Boosted Tops from EFT

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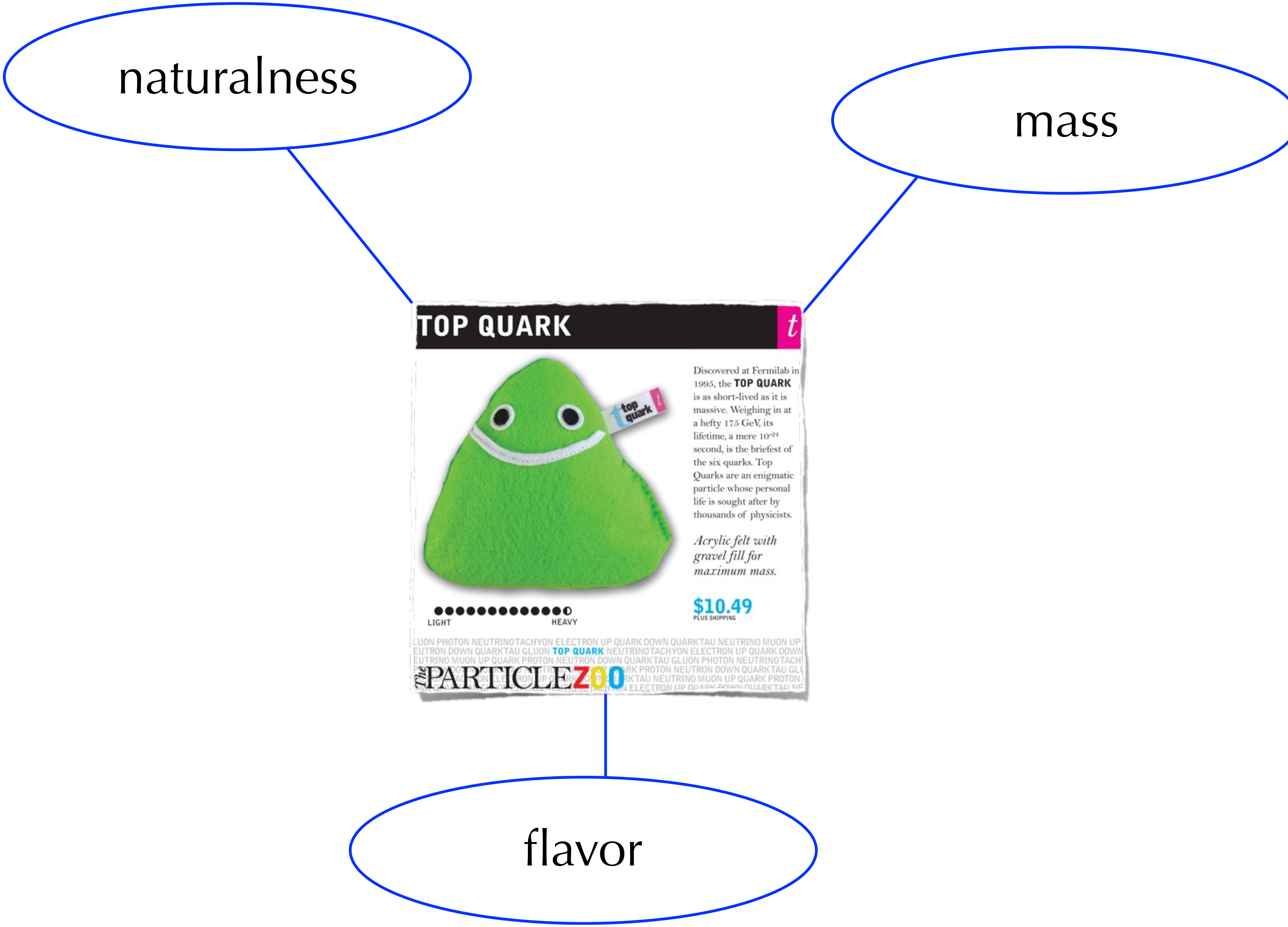
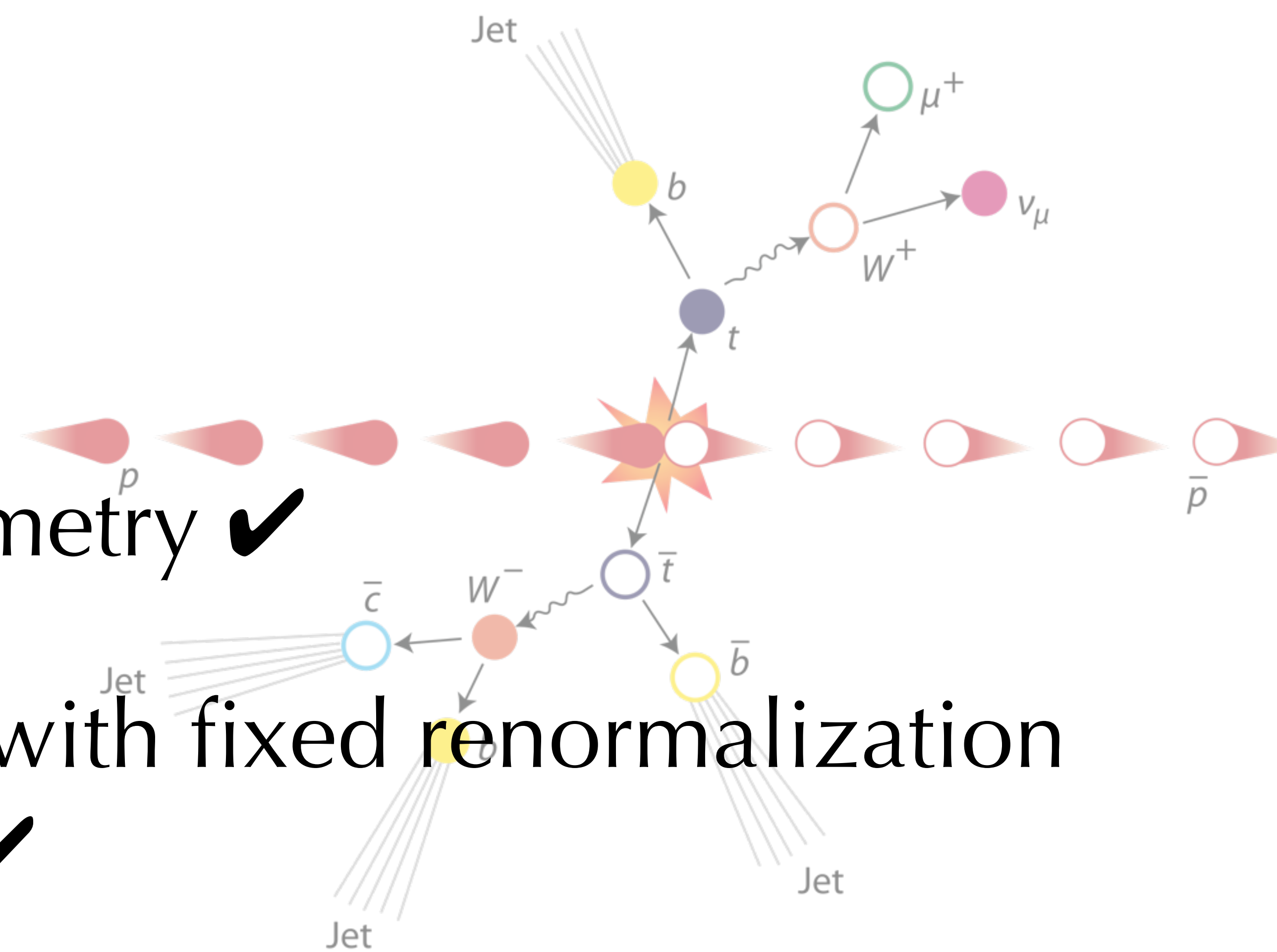
In collaboration with Andrea Ferroglia, Benjamin D. Pecjak, Darren J. Scott and Xing Wang


naturalness
mass
flavor
TOP QUARK
t
top quark
Discovered at Fermilab in 1995, the TOP QUARK is as short-lived as it is massive. Weighing in at a hefty 175 GeV, its lifetime, a mere 10-24 second, is the briefest of the six quarks. Top Quarks are an enigmatic particle whose personal life is sought after by thousands of physicists.
Acrylic felt with gravel fill for maximum mass.
LIGHT
HEAVY
$10.49
PLUS SHIPPING
The PARTICLE ZOO

