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N3PDF
Machine Learning • PDFs • QCD

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HEAVY FLAVOR PRODUCTION PROCESSES

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QCD@LHC

Dresden, August 30, 2018

HEAVY QUARKS
IN QCD AT THE LHC

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HEAVY QUARKS: WHAT AND WHERE?

- FINAL STATE: PRODUCTION
- INITIAL STATE: PDFS AND MATCHING
- LOOPS: HQ INDUCED PROCESSES

HEAVY QUARKS COME FIRST

CHARM: FIRST EVIDENCE FOR QCD!

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen,
J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman,
G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth,
H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl,
B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum,
and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

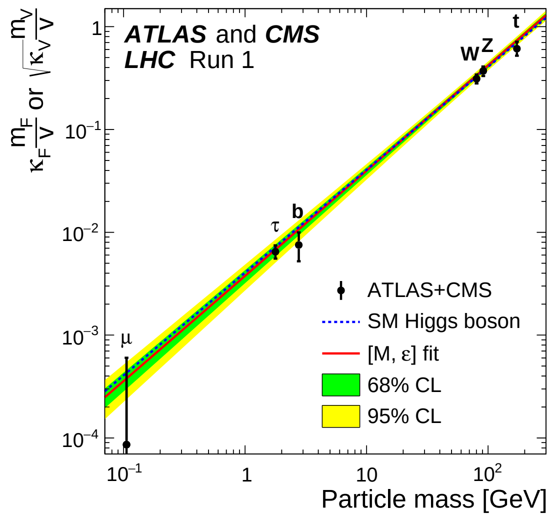
G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek,
J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker,
J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

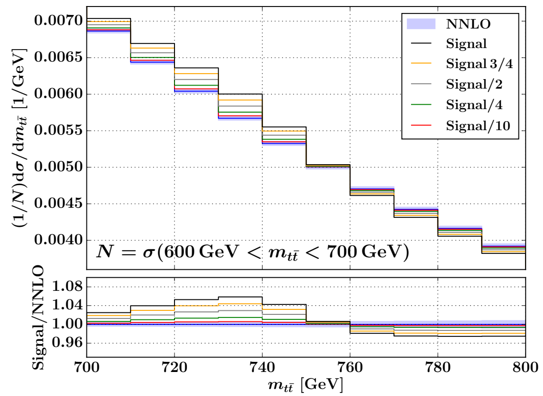
- CHARM PRODUCTION: FIRST HIGH ENERGY (BFKL) RESUMMATION OF COLLIDER PROCESS (Catani, Ciafaloni, Hautmann, 1990)
- BOTTOM: FIRST MATCHED p_t RESUMMATION (Cacciari, Greco, Nason, 1998)
- TOP: FIRST RESUMMED PHENOMENOLOGY FOR HADRON COLLIDER PROCESS (Catani, Mangano, Nason, Trentadue, 1996)

HEAVY QUARKS AT THE LHC

HIGGS COUPLINGS



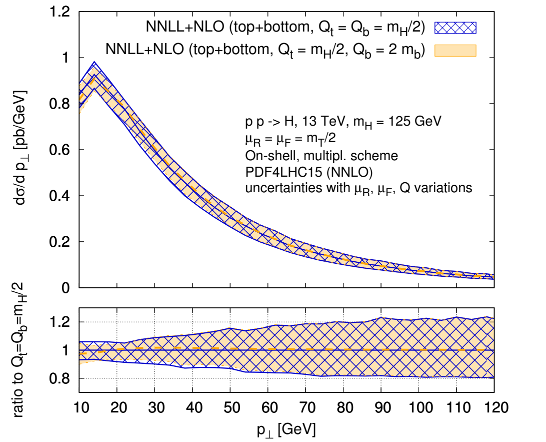
BUMP HUNTING IN $t\bar{t}$



(Czakon, Heymes, Mitov, 2016)

HIGGS p_T SPECTRUM

FOR $m_b < p_t m_t$



(Caola, Lindert, Melnikov, Monni, Tancredi, Wever, 2018)

- NEW PHYSICS FROM HIGGS COUPLINGS
- CLEAN BACKGROUND TO NEW HEAVY PARTICLES
- MULTISCALE QCD STUDIES

HEAVY QUARKS: WHAT AND WHERE?

- FINAL STATE: PRODUCTION
  - TOP PAIRS
  - SINGLE TOP
  - $t\bar{t}j$, $t\bar{t}H$, $t\bar{t}b\bar{b}$ ...
- INITIAL STATE: PDFS AND MATCHING
  - FITTING THE CHARM PDF
  - THE b PDF AND MASSIVE EVOLUTION
  - MULTISCALE MATCHING
- LOOPS: HQ INDUCED PROCESSES
  - HIGGS IN GLUON FUSION: THE TOP MASS
  - HIGGS IN GLUON FUSION: T-B INTERFERENCE
- THE TOP MASS

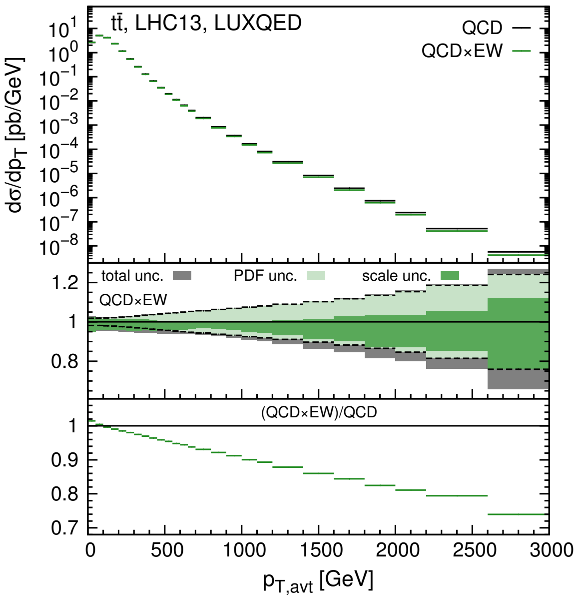
HEAVY QUARKS IN THE FINAL STATE

TOP PAIR PRODUCTION

- FULLY DIFFERENTIAL RESULTS AT NNLO SINCE 2015 (Czakon, Mitov et al.), SOLVED "TEVATRON ASYMMETRY" PUZZLE
- NNLO NOW
  - MATCHED TO FULL NLO EW (up to $O(\alpha_s^3)$, $O(\alpha_s^2\alpha)$, $O(\alpha\alpha_s^2)$, $O(\alpha^3)$)
  - MATCHED TO NNLL THRESHOLD+BOOSTED RESUMMATION
  - MATCHED TO NLL p_t RESUMMATION
  - APPROXIMATE N^{3}LL THRESHOLD RESUMMATION AVAILABLE (Piclum, Schwinn, 2018)
- FULLY DIFFERENTIAL NNLO DECAY (Gao, Papanastasiou, 2017)

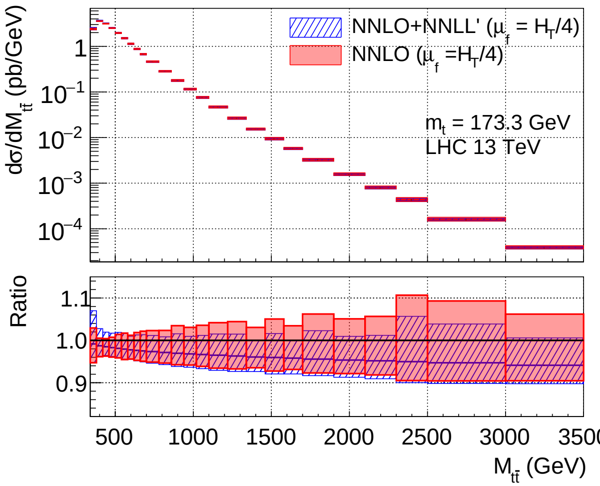
AVERAGE p_t OF $t\bar{t}$ PAIR

NNLO QCD+ NLO EW



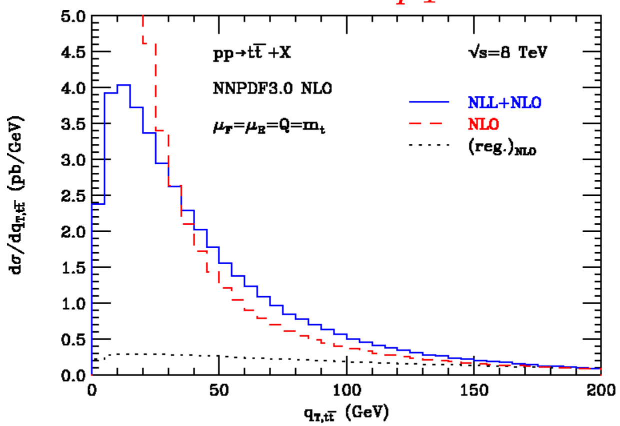
(Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro, 2017)

NNLO+NNLL THRESHOLD



(Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, Yang, 2018)

NLO+NNLL p_T

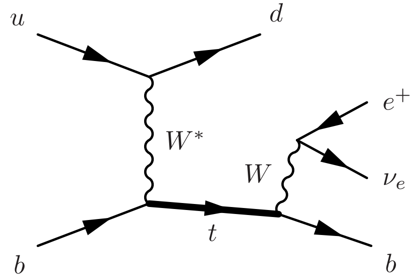


(Catani, Grazzini, Sargsyan, 2018)

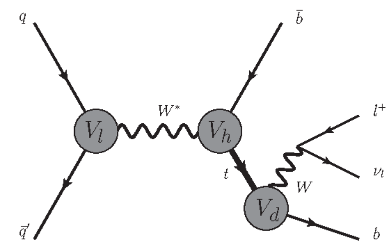
SINGLE TOP

- FULLY DIFFERENTIAL NNLO t-CHANNEL NOW CROSS-CHECKED, PHENO PREDICTIONS AVAILABLE FOR PDF FITS (Berger, Gao, Zhu, 2017)
- FULLY DIFFERENTIAL NNLO s-CHANNEL (Liu, Gao, 2018)
- t CHANNEL + JET MATCHED TO PS WITH POWHEG+MINLO (Carrazza, Frederix, Hamilton, Zanderighi, 2018)

