Advances in perturbative QCD for LHC physics

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Outline

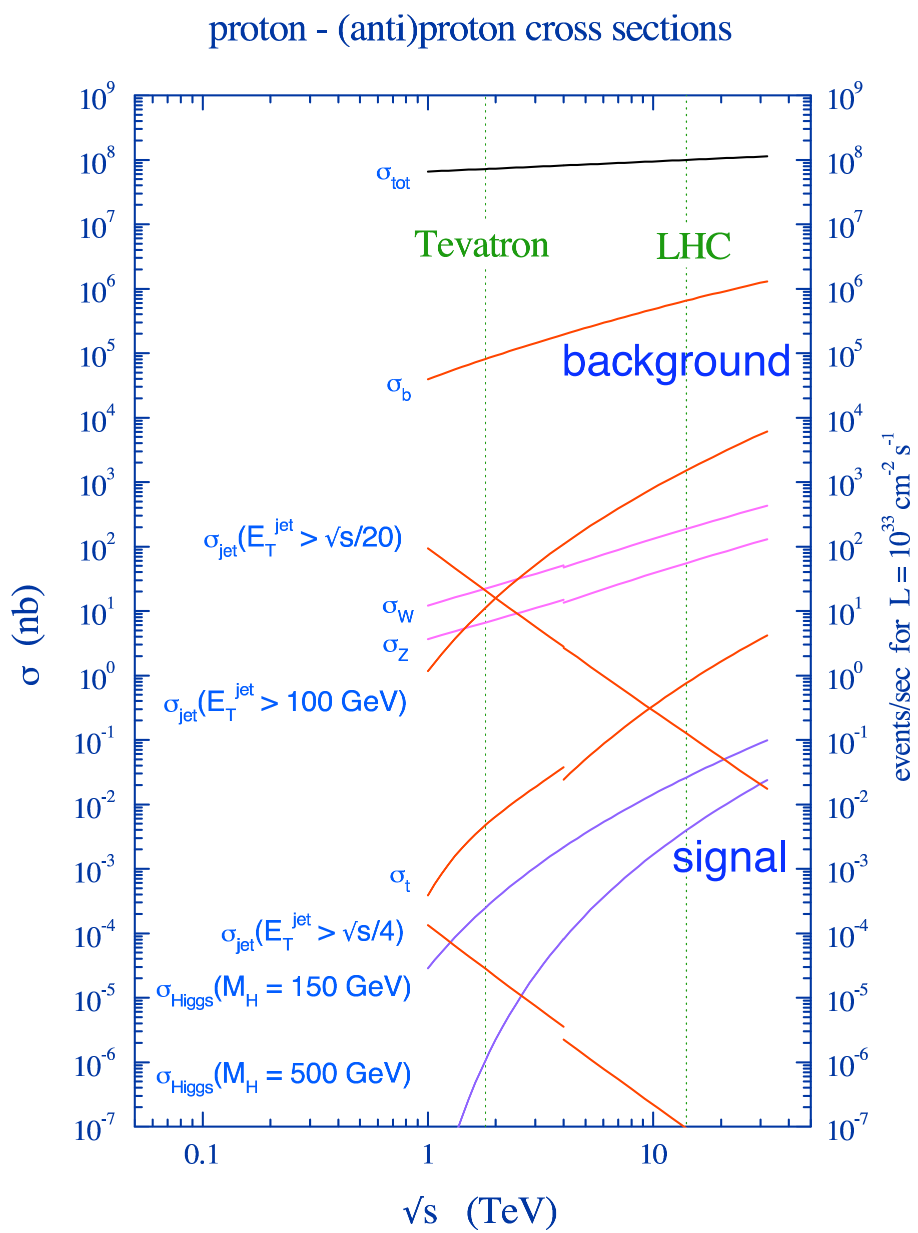
- Motivation
  - Importance of perturbative QCD at colliders
  - Testing tools with HERA, Tevatron data
- Merging LO with parton showers
- Status of NLO calculations
  - LHC phenomenology at NLO
  - Difficulties at NLO: $2 \to 3, 4, \ldots$ processes
  - New techniques for NLO calculations
- Status of NNLO calculations
  - DGLAP evolution at NNLO
  - NNLO W, Z cross sections with spin correlations and Tevatron data

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)

