QCD at the LHC
IV: HIGGS

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XLIX Herbstschule für Hochenergiephysik

Maria Laach, 14 September 2017

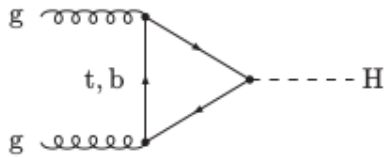
SUMMARY

LECTURE IV: HIGGS

- HIGGS PRODUCTION: CHANNELS AND UNCERTAINTIES
- HIGGS IN GLUON FUSION: EXACT VS. EFT APPROACH
- THE TRANSVERSE MOMENTUM DISTRIBUTION
- MULTISCALE PROCESSES AND HEAVY QUARK MASS DEPENDENCE
- HIGH-ENERGY APPROXIMATION AND QUALITATIVE BEHAVIOUR
- SIGNAL, BACKGROUND, AND OFF-SHELL

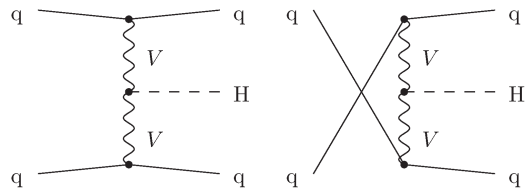
HIGGS PRODUCTION CHANNELS

GLUON FUSION



$$\sim \alpha_s^2 G_F m_H^2$$

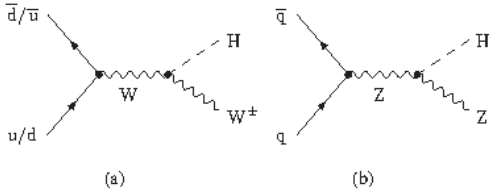
VECTOR BOSON FUSION



$$\sim \alpha_s^0 \left(G_F m_V^2\right)^2 G_F \frac{m_V^4}{Q^2}$$

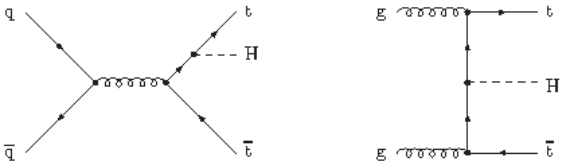
t-channel DOMINANT
$\Rightarrow$ LIKE DIS SQUARE

WH/ZH ASSOCIATE



$$\sim \alpha_s^0 \left(G_F m_V^2\right)^2$$

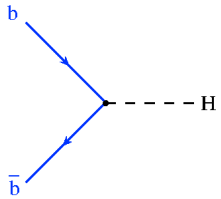
TOP FUSION



$$\sim \alpha_s^2 G_F m_t^2$$

NO TOP QUARKS
IN THE PROTON!

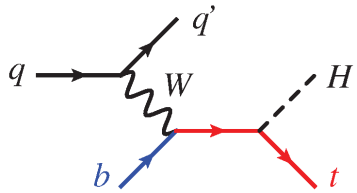
BOTTOM FUSION

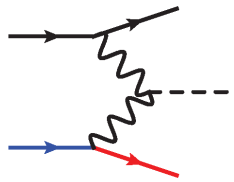


$$\sim \alpha_s^2 G_F m_b^2$$

B PDF IN 5 FLAVOR
SCHEME ONLY!

