PROSPECTS FOR SM HIGGS PHYSICS
AT THE LHC: R2 TO HL-LHC

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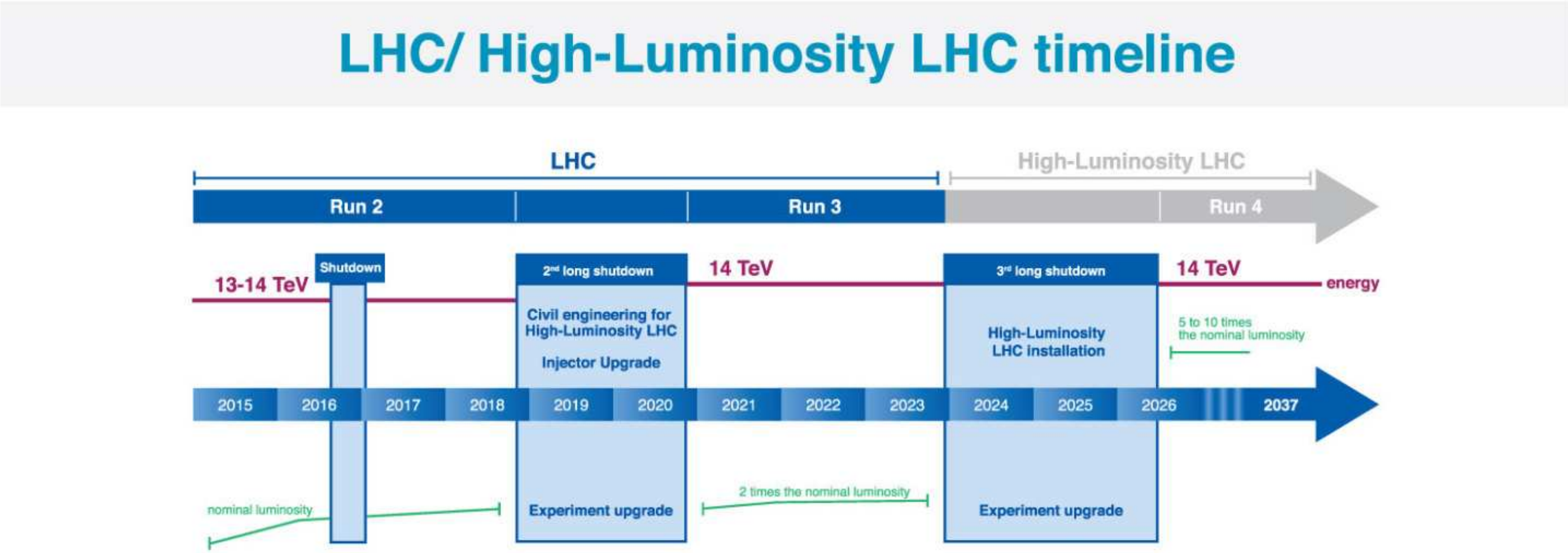
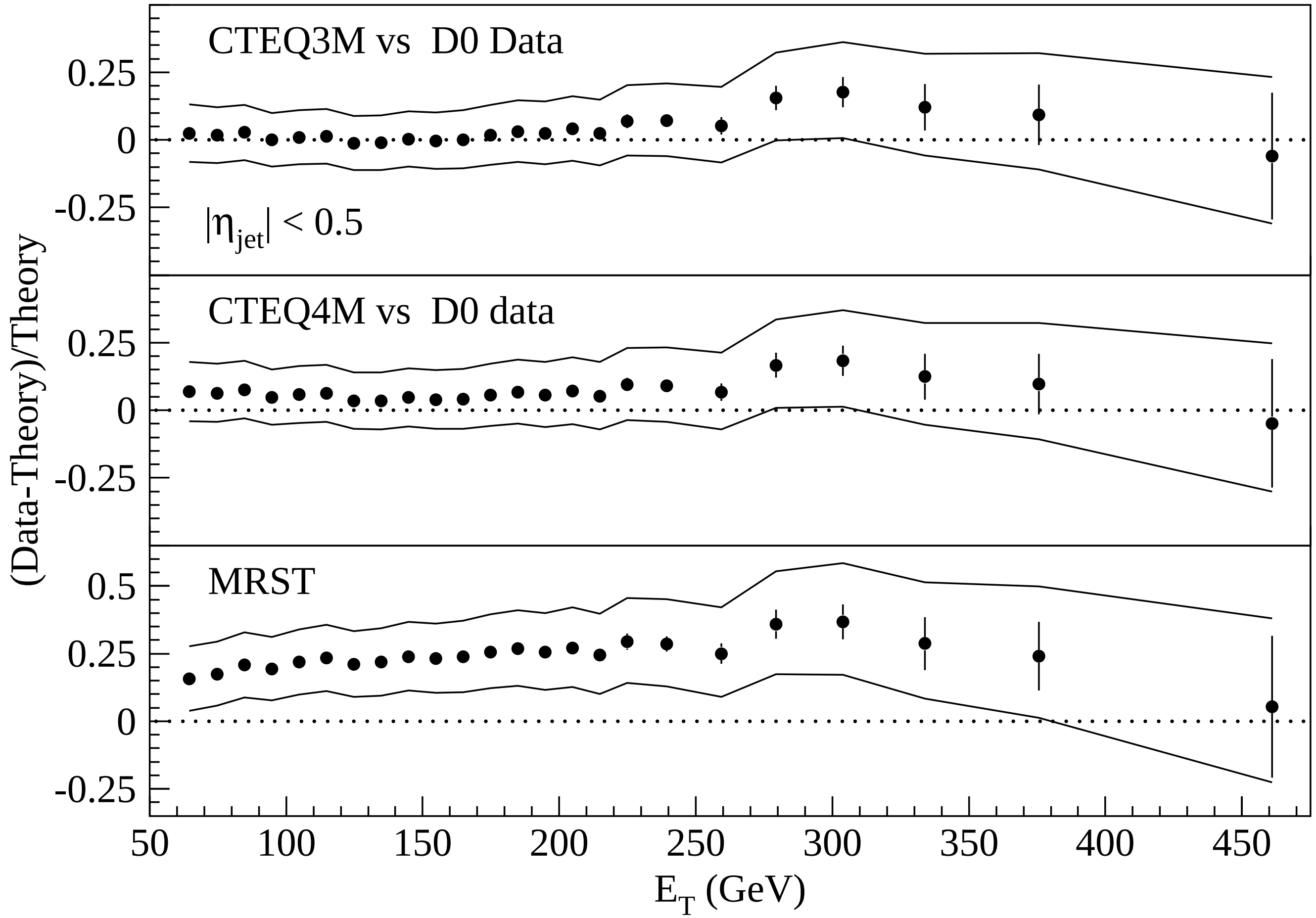
29TH RENCONTRES DE BLOIS
BLOIS, MAY 29, 2017

THE HL-LHC: 2025-2035



THE HL-LHC: 2025-2035

HOW WERE THINGS 18 YEARS AGO?



"The current agreement between theory and data is at the level of 30% over 8 orders of magnitude..."

(M. Mangano, EPS 1999)

(IT IS SUPPOSED TO BE A GOOD THING)

QCD in the year 2000

- DGLAP splitting functions known up to NLO
  NNLO splitting functions published in 2002-2004
  (Moch, Vermaseren, Vogt)

- only inclusive total cross sections with colorless final states (Drell-Yan, Higgs) known at NNLO
  rapidity distributions computed to NNLO in 2003 (Higgs), 2004 (DY) (Anastasiou, Melnikov, Petriello)

- PDF uncertainties estimated by comparing different PDF sets
  first gobal PDF sets with uncertainties published 2002
  (CTEQ, MRST)

- EW corrections mostly available for lepton collider processes
  EW corrections to Higgs production 2004-2006
  (Aglietti, Degrassi et al., Passarino et al., Dittmaier et al.)

