Automated NNLL+NLO resummation for jet-veto cross sections

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What are we looking at?

Production cross section of one or several **weak bosons**

$$Z,\ W^+,\ W^-,\ \ H$$

with a **jet veto**, which only allows for jets with low transverse momentum

$$p_T^{\text{Jet}} < p_T^{\text{Veto}} \sim 15 - 30\ \text{GeV}$$

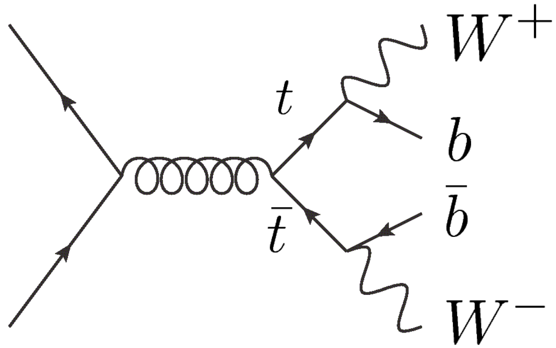
Why?

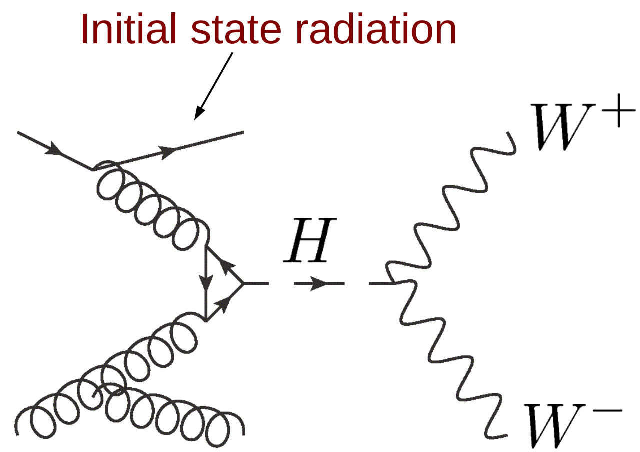
- Analysis is done in jet bins, needs precise prediction of the 0-jet bin.
- Suppress background
- Excess in W^+W^- cross section measured at the LHC. New Physics?

Role of the Jet Veto

Suppression of top-quark background in processes involving *W* bosons

- For example in $H \to W W^*$





Multiple scales ⇨ **enhancement by large Sudakov logarithms**

$$\alpha_s^n \ln\left(\frac{p_T^{\text{veto}}}{Q}\right)^k \qquad k \leq 2n$$

Q Invariant mass of the boson system

⇨ **Resummation**

Resummation for the Jet Veto

Recently, several papers have addressed this issue:

- W^+W^- production:

  Jaiswal, Okui ´14; Meade, Ramani, Zeng ´14; Monni, Zanderighi ´14; Becher, Frederix, Neubert, LR ´14

- Higgs production:

  Banfi, Salam, Zanderighi ´12; +Monni ´12; Becher, Neubert ´12; + LR ´13; Tackmann, Walsh, Zuberi ´12; + Stewart ´13; Liu, Pertiello ´13; + Boughezal, Tackmann, Walsh ´14

I will present our work and discuss how it is related to these.

In the following I will discuss the case of W^+W^- production but our formalism applies to any number of massive color-singlet particles.

Resummation by SCET

Resummation in general can be achieved using Soft-Collinear Effective Theory (SCET) or QCD based resummation techniques.

SCET framework:

- Low-energy degrees of freedom: **Soft** and **Collinear** fields
- Off-shell modes are integrated out. Hard-scattering encoded in the **Wilson coefficents** of the operators.

