Recent advances in perturbative QCD and LHC physics

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Outline

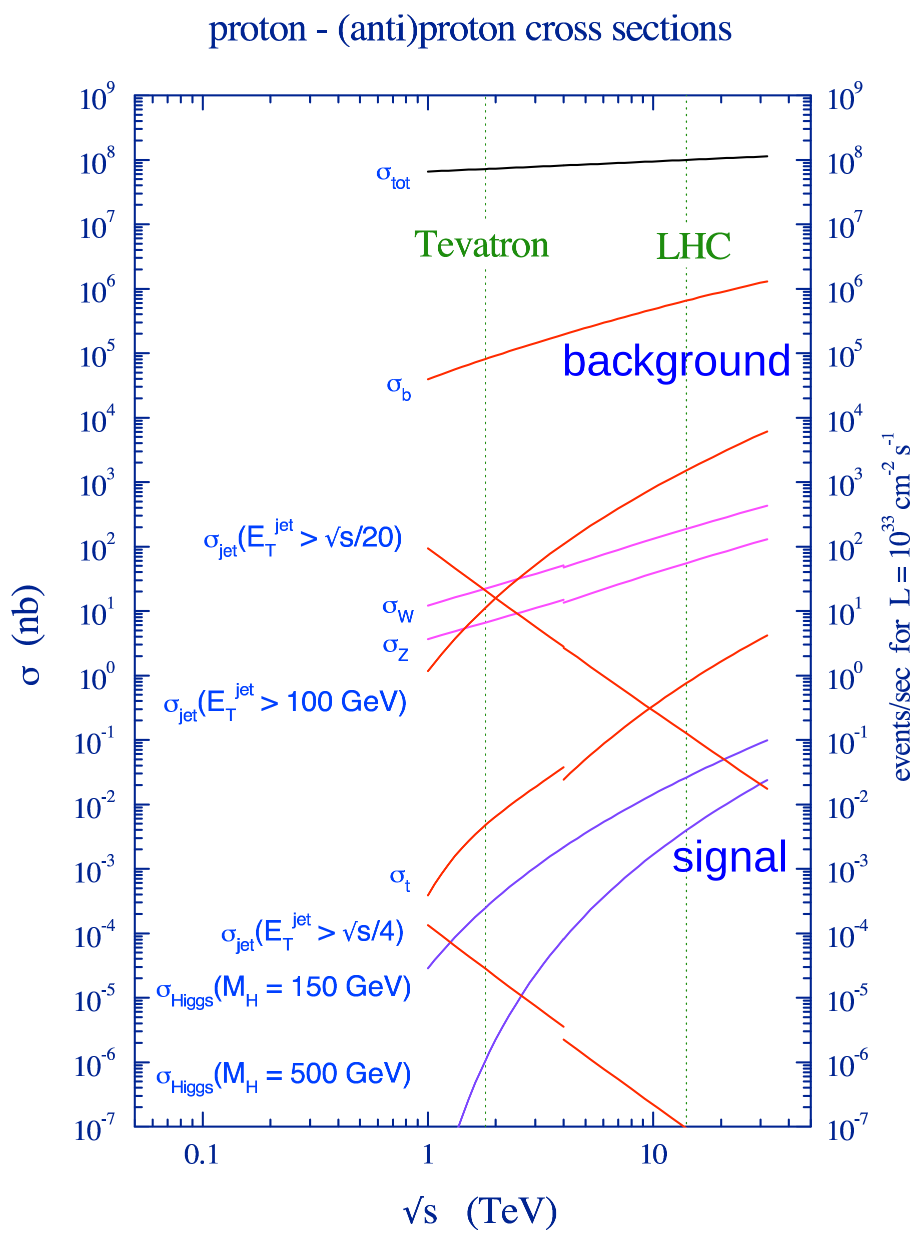
- Motivation
  - Importance of perturbative QCD at colliders
  - Testing tools with HERA, Tevatron data
- Merging LO with parton showers
- Status of NLO calculations
  - LHC phenomenology at NLO
  - Difficulties at NLO: $2 \to 3, 4, \ldots$ processes
  - Automating NLO calculations: $pp \to VVV$ (Lazopoulos, Melnikov, FP)
- 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)

