Getting ready for the LHC

QCD at next-to-leading-order and beyond

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Fermilab theory seminar

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Outline

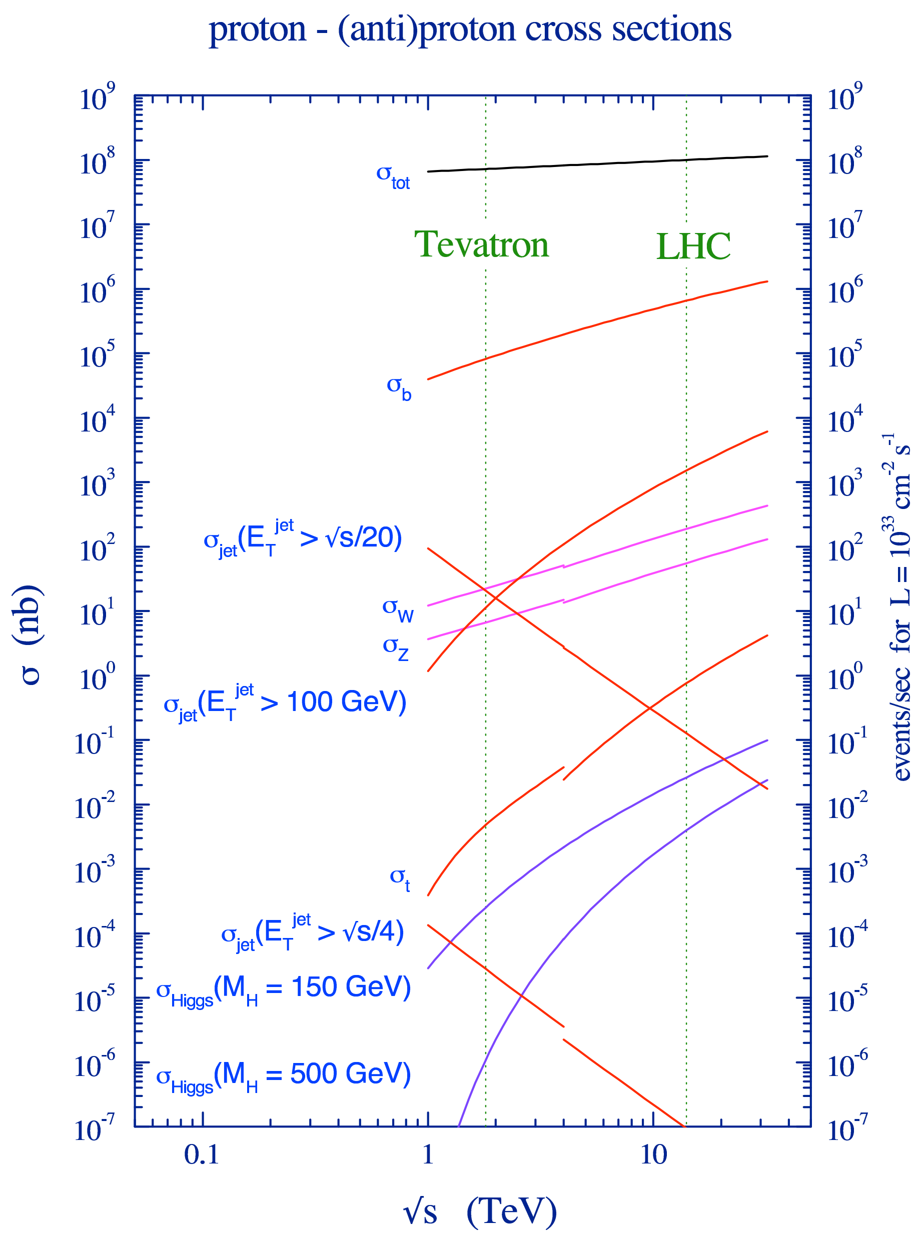
- Overview of QCD tools for colliders
  - Importance of fixed-order QCD approach
  - Higgs at the LHC: necessity of NLO for discovery
  - Status of NNLO corrections for benchmark measurements
- W, Z production at NNLO
  - Importance of W, Z production
  - Spin correlations
  - New techniques for NNLO calculations
  - Results $\Rightarrow$ large dependence on experimental cuts
- Conclusions

Physics at the LHC

- LHC turns on in ≈ 1 year!
- Excellent discovery reach at $\sqrt{s} = 14$ TeV:
  - SUSY: squark/gluino reach of 2.5-3 TeV
  - Z', graviton reach of 5-6 TeV
- Enormous event rates at $10\,\mathrm{fb}^{-1}$/year:
  - $W \to e\nu$: 10^8 events
  - $Z \to e^+e^-$: 10^7 events
  - $t\bar{t}$: 10^7 events
  - Higgs ($m_H = 700$ GeV): 10^4 events

$\Rightarrow$ Both an opportunity (precision, low systematics) and a challenge (backgrounds)

