HEAVY QUARK PRODUCTION

THEORY

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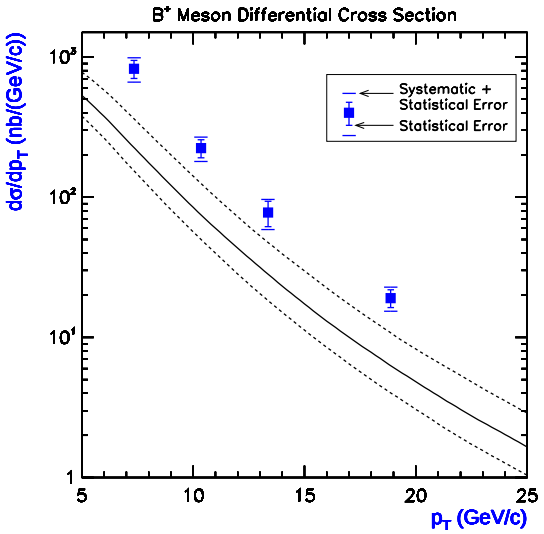
BEAUTY 2013

BOLOGNA, APRIL 8, 2013

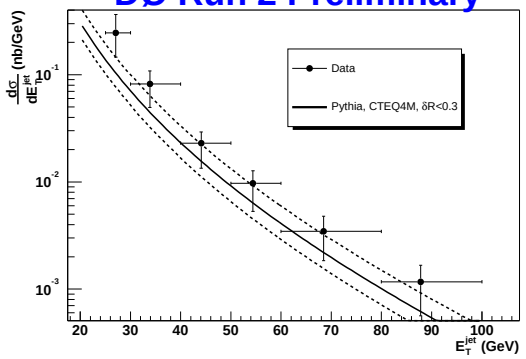
HEAVY QUARK PRODUCTION:
A SUCCESS STORY!

B PRODUCTION: HISTORY

DATA (CDF R,I) VS TH 2001

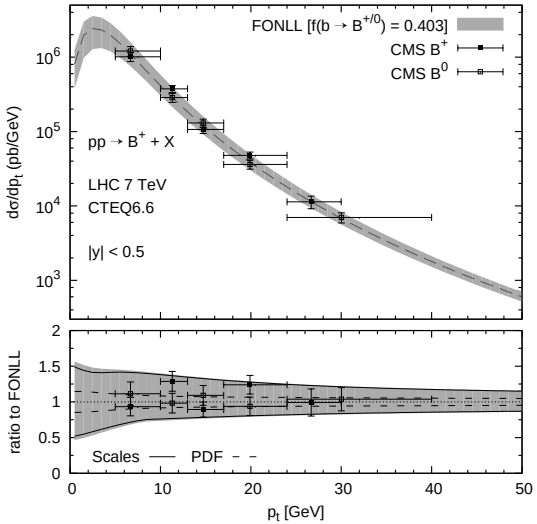


DATA (CDF R.II) VS TH 2003



(CDF, talk at Beauty 2003)

DATA (CMS) VS TH 2012



(Cacciari et al. 2012)

HEAVY QUARK PRODUCTION STRAINS PERTURBATIVE & NONPERTURBATIVE QCD:

- PDFs AND FRAGMENTATION FUNCTIONS
- PERTURBATIVE COMPUTATION AND RESUMMATION
- PARTON SHOWERING AND HADRONIZATION

CHARM AND BEAUTY
THE STATE OF THE ART

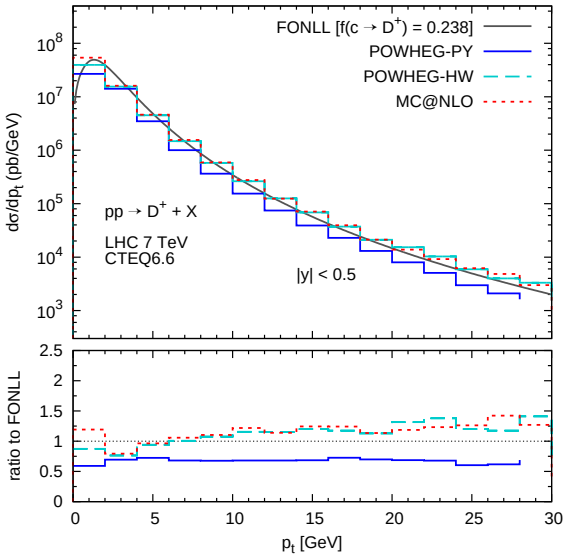
- FONLL
  - COMBINE FIXED ORDER CALCULATION (FO) WITH LEADING-LOG (E.G. p_T) RESUMMATION (NLL) (Cacciari, Greco, Nason, 1998)
  - ORIGINALLY PERFORMED AT NLO+NLL, EACH OF TWO INGREDIENTS CAN BE PUSHED TO HIGH ORDERS
  - AVAILABLE ALSO FOR PHOTOPRODUCTION (Cacciari, Frixione, Nason, 2001) & ELECTROPRODUCTION (S.F.,Laenen, Nason, Rojo, 2010)
  - HADRONIZATION REQUIRES FRAGMENTATION FUNCTION
- NLO+PS
  - COMBINE NLO CALCULATION WITH PARTON SHOWERING: POWHEG (Frixione, Nason, Ridolfi, 2007), MC@NLO (Fixione, Nason, Webber, 2003)
  - CAN MATCH TO HADRONIZATION, FULLY EXCLUSIVE DESCRIPTION OF FINAL STATE
  - ONLY A SUBSET OF LARGE LOGS $\ln P_T/m_q$ RESUMMED

CHARM

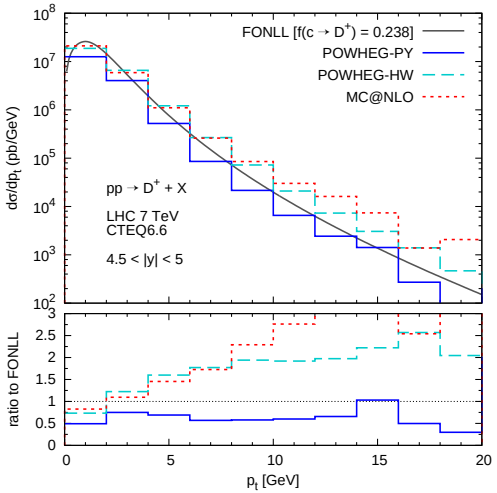
CHARM PRODUCTION:

OPEN CHARM

low rapidity



high rapidity



(Cacciari, Frixione, Houdeau, Mangano, Nason, Ridolfi 2012)

- NONPERTURBATIVE FRAGMENTATION WITH PARM FROM ALEPH
- NLO+PS LOOSES ACCURACY AT LARGE p_t

CHARM PRODUCTION:

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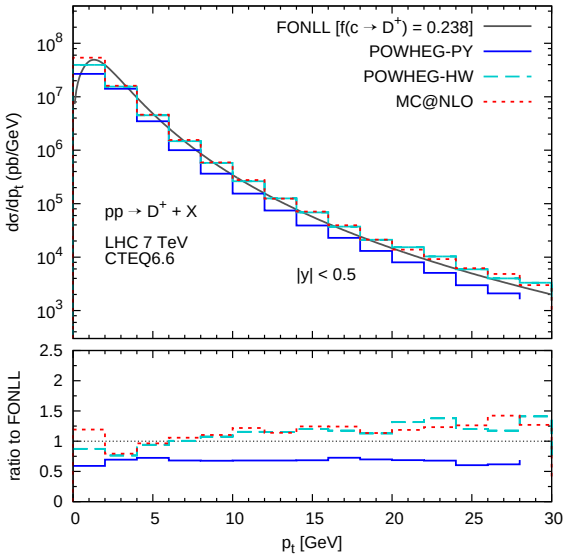

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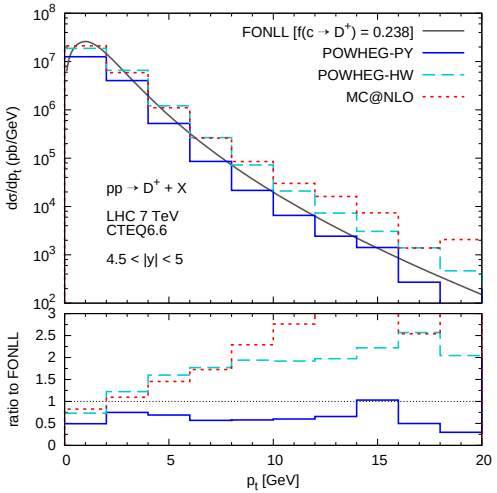
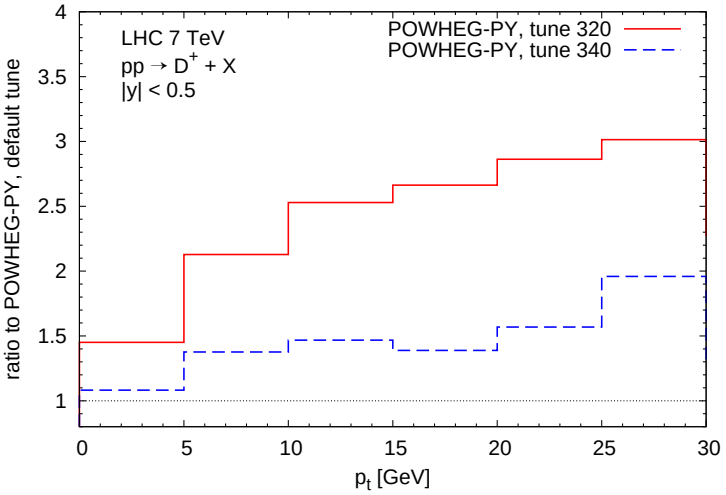


(Cacciari, Frixione, Houdeau, Mangano, Nason, Ridolfi 2012)

DEPENDENCE ON MC TUNES

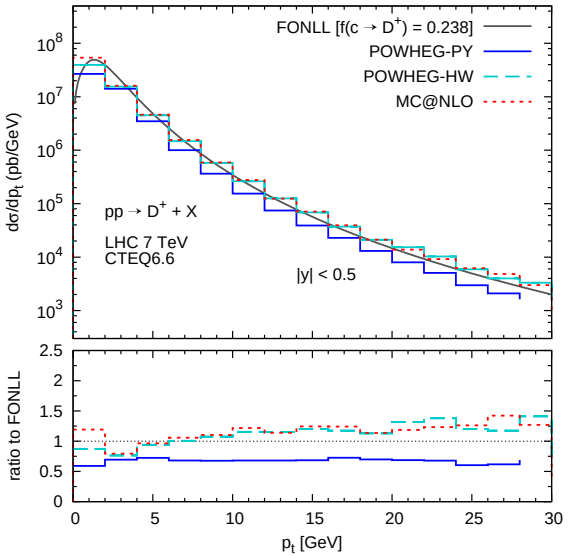


- NONPERTURBATIVE FRAGMENTATION WITH PARM FROM ALEPH
- NLO+PS LOOSES ACCURACY AT LARGE p_t
- SIGNIFICANT DEPENDENCE ON MC TUNE

