GLUON-GLUON FUSION:
SUMMARY AND PROSPECTS

STEFANO FORTE
UNIVERSITÀ DI MILANO & INFN

UNIVERSITÀ DEGLI STUDI DI MILANO

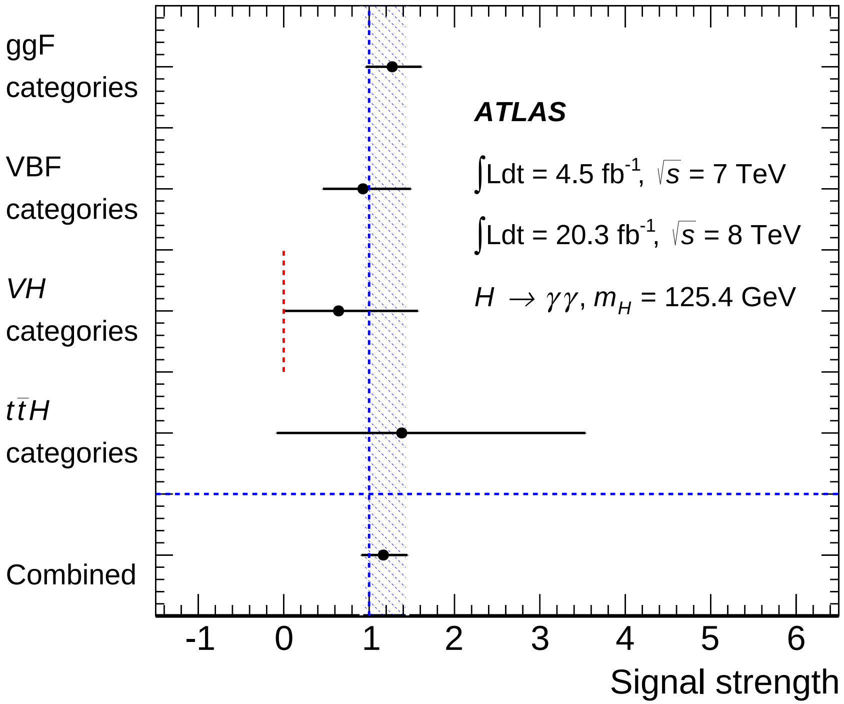
INFN Istituto Nazionale di Fisica Nucleare

HIGGS COUPLINGS 2014

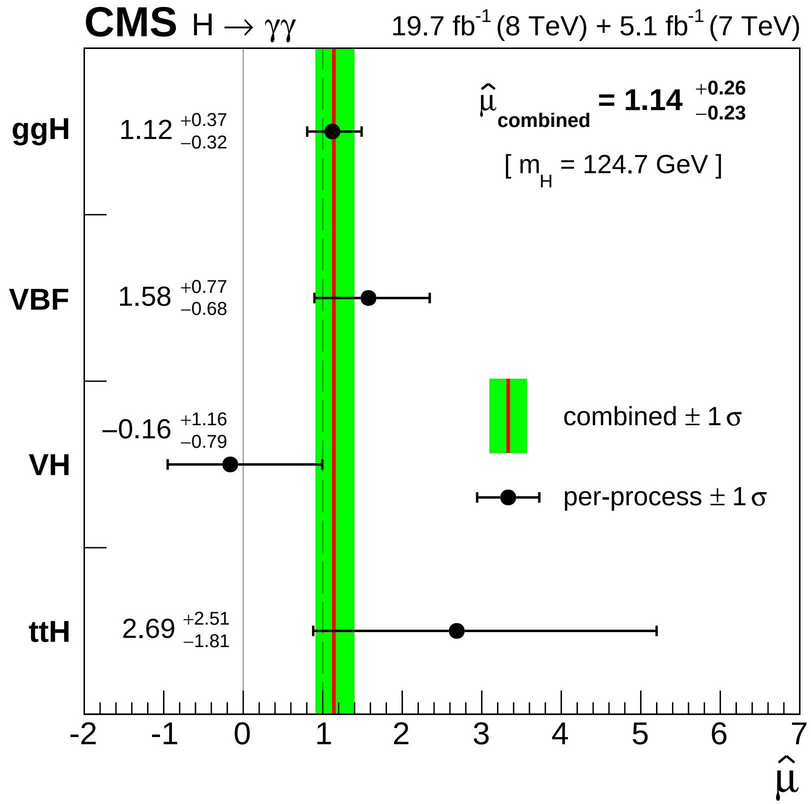
TORINO, OCTOBER 1, 2014

THE CHALLENGE FROM EXPERIMENTS

SIGNAL STRENGTH: $H \to \gamma\gamma$



ATLAS, August 2014



CMS, August 2014

THEORETICAL PROGRESS:

- THE TOTAL CROSS SECTION
- HIGGS + JET & JET VETOS
- TOP MASS AND B MASS
- MATCHING TO MONTE CARLO

FOCUS ON RECENT PROGRESS SINCE THE FREIBURG 2013 MEETING

NO ATTEMPT OF COMPLETENESS

THE TOTAL CROSS SECTION

THE PIECES OF THE PUZZLE

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV#gluon_gluon_Fusion_Process

$$m_h = 125 \text{ GeV}; \qquad \sigma = 19.27 \text{ pb}^{+7.2}_{-7.8} \text{ (SCALE) } {}^{+7.5}_{-6.9} \text{ (PDF+}\alpha_s\text{)}$$

$$\text{(NOTE: IF } m_H = 125.5 \to \sigma = 19.12 \text{ pb)}$$

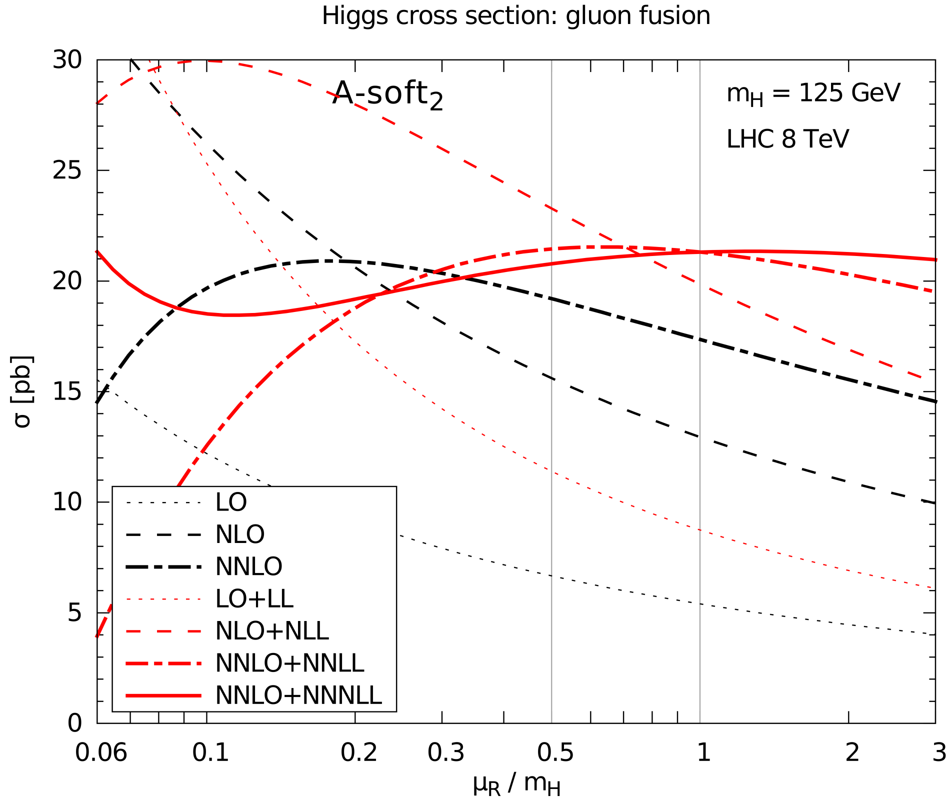
(De Florian, Grazzini, 2012)

- NNLO+NNLL
- TOP MASS DEP, AND BOTTOM AND CHARM CONTRIBUTIONS AT NLO+NLL
  DECREASE $\sim 1.5\%$ DUE TO TOP+BOTTOM (MOSTLY BOTTOM)+
  FURTHER $\sim 1\%$ DUE TO CHARM
- NLO ELECTROWEAK CORRECTIONS (COMPLETE FACTORIZATION)
  INCREASE $\sim 5\%$ (WOULD CHANGE BY A FEW PERCENT WITH
  PARTIAL FACTORIZATION)
- COMPLEX-POLE (OFFP)
  FINITE-WIDTH BELOW $\sim 1\%$ FOR LIGHT HIGGS
- NO MIXED QCD-EW AND REAL EW RADIATION
  BELOW $\sim 1\%$

FIXED ORDER & RESUMMED

- LANDMARK CALCULATION: N^3LO N-SPACE CONSTANT (SEE BELOW) (Anastasiou et al, 2014)
- $\Rightarrow$ N^3LL RESUMMATION (ALMOST) POSSIBLE (Bonvini, Marzani, 2014; Catani et al., 2014)