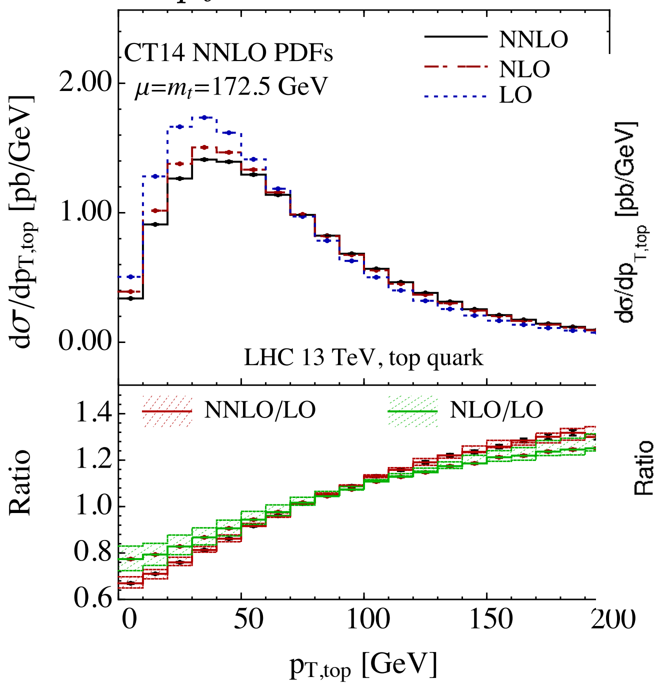
t-CHANNEL



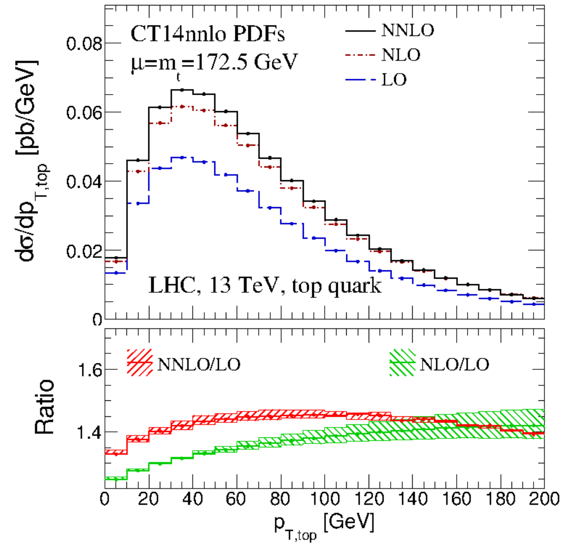
s-CHANNEL



p_t SPECTRUM



p_t SPECTRUM



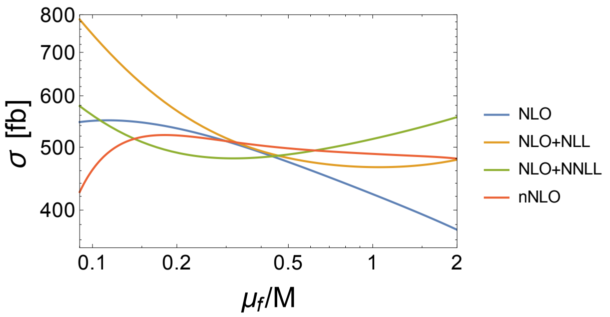
ASSOCIATED PRODUCTION OF TOP PAIRS

$t\bar{t}H \Rightarrow$ HIGGS COUPLING SIGNAL; $t\bar{t}W$, $t\bar{t}b\bar{b}$ ... $\Rightarrow$ BACKGROUNDS

HIGHLIGHTS

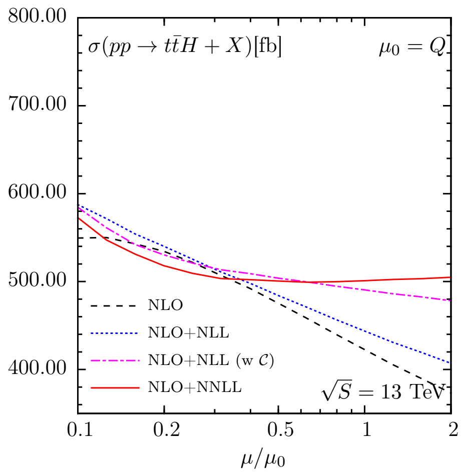
- NLO+NNLL THRESHOLD RESUMMATION $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$ TOTAL CROSS SECTION & p_t DISTRIBUTION SCET APPROACH (Broggio, Ferroglia, Pecjak et al, 2017) $\Rightarrow$ INCREASE OF CROSS-SECTION
- NLO+NNLL THRESHOLD RESUMMATION $t\bar{t}H$ TOTAL CROSS SECTION & MASS DISTRIBUTION DQCD (Kulesza, Motyka, Stebel, Theeuwes, 2017)
  $\Rightarrow$ CONSIDERABLE STABILIZATION OF SCALE DEPENDENCE
  $\Rightarrow$ REASONABLE AGREEMENT WITH SCET AT NNLL FOR SAME SCALE CHOICE, DIFFERENT HANDLING OF SCALES AND MHOU ESTIMATES
- NLO MEPS QCD+EW $t\bar{t}$ PLUS JET VETO, ONE JET, MULTI-JET MERGED (Gütschow, Lindert, Schönherr, 2018) $\Rightarrow$ LARGE EW SUDAKOV AT LARGE p_t, $Mt\bar{t}$
- OFF-SHELL WITH DECAYS TO $b\bar{b}\, W^+W^-$ WITH POWHEG NLO+PS (Heinrich, Maier, Nisius, Schlenk, Schulze, Scyboz, Winter, 2018)
  DITTO PLUS JET AT NLO (Bevilacqua, Hartanto, Kraus, Worek 2016-2018)
  $\Rightarrow$ TOP MASS DETERMINATIONS

$\bar{t}t$ TOTAL SCET RESUM



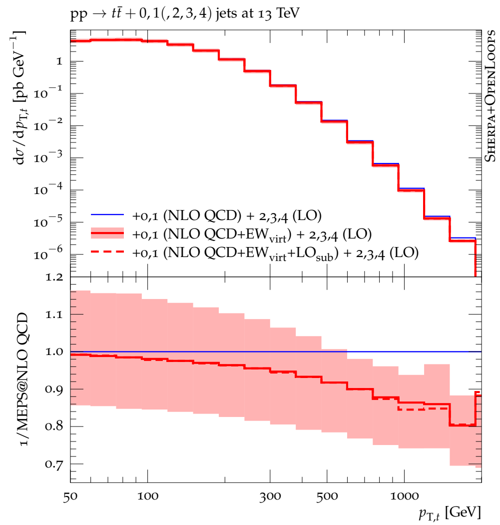
(Broggio et al.)

$\bar{t}t$ TOTAL DQCD RESUM



(Kulesza et al.)

$t\bar{t}\ p_t$ SPECTRUM, JET MERGED



(Gütschow et al.)

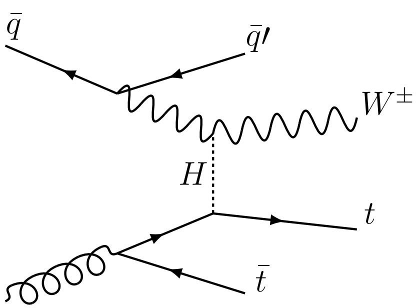
ASSOCIATED PRODUCTION OF TOP PAIRS

$t\bar{t}W$ WITH FULL EW CORRECTIONS

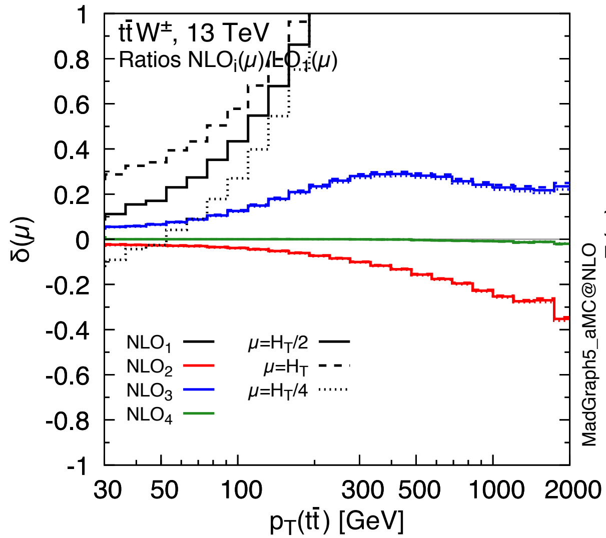
(Frederix, Pagani, Zaro, 2018)

- FULL NLO QCD-EW CORRECTIONS COMPUTED: $O(\alpha_s^4)$ (NLO$_1$), $O(\alpha_s^3\alpha)$ (NLO$_2$), $O(\alpha_s^2\alpha^2)$ (NLO$_3$) $O(\alpha^4)$ (NLO$_4$)
- NAIVE COUNTING $O(\alpha) = O(\alpha_s^2) = O(1/100)$ VIOLATED
- LARGE $tW \to tW$ SCATTERING CONTRIBUTIONS, NLO$_3$=20% OF NLO$_1$ AT LHC13! (WOULD BE 70% AT FCC!)

