Hadronic final states and resummation

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LPTHE — Univ. Paris VI & VII and CNRS

HERA–LHC workshop
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Background and Aim [of HERA LHC Workshop]

`http://www.desy.de/~heralhc/#aim`

The impact of measurements made at HERA, present and future, on the physics of the LHC is potentially large. However, this potential is currently not as well explored as e.g. the more obvious connection between the Tevatron and the LHC.

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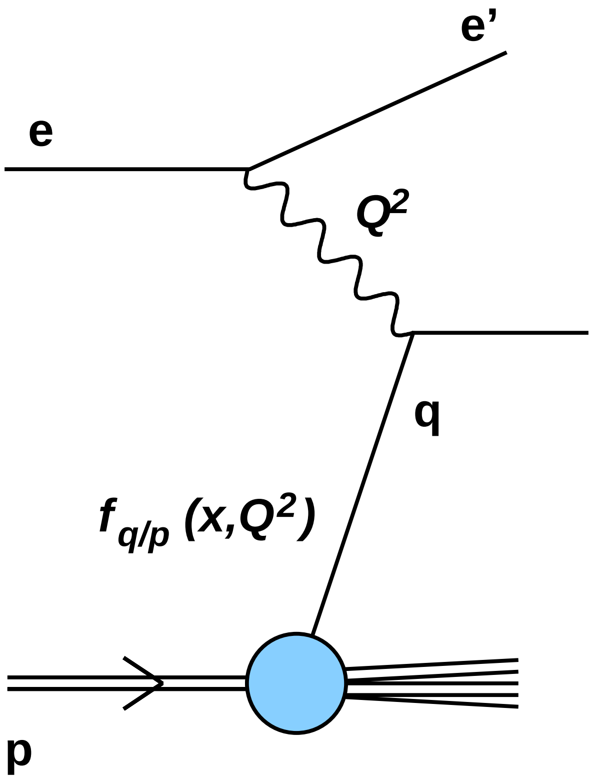
The most obvious area of impact is in the determination of proton structure from very low to very high x, which is measured precisely at HERA. Other topics include QCD production of heavy flavors and the study of multi-jet final states, energy flows and structure of underlying events.

‘Problem’ is (collinear) factorization



- Measure PDFs, measure $\alpha_s(Q^2)$, evolve with DGLAP

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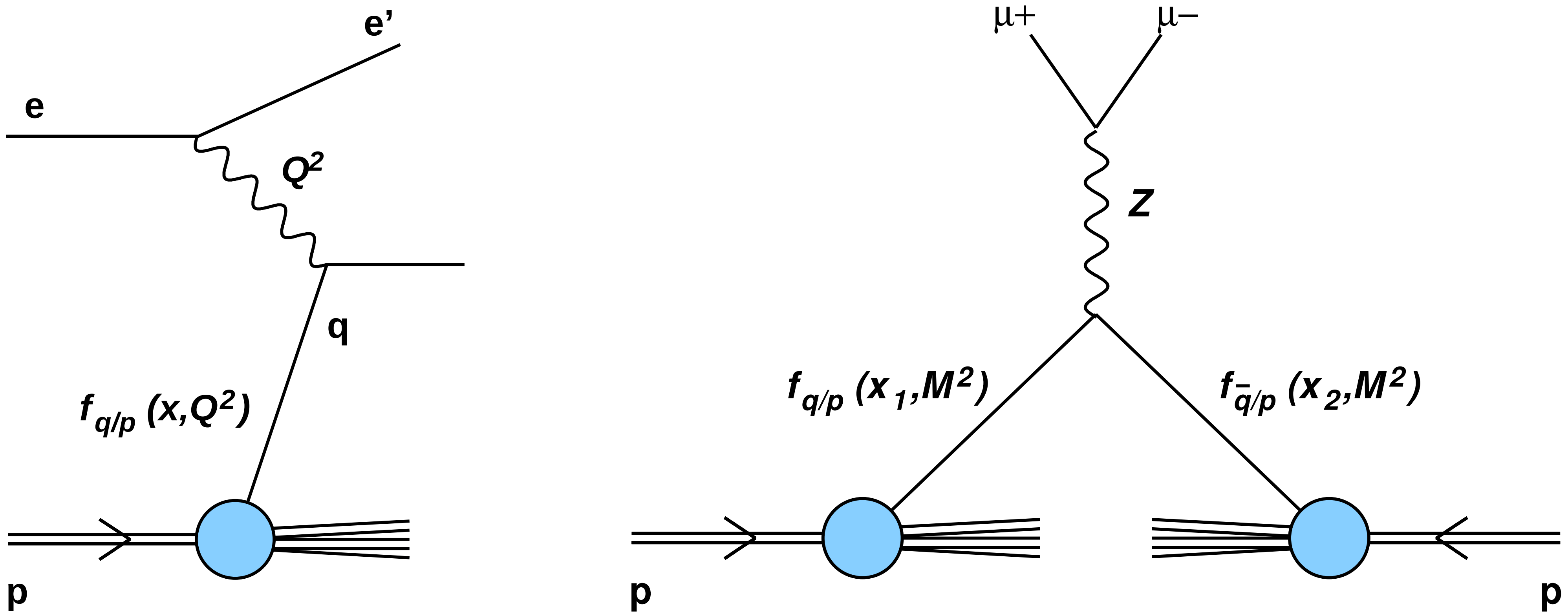

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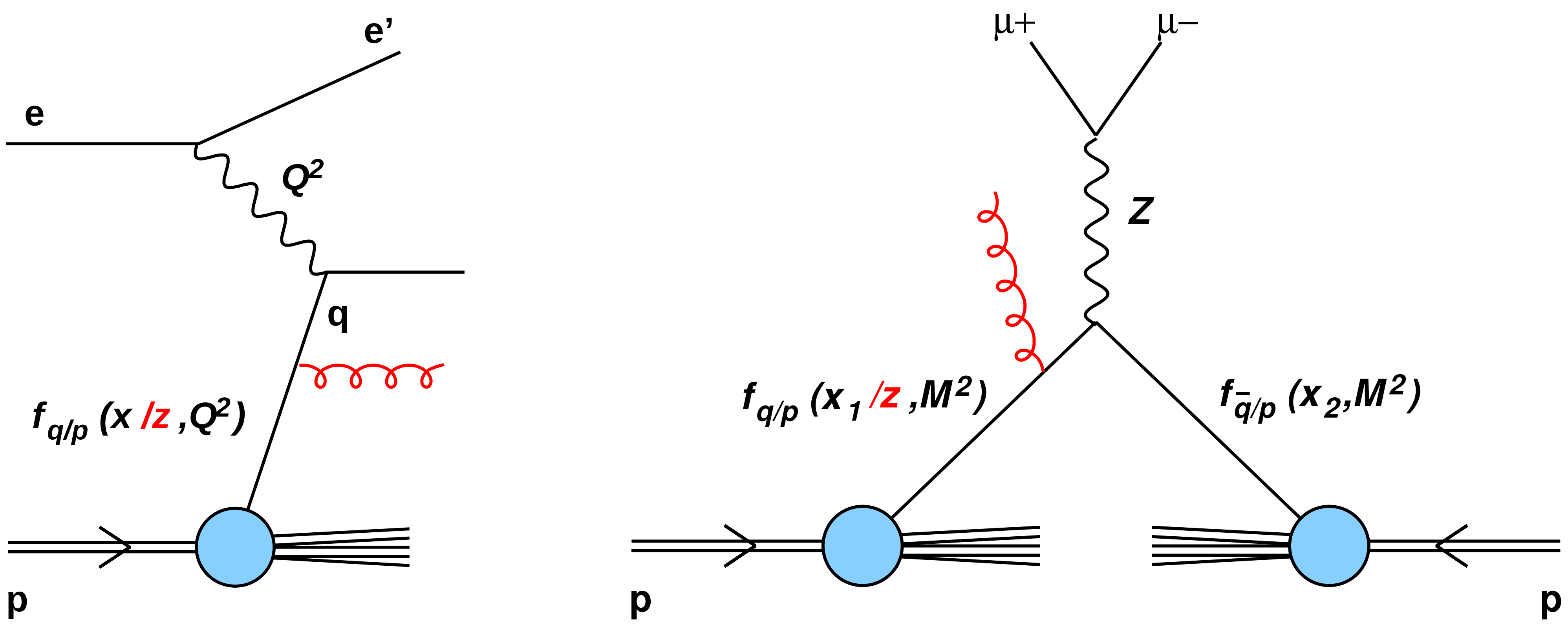

- Measure PDFs, measure $\alpha_s(Q^2)$, evolve with DGLAP
- Predict, perturbatively, cross sections for other hard processes
- Predict, perturbatively, any (infrared-collinear safe) final-state observable

  $\left[\text{Initial-state collinear singularities are absorbed into PDFs}\right]$

Final-state tools based on pert. QCD & coll. fact.

- LO calculations with many partons / arbitrary final states
  - NJETS, VECBOS, ALPGEN, COMPHEP, GRACE, AMEGIC, ...
- NLO calculations (2 jets, 3 jets)
  - JETRAD, DYRAD, MEPJET, DISENT, DISASTER++, JETVIP, NLOJET, MCFM, PHOX family, ...
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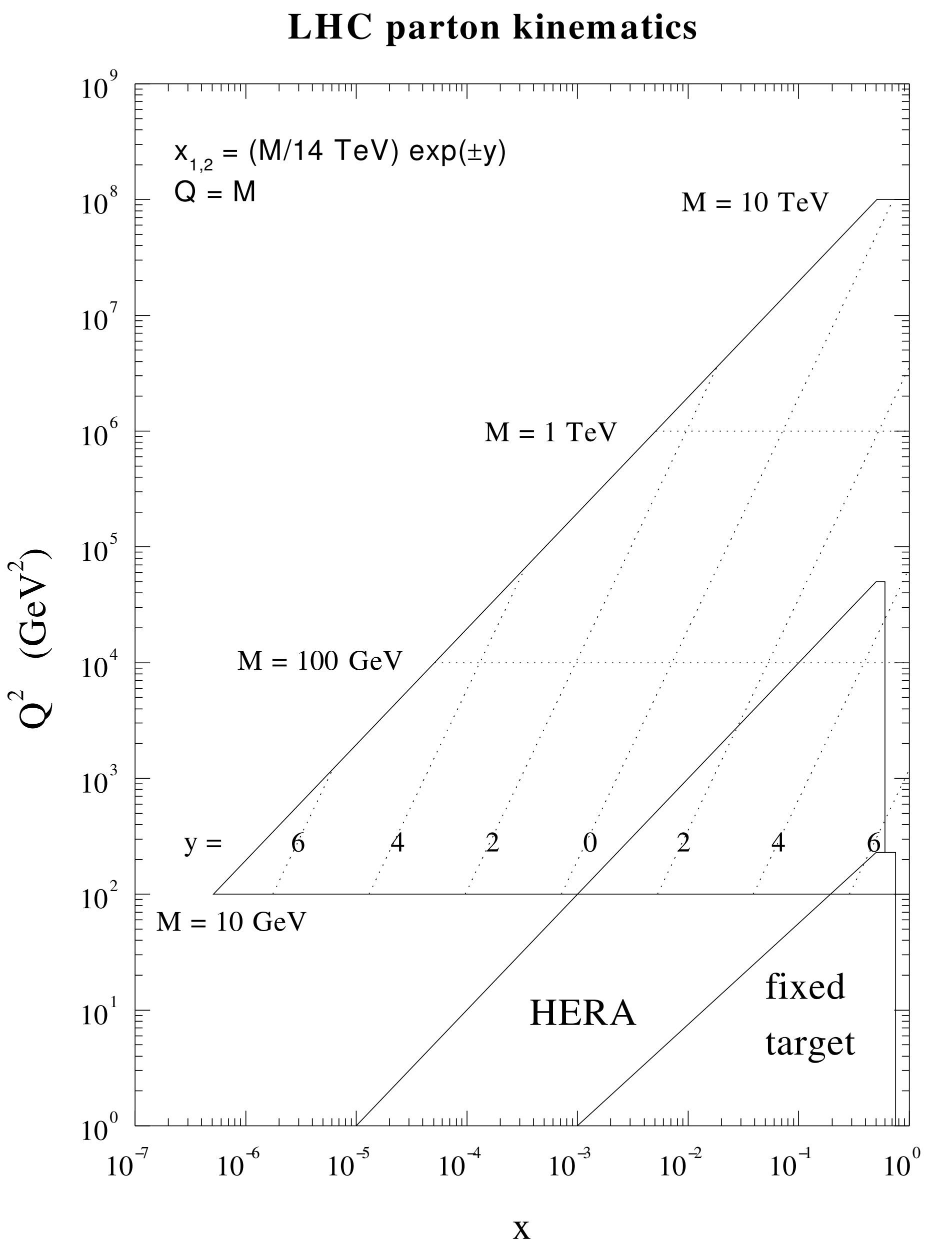
So that's all we need from HERA...

How might HERA final-states be useful to LHC?

Answer depends on kinematic domain



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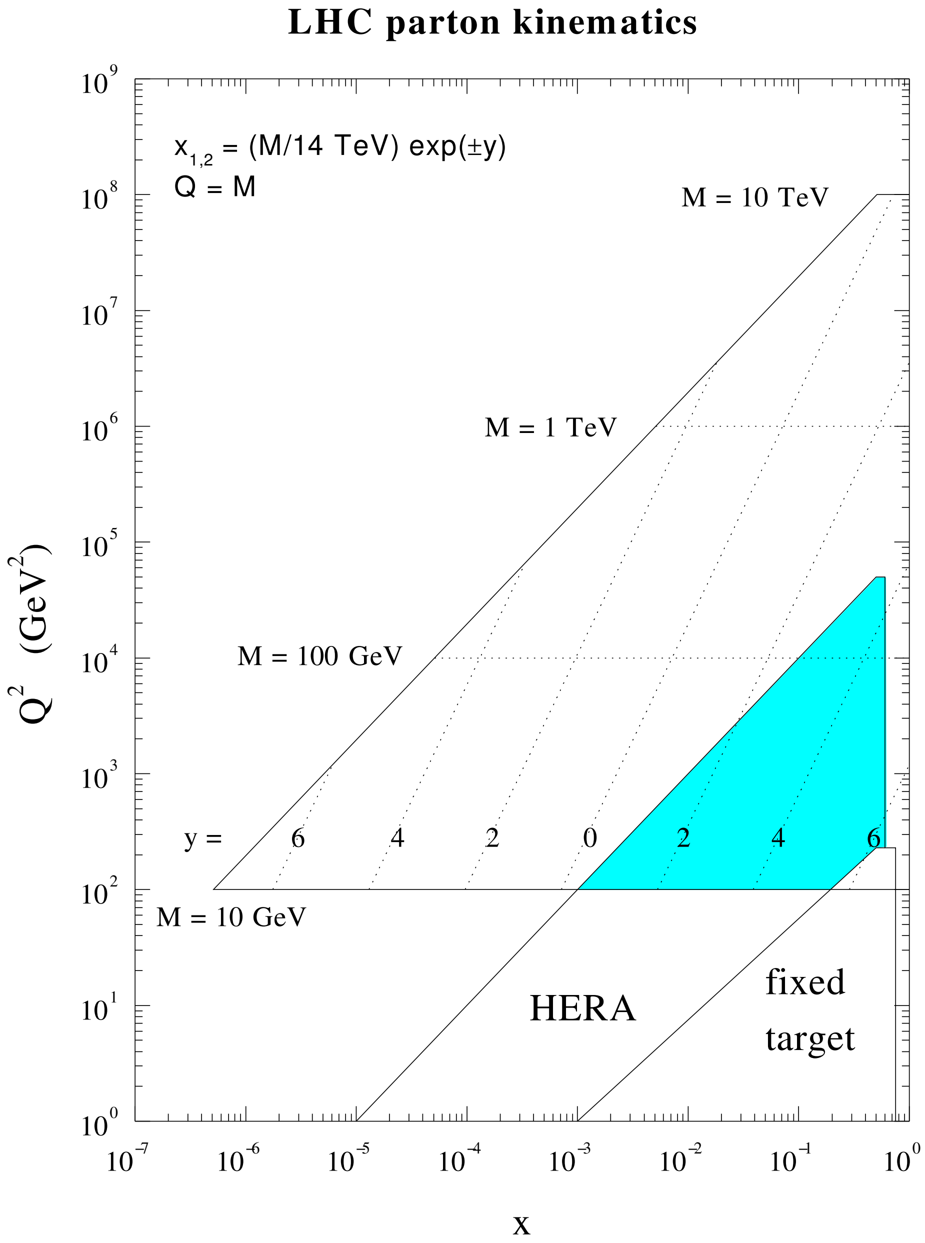