CHARM PRODUCTION:

OPEN CHARM

low rapidity



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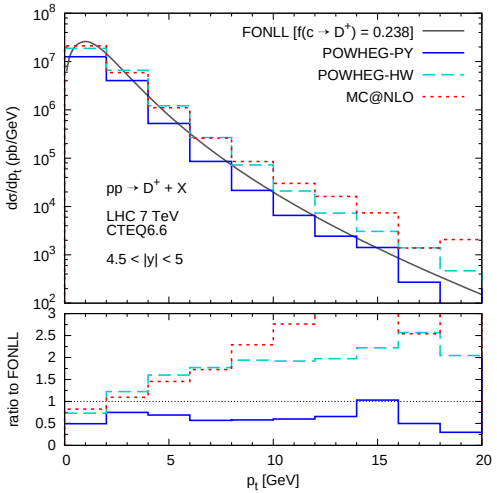

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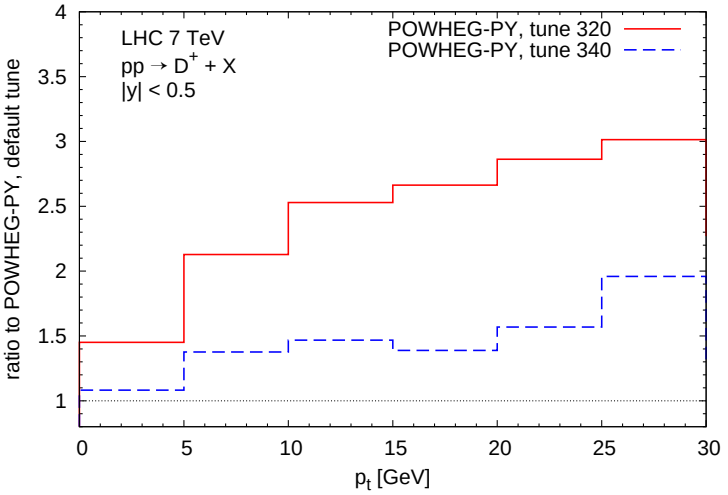
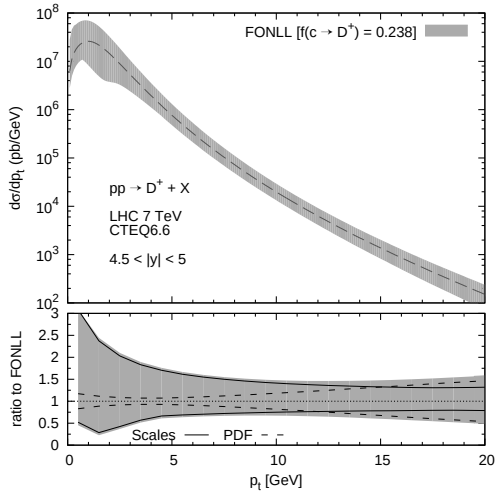
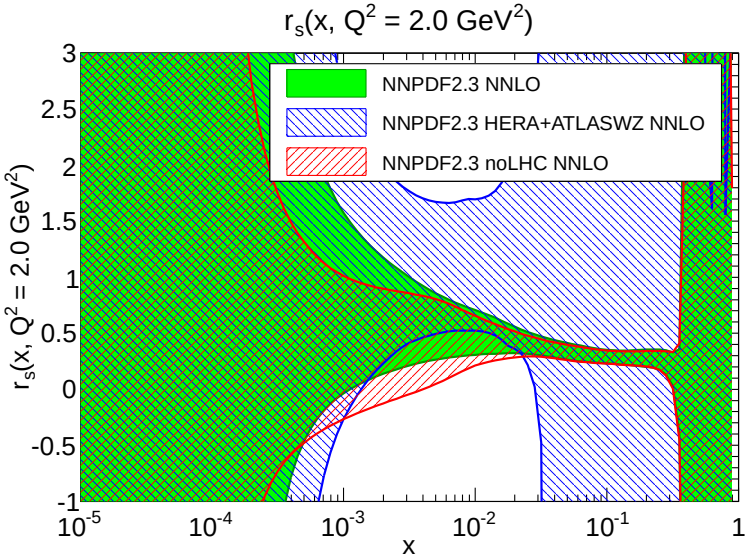


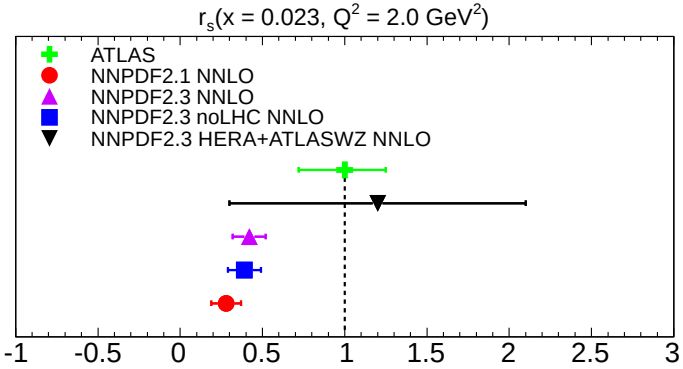
high rapidity TH. UNC.



- NONPERTURBATIVE FRAGMENTATION WITH PARM FROM ALEPH
- NLO+PS LOOSES ACCURACY AT LARGE p_t
- SIGNIFICANT DEPENDENCE ON MC TUNE
- PDF & SCALE UNCERTAINTY COMPARABLE

CHARM PRODUCTION AND NUCLEON STRANGENESS

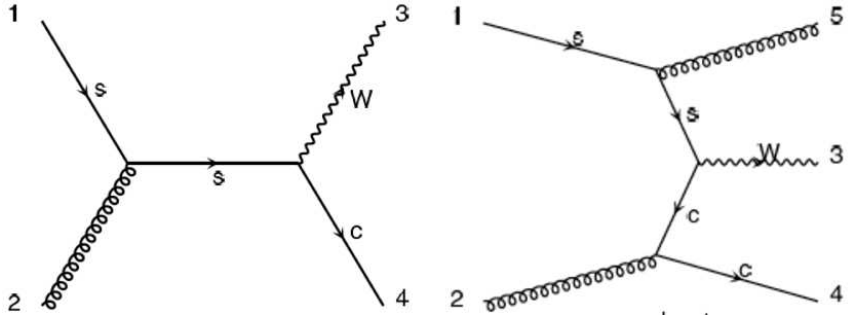




- STRANGE CONTENT OF NUCLEON TRADITIONALLY DETERMINED FROM DEEP-INELASTIC CHARM NEUTRINO-PRODUCTION
- ATLAS (2012) CLAIMS LARGE (≈ 1) VALUE OF $r_s(x, Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{2\bar{d}(x,Q^2)}$
- RESULT BASED ON THE HERAPDF+HERAFITTER APPROACH APPLIED TO HERA+ATLAS INCLUSIVE W PRODUCTION DATA
- NNPDF2.3 FINDS HERA+ATLAS DATA CANNOT DETERMINE STRANGENESS WITH SUFFICIENT ACCURACY

$W + c$ PRODUCTION AT THE LHC

- STRANGENESS PROBED DIRECTLY
- MIGHT REPLACE NEUTRINO DATA



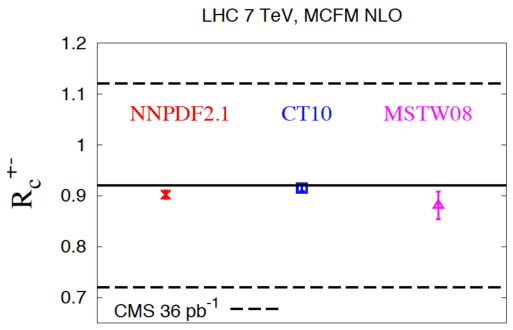
THE CMS MEASUREMENT

$$R_c^{\pm} \equiv \frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)}; \quad R_c \equiv \frac{\sigma(W + c)}{\sigma(W + \text{jets})}$$

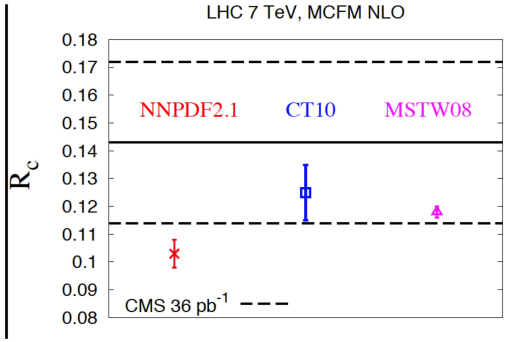
$$R_c^{\pm} = 0.92 \pm 0.19\text{stat.} \pm 0.04\text{syst.}$$
$$R_c = 0.143 \pm 0.015\text{stat.} \pm 0.024\text{syst.}$$

Ratio	MCFM (CT10)	MCFM (MSTW08)	MCFM (NNPDF21)
$R_c^{\pm}$	$0.915^{+0.006}_{-0.006}$	$0.881^{+0.022}_{-0.032}$	0.902 ± 0.008
R_c	$0.125^{+0.013}_{-0.007}$	$0.118^{+0.002}_{-0.002}$	0.103 ± 0.005

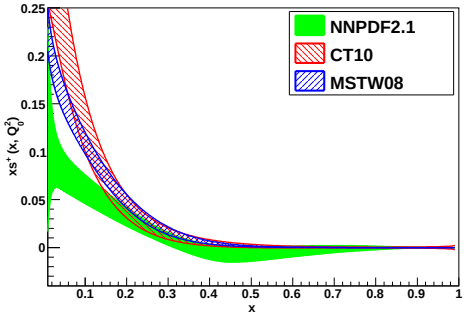
$R_c^{\pm}$ DATA VS TH.



R_c DATA VS TH.



TOTAL STRANGENESS



- DIFFERENCES BETWEEN AVAILABLE SETS SIZABLE
- DATA STILL TOO IMPRECISE, BUT...

$W + c$ PRODUCTION AT THE LHC

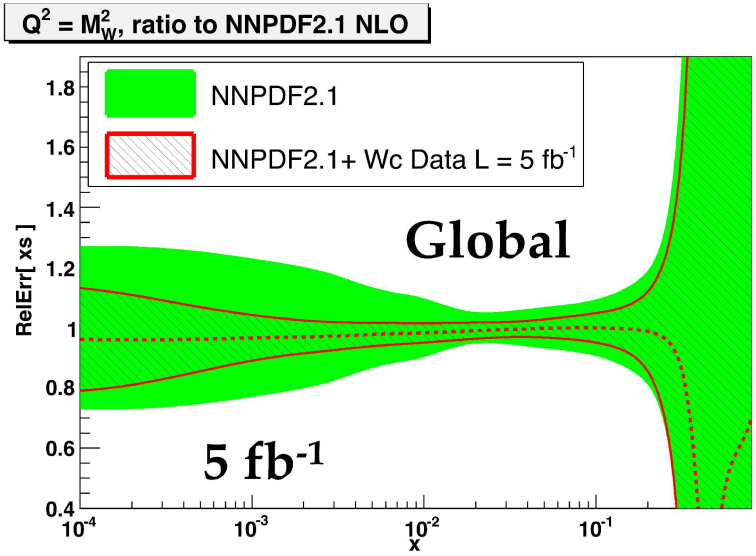
- SIMULATED MEASUREMENT OF c RAPIDITY DISTRIBUTION WITH aMC@NLO

(J. Rojo, S. Frixione, M. Mangano, work in progress.)

