Recent progress in QCD theory

Frank Petriello

2007 Aspen Winter Conference

January 2007

Outline

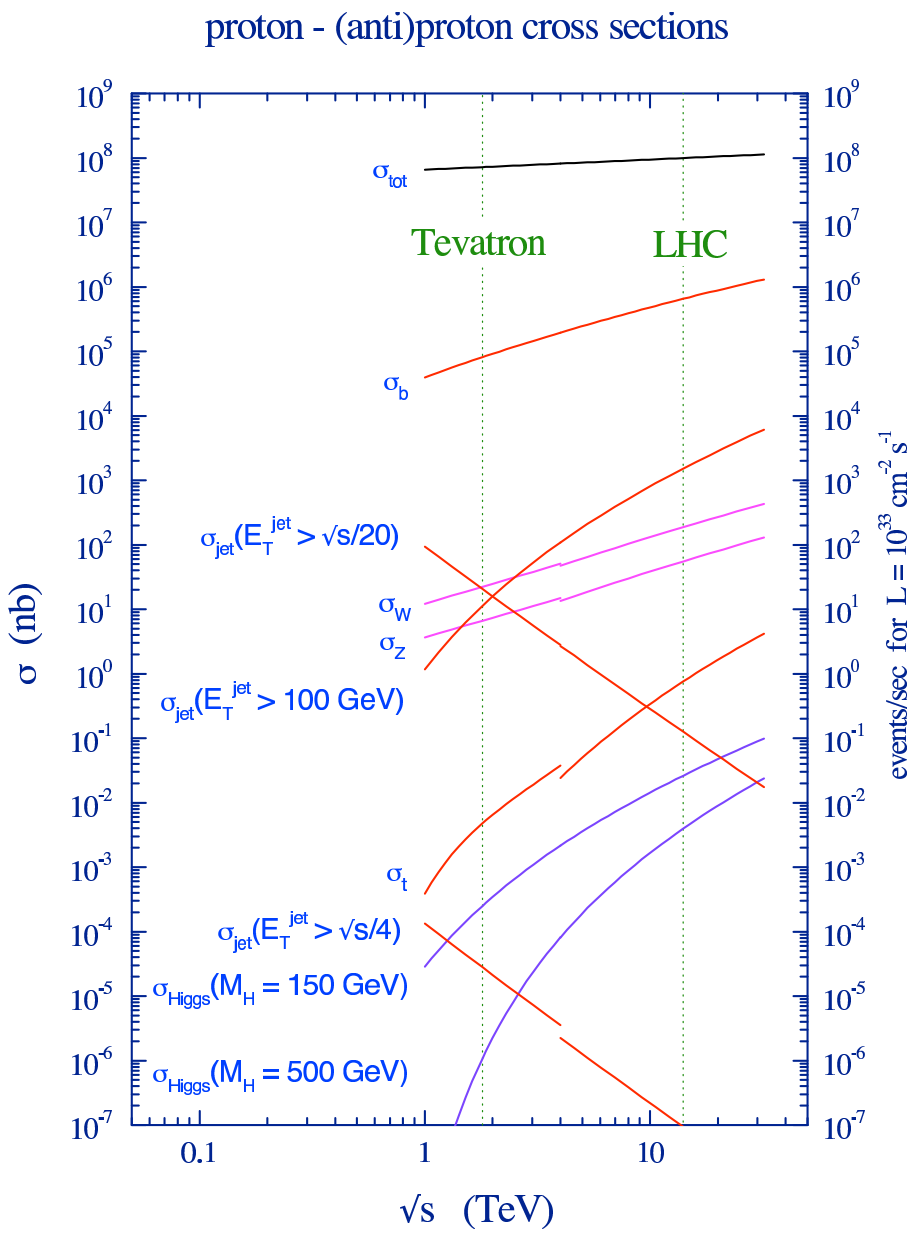
- Focus: perturbative QCD for LHC physics
- Motivation
  - Limitations of parton shower Monte Carlos
  - Importance of perturbative QCD to verify and improve Monte Carlo tools
  - Testing tools with HERA, Tevatron data
- Merging LO with parton showers
- Status of NLO calculations
  - Automating NLO calculations: $pp \to Hjj$ at the LHC
  - $gg \to H \to WW$ at the LHC: NLO for discovery
  - Resummation, fragmentation, and di-photons at the Tevatron
  - Merging NLO with parton showers
- Status of NNLO calculations
  - NNLO W, Z cross sections with spin correlations and Tevatron data
  - Higgs couplings at NNLO