FIXED ORDER VS RESUMMED



(Bonvini, Marzani, 2014)

- QCD CORRECTIONS LARGE; SERIES SLOWLY CONVERGENT
- FACT. SCALE MILD
- REN SCALE DEP. SOMEWHAT MILDER AT RESUMMED LEVEL
- REN. SCALE FLATTENS AT N^3LL
- RESUMMED VS UNRESUMMED DIFFERENCE RATHER LARGER FOR $\mu_r = m_h$ THAN FOR $\mu_r = m_h/2$ ($\sim 20\%$ VS. $\sim 5\%$ FOR N^3LL)

RESUMMATION AND ITS AMBIGUITIES

THE RESUMMED COEFFICIENT FUNCTION

$$\sigma_{\rm res}(N,\alpha_s)=\sigma_0 g_0(\alpha_s)\exp\left[\frac{1}{\alpha_s}g_1(\alpha_s\ln N)+g_2(\alpha_s\ln N)+\alpha_s g_3(\alpha_s\ln N)+\dots\right];$$

$$g_0(\alpha_s)=1+\alpha_s g_{0,1}+\alpha_s^2 g_{0,2}+\mathcal{O}(\alpha_s^3);\quad \sigma(N,m_H^2)\equiv\int_0^1 d\tau\,\tau^{N-2}\sigma(\tau,m_H^2);\quad z=\frac{M_h^2}{s}$$

RESUMMATION SCHEMES

- RESUMMATION PREDICTS LOG ENHANCED TERMS TO ALL ORDERS

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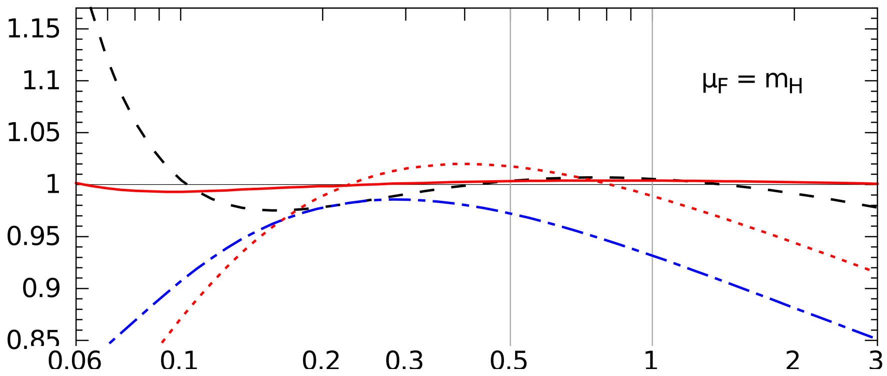
CONSTANT & SUBLEADING TERMS



μ_r/m_H

(Bonvini, Marzani, 2014)

- RESUMMATION PREDICTS LOG ENHANCED TERMS TO ALL ORDERS
- $\ln N$ AND $\psi_0(N)$ BEHAVE IN THE SAME WAY AS $N \to \infty \to \sim 6\%$ DIFFERENCE AT $\mu_r = m_H$
- SHOULD g_0 SIT IN THE EXPONENT? NOT [dashes] (OR PARTLY) EXPONENTIATED g_0 HAS A 2% EFFECT AT $\mu_r = m_H$ (BUT STRONGER SCALE DEP.)

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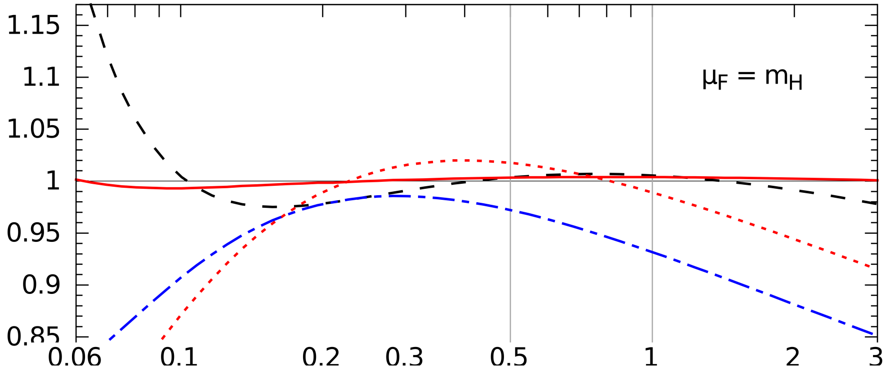

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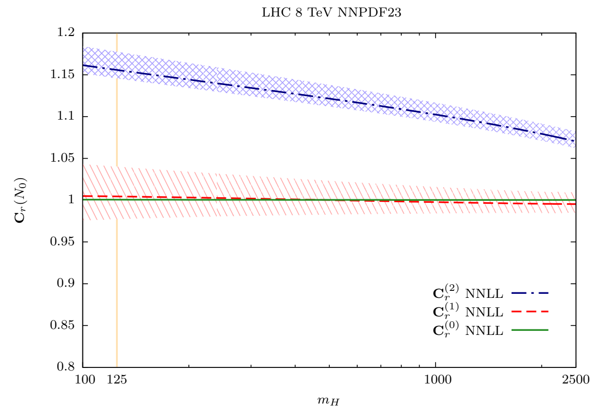
DQCD VS. SCET



m_H

(Bonvini, s.f, Ridolfi, Rottoli 2014)

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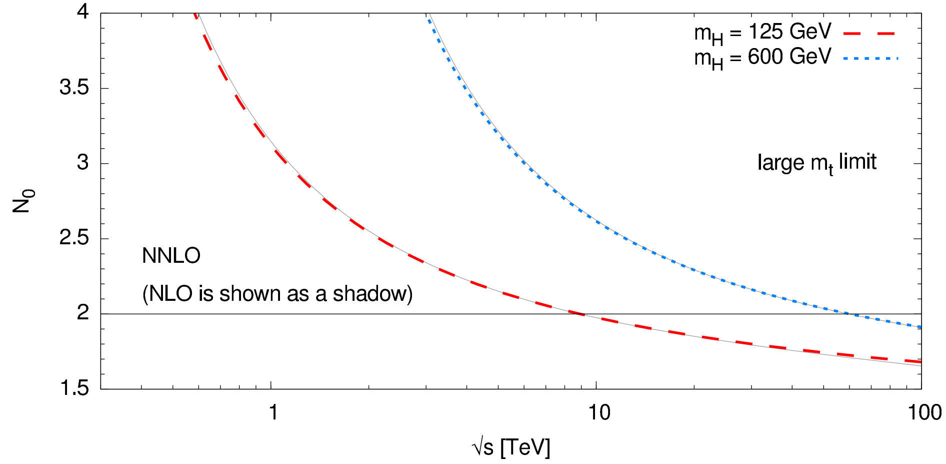
- "SCET" (Becher, Neubert, Ahrens, 2009) MOMENTUM-SPACE RESUMMATION $\Rightarrow$ TREATMENT OF LANDAU POLE MAKES NO DIFFERENCE
- MELLIN OF $\ln(1-z)$ VS $\ln N$ BIG DIFFERENCE $\Rightarrow$ IN SCET (BN IMPLEMENTATION) RESUMMATION HAS NO IMPACT AT $\mu_r = m_H$

FROM RESUMMATION TO N^{3}LO

TECHNICAL INTERLUDE

- PARTONIC CROSS SECTIONS $\hat{\sigma}(z, \alpha_s)$ ARE DISTRIBUTIONS, $0 \leq z = \frac{M_h^2}{s} \leq 1$
- THEIR MELLIN TRANSFORMS $\hat{\sigma}(N, \alpha_s)$ ARE ORDINARY FUNCTIONS
- FOR GIVEN m_H^2 AND s ONLY ONE "SADDLE" N VALUE CONTRIBUTES
- BONUS: HAD. XSCT PRODUCT OF PARTONIC TIMES LUMI: $\sigma(N, m_H^2) = \hat{\sigma}\left(m_H^2, \alpha_s\right) \mathscr{L}(N)$

SADDLE VS COLLIDER ENERGY



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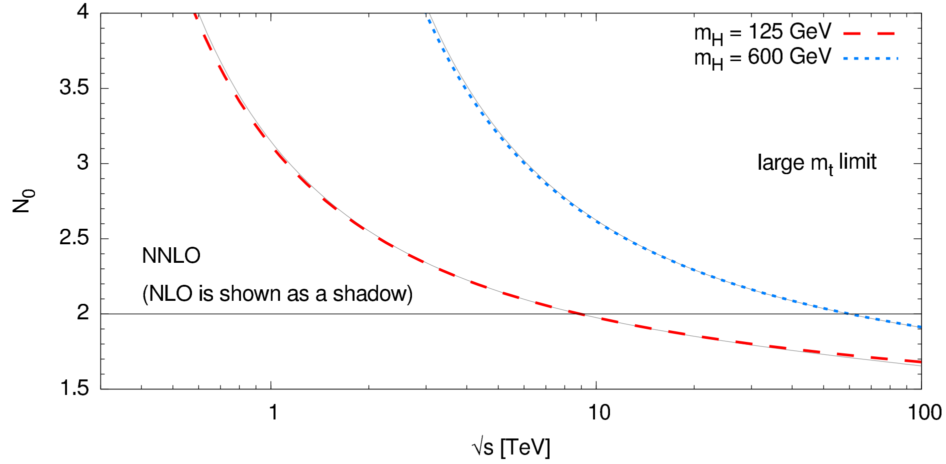

