

Electroweak gauge boson production at hadron colliders

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LoopFest VI

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Outline

- W, Z at the LHC \Rightarrow percent level QCD needed
- QCD to next-to-next-to leading order
- New approaches to handling IR singularities in QCD
- Fully exclusive W, Z with spin correlations at NNLO

Electroweak gauge bosons in QCD

- W, Z production has long history of spurring progress in QCD
- Multiple landmark perturbative QCD calculations:
 - First NLO QCD hadron collider calculation: 1979, Altarelli, Ellis, Martinelli
⇒ the realization that NLO has a large effect
 - First inclusive NNLO QCD hadron collider calculation: 1990, van Neerven et al.
⇒ precision QCD, scale variation at the 1% level
 - Resummation of large p_T logarithms in QCD expansions: 1979-1983, Dokshitzer et al., Collins and Soper, ...

W, Z at the LHC

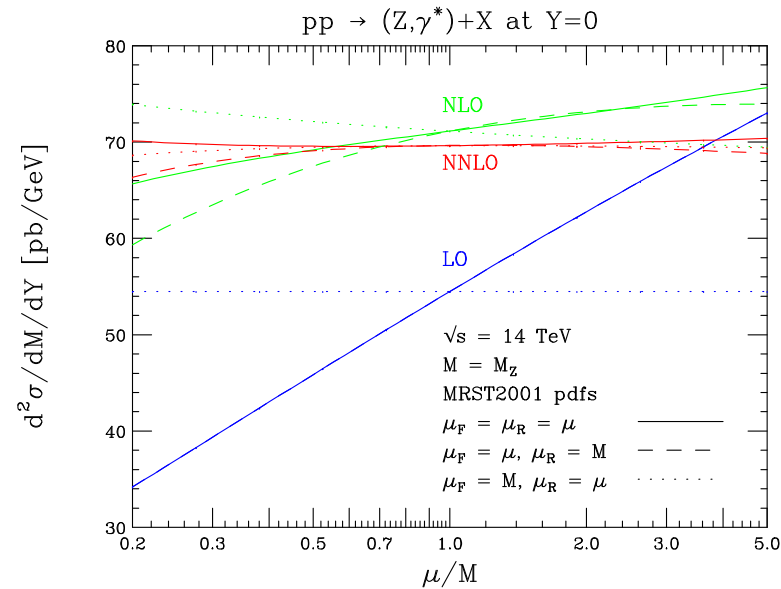
- Applications at the LHC:
 - Further improvements in EW parameters $M_W, \sin^2\theta_W$
 - If Z' discovery, use to distinguish models (reviewed by T. Rizzo)
 - Calibration of detectors, lepton energy scale
 - PDF measurements with LHC data: $A_l(\eta), d\sigma_Z/dY$
 - Luminosity determination to the percent level (Dittmar et al.)
 - ...
- Benchmark processes at the LHC \Rightarrow need percent-level theory, reliable error estimates

QCD to the percent level

- **Myriad issues to consider** (Nadolsky hep-ph/0412146)
 - Resummation of $\ln(M_{ll}/q_T^W)$ for some observables (RESBOS: Balazs, Nadolsky, Yuan)
 - $\mathcal{O}(\alpha)$ EW corrections (U. Baur, Wackerroth et al.), particularly **FSR**
 - Possible resummation in $x \rightarrow 0, 1$ limits
 - **Fixed order QCD to NNLO: $\mathcal{O}(\alpha_s^2)$**
 - **Need complete kinematics!** Experimental cuts, distributions such as $A_l(\eta)$
 - W, Z are spin-1: "spin correlations" between production, decay: $p_q \cdot p_l$
 - ⇒ difficult for **NNLO** calculations, can't separate production and decay
- ⇒ **still motivating progress in QCD!**

Drell-Yan circa 2004

- Rapidity distributions at NNLO known



Anastasiou, Dixon, Melnikov, FP

- Drastically reduced μ dependence, uncertainty from N^n LO below 1%
- Needed for consistent pdf extraction at NNLO

