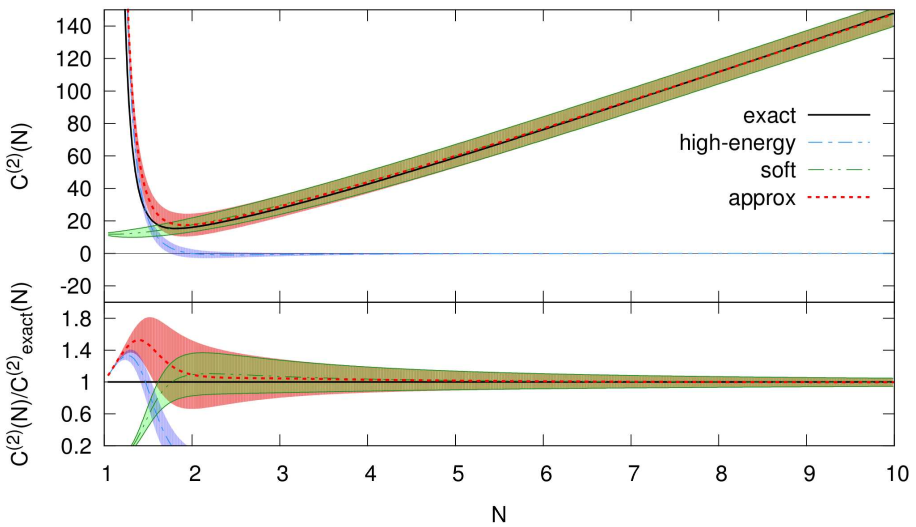


(Bühler, Lazopoulos, 2013)

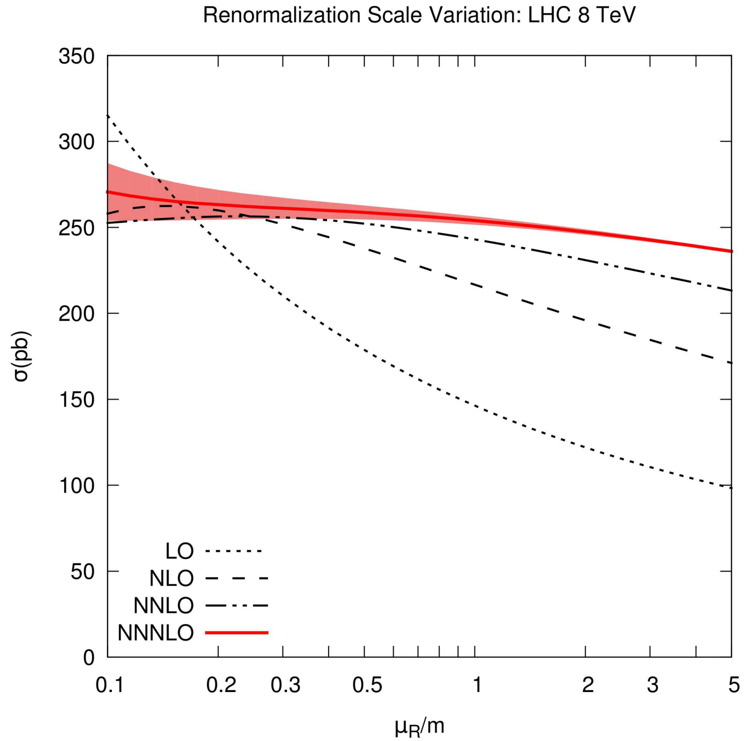
- EXACT N^{3}LO PUBLISHED
  OBTAINED AS SERIES EXPANSION ABOUT THE SOFT LIMIT, IN POINTLIKE APPROX
- SMALL SCALE DEPENDENCE $\Rightarrow$ PERTURBATIVE STABILITY!
- IN GOOD AGREEMENT WITH RESUMMATION/APPROX.!

TOP PRODUCTION AT APPROXIMATE N^{3}LO

NNLO MELLIN-SPACE RESULT
APPROXIMATE VS. EXACT



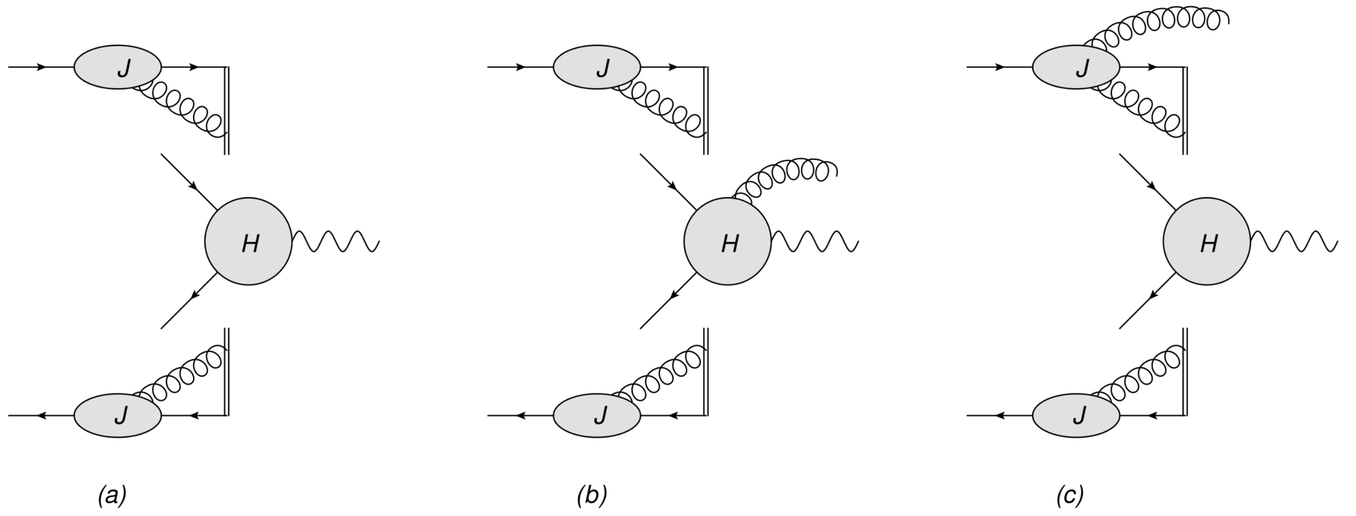
TOTAL CROSS-SECTION
SCALE DEPENDENCE



(Bonvini, S.F., Muselli, Ridolfi, 2015)

- FULL NNLO TOP PRODUCTION COMPUTED RECENTLY! (Czakon, Mitov et al., 2012-2013)
- AGREES WELL WITH "ANALYTIC" NNLO APPROXIMATION
- CAN CONSTRUCT APPROXIMATE N^{3}LO $\rightarrow$
- SIGNIFICANTY REDUCES SCALE DEPENDENCE, $\sim 10\%$ CORRECTION AT LHC8

