QCD tests through hadronic final-state measurements

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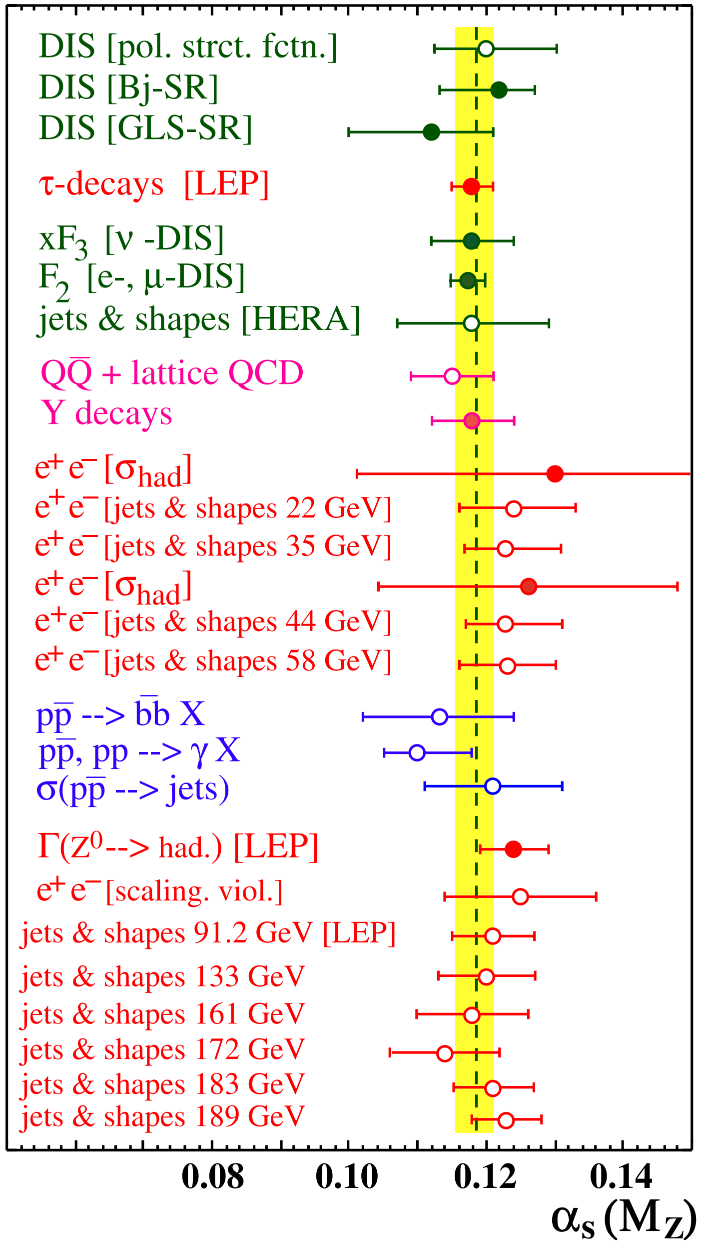
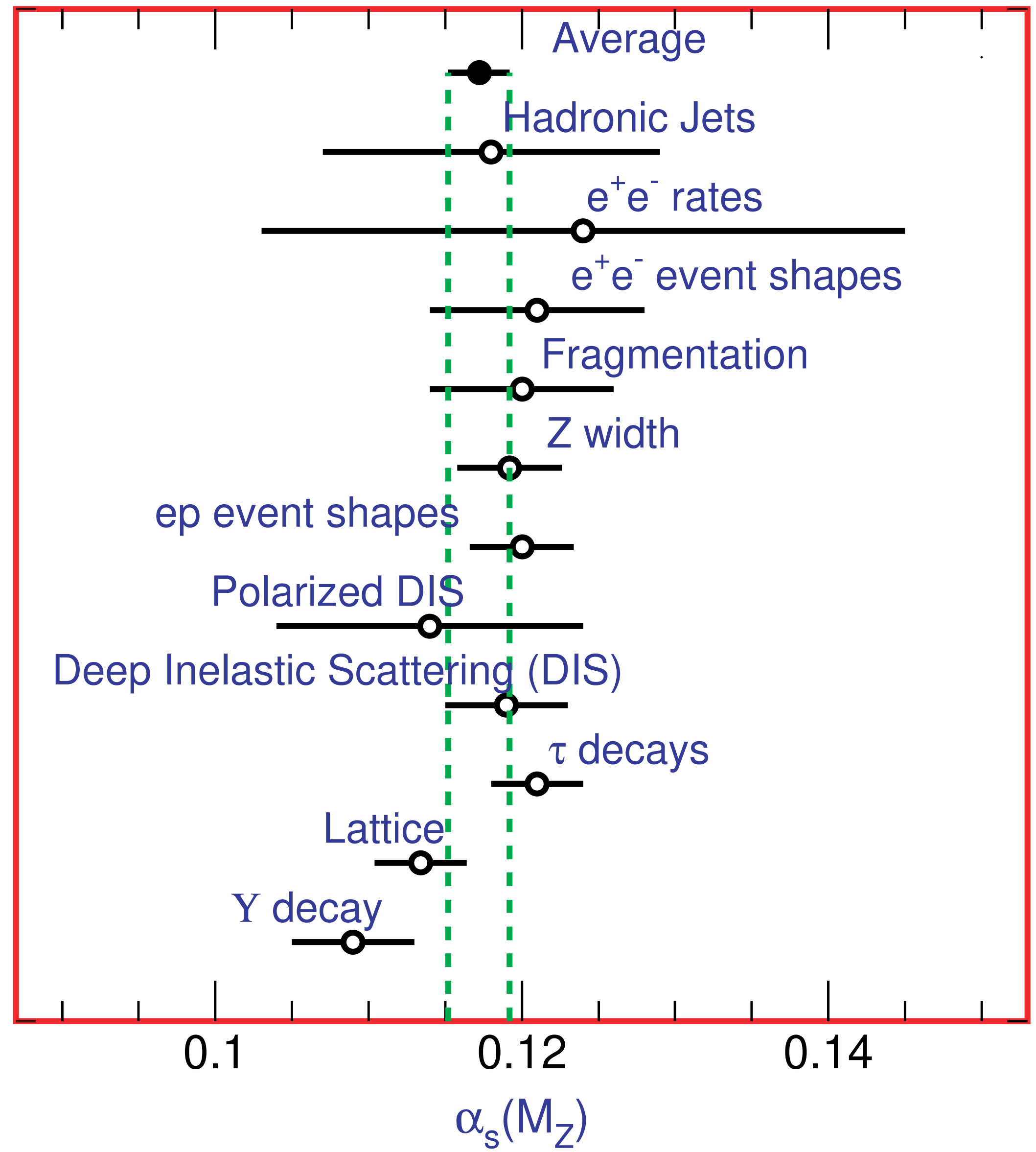
LPTHE — CNRS & Paris Univ VI & VII