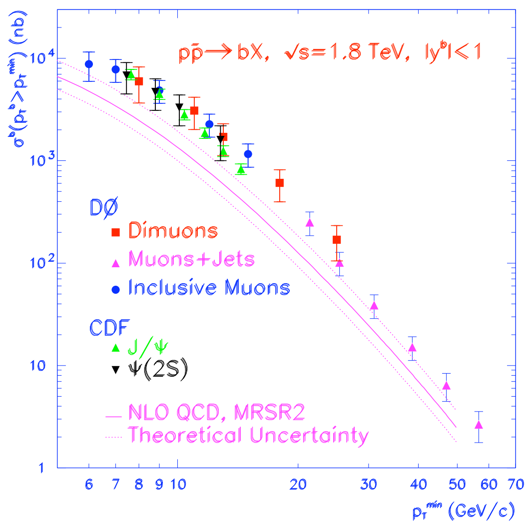
Physics at the LHC



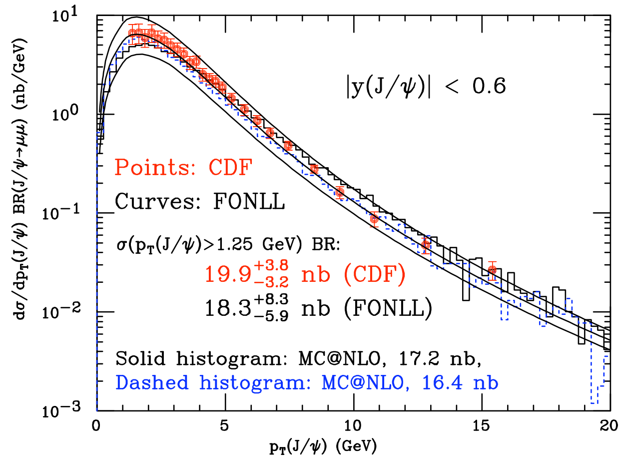
- Not all discovery channels produce dramatic signatures!
- Need theoretical control of distribution shapes, backgrounds, uncertainties, . . .
- Measurements of new physics parameters needs theory
- Incorrect theory leads to:
  - Tevatron high E_T jets
  - Tevatron B-meson production
  - NuTeV $\sin^2\theta_W$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

Bottom production at the Tevatron

- Long-standing discrepancy for B-hadron production
  - Tevatron Run I: factor of 3 ± 0.4 higher than QCD prediction!
  - Motivated light sbottom/gluino interpretation of data (Berger et al.)

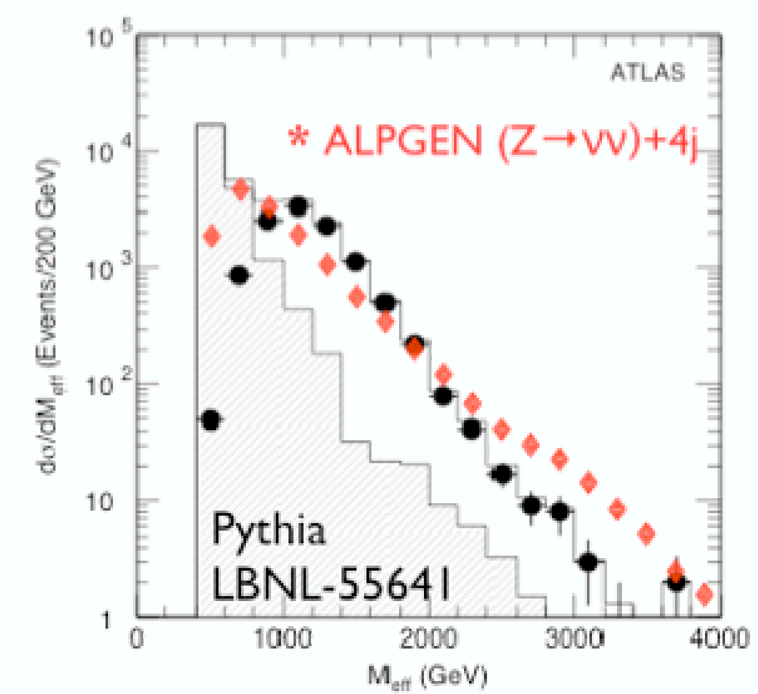


$\Rightarrow$



  - Missing theory components: inconsistent $b \to B$ fragmentation functions, updated PDF extractions, $p_\perp/m_b$ resummation, underestimated uncertainties, ... (Cacciari et al.)
  - Detailed theory analysis needed to understand data

SUSY searches and PYTHIA



- $\mathrm{M_{eff}} = \sum_j p_\perp^j + E_\perp^{\mathrm{miss}}$: standard SUSY discriminator
- Current tools (PYTHIA) underestimate background by factor of 10! (Mangano et al.)
- PYTHIA: extra jets generated via parton shower $\Rightarrow$ wrong hard emissions
- Need exact matrix elements from QCD
- Incorrect simulation in ATLAS TDR

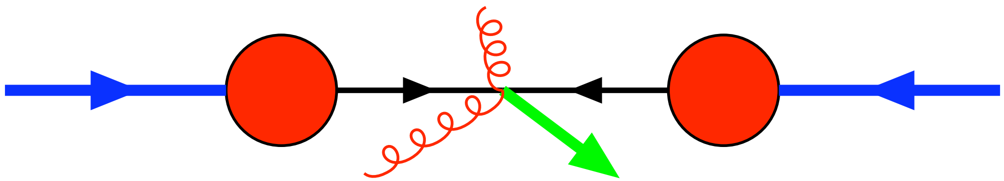
Moral

- Moral: need systematic, controlled QCD expansion
  - pQCD expansion in α_s augmented with necessary resummation
  - Cross-check and improve simulation tools
- Issues to consider:
  - Are the kinematics described correctly?
  - What is the correct normalization, and what is its uncertainty?
  - Where do new qualitative effects like the gluon pdf (large at the LHC) appear in the calculation?
  - Have kinematic boundaries where resummation may be required been considered?