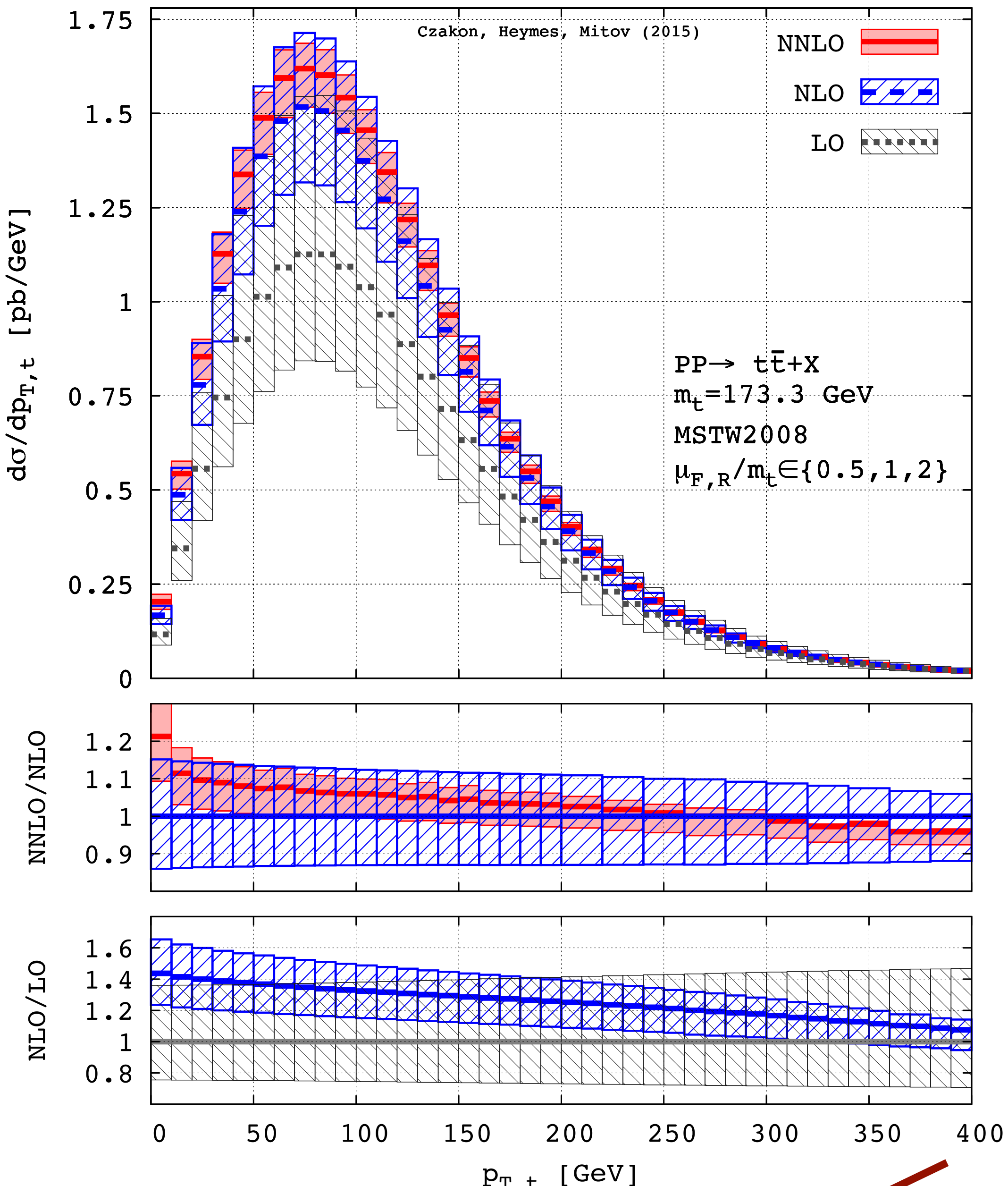
QCD@NNLO

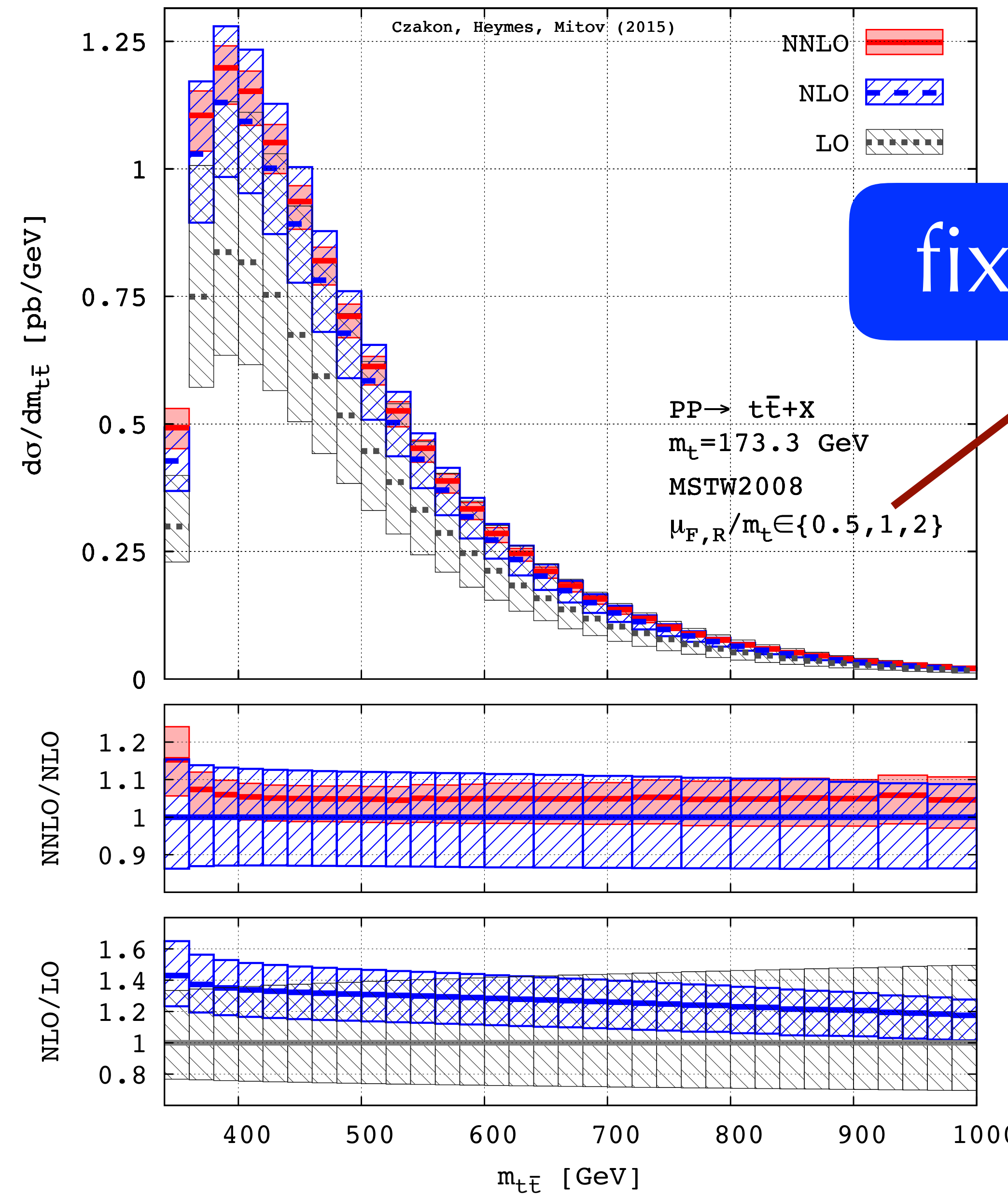
Bärnreuther, Czakon, Fiedler, Mitov (2012-2016)



- Total cross section ✔
- Forward-backward asymmetry ✔
- Differential distributions with fixed renormalization and factorization scales ✔

