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Off-shell Top Quarks with One Jet at the LHC

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Seminar for Theory of Elementary Interactions, University of Warsaw, 13 March 2017

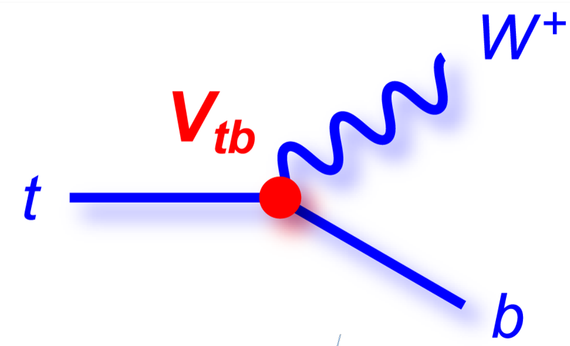
Plan

1. Motivation for Top Quark Physics
2. Top-quark off-shell effects
3. Status of theoretical predictions for ttj
4. Top-quark off-shell effects for ttj with **HELAC–NLO**
5. Results in dilepton channel @ LHC Run 2
6. Summary & Outlook

Collaborators:

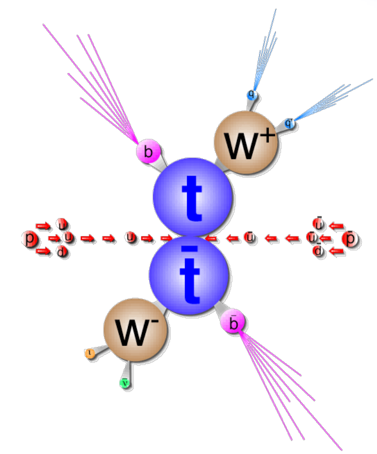
G. Bevilacqua (University of Debrecen)
H. B. Hartanto (University of Durham)
M. Kraus (Humboldt-Universität zu Berlin)

Top-Quark Physics



- Huge progress on the theoretical side:
  - ❑ NNLO+NNLL for **σ (tt) with on-shell top-quarks**
  - ❑ NNLO for differential cross sections **dσ (tt) /dX**

M. Czakon, P. Fiedler, A. Mitov '13
M. Czakon, D. Heymes, A. Mitov '16



- Why the top quark is interesting ?
  - ❖ Infrared structure of QCD
  - ❖ Extract parameters of the SM: α_s & m_t
  - ❖ Constraints on the large-x gluon PDF

M. Czakon, M. L. Mangano, A. Mitov, J. Rojo '13
M. Czakon, N. P. Hartland, A. Mitov, E. R. Nocera, J. Rojo '16

  - ❖ Background process to various SM & BSM physics

LHC Top-Quark Factory

LHC Run 1

LHC	σ(tt) [pb]	L [fb^{-1}]	N_{event}
7 TeV	172.676	5	8.6 x 10^5
8 TeV	246.652	19.7	4.8 x 10^6
13 TeV	807.296	2.3	1.8 x 10^6

LHC Run 2

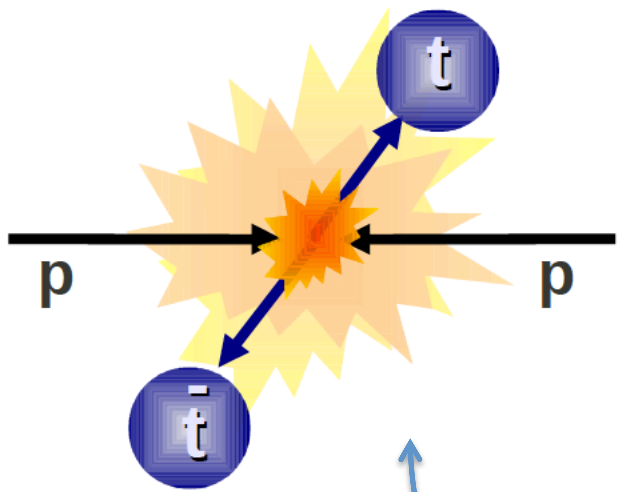
LHC Run 2

LHC	σ (tt) [pb]	L [fb^{-1}]	N_{event}
13 TeV	807.296	100	8.1 x 10^7
13 TeV	807.296	300	2.4 x 10^8

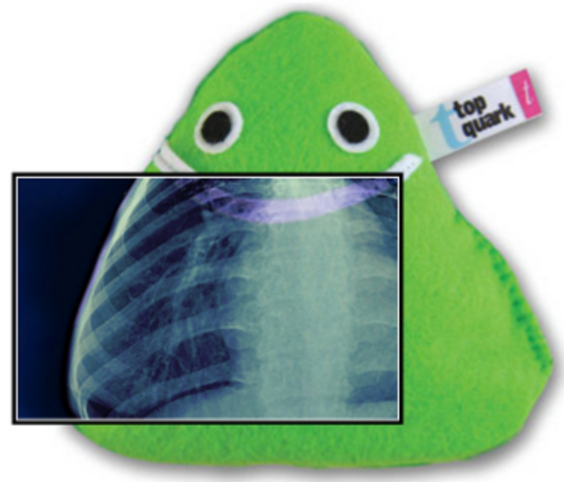
$$m_t = 173.2 \text{ GeV}$$

TOP++ with CT14 NNLO PDF set

M. Czakon, A. Mitov '14

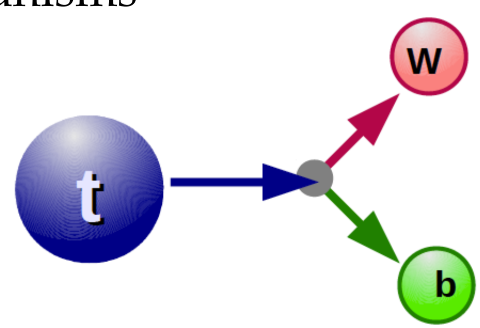


Intrinsic properties:
- Top quark mass
- Charge
- Lifetime
- Width

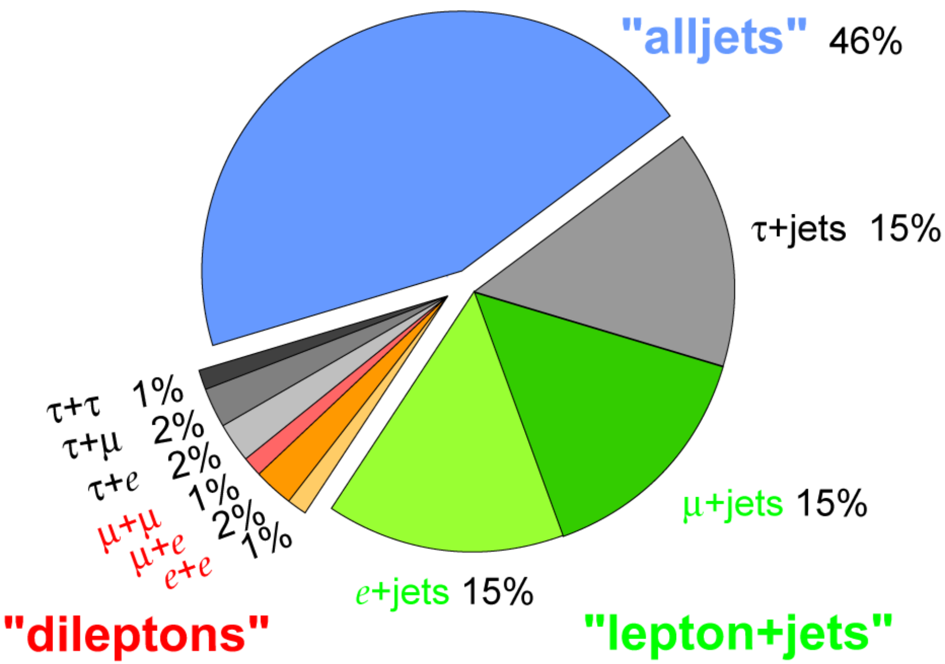


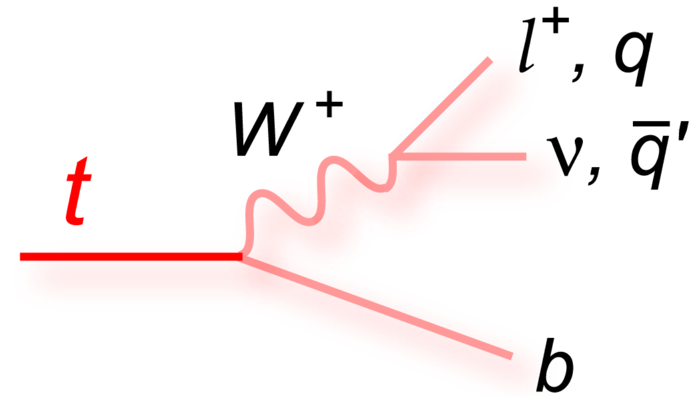
Production:
- Production rate
- Differential distributions
- New production mechanisms

Decay:
- Decay channels *(SM and new)*
- Couplings W, Z, γ and H
- Spin correlations



Top Pair Branching Fractions





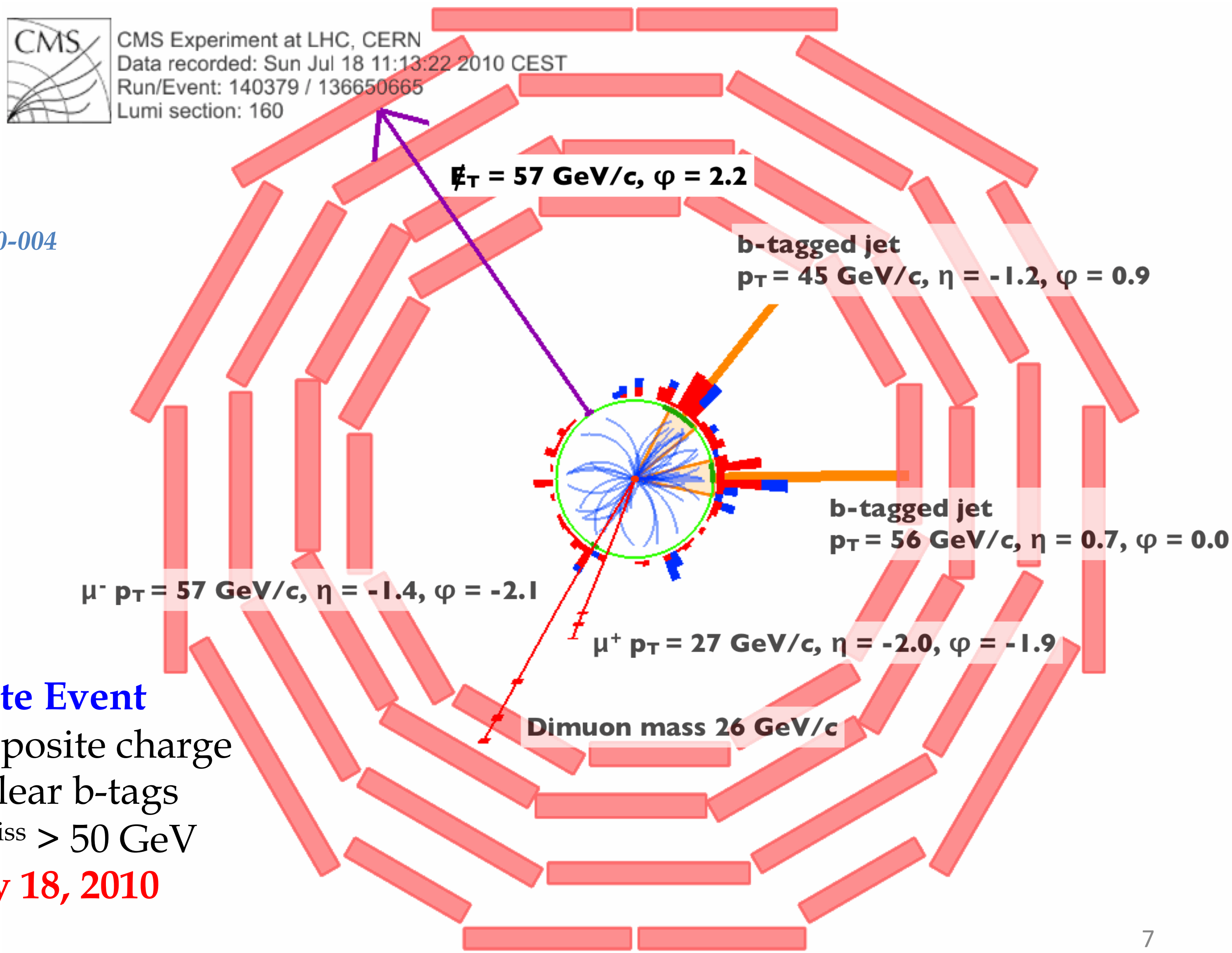
- The only known way the top quark can decay is through the weak interaction
- Producing W-boson and a down-type quark (down, strange, or bottom)

$$\mathcal{BR}(t \to Wb) = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} \approx 0.99$$

$$\mathrm{SM}: \quad t \to Wb \approx 100\%$$

Top-quark di-lepton candidate
Observed in pp collisions @ LHC @ 7 TeV

CMS PAS TOP-10-004



μμ Candidate Event

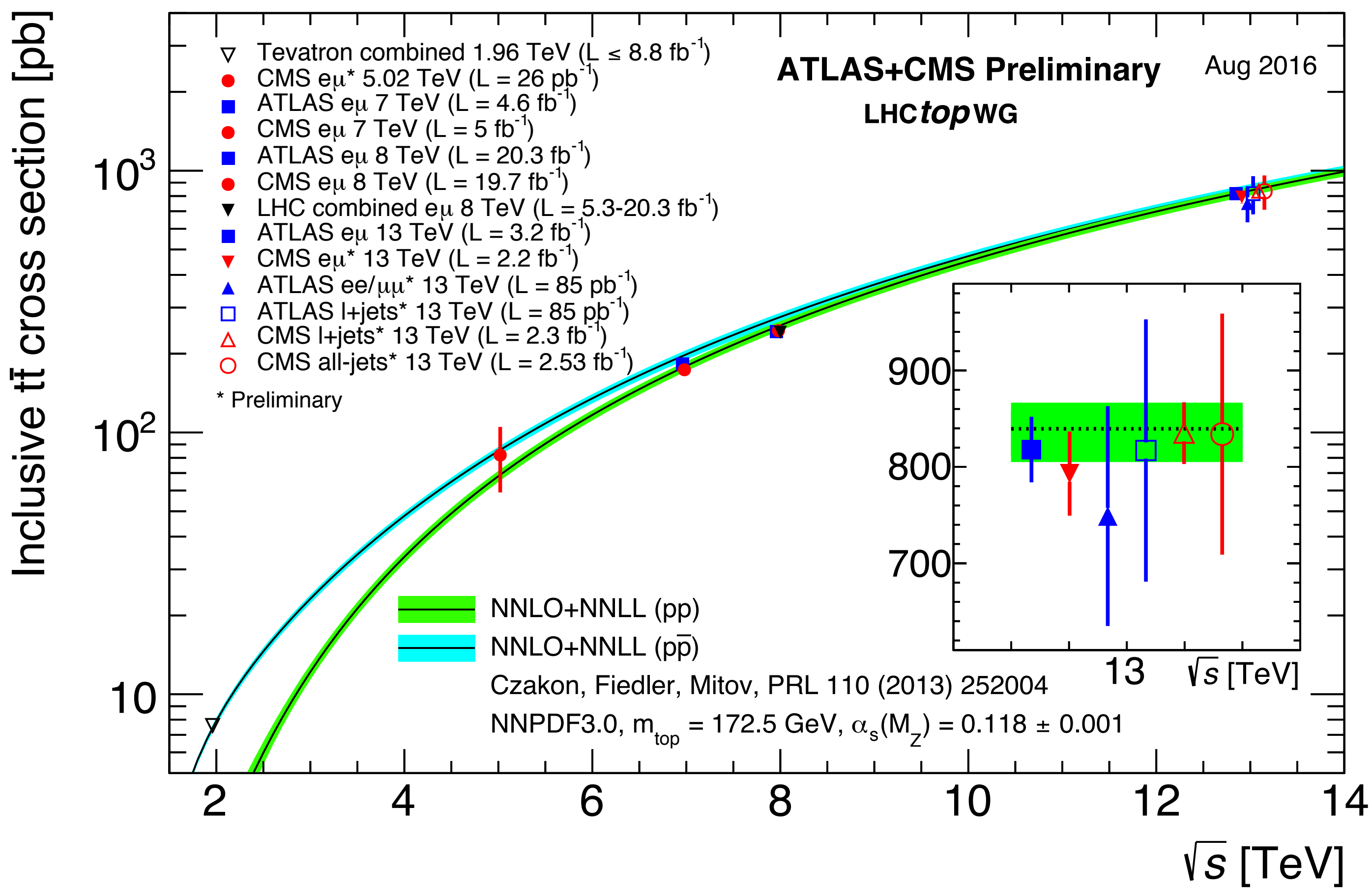
2 muons with opposite charge

2 jets, good/clear b-tags

significant $E_T^{miss} > 50$ GeV

CMS on July 18, 2010

Inclusive cross section



LHC and Tevatron measurements as a function of the centre-of-mass energy versus the NNLO QCD calculation complemented with NNLL resummation (Top++)

Motivation For ttj

- @ LHC tops are produced with large energies & high transverse momenta
- Increase probability for additional (hard) radiation of gluons → ttj final state
- How big is the contribution of ttj in the inclusive tt sample ?

