QCD Phenomenology

Mike Seymour
University of Manchester/CERN PH-TH

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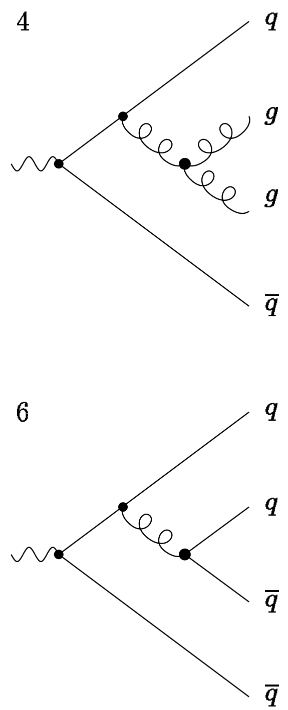
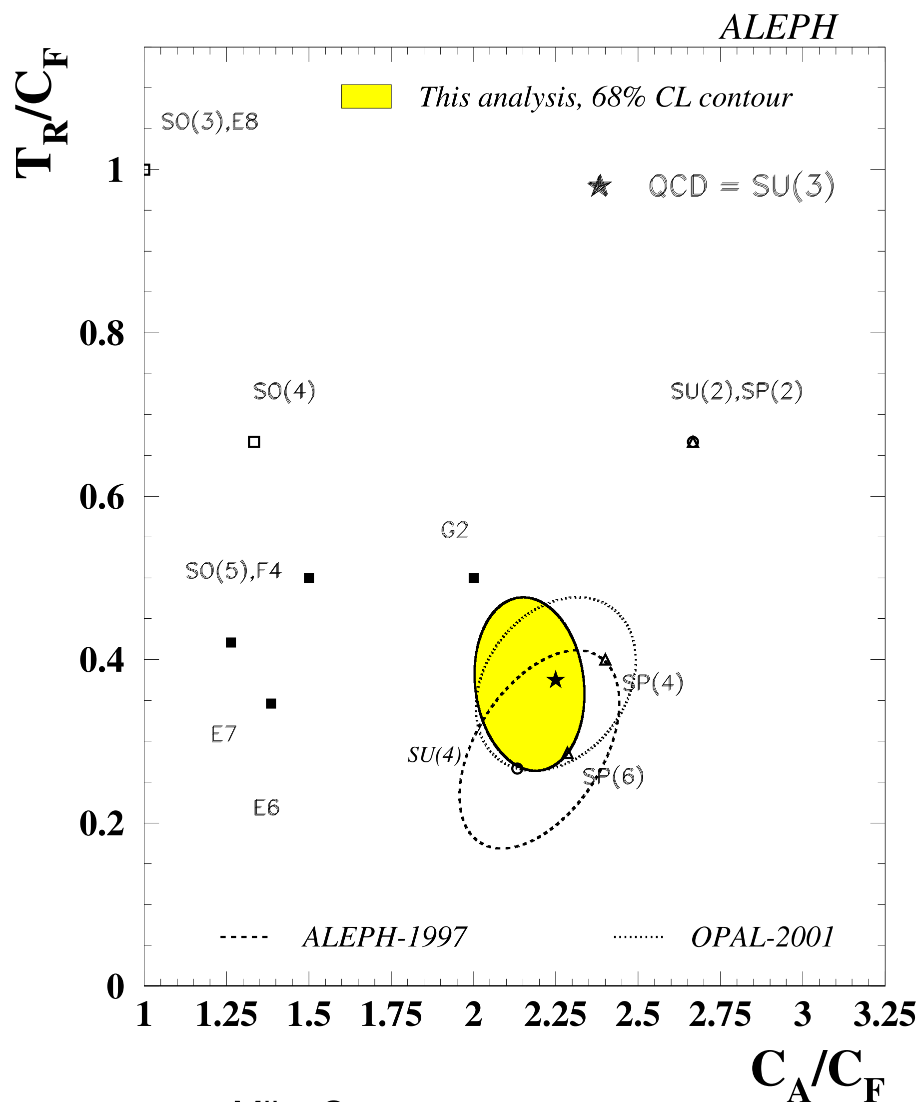
Tools of the Trade

- Fixed-order perturbation theory
- All-order perturbation theory
- ‘Best of both’
- Non-perturbative fits and models
- Analysis tools

QCD Phenomenology – Why?

- Testing QCD
  - Again???

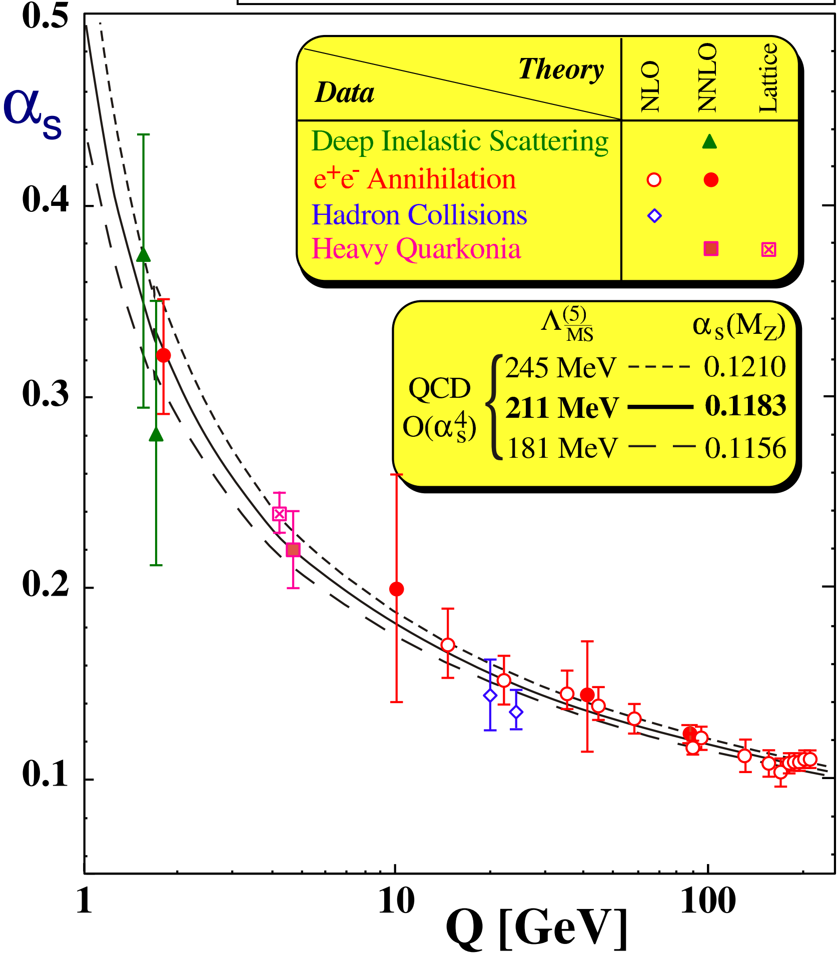


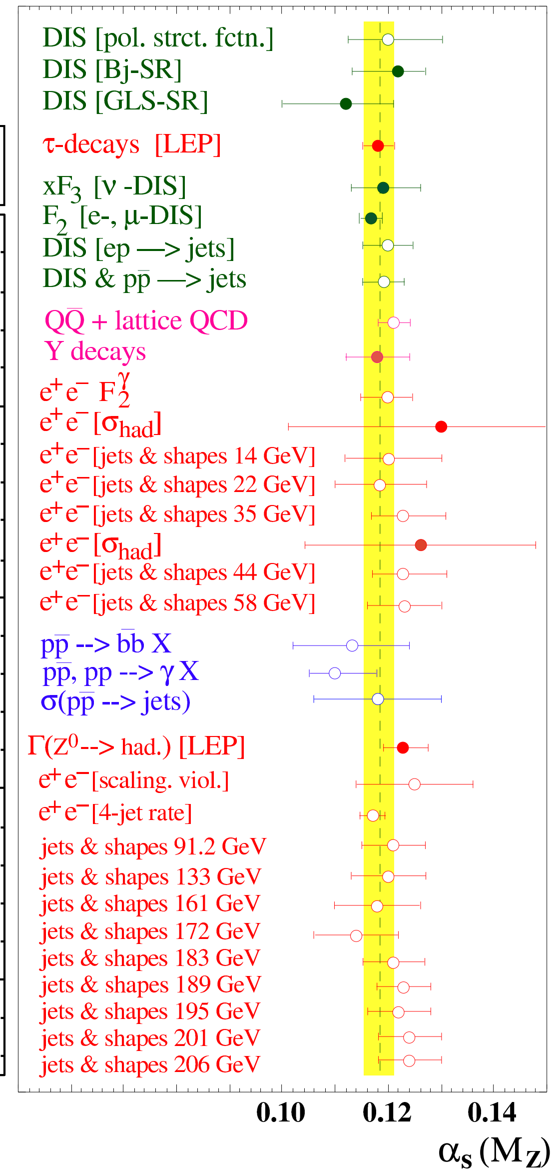


QCD Phenomenology – Why?