DIS 2002, 30 April 2002

$\mathcal{The}$ test

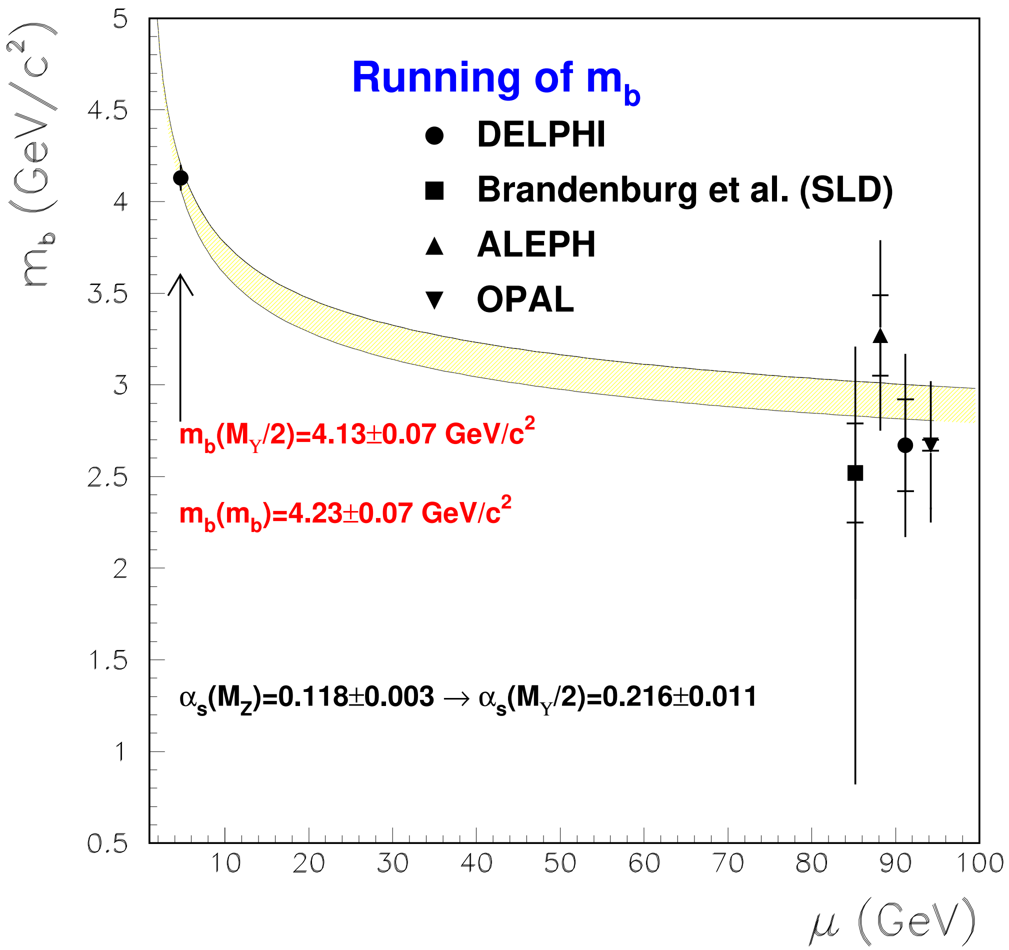


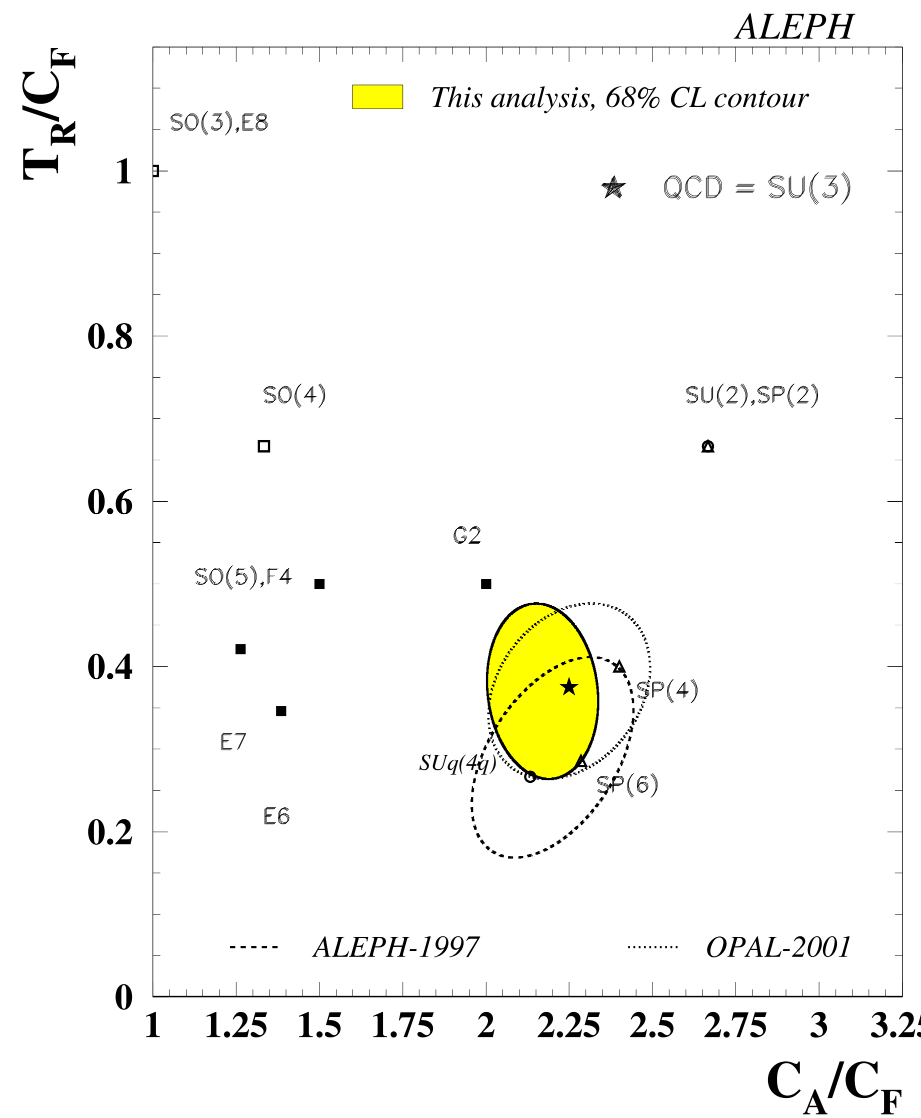
Bethke hep-ex/0004021



PDG

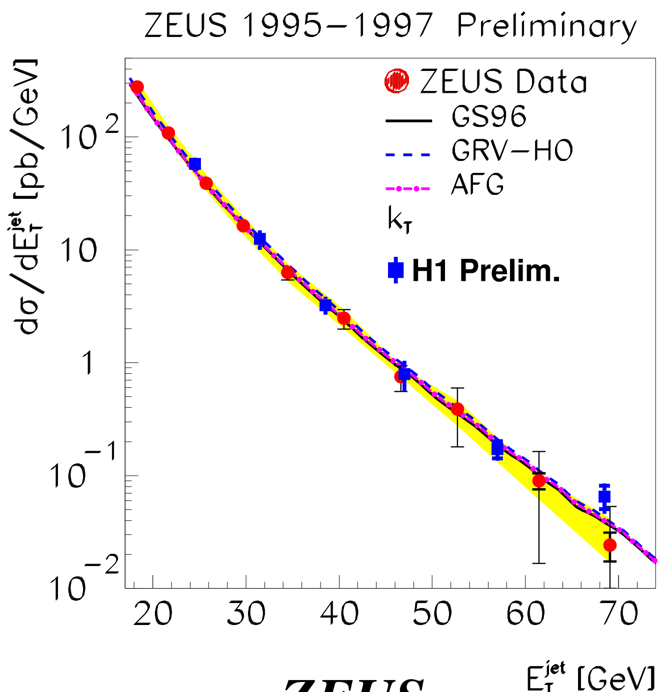
More detailed tests

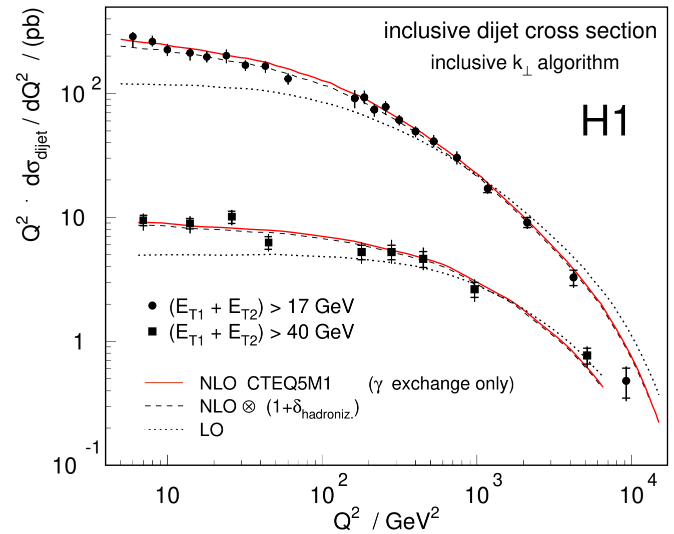


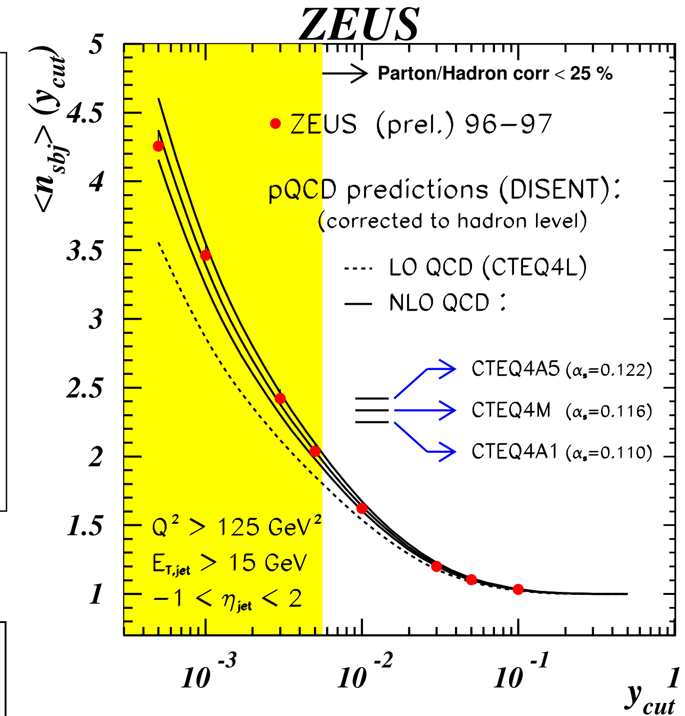


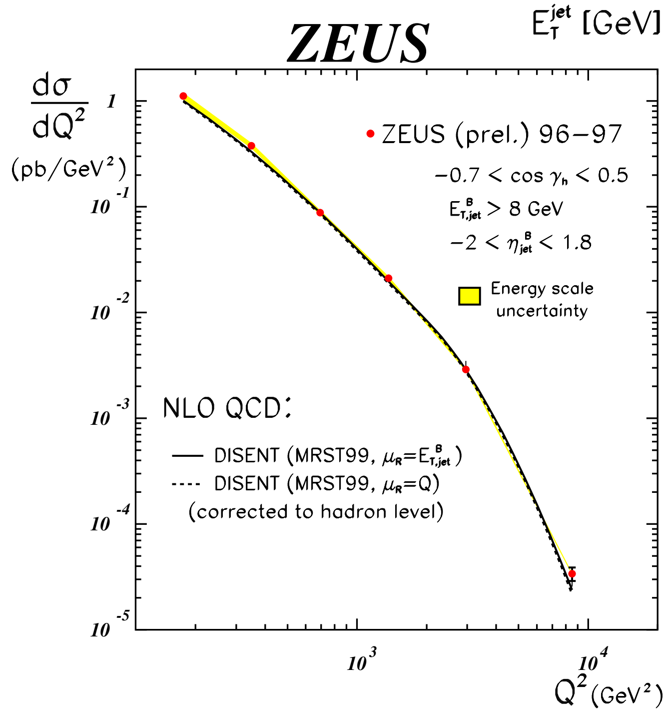
➥talk by Tortosa

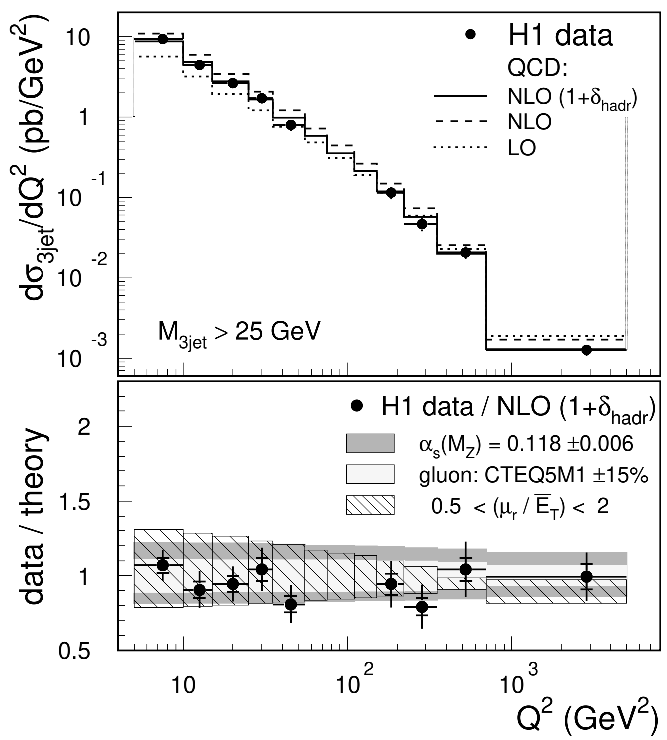
Could spend whole talk just on QCD's successes at HERA

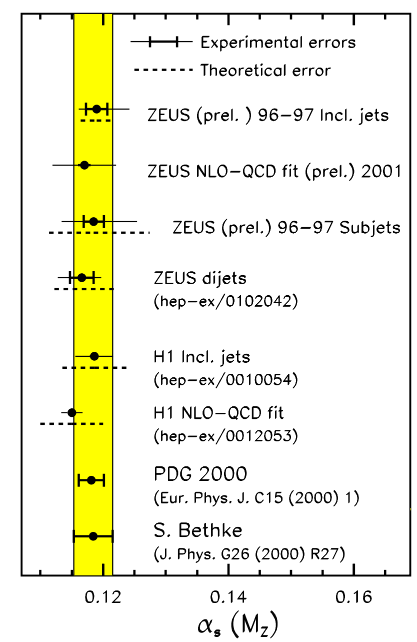












What do we mean by testing QCD?

QCD *is* the right theory of hadronic physics

Constraining it

- ✗ measuring fundamental unknowns (α_s, quark masses)
- ✗ measuring quantities which could be predicted if only we had the right theoretical tools (structure functions, fragmentation functions)
- ✗ understanding, improving and verifying accuracy of QCD (NNLO, MC+NLO)

Exploring it

- ✗ developing an understanding of non-perturbative phenomena (hadronization, diffraction)
- ✗ pushing it to new limits (small-x, saturation)
- ✗ new phenomena and phases (instantons, quark-gluon plasma, colour superconductor)

$\Downarrow$ providing a reference (search for 'new physcs') $\Longleftrightarrow$ $\Downarrow$ mining the wealth of QCD

Final-states: complementary & discriminatory

This talk: a few selected topics

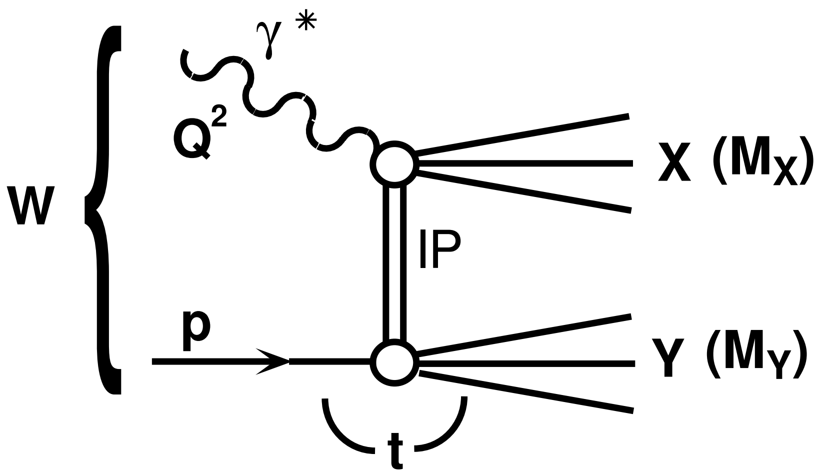
- ✗ Two examples where final states have taught us something fundamentally new over the past few years:
  - ☛ Jets and factorization in diffraction
  - ☛ Event shapes and power corrections (hadronization)
- ✗ b-production: a big thorn in the side? Various observations have been made...
- ✗ Something to keep an eye out for in the future: event generators accurate to NLO.

