# QCD Studies at the LHC

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# Contents

## Exploiting QCD Observables at LHC

- Precision measurements
- Determination of auxiliary quantities
- Input to new physics searches

# Precision Measurements

QCD is experimentally well established

- QCD is now precision physics

LEP precision physics:

Electroweak processes

Tevatron/LHC precision physics:

QCD processes

# Precision Measurements

Precise determination of

- strong coupling constant
- quark masses ($\rightarrow$ Top working group)
- electroweak parameters ($\rightarrow$ EW)

Precision observables

- single jet inclusive cross section
- gauge boson prouction

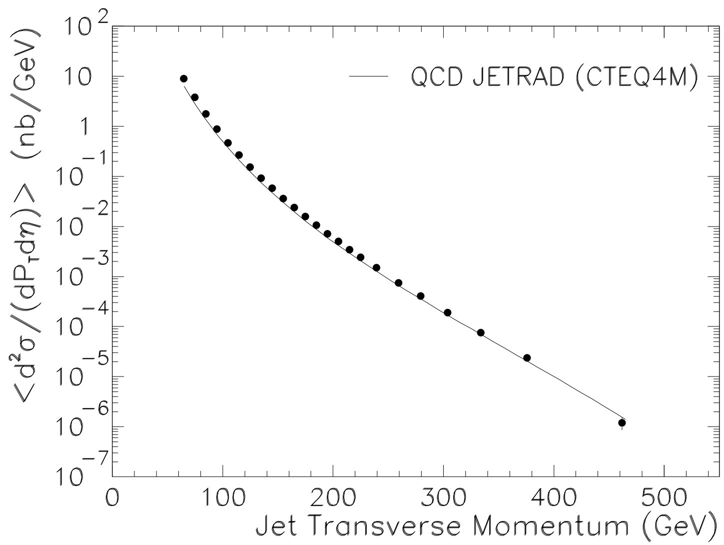
# Jet Production

## Single jet inclusive cross section at Tevatron

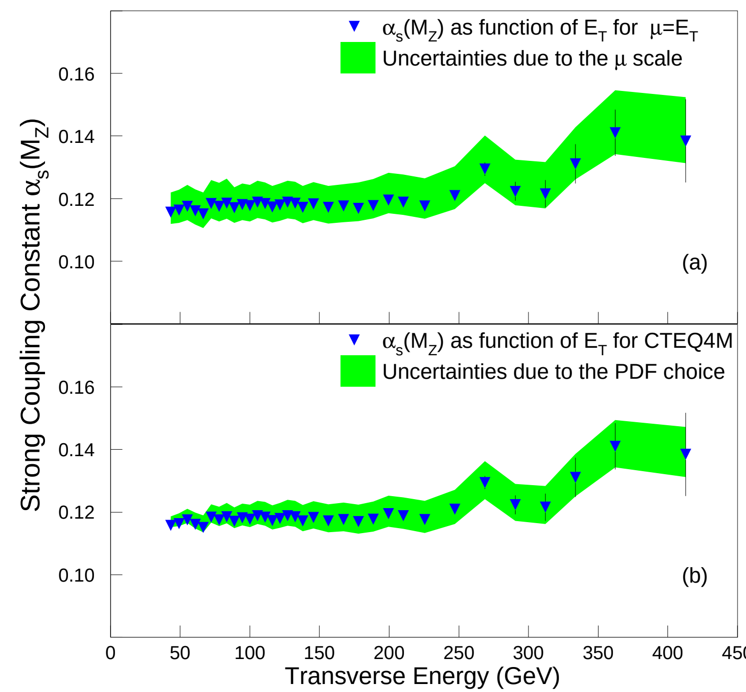
precision determination of $\alpha_s$

test of QCD over wide energy range

D0 Collaboration



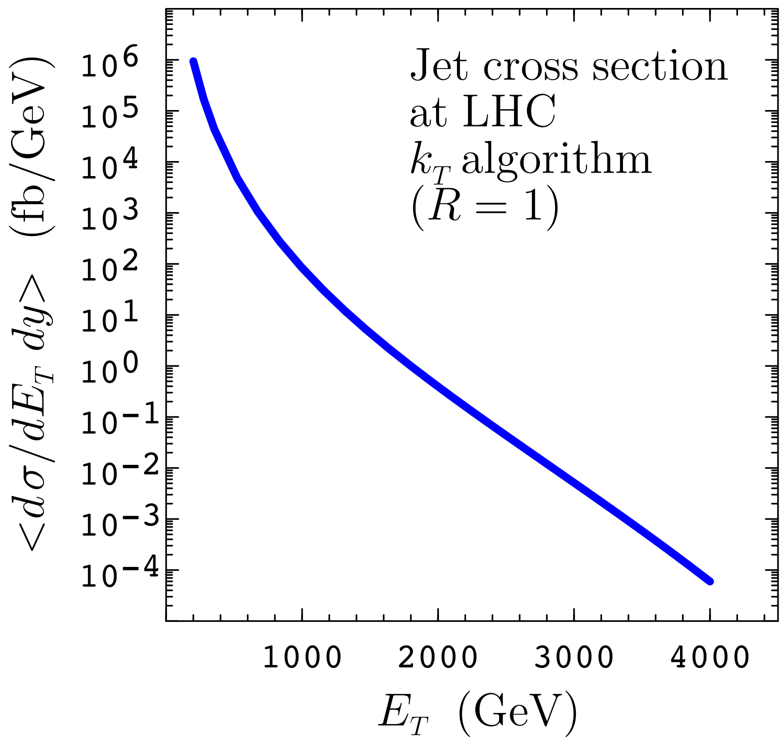

CDF Collaboration




$$\alpha_s^{\mathrm{CDF}}(M_Z) \quad = \quad 0.1178 \pm 0.0001(\text{stat})^{+0.0081}_{-0.0095}(\text{sys})\ ^{+0.0071}_{-0.0047}(\text{scale}) \pm 0.0059(\text{pdf})$$