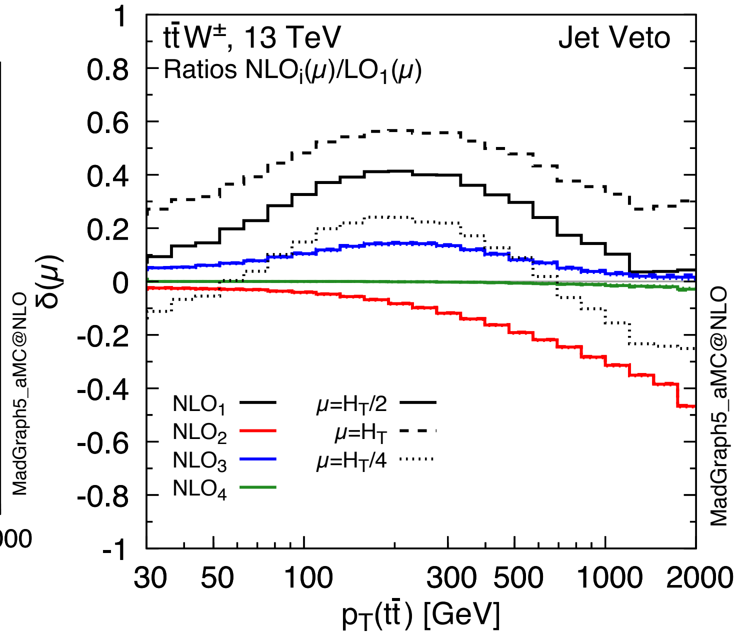
$t\bar{t}W$ WITH FULL EW CORRECTIONS



$t\bar{t}$ p_t SPECTRUM



$t\bar{t}$ p_t SPECTRUM - JET VETO

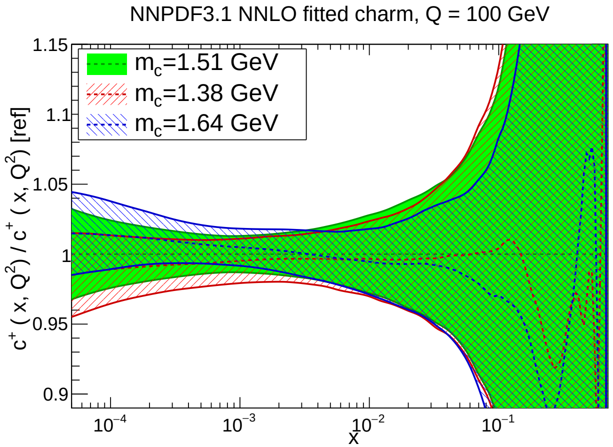


HEAVY QUARKS IN THE INTIAL STATE

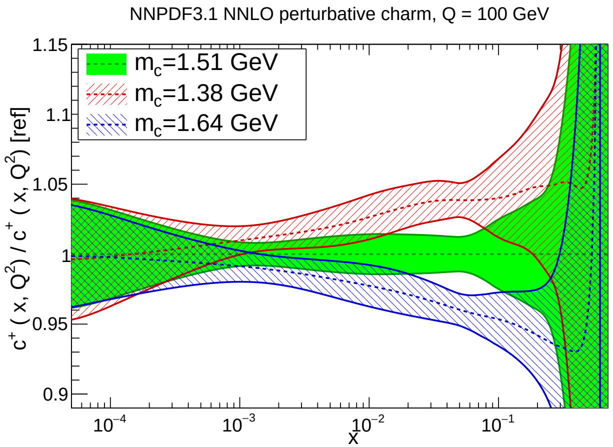
METHODOLOGICAL PROGRESS:
CHARM FROM DATA

- CHARM PDF SHOULD NOT DEPEND STRONGLY ON CHARM MASS

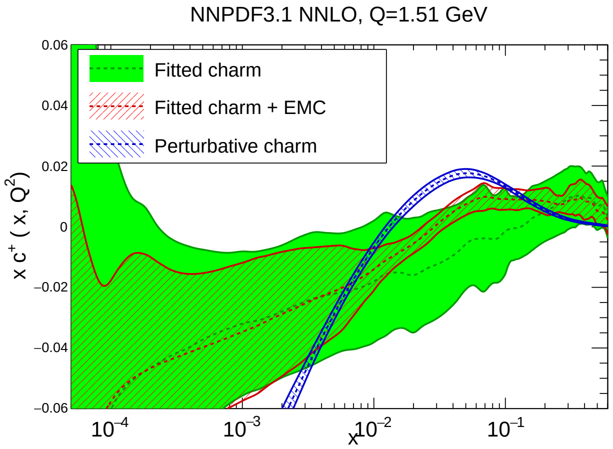
FITTED CHARM VS m_c



PERTURBATIVE CHARM VS m_c



FITTED VS. PERTURBATIVE CHARM



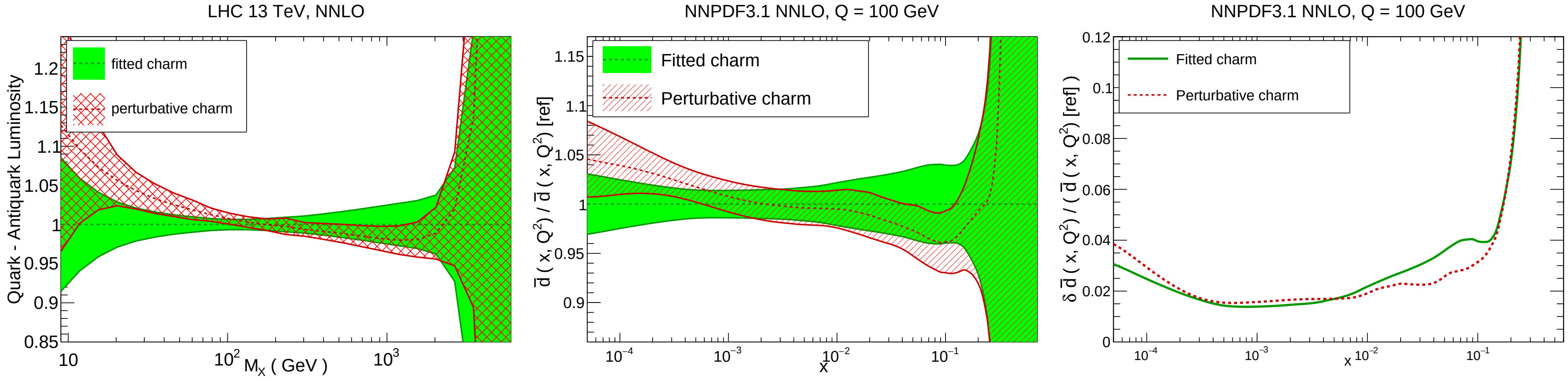
- ITS SHAPE SHOULD NOT BE DETERMINED BY FIRST-ORDER MATCHING (NO HIGHER NONTRIVIAL ORDERS KNOWN)
- MIGHT EVEN HAVE A NONPERTURBATIVE COMPONENT

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

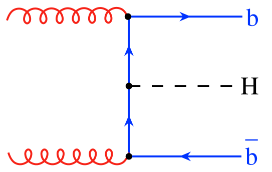


- QUARK (ESPECIALLY QUARK-ANTIQUARK) LUMI AFFECTED BECAUSE OF CHARM SUPPRESSION AT MEDIUM-x
- FLAVOR DECOMPOSITION ALTERED
- UNCERTAINTIES ON LIGHT QUARKS NOT SIGNIFICANTLY INCREASED
- AGREEMENT OF 13TeV W,Z PREDICTED CROSS-SECTIONS IMPROVES!

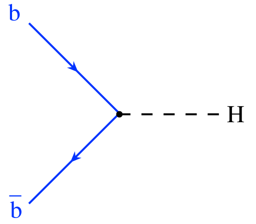
AN OLD PROBLEM: MASSIVE QUARK SCHEMES

EXAMPLE: $b\bar{b} \to H$

LO 4 FLAVORS



LO 5 FLAVORS



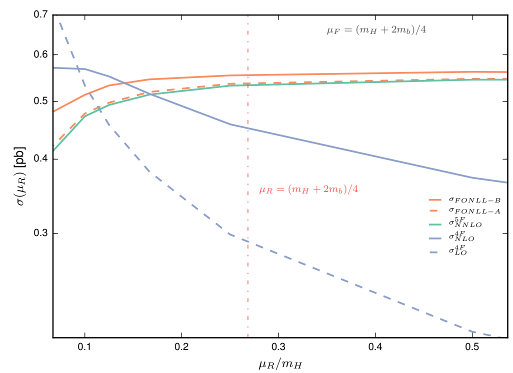
- 4FS $\Rightarrow$ MASSIVE B, NO b IN DGLAP EVOLUTION AND β FUNCTION
- 5FS $\Rightarrow$ Mb IN DGLAP EVOLUTION AND β FUNCTION BUT b MASS NEGLECTED

CLASSIC SOLUTION: MATCHED SCHEMES (FONLL, ACOT,. . .)

- COLLINEAR FACTORIZATION ALSO HOLDS FOR MASSIVE QUARKS (Collins, 1998)
- RE-EXPRESS 4FS IN TERMS OF 5FS (OR VICE-VERSA)
- COMBINE & SUBTRACT DOUBLE COUNTING
- YES?:
  - $b\bar{b}H$: PERTURBATIVE INSTABILITY OF 4FS REMOVED BY RE-SUMMATION
  - MASS CORRECTIONS NEEDED FOR PERCENTAGE ACCURACY, EVEN FOR TOTAL XSECTS
- NO?:
  - CUMBERSOME, ESPECIALLY FOR DIFFERENTIAL OBSERV-ABLES
  - NOT EASY TO IMPLEMENT/INTERFACE IN MONTECARLOS
- ALTERNATIVES? DEPENDS....(ON PROCESS)

4FS, 5FS VS MATCHED (FONLL)

RENORM. SCALE DEP.

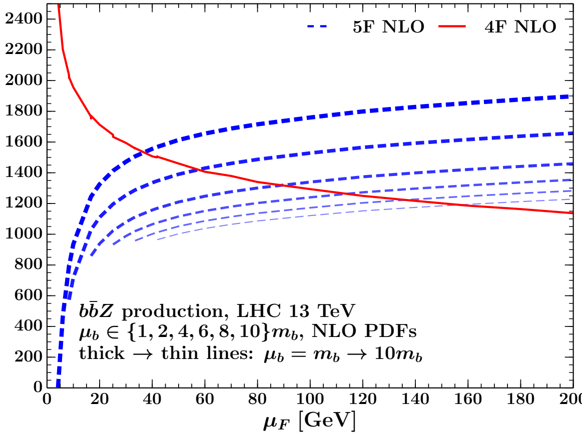


TUNING THE MATCHING SCALE?

- HIGH CHOICE OF MATCHING SCALE $\mu_m \sim 10 m_h$:(Mitov et al., 2017)
  - INITIAL HQ PDF PERTUBATIVELY ACCURATE
  - RESUMMATION OF HQ LOGS SUPPRESSED
  - CONSTANT VS LOGS!
- TOY CASE $b\bar{b}Z$ / $b\bar{b}H$:
  - 4FS & 5FS GET CLOSER AT HIGHER MATHCHING SCALE
  - BUT 4FS $\rightarrow$ STRONG μ_r DEPENDENCE, PERT. INSTABILITY
  - COMPARISON TO MATCHED: LOGS DOMINATE OVER CONST.

