Funded by
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PROJECT REPORTS:

Collider Phenomenology

B1a, B1b, B1c & Heavy particles @ the LHC

MALGORZATA WOREK

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Annual Meeting of the CRC TRR 257, 26-28 May 2021

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Project reports:

High Precision SM Collider Phenomenology

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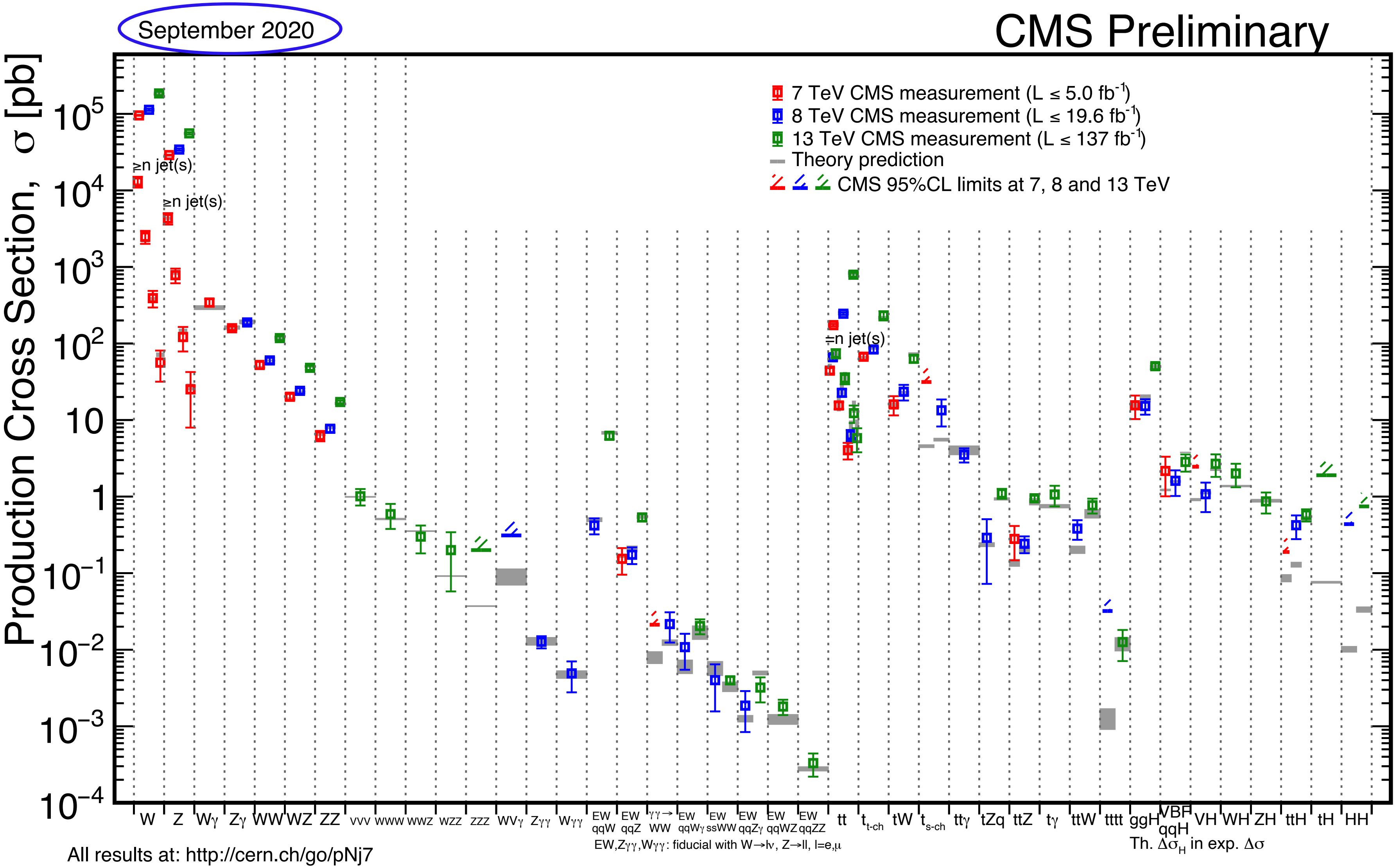
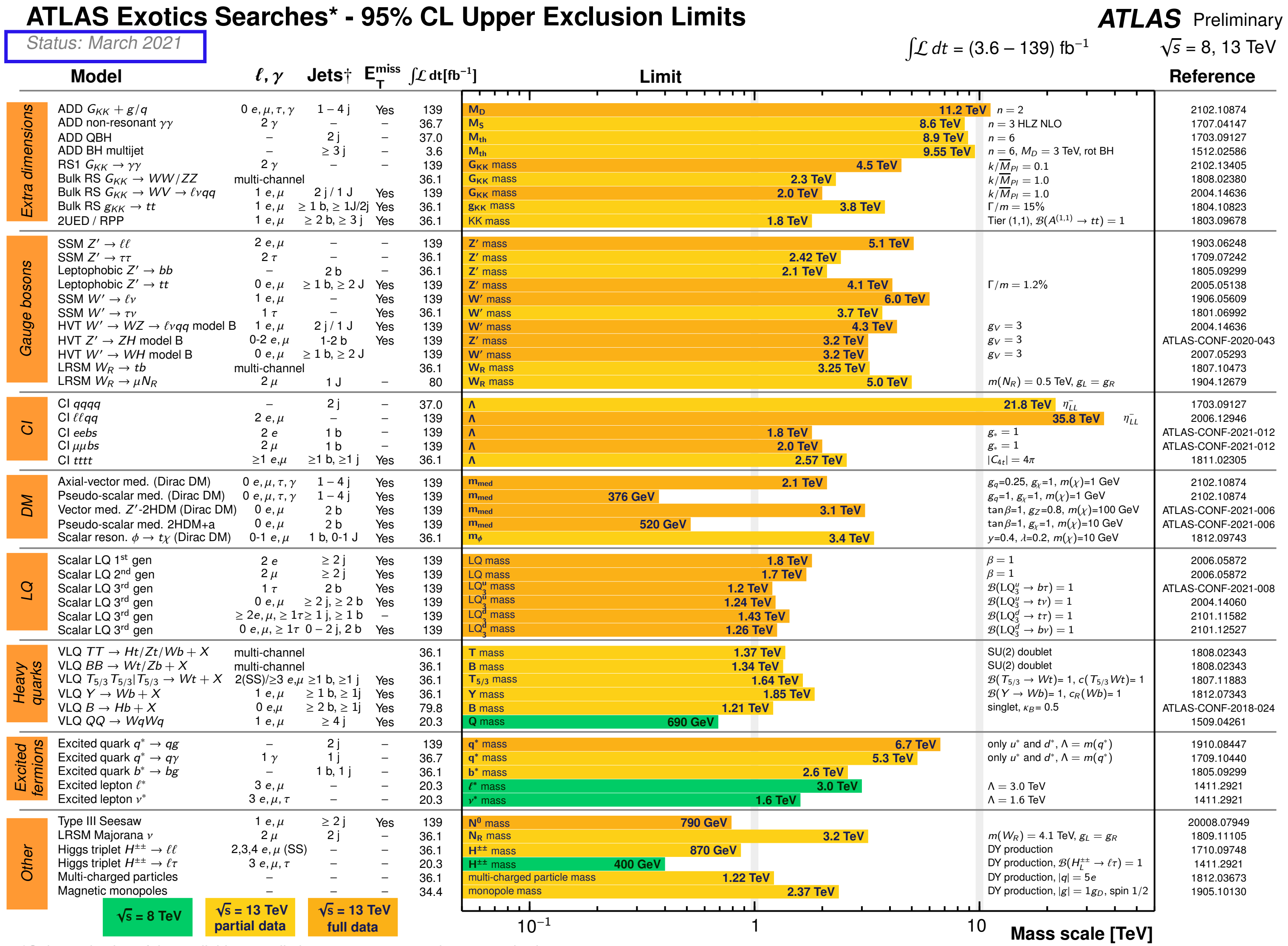
LHC continues to confirm Standard Model



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

No sign of New Physics in TeV range



*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

ATL-PHYS-PUB-2021-009

Instead of Introduction

- BSM Direct Searches
  - Many proposals for New Physics
  - No model of New Physics really stands out ⇨ No obvious Candidates to look for BSM @ LHC
- BSM Indirect Searches
  - New Physics can be seen as small corrections to SM reactions
  - Precision SM measurements @ LHC ⇨ BSM Physics ⇨ High Luminosity LHC
  - Fully exploit experimental program ⇨ High Precision Theoretical Predictions

CERN webpage: LHC/ HL-LHC Plan (last update January 2021)

Instead of Introduction

- **Precision Physics**
  - Infrared structure of *QCD*
  - Electroweak sector of SM
  - Perturbative calculations

- **Precision physics & BSM Direct Searches**
  - SM processes main backgrounds to many BSM scenarios

- **Precision physics & BSM Indirect Searches**
  - Various production modes & decay channels & properties & rare decays & …
  - Extract SM parameters
  - Constraining PDFs
  - Verify Higgs boson couplings to other particles
  - Study specific infra-red safe observables
  - Cross section ratios
  - Various asymmetries

- **Discrepancies between Precise measurements & Precise Theory**

Projects

- *B1a - Production of colour-singlet final states through N^{3}LO QCD*

  Michal Czakon & Kirill Melnikov

- *B1b - Precision top-quark physics at the LHC*

  Michal Czakon & Malgorzata Worek

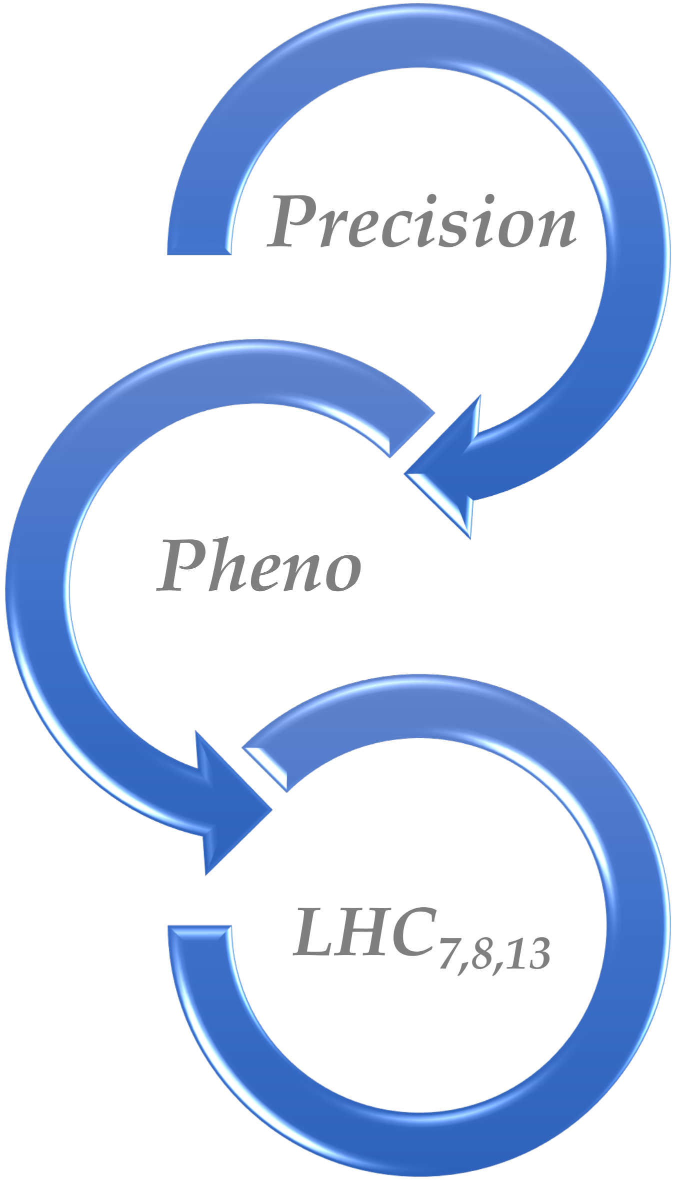
- *B1c - Central Jets in Vector-Boson Scattering*

  Dieter Zeppenfeld

- *Heavy particles @ LHC*

  Gudrun Heinrich

- *Any other work related to SM phenomenology & unrelated to other projects*



Projects

- Not all projects have produced results yet
- Some projects take longer than others
- Many results in other projects
- Selection needed ⇨ Latest & state-of-the-art results
- Three Parts
  - *Top Quark* Physics
  - *W & Z* Boson Physics
  - *γ & Jet* Physics
- Only SM & without Higgs boson

Top Quark Physics → *W & Z Physics* → *Photon & Jet Physics*

LHC as Top Quark Factory

Czakon, Mitov
arXiv:1112.5675 [hep-ph]

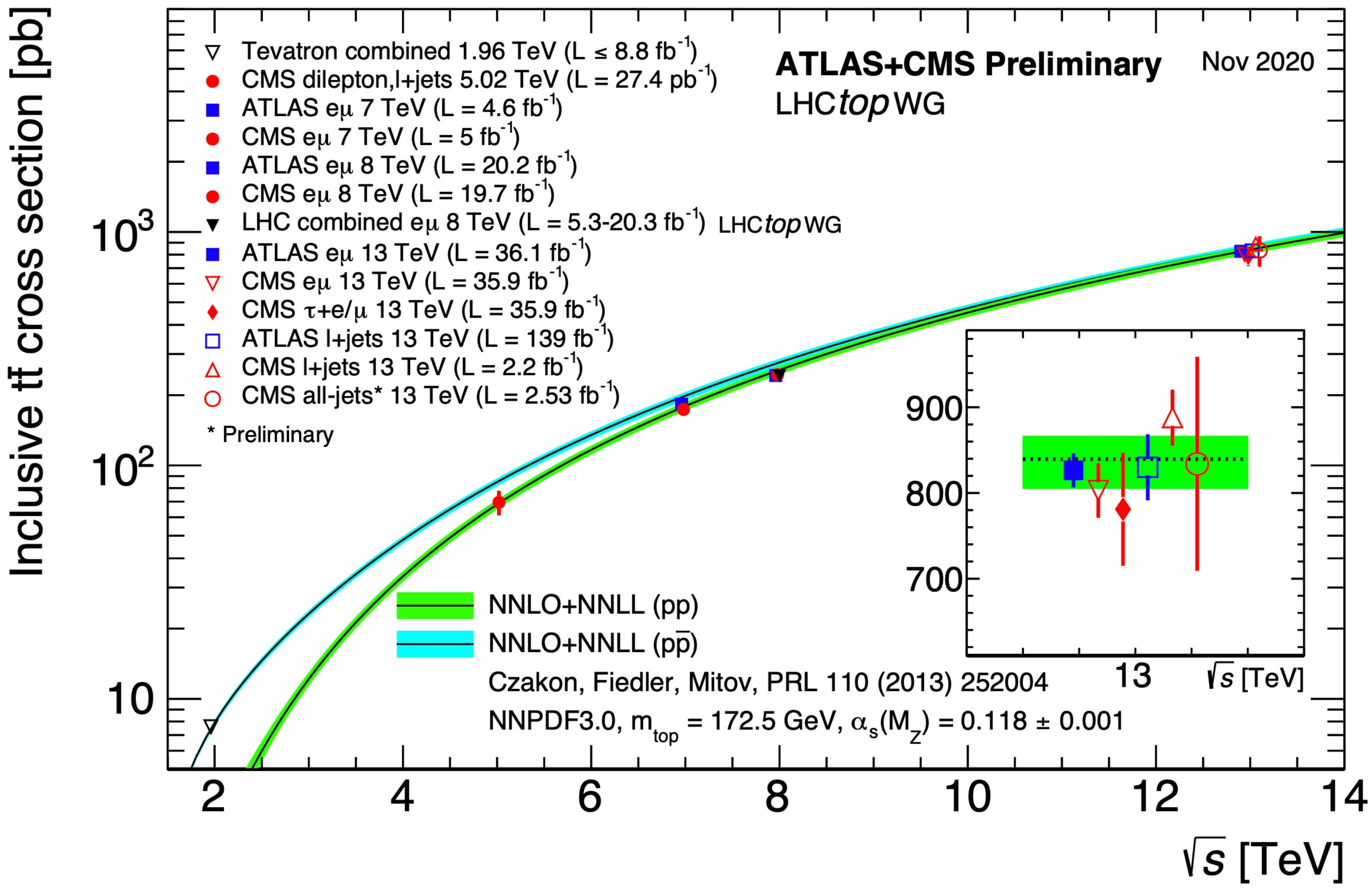
	Collider	σ_{tt} [pb]	L [fb^{-1}]	N_{event}
LHC Run 1	$LHC_{7\ TeV}$	180	5.0	9×10^5
	$LHC_{8\ TeV}$	256	19.7	5×10^6
LHC Run 2	$LHC_{13\ TeV}$	835	139	1×10^8
High Luminosity	$HL\text{-}LHC_{14\ TeV}$	987	3000	3×10^9
High Energy	$HE\text{-}LHC_{27\ TeV}$	3840	15000	6×10^{10}

ATLAS & CMS
Statistics doubled

Top quark pair production @ NNLO *QCD* with *TOP++*
CT14nnlo PDF & $m_t = 173.2$ GeV
$\mu_R = \mu_F = \frac{1}{2} m_t$

Theoretical uncertainties:
NNLO *QCD*: *5% - 6%* & NNLO *QCD* + NNLL: *3% - 4%*

Top Quark



Inclusive tt̄ cross section [pb]
Tevatron combined 1.96 TeV (L ≤ 8.8 fb-1)
CMS dilepton,l+jets 5.02 TeV (L = 27.4 pb-1)
ATLAS eμ 7 TeV (L = 4.6 fb-1)
CMS eμ 7 TeV (L = 5 fb-1)
ATLAS eμ 8 TeV (L = 20.2 fb-1)
CMS eμ 8 TeV (L = 19.7 fb-1)
LHC combined eμ 8 TeV (L = 5.3-20.3 fb-1) LHCtopWG
ATLAS eμ 13 TeV (L = 36.1 fb-1)
CMS eμ 13 TeV (L = 35.9 fb-1)
CMS τ+e/μ 13 TeV (L = 35.9 fb-1)
ATLAS l+jets 13 TeV (L = 139 fb-1)
CMS l+jets 13 TeV (L = 2.2 fb-1)
CMS all-jets* 13 TeV (L = 2.53 fb-1)
* Preliminary
ATLAS+CMS Preliminary
Nov 2020
LHCtopWG
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
NNPDF3.0, m_top = 172.5 GeV, α_s(M_Z) = 0.118 ± 0.001
√s [TeV]

Top-Quark Pair Production & Decay @ NNLO

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{\mathrm{LO}} + \alpha_s \mathrm{d}\sigma^{\mathrm{NLO}} + {\alpha_s}^2 \mathrm{d}\sigma^{\mathrm{NNLO}}$$

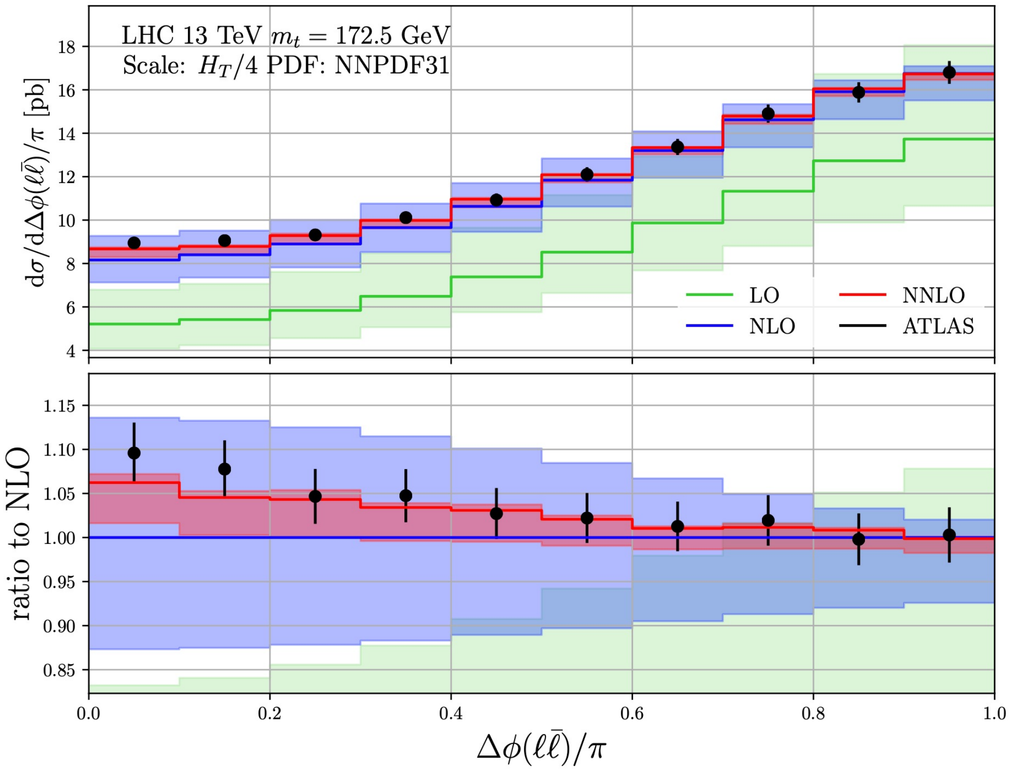
- Predictions in NWA

$$\mathrm{d}\sigma^{\mathrm{LO}} = \sigma^{\mathrm{LOxLO}} ,$$

$$\mathrm{d}\sigma^{\mathrm{NLO}} = \mathrm{d}\sigma^{\mathrm{NLOxLO}} + \mathrm{d}\sigma^{\mathrm{LOxNLO}} - \frac{2\Gamma_t^{(1)}}{\Gamma_t^{(0)}} \mathrm{d}\sigma^{\mathrm{LO}} ,$$

$$\mathrm{d}\sigma^{\mathrm{NNLO}} = \mathrm{d}\sigma^{\mathrm{NNLOxLO}} + \mathrm{d}\sigma^{\mathrm{NLOxNLO}} + \mathrm{d}\sigma^{\mathrm{LOxNNLO}} - \frac{2\Gamma_t^{(1)}}{\Gamma_t^{(0)}} \mathrm{d}\sigma^{\mathrm{NLO}} + \left(\frac{3\Gamma_t^{(1)2}}{\Gamma_t^{(0)2}} - \frac{2\Gamma_t^{(0)}\Gamma_t^{(2)}}{\Gamma_t^{(0)2}} \right) \mathrm{d}\sigma^{\mathrm{LO}}$$