- Testing QCD
  - Again???
- Measuring α_s
  - Again???

S.Bethke hep-ex/0211012





QCD Phenomenology – Why?

- Testing QCD
  - Again???
- Measuring α_s
  - Again???
- Testing our understanding of QCD
  - Perturbative calculations
  - Non-perturbative models
  - Perturbative/non-perturbative interface
- QCD as a tool
  - Electroweak measurements
  - Searches for new physics

Tools of the Trade

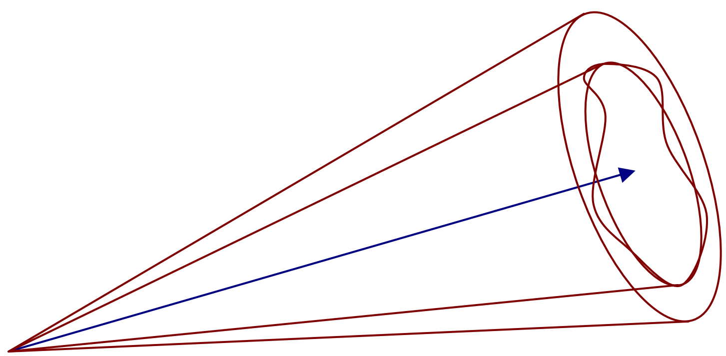
- Fixed-order perturbation theory
  - LO – state of the art for high parton multiplicity – highly automated
  - NLO – up to five partons – partly automated
  - NNLO – two partons ($\sigma(e^+e^-)$, DIS, Drell–Yan)
  - Valid for infrared safe observables
- All-order perturbation theory
- ‘Best of both’
- Non-perturbative fits and models
- Analysis tools

Higher Order Perturbation Theory – Why?

- α_s not so small – need several orders for ~ % accuracy
- Renormalization/Factorization scales ⇒ LO perturbation theory not predictive

$$\sigma(s) = \int \mathrm{d}x_1\, f_i(x_1,\mu_F)\, \mathrm{d}x_2\; f_j(x_2,\mu_F)\; \sigma_{ij}(x_1 x_2 s, \mu_F, \mu_R; \alpha_s(\mu_R))$$

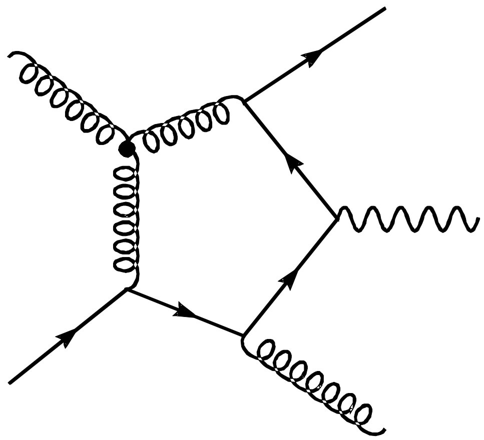
- Higher orders can be enhanced by large coefficients
- 1 parton = 1 jet ⇔ no dependence on jet definition

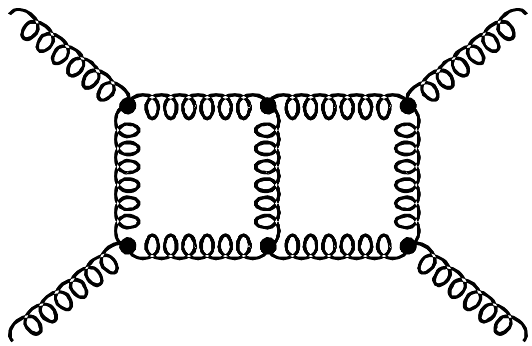


Higher Order Calculations – Why So Hard?

1) Loop integrals for virtual matrix elements

- Get harder with increasing number of legs
- State of the art: one-loop pentagon, two-loop box





- Some progress with automation?

Higher Order Calculations – Why So Hard?

2) Numerical cancellation of infrared poles

- Real and virtual emission each divergent in infrared

→ Divergences must be extracted analytically

- Must be integrated over different phase spaces
- Observable arbitrarily complicated

→ Must be integrated numerically

Monte Carlo Calculations of NLO QCD

Two separate divergent integrals:

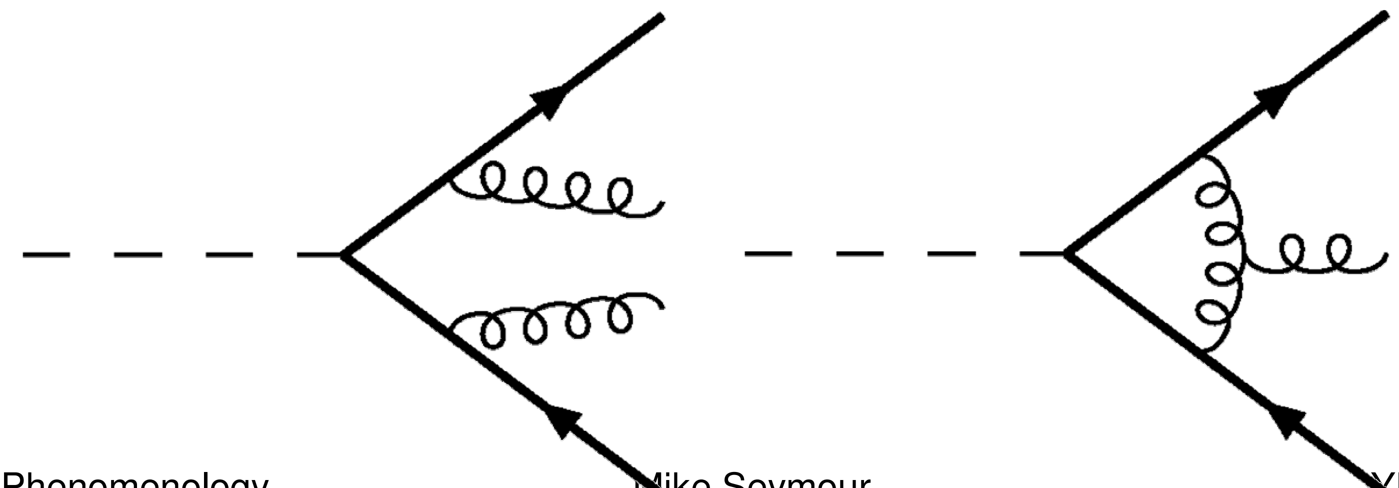
$$\sigma_{NLO} = \int_{m+1} d\sigma^R + \int_m d\sigma^V$$

Must combine before numerical integration.

Jet definition could be arbitrarily complicated.

$$d\sigma^R = d\Pi_{m+1}\,|\mathcal{M}_{m+1}|^2\,F^J_{m+1}(p_1,\ldots,p_{m+1})$$

How to combine without knowing F^J?



Subtraction Method

- Seek to define an approximate cross section that matches all the real singularities

$$\sigma^{NLO} = \int_{m+1} \left[d\sigma^R - d\sigma^A \right] + \int_{m+1} d\sigma^A + \int_m d\sigma^V$$

- but is feasible to integrate analytically

$$\sigma^{NLO} = \int_{m+1} \left[\left(d\sigma^R \right)_{\epsilon=0} - \left(d\sigma^A \right)_{\epsilon=0} \right] + \int_m \left[d\sigma^V + \int_1 d\sigma^A \right]_{\epsilon=0}$$

- To avoid dependence on unknown F^J, approximate cross section must project event kinematics onto an m-parton configuration and calculate F^J from that.

