QCD@LHC

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PHENO 07 – Prelude to the LHC
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Resources

- TeV4LHC (hep-ph/0610012), HERA and the LHC (hep-ph/0601013), and Les Houches (hep-ph/0604120) workshop reports
- Talks at the LoopFest workshops, see http://quark.phy.bnl.gov/lcwg
  Talks at DIS 2007, see www.mppmu.mpg.de/dis2007
- Durham HEP database: http://durpdg.dur.ac.uk/HEPDATA
- ATLAS and CMS TDRs and Notes
  CDF Physics results at www-cdf.fnal.gov/physics/physics.html
  D0 Physics results at
  www-d0.fnal.gov/Run2Physics/WWW/results.htm
- *Hard interactions of quarks and gluons: A primer for LHC physics*, J.Campbell, J.Huston, W.J.Stirling, hep-ph/0611148
- and references on slides

Many Thanks !

"All that is gold does not glitter, ..."

J.R.R. Tolkien

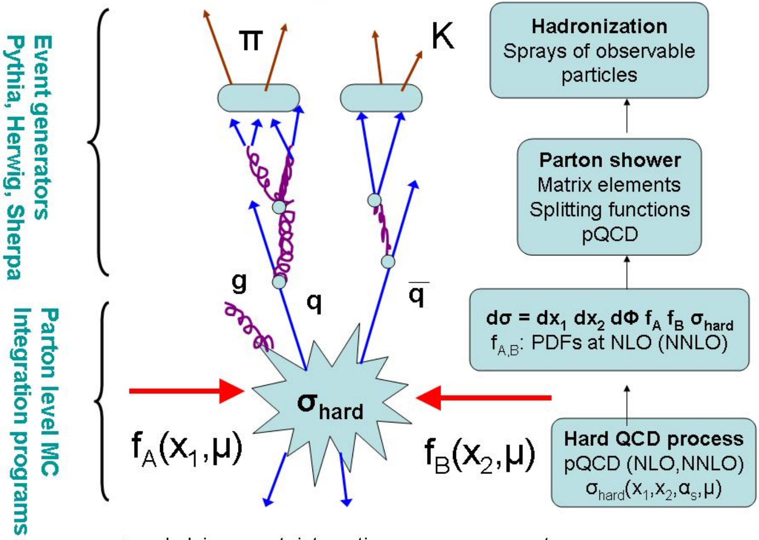
Tevatron $\rightarrow$ LHC:

- dominance of gluon initiated processes,
- access to new kinematic regions: small x, high p_T,
- more phase space for gluon emisson, i.e. more jets,
- more QCD processes measured at a few percent precision.

Precision QCD@LHC - Challenges and Opportunities

- *Discovery*
  to model the signal and background processes for Higgs and new physics searches *"to distinguish the new from the known"*,
- *Identity*
  to precisely extract parameters of the underlying model from data (M_W, m_{top}, M_H, $y_{b,t}$, $\ldots$),
- *Precision*
  to reduce systematic errors, e.g., improve studies of effects of selection/analysis of data, $\sigma_{W,Z}$ as luminosity monitor, constrain PDFs (W asymmetry, γ, jet production), ...,
- *Fundamentals*
  and, finally, to keep probing and exploring the quantum field theoretical structure of QCD, which is interesting on its own right.

Anatomy of a QCD prediction at hadron colliders



+ underlying event, interactions among remnants

Precision QCD@LHC - Challenges and Opportunities

- *multi-loops* and *multi-legs*
  Fixed-order calculations of σ_{hard} at NLO and NNLO:

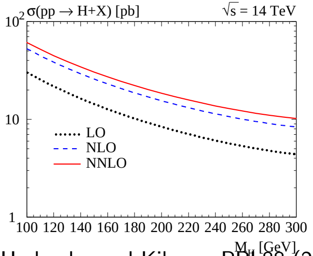
$$\sigma_{hard}(\mu_r,\mu_f) = \alpha_s^k(\mu_r)[\sigma_{hard}^{LO} + \alpha_s(\mu_r)\sigma_{hard}^{NLO}(\mu_r,\mu_f) + \alpha_s^2(\mu_r)\sigma_{hard}^{NNLO}(\mu_r,\mu_f) + \ldots]$$