Signal excavation



- Not all discovery channels produce dramatic signatures!
- Need theoretical control of distribution shapes, backgrounds, uncertainties, . . .
- Measurements of new physics parameters needs theory
- Incorrect theory leads to:
  - Tevatron high E_T jets
  - Tevatron B-meson production
  - NuTeV $\sin^2\theta_W$
  - Brookhaven $g-2$ of the muon

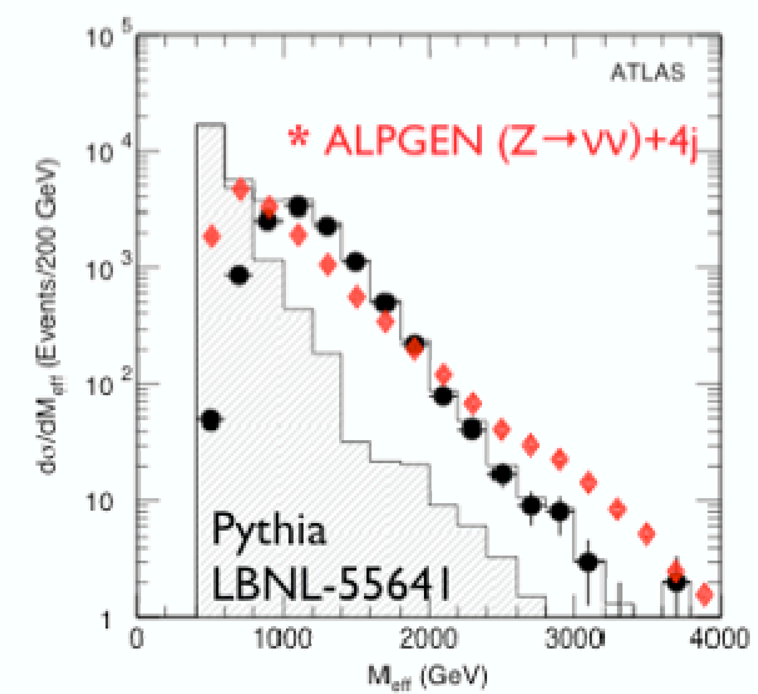
QCD tools for hadron colliders

- Develop, test QCD tools at HERA, Tevatron
- What are the possible approaches?
  - Fixed-order pQCD: systematic expansion in α_s $(\mathrm{LO}, \mathrm{NLO}, \mathrm{N^nLO})$
    - Quantify, reduce error by studying $\mu_{R,F}$ variation at each order
  - Analytic resummation: treat large logarithms to all orders in α_s
    $\Rightarrow \ln(m_H^2/p_T^2), \ln(1-m_H^2/\hat{s})$
  - Parton shower Monte Carlos (HERWIG, PYTHIA)
    - Generate many partons in collinear (leading log) approximation
    - Shower is universal; codes contain many processes

- HERWIG, PYTHIA: many partons allows hadronization, detector simulation; can access most physics processes; leading log resummation of dangerous kinematic regions
  $\Rightarrow$ default for many studies

How well do they do?

SUSY searches and PYTHIA

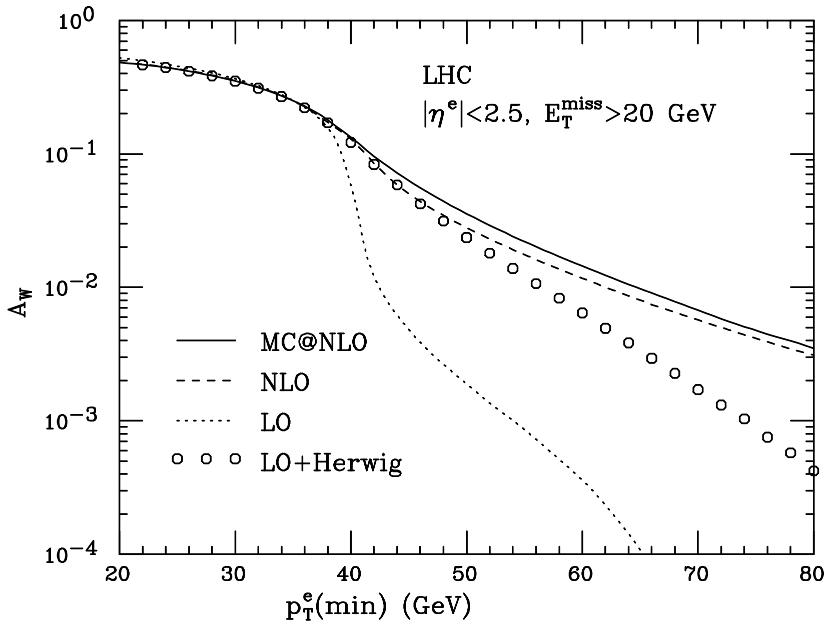


- $\mathrm{M_{eff}} = \sum_j p_\perp^j + E_\perp^{\mathrm{miss}}$: standard SUSY discriminator
- ALPGEN (Mangano et al.): exact LO matrix elements, correct hard emissions
- PYTHIA: extra jets generated via parton shower