- NLO on-shell **tt & ttj** productions for **m_t = 173.2 GeV @ $LHC_{13\ TeV}$** with **CT14**

σ (tt) = 715.58 pb

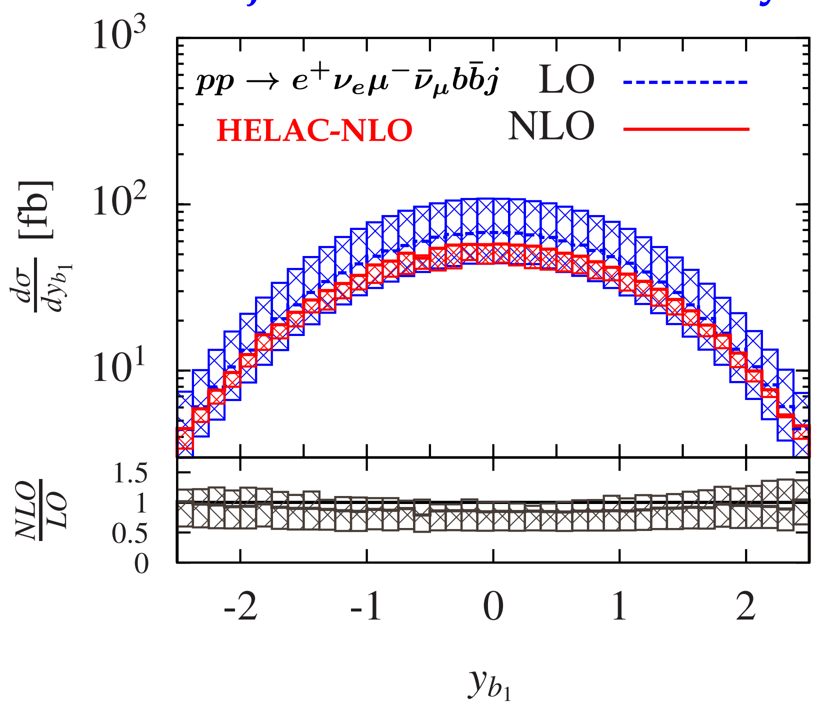
Jet p_T cut [GeV]	σ (ttj) [pb]	σ (ttj)/σ (tt) [%]
40	296.97 ± 0.29	41
60	207.88 ± 0.19	29
80	152.89 ± 0.13	21
100	115.60 ± 0.14	16
120	89.05 ± 0.10	12

HELAC-NLO, G. Bevilacqua et al. '13

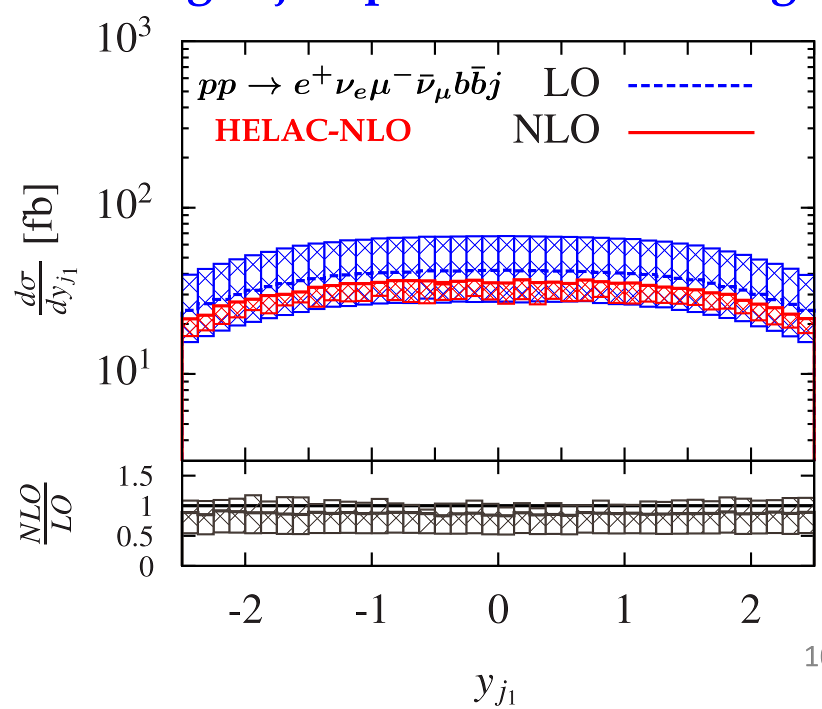
Motivation For ttj

- Background to SM Higgs production in VBF: $qq \to Hqq \to W^+W^-qq$
- 2 tagging jets: $\Delta y_{j_1 j_2} = |y_{j_1} - y_{j_2}| > 4 \;\&\; y_{j_1} \times y_{j_2} < 0$
- ↓ **tt background:** tt → WWbb & ↑ **ttj background:** ttj → WWbbj

b-jets distributed centrally



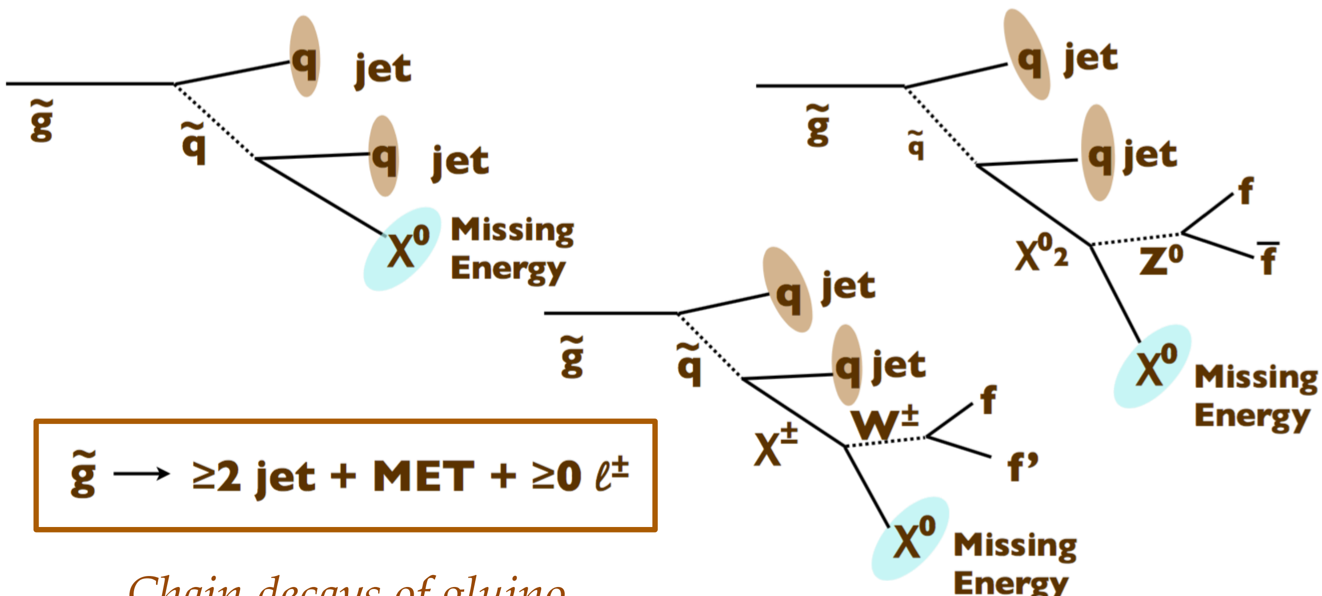
light-jet spans a broader range



Motivation For ttj

- Background to supersymmetric particle production

  - ❖ *ttj signature* → light and bottom jets, charged lepton(s) & p_T^{miss} from invisible neutrinos
  - ❖ *Typical signals* → jets, charged lepton(s) & p_T^{miss} due to escaping lightest supersymmetric particle (neutralino)



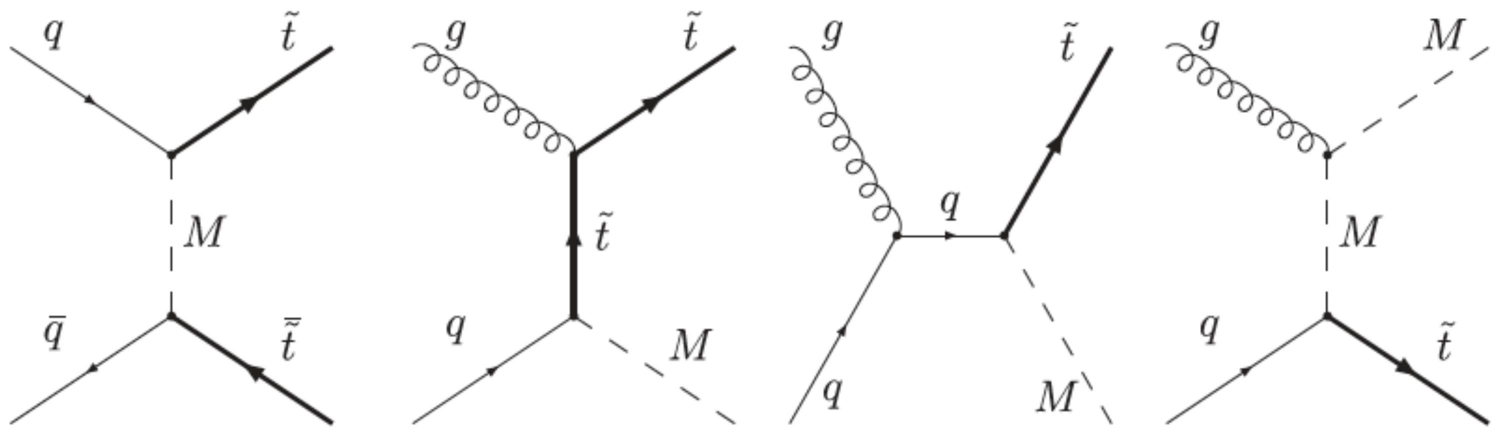
Chain decays of gluino

M. L. Mangano '09

Motivation For ttj

- Background to production of top flavor violating resonances $\mathbf{pp \to M\tilde{t} \to t\bar{t}j}$

M. I. Gresham, I.-W. Kim, K. M. Zurek '11



$(M = \phi^a \; only)$

$\tilde{t} = t$ **for** $M = W', Z'_H$ **and** $\tilde{t} = \bar{t}$ **when** $M = \phi^a$ **(color triplet or sextet)**

- W′ signal: $\mathbf{W' \to \bar{t}q}$
- Production processes: $\mathbf{pp \to W't \to t\bar{t}j}$

$$m_{W'} \in \{200, \ldots, 600\} \text{ GeV}$$

$$\sigma_{7\text{TeV}} \in \{40, \ldots, 4\} \text{ pb}$$

$$\mathcal{L}_{W'} = \frac{1}{\sqrt{2}} \bar{d}\gamma^\mu g_R P_R t W'_\mu + \text{H.c.},$$

$$\mathcal{L}_{Z'_H} = \frac{1}{\sqrt{2}} \bar{u}\gamma^\mu g_R P_R t Z'_{H\mu} + \text{H.c.},$$

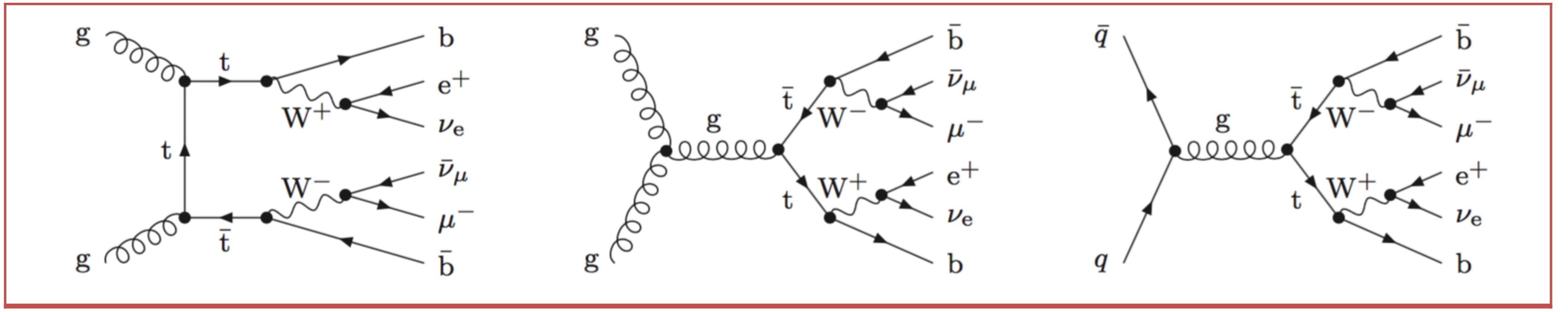
$$\mathcal{L}_\phi = \bar{t}^c T^a_r (g_L P_L + g_R P_R) u \phi^a + \text{H.c.},$$

- *ATLAS: $m_{W'} >$ 430 GeV* *ATLAS Collaboration, CERN-PH-EP-2012-219*

NWA & Off-Shell Effects

- NWA → Tops are restricted to on-shell states
- Approximation is controlled by the ratio: $\Gamma_t/m_t \approx 10^{-2}$
- Contributions from diagrams involving two top-quark resonances

$pp \to t\bar{t}$



- Should be accurate for sufficiently inclusive observables
- Indeed → **top-quark off-shell effects for σ @ 1% - 2% level**

✧ **pp → tt** — *A. Denner et al. '11, G. Bevilacqua et al. '11, A. Denner et al. '12 R. Frederix '14, F. Cascioli et al. '14, G. Heinrich et al '14 , A. Denner et al. '16*

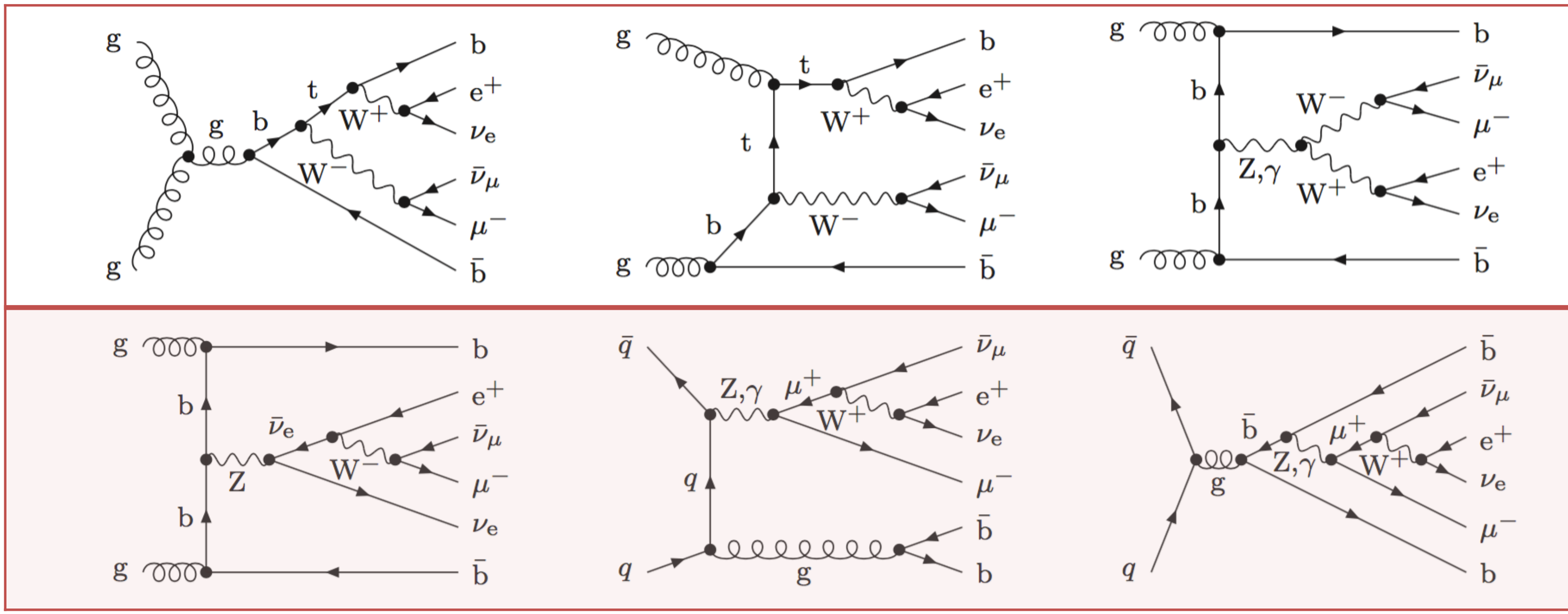
✧ **pp → ttH** — *A. Denner, R. Feger '15, A. Denner, J. Lang, M. Pellen, S. Uccirati '17*

✧ **pp → ttj** — *G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16*

NWA & Off-Shell Effects

- Single-resonant and non-resonant contributions
- Interferences between double-, single-, and non-resonant diagrams

$\mathbf{pp \to t\bar{t}}$



- Diagrams in NWA versus Full calculation with on-shell and off-shell W for the *gg initial state:*
  - ✧ *LO: 3 → 31 → 79*
  - ✧ *Real Emission: 28 → 208 → 508*

NWA & Off-Shell Effects

- **gg channel** comprises **3554 one-loop diagrams** → according to **QGRAF**

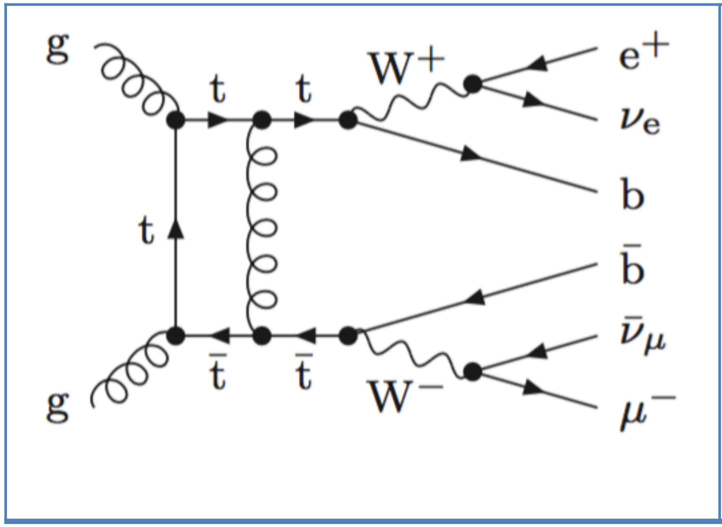
P. Nogueira '93

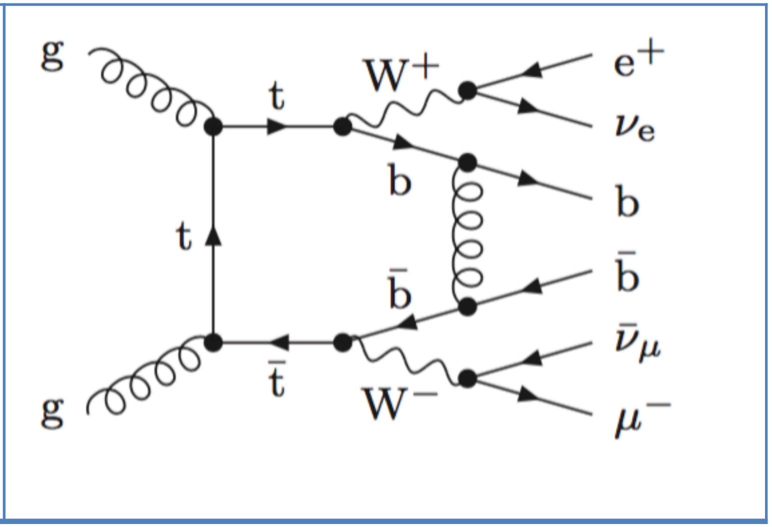
- The most complicated ones: **213 pentagons & 20 hexagons**
- Tensor integrals up to rank five

NWA for tt – up to boxes only !