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A: BECAUSE $\beta_0\alpha_s \ln 2 \approx 0.04 \ll 1$:

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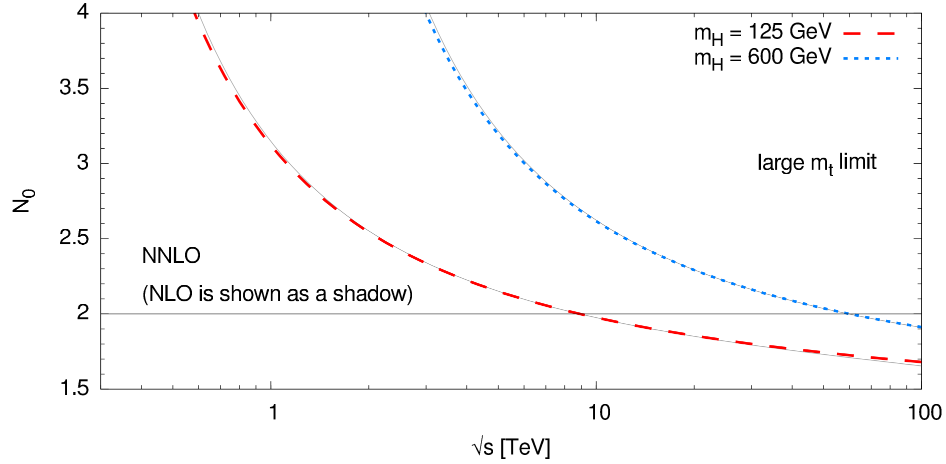
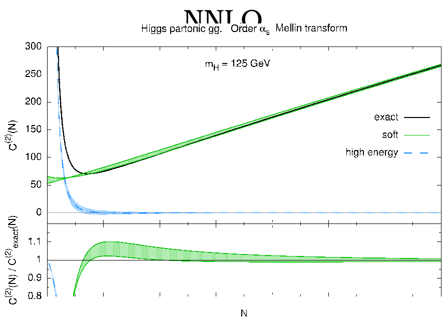


Q: WHY ARE THERE LARGE RESUMMATION AMBIGUITIES?

A: BECAUSE $\beta_0\alpha_s \ln 2 \approx 0.04 \ll 1$:RESUMMATION IS PERTURBATIVE!

IN ALL FLAVOURS OF RESUMMATION DISCUSSED ABOVE
BETWEEN 2/3 AND 3/4 OF THE NNLL OR N^{3}LL RESUMMATION COMES FROM N^{3}LO,
ALL REMAINING INFINITE ORDERS CONTRIBUTING $\sim 1 \div 2\%$
RESUMMATION IS AMBIGUOUS BECAUSE N^{3}LO IS APPROXIMATE!

N^{3}LO: WHAT DO WE KNOW



- EIKONAL OR SOFT EXPANSION: AS $N \to \infty$ (I.E. $z \to 1$)

  $\hat{\sigma}^{(3)}(N) = c_{06} \ln^6 N + c_{05} \ln^5 N + \cdots + c_{02} \ln^2 N + c_{01} \ln N + c_{00} +$

  $\frac{1}{N} \left(c_{15} \ln^5 N + c_{14} \ln^4 N + \cdots + c_{10} \right) + \frac{1}{N^2} \left(c_{24} \ln^4 N + \cdots + c_{20} \right) + \ldots$

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- BFKL OR HIGH-ENERGY EXPANSION: AS N DECREASES (I.E. $z \to 0$)

  RIGHTMOST SINGULARITY AT $N = 1$:

  $\hat{\sigma}^{(3)}(N) = \left(d_{13} \frac{1}{(N-1)^3} + d_{12} \frac{1}{(N-1)^2} + d_{11} \frac{1}{(N-1)} \right) + \left(d_{06} \frac{1}{N^6} + \cdots + d_{01} \frac{1}{N} \right) + \ldots$

  - ONLY d_{13} KNOWN EXACTLY FROM BFKL+SMALL x RESUMMATION
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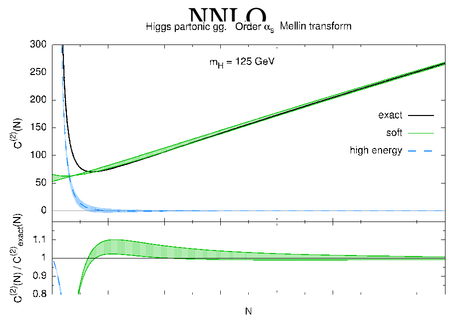

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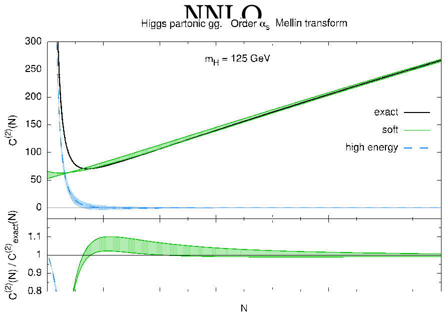

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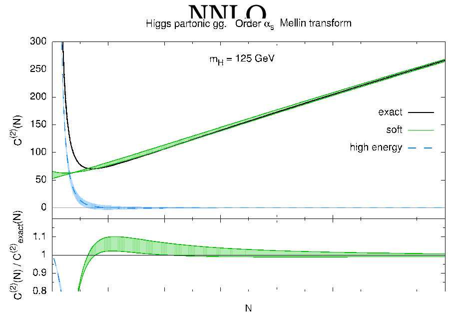

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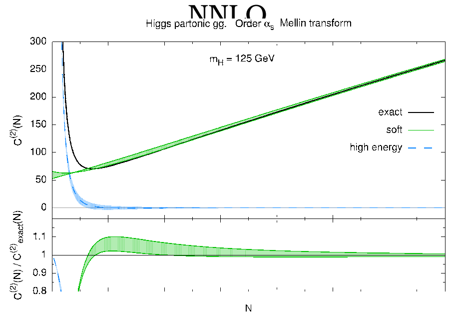

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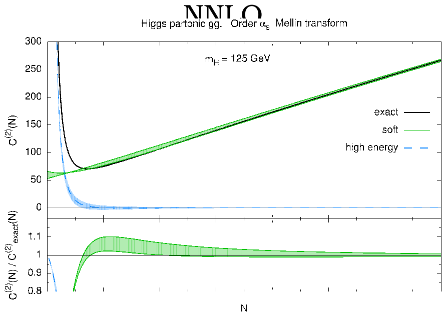

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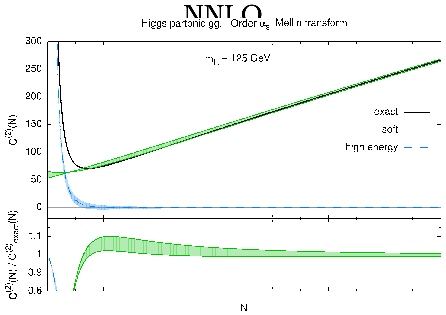

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  - c_{15}, c_{24},... c_{51} KNOWN FROM LL RESUMMATION (Catani, deFlorian, Grazzini, 2001)
  - c_{14} COMPUTED RECENTLY BASED ON A CONJECTURE ON THE LOG STRUCTURE OF THE HADRONIC CROSS-SECTION (deFlorian, Mazzitelli, Moch, Vogt, 2014)

- BFKL OR HIGH-ENERGY EXPANSION: AS N DECREASES (I.E. $z \to 0$)

  RIGHTMOST SINGULARITY AT $N = 1$:

  $\hat{\sigma}^{(3)}(N) = \left(d_{13} \frac{1}{(N-1)^3} + d_{12} \frac{1}{(N-1)^2} + d_{11} \frac{1}{(N-+1)} \right) + \left(d_{06} \frac{1}{N^6} + \dots + d_{01} \frac{1}{N} \right) + \dots$

  - ONLY d_{13} KNOWN EXACTLY FROM BFKL+SMALL x RESUMMATION
  - CLASS OF DOMINANT (?) CONTRIBUTIONS TO d_{12}, d_{11} KNOWN FROM NL BFKL
  - ALL SUBLEADING SINGS UNKNOWN

APPROXIMATE N^{3}LO?