# Jet Production

## Single jet inclusive cross section at LHC




- requires only central jets $-1 < y < 1$
- measureable to $E_T = 3$ TeV at low luminosity
- extraction of $\alpha_s$ limited by theory (NLO at present) and experimental systematics

# Jet Production

## Jet algorithms

two types of jet algorithms for hadron colliders

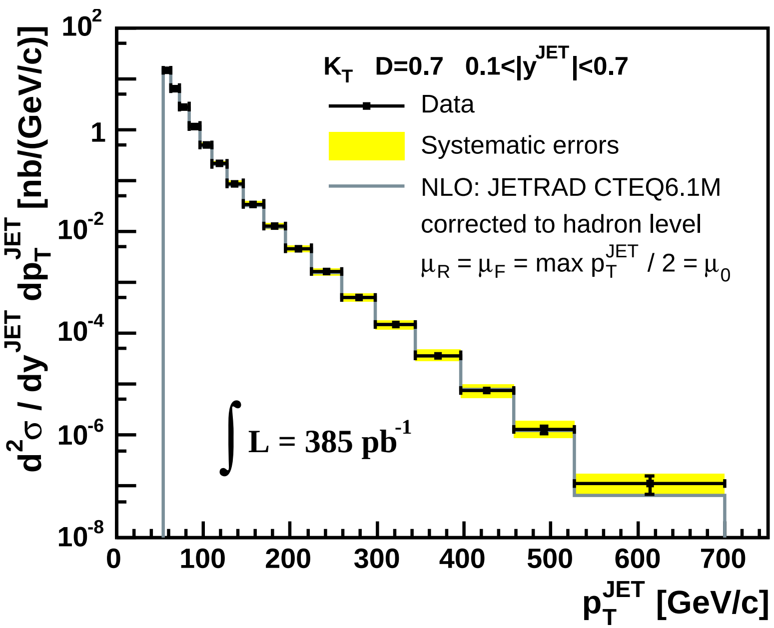
- Cone algorithms
  - attribute all hadronic energy inside a cone in $(\eta - \phi)$ to a given jet
  - define procedures for finding cone axis and for splitting/merging nearby jets
  - $+$ intuitive
  - $+$ appropriate for reconstructing heavy particles, e.g. top quark
  - $-$ theoretical description of splitting/merging not always possible
  - $-$ sometimes large hadronization corrections
- $k_T$ algorithms
  - recombine particles into jets using an iterative procedure on particle pairs
  - $+$ theoretically unproblematic
  - $+$ certain aspects of jet cross sections can be computed analytically
  - $+$ small hadronization corrections
  - $-$ application time-consuming
  - $-$ not appropriate for reconstruction of resonances