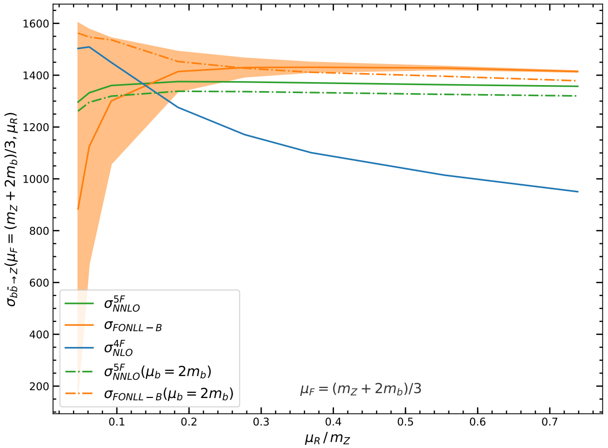
$Zb\bar{b}$

SCALE DEP. VS. MATCHING

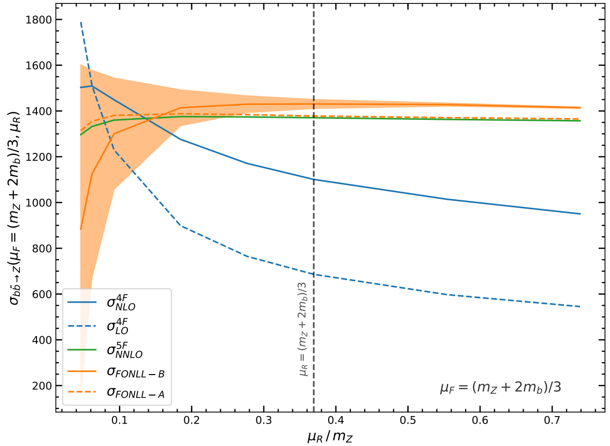


(Bertone, Glazov, Mitov, Papanastasiou, Ubiali, 2017)

SCALE DEP.: MATCHING SCALE



SCALE DEP.: PERT. STABILITY



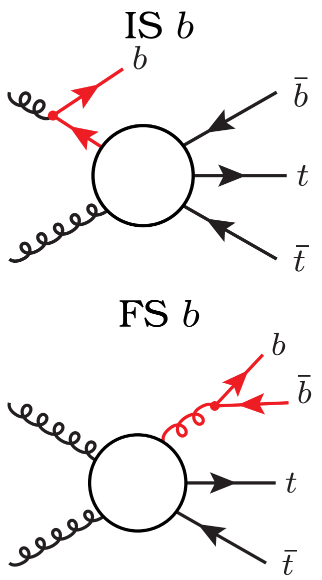
(SF, Napoletano, Ubiali, 2018)

SHOWERING BS

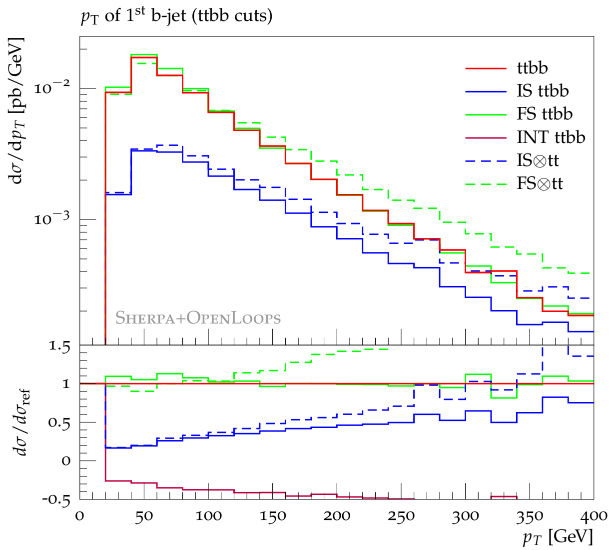
$t\bar{t} + b$-jet

(Jezo, Lindert, Moretti, Pozzorini, 2018)

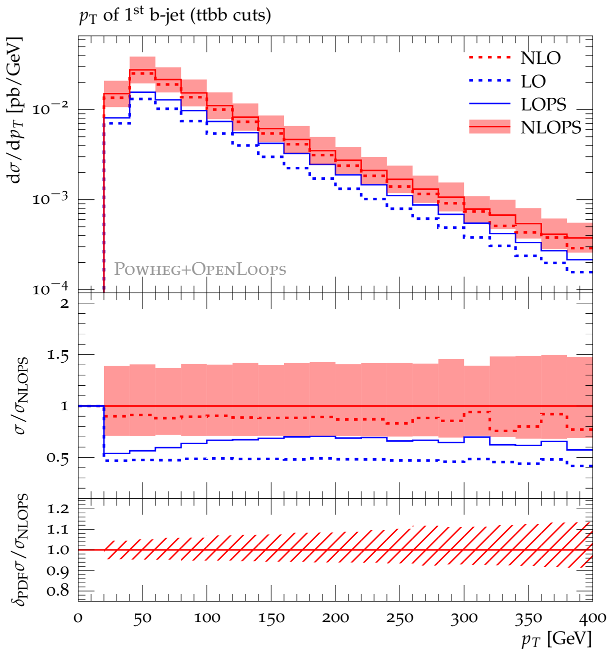
- IN 5FS, B-JET MOSTLY DRIVEN BY PS, NEGLIGIBLE MATRIX ELEMENT
- IN 4FS, DOMINANT CONTRIBUTION FROM FS GLUON SPLIITING
- NEW POWHEG GENERATOR: 4FS+NLOPS $\Rightarrow$ PS EFFECTS MODERATE, $\sim 10\%$ AT LARGE p_T FOR $t\bar{t}b\bar{b}$.



p_T OF b-JET: IS VS FS



p_T OF b-JET: PERT. ORDERS



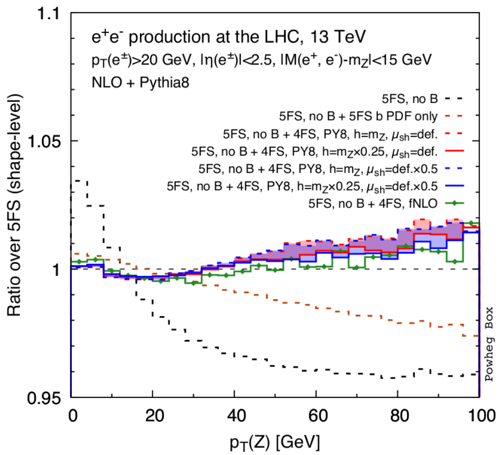
APPROXIMATE 4FS-5FS PS MATCHING

W Z production and the W mass

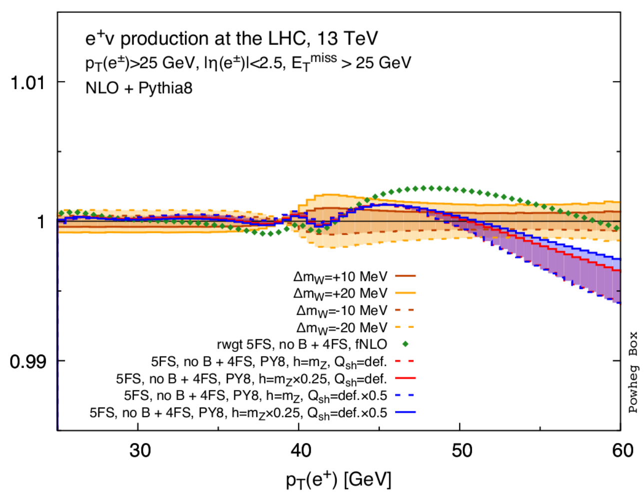
(Bagnaschi, Maltoni, Vicini, Zaro, 2018)

- MATCH 4FS WITH MASS EFFECTS TO 5FS PS & SUBTRACT (VETO) ALL FINAL STATE bS
- TUNE MATCHING SCHEME TO Z PRODUCTION
- USE FOR W PRODUCTION $\Rightarrow \Delta M_W \sim 5$ GeV EFFECT ON M_W DETERMINATION

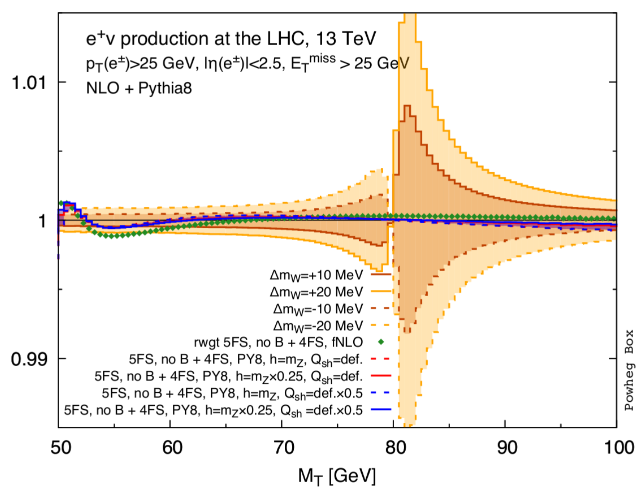
Z: IMPROVED TUNES VS 5FS



p_T LEPTON



M_W TEMPLATES VS. IMPROVED TUNES m_t



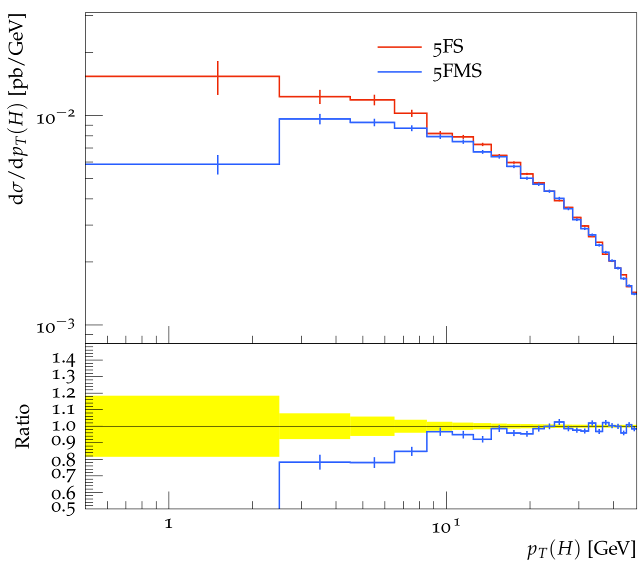
MASSIVE EVOLUTION

(Krauss, Napoletano, 2018)

- MASSIVE FIVE-FLAVOR SCHEME: MASS INCLUDED IN SPLITTING KERNELS
- +: 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