Spin correlations

- Not good enough for 1% precision at LHC
 - Study of spin correlations at NLO and with MC@NLO (Frixione, Mangano)
 - Cut 1: $p_T^e > 20 \text{ GeV}$, $|\eta^e| < 2.5$, $\cancel{E}_T > 20 \text{ GeV}$ (LHC)
 - Cut 2: $p_T^e > 40 \text{ GeV}$, $|\eta^e| < 2.5$, $\cancel{E}_T > 20 \text{ GeV}$ (LHC)

	Tevatron			LHC		
	LO	NLO	MC@NLO	LO	NLO	MC@NLO
Cut 1	0.409	0.385	0.383	0.524	0.477	0.485
Cut 1, no spin	0.413	0.394	0.394	0.553	0.510	0.515
Cut 2	0.356	0.340	0.336	0.058	0.129	0.133
Cut 2, no spin	0.389	0.374	0.370	0.075	0.150	0.157

- Spin correlations at NLO a 10% effect
- ⇒ For 1% measurements (e.g., luminosity) need NNLO with spin correlations
- ⇒ Fully exclusive $q\bar{q} \rightarrow (W, Z) \rightarrow (l\nu, ll)$ required

Approach to fully exclusive NNLO

- Fully differential results at NLO typically use dipole subtraction
 - Manual reconstruction of all singular limits
 - Analytic integration of dipoles
- Can devise a general technique based on the infrared structure of higher-order QCD (Anastasiou, Melnikov, FP)
 - Automated finding and subtraction of divergences
 - Produces an epsilon expansion for real radiation graphs ($d = 4 - 2\epsilon$)

$$\sigma_{\text{real}} = \frac{A_4 [Obs]}{\epsilon^4} + \frac{A_3 [Obs]}{\epsilon^3} + \dots + A_0 [Obs]$$

- Fully numerical, no analytic integrations required
- Produces finite, fully differential results that can be subjected to arbitrary experimental cuts

Sketch of the method

- The algorithm:

- Map the integration to the unit hypercube

$$\int d^d p_i \delta(p_{in} - \sum p_i) \delta(p_i^2 - m_i^2) \dots \Rightarrow \int_0^1 dx_i x_i^{a_i \epsilon} (1 - x_i)^{b_i \epsilon}$$

Non-zero a_i, b_i regulate singularities, which appear as $1/x_i, 1/(1 - x_i)$

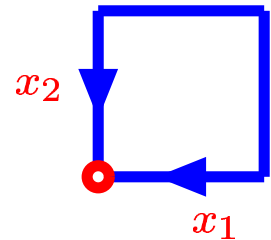
- Use **sector decomposition** to disentangle overlapping singularities
- Extract singularities using **plus distribution** expansion

$$x^{-1+\epsilon} = \frac{1}{\epsilon} \delta(x) + \left[\frac{1}{x} \right]_+ + \epsilon \left[\frac{\ln(x)}{x} \right]_+ + \dots$$

- All singularities appear as poles in ϵ ; check that they cancel, then discard
- Numerically integrate finite remainder with arbitrary final-state restrictions
- Can do same for Feynman parameters of virtual component (Binoth, Heinrich)

Overlapping singularities

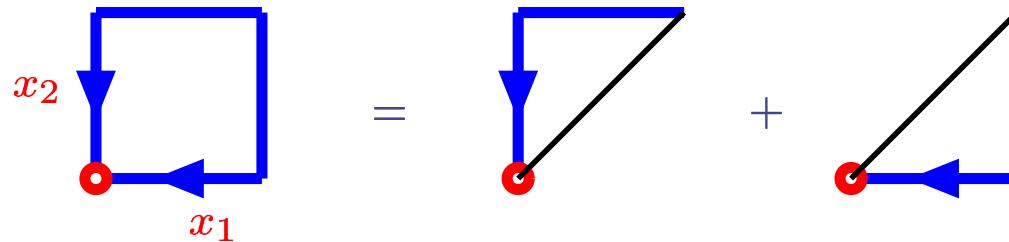
- Singularity when two (or more) variables reach the same corner



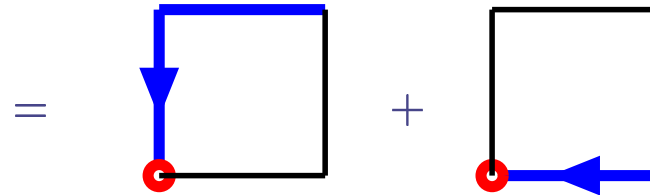
:

$$\frac{x_1^\epsilon x_2^\epsilon}{(x_1 + x_2)^2} f(x_1, x_2; \text{Obs}(x_1, x_2))$$

- Split into sectors



- map each sector to $[0, 1]$



- Repeat until singularities are fully **factorized** in all phase-space variables.