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

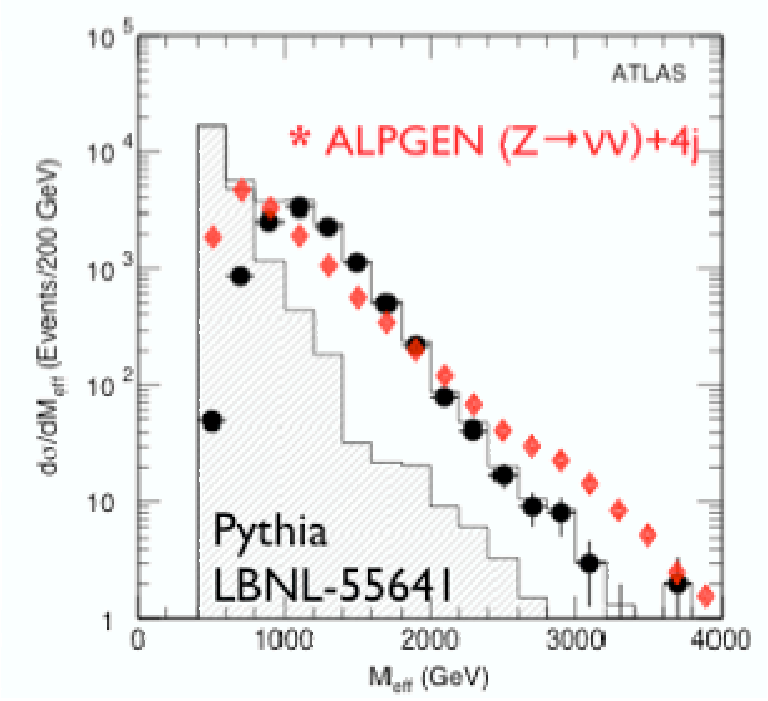
QCD tools for hadron colliders

- 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
    - 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)

- 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

Important to cross-check and understand their limitations!