- Q: WHY IS N^{3}LO FROM RESUMMATION APPROXIMATE?
- A: BECAUSE $\ln N$ AND $\ln N \frac{N}{1+N}$ ARE THE SAME AT LARGE N (REMEMBER $N \approx 2$)

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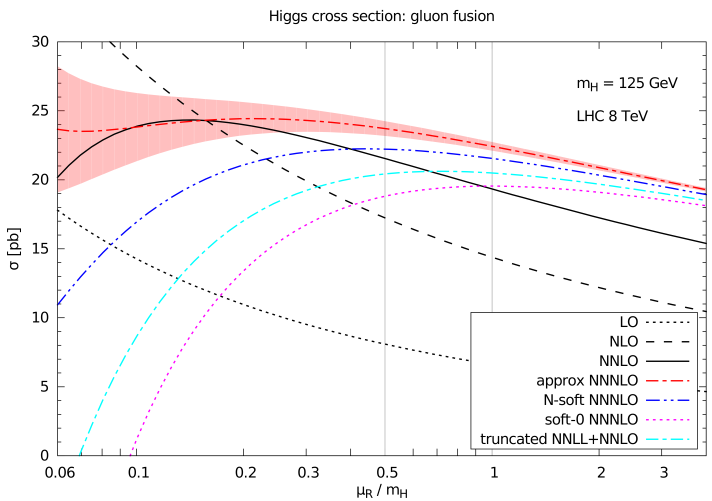
APPROXIMATIONS: LHC8



(Ball et al., 2014)

WHAT IS THE ENHANCEMENT WR TO NNLO?

AT $\mu_R = m_H$, AS USUALLY DONE FOR RESUMMATION

- x-SPACE: $\sim$ (Becher, Neubert; Anastasiou et al.) NO ENHANCEMENT
- PURE N $\sim$ (truncation of de Florian, Grazzini) $\sim 6\%$ ENHANCEMENT
- +CONSTANT OF Anastasiou et al. 2014 (trunc. of "N^{3}LL de Florian, Grazzini") $\sim 10\%$ ENHANCEMENT
- +ANALYTIC IMPROVEMENT (Ball et al., truncation of Bonvini-Marzani) $\sim 15\%$ ENH.

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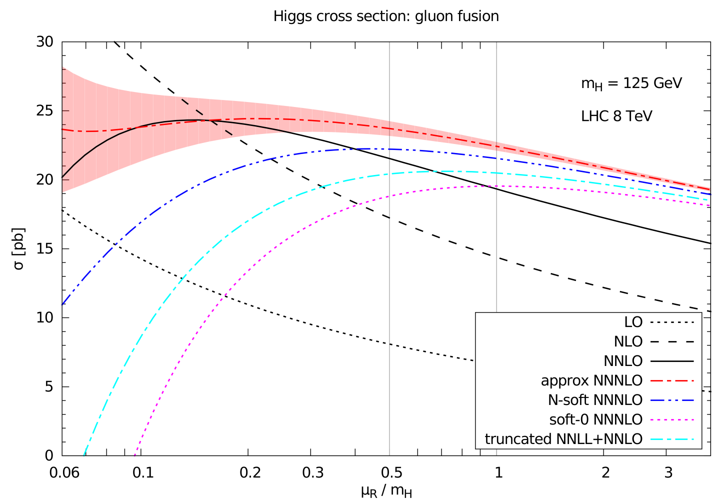
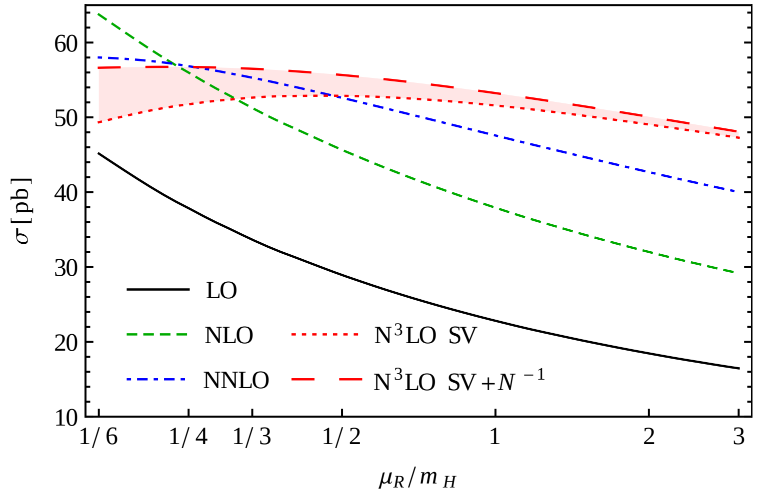


(Ball et al., 2014)

EIKONAL EXPANSION LHC14



(deFlorian, Mazzitelli, Moch, Vogt, 2014)

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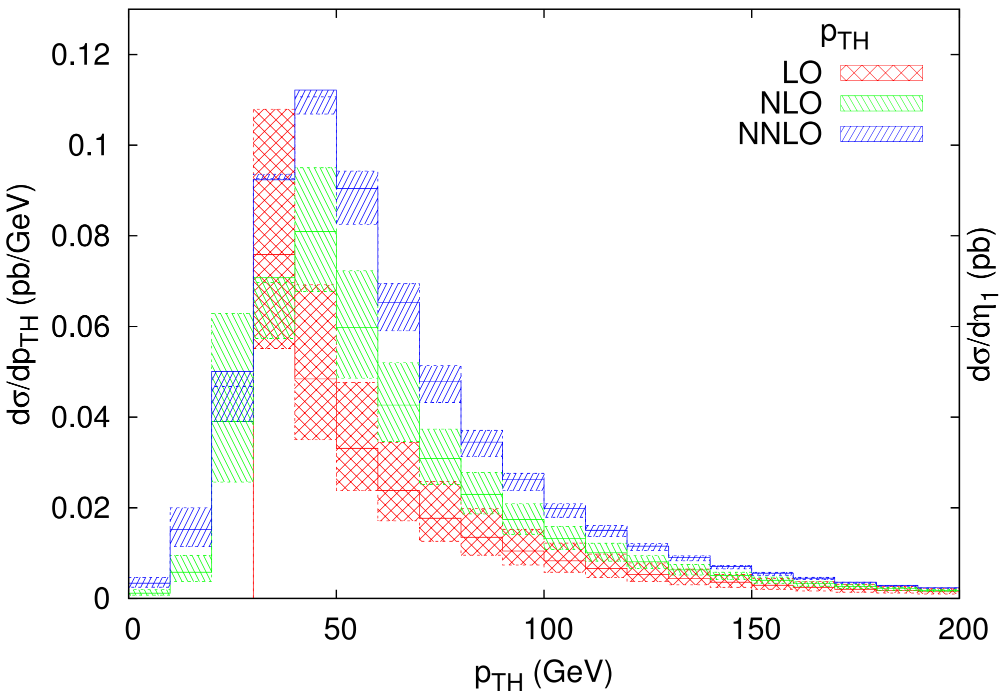
- IF INSTEAD ADD EIKONAL N^3LL+ NEXT-TO-EIKONAL NLL (deFlorian et al 2014) SIMILAR TO ANALYTIC; (NOTE THIS IS A DIFFERENT EXPANSION: DOUBLE COUNT IF COMBINED)

JETS AND JET VETOS

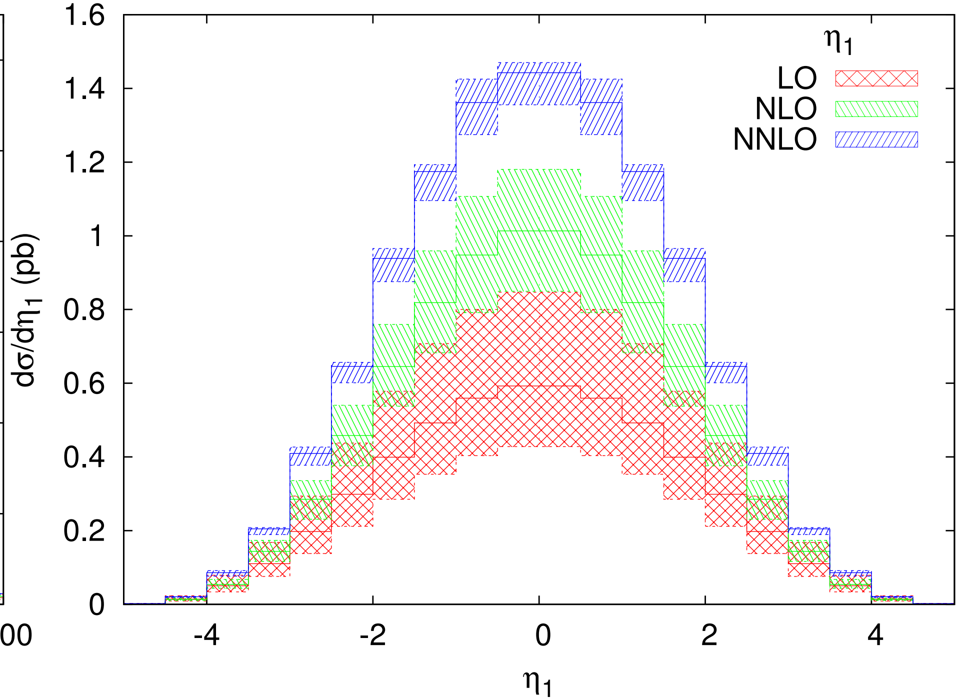
HIGGS+JET AT NNLO

- FIRST INCLUSIVE NNLO IN GG CHANNEL IN 2013 BY BOUGHEZAL ET AL.
- NOW ALSO FULLY DIFFERENTIAL PARTON-LEVEL EVENT GENERATOR, INCLUDING $\gamma\gamma$ DECAY
- NNLO/NLO K-FACTOR LARGE, OF ORDER 40%, WEAKLY DEPENDENT ON p_T AND RAPIDITY
- NNLO/NLO LARGER THAN NLO/LO AT AT LARGE RAPIDITIES & INTERMEDIATE p_T

HIGGS p_T DISTN.