Advantages

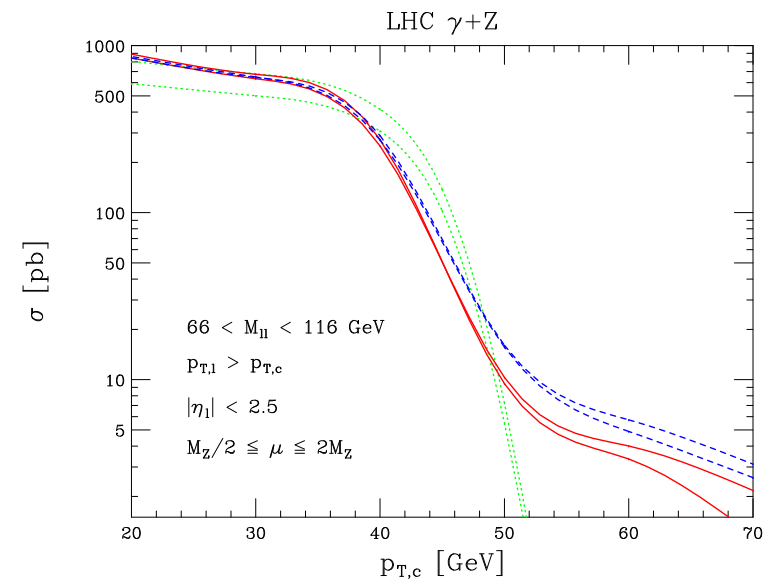
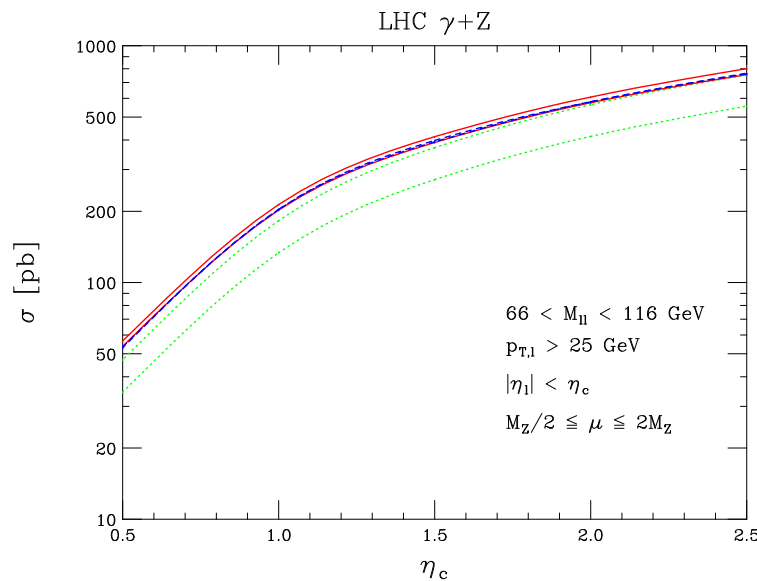
- Very easy to automate entire procedure
- No need to determine physical origin of singular regions (UV, soft, collinear); just search for factorized and entangled forms
- Only integration required is a numerical integration of the finite remainder; divergent parts are found separately as poles in ϵ and discarded
- ⇒ in principle, a solution to extracting and canceling singularities to $N^n\text{LO}$
- Fully differential results; in principle, can be used to make an event generator
- Method is topological:

$$|\mathcal{M}|^2 \sim \frac{N(s_{ab}, F_J)}{\prod s_{ij}}$$

- ⇒ algorithm applied only to denominator ⇒ same for all $2 \rightarrow 1$ processes
- Applied also to Higgs production, muon decay

Electroweak gauge bosons at NNLO

- NNLO QCD result for W, Z production (Melnikov, FP)
 - Contains spin correlations, finite-width effects, $\gamma - Z$ interference, all kinematics