SUSY searches and PYTHIA



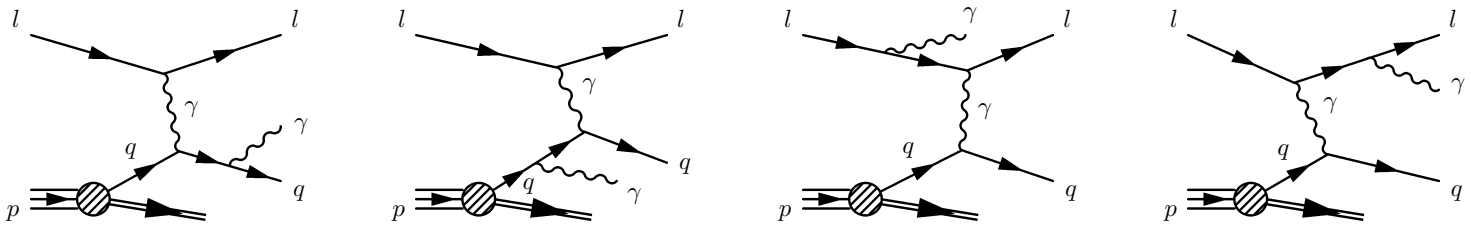
Mangano et al. hep-ph/0504221

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

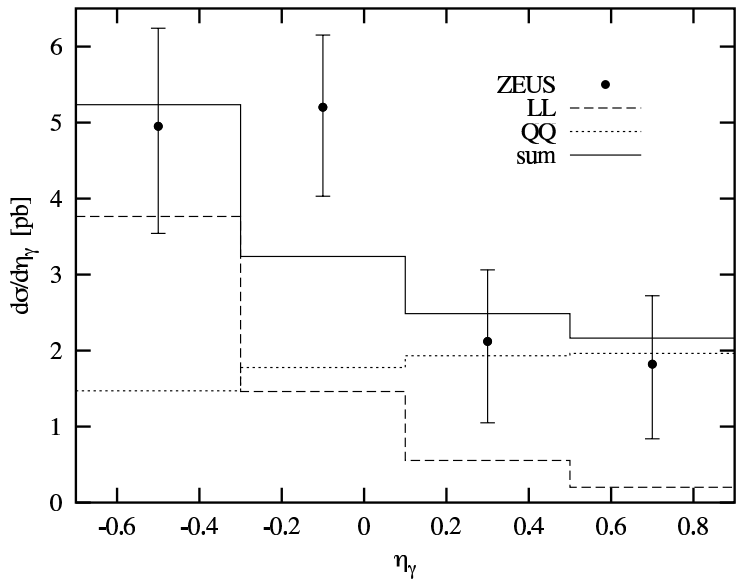
$\Rightarrow$ Without tuning, PYTHIA does not describe multiple hard emissions well

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

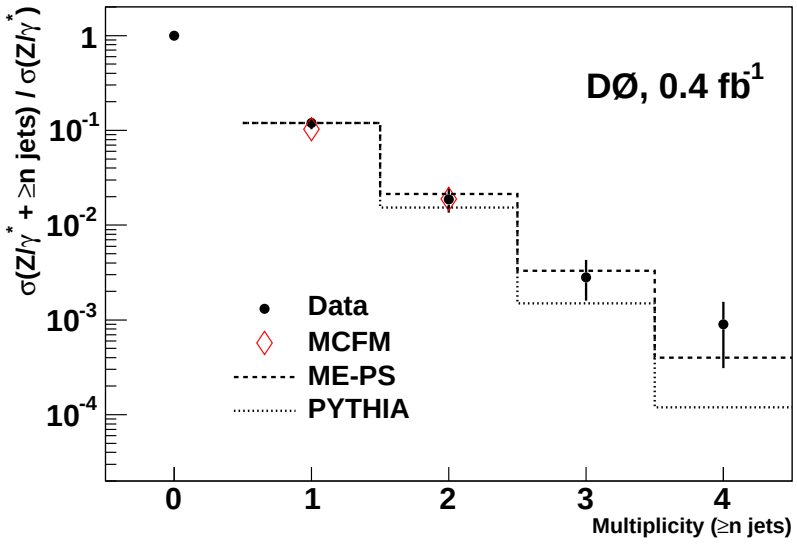
  (Gehrmann et al. hep-ph/0601073)

Moral

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

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 desribe soft/collinear
- CKKW (Catani, Krauss, Kuhn, Webber): prescription to cover entire phase-space correctly



hep-ex/0608052

- Generate $m < N$ hard jets; probability is

  $P_m = \frac{\sigma_m}{\sigma_0 + \sigma_1 + \ldots \sigma_N}$
- Parton shower from this configuration; veto hard emissions
- Depends on parameter defining "hard" jet
- SHERPA: includes ME generator
- HERWIG, PYTHIA: use external tree-level generator, e.g. MADGRAPH and apply CKKW (Mrenna, Richardson)

$\Rightarrow$ Describes Run II data well

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: 10-30% for quark-initiated, 50-100% for gluon-initiated
    - New channels open up at higher orders $\leftrightarrow$ gluon pdf large at small x
    - Large coefficients in perturbative corrections (π^2 for s-channel processes)
    - Proportional to high power of α_s

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)
  - $pp \to t\bar{t}j$ (Dittmaier, Uwer)
  - $e^+e^- \to 4f$: first complete $2 \to 4$ result (Denner, Dittmaier et al. hep-ph/0505042)

Automating NLO calculations

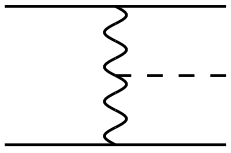
- Sticking point: loops for $n = 5, 6, \ldots$ external legs
  - Numerics complicated by soft, collinear singularities
  - Reduction to master integrals induces fictitious singularities
  - Many mass scales and internal thresholds complicate both singularity extraction and numerics
- Much recent activity:
  - 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)
  - Contour deformation (Nagy, Soper)
  - Twistor-inspired (C. Berger, Bern, Dixon, Kosower; Britto, Cachazo, Feng; . . .)