SINGLE TOP

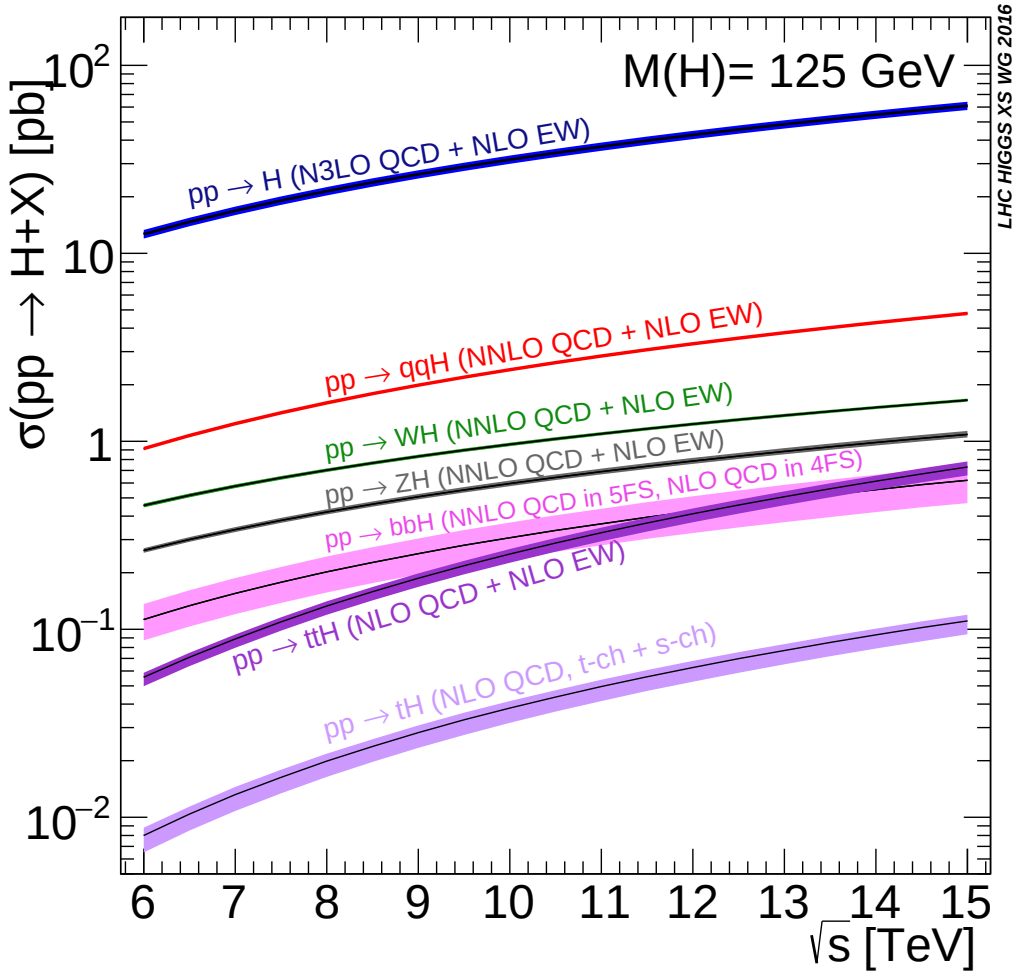




A CHARGED-CURRENT
VERSION OF VBF

THE HIGGS PRODUCTION CROSS-SECTION

AT p-p COLLIDERS, VS. COLLIDER ENERGY

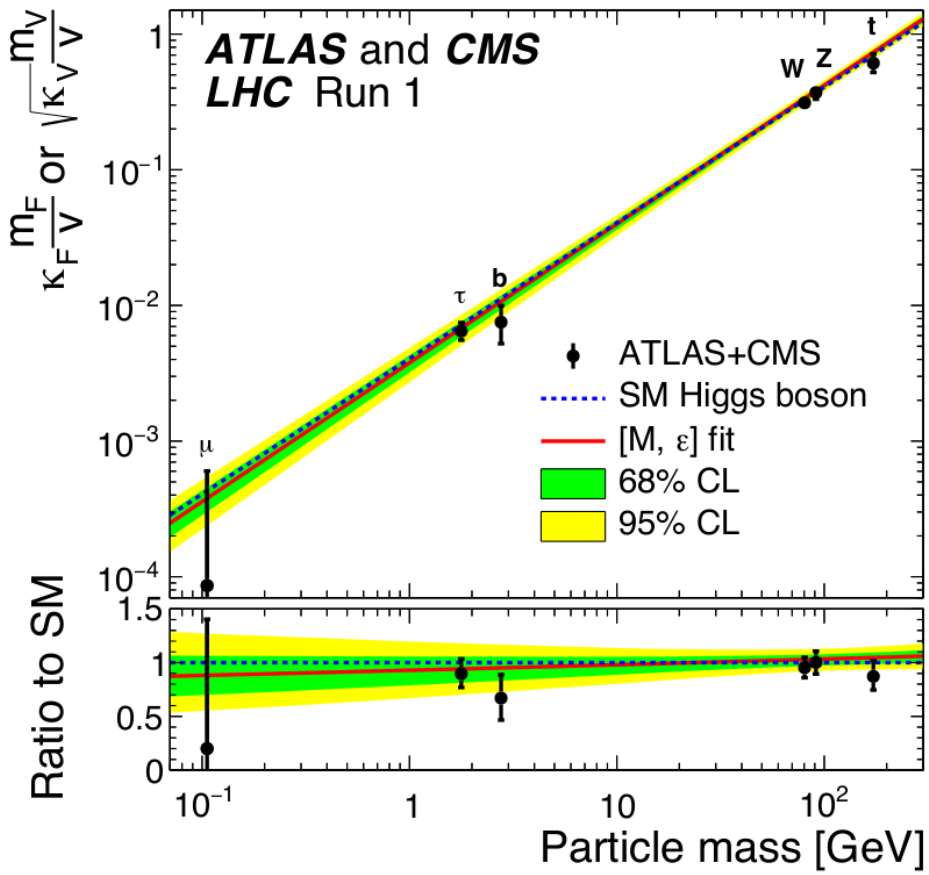


- GLUON FUSION DOMINANT CHANNEL
- ttH, bbG DIRECTLY PROBE HQ COUPLINGS
- MOST CHANNELS ACCURATELY KNOWN

COUPLINGS AND ACCURACY

- NO SIGNALS OF NEW PHYSICS
- NEW PHYSICS IN HIGGS COUPLINGS?
- ONLY GAUGE COUPLINGS ACCURATELY TESTED

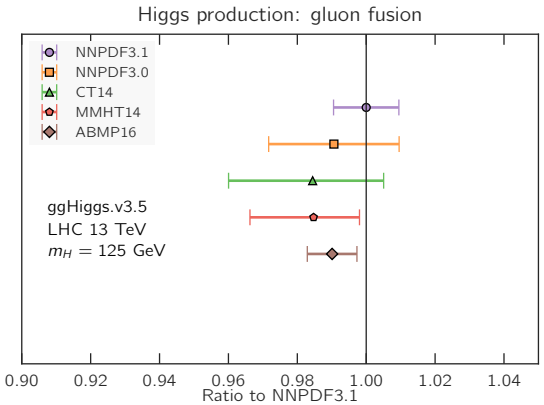
ATLAS & CMS, 1606.02266



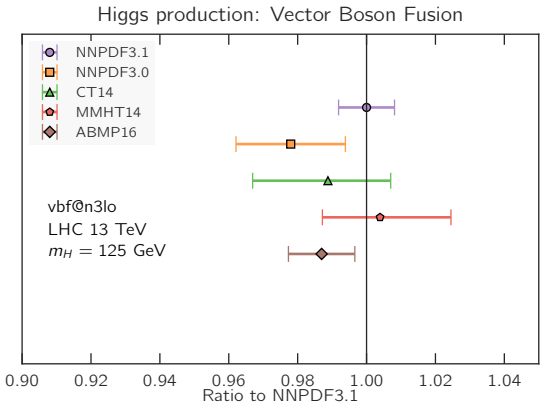
- DOMINANT UNCERTAINTIES COME FROM QCD
- PDFS & MISSING HIGHER-ORDER CORRECTIONS

PDF UNCERTAINTIES

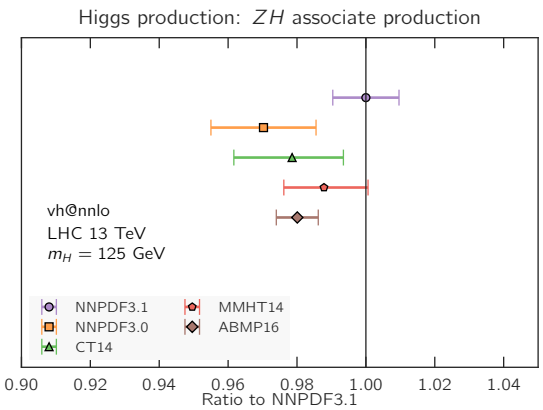
GLUON FUSION



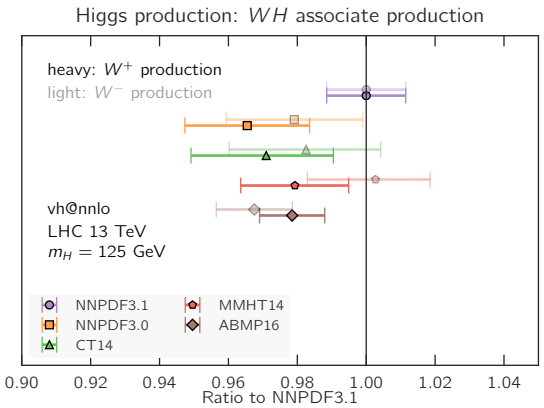
VECTOR BOSON FUSION



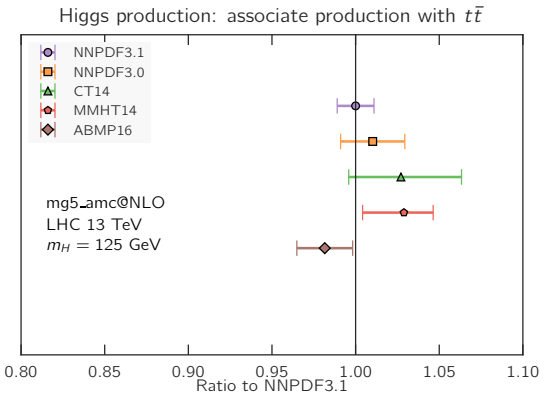
ZH ASSOCIATE



WH ASSOCIATE



TOP FUSION



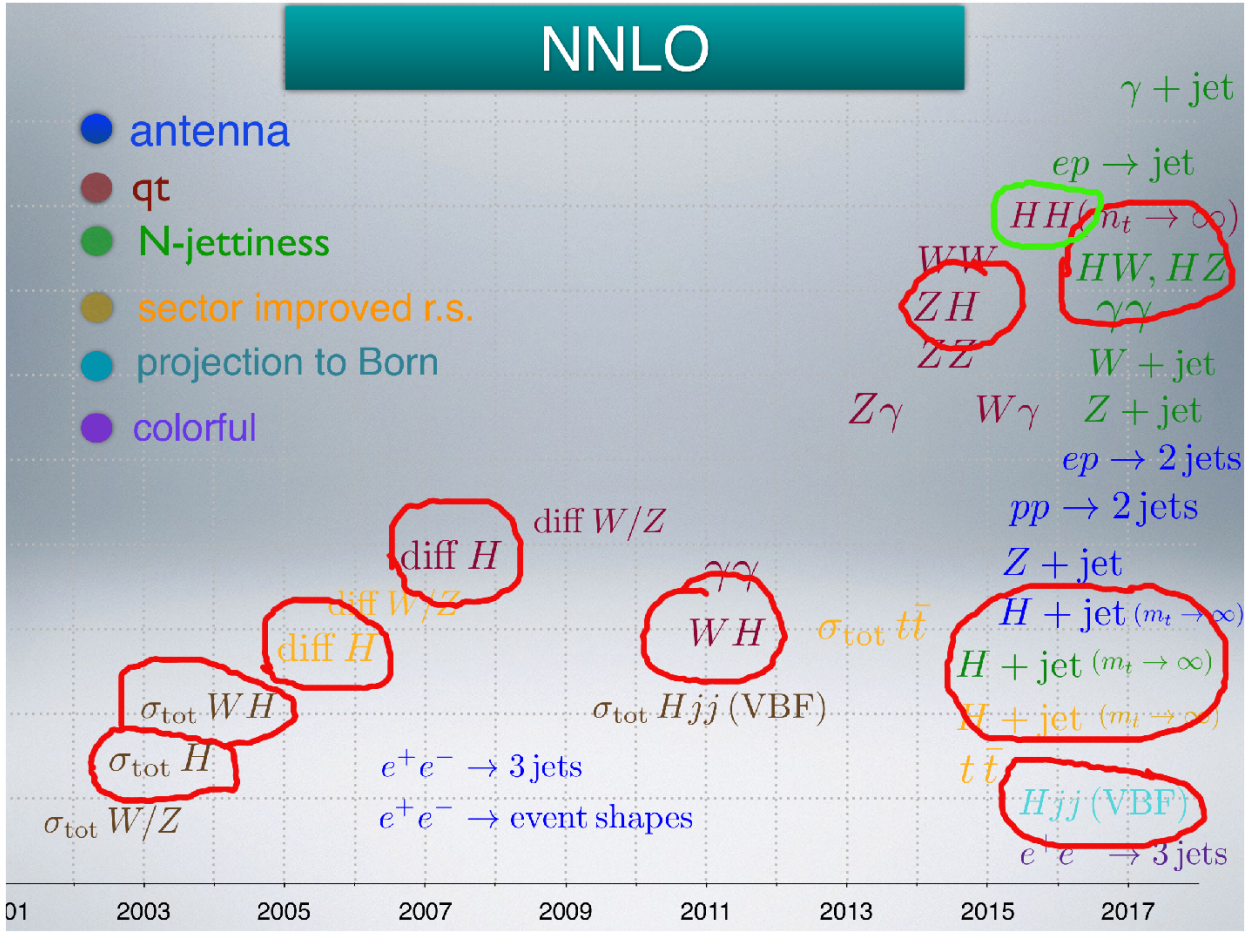
- GOOD AGREEMENT BETWEEN GLOBAL SETS
- UNCERTAINTIES BELOW THE 5% LEVEL

MISSING HIGHER ORDER CORRECTIONS

MHOU UNCERTAINTIES
ON TOTAL XSECTS (HXSWG)

GGF	N^3LO	4%
VBF	NNLO	0.5%
WH	NNLO	$< 1\%$
ZH	NNLO	$\sim 2\%$
$t\bar{t}H$	NLO+NNLL	5%

- NNLO CORRECTIONS KNOWN FOR MOST HIGGS PRODUCTION CHANNELS
- TYPICAL "SCALE" UNCERTAINTIES TINY
- WHAT ARE "SCALE UNCERTAINTIES"?