→ m- … erent
kin … arbitrarily
large weights

$$d\sigma^A = d\Pi_{m+1} \, |\mathcal{M}_{m+1}^{approx}|^2 \, F_m^J(\tilde{p}_1, \ldots, \tilde{p}_m).$$

$$\tilde{p}_i = \tilde{p}_i(p_1, \ldots, p_{m+1})$$

Implementations

- NLOJET++ (Zoltan Nagy) for pure jet processes
  - 1-, 2- and 3-jet production
- MCFM (John Campbell and Keith Ellis) for everything else
  - Monte Carlo for FeMtobarn processes

nproc	$f(p_1)+f(p_2)\to\ldots$	Order
1	$W^+(\to\nu(p_3)+e^+(p_4))$	NLO
6	$W^-(\to e^-(p_3)+\bar\nu(p_4))$	NLO
11	$W^+(\to\nu(p_3)+e^+(p_4))+f(p_5)$	NLO
12	$W^+(\to\nu(p_3)+e^+(p_4))+\gamma(p_5)$	NLO
13	$W^+(\to\nu(p_3)+e^+(p_4))+\bar c(p_5)$	LO
14	$W^+(\to\nu(p_3)+e^+(p_4))+\bar c(p_5)$ [massless]	NLO
16	$W^-(\to e^-(p_3)+\bar\nu(p_4))+f(p_5)$	NLO
17	$W^-(\to e^-(p_3)+\bar\nu(p_4))+\gamma(p_5)$	NLO
18	$W^-(\to e^-(p_3)+\bar\nu(p_4))+c(p_5)$	LO
19	$W^-(\to e^-(p_3)+\bar\nu(p_4))+c(p_5)$ [massless]	NLO
20	$W^+(\to\nu(p_3)+e^+(p_4))+b(p_5)+\bar b(p_6)$ [massive]	LO
21	$W^+(\to\nu(p_3)+e^+(p_4))+b(p_5)+\bar b(p_6)$	NLO
22	$W^+(\to\nu(p_3)+e^+(p_4))+f(p_5)+f(p_6)$	NLO
23	$W^+(\to\nu(p_3)+e^+(p_4))+f(p_5)+f(p_6)+f(p_7)$	LO
24	$W^+(\to\nu(p_3)+e^+(p_4))+b(p_5)+\bar b(p_6)+f(p_7)$	LO
25	$W^-(\to e^-(p_3)+\bar\nu(p_4))+b(p_5)+\bar b(p_6)$ [massive]	LO
26	$W^-(\to e^-(p_3)+\bar\nu(p_4))+b(p_5)+\bar b(p_6)$	NLO
27	$W^-(\to e^-(p_3)+\bar\nu(p_4))+f(p_5)+f(p_6)$	NLO
28	$W^-(\to e^-(p_3)+\bar\nu(p_4))+f(p_5)+f(p_6)+f(p_7)$	LO
29	$W^-(\to e^-(p_3)+\bar\nu(p_4))+b(p_5)+\bar b(p_6)+f(p_7)$	LO
31	$Z^0(\to e^-(p_3)+e^+(p_4))$	NLO
32	$Z^0(\to 3\times(\nu(p_3)+\bar\nu(p_4)))$	NLO
33	$Z^0(\to b(p_3)+\bar b(p_4))$	NLO
41	$Z^0(\to e^-(p_3)+e^+(p_4))+f(p_5)$	NLO
42	$Z_0(\to 3\times(\nu(p_3)+\bar\nu(p_4)))-$ [sum over 3 ν] $+f(p_5)$	NLO
43	$Z^0(\to b(p_3)+\bar b(p_4))+f(p_5)$	NLO
44	$Z^0(\to e^-(p_3)+e^+(p_4))+f(p_5)+f(p_6)$	NLO
45	$Z^0(\to e^-(p_3)+e^+(p_4))+f(p_5)+f(p_6)+f(p_7)$	LO
48	$Z^0(\to e^-(p_3)+e^+(p_4))+\gamma(p_5)$	NLO
49	$Z^0(\to 3\times(\nu(p_3)+\bar\nu(p_4)))-$ [sum over 3 ν] $+\gamma(p_5)$	NLO
50	$Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)+b(p_6)$ [massive]	LO
51	$Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)+\bar b(p_6)$	NLO
52	$Z_0(\to 3\times(\nu(p_3)+\bar\nu(p_4)))+b(p_5)+\bar b(p_6)$	NLO
53	$Z^0(\to b(p_3)+\bar b(p_4))+b(p_5)+\bar b(p_6)$	NLO
56	$Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)+\bar b(p_6)+f(p_7)$	LO

nproc	$f(p_1)+f(p_2)\to\ldots$	Order
61	$W^+(\to\nu(p_3)+e^+(p_4))+W^-(\to e^-(p_5)+\bar\nu(p_6))$	NLO
62	$W^+(\to\nu(p_3)+e^+(p_4))+W^-(\to q(p_5)+\bar q(p_6))$	NLO
63	$W^+(\to q(p_3)+\bar q(p_4))+W^-(\to e^-(p_5)+\bar\nu(p_6))$	NLO
64	$W^+(\to\nu(p_3)+e^+(p_4))+W^-(\to e^-(p_5)+\bar\nu(p_6))$ [no pol]	NLO
71	$W^+(\to\nu(p_3)+\mu^+(p_4))+Z^0(\to e^-(p_5)+e^+(p_6))$	NLO
72	$W^+(\to\nu(p_3)+\mu^+(p_4))+Z^0(\to\nu_e(p_5)+\bar\nu_e(p_6))$	NLO
73	$W^+(\to\nu(p_3)+\mu^+(p_4))+Z^0(\to b(p_5)+\bar b(p_6))$	NLO
76	$W^-(\to\mu^-(p_3)+\bar\nu(p_4))+Z^0(\to e^-(p_5)+e^+(p_6))$	NLO
77	$W^-(\to e^-(p_3)+\bar\nu(p_4))+Z^0(\to\nu(p_5)+\bar\nu(p_6))$	NLO
78	$W^-(\to e^-(p_3)+\bar\nu(p_4))+Z^0(\to b(p_5)+\bar b(p_6))$	NLO
81	$Z^0(\to\mu^-(p_3)+\mu^+(p_4))+Z^0(\to e^-(p_5)+e^+(p_6))$	NLO
82	$Z^0(\to 3\times(\nu(p_3)+\bar\nu(p_4)))+Z^0(\to e^-(p_5)+e^+(p_6))$	NLO
83	$Z^0(\to e^-(p_5)+e^+(p_6))+Z^0(\to b(p_3)+\bar b(p_4))$	NLO
84	$Z^0(\to 3\times(\nu(p_3)+\bar\nu(p_4)))+Z^0(\to b(p_5)+\bar b(p_6))$	NLO
86	$Z^0(\to e^-(p_5)+e^+(p_6))+Z^0(\to\mu^-(p_3)+\mu^+(p_4))$ [no γ^*]	NLO
87	$Z^0(\to e^-(p_5)+e^+(p_6))+Z^0(\to 3\times(\nu(p_3)+\bar\nu(p_4)))$ [no γ^*]	NLO
88	$Z^0(\to e^-(p_5)+e^+(p_6))+Z^0(\to b(p_3)+\bar b(p_4))$ [no γ^*]	NLO
89	$Z^0(\to 3\times(\nu(p_3)+\bar\nu(p_4)))+Z^0(\to b(p_5)+\bar b(p_6))$ [no γ^*]	NLO
91	$W^+(\to\nu(p_3)+e^+(p_4))+H(\to b(p_5)+b(p_6))$	NLO
96	$W^-(\to e^-(p_3)+\bar\nu(p_4))+H(\to b(p_5)+\bar b(p_6))$	NLO
101	$Z^0(\to e^-(p_3)+e^+(p_4))+H(\to b(p_5)+\bar b(p_6))$	NLO
102	$Z^0(\to 3\times(\nu(p_3)+\bar\nu(p_4)))+H(\to b(p_5)+\bar b(p_6))$	NLO
103	$Z^0(\to b(p_3)+\bar b(p_4))+H(\to b(p_5)+\bar b(p_6))$	NLO
111	$H(\to b(p_3)+\bar b(p_4))$	NLO
112	$H(\to\tau^-(p_3)+\tau^+(p_4))$	NLO
113	$H(\to W^+(\nu(p_3)+e^+(p_4))+W^-(e^-(p_5)+\bar\nu(p_6)))$	NLO
114	$H(\to Z^0(\mu^-(p_3)+\mu^+(p_4))+Z^0(e^-(p_5)+e^+(p_6))$	NLO
115	$H(\to Z^0(3\times(\nu(p_3)+\bar\nu(p_4)))+Z^0(e^-(p_5)+e^+(p_6))$	NLO
116	$H(\to Z^0(\mu^-(p_3)+\mu^+(p_4))+Z^0(b(p_5)+\bar b(p_6))$	NLO
141	$H(\to b(p_3)+\bar b(p_4))+b(p_5)(+g(p_6))$	NLO
142	$H(\to b(p_3)+\bar b(p_4))+\bar b(p_5)(+b(p_6))$	NLO
143	$H(\to b(p_3)+\bar b(p_4))+b(p_5)+\bar b(p_6)$ [both observed]	NLO