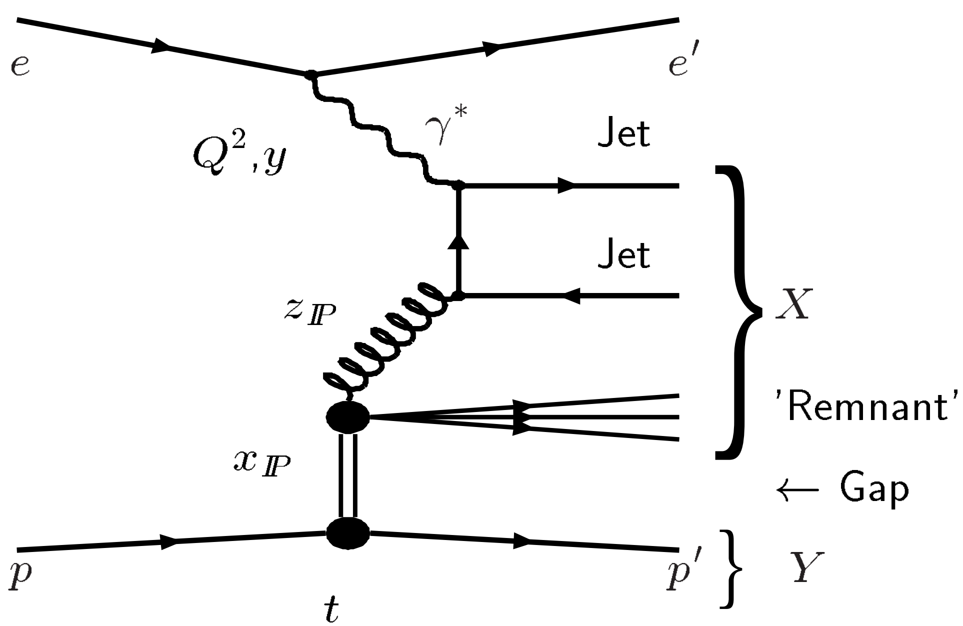
Not in this talk!

- ✗ Small-x
- ✗ NNLO
- ✗ Prompt photons
- ✗ DVCS
- ✗ Instantons
- ✗ Polarization
- ✗ ...

➥parallel sessions

Jets in diffraction & factorization





Partonic picture of pomeron

- ✗ Define diffractive parton densities

$$f_{a/p}^{\text{diff}}(x, x_{\text{IP}}, \mu^2, t)$$

pQCD says this is possible, i.e. they *factorize,* obey DGLAP evolution, have usual DIS coefficient functions etc...

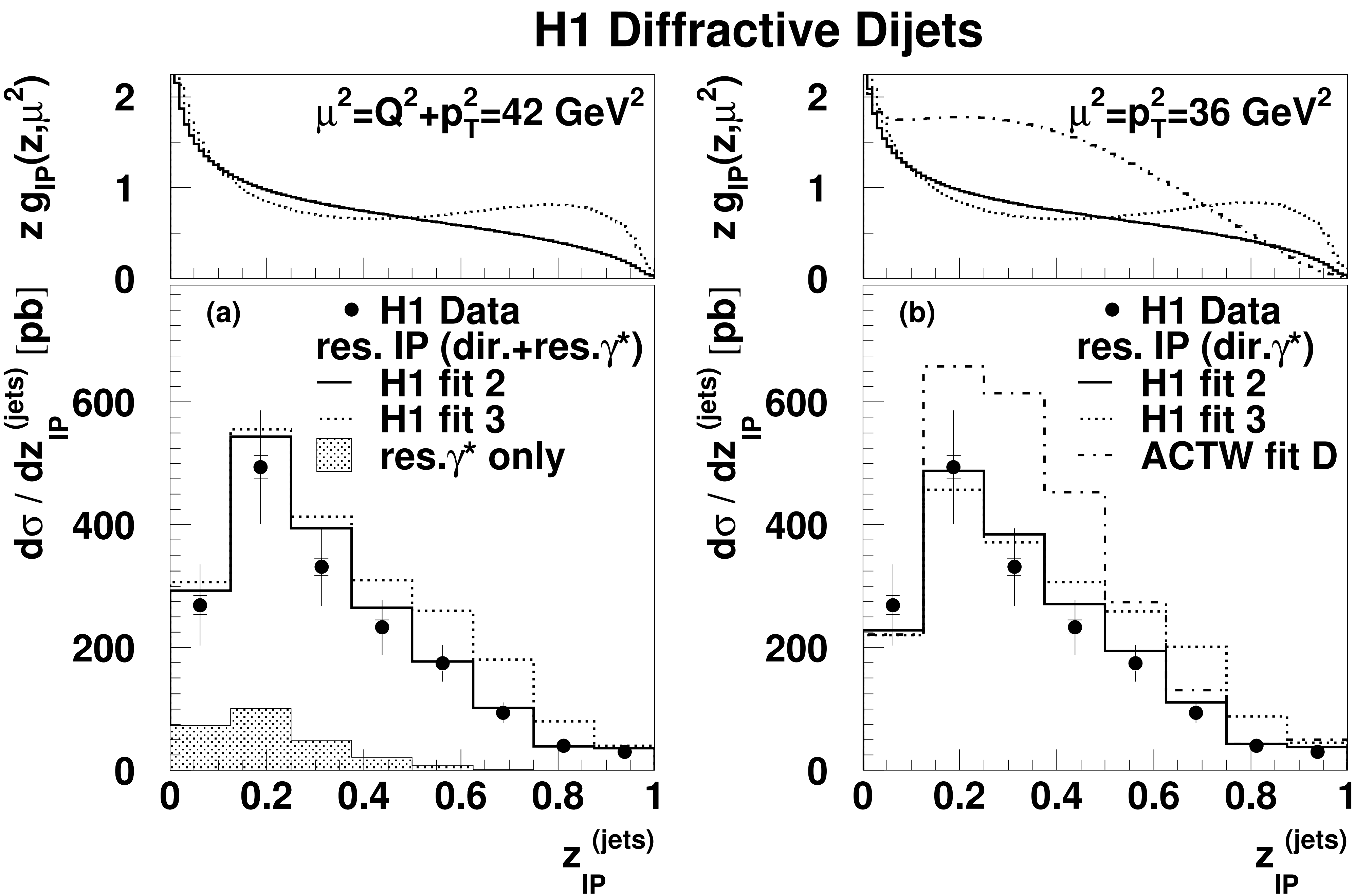
Veneziano, Trentadue, Grazzini
Berera, Soper; Collins

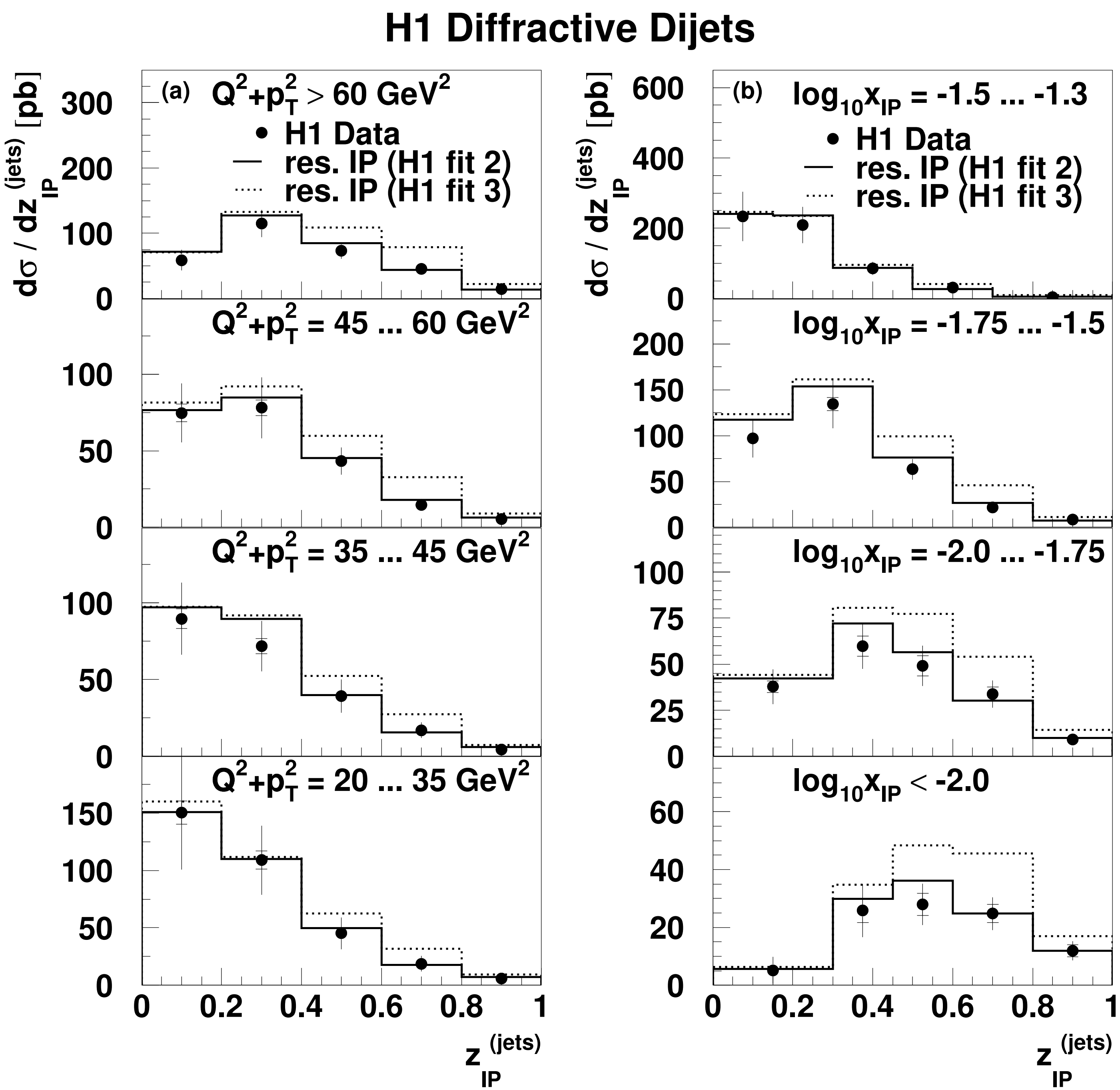
- ✗ Stronger statement (beyond pQCD): *Regge factorization.* Treat pomeron almost like a real object

$$|\beta_p(t)|^2 x_{\text{IP}}^{-2\alpha(t)} f_{a/\text{IP}}(x/x_{\text{IP}}, \mu^2, t)$$