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

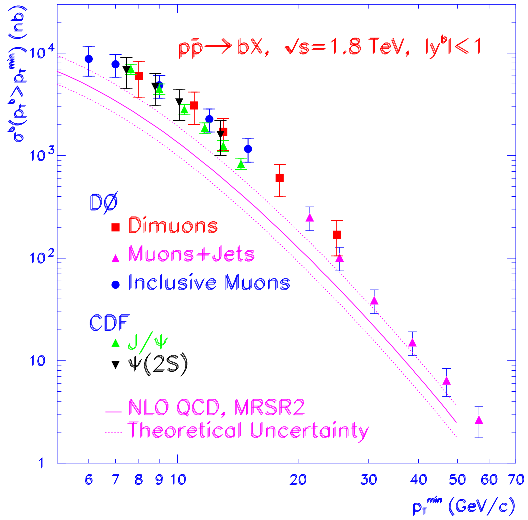
QCD tools for hadron colliders

- 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
    - Typical cases: $\ln(m_H^2/p_T^2)$, $\ln(1-m_H^2/\hat{s})$
  - Parton shower Monte Carlos (HERWIG, PYTHIA)
    - Generate many partons in collinear (leading log) approximation
    - Shower is probablistic and universal; codes contain many processes
  - Combinations of the above (CKKW, MC@NLO)

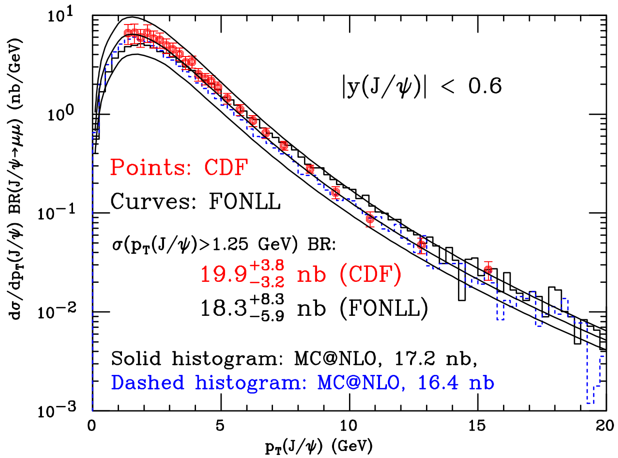
Important to cross-check and understand their limitations!

Bottom production at the Tevatron

- Long-standing discrepancy for B-hadron production
  - Tevatron Run I: factor of $2-3 \pm 0.4$ higher than NLO QCD!
  - Motivated light sbottom/gluino interpretation of data (Berger et al.)