- Residual scale dependences $< 1\%$ for standard cuts
 - Comparison with recent CDF result for forward W production; take ratio of $|\eta_e| < 1$ over $1 < |\eta_e| < 2.8$
 $R_{c/f}^{CDF} = 0.925(33); R_{c/f}^{NLO} = 0.940(12); R_{c/f}^{NNLO} = 0.927(2)$
- ⇒ potential stringent constraint on pdfs with more data

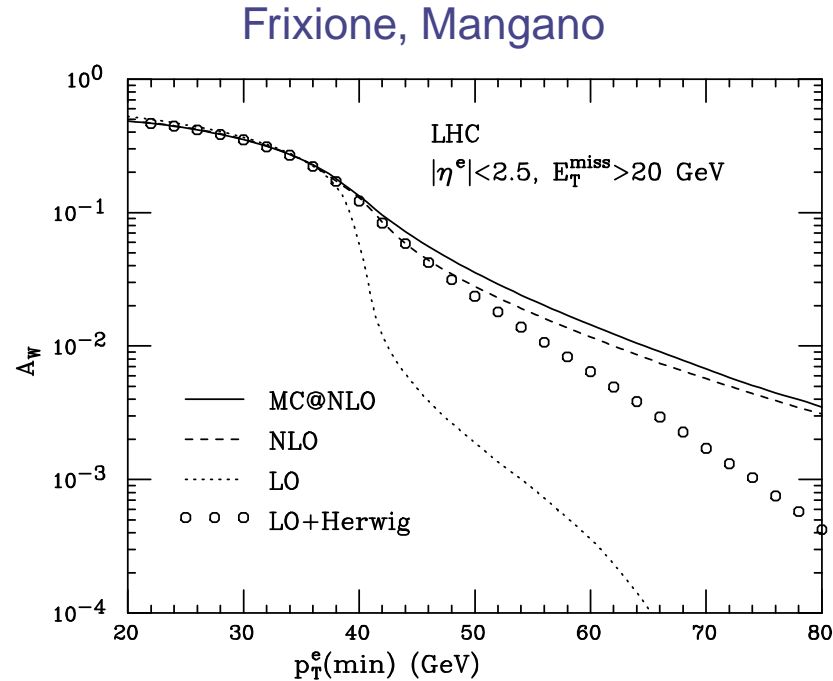
Comparisons

- Comparison to **NLO**, **MC@NLO** for LHC cuts

LHC	A(MC@NLO)	$\frac{\sigma_{MC@NLO}}{\sigma_{NLO}}$	$\mu = m_W$	
			A(NNLO)	$\frac{\sigma_{NNLO}}{\sigma_{NLO}}$
Inc	-	1.00	-	0.975
Cut 1	0.485	1.02	0.492	0.983
Cut 2	0.133	1.03	0.155	1.21

- Cut 1: $p_T^e > 20$ GeV, $|\eta^e| < 2.5$, $\cancel{E}_T > 20$ GeV (LHC)
- Cut 2: $p_T^e > 40$ GeV, $|\eta^e| < 2.5$, $\cancel{E}_T > 20$ GeV (LHC)
- Large **NNLO** perturbative corrections when $p_T^e > 40$ GeV
- ⇒ region where $p_T^e > m_W/2$ only opens at NLO, **NNLO** first correction to this region
- Strong cut dependence of **K**-factor
- Large disagreement with **MC@NLO**

Plausibility



- LO+parton shower (HERWIG) underestimates NLO by 2-10 for $p_T^e \geq 50 \text{ GeV}$
 - 20% shift consistent with NLO correction size for $p_T^e > m_W / 2$
 - $\sigma_{inc}^{NNLO} \approx 10 \text{ nb}$; magnitude of NLO \rightarrow NNLO shift for $p_T^e = 40, 50$: 0.1 nb
- \Rightarrow consistent with $\mathcal{O}(\alpha_s^2)$ effect

Conclusions

- Critical importance of W, Z production
 - Numerous experimental applications requiring percent-level theory
 - Historically, this channel has driven progress in QCD techniques
- Discussed technique for real radiation at NNLO
- Fully exclusive W, Z with spin correlations complete
 - $< 1\%$ scale uncertainties for standard cuts
 - Can get fooled by Monte Carlo simulations for non-standard cuts!