⇒ PYTHIA does not describe multiple hard emissions well

W production and HERWIG

Frixione, Mangano



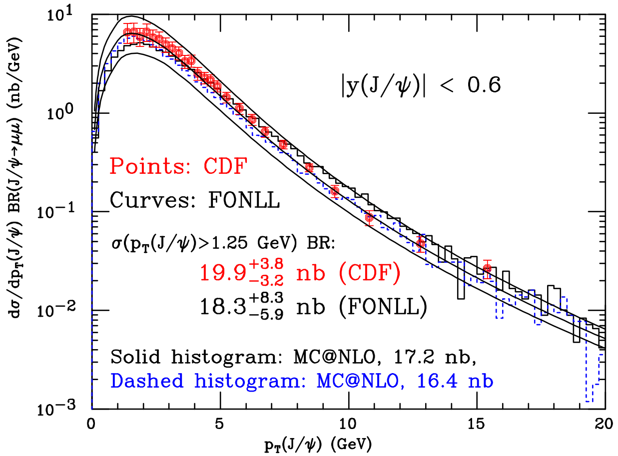
- $\frac{A_W[NLO]}{A_W[HERWIG]} \approx 2 - 10$ for $p^e_{T,min} \geq 50$ GeV
- Extra hard emission at NLO generates all events for $p^e_{T,min} > M_W/2$

$\Rightarrow$ HERWIG misses important effects for the W acceptance

Moral

- Moral: need systematic, controlled QCD expansion
  - pQCD expansion in α_s augmented with necessary resummation
  - Verify and improve Monte Carlo tools

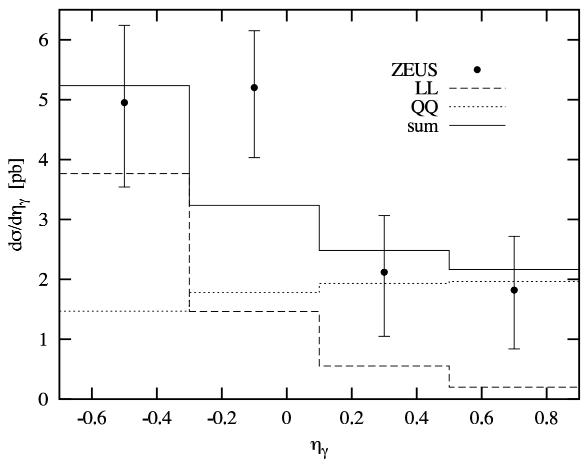
Cacciari et al.



B production at Tevatron

- Run I: data/theory ratio was 2-4
- Use consistent fragmentation extraction
- Resummation of $p_\perp/m_b$, new pdfs

Gehrmann et al.



Isolated photons at ZEUS

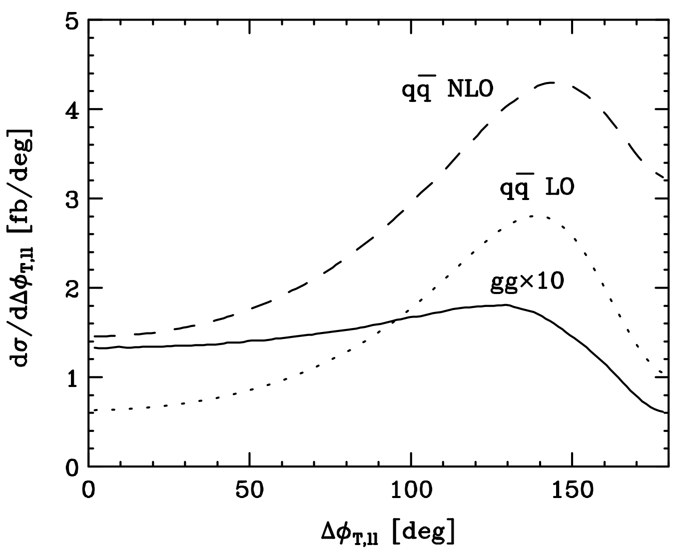
- Data/PYTHIA=2.3, Data/HERWIG=7.9
- Both have incorrect kinematics
- PYTHIA γ from lepton, HERWIG γ from quark
- LO QCD gets rate and shapes correct