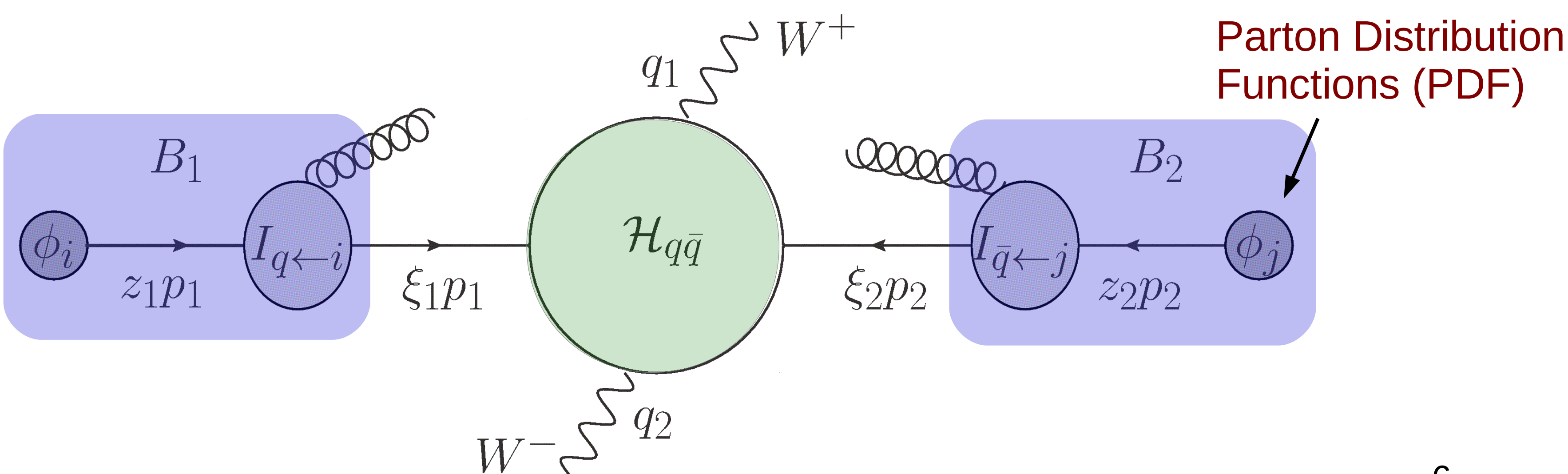
- Advantages:
  - Operator definition (manifest gauge invariance).
  - Systematic scale separation. Resummation by **RG evolution.**
  - **Power corrections** can be included.

All-order Factorization Theorem from SCET

$$\frac{d^3\sigma(p_T^{\text{veto}})}{dy\,dQ^2\,d\hat{t}} = \underbrace{\sigma_0(Q^2,\hat{t},\mu)}_{\text{Born-level CS}}\ \underbrace{\mathcal{H}_{q\bar{q}}(Q^2,\hat{t},\mu_h)}_{\text{Hard function}}\ \underbrace{U_q(Q^2,\mu_h,\mu)}_{\text{Evolution factor}}$$

$$\times \underbrace{\left(\frac{Q}{p_T^{\text{veto}}}\right)^{-2F_q(p_T^{\text{veto}},\mu)}}_{\text{Collinear Anomaly}}\ \underbrace{B_q(\xi_1,\mu,p_T^{\text{veto}})\,B_{\bar{q}}(\xi_2,\mu,p_T^{\text{veto}})}_{\text{Beam-jet functions}}$$

Factorization theorem up to **first order** power corrections p_T^{veto}/Q and non-perturbative effects Λ_{QCD}/p_T^{veto}.



All-order Factorization Theorem from SCET

Born-level CS | Hard function | Evolution factor

$$\frac{d^3\sigma(p_T^{\rm veto})}{dy\, dQ^2\, d\hat{t}} = \sigma_0(Q^2,\hat{t},\mu)\, \mathcal{H}_{q\bar{q}}(Q^2,\hat{t},\mu_h) U_q(Q^2,\mu_h,\mu)$$

$$\times \left(\frac{Q}{p_T^{\rm veto}}\right)^{-2F_q(p_T^{\rm veto},\mu)} B_q(\xi_1,\mu,p_T^{\rm veto})\, B_{\bar{q}}(\xi_2,\mu,p_T^{\rm veto})$$

Collinear Anomaly | Beam-jet functions

For NNLL resummation:

- Perturbative kernels $I_{i\leftarrow k}$: 1-loop
- Anomaly exponent F_i : 2-loop
- Hard function $\mathcal{H}_{ij}$: 1-loop process dependent!

Resummed result has Born kinematics in the limit $p_T^{veto} \to 0$.

⇨ First automated resummation (NNLL+NLO) in SCET using the event generator MadGraph5_aMC@NLO.

Advantages of an Automated Resummation

- Much more efficient and less error prone.