Full calculations for tt – up to hexagons !

$$\mathbf{pp \to t\bar{t}}$$





Intermediate Top Resonances

- Putting simply $\Gamma_t \neq 0$ violates gauge invariance
- **Gauge-invariant treatment → complex-mass scheme**
- Γ_t → incorporated into top mass via:

$$\mu_t^2 = m_t^2 - i\, m_t \Gamma_t$$

A. Denner, S. Dittmaier, M. Roth, D. Wackeroth '99
A. Denner, S. Dittmaier, M. Roth, L. H. Wieders '05

- All matrix elements evaluated using complex masses
- μ_t^2 → identified with the position of pole of top-quark propagator
- Top-mass counter-term $\delta\mu_t$ related to top-quark self-energy at: $p_t^2 = \mu_t^2$

- **Another non trivial aspect**: evaluation of one-loop scalar integrals !
- Scalar integrals with complex masses → supported e.g. by **ONELOOP**

A. van Hameren '11

Top Quark Width

- Finite W width contributions included in matrix elements & in top quark width
- **Top width for unstable W bosons, neglecting bottom quark mass @ LO & NLO**

$$\Gamma_{\mathrm{t}}^{\mathrm{LO}} = \frac{G_\mu m_{\mathrm{t}}^5}{16\sqrt{2}\pi^2 M_{\mathrm{W}}^2} \int_0^1 \frac{\mathrm{d}y\, \gamma_{\mathrm{W}}}{(1-y/\bar{y})^2 + \gamma_{\mathrm{W}}^2} F_0(y)$$

M. Jezabek, J. H. Kühn '89
A. Denner, et al. '12

$$\gamma_{\mathrm{W}} = \Gamma_{\mathrm{W}}/M_{\mathrm{W}},\ \bar{y} = (M_{\mathrm{W}}/m_{\mathrm{t}})^2 \qquad F_0(y) = 2(1-y)^2(1+2y)$$

$$\Gamma_{\mathrm{t}}^{\mathrm{NLO}} = \frac{G_\mu m_{\mathrm{t}}^5}{16\sqrt{2}\pi^2 M_{\mathrm{W}}^2} \int_0^1 \frac{\mathrm{d}y\, \gamma_{\mathrm{W}}}{(1-y/\bar{y})^2 + \gamma_{\mathrm{W}}^2} \left[F_0(y) - \frac{2\alpha_{\mathrm{s}}}{3\pi} F_1(y)\right]$$

$$\begin{aligned} F_1(y) = {} & 2(1-y)^2(1+2y)\left[\pi^2 + 2\,\mathrm{Li}_2(y) - 2\,\mathrm{Li}_2(1-y)\right] \\ & + 4y(1-y-2y^2)\ln(y) + 2(1-y)^2(5+4y)\ln(1-y) \\ & - (1-y)(5+9y-6y^2). \end{aligned}$$

- In the limit $\gamma_W \longrightarrow 0$

$$\frac{\gamma_{\mathrm{W}}}{(1-y/\bar{y})^2 + \gamma_{\mathrm{W}}^2} \to \pi\bar{y}\,\delta(y-\bar{y}).$$

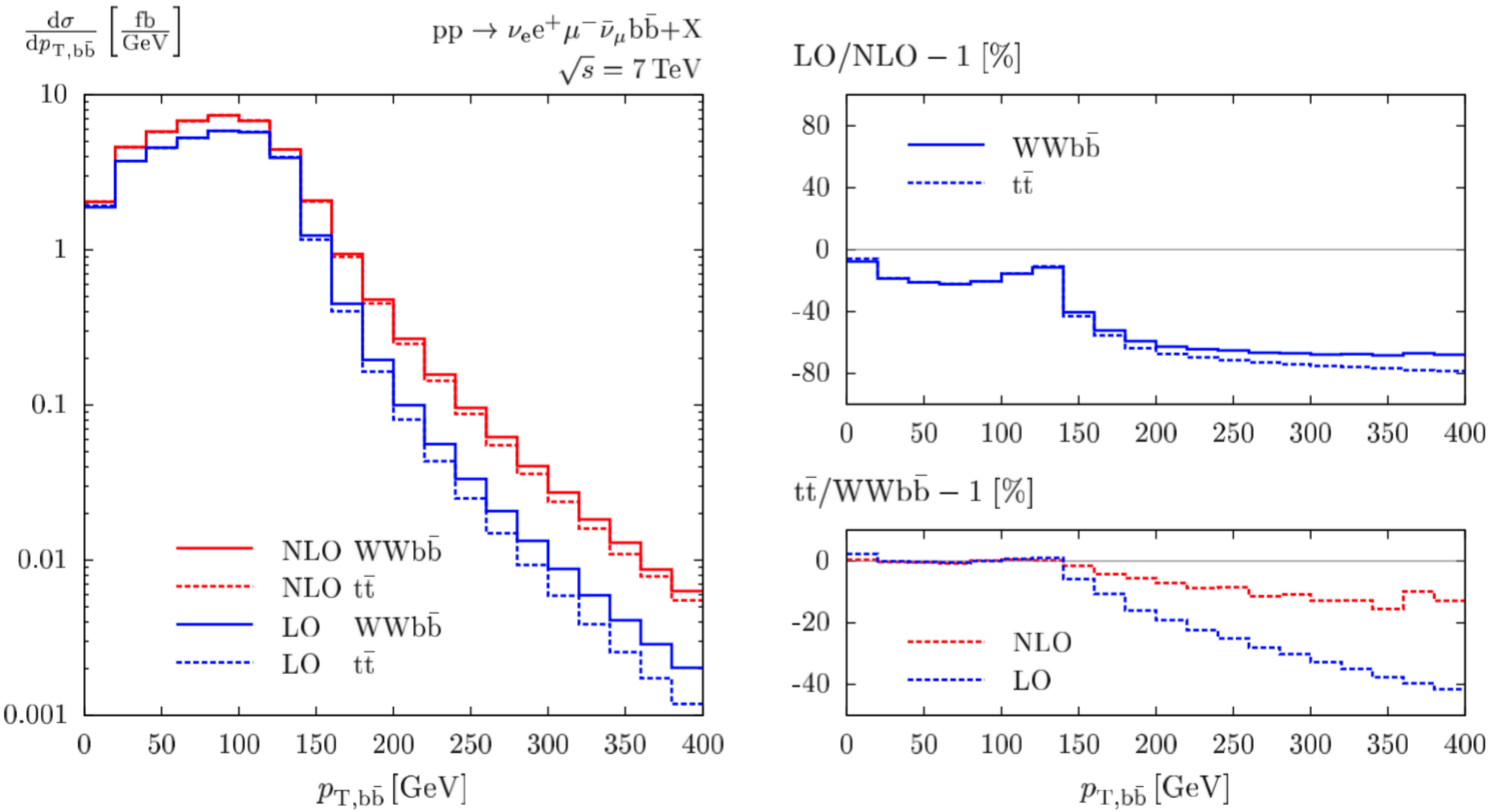
Top Quark Width

m_t [GeV]	$\Gamma_{\mathrm{t}}^{\mathrm{LO}}$ [GeV]	$\Gamma_{\mathrm{tW}}^{\mathrm{LO}}$ [GeV]	$\Gamma_{\mathrm{t}}^{\mathrm{NLO}}$ [GeV]	$\Gamma_{\mathrm{tW}}^{\mathrm{NLO}}$ [GeV]
168.2	1.33273	1.35426	1.21823	1.23792
170.7	1.40449	1.4269	1.28389	1.30438
173.2	1.47834	1.50162	1.35146	1.37276
175.7	1.55429	1.57847	1.42097	1.44309
178.2	1.63237	1.65746	1.49243	1.51538

Γ_{t}	top quark width with W gauge boson off-shell effects included
Γ_{tW}	top-quark width with the on-shell W gauge boson

NWA & Off-Shell Effects

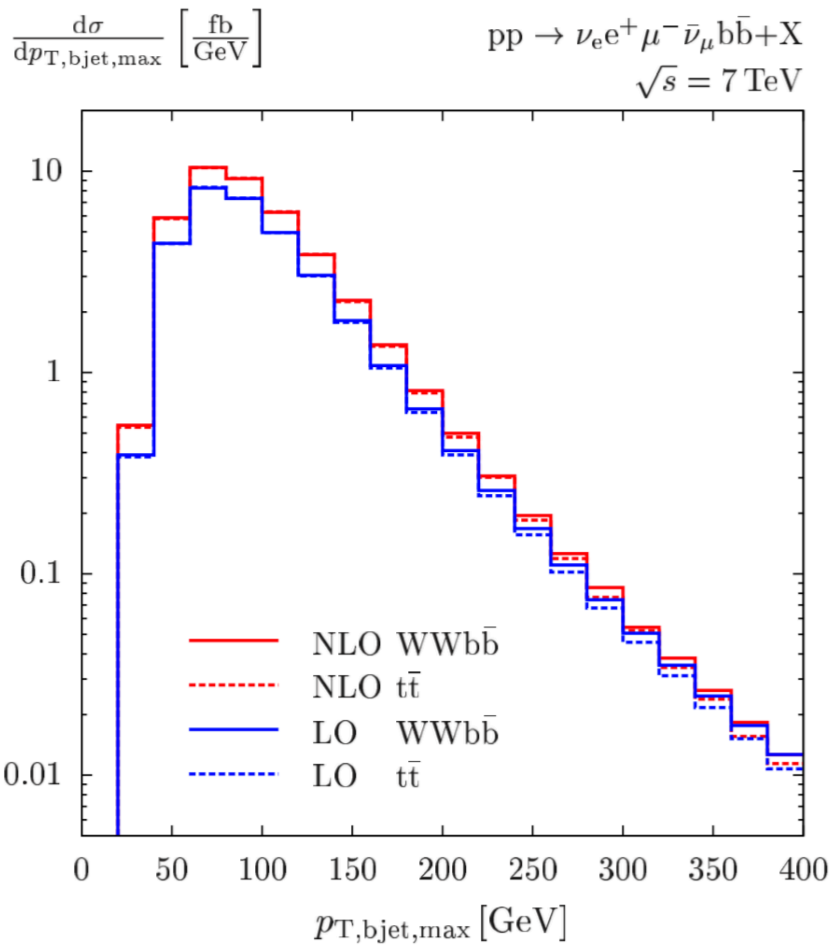
- NWA not accurate for differential cross sections even for inclusive setup
- **Full NWA (tt)** versus **full calculation (WWbb)** for **p_T(bb)**

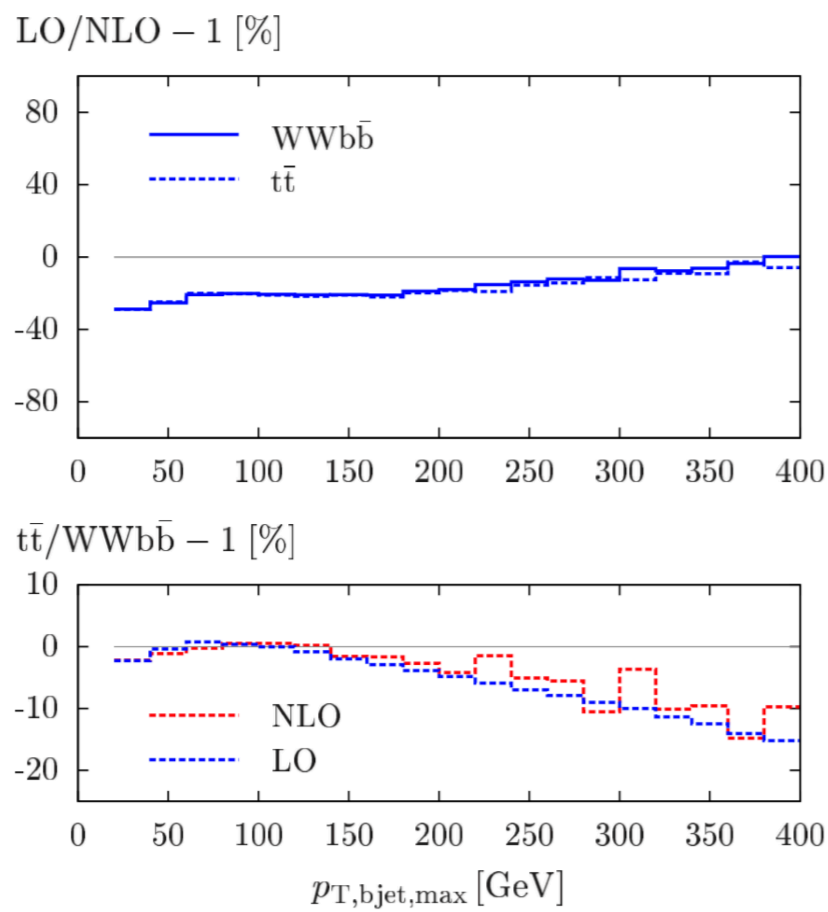


A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini, M. Schulze '12

NWA & Off-Shell Effects

- NWA not accurate for differential cross sections even for inclusive setup
- **Full NWA (tt)** versus **full calculation (WWbb)** for **p_T(b)**

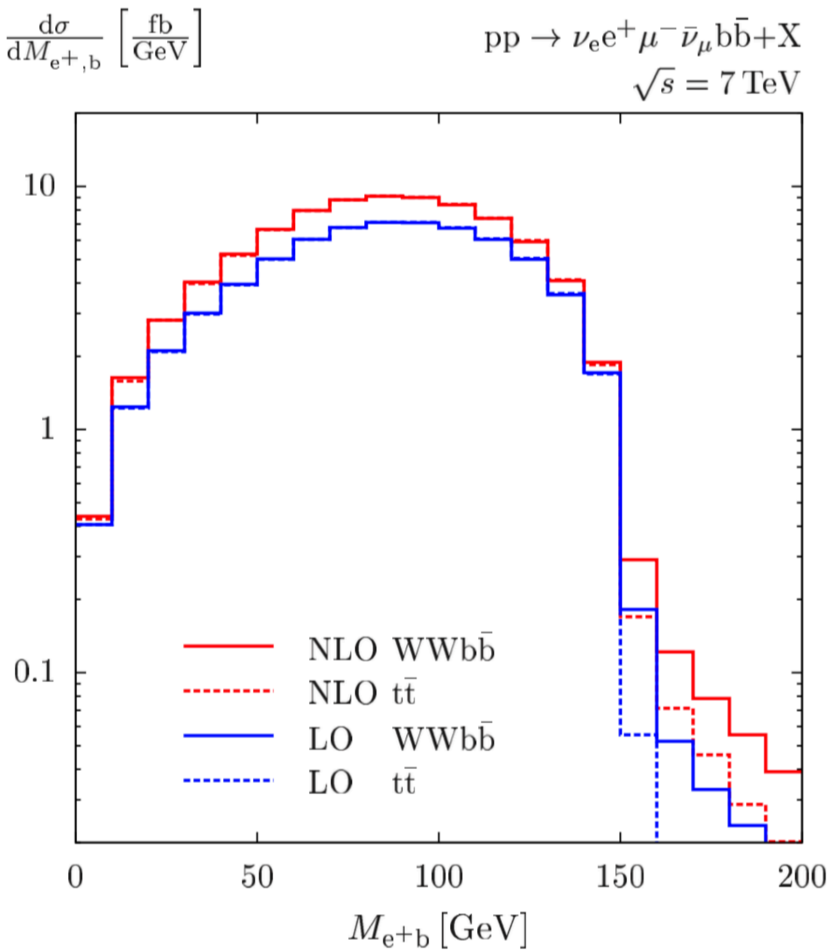




A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini, M. Schulze '12

NWA & Off-Shell Effects

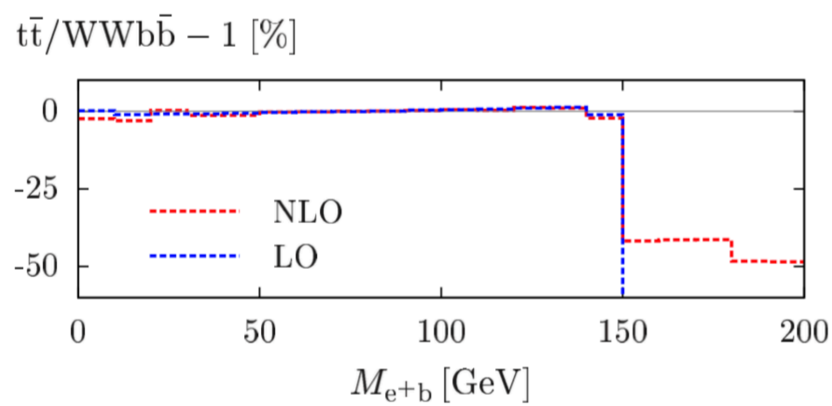
- NWA not accurate for differential cross sections even for inclusive setup
- **Full NWA (tt)** versus **full calculation (WWbb)** for M_{e+b}



- If top and W decay on-shell @ LO → end-point given by sharp cut

$$M_{e+b} = \sqrt{m_t^2 - m_W^2} \approx 152\ \text{GeV}$$

- Additional radiation & off-shell effects introduce smearing



A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini, M. Schulze '12

Theoretical Predictions For ttj

- NLO QCD corrections to on-shell ttj production

  S. Dittmaier, P. Uwer, S. Weinzierl '07 '09

- NLO QCD correction to on-shell ttj production with LO decays

  K. Melnikov, M. Schulze '10

- NLO QCD corrections to ttj in NWA (with jet radiation in top-quark decays)

  K. Melnikov, M. Schulze '12

- NLO QCD corrections to ttj with full top-quark and W off-shell effects

  G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Worek '16

- NLO QCD correction to on-shell ttj production + PS

  ✧ **POWHEG + PYTHIA** → no spin correlations

  A. Kardos, C. G. Papadopoulosa, Z. Trocsanyi '11

  ✧ **POWHEG + PYTHIA/HERWIG** → with spin-correlations @ LO

  S. Alioli, S.Moch, P. Uwer '12

  ✧ **MC@NLO + DEDUCTOR** → without top-quark decays

  M. Czakon, H. B. Hartanto, M. Kraus, M. Worek '15

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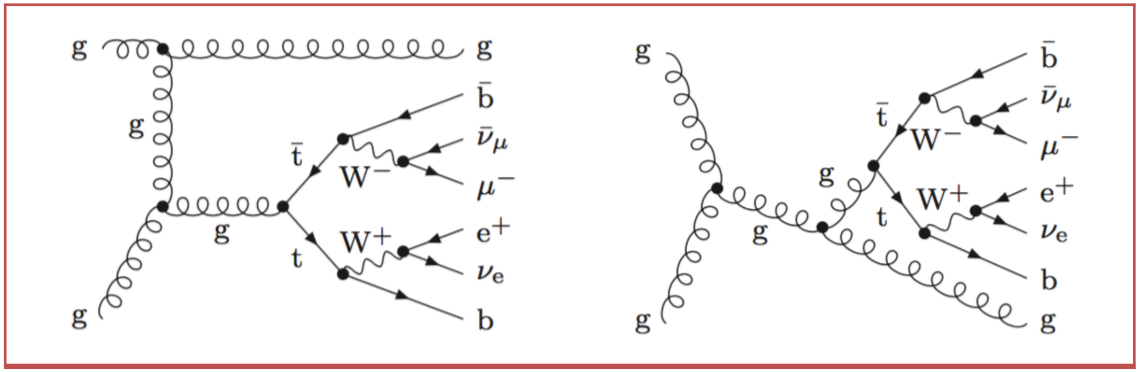
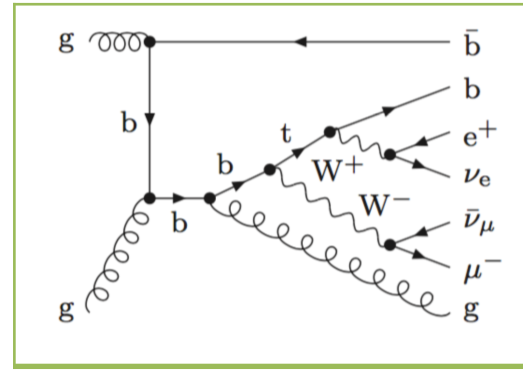
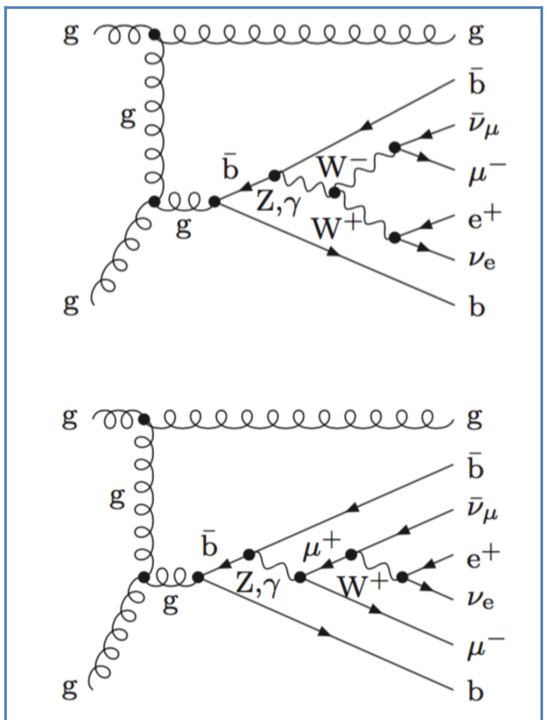
Off-Shell Effects For ttj