QCD@NNLO





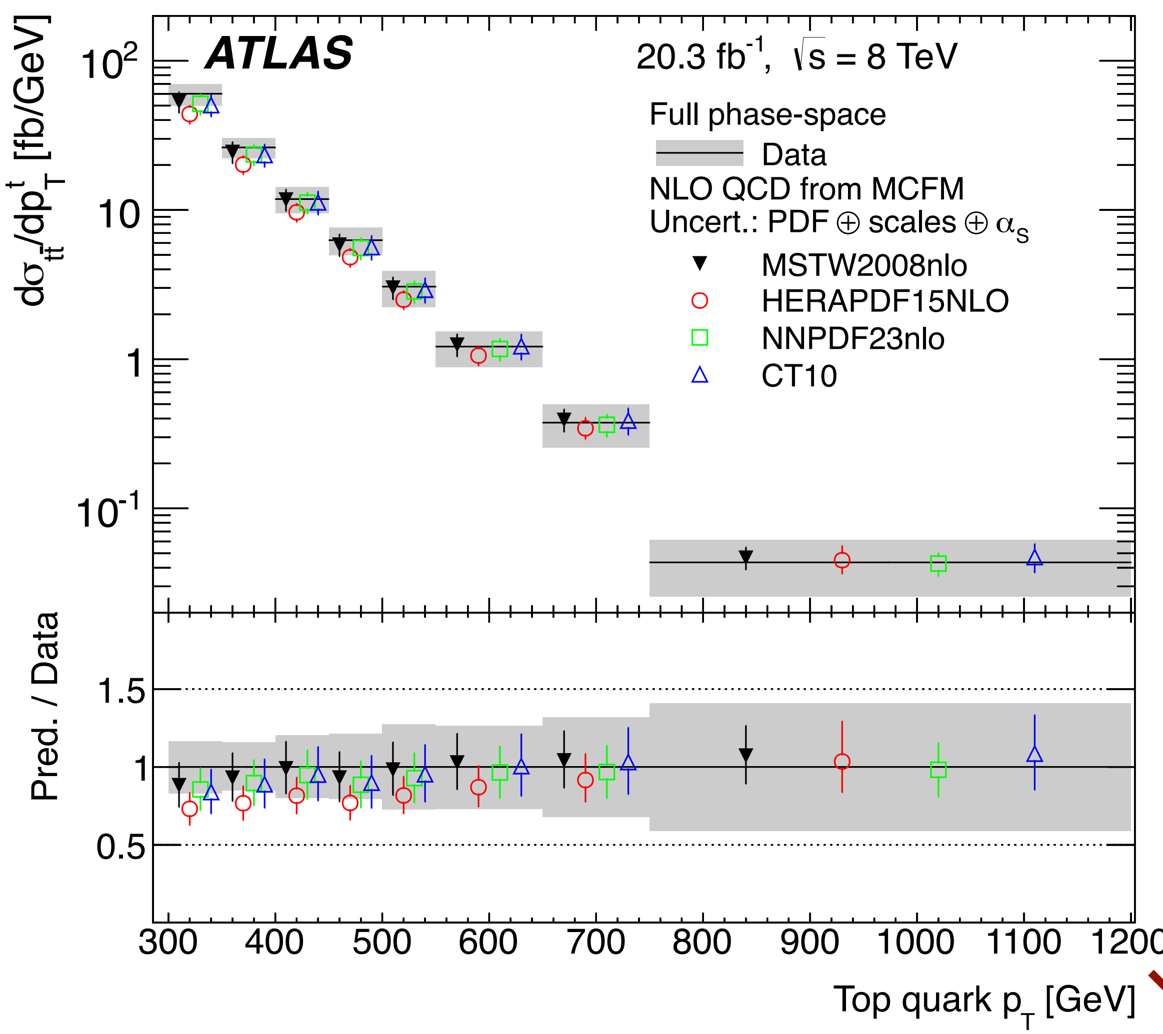
fixed scales

moderate energy

Czakon, Heymes, Mitov: 1511.00549

Experiments

arXiv:1510.03818



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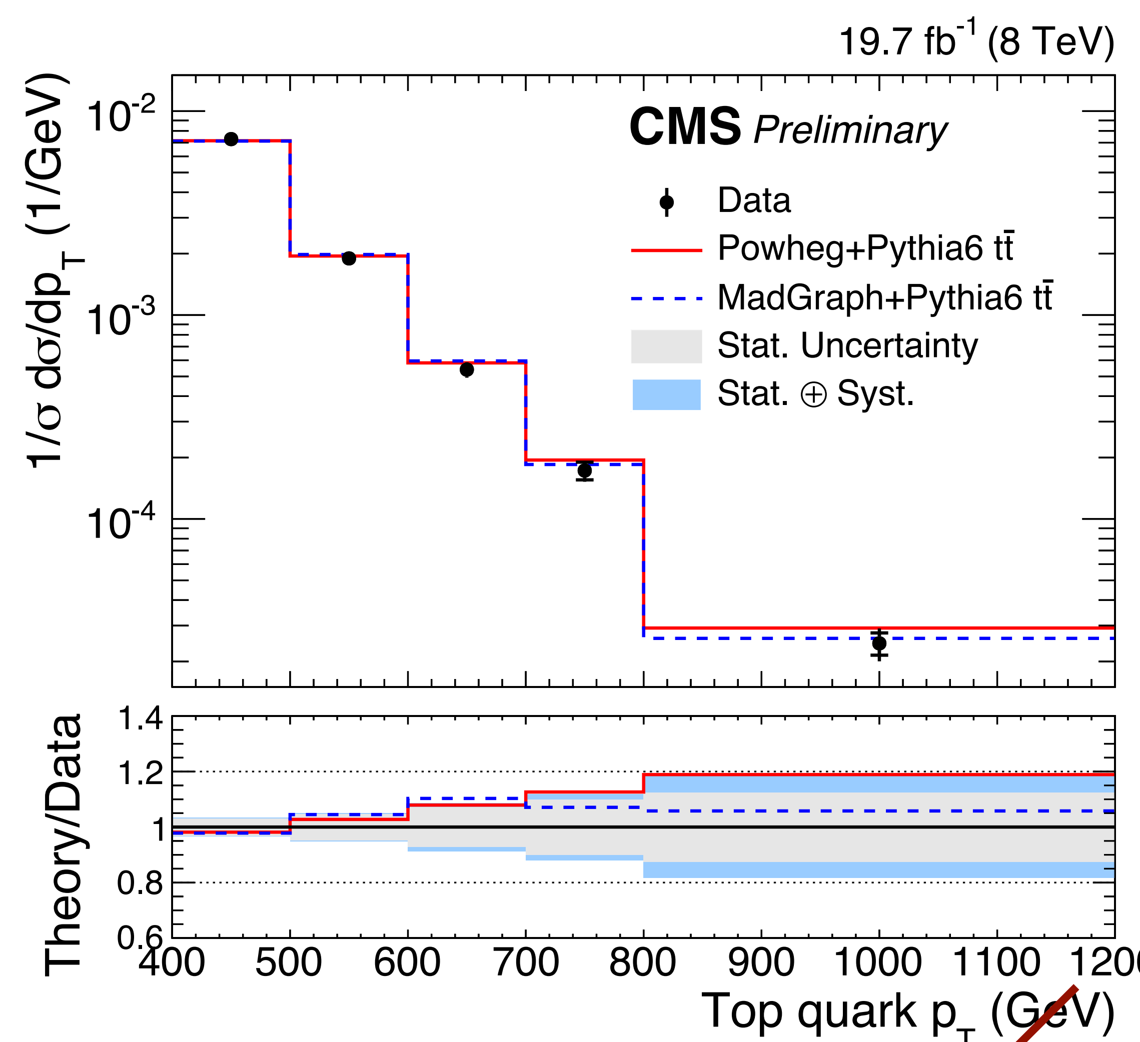
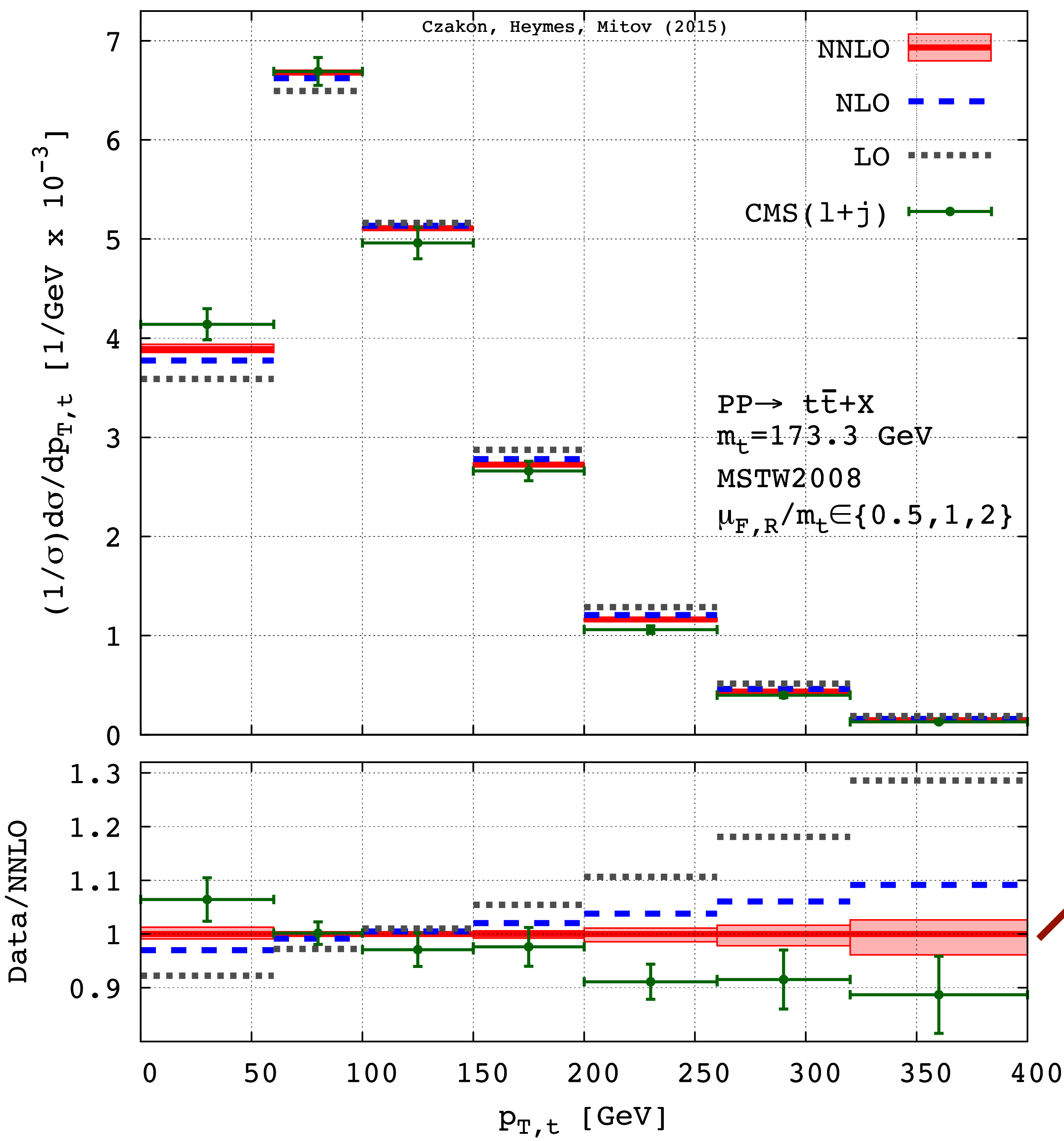


high energy (boosted)

Theory vs. Experiment



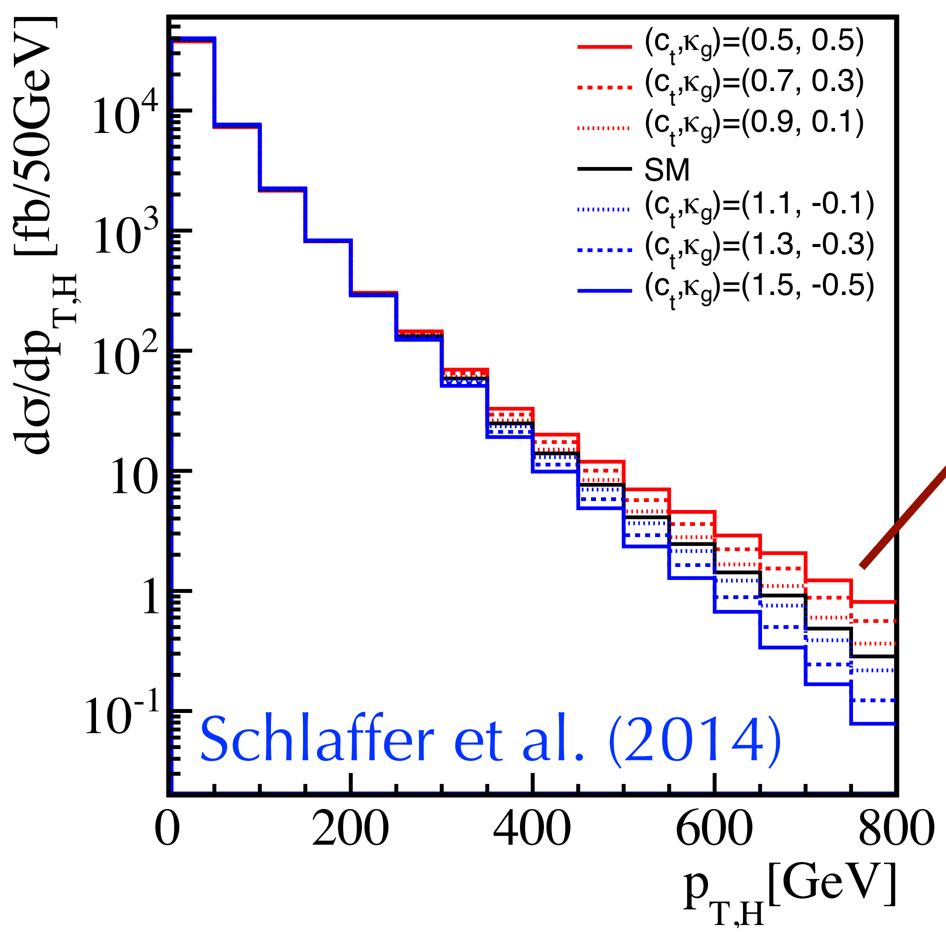
- Theoretical p_T spectrum (with fixed-scales) harder than data
- NNLO: marginal agreement

Higher p_T?
Higher orders?

Czakon, Heymes, Mitov: 1511.00549

Boosted kinematics

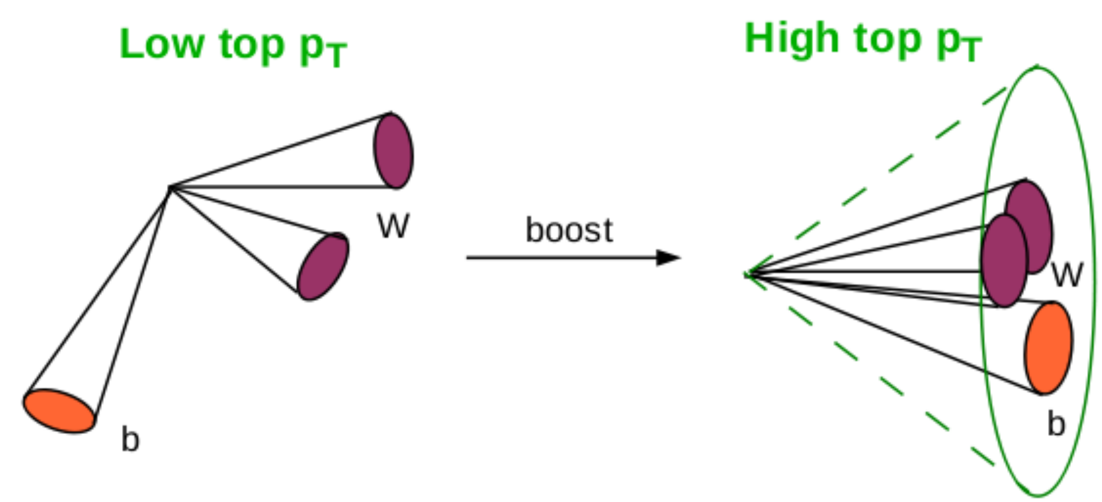
$$\mathcal{L} = \mathcal{L}_0 + \sum_{n,i} \frac{c_{n,i}}{\Lambda^{4+n}} O_{n,i}$$

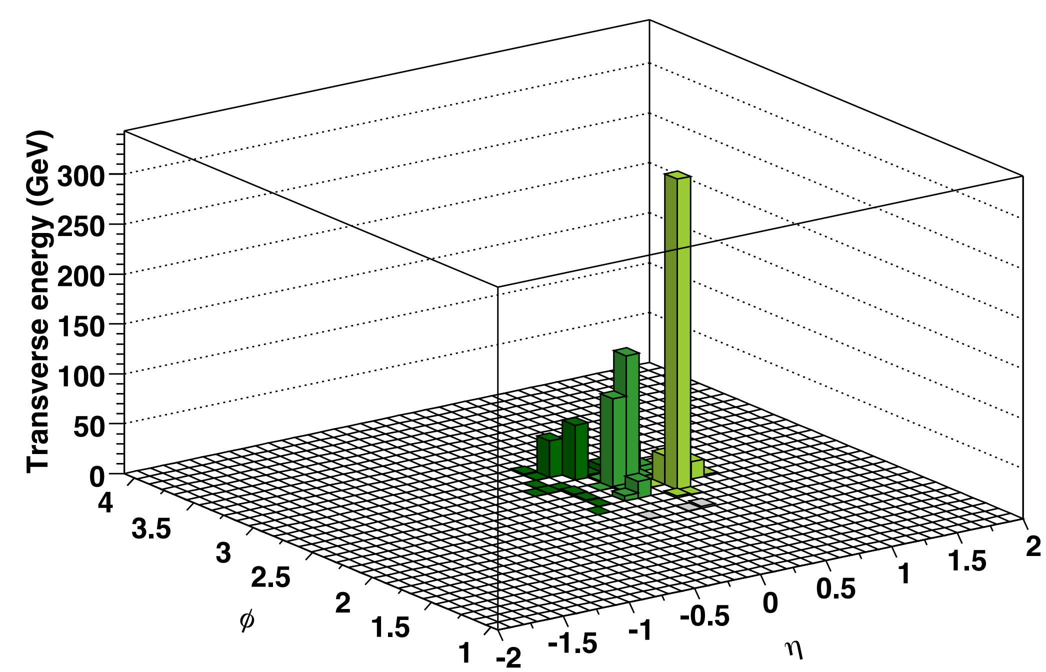


- Tails of distributions sensitive to new physics
- Testing the SM in the energy frontier
- Important background to BSM scenarios

Tagging boosted tops

- Moderately-boosted tops: substructures of fat jets
  - John-Hopkins Top Tagger: Kaplan, Tehermann, Schwartz, Tweedie (2008)
  - HEP Top Tagger: Plehn, Spannowsky, Takeuchi, Zerwas (2010)
- Highly-boosted tops at 13 TeV
  - Schätzel, Spannowsky (2013)
- Hyper-boosted tops at 100 TeV?
  - Larkoski, Maltoni, Selvaggi (2015)





Producing boosted tops

Two dangerous contributions

soft gluons

quasi-collinear gluons

$$\ln \frac{\hat{s} - M_{t\bar{t}}^2}{M_{t\bar{t}}^2}$$

$$\ln \frac{m_t^2}{M_{t\bar{t}}^2}$$

A tale of three scales

$$\hat{\sigma}\left(M_{t\bar{t}}^2, \hat{s} - M_{t\bar{t}}^2, m_t^2, \mu_f^2\right)$$

Mellin/Laplace transform

$$\hat{\sigma}\left(M_{t\bar{t}}^2, M_{t\bar{t}}^2/\bar{N}^2, m_t^2, \mu_f^2\right) \ni \ln\frac{M_{t\bar{t}}^2}{\mu_f^2}, \ln\frac{M_{t\bar{t}}^2}{\bar{N}^2\mu_f^2}, \ln\frac{m_t^2}{\mu_f^2}$$

Question: what should μ_f be?