nproc	$f(p_1)+f(p_2)\to\ldots$	Order
151	$t(\to\nu(p_3)+e^+(p_4)+b(p_5))+\bar t(\to b(p_6))+e^-(p_7)+\bar\nu(p_8))$	LO
152	$t(\to\nu(p_3)+e^+(p_4)+b(p_5))+\bar t(\to\bar b(p_6))+q(p_7)+\bar q(p_8))$	LO
156	$t(\to\nu(p_3)+e^+(p_4)+b(p_5))+\bar t(\to\bar\nu(p_7)+e^-(p_8)+b(p_6))+g(p_9)$	LO
157	$t\bar t$ [for total Xsect]	NLO
158	$b\bar b$ [for total Xsect]	NLO
159	$c\bar c$ [for total Xsect]	NLO
161	$t(\to\nu(p_3)+e^+(p_4)+b(p_5))+q(p_6)$ [t-channel]	NLO
162	$t(\to\nu(p_3)+e^+(p_4)+b(p_5))+q(p_6)$ [decay]	NLO
166	$\bar t(\to e^-(p_3)+\bar\nu(p_4)+\bar b(p_5))+q(p_6)$ [t-channel]	NLO
167	$\bar t(\to e^-(p_3)+\bar\nu(p_4)+\bar b(p_5))+q(p_6)$ [decay]	NLO
171	$t(\to\nu(p_3)+e^+(p_4)+b(p_5))+\bar b(p_6))$ [s-channel]	NLO
172	$t(\to\nu(p_3)+e^+(p_4)+b(p_5))+\bar b(p_6))$ [decay]	NLO
176	$\bar t(\to e^-(p_3)+\bar\nu(p_4)+\bar b(p_5))+b(p_6))$ [s-channel]	NLO
177	$\bar t(\to e^-(p_3)+\bar\nu(p_4)+\bar b(p_5))+b(p_6))$ [decay]	NLO
180	$W^-(\to e^-(p_3)+\bar\nu(p_4))+t(p_5)$	LO
181	$W^-(\to e^-(p_3)+\bar\nu(p_4))+t(\nu(p_5)+e^+(p_6)+b(p_7))$	LO
185	$W^+(\to\nu(p_3)+e^+(p_4))+\bar t(p_5)$	LO
186	$W^+(\to\nu(p_3)+e^+(p_4))+\bar t(e^-(p_5)+\bar\nu(p_6)+\bar b(p_7)$	LO
190	$t(p_3)+\bar t(p_4)+H(p_5)$	LO
191	$t(\to\nu(p_3)+e^+(p_4)+b(p_5))+\bar t(\to\bar\nu(p_7)+e^-(p_8)+\bar b(p_6))+H(p_9+p_{10})$	LO
196	$t(\to\nu(p_3)+e^+(p_4)+b(p_5))+\bar t(\to\bar\nu(p_7)+e^-(p_8)+\bar b(p_6))+Z(e^-(p_9),e^+(p_{10}))$	LO
197	$t(\to\nu(p_3)+e^+(p_4)+b(p_5))+\bar t(\to\bar\nu(p_7)+e^-(p_8)+\bar b(p_6))+Z(b(p_9),\bar b(p_{10}))$	LO
201	$H(\to b(p_3)+b(p_4))+f(p_5)$ [full mt dep.]	LO
202	$H(\to\tau^-(p_3)+\tau^+(p_4))+f(p_5)$ [full mt dep.]	LO
203	$H(\to b(p_3)+\bar b(p_4))+f(p_5)$	NLO
204	$H(\to\tau^-(p_3)+\tau^+(p_4))+f(p_5)$	NLO
206	$A(\to b(p_3)+\bar b(p_4))+f(p_5)$ [full mt dep.]	LO
207	$A(\to\tau^-(p_3)+\tau^+(p_4))+f(p_5)$ [full mt dep.]	LO
211	$H(\to b(p_3)+\bar b(p_4))+f(p_5)+f(p_6)$ [WBF]	NLO
212	$H(\to\tau^-(p_3)+\tau^+(p_4))+f(p_5)+f(p_6)$ [WBF]	NLO
216	$H(\to b(p_3)+\bar b(p_4))+f(p_5)+f(p_6)+f(p_7)$ [WBF+jet]	NLO
217	$H(\to\tau^-(p_3)+\tau^+(p_4))+f(p_5)+f(p_6)+f(p_7)$ [WBF+jet]	NLO
221	$\tau^-(\to e^-(p_3)+\bar\nu_e(p_4)+\nu_\tau(p_5))+\tau^+(\to\bar\nu_\tau(p_6)+\nu_e(p_7)+e^+(p_8))$	LO

nproc	$f(p_1)+f(p_2)\to\ldots$	Order
261	$Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)$	NLO
262	$Z^0(\to e^-(p_3)+e^+(p_4))+c(p_5)$	NLO
263	$Z^0(\to e^-(p_3)+e^+(p_4))+\bar b(p_5)+b(p_6)$ [1 b-tag]	NLO
264	$Z^0(\to e^-(p_3)+e^+(p_4))+\bar c(p_5)+c(p_6)$ [1 c-tag]	NLO
266	$Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)(+\bar b(p_6))$	NLO
267	$Z^0(\to e^-(p_3)+e^+(p_4))+c(p_5)(+\bar c(p_6))$	NLO
271	$H(b(p_3)+\bar b(p_4))+f(p_5)+f(p_6)$ [in heavy top limit]	LO
272	$H(\tau^-(p_3)+\tau^+(p_4))+f(p_5)+f(p_6)$ [in heavy top limit]	LO
311	$f(p_1)+b(p_2)\to W^+(\to\nu(p_3)+e^+(p_4))+b(p_5)+f(p_6)$	LO
316	$f(p_1)+b(p_2)\to W^-(\to e^-(p_3)+\bar\nu(p_4))+b(p_5)+f(p_6)$	LO
321	$f(p_1)+b(p_2)\to W^+(\to\nu(p_3)+e^+(p_4))+c(p_5)+f(p_6)$	LO
326	$f(p_1)+b(p_2)\to W^-(\to e^-(p_3)+\bar\nu(p_4))+c(p_5)+f(p_6)$	LO
331	$W^+(\to\nu(p_3)+e^+(p_4))+c(p_5)+f(p_6)$ [c-s interaction]	LO
336	$W^-(\to e^-(p_3)+\bar\nu(p_4))+c(p_5)+f(p_6)$ [c-s interaction]	LO
902	[Check of Volume of 2 particle phase space]	–
903	[Check of Volume of 3 particle phase space]	–
904	[Check of Volume of 4 particle phase space]	–
905	[Check of Volume of 5 particle phase space]	–
906	[Check of Volume of 6 particle phase space]	–
908	[Check of Volume of 8 particle phase space]	–
909	[Check of Volume of 4 particle massive phase space]	–
910	[Check of Volume of 3 particle (2 massive) phase space]	–

Tools of the Trade

- Fixed-order perturbation theory
- All-order perturbation theory
  - Identification of large logarithmic terms at every order
  - Evolution (Altarelli–Parisi , BFKL)
  - Exponentiation and resummation (Sudakov)
  - Only possible for well-defined observables
  - Numerical resummation (parton showers)
- ‘Best of both’
- Non-perturbative fits and models
- Analysis tools