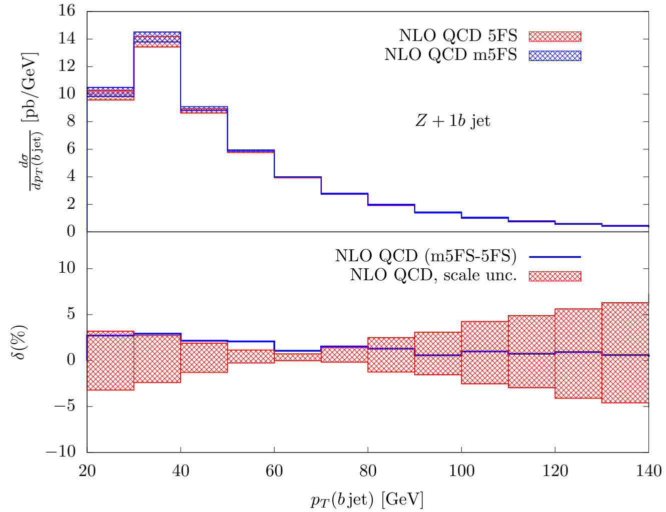
5FS VS MFS

$b\bar{b} \to H$



(Krauss, Napoletano, 2018)

Z+B: p_t SPECTRUM OF B JET



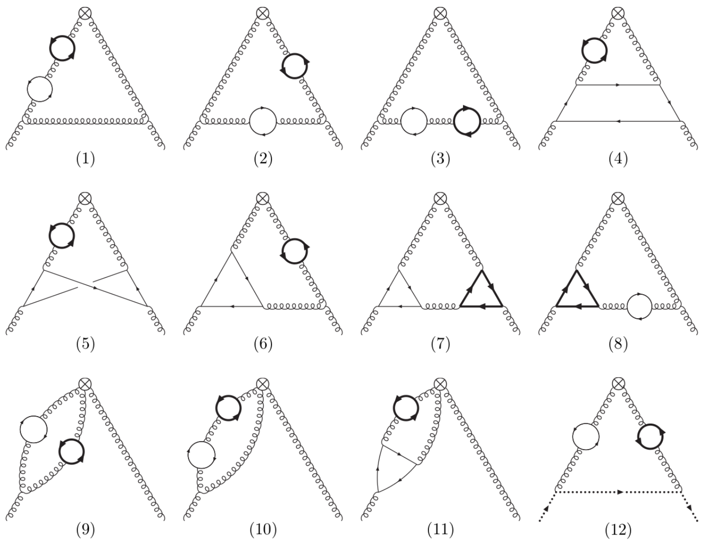
(Figueroa, Honeywell, Quackenbusch, Reina, Reuschle, Wackeroth, 2018)

TWO HEAVY QUARKS!

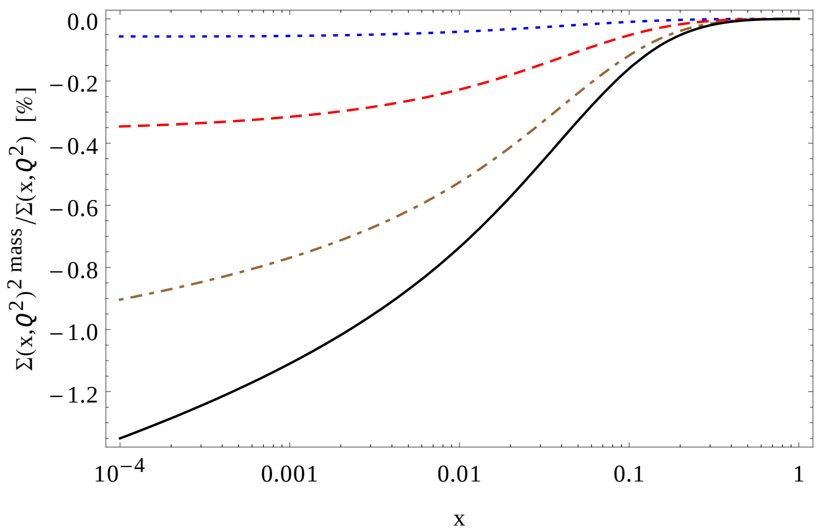
((Ablinger), Blümlein, De Freitas, (Goedicke), Schneider, Scönwald, 2017-2018)

- m_b, m_c NOT SO DIFFERENT: DECOUPLE BOTH AT ONCE:
  - IN 3FS-5FS MATCHING, RETAIN $\ln m_b/\mu^2 \ln m_c/\mu^2$ TERMS
  - IN 3FS (MASSIVE) RETAIN FULL DEPENDENCE ON m_b^2/m_c^2 RATIO
- VFN SCHEME FULLY AVAILABLE AT NLO
- TWO-MASS GLUONIC OPERATOR ME FULLY AVAILABLE AT THREE LOOPS
- TWO-MASS GM-VFSN (FONL, ACOT)?
- TWO-MASS MATCHING AT OR BELOW PERCENT OF TOTAL

3 LOOP TOPOLOGIES



SINGLET: MATCHED VS TOTAL

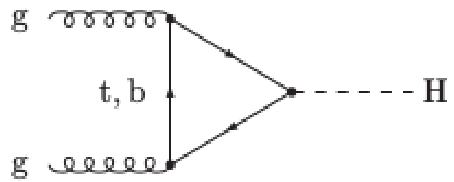


HEAVY QUARKS IN LOOPS

HIGGS IN GLUON FUSION (TOTAL XSECT)

THE PROBLEM?: MULTISCALE!

- EXACT RESULT ONLY KNOWN UP TO NLO, HEAVY TOP UP TO N^3LO
- 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

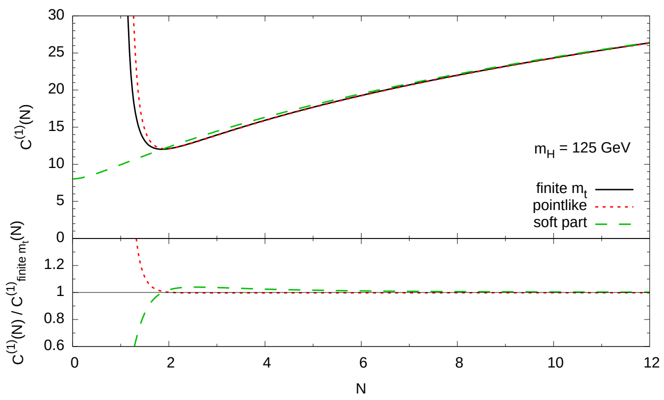


AT LHC 13

- 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)

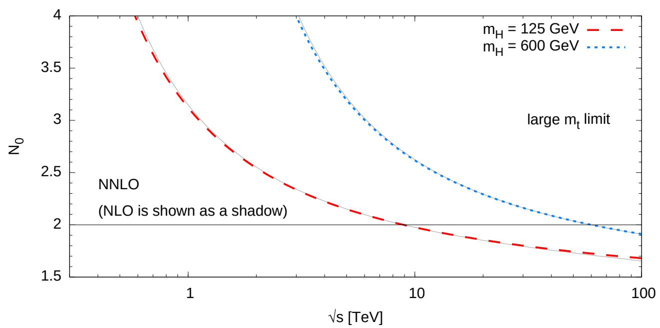
NLO N-SPACE PARTONIC XSECT

EFT VS EXACT BEHAVIOUR



	$\overline{\text{MS}}$	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%

SADDLE POINT VS COLL. ENERGY

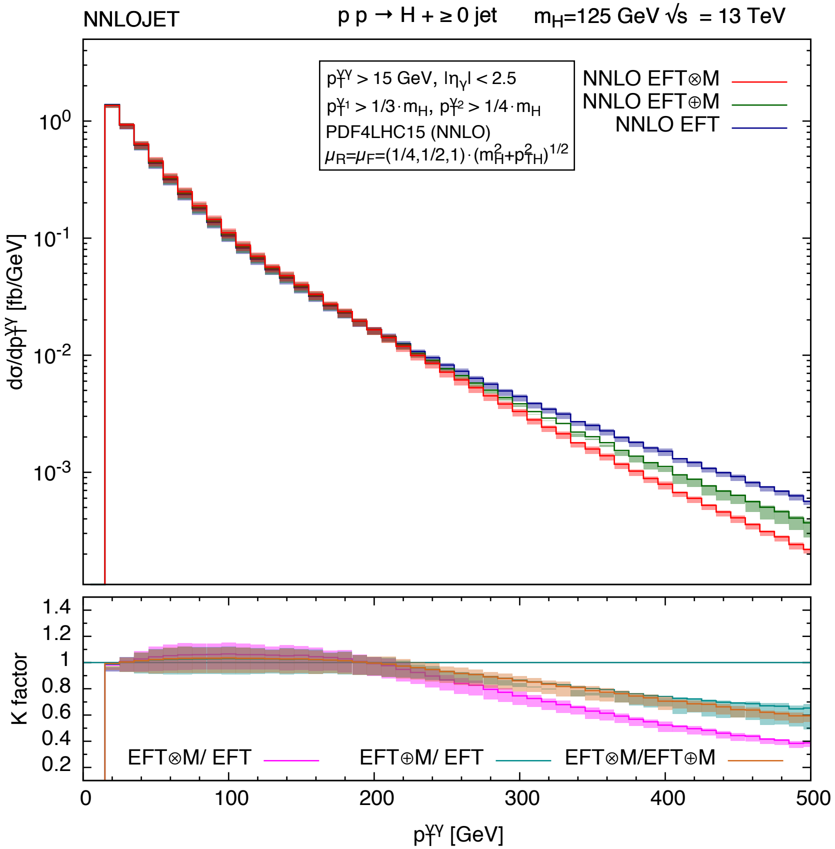


HIGGS IN GLUON FUSION (p_T SPECTRUM)

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



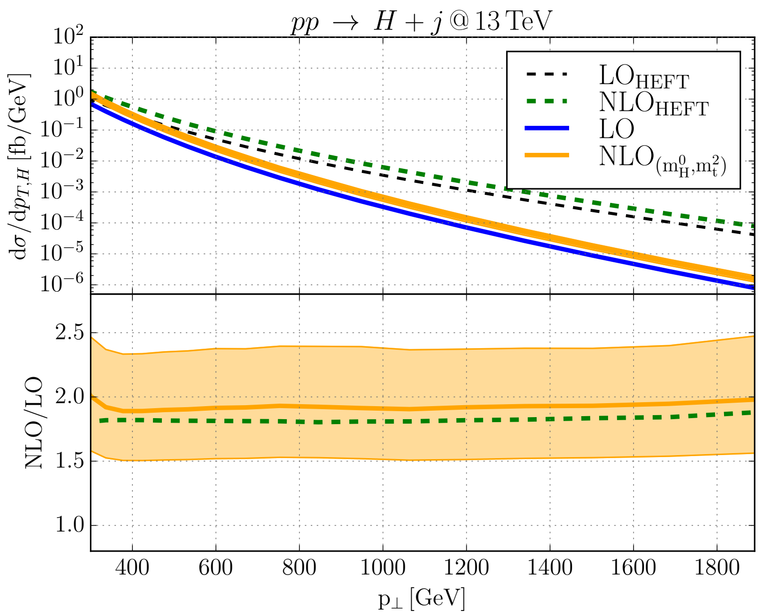
(Chen, Cruz-Martinez, Gehrmann, Glover, Jacquier, 2016)