# Jet Production

## Jet algorithms

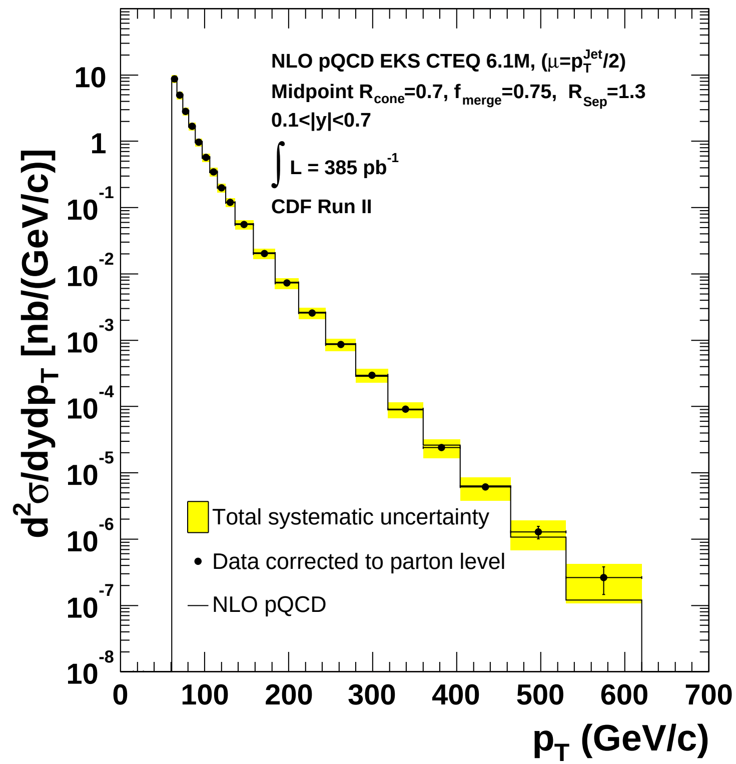
$k_T$-algorithm

CDF Collaboration




Cone algorithm

CDF Collaboration

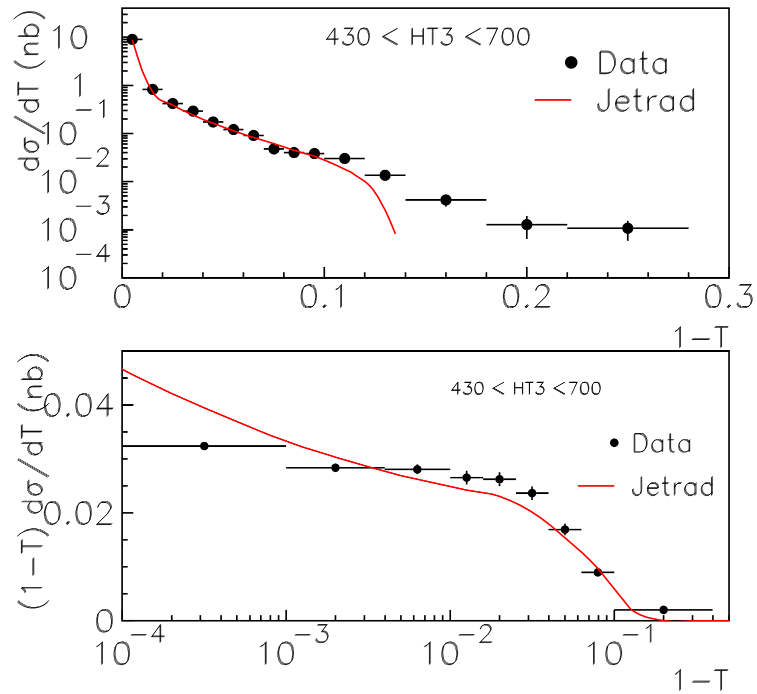


# Jet Production

## Event shapes

- characterize event by event shape variable $\{p_n\} \to T$
- intensively studied in $e^+e^-$ annihilation
- may be used to determine $\alpha_s$
- theoretically well understood
- most common example: Thrust

D0 collaboration

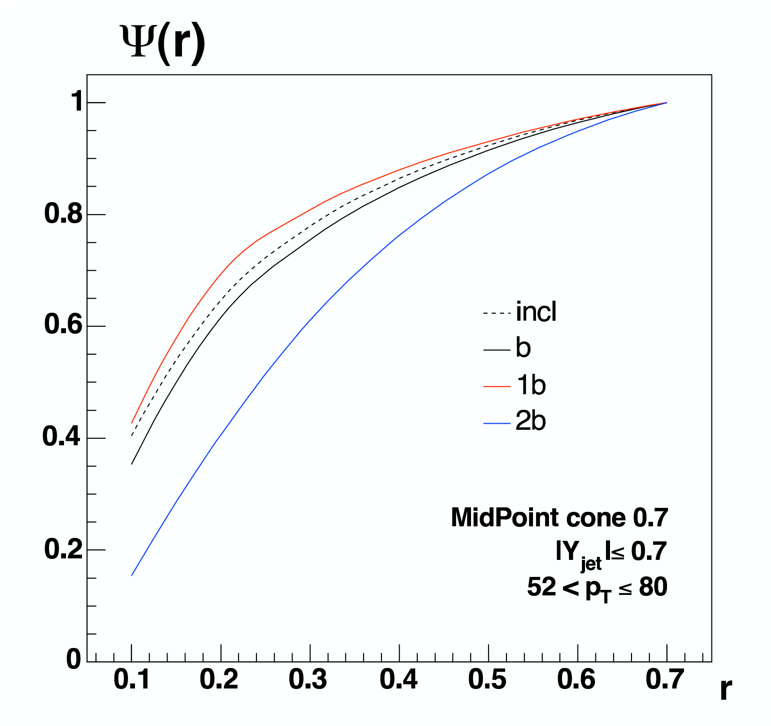



at present: only poorly studied at Tevatron, certainly still potential for precise measurements here

# Jet Production

## Heavy quark jets

CDF: Thesis A. Lister (ETH)