QCD at hadron colliders

- Observables in hadronic collisions

$$N_{events} = L \int f_i(x_1,\mu^2)\, f_j(x_2,\mu^2)\, \sigma_{ij}(x_1,x_2,\mu^2)$$

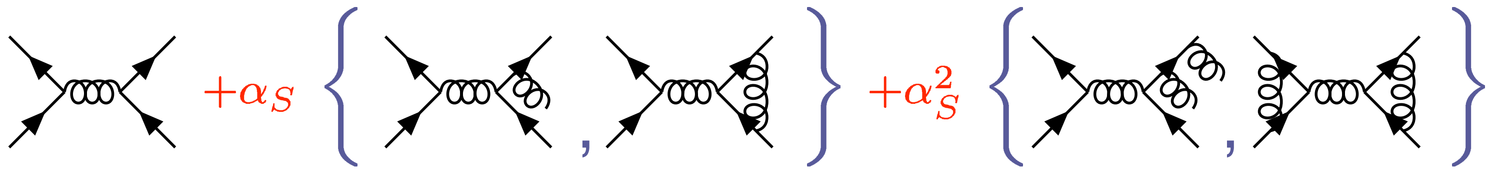


- Require
  - luminosity measurement
  - parton distribution functions
  - scattering cross sections

⇒ All of these require precise QCD cross sections!

Cross sections in QCD

- $\sigma = \sigma_0 \left\{ 1 + \frac{\alpha_S}{\pi} (l + \sigma_1) + \frac{\alpha_S^2}{\pi^2} (l^2 + l + \sigma_2) + \mathcal{O}(\alpha_S^3) \right\}$



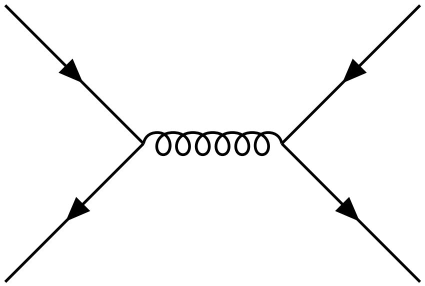
- Strong coupling constant not small: $\alpha_S(M_Z) \approx 0.12$
- Contains scales $l = \ln(\mu^2/Q^2)$
  - Get scales from UV and IR renormalization
  - Scales are arbitrary: $\frac{d\sigma}{d\mu} = 0$

  $\Rightarrow$ but truncation of expansion at $\mathcal{O}(\alpha_S^n)$ induces a scale dependence of $\mathcal{O}(\alpha_S^{n+1})$
  - Residual scale dependences provide estimate of neglected higher order effects

Parton shower simulations

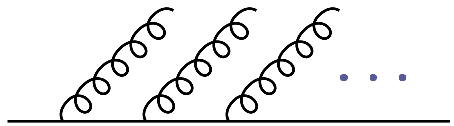
- Usual first attempt at hadron collider prediction

Begin with:



⇒

PS generates shower for each line:



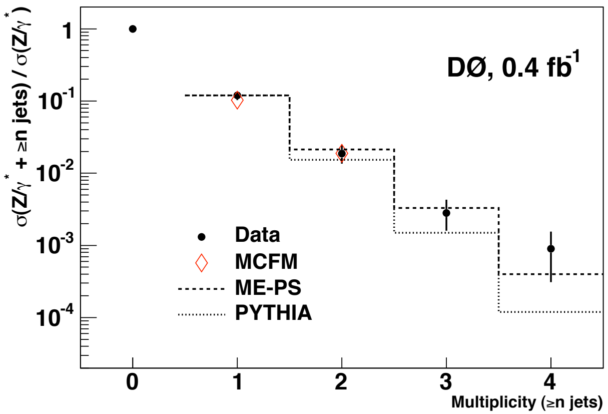
- In the soft+collinear limit, extra emissions simplify
- Can sum to all orders, incorporates large swath of QCD corrections
- Doesn't get extra hard jet, need exact matrix elements

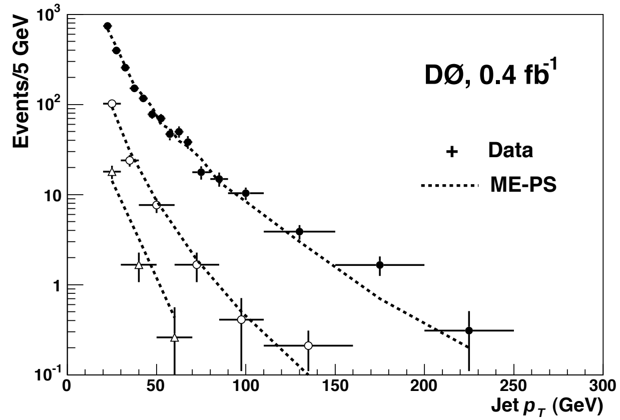
⇒ this was the SUSY study problem shown before

- Also misses correlations between extra jets
- Can the resummation and the hard emissions be combined?