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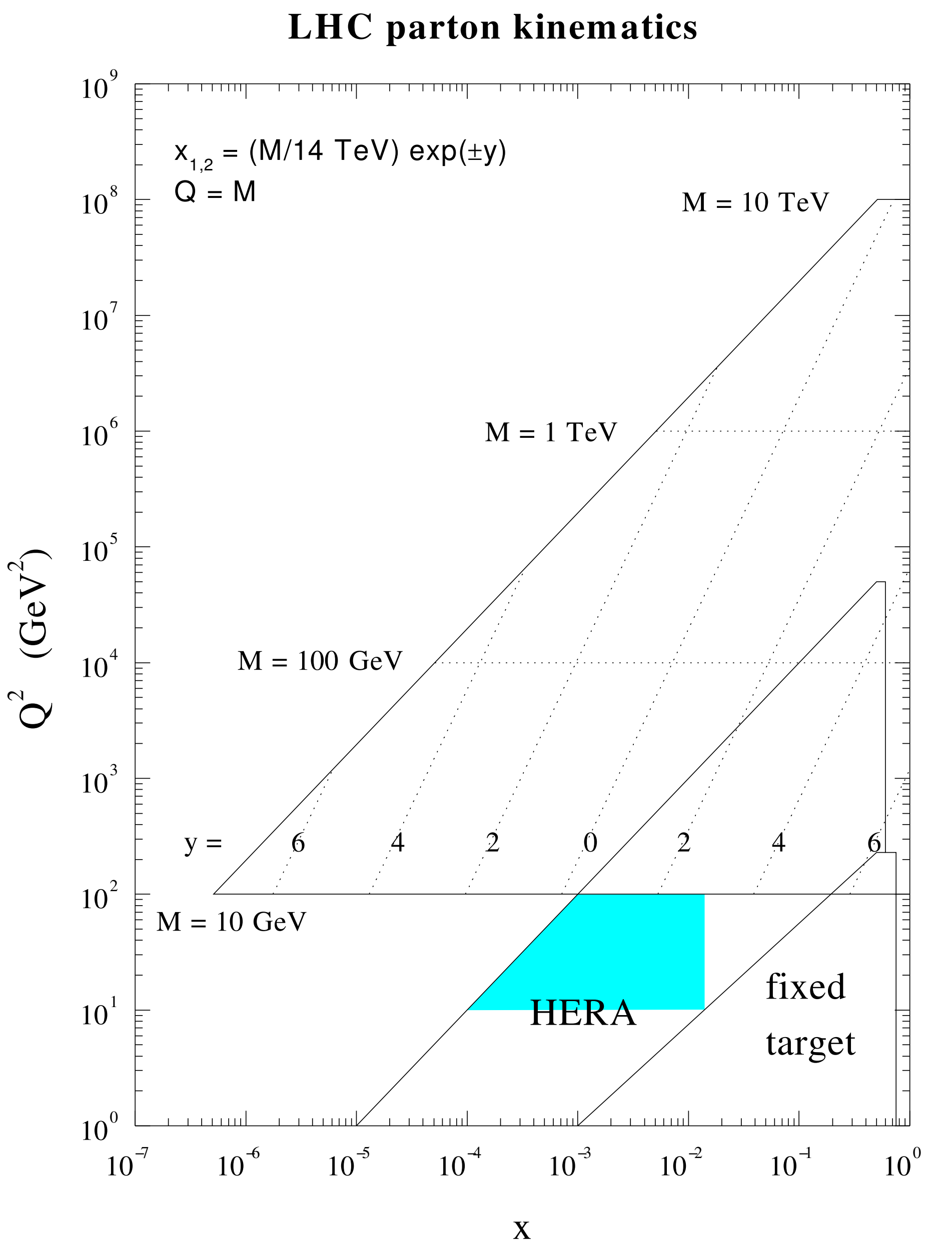

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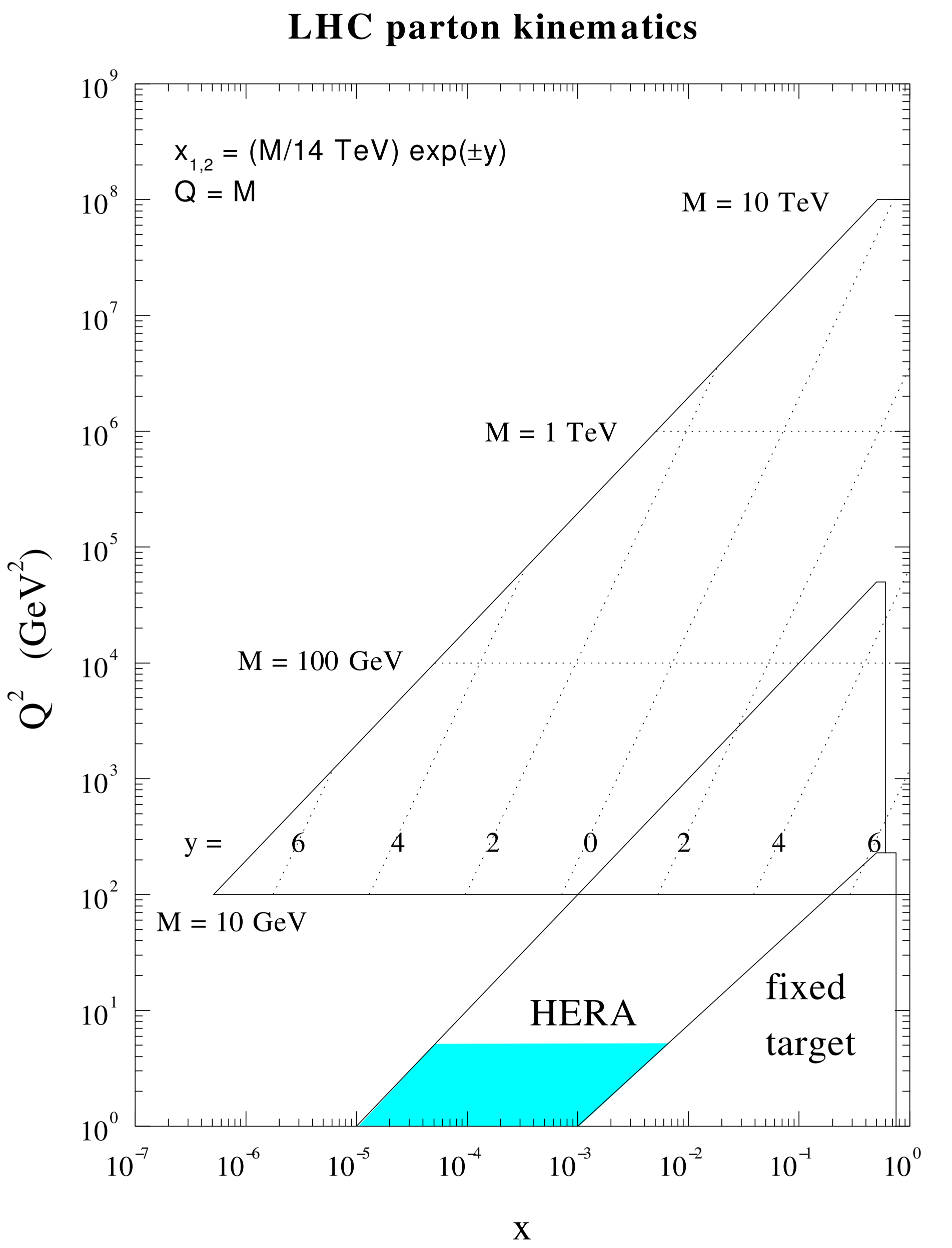

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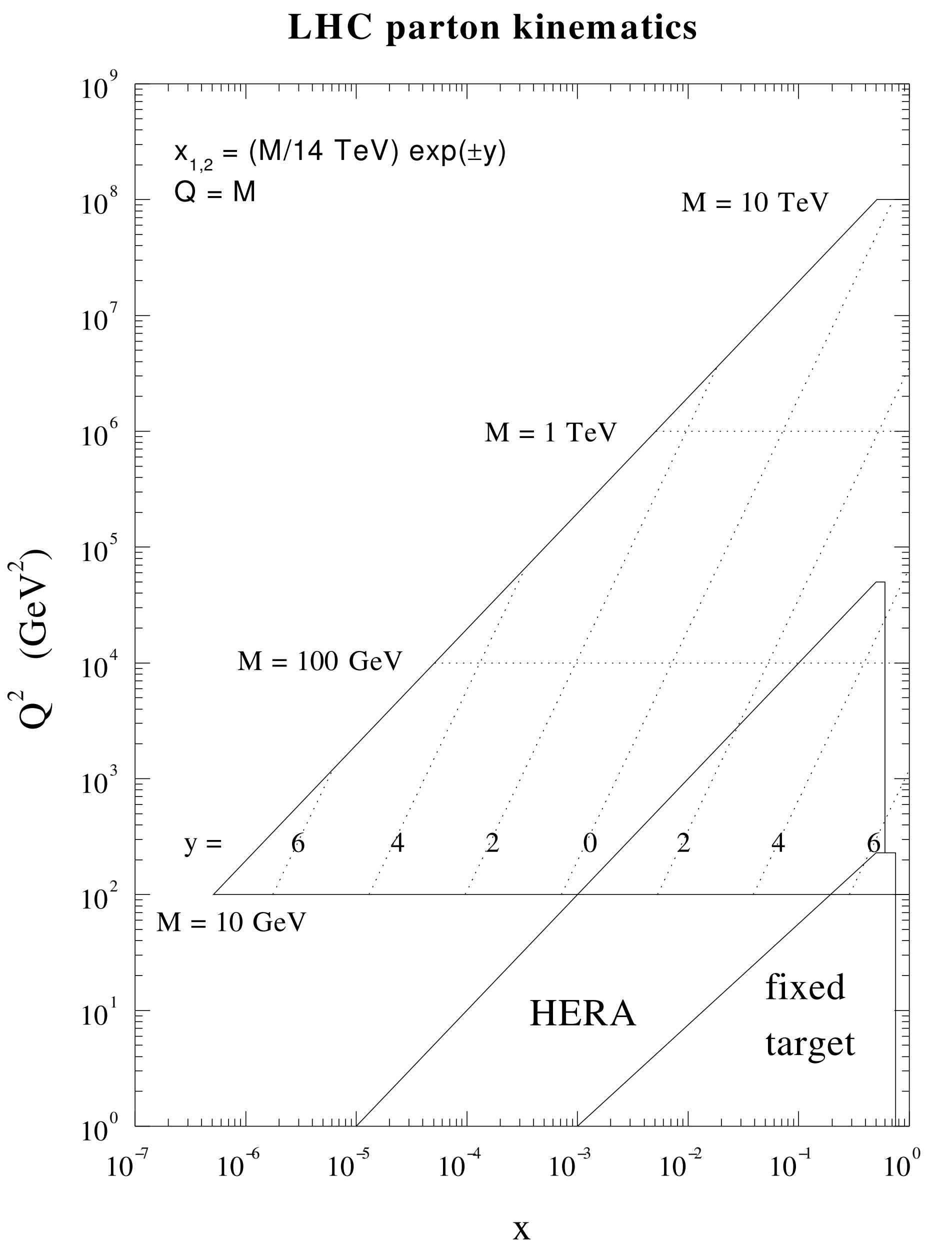

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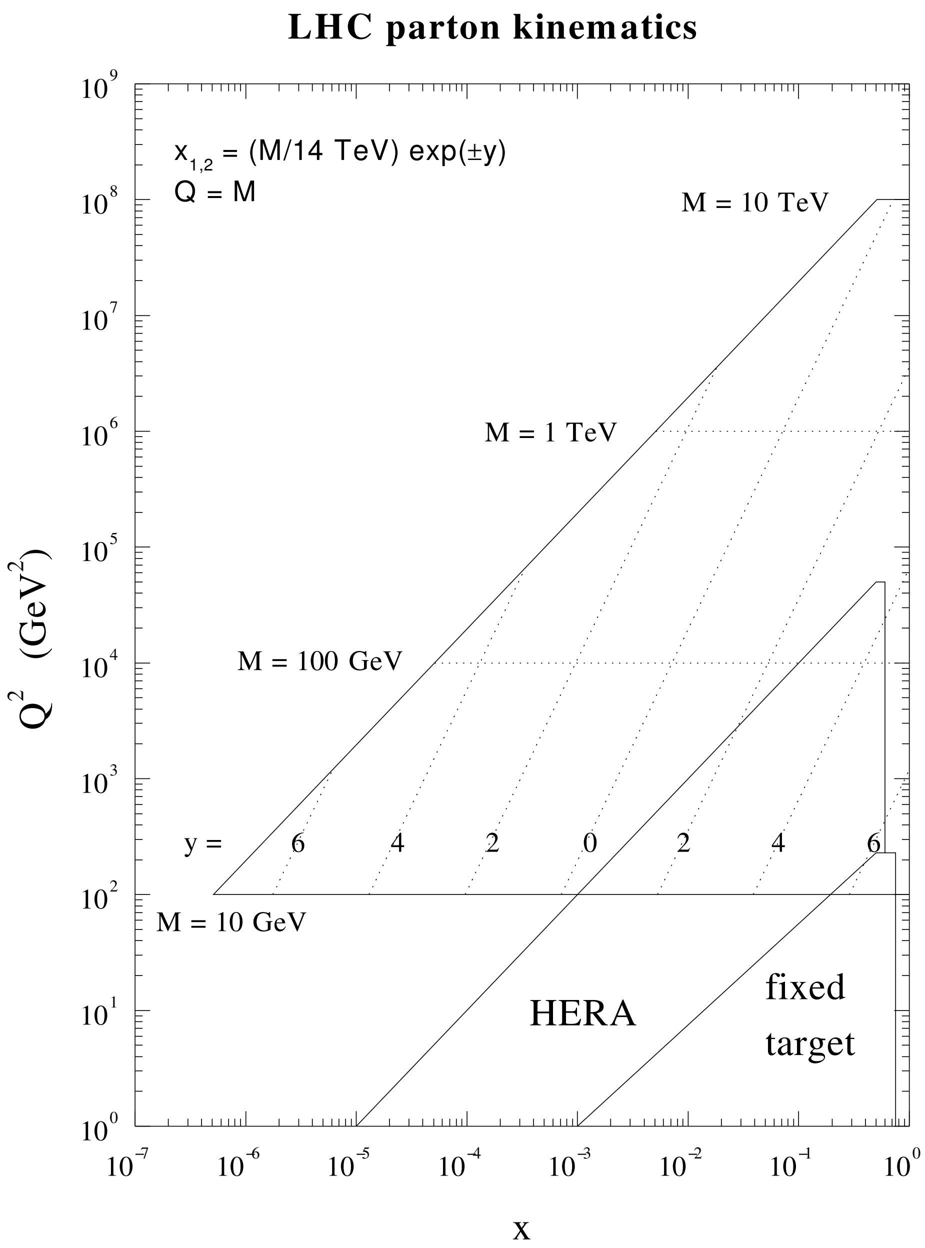
➥Bartels



What works, what does not

SMALLX 'collaboration' hep-ph/0312333	collinear factorization direct		resolved		k_t- factorization
	LO+PS	higher order NLO (dijet)	LO+PS	higher order NLO (dijet)	LO+PS
HERA observables					
DIS D* production		ok	?	?	ok
photoprod. of D*	ok	ok	ok	no	ok
DIS B production (visible)	ok	ok	—	—	ok
DIS B production (total)	no	ok	—	—	no
photoprod. of B (visible)	ok	?			ok
photoprod. of B (total)	no	no	?	?	ok
high Q^2 di-jets	?	ok	?	?	?
low Q^2 di-jets (cross sec.)	?	ok	?	no	?
low Q^2 di-jets (azim.corr.)	no	no	ok	?	ok
		NLO 3-jet no			
photoprod. of di-jets	?	ok	?	no	?
				ok	
particle spectra	no	—	ok	—	ok
energy flow	no	—	ok	—	?
HERA small-x observables					
DIS forward jet production	no	no	ok	ok	ok
DIS forward π production	no	?	ok	?	1/2
DIS J/ψ prod.	?		?	?	ok
photoprod. of J/ψ	no	ok		ok	ok
J/ψ polarization				low.stat.	low.stat.