- study jet shape $\Phi(r)$ (fraction of jet energy in a sub-cone)
- expect different $\Phi(r)$ for quark and gluon jets
- expect different $\Phi(r)$ for massive and massless quark jets
- first data soon

could be used as additional information in $b$-tagging

# Tasks for Jet Production

## Theory

- current NLO theory clearly insufficient for precision measurements
- compute NNLO corrections
- improve jet algorithms
- find most appropriate event shape variables for precision studies

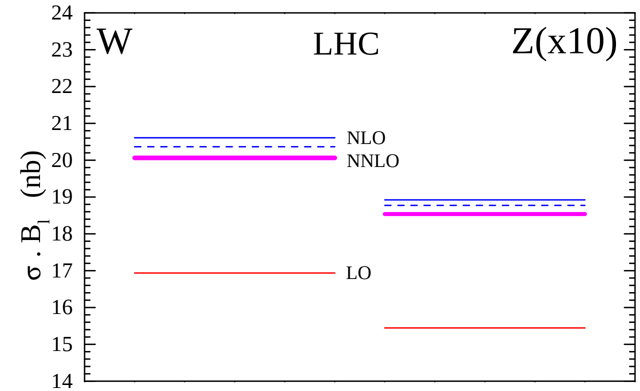
## Experiment

- understand systematic uncertainties in jet production at LHC
- study feasibility of measuring $\alpha_s$ from jets
- jet algorithms for LHC