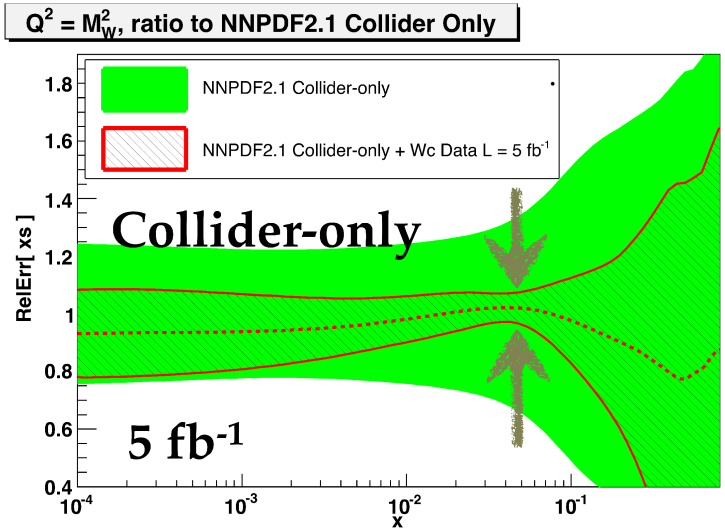
- CMS KINEMATICS $p_T^{\rm jet} > 20$ GeV, $p_T^{\mu} > 25$ GeV $\eta^{\rm jet}$, $\eta^{\mu} < 2.1$
- 15% CHARM TAGGING EFFICIENCY (CMS)
- CURRENTLY 36 PB^{-1}, BUT 5 FB^{-1} SUFFICIENT

THE IMPACT ON STRANGENESS

IN THE NNPDF2.1 FIT



IN THE COLLIDER-ONLY FIT



- IMPACT SIGNIFICANT EVEN ON CURRENT GLOBAL FIT
- COULD DO WITHOUT NEUTRINO DATA

BEAUTY

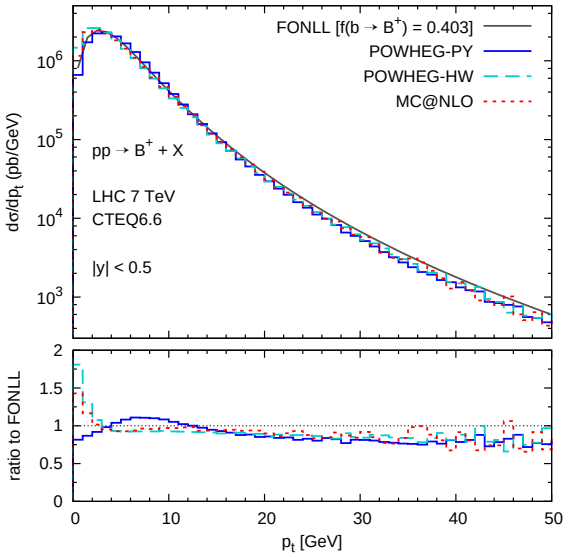
BOTTOM PRODUCTION:

PAST PROBLEMS & SOLUTIONS

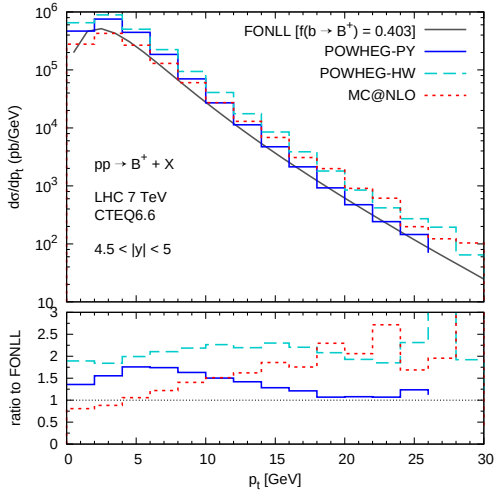
- FONLL $\Rightarrow$ CONSISTENT EXTRACTION OF FRAGMENTATION FUNCTIONS
- FONLL $\Rightarrow$ ENHANCEMENT AT LARGE p_T
- MC@NLO/POWHEG: ACCURATE TREATMENT AT LOW p_T

OPEN BOTTOM FROM $H_b \to J/\psi,\ \psi(2s)$

low rapidity



high rapidity



(Cacciari, Frixione, Houdeau, Mangano, Nason, Ridolfi 2012)

- DEPENDENCE ON MC TUNE MODERATE
- FRAGM. FUNCTION FITTED TO A VARIETY OF LEP DATA

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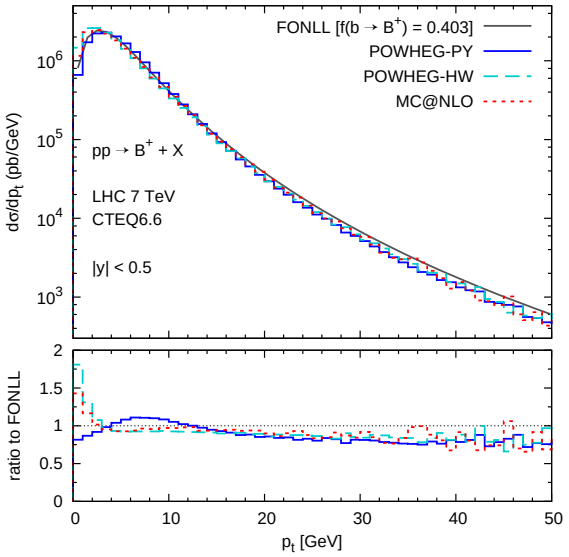

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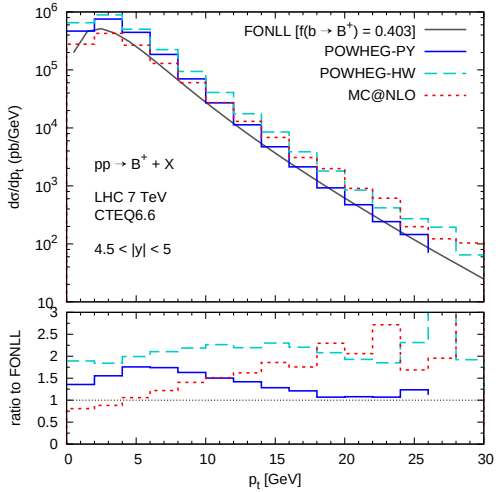
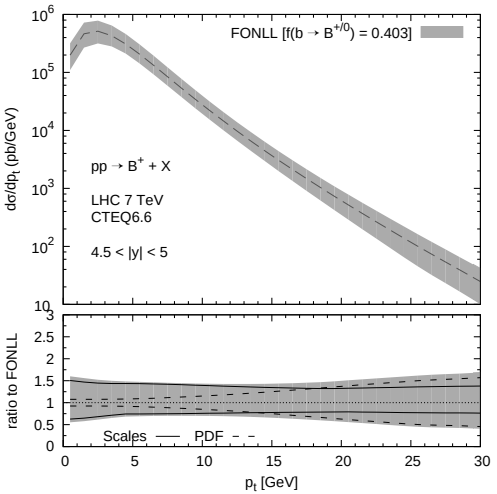


(Cacciari, Frixione, Houdeau, Mangano, Nason, Ridolfi 2012)

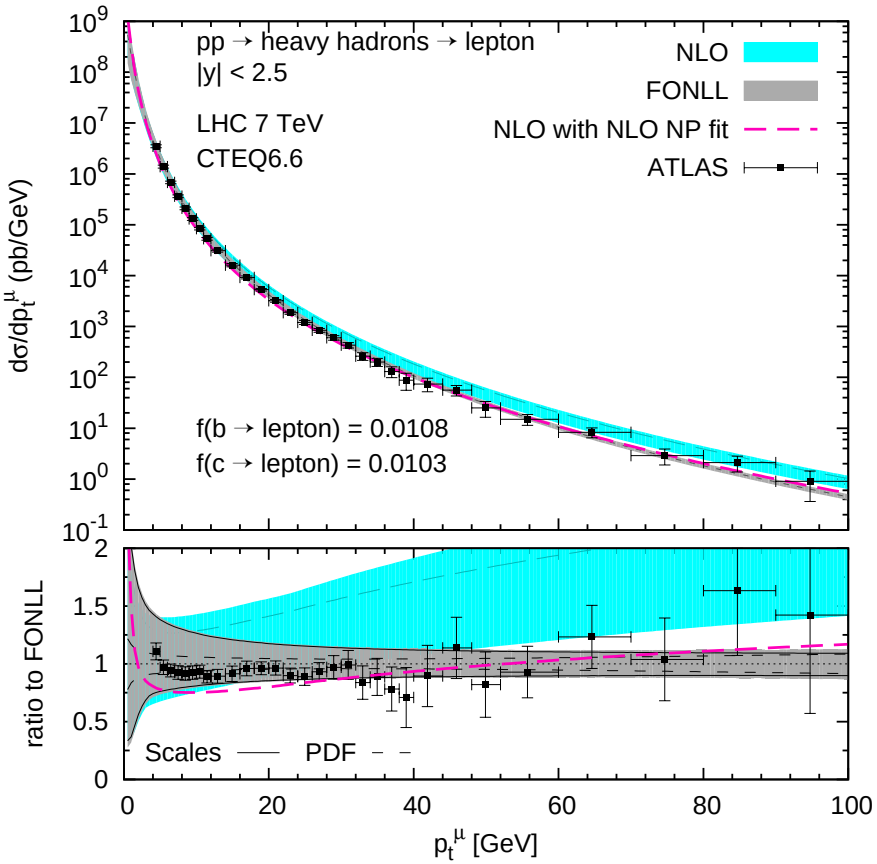
high rapidity: th. unc.