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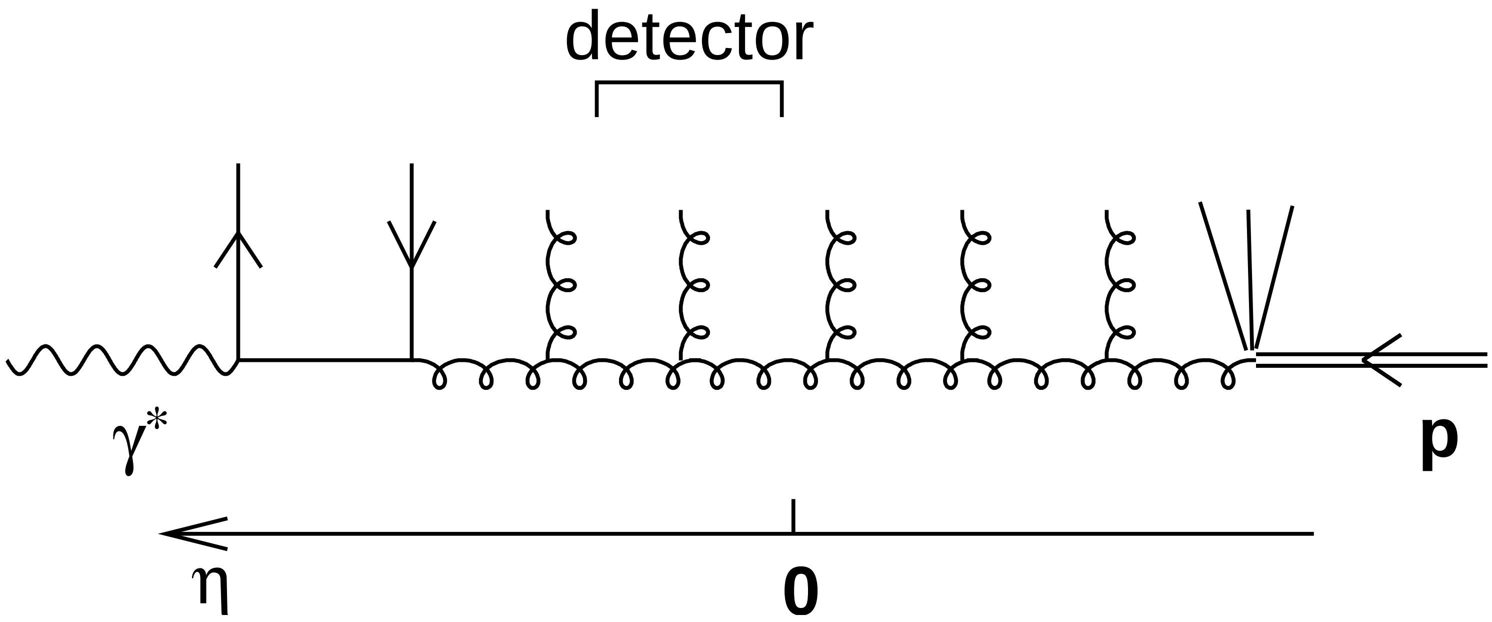
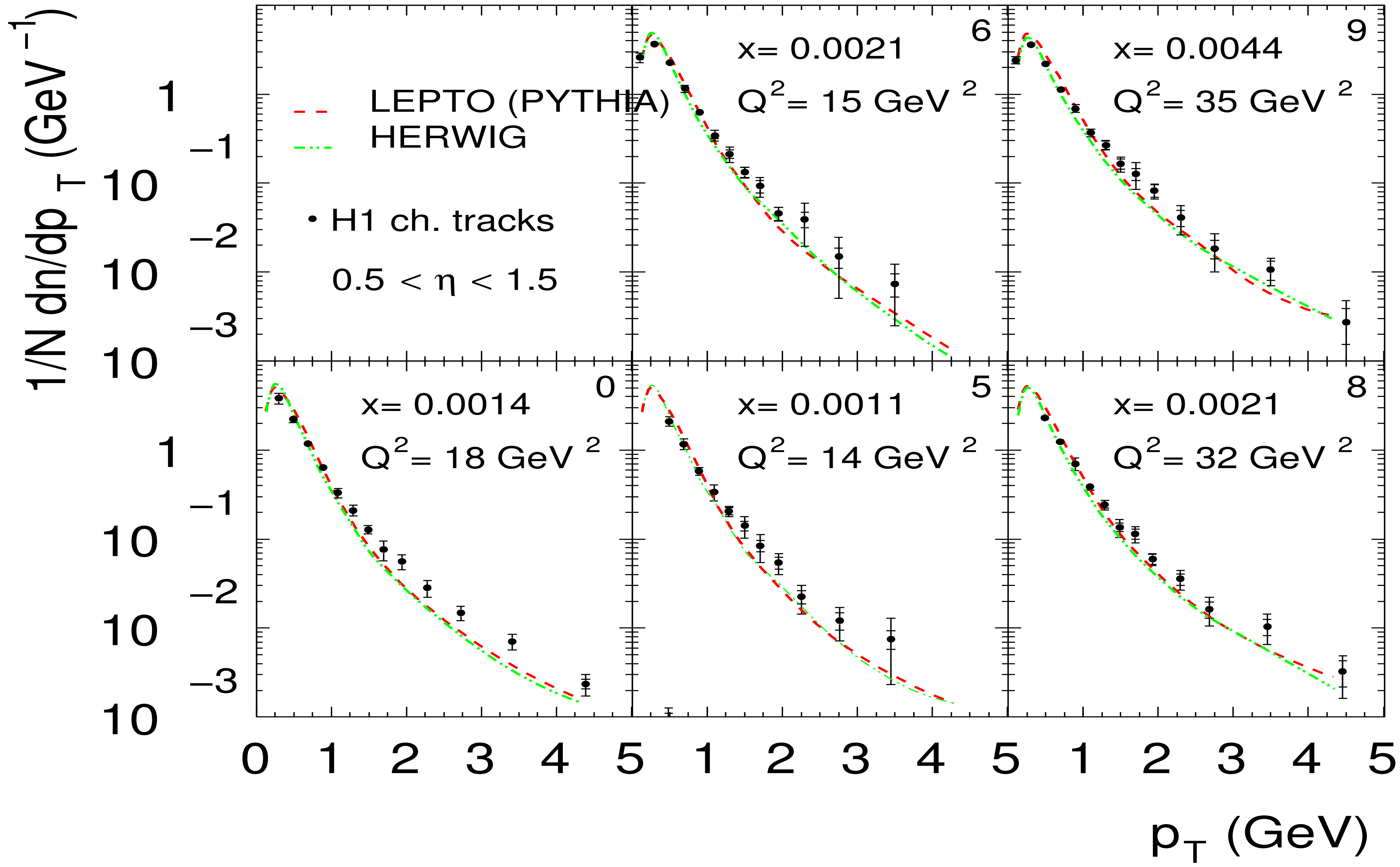
E.g.: charged-particle p_t spectra



Study charged particle spectra as a function of

- photon virtuality Q^2
- Bjorken-x
- particle rapidity

Measured spectra



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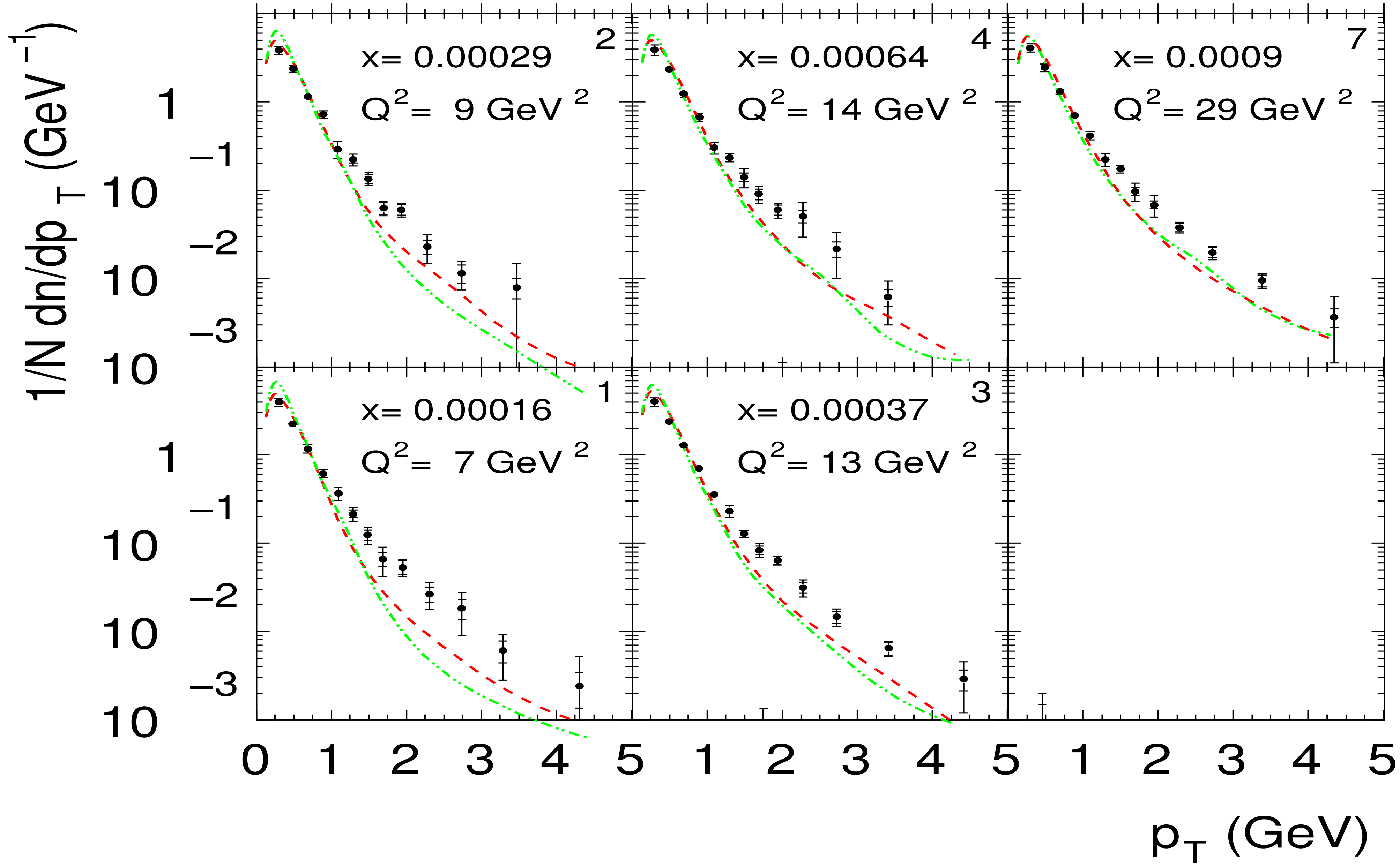

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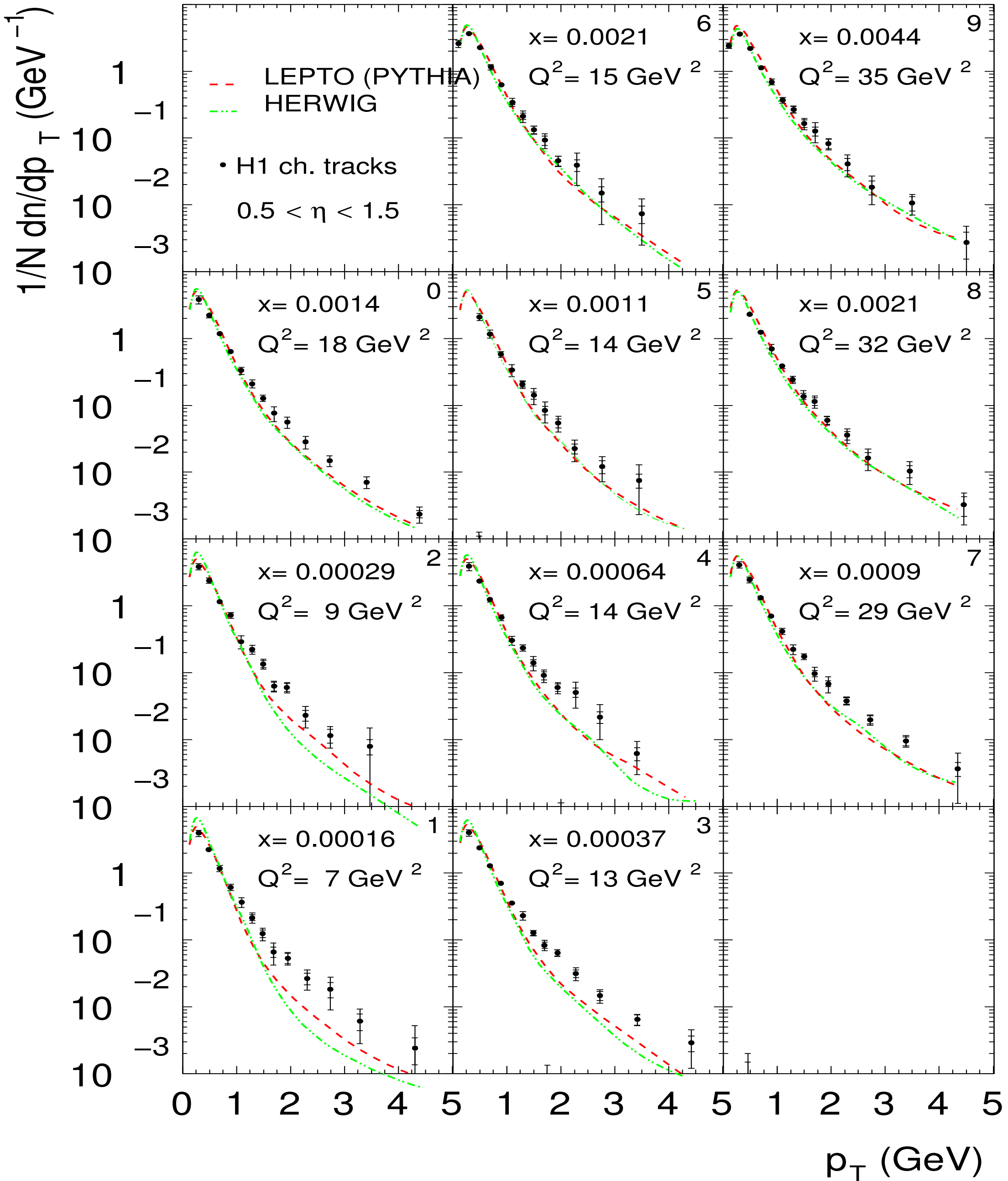