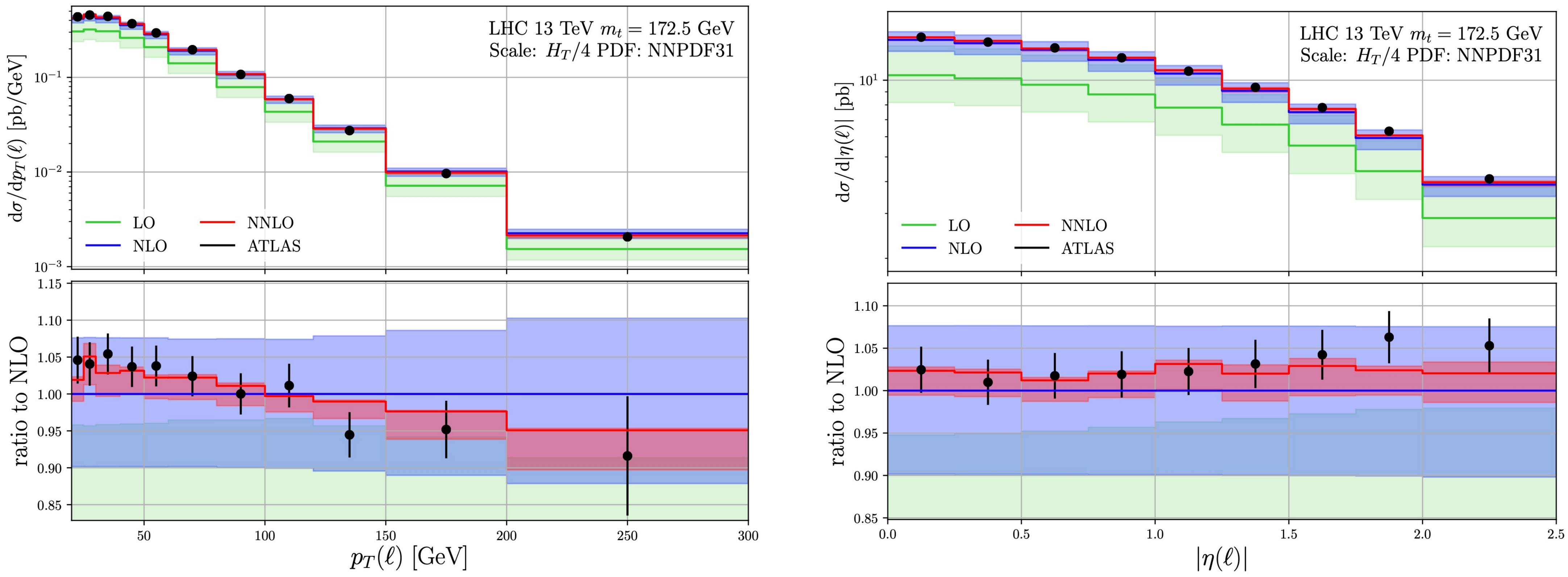
Czakon, Mitov, Poncelet
arXiv:2008.11133 [hep-ph]



$$pp \to t\bar{t} + X \to W^+W^-b\bar{b} + X \to \ell^+\nu_\ell\, \ell^-\bar{\nu}_\ell\, b\bar{b} + X$$

Top-Quark Pair Production & Decay @ NNLO

Czakon, Mitov, Poncelet
arXiv:2008.11133 [hep-ph]



$$pp \to t\bar{t} + X \to W^+W^-b\bar{b} + X \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b} + X$$

TTW Production & Decay @ NLO

- NNLO *QCD* theoretical predictions only for *tt*
  - di-lepton channel

- More exclusive final states produced @ LHC

- MOTIVATION ⇨ *ttW production @ LHC*
- Background for *ttH* ⇨ *2lSS & 3l*
  - Higher normalization for *ttW* compared to SM predictions from multipurpose MC generators *30%−70%*
  - Problems with modeling of final states in phase space regions dominated by *ttW*

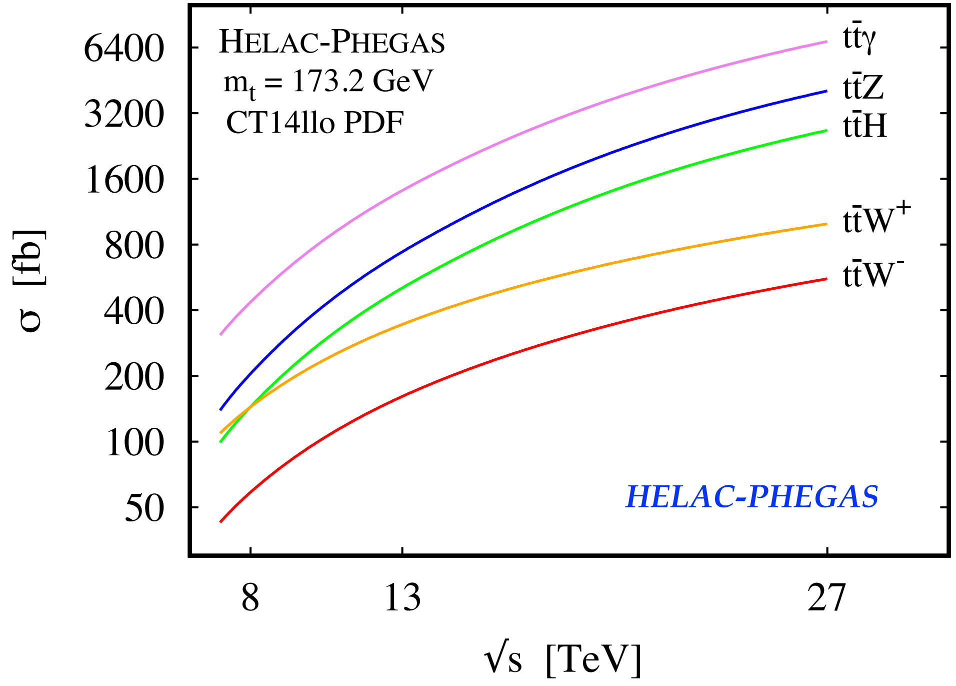
ATLAS-CONF-2019-045

- Improved description of *ttW* background needed to reach greater precision in future
- First calculations for off-shell *ttW* confirmed by second group ⇨ di-lepton channel

Bevilacqua, Bi, Hartanto, Kraus, Worek arXiv:2005.09427 [hep-ph]
Denner, Pellicciolі arXiv:2007.12089 [hep-ph]

Stable top quarks

$t\bar{t}\gamma, t\bar{t}Z, t\bar{t}H, t\bar{t}W^+, t\bar{t}W^-$ *@LHC*



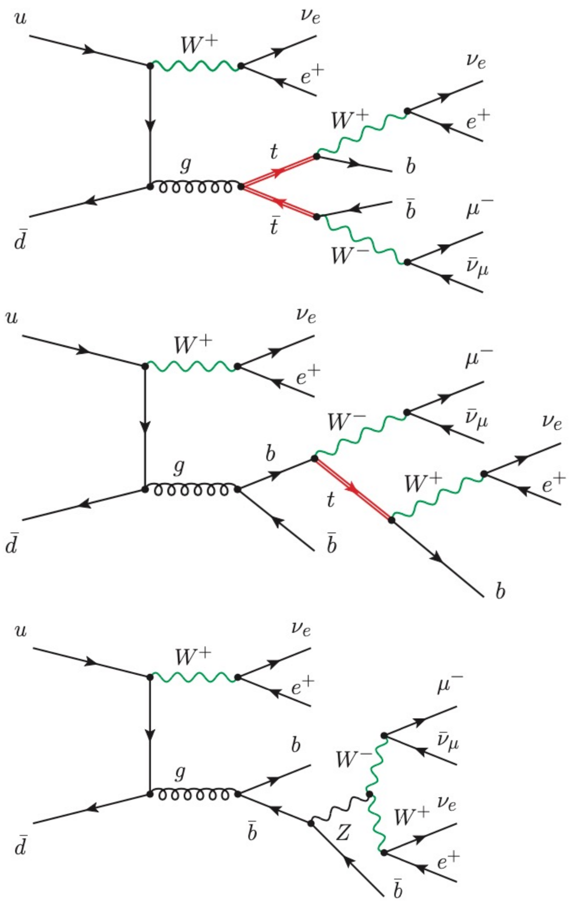
Cafarella, Papadopoulos, Worek arXiv:0710.2427 [hep-ph]

TTW Production & Decay @ NLO

Bevilacqua, Bi, Hartanto, Kraus, Worek
arXiv:2005.09427 [hep-ph]

- **Complete off-shell effects:**
  - Off-shell top quarks described by Breit-Wigner propagators
  - Double-, single- & non-resonant top-quark contributions included
  - All interference effects incorporated at matrix element level

$pp \to e^+\nu_e\,\mu^-\,\bar{\nu}_\mu\,e^+\nu_e\,b\bar{b} + X$
$pp \to e^-\bar{\nu}_e\,\mu^+\,\nu_\mu\,e^-\bar{\nu}_e\,b\bar{b} + X$



- **NWA:**
  - Works in the limit ⇨ $\Gamma_t/m_t \to 0$

$$\Gamma_t = 1.35159\ \text{GeV},\ m_t = 173.2\,\text{GeV},\ \Gamma_t/m_t \approx 0.008$$

  - Incorporates only double resonant contributions
  - Restricts unstable top quarks & W gauge bosons to on-shell states

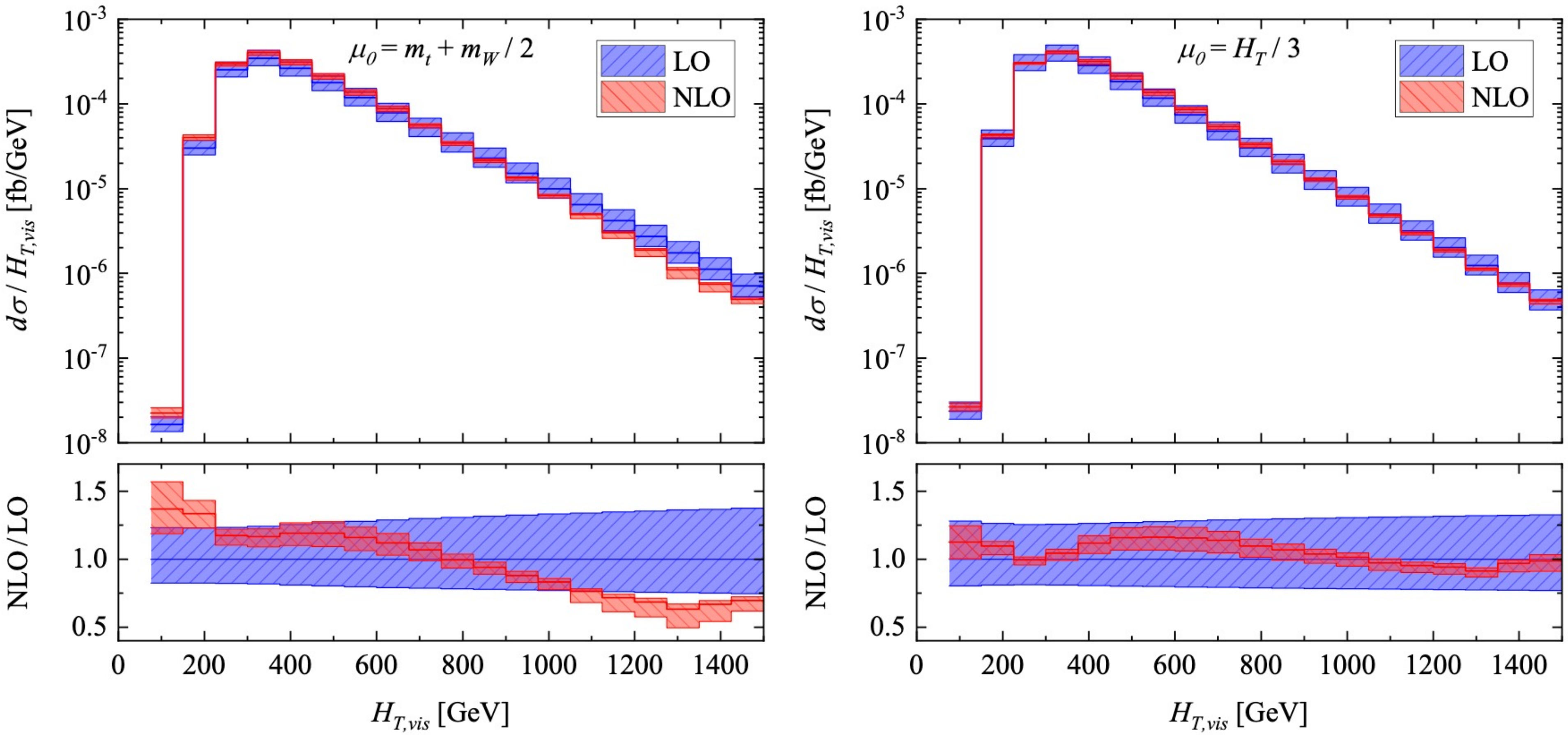
$$pp \to t\bar{t}W^+ + X \to W^+W^+W^-\,b\bar{b} + X \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,e^+\nu_e\,b\bar{b}$$

TTW Production & Decay @ NLO

Off-shell ttW^+

Bevilacqua, Bi, Hartanto, Kraus, Worek
arXiv:2005.09427 [hep-ph]

$$H_T^{vis} = p_T(\mu^-) + p_T(\ell_1) + p_T(\ell_2) + p_T(j_{b_1}) + p_T(j_{b_2})$$

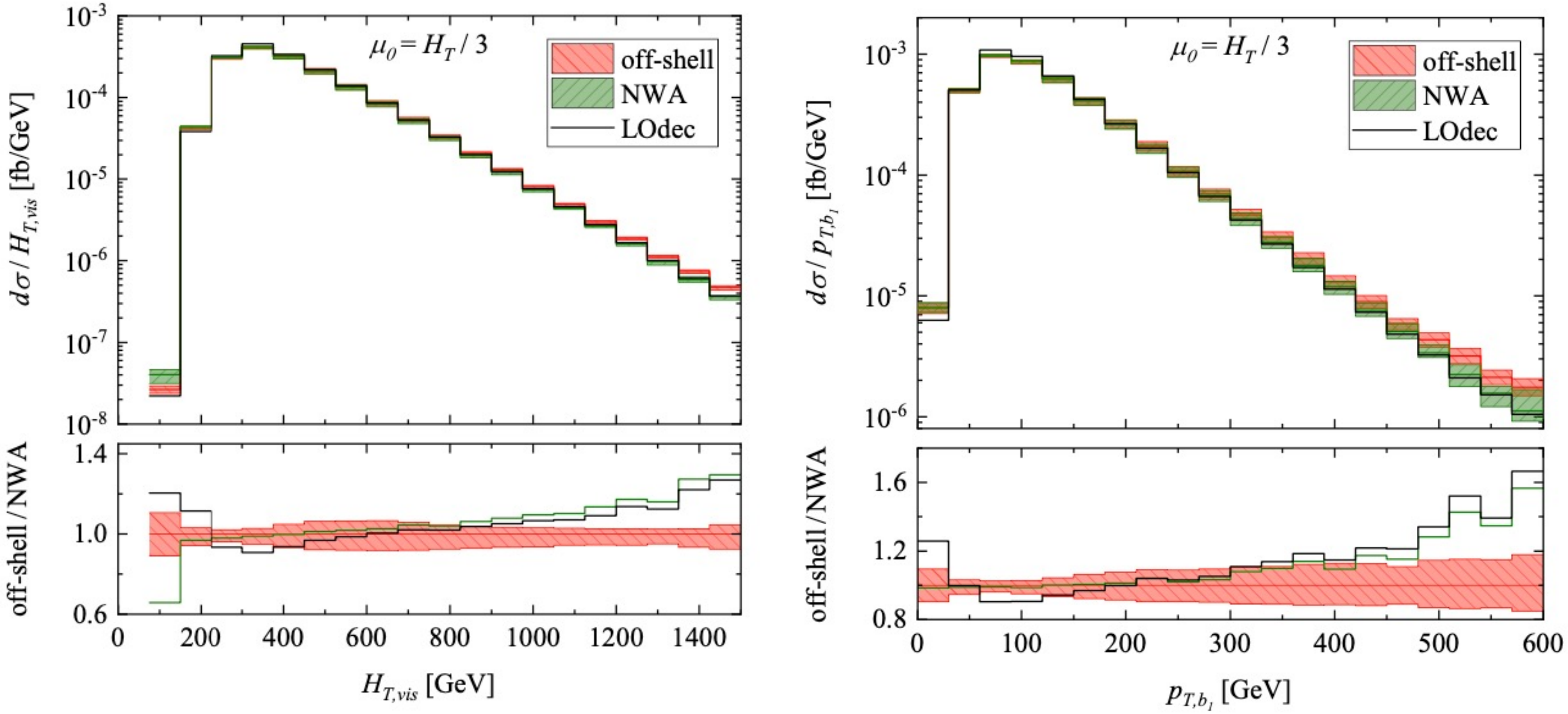


- *Fixed scale choice* ⇨ Leads to perturbative instabilities in TeV region of differential cross & Large distortions
- *Dynamical scale choice* ⇨ Stabilises tails & keeps NLO uncertainties bands within LO ones

TTW Production & Decay @ NLO

Off-shell & NWA & $NWA_{LOdecay}$

$$H_T^{vis} = p_T(\mu^-) + p_T(\ell_1) + p_T(\ell_2) + p_T(j_{b_1}) + p_T(j_{b_2})$$



Bevilacqua, Bi, Hartanto, Kraus, Worek
arXiv:2005.09427 [hep-ph]

$$pp \to e^+\nu_e \, \mu^-\bar{\nu}_\mu \, e^+\nu_e \, b\bar{b} + X$$

Differential level:

- Off-shell up to *60% - 70%*
- NLO *QCD 10% - 20%*
- PDF up to *10%*
- Scales *10% - 20%*
- For central value of scale substantial differences between NWA & $NWA_{LOdecay}$

- *Similar effects for ttW⁻*

Integrated level:

- Complete top-quark off-shell effects *0.2%*
- NLO *QCD* around *10%* & Theoretical uncertenties: Scales *6%-7%* ⇨ PDF *2%*
- NLO *QCD* corrections to decays *3%-5%*

TTW^+ / TTW^- @ NLO

Searching for more precise observables

$\mu_0 = m_t + m_W/2$ NNPDF3.0	$\sigma^{NLO}_{t\bar{t}W^+} \pm \delta_{scale} \pm \delta_{PDF}$ [ab]	$\sigma^{NLO}_{t\bar{t}W^-} \pm \delta_{scale} \pm \delta_{PDF}$ [ab]	$\sigma^{NLO}_{t\bar{t}W^+}/\sigma^{NLO}_{t\bar{t}W^-}$ $\mathcal{R}$
$p_{T,b} > 25$ GeV	$123.2^{+6.3\,(5\%)}_{-8.7\,(7\%)}{}^{+2.1\,(2\%)}_{-2.1\,(2\%)}$	$68.0^{+4.8\,(7\%)}_{-5.5\,(8\%)}{}^{+1.2\,(2\%)}_{-1.2\,(2\%)}$	$1.81 \pm 0.03\,(2\%)$
$p_{T,b} > 30$ GeV	$113.1^{+5.4\,(5\%)}_{-7.8\,(7\%)}{}^{+1.9\,(2\%)}_{-1.9\,(2\%)}$	$62.3^{+4.2\,(7\%)}_{-4.9\,(8\%)}{}^{+1.1\,(2\%)}_{-1.1\,(2\%)}$	$1.81 \pm 0.03\,(2\%)$
$p_{T,b} > 35$ GeV	$102.6^{+4.7\,(5\%)}_{-6.8\,(7\%)}{}^{+1.7\,(2\%)}_{-1.7\,(2\%)}$	$56.3^{+3.7\,(7\%)}_{-4.4\,(8\%)}{}^{+1.0\,(2\%)}_{-1.0\,(2\%)}$	$1.82 \pm 0.03\,(2\%)$
$p_{T,b} > 40$ GeV	$92.0^{+4.0\,(4\%)}_{-6.1\,(7\%)}{}^{+1.6\,(2\%)}_{-1.6\,(2\%)}$	$50.3^{+3.3\,(6\%)}_{-3.9\,(8\%)}{}^{+0.9\,(2\%)}_{-0.9\,(2\%)}$	$1.83 \pm 0.04\,(2\%)$

NLO QCD integrated fiducial cross sections & cross section ratios

Off-shell $ttW^{\pm}$

Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek arXiv:2012.01363 [hep-ph]