No good answer!

Factorization?

Factorization of scales

Separating two scales at NLO is simple:

$$1 + \alpha_s \left(\ln \frac{Q_1^2}{\mu^2} + \ln \frac{Q_2^2}{\mu^2} \right) \approx \left(1 + \alpha_s \ln \frac{Q_1^2}{\mu^2} \right) \left(1 + \alpha_s \ln \frac{Q_2^2}{\mu^2} \right)$$

However

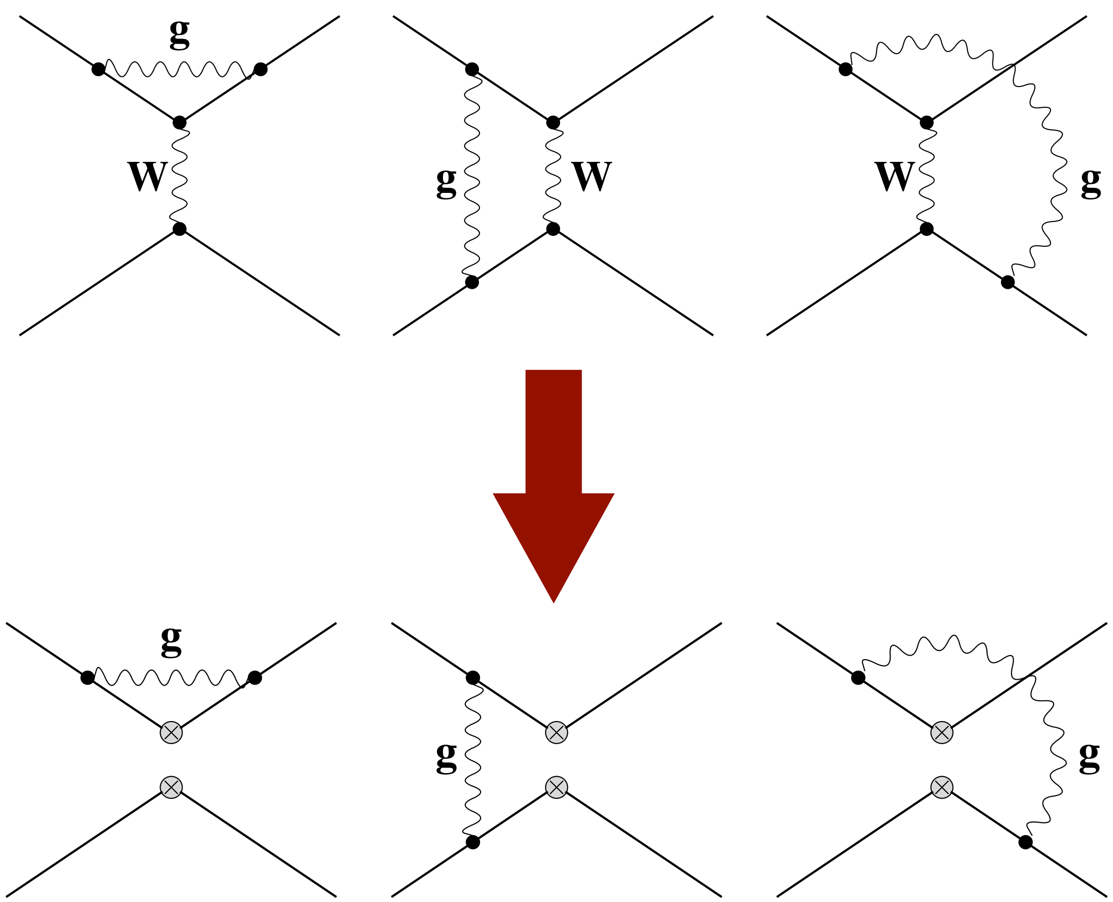
- Valid at higher orders?
- Power corrections: a price to pay $\longrightarrow \left(\frac{Q_1}{Q_2} \right)^p$

Need a systematic framework!

Effective Field Theory

Systematic framework to deal with multi-scale problems in Wilson's RG approach

Classic example: weak decays

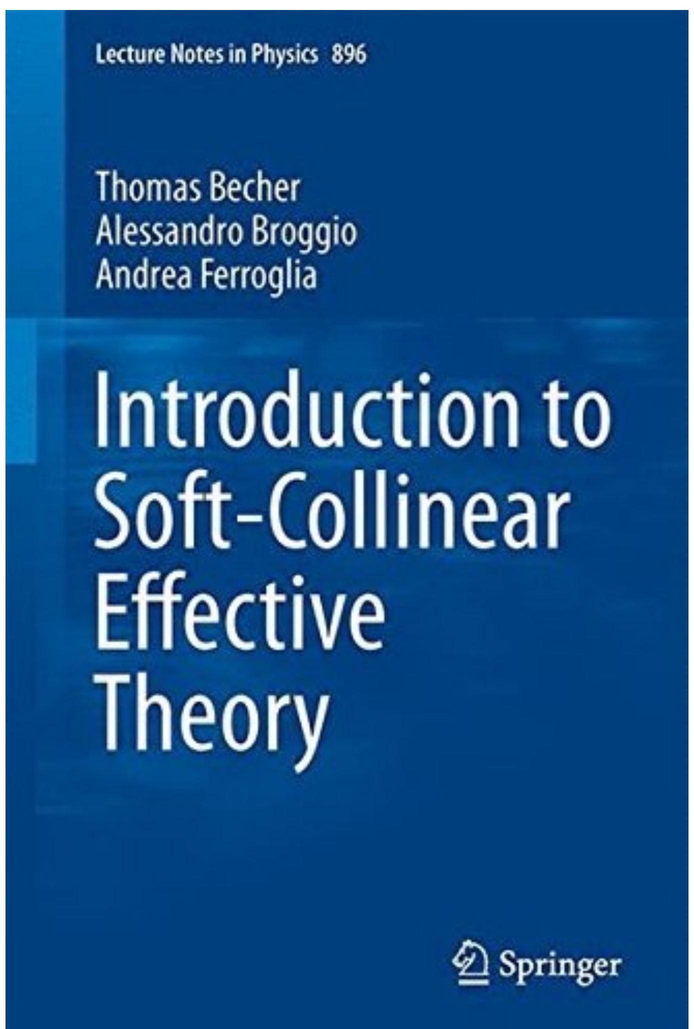


Here: soft-collinear effective theory (SCET)

Bauer, Flemming, Pirjol, Stewart (2001);
Beneke, Chapovsky, Diehl, Feldmann (2002)

Introducing SCET

- Low energy effective theory of QCD
- A field-theoretic language for soft and collinear modes



arXiv:1410.1892v2 [hep-ph] 27 Apr 2015

Introduction to Soft-Collinear Effective Theory

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Abstract: These lectures provide an introduction to Soft-Collinear Effective Theory. After discussing the expansion of Feynman diagrams around the high-energy limit, the effective Lagrangian is constructed, first for a scalar theory, then for QCD. The underlying concepts are illustrated with the Sudakov form factor, i.e. the quark vector form factor at large momentum transfer. We then apply the formalism in two examples: We perform soft gluon resummation as well as transverse-momentum resummation for the Drell-Yan process using renormalization group evolution in SCET, and we derive the infrared structure of n-point gauge theory amplitudes by relating them to effective theory operators. We conclude with an overview of the different applications of the effective theory.

Keywords: Effective field theory, QCD, renormalization group

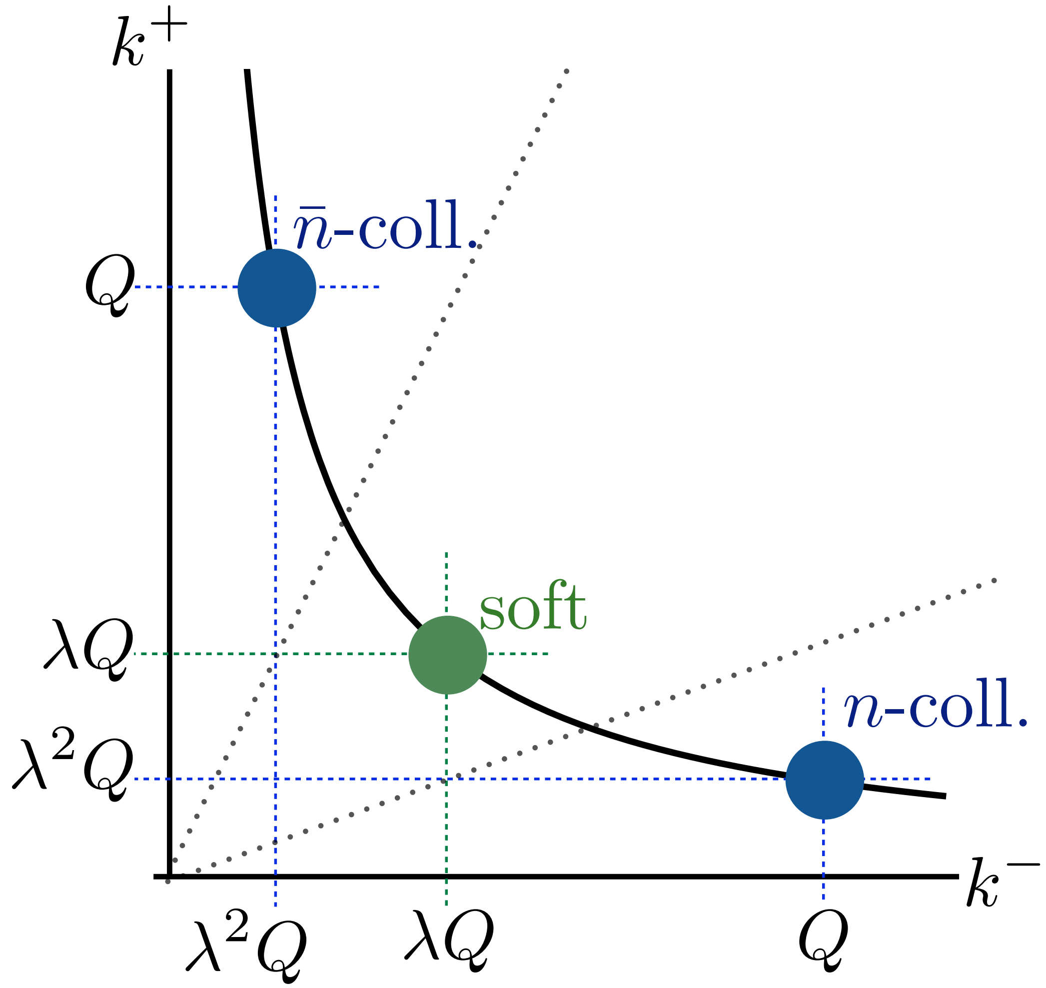
ArXiv ePrint: 1410.1892

Applications of SCET

* Factorization and resummation
* Infrared singularities of scattering amplitudes
* Subtraction methods for NNLO calculations
* Jets: event shapes, jet cross sections, jet substructures, non-global logarithms…
* TMD PDFs

TMD PDFs

Rapidity divergences or why TMD PDFs are difficult



A Lorentz invariant regulator (like DREG) cannot distinguish collinear, anti-collinear and soft!