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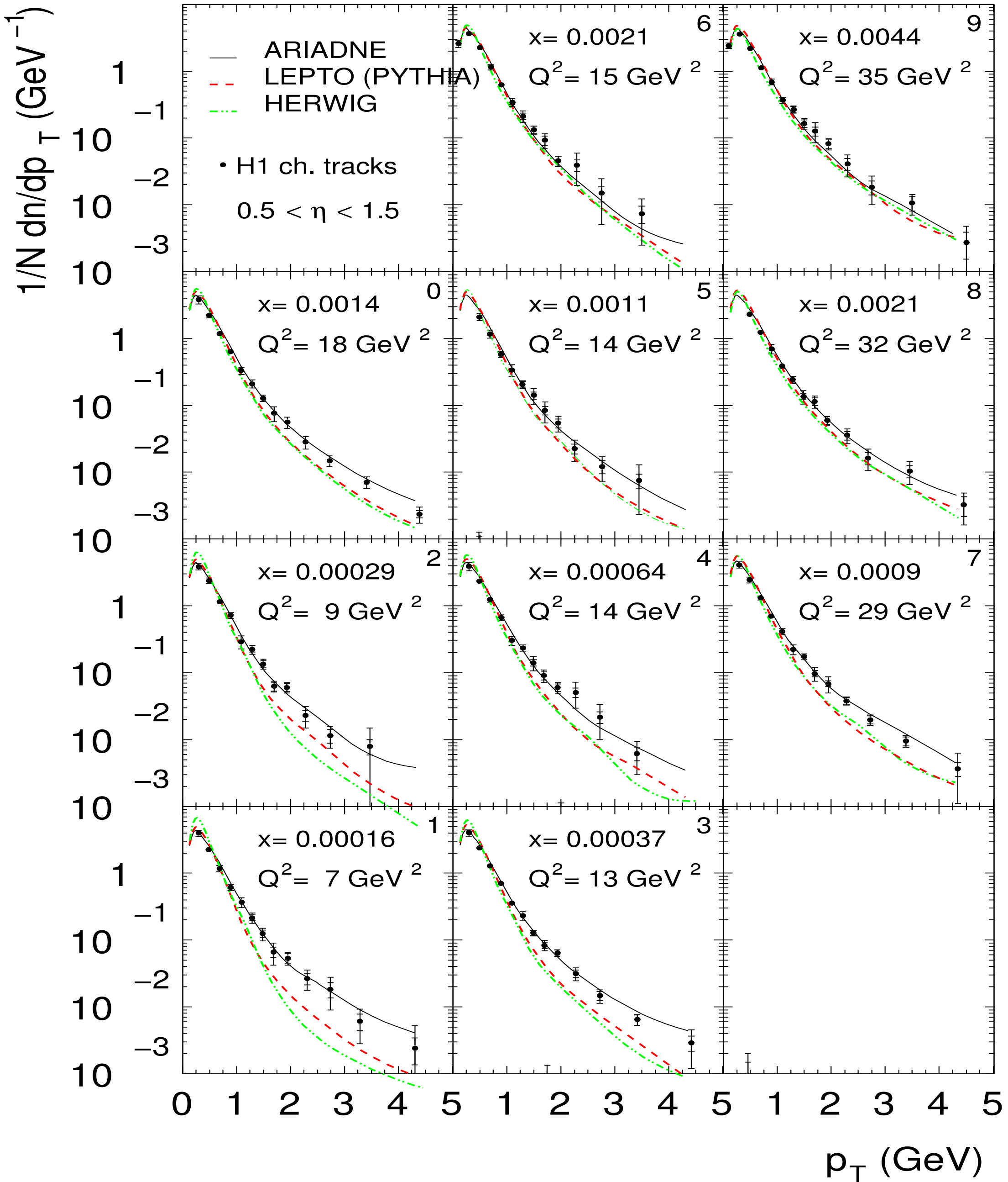

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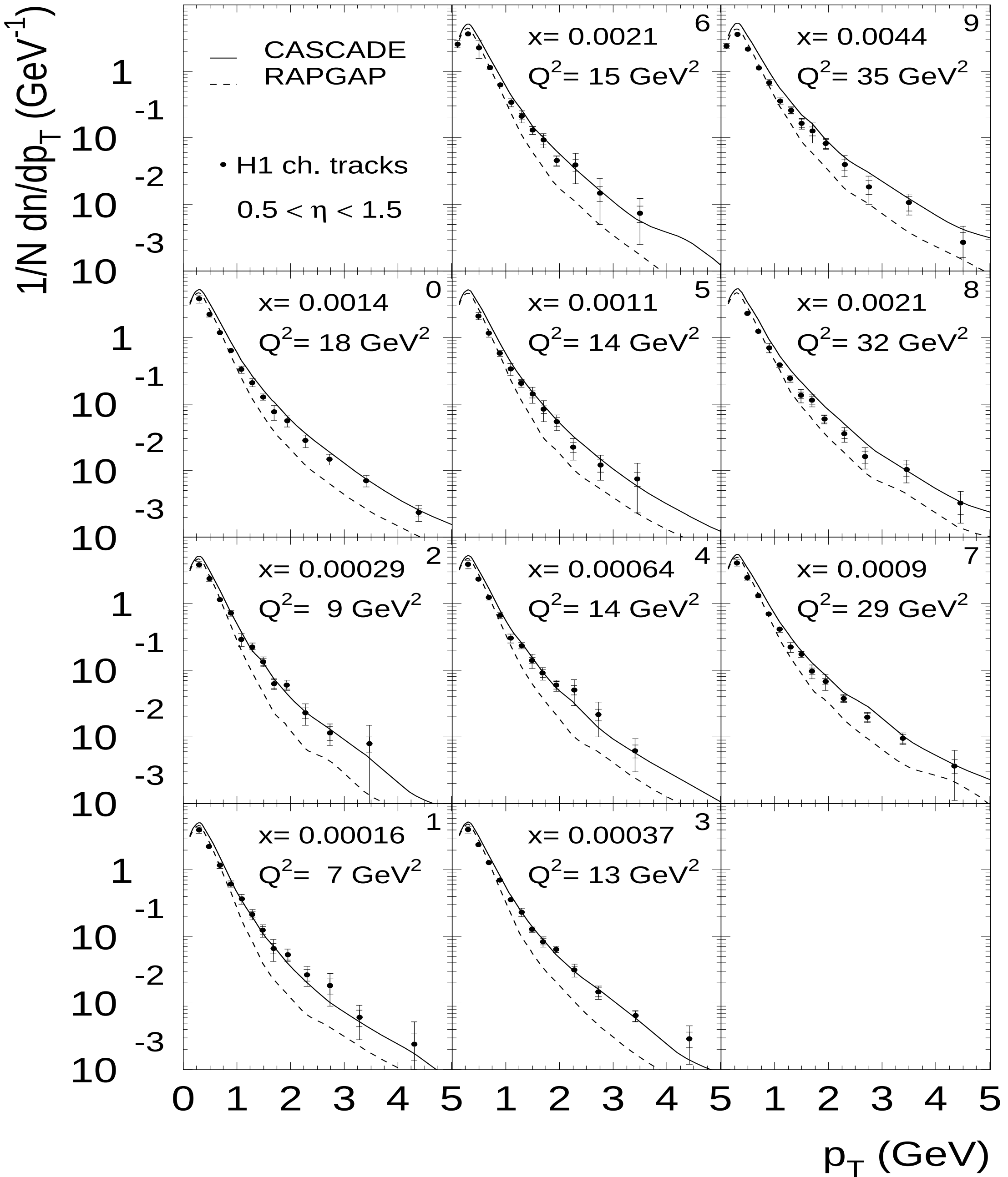

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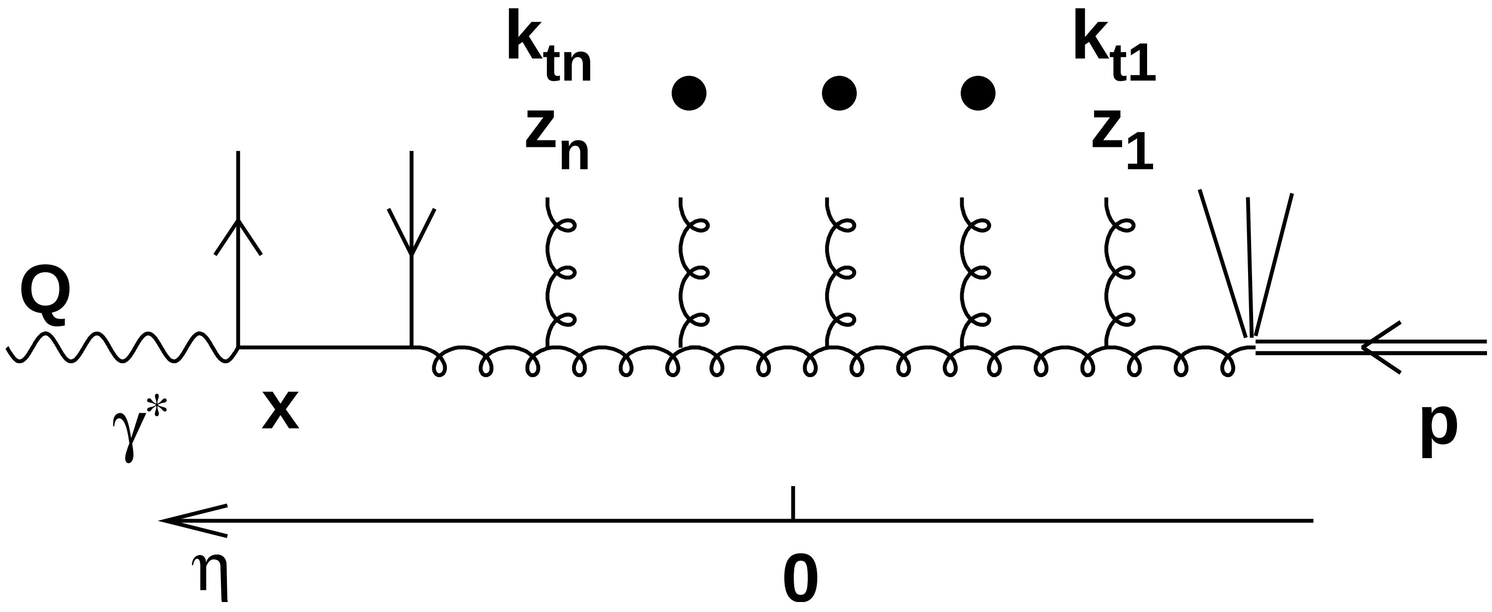
  - Theoretical interpretation unclear
- CASCADE (& LDC) does too
  - CASCADE & LDC are CCFM/BFKL based — they resum $(\alpha_s \ln x)^n$
  - Is this a sign of onset of small-x effects?

Brief recap on small-x effects (BFKL/CCFM)



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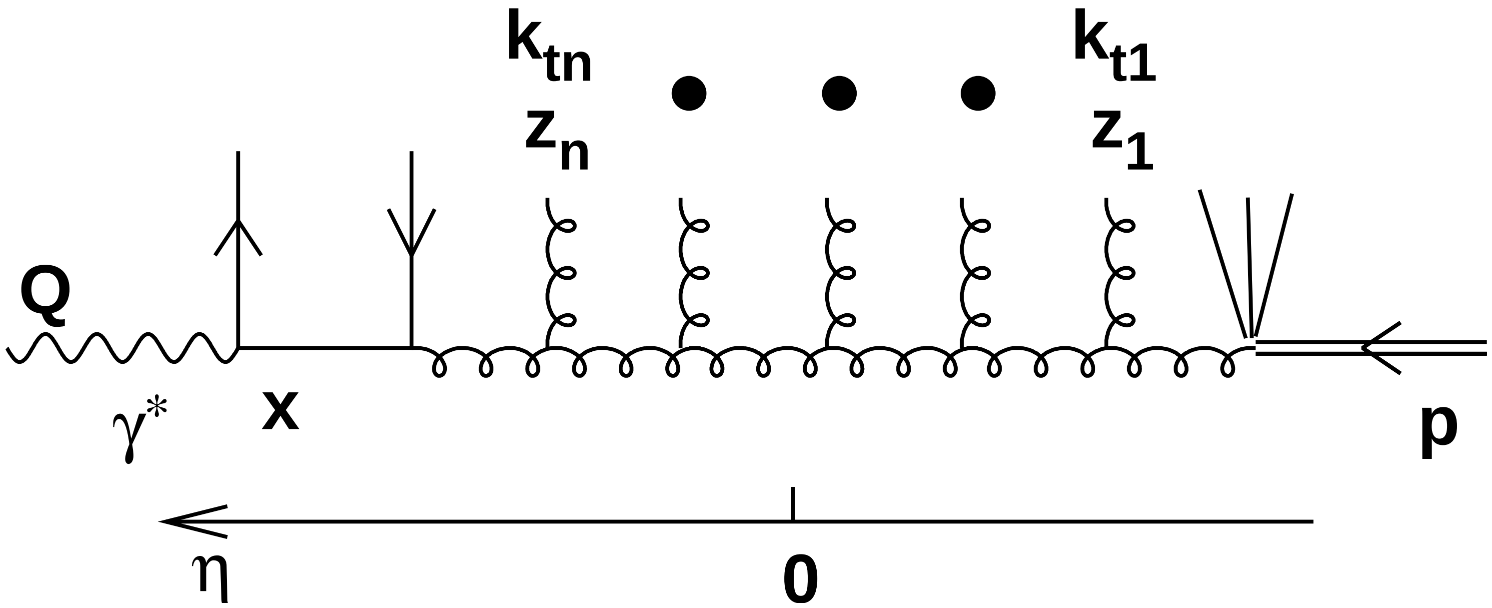

Collinear factorization

- transverse momentum ordering $Q \gg k_n \gg \cdots \gg k_1$
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- k_t unordered configs are suppressed by powers of α_s
- theoretically very well understood

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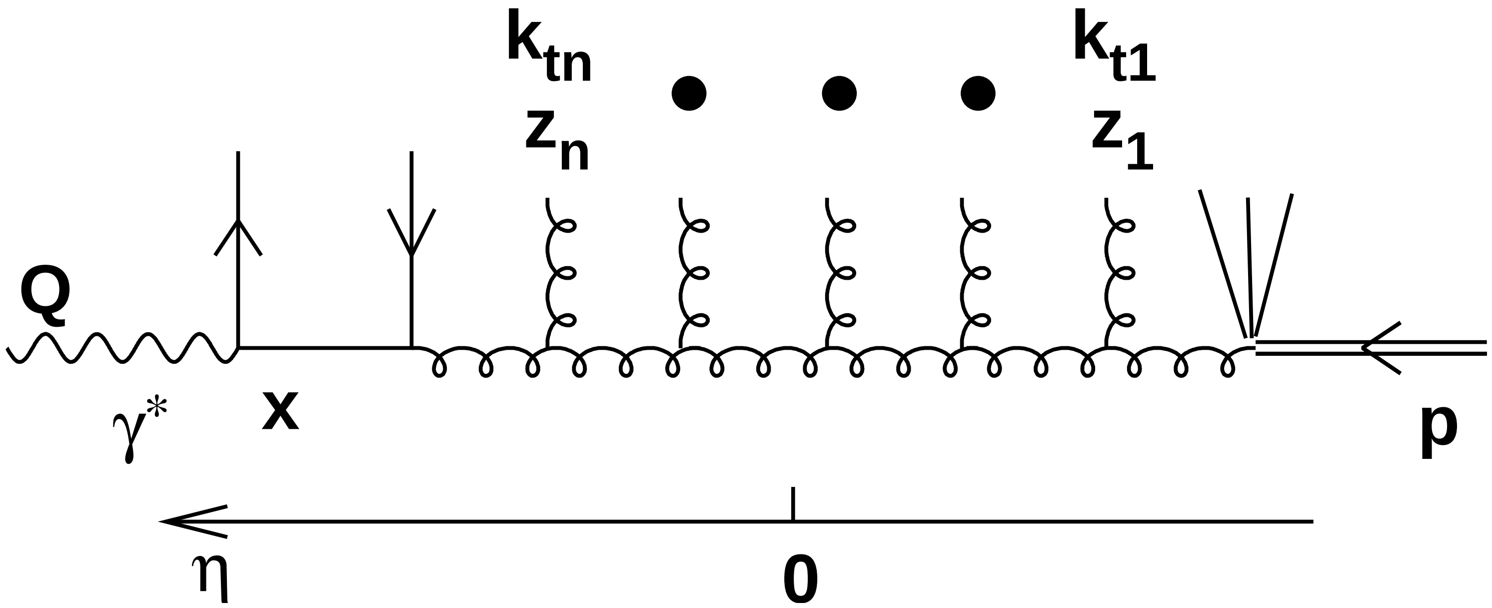

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<u>Small-x resummation</u>

- longitudinal momentum ordering $x_{Bj} \ll z_n \ll \cdots \ll z_1$
- resummation of $(\alpha_s \ln x)^n$
- k_t unordered configs *dominate*
- theory treatment is 'work in progress'

W/Z and Higgs q_T spectra

- Light Higgs and W/Z bosons are produced at moderately small $x \lesssim 10^{-2}$.
- Effective scale for PDFs in total X-section is $\sim M_{W/Z/H}$