  State-of-the art: $2 \to 3$ @ NLO, $2 \to 2$ @ NNLO (fully differential)
  NLO: Higgs and $VVjj$ via VBF, $t\bar{t}H/b\bar{b}H$, $t\bar{t}j$, 6-photon/6-gluon amplitudes
  NNLO: $gg \to H \to \gamma\gamma$, DY, AP splitting functions, PDFs, $e^+e^- \to 3$ jets

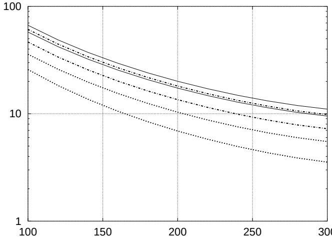
- *multi-scales*
  Logarithmic enhanced corrections: $\alpha^k \log^n(Q_1^2/Q_2^2)$, $Q_1^2 \gg Q_2^2$
  Q_T distributions in $pp \to \gamma\gamma$, threshold corrections in inclusive jet and top-pair production, EW Sudakov logs.

- *hard-soft transition*
  LO/NLO/NNLO matrix elements and multiple soft parton radiation: interface/match or merge fixed-order with parton showers, or improve parton showers.

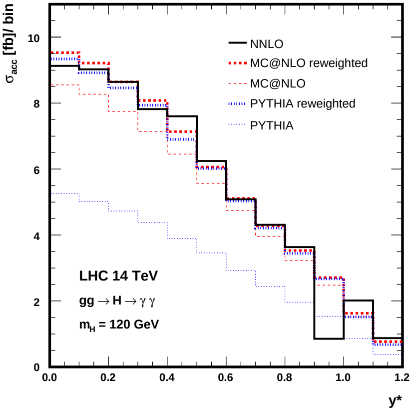
Discovery: $gg \to H$@NNLO - fully differential



Harlander and Kilgore, PRL88 (2002)



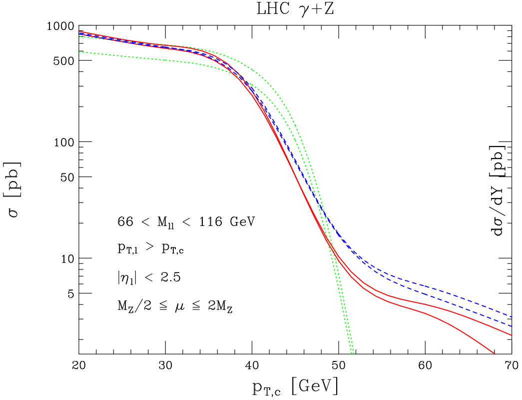
Anastasiou and Melnikov, NPB 646 (2002)

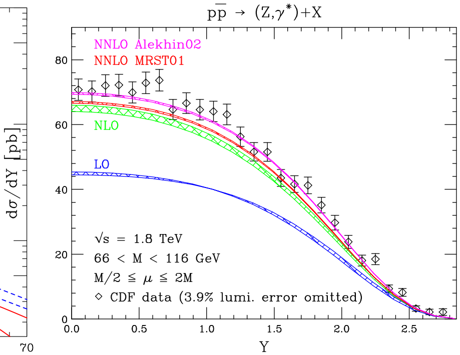


Davatz *et al.*, hep-ph/0604077

Precision: DY@NNLO - fully differential

p_T cut dependence of σ_Z





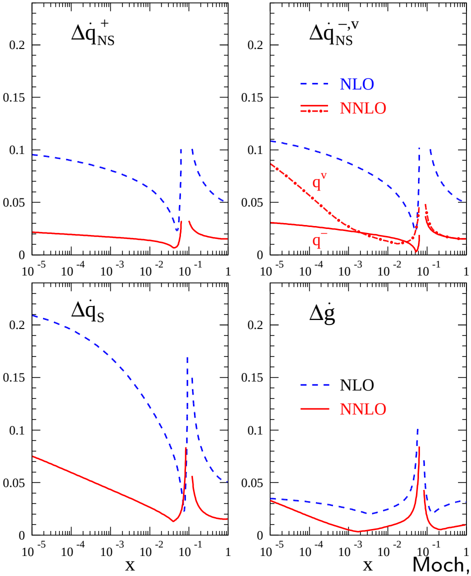
Alekhin, Melnikov, Petriello, hep-ph/0606237

see also Melnikov, Petriello, PRD74 (2006)

see also Kilgore, NPPS160 (2006)