- $R^{LO}(p_T) = \left(\frac{d\sigma_{LO}^{m_t, m_b, m_c}}{dp_T} \Big/ \frac{d\sigma_{LO}^{EFT}}{dp_T} \right)$
- EFT$\otimes$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

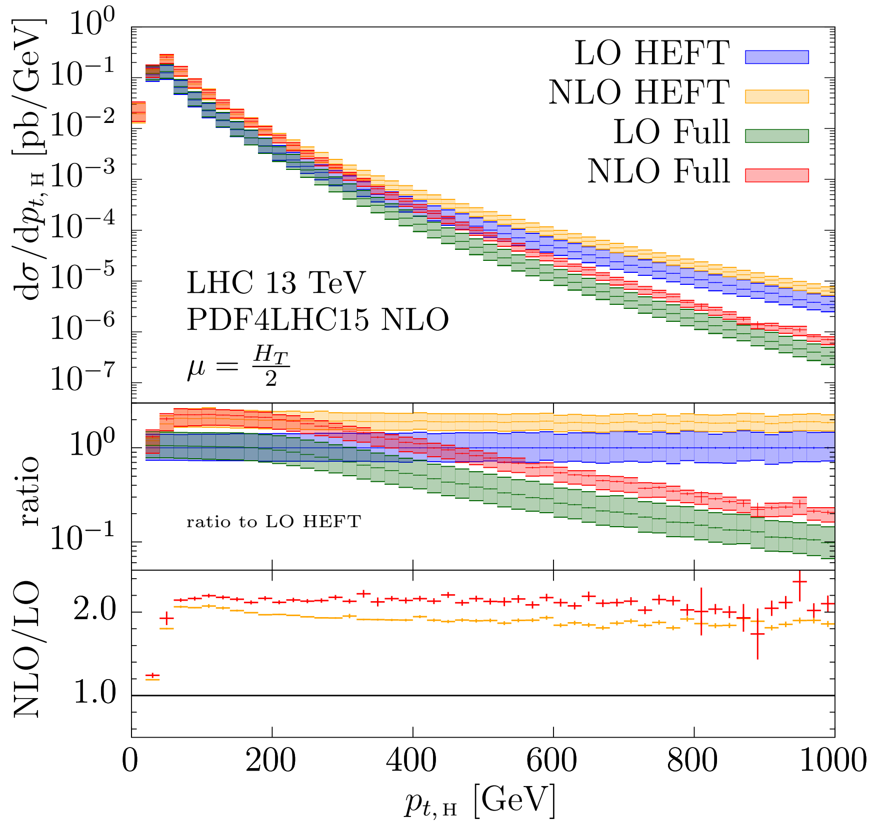
- ELUCIDATED BY HIGH-ENERGY LIMIT
- LEADING POWER BEHAVIOUR DIFFERS BETWEEN EFT AND WITH MASS DEPENDENCE, BUT IS SAME TO ALL ORDERS

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 PARMS FOR FIXED KINEMATICS, THEN INTERPOLATED



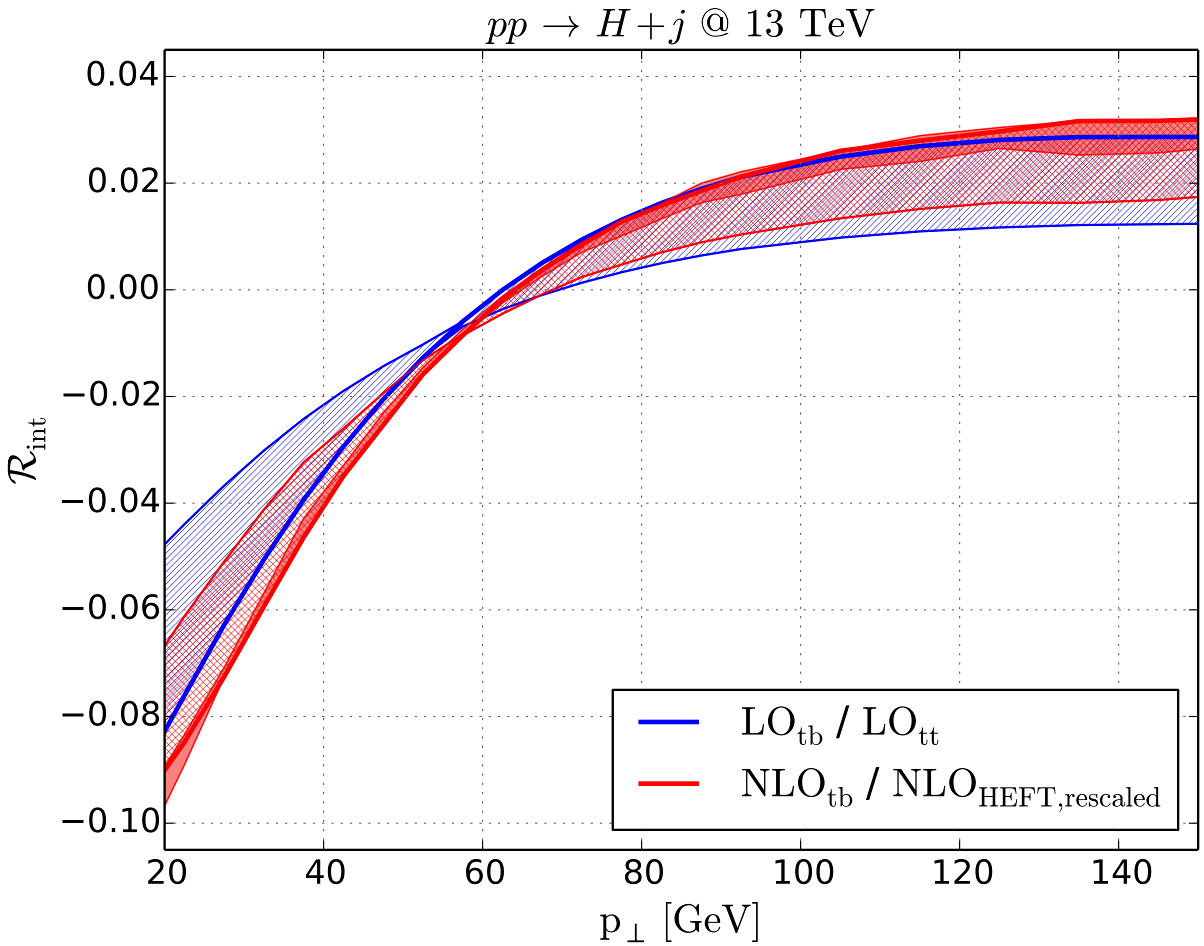
(Lindert, Kudashin, Melnikov, Wever, 2018)



(Jones, Kerner, Luisoni, 2018)

HIGGS IN GLUON FUSION (p_T SPECTRUM)

WHAT'S THE PROBLEM WITH THE B MASS



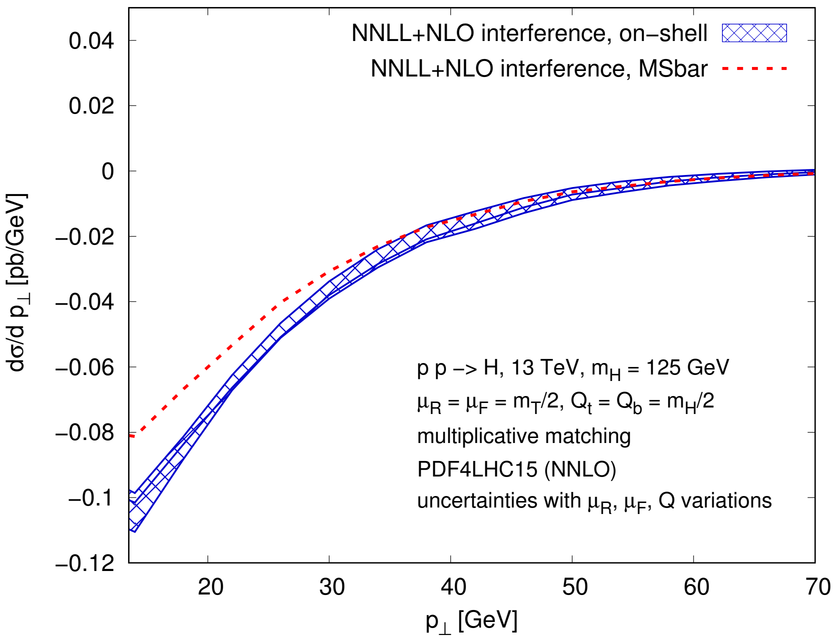
- $A^b_{gg\to Hg} \sim m_b^2/m_H^2 \ln^2(p_T^2/m_b^2) \Rightarrow$ SUDAKOV-LIKE NON-SUDAKOV DOUBLE LOGS FROM BOTTOM LOOPS, RESUMMED TO ALL ORDERS IN ABELIAN LIMIT (Melnikov, Penin, 2016)
- LARGE tb INTERFERENCE, MUST EXTRACT NON-ANALYTIC TERM WHEN EXPANDING IN m_b
- CORRECTION AS LARGE AS 10% FOR $p_T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