SOFT RESUMMATION BEYOND THE LEADING POWER



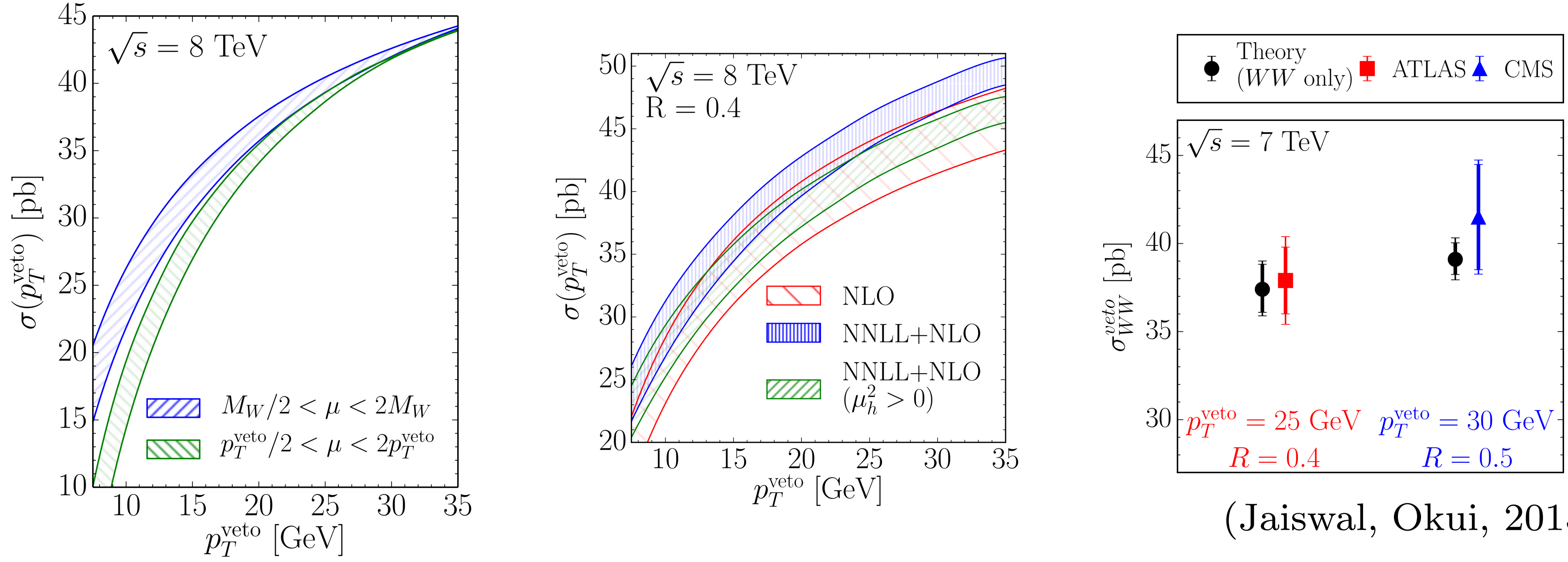
- IMPRESSIVE PROGRESS IN THE ORGANIZATION OF RESUMMATION BEYOND THE EIKONAL LEVEL: NEXT-TO-EIKONAL $\frac{ln^k N}{N}$; NEXT-TO-NEXT-TO-EIKONAL $\frac{ln^k N}{N^2}$ ETC (Laenen, Magnea, C.White+ Bonocore, Melville, Stavenga, Vernazza, 2012-2105)

- "METHOD OF REGIONS": SEPARATE INTEGRATION REGIONS OVER MOMENTA THROUGH APPROPRIATE SCALING

- COMBINE WITH FACTORIZATION TO CLASSIFY EMISSIONS FROM INTERNAL BLOBS, DRESSED WITH RADIATION FROM EXTERNAL LINES

p_T RESUMMATION AND JETS

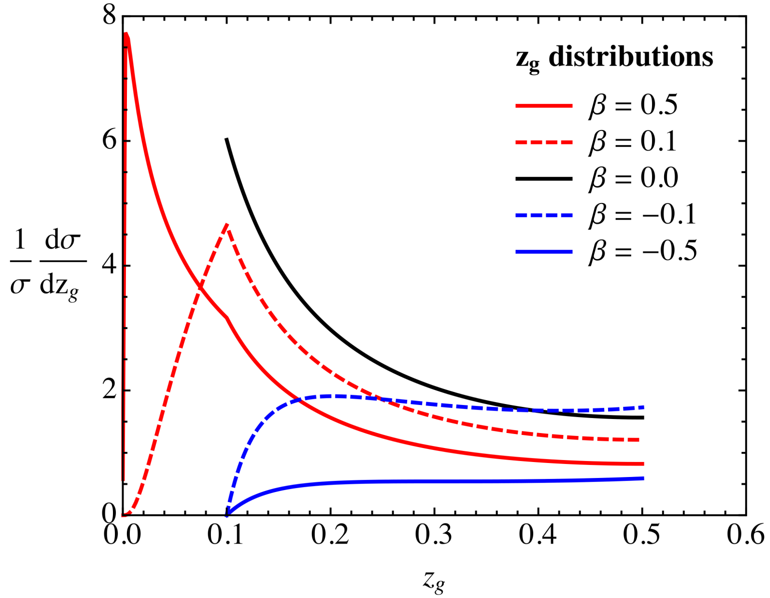
W PAIR PRODUCTION
JET VETO RESUMMATION



(Jaiswal, Okui, 2015)

- JET VETO $p_T < p_{T,\,veto}$ IS IMPOSED BY ATLAS, CMS TO REDUCE BACKGROUND FROM TOP
- K-FACTOR REDUCED BY $\sim 40\%$ BY JET VETO $\Rightarrow$ LARGE CANCELLATION BETWEEN VIRTUAL CORRECTIONS AND SMALL p_T REAL EMISSION: STRONG SCALE DEPENDENCE
- CROSS-SECTION FOR HIGGS+ AT LEAST ONE JET CONTAINS DOUBLE LOGS OF MINIMAL p_T OF JET $\Rightarrow$ CROSS SECTION WITH JET VETO CONTAINS DOUBLE LOGS OF $p_t^{\rm veto}$: $\sigma_{\geq 1} \sim (\alpha L^2)^n$; $\sigma_{\rm tot} \sim \alpha^n \to \sigma_o \equiv \sigma_{\rm tot} - \sigma_{\geq 1} \sim (\alpha L^2)^n$;
- RESUMMED UP TO NNLL (Jaiswal, Okui, 2015); AGREEMENT AT FIDUCIAL LEVEL, EXTRAPOLATION WITH POWHEG LEADS TO OVERESTIMATE THE TOTAL CROSS SECTION, GOOD AGREEMENT IF EXTRAPOLATION PERFORMED USING ANALYTIC RESUMMATION (Zanderighi, Monni, 2015)

JETS: COLLINEAR SAFETY AND SUDAKOV SAFETY



(Larkoski, Marzani, Thaler, 2015)

- PROGRESS IN THE DEVELOPMENT OF TOOLS FOR JET DEFINITION AND CHARACTERIZATION
- JET-SHAPE OBSERVABLES CHARACTERIZING A SINGLE JET (JET MASS, BROADENING) DEFINED, NON-GLOBAL LOGS RESUMMED, ANALYTIC RESULTS FOR JET SUBSTRUCTURE TOOLS
- SUDAKOV SAFE: NO α_s EXPANSION, BUT CALCULABLE AT RESUMMED LEVEL
- EXAMPLE: MOMENTUM SHARING $z_g \equiv \frac{\text{MIN}(p_t^1, p_t^2)}{p_t^1 + p_T^2}$;