Ingelman & Schlein

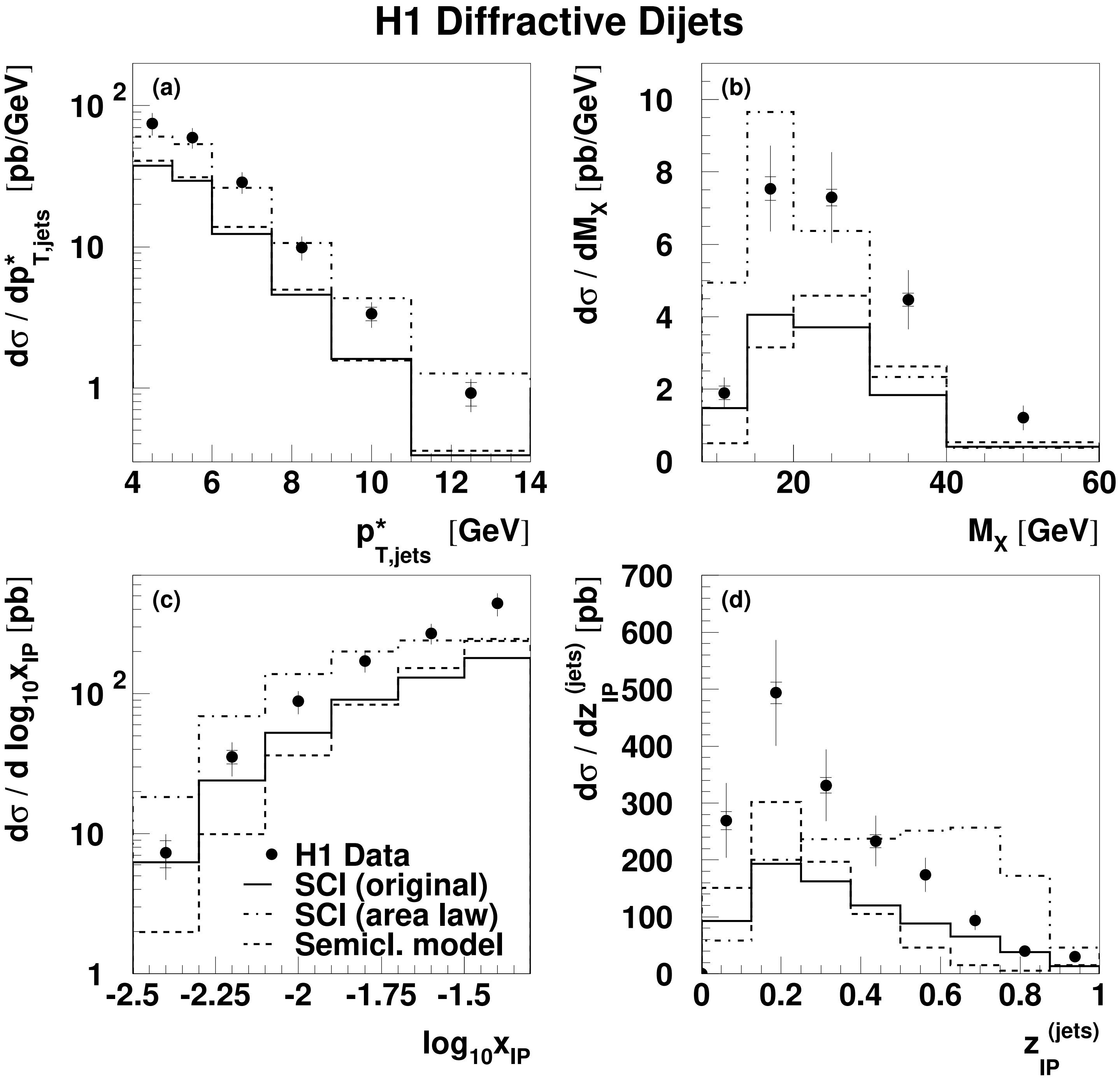
Works for F_2^d (various $f_{a/\text{IP}}$ are possible; various models also work). *What about jets?*


H1 Diffractive Dijets
$\mu^2=Q^2+p_T^2=42$ GeV^2
$\mu^2=p_T^2=36$ GeV^2
$z\,g_{IP}(z,\mu^2)$
$d\sigma / dz_{IP}^{(jets)}$ [pb]
(a)
● H1 Data
res. IP (dir.+res.γ^*)
H1 fit 2
H1 fit 3
res.γ^* only
(b)
● H1 Data
res. IP (dir.γ^*)
H1 fit 2
H1 fit 3
ACTW fit D
$z_{IP}^{(jets)}$



- ✗ Remarkable agreement.
- ✗ Many other models put in difficulty by the data...
- ✗ Able to distinguish different possibilites for $I\!P$ parton distributions.

➥talk by Thompson



H1 Diffractive Dijets
(a)
(b)
(c)
(d)
dσ / dp*_T,jets [pb/GeV]
p*_T,jets [GeV]
dσ / dM_X [pb/GeV]
M_X [GeV]
dσ / d log10 x_IP [pb]
log10 x_IP
dσ / dz_IP^(jets) [pb]
z_IP^(jets)
H1 Data
SCI (original)
SCI (area law)
Semicl. model

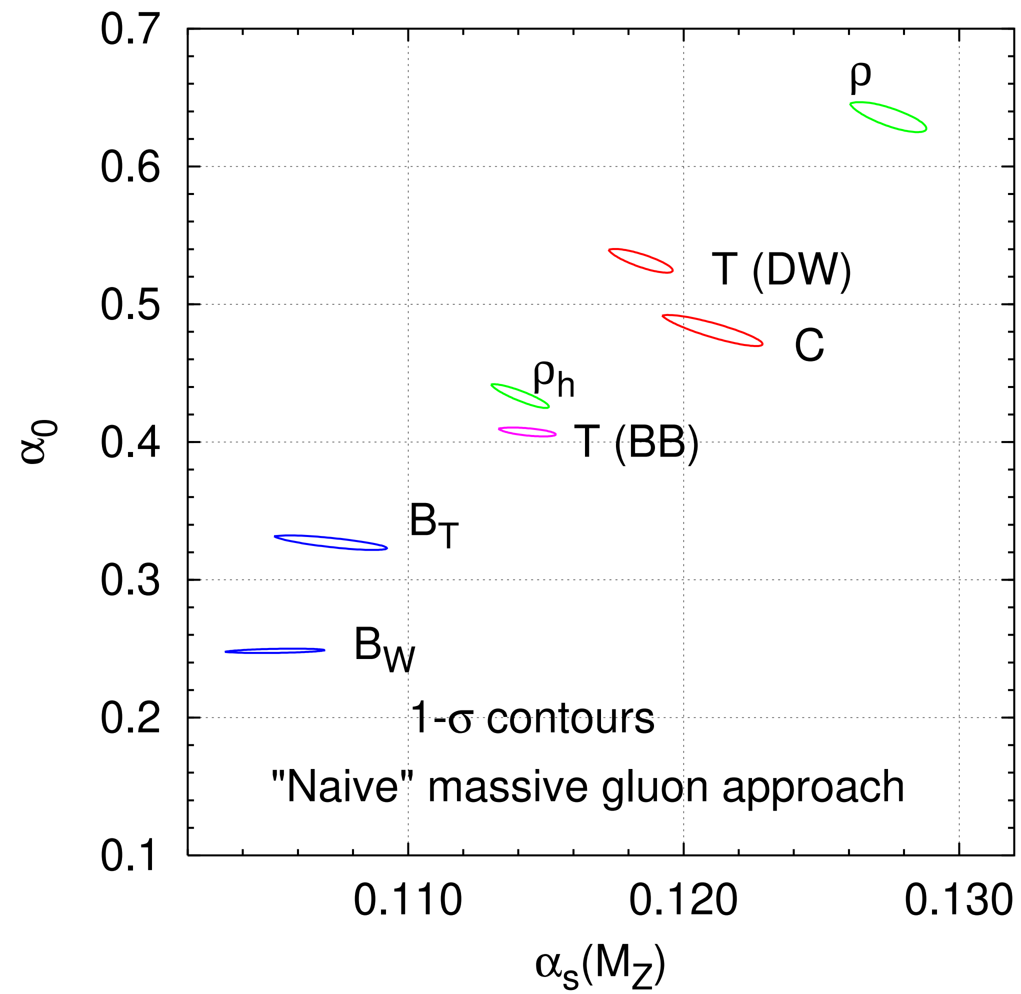
Hadronization: birth of $1/Q$ corrections

Until the mid 90's the *only way* of estimating hadronisation corrections in final-state measurements was by *comparing 'parton' and hadron level Monte Carlo events.*

$\sim$1995, theoretical calculations (renormalons, massive gluons) suggested that for *event shapes* (thrust, jet mass, broadening, C-parameter,...), hadronization gives

$$\mathcal{V}_{\mathrm{NP}} = \mathcal{V}_{\mathrm{PT}} + \delta\mathcal{V}, \quad \delta\mathcal{V} \sim c_{\mathcal{V}} \frac{\alpha_0}{Q}$$

- ✗ $c_{\mathcal{V}}$ is *calculable*
- ✗ α_0 is *universal(?)* (observable and process independent)
- ✗ *test it by fitting α_0* and α_s for a variety of observables in different processes.



1995 theory, 2001 e^+e^- mean values

$1/Q$: growing up

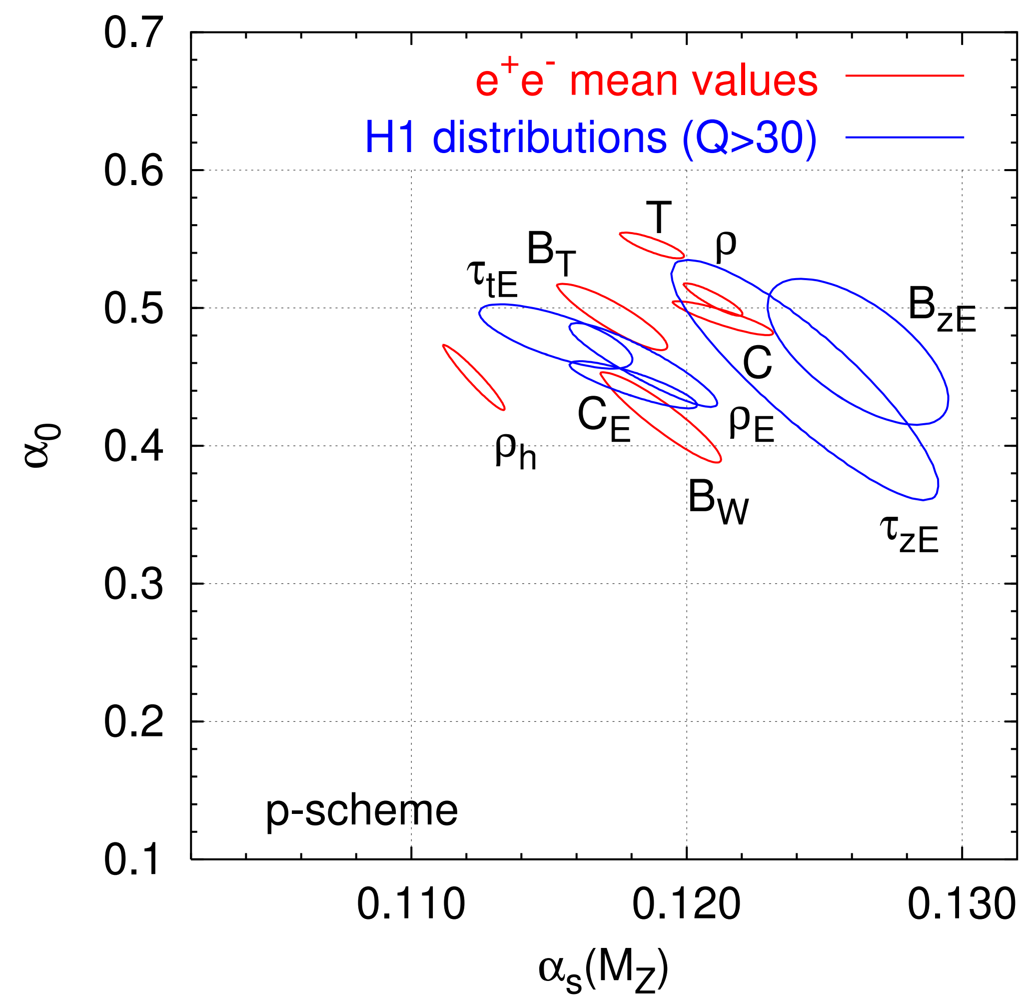
Back in 1995, data were not so good — and early ideas were spared...