Anastasiou *et al.*, PRD69 (2004)

Precision: PDFs@NNLO



NNLO precision requires coefficient and splitting functions $P_{ff'}$ at NNLO:

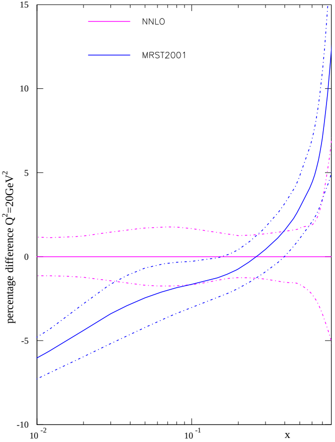
$$P^{\rm NNLO}_{\rm ff'} = \alpha_s P^{(0)}_{\rm ff'} + \alpha_s^2 P^{(1)}_{\rm ff'} + \alpha_s^3 P^{(2)}_{\rm ff'}$$

Shown is the renormalization scale uncertainty at NLO and NNLO.

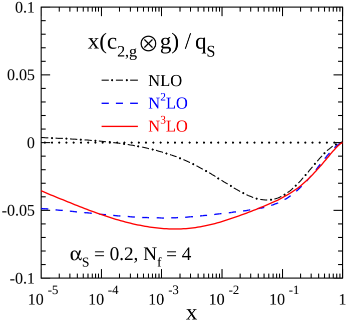
Moch, Vermaseren, Vogt, hep-ph/0408075

Precision: PDFs@NNLO

NLO vs. NNLO up-quark distribution



gluon 3-loop contrib. to F_2



Moch, Vermaseren, Vogt, hep-ph/0608307

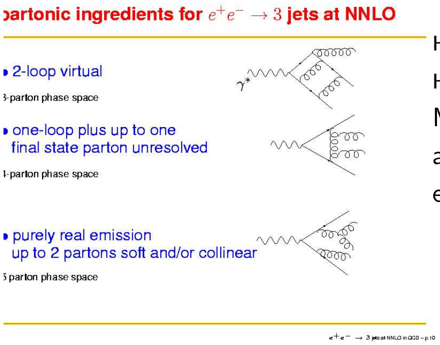
see also talk by Vogt at DIS 2007

Martin, Stirling, Thorne, hep-ph/0606244

see also CTEQ PDFs update, hep-ph/0702159

Precision: $e^+e^- \to 3$ jets@NNLO

World average (2006): $\alpha_s(M_Z^2) = 0.1189 \pm 0.0010$ from S.Bethke (hep-ex/0606035): "NNLO calculations are eagerly awaited by experimentalists."



Heinrich, talk at LoopFest VI

Heinrich, Gehrmann-de Ritter, Gehrmann, Glove

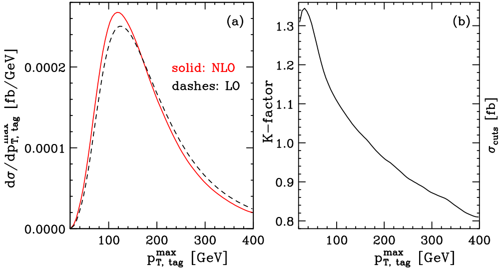
MC program EERAD3 completed and and phenomenlogical results are expected to follow soon.

Discovery: Higgs and *VVjj* production via VBF@NLO

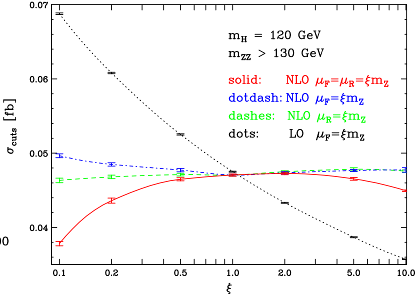
$pp \to Hqq, H \to VV$: Higgs discovery and measurement of Higgs couplings