(G. Heinrich, LHCP, May 2017)

MISSING HIGHER ORDER CORRECTIONS
SCALE VARIATION

BASIC IDEA:

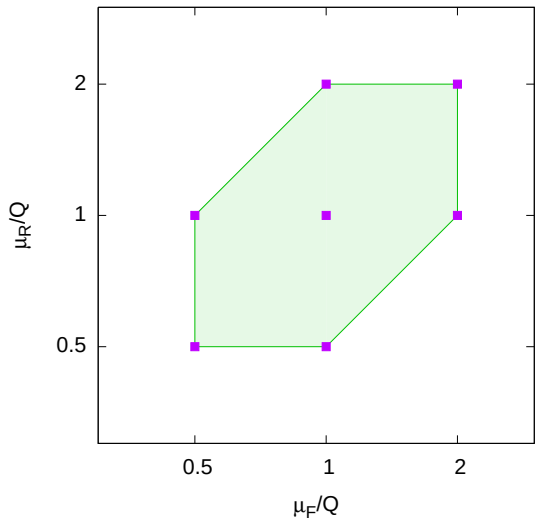
- $\sigma(N, M^2) = \sum_{ij} \mathcal{L}_{ij}\left(N, \mu_F^2\right) \hat{\sigma}_{ij}\left(N, \alpha_s(\mu_R^2), \frac{M^2}{\mu_R^2}, \frac{M^2}{\mu_F^2}\right)$
  DOES NOT DEPEND ON μ_R^2, μ_F^2, UP TO HIGHER ORDERS
- $\hat{\sigma}_{ij}\left(N, \alpha_s(\mu_R^2), \frac{M^2}{\mu_R^2}, \frac{M^2}{\mu_F^2}\right) = \sum_k \alpha_s^k(\mu_R^2)\hat{\sigma}_{ij}^{(k)}\left(N, \frac{M^2}{\mu_R^2}, \frac{M^2}{\mu_F^2}\right)$
- $\alpha_s(k\mu_R^2) = \left[1 - \beta_0 \alpha_s^2 \ln k\right] \alpha_s(\mu_R^2) = +O(\alpha_s^2)$
- $\mathcal{L}_{ij}\left(N, k'\mu_F^2\right) =$
  $\left(\delta_{ii'} + \alpha_s(\mu_f^2 + O(\alpha_s^2))P_{ii'}^{(0)}(N)\ln k'\right)\left(\delta_{jj'} + \alpha_s(\mu_f^2)P_{jj'}^{(0)}(N)\ln k' + O(\alpha_s^2)\right)\mathcal{L}_{i'j'}\left(N, k'\mu_F^2\right)$
- DEPENDENCE OF $\hat{\sigma}_{ij}^{(1)}$ ON μ_F, μ_r ENTIRELY FIXED IN TERMS OF $\hat{\sigma}_{ij}^{(0)}$, β_0, $P_{ii'}^{(0)}$
- DEPENDENCE OF σ ON μ_r, μ_f STARTS AT $O(\alpha_s^2)$ IF $\hat{\sigma}$ COMPUTED TO $O(\alpha) \Rightarrow$
  ESTIMATE OF THE SIZE OF MISSING $O(\alpha_s^2)$ TERMS

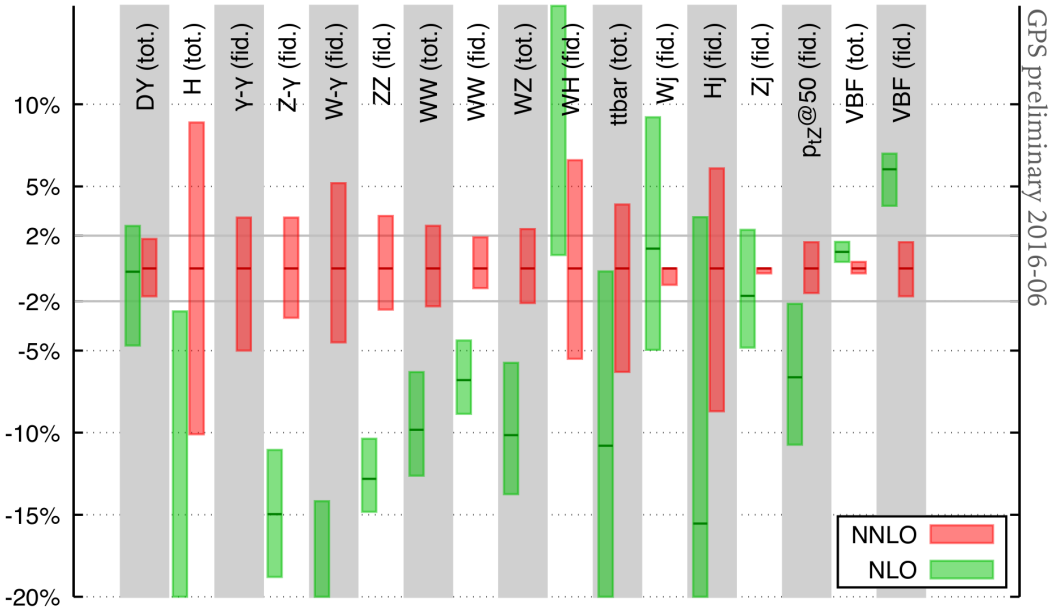
MISSING HIGHER ORDER CORRECTIONS

SCALE VARIATION

CAVEATS:

- NO UNNATURAL SCALE RATIOS ⇒ "SEVEN-POINT" SCALE VARIATION
- APPROPRIATE RANGE FOR SCALE VARIATION? TRADITIONALLY, A FACTOR 2: HOW WELL DOES IT WORK??
- LOOK FOR NEW METHODS: BAYESIAN ESTIMATES?





NNLO WITHIN 7-POINT NLO BAND IN 3/17 CASES

SCALE VARIATION DOES NOT ACCOUNT FOR NEW CHANNELS, STRUCTURES

GLUON FUSION

THE TOTAL CROSS-SECTION

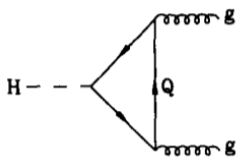
LEADING ORDER

(one quark in loop, mass m_q): $\hat{\sigma} = \frac{\sigma_0}{m_H^2}\delta(\hat{s} - m_h^2)$; $\sigma_0 = \frac{G_F \alpha_s^2(\mu_R^2)}{288\sqrt{2}\pi}|I(\tau_q)|^2$

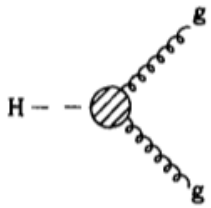
$$\tau_q = \frac{m_q^2}{m_H^2}; \begin{cases} \lim_{\tau\to 0} I(\tau) = 0 & \text{infintely massive Higgs decouples} \\ \text{finite } \tau :\sim +6\% \text{ corrn. for top, down to } -1\% \text{including t \& b (interf.)} \\ \lim_{\tau\to\infty} I(\tau) = 1; & \text{infintely massive quark} \to \text{pointlike coupling} \end{cases}$$

$\tau \to \infty \to$ EFFECTIVE INTERACTION: $\mathcal{L} = \frac{\alpha_s}{12\pi}\left(\sqrt{2}G_F\right)^{1/2} H G^a_{\mu\nu} G^a_{\mu\nu}$