Bit by bit, theorists thought (and fought) harder, experimenters pushed them into corners...

- ✗ calculate massive gluon decay
- ✗ account for interplay between PT and NP effects
- ✗ define observables so that they're less sensitive to hadron masses

Basic idea survives, only the c_γ coefficients change

Amazing that such a simple approach works so well



2002 theory, 2001 data
(exp. errors only)

$1/Q$: maturity?

Many other issues still to be properly dealt with and tested

- ✗ Going beyond pure $1/Q$: shape functions, dressed gluon exponentiation

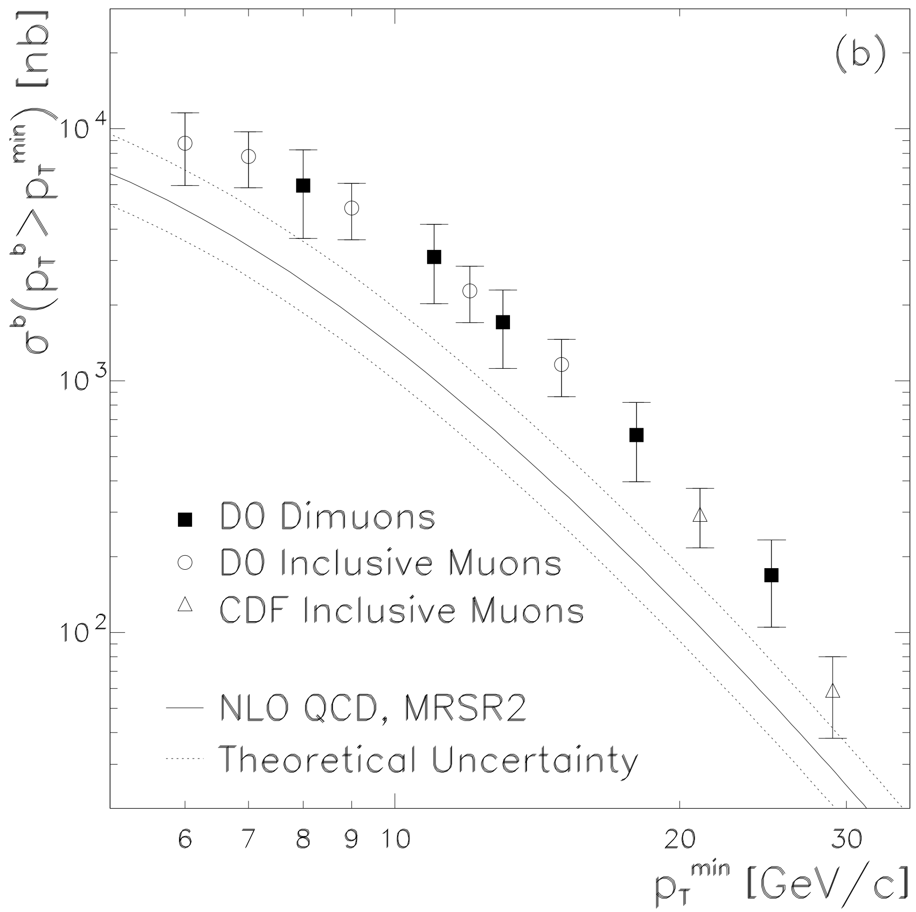
  Korchemsky & Sterman; Gardi & Rathsman

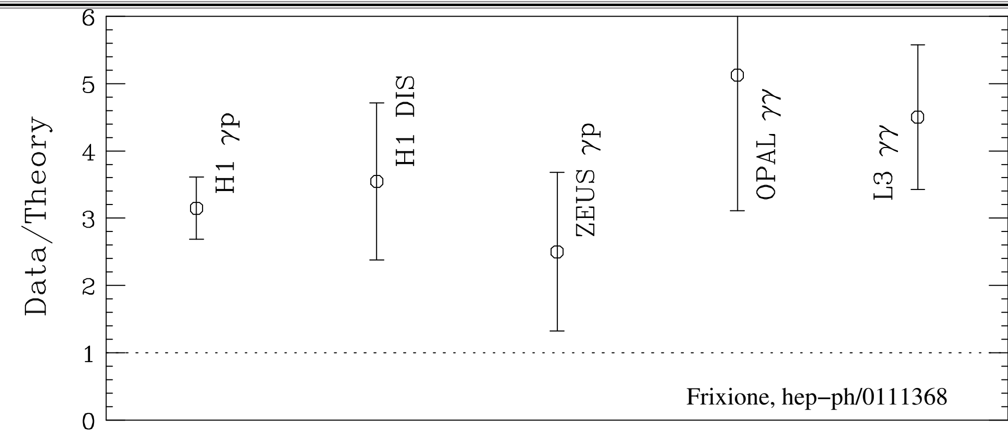
- ✗ Understanding hadronization of multi-jet events and of gluons: theory is currently less robust — will it work as well? ➥talks by Banfi, Zanderighi

- ✗ Do we need hadronization at all: renormalization group improved methods work fine without for e^+e^- mean values.

  some provocative analyses by Delphi...

b-production





✗ Significant excess ($\sim \times 3$) in all 'QCD' production experiments.

➥talks in multi-hadron WG

✗ b production (heavier) *should be better* described by QCD than c production (lighter) — but actually *much worse.*

Some 'explanations' (Tevatron)

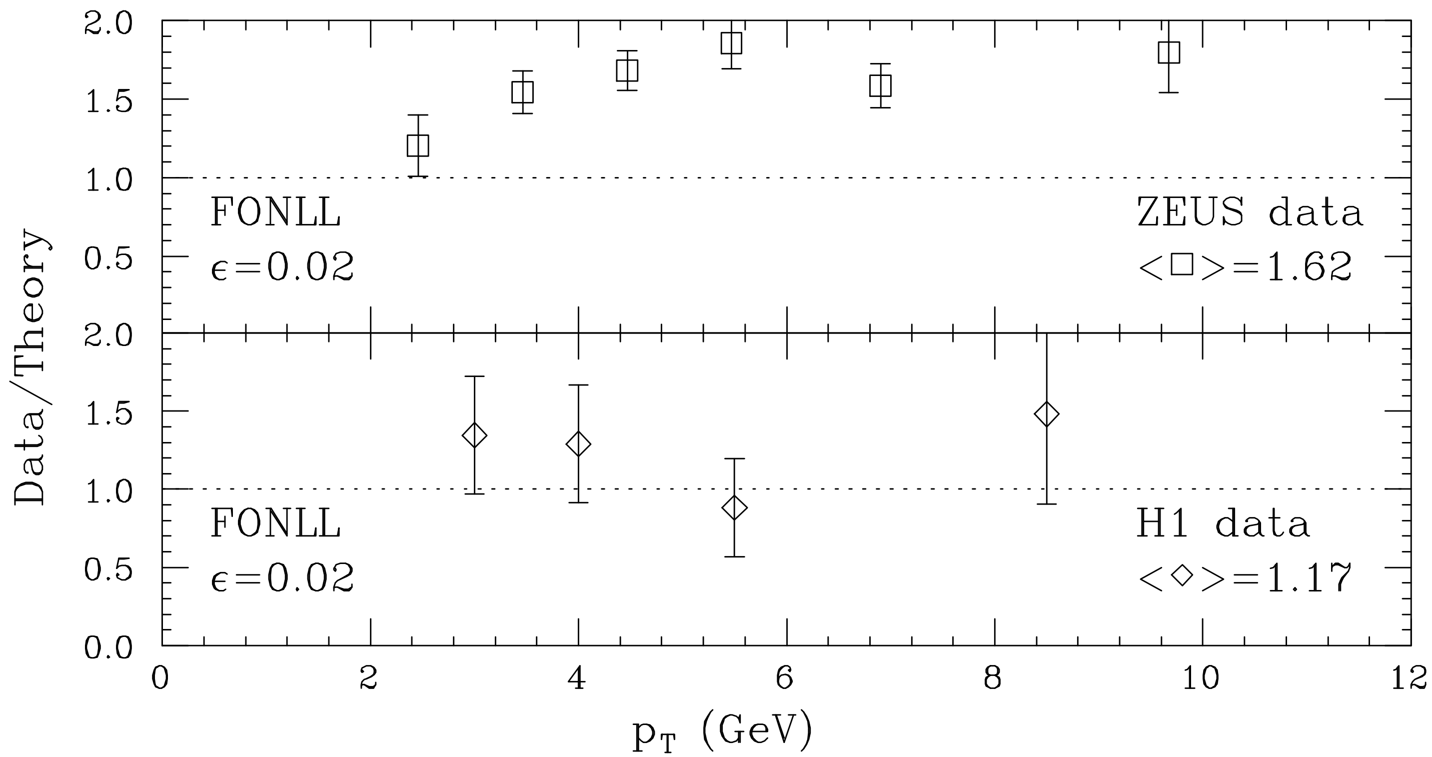
✗ Unintegrated k_t distributions (BFKL)