- DEPENDENCE ON MC TUNE MODERATE
- FRAGM. FUNCTION FITTED TO A VARIETY OF LEP DATA
- UNCERTAINTY PATTERN SIMILAR TO CHARM, BUT SMALLER

CHARM+BOTTOM PRODUCTION:

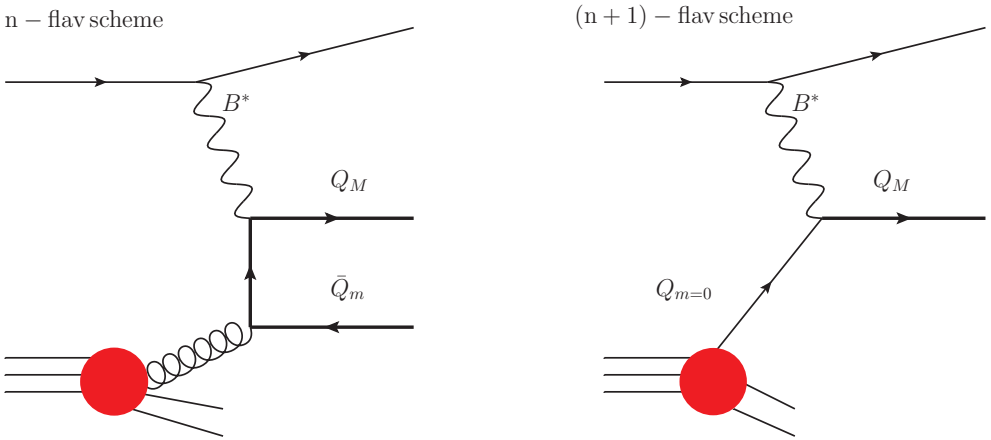
OPEN CHARM AND BOTTOM FROM SEMILEPTONIC DECAYS



(Cacciari, Frixione, Houdeau, Mangano, Nason, Ridolfi 2012)

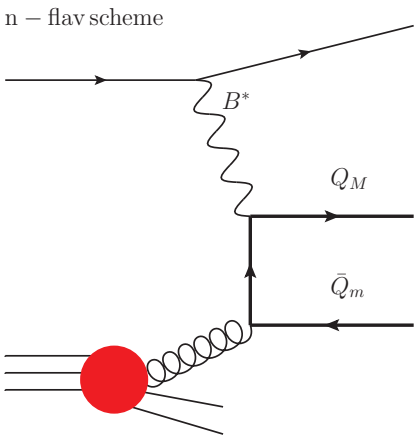
- SUM OF $H_c \to \ell$, $H_b \to \ell$, $H_b \to H_c \to \ell$
- SIGNIFICANT DISCREPANCY BETWEEN FONLL & MC@NLO @ LARGE p_T
- REABSORBED IF NLO ALSO USED FOR FRAGMENTATION FUNCTION FIT
  BUT CAN ONLY USE WHEN $p_t \sim M_Z$ SCALE OF FRAGMENTATION FUNCTION

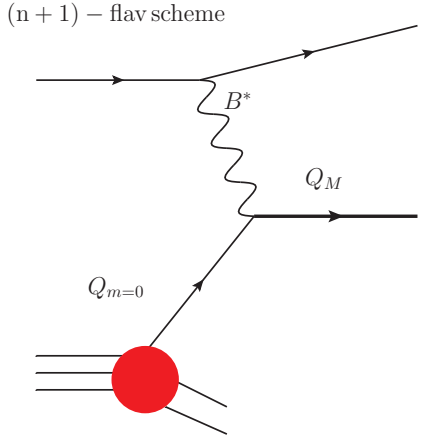
IS BOTTOM A PARTON?

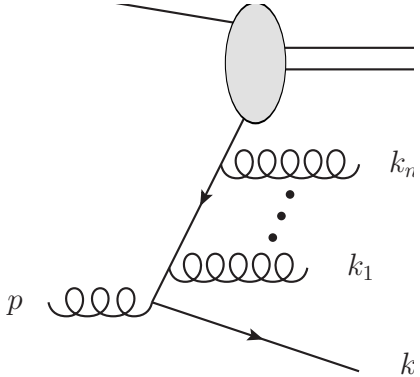


- IN FOUR-FLAVOR SCHEME, BOTTOM IS A MASSIVE QUARK PRODUCED BY GLUON SPLITTING $\Rightarrow$ b-MASS INCLUDED
- IN FIVE-FLAVOUR SCHEME, BOTTOM IS A MASSLESS PARTON $\Rightarrow$

IS BOTTOM A PARTON?







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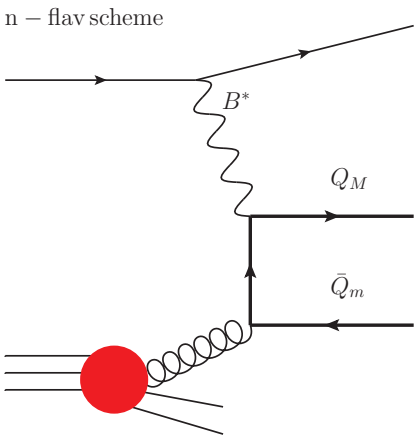
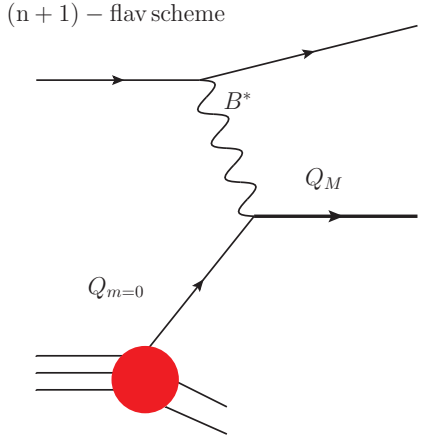
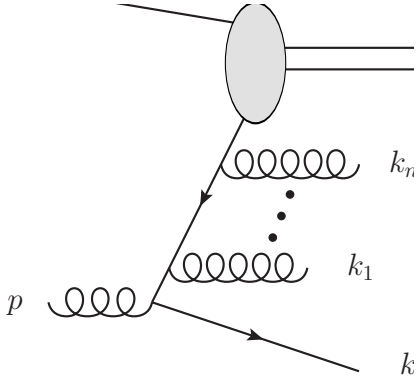
IS BOTTOM A PARTON?







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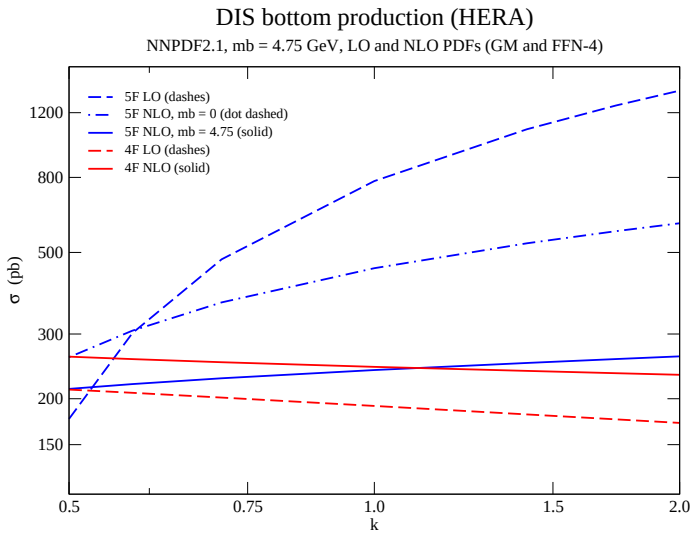
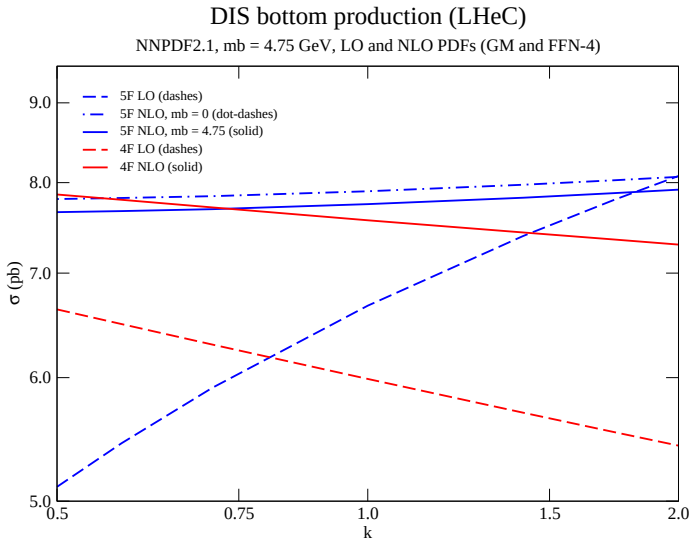
- IN FIVE-FLAVOUR SCHEME, BOTTOM IS A MASSLESS PARTON $\Rightarrow$ COLLINEAR (ALTARELLI-PARISI) RESUMMATION INCLUDED
- FONLL MERGES THE TWO SCHEMES

IS BOTTOM A PARTON?

AN EXAMPLE: DEEP-INELASTIC b PRODUCTION: HERA VS. LHEC





(Maltoni, Ridolfi, Ubiali, 2012)

TOTAL BBAR CROSS SECTION,

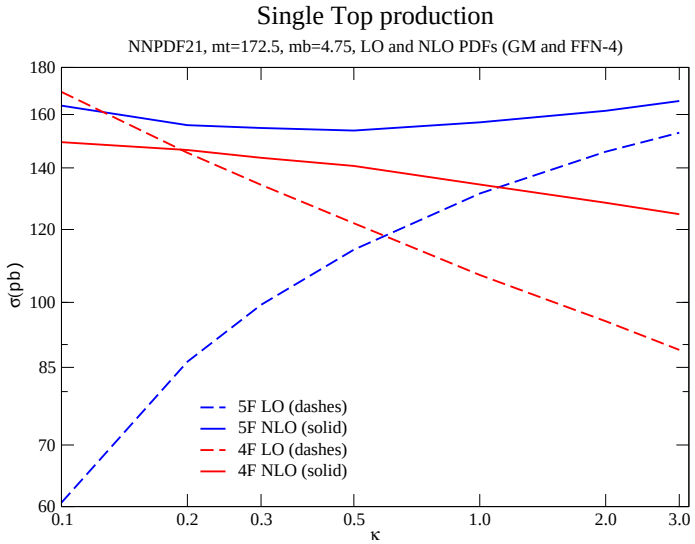
HERA: $E_p = 920$ GeV, $E_e = 27.5$ GeV; $Q^2 \geq 20$ GeV^2, $0.05 \leq y \leq 0.7$

LHEC: $E_p = 7$ TeV, $E_e = 50$ GeV; $Q^2 \geq 2000$ GeV^2, $0.1 \leq y \leq 0.9$

- HERA: FONLL NLO RESULT CLOSE TO FOUR FLAVOR
  - MASSLESS (DOTDASHED) $\Rightarrow$ POOR APPROX
  - COLLINEAR RESUMMATION NOT SO IMPORTANT
- LHEC: FONLL NLO RESULT CLOSE TO FIVE FLAVOR (DOTDASHED)
  - FOUR FLAVOR $\Rightarrow$ POOR APPROX
  - MASS EFFECTS NOT SO IMPORTANT

IS BOTTOM A PARTON?

SINGLE TOP PRODUCTION AT THE LHC: $W^* + b \to c$



(Maltoni, Ridolfi, Ubiali, 2012)

TOTAL SINGLE TOP, LHC 14 TeV, $M_t = 175.3$ GeV

- m_b IRRELEVANT FOR TOP PRODUCTION, BUT FIVE-FLAVOR RESUMMATION ONLY DOABLE FOR INCLUSIVE OBSERVABLES
- FIVE FLAVOR NLO ONLY 10% LARGER THAN FOUR FLAVOR WITH SUITABLE SCALE

IS BOTTOM A PARTON?