# Vector Boson Production

## Inclusive cross section

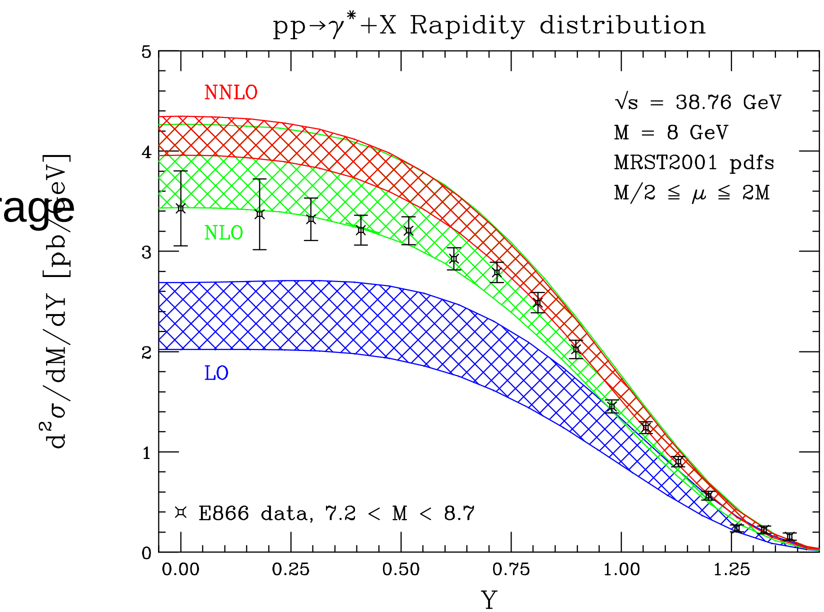
- can be measured precisely
- are theoretically well understood
  - NNLO corrections known
  - relevant partons well constrained
- benchmark reaction for LHC
  (luminosity monitor?)




A. Martin, J. Stirling, R. Roberts, R. Thorne

## Rapidity distribution

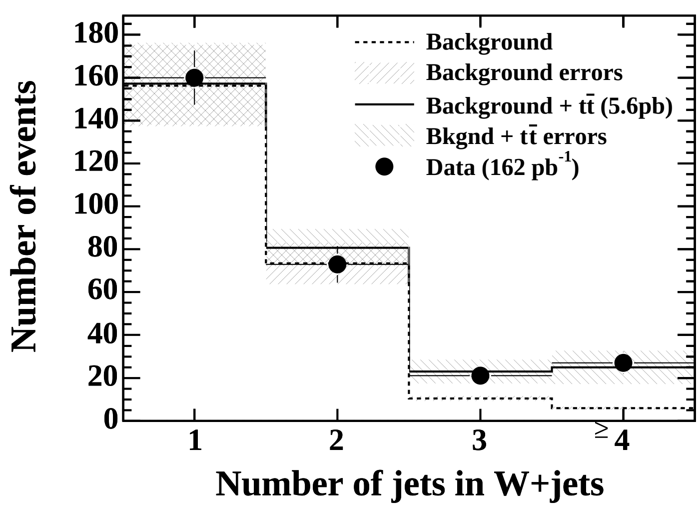
- allows to account for limited detector coverage
- known to NNLO
  C. Anastasiou, L. Dixon, K. Melnikov, F. Petriello



# Vector Boson Production

## Vector boson plus jet production

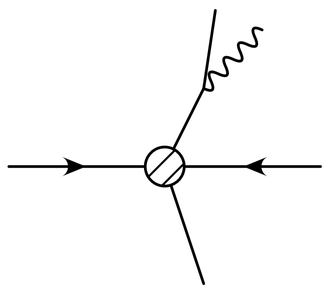
- influences kinematical event reconstruction of inclusive vector boson production (e.g. transverse mass of $W^{\pm}$)
- is background to new physics searches
- for example: top quark discovery
  CDF collaboration