$pp \to VVjj$: background and new physics search

p_T distribution in *ZZjj* at the LHC



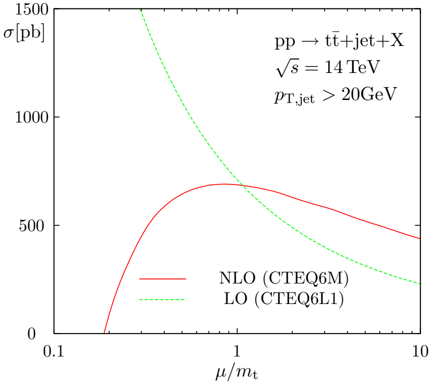
scale dep. of $\sigma(ZZjj)$

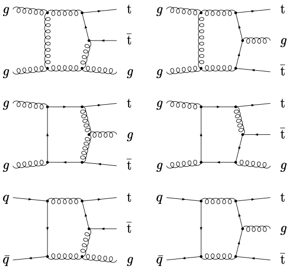


Jaeger, Oleari, Zeppenfeld, hep-ph/0608272

Discovery: $t\bar{t}j$@NLO

$pp \to t\bar{t}$+jet: background to $t\bar{t}H$, Higgs via VBF

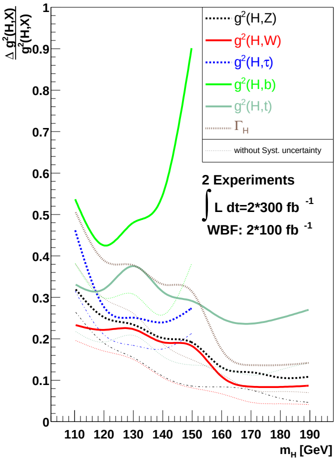




Dittmaier, Uwer, Weinzierl, hep-ph/0703120

Identity: extraction of Higgs couplings at the LHC

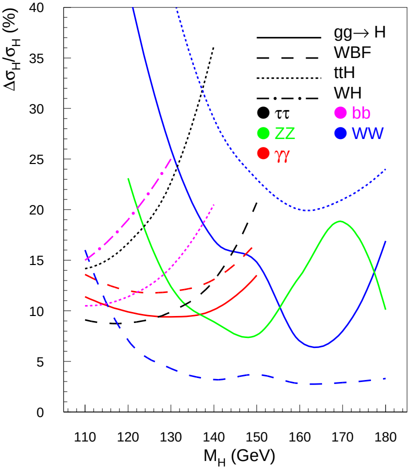
Once a Higgs boson is discovered, to fully exploit the potential of the LHC to determine its properties it is crucial to provide higher-order QCD and EW calculations of signal and background processes.



The LHC can measure Higgs couplings to t, τ, W, Z with 10-20 % accuracy in multi-Higgs-doublet models (300 fb^{-1})

from M.Dührssen *et al.*, hep-ph/0407190

Expected relative errors on σ_{Higgs} at the LHC:



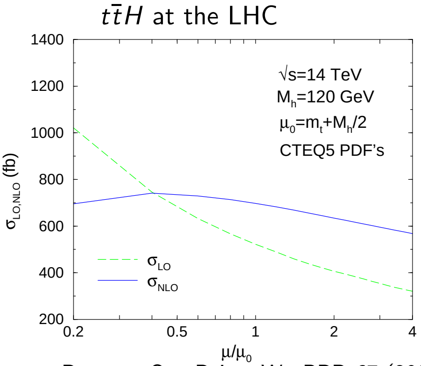
from A.Belyaev and L.Reina, JHEP 0208 (2002)

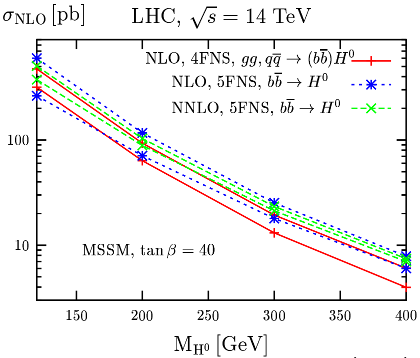
see also review by D.Zeppenfeld, hep-ph/0203123

Based on studies by ATLAS, CMS, A.Belyaev, N.Kaur F.Maltoni, T.Plehn, D.Rainwater, L.Reina, S.Willenbrock, D.Zeppenfeld