- Straightforward to **include decays** and **cuts** on the decay products.
  - Complicated in analytic computations.
- Code publicly available (recent MadGraph5_aMC@NLO release).
- Other work on automated resummation :
  - Banfi, Monni, Salam, Zanderighi (CAESAR, ARES)
  - Farhi, Feige, Freytsis, Schwartz ´15
  - Gerwick, Hoeche, Marzani, Schumann ´15

Automated Resummation using aMC@NLO

Scheme A: NNLL from reweighting Born-level events.

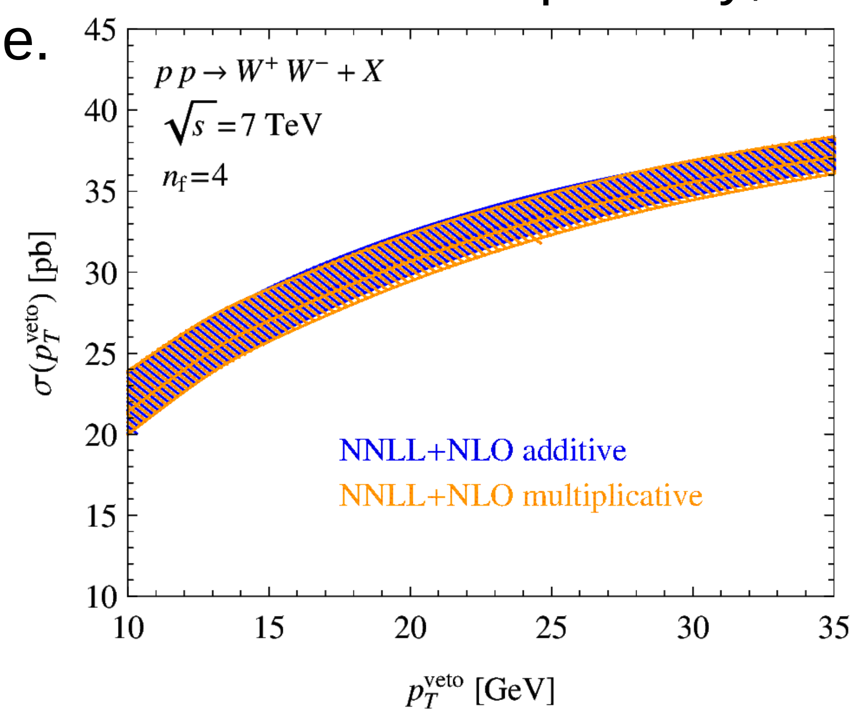
- Using a tree-level generator, rescale each event weight with the ratio to the resummed cross section.
- Beam functions included via modified PDFs.
  - Tabulate for a grid of values (same as for underlying PDF).
  - Use standard PDF interpolation routine.
- Hard function (only process dependent piece) computed using the MadGraph5_aMC@NLO code itself.
- Result is matched to NLO fixed-order in an purely additive way.

$$\sigma_{\mathrm{NNLL+NLO}} = \sigma_{\mathrm{NNLL}}(\mu, \mu_h) + \left(\sigma_{\mathrm{NLO}}(\mu_m) - \sigma_{\mathrm{NNLL}}(\mu_m)\big|_{\mathrm{expanded\ to\ NLO}} \right)$$

Automated Resummation using aMC@NLO

Scheme B: NNLL+NLO with automated computation of the beam functions and matching corrections.

- Run aMC@NLO in fixed-order mode, subtract the logarithmically enhanced pieces and multiply them back in resummed form.
- Matching is multiplicative.
- Advantage: Beam functions and matching are computed on the fly.
- Disadvantage: Matching corrections cannot be extracted separately; extension to higher order is not possible.



- Numerically the two schemes are almost indistinguishable.