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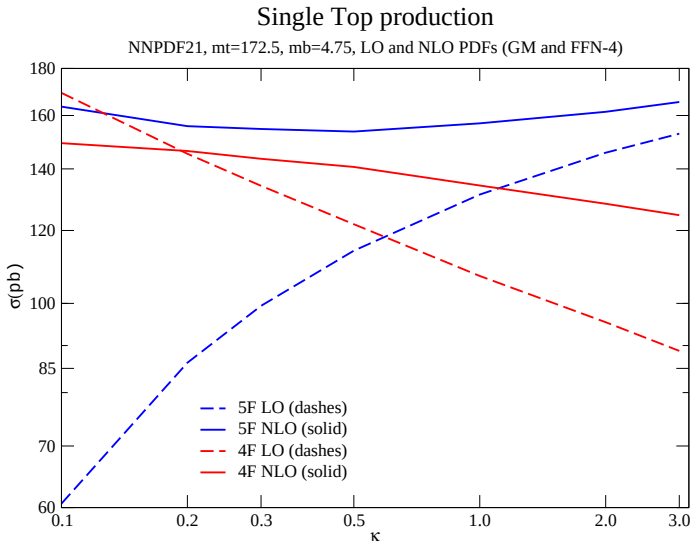

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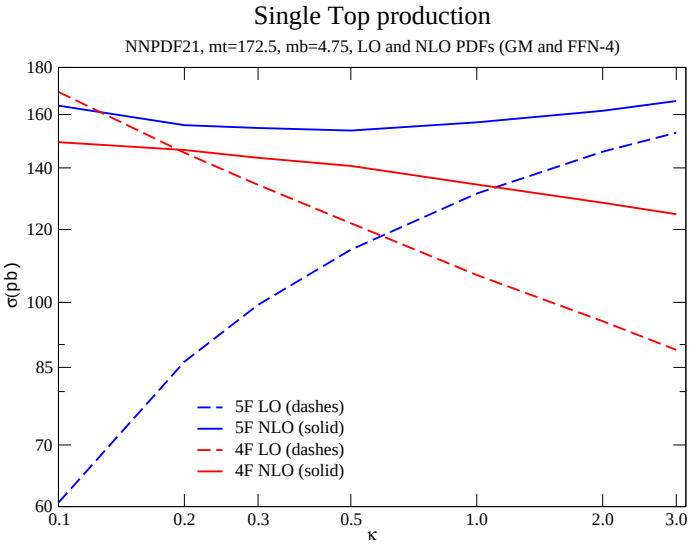
WHY?

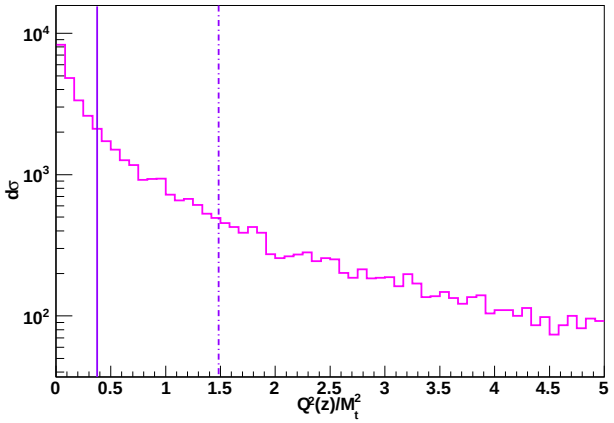
- EFFECTIVE SCALE IS $\mathcal{Q}^2 \equiv \frac{(m_t^2+Q^2)^2}{M_t^2+(1-z)Q^2}\frac{(1-z)^2}{z}$, ($Q^2$ VIRTUALITY OF W, $z = \frac{m_t^2+Q^2}{s+Q^2}$)
- DEPENDS ON EVENT-BY-EVENT BASIS ON MOMENTUM FRACTION OF PARTON: RESCALED BY FACTOR $\frac{(1-z)^2}{z}$ (SUDAKOV RESUMMATION)

IS BOTTOM A PARTON?

SINGLE TOP PRODUCTION AT THE LHC: $W^* + b \to c$



$\mathcal{Q}^2(z)/m_t^2$



(Maltoni, Ridolfi, Ubiali, 2012)

TOTAL SINGLE TOP, LHC 14 TeV, $M_t = 175.3$ GeV

- m_b IRRELEVANT FOR TOP PRODUCTION, BUT FIVE-FLAVOR RESUMMATION ONLY DOABLE FOR INCLUSIVE OBSERVABLES
- FIVE FLAVOR NLO ONLY 10% LARGER THAN FOUR FLAVOR WITH SUITABLE SCALE

WHY?

- EFFECTIVE SCALE IS $\mathcal{Q}^2 \equiv \frac{(m_t^2+Q^2)^2}{M_t^2+(1-z)Q^2}\frac{(1-z)^2}{z}$, ($Q^2$ VIRTUALITY OF W, $z = \frac{m_t^2+Q^2}{s+Q^2}$)
- DEPENDS ON EVENT-BY-EVENT BASIS ON MOMENTUM FRACTION OF PARTON: RESCALED BY FACTOR $\frac{(1-z)^2}{z}$ (SUDAKOV RESUMMATION)
- FOR 50% OF EVENTS $Q^2(z)/m_t^2 \lesssim 0.5$, FOR 80% $Q^2(z)/m_t^2 \lesssim 1.5$
- FOUR-FLAVOR GOOD TO 10%, CAN USE FOR EXCLUSIVE OBSERVABLES

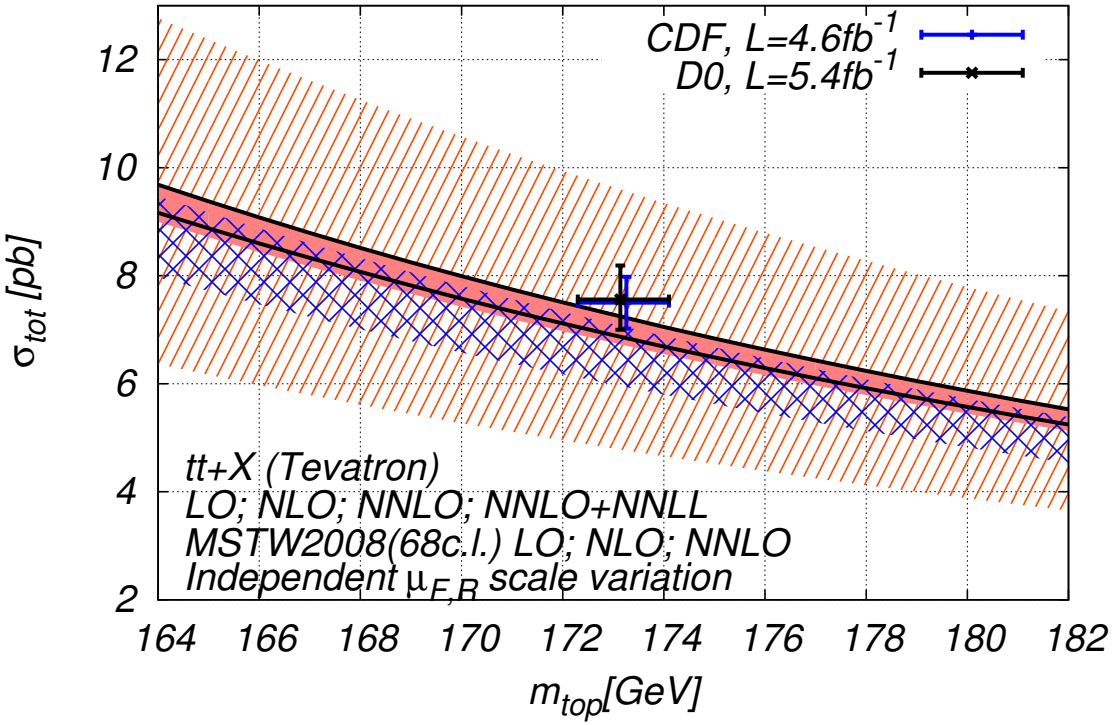
TOP

TOP PRODUCTION

- DECAYS BEFORE HADRONIZING $\Rightarrow$ AMENABLE TO ACCURATE PERTURBATIVE TREATMENT
- NNLL THRESHOLD RESUMMATION AVAILABLE (Czakon, Mitov, Sterman; Beneke, Falgari, Schwinn, 2009)
- RECENTLY COMPUTED UP TO NNLO (Czakon, Mitov+ coll, 2012-2013)

PERTURBATIVE STABILITY

TOP PRODUCTION AT THE TEVATRON



(Bärnreuther, Czakon, Mitov, 2012)

TOP PRODUCTION AT NNLO+NNLL

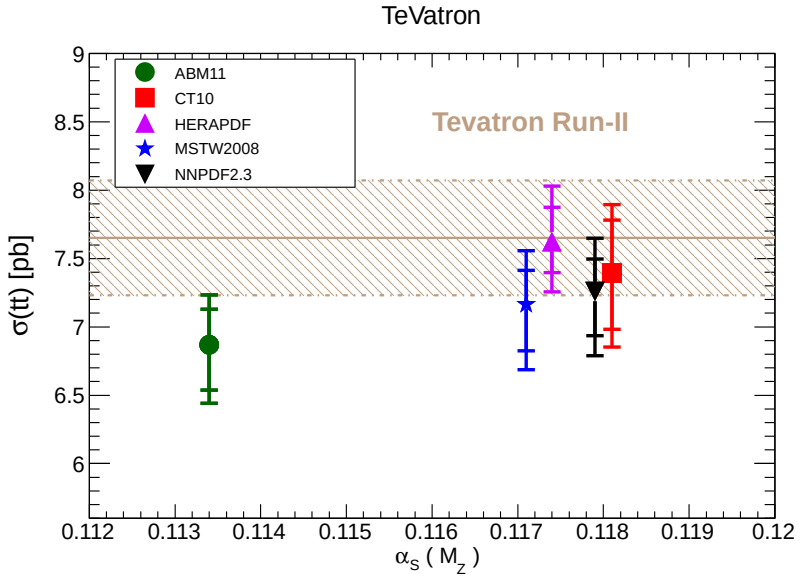
PARTONIC SUBCHANNELS

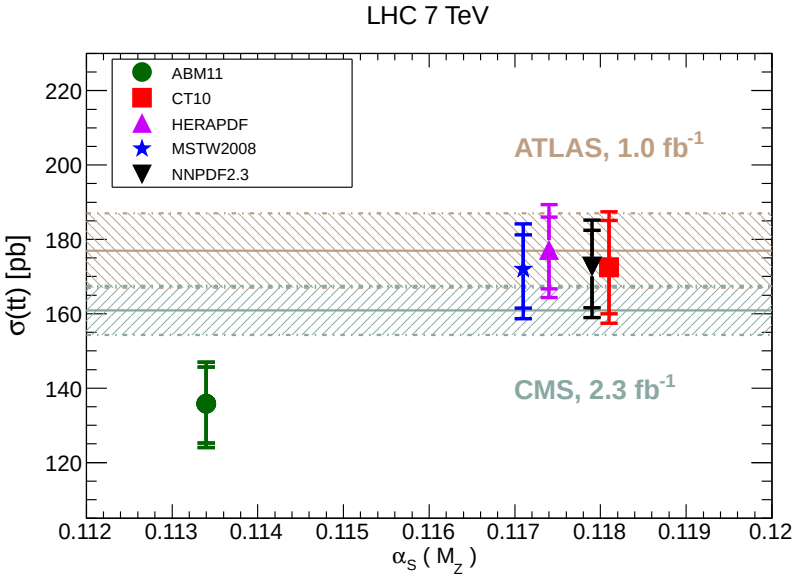
	TeVatron	LHC 7 TeV	LHC 8 TeV	LHC 14 TeV
gg	15.4%	84.8%	86.2%	90.2%
$qg + \bar{q}g$	-1.7%	-1.6%	-1.1%	0.5%
qq	86.3%	16.8%	14.9%	9.3%