HIGGS RAPIDITY DISTN.

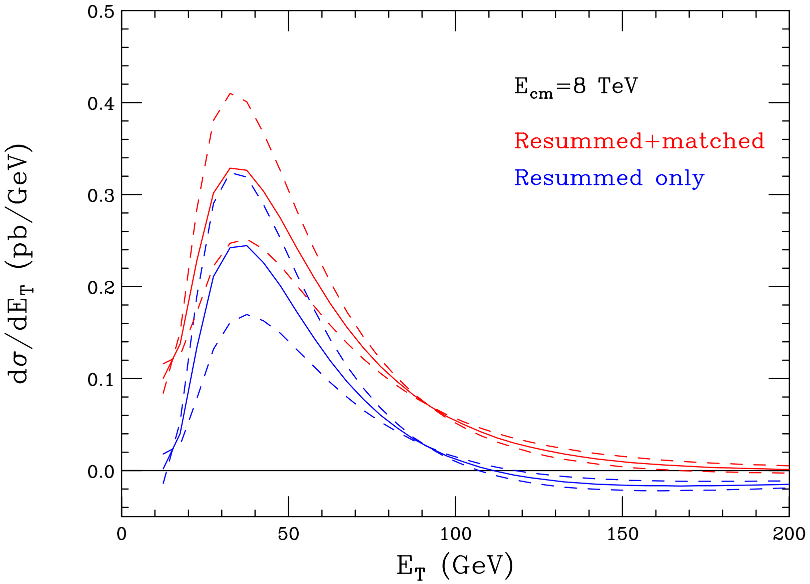


(Chen, Gehrmann, Glover, Jacquier, 2014)

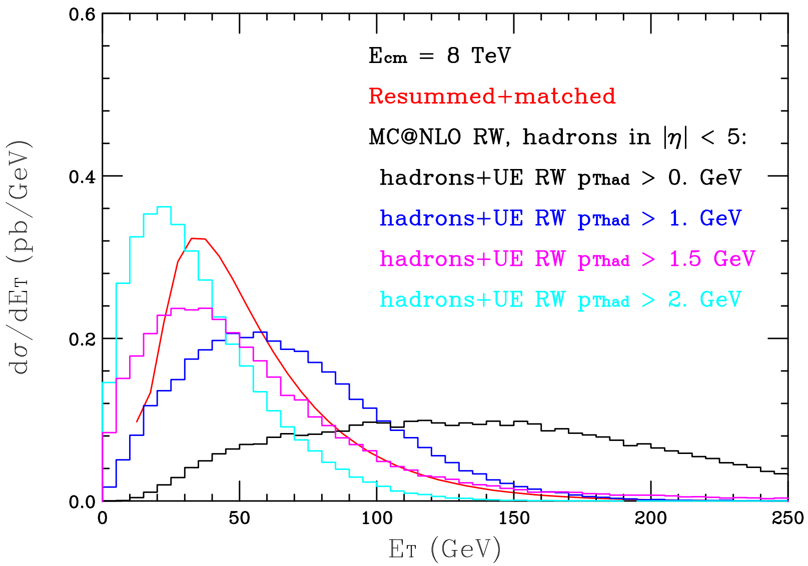
RESUMMATION OF THE TRANSVERSE ENERGY DISTRIBUTION

- E_T DISTRIBUTION SENSITIVE TO INITIAL-STATE RADIATION
  $\Rightarrow$ USEFUL IN DISENTANGLING GLUON FUSION FROM VBF
- RESUMMATION (Papaefstathiou, Smillie, Webber, 2010) MATCHED TO NLO FOR ALL E_T
- HADRON-LEVEL RESULT DETERMINED, INCLUDING HADRONIZATION AND UNDERLYING EVENT
- HADRONIZATION MODERATE WITH RAPIDITY CUT, BUT
  SIZABLE EFFECT OF UNDERLYING EVENT

FO VS RESUMMED VS MATCHED



HADRON LEVEL

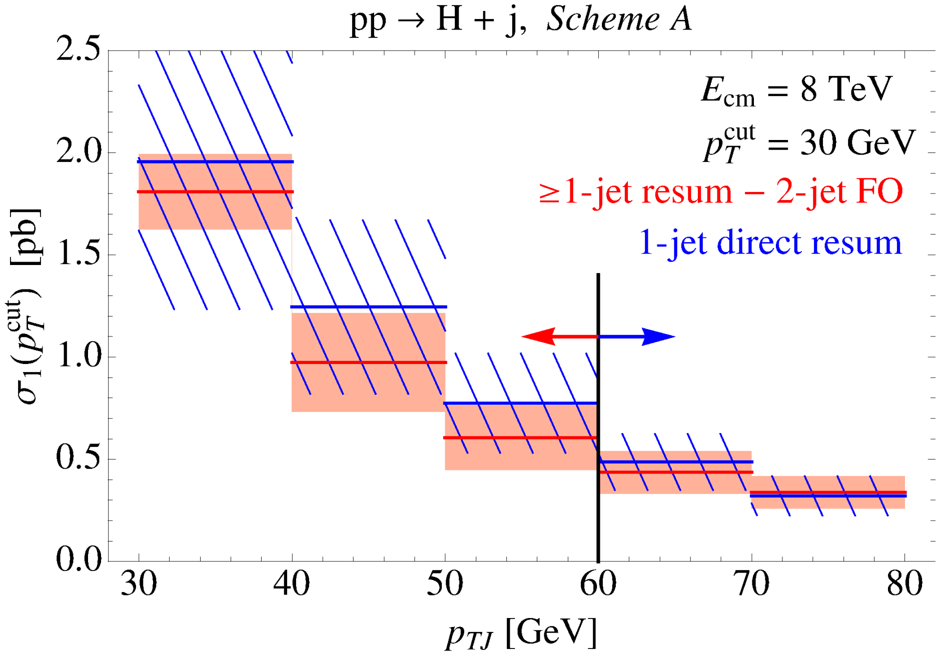


(Grazzini, Papaefstathiou, Smillie, Webber, 2014)

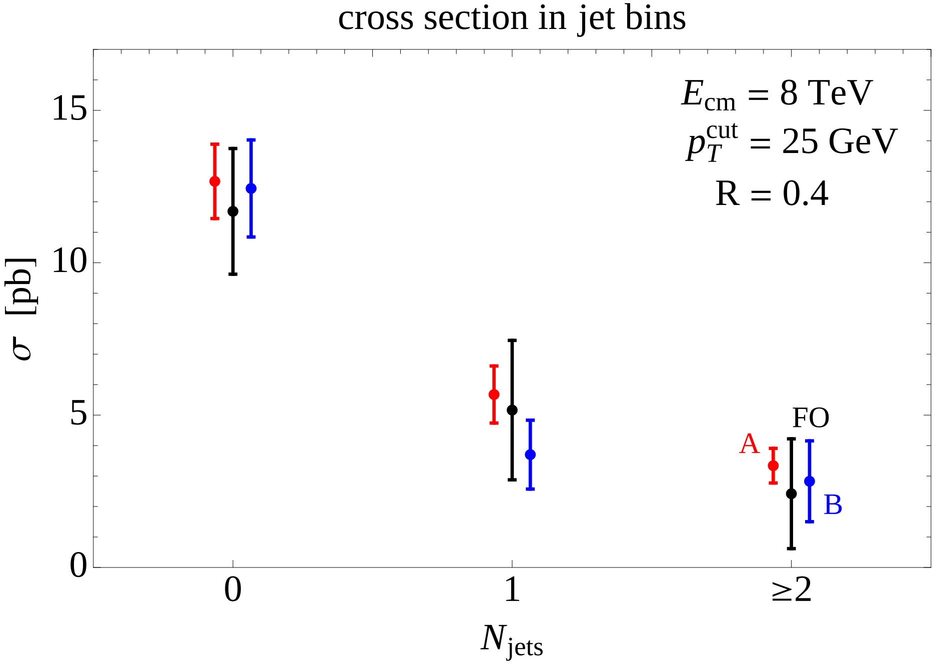
JET VETO RESUMMATION

- RESUMMATION NOW EXTENDED TO FULL "TOWER" OF CROSS SECTIONS: σ_0 (no jets with $p_T > p_T^{\rm veto}$), $\sigma_{\geq 1}$ (at least one jet), σ_1 (exclusively one jet), $\sigma_{\geq 2}\ldots$
- RESUMMATION OF σ_1 EXTENDED TO LOW $p_T \sim p_T^{\rm veto}$
$\Rightarrow$ CONSTRUCTED AS DIFFERENCE BETWEEN $\sigma_{\geq 2}$ AND $\sigma_{\geq 1}$;
$\sigma_{\geq 2}$ COMPUTED TO NLO, $\sigma_{\geq 1}$ TO NNLL+NLO
- COVARIANCE MATRIX BETWEEN DIFFERENT CROSS-SECTIONS DETERMINED
$\Rightarrow$ INVOLVES DETERMINATION OF "MIGRATION UNCERTAINTY" BETWEEN BINS

ONE-JET CROSS SECTION



CROSS-SECTIONS IN JET BINS



(Boughezal, Liu, Petriello, Tackmann, Walsh, 2014)

- SMOOTH MATCHING OF p_T REGIONS FOR ONE-JET
- GREAT REDUCTION OF UNCERTAINTIES

HEAVY QUARK MASS DEPENDENCE

JET VETOS+ HQ MASSES!