EXACT

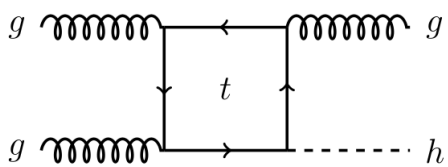


EFFECTIVE FIELD THEORY

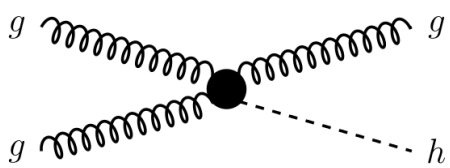


NEXT-TO-LEADING ORDER

EXACT



EFFECTIVE FIELD THEORY



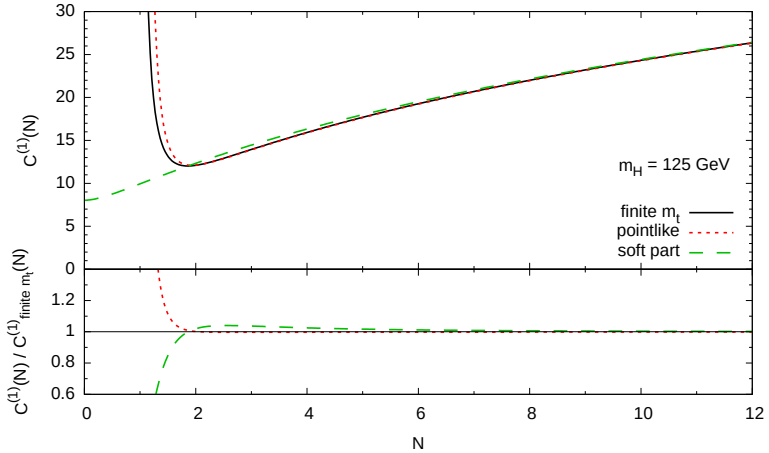
REFT: $\sigma^{\rm NLO} = R_{\rm LO}\sigma^{\rm NLO}_{\rm EFT}$; $R_{\rm LO} \equiv \frac{\sigma^{\rm LO}_{ex;\,t}}{\sigma^{\rm LO}_{\rm SFT}}$ WILSON COEFFICIENT

$\Rightarrow$ .7% ACCURATE (b interf. -4%)

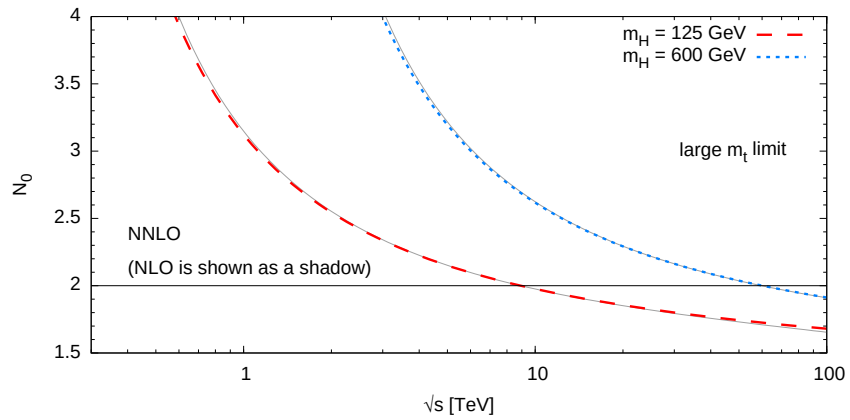
THE TOTAL CROSS-SECTION
SOFT DOMINANCE

- AT LARGE $\tau \to 1$ (LARGE $N \to \infty$) THE NLO CROSS-SECTION BEHAVES AS $\left[\frac{\ln(1-\tau)}{1-\tau}\right]_+ \Leftrightarrow \ln^2 N$
  EXACT & EFT COINCIDE IN THIS LIMIT
- AT SMALL $\tau \to 0$ (LARGE $N \to 1$) THE NLO CROSS-SECTION BEHAVES AS const. $(\frac{1}{N-1})$ BUT IN EFT AS $\ln \frac{1}{\tau}$ $(\frac{1}{(N-1)^2})$
- WHERE SHOULD WE LOOK? RECALL SADDLE!

NLO N-SPACE PARTONIC XSECT



SADDLE POINT VS COLL. ENERGY



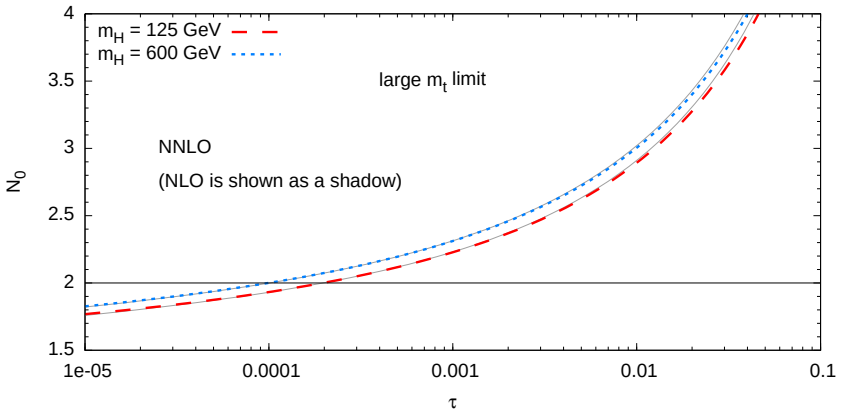
- "SOFT" (LOG) APPROX SURPRISINGLY GOOD!
- LHC ENERGY STILL IN SOFT REGION (JUST!)
- WHY?

THE TOTAL CROSS-SECTION

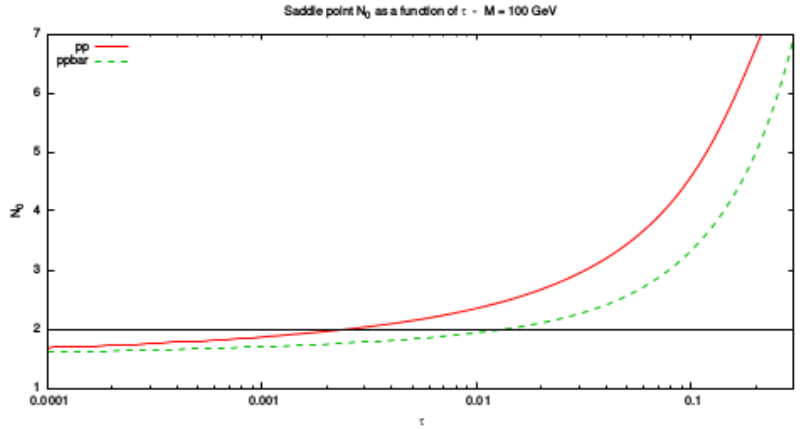
HIGGS VS. Z (DRELL-YAN)

SADDLE POINT VS COLL. ENERGY

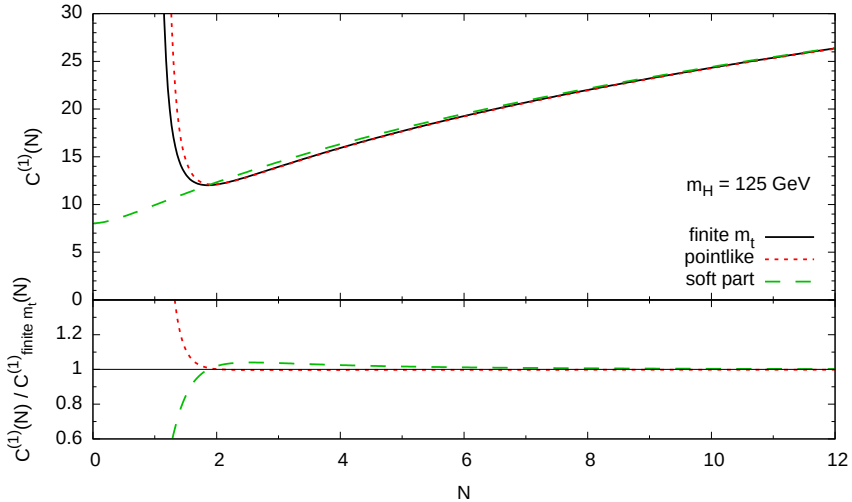
HIGGS

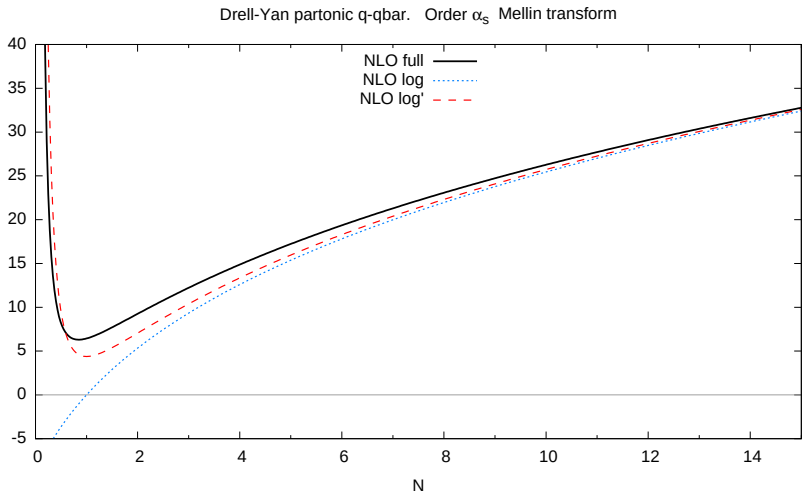


Z (DRELL-YAN)



NLO N-SPACE PARTONIC XSECT





WHY IS HIGGS SPECIAL?