  USED FOR SOFT-DROP DECLUSTERING,

  $\Rightarrow$ REMOVE WIDE-ANGLE SOFT RADIATION (REDUCE CONTAMINATION),

  $z_g > z_{cut}\left(\frac{R_{12}}{R_0}\right)^\beta$, R_0 JET RADIUS
- z_g NOT IRC SAFE IF $\beta > 0$
- SUDAKOV SAFE IF z_g CONDITIONAL TO VALUE OF $\frac{R_{12}}{R_0}$, RESUMMING THE DISTN. OF THE LATTER

JETS: THE XCONE ALGORITHM

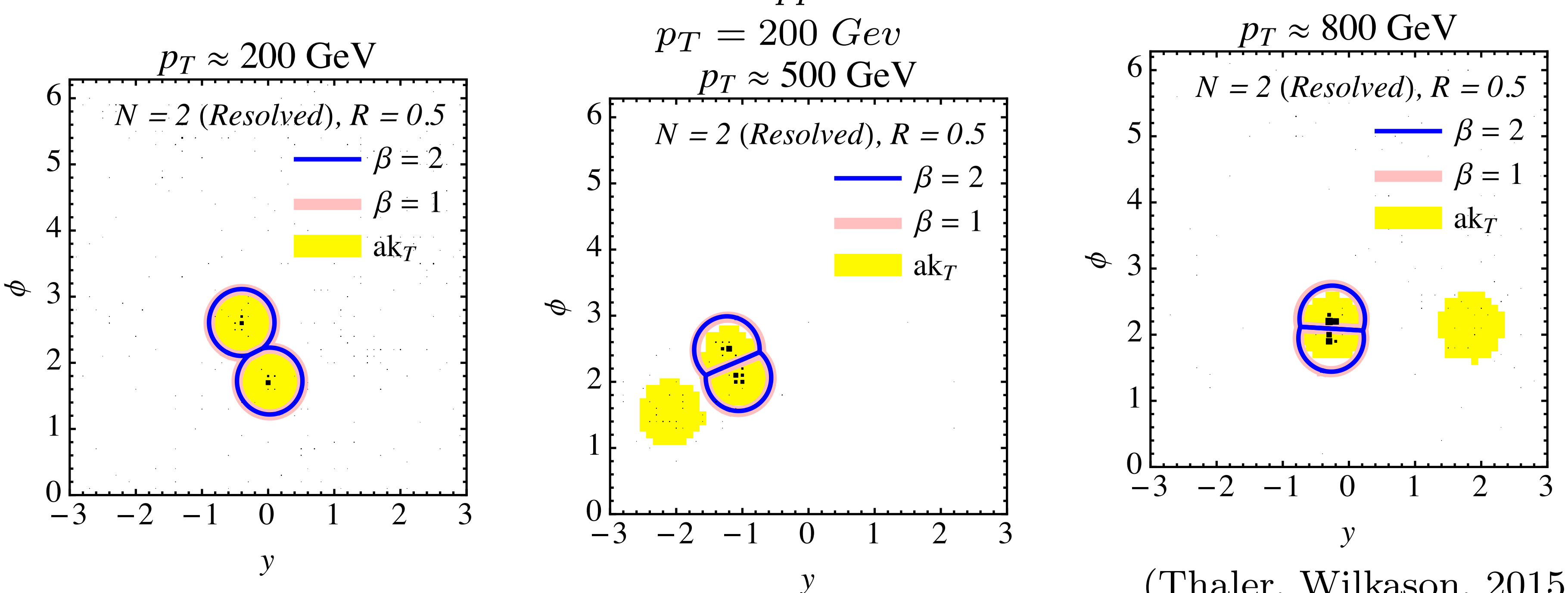
(Stewart, Tackmann, Thaler, Vermilion, Wilkason, 2015)

- A NEW EXCLUSIVE JET ALGORITHM DEFINED BY MINIMIZING N-JETTINESS: $\mathcal{T}_N = \sum_i \{\min \rho_{\rm jet}(p_i, n_1) \ldots \rho_{\rm jet}(p_i, n_N), \rho_{\rm beam}(p_i)\}$; $\rho_{\rm jet}(p_i, nA)$ DISTANCE TO A-TH AXIS, $\rho_{\rm beam}(p_i)$ DISTANCE TO THE BEAM;
  OPTIMIZED CHOICE OF MEASURE; ITERATIVE MINIMIZATION WITH SUITABLE SEED CHOICE

- INTERPOLATES SMOOTHLY BETWEEN RESOLVED AND BOOSTED KINEMATICS

- IN VERY BOOSTED CASE, INCLUSIVE ALGORITHMS (SUCH AS ANTI-k_T) TEND TO MERGE JETS AND IDENTIFY ISR AS 2ND JET, WHILE XCONE MAINTAINS GOOD PERFORMANCE

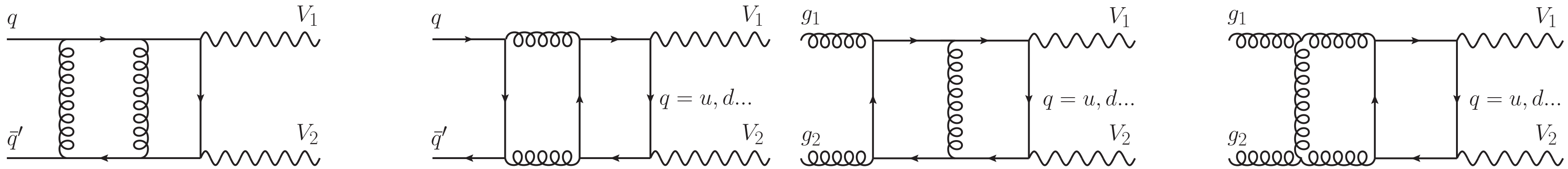
BOOSTED HIGGS: $pp \to HZ \to b\bar{b}\nu\bar{\nu}$



(Thaler, Wilkason, 2015)

OFF-SHELL

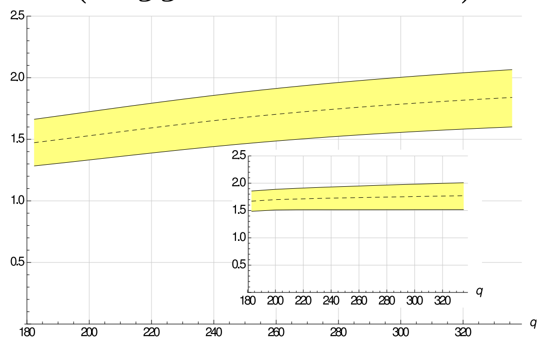
W/Z PAIR PRODUCTION
OFF-SHELL EFFECTS AND GLUON FUSION



- NO WS IN FINAL STATE: FOR ACCURATE PHENOMENOLOGY, MUST COMPUTE $pp \to V_1 V_2 \to (l_1 \bar{l}'_1)(l_2 \bar{l}'_2)$
  $\Rightarrow$ TWO-LOOP HELICITY AMPLITUDES IN QUARK-ANTIQUARK CHANNEL RECENTLY COMPLETED (Caola, Henn, Melnikov, Smirnov^2, 2014) $\Rightarrow$ MADE NNLO RESULT POSSIBLE!