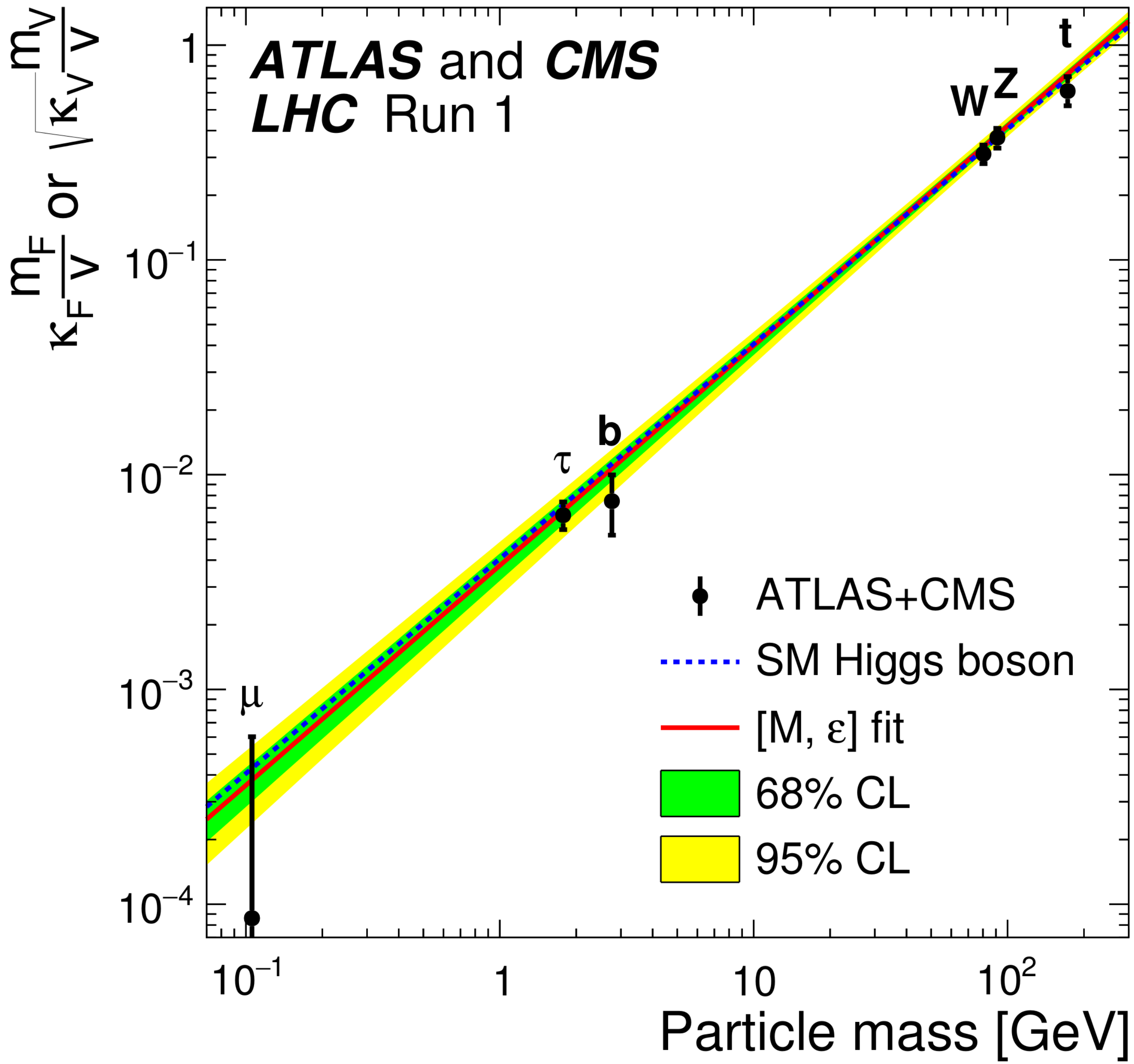
HIGGS IN THE YEAR 2035?

- THE STATE OF THE ART
  - THE NNLO REVOLUTION ⇒ Caola's talk, Mistlberger's talk
  - RESUMMATION ⇒ Bagnaschi's talk
  - MATCHING ⇒ Richardson's talk
- CHALLENGES
  - PDFS
  - HEAVY QUARK MASSES
  - ELECTROWEAK ⇒ Pellen's talk
- LATERAL THINKING
  - HIGGS TRILINEAR COUPLINGS
  - COUPLING TO TOP ⇒ Zaro's talk

WHY?

HIGGS COUPLINGS

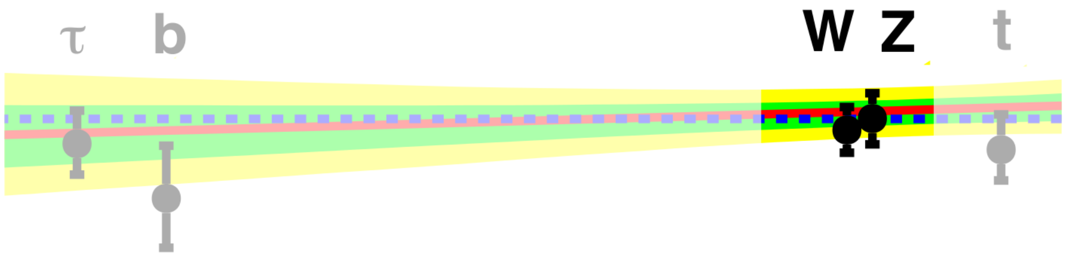
GAUGE+YUKAWAS



(ATLAS+CMS, 2016)

HIGGS COUPLINGS

GAUGE



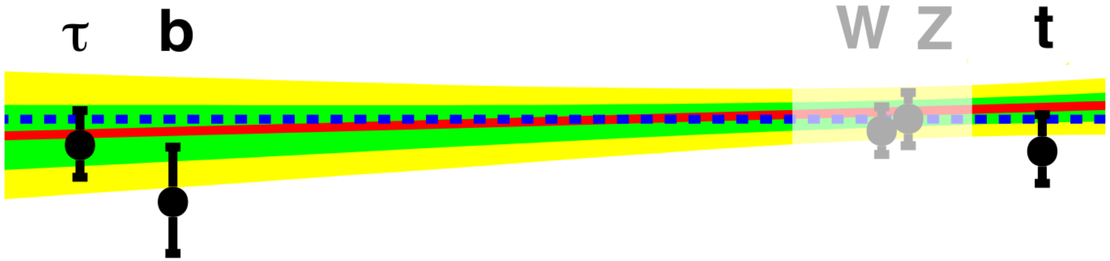
(ATLAS+CMS, elaboration U.Haisch/G.Salam 2017)

$$\mathcal{L} = (D_\mu H)^\dagger D_\mu H$$

WELL MEASURED & STANDARD

HIGGS COUPLINGS

YUKAWA



(ATLAS+CMS, elaboration U.Haisch/G.Salam 2017)

$$\mathcal{L} = -Y_f \bar{f}_L H f_R + \text{h.c.}$$

- τ DIRECTLY & REASONABLY WELL MEASURED
- t, b INDIRECTLY MEASURED & POORLY KNOWN

HIGGS COUPLINGS

POTENTIAL

$$V(H) = \frac{m_H^2}{2} + H^2 + \lambda_3 v H^3 + \lambda_4 H^4$$

- IN SM $m_h^2 = 2\lambda v^2$; $\lambda^3 = \lambda$ $\lambda_4 = \frac{\lambda}{4}$
- MASS MEASURED; λ_3 λ_4 UNKNOWN

WHERE SHOULD WE LOOK?

- TOP COUPLING
- HIGGS TRILINEAR

RESOLVING THE TOP COUPLING

THE DEGENERACY

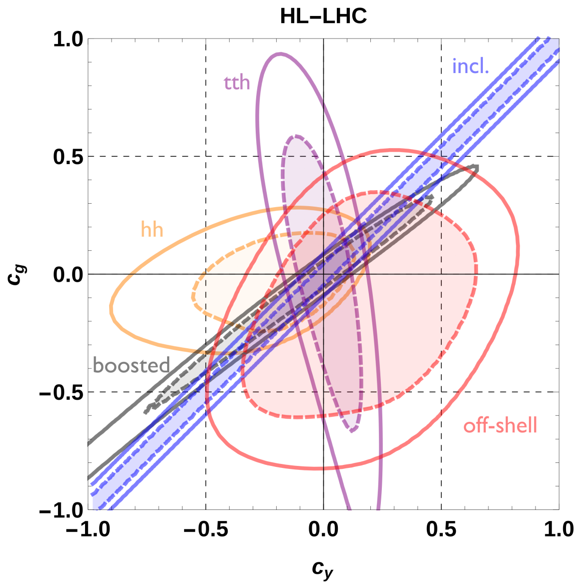
- NEW STATES MOST LIKELY REVEALED THROUGH HIGGS-TOP COUPLINGS
- DEGENERACY IN HIGGS COUPLINGS TO DIMENSION 6 OPERATORS:

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

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

LIFTING THE DEGENERACY

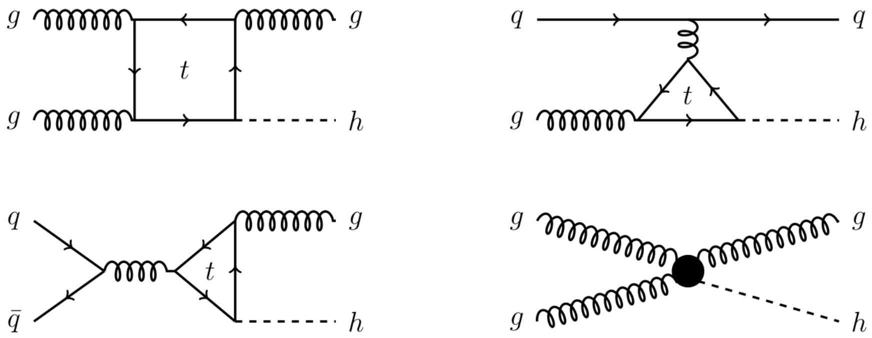
EXCLUSION REGIONS AT HL-LHC



(Azatov, Paul, Grojean, Salvioni, 2016)

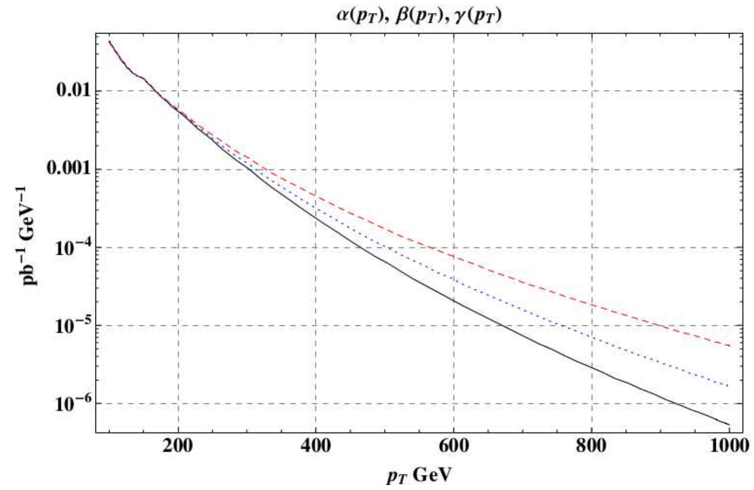
- DOUBLE HIGGS
- OFF-SHELL
- PRODUCTION IN ASSOCIATION WITH TOP
- BOOSTED

BOOSTED HIGGS: THE TRANSVERSE MOMENTUM SPECTRUM



(Grojean, Salvioni, Schlaffer, Weiler, 2013)