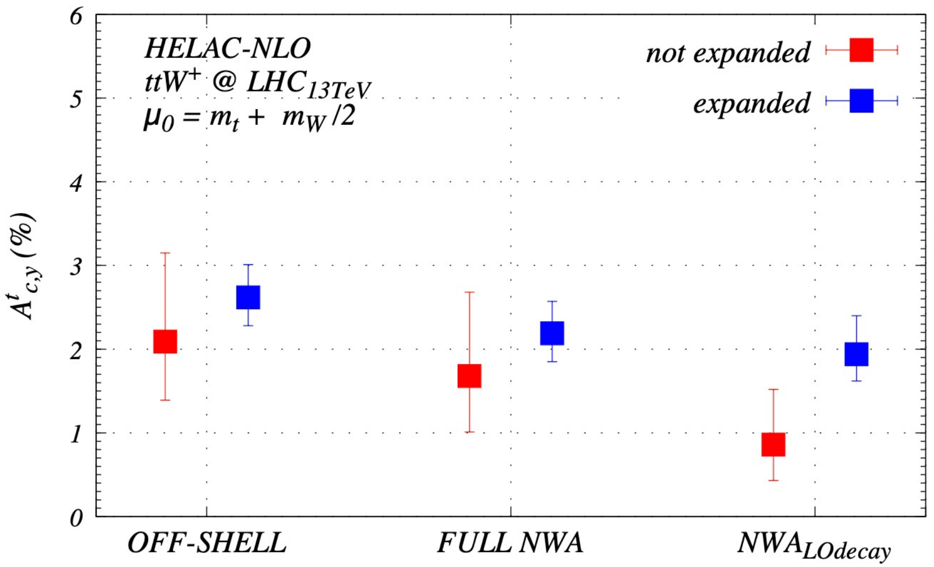
- *ttW^+ & ttW^-* similar from NLO *QCD* point of view ⇨ Integrated & differential level
- Scale uncertainties can be taken correlated
- Cross section ratios stable with respect to $p_T(b)$
- Insensitive to details of modelling of top quark production & decays ⇨ Off-shell/NWA/$NWA_{LOdecay}$
- Insensitive to scale choice ⇨ $\mu_0 = m_t + m_W/2$ versus $\mu_0 = H_T/3$

Top Quark Charge Asymmetry @ NLO

Searching for more precise observables

$$A_c^t = \frac{\sigma^+_{\text{bin}} - \sigma^-_{\text{bin}}}{\sigma^+_{\text{bin}} + \sigma^-_{\text{bin}}}, \qquad \sigma^{\pm}_{\text{bin}} = \int \theta(\pm\Delta|y|)\,\theta_{\text{bin}}\,d\sigma$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



- $A^t{}_c$ charge asymmetry @ NLO for $pp \to ttW^+$

Off-shell ttW⁺

Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek
arXiv:2012.01363 [hep-ph]

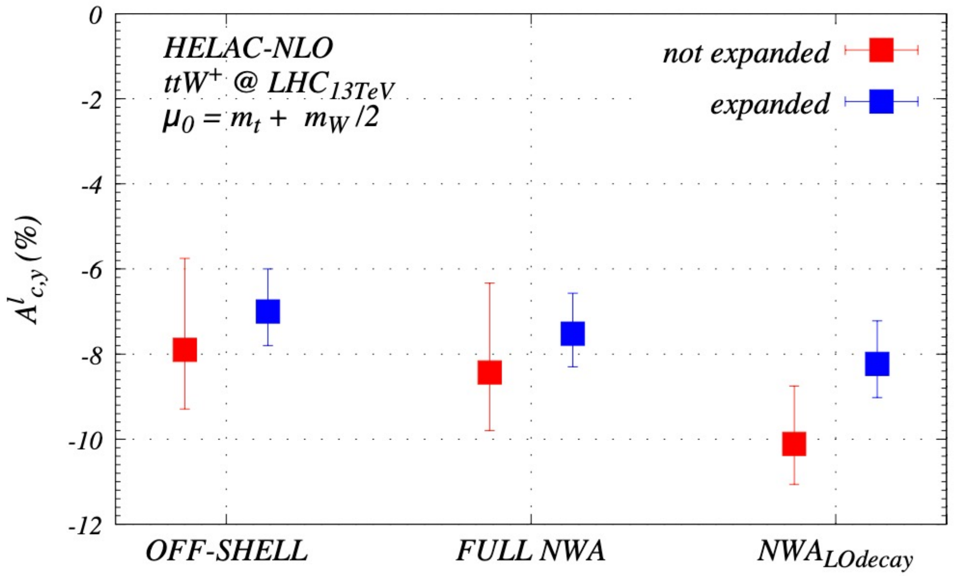
- Asymmetry larger than for $pp \to tt$
- Top quark momenta must be reconstructed
- Scales no important
- Modelling important

$t\bar{t}W^+$, $\mu_0 = H_T/3$	Off-shell	Full NWA	NWA$_{\text{LOdecay}}$
$A^t_{c,y}$ [%]	$2.36(8)^{+1.19\,(50\%)}_{-0.77\,(33\%)}$	$1.93(5)^{+1.23\,(64\%)}_{-0.72\,(37\%)}$	$1.11(3)^{+0.55\,(49\%)}_{-0.53\,(48\%)}$
$A^t_{c,exp,y}$ [%]	$2.66(10)^{+0.38\,(14\%)}_{-0.34\,(13\%)}$	$2.20(5)^{+0.45(20\%)}_{-0.31(14\%)}$	$2.08(5)^{+0.24\,(11\%)}_{-0.40\,(19\%)}$
$t\bar{t}W^+$, $\mu_0 = m_t + m_W/2$	Off-shell	Full NWA	NWA$_{\text{LOdecay}}$
$A^t_{c,y}$ [%]	$2.09(8)^{+1.06\,(51\%)}_{-0.70\,(33\%)}$	$1.68(4)^{+1.00(60\%)}_{-0.67(40\%)}$	$0.86(3)^{+0.66\,(77\%)}_{-0.43\,(50\%)}$
$A^t_{c,exp,y}$ [%]	$2.62(10)^{+0.39\,(15\%)}_{-0.34\,(13\%)}$	$2.19(4)^{+0.38(17\%)}_{-0.34(16\%)}$	$1.94(5)^{+0.46\,(24\%)}_{-0.32\,(16\%)}$

Lepton Charge Asymmetry @ NLO

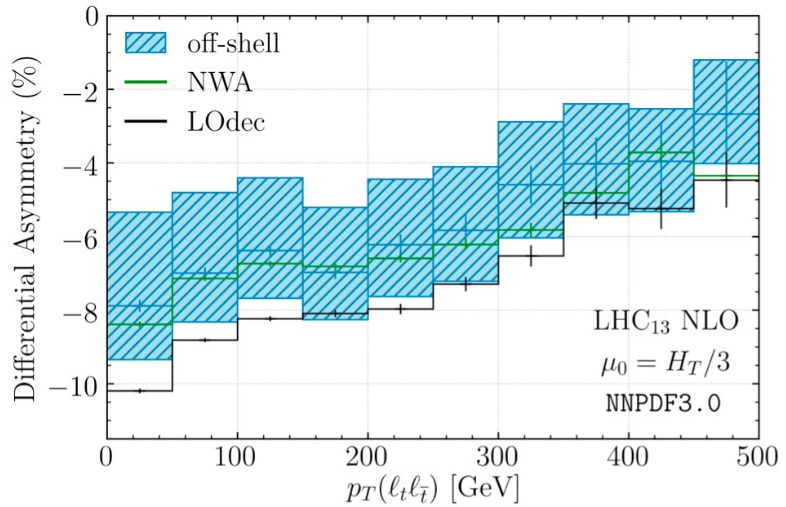
Off-shell $ttW^{\pm}$

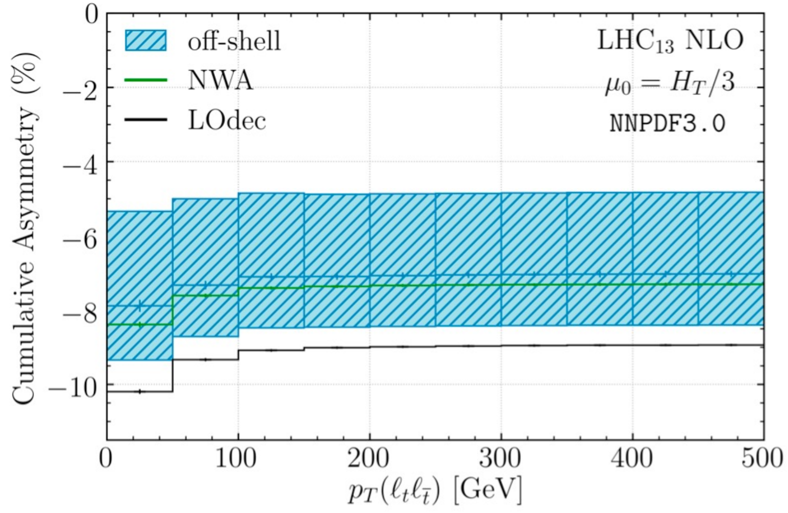
Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek
arXiv:2012.01363 [hep-ph]



$t\bar{t}W^+$ $\mu_0 = H_T/3$	Off-shell	Full NWA	$\mathrm{NWA_{LOdecay}}$
$A^\ell_{c,y}$ [%]	$-7.46(11)^{+2.46\,(33\%)}_{-1.55\,(21\%)}$	$-7.94(4)^{+2.45(31\%)}_{-1.54(19\%)}$	$-9.81(4)^{+1.46\,(15\%)}_{-1.03\,(10\%)}$
$A^\ell_{c,exp,y}$ [%]	$-6.93(13)^{+1.01\,(14\%)}_{-0.81\,(12\%)}$	$-7.43(5)^{+0.99(13\%)}_{-0.79(11\%)}$	$-8.14(5)^{+1.00\,(12\%)}_{-0.81\,(10\%)}$

Differential & Cumulative A^l_c
NLO QCD for $pp \to ttW^{\pm}$





- A^l_c charge asymmetry @ NLO for $pp \to ttW^+$
- Directly measurable ⇨ No top quark reconstruction needed

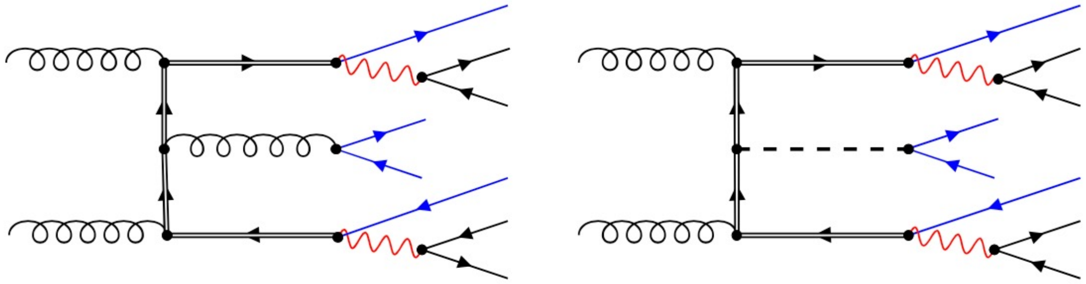
Off-Shell TTBB @ NLO

- Irreducible background for Higgs boson studied
- ttH ⇨ Observation in 2018
- Top-Yukawa coupling Y_t ⇨ Probed directly
- ATLAS & CMS reported measurements for $ttH(H \to bb)$ decay channel of Higgs boson

Experimental Challenges

- Identification of candidates for Higgs decay
- Combinatorial background
- Misidentification of light jets with b-jets
- b-jet tagging
- SM backgrounds

$$pp \to t\bar{t}H \to t\bar{t}b\bar{b} \to W^+W^-b\bar{b}b\bar{b}$$



$pp \to t\bar{t}b\bar{b}$ & $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$

Theory Challenges

- Two very different & distinctive scales
- m_t ⇨ tt production & top-quark decays
- $p_T(b)$ ⇨ Describes b-jets from $g \to bb$ splitting

- Second calculation for off-shell $ttbb$ in di-lepton channel ⇨ Agreement with first calculations

$$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b} + X$$

Denner, Lang, Pellen arXiv:2008.00918 [hep-ph]
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek arXiv:2105.08404 [hep-ph]

Off-Shell TTBB @ NLO

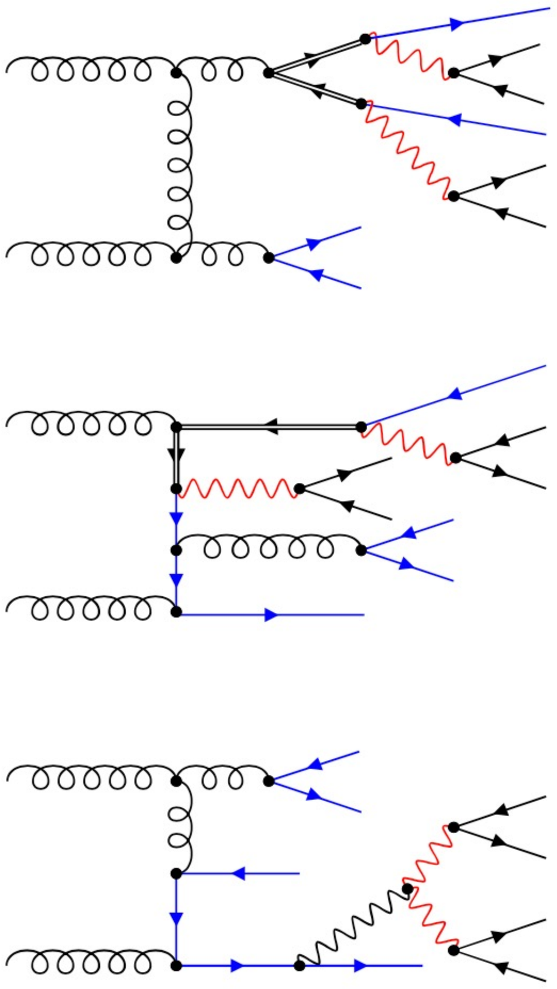
Off-shell ttbb

Integrated fiducial cross sections for ttbb

$p_T(b)$	$\sigma^{\rm LO}$ [fb]	$\delta_{\rm scale}$	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
$\mu_R = \mu_F = \mu_0 = m_t$						
25	6.998	$+4.525$ (65%) -2.569 (37%)	13.24	$+2.33$ (18%) -2.89 (22%)	$+0.19$ (1%) -0.19 (1%)	1.89
30	5.113	$+3.343$ (65%) -1.889 (37%)	9.25	$+1.32$ (14%) -1.93 (21%)	$+0.14$ (2%) -0.14 (2%)	1.81
35	3.775	$+2.498$ (66%) -1.401 (37%)	6.57	$+0.79$ (12%) -1.32 (20%)	$+0.10$ (2%) -0.10 (2%)	1.74
40	2.805	$+1.867$ (67%) -1.051 (37%)	4.70	$+0.46$ (10%) -0.91 (19%)	$+0.08$ (2%) -0.08 (2%)	1.68
$\mu_R = \mu_F = \mu_0 = H_T/3$						
25	6.813	$+4.338$ (64%) -2.481 (36%)	13.22	$+2.66$ (20%) -2.95 (22%)	$+0.19$ (1%) -0.19 (1%)	1.94
30	4.809	$+3.062$ (64%) -1.756 (37%)	9.09	$+1.66$ (18%) -1.98 (22%)	$+0.16$ (2%) -0.16 (2%)	1.89
35	3.431	$+2.191$ (64%) -1.256 (37%)	6.37	$+1.07$ (17%) -1.36 (21%)	$+0.11$ (2%) -0.11 (2%)	1.86
40	2.464	$+1.582$ (64%) -0.901 (37%)	4.51	$+0.72$ (16%) -0.95 (21%)	$+0.09$ (2%) -0.09 (2%)	1.83

- Results for NNPDF3.1 LO & NLO with ***$\alpha_s(m_Z)$ = 0.118***
- LO NNPDF3.1 PDF set with ***$\alpha_s(m_Z)$ = 0.130*** ⇨ ***K = 1.45***
- Other PDF sets give K-factor ***∈ (1.81 & 1.37 & 1.23)***
- With jet veto of 50 GeV ***K = 1.11 & K = 1.23***

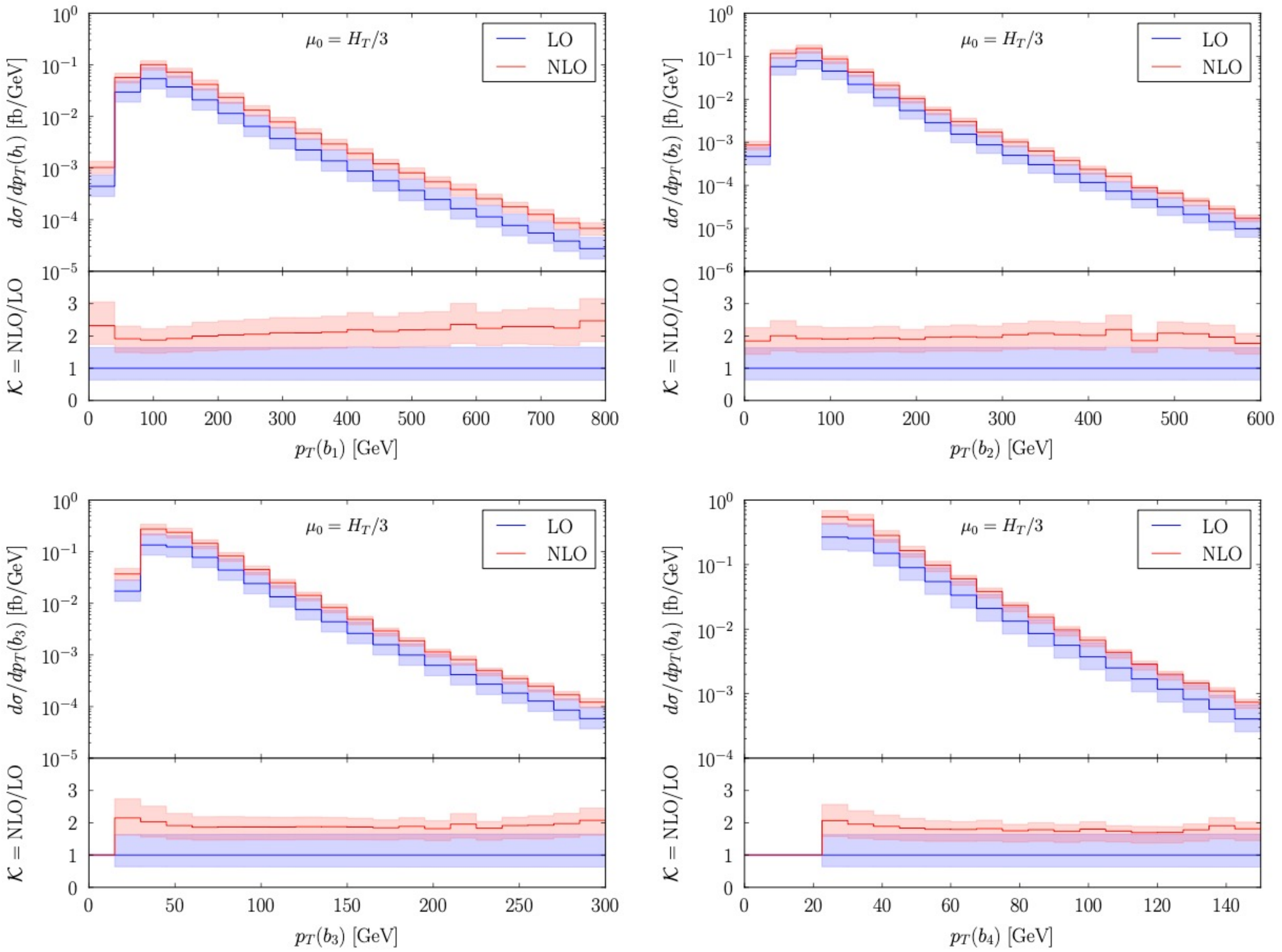
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek
arXiv:2105.08404 [hep-ph]



FeynGame

Harlander, Klein, Lipp
arXiv:2003.00896 [physics.ed-ph]

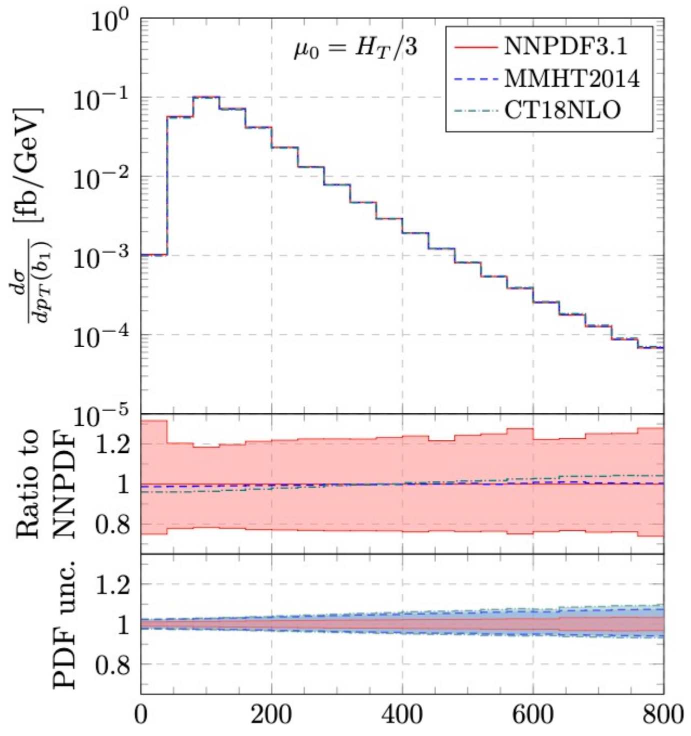
Off-Shell TTBB @ NLO



Off-shell ttbb

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek
arXiv:2105.08404 [hep-ph]