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

- ttj with leptonic decays at $\mathcal{O}(\alpha_s^4\alpha^4)$
- 2 → 5 process from the QCD point of view (WWbbj)
- Diagrams with complete off-shell effects for top quarks & W gauge boson for **gg initial state**:
  - ✧ **LO: 508**
  - ✧ **Real emission: 4447**

Off-Shell Effects For ttj

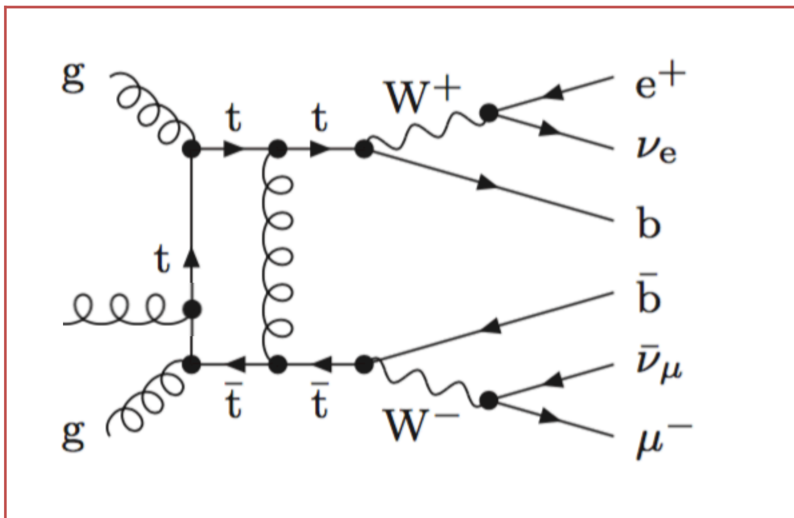
- **gg channel comprises 39 180 one-loop diagrams** → according to **QGRAF**

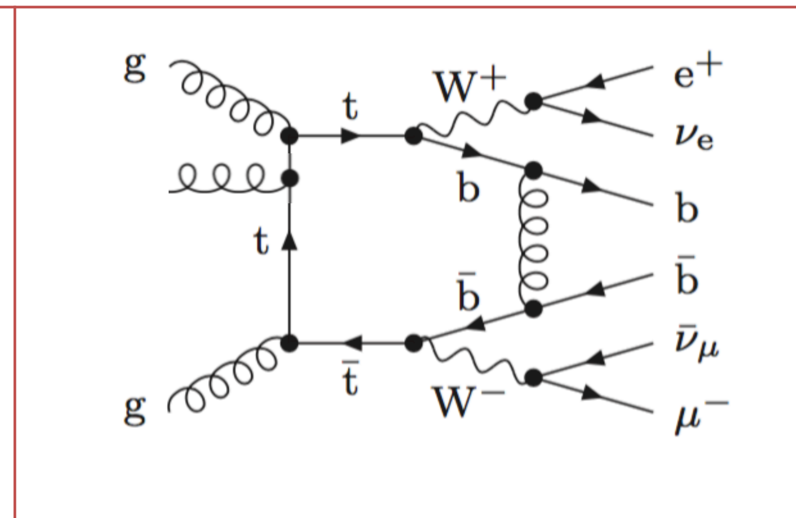
P. Nogueira '93

- The most complicated ones are **1155 hexagons & 120 heptagons**
- Tensor integrals up to rank six

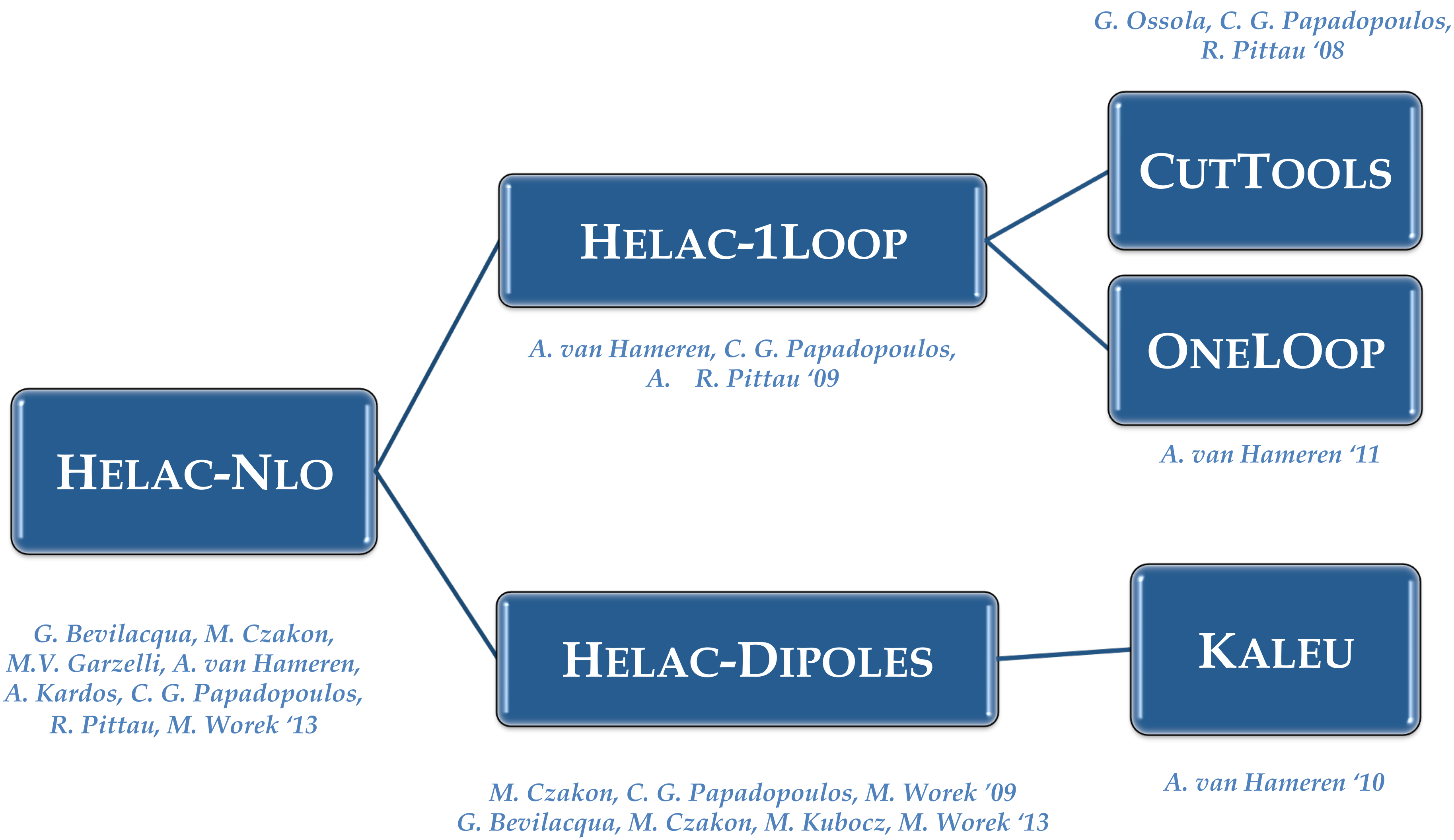
NWA for ttj (on-shell top-quark production) – up to pentagons !

Full calculations for ttj – up to heptagons !





HELAC-NLO


G. Ossola, C. G. Papadopoulos,
R. Pittau '08
CutTools
Helac-1Loop
OneLOop
A. van Hameren, C. G. Papadopoulos,
A. R. Pittau '09
A. van Hameren '11
Helac-Nlo
Helac-Dipoles
Kaleu
G. Bevilacqua, M. Czakon,
M.V. Garzelli, A. van Hameren,
A. Kardos, C. G. Papadopoulos,
R. Pittau, M. Worek '13
A. van Hameren '10
M. Czakon, C. G. Papadopoulos, M. Worek '09
G. Bevilacqua, M. Czakon, M. Kubocz, M. Worek '13

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

- **HELAC-1LOOP** → Virtual corrections in ’t Hooft-Veltman version of dimensional regularization
- **CUTTOOLS** → Ossola-Papadopoulos-Pittau (OPP) reduction technique
- **ONELOOP** → Evaluation of scalar integrals with complex masses

- **HELAC-DIPOLES** → The singularities from soft or collinear parton emissions isolated via subtraction methods for NLO QCD:
  - ✧ Catani-Seymour dipole subtraction
  - ✧ Nagy-Soper subtraction scheme
  - ✧ Both for massive and massless cases
  - ✧ Restriction on the phase space of the subtraction → α_{max}

- Reweighting & unweighting techniques, helicity, and color sampling methods for optimization

- **KALEU** → Phase-space integration
  - ✧ Multi-channel Monte Carlo techniques
  - ✧ Adaptive weight optimization
  - ✧ Dedicated additional channels for each subtraction term for both subtractions

https://helac-phegas.web.cern.ch/helac-phegas/

Setup

- Different lepton generations: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$
  - ✧ $\gamma^* \to \ell^\pm\ell^\mp$ **interference effects neglected → per-mille level @ LO**
  - ✧ Feynman Diagrams for gg initial state @ LO:

    508 for $e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,j \longrightarrow$ **1240 for** $e^+\nu_e\,e^-\bar{\nu}_e\,b\bar{b}\,j$

- **Top width for unstable W bosons, neglecting bottom quark mass**
- All light quarks including **b-quarks** and leptons **are massless**
- **Contribution from b quarks** in the initial state **neglected → effect < 1% @ LO**
- **Jets:** Final-state quarks and gluons with pseudo-rapidity **|y| < 5** recombined into jets using **anti-k_T jet** algorithm with **R = 0.5**
- **Requirement:** exactly 2 b-jets, at least one light-jet, 2 charged leptons, and missing p_T → fairly inclusive cuts

Inclusive Selection Cuts

$p_{T,\ell} > 30 \text{ GeV}\,,$	$p_{T,j} > 40 \text{ GeV}\,,$
$\not{p}_T > 40 \text{ GeV}\,,$	$\Delta R_{jj} > 0.5\,,$
$\Delta R_{\ell\ell} > 0.4\,,$	$\Delta R_{\ell j} > 0.4\,,$
$\lvert y_\ell \rvert < 2.5\,,$	$\lvert y_j \rvert < 2.5\,,$

$$p_{T,i} = \sqrt{p_{x,i}^2 + p_{y,i}^2}\,,$$

$$y_i = \frac{1}{2}\ln\left(\frac{E_i + p_{z,i}}{E_i - p_{z,i}}\right)\,,$$

$$\Delta R_{ik} = \sqrt{\Delta\phi_{ik}^2 + \Delta y_{ik}^2}\,.$$

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SM Parameters & Widths

$G_\mu = 1.16637 \cdot 10^{-5}\ \text{GeV}^{-2}\,,$ $m_W = 80.399\ \text{GeV}\,,$ $m_Z = 91.1876\ \text{GeV}\,,$	$m_t = 173.2\ \text{GeV}$ $\Gamma_W = 2.09875\ \text{GeV}\,,$ $\Gamma_Z = 2.50848\ \text{GeV}\,.$
$\alpha = \frac{\sqrt{2}}{\pi} G_\mu m_W^2 \sin^2\theta_W$	$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$
$\Gamma_t^{\text{LO}} = 1.47834\ \text{GeV}\,,$	$\Gamma_t^{\text{NLO}} = 1.35146\ \text{GeV}\,.$

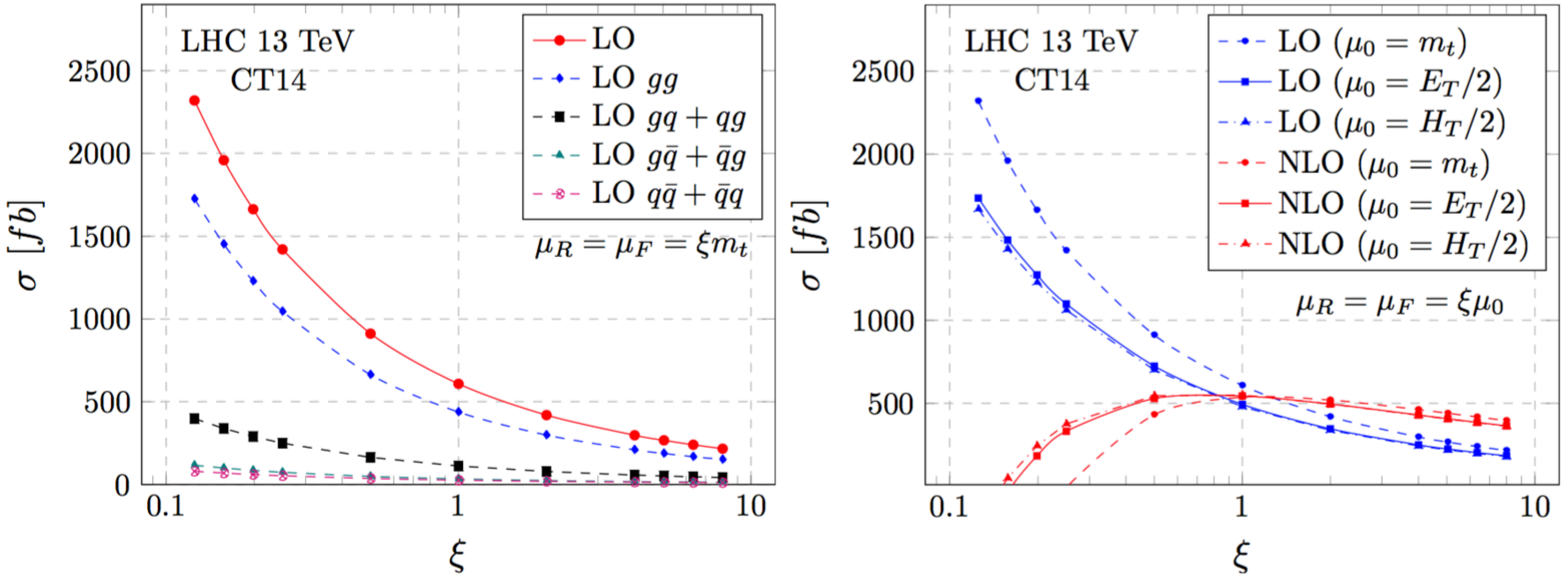
Scale Dependence

- Total cross section **@ LHC** $_{\mathbf{13\ TeV}}$
- Scales:

$$\mu_R = \mu_F = \mu_0 = m_t,\ E_T/2,\ H_T/2$$

$$H_T = \sum_i p_{T,\,i} + p_T^{\text{miss}}$$

$$E_T = m_{T,\,t} + m_{T,\,\bar{t}}$$



- LO contributions: $gg : 72\%,\ gq : 18\%,\ g\bar{q} : 6\%,\ q\bar{q} : 4\%$

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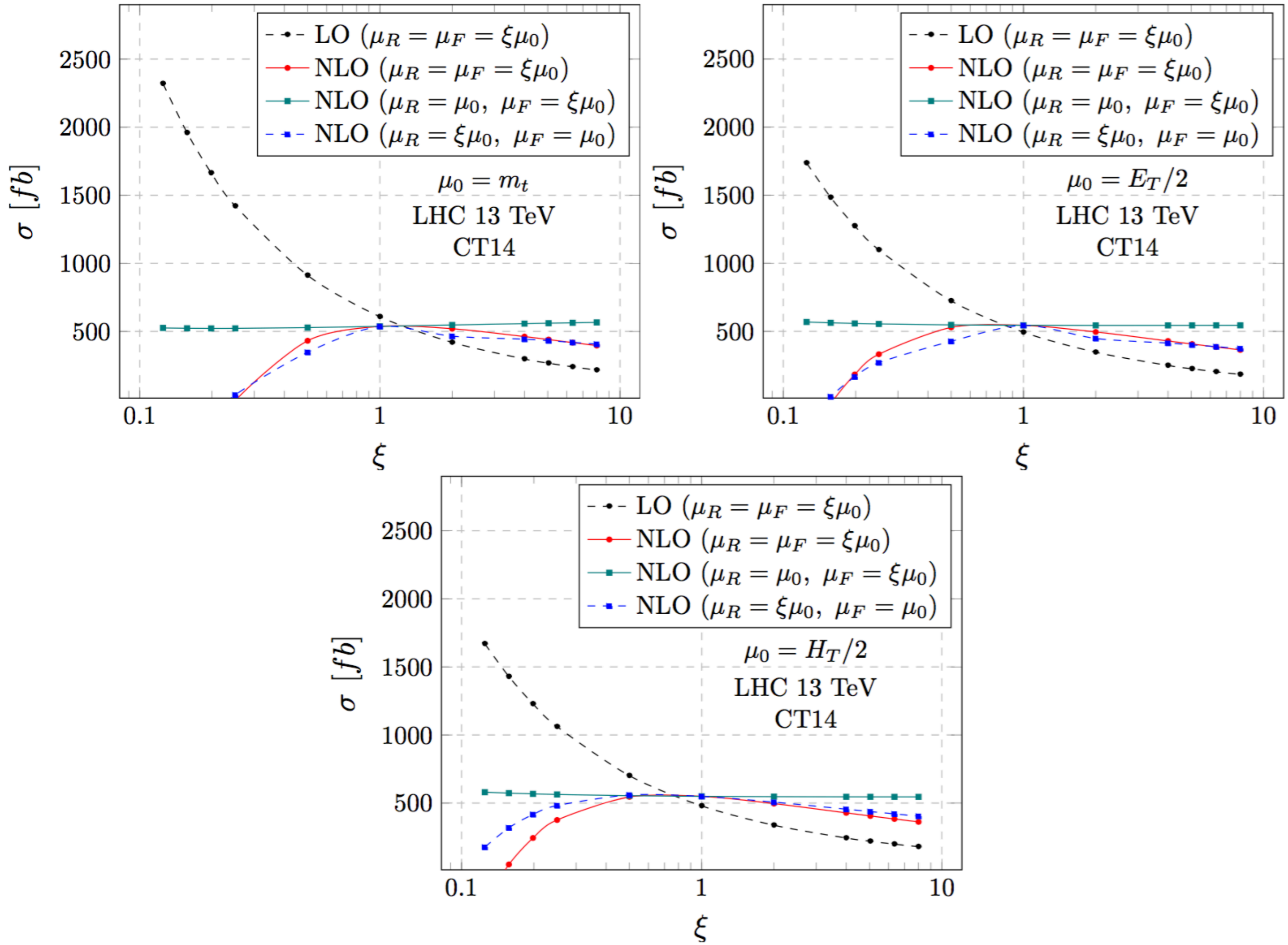
Scale Dependence