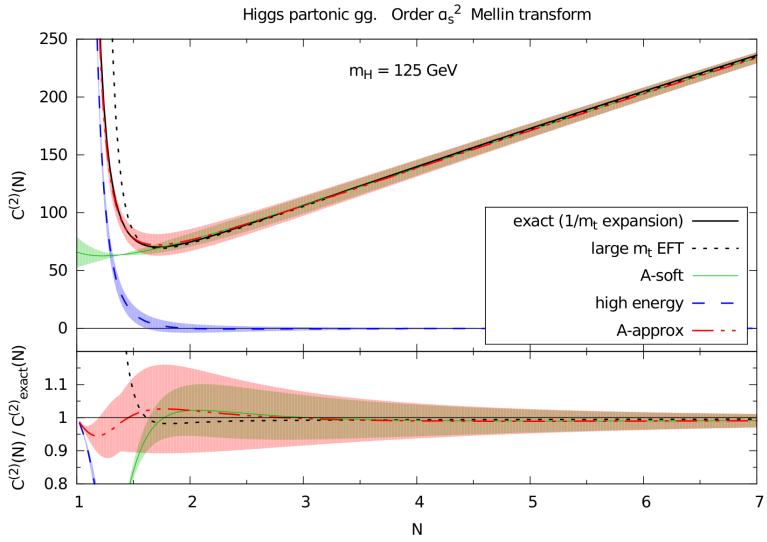
- GLUONS $\rightarrow$ SMALLER MOMENTUM FRACTION THAN QUARKS $\Leftrightarrow$ HIGGS SADDLE LARGER N
- SOFT APPROX TO HIGGS GOOD ALL THE WAY DOWN TO MIN.

THE TOTAL CROSS-SECTION

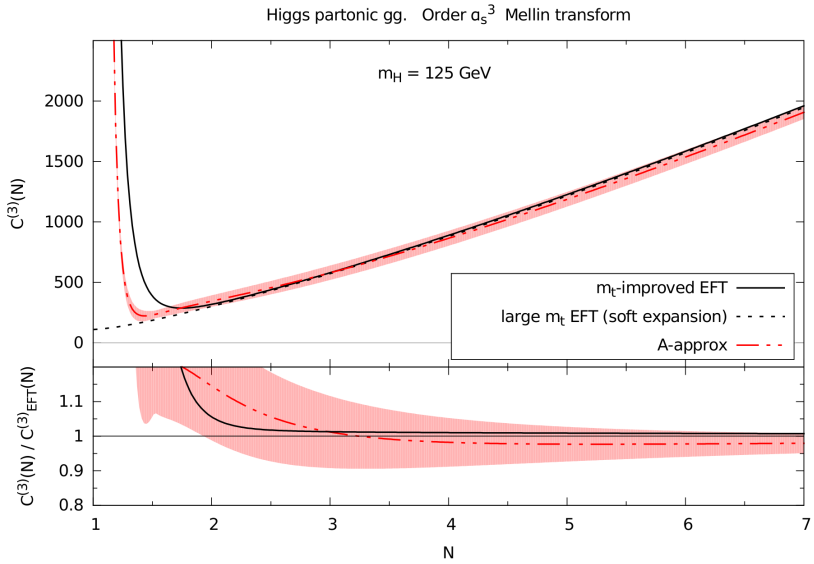
MASS DEPENDENCE FROM RESUMMATION

- SMALL N (LL) & LARGE N (NNLL) BEHAVIOUR KNOWN TO ALL ORDERS IN α_s
  NOTE LARGE N WELL KNOWN: E.G. AT NNNLO COEFFICIENTS OF $\ln^k N$ KNOWN FOR $0 < k \leq 6$
- SMALL N KNOWN BOTH IN EXACT AND EFT
- LARGE N SAME IN EXACT & EFT
- CAN CORRECT NNNLO FOR FINITE m_t

NNLO



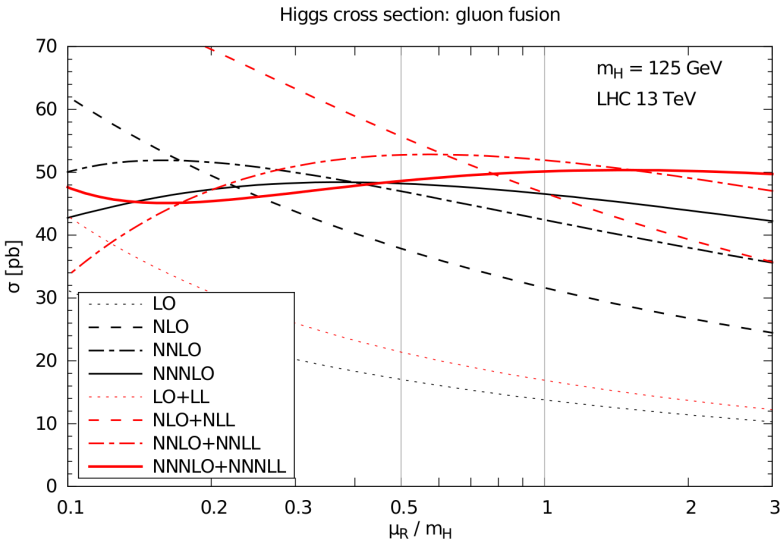
NNNLO



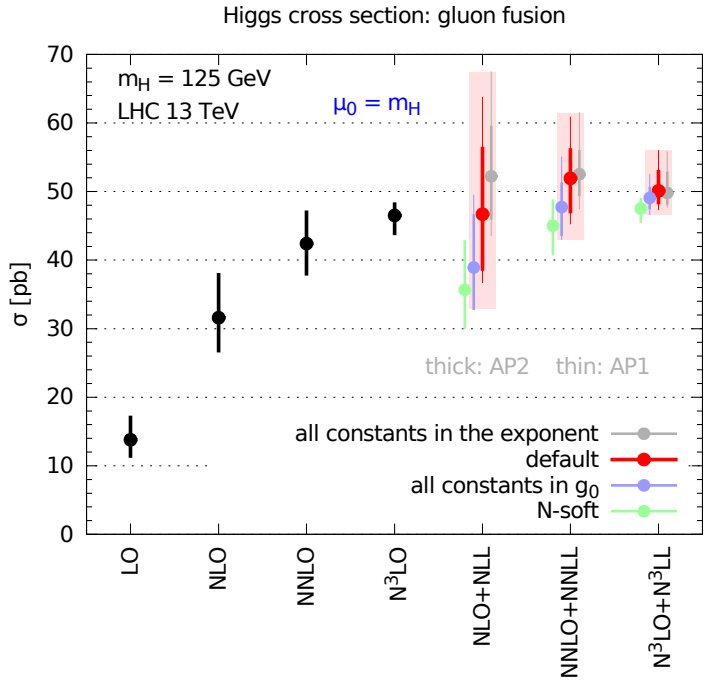
THE TOTAL CROSS-SECTION

PERTURBATIVE CONVERGENCE

σ VS. $\mu_r = \mu_f$



σ VS. PERT. ORDER

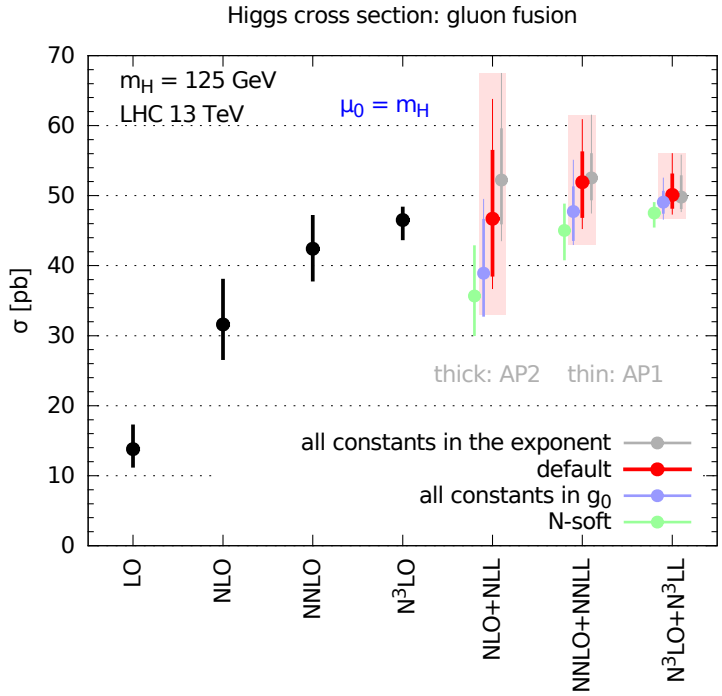


- UNUSUALLY SLOW PERTURBATIVE CONVERGENCE $\Rightarrow$ LARGE SCALE DEPENDENCE
- SCALE DEPENDENCE DOES NOT PREDICT WELL UNCERTAINTIES
- RESUMMATION IMPROVES $\Leftrightarrow$ SOFT DOMINANCE