  $\Rightarrow$ both traditional analytic and new semi-numerical methods

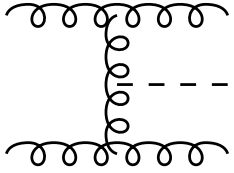
Extracting Higgs couplings

- Measure HWW coupling with WBF (ATLAS; E. Berger, Campbell)

Signal: WBF

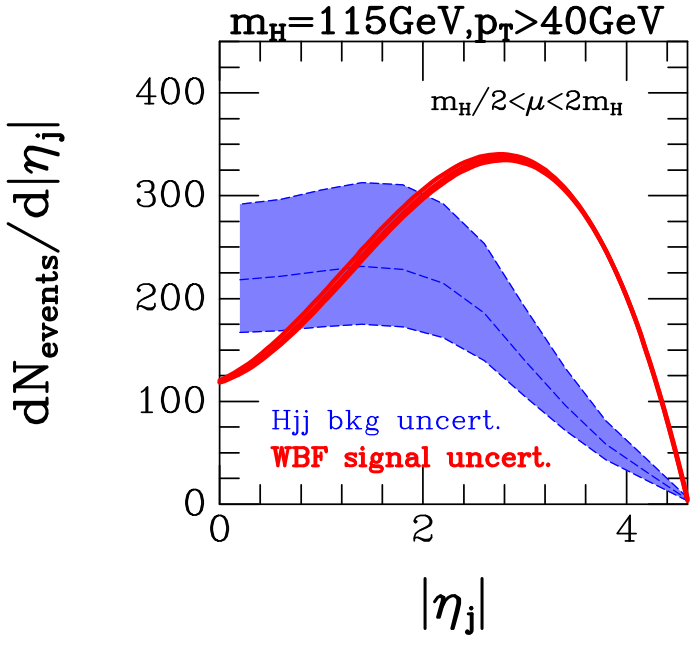


Background: QCD Hjj



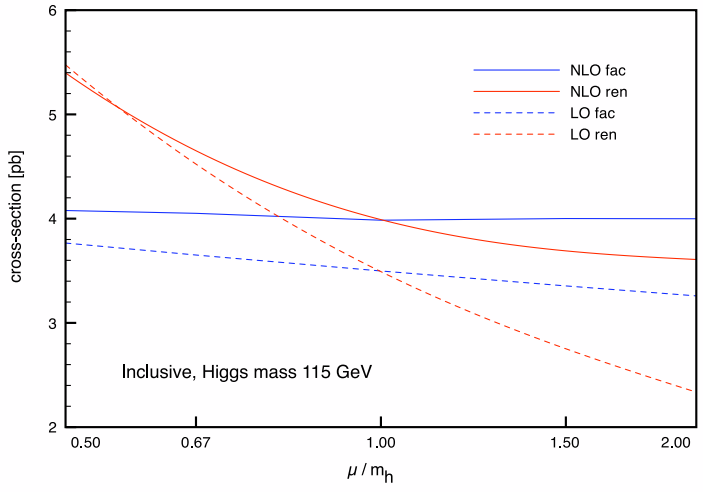
$\Rightarrow$ Higgs production now a background!