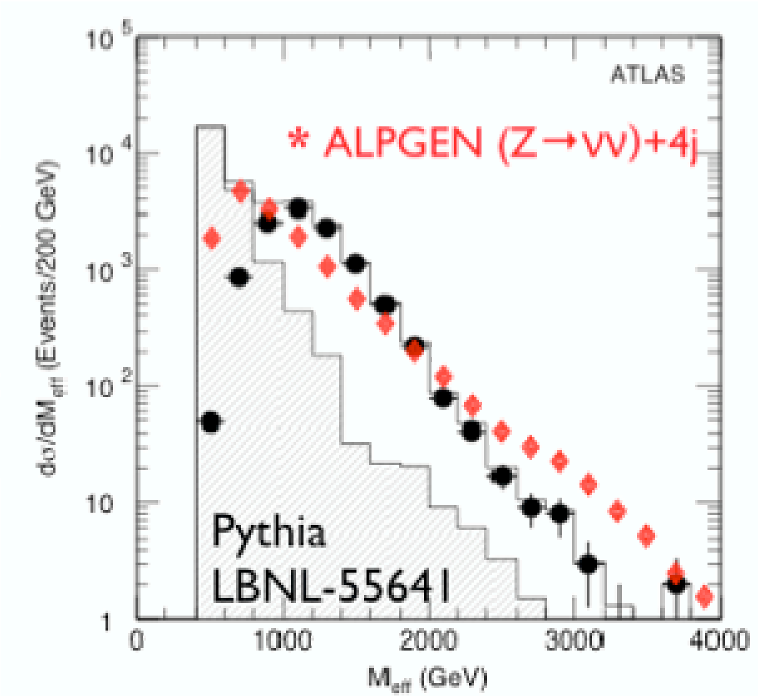


$\Rightarrow$



  - 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

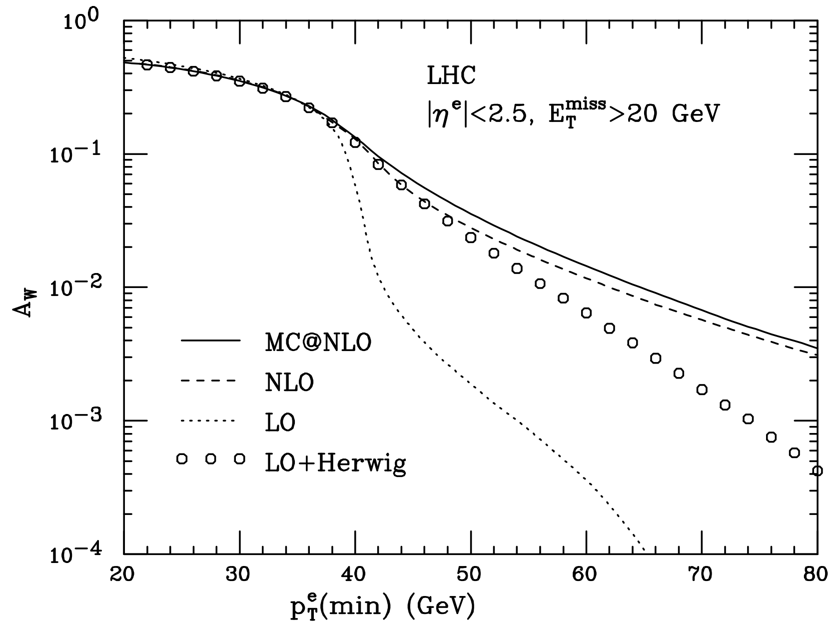


- $\mathrm{M_{eff}} = \sum_j p_\perp^j + E_\perp^{\mathrm{miss}}$: standard SUSY discriminator
- ALPGEN (Mangano et al.): exact LO matrix elements, correct hard emissions
- PYTHIA: extra jets generated via parton shower

⇒ PYTHIA does not describe multiple hard emissions well

W production and HERWIG

Frixione, Mangano

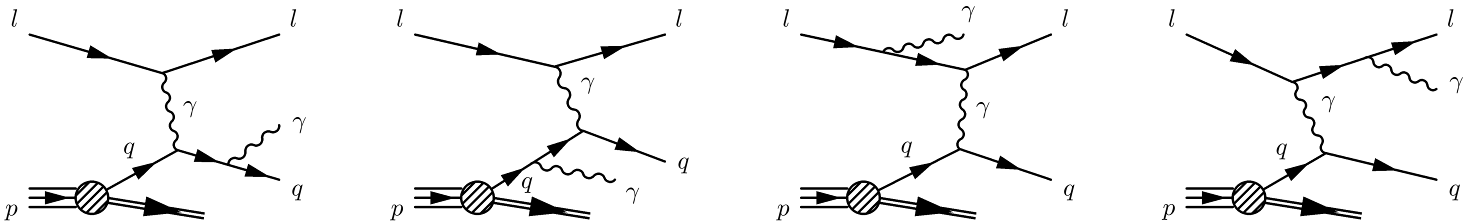


- $\frac{A_W[NLO]}{A_W[HERWIG]} \approx 2 - 10$ for $p^e_{T,min} \geq 50$ GeV
- Extra hard emission at NLO generates all events for $p^e_{T,min} > M_W/2$

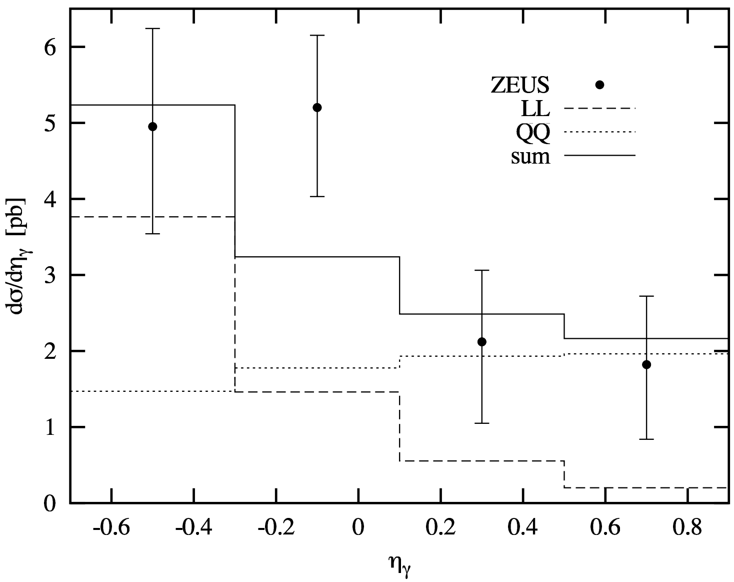
$\Rightarrow$ HERWIG misses important effects for the W acceptance

Isolated photons at HERA

- Production of isolated photons in $e^{\pm}p$ studies by H1, ZEUS



  - Data/Pythia = 2.3; Data/Herwig = 7.9; both get kinematics incorrect



- PYTHIA γ only from lepton
- HERWIG γ from quark
- Simple LO QCD gets both effects

  (Gehrmann et al. hep-ph/0601073)