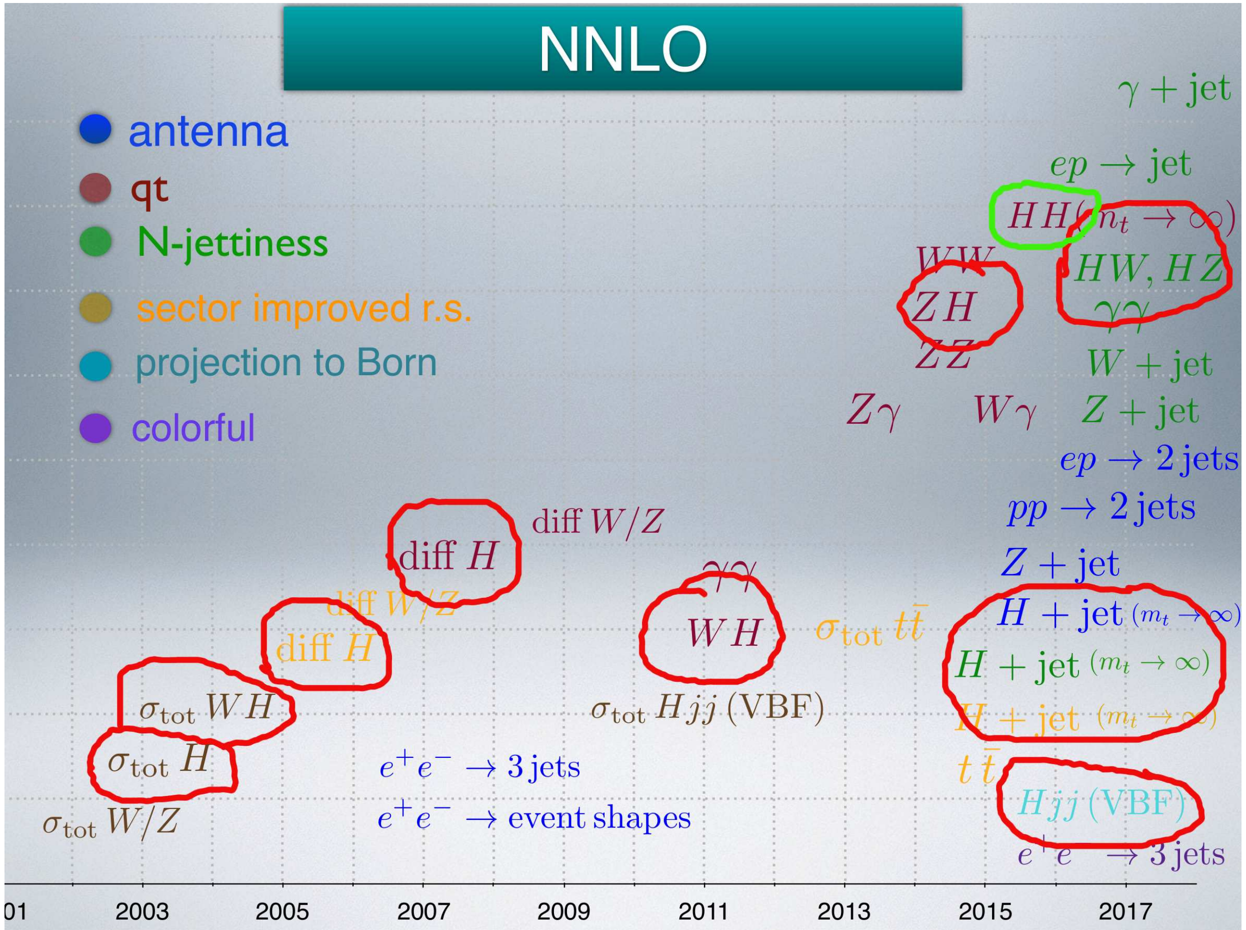
- HIGGS+ JET CROSS SECTION: EFFECTIVE c_g INDUCED BY CONTACT TERM
- CROSS-SECTION $\frac{d\sigma}{dp_T} = \alpha(p_T)c_t^2 + 2\gamma(p_t)c_t c_g + \beta(p_T)c_g^2$
- CAN DISENTAGLE CONTACT TERM BY SLOWER DROP WITH p_T



(Azatov, Paul, 2013)

WHERE WE ARE

NNLO AND HIGGS



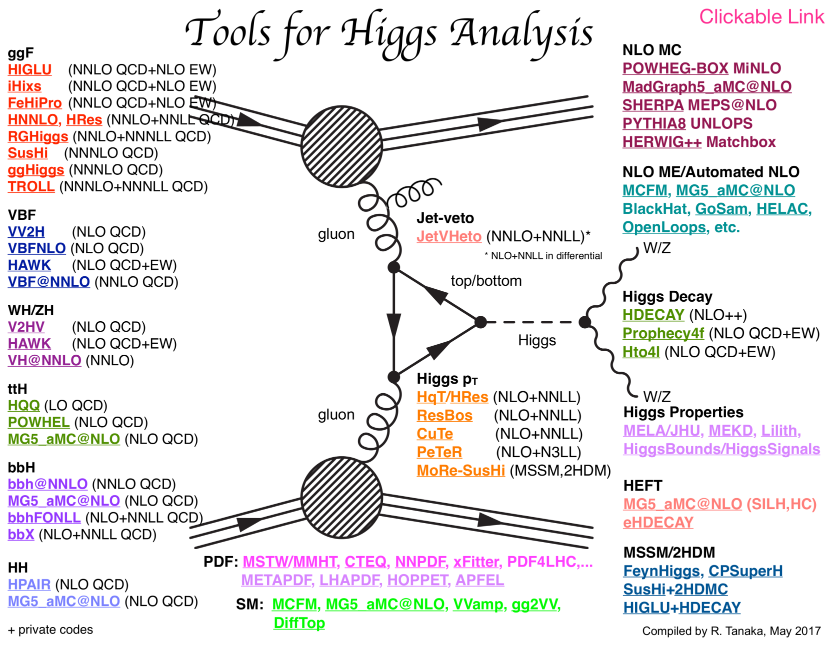
(G. Heinrich, LHCP, May 2017)

- NNLO corrections known for most Higgs production channels
- typical scale uncertainties tiny
- beware of fiducial cuts
- ggF: is EFT adequate?
- PDF uncertainties?
- EW corrections?

QCD uncertainties on total xsects

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

NNLO AND HIGGS



(R. Tanaka, HXSWG, May 2017)

- NNLO codes available for most Higgs production channels
- decay & fully inclusive final state generally available
- typical scale uncertainties tiny
- beware of fiducial cuts
- ggF: is EFT adequate?
- PDF uncertainties?
- EW corrections?

QCD uncertainties on total xsects

ggF	N^3LO	4%
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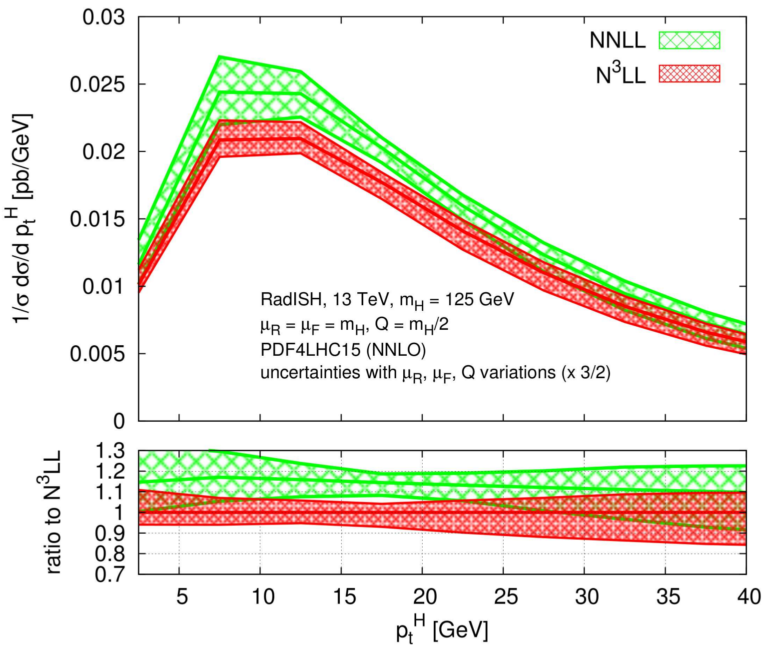
RESUMMATION I

MOMENTUM-SPACE SMALL-p_T RESUMMATION

- TRANSVERSE MOMENTUM RESUMMATION PERFORMED IN b-SPACE BECAUSE $\vec{p}_t \to 0$ VECTORIALLY
- CAN RESUM IN MOMENTUM SPACE EXPANDING ABOUT p_T^1 (1ST EMISSION) (Monni, Re, Torrielli, 2016)
- RESULT APPLIES TO ANY "TRANSVERSE" OBSERVABLE, COMPUTATIONALLY EFFICIENT



(Bizón, Monni, Re, Rottoli, Torrielli, 2017)

- USED TO COMPUTE HIGGS p_T AT N^{3}LL+NNLO
- N^{3}LL CORRECTION AMOUNT TO $\sim 10\%$ TO NNLL AT THE PEAK, BUT SMALL EFFECT ON UNCERTAINTY