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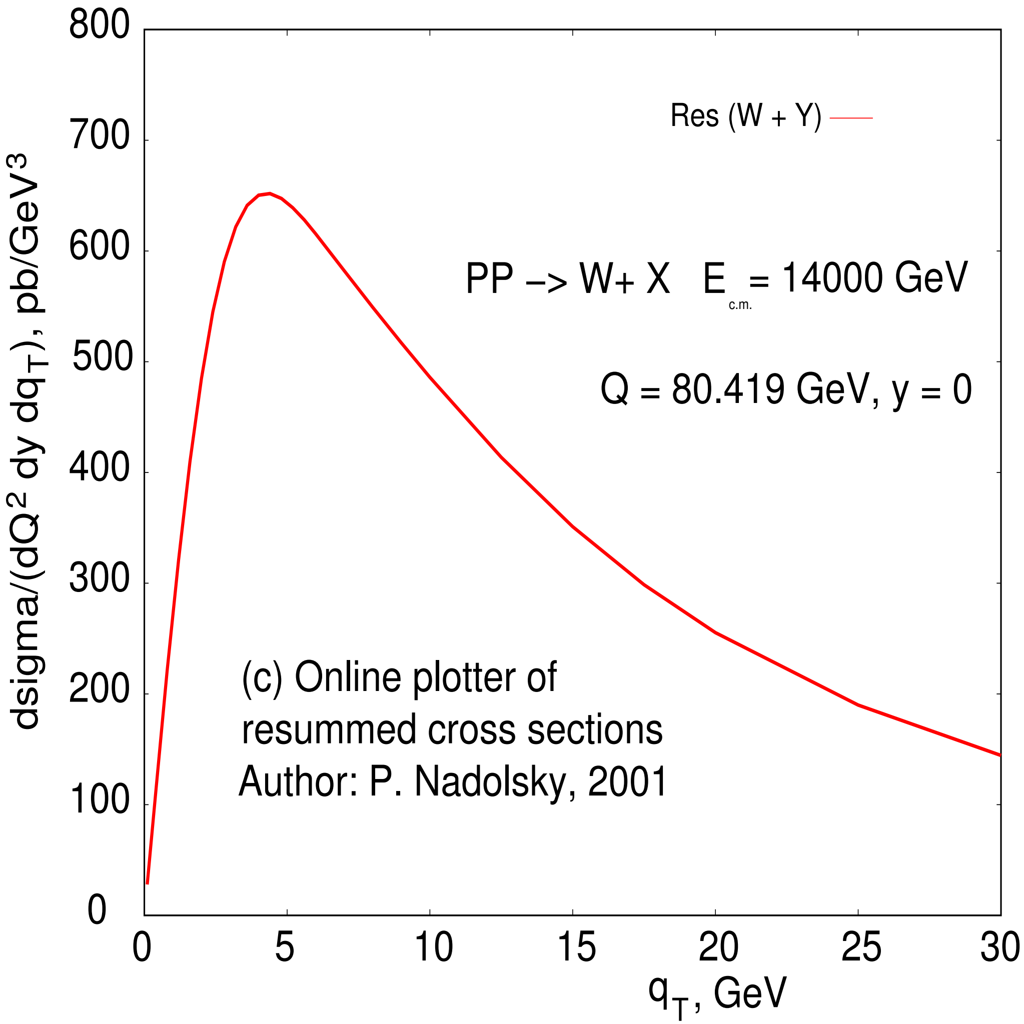
- Light Higgs and W/Z bosons are produced at moderately small $x \lesssim 10^{-2}$.
- Effective scale for PDFs in total X-section is $\sim M_{W/Z/H}$
- But q_T distribution of boson is concentrated in small(ish) q_T region
  ➥dangerous region at HERA?



Relevance of HERA 'problems' to LHC W/Z/H q_T dists.?

Not a simple issue

- Small-x discrepancy is in *tail* of particle p_t-spectrum at HERA: at $Q \sim 5\,\mathrm{GeV}$, particles with $p_t \simeq 5\,\mathrm{GeV}$ are quite rare.
- q_T of W/Z/H has origin in Sudakov logarithms, $\alpha_s \ln^2(M^2/q_T^2)$ — the $5\,\mathrm{GeV}$ peak is the *typical* transverse momentum.
- Rare small-x effects may well be swamped by Sudakov effects.

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Two existing approaches

- Apply usual Sudakov q_T resummation approach at HERA
  - extract 'extra' x-dependence
  - put it into calculations for LHC
- Apply CCFM/Cascade approach directly to LHC (only H)

Sudakov resummation at HERA?

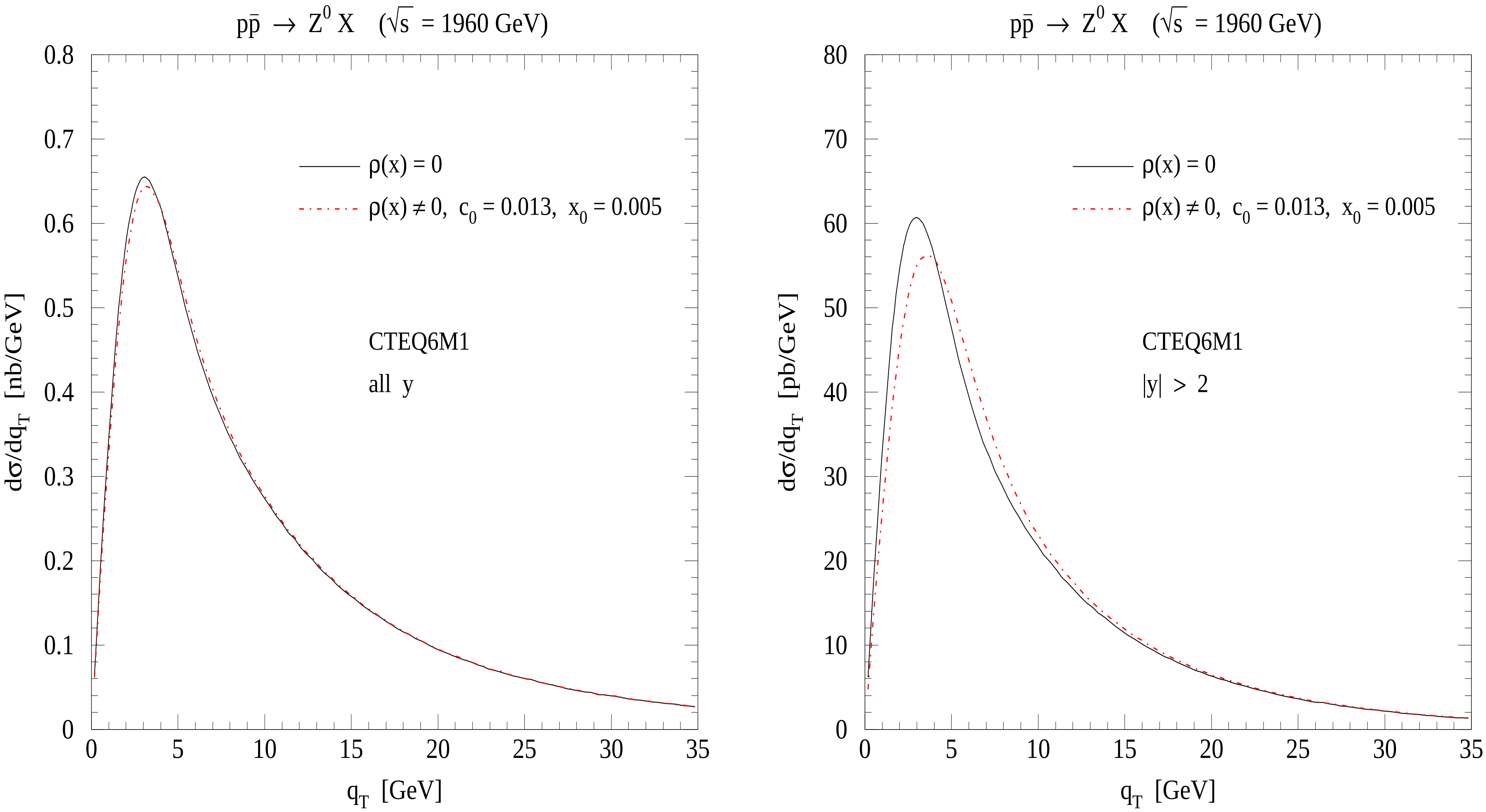
Use crossing symmetry — Meng, Olness & Soper, '95

$$h_1 h_2 \to \ell^+\ell^- + X \quad \Longleftrightarrow \quad h_1 \ell^- \to \bar{h}_2 \ell^- + X$$

- trade incoming proton for (energy-weighted sum over all) outgoing hadrons
- resum the photon relativistically invariant transverse momentum (q_T) with respect to $h_1, \bar{h}_2$.
  - q_T is closely related to h_2's rapidity, not its p_t!
- Allow for small-x effects in a 'non-perturbative' correction to Sudakov form factor
  - found, phenomenologically, to grow rapidly with decreasing $x \lesssim 10^{-2}$

Nadolsky, Stump, Yuan, '00

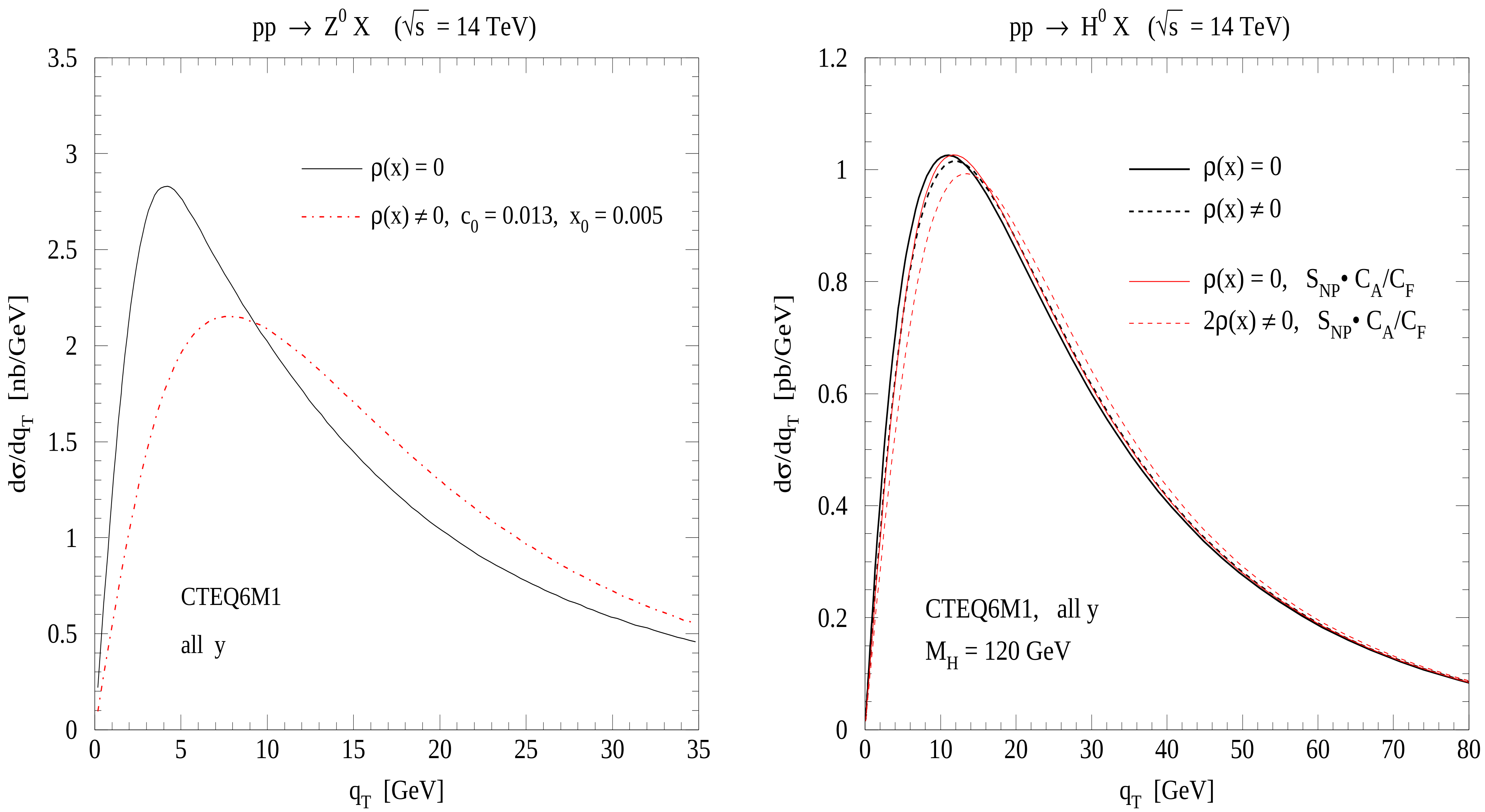
Apply fitted small-x effects to Tevatron



Small but measurable effect for forward Z^0 production

Berge et al '04

Works at Tevatron? Apply to LHC...



Big effect for Z^0; almost negligible for Higgs

Berge et al '04

What about small-x predictions?

- Recent study using CCFM-based CASCADE

  NB: CCFM is like BFKL
  - resums leading logs of $1/x$
  - but with correct Sudakov double logs
  - consistent merging of $z \to 0$ and $z \to 1$ effects
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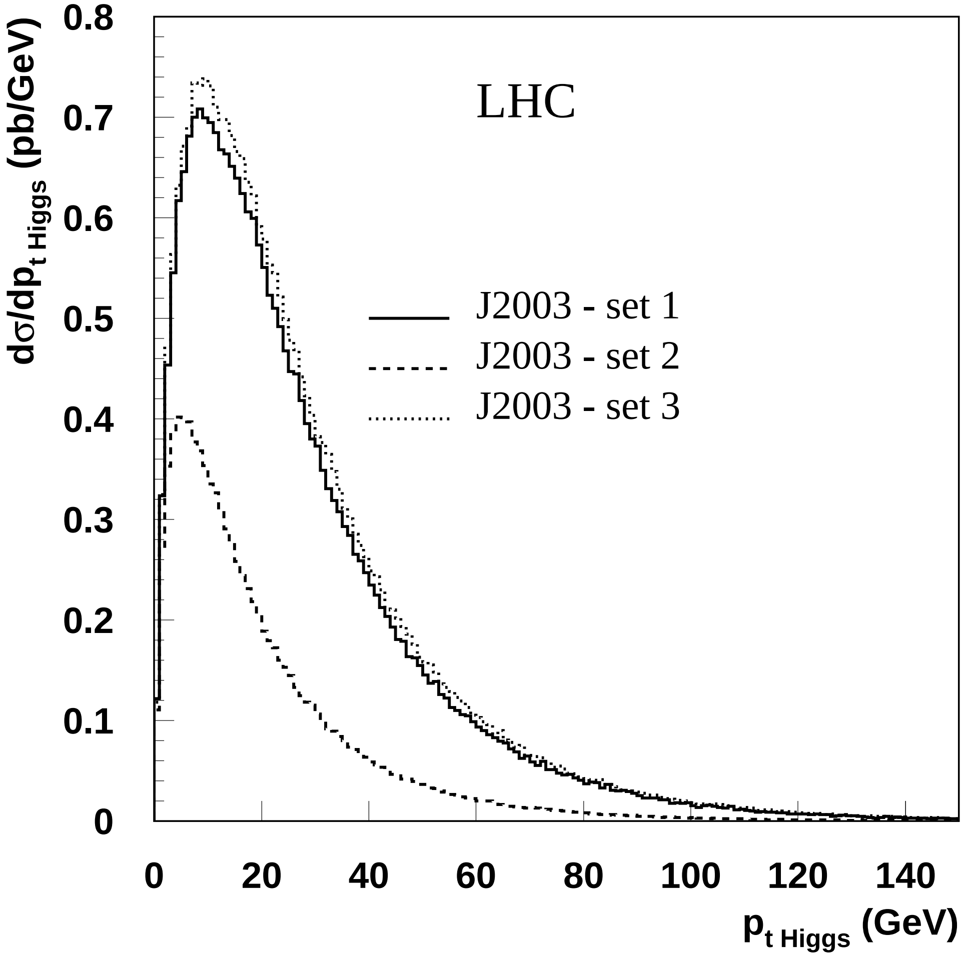

Jung '03

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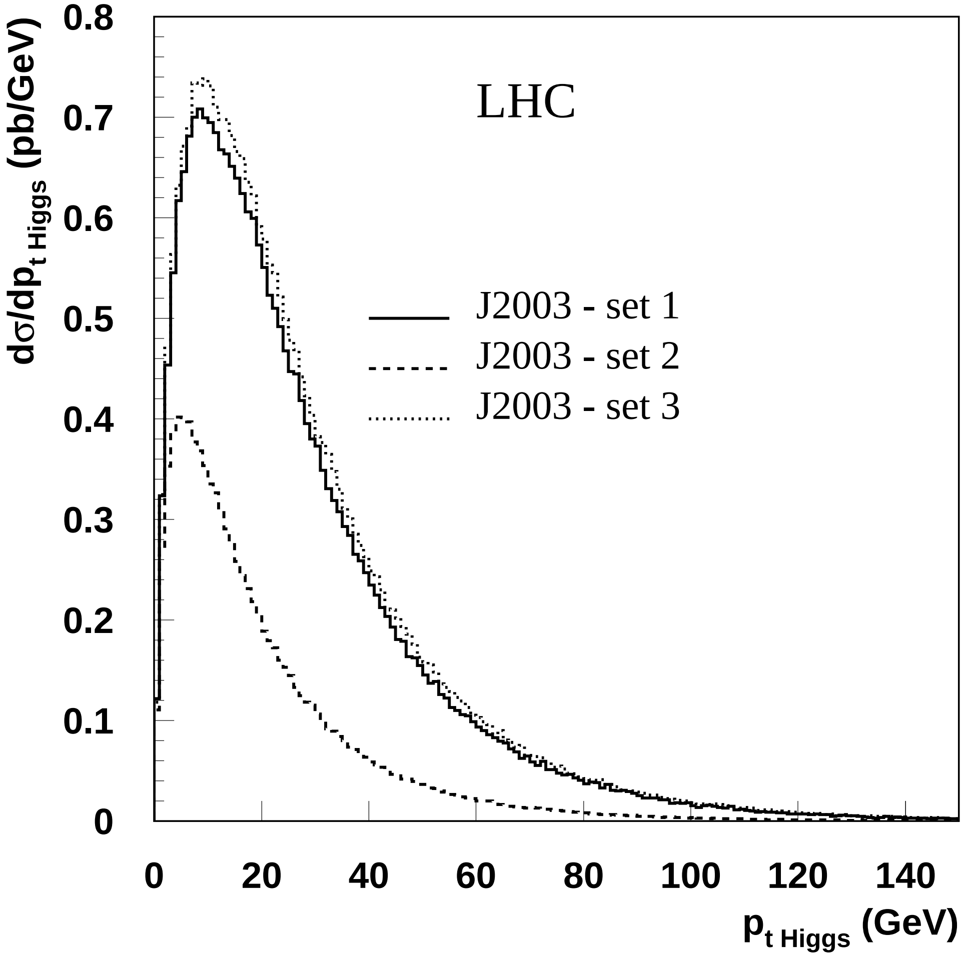
  - quark induced processes are trickier, so W/Z difficult for now. . .