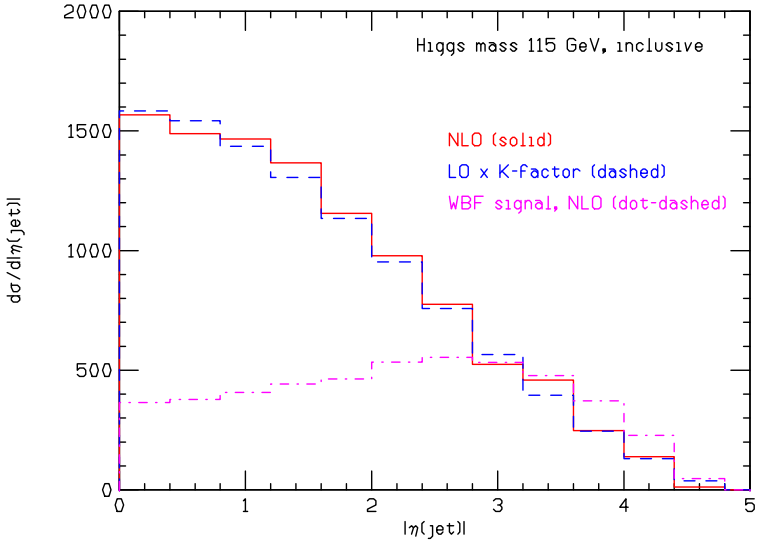
- Separate S, B with kinematics
- Uncertainty dominated by $\delta S/S, \delta B/B$
  $\delta B/B = \pm 20\%$, $\delta S/S = \pm 4\%$ (ATLAS)
  $\delta B/B = \pm 30\%$, $\delta S/S = \pm 10\%$ (BC)
- Estimate $\delta g/g \approx 10\%$ after $200\,\mathrm{fb}^{-1}$ (BC)
- Background known only at LO
  $\Rightarrow$ need NLO computation of QCD Hjj production



H+2 jets at NLO

- QCD corrections to Hjj recently computed
  (Campbell, Ellis, Zanderighi hep-ph/0608194)
  - First output from semi-numerical methods for NLO computations

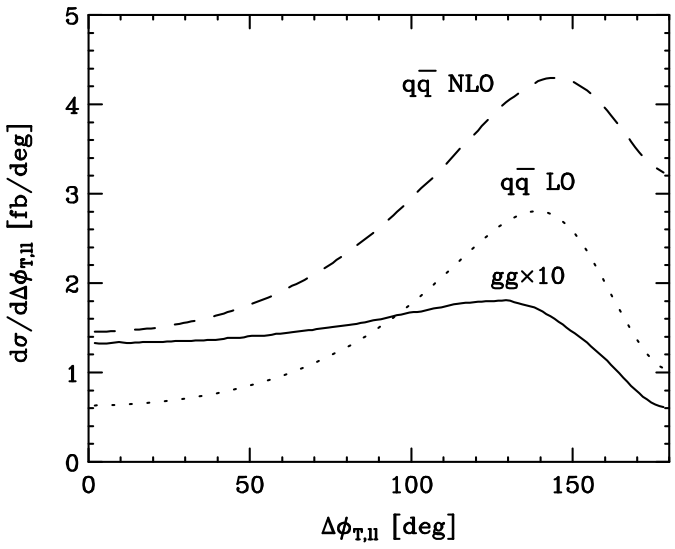


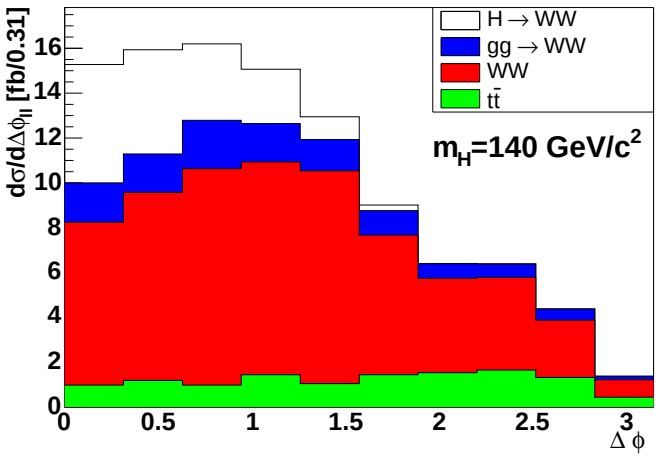


  - Residual scale dependence greatly reduced
  - $\sigma_{NLO}/\sigma_{LO} = 15 - 25\%$; corrections are kinematic-independent
  - How generic is this feature for relevant $2 \to n$, $n \geq 3$ observables?