SOURCES OF UNCERTAINTY

LHC 8 TeV (NNPDF2.3)

σ_{tt} (pb)	$\delta_{\rm scale}$ (pb)	$\delta_{\rm PDF}$ (pb)	δ_{α_s} (pb)	$\delta_{\rm m_t}$ (pb)	$\delta_{\rm tot}$ (pb)
248.1	$^{+6.4}_{-8.7}$ $^{(+2.6\%)}_{(-3.5\%)}$	$^{+6.6}_{-6.6}$ $^{(+2.7\%)}_{(-2.7\%)}$	$^{+3.7}_{-3.7}$ $^{(+1.5\%)}_{(-1.5\%)}$	$^{+7.5}_{-7.2}$ $^{(+3.0\%)}_{(-2.9\%)}$	$^{+17.1}_{-19.1}$ $^{(+6.9\%)}_{(-7.7\%)}$

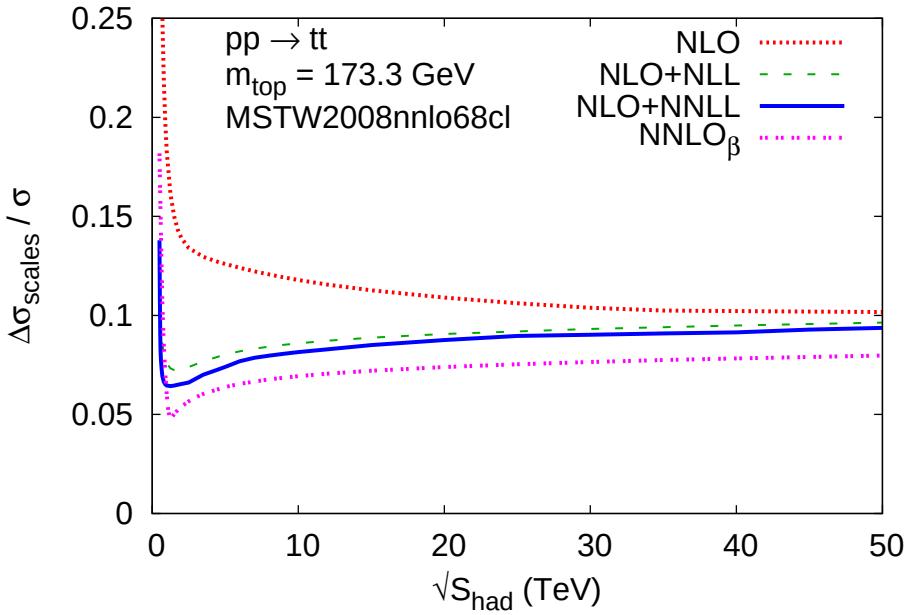




(Czakon, Mangano, Mitov, Rojo, 2013)

TOP PRODUCTION: RESUMMATION

TH UNCERTAINTY (SCALE VARIATION)



(Cacciari, Czakon, Mangano, Mitov, Nason, 2012)

THRESHOLD RESUMMATION:

- MODERATE BUT NON-NEGLIGIBLE IMPACT ON CROSS SECTION
- RATHER SIGNIFICANT IMPACT ON UNCERTAINTY
- WHY? EVEN FAR FROM THRESHOLD? $\tau = \frac{m_t^2}{s} \sim 5 \cdot 10^{-4}$ @ LHC8

TOP PRODUCTION: RESUMMATION

WHAT IS THE THRESHOLD REGION?

- IN A HADRONIC PROCESS, IT IS THE C.M. ENERGY OF THE PARTONIC SUBPROCESS WHICH DETERMINES WHETHER ONE IS CLOSE TO THRESHOLD
- IN A GLUON DOMINATED PROCESS PARTONIC ENERGY CAN BE RATHER SMALLER THAN HADRONIC

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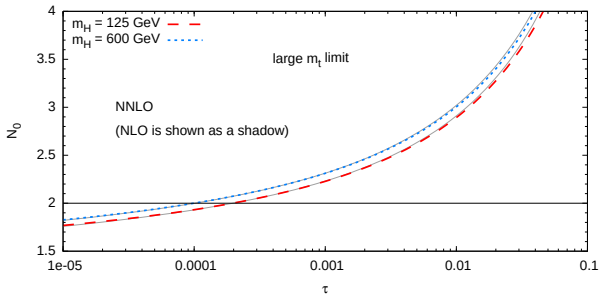
- QUANTITATIVE ASSESSMENT: LOOK AT (MELLIN) N-SPACE DOMINANT (SADDLE) VALUE FOR GIVEN TAU (MOSTLY DETERMINED BY PARTON LUMI): TOP $N \sim 2.5$

N SADDLE VS τ



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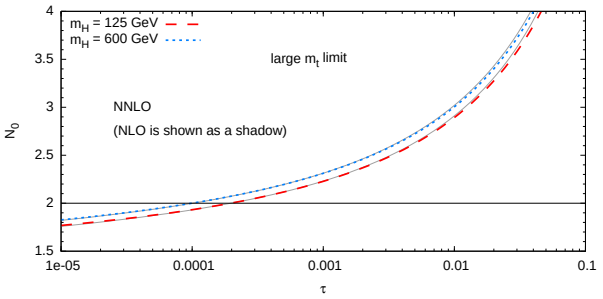
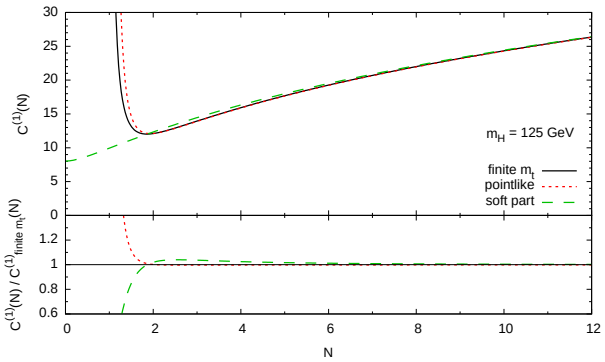
- COMPARE SOFT APPROX WITH EXACT FOR GIVEN $N \Rightarrow$ FOR HIGGS WOULD BE IN SOFT REGION (TOP LIKELY ALMOST SO)

N SADDLE VS τ



HIGGS IN GLUON FUSION:

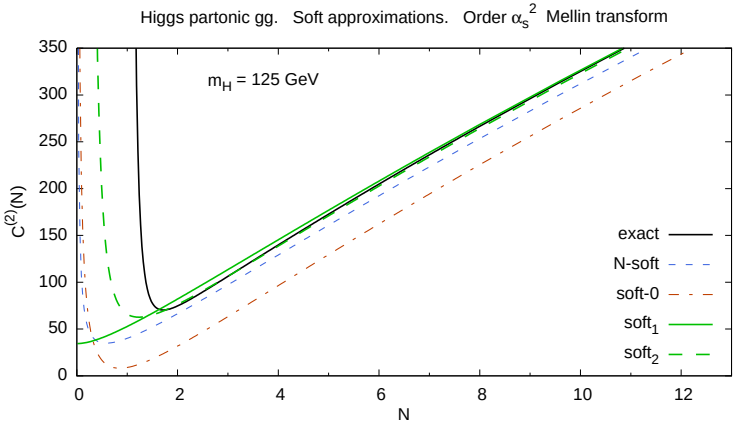
SOFT VS. EXACT



(Bonvini, SF, Ridolfi, 2012)

TOP PRODUCTION: RESUMMATION AMBIGUITIES

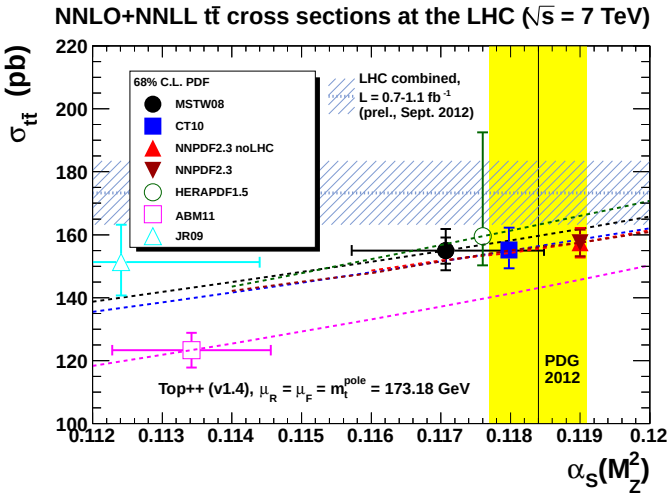
HIGGS IN GLUON FUSION: DIFFERENT SOFT APPROX



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

- FAR FROM THRESHOLD, POWER-SUPPRESSED BUT LOG ENHANCED TERMS CAN COMPETE WITH LEADING RESUMMATION
- RESUMMATION AMBIGUITIES SIZABLE
- HOWEVER, HIGHER-ORDER PERTURBATIVE BEHAVIOUR UNPROBLEMATIC
- POSSIBLE DIFFERENCES VS QCD IN SCET APPROACH TO RESUMMATION (Bonvini, SF, Ghezzi, Ridolfi, 2012): HADRONIC SCALE (FAR FROM THRESHOLD) IS RESUMMED INSTEAD OF PARTONIC (Ahrens, Ferroglia, Neubert, Pecjak, Yang, 2010); IF PARTONIC SCALE RESUMMED (Beneke, Falgari, Schwinn, 2009) DEPENDENCE ON CUTOFF & PARTONIC SOFT SCALE

TOP: THE IMPACT ON PDFS... (& α_s)



(SF, Watt, 2013)

- CROSS SECTION STARTS AT $O(\alpha_s^2)$ AND DRIVEN BY GLUON-GLUON FUSION
- $\Rightarrow$ DEPENDS STRONGLY BOTH ON GLUON-GLUON LUMINOSITY & α_s
- CAN BE USED TO DETERMINE EITHER...OR BOTH?