Phenomenological Result

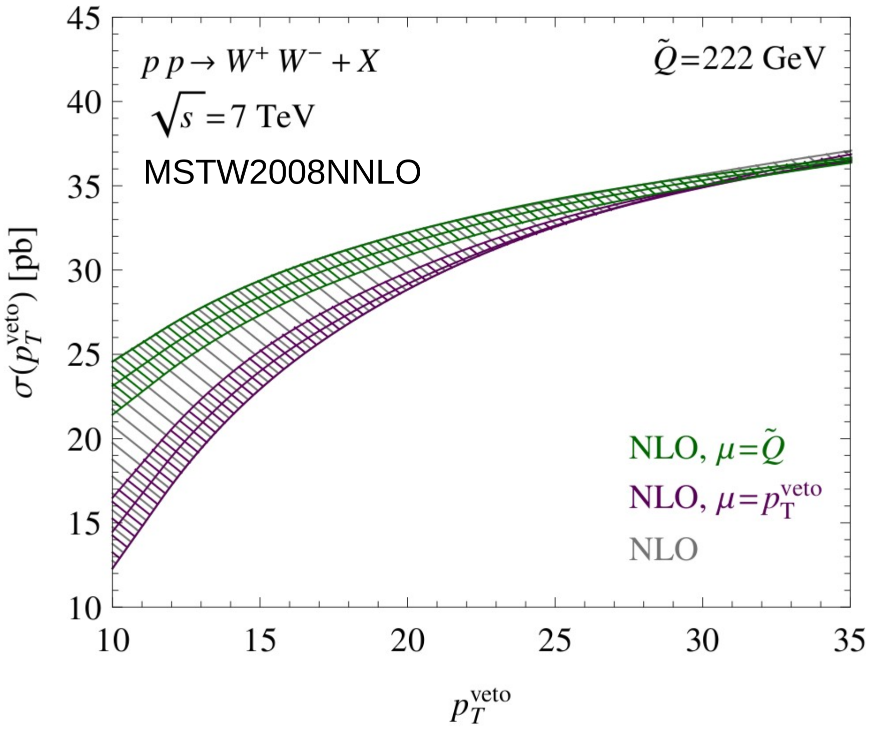
In the following I will show phenomenological results for a center of mass energy of 7 TeV and jet radius $R = 0.4$.

Scales are varied independently by factors of 2 about their default values $\mu = p_T^{veto}$ and $\mu_h = Q$.

For fixed-order expressions at NLO we vary the scale form

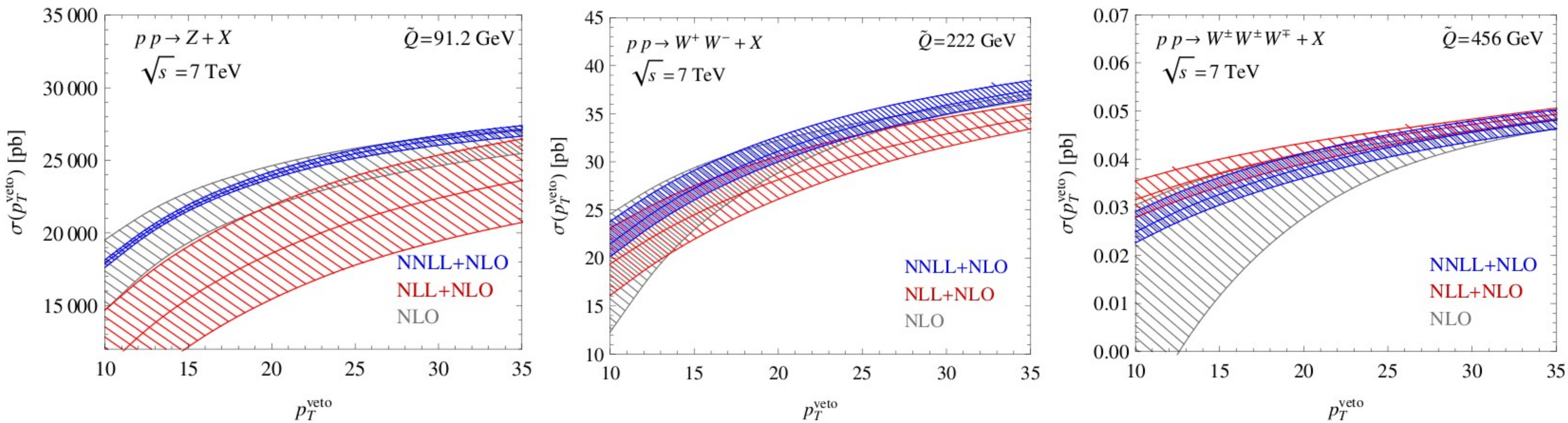
$$p_T^{\rm veto}/2 < \mu < 2\tilde{Q}$$

The average hard scale is defined by the median value $\tilde{Q}$ of the invariant-mass distribution.