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Degree of reliability of these predictions?

Both have 'issues'. . .

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- Parametrization of 'non-perturbative' small-x effects rises very steeply $\sim 1/x$ — unnatural theoretically?

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- This could matter: Higgs production involves scales up to m_t.
- tested in limited kinematical domain

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Ways forward?

New HERA measurements?

- distribution of $\sum_{i \in \text{current}} \vec{p}_{ti}$
- less sensitive to hadronisation
- more complicated perturbatively

Better theory?

- Put quarks into CCFM (hard!?)
- Learn how to how incorporate small-x resummation analytically in the Sudakov resummation

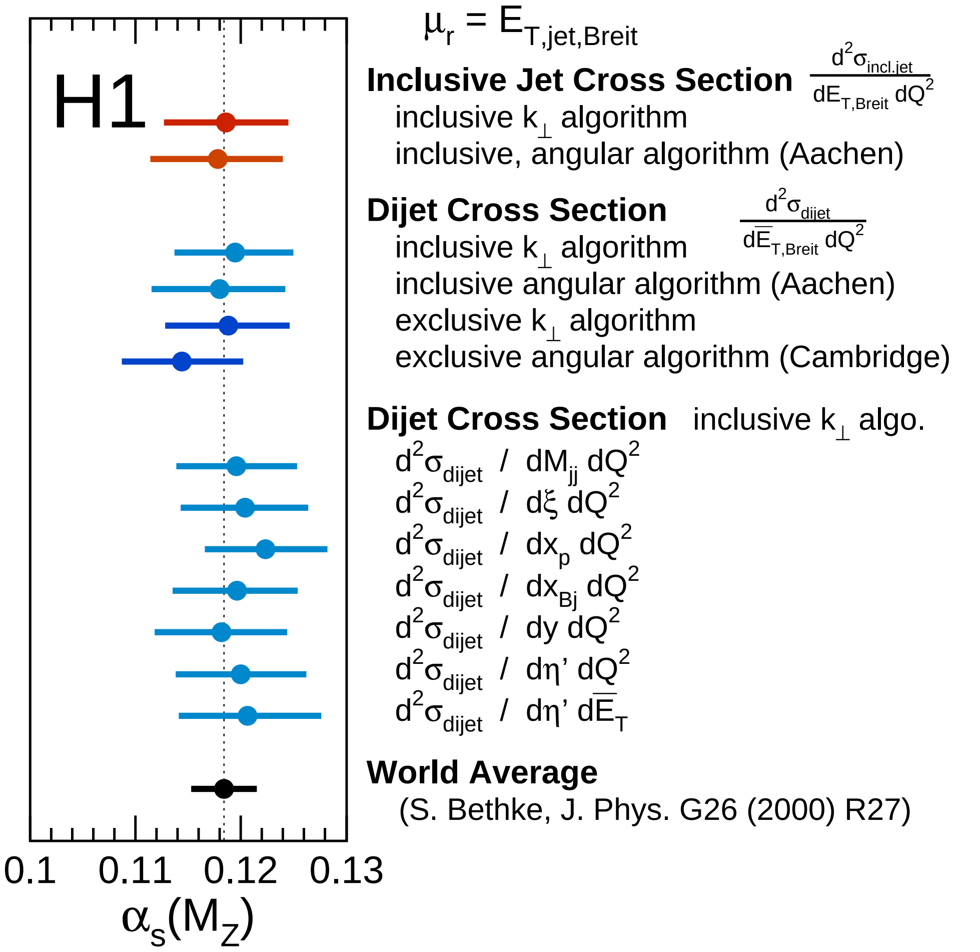
Jets at moderate & high(ish) Q, E_T

Jets are (next) most basic element of QCD final-state studies

Amazing array of results from HERA

- Measurements of the coupling
- Measurements of the gluon density
- Tests of multi-jet structure in QCD

α_s from jet production in DIS



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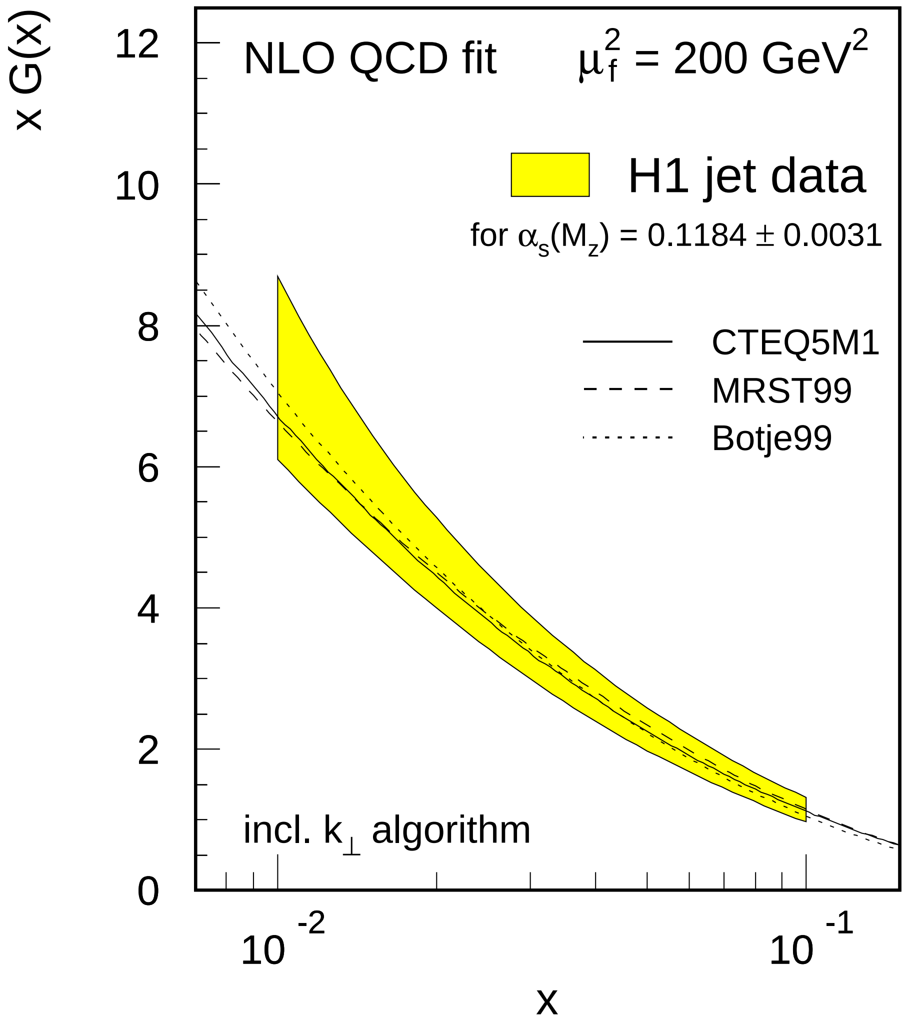

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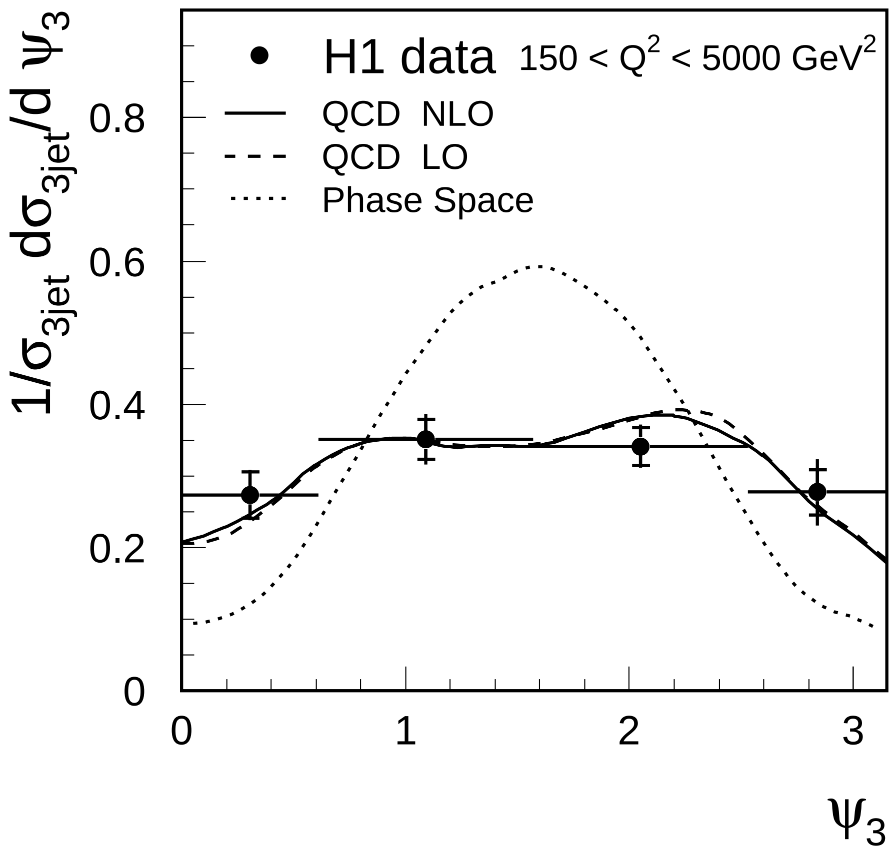

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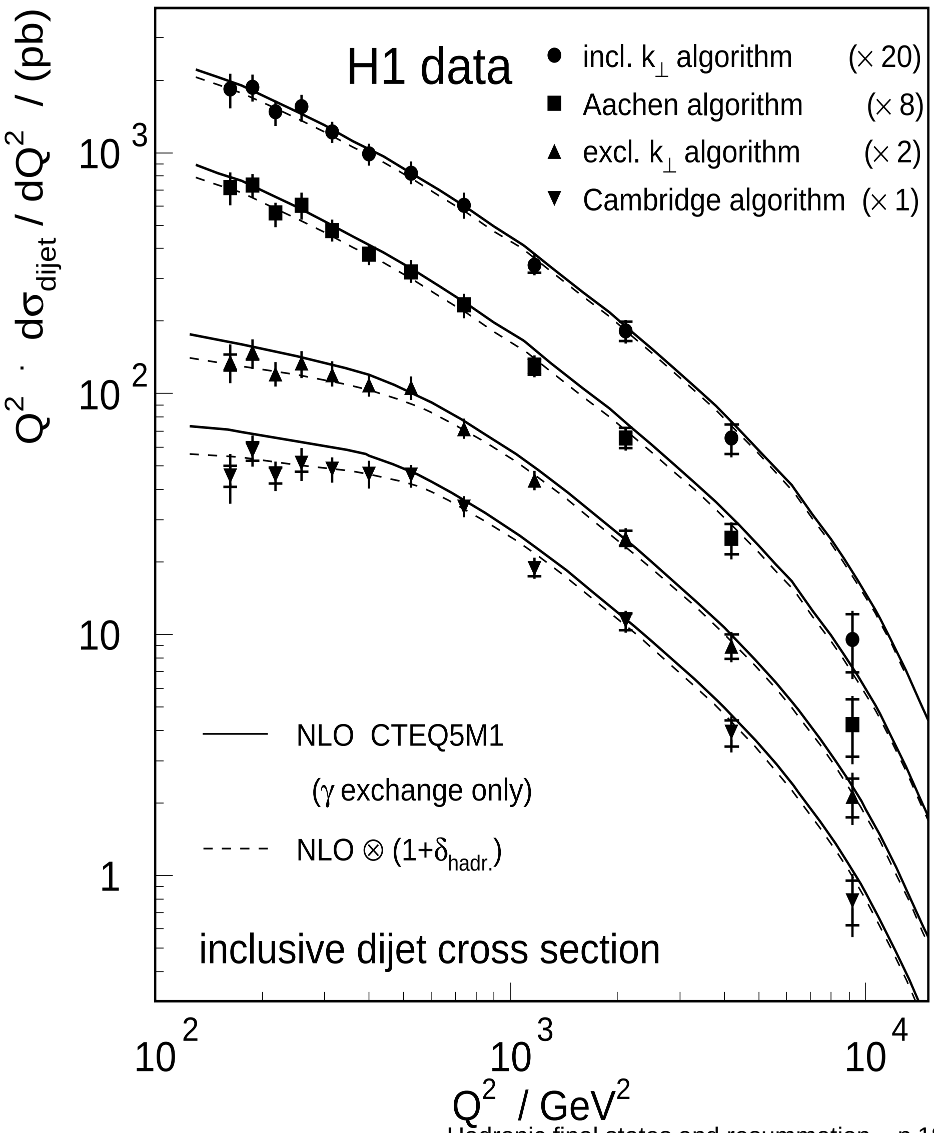
A theorist's litany: the k_t algorithm

- HERA is a convert!
- LHC seems not to be (yet. . .)
  - Algorithm of choice is cone with R=0.4(?)
  - Advantage: simple; intuitive. A 'standard' for searches



Can k_t provide concrete advantages? HERA experience?

A role of the workshop should be to investigate such questions

Jet algorithms are not just about finding jets of particles

- Connect experimental observations (hadrons) with QCD calculations (partons)
- Connect a shower of particles with intuitive picture of a single hard parton
- Should provide a handle on the ambiguity in making such connections – a meaningful *resolution parameter*
  - This is a strength of the k_t clustering algorithms
  - Construction of a jet $\sim$ inverse of QCD showering
  - At finer resolutions, jet is broken into subjets, each of which maintains intuitive connection with a QCD parton

Can k_t provide concrete advantages? HERA experience?