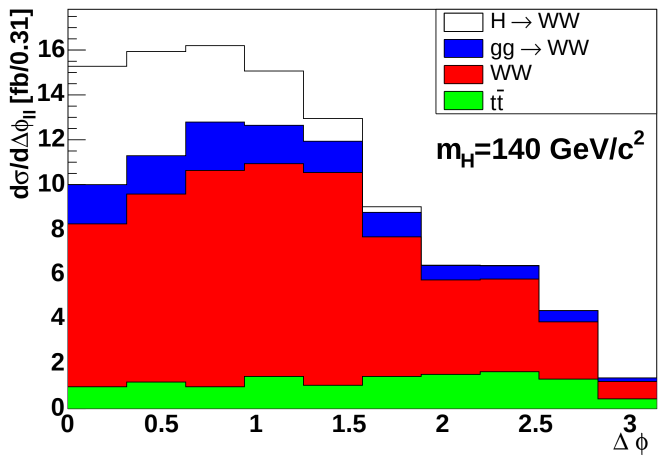
Status of NLO calculations

- Parton-level results available for all $2 \to 2$ and some $2 \to 3$ processes:
  - AYLEN/EMILIA (de Florian et.al.): $pp \to (W, Z) + (W, Z, \gamma)$
  - DIPHOX (Aurenche et.al.): $pp \to \gamma j, \gamma\gamma, \gamma^* p \to \gamma j$
  - HQQB (Dawson et.al.): $pp \to t\bar{t}H, b\bar{b}H$
  - MCFM (Campbell, Ellis): $pp \to (W, Z) + (0, 1, 2)\, j,\ (W, Z) + b\bar{b}, V_1 V_2, \ldots$
  - NLOJET++ (Nagy): $pp \to (2, 3)\, j$, $ep \to (3, 4)\, j$, $\gamma^* p \to (2, 3)\, j$
  - VBFNLO (Figy et.al.): $pp \to (W, Z, H) + 2\, j$
  - $\ldots$
- Reduced theoretical uncertainty from $\mu_{R,F}$ dependence
- New qualitative effects, e.g., gluon pdf, p_T generation

Higgs discovery at higher orders

- NLO essential for discovery
  - Important Higgs mode for $140 < m_H < 180$ GeV is $gg \to H \to WW \to ll\nu\nu$
  - Cannot reconstruct mass peak; rely upon kinematic distributions





  - NLO $pp \to WW$ background correction large: $\sigma_{NLO}/\sigma_{LO} > 1.5$
  - Loop-induced $gg \to WW$ formally NNLO; enhanced by $\Delta\phi_{T,ll} < 45^o$

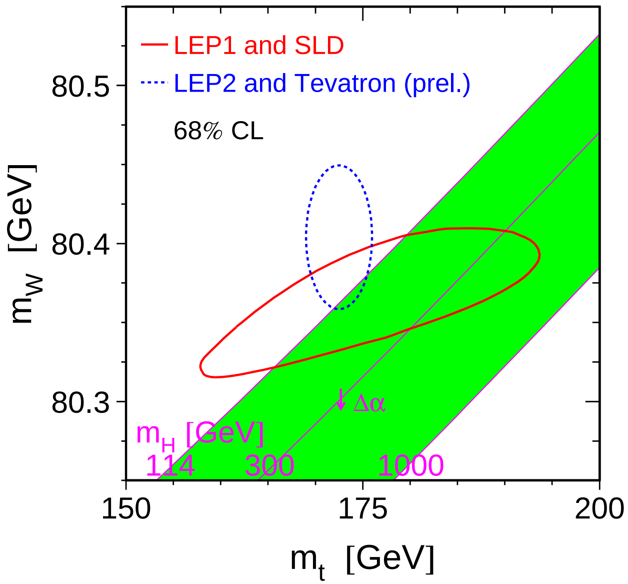
$\Rightarrow$ further increases background by 30% (Binoth et al., Dührssen et al.)

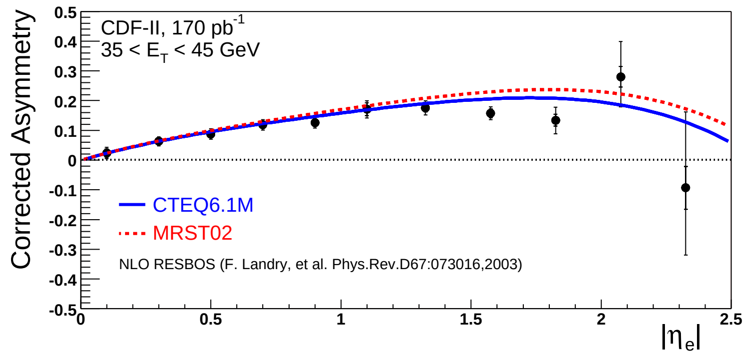
Status of NNLO calculations

- When is NNLO needed?
  - When corrections are large (H production, fixed target energies)
  - For benchmark measurements, where expected errors are small ($W, Z, t\bar{t}$ production)
- What is known?
  - Several inclusive $2 \to 1$ processes (W, Z, H production) (van Neerven, Harlander, Kilgore, Anastasiou, Melnikov, Ravindran, Smith)
  - A few "semi-inclusive" $2 \to 1$ distributions (W, Z rapidity distributions) (Anastasiou, Dixon, Melnikov, FP)
  - Fully differential $2 \to 1$ result ($pp \to H, W, Z + X$) (Anastasiou, Melnikov, FP)
  - DGLAP splitting kernels (Moch, Vermaseran, Vogt)
  - Various approximate results (soft approximations)