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Scale & PDF Uncertainties

$$\frac{1}{2}\,\mu_0 \le \mu_R\,,\mu_F \le 2\,\mu_0\,, \qquad \frac{1}{2} \le \frac{\mu_R}{\mu_F} \le 2\,.$$

$$\left(\frac{\mu_R}{\mu_0}\,,\frac{\mu_F}{\mu_0}\right) = \Big\{(2,1)\,,(0.5,1)\,,(1,2)\,,(1,1),(1,0.5),(2,2),(0.5,0.5)\Big\}$$

$$\sigma^{\rm LO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm CT14},\mu_0=m_t) = 608.09^{+303.52\ (+50\%)}_{-188.85\ (-31\%)}\ [{\rm scales}]\ {\rm fb}\,,$$

$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm CT14},\mu_0=m_t) = 537.24^{+10.12\ (+2\%)}_{-190.35\ (-35\%)}\ [{\rm scales}]\ ^{+17.32\ (+3\%)}_{-18.34\ (-3\%)}\ [{\rm PDF}]\ {\rm fb}$$

$$\sigma^{\rm LO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm CT14},\mu_0=E_T/2) = 493.54^{+230.40\ (+47\%)}_{-147.02\ (-30\%)}\ [{\rm scales}]\ {\rm fb}\,,$$

$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm CT14},\mu_0=E_T/2) = 544.64^{+2.95\ (+1\%)}_{-117.47\ (-22\%)}\ [{\rm scales}]\ ^{+18.10\ (+3\%)}_{-18.92\ (-3\%)}\ [{\rm PDF}]\ {\rm fb}$$

$$\sigma^{\rm LO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm CT14},\mu_0=H_T/2) = 479.38^{+221.91\ (+46\%)}_{-142.05\ (-30\%)}\ [{\rm scales}]\ {\rm fb}\,,$$

$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm CT14},\mu_0=H_T/2) = 549.65^{+10.25\ (+2\%)}_{-53.42\ (-10\%)}\ [{\rm scales}]\ ^{+18.00\ (+3\%)}_{-19.15\ (-3\%)}\ [{\rm PDF}]\ {\rm fb}$$

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Theoretical Uncertainties

- Size of NLO corrections for CT14 NLO

$\mu_0 = m_t$	$\mathcal{K} = 0.88$	-12%
$\mu_0 = E_T/2$	$\mathcal{K} = 1.10$	$+10\%$
$\mu_0 = H_T/2$	$\mathcal{K} = 1.12$	$+12\%$

$1/2\mu_0 \le \mu_R,\, \mu_F \le 2\mu_0$
$1/2 \le \mu_R/\mu_F \le 2$

- PDFs: **CT14, MMHT14, NNPDF3.0**
- Total cross sections for $\mu_0 = H_T/2$

68% C.L.

$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm CT14}, \mu_0 = H_T/2) = 549.65^{+10.25\,(+2\%)}_{-53.42\,(-10\%)}\,[\text{scales}]\;^{+18.00\,(+3\%)}_{-19.15\,(-3\%)}\,[\text{PDF}]\ \text{fb}$$

$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm MMHT14}, \mu_0 = H_T/2) = 554.61^{+10.85\,(+2\%)}_{-54.51\,(-10\%)}\,[\text{scales}]\;^{+12.06\,(+2\%)}_{-12.22\,(-2\%)}\,[\text{PDF}]\ \text{fb}$$

$$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j}({\rm NNPDF3.0}, \mu_0 = H_T/2) = 572.18^{+11.14\,(+2\%)}_{-56.23\,(-10\%)}\,[\text{scales}]\;^{+11.31\,(+2\%)}_{-11.31\,(-2\%)}\,[\text{PDF}]\ \text{fb}$$

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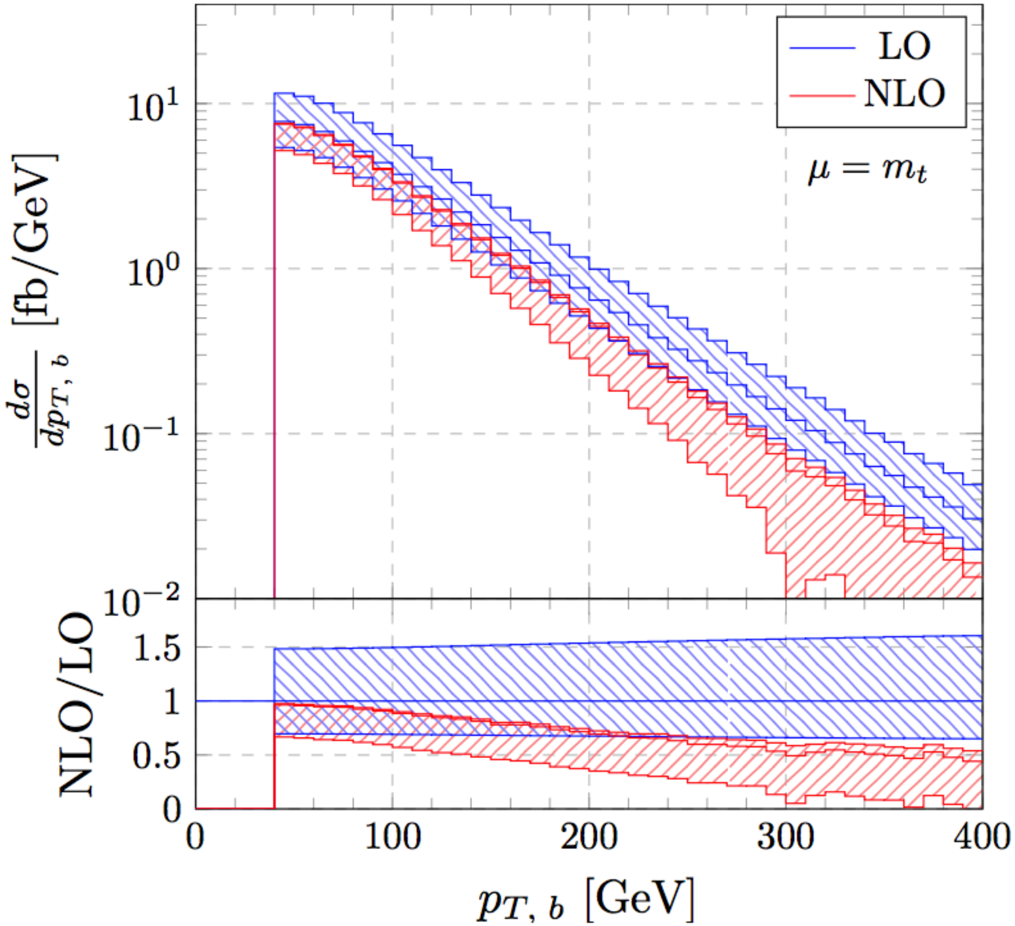
p_T(b-Jet)

- 16 differential cross sections have been examined, here are just two examples…
- **Dimensionful observable: p_T(b) with $\mu_0 = m_t$**



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

- NLO do not rescale shape of LO
- NLO corrections up to **-55%**
- Properly described only via NLO
- Negative NLO in p_T tails
- LO higher than NLO in p_T tails

- The dynamic scale should depend on p_T of hardest jet and/or top decay products ↑
- Asymptotic freedom → α_s ↓ in tails
- Dependence on α_s @ LO >> @ NLO
- Would drive positive NLO/LO ratio in this region

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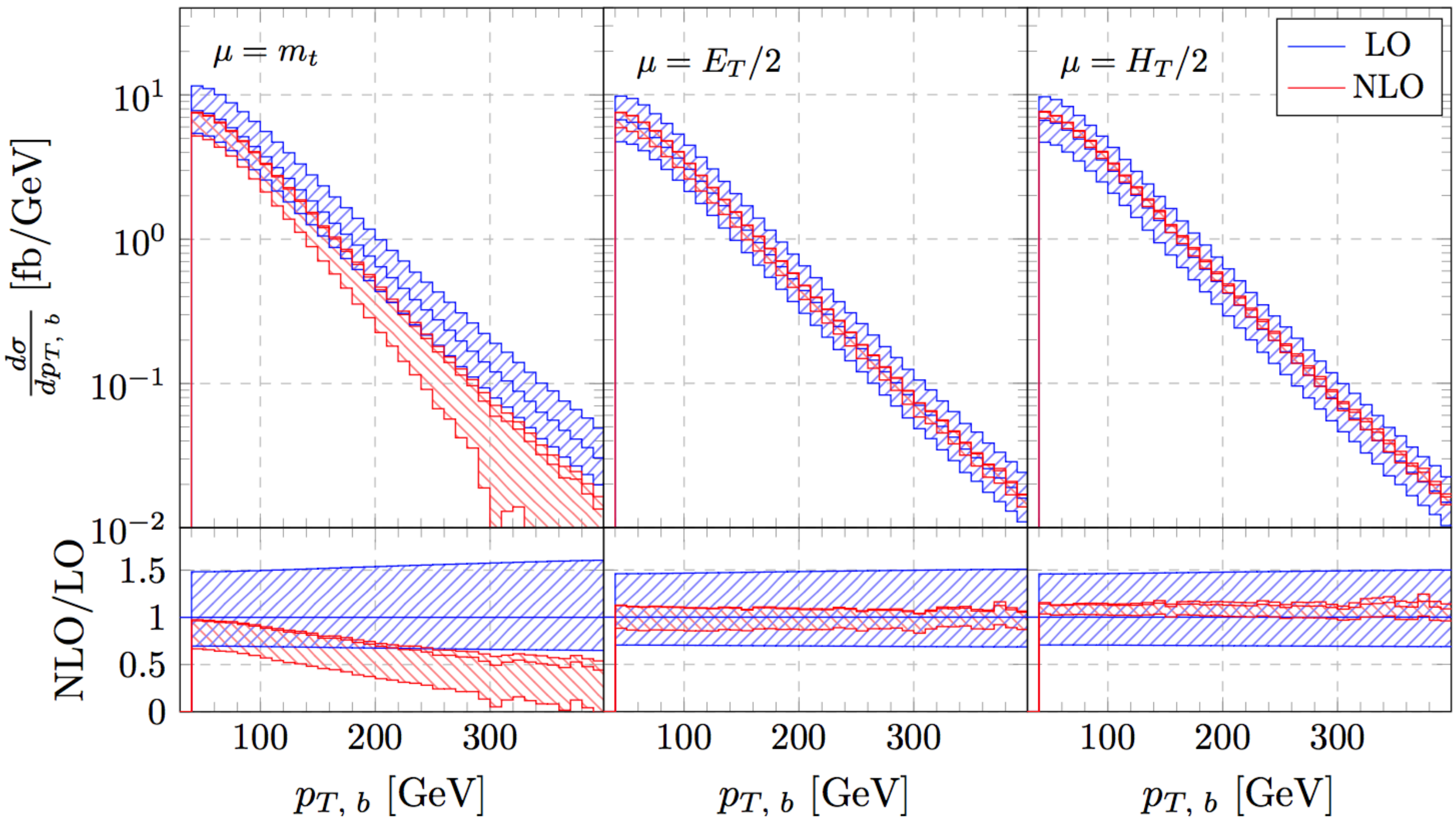
p_T(b-Jet)

- Dimensionful observable: **$p_T(b)$** with all 3 scales
- Positive corrections below 20% when $E_T/2$ or $H_T/2$ has been used instead



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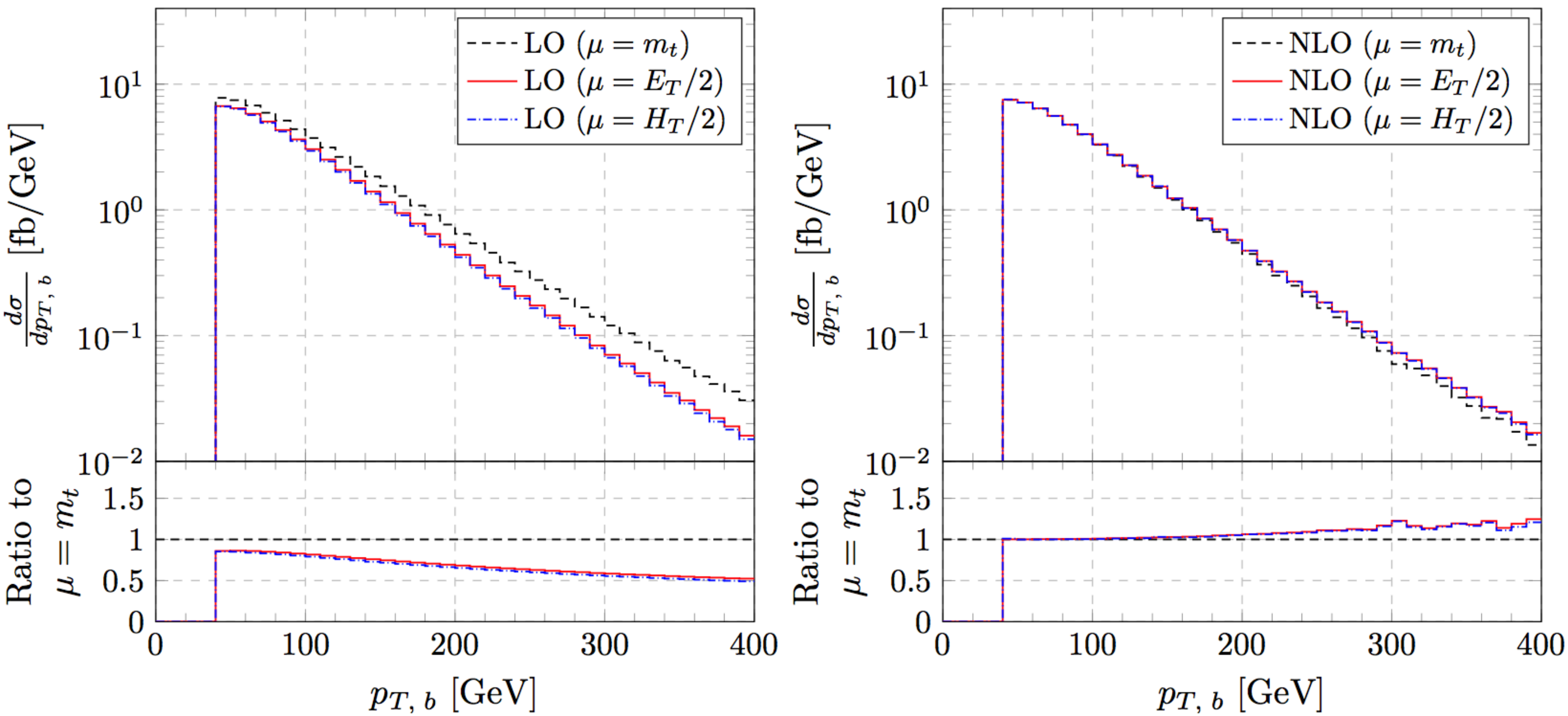
p_T(b-Jet)

- Central values & ratios to the fixed scale @ LO & @ NLO

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



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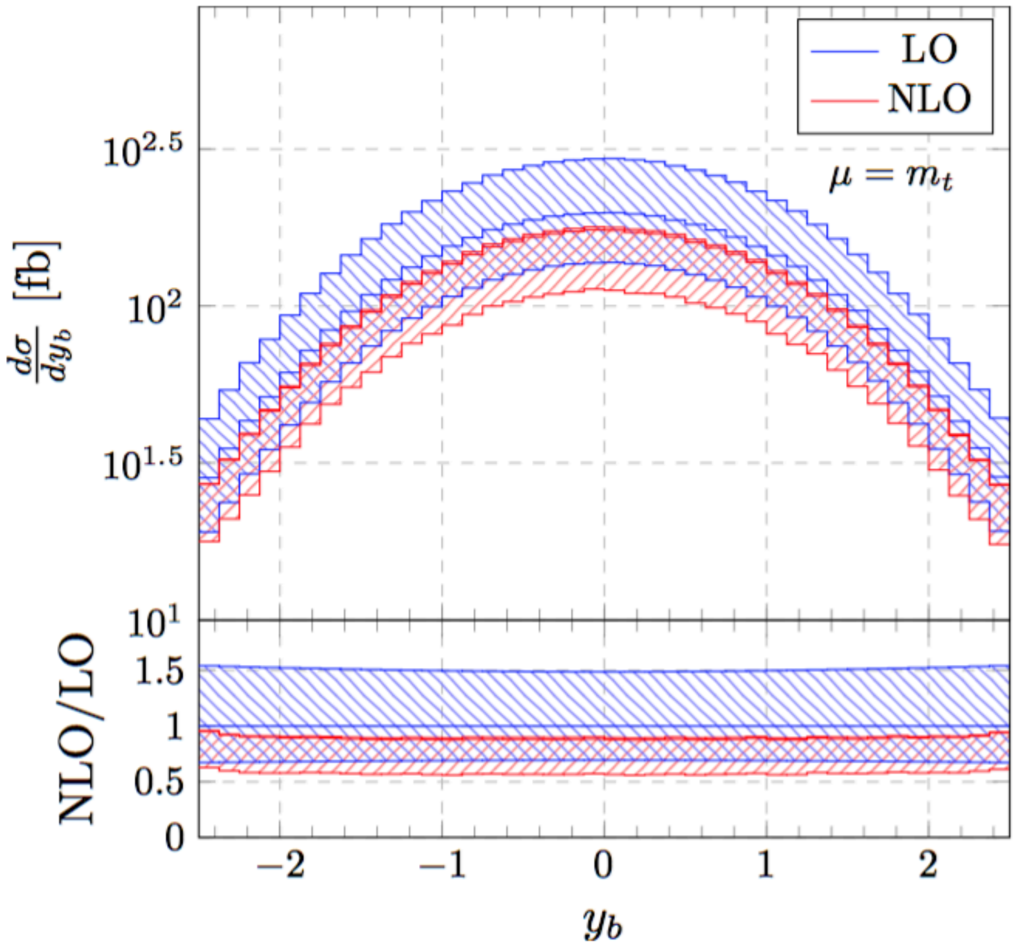
b-Jet Rapidity

- **Dimensionless observable: y_b with $\mu_0 = m_t$**



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

- Negative, moderate 10% → but quite stable NLO corrections
- Receives contributions from various scales → also from these sensitive to threshold for tt production
- For $\mu_0 = m_t$ effects of phase-space regions close to ttj threshold dominate