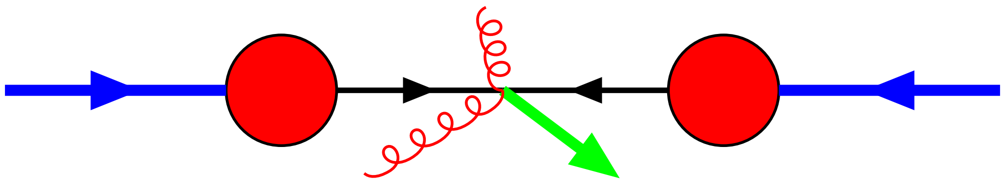
Moral

- Moral: need systematic, controlled QCD expansion
  - pQCD expansion in α_s augmented with necessary resummation
  - Cross-check and improve Monte Carlo tools
- Issues to consider:
  - Are the kinematics described correctly? Hard jets, azimuthal correlations require matrix elements; multiple soft/collinear emissions better described by parton showers
    $\Rightarrow$ full phase-space coverage requires merging parton-shower with multi-parton tree-level (CKKW)
  - What is the correct normalization, and what is its uncertainty?
    $\Rightarrow$ requires $\mathrm{N^nLO}$ fixed-order calculations
  - Do new qualitative effects like the gluon pdf (large at the LHC) appear at higher orders?
  - Have kinematic boundaries where resummation may be required been considered?

Precision QCD

- Observables in hadronic collisions

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

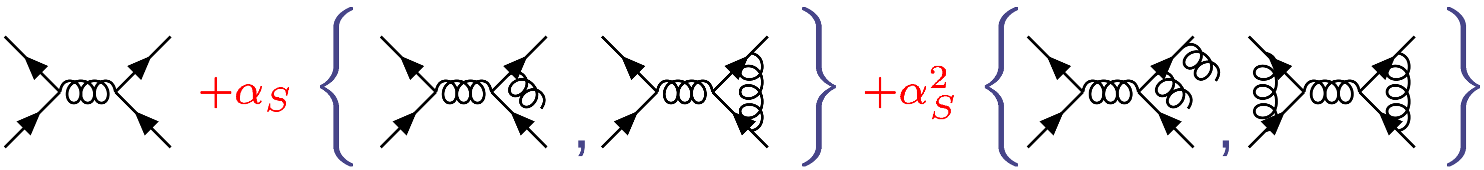


- Require
  - luminosity measurement
  - parton distribution functions
  - scattering cross sections

$\Rightarrow$ All of these require precise QCD cross sections!

Cross sections in QCD

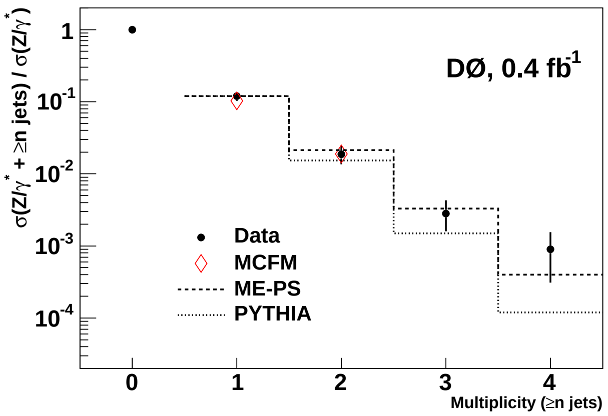
- $\sigma = \sigma_0 \left\{ 1 + \frac{\alpha_S}{\pi}(l + \sigma_1) + \frac{\alpha_S^2}{\pi^2}(l^2 + l + \sigma_2) + \mathcal{O}(\alpha_S^3) \right\}$

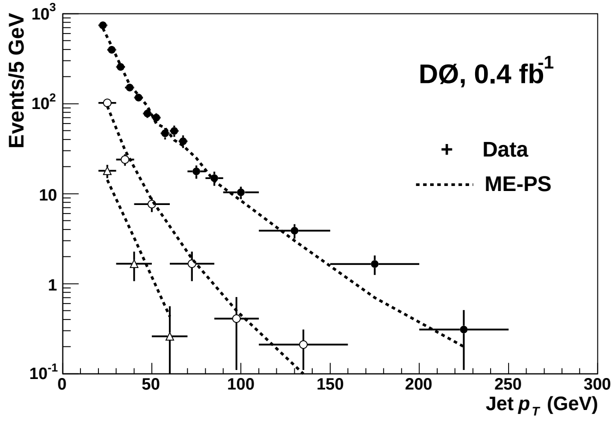


- Strong coupling constant not small: $\alpha_S(M_Z) \approx 0.12$
- Contains scales $l = \ln(\mu^2/Q^2)$
  - Get scales from UV and IR renormalization
  - Scales are arbitrary: $\frac{d\sigma}{d\mu} = 0$
  - $\Rightarrow$ but truncation of expansion at $\mathcal{O}(\alpha_S^n)$ induces a scale dependence of $\mathcal{O}(\alpha_S^{n+1})$
  - Residual scale dependences provide estimate of neglected higher order effects

Merging LO with parton showers

- An N jet event: $N - m$ jets from parton shower, m from MEs, $m = 0, \ldots, N$
- MEs describe hard/large angle emissions, PS describes soft/collinear
- 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)