RESUMMATION II

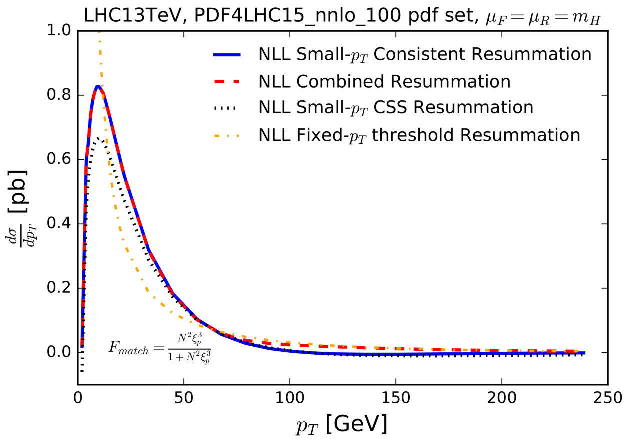
COMBINED p_T & SOFT RESUMMATION

- SMALL p_t AND SOFT LIMIT DO NOT COMMUTE
  - INTEGRAL OF CSS TRANSVERSE MOMENTUM RESUMMATION DOES NOT GIVE SOFT-RESUMMED TOTAL XSECT
  - SMALL p_T LIMIT OF SOFT-RESUMMED TRANSVERSE MOMENTUM DISTRIBUTION DOES NOT REPRODUCE CSS

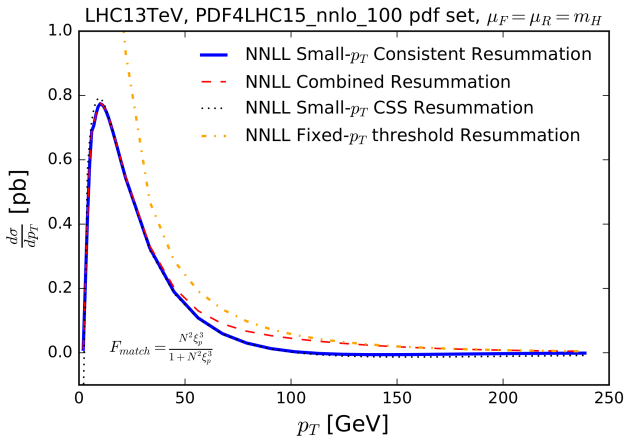
- CAN CONSTRUCT COMBINED RESUMMATION: INCLUDES SOFT FOR ALL p_T (INCLUDING AT INTEGRATED LEVEL) & REPRODUCES CSS AS $p_T \to 0$

(sf, Muselli, Ridolfi, 2017)

NLL



NNLL



- AGREES WITH STANDARD CSS AT SMALL p_T, ANTICIPATES THE HIGHER-ORDER PEAK, BUT DEVIATES AT MEDIUM p_T

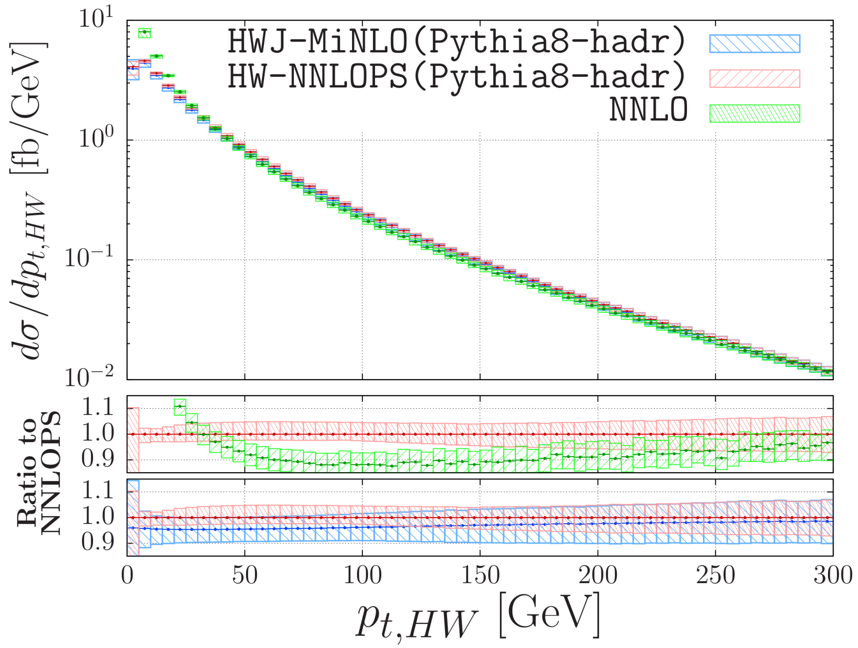
- AGREES WITH FIXED p_T THRESHOLD AT LARGER p_T

MATCHING AND SCALES

MINLO SCALE SETTING

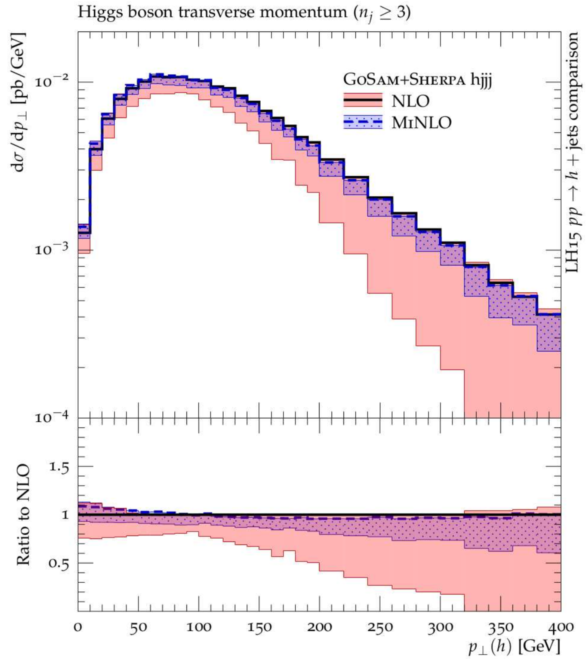
- MINLO PROCEDURE:ASSIGN MOMENTUM SCALES TO SPLITTINGS AND DRESS WITH NLL SUDAKOV $\Rightarrow$ SUDAKOV LOGS RESUMMED
- NNLO X PRODUCTION + MERGED X AND $X+J$ GENERATOR $\Rightarrow$ NNLOPS

HW



(Astill, Bizón, Re, Zanderighi, 2017)

H+3J



(Febres Cordero, Höche, Schönherr, 2017)

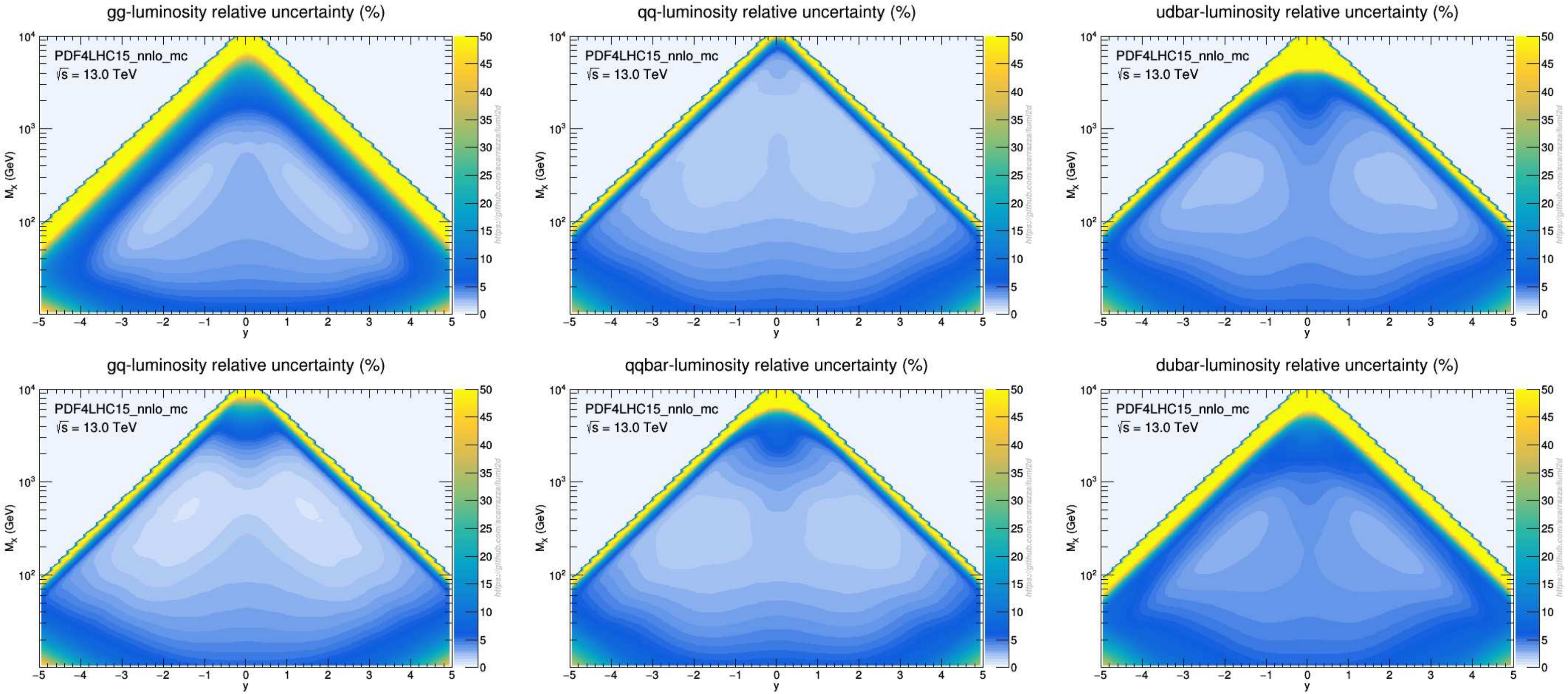
- HW $\Rightarrow$ SMALL p_T MINLO RESUMS SUDAKOV; LARGE p_T ENHANCEMENT
- H+3J $\Rightarrow$ SIGNIFICANT ENHANCEMENT IN COMPARISON TO STANDARD E_T SCALE CHOICE