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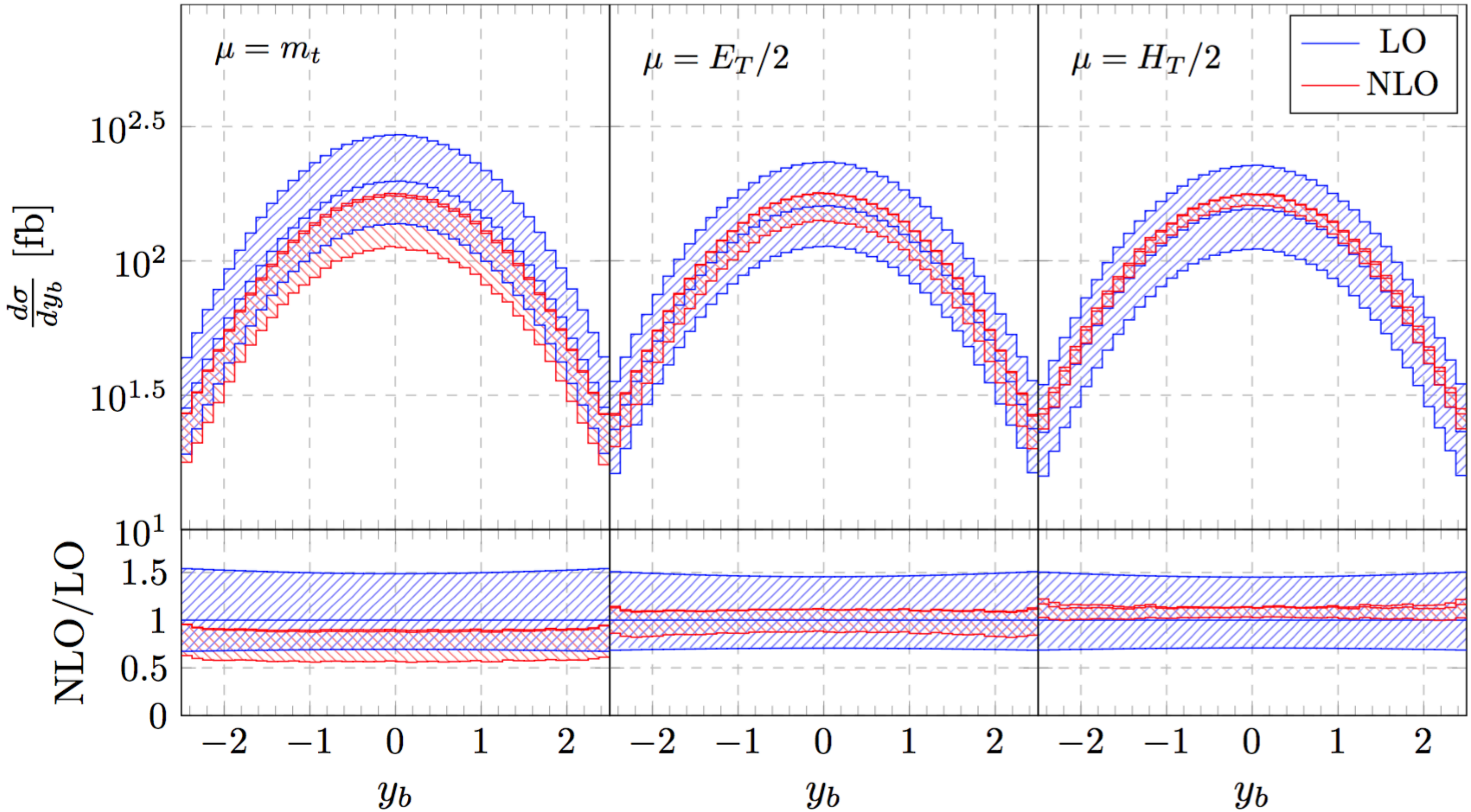
b-Jet Rapidity

- Dimensionless observable: $\mathbf{y_b}$
- Replaced by positive moderate NLO corrections for dynamical scales



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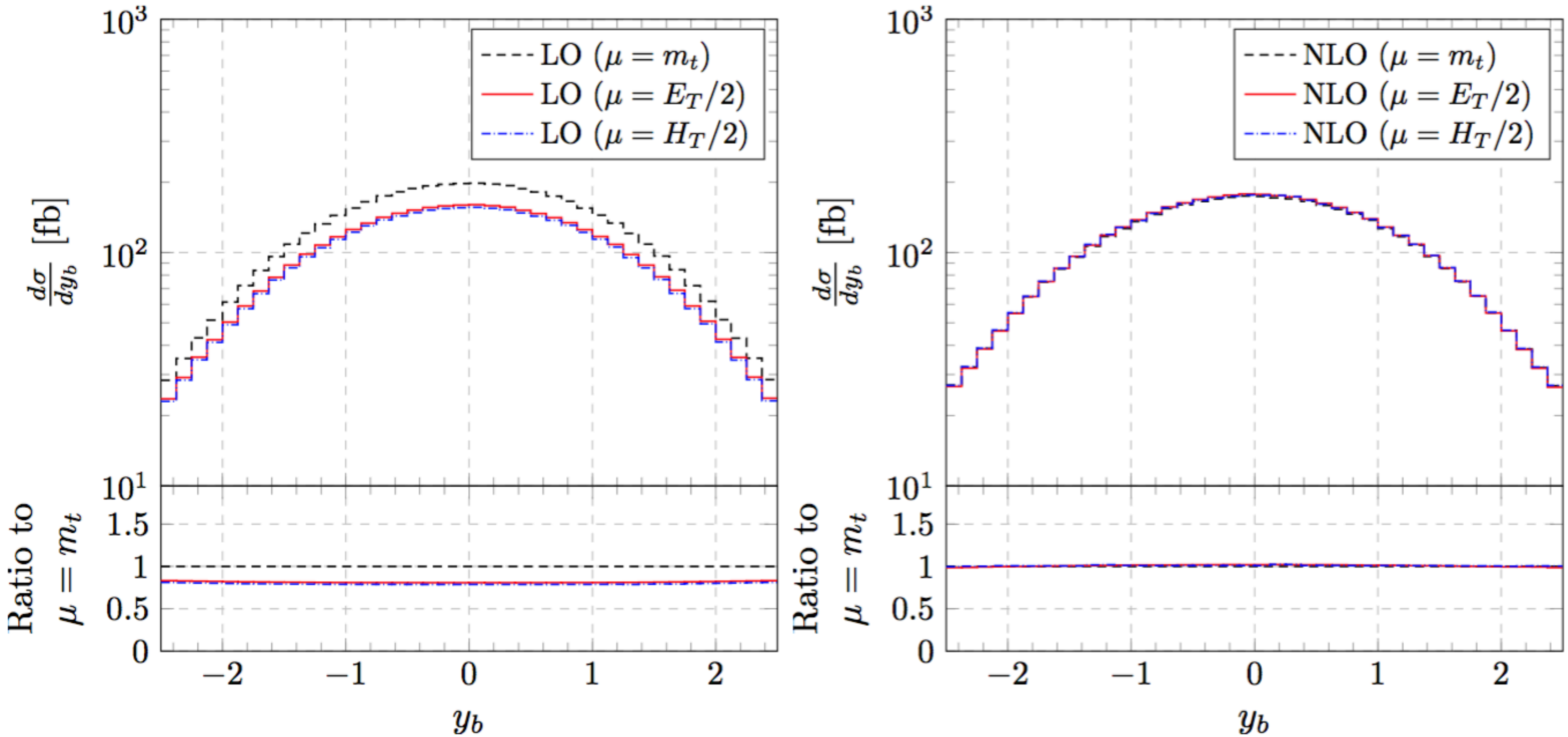
b-Jet Rapidity

- Central values & ratios to the fixed scale @ LO & @ NLO

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



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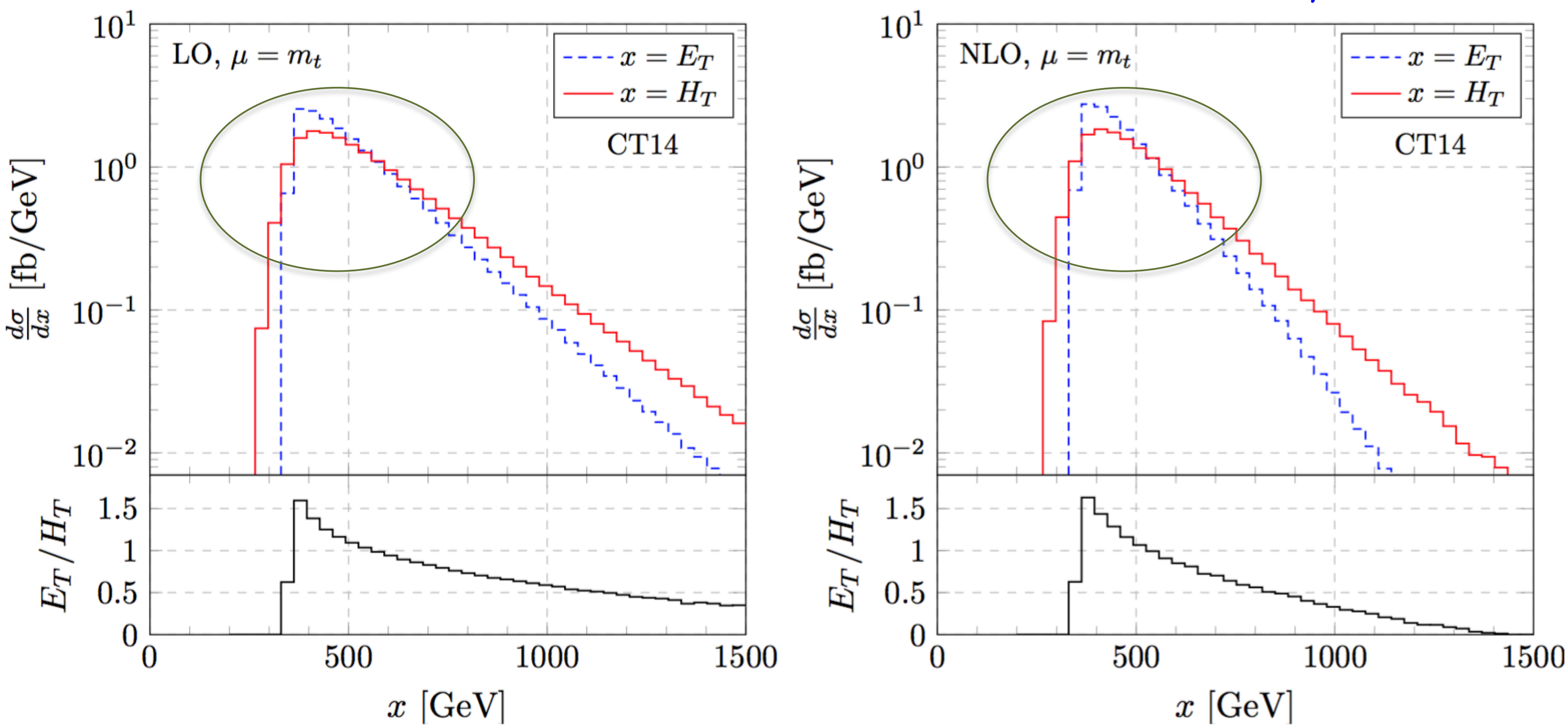
E_T & H_T

$$H_T = \sum_i p_{T,i} + p_T^{\text{miss}}$$

$$E_T = m_{T,t} + m_{T,\bar{t}}$$

- E_T and H_T @ LO & @ NLO as well as E_T / H_T ratio for $\mu_0 = m_t$

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



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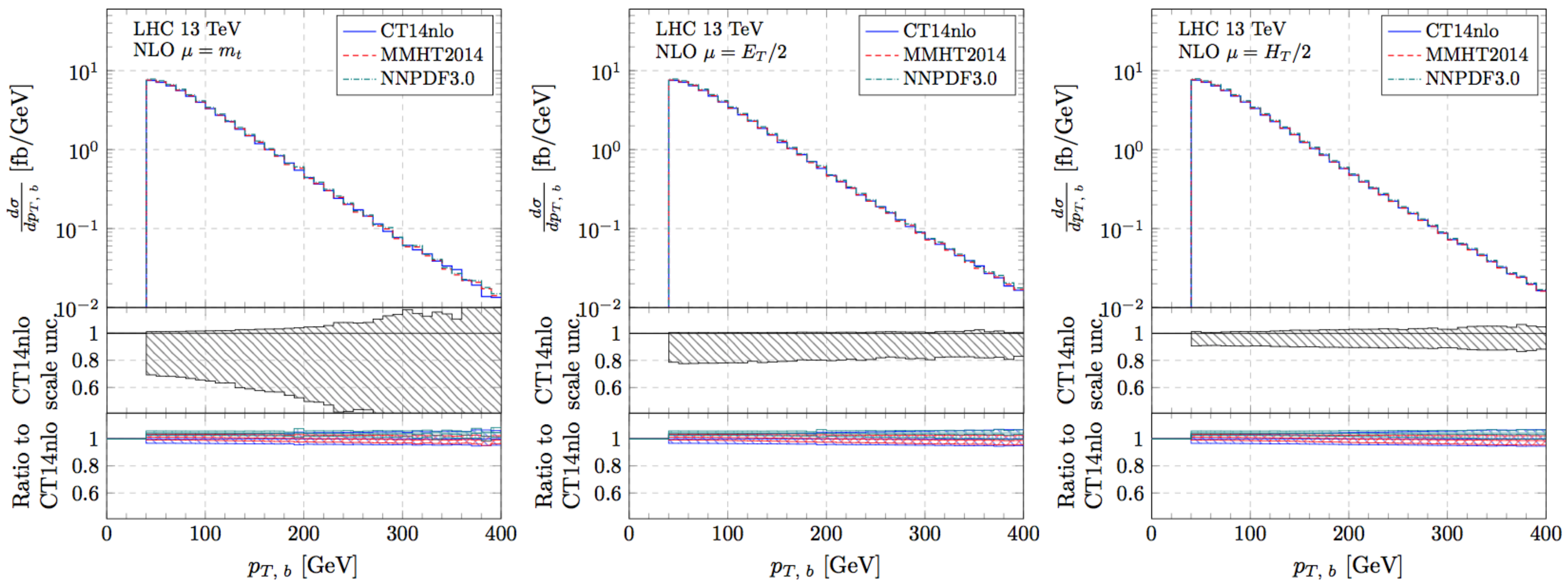
Uncertainties

- **Upper panel**
  - ✧ NLO prediction for three different PDF sets at $\mu_0=\mu_F=\mu_R$
- **Middle panel**
  - ✧ NLO scale-dependence band normalized to the central CT14 NLO
- **Lower panel**
  - ✧ PDF uncertainties obtained for each PDF set separately, normalized to the central NLO prediction with the CT14 PDF set



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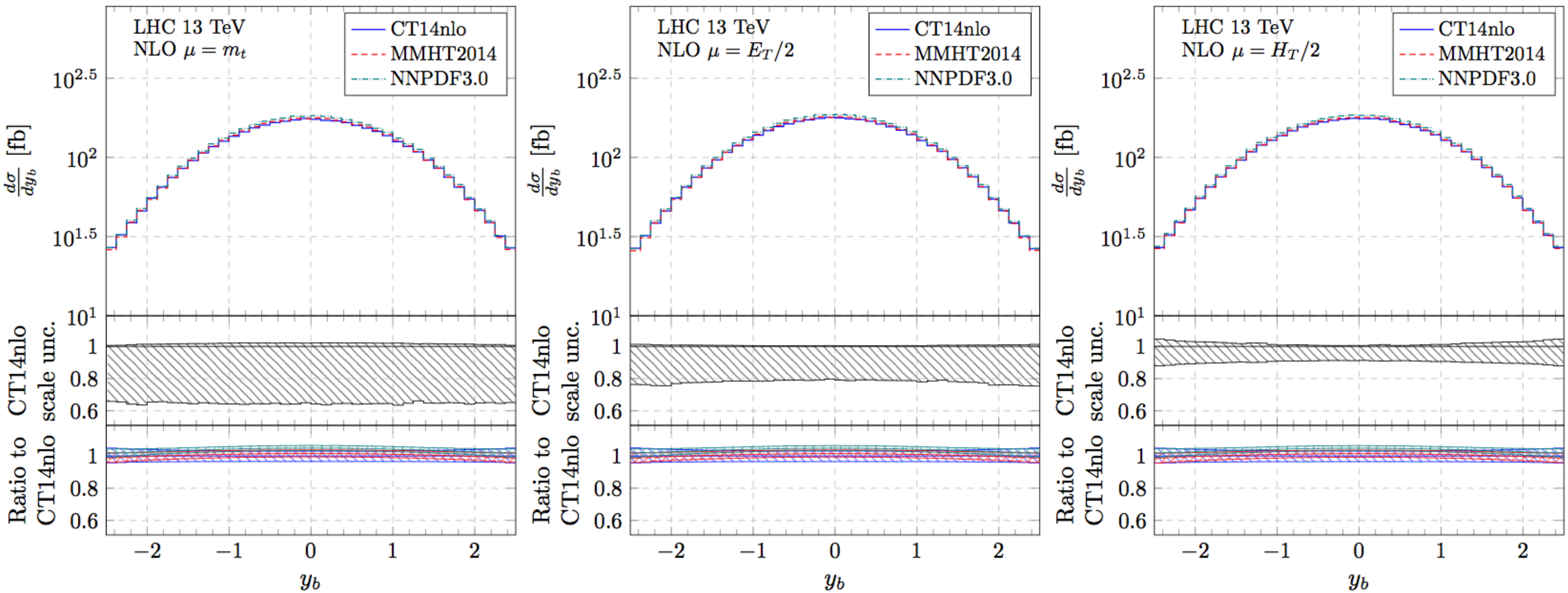
Uncertainties

- Transverse momentum distribution of the bottom-jet → For H_T scale uncertainties have reached almost 10% → PDF uncertainties stayed below 6%
- Rapidity distribution of the bottom-jet → For H_T scale uncertainties are below 8% → PDF uncertainties are in the range 3% − 5%



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Applications

- Alternative method for m_t
- m_t from normalized differential cross section for ttj