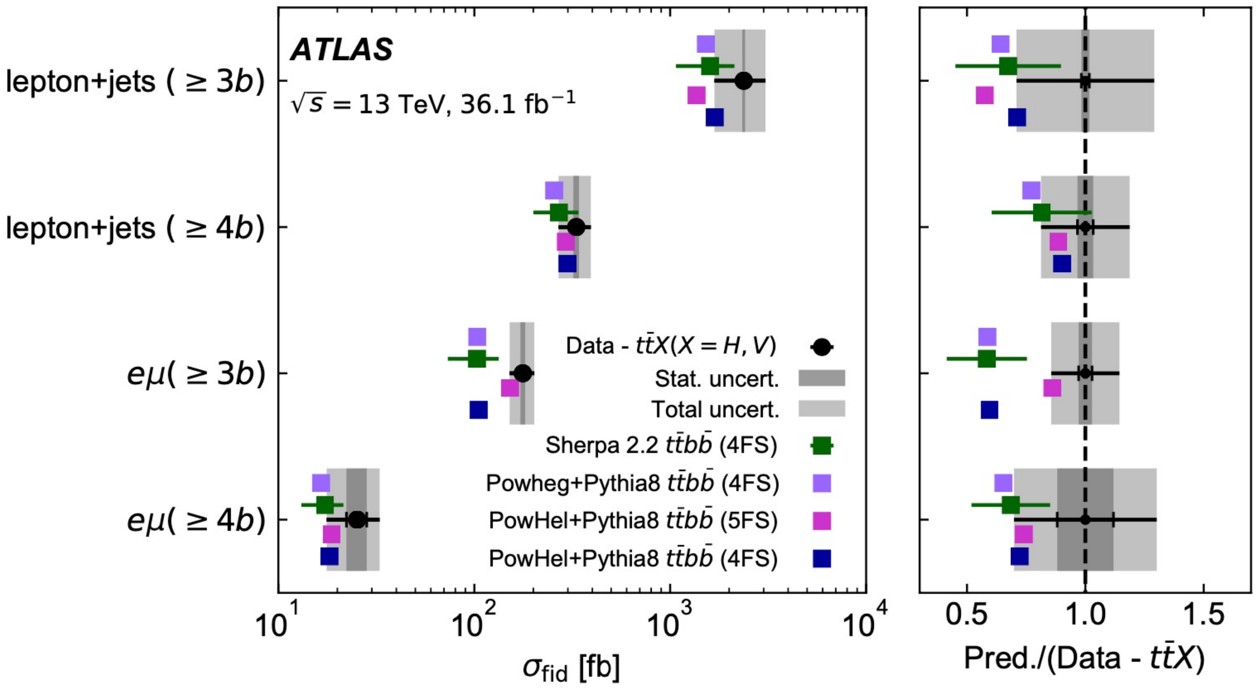
- Large but rather stable NLO corrections @ differential level
- Dynamical scales important
- PDF uncertainties small



Off-Shell TTBB @ NLO

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek
arXiv:2105.08404 [hep-ph]

ATLAS arXiv:1811.12113 [hep-ex]



Theoretical predictions	$\sigma_{e\mu+4b}$ [fb]
Sherpa+OpenLoops (4FS)	17.2 ± 4.2
Powheg-Box+Pythia 8 (4FS)	16.5
PowHel+Pythia 8 (5FS)	18.7
PowHel+Pythia 8 (4FS)	18.2
Helac-Nlo (5FS)	19.4 ± 4.2

$$\sigma^{\mathrm{ATLAS}}_{e\mu+4b} = (25 \pm 6.5)\ \mathrm{fb}$$

$$\sigma^{\mathrm{HELAC\text{-}NLO}}_{e\mu+4b} = (20.0 \pm 4.3)\ \mathrm{fb}$$

- Comparison to ATLAS results
- *eμ channel @ 13 TeV*
- Agreements within theoretical uncertainties

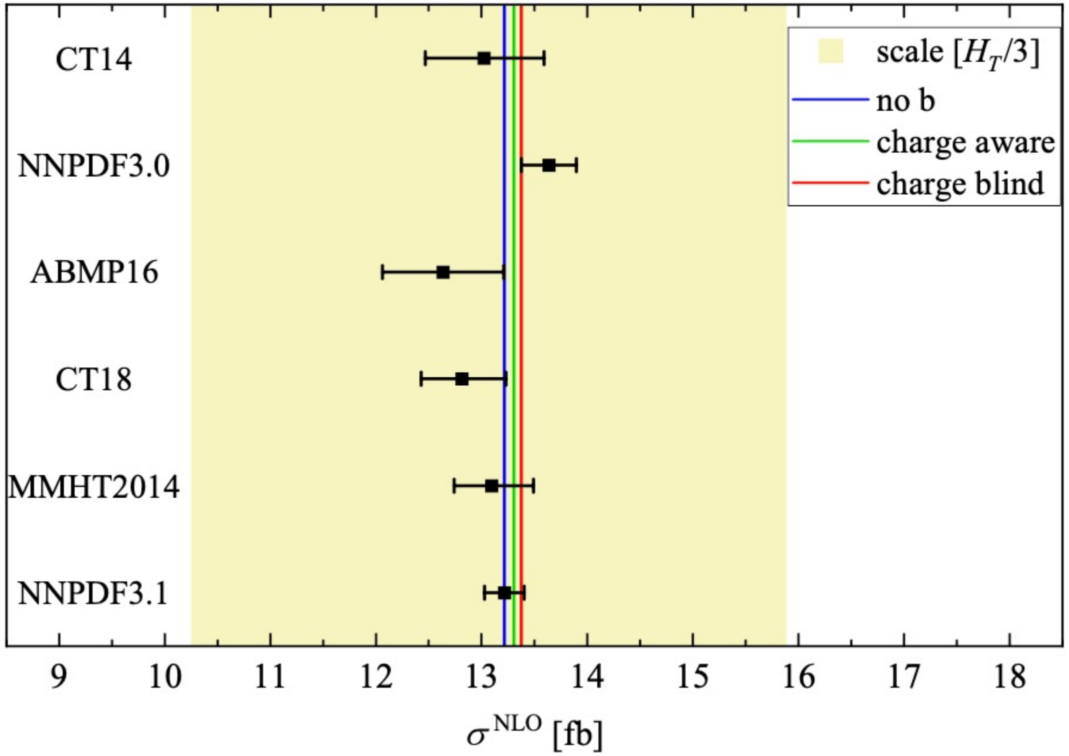
- Higher with leptonic τ decays into l
- For similar scale choice *HELAC-NLO* result is even higher *~ 21 fb*

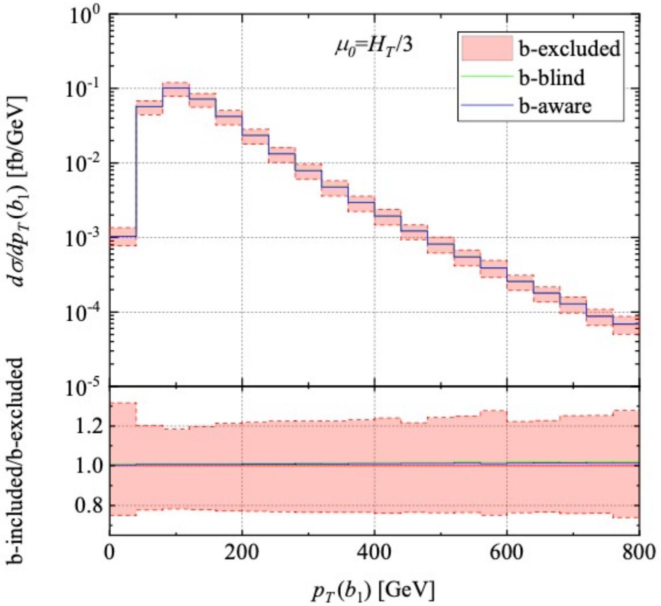
Off-Shell TTBB @ NLO

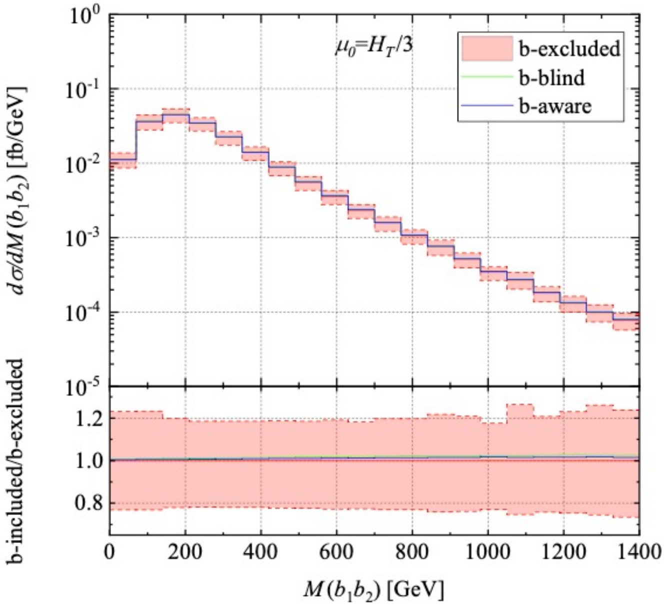
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek
arXiv:2105.08404 [hep-ph]

Initial state bottom

- Charge aware and charge blind schemes for *b*-jet tagging
- ***@ LO*** initial state *b*-quark contributions ⇨ ***0.1% − 0.2%***
- ***@NLO*** ⇨ ***1%*** *&* up to ***1.5%*** with $p_T(b)$ scan *&* up to ***2%*** for jet veto of ***50 GeV*** ⇨ Negligible contribution







B-hadron production @ NNLO

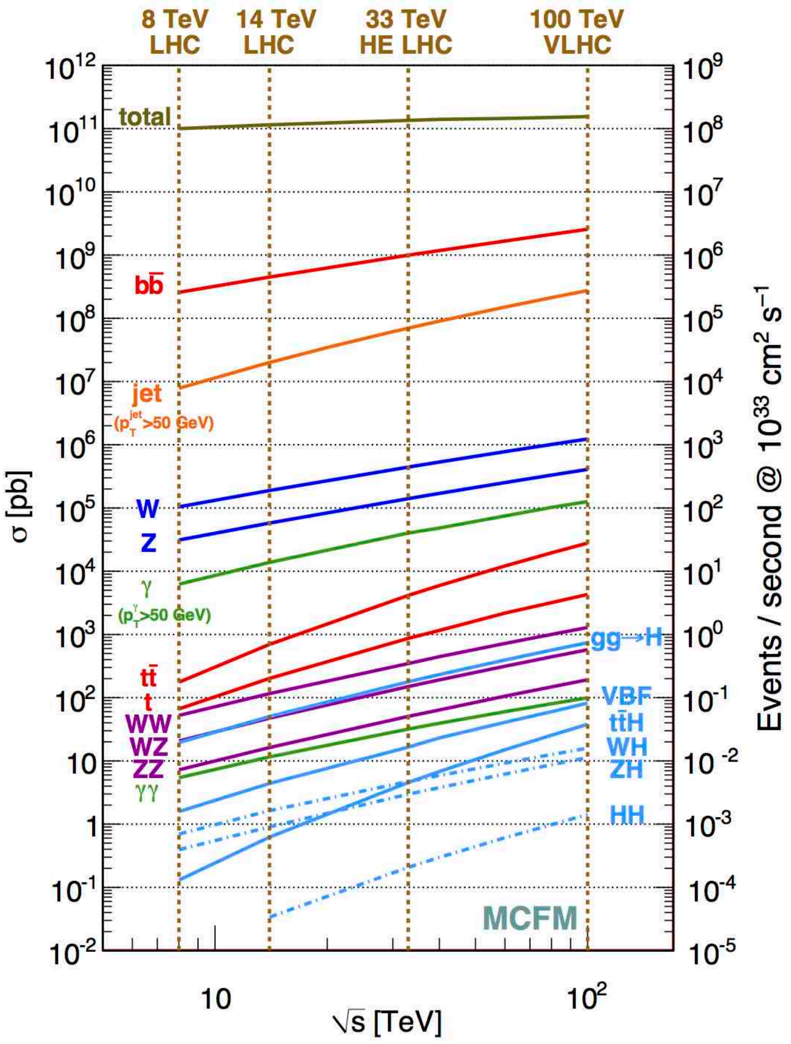
- Heavy flavours copiously produced @ LHC
- *bb & cc* cross sections among largest @ LHC
- Precise measurements in wide kinematic ranges

- Theoretical description of these processes @ NLO
- Lags behind experimental needs

- NNLO *QCD* corrections needed

heavy flavour of mass m_b

low p_T regime where $p_T \sim m_b$	*high p_T one where $p_T \gg m_b$*
• Fixed order perturbation • Expansion in $\alpha_s(m_b)$ ⇨ Slow convergence • Full dependence of heavy quark mass m_b included	• Fixed order perturbation theory no longer adequate • Large quasi-collinear logarithms $log(p_T/m_b)$ • Resummation of logs needed • Consistently carried out in perturbative fragmentation function (PFF) formalism



[MCFM webpage]

BB production @ NNLO

Total cross section for bb production
@ LO & NLO & NNLO
m_b = 4.92 GeV

σ [μb]	$p\bar{p}$ @ 1.96 TeV	pp @ 7 TeV	pp @ 13 TeV
$\mu_0 = m_b$			
LO	$34.66\,^{+51\%}_{-32\%}$	$138.7\,^{+51\%}_{-46\%}$	$249.0\,^{+59\%}_{-51\%}$
NLO	$60.23\,^{+54\%}_{-28\%}$	$219.8\,^{+61\%}_{-39\%}$	$378.6\,^{+65\%}_{-45\%}$
NNLO	$75.4(3)\,^{+22\%}_{-21\%}$	$288(2)\,^{+30\%}_{-24\%}$	$508(3)\,^{+32\%}_{-25\%}$
$\mu_0 = 2m_b$			
LO	$30.94\,^{+41\%}_{-25\%}$	$145.8\,^{+41\%}_{-32\%}$	$281.9\,^{+41\%}_{-37\%}$
NLO	$51.16\,^{+33\%}_{-23\%}$	$203.3\,^{+36\%}_{-26\%}$	$362.9\,^{+34\%}_{-28\%}$
NNLO	$66.7(2)\,^{+21\%}_{-18\%}$	$258(1)\,^{+20\%}_{-18\%}$	$458(2)\,^{+20\%}_{-18\%}$

K_{NNLO} = NNLO/NLO ranging from 1.25 to 1.34

Uncertainties for bb production @ NNLO

	$\sigma_{\rm NNLO}(\mu{\rm b})$	$\Delta\sigma_{\rm scale}$	$\Delta\sigma_{\rm mass}$	$\Delta\sigma_{\rm PDFs}$	$\Delta\sigma_{\alpha_S}$
$p\bar{p}$ @ 1.96 TeV	75.4(3)	$^{+22\%}_{-21\%}$	$^{+9.8\%}_{-8.7\%}$	$\pm1.3\%$	$^{+0.9\%}_{-3.0\%}$
pp @ 7 TeV	288(2)	$^{+30\%}_{-24\%}$	$^{+7.9\%}_{-7.2\%}$	$\pm2.8\%$	$^{+0.3\%}_{-2.9\%}$
pp @ 13 TeV	508(3)	$^{+32\%}_{-25\%}$	$^{+7.4\%}_{-6.8\%}$	$\pm4.6\%$	$^{+0.0\%}_{-3.0\%}$

- NNLO *QCD* reduce theoretical uncertainties
- *K_{NNLO} < K_{NLO}*
- Values of *σ_{NNLO} & σ_{NLO}* consistent within their scale uncertainties
- Values of *σ_{NLO} & σ_{LO}* consistent as well
- Slow convergence of perturbative series comparing to *tt*
- NNLO effects considerably larger than for *tt*

Catani, Devoto, Grazzini, Kallweit, Mazzitelli arXiv:2010.11906 [hep-ph]

B-hadron production @ NNLO

Czakon, Generet, Mitov, Poncelet
arXiv:2102.08267 [hep-ph]

- Heavy flavour production *@ high p_T* performed with *massless b quark* ⇰ High-energy limit
- All mass terms are negligible
- Mass-independent terms & Logarithmically enhanced ones automatically accounted for by *PFF formalism*
- Current state NLO + NLL accuracy
- First results for NNLO in QCD
- *B-hadron* differential distributions in *tt* production & decay

Motivation For tt

- B-hadron production is central to top quark physics
- B-hadron related observables great tool for precise top quark mass determination
- Top quark mass provides large hard scale ⇰ Power suppressed effects $\sim (m_b)^n$ negligible

- Instead of *b-jet* based observables ⇰ Observables involving momentum of single hadron *H*
- *Experiment:* jet energy scale uncertainties dominate total uncertainty on jet-based observables ⇰ *Reduced for H*
- *Fragmentation functions:* Analogue parton distribution functions ⇰ Transitions from partons to hadrons ⇰ *Perturbative* (calculate) + *Nonperturbative* (fit to data)
- Fragmentation functions depend on hadron *H* ⇰ Otherwise universal & extracted from experimental data

$$\frac{d\sigma_h}{dE_h}(E_h) = \sum_i \left(D_{i\to h} \otimes \frac{d\sigma_i}{dE_i} \right)(E_h) \equiv \sum_i \int_0^1 \frac{dx}{x} D_{i\to h}(x) \frac{d\sigma_i}{dE_i}\left(\frac{E_h}{x}\right)$$

Hadron's energy

Partonic cross-section & Fragmentation function

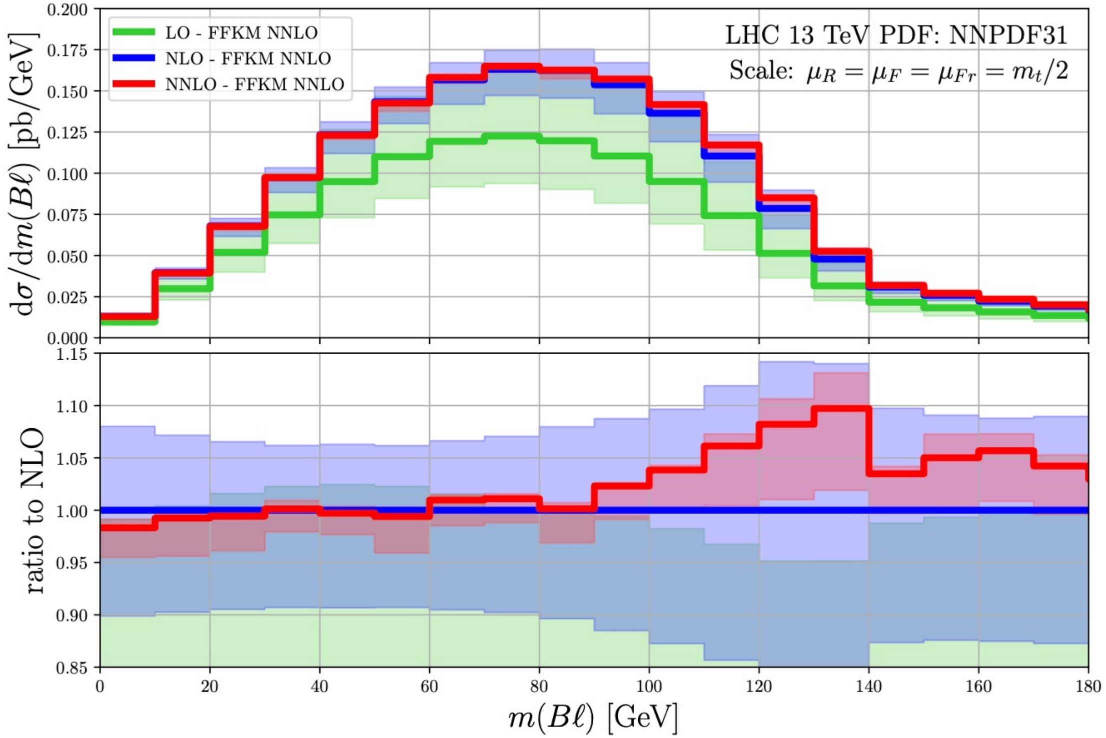
B-hadron production @ NNLO

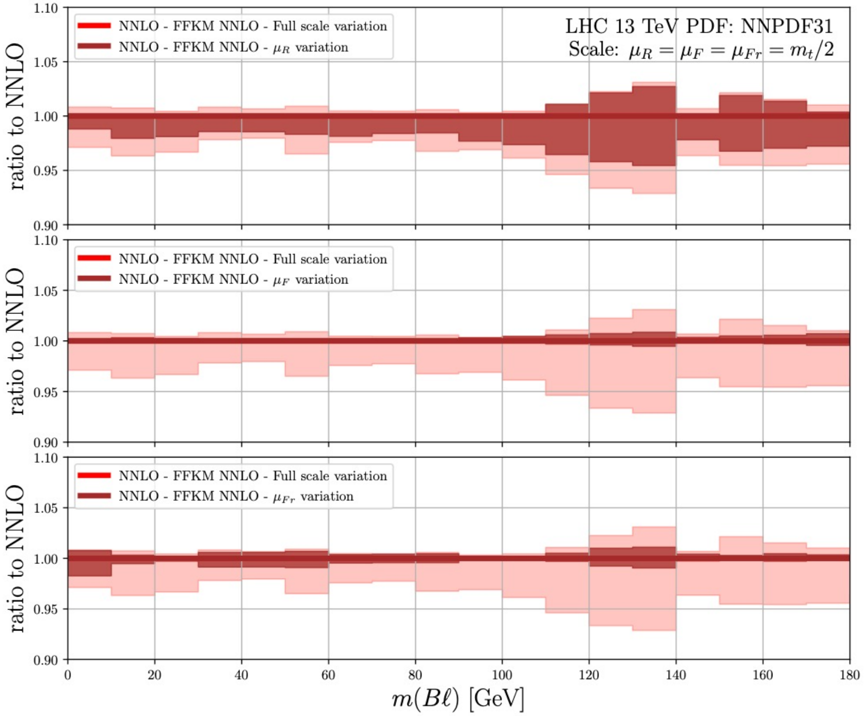
Czakon, Generet, Mitov, Poncelet
arXiv:2102.08267 [hep-ph]