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



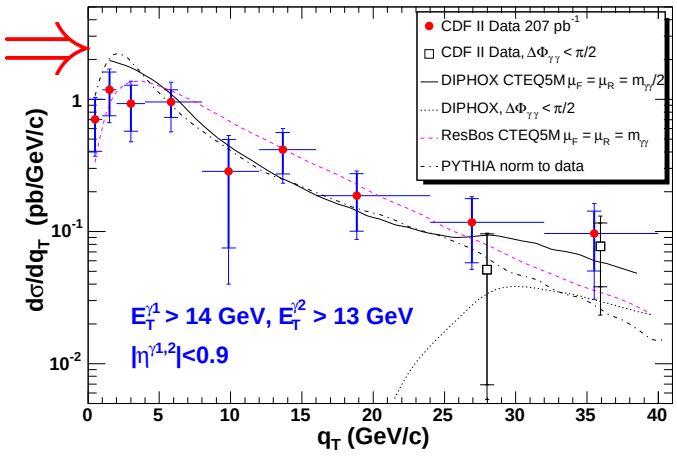


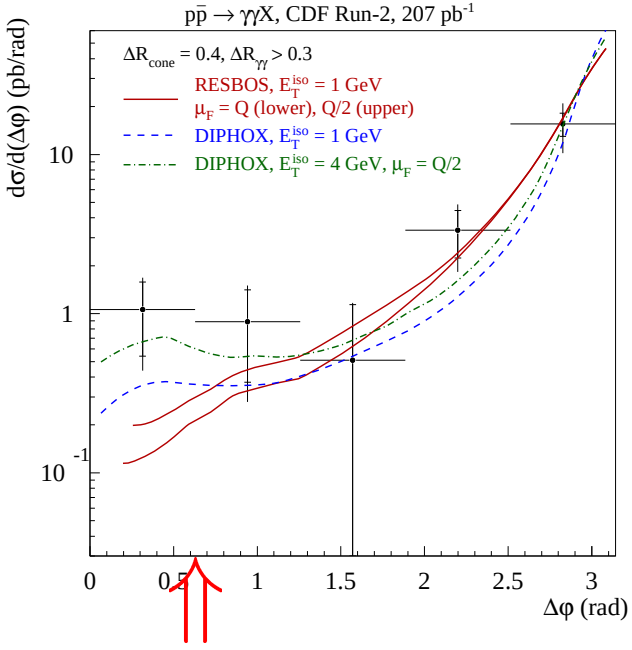
- NLO $pp \to WW$ background correction large: $\sigma_{NLO}/\sigma_{LO} > 1.5$
- Loop-induced $gg \to WW$ formally NNLO; enhanced by $\Delta\phi_{T,ll} < 45^o$

$\Rightarrow$ further increases background by 30% (Binoth et al., Dührssen et al. hep-ph/0504006, hep-ph/0611170)

Di-photon production

- $pp \to \gamma\gamma$ important for Higgs discovery and measurements
  - Many subtle effects to include in background calculation:
    - $gg \to \gamma\gamma$ subprocess formally NNLO but large
    - Resummation for low $q_T^{\gamma\gamma}$ (Balazs, E. Berger, Nadolsky, Yuan hep-ph/0603037)
    - Fragmentation $q \to \gamma$ important at $q_T^{\gamma\gamma} > Q$, low $\Delta\phi$



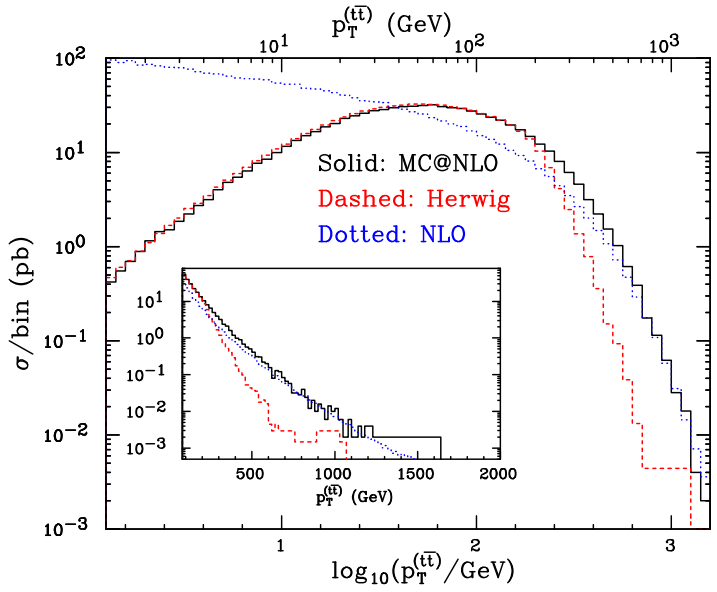


  - Resummation only in RESBOS; large sensitivity to tuneable parameters in DIPHOX fragmentation $\Rightarrow$ do we really understand low $\Delta\phi$ region?
  - Need better understanding, especially when $1\ \mathrm{fb}^{-1}$ is analyzed