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

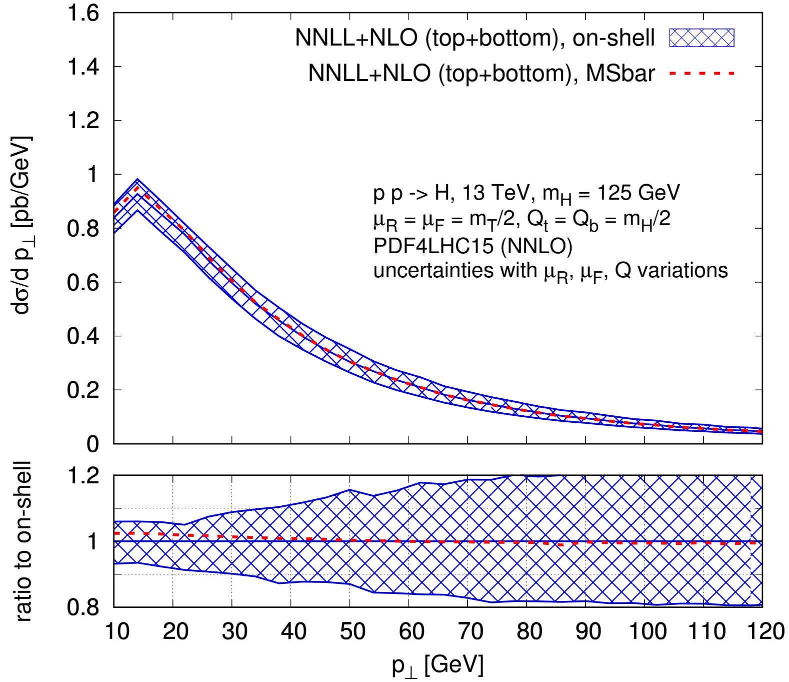
(Caola, Lindert, Melnikov, Monni, Tancredi, Wever, 2017)

- 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



THE TOP MASS

WHICH MASS?

if $m_t(m_t) = 163.6$ GeV, to four loops $m_p = 163.643 + 7.557 + 1.617 + 0.501 + 0.195$

(Marquard, Smirnov, Smirnov, Steinhauser, 2015)

RENORMALON ESTIMATE OF REMAINDER (AMBIGUITY):

$$\Delta^{(5+)} m_p = 0.304^{+0.012}_{-0.063}(N) \pm 0.030(m_{b,\,c}) \pm 0.009(\alpha_s) \pm 0.108(\text{ambiguity})\ \text{GeV}$$

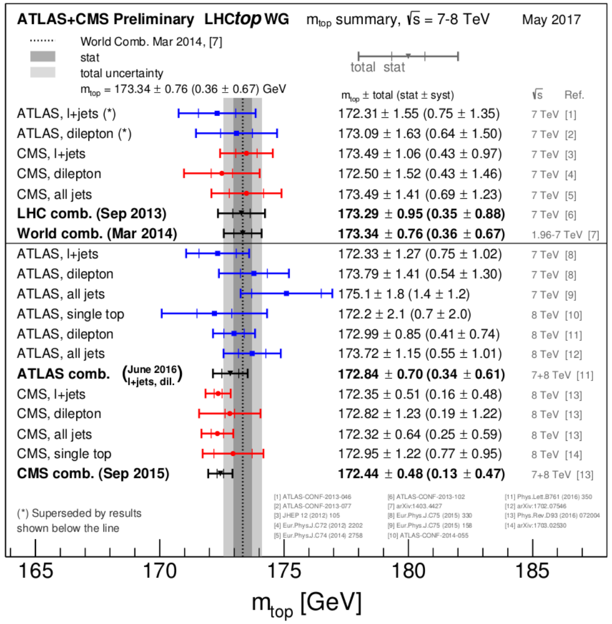
110 MeV AMBIGUITY SMALLER THAN LHC ACCURACY BUT LARGER THAN FUTURE e^+e^- LINEAR COLLIDER

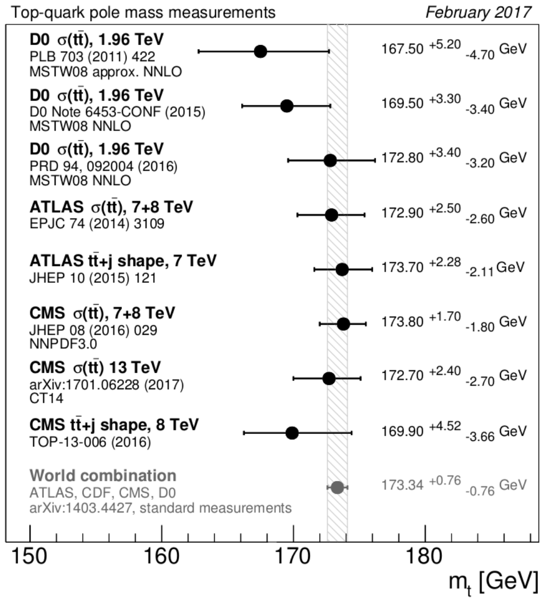
(Beneke, Marquard, Steinhauser, Nason, 2017)

- RENORMALON AFFECTS RELATION BETWEEN POLE & $\overline{\text{MS}}$ MASS
- KINEMATIC OBSERVABLES DEPEND ON POLE MASS
  $\Rightarrow$ ALL-ORDER QUANTITY MEASURABLE
- SHORT-DISTANCE COMPUTABLE PROPERTIES DEPEND ON $\overline{\text{MS}}$ MASS
  $\Rightarrow$ FINITE-ORDER QUANTITY COMPUTABLE
- TRADEOFF:
  - DIRECT MEASUREMENTS DETERMINE ALL-ORDER QUANTITY
    CURRENTLY MOST ACCURATE
  - CROSS-SECTION "OFF-SHELL" MEASUREMENTS DETERMINE PERTURBATIVELY COMPUTABLE SHORT-DISTANCE QUANTITY

"MC MASS?": AN ONGOING DEBATE

Controversies: Pole mass versus "?"





- Some measurements are classified as "Pole Mass" measurements
- Direct measurements do not state what they measure, or are presented as "Monte Carlo mass measurements".
- EW fits, or vacuum stability studies, use the mass from direct measurements as "Pole mass", often enlarging the error.

(Corcella, Hoang, Yokoya Nason, CERN HL WS, June 2018)

EMERGING CONSENSUS?

- MASS FROM DIRECT MEASUREMENTS DIFFERS FROM POLE MASS BY NON-PERTURBATIVE CORRECTIONS $\Rightarrow$ "MC" MASS:
  - ~~VIEW A: MC MASS & POLE MASS COULD DIFFER BY~~ $\cancel{m_t \alpha_s(m_t)}$ ~~(SCHEME CHOICE)~~
  - VIEW H: RELATE GENERATOR MASS WITH SHOWER CUTOFF Q_0 TO SHORT-DISTANCE $m(Q_0)$ & COMPUTE IT
  - VIEW N: ESTIMATE NONPERTURBATIVE $O(\Lambda)$ CORRECTIONS FROM MC

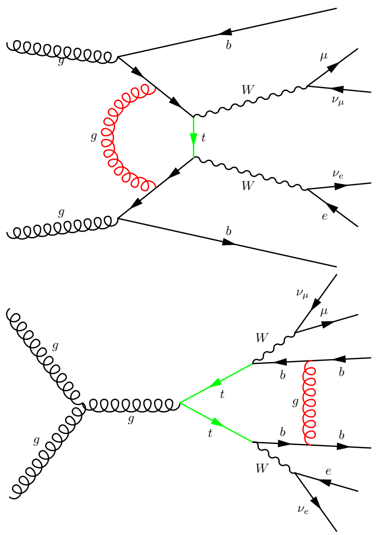
PROGRESS!

- OFF-SHELL CROSS-SECTIONS COMPUTATIONS
- SCET COMPUTATION OF SHOWER PEAK MASS
- DETAILED STUDIES OF THE UNCERTAINTIES & GENERATOR DEPENDENCE

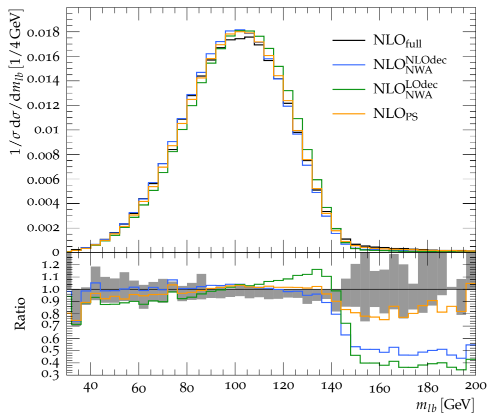
OFF-SHELL COMPUTATIONS I

(Henirich, Maier, Nisius, Schlenk, Schulze, Scyboz, Winter, 2018)

- FULL NLO COMPUTATION WITH $b\bar{b}4\ell$ FINAL STATE
- VARIABLES: $m_{lb}^2 = (p_\ell + p_b)^2$, m_{T2}, $E_T^{\Delta R}$, $m_{\ell\ell}$, $p_{T,\mu}$, η_μ
- SUBSTANTIAL SHIFTS BETWEEN OFF-SHELL & NWA
- PS PROVIDES GOOD DESCRIPTION

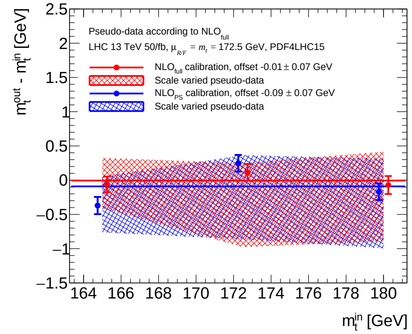


m_{lb} DISTRIBUTION

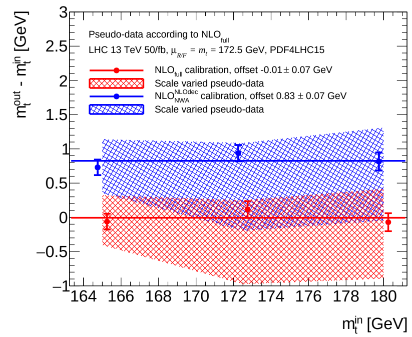


m_t SHIFT

FULL NLO VS PS



OFF-SHELL VS NWA



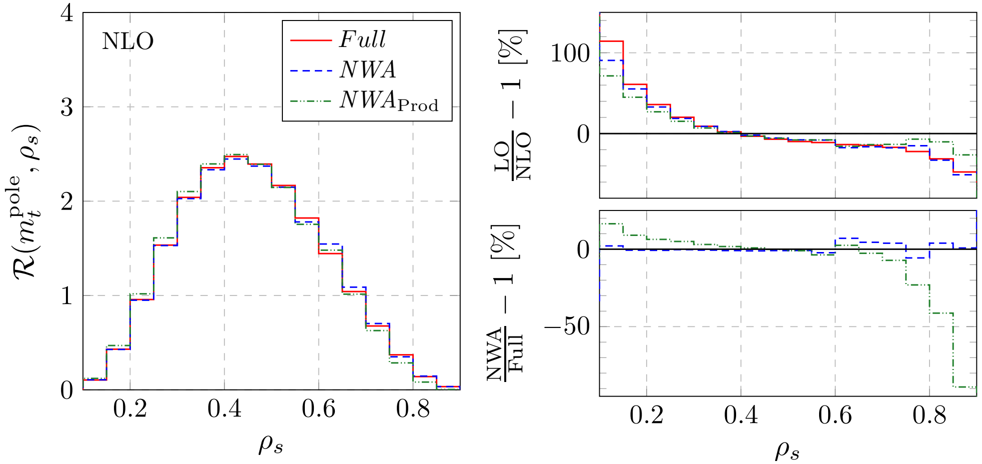
OFF-SHELL COMPUTATIONS II

(Bevilacqua, Hartanto, Kraus, Schulze, Worek, 2018)