$t \to B + W + X$	$W \to \ell + \nu$

- Energy cut-off of *E(B) > 5 GeV* implemented
- To avoid low x region of FF where predictions not valid

- *m(Bl)* ⇨ m_t
- All curves convoluted with same FF ⇨ FFKM @ NNLO
- Shown comparison for *LO* & *NLO* & *NNLO*
- Breakdown of scale variation





Directly measurable ⇨ No need to reconstruct frames associated with top quark

$$\mu_R = \mu_F = \mu_{Fr} = \frac{m_t}{2}$$

B-hadron production @ NNLO

Czakon, Generet, Mitov, Poncelet
arXiv:2102.08267 [hep-ph]

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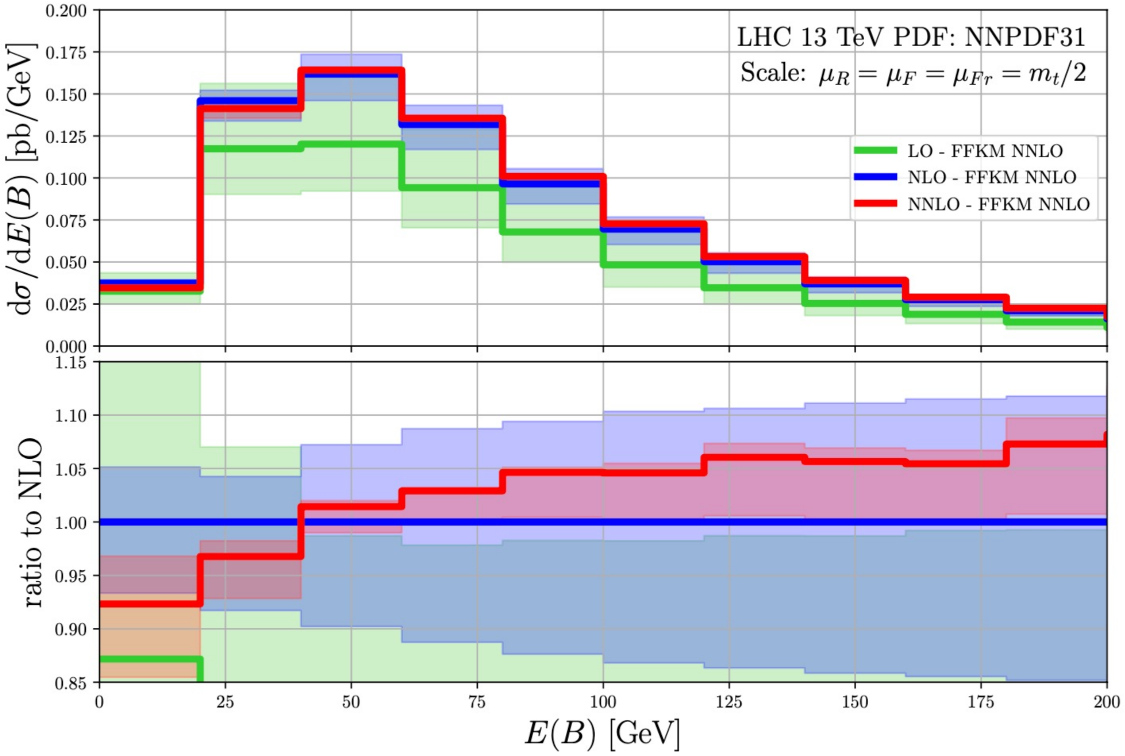

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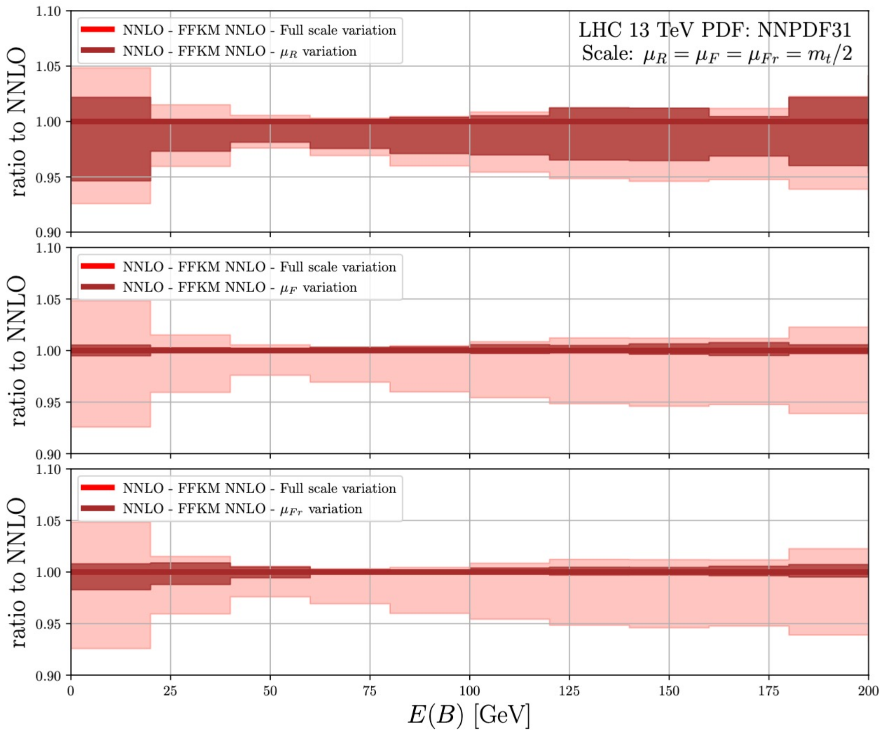
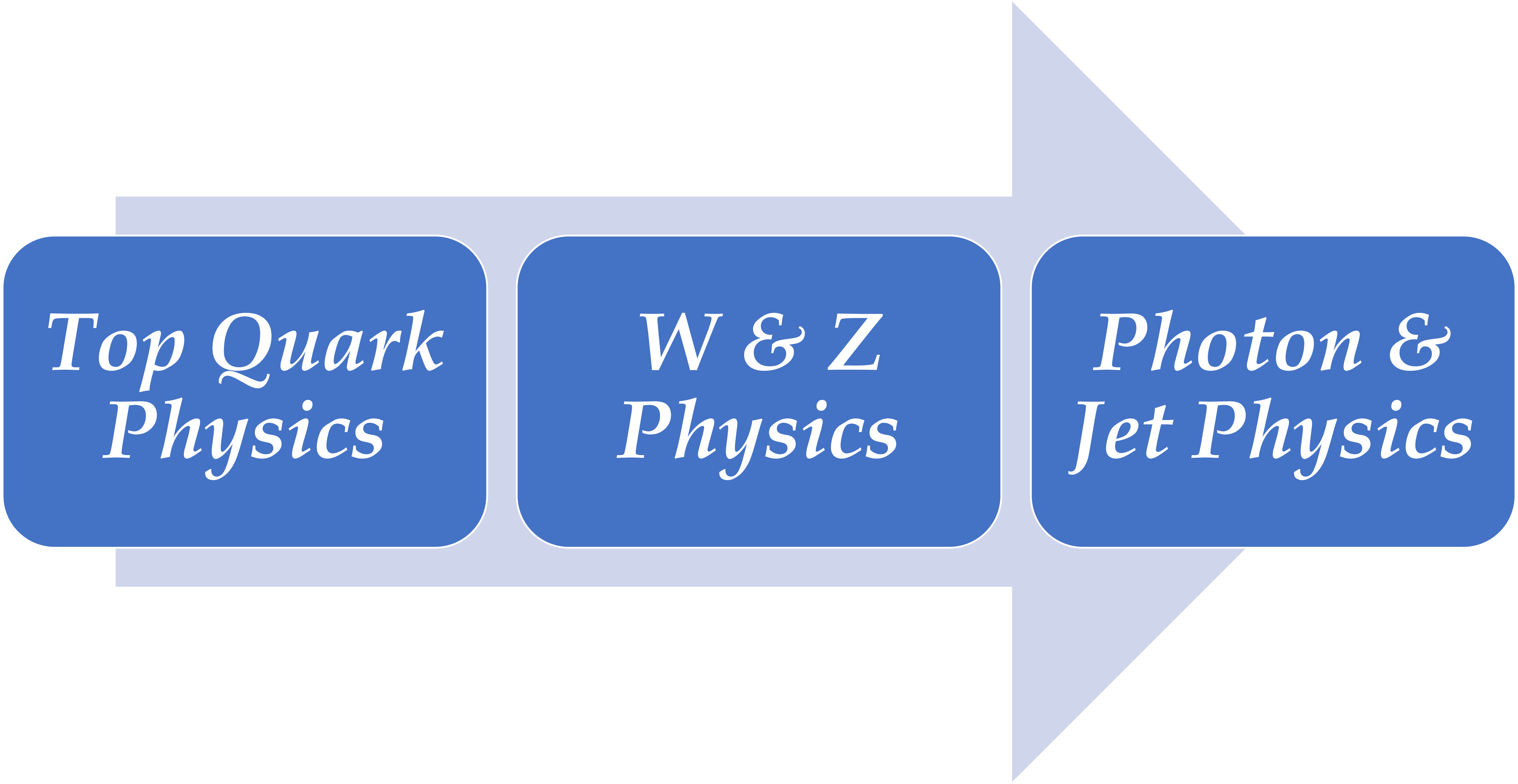
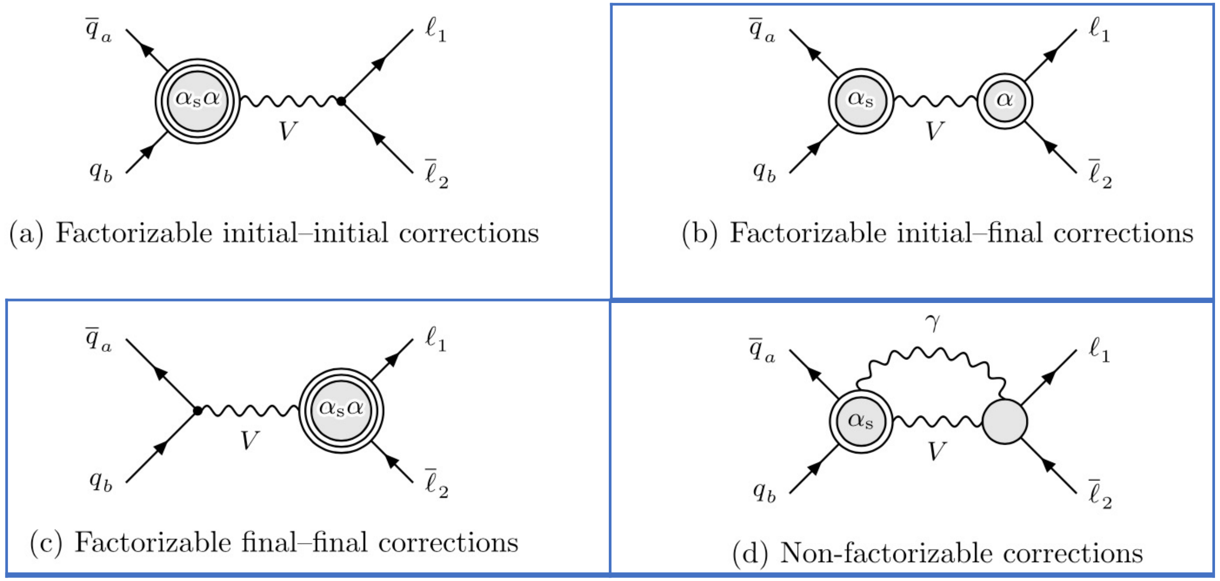


$$\mu_R = \mu_F = \mu_{Fr} = \frac{m_t}{2}$$


Top Quark Physics
W & Z Physics
Photon & Jet Physics

Mixed QCD-EW corrections to Z & W

- **Motivation For Drell-Yan Process**
  - "standard candle" processes
  - Allow for precision measurement of m_W & effective weak mixing angle
  - Constraining PDF
  - *BSM:* M_{ll} @ 1 TeV
- *Mixed QCD-EW* corrections to on-shell *Z & W* production



Dittmaier, Huss, Schwinn arXiv:1403.3216 [hep-ph] & arXiv:1511.08016 [hep-ph]

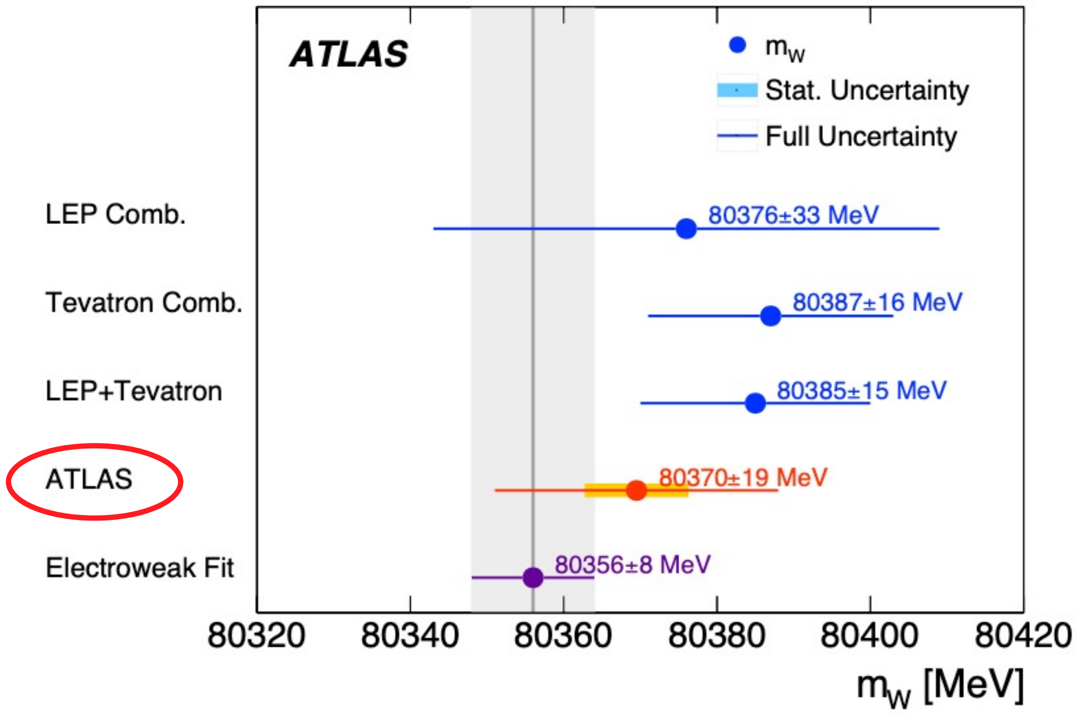
- **A**
  NNLO-like ⇨ Two loop $\mathcal{O}(\alpha_s\alpha)$ corrections to on-shell Z & W. W/Z + jet @ $\mathcal{O}(\alpha)$. W/Z + γ @ $\mathcal{O}(\alpha_s)$. W/Z + γ + jet @ tree level.
- **B**
  NLO ⊗ NLO ⇨ $\mathcal{O}(\alpha_s)$ corrections to *W/Z* production combined with $\mathcal{O}(\alpha)$ corrections to leptonic *W/Z* decay ⇨ Large corrections. *Dominant*
  Impact on shape of distributions & on m_W

$$\delta m_W = -14 \text{ MeV}$$

- **C**
  QCD corrections to *W/Z* self-energies. No impact on shape of distributions. *Negligible*
- **D**
  Soft-photon corrections connecting initial state, intermediate *W/Z* & final-state leptons combined with QCD corrections to *W/Z* production. *@ 0.1% level. Negligible*

Mixed QCD-EW corrections to Z & W

CERN-EP-2016-305



- *ATLAS* measurement of m_W
- SM prediction from global electroweak fit
- Combined values of m_W measured at *LEP & Tevatron* collider

- **Experiment**
  - *Direct:* ATLAS & CMS collaborations aim to reduce uncertainty on m_W below *10 MeV*

    ATL-PHYS-PUB-2018-026

  - *Indirect:* Match uncertainty obtained from precision electroweak fits *8 MeV* ⇨ *Gfitter, HEPfit & Δr* radiative corrections within SM to μ decay

    arXiv:1407.3792 [hep-ph], arXiv 1608.01509 [hep-ph]
    Awramik, Czakon, Freitas, Weiglein '04

- **Theory**
  - Fixed-order perturbation theory reach at most *~ 1%* uncertainties *@ N^3LO*
  - Not enough to much precision of *0.01%*
  - Cannot predict $p_T(e^+)$ & $M_T(W)$ to this precision

- **Instead**
  - Combine *W & Z* predictions ⇨ Correlations
  - Make use of available precision for m_Z from LEP

Mixed QCD-EW corrections to Z & W

- Initial-Initial corrections to on-shell *Z & W* production
- LO leptonic decays of *Z & W* in NWA
- Corrections small @ per mill level

Behring, Buccioni, Caola, Delto, Jaquier, Melnikov, Roentsch
arXiv:2005.10221 [hep-ph] & *arXiv:2009.10386 [hep-ph]* & *arXiv:2103.02671 [hep-ph]*

$$\sigma_{pp\to W^+} = \sigma_{\rm LO} + \Delta\sigma_{{\rm NLO},\alpha_s} + \Delta\sigma_{{\rm NLO},\alpha}, + \Delta\sigma_{{\rm NNLO},\alpha\alpha_s} + \ldots$$

σ[pb]	channel	$\mu = M_W$	$\mu = M_W/2$	$\mu = M_W/4$	
$\sigma_{\rm LO}$		6007.6	5195.0	4325.9	
$\Delta\sigma_{{\rm NLO},\alpha_s}$	all ch.	508.8	1137.0	1782.2	22%
	$q\bar{q}'$	1455.2	1126.7	839.2	
	qg/gq	-946.4	10.3	943.0	
$\Delta\sigma_{{\rm NLO},\alpha}$	all ch.	2.1	-1.0	-2.6	0.02%
	$q\bar{q}'$	-2.2	-5.2	-6.7	
	$q\gamma/\gamma q$	4.2	4.2	4.04	
$\Delta\sigma_{{\rm NNLO},\alpha_s\alpha}$	all ch.	-2.4	-2.3	-2.8	0.04%
	$q\bar{q}'/qq'$	-1.0	-1.2	-1.0	
	qg/gq	-1.4	-1.2	-2.1	
	$q\gamma/\gamma q$	0.06	0.03	-0.04	
	$g\gamma/\gamma g$	-0.12	0.04	0.30	

$$pp \to W^+ + X \to e^+\nu_e + X \text{ @ 13 TeV}$$

- Estimate Impact on m_W measurement ⇨ $\langle p_T(e^+) \rangle$

$\sim m_W$ LHC

$$m_W^{\rm meas} = \frac{\langle p_\perp^{l,W}\rangle^{\rm meas}}{\langle p_\perp^{l,Z}\rangle^{\rm meas}}\, m_Z\, C_{\rm th}$$

$\sim m_Z$ LHC

LEP
δm_Z = 2.1 MeV

- Theoretical correction factor

$$C_{\rm th} = \frac{m_W}{m_Z}\frac{\langle p_\perp^{l,Z}\rangle^{\rm th}}{\langle p_\perp^{l,W}\rangle^{\rm th}}$$

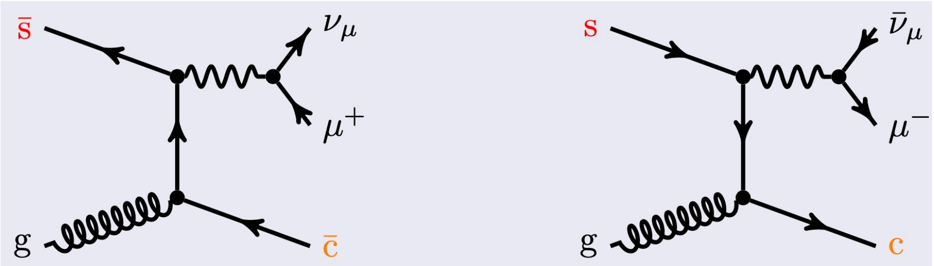
- Adding new correction to theory changes both
  - C_{th} & m_W

$$\frac{\delta m_W^{\rm meas}}{m_W^{\rm meas}} = \frac{\delta C_{\rm th}}{C_{\rm th}} = \frac{\delta\langle p_\perp^{l,Z}\rangle^{\rm th}}{\langle p_\perp^{l,Z}\rangle^{\rm th}} - \frac{\delta\langle p_\perp^{l,W}\rangle^{\rm th}}{\langle p_\perp^{l,W}\rangle^{\rm th}}$$

$$\delta m_W^{\rm QCD-EW} = -7\,{\rm MeV} \qquad \delta m_W^{\rm EW} = +1\,{\rm MeV}$$

NNLO QCD for W+c jet Production @ LHC

$pp \to \mu^- \bar{\nu}_\mu \, j_c + X$ & $pp \to \mu^+ \nu_\mu \, j_c + X$



- Direct link between *W+c* measurements & strange PDF
- Precision test of (perturbative) QCD
- Study of flavour jets