Merging LO with parton showers

- CKKW (Catani, Krauss, Kuhn, Webber): prescription to cover entire phase-space correctly
- Define $P_m = \frac{\sigma_m}{\sigma_0 + \ldots + \sigma_N}$; generate m hard jets from MEs; feed this into showering algorithm and veto hard jets from shower





- ME/PS matching describes Run II data well (hep-ex/0608052)
- Codes: SHERPA includes ME generator, HERWIG, PYTHIA use external tree-level generator (MADGRAPH) and apply CKKW (Mrenna, Richardson)
- Kinematics seemingly well described by this procedure

The need for NLO

- Still not good enough for LHC physics
- Predictions at LO suffer from debilitating theory errors
  - Example: $pp \to \nu\bar{\nu} + N$ jets, $p_T^j > 80$ GeV, $|\eta^j| < 2.5$, $\mu = \sqrt{m_Z^2 + \sum p_T^{j,2}}$

N	$\sigma(2\mu)$	$\sigma(\mu/2)$
3	6.47 pb	13.52 pb
4	0.90 pb	2.48 pb

  - Uncertainty from μ variation must vanish at higher orders $\Rightarrow$ large NLO corrections
  - Typical NLO size: 30-100% $\Rightarrow$ not just naive α_s/π expansion!
    - New channels open up at higher orders $\to$ gluon pdf large at small x
    - New kinematics regions allowed $\to$ generate $p_\perp$, other effects
    - Large coefficients in perturbative corrections (π^2 for s-channel processes)
- NLO calculations needed for LHC physics!

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.): $pp \to (W, Z, H) + 2\, j$
- Recent:
  - $pp \to Wb\bar{b}$, $m_b \neq 0$ (Cordero, Reina, Wackeroth hep-ph/0606102)
  - $pp \to Hjj$ (Campbell, Ellis, Zanderighi hep-ph/0608194)
  - $pp \to t\bar{t}j$ (Dittmaier, Uwer, Weinzierl, hep-ph/0703120)
  - $pp \to VVV$ (Lazopoulos, Melnikov, FP, hep-ph/0703273)

NLO wishlist

An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

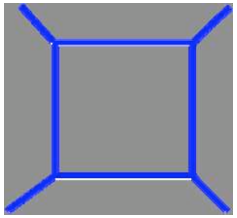
Single boson	Diboson	Triboson	Heavy flavour
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}+\leq 3j$	$WW+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 3j$	$WW+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$ZZ+b\bar{b}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{b}+\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$		$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}+\leq 3j$	$\gamma\gamma+b\bar{b}+\leq 3j$		
$\gamma+c\bar{c}+\leq 3j$	$\gamma\gamma+c\bar{c}+\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}+\leq 3j$		
	$WZ+c\bar{c}+\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

Campbell, Knuteson

- Want flexibile, automated approach $\Rightarrow$ many backgrounds, possible new states

Example of difficulty

Consider a tensor integral:

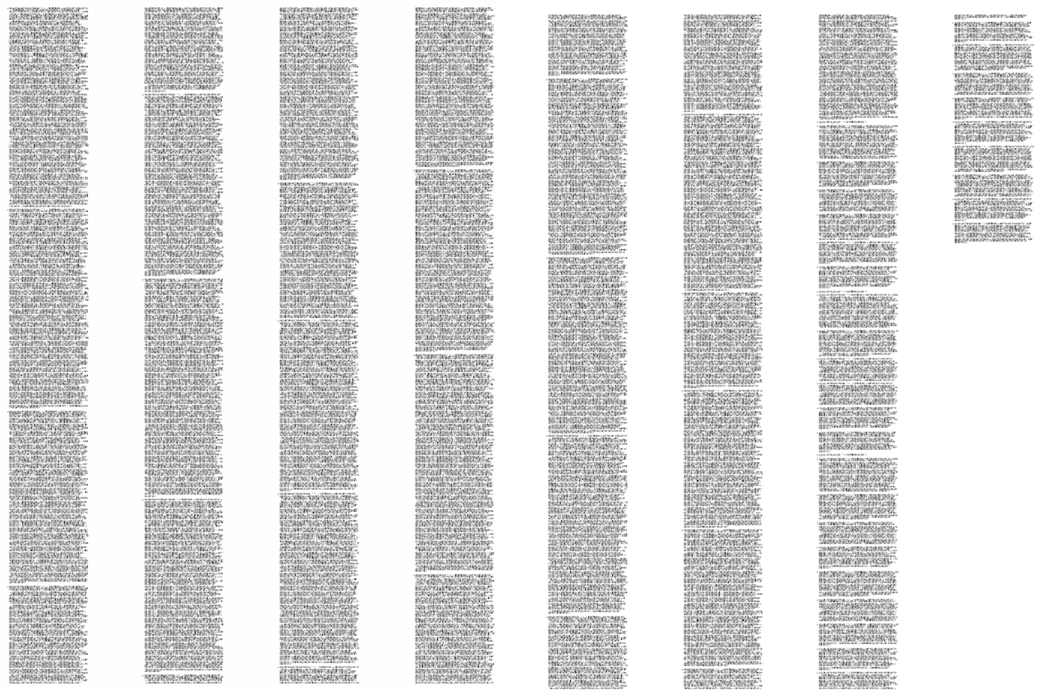


$$\int \frac{d^{4-2\epsilon}\ell}{(2\pi)^{4-\epsilon}} \frac{\ell^\mu\, \ell^\nu\, \ell^\rho\, \ell^\lambda}{\ell^2\,(\ell-k_1)^2\,(\ell-k_1-k_2)^2\,(\ell+k_4)^2}$$

Evaluate this integral via Passarino-Veltman reduction. Result is …

The result...

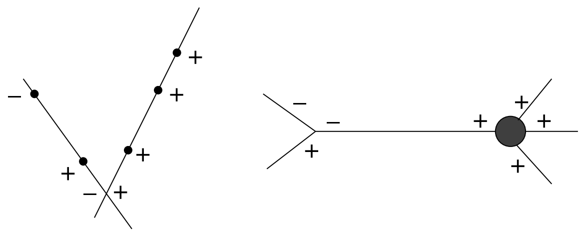
Result of performing the integration



Numerical stability is a key issue.
Clearly, there should be a better way

Improved techniques for NLO

- Sticking point: loops for $n = 5, 6, \ldots$ external legs
- Much recent activity on new methods:
  - Twistor-inspired: (Witten; Cachazo et al.; Bern, Dixon et al.; . . .)

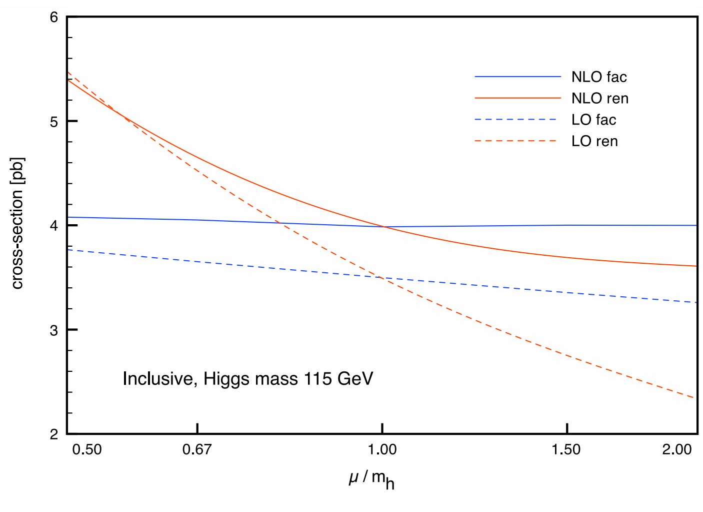


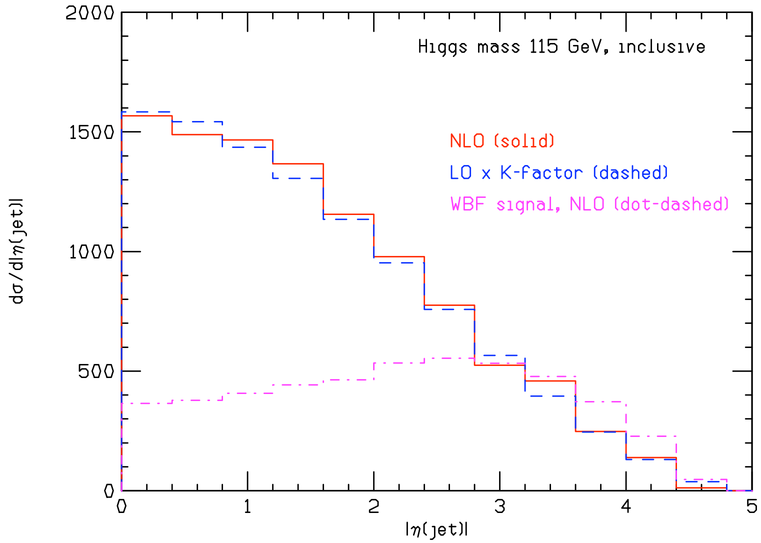
(a) (b)

    - String theory in twistor-space ⇔ QCD amplitudes
    - Use “MHV” amplitudes rather than Feynman diagrams
    - Drastically simplified analytic structure
  - Semi-numerical techniques: (Ellis, Giele, Zanderighi, et al.; Soper; Lazopoulos, Melnikov, FP; . . .)
    - Can we avoid reducing the loop integrals, or store coefficients as numbers?
    - Need to numerically handle IR singularities, internal thresholds, . . .