- GLUON FUSION CONTRIBUTION STARTS AT NNLO, AMOUNTS TO ABOUT 5%:
  WHAT IF IT IS OFF BY A FACTOR 2 DUE TO RADIATIVE CORRNS.?:
  - TWO-LOOP CONTRIBUTION MEDIATED BY MASSLESS QUARK LOOPS JUST COMPLETED, AVAILABLE WITH OFF-SHELL GAUGE BOSONS (Caola, Henn, Melnikov, Smirnov^2, 2015)
  -
    * CONTRIBUTION FOR OFF-SHELL ZZ MEDIATED BY TOP LOOP IN $m_t \to \infty$ LIMIT JUST COMPLETED (Melnikov, Dowling, 2015)
    * BEHAVIOUR OF K-FACTOR SIMILAR TO THAT OF $gg \to H$ K-FACTOR; IN GOOD AGREEMENT WITH PREVIOUS ANALYTIC APPROX. (Bonvini, Caola, SF, Marzani, Melnikov, 2013)

$gg \to ZZ$ K-factor
(& $gg \to h$ K-factor)



OFF-SHELL HIGGS PRODUCTION

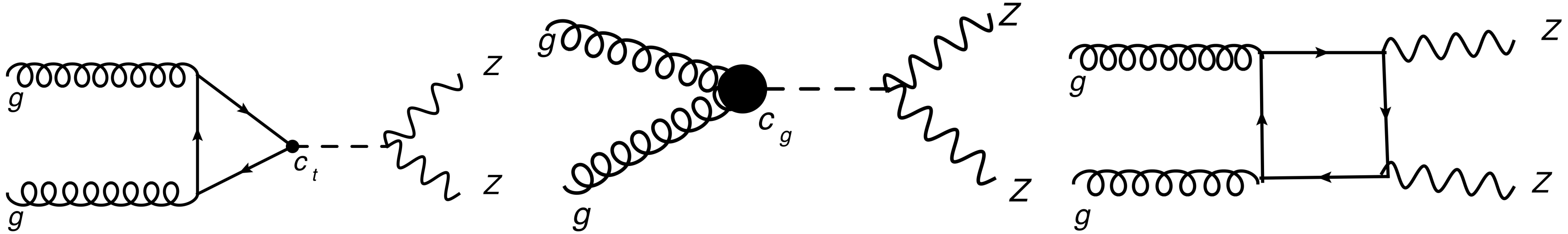
SIMPLE OBSERVATION (Caola, Melnikov, 2013):

$\sigma_{\rm on-shell}(gg \to H \to e^- e^+ \mu^- \mu^+) \sim \frac{g_i^2 g_f^2}{\Gamma}$ BUT $\sigma_{\rm off-shell}(gg \to H \to e^- e^+ \mu^- \mu^+) \sim g_i^2 g_f^2$

- OFF-SHELL/ON-SHELL RATIO $\Rightarrow$ WIDTH DETERMINATION (CMS, ATLAS)
- OFF-SHELL MEASUREMENTS $\Rightarrow$ COUPLINGS INDEPENDENT OF WIDTH

CAN PLAY THE SAME GAME WITH VBF HIGGS PRODUCTION
$\Rightarrow$ κ_V COUPLINGS FROM $qq \to WWqq$ (Campbell, K.Ellis, 2015)

SETTING LIMITS ON COUPLINGS

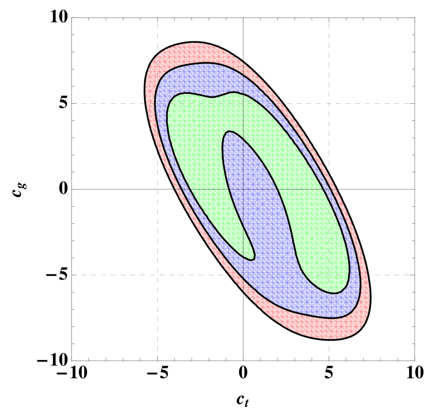


$$\mathcal{M}_{gg\to ZZ} = \mathcal{M}_h + \mathcal{M}_{bkg} = c_t \mathcal{M}_{c_t} + c_g \mathcal{M}_{c_g} + \mathcal{M}_{bkg}$$

WHERE $\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$

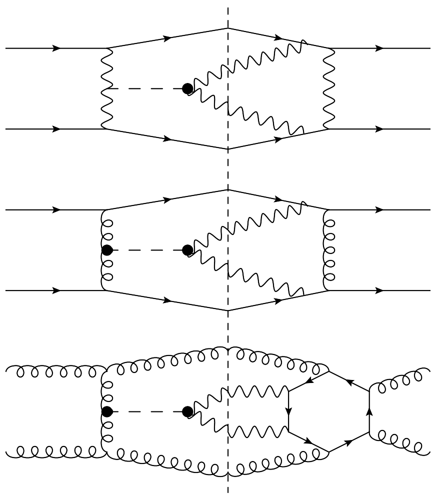
- ON-SHELL CAN INTEGRATE OUT TOP, $\sigma \sim |c_t + c_g|^2$
- OFF-SHELL, CAN MEASURE c_t, c_g INDEPENDENTLY;
  IN SM $c_t + c_g = 1$, NO MODEL-INDEP CONSTRAINT YET

(Azatov, Grojean, Paul, Salvioni, 2014)

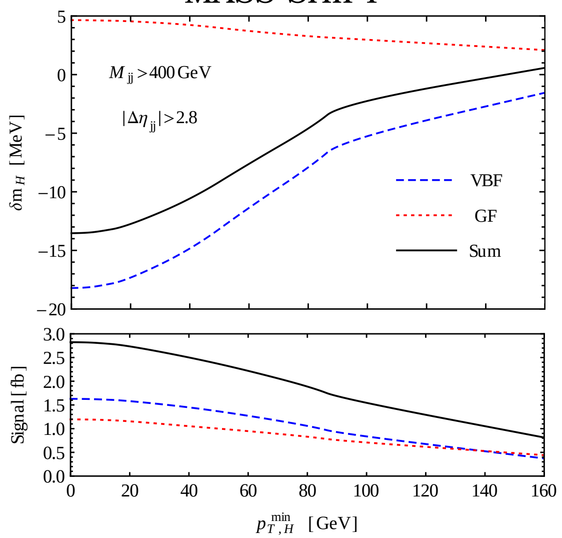


HIGGS WIDTH & INTERFEROMETRY

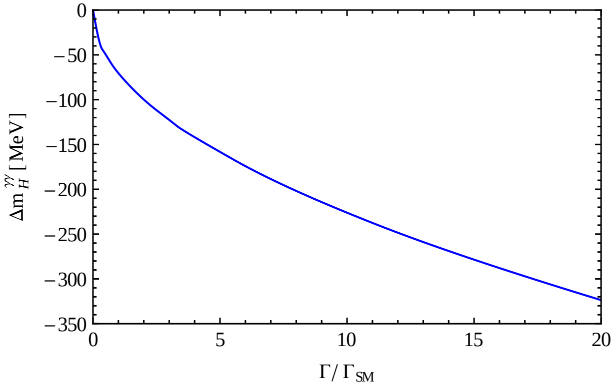
SIMPLE OBSERVATION: SIGNAL-BACKGROUND INTEFERENCE SHIFTS HIGGS MASS; SHIFT PROPORTIONAL TO WIDTH, CAN BE USED TO CONSTRAIN IT (Dixon, Li, 2013)