Weak Boson Production with a Jet Veto

Numerical results for Z, W^+W^-,$W^+W^-W^\pm$ production

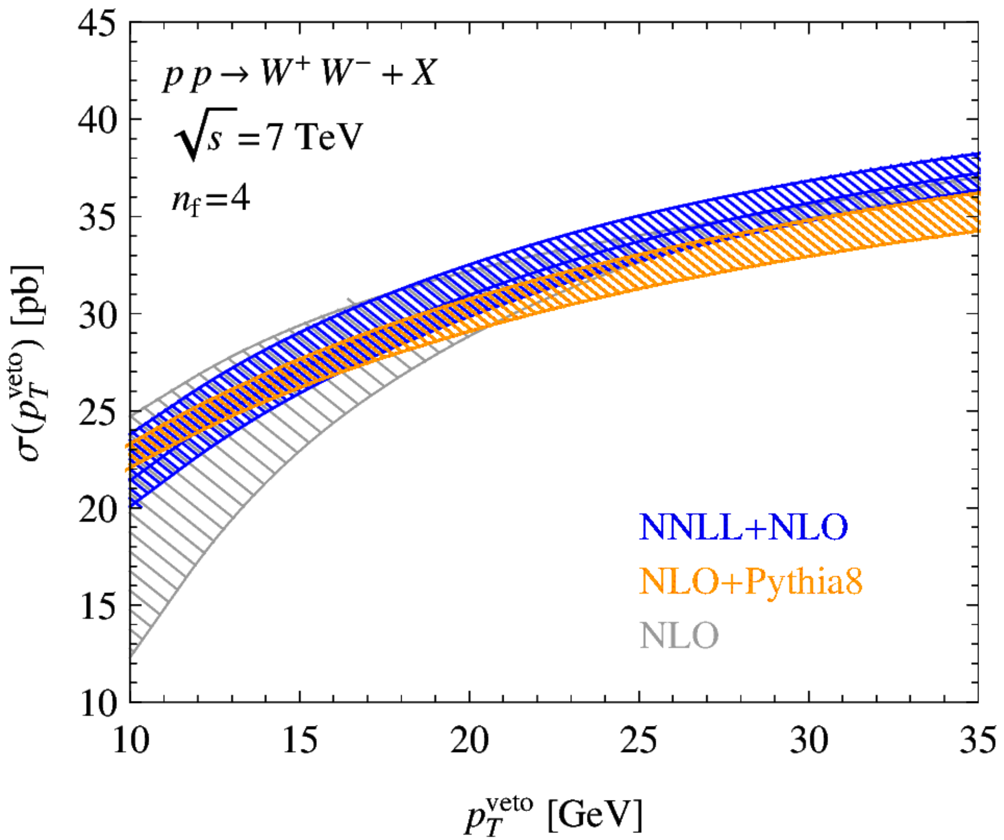


- NNLL+NLO lies close to NLO at the high scale $\mu = Q$.
- Width of the uncertainty band for resummed results depends weakly on the veto scale.
- Matching corrections to NNLL:
  Grow linearly up to 3% at p_T^{veto} = 80 GeV in all cases (matching can be safely ignored at low p_T^{veto} values).

Resummation vs NLO + Parton Shower

Observation: At higher values of p_T^{veto} the matched parton shower leads to lower results, which is not expected.

Unitarity of the shower, leads to compensation of changes at low transverse momentum.



Use of a matched parton shower underestimates jet-veto cross section!

In line with conclusions of Monni, Zanderighi ´14.

Decays and Cuts

Advantage of our framework:

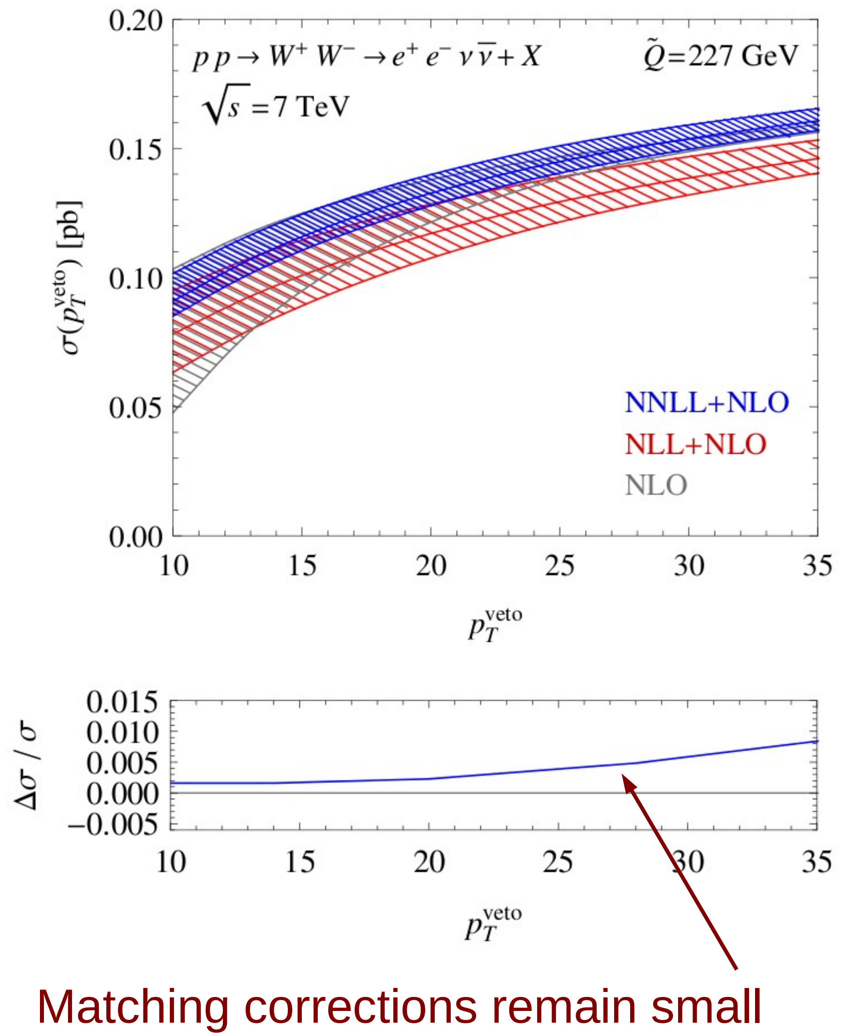
Straightforward to include the decay of the vector bosons and cuts on the final state leptons.

Cuts imposed in the ATLAS analysis for the e^+e^- channel

- Lepton $p_T > 20 \quad \mathrm{GeV}$
- Leading lepton $p_T > 25 \quad \mathrm{GeV}$
- Lepton pseudorapidity

  $\eta_e < 1.37 \text{ or } 1.52 < \eta_e < 2.47$
- Dilepton invariant mass

  $m_{e^+e^-} > 15 \text{ and } |m_{e^+e^-} - m_Z| > 15$



Summary

We have an automated framework for theoretical predictions for the production cross section of any number of weak bosons with a jet veto at NNLL+NLO accuracy.

Is based on a factorization theorem derived in SCET and implemented within the MadGraph5_aMC@NLO code.

- Public code (easily accessible).
- Straightforward to include decays and cuts on the decay products.
- Two schemes (additive and multiplicative matching) that allow for a cross check.
- The scheme with additive matching, can be easily extended to higher accuracy if the necessary ingredients are provided.

  The hard function for W^+W^- production can be extracted from recent two-loop results (1408.6409, 1503.04812).

Conclusions concerning W^+W^- Production

- NNLL resummation effects are small (NNLL+NLO in good agreement with NLO at $\mu_f \sim \mu_r \sim Q$).
- Several effects can lead to sizable changes in the jet veto cross section:
  - Hard scale choice can lead up to ~7% higher NNLL+NLO results.
  - NNLO effects increase the total rate by ~9%.
  - Two loop beam functions are enhanced by logarithms of the jet radius starting at this order. This enhancement is not captured by one loop scale variation.

    In Higgs production: NNLL+NLO $\xrightarrow{-\,15\%}$ N^{3}LL+NNLO (at $R = 0.4$)
  - Matched parton shower underestimates jet-veto cross section.
  - Non-perturbative corrections are logarithmically enhanced and can be underestimated by Pythia hadronization effects.

Accounting for all these effects will be important before drawing any conclusions from the two sigma excess.