➥talk by de Roeck

✗ SUSY

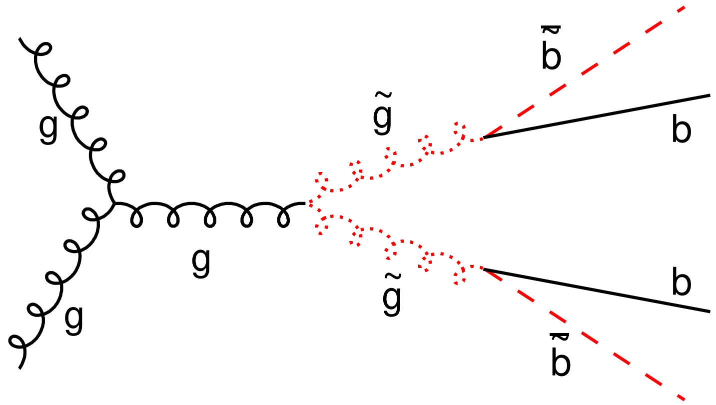
✗ Fragmentation

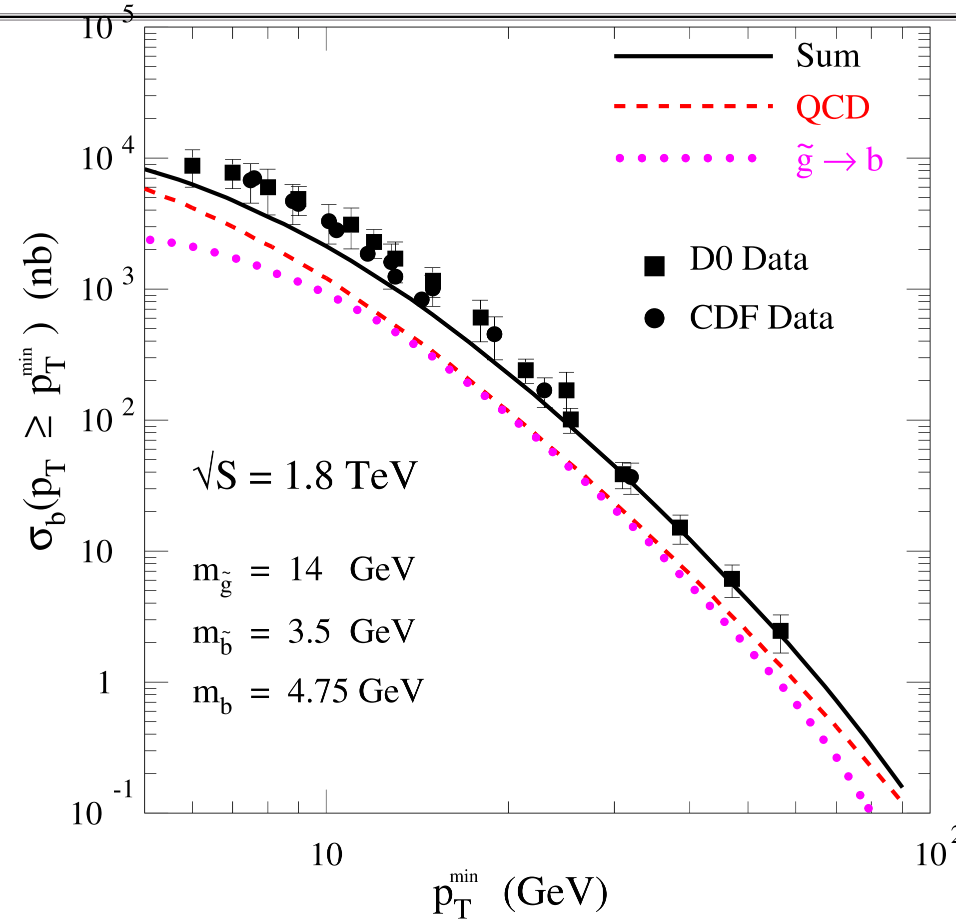
c-production



Frixione, hep-ph/0111368

SUSY explanation — lightish gluino, light sbottom





Berger et al., hep-ph/0012001

- ✗ $m_{\tilde{g}} \simeq 12 - 16\,\mathrm{GeV}$, $m_{\tilde{b}} \simeq 3.5 - 5.5\,\mathrm{GeV}$
- ✗ Mixing angles such that $\tilde{b}$ *decouples from* Z at LEP.
- ✗ Signal of *like-sign b production* (comes also from B_0–$\bar{B}_0$ mixing), varies with p_t.
- ✗ *Slows running of α_s* above $m_{\tilde{g}}$ (+0.007 from $m_{\tilde{g}}$ to M_Z); better GUT-SUSY unification of couplings.
- ✗ Small enhancement of HERA b-production rates (suppression due to $\tilde{g}$ mass) — insufficient to explain data.

Fragmentation of b's

'Is There a Significant Excess in Bottom Hadroproduction at the Tevatron?'

Cacciari & Nason, hep-ph/0204025

For any paper whose title is a question, the answer is "no"

Hinchliffe's theorem

QCD calculates $\hat{p}_t$ distribution of *b-quarks.* Experiments measure p_t of *B-mesons.*

$$\underbrace{\frac{d\sigma}{dp_t}}_{\text{measured}} = \int d\hat{p}_t dz \underbrace{\frac{d\sigma}{d\hat{p}_t}}_{\text{PT QCD}} \underbrace{D(z)}_{\text{fragmentation}} \delta(p_t - z\hat{p}_t)$$

Fragmentation functions are a bit like structure functions:

✗ Shape of the fragmentation function depends on order of QCD at which one calculates.

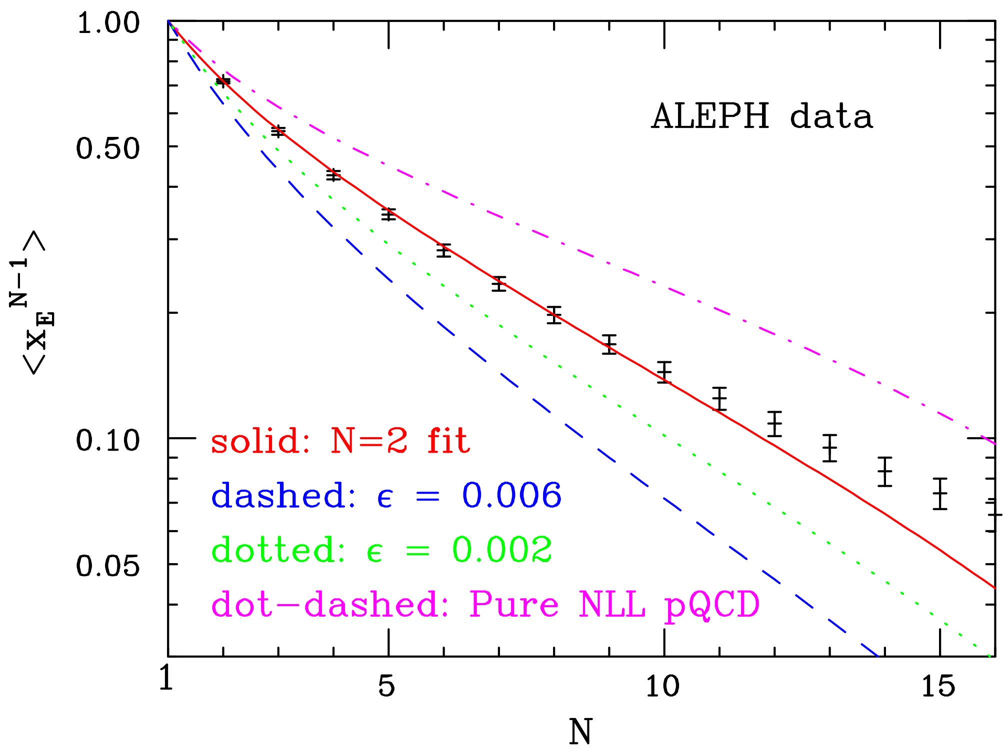
✗ If $p_t \gg m_b$ there are *scaling violations* (NLL).

✗ If $p_t \gtrsim m_b$ we need to *match fixed order (FO) and NLL* corrections (like VFNS).

Tevatron data are steeply falling with p_t ➥very sensitive to fragmentation details.

Need a consistent analysis from start to end.

Measure fragmentation function in e^+e^-



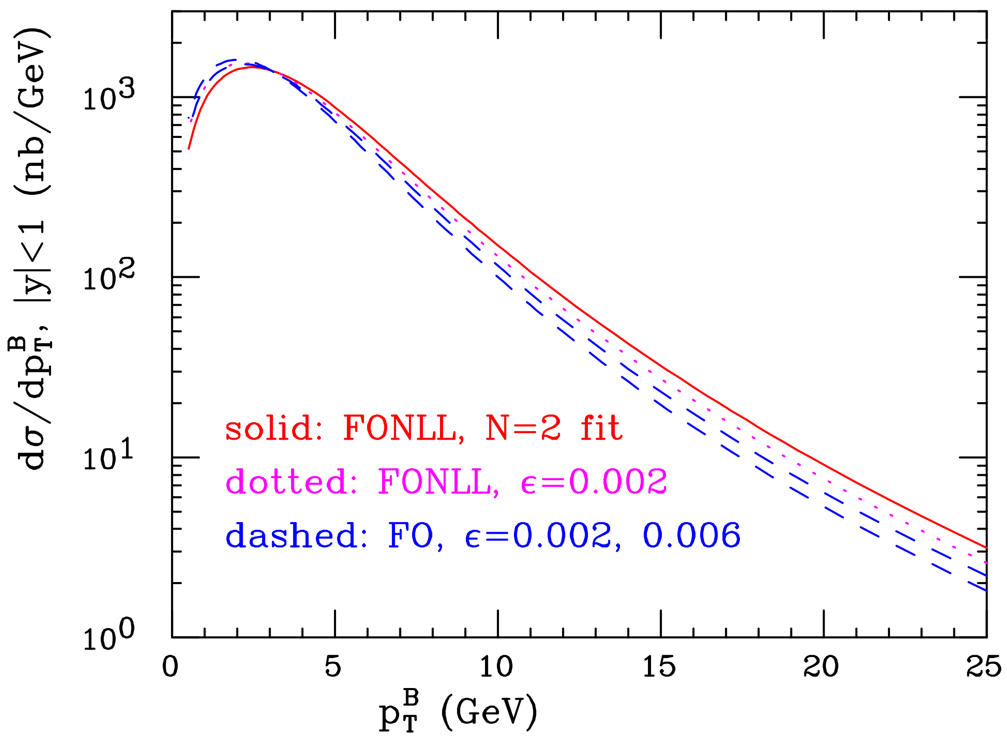
Convolution of steeply falling fragmentation function is *like taking a moment* (for CDF data, relevant moment is $N \simeq 5$). Study of moments reduces systematics.

LEP has measured spectrum of B-mesons. Compare to pQCD calculation (NLL since $Q \gg m_b$) convoluted with a fragmentation function.

CDF (2002) have used Peterson $\epsilon = 0.006$ (a value extracted from LO MC calculations) to calculate theory B-meson spectrum with FO (NLO) QCD. Should *repeat theory calculation with new fragmentation function* (and FONLL pQCD).

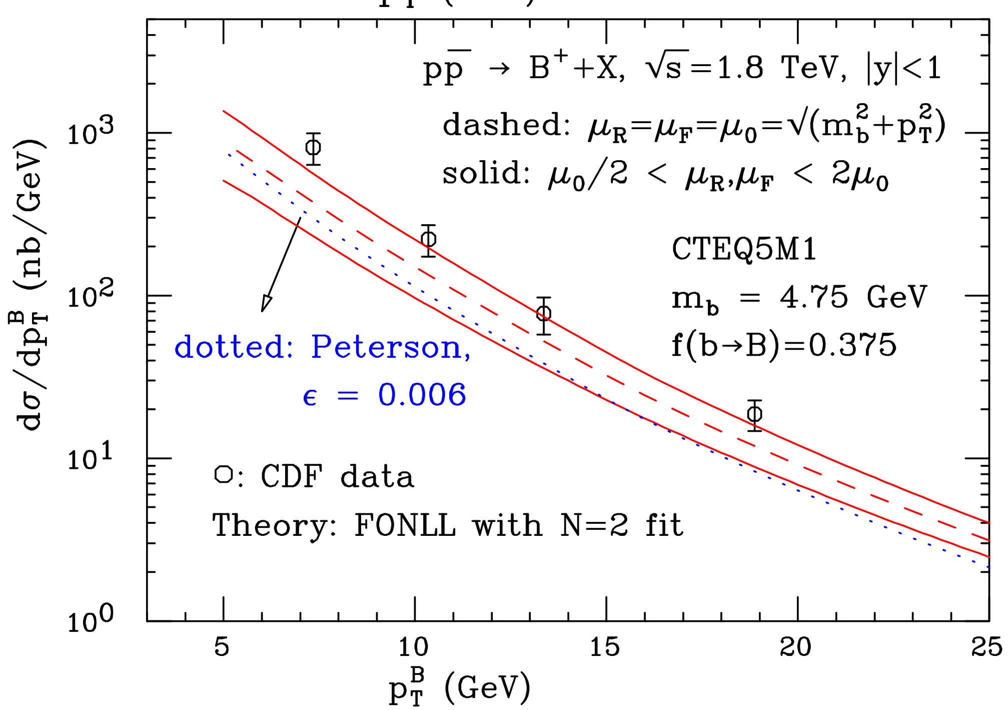
[Some previous Tevatron papers extracted b-quark spectrum by a deconvolution with fragmentation function; then compared to FO QCD. Harder to cross-check with new calculations.]