All Orders Resummation

- For cross sections that force us close to phase space boundary, real–virtual cancellation spoiled $\rightarrow$ large logarithms
- Cross sections can be calculated by recurrence relations or evolution equations $\rightarrow$ multiple emissions factorize
- Must ensure observable does not disturb factorization

$\rightarrow$ Possible only for limited set of observables

- Rule of thumb: $P(\text{no emission}) = \exp\left\{-P_0(\text{emission})\right\}$

  (Sudakov form factor) (exponentiation)

eg Thrust Distribution

- Thrust→1 ⇒ very two-jet-like events
- Suppression of radiation harder than 1–T
- Leading order probability of radiation harder than 1–T:

$$C_F \frac{\alpha_s}{2\pi} 2L^2 \quad (L = \log 1 - T)$$

⇒ all orders probability for thrust above T

$$e^{-C_F \frac{\alpha_s}{2\pi} 2L^2}$$

- State of the art:
  - next-to-leading log generalized exponentiation:

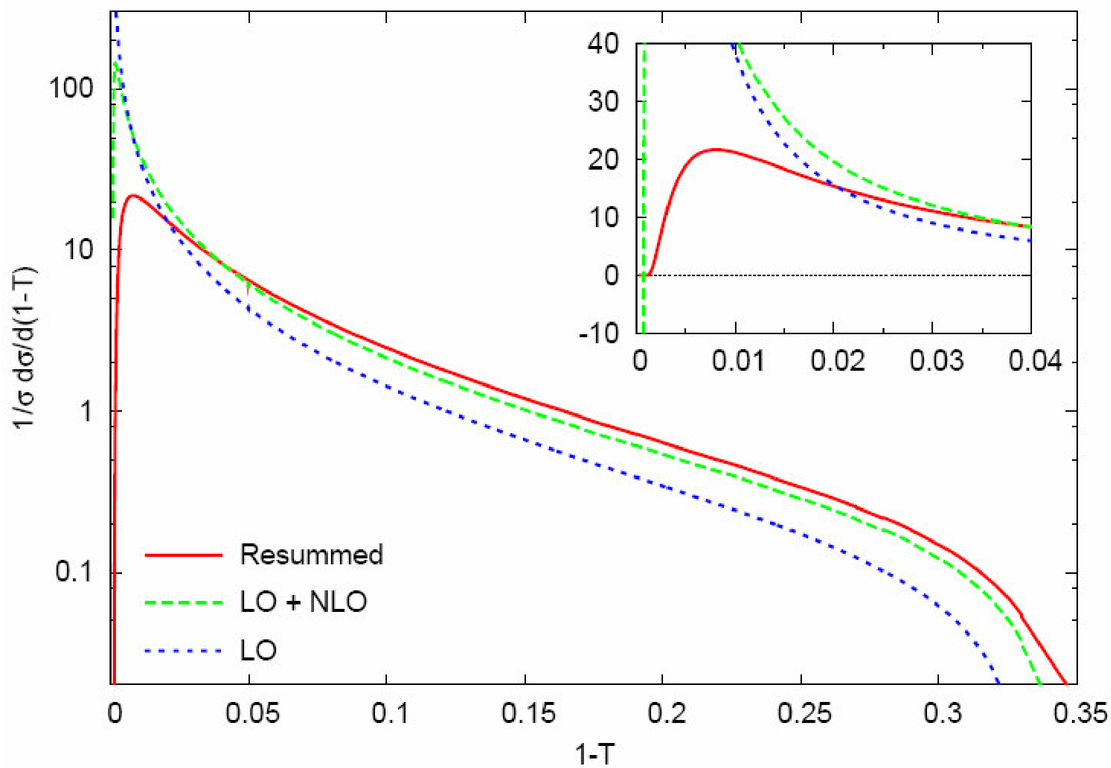
$$(1 + C\alpha_s) e^{-Lg_1(\alpha_s L) + g_2(\alpha_s L)}$$

Leading log: sums terms like $\alpha_s^n L^{n+1}$

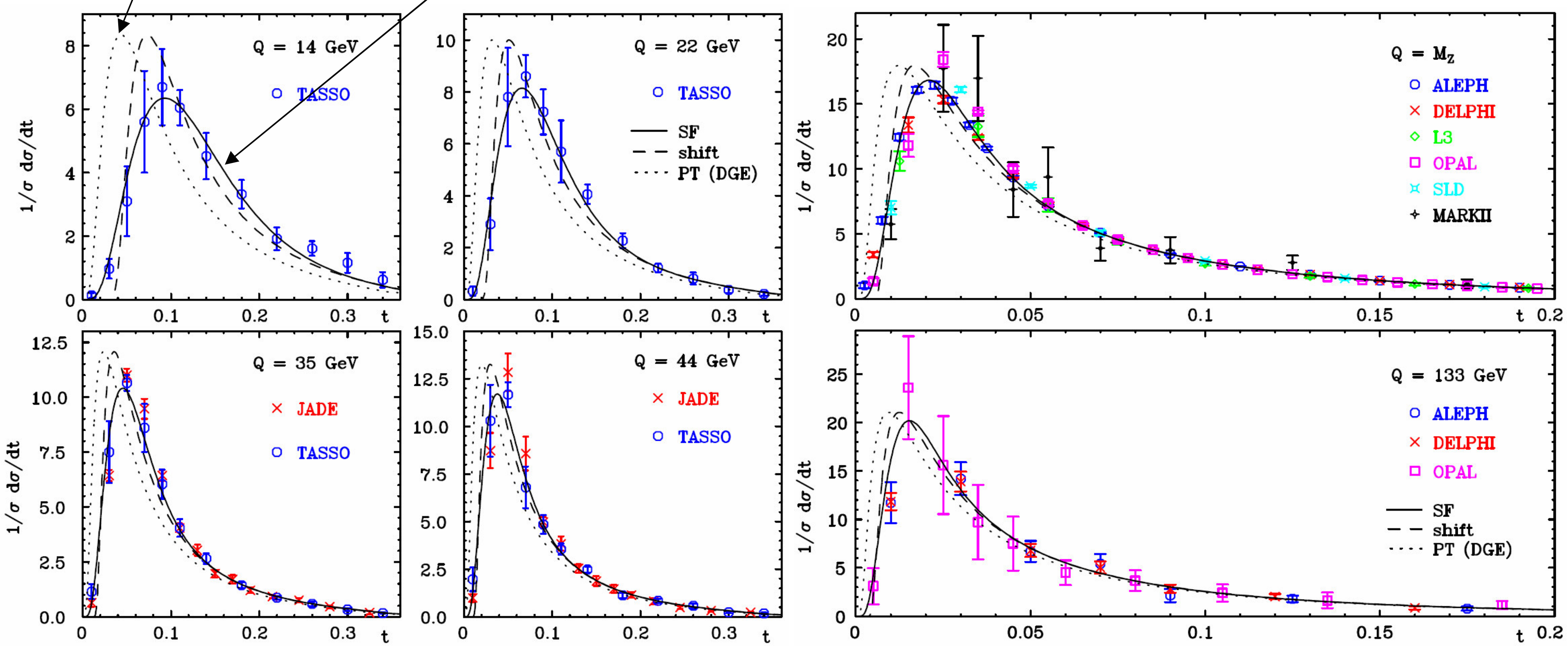
Next-to-leading log: sums terms like $\alpha_s^n L^n$

- Effect of resummation

M. Dasgupta and G. Salam, J. Phys. G30 (2004) R143



- Resummation alone not enough to fit data also need non-perturbative power corrections (shape functions)