Outlook: Effective Theory for Jet Processes

- Jet processes: SCET not very successful so far, problem of so-called non-global logarithms (NGLs).
- Usual H*J*S factorization does not achieve complete scale separation.
- In Becher, Neubert, LR, Shao (1508.06645) we perform an EFT analysis of cone-jet cross sections:
  - Find additional mode (besides soft, collinear), describing soft small angle radiation.
  - Factorized form (full scale separation).

$$\widetilde{\sigma}(\tau) = \sigma_0 \, H(Q) \, \widetilde{S}(Q\tau) \left[\sum_{m=1}^{\infty} \left\langle \mathcal{J}_m(Q\delta) \otimes \widetilde{\mathcal{U}}_m(Q\delta\tau) \right\rangle \right]^2$$

  - Solving the associated (highly non-trivial) RG equations resums all large logs (also NGLs). Framework not limited to leading logs or leading color.

Backup Slides

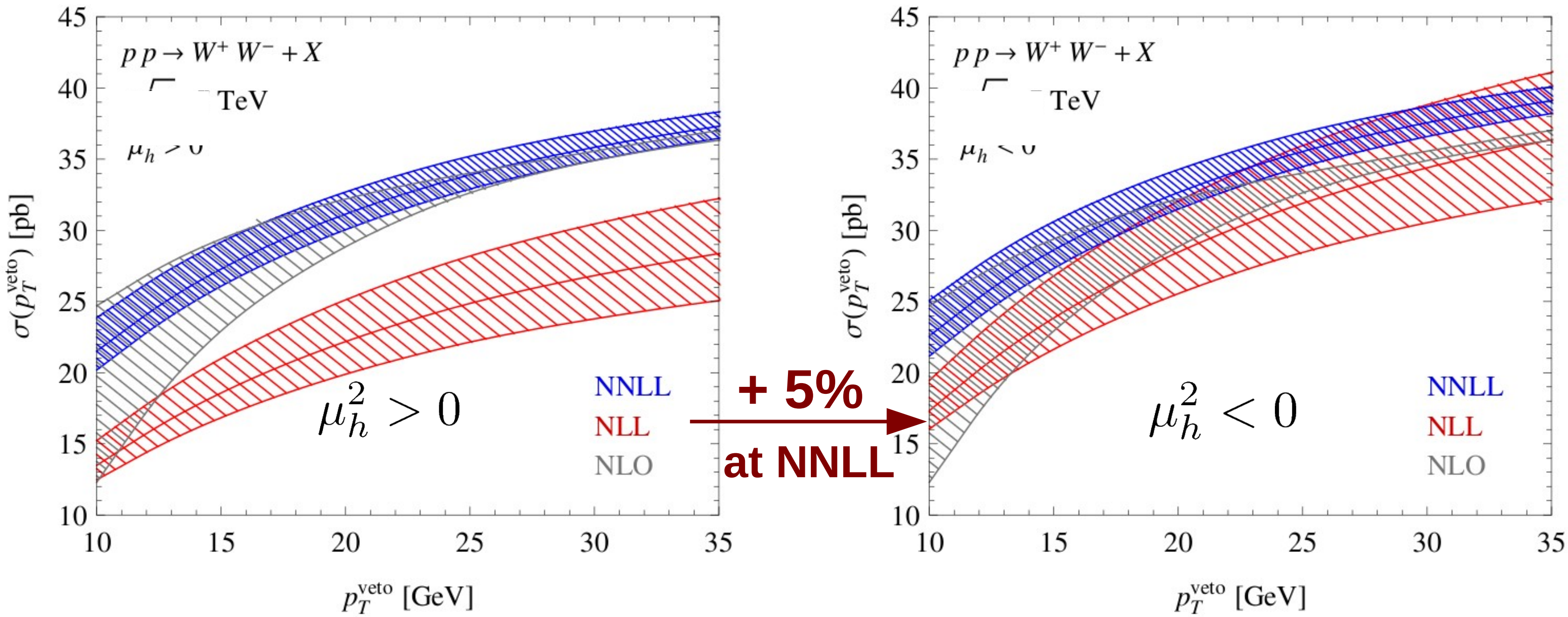
Choice of the Hard Scale

Standard choice for the hard matching scale: $\mu_h^2 \approx Q^2$