MOVING AHEAD

PDFs I

UNCERTAINTIES: THE STATE OF THE ART (PDF4LHC15, NNLO)

GLUON | SINGLET | FLAVORS



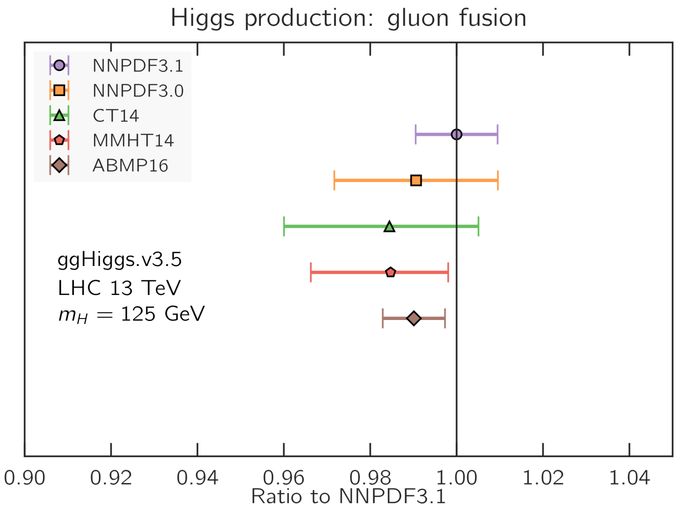
- TYPICAL UNCERTAINTIES BETWEEN 2-3%
- SWEET SPOT: VALENCE Q - G; UNCERTAINTIES DOWN TO 1%

CAN WE BELIEVE IN 1% LEVEL PDF UNCERTAINTIES?

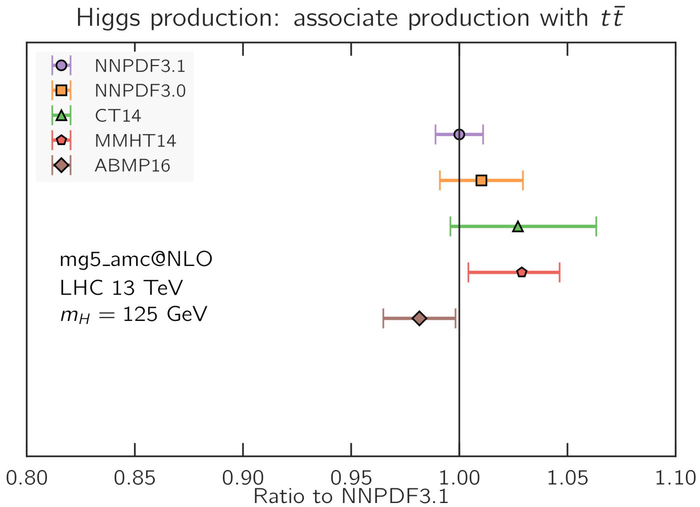
PDFs II

UNCERTAINTIES ON HIGGS PRODUCTION
TOWARDS NEXT-GENERATION PDFs

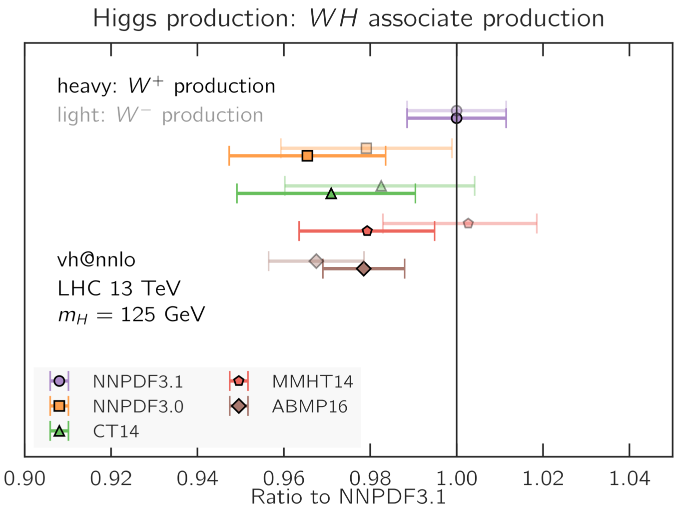
GGF



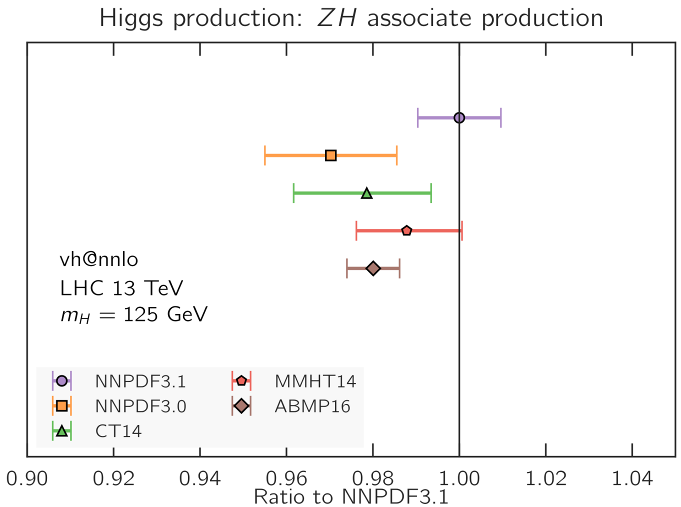
$t\bar{t}$H



WH



ZH



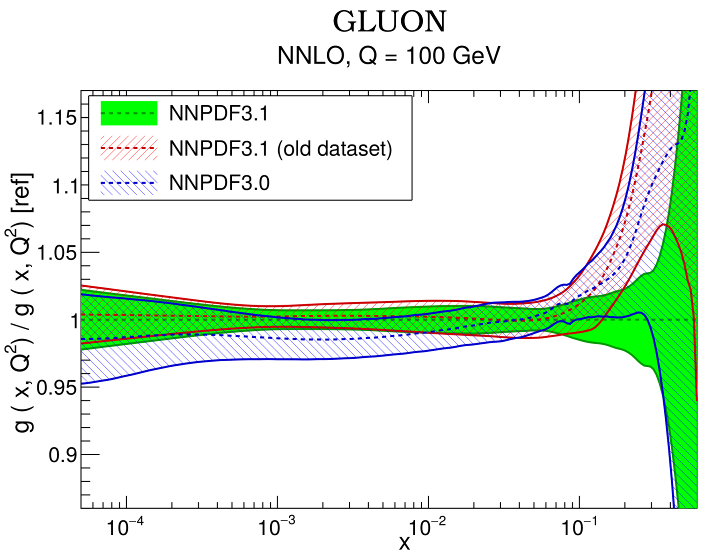
- TYPICAL PDF UNCERTAINTY AT THE FEW PERCENT LEVEL
- NEW NNPDF3.1 $\Rightarrow$ SIGNIFICANT REDUCTION IN UNCERTAINTY & SHIFT IN CENTRAL VALUE!