$t\bar{t}h$ directly probes the top quark Yukawa coupling: at the LHC with 200 fb^{-1} and $M_H \lesssim 130$ GeV g_{ttH} can be measured with a precision of 15-20 %. from D.Zeppenfeld, hep-ph/0203123

Discovery/Identity: $b\bar{b}h$ and $t\bar{t}h$ @NLO





Dawson, Orr, Reina, W., PRD 67 (2003)   Dawson, Jackson, Reina, W., MPLA 21 (2006)

Dawson *et al.*, PRD 68 (2003), W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003)

$gb(\bar{b}) \to (b\bar{b})h$: NLO by J.Campbell, R.K.Ellis, F.Maltoni, and S.Willenbrock (MCFM)

$gb(\bar{b}) \to (b\bar{b})h$: NNLO by R.Harlander, W.Kilgore, PRD 68 (2003)

Recently improved by including threshold resummation. See talk by B.Fields at Pheno 07

multi-legs@NLO: wishlist of NLO calculations

G.Heinrich, J.Huston, Les Houches 2005	
process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \to V\,V + \text{jet}$	$t\bar{t}H$, new physics
2. $pp \to H + 2$ jets	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
5. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$
7. $pp \to V + 3$ jets	various new physics signatures
8. $pp \to V\,V\,V$	SUSY trilepton searches
LHC-TI white paper	
9. $pp \to t\bar{t} \to 6$ fermions	background to Higgs
10. $pp \to t\bar{t}j$	background

see also talk by J.Huston at LoopFest VI.

LHC Theory Initiative (LHC-TI)

NSF funded fellowships for graduate students and postdocs involved in LHC related theoretical research.
Recipients of the 2007 LHC-TI Graduate $40,000 Fellowship Awards are:

- Randall Kelly (University of California, San Diego)
- Jonathan Walsh (University of Washington).

and $3K travel awards: D.DeChang, W.Gong, D.Krohn, K.Rehermann.

Congratulations !

The first LHC-TI Fellow's meeting will be held following PHENO 08.
Plans for 07-08: 1 postdoc + 2 graduate students
For more information see www.pas.rochester.edu/∼orr/LHC-TI.html
or contact the LHC-TI organizers:
Jonathan Bagger (bagger@jhu.edu)
Ulrich Baur (baur@ubhex.physics.buffalo.edu)
Sekhar Chivukula (sekhar@pa.msu.edu)
Lynne Orr (orr@pas.rochester.edu)

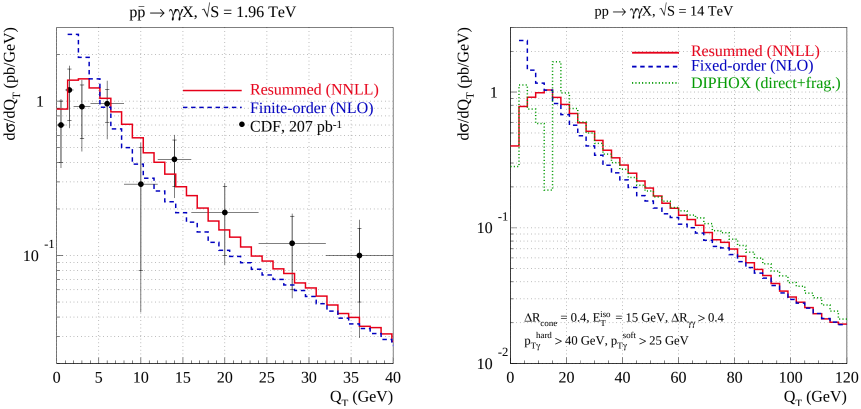
multi-loops and multi-legs@NLO: innovations

virtual: loop amplitudes in terms of tensor integrals → reduction to scalar integrals (IR, UV, threshold, spurious singularities)
real: IR singularities extracted using phase space slicing or subtraction methods.