Combining NLO with parton showers

- Fixed order, parton showers complimentary
  - PS: universal, hadronization,detector simulation
  - FO: correct rates, hard emissions, reduced and quantifiable errors

  ⇒ want the advantages of both approaches!



- MC@NLO (Frixione, Webber)
- Smoothly matches soft/collinear (MC) and hard (NLO) regions
- Unweighted events, NLO normalization
- Available for $W, Z, H, \gamma^*, b\bar{b}, t\bar{t}, WW, ZZ, WZ, tb$

- Recent detailed study for LHC top production (Mangano et al. hep-ph/0611129)
- Work on alternate implementations (Giele, Skands; Bauer, Schwartz)

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)
- 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 $2 \to 1$ processes ($pp \to jj, t\bar{t}$) very difficult

W, Z production at hadron colliders

- $q\bar{q} \to (W, Z) \to (l\nu, ll)$: numerous important applications
  - M_W: important contraints on m_H and new physics through global EW fit
  - Provide pdf information at fixed-target and high energies:
    $\Rightarrow$ for example, $A_l(\eta) = \frac{d\sigma(e^+)/d\eta - d\sigma(e^-)/d\eta}{d\sigma(e^+)/d\eta + d\sigma(e^-)/d\eta} \approx \frac{d(x)}{u(x)}$
  - Calibration of detectors (lepton energy scale)
  - Luminosity determination to the percent level (Dittmar et al.)
  - Distinguish different Z' scenarios (Rizzo hep-ph/0610104)
  - ...
- W, Z production are benchmark processes

$\Rightarrow$ need percent-level theory, reliable error estimates

Components of the theory calculation

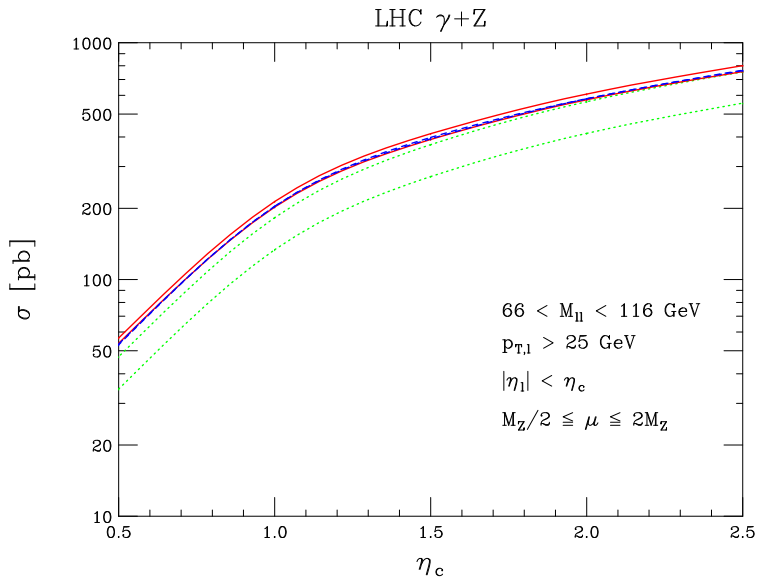
- Myriad issues to consider:
  - Fixed order QCD to NNLO: $\mathcal{O}(\alpha_s^2)$
  - Resummation of $\ln(M_{ll}/q_T^W)$ for low q_T^W observables (RESBOS: Balazs, Nadolsky, Yuan)
  - $\mathcal{O}(\alpha)$ EW corrections (U. Baur, Wackeroth et al.), particularly FSR
  - Possible resummation in $x \to 0, 1$ limits