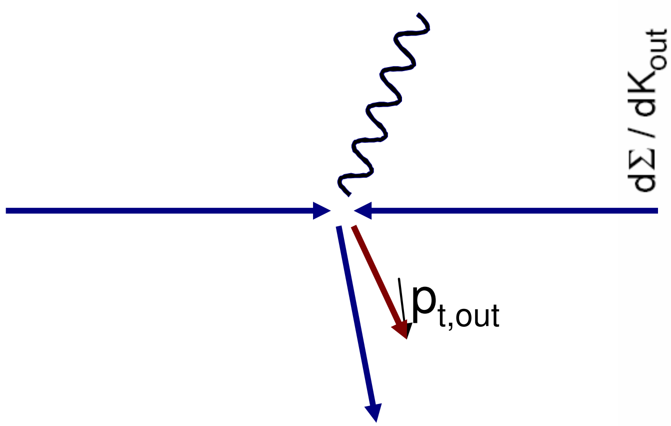


E. Gardi and J. Rathsman, Nucl. Phys. B609 (2001) 123

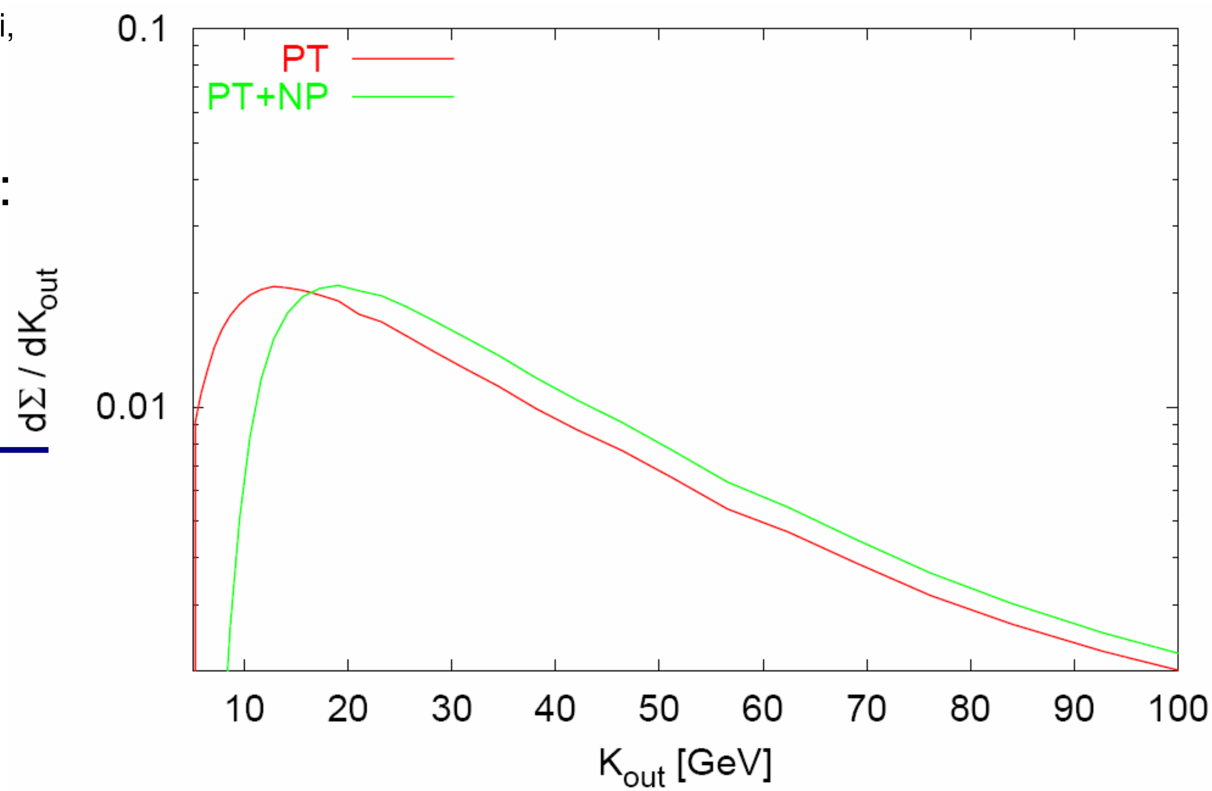
Event Shapes in hadron–hadron collisions

- In their early days
  - ‘transverse thrust’
  - ‘K_{out}’ (A. Banfi, G. Marchesini, G. Smye and G. Zanderighi, JHEP 0108 (2001) 047)

  High-p_t W/Z events:



$$K_{out} \equiv \sum_i |p_{t,out,i}|$$



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  - Only possible for well-defined observables
  - Numerical resummation (parton showers)
- ‘Best of both’
  - Parton showers with matrix element matching
- Non-perturbative fits and models
- Analysis tools

Parton Showers

- Numerical attempt to calculate all exclusive final states

$\rightarrow$ all orders calculation for any observable

- Must introduce resolution criterion: large logs

$\rightarrow$ evolution driven by Sudakov form factor

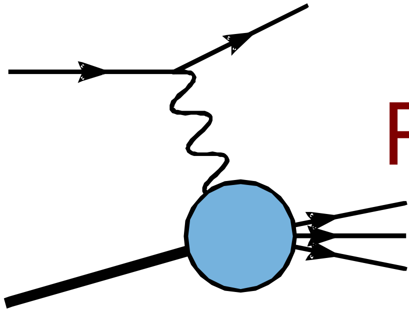
Matrix element matching

- Parton shower accurate in soft and collinear limits
  model dependent extrapolation to hard emission
- Fixed order accurate for hard well separated partons
  divergent in soft and collinear regions

$\rightarrow$ need to combine

Tools of the Trade

- Fixed-order perturbation theory
- All-order perturbation theory
- ‘Best of both’
- Non-perturbative fits and models
  - Parton distribution functions
  - Fragmentation functions
  - Hadronization models
  - Underlying event models
- Analysis tools



Parton Distribution Functions

- Cross section for deep inelastic scattering:

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\Big[(1+(1-y)^2)F_2(x,Q^2) - y^2 F_L(x,Q^2)\Big]$$

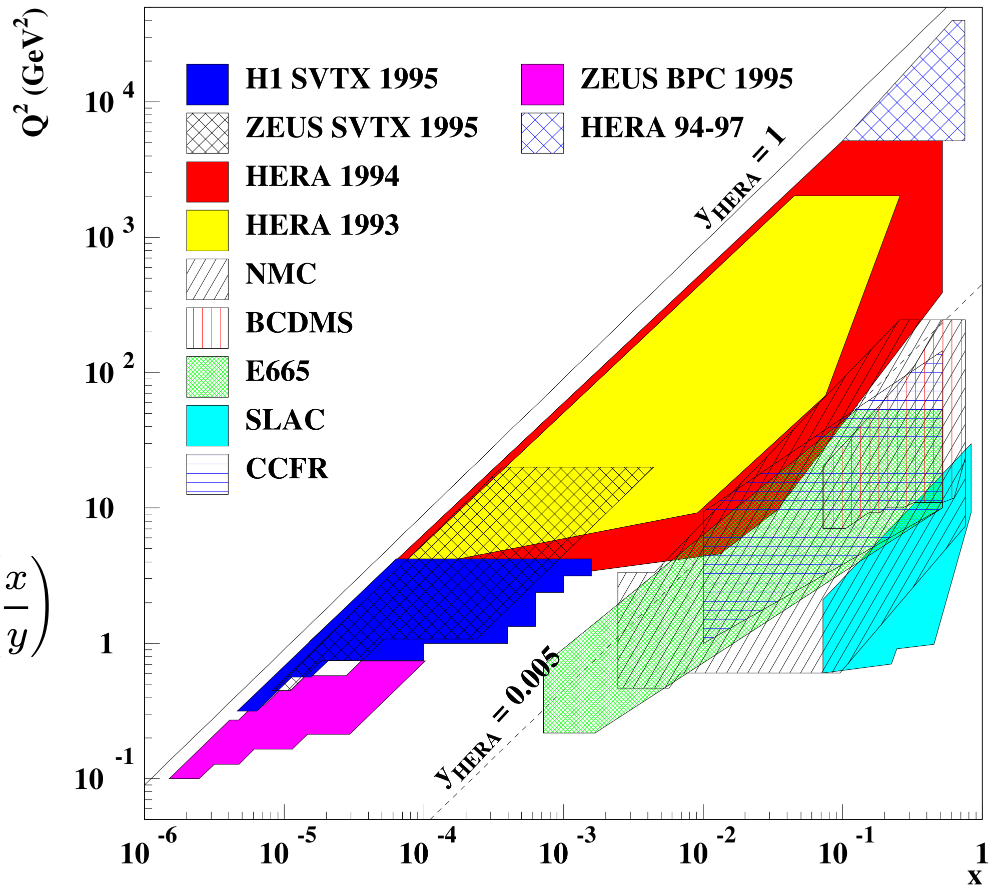
- Parton model:

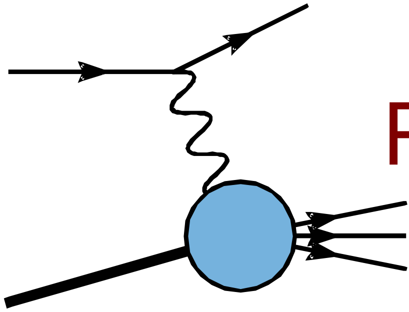
$$F_2(x,Q^2) = \sum_q e_q^2\, x\, f_q(x)$$

- Collinear factorization: Q^2-dep.
- DGLAP evolution:

$$f_q(x,Q^2) = \frac{\alpha_s}{2\pi}\log\frac{Q^2}{Q_0^2}\int_x^1 \frac{dy}{y} f_q(y,Q_0^2)\,P_{qq}\left(\frac{x}{y}\right) + \alpha_s^2 \log^2 \int\int + \dots$$

- pdf at some x and Q^2 point depends on pdf at all lower Q^2 and **higher x** values





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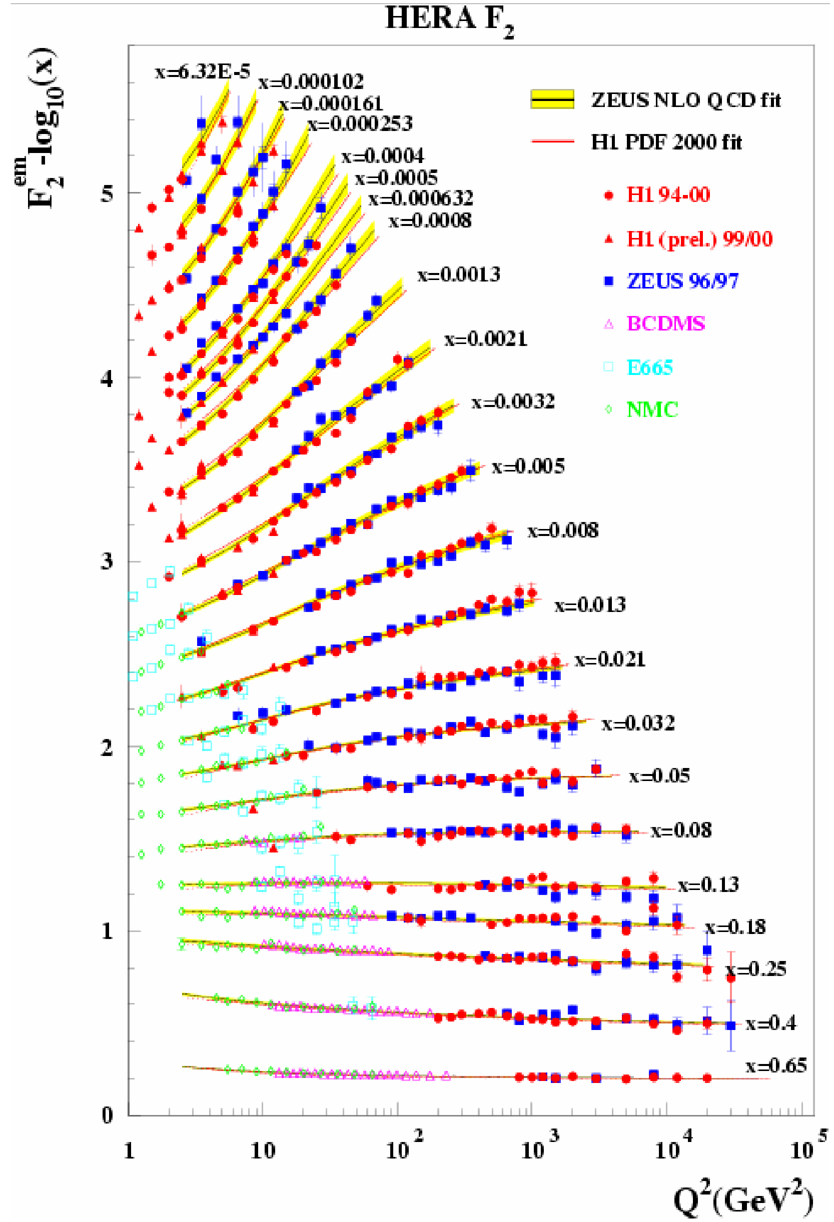


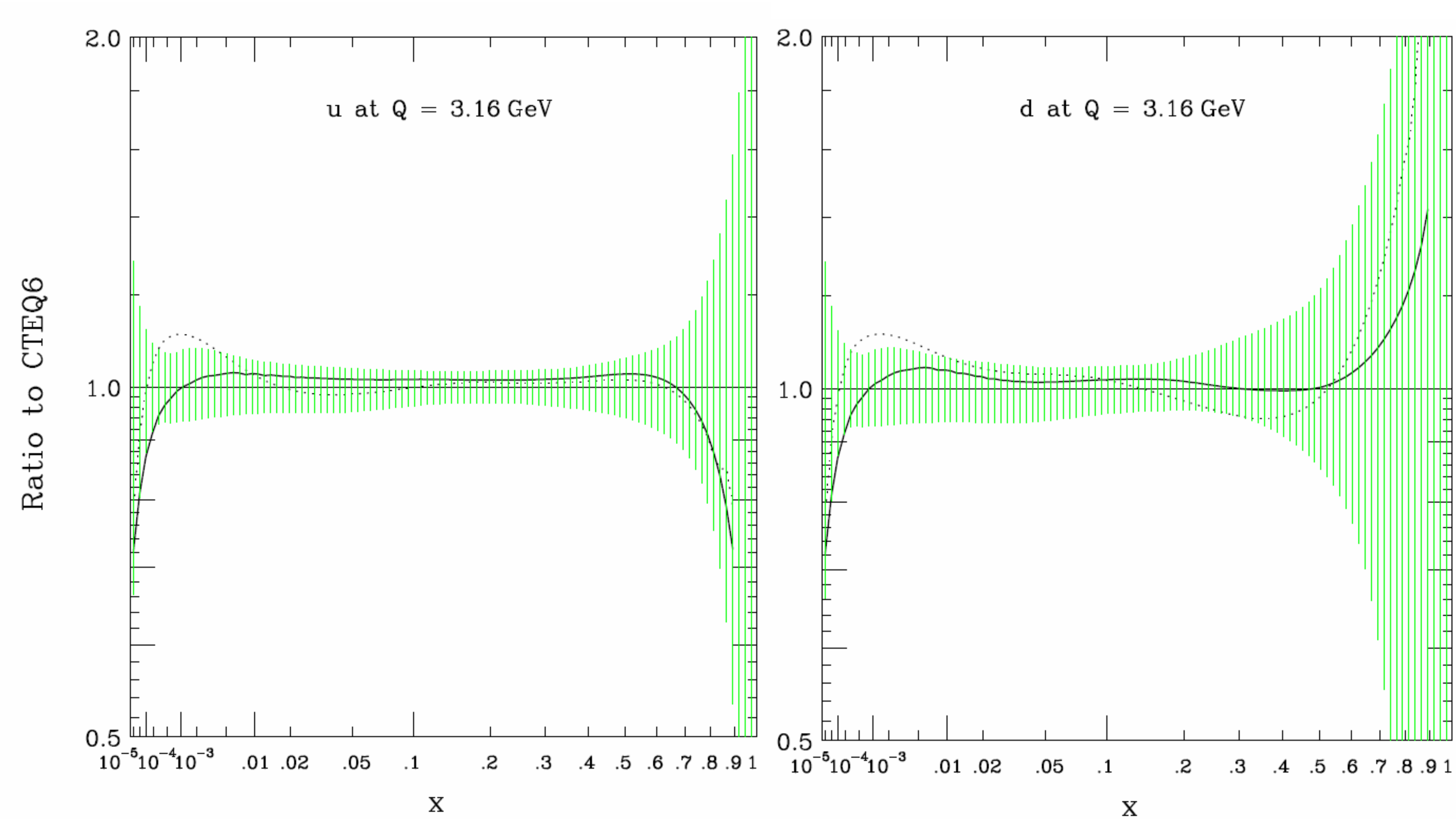
Global Fits

- State of the art: NLO cross sections with NLO evolution
  - Deep Inelastic Scattering (NNLO starting to be used)
    - electron/positron/neutrino/antineutrino
    - neutral current/charged current
    - proton/deuterium/nuclear targets
    - charm-tagged final states
  - Drell–Yan production (hh$\rightarrow$ll+X)
    - fixed target (virtual photon)
    - W/Z production and forward/backward asymmetry
  - Tevatron high–E_T jet data
    - rapidity–dependence crucial
    - cf previous high–E_T excess