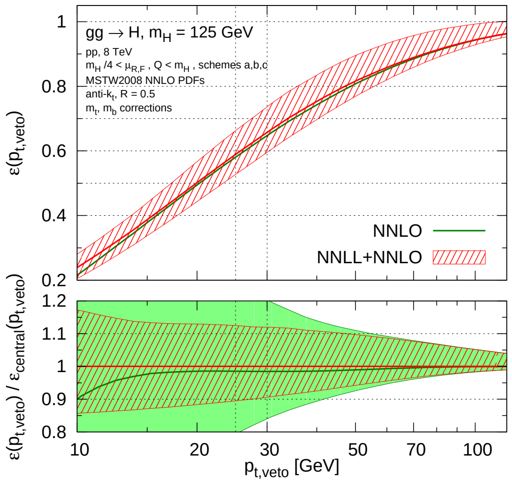
(Banfi, Monni, Zanderighi, 2013)

- ZERO-JET VETO XSECT & EFFICIENCY COMPUTED WITH FULL INCLUSION OF BOTTOM & TOP MASSES UP TO NNLO+NNLL
- MULTISCALE, NON FACTORIZED $\ln \frac{m_b}{p_T^{\text{veto}}}$ IN $p_T^{\text{veto}} > m_b$ REGION
- m_B, m_t CANCELLATION, GENERALLY SMALL CORRECTIONS UNLIKE p_T DISTRIBUTION: WHY?

EFFICIENCY VS p_T^{veto}

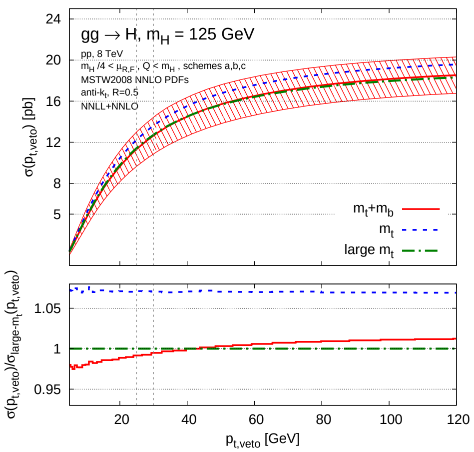
RESUMMED VS.

FIXED ORD.



POINTLIKE VS FINITE m_b

VS FINITE m_b, m_t



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- m_B, m_t CANCELLATION, GENERALLY SMALL CORRECTIONS UNLIKE p_T DISTRIBUTION: WHY?
- LARGE EFFECTS AT NLO+NLO, SMALL AT NNLO+NNLO: RESUMMATION PERTURBATIVE!

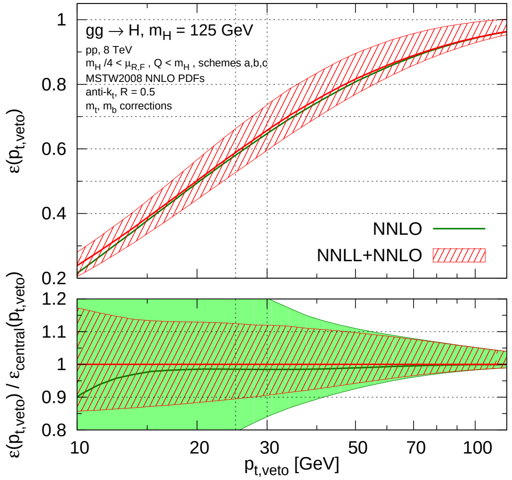
EFFICIENCY VS $p_T^{\rm veto}$

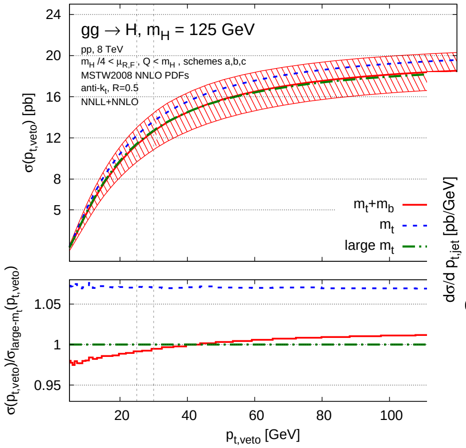
RESUMMED VS. FIXED ORD.

POINTLIKE VS FINITE m_b VS FINITE m_b, m_t

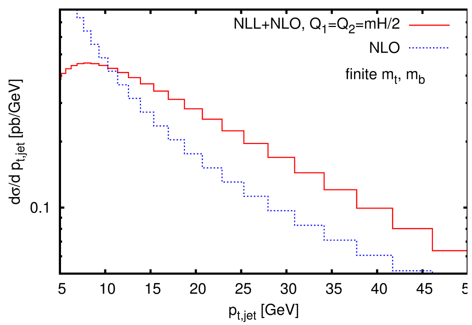
p_T DISTRIBUTION

RESUMMED VS FIXED ORD.