A role of the workshop should be to investigate such questions

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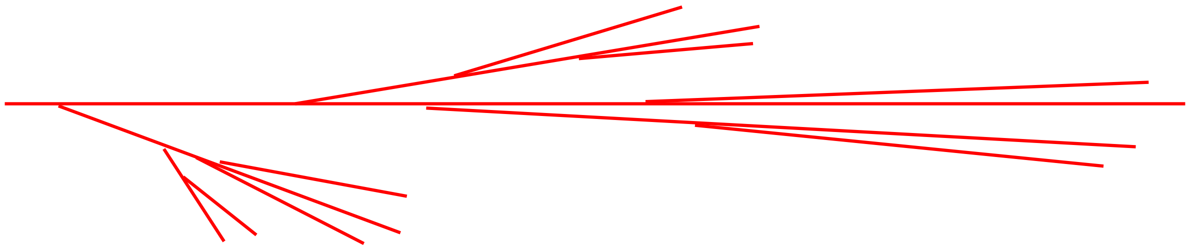

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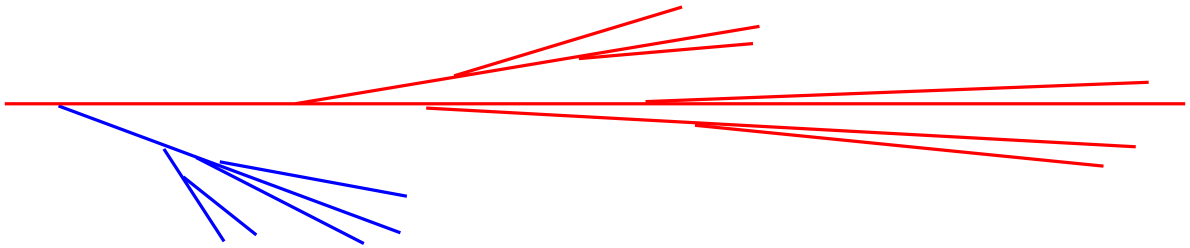

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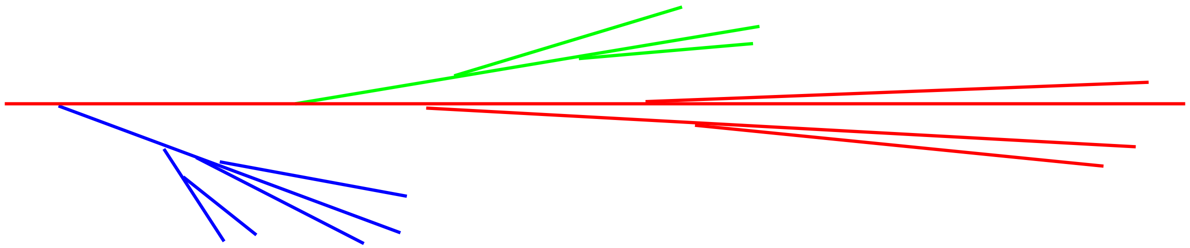

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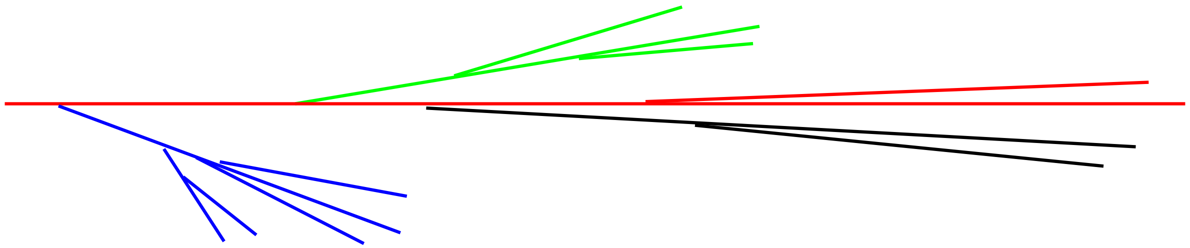


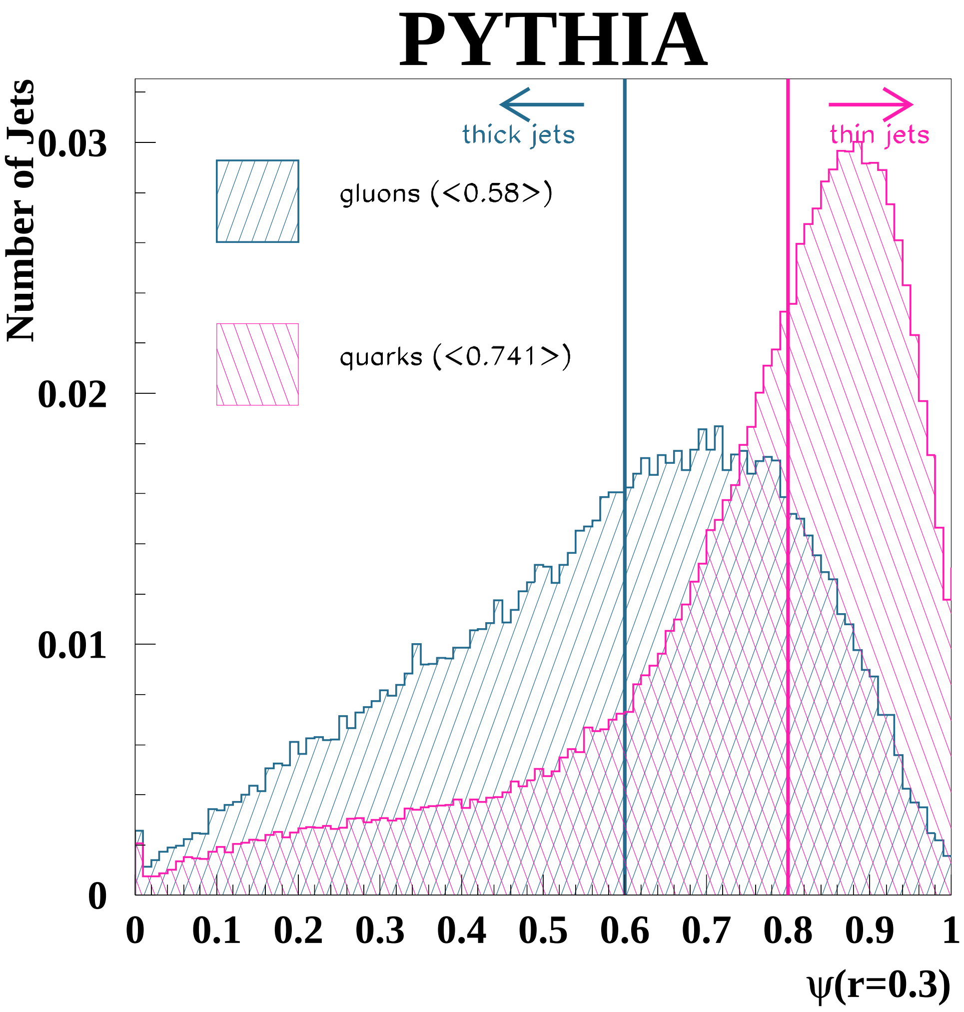
Distinguishing quark and gluon jets

ZEUS study of theory predictions

Dokshitzer et al '92, Seymour '94, '96

Forshaw & Seymour '98

- Gluons give wider jets



Distribution of $\Psi(r) \equiv$ fraction of jet energy inside radius r.

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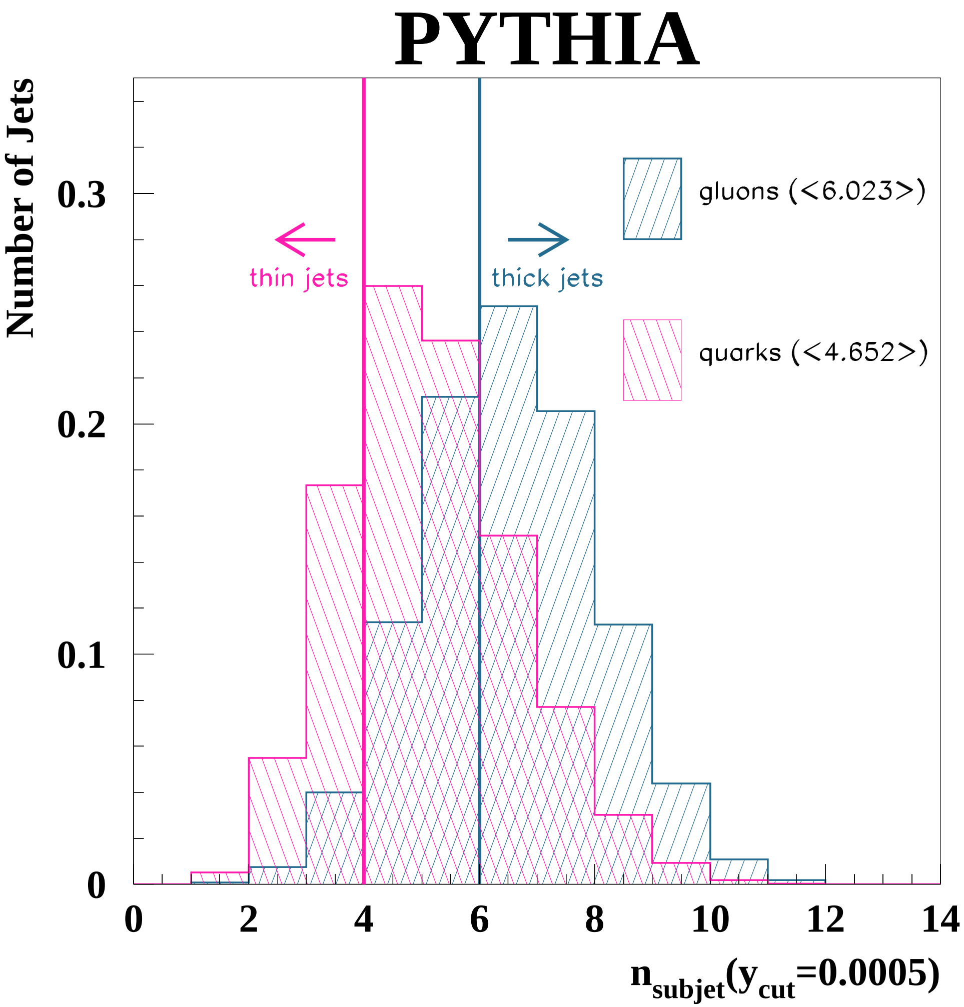

Distribution of # of subjets for a small resolution parameter $y_{\rm cut}$.

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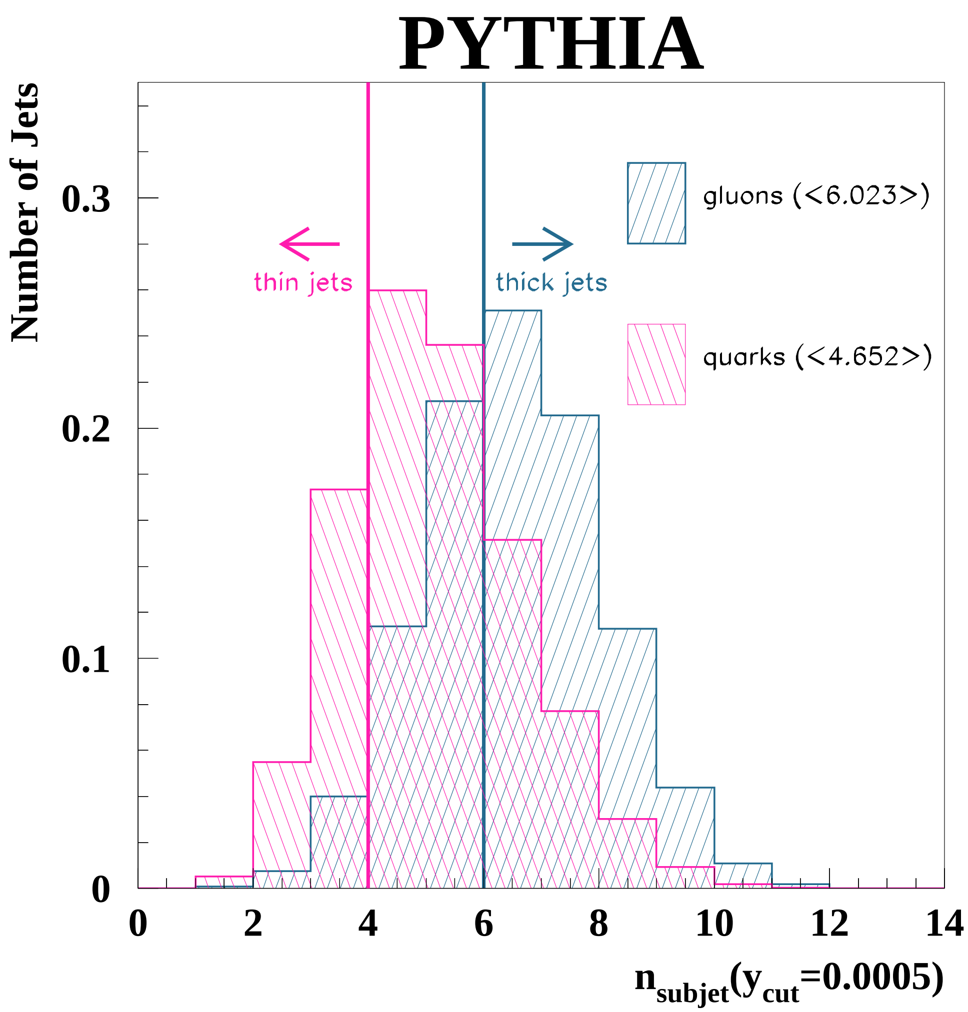
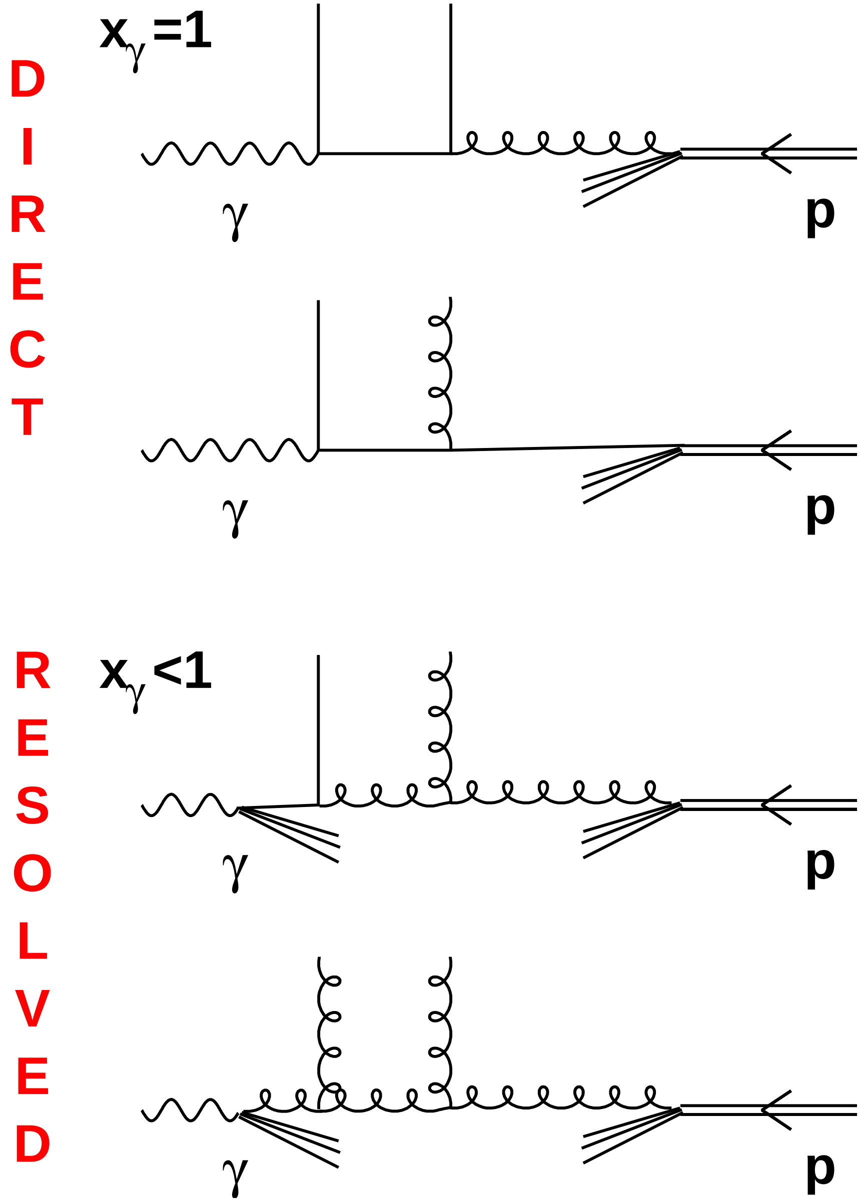
Select gluon and quark jets