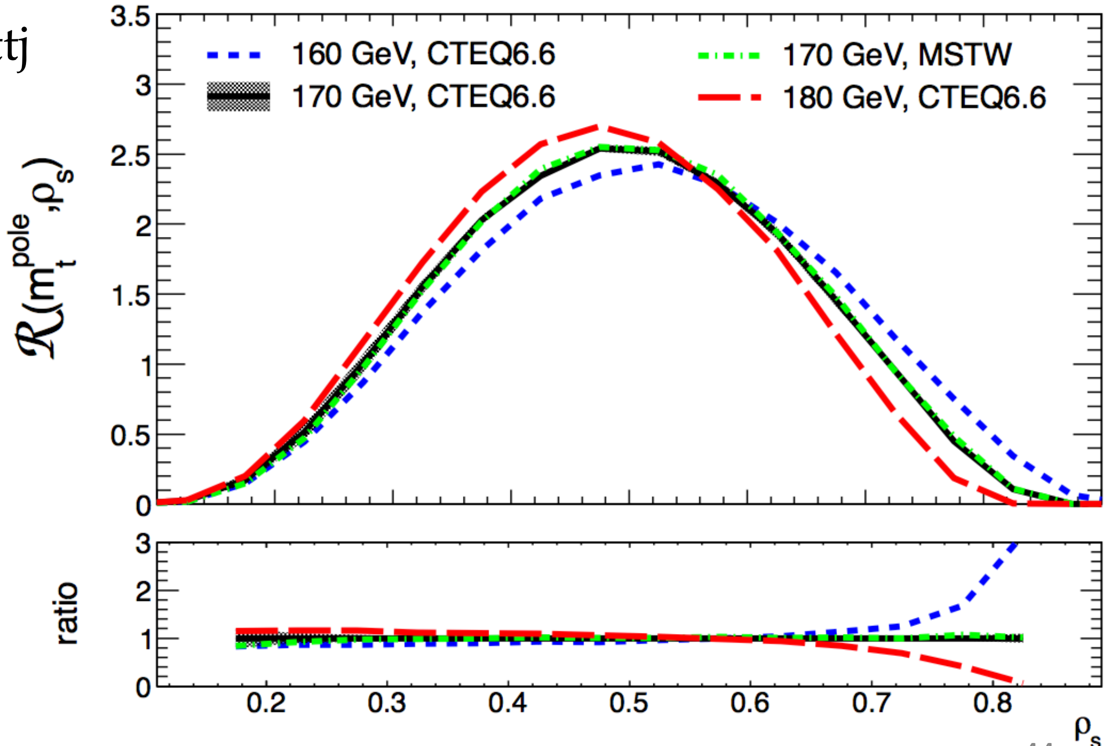
$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s)$$

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}.$$

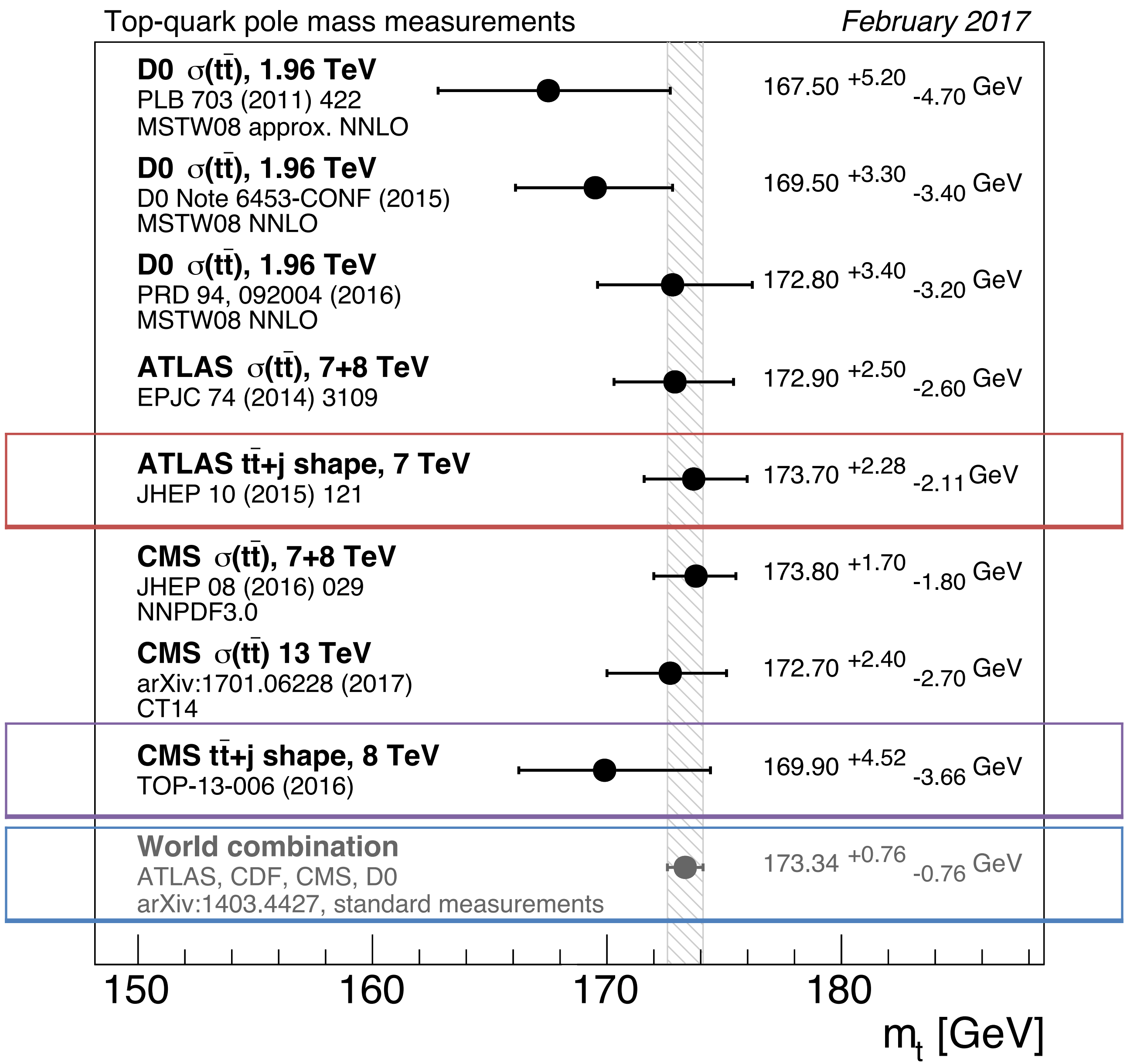
- $\mathcal{R}$ has been calculated using ttj @ NLO + **POWHEG** matched with **PYTHIA**
- Theoretical uncertainties & PDF uncertainties affect m_t extraction < 1 GeV

S. Alioli, et al. '13

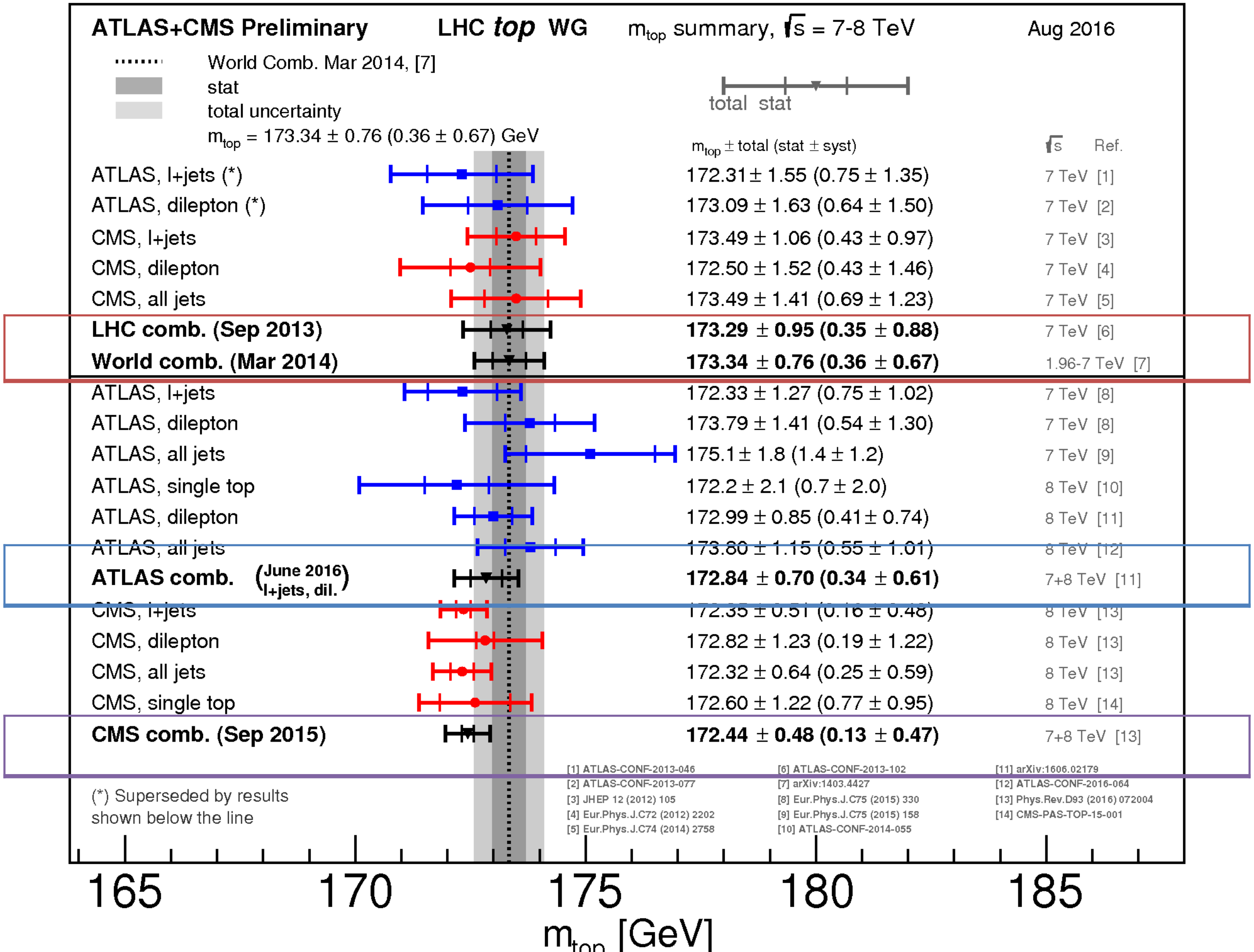
- Worth looking at …



Top Quark Mass



Top Quark Mass



Summary

- Complete description for ttj process with **HELAC-NLO**
  - ✧ "resonant" and "non-resonant" contributions at NLO QCD

- Various scales: **m_t & $E_T/2$ & $H_T/2$**
- **$H_T/2$** "better" than $E_T/2$ → both stabilizes tails but **$H_T/2$** gives smaller error

- Scale and PDF uncertainties for σ & various $d\sigma/dX$

- Further studies are needed:
  - ✧ Bottom-mass effects → comparisons between Five- & Four-Flavour schemes
  - ✧ Off-shell versus NWA effects for differential distributions

- Phenomenological applications → Alternative method for m_t extraction
  - ✧ Shape-based m_t measurement (e.g. the end point of M_{e+b} and/or ρ_s)
    - ❖ Relies on precise modeling of top-quark decays
  - ✧ Goal: m_t extraction < 1 GeV
  - ✧ For many predictions should go beyond simple approximation of factorizing top quark production & decays

Backup Slides

Ntuple

- Number of events, number of files, averaged number of events per file & total size per contribution for the different Ntuple samples

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

Contribution	Nr. of Events	Nr. of files	(avg) events/file	Size
Born	21×10^6	60	350×10^3	38 GB
Born + Virtual	33×10^6	380	87×10^3	72 GB
Integrated dipoles	80×10^6	450	178×10^3	160 GB
Real + Sub. Real	626×10^6	18000	35×10^3	1250 GB
Total:	760×10^6	18890	40×10^3	1520 GB

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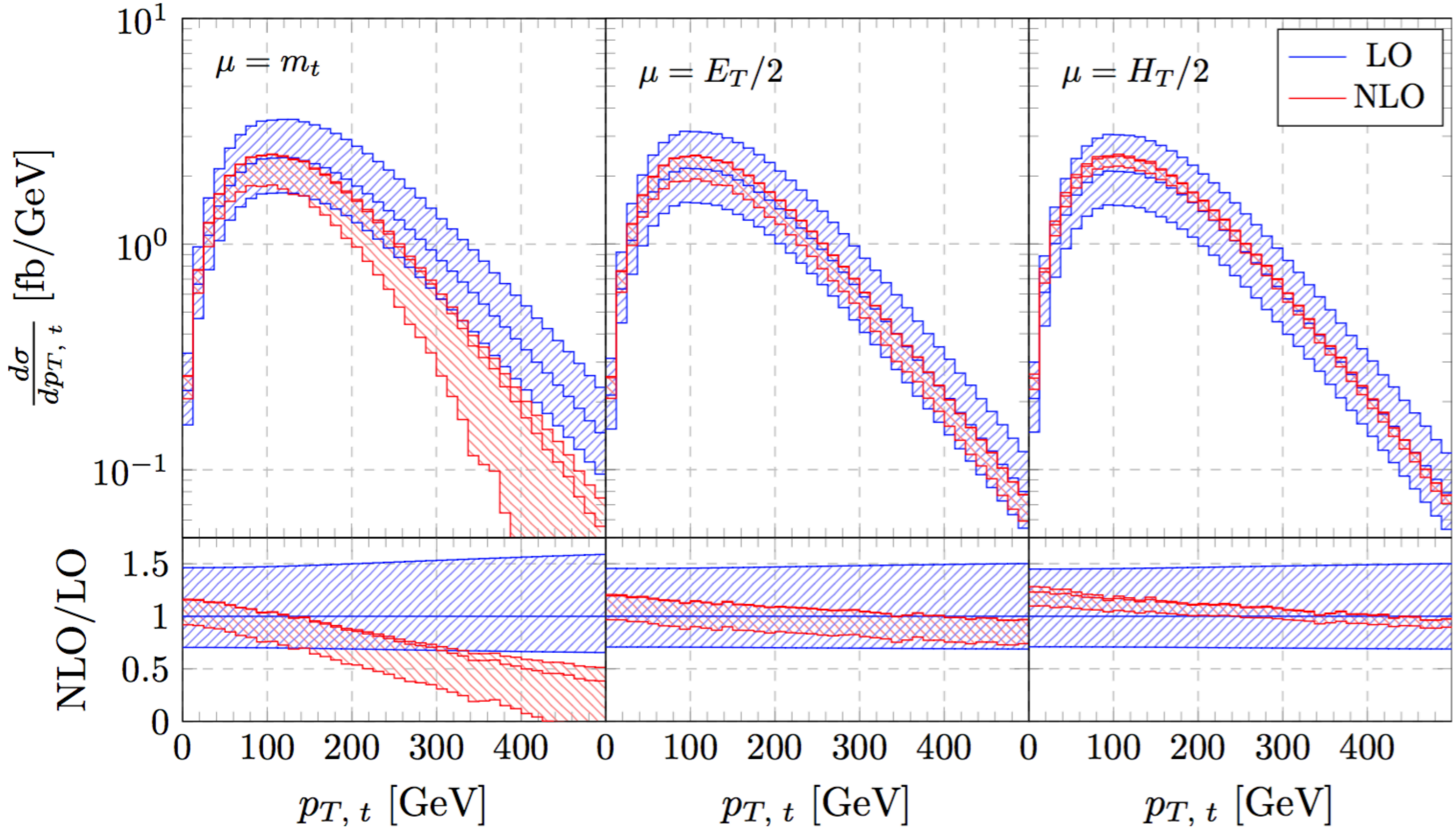
Top Quark



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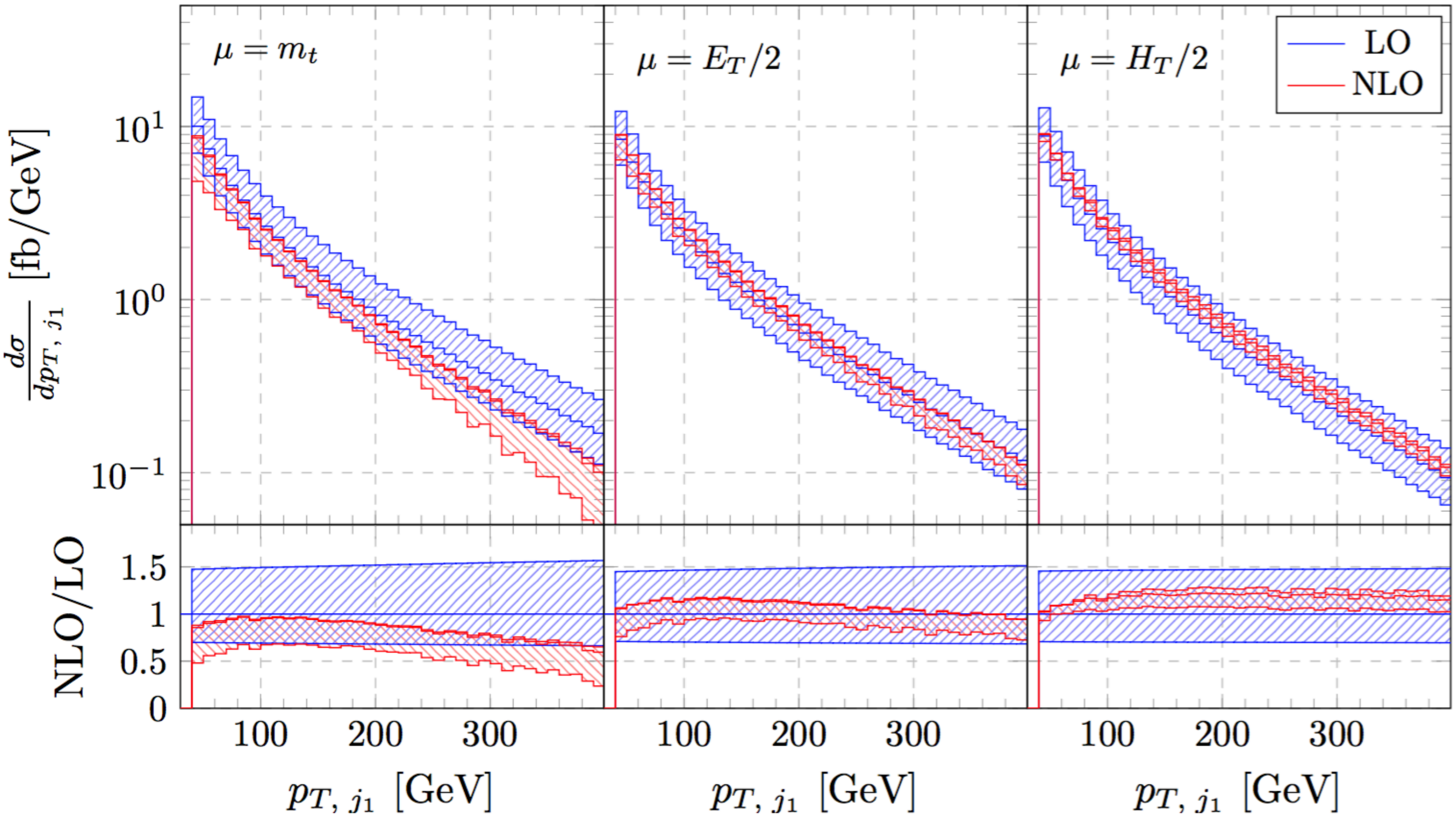
Hardest Light Jet