(Czakon, Mangano, Mitov, Rojo, 2013)

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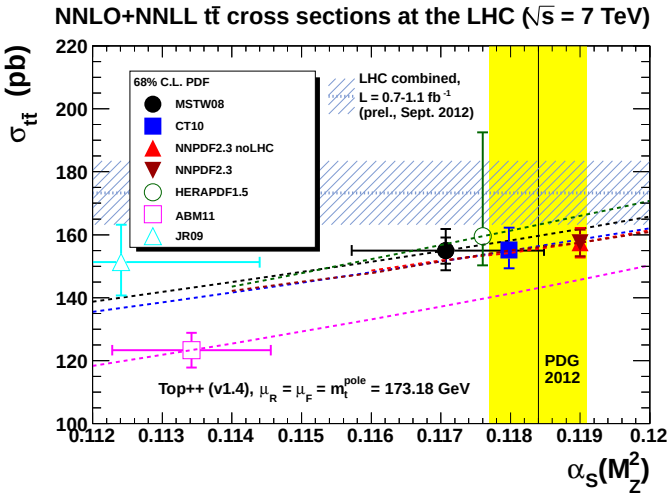

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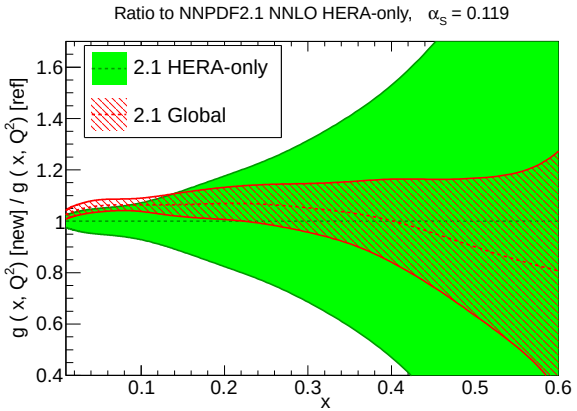
GLUON BEST-FIT

HERA VS GLOBAL FIT



(Czakon, Mangano, Mitov, Rojo, 2013)

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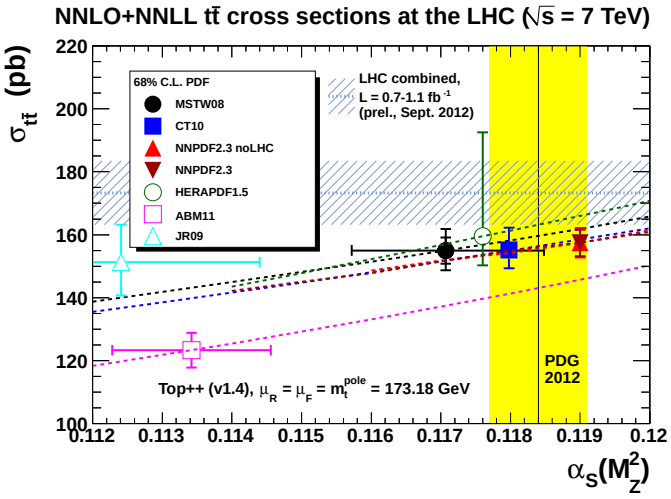

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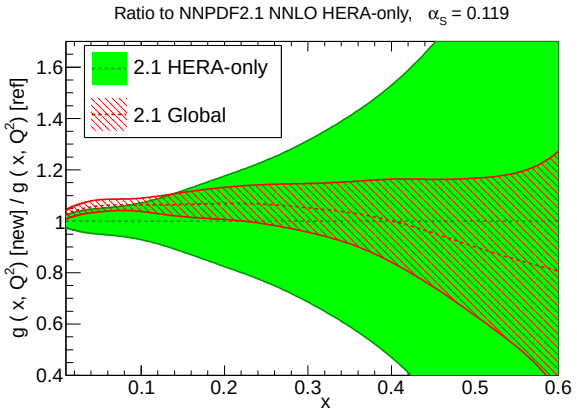
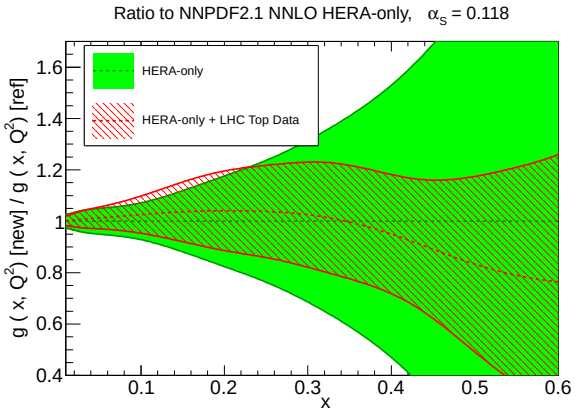


HERA VS HERA+TOP



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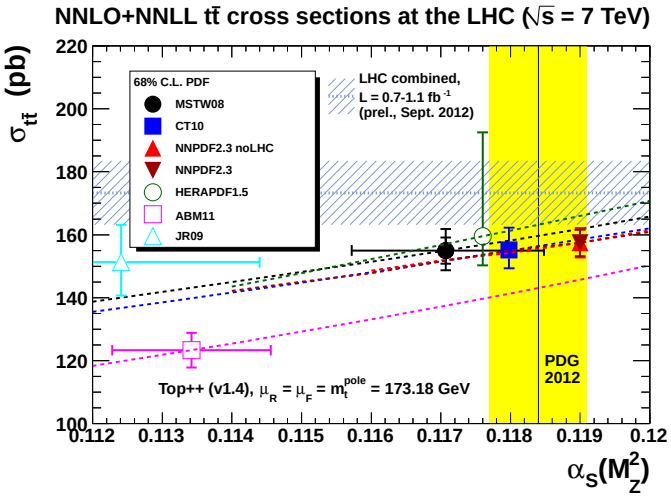

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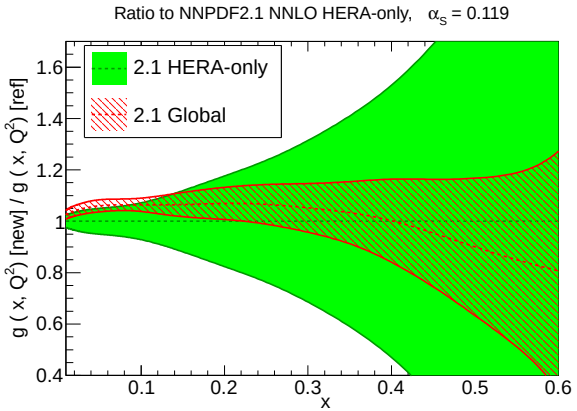
- GLUON FROM HERA DATA UNDERDETERMINED, NEED GLOBAL FIT
- GLUON FROM HERA+TOP COMPARABLE TO GLOBAL FIT!
- GLUON FROM GLOBAL FIT AND α_s POSITIVELY CORRELATED IN TOP REGION $\Rightarrow$ CAN DETERMINE BOTH!

GLUON BEST-FIT

HERA VS GLOBAL FIT



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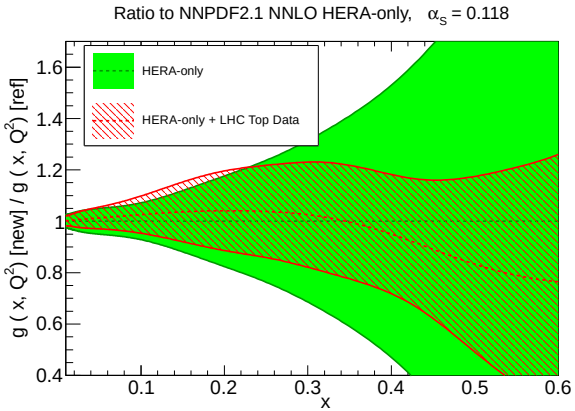

(Czakon, Mangano, Mitov, Rojo, 2013)

TOP MASS DETERMINATION

PDG AVERAGE: $173.3 \pm 0.6 \pm 0.8$ GeV

- AVERAGE OF TEVATRON RUN-I AND RUN-II + CMS MEASUREMENTS
- POLE MASS EXTRACTED FROM KINEMATICS OF EVENTS COMPARING TO MC
- THEORETICAL UNCERTAINTY OF MC HARD TO QUANTIFY

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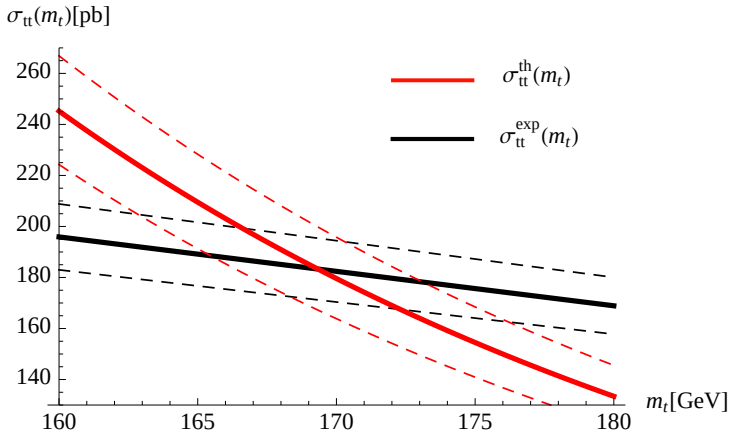
- CAN WE EXTRACT THE TOP MASS FROM THE TOTAL CROSS-SECTION? THEORETICALLY VERY CLEAN...
- YES! BUT NOT COMPETITIVE: $\sim 3\%$ ACCURACY



(Beneke, Falgari, Klein, Schwinn, 2011)

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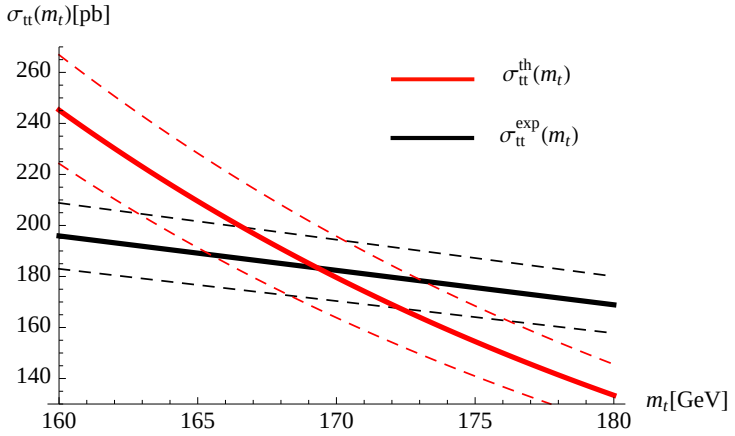


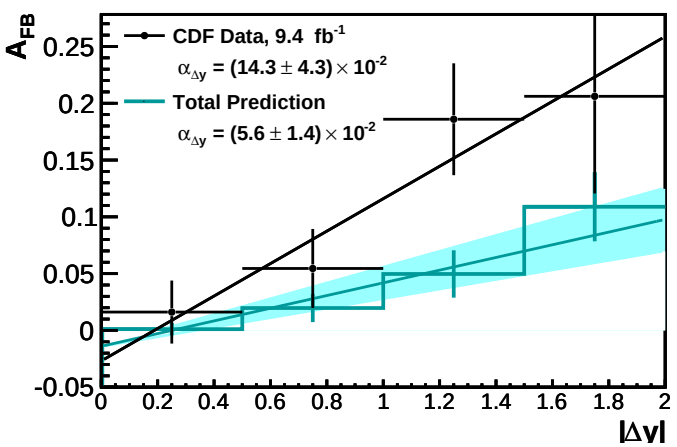
(Beneke, Falgari, Klein, Schwinn, 2011)

MANY ALTERNATIVE SUGGESTIONS...