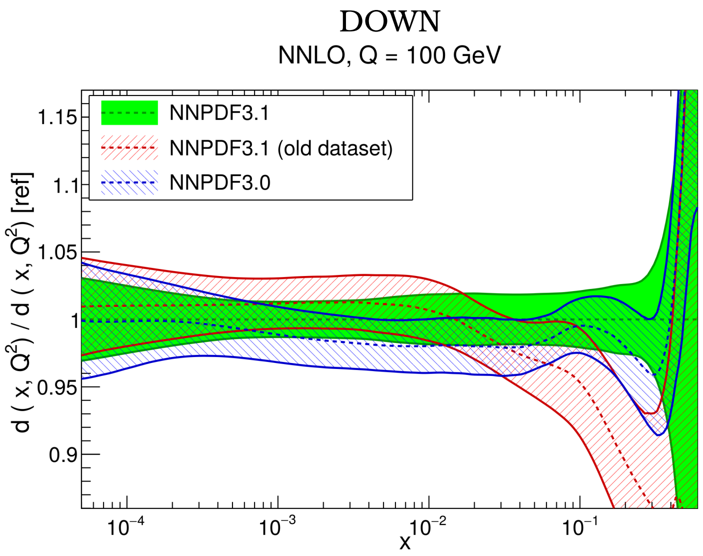
PDFs III

PRECISION VS. ACCURACY

NNPDF3.1 VS. 3.0

- METHODOLOGY: INDEPENDENTLY PARAMETRIZED CHARM PDF
- LHC DATA : TOP RAPIDIDITY, Z p_T, LHCB & ATLAS W & Z PRODUCTION



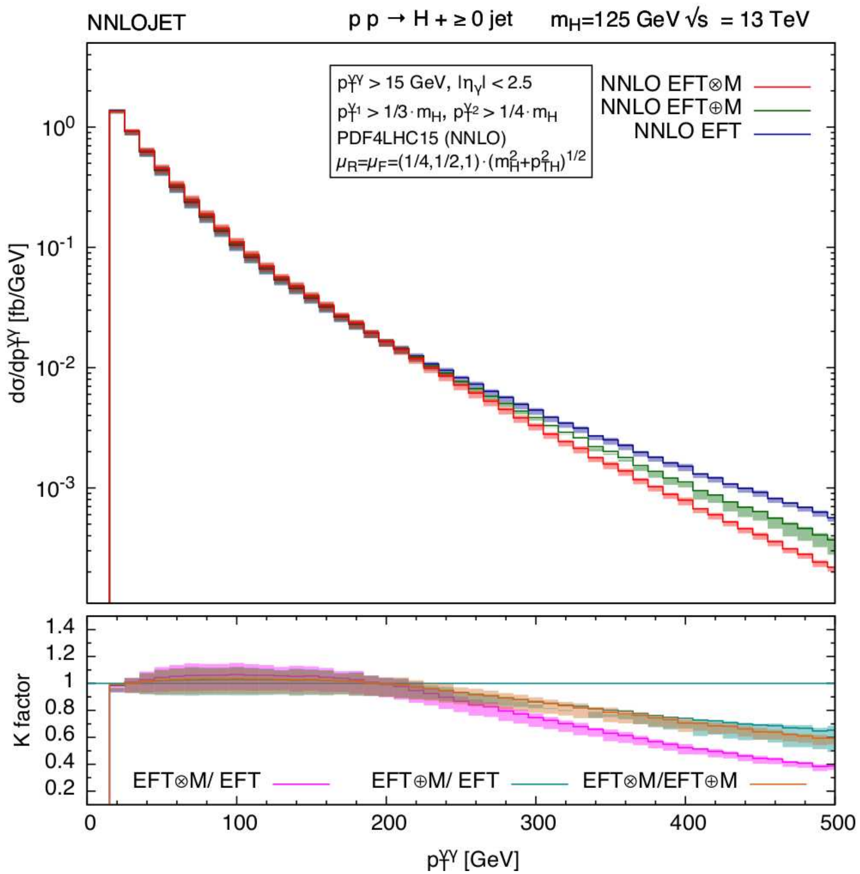


- FITTING CHARM ENHANCES GLUON IN GGF RANGE BY SEVERAL PERCENT
- NEW DATA (ESPECIALLY LHCB & ATLAS w z 2011) ENHANCE QUARKS IN VALENCE REGION

THE p_T SPECTRUM AND THE TOP MASS I

- MASS DEPENDENCE KNOWN EXACTLY ONLY AT LO
- INCLUSION BEYOND LO SUBJECT TO LARGE UNCERTAINTIES?

MASS DEPENDENCE: MULTIPLICATIVE VS. ADDITIVE

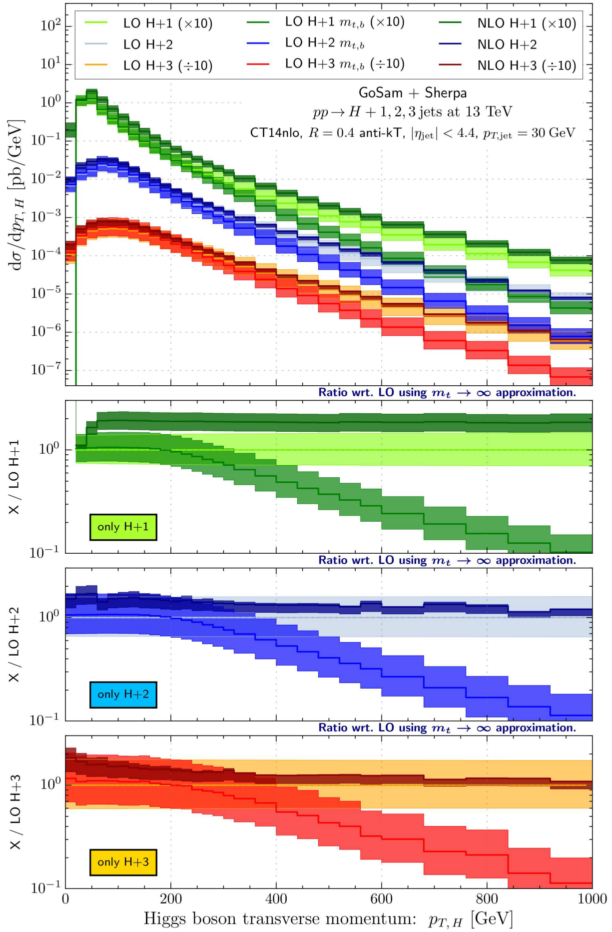


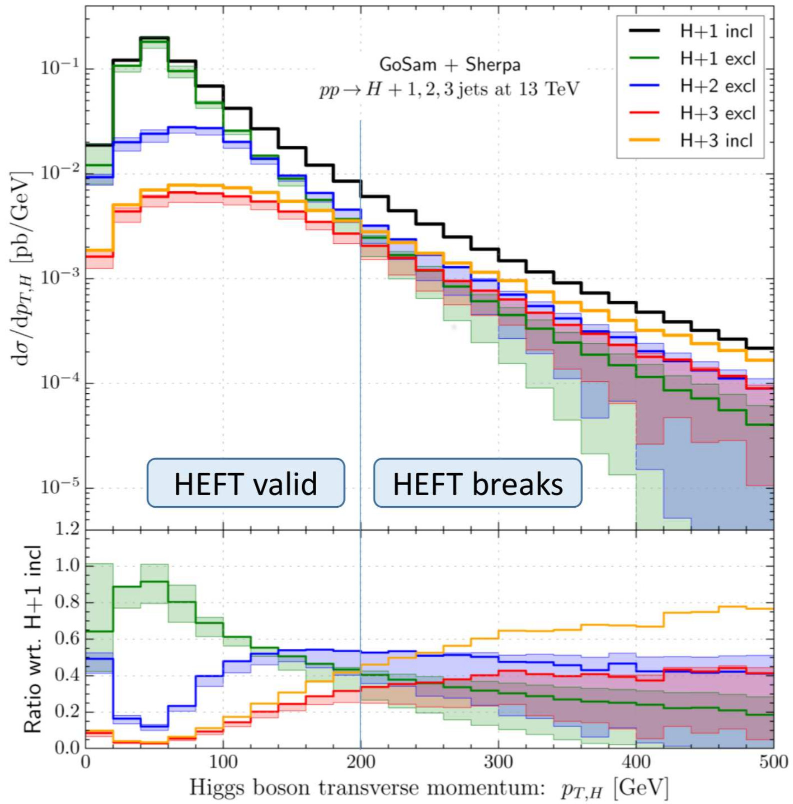
(Chen, Cruz-Martinez, Gehrmann, Glover, Jacquier, 2016)

- $R^{LO}(p_T) = \left(\frac{d\sigma_{LO}^{m_t,m_b,m_c}}{dp_T} \Big/ \frac{d\sigma_{LO}^{EFT}}{dp_T} \right)$
- EFT⊗M: $\frac{d\sigma}{dp_T} = R^{LO}(p_T) \frac{d\sigma_{NNLO}^{EFT}}{dp_T}$ (MULTIPLICATIVE)
- EFT⊕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

THE p_T SPECTRUM AND THE TOP MASS II

SHERPA H+NJ WITH MASS





(Greiner, Höche, Luisoni, Schönherr, Winter, 2016)

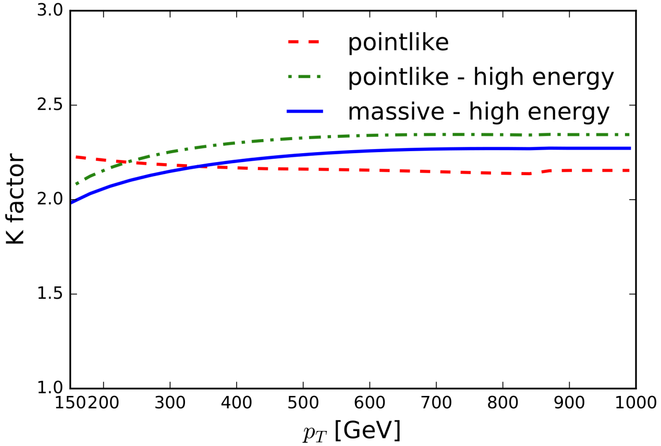
- EFT BREAKS DOWN FOR $p_T \sim 200$ GeV
- SIMILAR LEADING BEHAVIOUR OF DIFFERENT JET MULTIPLICITIES
- AS MULTIPLICITY INCREASES, CROSS-SECTION DROPS LESS