[NB $\epsilon = 0.002$ has been used in some other NLL calculations.]



Combination of several small effects which each increase large-p_t cross section.

- ✗ $\epsilon = 0.006 \rightarrow \epsilon = 0.002$: 20%
- ✗ FO $\rightarrow$ FONLL: 20%
- ✗ $\epsilon = 0.002 \rightarrow N = 2$: 20%



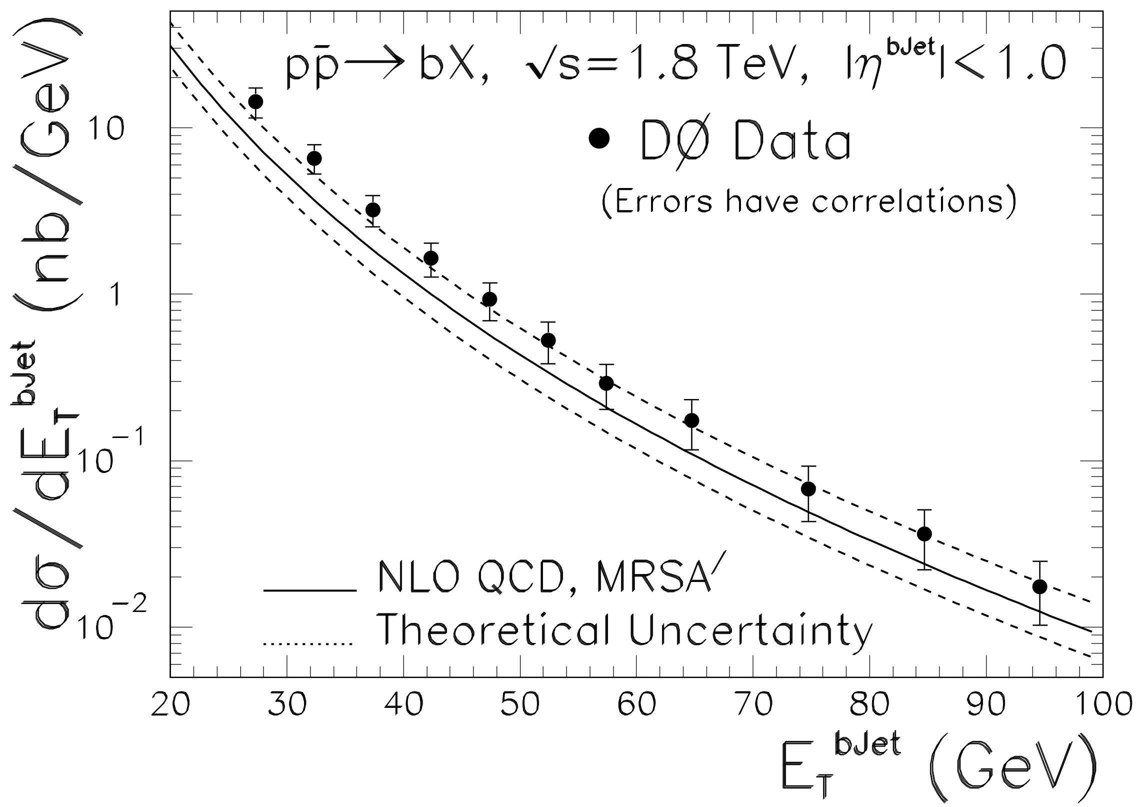
Result:

- ✗ Data and theory are consistent to within errors (ratio of about $1.7 \pm 0.5 \pm 0.5$).

Other experiments?

- ✗ H1 & ZEUS also use $\epsilon = 0.006$
- ✗ But p_t is lower, so effect smaller?

Can eliminate fragmentation by looking at b-jets



- ✗ No need to know the details of fragmentation

  Frixione & Mangano
  hep-ph/9605270

- ✗ Agreement is better than standard b-quark measurements ($\sim$ Cacciari-Nason results)

- ✗ But a different p_t region.

Messages?

Care is needed in treatment of fragmentation.
It can be helpful to look also at observables insensitive to fragmentation

Combining fixed-order calculations and event generators

Next generation of MC event generators: quest for wider applicability, higher accuracy

Very active area of current research. Two directions:

✗ MC + LO n-particle generation (e.g. 3-jets in DIS).

- Much practical progress
- Many of the results already implemented in publicly available MC's.

➥talks by Krauss, Lönnblad

✗ MC + NLO corrections.

- Lots of effort dedicated to the problem
- Two approaches have been implemented by 3 groups

Inexhaustive list of past 2 years' articles:

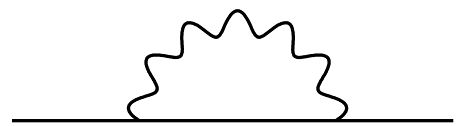
S. Frixione and B. R. Webber, arXiv:hep-ph/0204244.
J. C. Collins and X. M. Zu, arXiv:hep-ph/0204127.
L. Lonnblad, arXiv:hep-ph/0112284.
M. Dobbs, arXiv:hep-ph/0111234.
Y. J. Chen, J. Collins and X. m. Zu, arXiv:hep-ph/0110257.
J. Collins, arXiv:hep-ph/0110113.
B. Potter, J. Phys. G **28** (2002) 871 [arXiv:hep-ph/0110009].
S. Catani, F. Krauss, R. Kuhn and B. R. Webber, JHEP **0111** (2001) 063 [arXiv:hep-ph/0109231].
M. L. Mangano, M. Moretti and R. Pittau, arXiv:hep-ph/0108069.
S. Weinzierl, JHEP **0108** (2001) 028 [arXiv:hep-ph/0106146].
Y. Chen, J. C. Collins and N. Tkachuk, JHEP **0106** (2001) 015 [arXiv:hep-ph/0105291].
F. Hautmann, arXiv:hep-ph/0105098.
B. Potter and T. Schorner, Phys. Lett. B **517** (2001) 86 [arXiv:hep-ph/0104261].
M. Dobbs, Phys. Rev. D **64** (2001) 034016 [arXiv:hep-ph/0103174].
F. Hautmann, arXiv:hep-ph/0101006.
F. Hautmann, Int. J. Mod. Phys. A **16S1A** (2001) 238 [arXiv:hep-ph/0011381].
J. C. Collins and F. Hautmann, JHEP **0103** (2001) 016 [arXiv:hep-ph/0009286].
S. Moretti, arXiv:hep-ph/0008197.
B. R. Webber, arXiv:hep-ph/0005035.
J. C. Collins, JHEP **0005** (2000) 004 [arXiv:hep-ph/0001040].

Difficulties in NLO + event generator

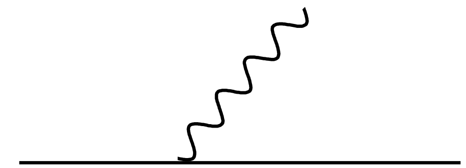
Take a simple *toy model* ($c.f.$ Frixione & Webber), to illustrate the problems.

Consider how we *calculate an observable O* at NLO, (x is the momentum fraction of emitted 'photons')

$O(0)$



$$-\alpha O(0) \int_0^1 \underbrace{\frac{dx}{x} V(x)}_{\text{loop}}$$



$$\alpha \int_0^1 \underbrace{\frac{dx}{x} R(x)}_{\text{matr. element}} \quad O(x)$$

Real and virtual corrections are separately *divergent* $\rightarrow$ events have *large (fluctuating) positive and negative weights.*

Final result is finite (for infrared-collinear-safe observable) because

$$\boxed{\text{for } x \to 0,\ R(x) = V(x)}$$

But unsuitable for event generator (bad convergence).

Patching NLO + MC together

Method developed and implemented by Pötter, hep-ph/0007172; Pötter & Schörner, hep-ph/0104261; Dobbs hep-ph/0111234. Extension of *Phase-space slicing.*

Step 1: NLO

Choose a *cutoff* x_{zero} such that Born & Virtual cancel (then throw 'em away):

$$1 - \alpha \int_{x_{\text{zero}}}^{1} \frac{dx}{x} V(x) = 0$$

Generate a real emission with a distribution $dxR(x)/x$ and the *same cutoff* x_{zero}*:*

$$\sigma_{\text{NLO}} = \sigma_0 \alpha \int_{x_{\text{zero}}}^{1} \frac{dx}{x} R(x)$$

[Generate *uniform (positive) weights* with $e.g.$ the `BASES/SPRING` package]

Step 2: MC

Choose a *separation parameter* $x_{\text{zero}} < x_{\text{sep}} < 1$ between hard (NLO) and soft (MC) emissions

- ✗ For $x > x_{\text{sep}}$, keep the NLO (hard) emission [and generate MC emissions below x].
- ✗ For $x < x_{\text{sep}}$ throw away NLO emission and generate MC parton shower below x_{sep}.

NB: many important (and complex) technical details left out.

Results

<u>Advantages</u>

✓ MC has just positive weights.

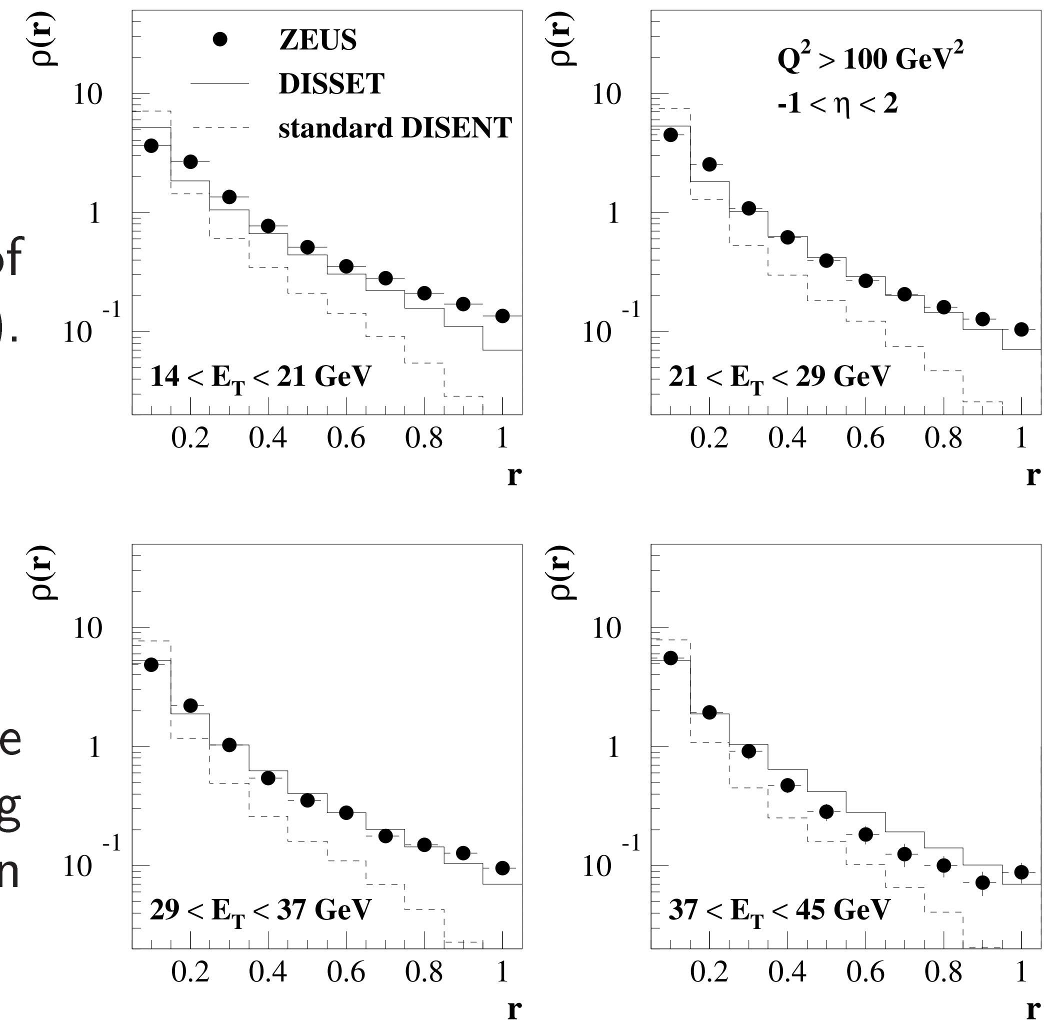
✓ It does not need knowledge of internals of MC (except for implementing x_{sep} cutoff).