$pp \to W^+ j_c$

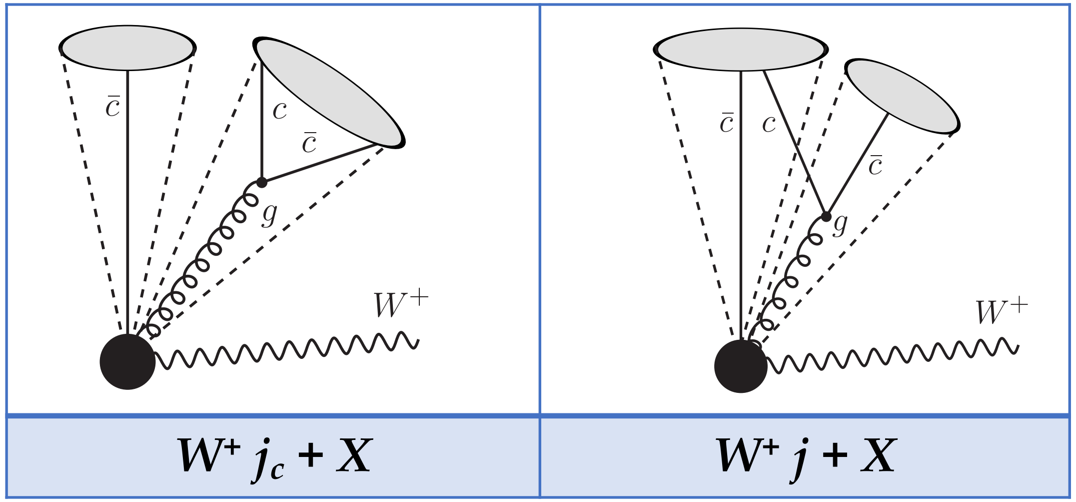
Contribution	LO	NLO	NNLO
$\bar{s}g$	✓	✓	✓
sg	X	X	✓
$s\bar{s}$	X	✓	✓
$\bar{s}\bar{s}$	X	✓	✓
$\bar{s}q$	X	✓	✓
qq'	X	✓	✓
gq	X	X	✓
gg	X	✓	✓

$pp \to W^- j_c$

Contribution	LO	NLO	NNLO
$\bar{s}g$	X	X	✓
sg	✓	✓	✓
$s\bar{s}$	X	✓	✓
ss	X	✓	✓
sq	X	✓	✓
qq'	X	✓	✓
gq	X	X	✓
gg	X	✓	✓

List of initial-state contributions

Czakon, Mitov, Pellen, Poncelet arXiv:2011.01011 [hep-ph]



Large-angle soft gluon splitting to large-angle soft cc pair
cc clustered into different jets ⇨ *incorrect jet flavour assignment*

- @ NLO flavour criterion of pseudo-jet ensures that collinear splitting $g \to c\bar{c}$ is gluon (flavourless) jet
- *IR-safety* would be spoiled without this criterion
- @ NNLO flavour-dependent distance measure is needed
- *Flavour-kt algorithm* ⇨ Soft flavoured quarks recombined first to give gluon-like pseudo-jet

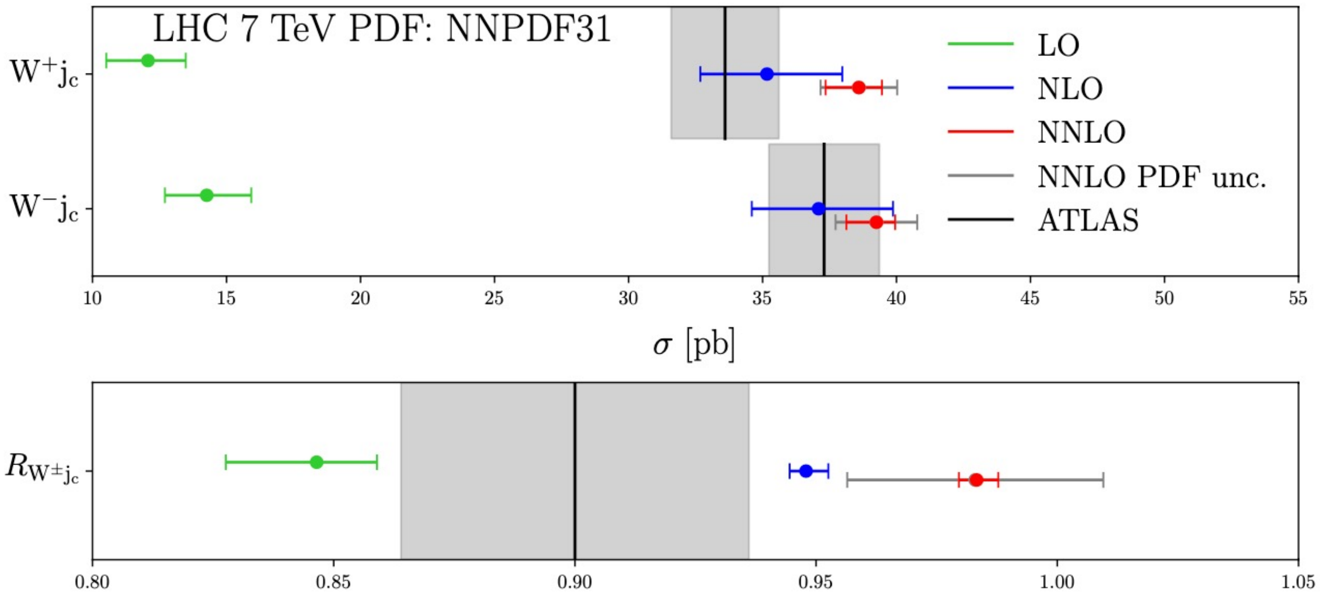
Banfi, Salam, Zanderighi arXiv:hep-ph/0601139

NNLO QCD for W+c jet Production @ LHC

Czakon, Mitov, Pellen, Poncelet arXiv:2011.01011 [hep-ph]

- Fiducial cross sections for *$pp \to W^+j_c$ & $pp \to W^-j_c$*
- Ratios @ LHC *$\sqrt{s}$ = 7 TeV*

Order	$\sigma_{W^+j_c}$ [pb]	$\sigma_{W^-j_c}$ [pb]	$R_{W^\pm j_c} = \sigma_{W^+j_c}/\sigma_{W^-j_c}$
LO	$12.0725(4)^{+11.6\%}_{-12.9\%}$	$14.2624(5)^{+11.6\%}_{-10.9\%}$	$0.84646(4)^{+1.48\%}_{-2.22\%}$
NLO	$35.164(9)^{+8.0\%}_{-7.0\%}$	$37.096(9)^{+7.5\%}_{-6.7\%}$	$0.9479(3)^{+0.49\%}_{-0.36\%}$
NNLO	$38.6(1)^{+2.2\%\ +3.8\%(\mathrm{PDF})}_{-3.2\%\ -3.8\%(\mathrm{PDF})}$	$39.3(1)^{+1.8\%\ +3.9\%(\mathrm{PDF})}_{-2.9\%\ -3.9\%(\mathrm{PDF})}$	$0.983(5)^{+0.45\%\ +2.7\%(\mathrm{PDF})}_{-0.37\%\ -2.7\%(\mathrm{PDF})}$



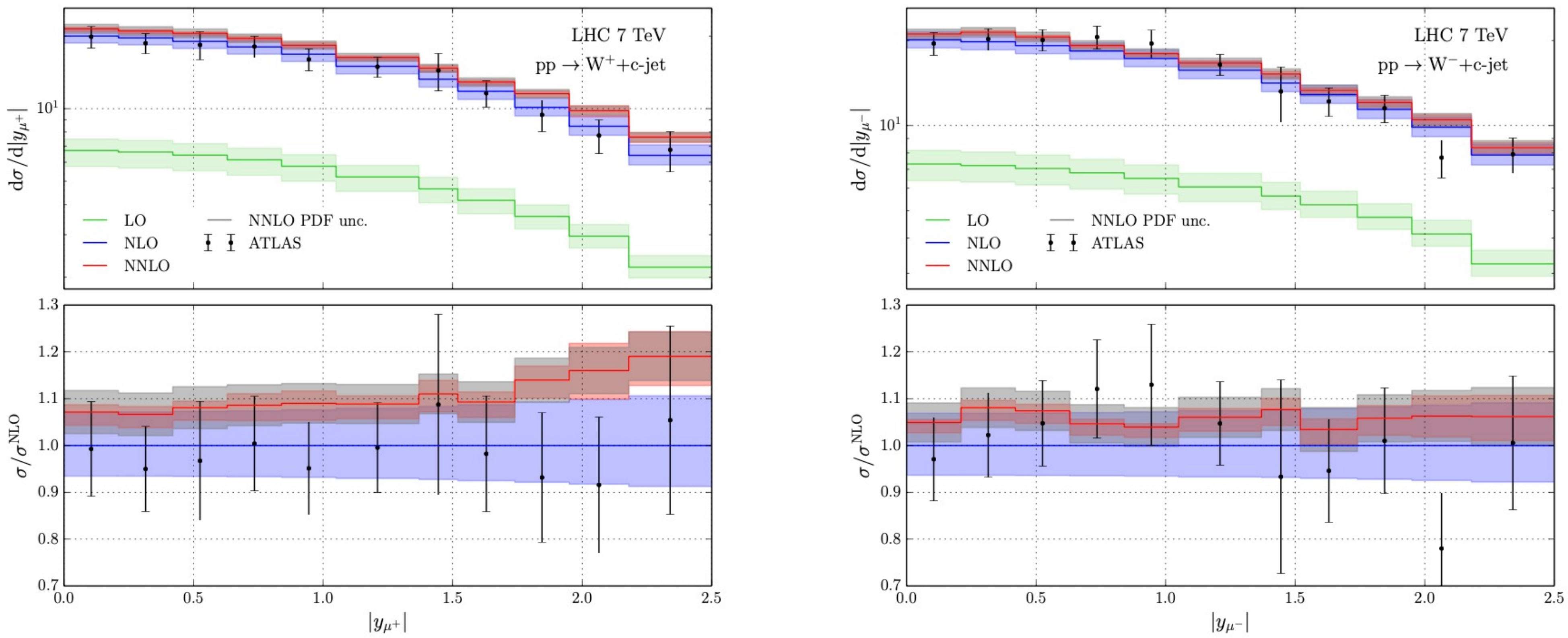
- NLO QCD ⇨ ***160%-200%*** ⇨ Giant ***K-factors*** due to di-jet topologies with soft-collinear ***W*** radiation
- NNLO QCD corrections ⇨ ***6%-10%***
- $R_{W^\pm j_c}$ ⇨ Scales uncertainties taken as correlated
- NNLO δ_{scale} ⇨ ***3%*** for σ & ***0.5%*** for R
- NNLO δ_{PDF} ⇨ ***4%*** for σ & ***3%*** for R

$\sigma^{\mathrm{ATLAS}}_{W^+j_c} = 33.6 \pm 0.9\ (\mathrm{stat}) \pm 1.8\ (\mathrm{syst})$ pb
$\sigma^{\mathrm{ATLAS}}_{W^-j_c} = 37.3 \pm 0.8\ (\mathrm{stat}) \pm 1.9\ (\mathrm{syst})$ pb
$R^{\mathrm{ATLAS}}_{W^\pm j_c} = 0.90 \pm 0.03\ (\mathrm{stat}) \pm 0.02\ (\mathrm{syst})$

ATLAS arXiv:1402.6263 [hep-ex]

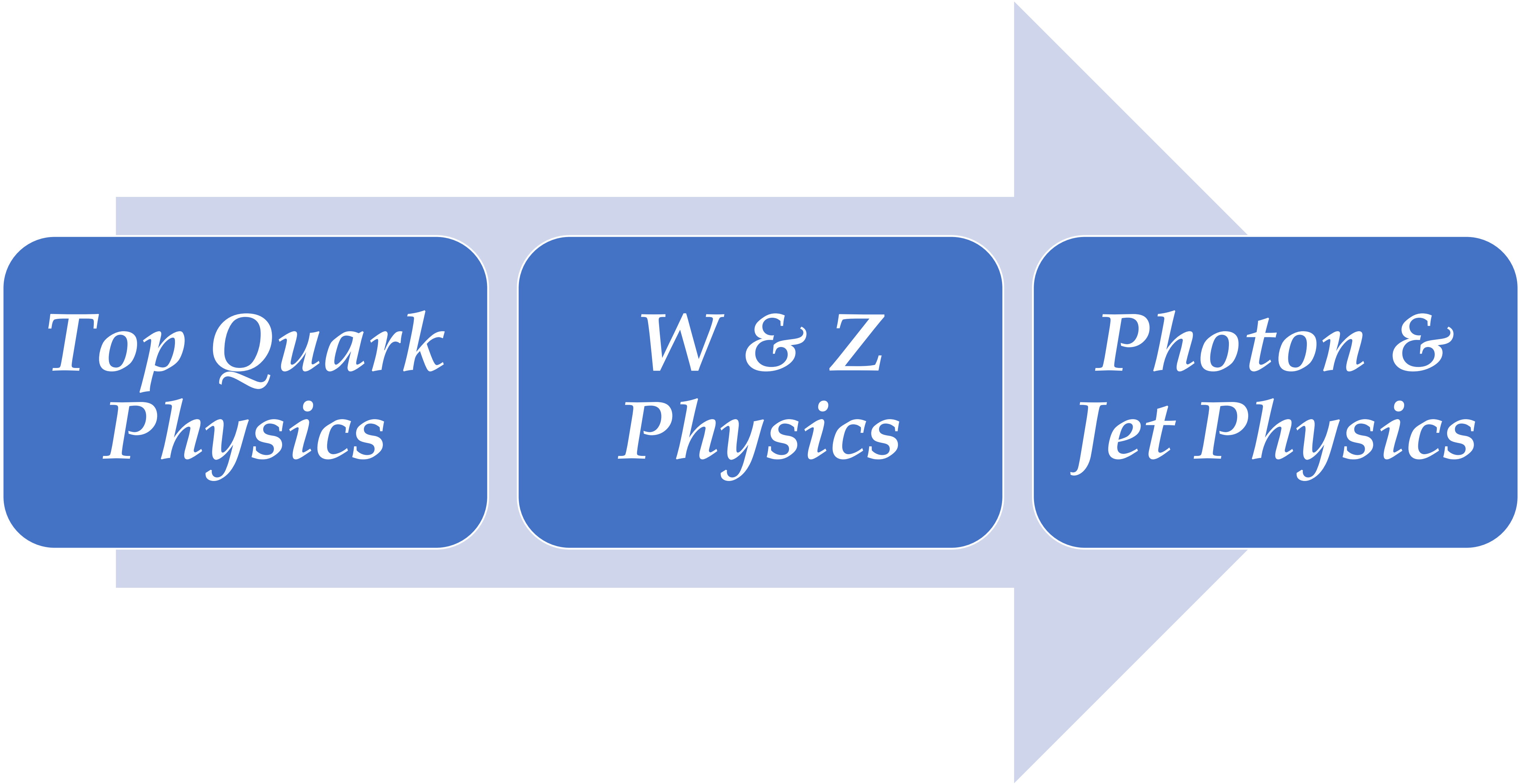
NNLO QCD for W+c jet Production @ LHC

Czakon, Mitov, Pellen, Poncelet *arXiv:2011.01011 [hep-ph]*



ATLAS arXiv:1402.6263 [hep-ex]
HEPData

- Rather good agreement ⇨ Data seem to be systematically lower than NNLO QCD predictions for $W^+ j_c$
  - *Differences in jet algorithm ⇨ Part of definition of observable*
- Grey band represents PDF uncertainties @ NNLO
- Further studies & comparisons with ATLAS & CMS data will follow

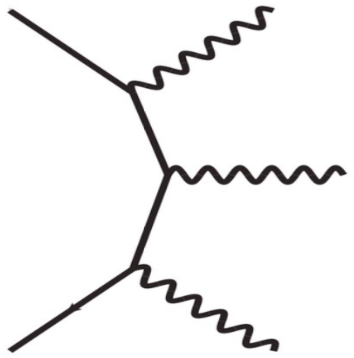

Top Quark Physics
W & Z Physics
Photon & Jet Physics

NNLO QCD for $\gamma\gamma\gamma$ @ LHC

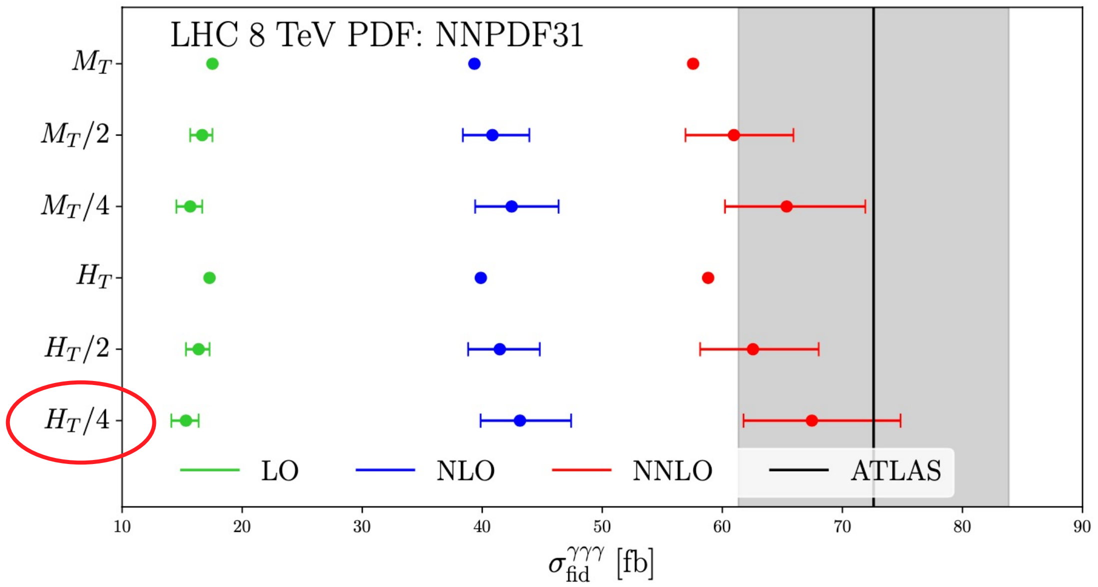
Chawdhry, Czakon, Mitov, Poncelet
arXiv:1911.00479 [hep-ph] & arXiv:2012.13553 [hep-ph]

- ***First NNLO QCD calculation for 2 → 3 process***
- Simplest among the 2 → 3 massless cases: colour singlet

- 2-loop in leading colour approximation
- $\gamma\gamma\gamma$ ⇨ Measured @ LHC   *ATLAS CERN-EP-2017-302*



- Significantly above NLO QCD prediction in wide kinematic region
- NLO theory error is completely dominated by missing higher-orders
- Large NNLO/NLO K-factors ⇨ NNLO QCD corrections essential for theory/data comparison



- Large shifts from LO to NLO & from NLO to NNLO
- Much larger than scale variations @ LO & NLO
- *NLO/LO* correction of about ***2.8***
- *NNLO/NLO* correction about ***1.6***

$$\sigma_{\text{fid}}(\text{ATLAS}) = 72.6 \pm 6.5(\text{stat.}) \pm 9.2(\text{syst.})\ \text{fb}$$

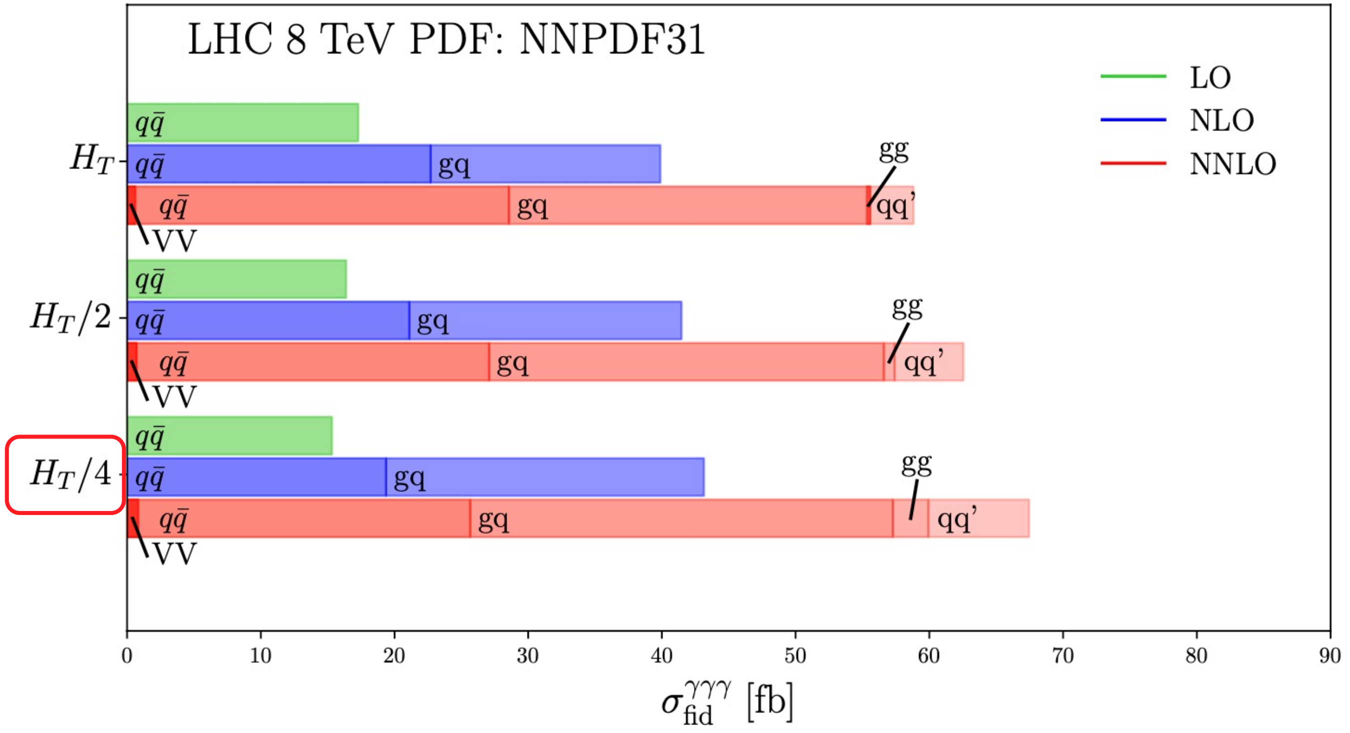
$$\sigma_{\text{fid}}(\text{NNLO QCD};\ H_T/4) = 67.5^{+7.4\ (11\%)}_{-5.7\ (8\%)}\ (\text{scales})\ \text{fb}$$