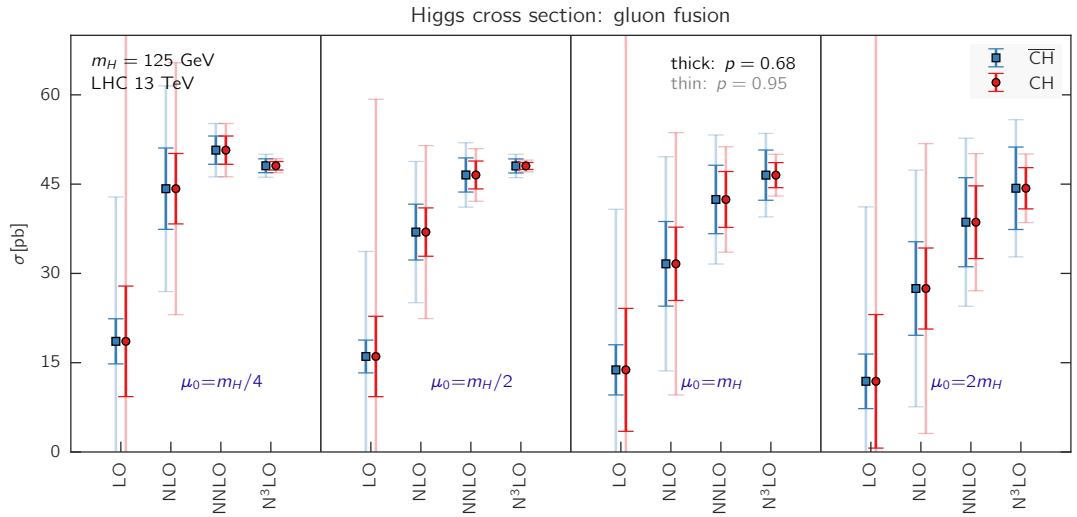
THE TOTAL CROSS-SECTION

PERTURBATIVE CONVERGENCE

SCALE UNCERTAINTIES



BAYESIAN ESTIMATE



- UNUSUALLY SLOW PERTURBATIVE CONVERGENCE
- SCALE DEPENDENCE DOES NOT PREDICT WELL UNCERTAINTIES
- BAYESIAN METHODS PROVIDE A MORE RELIABLE ESTIMATE

THE TRANSVERSE MOMENTUM DISTRIBUTION
AND HIGGS COUPLINGS

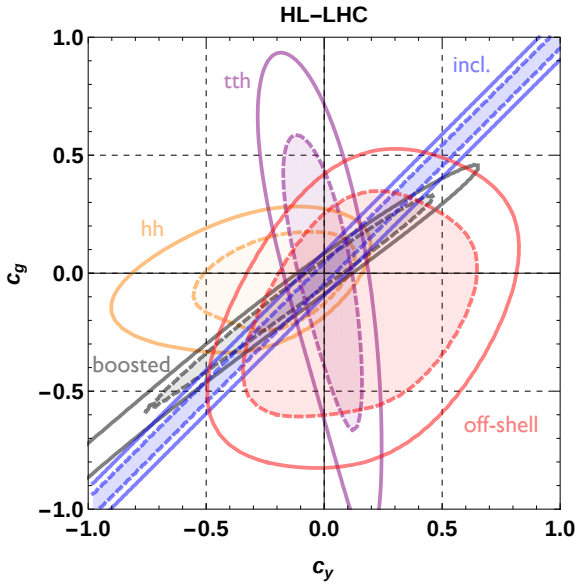
- NEW STATES MOST LIKELY REVEALED THROUGH HIGGS-TOP COUPLINGS
- DEGENERACY IN HIGGS COUPLINGS TO DIMENSION 6 OPERATORS:

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

- TOTAL CROSS-SECTIONS ONLY DEPENDS ON $c_g + c_t$

LIFTING THE DEGENERACY

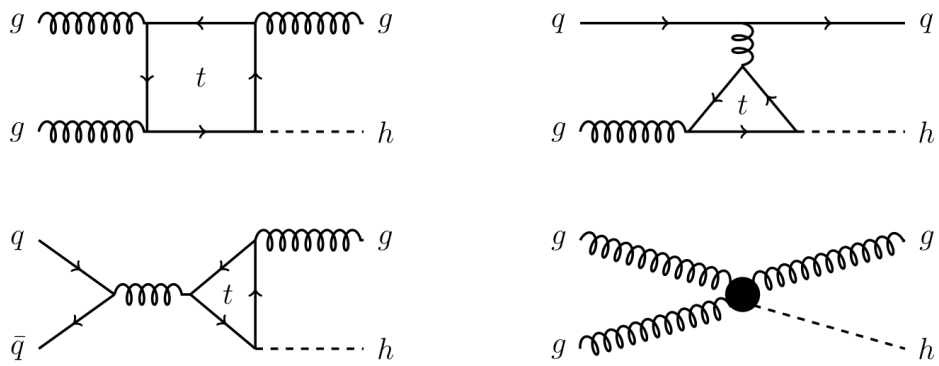
EXCLUSION REGIONS AT HL-LHC



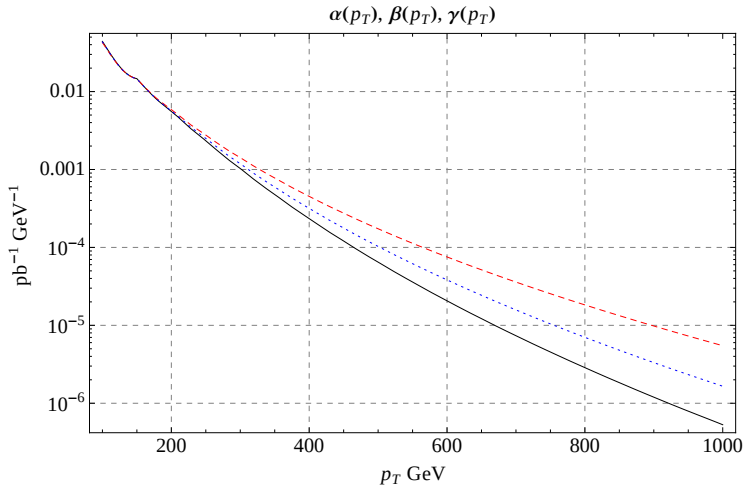
- DOUBLE HIGGS
- OFF-SHELL
- PRODUCTION IN ASSOCIATION WITH TOP
- BOOSTED

HIGGS AT LARGE p_T

"BOOSTED" HIGGS



- HIGGS+ JET CROSS SECTION: EFFECTIVE c_g INDUCED BY CONTACT TERM
- CROSS-SECTION $\frac{d\sigma}{dp_T} = \alpha(p_T)c_t^2 + 2\gamma(p_t)c_t c_g + \beta(p_T)c_g^2$
- CAN DISENTAGLE CONTACT TERM BY SLOWER DROP WITH p_T