<u>Drawbacks</u>

✗ Potentially discontinuous at x_{sep}

✗ Not strictly NLO everywhere in phase space ($i.e.$ expansion to order α_s is wrong in places) — how important is this in practice?

✗ For each observable, stability must be checked against large variations in x_{sep}.



Pötter & Schorner, hep-ph/0104261

Merging NLO and MC (Frixione & Webber)

Aims:

- ✗ all observables correct to NLO
- ✗ soft/hard emission treated as in MC/NLO
- ✗ smooth matching between hard and soft regions

Approach:

- ✗ use a *subtraction method*
- ✗ make use of knowledge of effective NLO corrections contained in default MC,

$$\pm\alpha \frac{dx}{x} M(x) \quad \text{for } {}^{real}_{virtual}$$

$$I_{\mathsf{MC,Born}} - \alpha\, I_{\mathsf{MC,Born}} \int \frac{dx}{x} \left(V(x) - M(x)\right) + \alpha \int \frac{dx}{x} \left(R(x) - M(x)\right) I_{\mathsf{MC,Born}+x}$$

- ✗ $I_{\mathsf{MC,Born}}$ means 'call the (Interface to) MC generator with the Born configuration'
- ✗ Subtract out from NLO corrections what is already included in the MC at Born level
- ✗ *Integrands are finite* because MC and NLO QCD contain same IR+collinear divergences ($R(x) - M(x)$) $\to 0$ for $x \to 0$): *MC needs only a small correction to get correct NLO.*

MC@NLO Results

Advantages

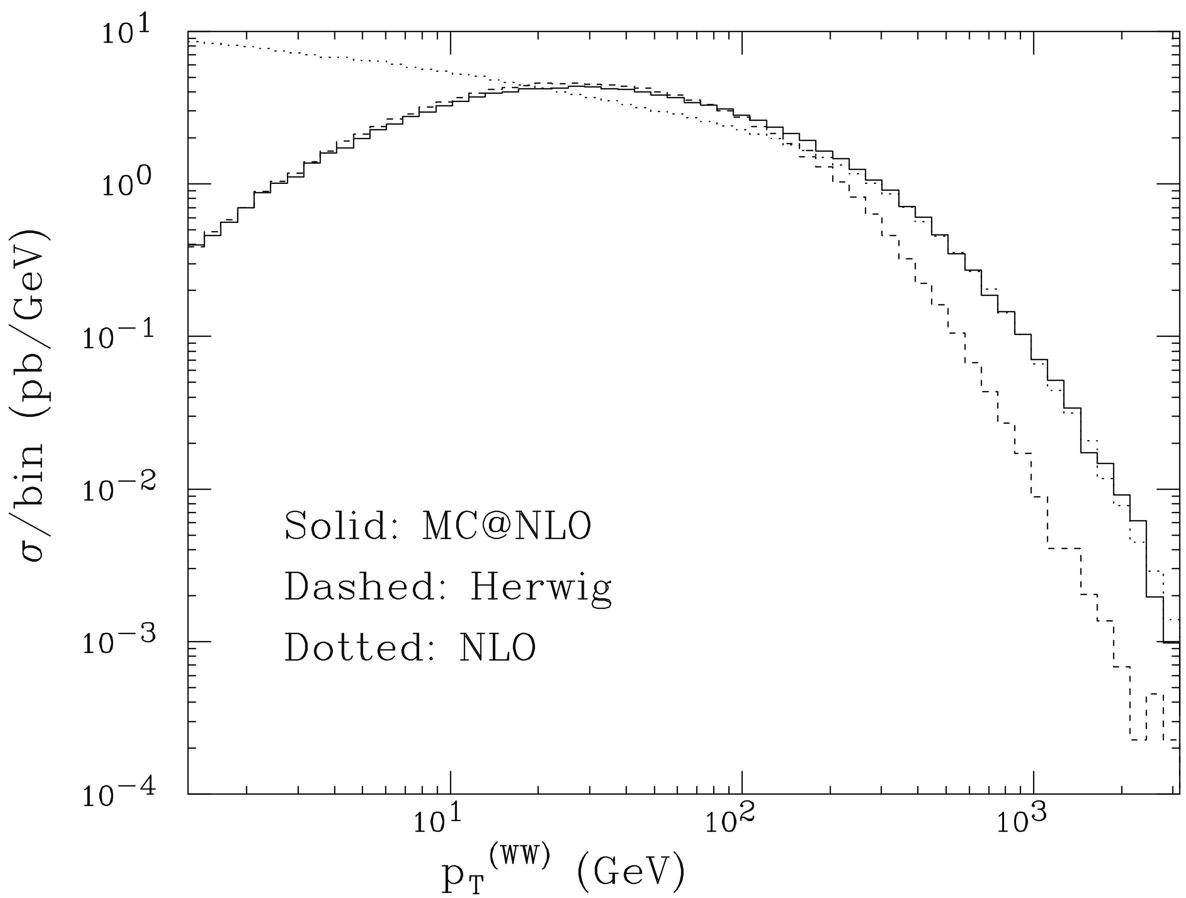
✓ Smooth procedure (no cutoffs).

✓ NLO guaranteed to be uniformally correct.

Drawbacks

✗ A small fraction of events have weight -1.

✗ Implementation needs understanding of the partial NLO corrections embodied in the default MC (but inevitable for true NLO).

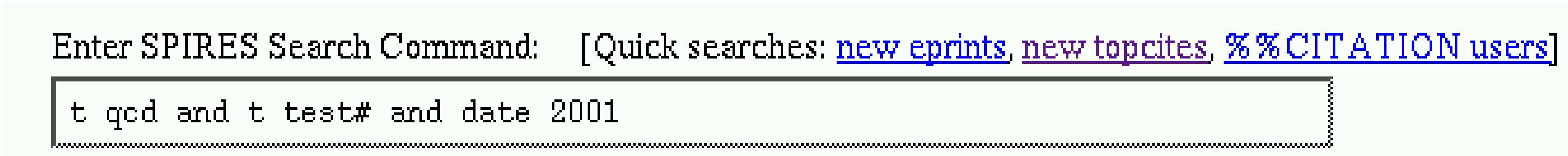


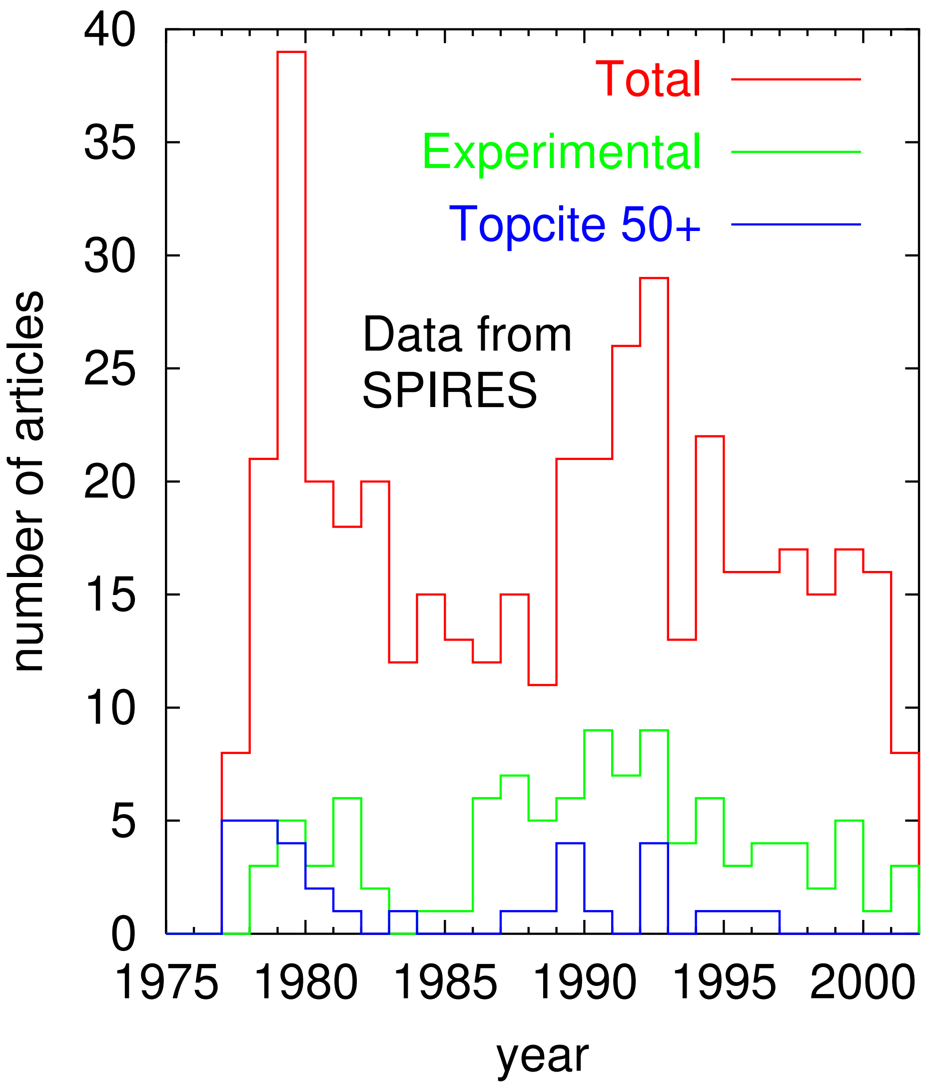
A field in rapid development: many subtle & interesting physics questions.
Doing it (properly!) vital for reducing systematics in many measurements

Conclusions: Testing QCD?

- ✗ Rather: testing our *understanding* of QCD
- ✗ Extending the domain in which we have confidence in our predictions
- ✗ Choosing measurements to be
  - ☛ as close as possible to what is seen in the detector (hadron level)
  - ☛ as uncontaminated as possible by the 'uncalculables of QCD'

Too much theory? An apology





- ✗ Testing QCD is only marginally an experimental job!
- ✗ First order literature searches are like first order QCD: qualitatively instructive, but quantitatively dubious: e.g. in 2001
  - ☞ Testing an approximation to large N_C QCD with a toy model. [hep-ph/0112042]
  - ☞ Parallel supercomputing pentium cluster and performance test in lattice QCD. [hep-lat/0107017]
- ✗ WG's will help put QCD testing back into the experimental domain!