"rapidity divergences"
or
"light-cone singularities"

Additional regulator required!

Regulators

- Off-the-light-cone: Collins, Soper; Ji, Ma, Yuan; Collins; Li, Wang

See also talk by H. N. Li

- On-the-light-cone (mostly from the SCET community)
  - Becher, Neubert (2009); Becher, Bell (2011)
  - Chiu, Jain, Neill, Rothstein (2011, 2012)
  - Echevarria, Idilbi, Scimemi (2011)
  - Li, Zhu (2016)

Two regimes for TMD PDFs

Genuinely non-perturbative $\Lambda \sim Q_T \longleftrightarrow \Lambda \sim 1/x_T$

Modeling + data fitting

Semi-perturbative $\Lambda \ll Q_T \longleftrightarrow \Lambda \ll 1/x_T$

Further separation of these two scales:
perturbative matching to collinear PDFs!

$$\tilde{B}_{a/A}(\Lambda, Q_T) \sim \tilde{I}_{ac}(Q_T) \otimes f_{c/A}(\Lambda)$$

Important for Q_T resummation!

TMD PDFs @ NNLO

$$\tilde{B}_{a/A}(\Lambda, Q_T) \sim \tilde{I}_{ac}(Q_T) \otimes f_{c/A}(\Lambda)$$

Calculated at two-loop Gehrmann, Lübbert, **LLY**: 1209.0682, 1403.6451

First validation of TMD framework at NNLO!

Other calculations:

Echevarria, Scimemi, Vladimirov (2015)
Lübbert, Oredsson, Stahlhofen (2016)
LLY, Zhu (in preparation)

However, only unpolarized at leading twist!
Open question: polarized / higher twists?

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Hard-soft Factorization

Ahrens, Ferroglia, Neubert, Pecjak, **LLY**: 1003.5827

Soft limit: M ~ $m_t \gg M/N$

$$\hat{\sigma}(N,\mu_f) \sim \mathrm{Tr}\big[\boldsymbol{H}(L_h,\mu_f)\,\boldsymbol{S}(L_s,\mu_f)\big]$$

$$\ln\frac{M^2}{\mu_f^2} \qquad\qquad \ln\frac{M^2}{\bar{N}^2\mu_f^2}$$

Applications to many other processes such as ttH:
Broggio, Ferroglia, Pecjak, Signer, **LLY**, 1510.01914

Hard-collinear factorization

Mele, Nason (1991)

Small-mass limit: $M \gg m_t$

perturbative fragmentation function

$$\hat{\sigma}(\mu_f) \sim C(L_h, \mu_f) \otimes D_t(L_c, \mu_f) \otimes D_{\bar{t}}(L_c, \mu_f)$$

$$\ln \frac{M^2}{\mu_f^2} \qquad \ln \frac{m_t^2}{\mu_f^2}$$

Double factorization

Ferroglia, Pecjak, **LLY**: 1205.3662

Boosted limit: $M \gg M/N$, m_t

$$\hat{\sigma}(N,\mu_f) \sim \mathrm{Tr}\big[\boldsymbol{H}(L_h,\mu_f)\,\boldsymbol{S}(L_s,\mu_f)\big]\,C_D^2(L_c,\mu_f)\,S_D^2(L_{sc},\mu_f)$$

$$\ln\frac{M^2}{\mu_f^2} \qquad \ln\frac{M^2}{\bar{N}^2\mu_f^2} \qquad \ln\frac{m_t^2}{\mu_f^2} \qquad \ln\frac{m_t^2}{\bar{N}^2\mu_f^2}$$

Emergence of a soft-collinear scale m_t/N!

The double faces of the top quark

Looking down from the high scale M_{tt}

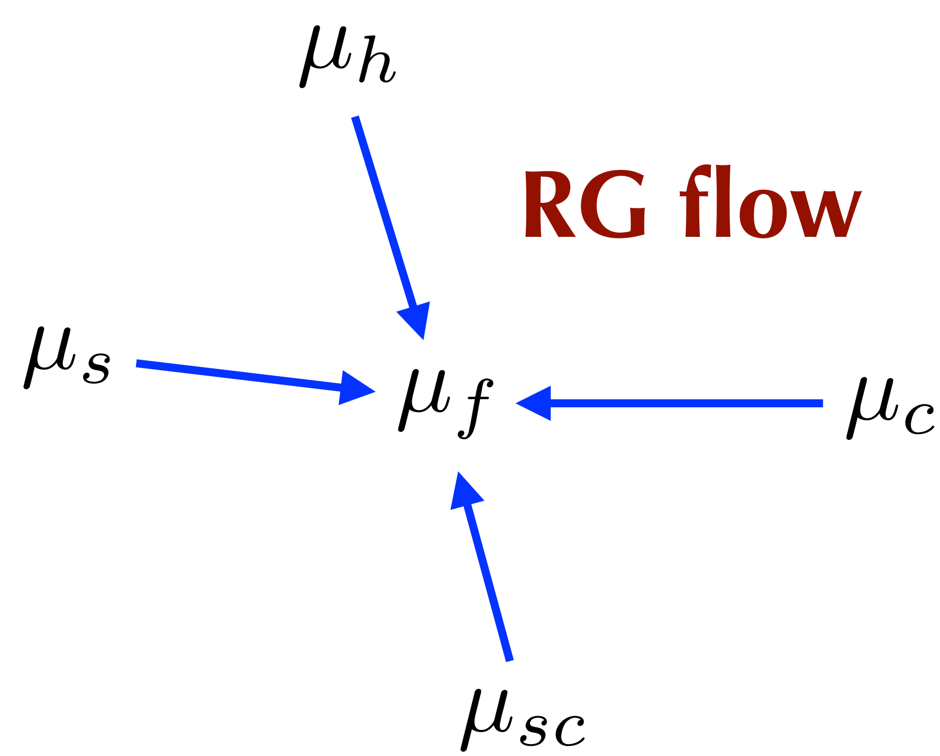
collinear quark
in SCET

boosted heavy
quark in HQET

Looking from the low scale m_t

NNLL′ resummation

- Two-loop anomalous dimensions: Ferroglia, Neubert, Pecjak, **LLY**, 0907.4791, 0908.3676
- Two-loop soft functions: Ferroglia, Pecjak, **LLY**, 1207.4798
- Two-loop hard functions: Broggio, Ferroglia, Pecjak, Zhang, 1409.5294



Anomalous dimensions and infrared singularities

Ferroglia, Neubert, Pecjak, **LLY**: 0907.4791, 0908.3676

A universal formula for the infrared singularity and scale dependence of any scattering amplitude in any gauge theory at two-loop order

$$\boldsymbol{Z} = 1 + \frac{\alpha_s^{\rm QCD}}{4\pi}\left(\frac{\Gamma_0'}{4\epsilon^2} + \frac{\boldsymbol{\Gamma}_0}{2\epsilon}\right) + \left(\frac{\alpha_s^{\rm QCD}}{4\pi}\right)^2 \left\{ \frac{(\Gamma_0')^2}{32\epsilon^4} + \frac{\Gamma_0'}{8\epsilon^3}\left(\boldsymbol{\Gamma}_0 - \frac{3}{2}\beta_0\right) + \frac{\boldsymbol{\Gamma}_0}{8\epsilon^2}(\boldsymbol{\Gamma}_0 - 2\beta_0) + \frac{\Gamma_1'}{16\epsilon^2} + \frac{\boldsymbol{\Gamma}_1}{4\epsilon} - \frac{2T_F}{3}\sum_{i=1}^{n_h}\left[\Gamma_0'\left(\frac{1}{2\epsilon^2}\ln\frac{\mu^2}{m_i^2} + \frac{1}{4\epsilon}\left[\ln^2\frac{\mu^2}{m_i^2} + \frac{\pi^2}{6}\right]\right) + \frac{\boldsymbol{\Gamma}_0}{\epsilon}\ln\frac{\mu^2}{m_i^2}\right]\right\} + \mathcal{O}(\alpha_s^3)$$

$$\begin{aligned}\boldsymbol{\Gamma}(\{\underline{p}\},\{\underline{m}\},\mu) &= \sum_{(i,j)} \frac{\boldsymbol{T}_i\cdot\boldsymbol{T}_j}{2}\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{\mu^2}{-s_{ij}} + \sum_i \gamma^i(\alpha_s) \\ &\quad - \sum_{(I,J)} \frac{\boldsymbol{T}_I\cdot\boldsymbol{T}_J}{2}\,\gamma_{\rm cusp}(\beta_{IJ},\alpha_s) + \sum_I \gamma^I(\alpha_s) + \sum_{I,j} \boldsymbol{T}_I\cdot\boldsymbol{T}_j\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{m_I\mu}{-s_{Ij}} \\ &\quad + \sum_{(I,J,K)} if^{abc}\,\boldsymbol{T}_I^a\boldsymbol{T}_J^b\boldsymbol{T}_K^c\,F_1(\beta_{IJ},\beta_{JK},\beta_{KI}) \qquad (5 \\ &\quad + \sum_{(I,J)}\sum_k if^{abc}\,\boldsymbol{T}_I^a\boldsymbol{T}_J^b\boldsymbol{T}_k^c\,f_2\Big(\beta_{IJ},\ln\frac{-\sigma_{Jk}\,v_J\cdot p_k}{-\sigma_{Ik}\,v_I\cdot p_k}\Big) + \mathcal{O}(\alpha_s^3)\,.\end{aligned}$$

After our work:

Mitov, Sterman, Sung: 1005.4646
Chien, Schwartz, Simmons-Duffin, Stewart: 1109.6010