W, Z production at the Tevatron

- $q\bar{q} \rightarrow (W, Z) \rightarrow (l\nu, ll)$: clean experimental signature
  - Important for several precision measurements at the Tevatron





  - M_W: important constraints on m_H and new physics
  - $A_l(\eta) = \frac{d\sigma(e^+)/d\eta - d\sigma(e^-)/d\eta}{d\sigma(e^+)/d\eta + d\sigma(e^-)/d\eta} \approx \frac{d(x)}{u(x)} \Rightarrow$ important in PDF fit

W, Z production at the LHC

- Calibration of detectors (lepton energy scale)
- Precision physics: distinguish Z' models (Dittmar, Djouadi, Nicollerat)
- Luminosity determination to percent level (Dittmar et al.)
- W, Z production are benchmark processes

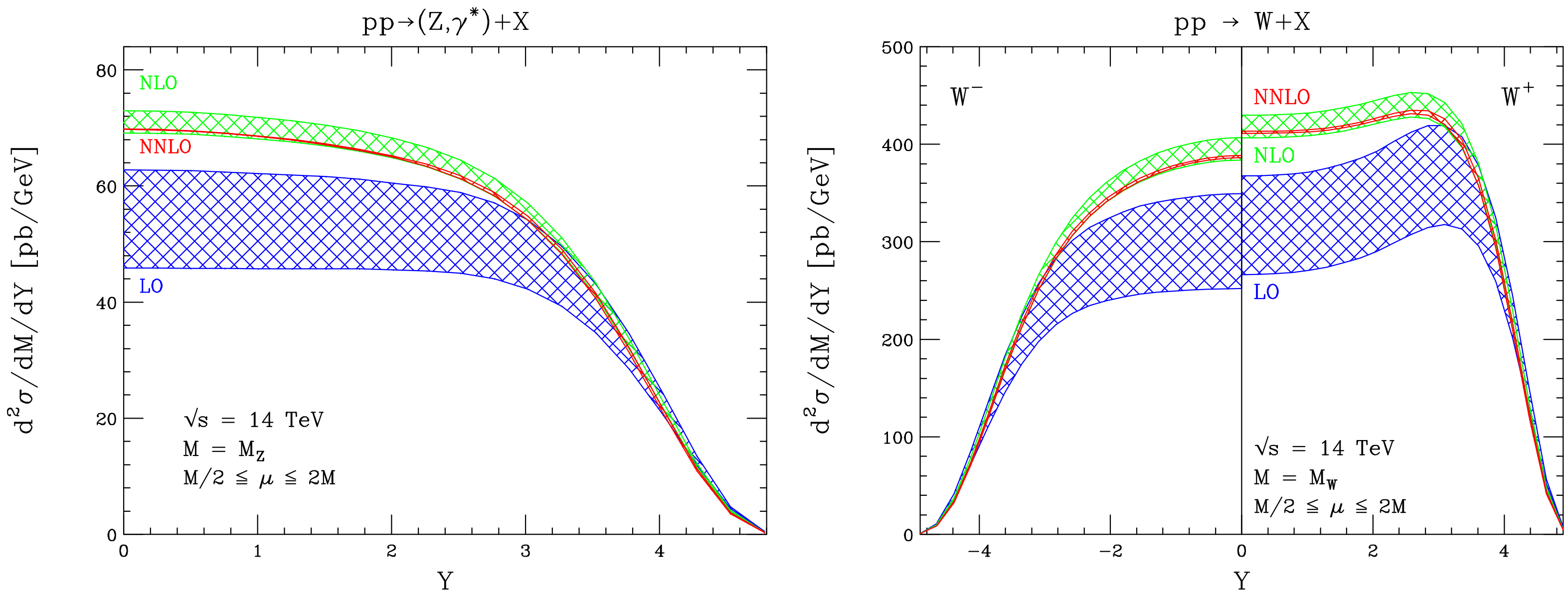
$\Rightarrow$ need theoretical prediction accurate to the percent level, understanding of uncertainties

Theoretical calculation components

- Needed for precision theoretical calculation:
  - Fixed-order QCD to $\mathcal{O}(\alpha_s^2) \Rightarrow$ sufficient for inclusive observables
  - Resummation of $\ln(Q/q_T)$ for observables restricted to low q_T (RESBOS, Balazs, Nadolsky, Yuan)
  - $\mathcal{O}(\alpha)$ EW corrections (Baur et al.), particularly FSR
  - Possible resummation of $x \to 0, 1$ limits
  - ...
- Reviewed by Nadolsky, hep-ph/0412146