TOTAL CROSS-SECTION VS TRANSVERSE MOMENTUM DISTRIBUTION

QUALITATIVE BEHAVIOUR

TOTAL CROSS-SECTION

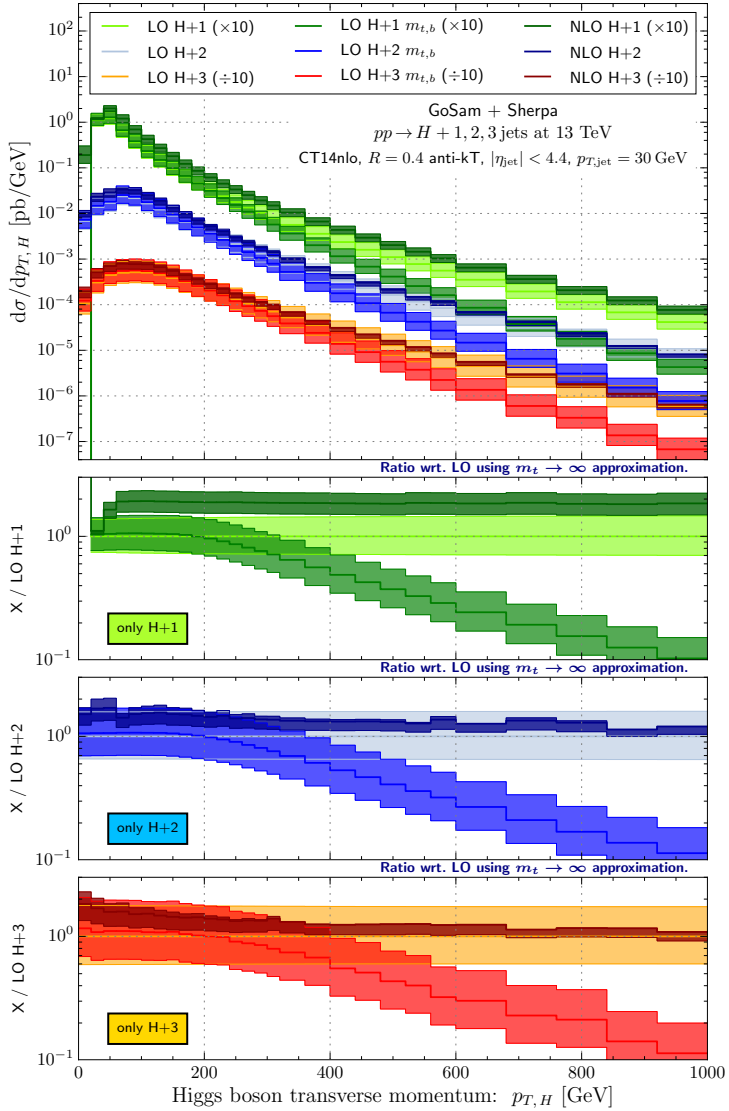
TRANSVERSE MOMENTUM DISTRIBUTION

$$\sigma \underset{x\to 0}{\sim} \sigma_{\rm LO} \times \begin{cases} \delta(1-x) + \sum_{k=1}^{\infty} c_k \alpha_s^k \ln^{2k-1}\frac{1}{x}, & \text{pointl.} \\ \delta(1-x) + \sum_{k=1}^{\infty} d_k \alpha_s^k \ln^{k-1}\frac{1}{x}, & \text{resolved} \end{cases} ; \quad \frac{d\sigma}{d\xi_p} \underset{x\to 0}{\sim} \frac{\sigma_{LO}}{\xi_p} \times \begin{cases} \sum_{k=1}^{\infty} \alpha_s^k \ln^{k-1}\frac{1}{x} \sum_{n=0}^{k-1} c_{kn} \ln^n \xi_p, \\ \sum_{k=1}^{\infty} \alpha_s^k \ln^{k-1}\frac{1}{x} d_k(\xi_p) \end{cases}$$

$$\xi_p = \frac{p_T^2}{Q^2}$$

- INCLUSIVE XSECT: DOUBLE ENERGY LOGS (POINTLIKE) VS SINGLE LOGS (RESOLVED)
- TRANSVERSE MOMENTUM DISTRIBUTION:
  - SINGLE ENERGY LOGS (ALWAYS) WHOSE COEFFICIENTS ARE
  - POINTLIKE:
    SERIES IN $\ln p_t$ WITH CONSTANT COEFFICIENTS (HARD PART p_t-INDEP.)
  - RESOLVED:
    COEFFICIENTS ARE $d_k(\xi_p)$ FUNCTIONS $\Rightarrow$ VANISH AS $\frac{1}{p_t}$ AT LARGE p_t;
    SMALL p_t: POINTLIKE LIMIT RECOVERED
- CAN DETERMINE EXACTLY LEADING LOG BEHAVIOR TO ALL ORDERS FROM HIGH-ENERGY RESUMMATION

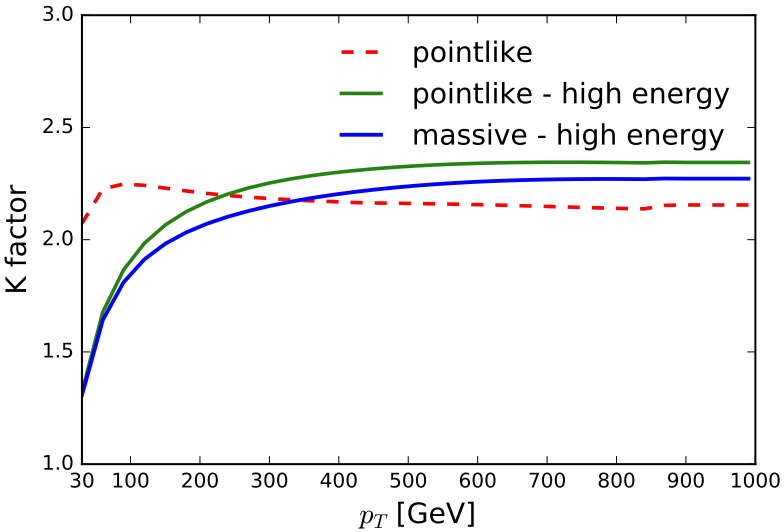
THE H+NJ TRANSVERSE-MOMENTUM SPECTRUM



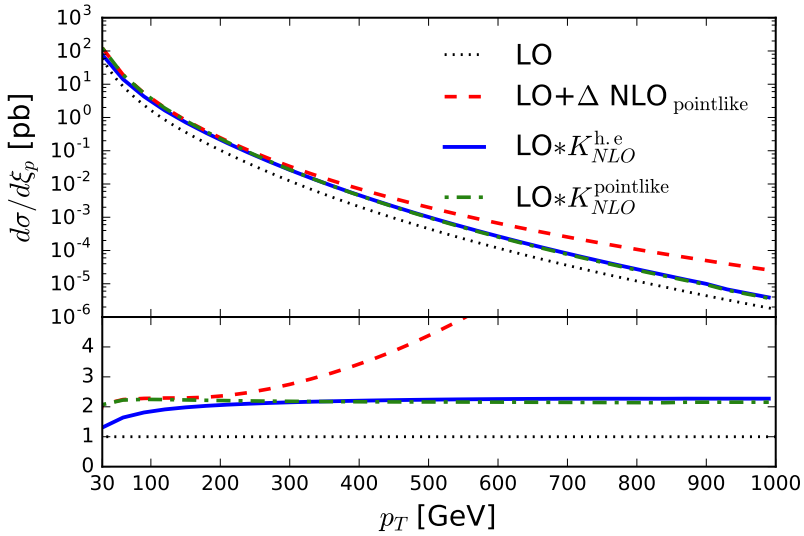
- AT SMALL p_T: TRASVERSE MOM. RESUMMATION: SUDAKOV PEAK
- AT LARGE p_T EFT FAILS
- BUT EXACT MASS DEPENDENT RESULT ONLY KNOWN AT LO!

HE IMPROVED SPECTRUM

$$K^{NLO} = 1 + \frac{d\sigma^{(1)}/dp_T}{d\sigma^{(0)}/dp_T}$$



$$d\sigma^{NLO}/dp_T$$

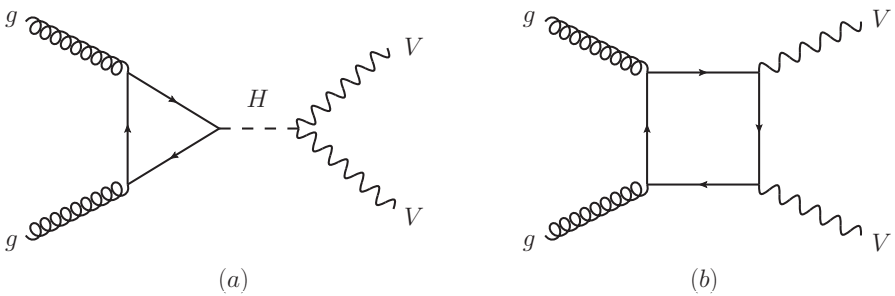


- POINTLIKE NLO FAILS FOR $p_t \gtrsim m_t$
- WRONG SCALING SIMPLIFIES IN K-FACTOR
- BEST APPROX AT LARGE p_t : EXACT LO$\times$ HE K-FACTOR
- UNCERTAINTY DRIVEN BY HE APPROX (ABOUT 30% AT LHC 13)