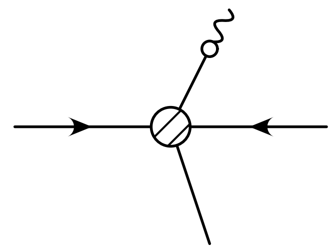

- cross sections for $V + n$ jets currently known to NNLO for $n = 0$, to NLO for $n \leq 2$, and LO otherwise

# Photon Production

## Two production processes for photons



direct



fragmentation

Photons never fully isolated from hadrons

- isolation cone: $E^{\mathrm{had}} < E^{\mathrm{isol}}$ for $R < R^{\mathrm{isol}}$
- cluster photon into jet: $E^{\gamma} > z_{\mathrm{cut}} E^{\mathrm{jet}}$

Both isolation criteria

- are infrared safe
- induce contribution from non-perturbative quark-to-photon fragmentation function

Cone-based isolation fails for small cones:

S. Catani, M. Fontannaz, J.P. Guillet, E. Pilon

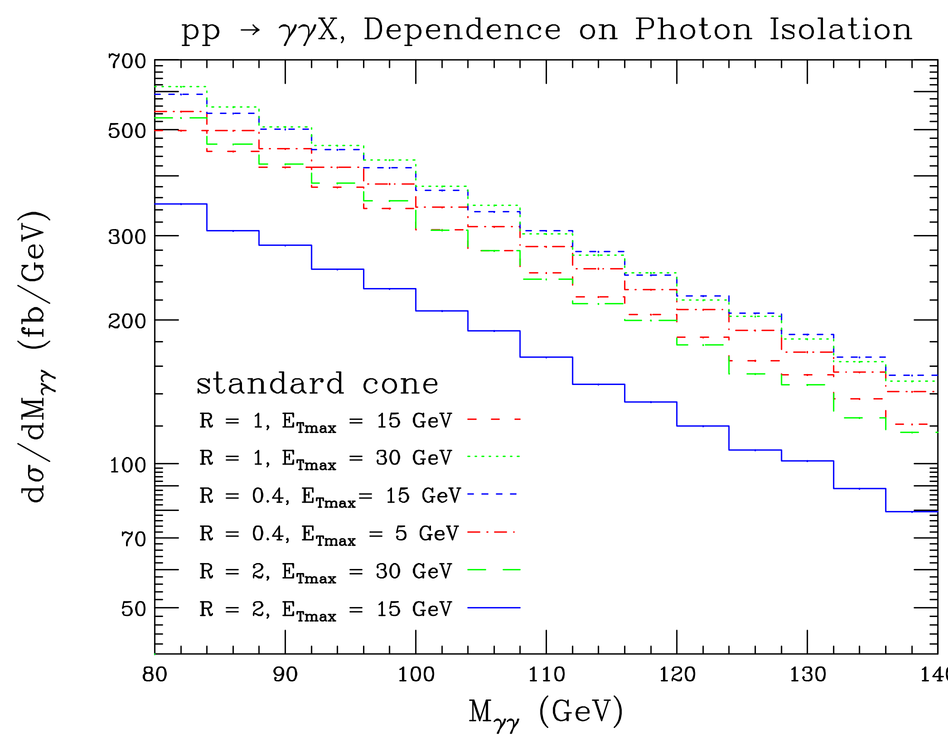
$$\sigma^{\mathrm{isol}} > \sigma^{\mathrm{incl}} \quad \text{for } R \leq 0.1 \quad (\alpha_s \ln R^{-2} \sim 1)$$

# Photon Production

- photon identification: need to distinguish photons from neutral mesons decaying into photon pairs: $\pi^0, \eta, \ldots$
- purity and efficiency of photon identification energy-dependent
- photon isolation helps to distinguish photons from neutral mesons, but can seriously affect photon production cross section

Example: $pp \to \gamma\gamma + X$

T. Binoth, J.P. Guillet, E. Pilon, M. Werlen



# Tasks for Gauge Bosons

## Theory

- compute NNLO corrections where needed for precision measurements: e.g. $V + 1j$
- compute NLO corrections for gauge boson plus multi-jet final states