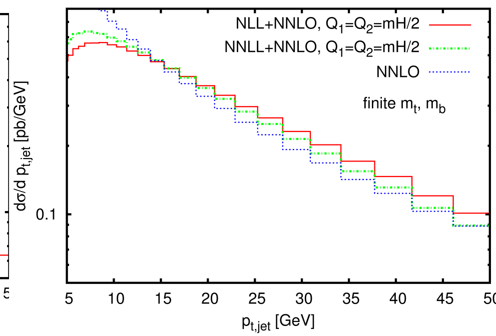




NLO



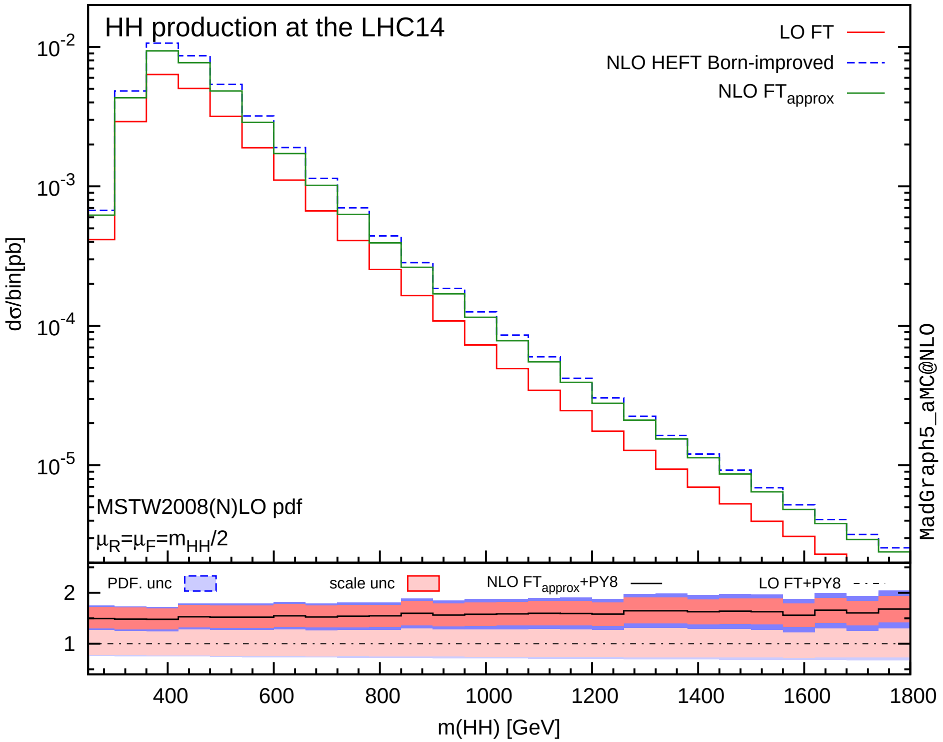
NNLO



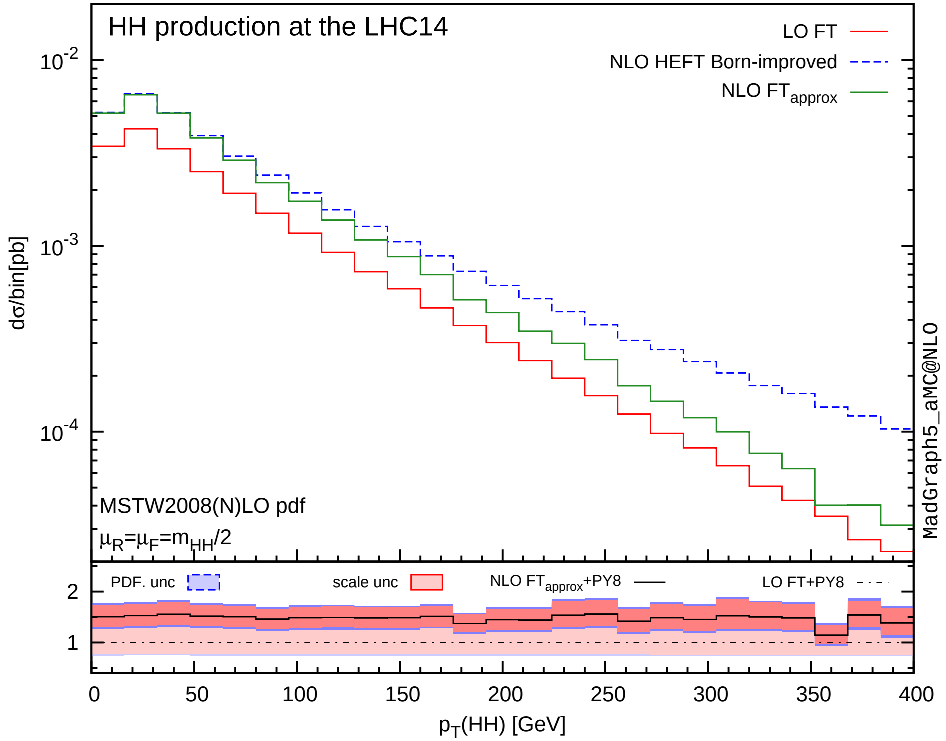
LOOKING FOR HQ MASS SENSITIVITY

m_t IN DOUBLE HIGGS PRODUCTION

INVARIANT MASS DISTN.



p_t



(Maltoni, Vryonidou, Zaro, 2014)

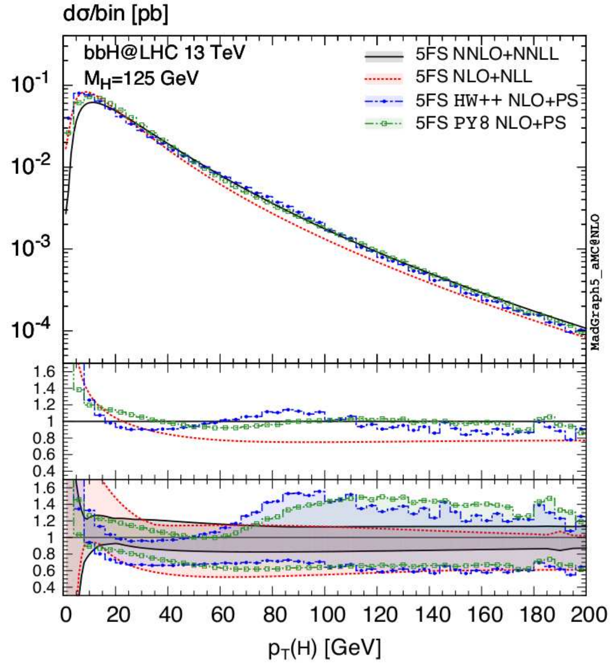
- TOP MASS DEPENDENCE STRONGER IN DOUBLE (& TRIPLE) HIGGS PRODUCTION
- FULL NLO FINITE m_t NOT AVAILABLE, APPROX BASED ON OMITTING 2-LOOP VIRTUAL
- AT LO, FINITE m_T 15% BIGGER THAN $m_t \to \infty$, BUT
  AT NLO FINITE m_T (APPROX) ONLY 6% BIGGER

(Frederix, Frixione et al., 2014)

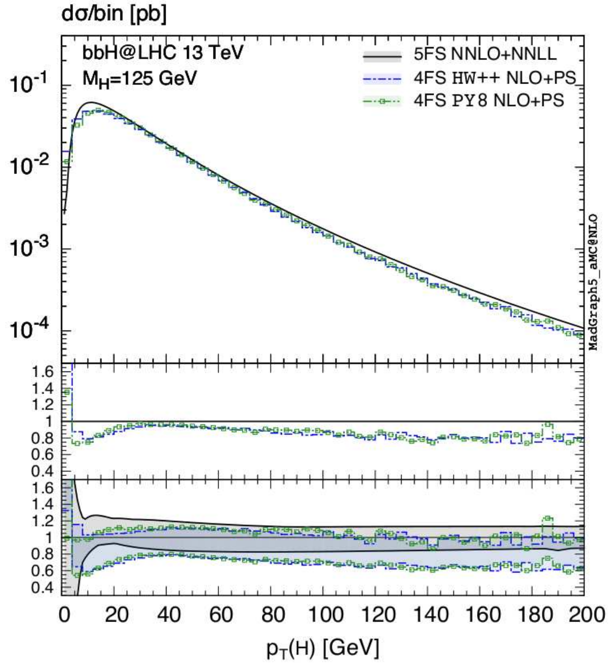
LOOKING FOR HQ MASS SENSITIVITY

m_B IN HIGGS WITH BOTTOM PAIRS

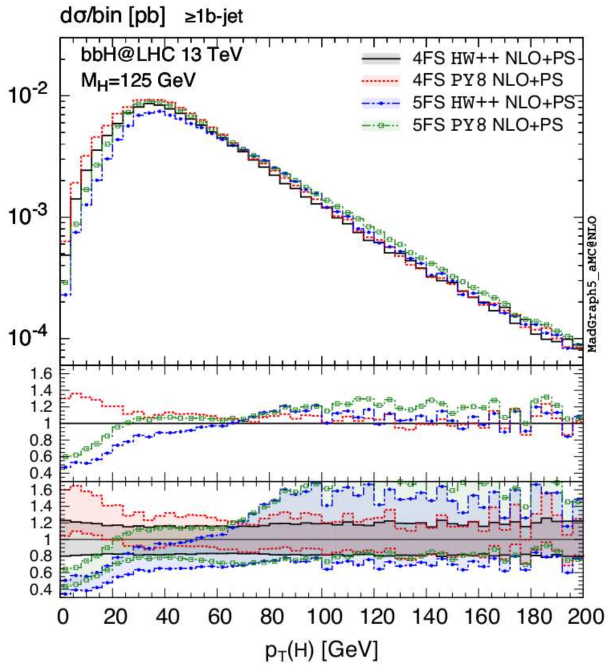
p_T DISTN., 5FS, RES VS PS



p_T DISTN., 4FS VS. 5FS



p_T DISTN. WITH ONE B, 4FS VS. 5FS

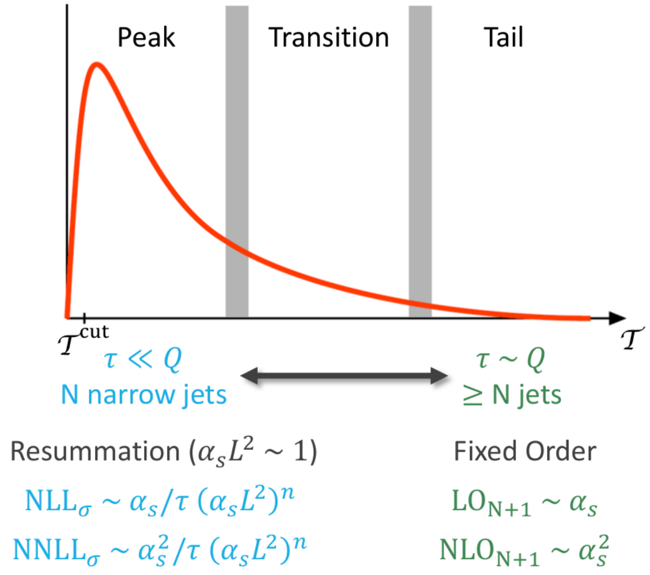


(Wiesemann, Frederix, Frixione et al., 2014)

- NLO CORRECTIONS LARGE, MATCHING TO PARTON SHOWER IMPORTANT
- GOOD AGREEMENT BETWEEN ANALYTIC RESUMMATION & PS
- 4FS & 5FS QUITE CLOSE FOR SOME OBSERVABLES (INCLUSIVE H p_T DISTRIBUTION)
- CLEARLY DISTINGUISHABLE IF AT LEAST ONE b-JET

CLOSER TO THE FINAL STATE

MATCHING: FIXED ORDER, RESUMMATION, SHOWER



(Alioli et al., 2012)