H+2 jets at NLO

- QCD corrections to Hjj recently completed
  (Campbell, Ellis, Zanderighi hep-ph/0608194)
  - First output from semi-numerical methods for NLO computations
  - NLO needed for extraction of HWW coupling in WBF

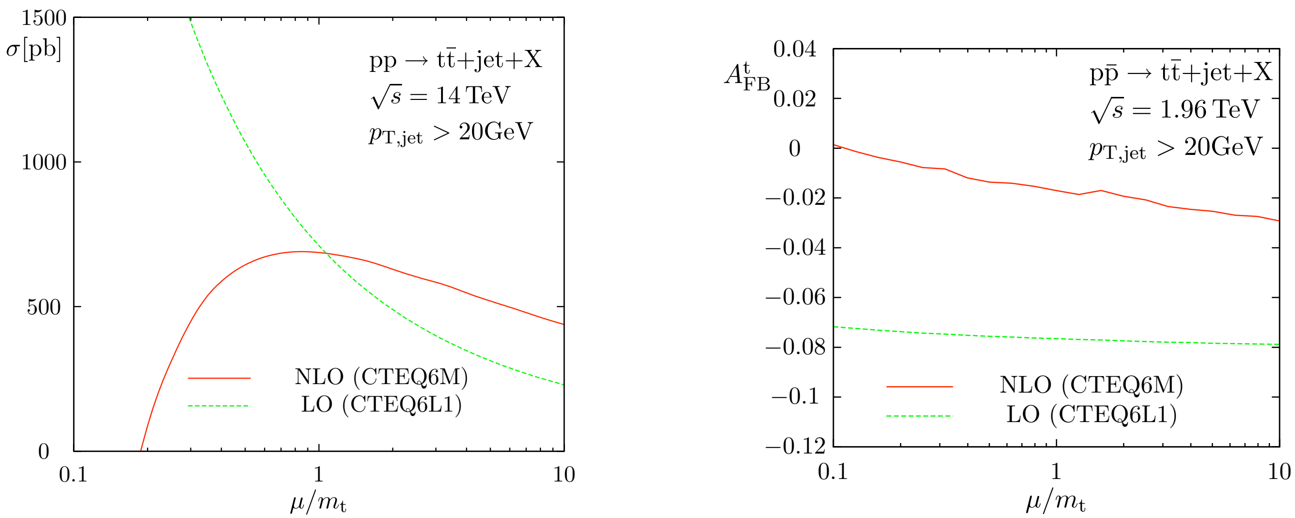




  - Residual scale dependence reduced
  - $\sigma_{NLO}/\sigma_{LO} = 15 - 25\%$; corrections are kinematic-independent
  - Maybe this kinematic independence is generic?

$t\bar{t}$+jet at NLO

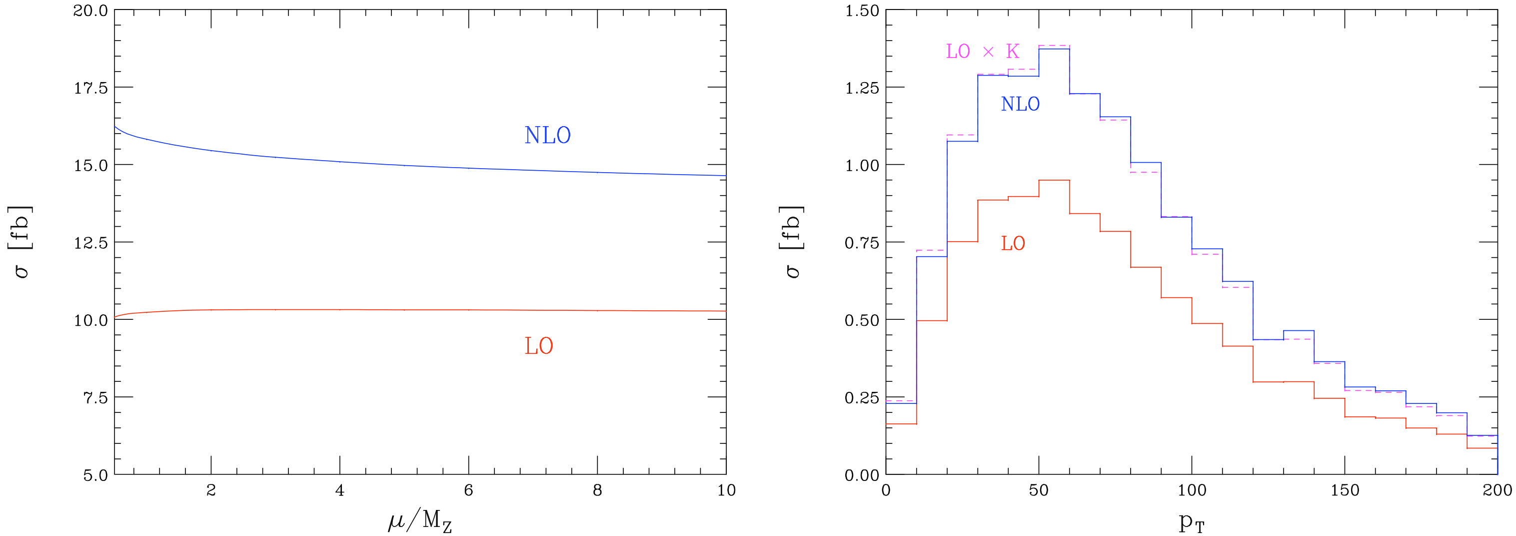
- QCD corrections to $t\bar{t}j$ recently completed (Dittmaier, Uwer, Weinzierl hep-ph/0703120)
  - Background to Higgs in WBF, $t\bar{t}H$ channels; measurement of t properties