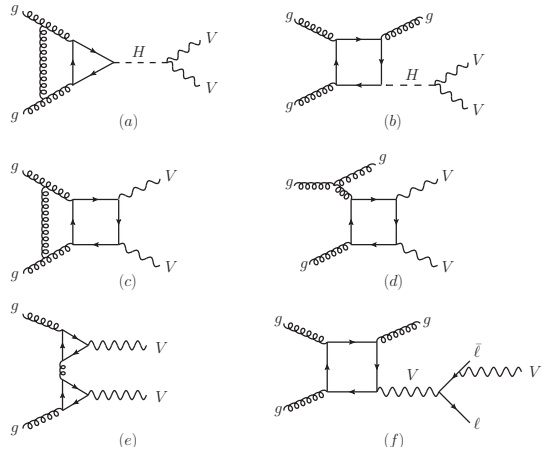
HIGGS AS A RESONANCE

$gg \to ZZ$: SIGNAL VS. BACKGROUND

LO

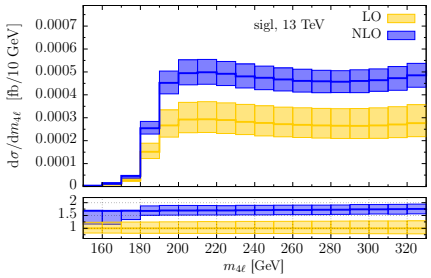


NLO

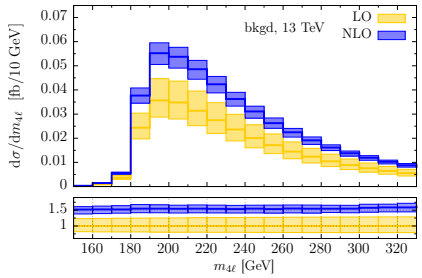


- THE HIGGS IS NARROW: $\Gamma \approx 4$ MeV (COMPARE $\Gamma_W \approx 2$ GeV)
- BUT STRONG INTERFERENCE BETWEEN $gg \to H \to ZZ$ & $gg \to ZZ \Leftrightarrow$ UNITARIZATION
- SIZABLE NLO CORRECTIONS

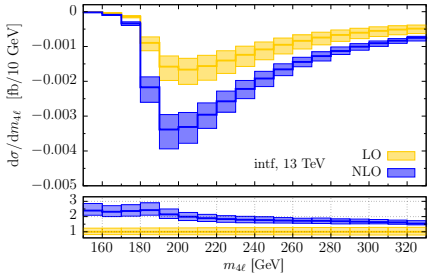
SIGNAL



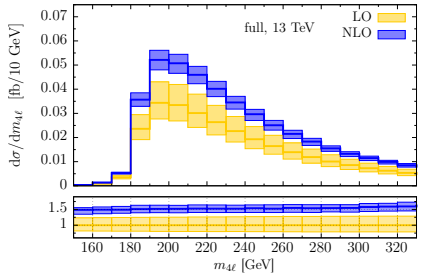
BACKGROUND



INTERFERENCE



TOTAL

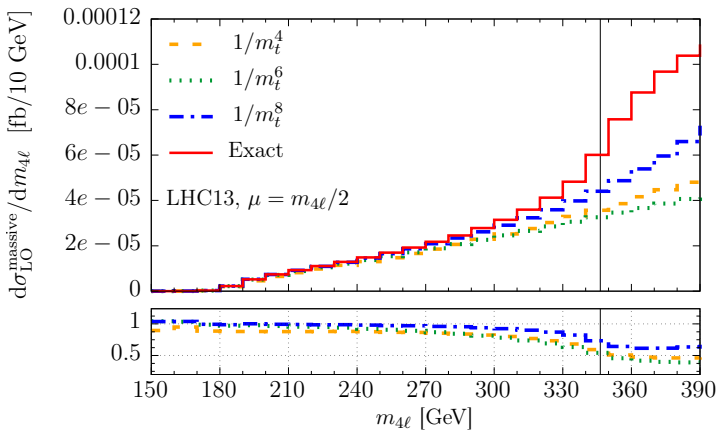


HIGGS AS A RESONANCE

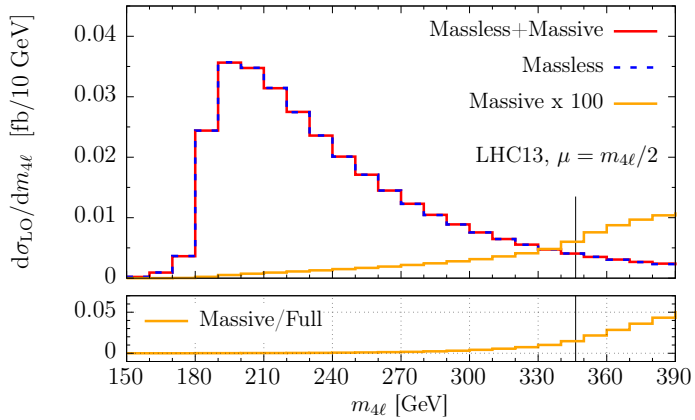
THE ROLE OF MASS CORRECTIONS

SIGNAL

LO MASSIVE



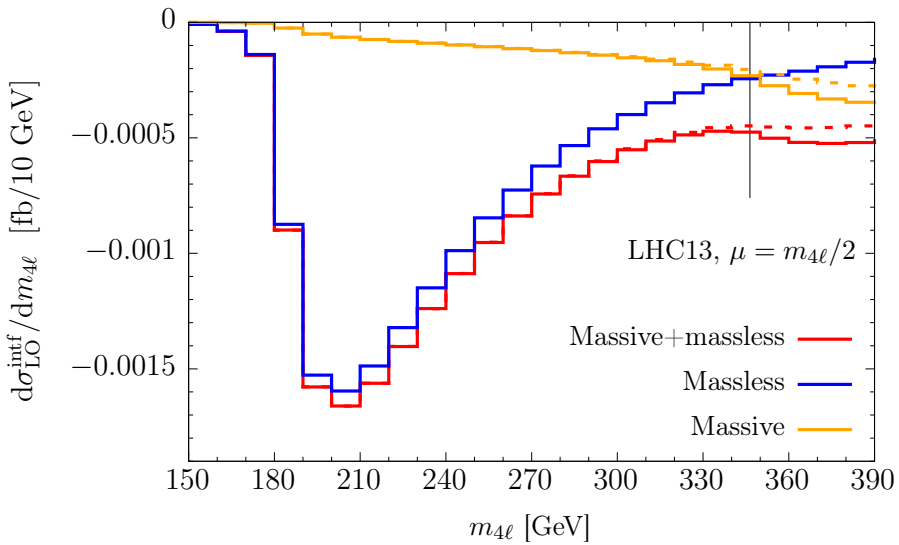
LO MASSIVE VS. MASSLESS



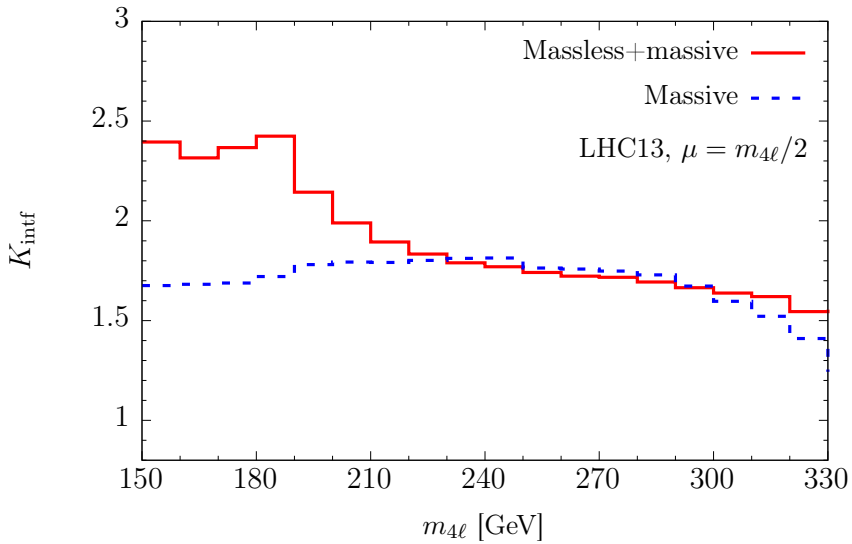
- MASSLESS APPROX. BREAKS DOWN FOR $m_{ll} \sim 2m_t$,
  BUT MASSIVE LOOPS CONTRIBUTION TO SIGNAL NEGLIGIBLE
- INTERFERENCE PROBES OFF-SHELL REGION $\Leftrightarrow$ MASSIVE LOOPS SIZABLE

INTERFERENCE

LO



NLO/LO



SUMMARY

- DRAMATIC PROGRESS IN ACCURACY:
  PDFs, FIXED ORDER CALCULATION, RESUMMATION
- SLOWLY CONVERGING EXPANSION: HOW DO WE ESTIMATE MHOU?
- GRADUAL INCLUSION OF MULTISCALE: HQ MASSES, VIRTUALITY, p_T
- FULL COMBINED TREATMENT OF PRODUCTION & DECAY NEEDED FOR PERCENT ACCURACY

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ET CREDI POCHO
RECTE