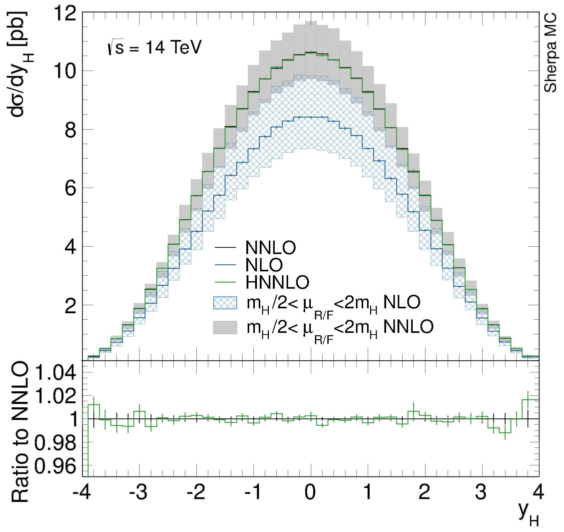
- Higgs production at LHC (especially in gluon fusion) sits in the transition region
  ⇒ must consider both & match resummation and fixed order
- accurate final state: merge with parton shower
- three proposals for NNLO+PS matching:
  - GENEVA (SCET-based): applied to thrust in e^+e^-, (Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi, 2012) ; general theory available (Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi, 2013)
  - NNLOPS: NNLO+NLL achieved for Higgs in gluon fusion (Hamilton, Nason, Re, Zanderighi, 2013) and Drell-Yan (Karlberg, Re, Zanderighi, 2014)
  - UN^{2}LOPS NNLO+NLL achieved for Higgs in gluon fusion & Drell-Yan (Höche, Li, Prestel, 2014)

THE UN^{2}LOPS METHOD

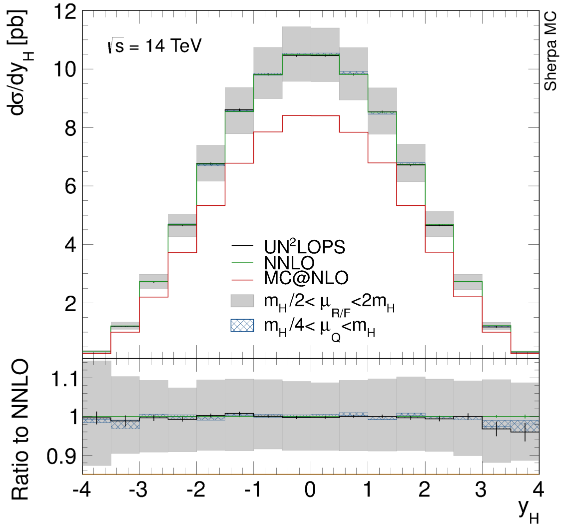
HIGGS IN GLUON FUSION

- UN^{2}LOPS IMPLEMENTED IN SHERPA:
  EXCELLENT AGREEMENT OF FIXED NNLO WITH STANDARD CODES
- RAPIDITY DISTN. AGREES WITH FIXED-ORDER CALCULATION
- p_T SPECTRUM AGREES WITH ANALYTIC RESUMMATION,
  WHILE REPRODUCING FIXED ORDER (LARGE p_T)
- LARGE UNCERTAINTY IN ZERO-p_T BIN BECAUSE SPECTRUM AT NLO+NLL

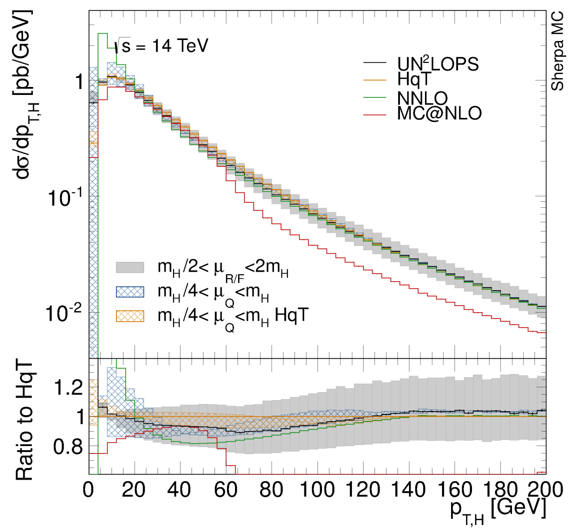
SHERPA VS NNLO



UN^{2}LOP VS. FIXED ORD.



UN^{2}LOP VS RESUMM.



(Höche, Li, Prestel, 2014)

SUMMARY

THEORETICAL PROGRESS IS KEEPING PACE WITH EXPERIMENTAL PROGRESS:

- BEYOND NNLO
- BEYOND FIXED ORDER
- BEYOND A SINGLE LARGE SCALE
- BEYOND THE PARTON LEVEL

"...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)

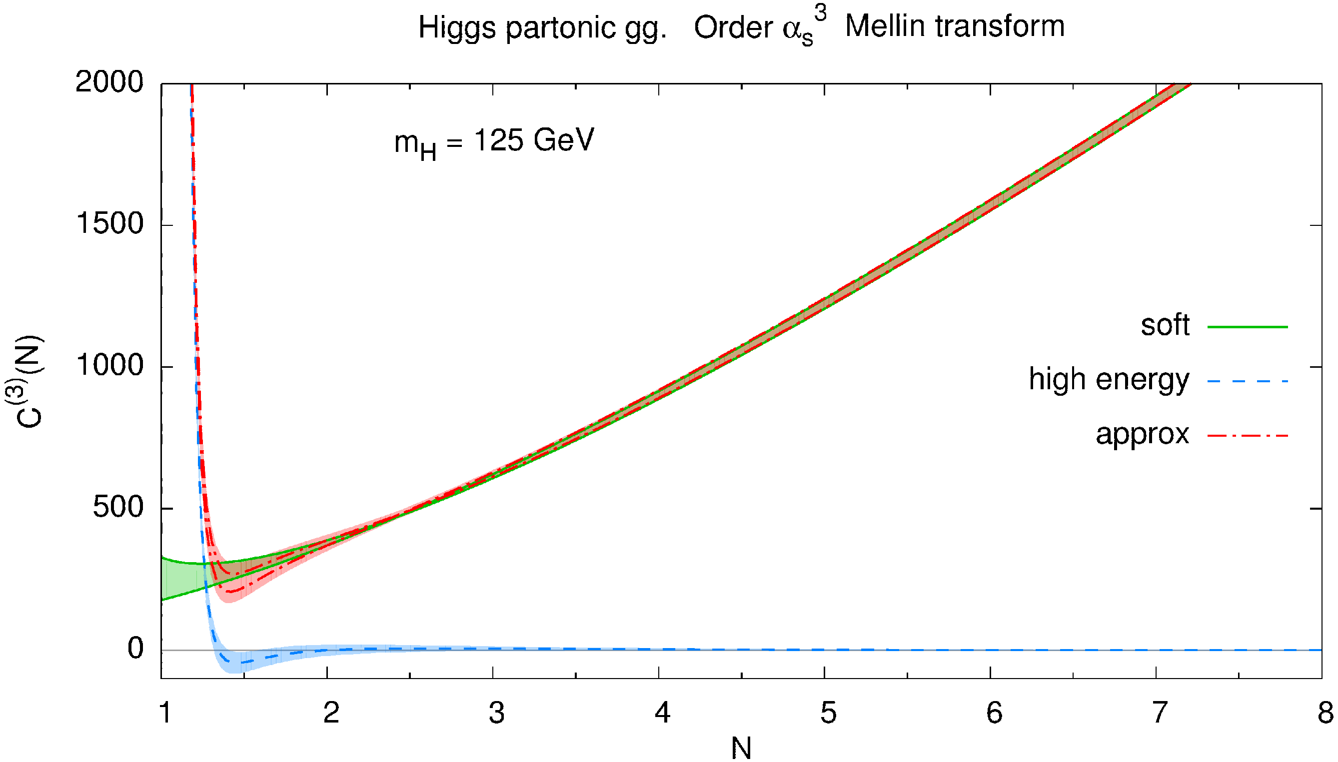
EXTRAS

ANALYTIC APPROXIMATION

THE N^3LO PARTON-LEVEL RESULT

EXACT+SOFT+HIGH ENERGY+APPROX.

$O(\alpha_s^3)$



(Ball, Bonvini, s.f., Ridolfi, Marzani 2014)

A (USEFUL) SIDE REMARK: SADDLE POINT

- THE CROSS SECTION IS DETERMINED FROM THE N-SPACE RESULT BY MELLIN INVERSION:
$$\frac{\sigma(\rho, m_H^2)}{\rho} = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} dN\,\rho^{-N}\,\sigma(N, m_H^2) = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} dN\,e^{E(N,\rho,m_H^2)}$$
$$E(N,\rho,m_H^2) \equiv N\ln\frac{1}{\rho} + \ln\sigma(N, m_H^2)$$

- DOMINATED BY SADDLE POINT $\left.\frac{\partial E(N,\rho,m_H^2)}{\partial N}\right|_{N=N_0} = 0$

- SADDLE N_0 ON THE REAL AXIS: $\sigma(N)$ MUST BE A DECREASING FUNCTION OF N; AS $\rho \to 0$, N_0 MOVES LEFTWARDS TOWARDS THE RIGHTMOST SING.

- MOST OF THE CONTRIBUTION COMES FROM A SMALL NEIGHBORHOOD OF N_0

- FOR $m_h = 125$ GEV, $N_0 \approx 2$ FOR $s = 7-8$ TEV, $N_0 \approx 1.8$ FOR $s = 14$ TEV

EXAMPLE: HIGGS PRODUCTION

EXACT VS SADDLE LL AND NLL GLUON FUSION CROSS-SECTION