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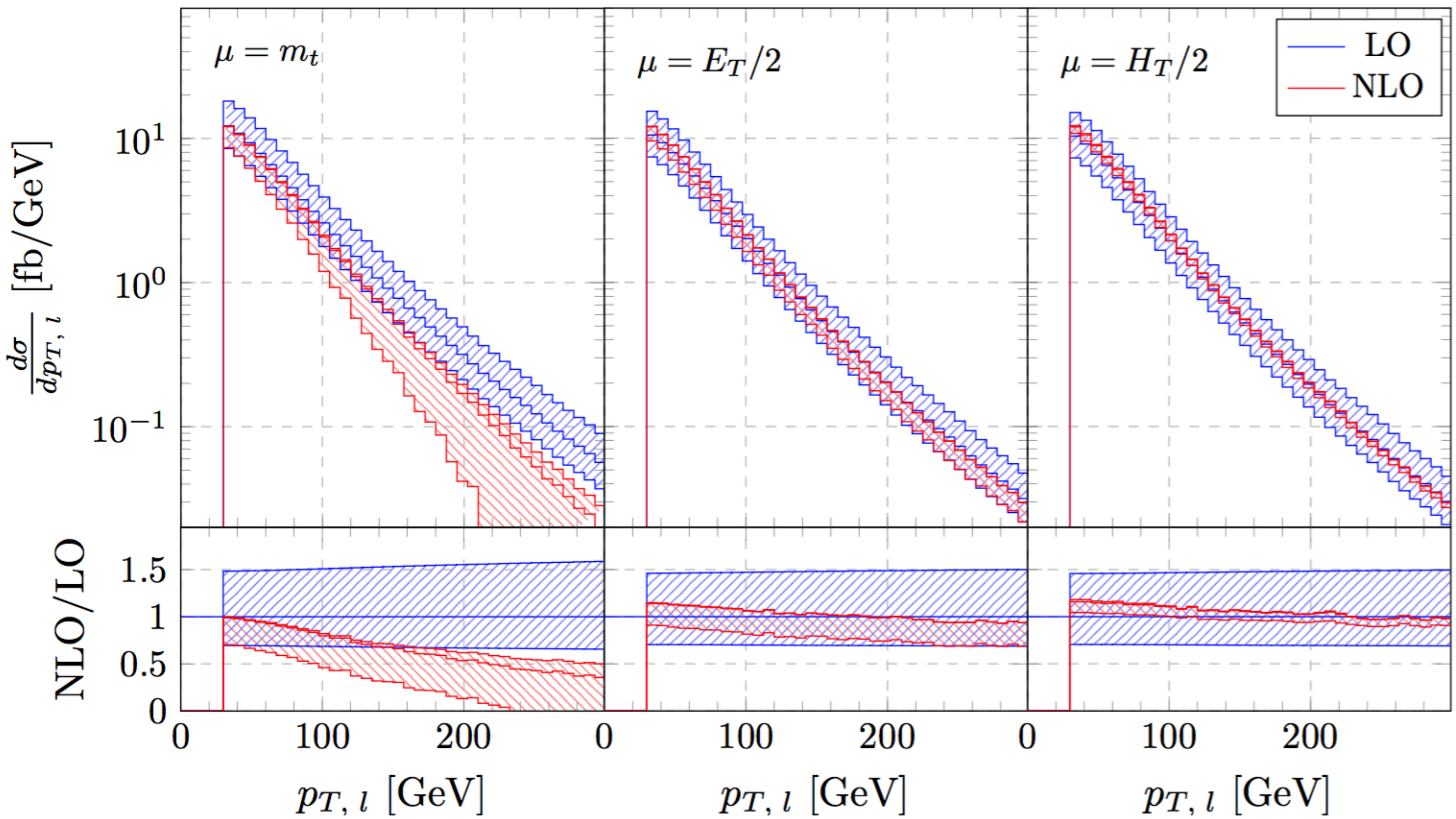
Lepton



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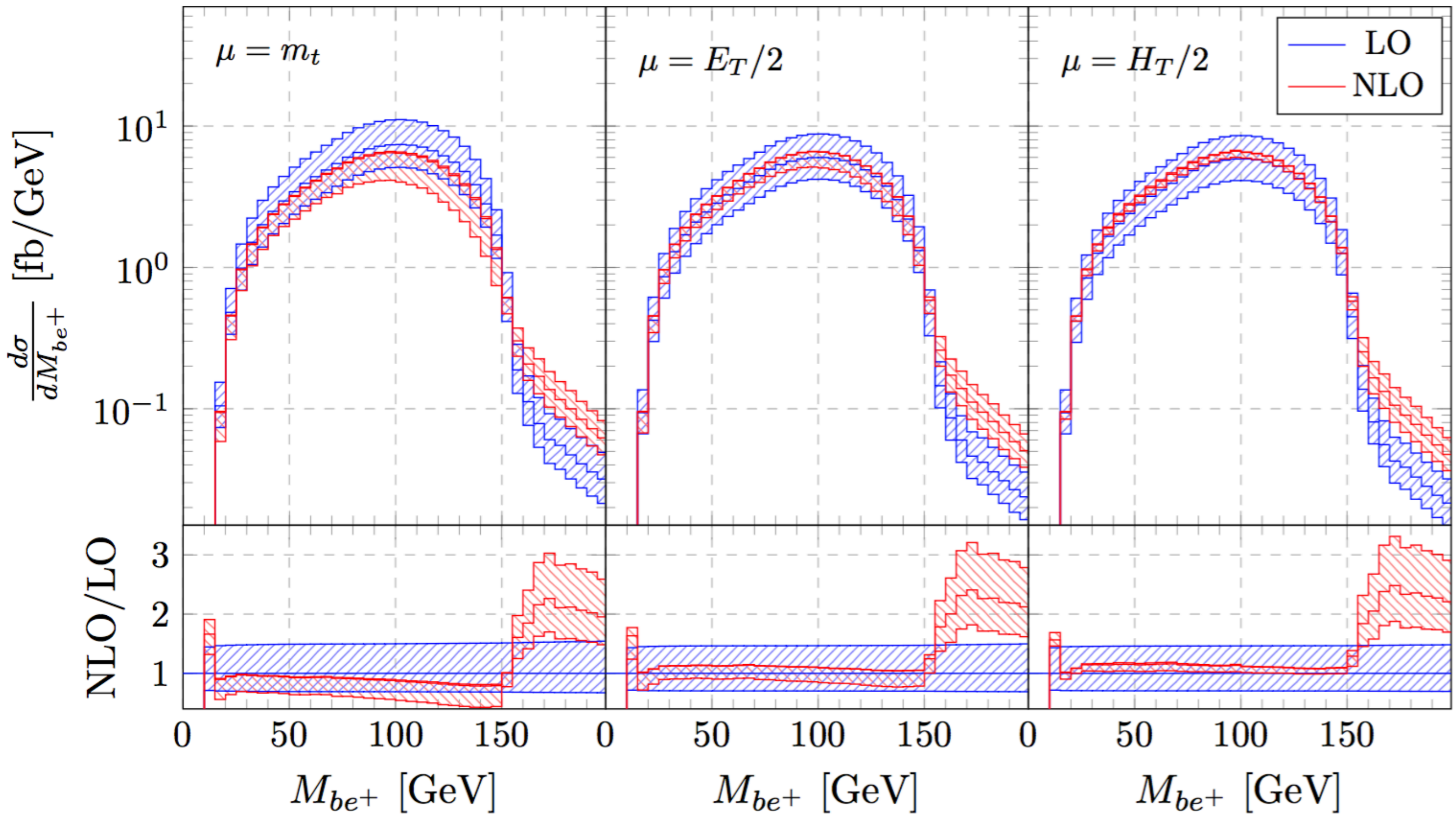
Lepton b-Jet System



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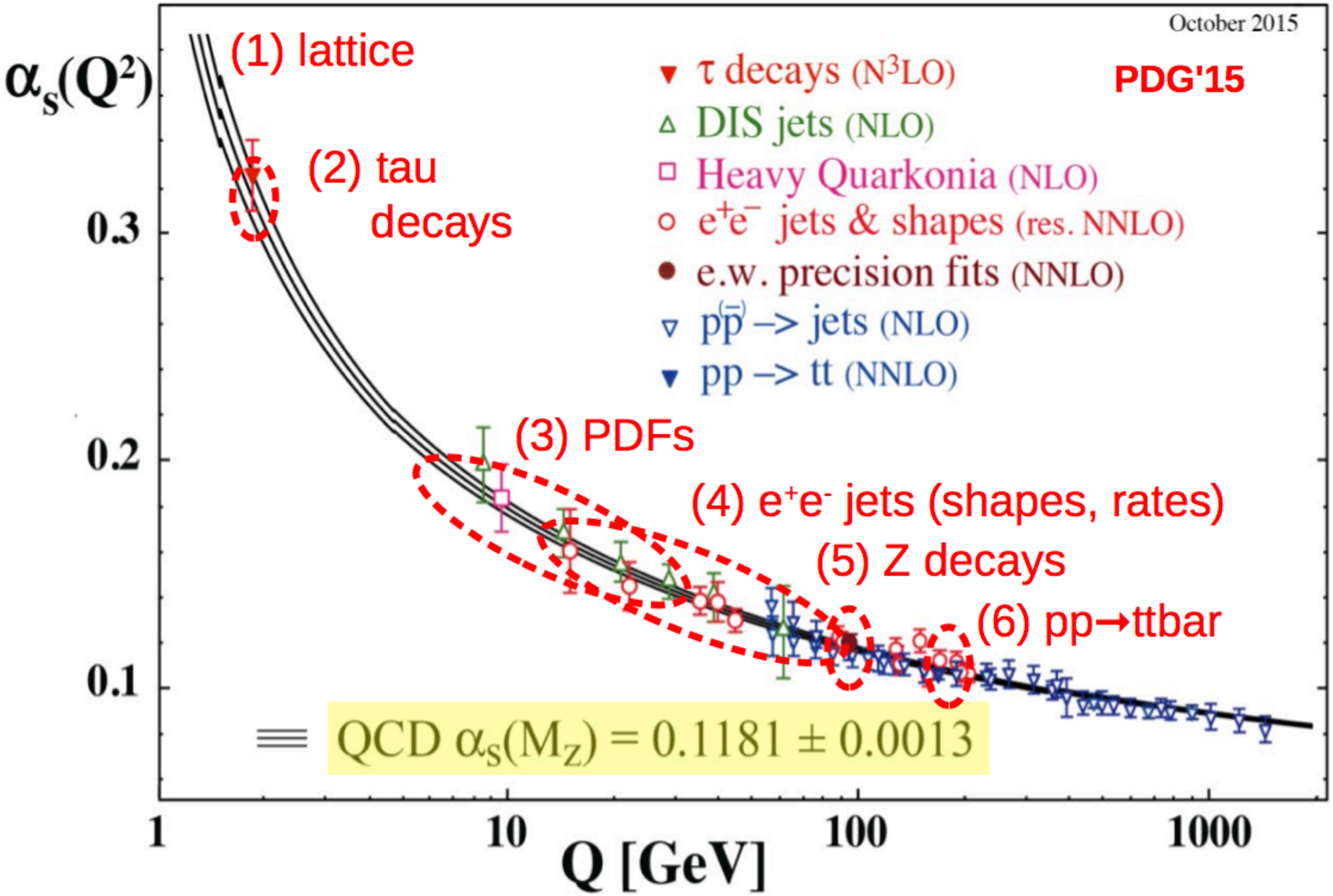
Status of α_s determination (PDG 2015)

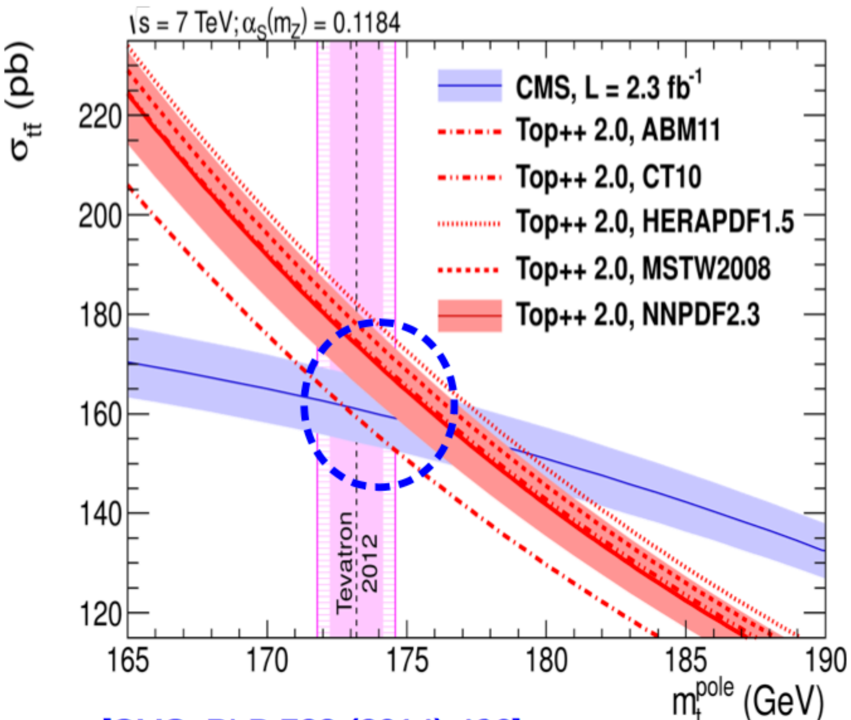
- Determined by comparing 6 experimental observables to pQCD NNLO, N^{3}LO predictions, plus performing a global average of their propagated values at the Z pole scale:



(6) α_s from top-pair p-p cross sections

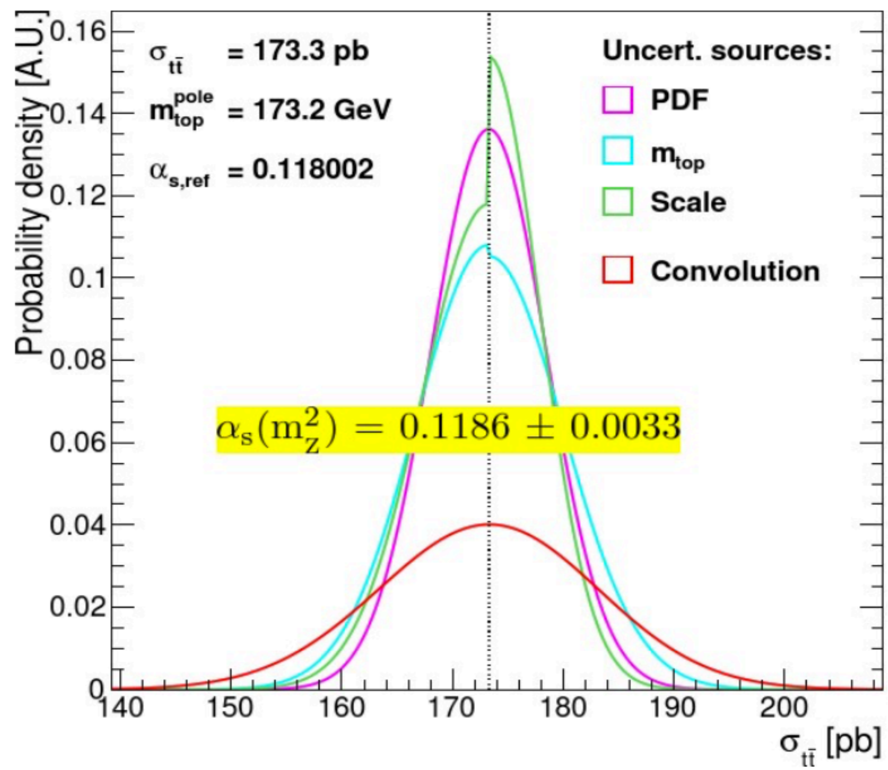
- Total top-antitop cross section (known at NNLO+NNLL) is the 1[st] p-p collider observable to constrain α_s at NNLO accuracy:

Data-theory x-section comparison for varying PDF+α_s as a function of m_{top}:



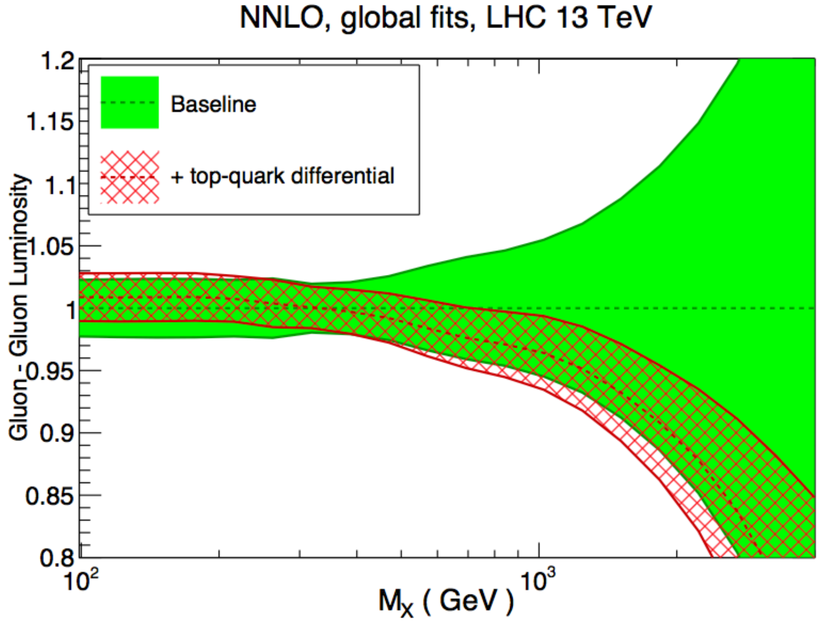
[CMS, PLB 728 (2014) 496]

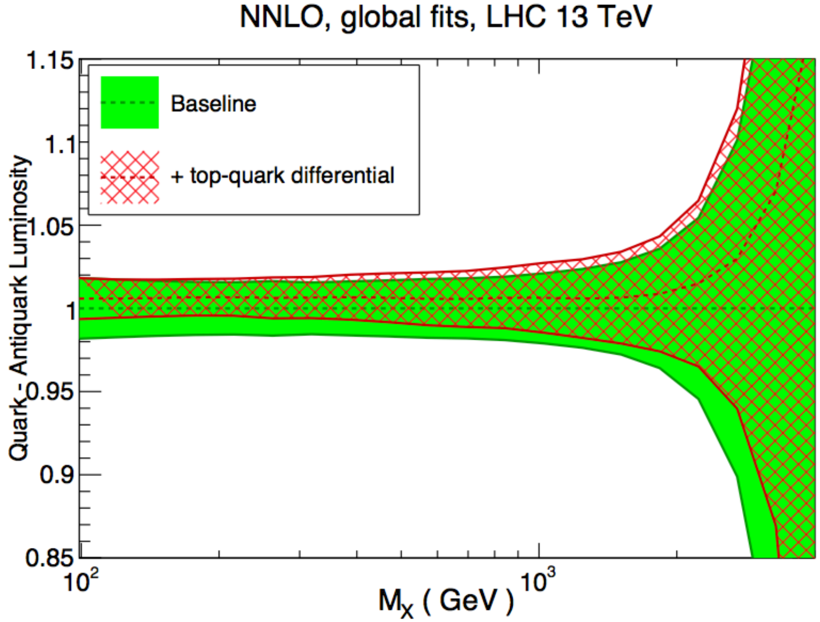
[G.Salam et al. arXiv:1512.05194]



Inclusion of full set of t-tbar data increases $\alpha_s(m_Z)$ & uncertainty: **±2.9%**

PDF





- Pinning down the large-x gluon with NNLO top-quark pair differential distributions
- The gluon-gluon and quark-antiquark NNLO luminosities as a function of the invariant mass M_X of the produced final state at the LHC with $\sqrt{s}$ = 13 TeV
- Global baseline fit is compared with the fit including the optimal combination of LHC top-quark pair differential data

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