  - Residual scale dependence reduced
  - NLO corrections wipe out forward-backward charge asymmetry!

ZZZ at NLO

- QCD corrections to ZZZ using numerical approach (Lazopoulos, Melnikov, FP hep-ph/0703273)
  - Background to various SUSY tri-lepton signatures, gauge boson coupling measurments
  - Completely numerical approach for loop calculations



  - Large, 50% corrections not seen by LO scale variation! $\Rightarrow$ 15% shift from pdfs, 35% shift from π^2 terms
  - Inclusive K-factor approximation works, however

NLO summary

- Corrections large, no obvious kinematic dependence pattern

$\Rightarrow$ for now, must have complete result for each process

- New approaches that promise to simplify
  and automate these calculations

- Stay tuned for progress!

Status of NNLO calculations

- When is NNLO needed?
  - When corrections are large (H production, fixed target energies for pdfs)
  - For benchmark measurements, where expected errors are small ($W, Z, t\bar{t}$ production)
  - Jet production at e^+e^- colliders:

$$\alpha_S(M_Z) = 0.1202 \pm 0.0003(\mathrm{stat}) \pm 0.0009(\mathrm{sys}) \pm 0.0009(\mathrm{had}) \pm 0.0047(\mathrm{th})$$

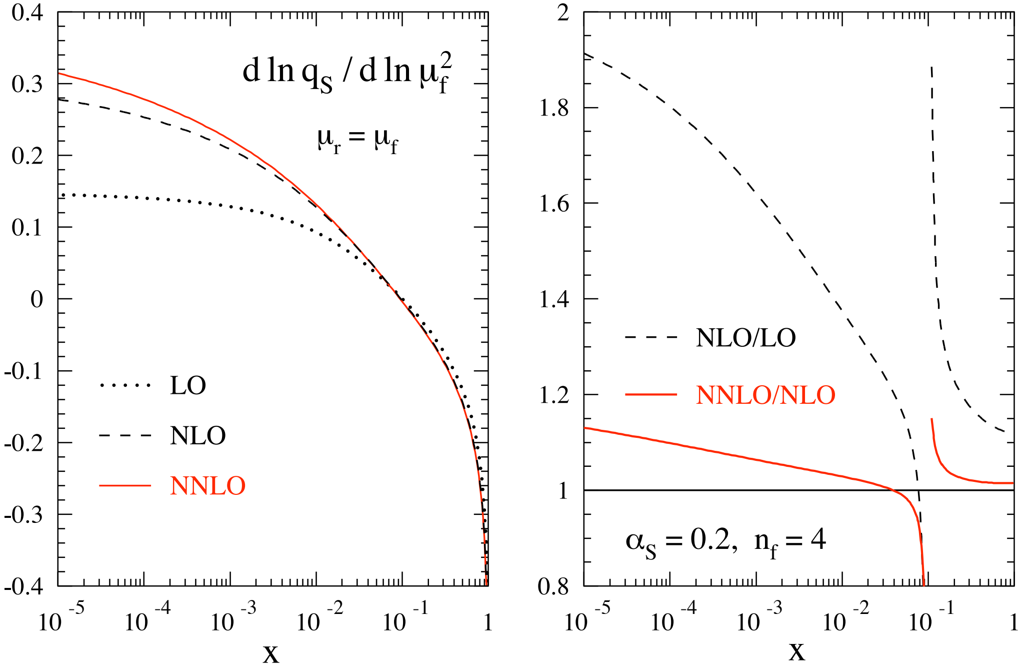
- What is known?
  - Several inclusive $2 \to 1$ processes (W, Z, H production) (van Neerven, Harlander, Kilgore, Anastasiou, Melnikov, Ravindran, Smith)
  - A few "semi-inclusive" $2 \to 1$ distributions (W, Z rapidity distributions) (Anastasiou, Dixon, Melnikov, FP)
  - Fully differential $2 \to 1$ result ($pp \to H, W, Z + X$) (Anastasiou, Melnikov, FP)
  - DGLAP splitting kernels (Moch, Vermaseran, Vogt)