## Experiment

- estimate systematic uncertainties for vector boson production (inclusive or in association with jets)
- reality check of photon isolation and photon identification

# Auxiliary Quantities

Theoretical prediction and interpretation of LHC results relies on

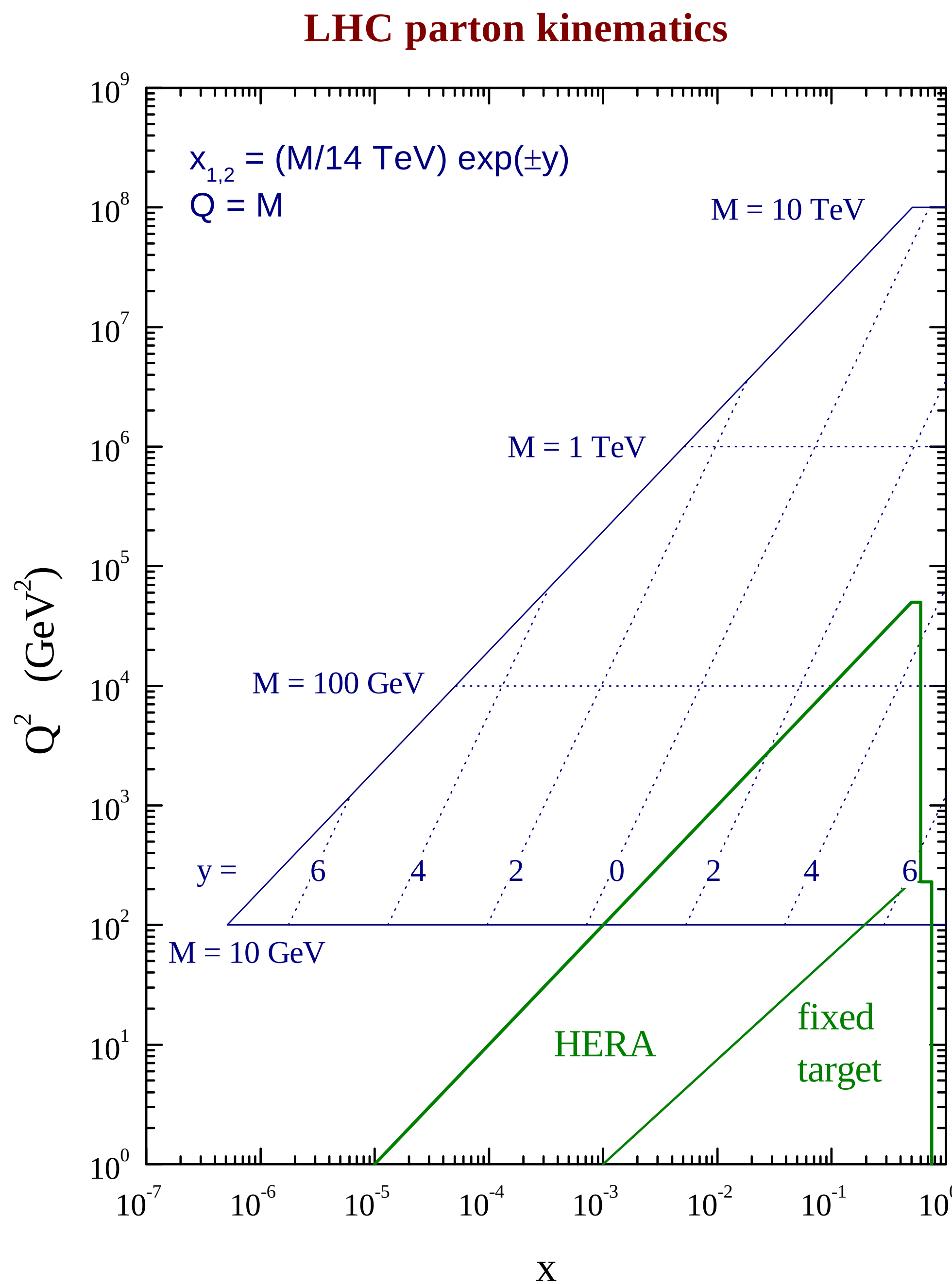
- parton distributions
- LHC collider luminosity