Fixed-order QCD

- Inclusive result known to NNLO (Hamberg, van Neerven, Matsuura; Harlander, Kilgore)
- W, Z rapidity distributions known to NNLO: (Anastasiou, Dixon, Melnikov, FP)



- Scale variation $< 1\%$ at NNLO
- For Z production, $d\sigma/dY \sim q(x_1)\bar{q}(x_2) + \mathcal{O}(\alpha_s)$, $x_{1,2} = \sqrt{\frac{m^2}{s}} e^{\pm Y}$

$\Rightarrow$ can fix functional dependence of PDFs

Experimental cuts

- Experiments measure $l^+l^-, l^\pm \not{E}_T$, not W, Z

⇒ impose cuts on lepton phase-space

Tevatron: $50 \leq m_T \leq 100$ GeV, $p_T^e > 20$ GeV, $\not{E}_T > 25$ GeV, $|\eta| < 1$

- Measurements such as require $A_l(\eta)$ lepton kinematics
- W, Z are spin-1 $\Rightarrow$ matrix elements contain "spin correlations" between production, decay: $p_q \cdot p_l$

⇒ not included in current NNLO calculations

Spin correlations at NLO

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

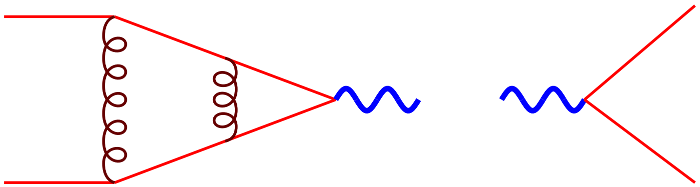
	Tevatron			LHC		
	LO	NLO	MC@NLO	LO	NLO	MC@NLO
Cut 1	0.409	0.385	0.383	0.524	0.477	0.485
Cut 1, no spin	0.413	0.394	0.394	0.553	0.510	0.515
Cut 2	0.356	0.340	0.336	0.058	0.129	0.133
Cut 2, no spin	0.389	0.374	0.370	0.075	0.150	0.157

- Spin correlations at NLO a 10% effect

$\Rightarrow$ For 1% measurements (e.g., luminosity) need NNLO with spin correlations

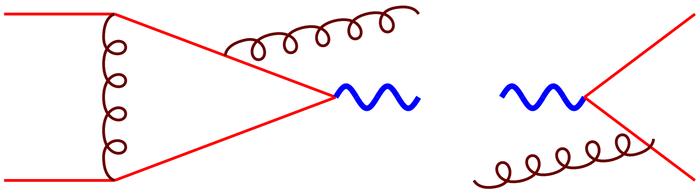
Anatomy of a NNLO calculation

- Virtual-Virtual



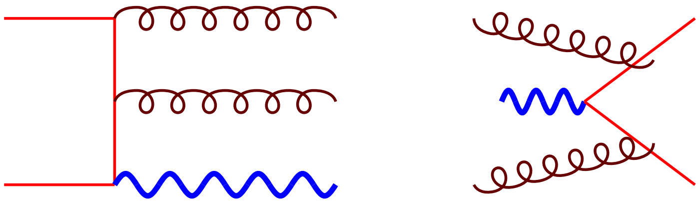
+ 100 terms

- Real-Virtual



+ 300 terms

- Real-Real



+ 500 terms

Two-loop integrals

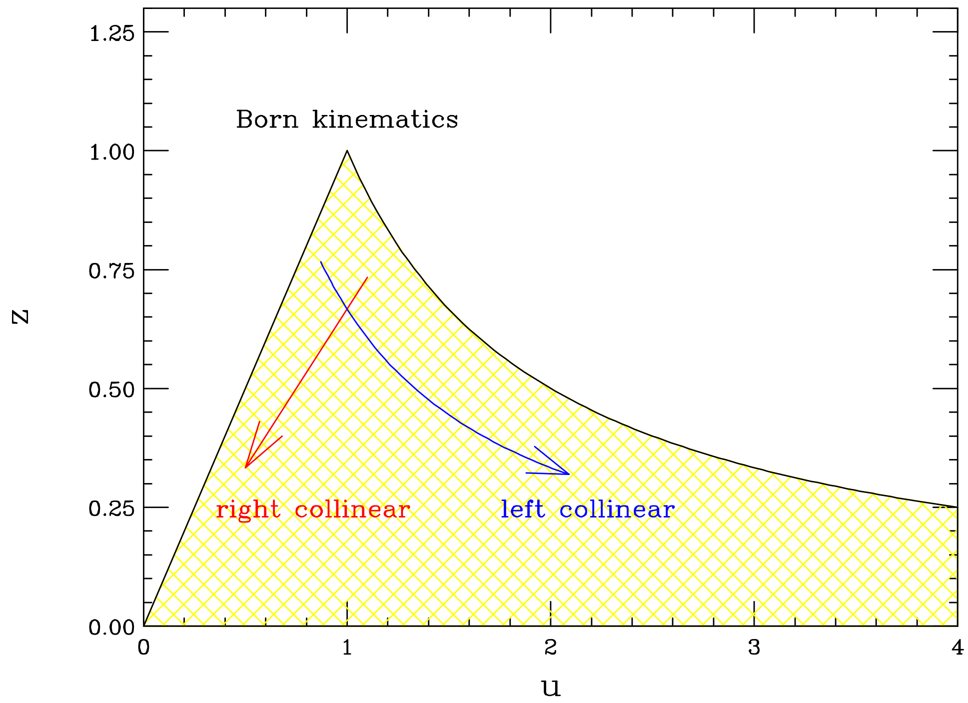
- Two-loop integrals not simple, but well understood
  - Loop integrals satisfy recurrence relations arising from Poincare invariance (Chetyrkin, Tkachov; Gehrmann, Remiddi)
  - Automated solution of recurrence relations (Laporta): reduce $100 \rightarrow 5$ master integrals
  - Use differential equations, Mellin-Barnes integral representations to compute master integrals (Smirnov; Tausk; Gehrmann, Remiddi)