- DILEPTON CHANNEL WITHOUT TOP RECONSTRUCTION (CLEAN, FULL NLO AVAILABLE) (Bevilacqua et al, 2010, Denner et al, 2010)
- CHARGED LEPTON + EXCLUSIVE B FINAL STATE (NLO AVAILABLE, ACCURATE BUT DEP. ON FRAGMENTATION) (Biswas, Melnikov, Schulze, 2010)
- INVARIANT MASS OF TTBAR+1 JET (LARGE RATES, NLO BUT DEP ON MC) (Alioli et al, 2013)

THE TOP FORWARD-BACKWARD ASYMMETRY

$$A(y) = \frac{N(y_t > y_{\bar{t}}) - N(y_t > y_{\bar{t}})}{N(y_t > y_{\bar{t}}) + N(y_t > y_{\bar{t}})}$$



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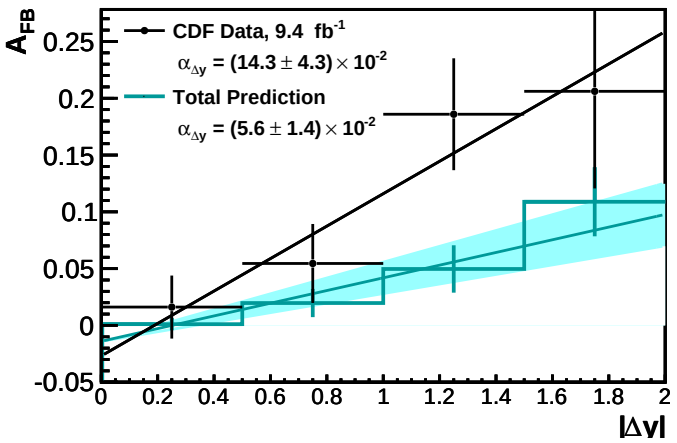

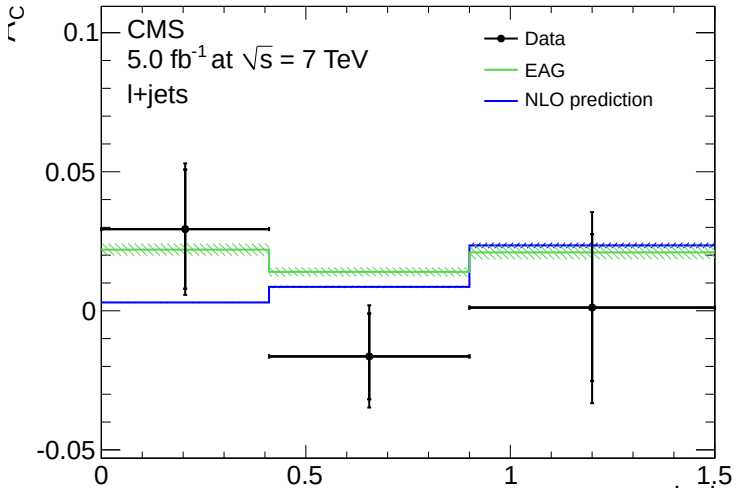

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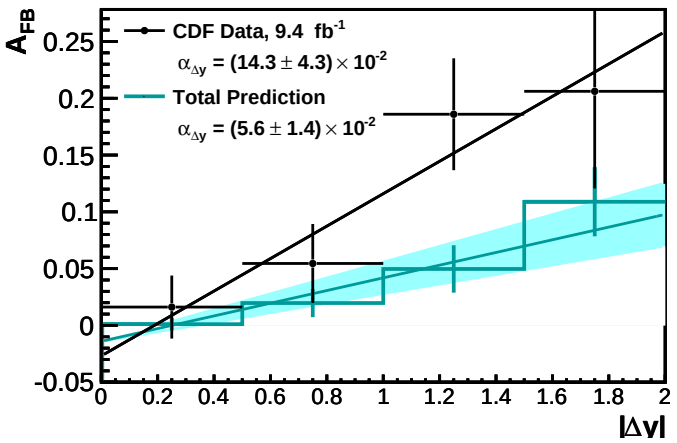

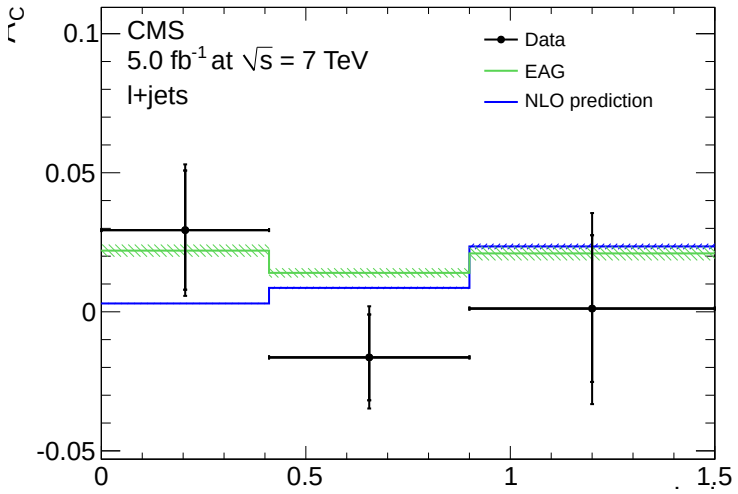

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EXPLANATIONS?

- LARGE VARIETY OF BSM EXPLANATIONS (AXIGLUONS?)
- QCD SUDAKOV CORRECTIONS (DON'T HELP) (Almeida, Sterman, Vogelsang 2008)
- FINAL-STATE INTERACTIONS (DON'T HELP) (Rosner 2012)
- QED AND EW CONTRIBUTIONS TO THE ASYM (HELP 20%) (Hollik, Pagani, 2011)
- EW SUDAKOV (DOUBLE) LOGS (HELP 5%) (Manohar, Trott, 2012)
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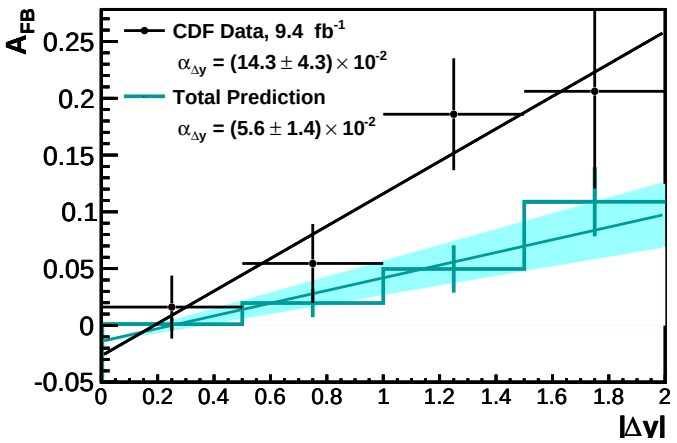

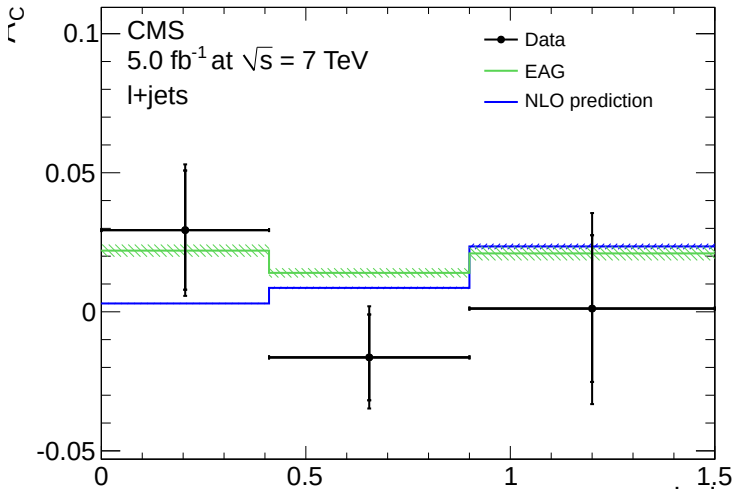

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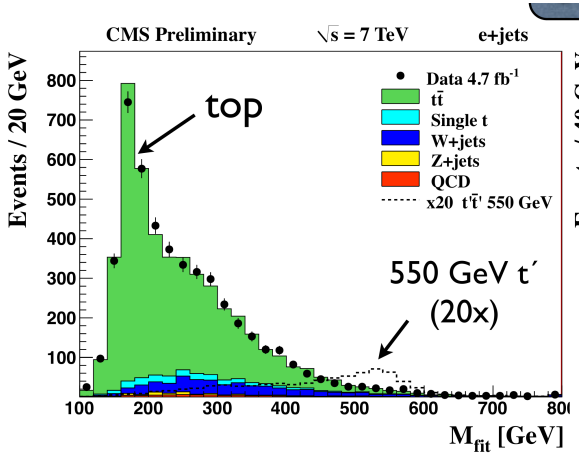
NNLO QCD CORRECTIONS UNKNOWN

TOP AS A WINDOW TO BSM

SEARCH FOR FOURTH GENERATION



$$\mathrm{M(bqq)} = \mathrm{M(bl}\nu) = \mathrm{M_{fit}}$$

(Vasquez Sierra, SEARCH wshop, 2012)

- SEARCHES FOR NEW RESONANCES
- FOURTH GENERATION
- . . .

TOP B PHYSICS

(Gedalia, Isidori, Maltoni, Perez, Selvaggi, Soreq, 2013)

- PRIMARY B CHARGE TAGGED BY W CHARGE FROM TOP DECAY
- DIMUONS FROM $t \to \ell^+ \nu b$
  - $\ell^+ \nu (b \to c) \to \ell^+ \ell^+ X$
  - $\ell^+ \nu (b \to \bar{b}) \to \ell^+ \ell^+ X$
  - $\ell^+ \nu (b \to \bar{b} \to c\bar{c}) \ell^+ \ell^+ X$ WITH ℓ^+ FROM c AND $\bar{c}$ DECAYS HADRONICALLY
- CONSTRUCT ASYMMETRY $\frac{N^{++} - N^{--}}{N^{++} - + N^{--}}$
- SENSITIVE TO CPV FROM BOTH MIXING AND DECAY

SUMMARY

- HEAVY QUARK PRODUCTION TESTS OUR UNDERSTANDING OF PERTURBATIVE QCD
- AT THE LHC, IT PROVIDES CHALLENGES TO PERTURBATIVE COMPUTATIONS AND A HANDLE ON PRECISION PHYSICS (PDFs, α_s)
- IT IS PERHAPS THE MOST PROMISING AVENUE TO POSSIBLE NEW PHYSICS