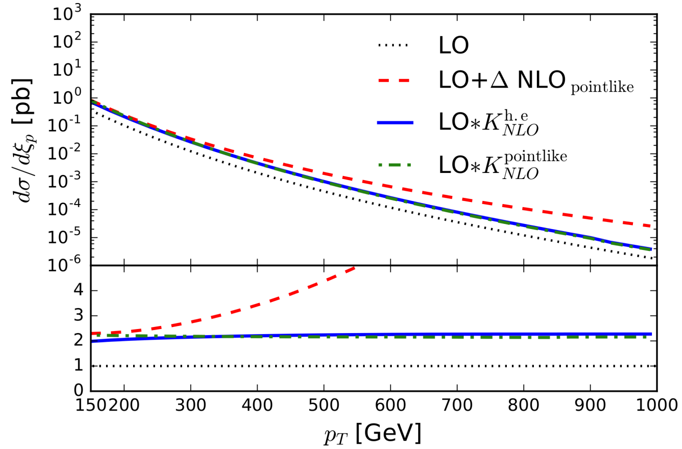
THE p_T SPECTRUM AND THE TOP MASS III

THE HIGH-ENERGY APPROXIMATION

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

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

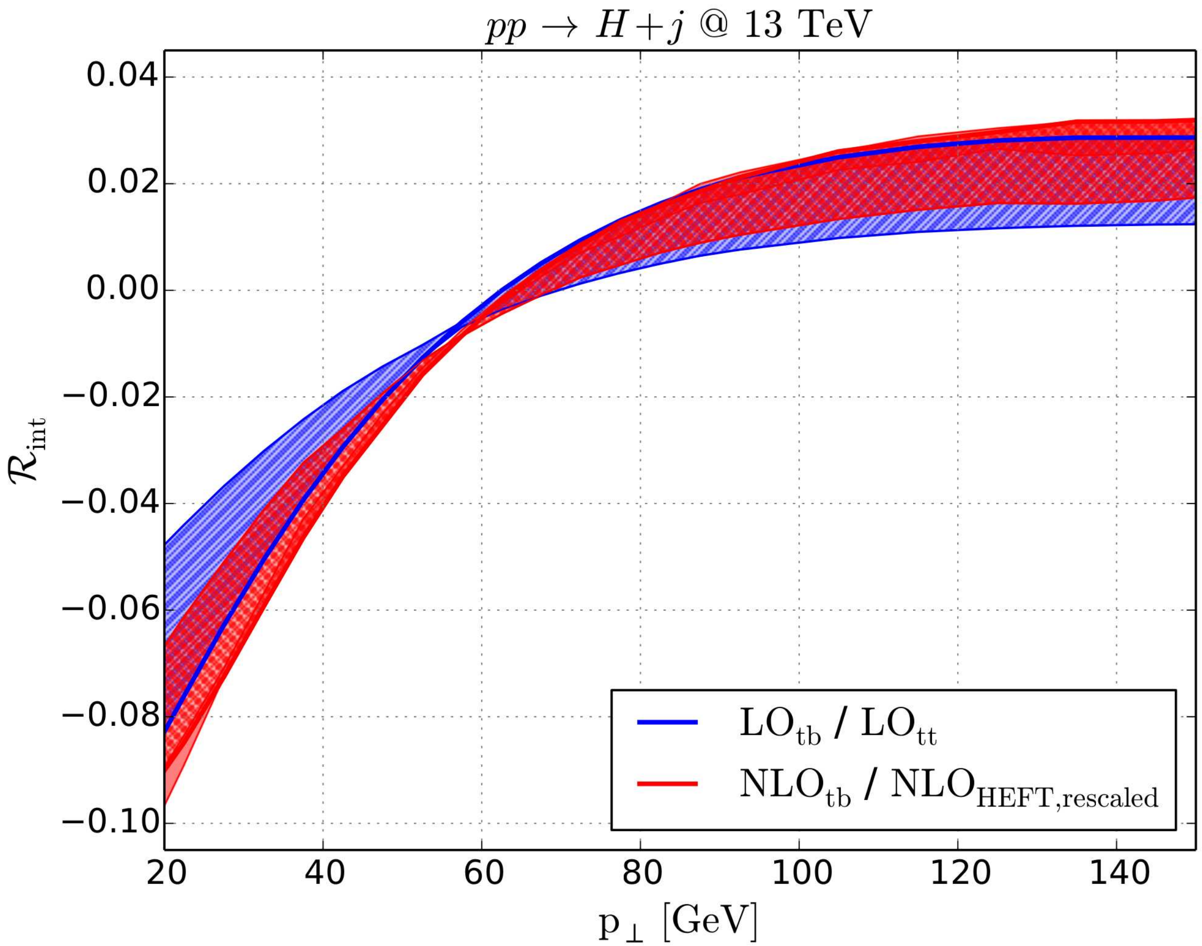




(Caola, sf, Marzani, Muselli, Vita, 2016)

- ALL ORDERS WITH MASS KNOWN IN HE LIMIT; HIGH-ENERGY APPROX. 20% ACCURATE FOR ALL $2m_t \lesssim p_t \lesssim \sqrt{s}/10$
- LEADING POWER BEHAVIOUR DIFFERS BETWEEN EFT AND WITH MASS DEPENDENCE, BUT IS SAME TO ALL ORDERS
- MULTIPLE REAL EMISSION $\Rightarrow$ INCREASINGLY HIGH POWERS OF $\ln p_T$
- ADDITIVE IMPLEMENTATION OF MASS CORRECTIONS REMOVES THE SPURIOUS POWER BEHAVIOUR FROM THE LO CONTRIBUTION BUT NOT FROM THE HO ONES

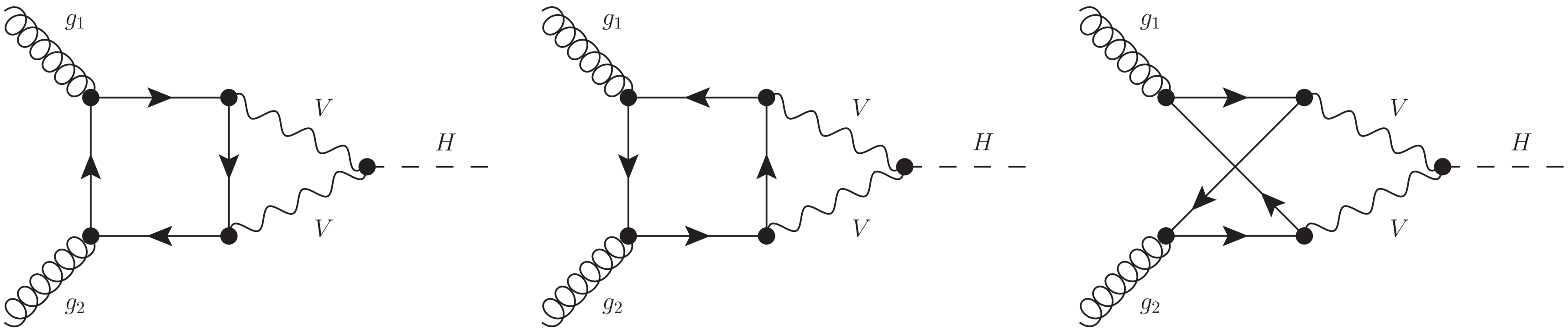
THE p_T SPECTRUM AND THE B MASS!



- $A^b_{gg\to Hg} \sim m_b^2/m_H^2 \ln^2(p_T^2/m_b^2) \Rightarrow$ 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)

ELECTROWEAK CORRECTIONS

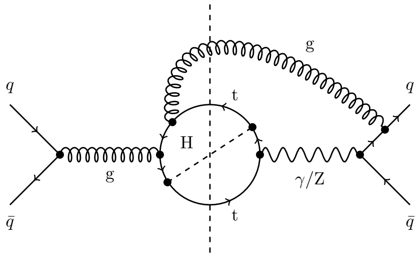
GLUON FUSION



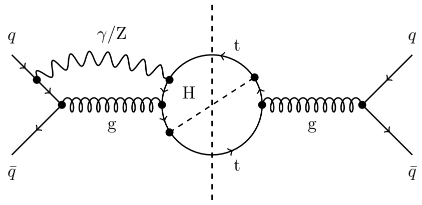
- EW corrections to gluon fusion of order 5% if multiplicative, 2% additive
- what is the mixed QCD-EW? Only known for $m_z, m_W \gg m_H$
- progress: form factor computed up to $O(\epsilon^2)$ in DR
  (Bonetti, Melnikov, Tancredi, 2017)

ELECTROWEAK CORRECTIONS
$t\bar{t}H$

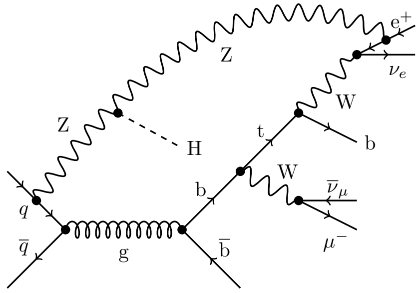
INTERFERENCE: REAL



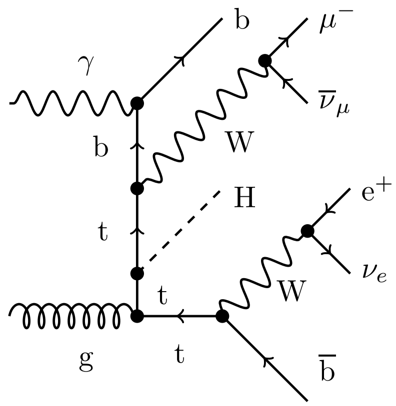
INTERFERENCE: VIRTUAL



TWO LOOP

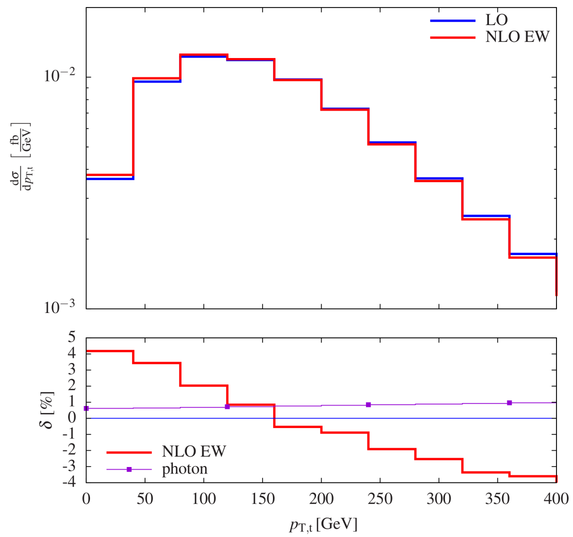


PHOTON-INDUCED



(Denner, Lang, Pellen, Uccirati, 2017)