$\Rightarrow$ Generalization to $2 \to 2$ processes ($pp \to jj, t\bar{t}$) very difficult

DGLAP evolution

- Full calculation of NNLO kernels recently completed
  (Moch, Vermaseren, Vogt)
  - Controls Q^2 evolution of parton distribution functions

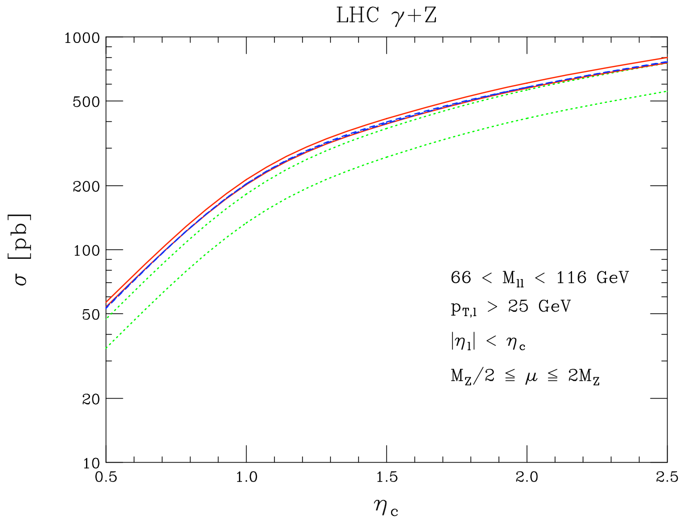
  ⇒ enters *every* hadron collider prediction!

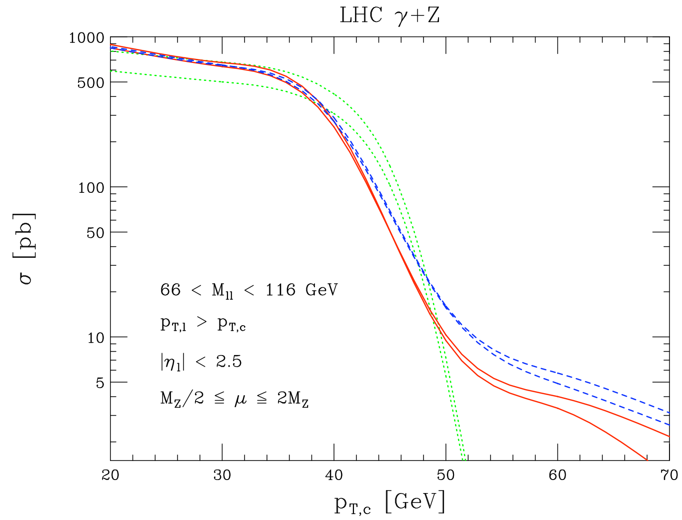


- Corrections $5-10\%$ for $x < 10^{-3}$
- New color stucture at NNLO!
- μ variation $1-2\%$ for $x > 10^{-3}$
  $< 8\%$ for $x < 10^{-3}$
- $\mathrm{N^3LO}$ likely important for small x
- LHC probes low x ...

W,Z at NNLO

- NNLO QCD result for W, Z production (Melnikov, FP)
  - Needed for M_W, pdfs, luminosity, calibration, ...
  - 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 $1 < |\eta_e| < 2.8$
    $R^{CDF}_{c/f} = 0.925(33)$; $R^{NLO}_{c/f} = 0.940(12)$; $R^{NNLO}_{c/f} = 0.927(2)$

$\Rightarrow$ potential stringent constraint on pdfs with more data

Conclusions

- Need more work on QCD tools for LHC physics!
  - Need higher order QCD+resummation, fixed-order+MC matching, . . .
  - Must accurately quantify, reduce uncertainties; test at HERA, Tevatron
- Highlights:
  - Test of ME+PS merging on Tevatron Z+jets
  - No obvious pattern in NLO corrections, except large
  - Theory progress on automated NLO coming! First results: $pp \to Hjj, ZZZ$

  $\Rightarrow$ large corrections badly missed by LO scale variation
  - DGLAP kernels at NNLO $\Rightarrow$ precicion pdf extractions
  - Differential W, Z result at NNLO with spin correlations for acceptances

  $\Rightarrow$ tested on Tevatron data, potential pdf implications