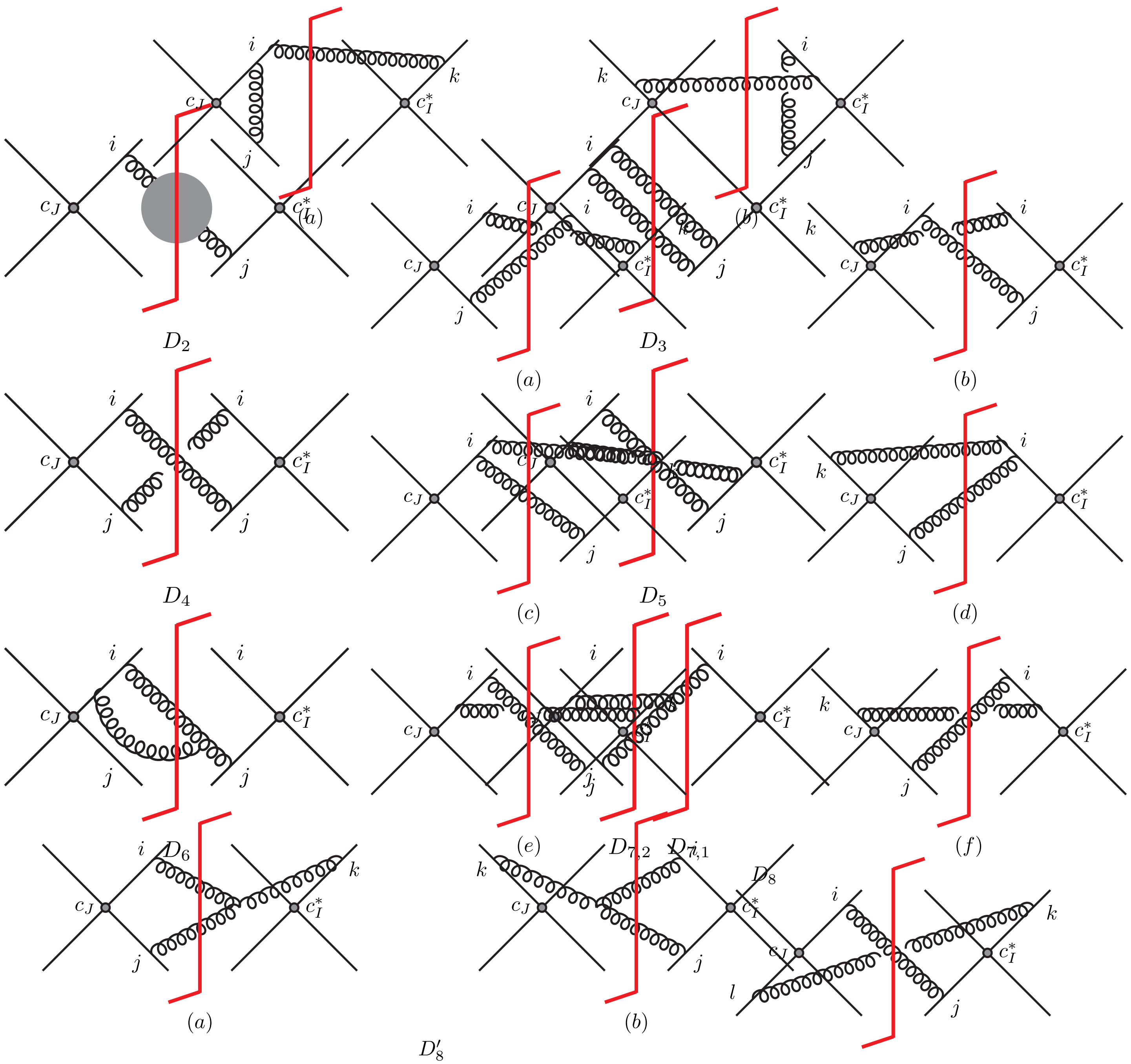
Two-loop IR for top pairs

Ferroglia, Neubert, Pecjak, **LLY**: 0907.4791, 0908.3676

	ϵ^{-4}	ϵ^{-3}	ϵ^{-2}	ϵ^{-1}
A^g	10.749	18.694	-156.82	262.15
B^g	-21.286	-55.990	-235.04	1459.8
C^g		-6.1991	-68.703	-268.11
D^g			94.087	-130.96
E_l^g		-12.541	18.207	27.957
E_h^g			0.012908	11.793
F_l^g		24.834	-26.609	-50.754
F_h^g			0.0	-23.329
G_l^g			3.0995	67.043
G_h^g				0.0
H_l^g			2.3888	-5.4520
H_{lh}^g				-0.0043025
H_h^g				
I_l^g			-4.7302	10.810
I_{lh}^g				0.0
I_h^g				

- Analytic formula! (too long to be shown here)
- Served as an important ingredients in the NNLO calculation by Czakon et al.

NNLO soft functions



Ferroglia, Pecjak, **LLY**: 1207.4798

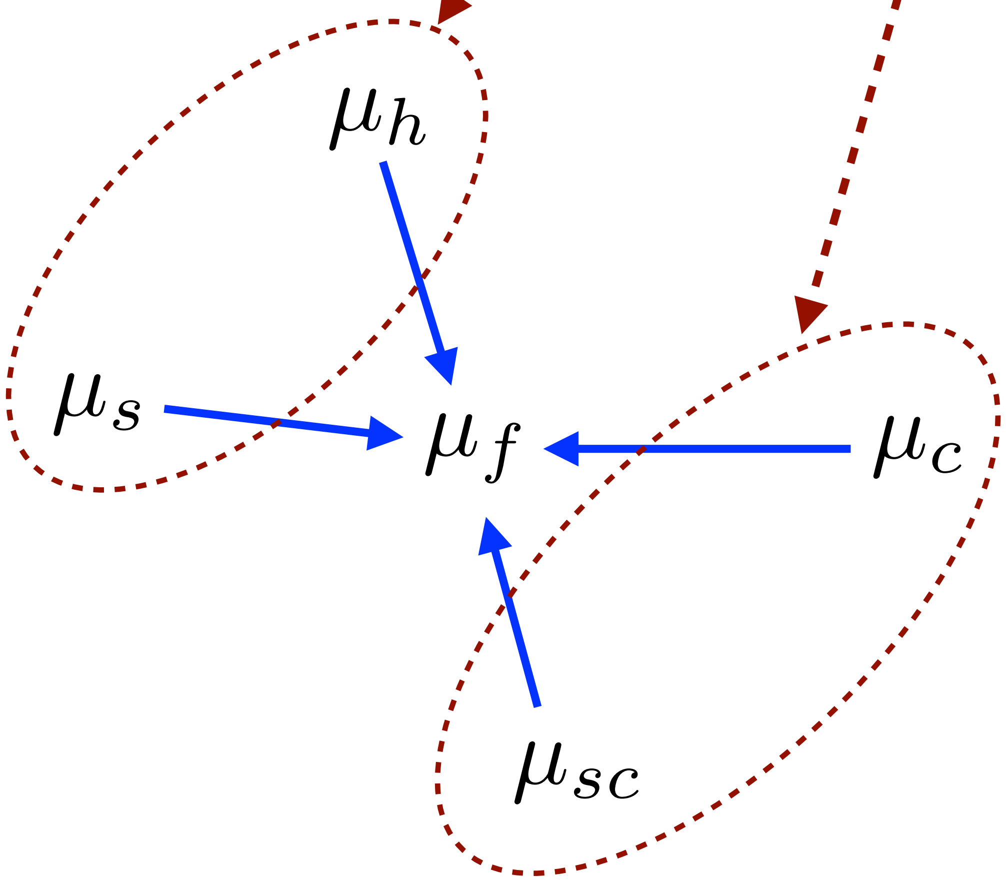
$$
\begin{aligned}
\tilde{s}^{(2)}_{qq\,11} = {} & \frac{19424}{27} - \frac{6464}{9}L + \frac{1072}{3}L^2 - \frac{176}{3}L^3 + \frac{128}{3}L^4 - \frac{2624}{81}N_l + \frac{896}{27}LN_l - \frac{160}{9}L^2N_l \\
& + \frac{32}{9}L^3N_l + \frac{268}{9}\pi^2 - \frac{16}{9}L^2\pi^2 - \frac{40}{27}N_l\pi^2 - \frac{56}{9}\pi^4 + \frac{64}{9}L\pi^2H_0(x_t) + \frac{64}{9}L\pi^2H_1(x_t) \\
& + \left[\frac{128}{3}L^2 - \frac{64}{9}\pi^2\right]H_2(x_t) - \frac{128}{3}LH_3(x_t) - 128H_4(x_t) + \left[\frac{128}{3}L^2 + \frac{64}{9}\pi^2\right]H_{0,0}(x_t) \\
& + \frac{128}{3}L^2H_{1,0}(x_t) + \frac{64}{9}\pi^2H_{1,0}(x_t) + \left[\frac{128}{3}L^2 - \frac{64}{9}\pi^2\right]H_{1,1}(x_t) - \frac{128}{3}LH_{1,2}(x_t) \\
& - 128H_{1,3}(x_t) + \frac{128}{3}LH_{2,0}(x_t) - 128LH_{2,1}(x_t) - \frac{128}{3}H_{2,2}(x_t) - \frac{128}{3}H_{3,0}(x_t) \\
& + \frac{128}{3}H_{3,1}(x_t) + 128LH_{0,0,0}(x_t) + 128LH_{1,0,0}(x_t) + \frac{128}{3}LH_{1,1,0}(x_t) \\
& - 128LH_{1,1,1}(x_t) - \frac{128}{3}H_{1,1,2}(x_t) - \frac{128}{3}H_{1,2,0}(x_t) + \frac{128}{3}H_{1,2,1}(x_t) + \frac{128}{3}H_{2,0,0}(x_t) \\
& - 128H_{2,1,0}(x_t) + 128H_{2,1,1}(x_t) + 128H_{0,0,0,0}(x_t) + 128H_{1,0,0,0}(x_t) + \frac{128}{3}H_{1,1,0,0}(x_t) \\
& - 128H_{1,1,1,0}(x_t) + 128H_{1,1,1,1}(x_t) - \frac{176}{3}\zeta_3 + 672L\zeta_3 + \frac{32}{9}N_l\zeta_3\,,
\end{aligned}
$$

one entry in the quark matrix

Final formula

Ferroglia, Pecjak, Scott, **LLY**: 1512.02535
Pecjak, Scott, Wang, **LLY**: 1601.07020

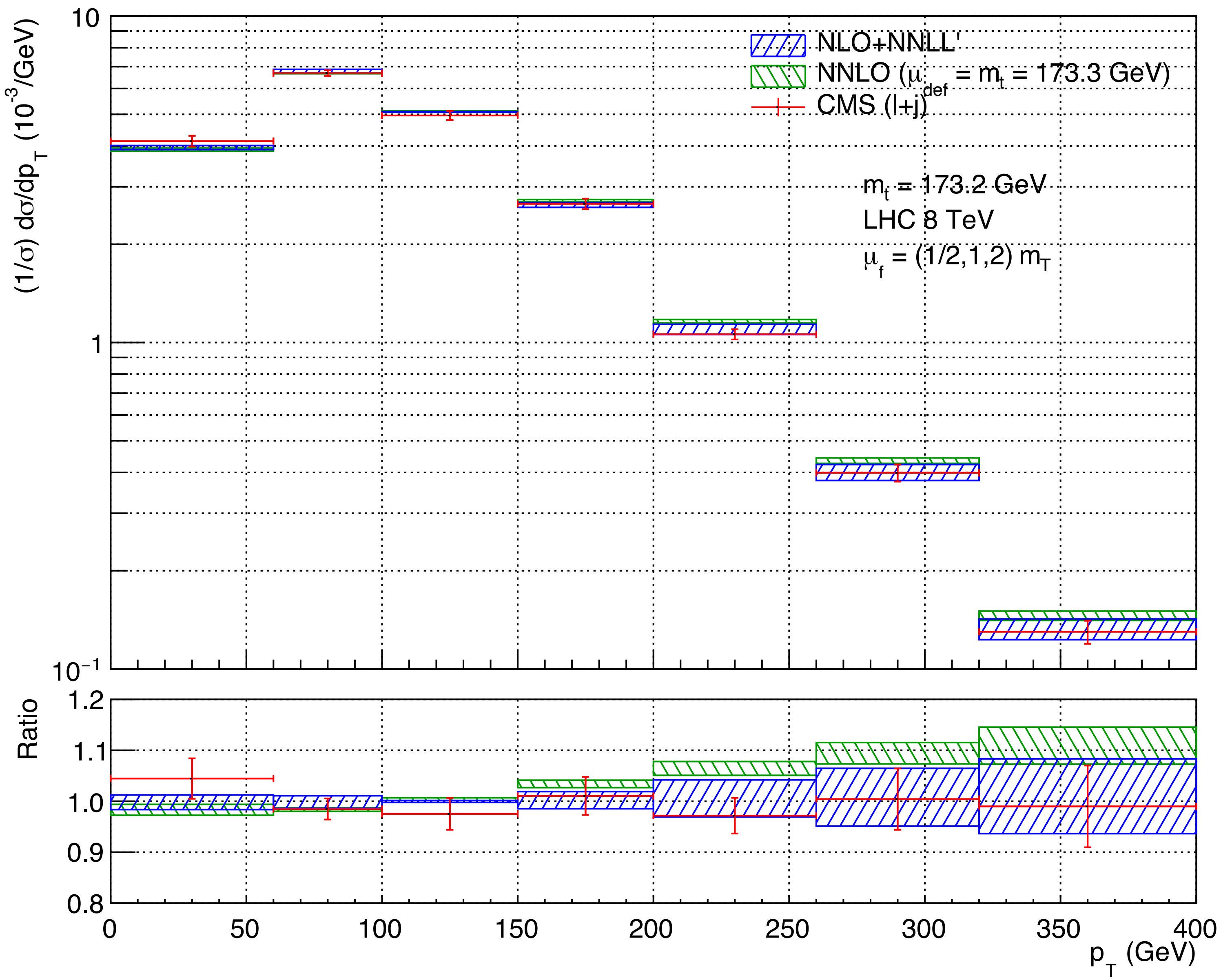
$$\hat{\sigma}(N,\mu_f) \sim \mathrm{Tr}\big[\boldsymbol{U}(\mu_f,\mu_h,\mu_s)\boldsymbol{H}(L_h,\mu_h)\boldsymbol{U}^\dagger(\mu_f,\mu_h,\mu_s)\boldsymbol{S}(L_s,\mu_s)\big]$$
$$\times\, U_D^2(\mu_f,\mu_c,\mu_{sc})C_D^2(L_c,\mu_c)S_D^2(L_{sc},\mu_{sc})$$



- Combined with NNLL threshold resummation in Ahrens, Ferroglia, Neubert, Pecjak, **LLY**, 1003.5827
- Combined with NLO result
- Applicable not only in the boosted region!