The need for NLO

- 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)

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

Theoretical status

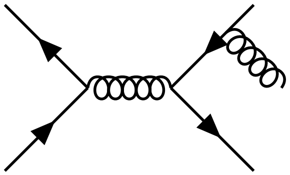
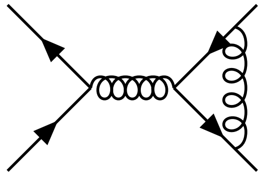
Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 2j$	$WW + \leq 0j$	$WWW + \leq 3j$	$t\bar{t} + \leq 0j$
$W + b\bar{b} + \leq 0j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 0j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 2j$	$ZZ + \leq 0j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 0j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 0j$
$Z + c\bar{c} + \leq 0j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 0j$
$\gamma + \leq 1j$	$\gamma\gamma + \leq 1j$		$b\bar{b} + \leq 0j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 0j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 0j$		
	$Z\gamma + \leq 0j$		

Campbell, Knuteson

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

Computing cross sections at NLO

- Two components of an NLO calculation:

Real:  Virtual: 

  - Obtain a cross section in the form:

$$\sigma_{NLO} = \int d\Phi_n \left(\sigma_B + \alpha_S \sigma_{virt}\right) + \alpha_S \int d\Phi_{n+1} \sigma_{real}$$

- Dealing with real emission divergences
  - Typically use dipole subtraction (Catani, Seymour)
    - Introduce counterterm D which reproduces IR divergences of σ_{real}:

$$\sigma_{NLO} = \int d\Phi_n \left(\sigma_B + \alpha_S \left[\sigma_{virt} + D_I\right]\right) + \alpha_S \int d\Phi_{n+1} \left[\sigma_{real} - D\right] \quad ,$$

with $D_I = \int d\Phi_1 \, D$

    - Cancel divergences analytically in $\sigma_{virt} + D_I = \sigma_{virt}^{fin}$
    - $\sigma_{real} - D$ is pointwise finite, numerically integrable
    - D is a simple function depending only on external particles
  - A simple, universal prescription

NLO difficulties

- Sticking point: loops for $n = 5, 6, \ldots$ external legs
  - Standard analytic treatment (Passarino-Veltman reduction) leads to I_{scalar}/D
    - For $pp \to t\bar{t}H$, $D \sim \sin^2\theta_{t\bar{t}} \sin^2\phi_{t\bar{t}}$ (Dawson et al.)
      $\Rightarrow$ vanishes in non-negligible phase-space region; spurious, but tough to establish cancellation analytically
    - Identify problem areas, extrapolate numerics from safe region
  - Thresholds in I_{scalar} where internal loop particles go on-shell
    - Feynman parameterization vanishes as $1/(-i\delta)^{n-2}$ $\Rightarrow$ unsuitable for numerics
    - Compute analytically in Euclidean region, continue resulting polylogs

    $\Rightarrow$ complex when many kinematics scales, masses present
  - Extraction of infrared singularities, simple algebriac complexity, production of numerical code with percent-level precision, . . .
- No simple, universal calculational method

$\Rightarrow$ Each a multi-year effort requiring ingenuity and great effort

Automating NLO calculations

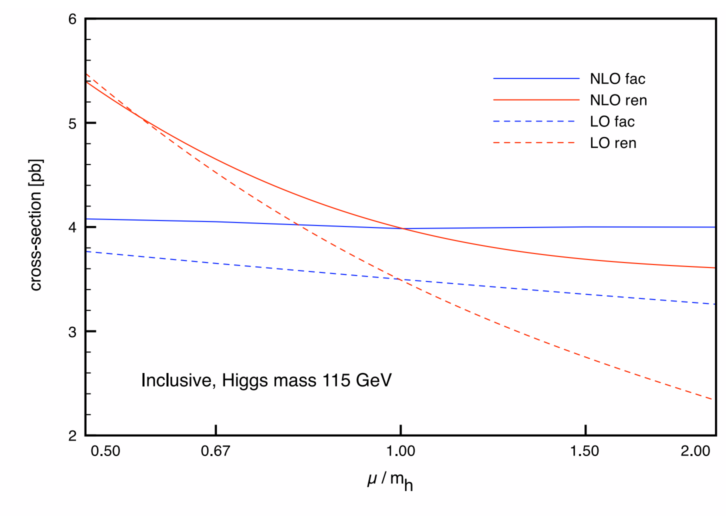
- Much recent activity on new methods:
  - Expand reduction coefficients around fictitious singularities (Denner, Dittmaier)
  - Numerical solution of reduction equations (R. K. Ellis, Giele, Glover, Zanderighi)
  - Sector decomposition for singularity extraction (Binoth, Heinrich; Lazopoulos et al.)
  - Contour deformation (Soper, Nagy; Lazopoulos et al.)
  - Twistor-inspired (C. Berger, Bern, Dixon, Kosower; Britto, Cachazo, Feng; . . .)