- ***NNLO QCD correction plays crucial role***

NNLO QCD for $\gamma\gamma\gamma$ @ LHC

Chawdhry, Czakon, Mitov, Poncelet
arXiv:1911.00479 [hep-ph] & arXiv:2012.13553 [hep-ph]

qg has dominant impact on large K-factors



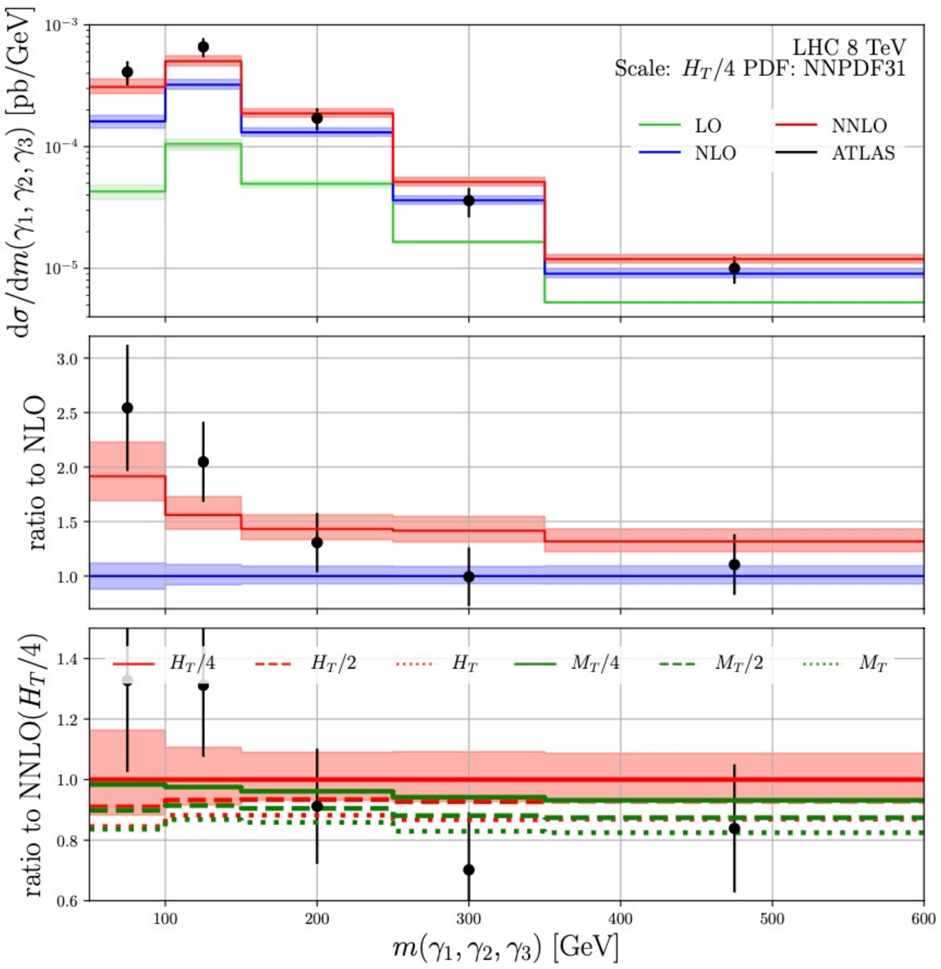
- Anatomy of higher-order corrections to $\gamma\gamma\gamma$ fiducial cross-section @ *LO* & *NLO* & *NNLO* by partonic channels
- *VV* ⇨ Double virtual scale-independent part of two-loop with leading colour

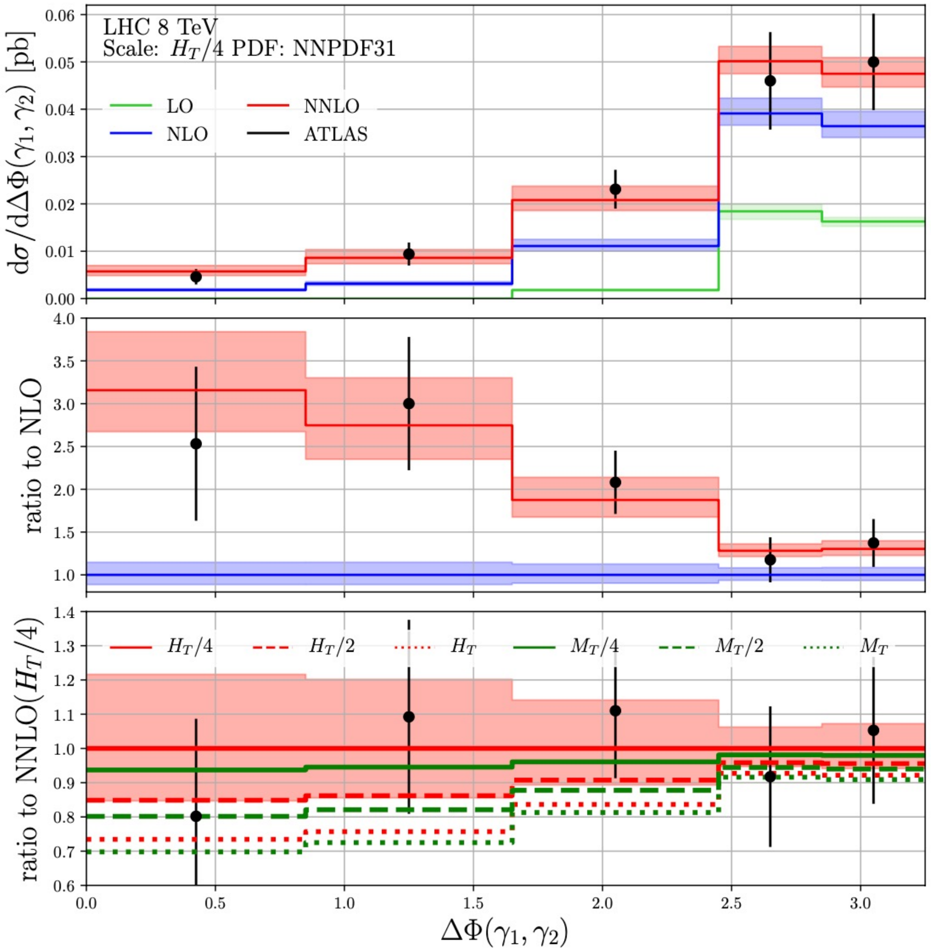
Large K-factors

- *qq* ⇨ Significant yet moderate correction @ NLO & NNLO
- *gg & qq′* ⇨ Effects is marginal ⇨ *Few %*
- Loop-induced amplitude $gg \to \gamma\gamma\gamma$ vanishes due charge conjugation ⇨ *Furry's theorem*
- *qg* ⇨ Opens up only @ NLO (LO-like) ⇨ Large corrections @ NNLO (NLO-like)
- *NNLO first order with all partonic reactions*
- *N³LO should show more convergent behaviour* ⇨ Scale variation should start to decrease

NNLO QCD for $\gamma\gamma\gamma$ @ LHC

Chawdhry, Czakon, Mitov, Poncelet
arXiv:1911.00479 [hep-ph] & arXiv:2012.13553 [hep-ph]



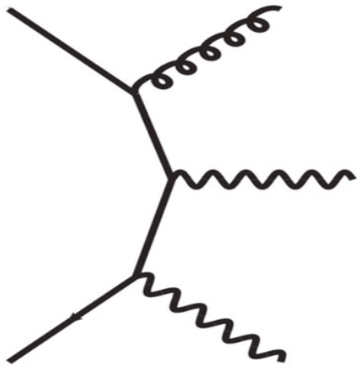


- Corrections to shape & normalization
- Typical for colour singlets: Scale uncertainty stays large

NNLO QCD for $\gamma\gamma$j @ LHC

Chawdhry, Czakon, Mitov, Poncelet
arXiv:2103.04319 [hep-ph] & *arXiv:2105.06940 [hep-ph]*

- Main background to cleanest Higgs boson decay $H \to \gamma\gamma$
- Higgs production @ high p_T & Higgs couplings & Angular diphoton observables important for spin measurements
- *Feature* ⇨ Very large higher-order QCD corrections ⇨ Reliability of higher-order predictions is in question
- N^3LO $\gamma\gamma$ ⇨ Ingredients: amplitudes for *$\gamma\gamma$ @ 3-loop* + *$\gamma\gamma j$ @ NNLO* — *Caola, Manteuffel, Tancredi arXiv:2011.13946 [hep-ph]*
- $p_T(\gamma\gamma)$ in $pp \to \gamma\gamma + X$ ⇨ @ LO $p_T(\gamma\gamma) = 0$
- $pp \to \gamma\gamma + X$ @ NNLO ⇨ NLO accuracy for $p_T(\gamma\gamma) > 0$
- NNLO accuracy for $p_T(\gamma\gamma)$ @ nonzero $p_T(\gamma\gamma)$ ⇨ NNLO QCD corrections for $pp \to \gamma\gamma j + X$



- First NNLO calculation for $pp \to \gamma\gamma j + X$
- 2-loop amplitude in leading colour approximation ⇨ *1% - 2%* contribution
- Loop-induced contribution $gg \to g\gamma\gamma$ included & Contributes @ NNLO ⇨ *5%*

$$\mu_F^2 = \mu_R^2 = \frac{1}{4}\left(m^2(\gamma\gamma) + p_T(\gamma\gamma)^2\right)$$

NNLO QCD for $\gamma\gamma j$ @ LHC

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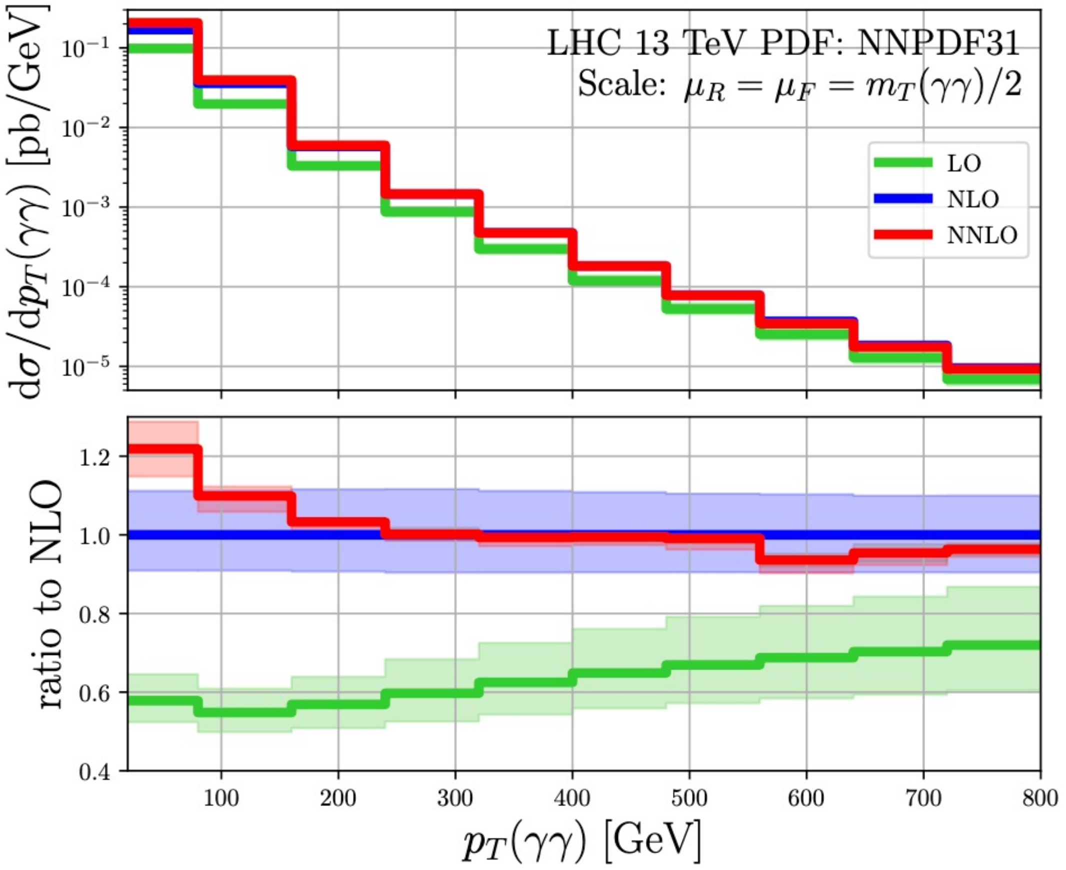
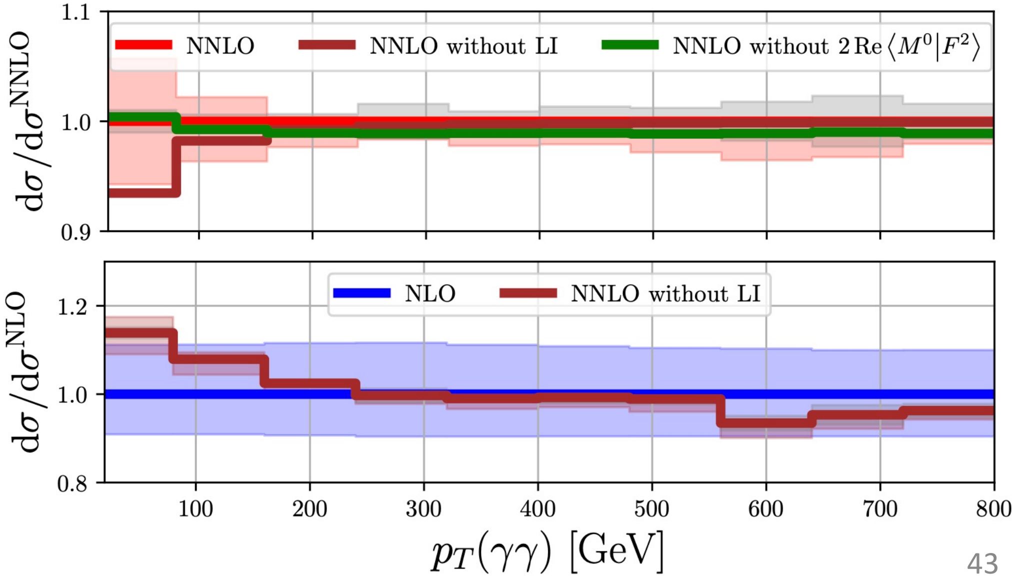


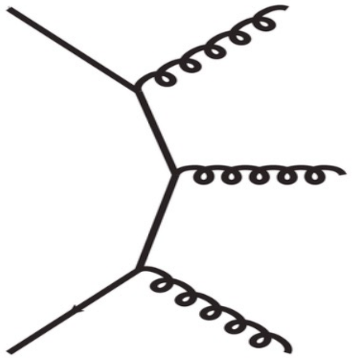
- Absolute $p_T(\gamma\gamma)$ differential distribution
- Predictions in *LO* & *NLO* & *NNLO*

- Scale dependence:
  - *NLO: ~10%* & *NNLO: ~1-2%*
- *Low p_T region ⇨ $p_T(\gamma\gamma)$ < 100 GeV*
  - Increased scale dependence & Larger *K= NNLO/NLO*
  - Strong effect from LI contribution $gg \to g\gamma\gamma$
  - NLO QCD corrections to LI contribution needed
    - 2-loop amplitude for $gg \to g\gamma\gamma$
- Small contribution from 2-loop finite remainder
- Sub-leading colour corrections should not be important



NNLO QCD for jjj @ LHC

Czakon, Mitov, Poncelet
RADCOR & LoopFest 2021



- Multi-jet rates provide an unique possibility to test QCD
- Measurements of α_s from jet ratios $\sim\alpha_s$
- Test of α_s running
- Multi-jet signatures backgrounds for many LHC signatures
- Allow to probe broad ranges of energy scales for heavy new physics
- Large cross sections
- Large statistics ⇨ In practice only limited by systematics

- ***NNLO QCD tri-jet production:***
  - Bottleneck double virtual amplitudes
  - Recently published in leading colour approximation

    Abreu, Febres Cordero, Ita, Page, Sotnikov
    arXiv:2102.13609 [hep-ph]

  - Handling of real radiation

    Czakon, Heymes
    arXiv:1005.0274 [hep-ph]
    arXiv:1101.0642 [hep-ph]
    arXiv:1408.2500 [hep-ph]

NNLO QCD for jjj @ LHC

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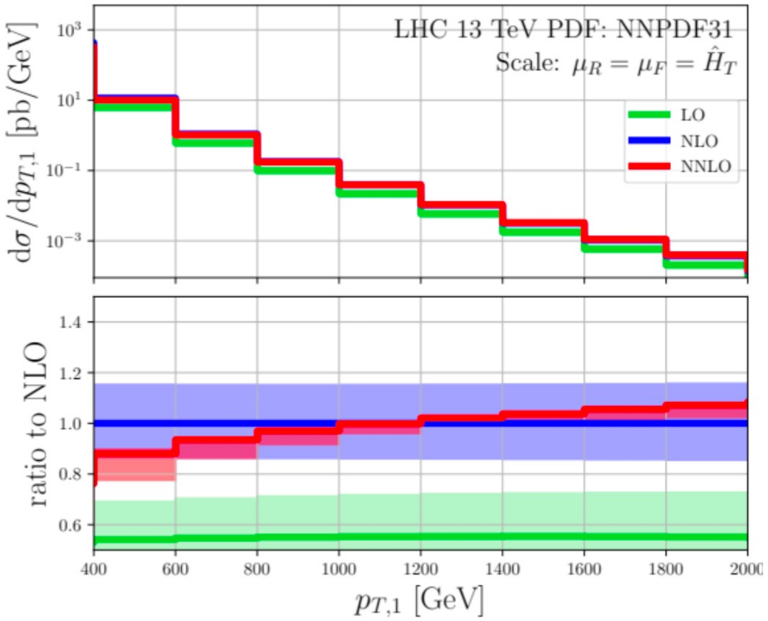
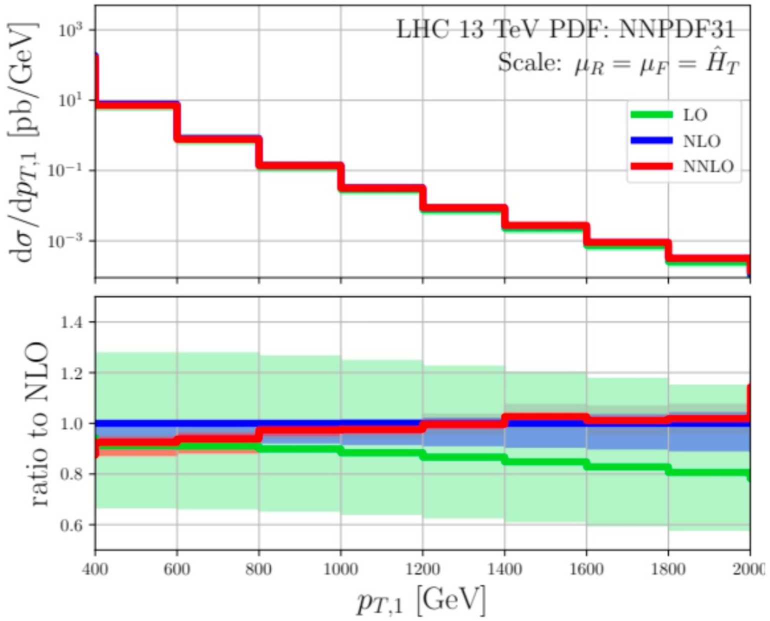
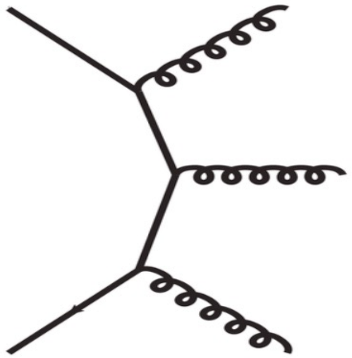
RADCOR & LoopFest 2021

Two Jets

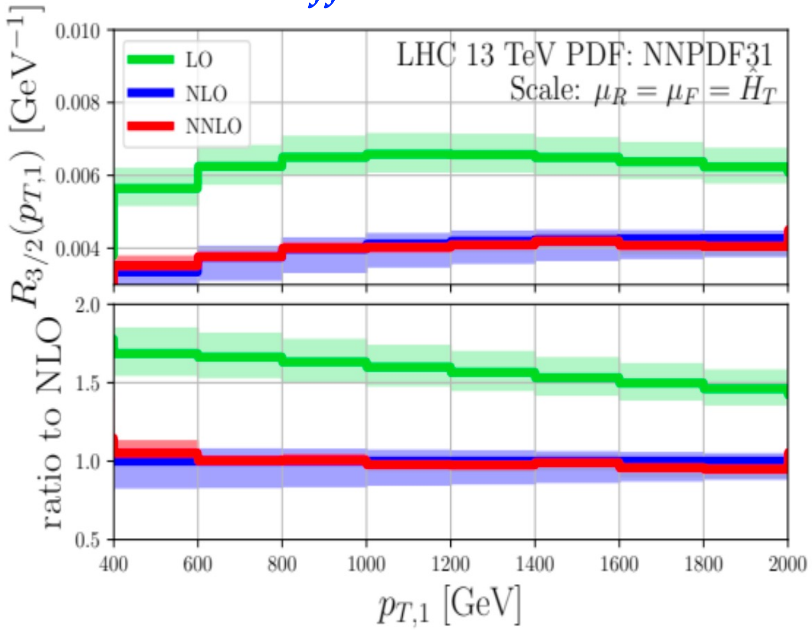


Three Jets





Differential ratio



- Hardest p_T in *jj & jjj* @ LHC
- All partonic subprocesses already present @ LO
- Nice convergence of perturbative expansion in α_s
- ***Paper in preparation***

Take-Home Message

- Huge amount of new high precision theoretical results !