8 TeV: p_T

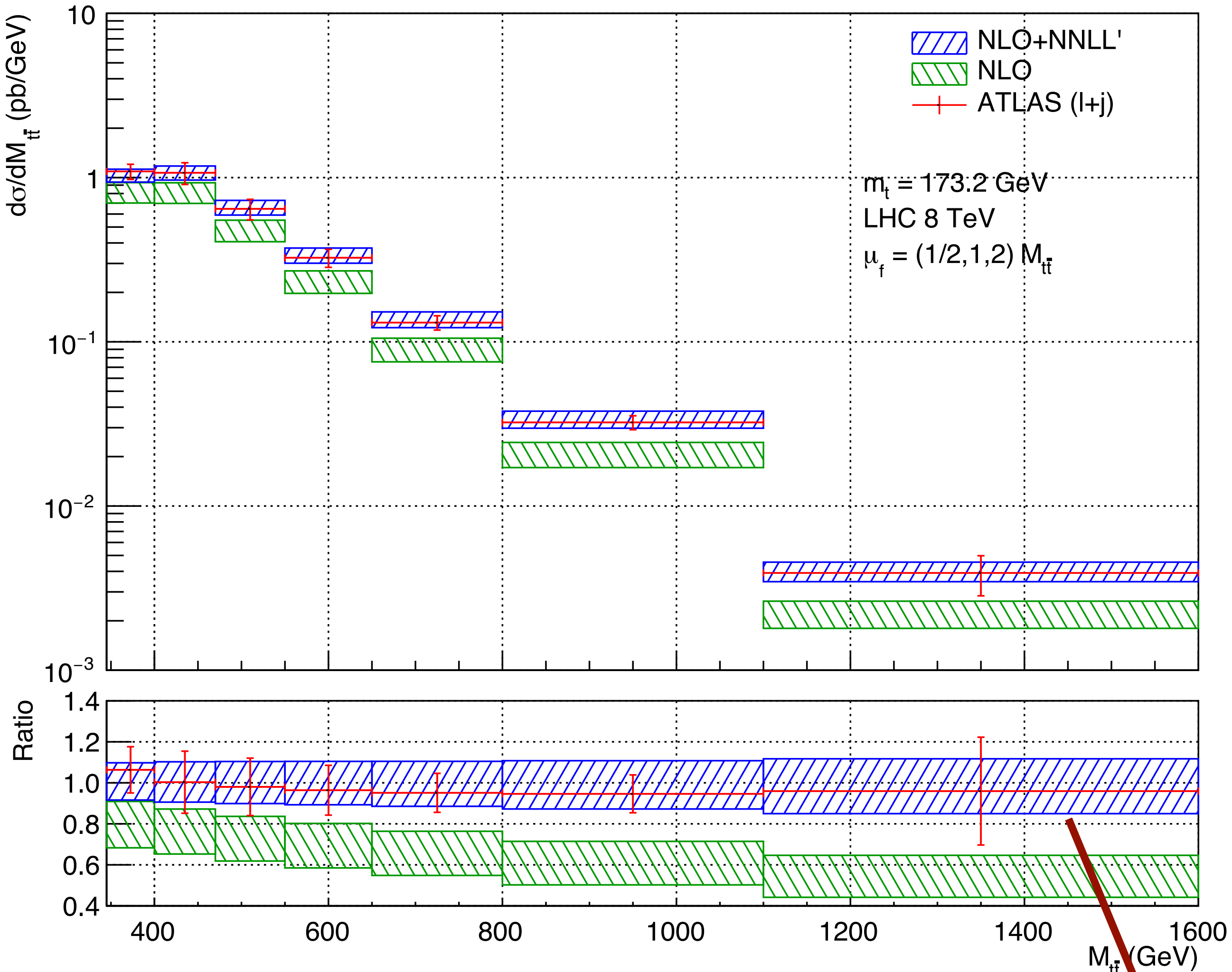
Ferroglia, Pecjak, Scott, **LLY**: 1512.02535
Pecjak, Scott, Wang, **LLY**: 1601.07020

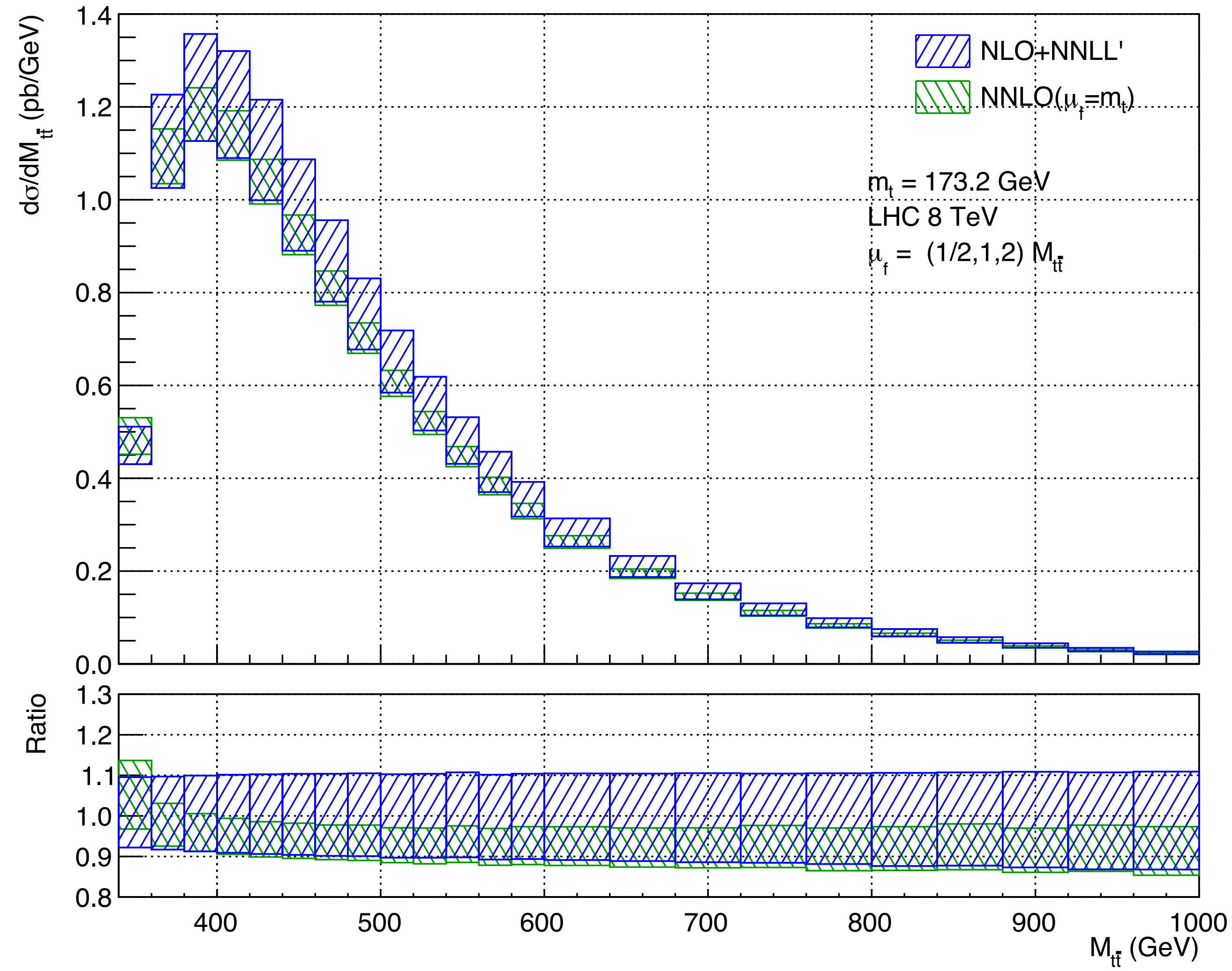


- Softer spectrum than NNLO (with fixed scales)
- Perfect agreement with data

8 TeV: M_{tt}

Ferroglia, Pecjak, Scott, **LLY**: 1512.02535
Pecjak, Scott, Wang, **LLY**: 1601.07020