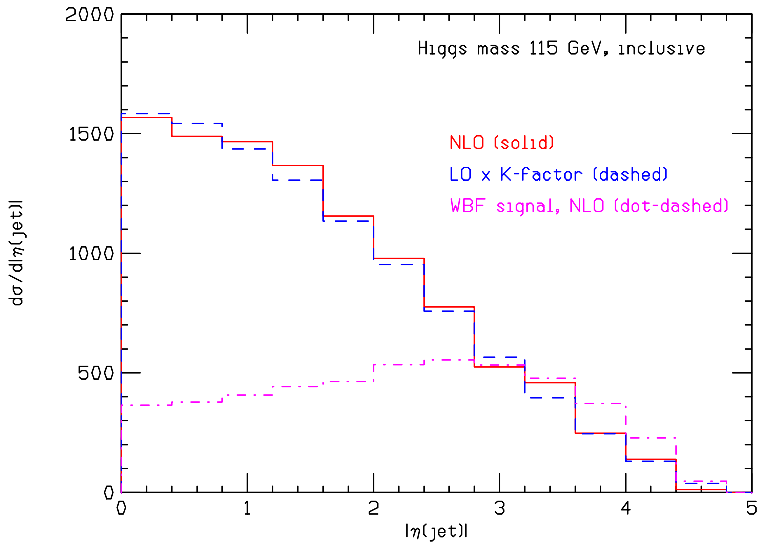
  $\Rightarrow$ both traditional analytic and new semi-numerical methods
- Important to gain experience with what to expect from NLO

$\Rightarrow$ will present several phenomenological results fi rst

H+2 jets at NLO

- QCD corrections to Hjj recently completed
  (Campbell, Ellis, Zanderighi hep-ph/0506196,hep-ph/0608194)
  - NLO needed for extraction of HWW coupling in WBF

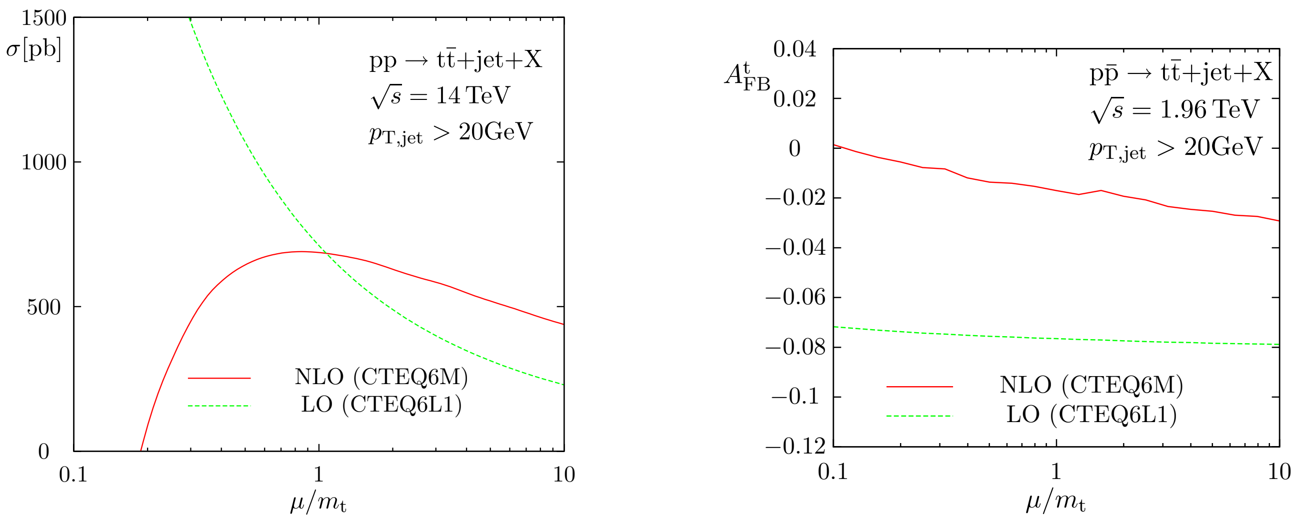




  - Residual scale dependence reduced
  - $\sigma_{NLO}/\sigma_{LO} = 15 - 25\%$; corrections are kinematic-independent
  - Could this kinematic independence have been guessed?