- *State-of-the-art:*
  - *N³LO* $2 \to 1$
  - *NNLO* $2 \to 2$ & $2 \to 3$
  - *NLO* $2 \to 5$ & $2 \to 6$ with full off-shell effects

- *Proper modelling of production & decay essential already now in presence of inclusive cuts*
  - Corrections to production & decays important ⇨ *At least full NWA*
  - NLO *tt* spin correlations
  - Possibility of using kinematic-dependent μ_R & μ_F scales
  - Complete off-shell effects for *top quarks & W/Z* gauge bosons

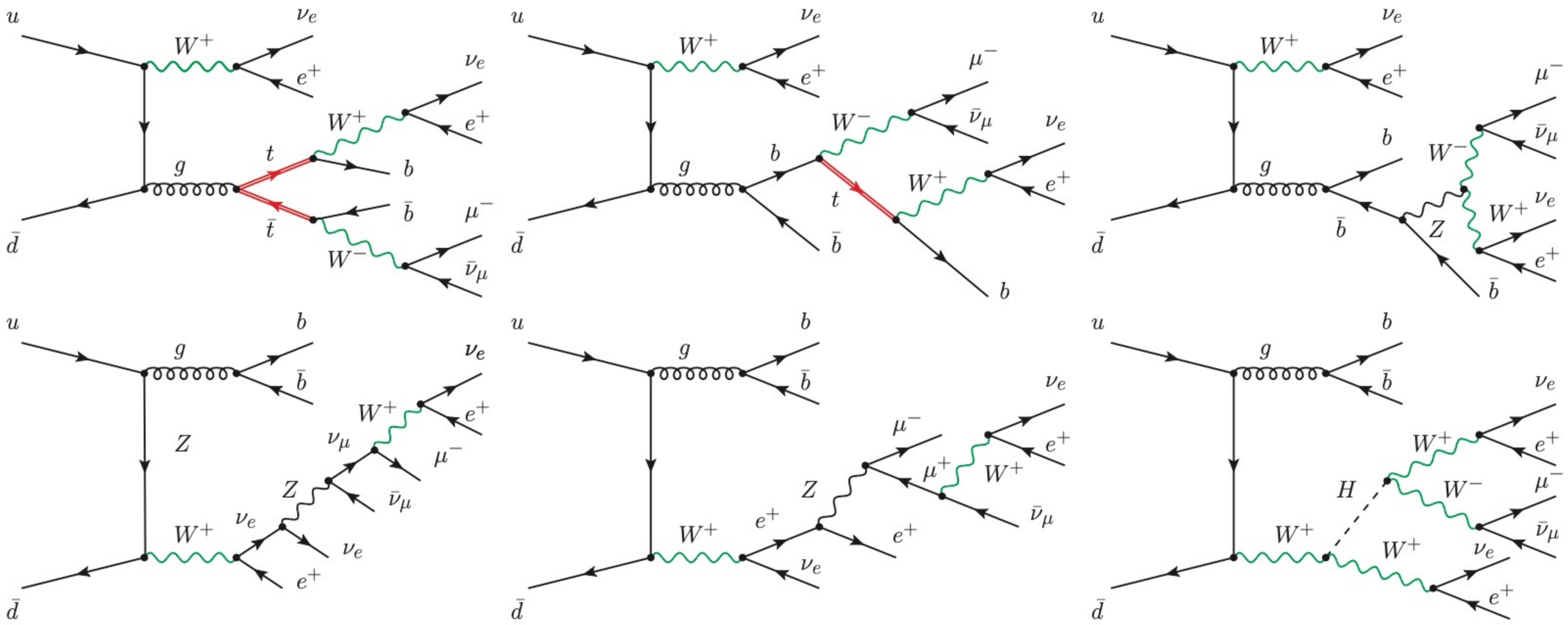
- *Even more important for:*
  - Exclusive cuts & High luminosity measurements
  - New Physics searches & Might impact exclusion limits
  - SM parameter extraction

Lots of data, sophisticated analyses, precision measurements
Should be compared to state-of-the-art theoretical predictions

Backup

TTW

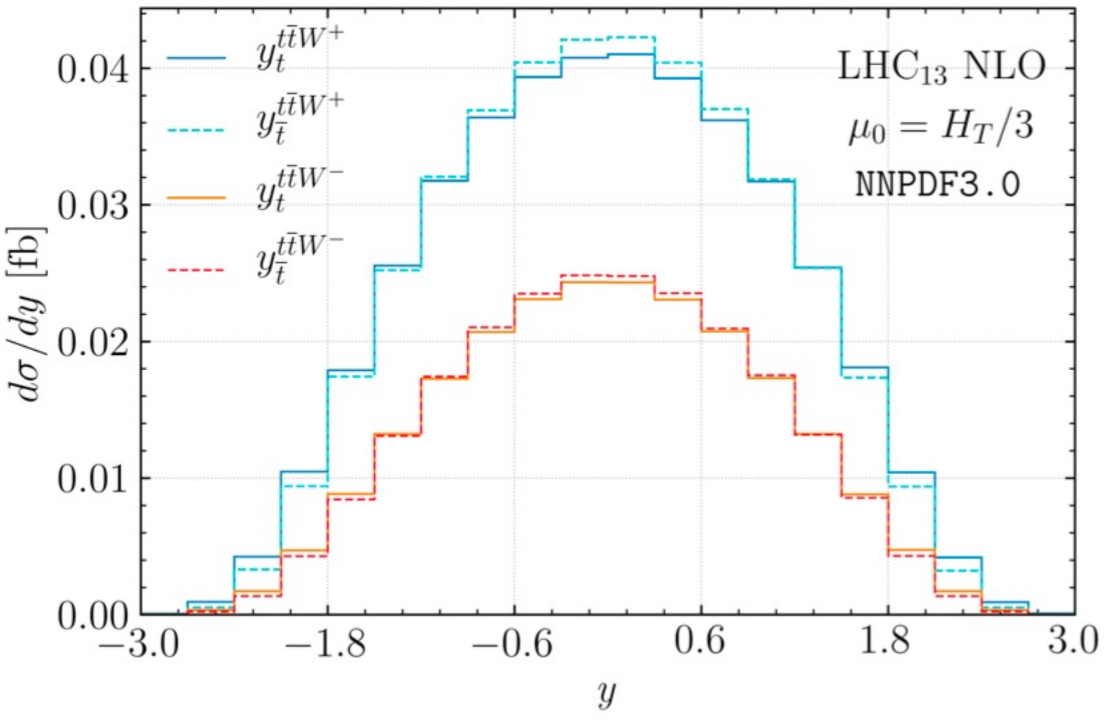
Bevilacqua, Bi, Hartanto, Kraus, Worek
arXiv:2005.09427 [hep-ph]

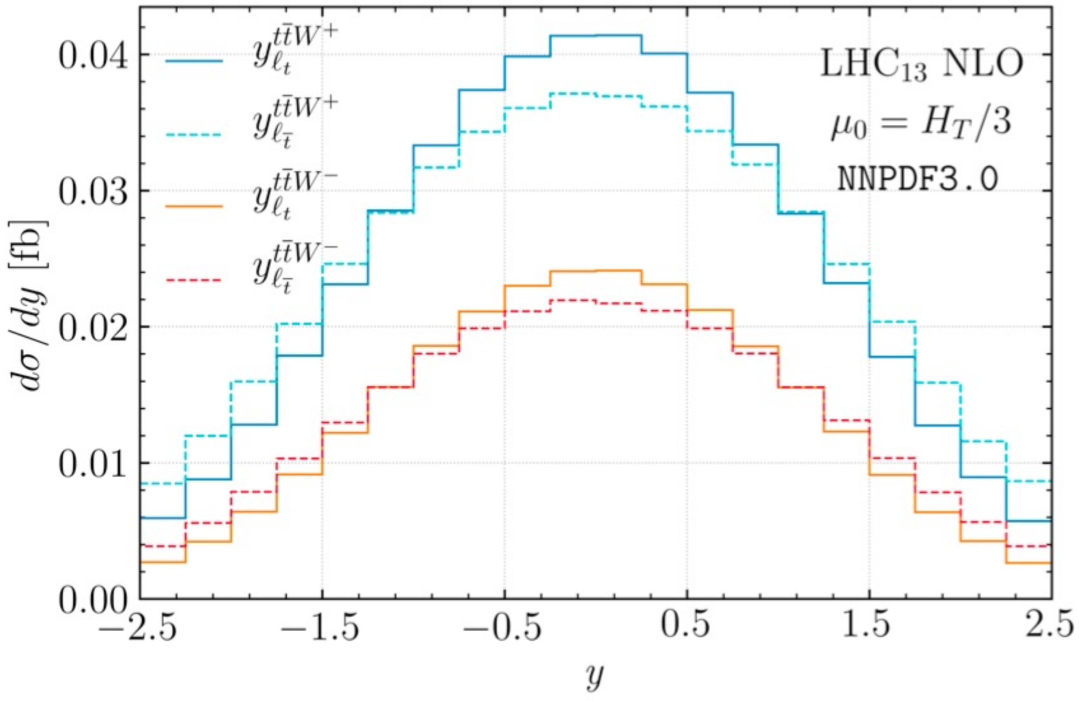


$$pp \to e^+\nu_e\,\mu^-\,\bar{\nu}_\mu\,e^+\nu_e\,b\bar{b} + X$$

TTW

Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek
arXiv:2012.01363 [hep-ph]



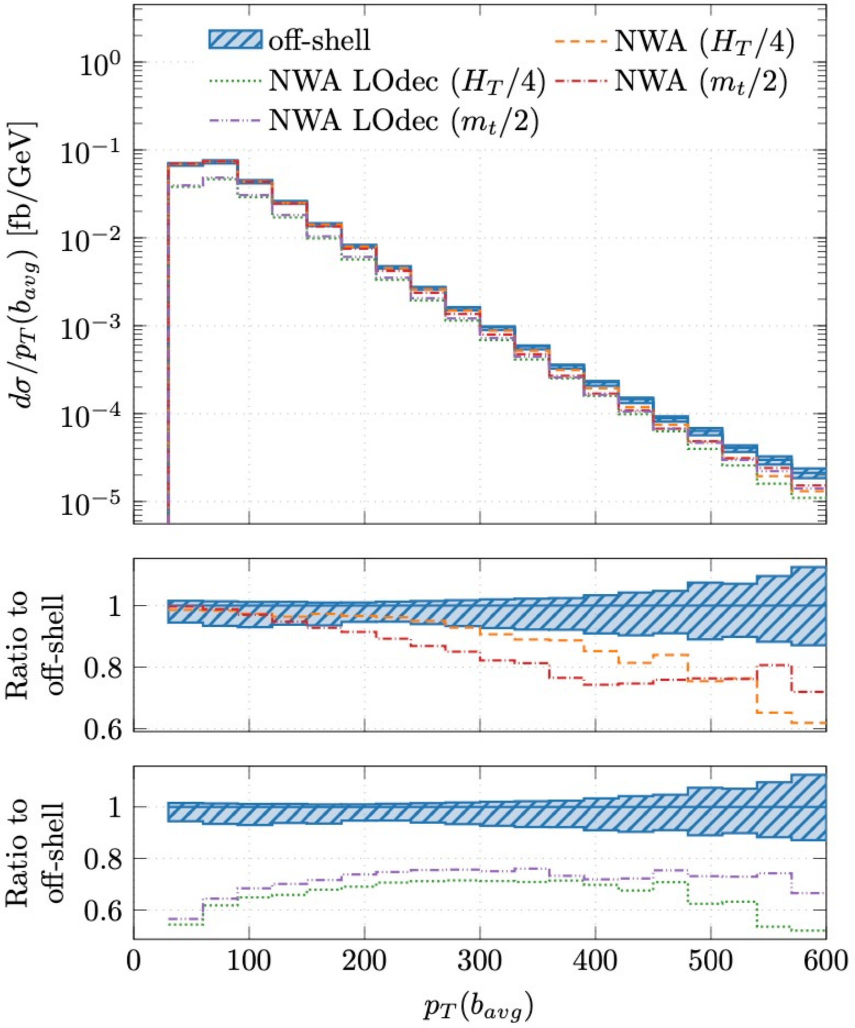


$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

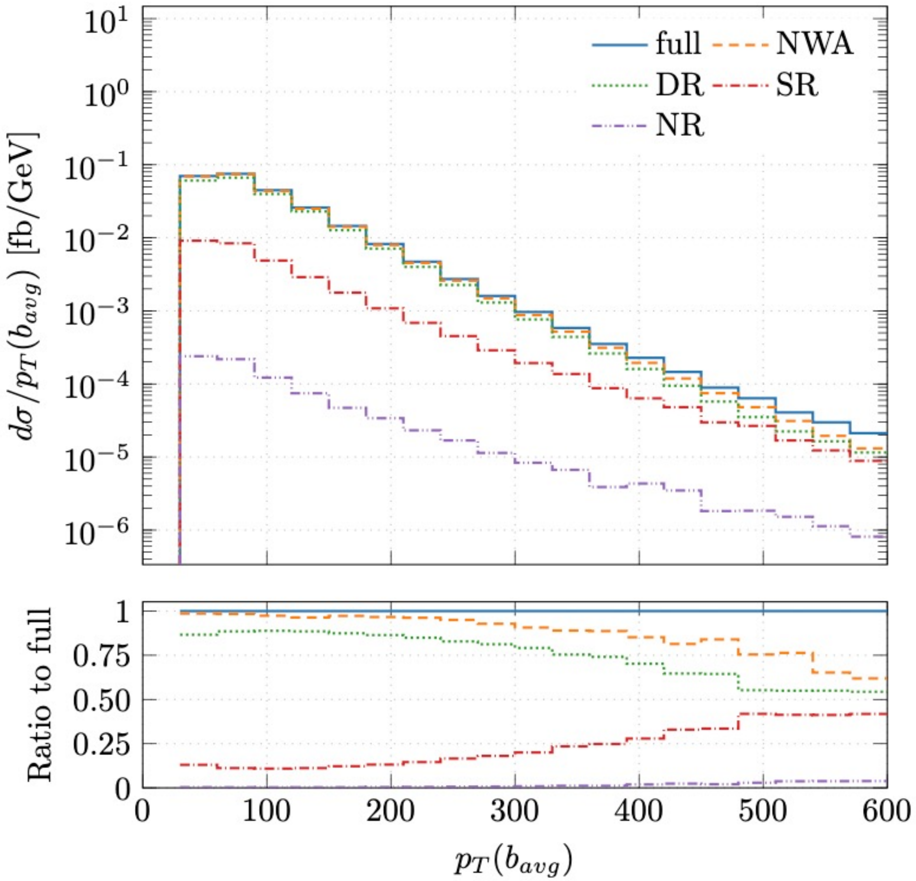
$$pp \to e^+\nu_e\, \mu^-\, \bar{\nu}_\mu\, e^+\nu_e\, b\bar{b} + X$$

TTγ

Bevilacqua, Hartanto, Kraus, Weber, Worek
arXiv:1912.09999 [hep-ph]



$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\gamma\,+X$



TTγ

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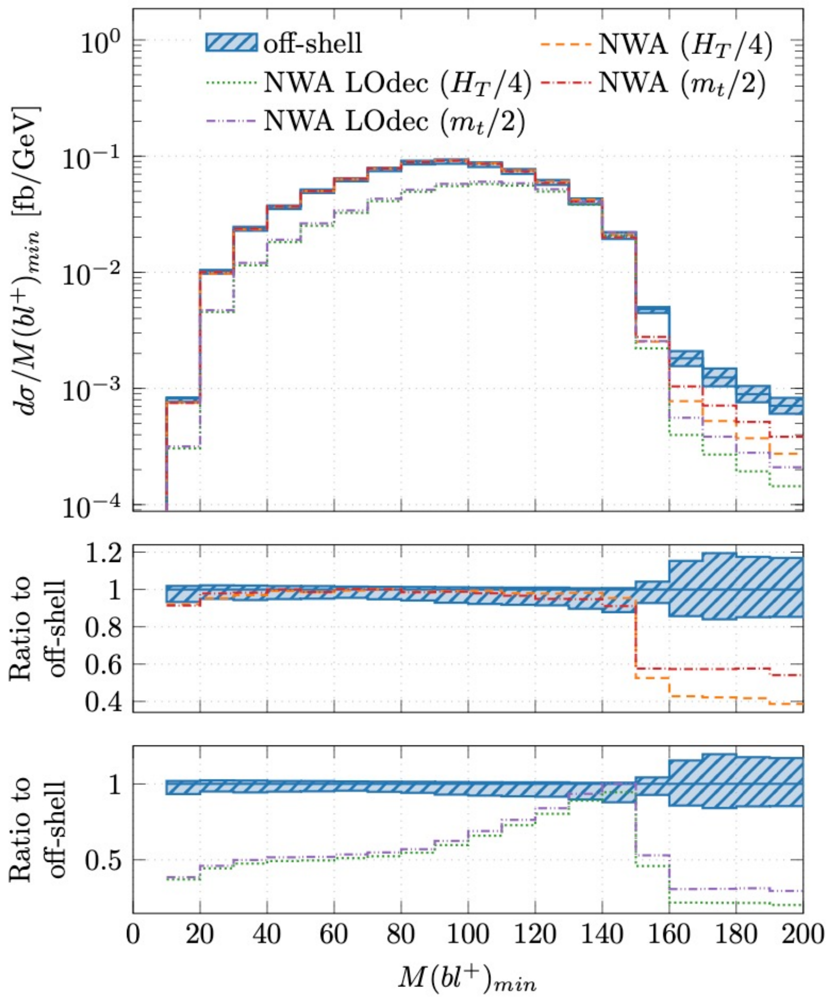
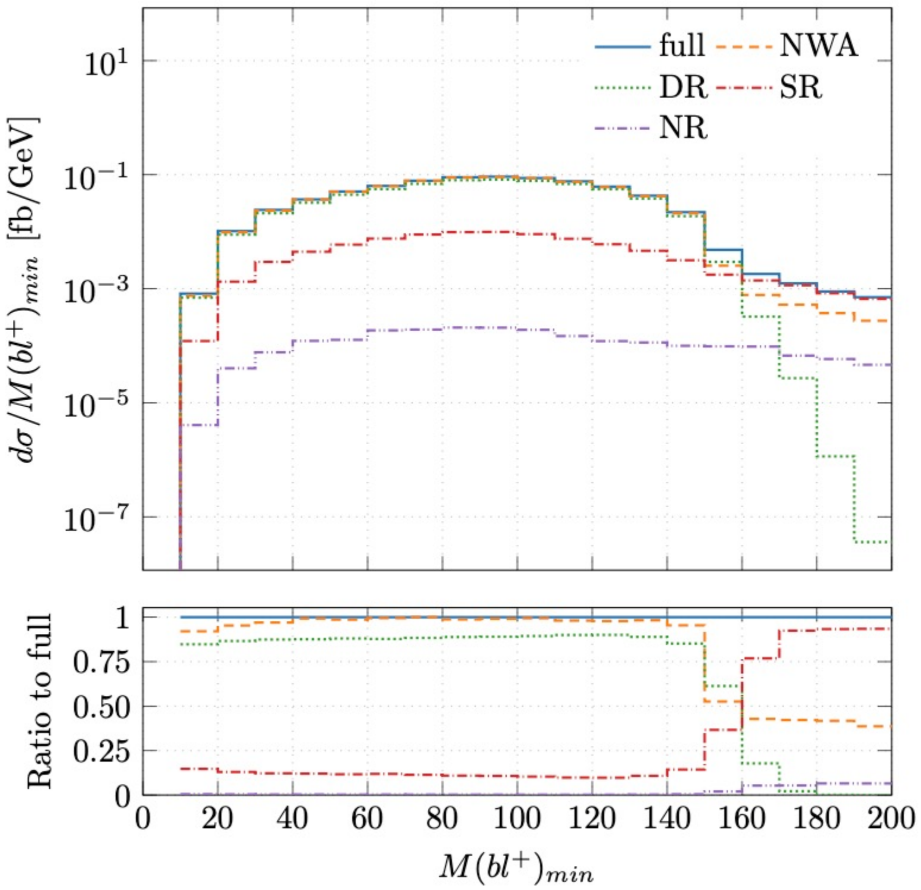


$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\gamma\ + X$



TTγ

Bevilacqua, Hartanto, Kraus, Weber, Worek
arXiv:1912.09999 [hep-ph]

$$pp \to e^+\nu_e\, \mu^-\bar{\nu}_\mu\, b\bar{b}\,\gamma\; + X$$

3 @ LO & 9 @ NLO different possibilities

$$Q = |M(t) - m_t| + |M(\bar{t}) - m_t|$$

(i) $t = W^+(\to e^+\nu_e)\, b$ and $\bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\, \bar{b}\,,$

(ii) $t = W^+(\to e^+\nu_e)\, b\gamma$ and $\bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\, \bar{b}\,,$

(iii) $t = W^+(\to e^+\nu_e)\, b$ and $\bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\, \bar{b}\gamma$

Double-resonant (DR) region

$|M(t) - m_t| < n\,\Gamma_t\,,$ and $|M(\bar{t}) - m_t| < n\,\Gamma_t$

Single-resonant (SR) regions

$|M(t) - m_t| < n\,\Gamma_t\,,$ and $|M(\bar{t}) - m_t| > n\,\Gamma_t$

or

$|M(t) - m_t| > n\,\Gamma_t\,,$ and $|M(\bar{t}) - m_t| < n\,\Gamma_t$

Non-resonant (NR) region

$|M(t) - m_t| > n\,\Gamma_t\,,$ and $|M(\bar{t}) - m_t| > n\,\Gamma_t$

Boundary parameter

- n = 5, 10, 15
- For n = 15

$$M(t) \in (152.9, 193.5)\ \text{GeV}$$