- Methods for automization/numerical evaluation of loop integrals: sector decomposition (IR), contour deformation (thresholds), no or new tensor reduction (spurious singularities due to Gram determinants) Nagy, Soper; Binoth, Guillet, Heinrich; Giele, Glover, Zanderighi; Anastasiou, Daleo; Ferroglia, Passarino, Passera, Uccirati; Melnikov, Petriello; Denner, Dittmaier
- Methods for dealing with real IR singular emission: phase space slicing and dipole or antenna subtraction (terms that approximate the ME in all singular limits are subtracted from real ME) Catani, Seymour; Gehrmann-de Ridder, Gehrmann, Glover; Kosower; Kilgore; Weinzierl

Alternatives: analytic on-shell methods obtain loop amplitudes directly from poles and cuts reducing to lower-leg/lower-point amplitudes for a review see Bern, Dixon, Kosower, hep-ph/0704.2798

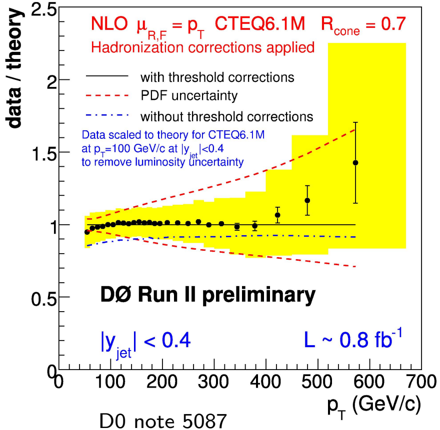
multi-scales: resummed Q_T distribution in $\gamma\gamma$ production



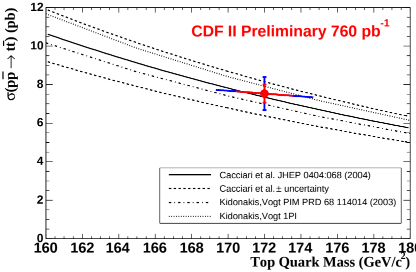
Balazs, Berger, Nadolsky, Yuan, hep-ph/0704.0001

multi-scales: threshold resummations in inclusive jet and $t\bar{t}$ production

$f_1(p_1) + f_2(p_2) \rightarrow F(p) + X, s_4 = s + t + u - \sum m^2 \rightarrow 0$ at threshold resulting in enhanced $\log(s_4/M^2)$ contributions for soft gluons, resummed to NNLO accuracy. for a brief review see N.Kidonakis, hep-ph/0606280

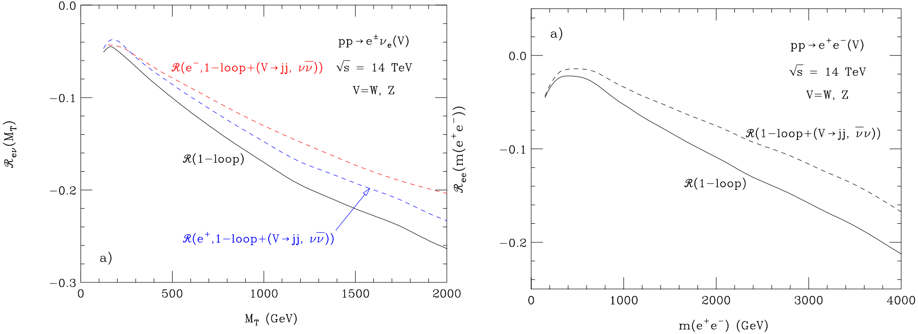


D0 note 5087



CDF Conference note 8148

multi-scales: electroweak corrections to W/Z production



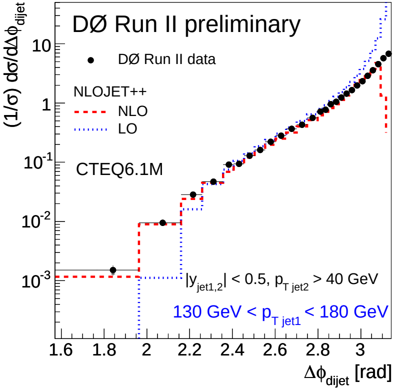
Baur, PRD75 (2007)

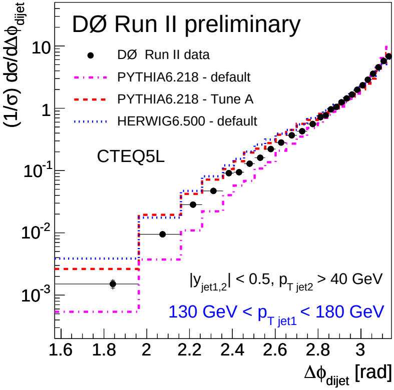
EW logarithmic corrections to 4-fermion processes are known up to 2-loop N^3LL order and are available in form of compact analytical formula. For a review see, e.g., J.Kühn's talk at Radcor 2005: `www-conf.kek.jp/radcor05`

soft-hard transition: LO/NLO/NNLO and parton showers

How to get the best of both worlds?