Can be extracted from QCD measurements

# Partons

## Parton distributions

- precise data from HERA and fixed target experiments
  → quark distributions very well known
  → tight constraints on gluon distribution for $x \leq 0.1$
- open issues:
  gluon distribution at large $x$
  partons at very small $x$



# Partons

## Measuring parton distributions at LHC

Gluon distribution at large $x$

- jet production at large $E_T$
- (photon production at large $E_T$)
- (heavy quark production at large $E_T$)

Parton distributions at very small $x$

- low-mass Drell-Yan pairs at very large rapidity
  $\rightarrow$ relevant for UHE neutrino and cosmic ray interactions
- mini-jet activity at very large rapidity

# Tasks for Partons

## Theory

- improve consistency of global fits by computing NNLO corrections to all relevant observables (especially jet production)
- treatment of errors on parton distributions (error propagation, correlated uncertainties)
- electroweak effects on parton distributions

## Experiment

- sensitivity of high-$E_T$ jet production on gluon distribution
- feasibility of measurements at very large rapidity

# LHC luminosity

## Luminosity required for all absolute cross section measurements

Tevatron luminosity

- from $p\bar{p} \to X$ inclusive cross section (forward detectors)
- experimentally difficult
- theory uncertain (extrapolation from lower energies)

Proposal for LHC (M. Dittmar, F. Pauss, D. Zürcher)

- use $pp \to W^{\pm}, Z^{0}$ (over limited rapidity coverage)
- theoretically well understood (NNLO)
- relevant parton distributions well constrained
- experimentally clean measurement

# Searching New Physics

## Requirements for searches

- fully differential description of expected signal and standard model background
  - design and optimize cuts
  - estabilsh observation of signal as opposed to background fluctuation
- signal: need to understand production mechanisms and decay signatures
- background: need to describe final states with many jets and vector bosons, heavy quarks

## Tools for searches

- multi-purpose leading order event generators ($\longrightarrow$ talk by S. Höche)
- leading order predictions for final states with many particles often insufficient
  - several scales in hard process $\longrightarrow$ overall normalization $(\sim \alpha_s^n(\mu_f))$ very uncertain
  - extra radiation from higher order contributions can modify kinematical distributions and affect cuts

# Searching New Physics

## Better background estimates

- extrapolation of measured background cross sections in signal regions
  - feasible if signal is a clean peak
  - difficult if signal is a broad enhancement over a smooth background
    N. Kauer
- combination of NLO calculations and parton showers
  MC@NLO: S. Frixione, B. Webber
  Z. Nagy, D. Soper
  W. Giele, D. Kosower, P. Skands
- automated approaches to NLO calculations
  A. Denner, S. Dittmaier; K. Ellis, W. Giele, G. Zanderighi;
  T. Binoth, J.P. Guillet, G. Heinrich, E. Pilon, C. Schubert;
  F. Boudjema, Y. Kurihara (GRACE collaboration);
  A. van Hameren, J. Vollinga, S. Weinzierl;
  Z. Nagy, D. Soper; C. Anastasiou, A. Daleo

# Tasks for Searches

## Theory

- be prepared for precise computation of multi-particle final states
- and to provide error estimates on these

## Experiment

- verify search tools (e.g. particle finding algorithms) on Standard Model processes
- tune event generator programmes on first LHC data
- check data-based background extrapolation on non-trivial example reactions

# Summary

## QCD processes at LHC

- can be measured already with low luminosity
- allow precision measurements
- determine parton distributions and LHC luminosity

## Implications of QCD studies

- demonstrate proper functioning of tools (jet algorithms, particle finding)
- detailed understanding mandatory for new physics searches

## This workshop

- prepare QCD studies for the LHC startup phase
- identify most promising observables