- Two-loop Bhabha scattering in massless QED — Bern, Dixon and Ghinculov
- All two-loop $2 \rightarrow 2$ QCD processes. — Anastasiou, Glover, Oleari and Tejeda-Yeomans; Bern, De Freitas, and Dixon
- $\gamma\gamma \rightarrow \gamma\gamma$ — Bern, Dixon, De Freitas, A. Ghinculov and H.L. Wong
- $gg \rightarrow \gamma\gamma$. (Background to Higgs decay.) — Bern, De Freitas, Dixon
- $\bar{q}q \rightarrow \gamma\gamma$, $\bar{q}q \rightarrow g\gamma$, $e^+e^- \rightarrow \gamma\gamma$ — Anastasiou, Glover and Tejeda-Yeomans
- $e^+e^- \rightarrow 3$ partons — Garland, Gehrmann, Glover, Koukoutsakis and Remiddi; Moch, Uwer, Weinzierl
- DIS 2 jet and $pp \rightarrow W, Z + 1$ jet — Gehrmann and Remiddi

$\Rightarrow$ Loop integrals not the sticking point!

Issues in real radiation

- Singularity structure: exclusive $\longrightarrow$ singular



- Need to extract these singularities from complicated phase-space integrals

Real radiation at NNLO

- Fully differential results at NLO typically use dipole subraction
- Tough to extend to NNLO, although some success recently (A. Gehrmann-De Ridder, T. Gehrmann, N. Glover; B. Kilgore; G. Somogyi, Z. Trocsanyi, V. Del Duca; S. Frixione, M. Grazzini)
- 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 ($d = 4 - 2\epsilon$)

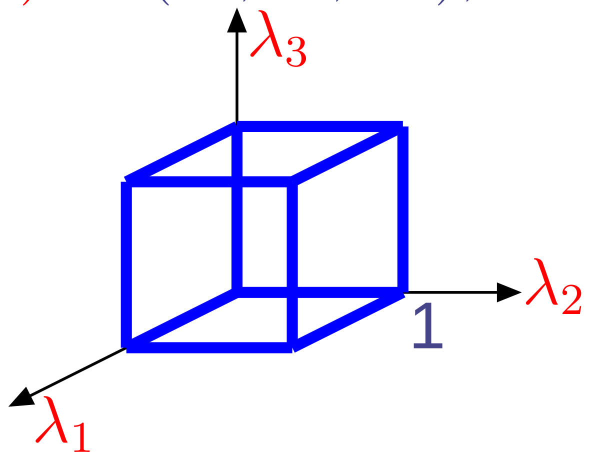
$$\sigma_{\text{real}} = \frac{A_4\,[Obs]}{\epsilon^4} + \frac{A_3\,[Obs]}{\epsilon^3} + \ldots + A_0\,[Obs]$$

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

Phase-space singularities

- Singularities have a complicated form in momentum space beyond NLO
- Map phase-space volume to the unit hypercube

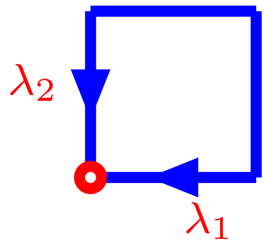
$$(E, p_x, p_y, p_z) \to (\lambda_1, \lambda_2, \ldots), \quad 0 \le \lambda_i \le 1$$



  - Simple geometry $\rightsquigarrow$ automatization
  - Easy to spot singular regions $\rightsquigarrow$ the edges