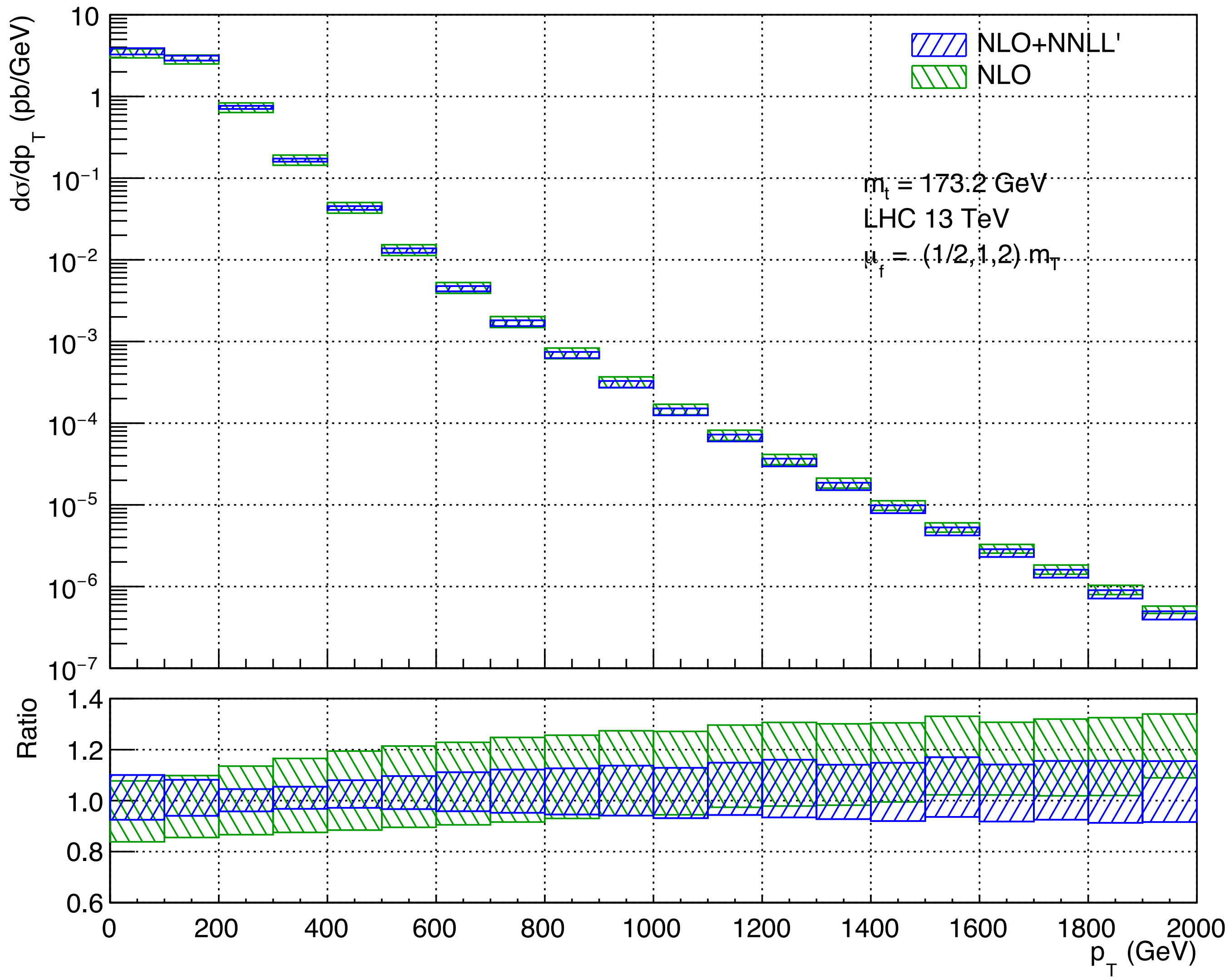




Perfect agreement

13 TeV: p_T

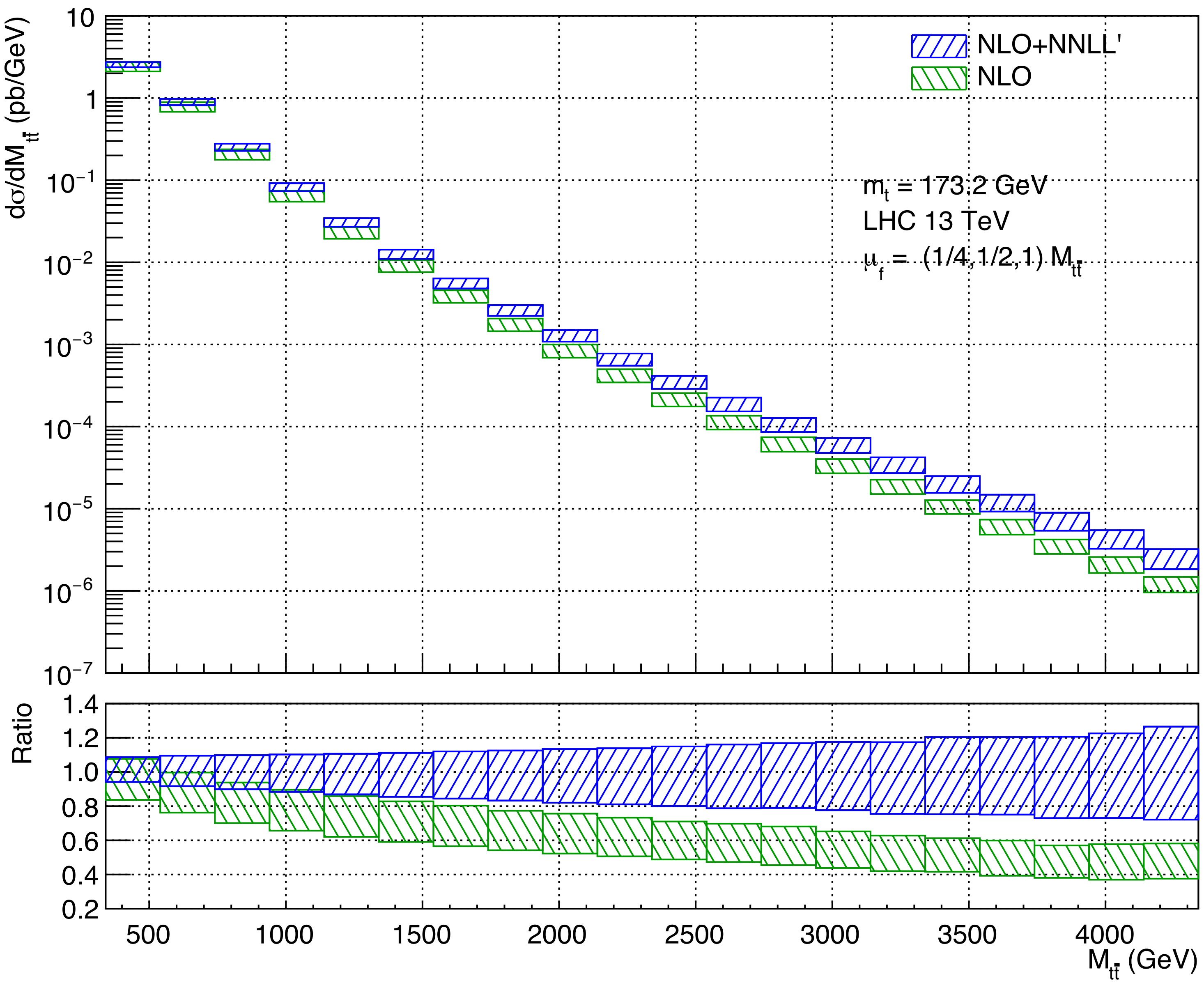
Ferroglia, Pecjak, Scott, **LLY**: 1512.02535
Pecjak, Scott, Wang, **LLY**: 1601.07020



- Trend continues: higher order corrections soften the spectrum
- Dynamic scale works well for the NLO

13 TeV: M_{tt}

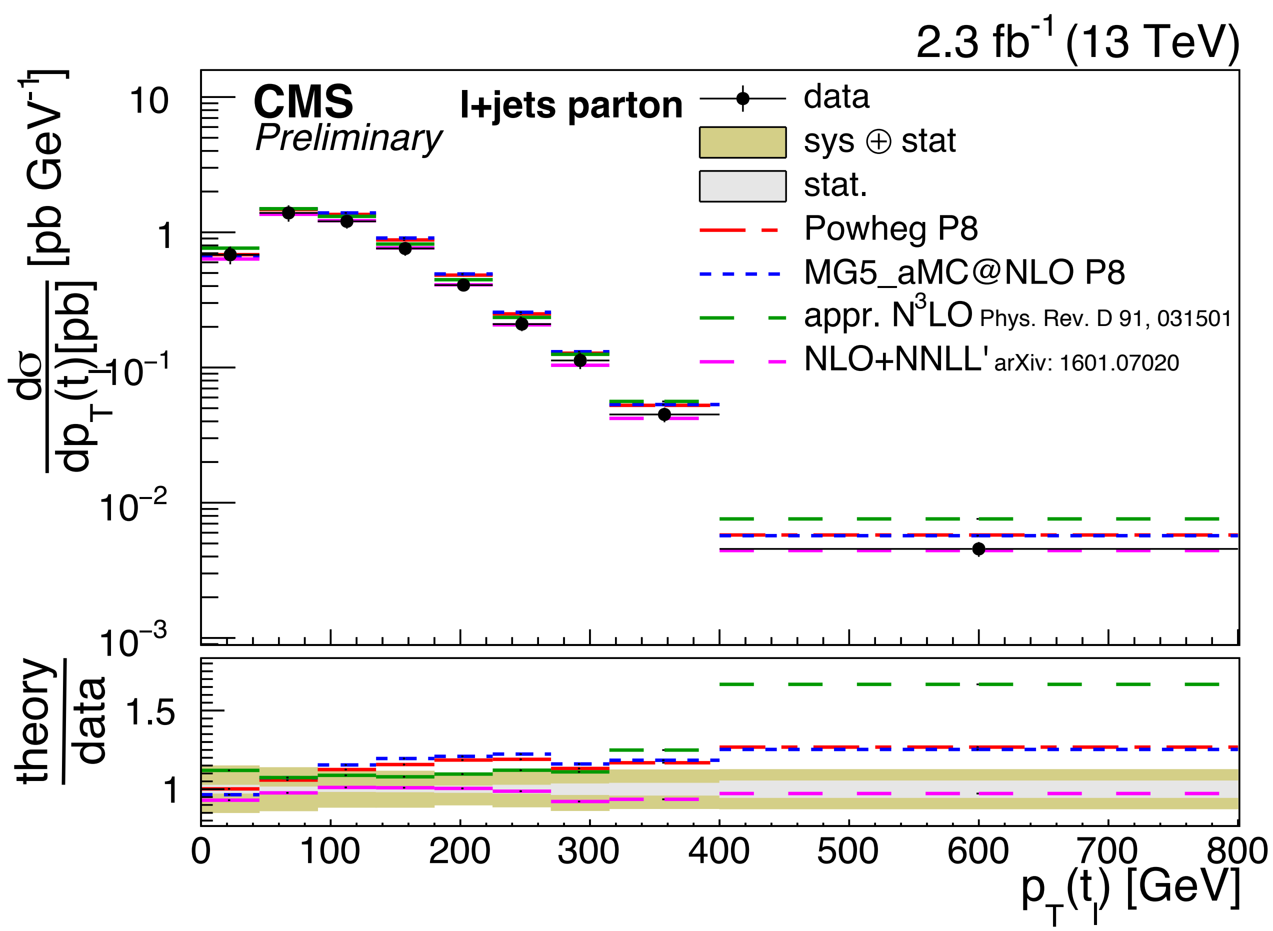
Ferroglia, Pecjak, Scott, **LLY**: 1512.02535
Pecjak, Scott, Wang, **LLY**: 1601.07020



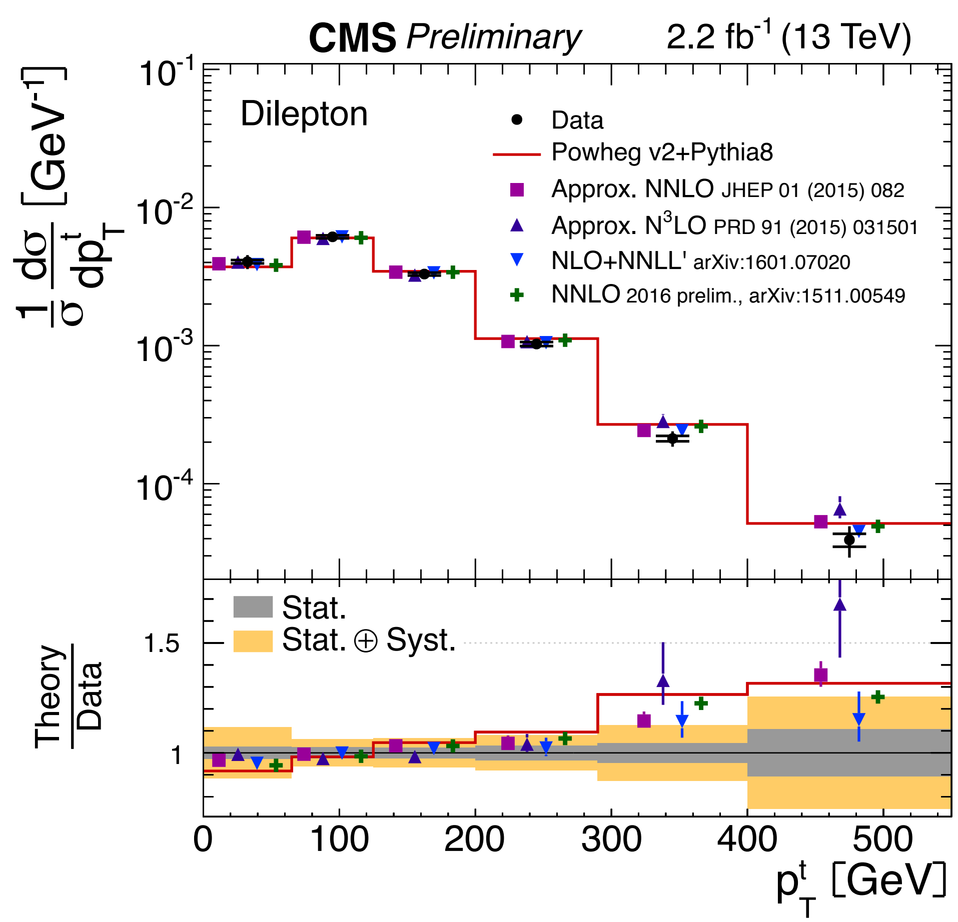
- Huge correction at high energy
- Scale variation of the NLO underestimates the uncertainty

13 TeV: new data

CMS PAS TOP-16-008



CMS PAS TOP-16-011



Summary

* Precision differential distributions for top quark pair production across the whole energy range

* Excellent agreements with experimental measurements

* Guidance for the scale choices in fixed-order calculations

* Validation of Monte-Carlo tools

Future prospects

* Matching with NNLO (with dynamic scales)
* 100 TeV collider
* Making tops unstable (top jets instead of on-shell tops)
* Bottom quarks (b-jets or B-hadrons)

Thank you!