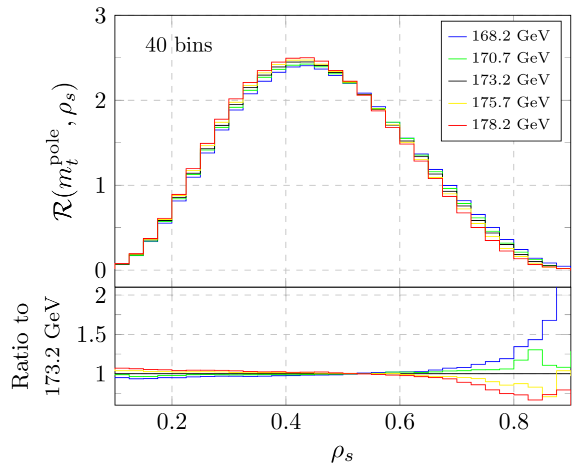
- $t\bar{t}j$, $\rho_s = \frac{340 \text{ GeV}}{M_{ttj}} \Rightarrow$ MASS OF $t\bar{t}j$
- OBSERVABLE: NORMALIZED DIFFERENTIAL CROSS-SECTION
- HIGHER SENSITIVITY TO OFF-SHELL EFFECTS THAN OTHER OBSERVABLES
- SOMEWHAT LOWER SENSITIVITY TO m_t THAN $m_{\bar{t}t}$

ρ_s DIFFERENTIAL DISTRIBUTION

THEORY DEP.



m_t DEP.



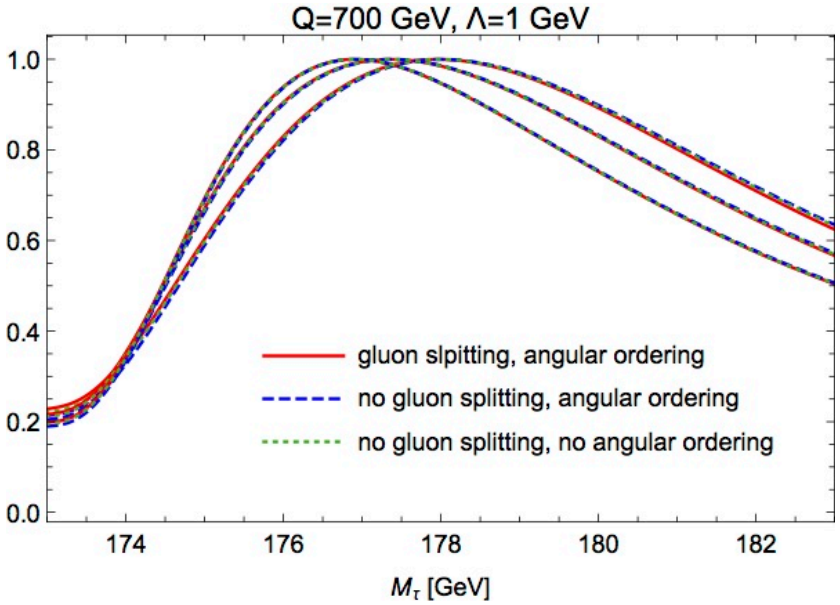
COMPUTING THE SHOWER PEAK MASS

(Hoang, Plätzer, Samitz, 2018)

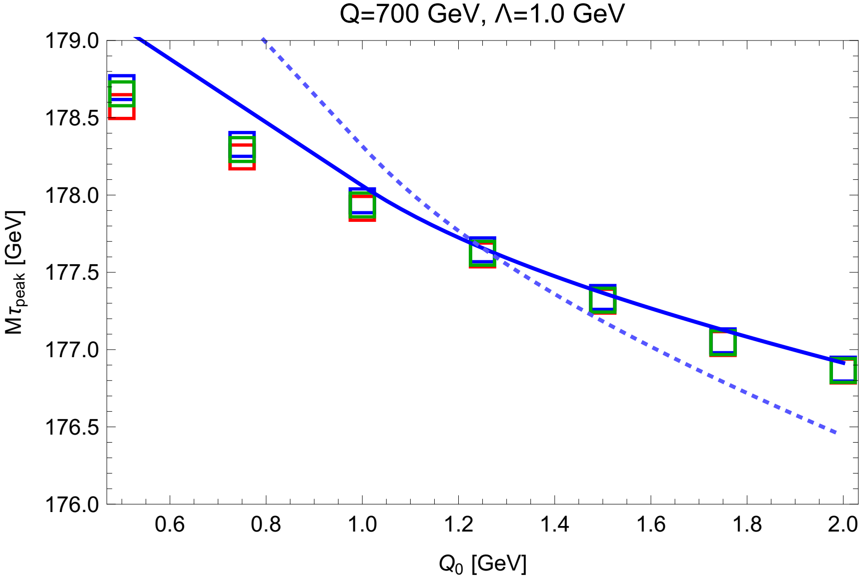
- MASS IN PARTON SHOWER $\Rightarrow$ POLE W/O CUTOFF; BUT SHIFTED BY CUTOFF Q_0
  Q hard scale, Λ nonperturbative scale
- SHIFT COMPUTED IN SCET FOR THRUST & HERWIG, PROPORTIONAL TO $Q_0 \alpha_s(Q_0)$
- EXCELLENT AGREEMENT BETWEEN THEORY & SIMULATION
- IS IT UNIVERSAL?

THRUST DISTRIBUTION

$Q_0 = 1,\ 1.5,\ 2$ GeV



PEAK SHIFT DUE TO CUTOFF

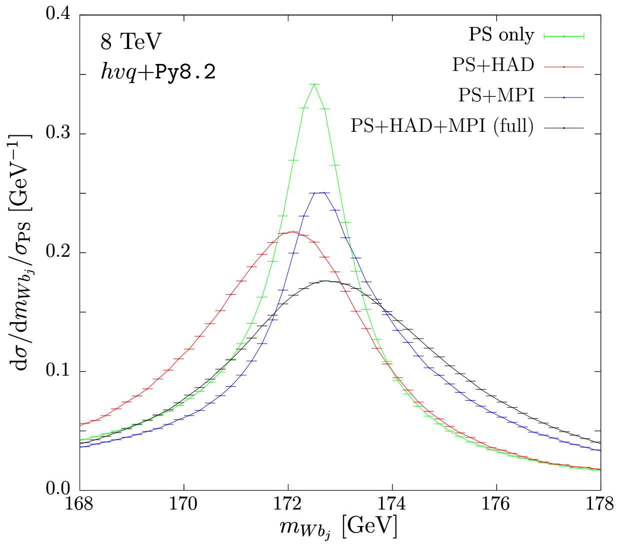


THEORY UNCERTAINTIES AND MC DEPENDENCE

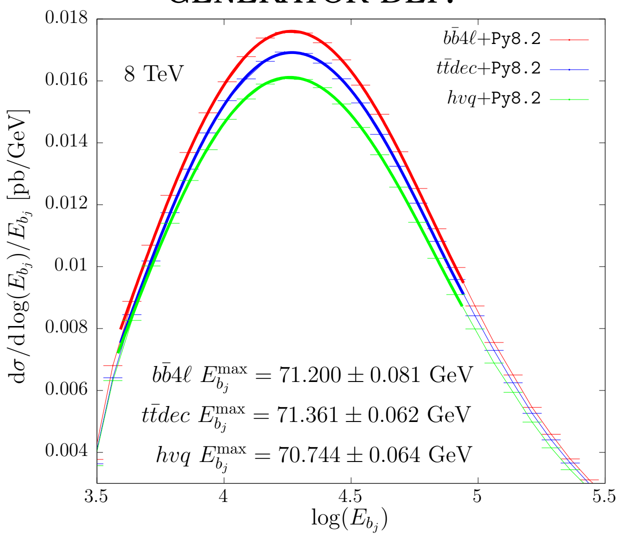
(Ferrario Ravasio, Jezo, Nason, Oleari, 2018)

- m_{Wb_j} DISTRIBUTION COMPUTED AT NLO+PS INCL. HADRONIZATION AND MPI
- EXCELLENT STABILITY W.R. TO SHOWER MODEL WITH PYTHIA
- INSTABILITY WITH HERWIG: MC DEP $\Rightarrow$ EXTRA THEORY UNCERTAINTY

m_{Wb_j} DISTN, VARIOUS APPROX

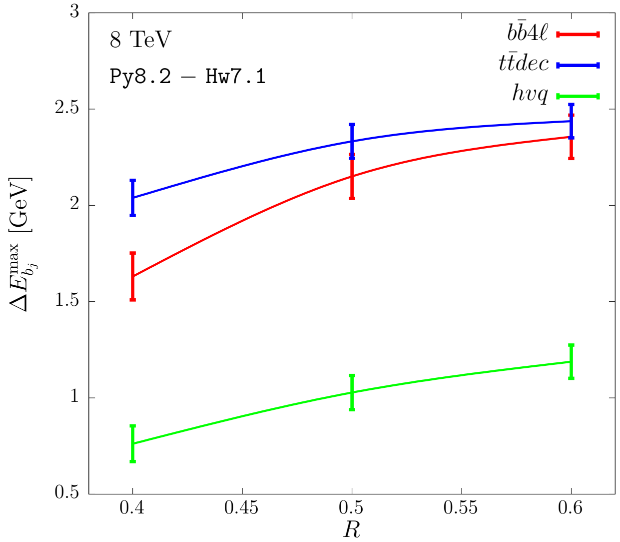


GENERATOR DEP.



HADRONIZATION DEP.

FULL NLO VS PS



SUMMARY

HQ PHYSICS IS TWO-SCALE:

- QCD NNLO MATCHED TO RESUMMATION STANDARD
- EW CORRECTIONS MANDATORY
- OFF-SHELL NEEDED

FRONTIER:

- MORE THAN TWO SCALES
- TOWARDS THE NONPERTURBATIVE REGIME

TAKE HOME MESSAGE:

HEAVY QUARKS…

….ARE GOOD FOR YOUR HEALTH