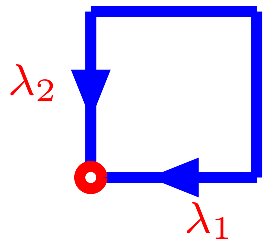
Overlapping singularities

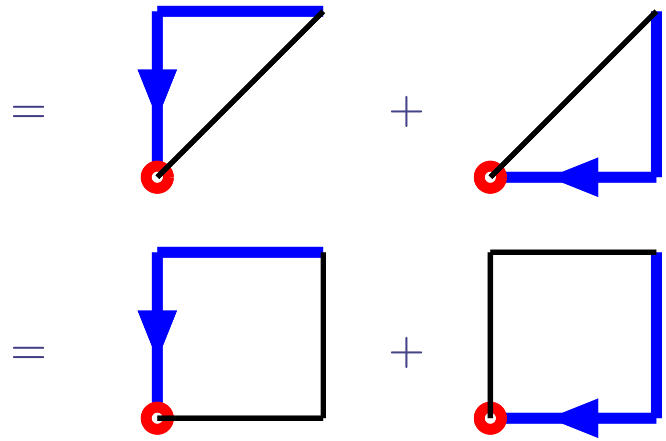
- Singularity when two (or more) variables reach the same corner



$$: \quad \frac{\lambda_1^{\epsilon}\lambda_2^{\epsilon}}{(\lambda_1+\lambda_2)^2} f(\lambda_1, \lambda_2; Obs(\lambda_1, \lambda_2))$$

- Split into sectors





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

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

LHC results

- Fully exclusive NNLO calculation with spin correlations complete (Melnikov, FP)

			$\mu = m_W/2$		$\mu = m_W$	
LHC	A(MC@NLO)	$\frac{\sigma_{MC@NLO}}{\sigma_{NLO}}$	A(NNLO)	$\frac{\sigma_{NNLO}}{\sigma_{NLO}}$	A(NNLO)	$\frac{\sigma_{NNLO}}{\sigma_{NLO}}$
Inc	-	1.00	-	1.00	-	0.975
Cut 1	0.485	1.02	0.497	1.02	0.492	0.983
Cut 2	0.133	1.03	0.161	1.27	0.155	1.21

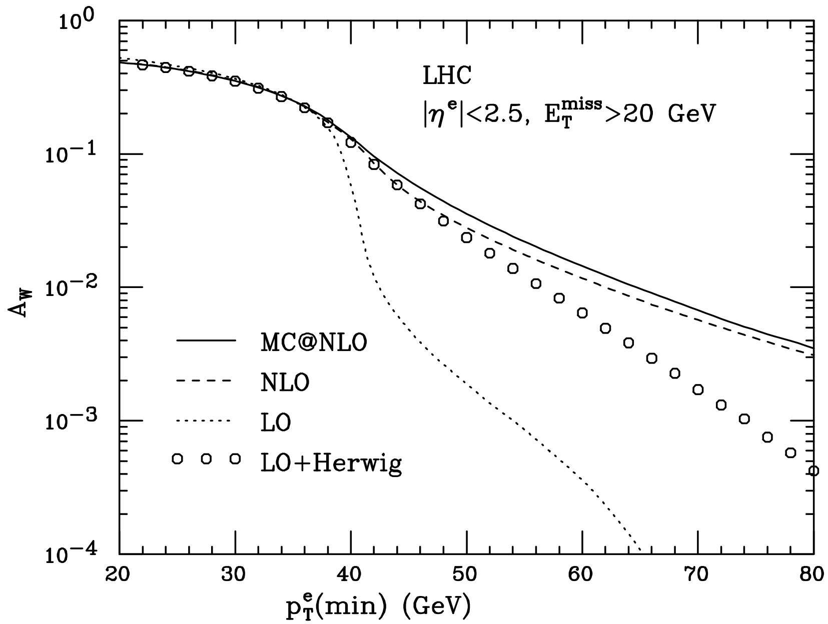
- Large NNLO perturbative corrections when $p_T^e > 40$ GeV

$\Rightarrow$ 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

Frixione, Mangano



- LO+parton shower (HERWIG) underestimates NLO by 2-10 for $p_T^e \geq 50$ GeV
- 20% shift consistent with NLO correction size for $p_T^e > m_W/2$
- $\sigma_{inc}^{NNLO} \approx 10$ 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

- Need more work on QCD tools for LHC physics!
  - Need fixed-order QCD+resummation to improve MC generators, quantify errors
  - $pp \to WW$ background shows *necessity* of NLO signal, background calculations
    $\Rightarrow$ also interplay between higher orders and experimental cuts
  - Many new techniques for $\mathrm{N^nLO}$ results for benchmark measurements
- W, Z cross sections:
  - Large perturbative corrections at NNLO for certain cuts
  - Disagreement with MC@NLO $\Rightarrow$ HERWIG shower too soft
  - Study of K-factor kinematic dependence for LHC analyses underway
  - Acceptances and NNLO corrections for Tevatron analyses underway

  $\Rightarrow$ for standard Tevatron cuts, no large effect from spin correlations