Azimuthal decorrelations between two leading jets tests the description of soft gluon radiation. Comparison of data with NLO and PS event generator predictions:





Martinez, hep-ex/0505047

soft-hard transition: LO/NLO/NNLO and parton showers

How to get the best of both worlds?

for a brief review see P.Skands, hep-ph/0507129, and talk at LoopFest VI

- *interface/match:*
  CKKW: matrix elements are only applied in regions where the jet resolution variable $y_{cut} > y_{ini}$, and the parton shower is used when $y_{cut} < y_{ini}$ (two jets are resolved if $y_{ij} > y_{cut}$).
  LO MEs are generated by, e.g., MADGRAPH, ALPGEN, and dressed with Sudakov form factors.
  Used in SHERPA, ARIADNE, HERWIG, PYTHIA.
  Catani, Krauss, Kuhn, Webber, hep-ph/0109231; see also Mangano; Mrenna, Richardson; Nagy, Soper; Hoeche *et al.*, hep-ph/0602031

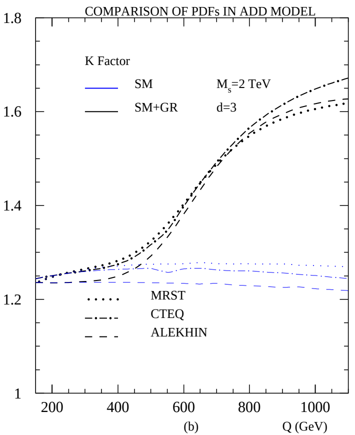
soft-hard transition: LO/NLO/NNLO and parton showers

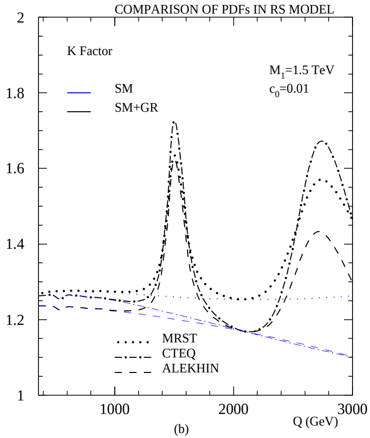
How to get the best of both worlds?

- *merge:*
  MC@NLO: based on full NLO ME for the hard process; cancellation of IR singularities and the avoidance of double counting is done by a modified subtraction formalism.
  Frixione, Nason, Webber, hep-ph/0305252
  P.Nason (hep-ph/0409146, see also hep-ph/0606275): provides an interface of NLO to parton shower but avoids negative weights, see also talk by C.Oleari at Pheno 07
- *improve:*
  Herwig/Pythia: matrix element corrections added to "dead zones" of shower algorithm (Herwig) or to get rid of too much radiation (Pythia).
  VINCIA: based on antennas Giele, Kosower, Skands

QCD and new physics

SM experience not necessarily applicable to BSM predictions - there may be surprises.
QCD K-factors for DY within the SM, ADD and RS models:





Kumar, Mathews, Ravindran, hep-ph/0604135

Conclusions

- Every aspect of LHC physics will be affected by QCD: precision measurements of SM observables, discovery of the Higgs and physics beyond the SM, and identification of BSM signals.
- We've seen a lot of activity and many advances in every aspect of accurately modeling QCD processes.
- Still, there is a lot of work ahead of us for the necessary improvements to reach the stage of 'tools' that can be readily applied to LHC data analysis.
- LHC-TI initiative is a huge step in the right direction. Many thanks to the organizers and NSF!

"All that is gold does not glitter, ..."

J.R.R. Tolkien

At the LHC, QCD phenomenology may not "glitter" but is definitely "golden".