MASS SHIFT



MEASURABLE MASS SHIFT



(Coradeschi, de Florian, Dixon, Fidanza, Höche, Ita, Li, Mazzitelli, 2015)

- MASS SHIFT IN $pp \to H(\to \gamma\gamma) + 2j + X$ MUCH SMALLER THAN IN INCLUSIVE CHANNEL
- CANCELLATION BETWEEN VBF AND GG CHANNEL (SEPARATION WELL DEFINED DUE TO COLOR AT TREE LEVEL, INTERFERENCE SMALL BEYOND IT)
- CANCELLATION CAN BE ENHANCED WHILE KEEPING SIZABLE SIGNAL BY CHOICES OF CUTS IN p_T, $\Delta\eta_{jj}$
- DEFINE MEASURABLE MASS SHIFT: $\Delta m_H^{\gamma\gamma} \equiv \delta m_H^{\gamma\gamma,\,\text{INCL}} - \delta m_H^{\gamma\gamma,\,\text{VBF}}$: SMALL BUT STRONGLY DEP. ON WIDTH, REASONABLE SIGNAL

THE STRONG COUPLING

THE VALUE OF α_s

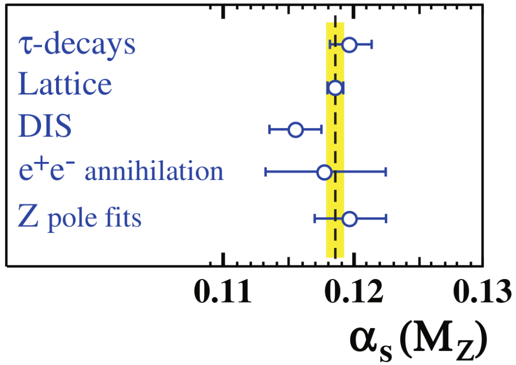
PDG VALUE (AUGUST 2014): $\alpha_s(M_Z) = 0.1185 \pm 0.0006$

- LATTICE UNCERTAINTY CURRENTLY ESTIMATED BY FLAG (arXiv:1310.8555) TO BE TWICE THE PDG VALUE (± 0.0012)
  (IF PDG WERE TO ADOPT THIS, COMBINED UNCERTAINTY LIKELY TO DOUBLE)
- IT IS AN AN AVERAGE OF AVERAGES
- SOME SUB-AVERAGES (E.G. DIS) INCLUDE MUTUALLY INCONSISTENT VALUES
- SOME SUB-AVERAGES (E.G. τ OR JETS) INCLUDE DETERMINATIONS WHICH DIFFER FROM EACH OTHER BY EVEN FOUR-FIVE σ
- AVERAGING THE TWO MOST RELIABLE VALUES (GLOBAL EW FIT & τ, BOTH N^{3}LO, NO DEP. ON HADRON STRUCTURE) GIVES

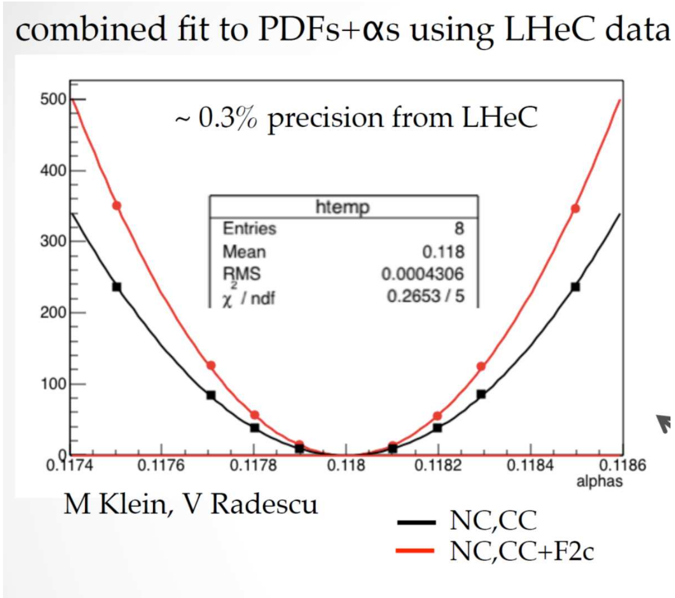
$$\alpha_s = 0.1196 \pm 0.0010$$

- LITTLE PROGRESS FOR MANY YEARS: PDG 1998-2006 $\Delta\alpha_s(M_Z) = 0.002$; PDG 2010-2014 $\Delta\alpha_s(M_Z) = 0.0006 \div 0.0008$ (CHANGE OF AUTHOR)
- UNLIKELY TO CHANGE - SHOULD DETERMINE α_s FROM HIGGS IN GLUON FUSION?

α_s DETERMINATIONS IN PDG



α_s AT THE LHEC



- COULD BE DETERMINED ACCURATELY AT THE LHEC OR AT A NEUTRINO FACTORY!

SUMMARY I

THEORETICAL PROGRESS IS KEEPING PACE WITH EXPERIMENTAL PROGRESS:

- PDF DETERMINATION: UNCERTAINTIES
- NNLO AND BEYOND
- THRESHOLD RESUMMATION AS A TOOL FOR APPROXIMATE H.O.
- JET RESUMMATION, CHARACTERIZATION & DEFINITION
- OFF-SHELL

"...the period of the famous triumph of quantum field theory. And what a triumph it was, in the old sense of the word: a glorious victory parade, full of wonderful things brought back from far places to make the spectator gasp with awe and laugh with joy" (Sydney Coleman, 1988)

SUMMARY II:

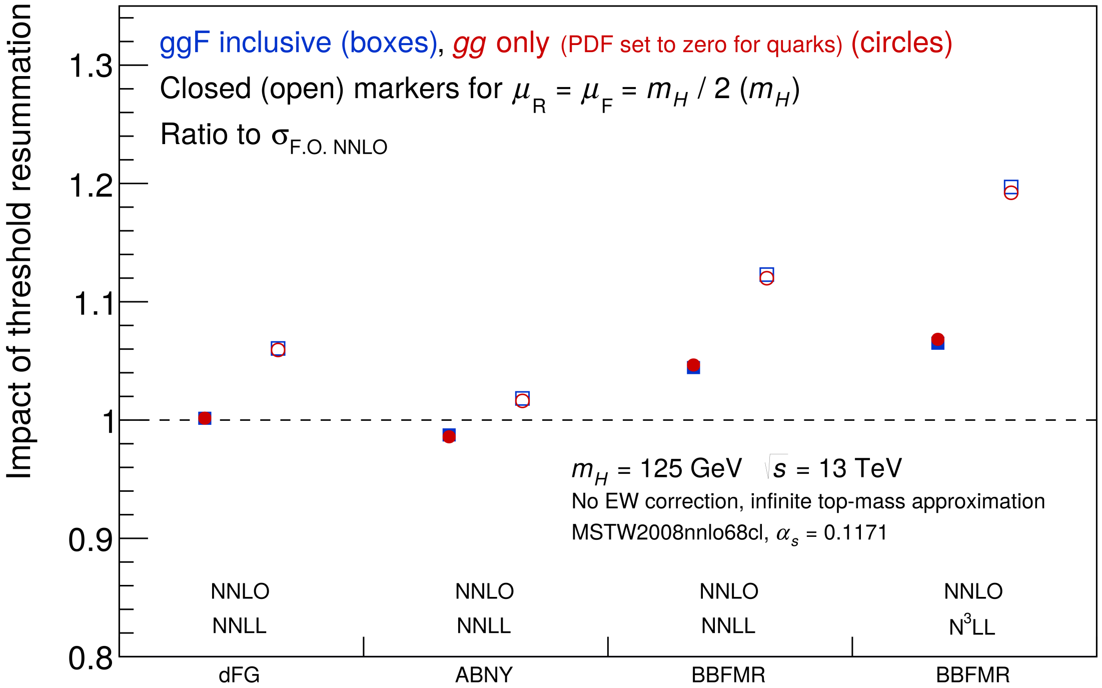
QCD IS NOT PLUMBING

EXTRAS

HIGGS IN GLUON FUSION: RESUMMATION AMBIGUITIES

- LARGE SUBLEADING TERMS $\Rightarrow$ LARGE AMBIGUITIES
- SCET RESUMMATION SMALLER, DUE TO $1/N$ TERMS (Bonvini, SF, Ridolfi, Rottoli)
- RESUMMATION EFFECTIVELY AMOUNTS TO APPROXIMATE HIGHER ORDERS

RESUMMED/UNRESUMMED RATIO (NO CONST. EXPONENTIATION)

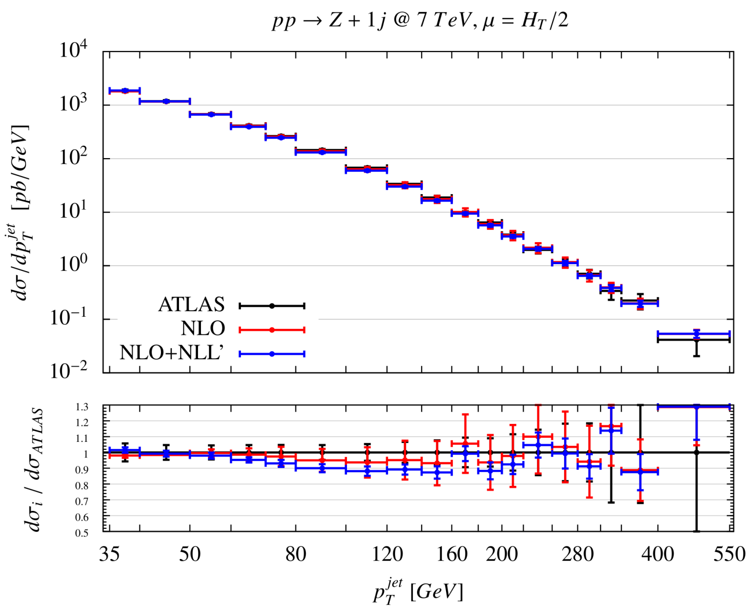


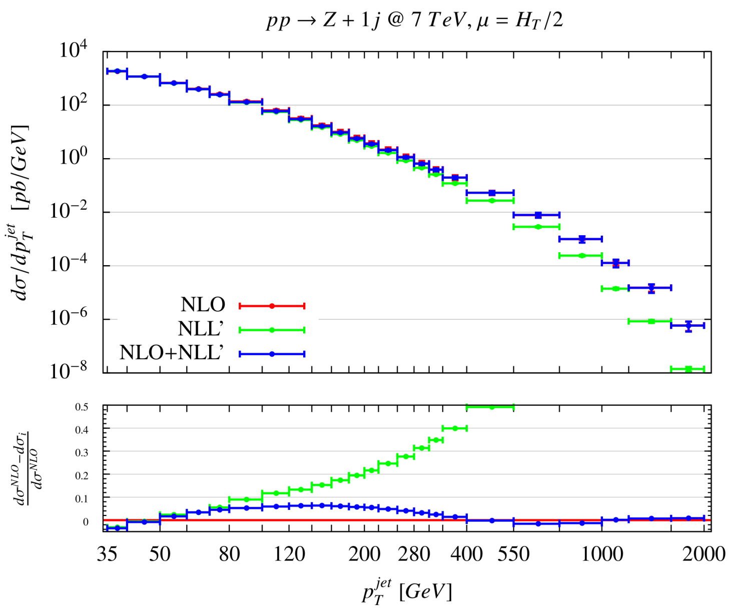
note k factor computed wr to NNLO at respective scale

- De Florian, Grazzini (DFG) (HXSWG REFERENCE) RESUM $\ln N$
- Becher, Neubert et al. (ABNY): SCET (z SPACE) APPROACH TO NNLL (REALLY N^{3}LL*)
- Ball et al. (BBFMR): RESUM $\ln N$, DIFFERS FROM DFG BECAUSE OF 'ANALYTIC' RESUMMATION (correct small-N singularities when expanded to finite order)
- BBFMR: N^{3}LL ALSO AVAILABLE

Z+jet production
Jet veto resummation vs. isolation criteria

- jet veto resummation recently extended to 0, 1-jet bins for Higgs production
- gauge boson+ jet "standard candle"; NNLO calculation recently available (Boughezal, Focke, Liu, Petriello, 2015)
- ATLAS data surprisingly agree with NLO result: no jet veto?
- "giant K-factor" (Rubin, Salam, Sapeta, 2010): ATLAS isolation criterion accepts two-jet events with one jet almost collinear to Z, compensates suppression due to jet veto
- goes away with different jet isolation criterion





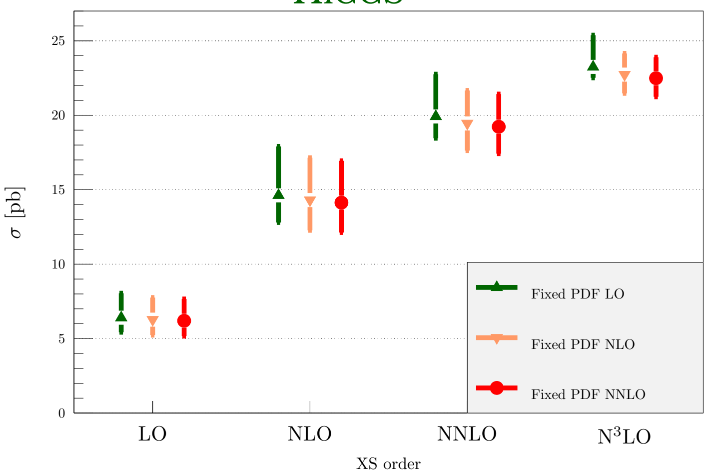
(Boughezal, Focke, Liu, 2015)

N^{3}LO PDFs:

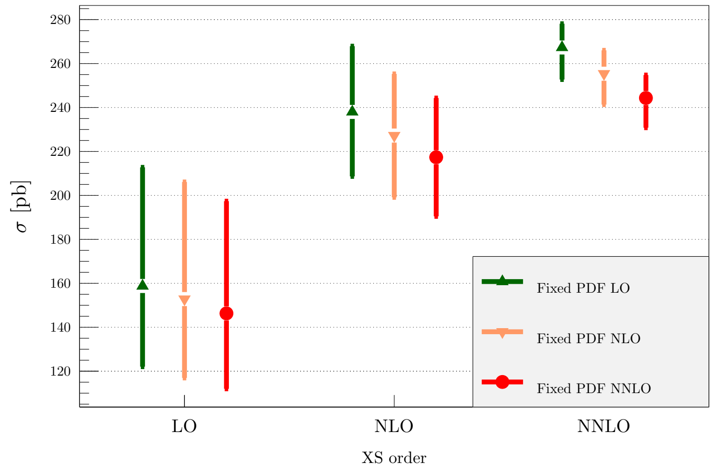
- NEEDED AT THE 1% ACCURACY LEVEL
- IMPACT OF N^3LO DEPENDS ON PROCESS:
  - HIGGS GLUON FUSION: PERTURBATIVE DEP. OF PDF NEGLIGIBLE IN COMPARISON TO MATRIX ELEMENT $\Rightarrow$ N^{3}LO NOT NEEDED
  - TOP: PERTURBATIVE DEP. OF PDF SMALLER, BUT NOT NEGLIGIBLE IN COMPARISON TO MATRIX ELEMENT, ANTICORRELATED TO IT $\Rightarrow$ N^{3}LO NECESSARY

SCALE UNCERTAINTY & DEP. ON PERTURBATIVE ORDER

HIGGS



TOP

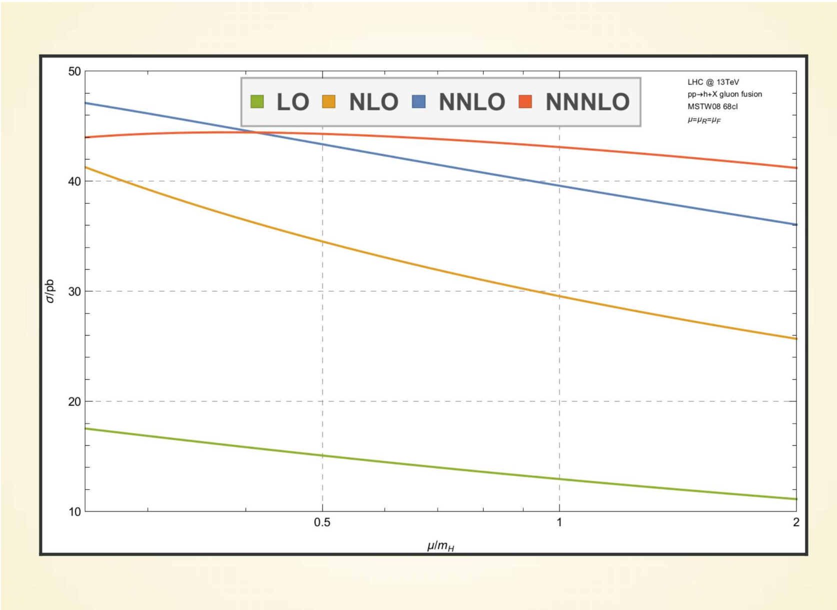


(s.f., Isgrò, Vita, 2014)

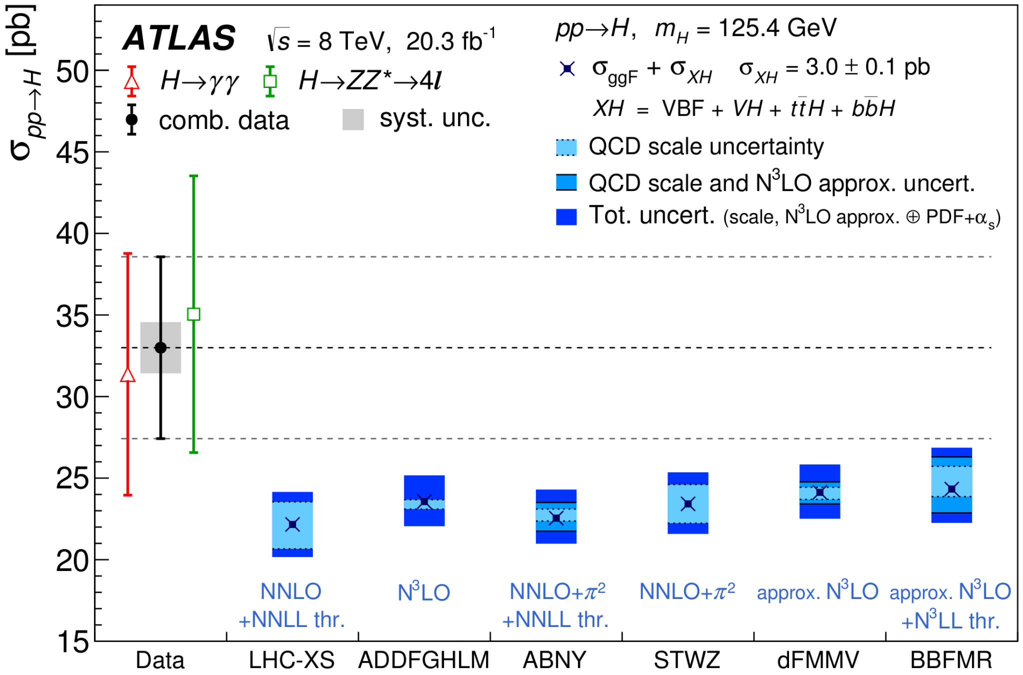
WHEN WILL WE HAVE THEM?

- N^{3}LO DIS COEFFICIENT FUNCTIONS KNOWN
- BOTTLENECK: N^3LO ANOMALOUS DIMENSIONS
- ANOMALOUS DIMENSIONS: LO: 1974; NLO: 1981; NNLO: 2004; N^{3}LO: 2030?

Higgs in gluon fusion:
EXACT N^{3}LO!



(Anastasiou et al, 2015)