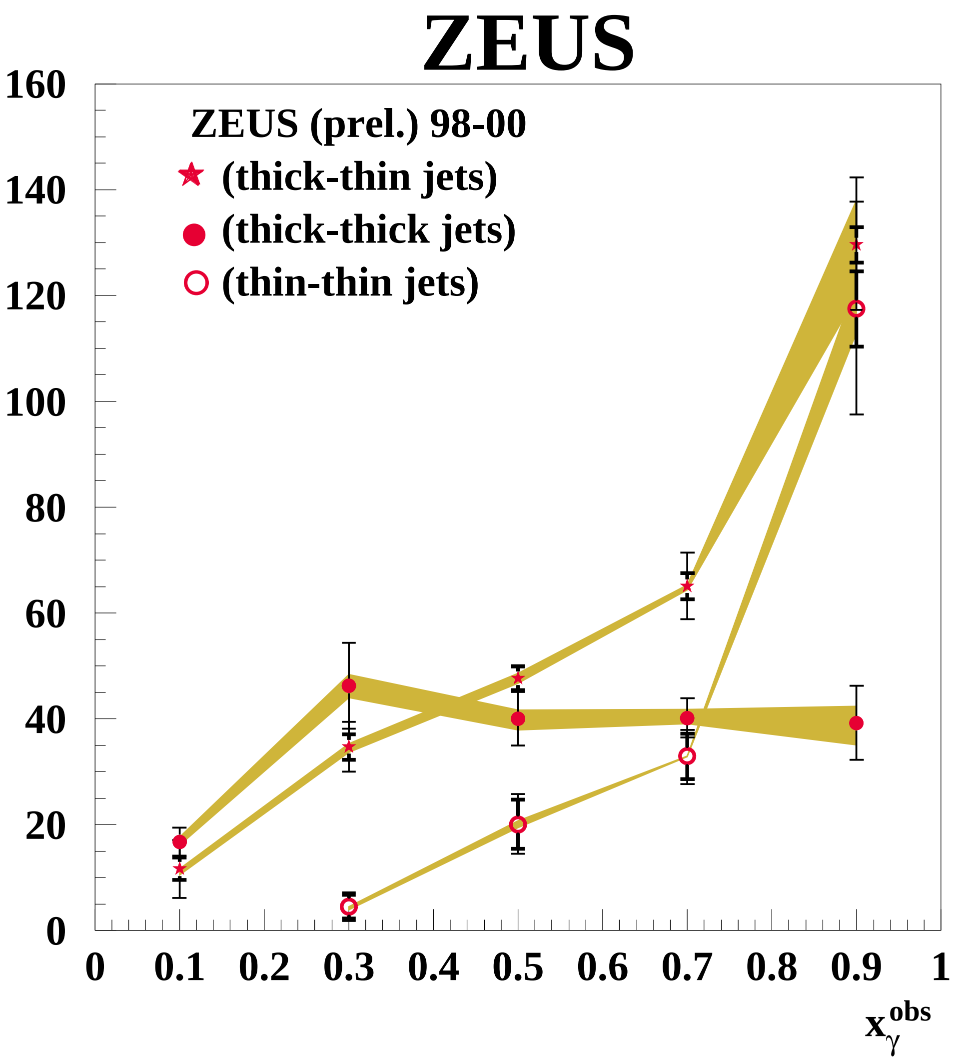
- Combine criteria to identify thin (quark) jets and thick (gluon) jets
  - 98% (61%) purity for quarks (gluons)
  - 15% (?) efficiency



Distribution of # of subjets for a small resolution parameter y_{cut}.

Distinguishing quark and gluon jets: application

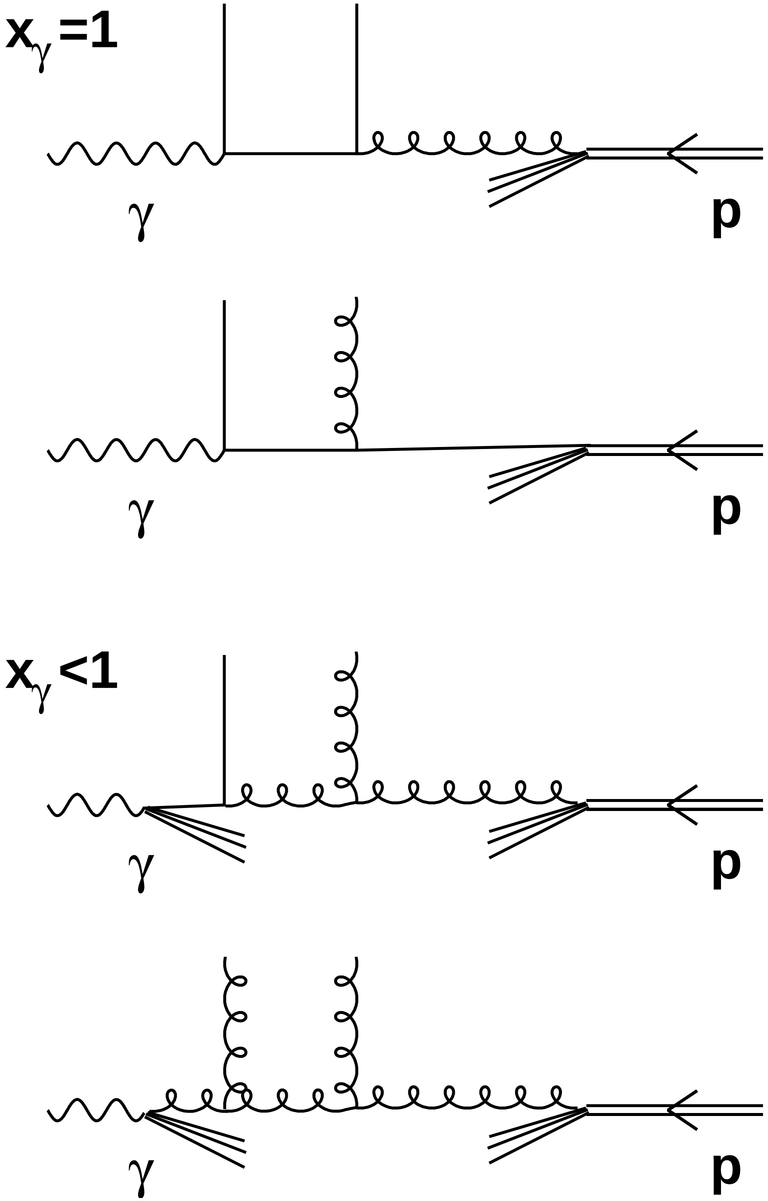


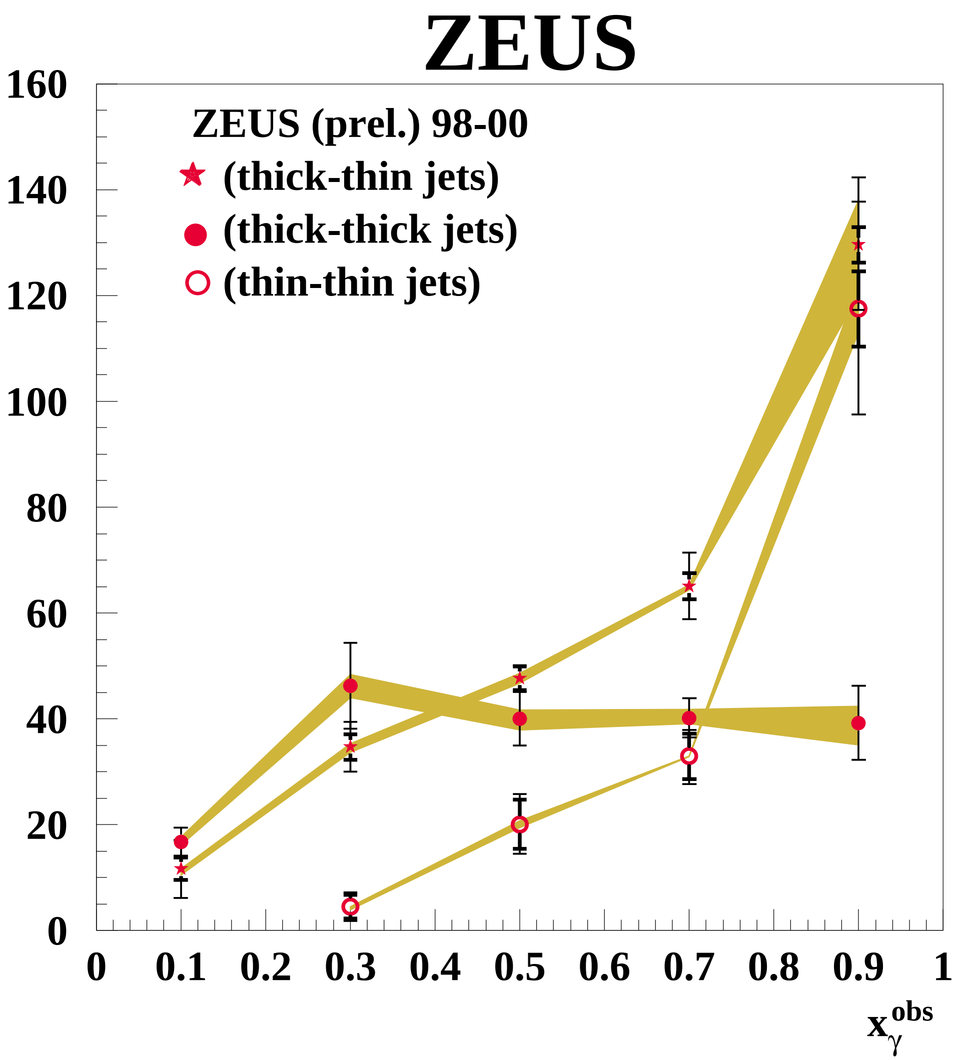


Distinguishing quark and gluon jets: application

DIRECT

RESOLVED





Can selection/efficiency be improved?
How might this be applied at LHC?

So many other topics. . .

Hard QCD

- Further (mis)uses of jet algorithms;
- Event shapes — in e^+e^- & DIS, a laboratory for QCD across a range of scales — how about at LHC?
- Diffraction!
- Rapidity gaps: 'Sudakov' QCD rapidity gaps v. true rapidity gaps. Perturbative gap survival. Non-perturbative gap survival.

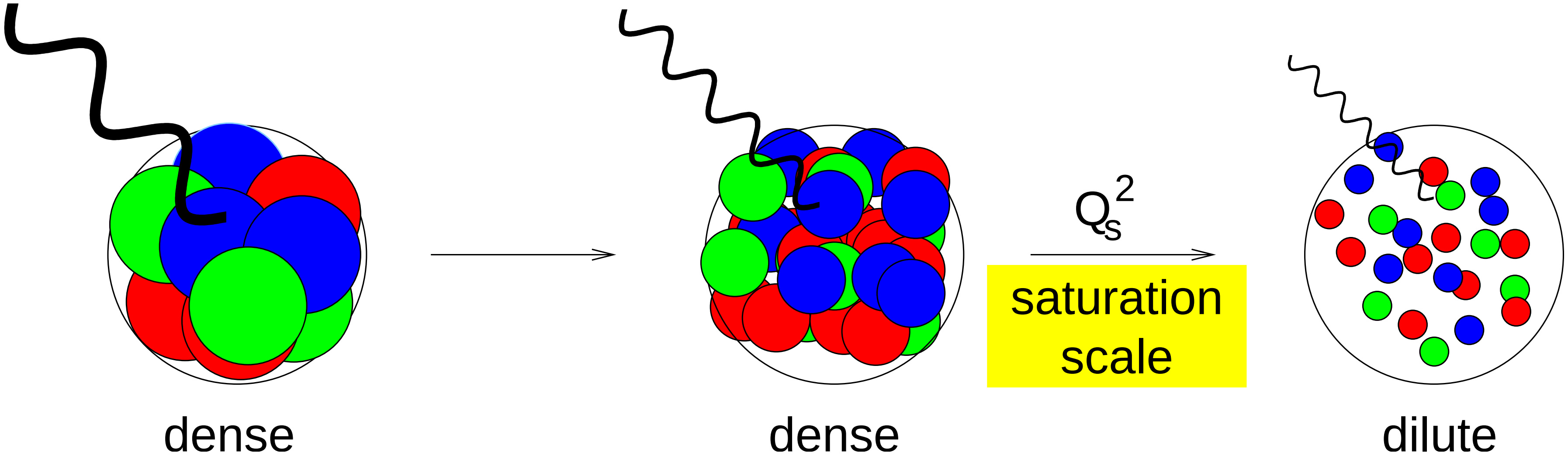
Moderately hard QCD

- BFKL for its own sake!

Softer QCD

- Underlying events, similarities between γp and pp?
- Minimum bias; ways of measuring it; models; connection with saturation;

Extra time: Saturation scales



Below saturation scale: *dense system of gluons* ($\rho \sim 1/\alpha_s$)

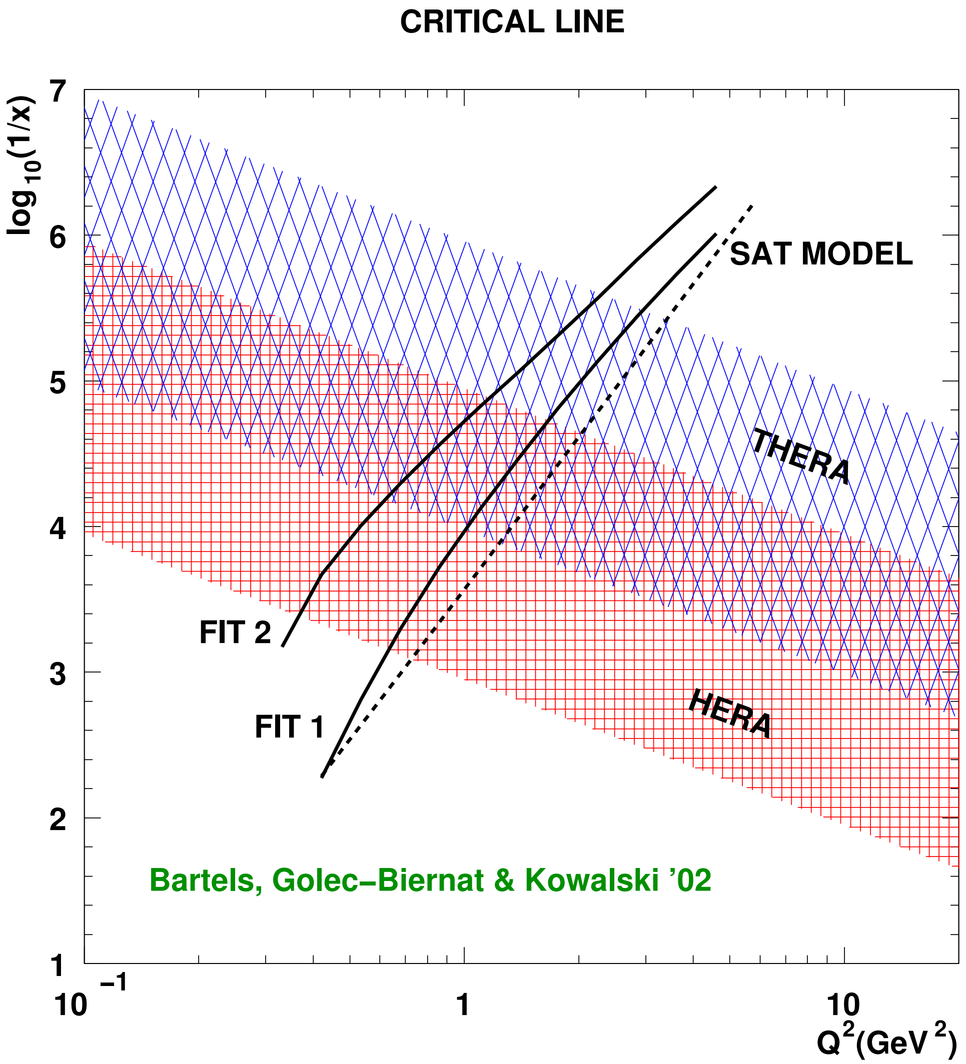
Above saturation scale: *dilute system of gluons* ($\rho \ll 1/\alpha_s$)

Saturation scales (cont.)

Big business at HERA

- Models including saturation are fitted to HERA data
- Saturation sets in (perhaps?) just at limit of perturbative region
- Rises with decreasing x

What's the connection with final states?



Saturation scales (cont.)

Back of the envelope: Tevatron? LHC?

- Typical transverse momentum in minimum bias is Q_s^2
- Convert from DIS using

$$x \sim \frac{Q_s^2(x)}{s}$$

- LHC minimum bias $k_T \simeq 2\times$ Tevatron minimum bias?
- Very rough? *But beware: transverse momentum/collision could rise much faster than the cross section*