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

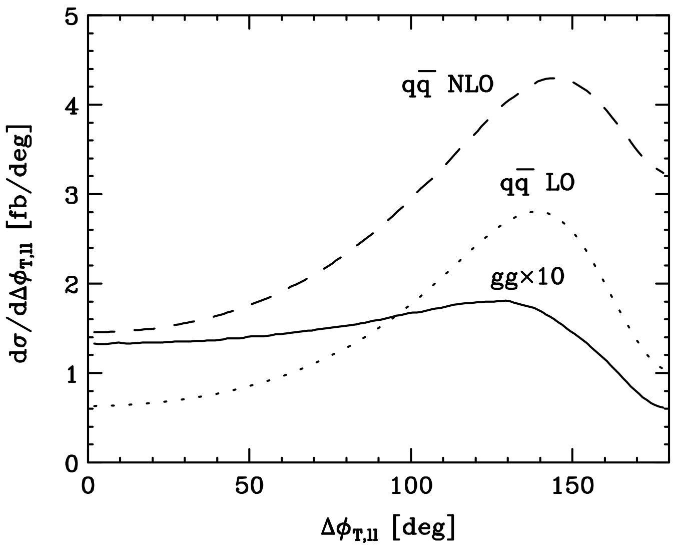
- QCD corrections to $t\bar{t}j$ recently completed
  (Dittmaier, Uwer, Weinzierl hep-ph/0408137,hep-ph/0703120)
  - Background to Higgs in WBF, $t\bar{t}H$ channels; measurement of t properties

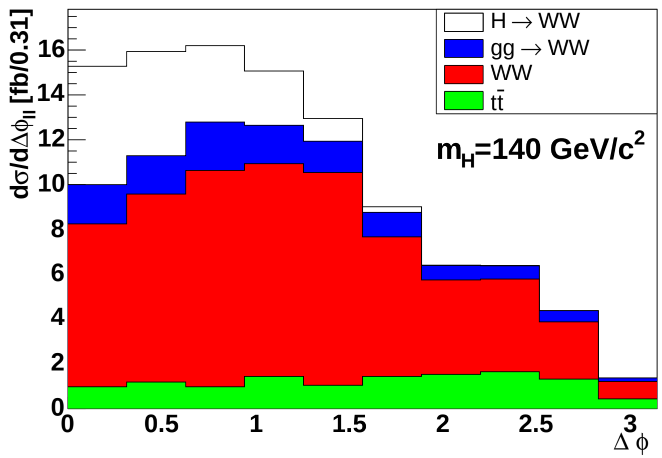


  - Residual scale dependence reduced
  - NLO corrections wipe out forward-backward charge asymmetry!

Higgs discovery at higher orders

- NLO important 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. hep-ph/0504006, hep-ph/0611170)

Numerical approach

- Corrections large, no obvious kinematic dependence pattern

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

- Can we construct an automated, numerical approach to multi-leg loop integrals?
- Must confront three main issues:
  - Find and extract soft/collinear singularities
  - Pick a good regulator for internal thresholds
  - If tensor integrals reduced, avoid vanishing denominators

Loop integral singularities

- IR loop singularities governed by Landau equations
  - In Feynman parameter representation, must have $k_i^2 - m_i^2 = 0$ or $x_i = 0$ for every propagator
  - After k integration, all singularities occur as some $x_i \to 0$
  - Loop integral in Feynman parameter space:

$$\int_0^1 dx_i \delta(1 - \sum x_i) \Delta^{-n-\epsilon}$$

  - If IR singularity only when a single $x = 0$, extract via

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

with

$$\int_0^1 dx f(x) \left[\frac{1}{x}\right]_+ = \int_0^1 dx \frac{f(x) - f(0)}{x}$$

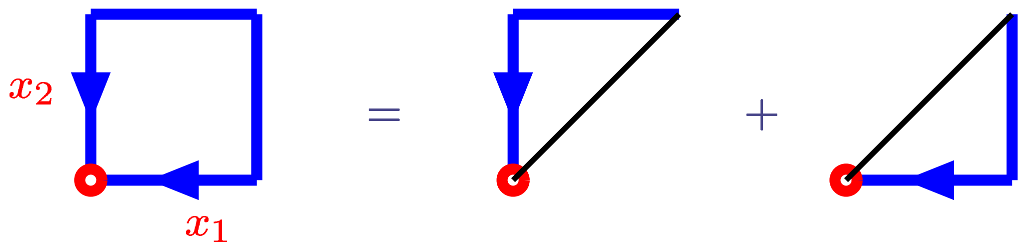
  - Simple, programmable procedure, numerical treatment possible

Decomposing entangled singularities

- How about when multiple x_i vanish?
  - Consider the simple example

$$I = \int_0^1 dx_1 dx_2 \, (x_1 + x_2)^{-2-\epsilon}$$

  - Divide the integration region by ordering the two variables:



  - Singularities factor in each region after the integration region is remapped into $[0, 1]$; consider the $x_2 < x_1$ region, and set $z = x_2/x_1$:

$$I(x_2 < x_1) = \int_0^1 dx_1 dz \, x_1^{-1-\epsilon} (1 + z)^{-2-\epsilon}$$

  - Extract singular terms as before $\Rightarrow$ again a simple, programmable procedure