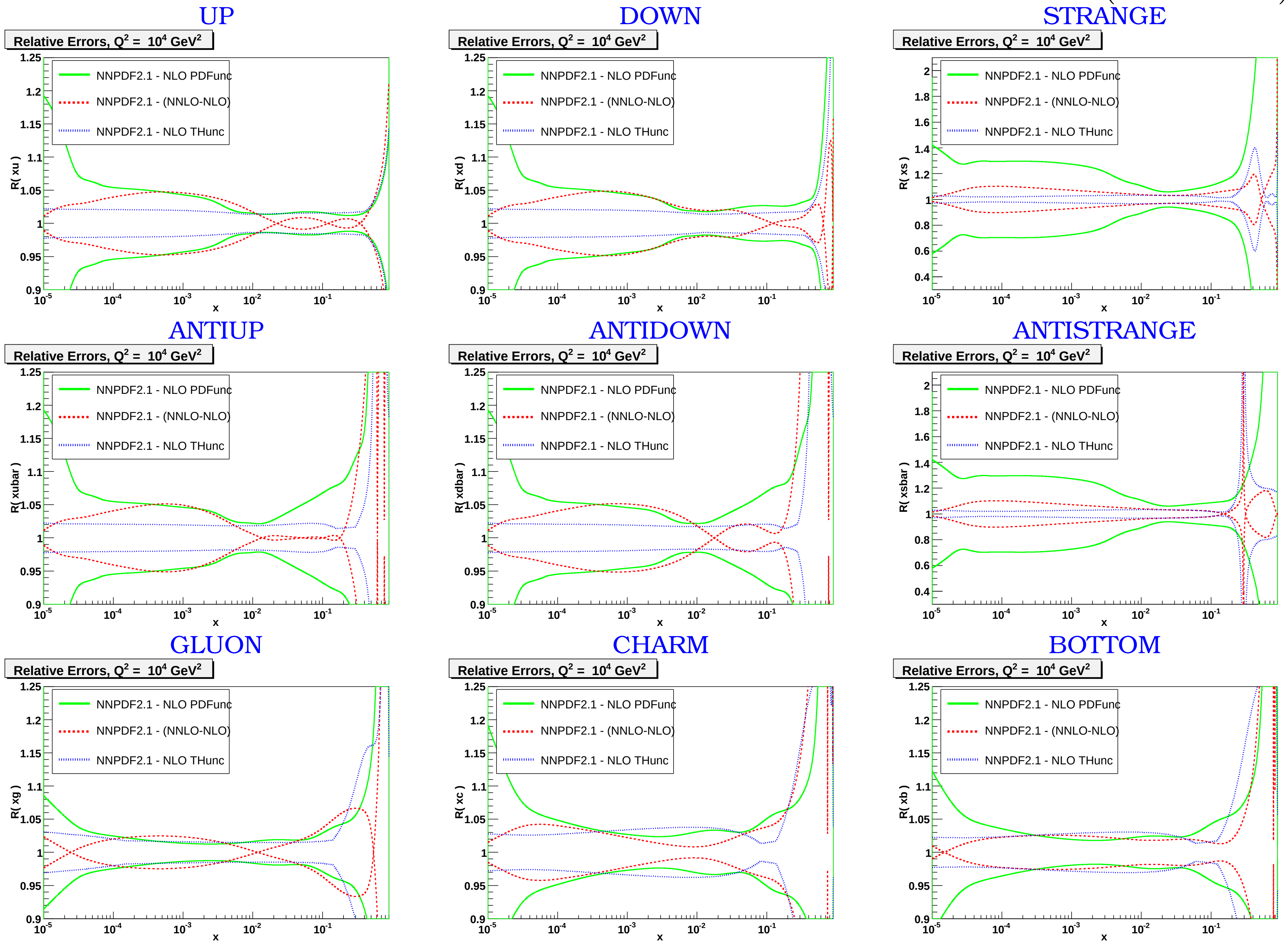


(ATLAS, 2015)

- EXACT N^{3}LO PUBLISHED IN PRELIMINARY FORM, OBTAINED AS SERIES EXPANSION ABOUT THE SOFT LIMIT, IN POINTLIKE APPROX
- HAS THE SERIES CONVERGED?
- IN GOOD AGREEMENT WIH RESUMMATION!

THEORETICAL UNCERTAINTIES

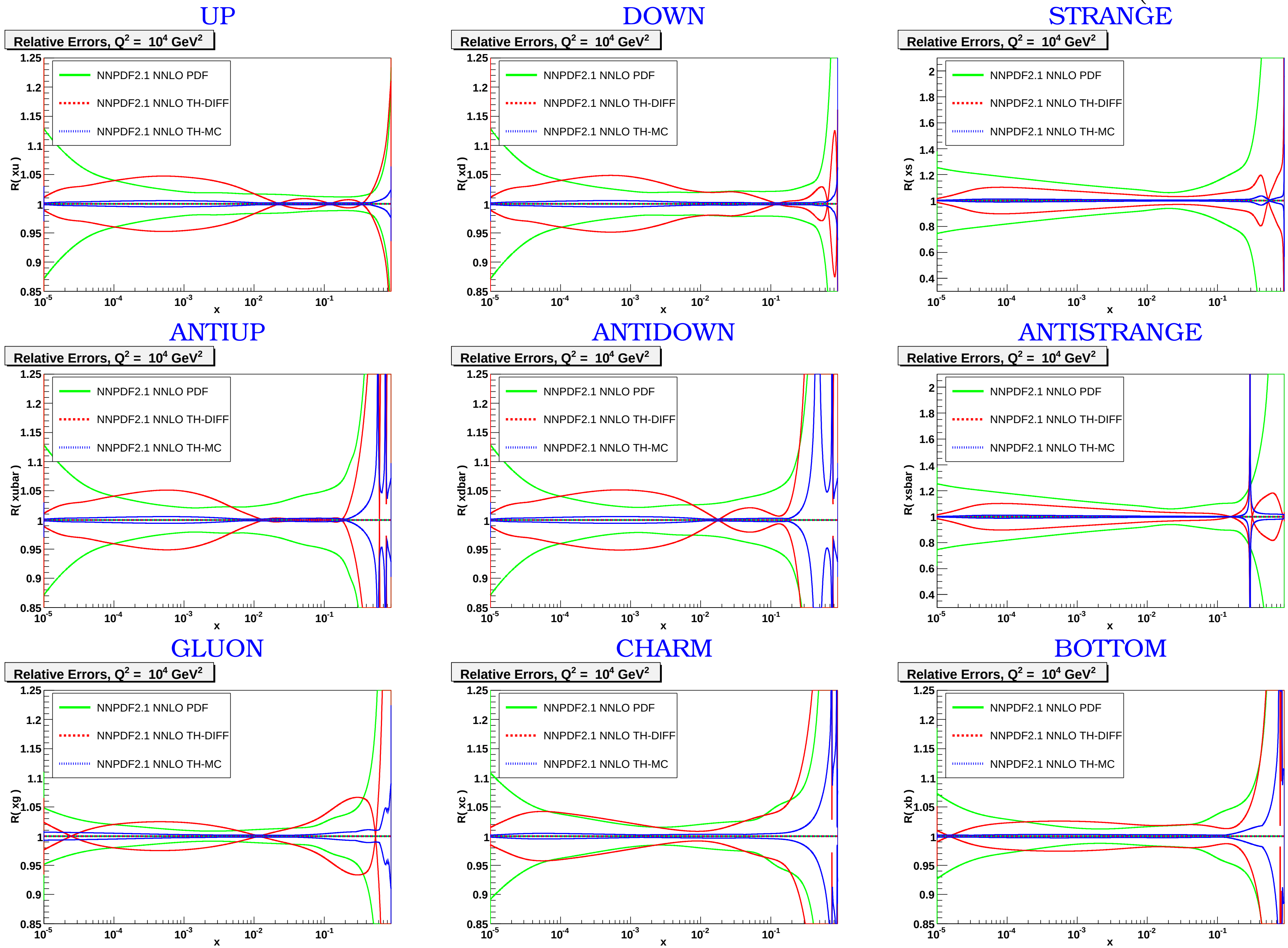
NLO PDF unc. vs NLO-NNLO shift vs NLO Cacciari-Houdeau (NNPDF2.1)



Theoretical uncertainty on NLO PDF is order 5% ⇒ comparable to PDF uncertainty

THEORETICAL UNCERTAINTIES

NNLO PDF unc. vs NLO-NNLO shift vs NNLO Cacciari-Houdeau (NNPDF2.1)



THEORETICAL UNCERTAINTY ON NNLO PDF IS ORDER 1% $\Rightarrow$ SMALLER THAN PDF UNCERTAINTY