HIGGS p_T SPECTRUM



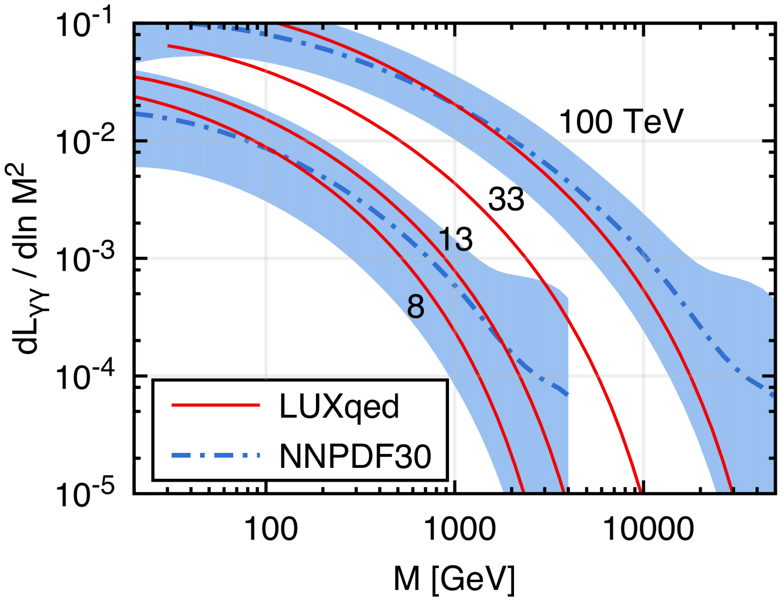
- AT PERCENT ACCURACY, CANNOT DISENTANGLE QCD & EW
- INTERFERENCE (REAL & VIRTUAL), LOOP, & PHOTON INDUCED
- CORRECTIONS $\sim 2-3\%$ LOW p_T, UP TO $\sim 6-7\%$ HIGH p_T
- PHOTON INDUCED SMALL: HOW DO WE KNOW?

THE PHOTON PDF BREAKTHROUGH

(Manohar, Nason, Salam, Zanderighi, 2016)

- QED IS PERTURBATIVE DOWN TO LOW SCALES $\Rightarrow$ THE PHOTON PDF COMPUTABLE IN TERMS OF THE INPUT QUARK SUBSTRUCTURE
- $\Rightarrow$ PDF EXPRESSED IN TERMS OF THE STRUCTURE FUNCTION INTEGRATED OVER ALL SCALES, INCLUDING ELASTIC FORM FACTORS
- VERY SMALL UNCERTAINTY, IN AGREEMENT WITH NNPDF3.0QED FIT, SMALLER CENTRAL VALUE AT HIGH SCALE

$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2}\right) F_2(x/z,Q^2) - z^2 F_L\left(\frac{x}{z},Q^2\right)\right] - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z},\mu^2\right)\right\},$$



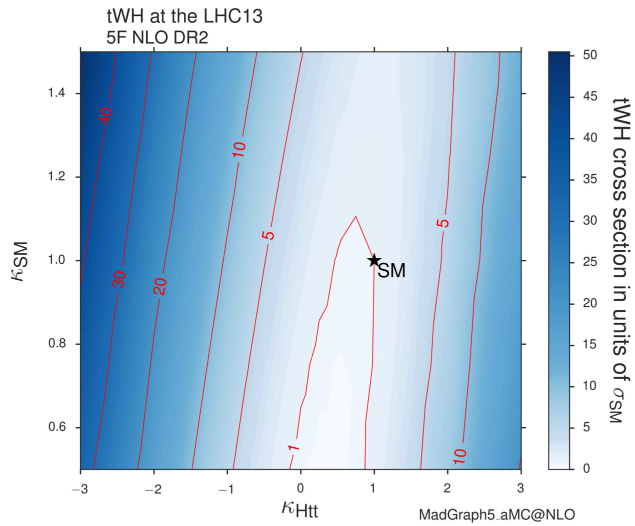
JUMPS

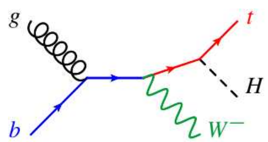
ACCESSING THE TOP COUPLING

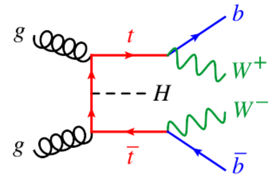
THE CASE FOR tWH

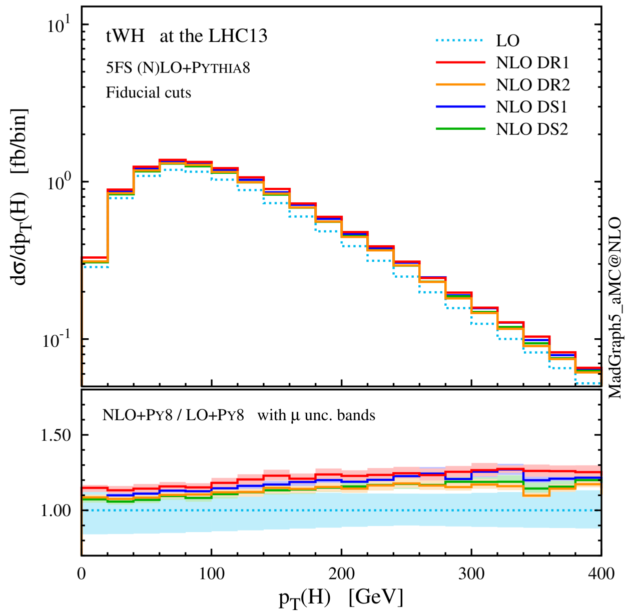
- THE GOOD NEWS: tWH ENHANCED SENSITIVITY TO SM DEVIATIONS (Farina, Grojean, Maltoni, Salvioni, Thamm, 2013) SM XSECT SITS AT A MIN. IN κ_{SM}, κ_{Htt} PLANE
- THE BAD NEWS: BEYOND LO RESONANT CONTRIBUTION MIXES WITH $t\bar{t}H$ WHOSE RATE IS $10\times$

$\kappa_{sm} \Rightarrow$ GAUGE; $\kappa_{Htt} \Rightarrow$ TOP



tWH: 

$t\bar{t}H$: 

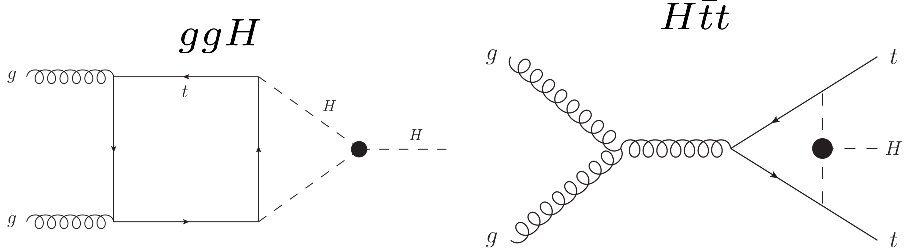


- TOTAL CROSS-SECTION DEPENDS STRONGLY ON DEFINITION
- FIDUCIAL CUTS: ONLY ONE LARGE p_T B, CENTRAL H AND TWO $W \Rightarrow t\bar{t}$ REDUCED $20\times$
- USING FURTHER MC TO IDENTIFY B FROM T, AGREEMENT BETWEEN DEFN'S TO WITHIN 1% (OTHERWISE $\sim 5\%$ DIFFERENCE)

(Demartin, Maier, Maltoni, Mawatari, Zaro, 2016)

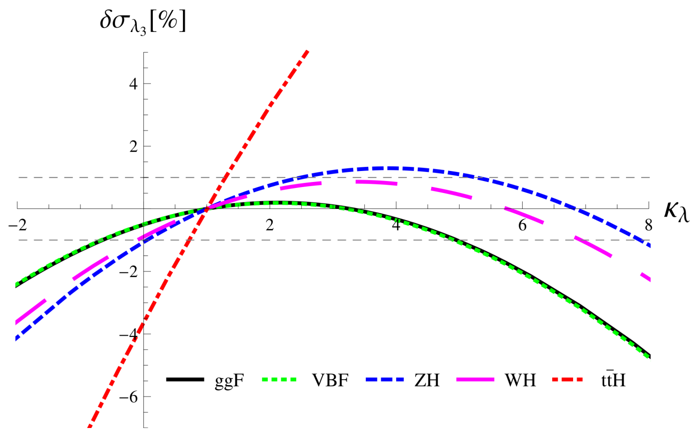
ACCESSING THE TRILINEAR COUPLING

THROUGH LOOPS



- TRILINEAR HIGGS COUPLINGS ENTER AT NLO INTO ALL PRODUCTION AND DECAY MODES
- DETERMINE THE EFFECT OF AN ANOMALOUS COUPLING (D=6 OPERATOR)

DEVIATION FROM SM VS κ



(Degrassi, Giardino, Maltoni, Pagani, 2017)

- SIZABLE EFFECT ON $\bar{t}tH$
- HOWEVER FLAT DIRECTION ALONG SELF-COUPLING, TOP, & CONTACT WITH GLUONS
- DOUBLE HIGGS REQUIRED TO REMOVE DEGENERACY (Di Vita, Grojean, Panico, Riembau, Vantalon, 2017)

LESSONS LEARNT

- EXPLOITING THE POTENTIAL OF HL-LHC REQUIRES PHYSICS AT PERCENT ACCURACY
- AT 1% LEVEL ACCURACY ISSUES BECOME IMPORTANT:
  - CANNOT SEPARATE QCD & EW
  - MUST INCLUDE ALL SCALES (CANNOT NEGLECT QUARK MASSES)
- "BRUTE FORCE" APPROACH NOT NECESSARILY BEST

NO EFFECT THAT REQUIRES MORE THAN 10% ACCURACY IN MEASUREMENT IS WORTH INVESTIGATING

Walther Nernst

~~NO EFFECT THAT REQUIRES MORE THAN 10% ACCURACY IN MEASUREMENT IS WORTH INVESTIGATING~~

Walther Nernst

ACCURACY OF OBSERVATION IS THE EQUIVALENT OF ACCURACY OF THINKING

Wallace Stevens