Regulating thresholds

- Feynman denominator can vanish in interior of x-space
  - Simple example: 1-loop bubble, with
$$\int_0^1 dx_1 dx_2\, \delta(1 - x_1 - x_2) \left(m^2 - x_1 x_2 s - i0\right)^{-\epsilon}$$
  - Occurs when unitarity cut leads to physical scattering process
  - Generic Feynman denominator has form
$$\Delta = Z + Y_i x_i + \frac{1}{2} X_{ij} x_i x_j + \frac{1}{3} W_{ijk} x_i x_j x_k + \ldots$$
  - Assume $W = 0$; deform contour by setting $x_i = y_i - i\tau_i$, get
$$-i\tau_i [Y_i + \sum_j X_{ij} y_j]$$
  - To make sign-definite, choose
$$\tau_i = \lambda y_i (1 - y_i)[Y_i + \sum_j X_{ij} y_j]$$

$\Rightarrow$ sign-definite, non-vanishing, easy to automate finding of $\Rightarrow$ a suitable regulator

  - Caveat: for $W \neq 0$, must approach as a series in λ

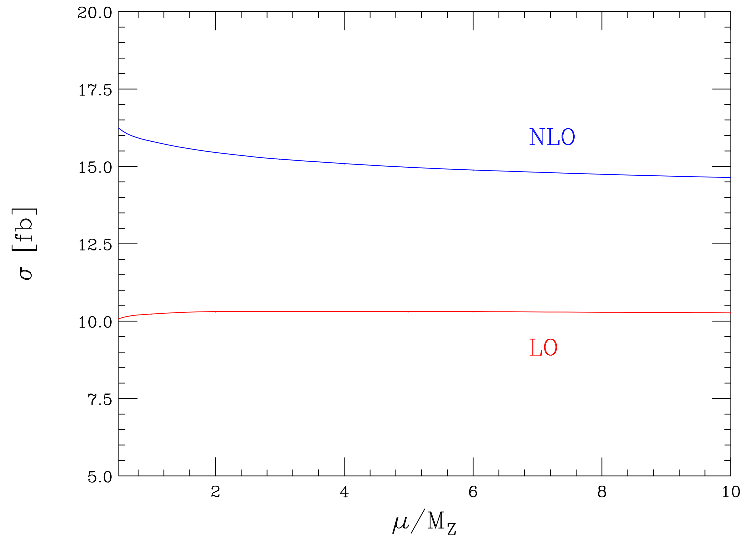
Summary of method

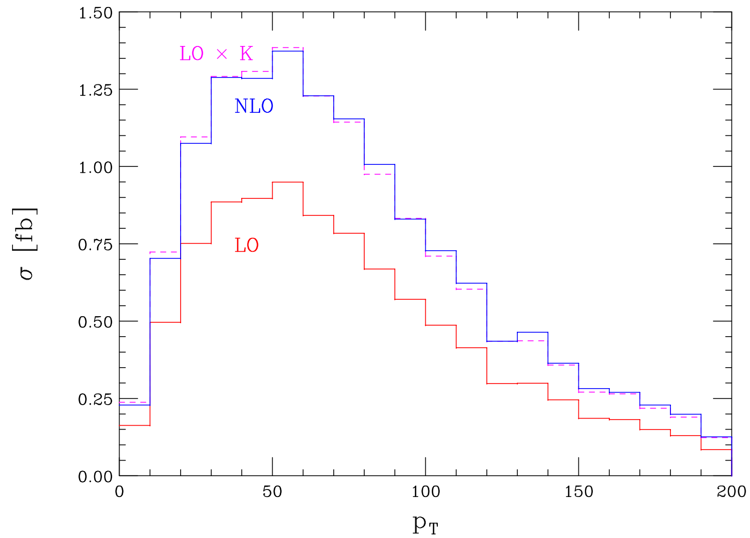
- Framework for automated, numerical NLO calculations
  - Singularity and threshold issues solved
  - Don't reduce tensor integrals; treat as polynomial in Feynman parameters

  $\Rightarrow$ judicious grouping of terms keeps algebraic complexity at bay
- Test on realistic LHC background: $pp \to ZZZ$

ZZZ at NLO

- QCD corrections to ZZZ using numerical approach (Lazopoulos, Melnikov, FP hep-ph/0703273)
  - Background to various SUSY tri-lepton signatures





  - 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

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
  - $pp \to WW$ background shows importance of NLO signal, background calculations
    $\Rightarrow$ also interplay between higher orders and experimental cuts
  - $pp \to Hjj, t\bar{t}j$ show no obvious pattern in NLO corrections, except large
  - Theory progress on automated NLO coming! First results: $pp \to ZZZ$

  $\Rightarrow$ large corrections badly missed by LO scale variation
  - Completely automated, numerical framework for loop calculations