We also consider using an imaginary value: $\mu_h^2 \approx -Q^2$

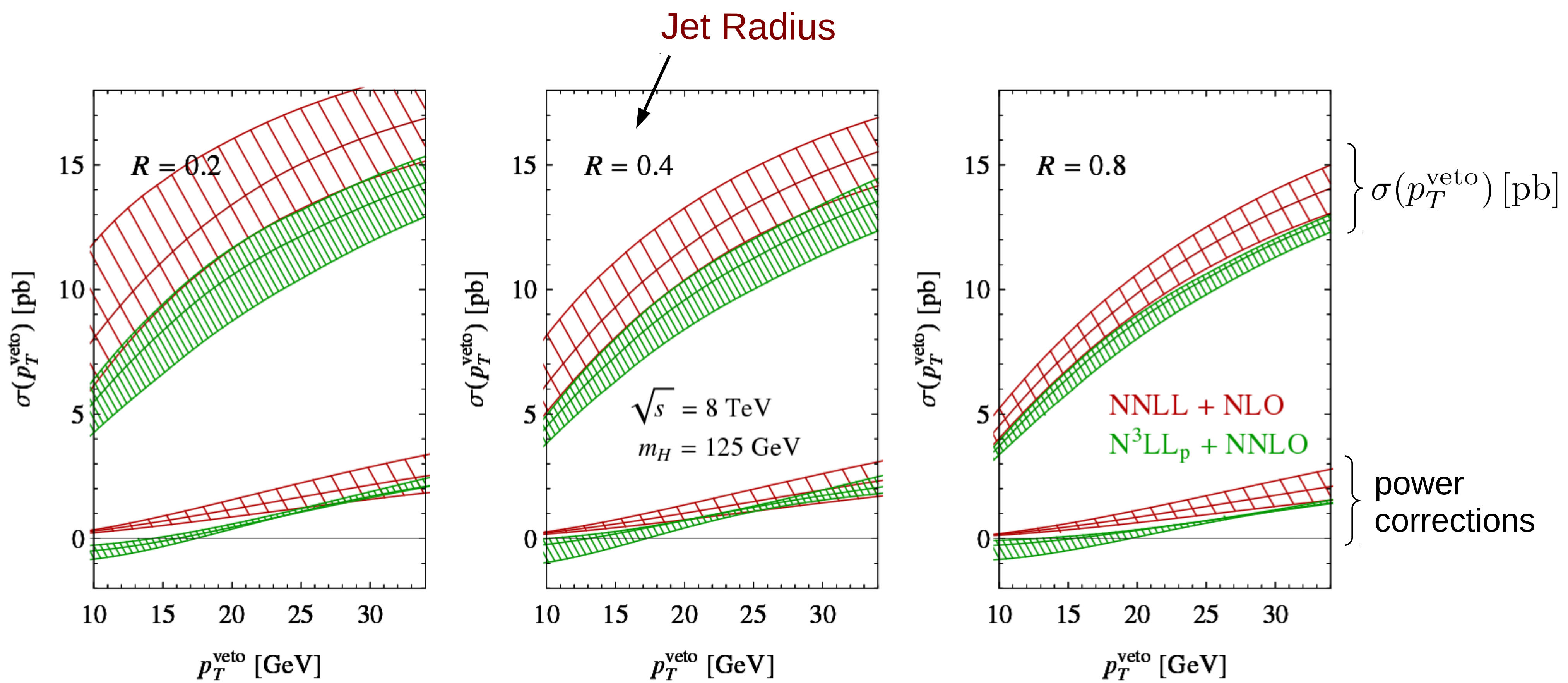
Imaginary choice resums $(\alpha_s \pi^2)^n$ terms in single boson production.

For multiparticle final states, no suitable choice that maps the hard function onto a Euclidean quantity ($\ln^2(-1)$ terms irrespective of scale choice).



Note: There is an ambiguity $\mu_h^2 = -Q^2 \pm i\epsilon$ for imaginary scale choice and depending on that choice the result can be 2% higher.

Higgs Production Cross Section with a Jet Veto



- We choose a scheme where scale variations are done separately and then quadratically added (avoid accidental cancellation and ensures good control over different sources of large corrections)

- Power corrections are small/suppressed (p_T/m_H)

Including photons

- $W\gamma$ resummed result: huge corrections from matching
- Indicates something is missing → Photon must be treated as a jet, therefore the zero jet framework is not the appropriate scheme.