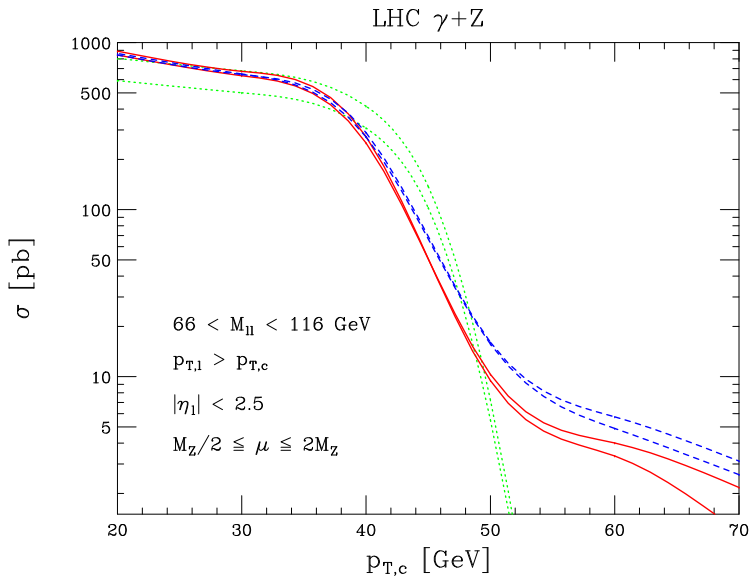
  $\Rightarrow$ this and more reviewed in Nadolsky hep-ph/0412146
- Further complication:
  - W, Z are spin-1: "spin correlations" between production, decay: $p_q \cdot p_l$
  - With typical Tevatron/LHC cuts, these are a 10% effect at NLO

  $\Rightarrow$ imposes a difficult requirement on NNLO calculations, can't separate production and decay channels

Results at NNLO

- NNLO QCD result for W, Z production (Melnikov, FP hep-ph/0609070)
  - 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

Higgs coupling extractions

- Analyses of Higgs couplings use relation

$$\sigma(H) \times BR(H \to xx) = \frac{\sigma(H)^{TH}}{\Gamma_p^{TH}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma}$$

$\Rightarrow$ calculate and assign theoretical uncertainty to σ/Γ, extract $\Gamma_p\Gamma_x/\Gamma \Rightarrow$ new states in loops should drop out from theory ratio, just QCD+PDFs

- Studies assign $\pm 20\%$ uncertainty to σ/Γ for $gg \to H$ production mode (Duhrssen et al.)

$$\Gamma \sim \alpha(\mu_R)^2 C_1(\mu_R)^2 \{1 + \alpha(\mu_R) X_1 + \ldots\}$$
$$\sigma \sim \alpha(\mu_R)^2 C_1(\mu_R)^2 \{1 + \alpha(\mu_R) Y_1 + \ldots\}$$

- Scale variation correlated, large μ_R variation cancels; $\Delta(\sigma/\Gamma) = \pm 5\%$ (Anastasiou et al., hep-ph/0509014)
- Recent work:
  - $\mathrm{N^3LO}$ soft+virtual corrections to $\sigma_{gg\to H}$ (Moch, Vermaseran, Vogt hep-ph/0508265)
  - $\mathrm{N^3LO}$ corrections to Γ_{gg} (Baikov, Chetyrkin hep-ph/0604194)
  - $\Delta\sigma$: $\pm 10\% \to \pm 3 - 4\%$; $\Delta\Gamma$: $\pm 5\% \to \pm 1 - 2\%$
- Need inclusion of these effects in Higgs coupling studies!

Conclusions

- Need more work on QCD tools for LHC physics!
  - Need fixed order QCD+resummation to verify, improve MC generators
  - 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
  - Theory progress on automated NLO coming! First result: $pp \to Hjj$ for HWW coupling determination
  - Di-photon results from Tevatron show importance of careful QCD analysis: resummation, fragmentation needed to describe all regions of phase-space
  - Differential W, Z result at NNLO with spin correlations for acceptances
    - Tested on Tevatron data, potential pdf implications
    - Tevatron luminosity analysis?
- Challenging and important work to do!