Global Fits

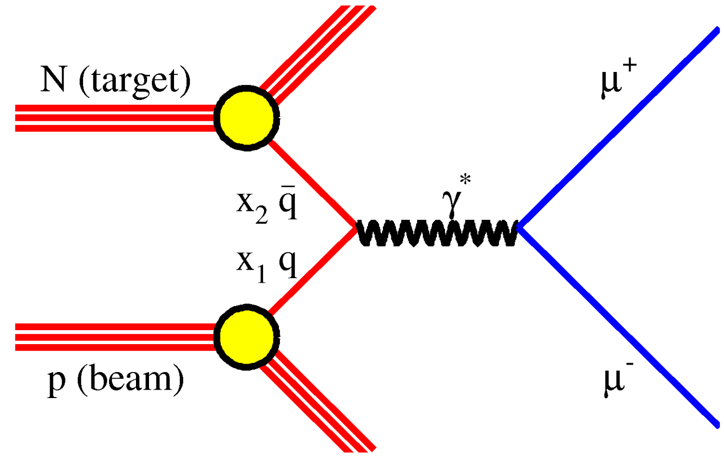
- State of the art: NLO cross sections with NLO evolution
- Global fits are reperformed $\sim$ once every two years
  - Martin, Roberts, Stirling and Thorne (MRST)
  - a Coordinated Theoretical and Experimental project for QCD (CTEQ)
- pdfs now come with uncertainties
  - propagated from experimental errors
  - uncertainties due to theoretical assumptions?

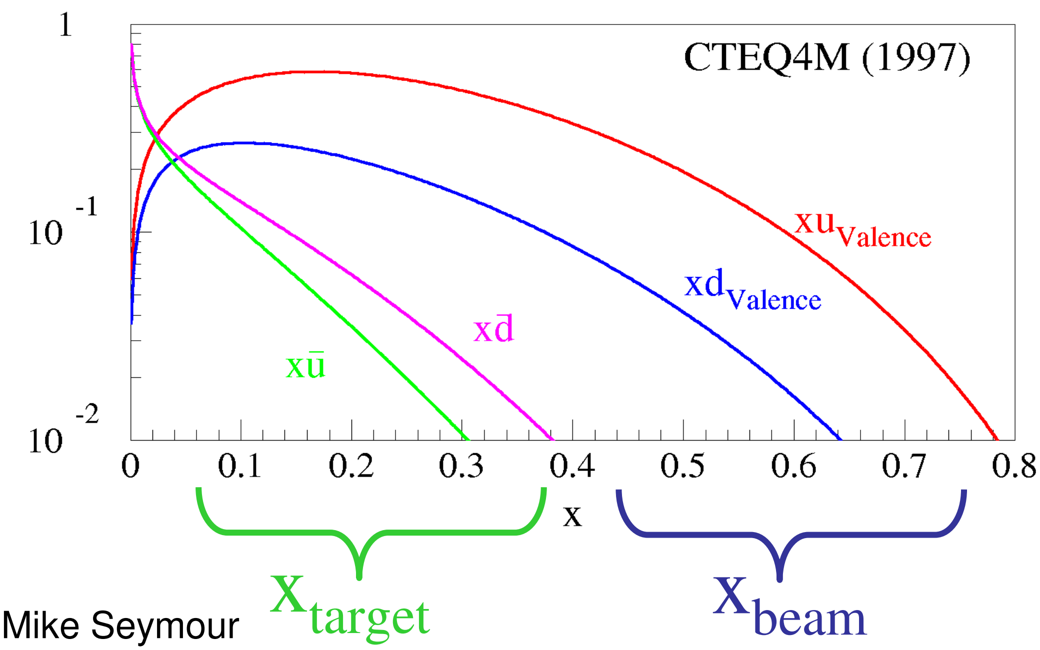
- Valence quarks very well known at intermediate x
- Gluons and sea quarks less so
- All poor at large x



Drell–Yan Production in p–p

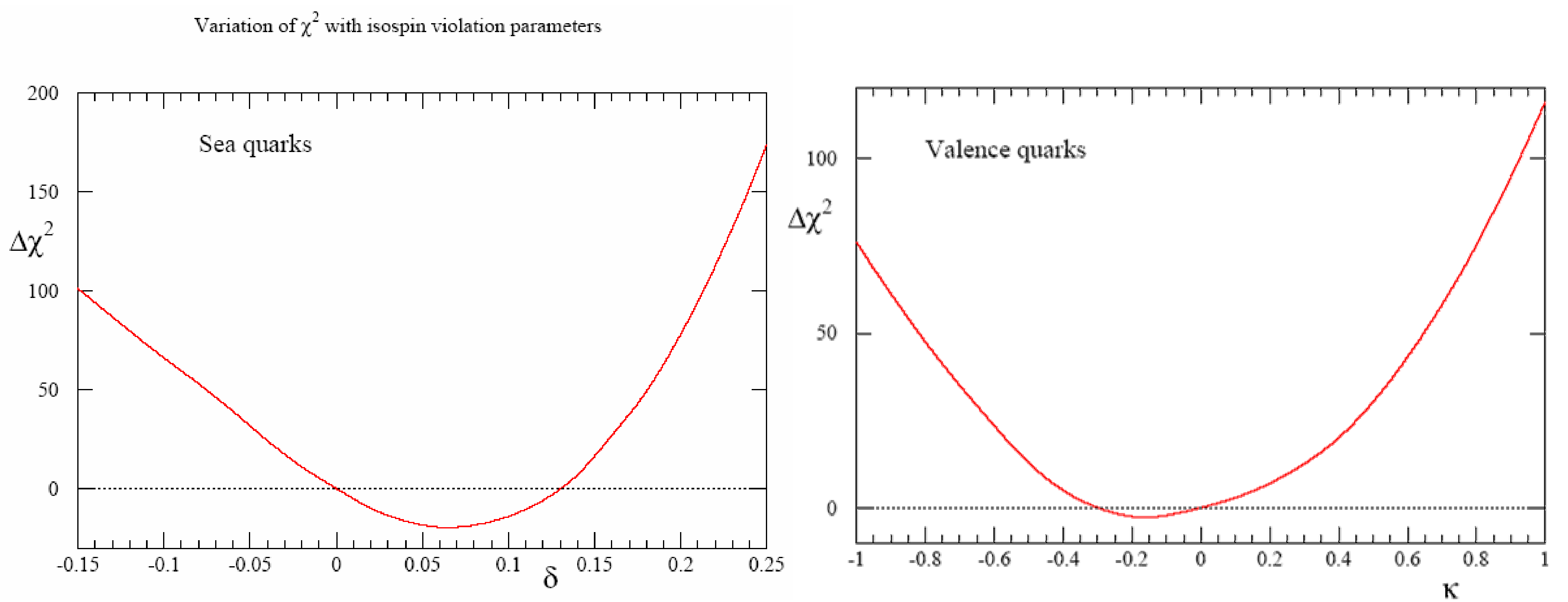
- Global fits dominated by HERA data, but don't forget fixed target DIS and Drell–Yan
- Best way to measure sea quark distributions
- Separate $\bar{d}$ and $\bar{u}$ shapes
- Fermilab E866/NuSea experiment





Isospin Violation in Valence Distributions

- Isospin $\Rightarrow f_{u/p}(x,Q^2) = f_{d/n}(x,Q^2)$ etc
- Models of explicit isospin violation at low $Q^2 \rightarrow$ small
- Global fit (MRST) $\Rightarrow \sim 0.5\%$ violation in momentum sum



A.D.Martin, R.G.Roberts, W.J.Stirling and R.S.Thorne, hep-ph/0308087

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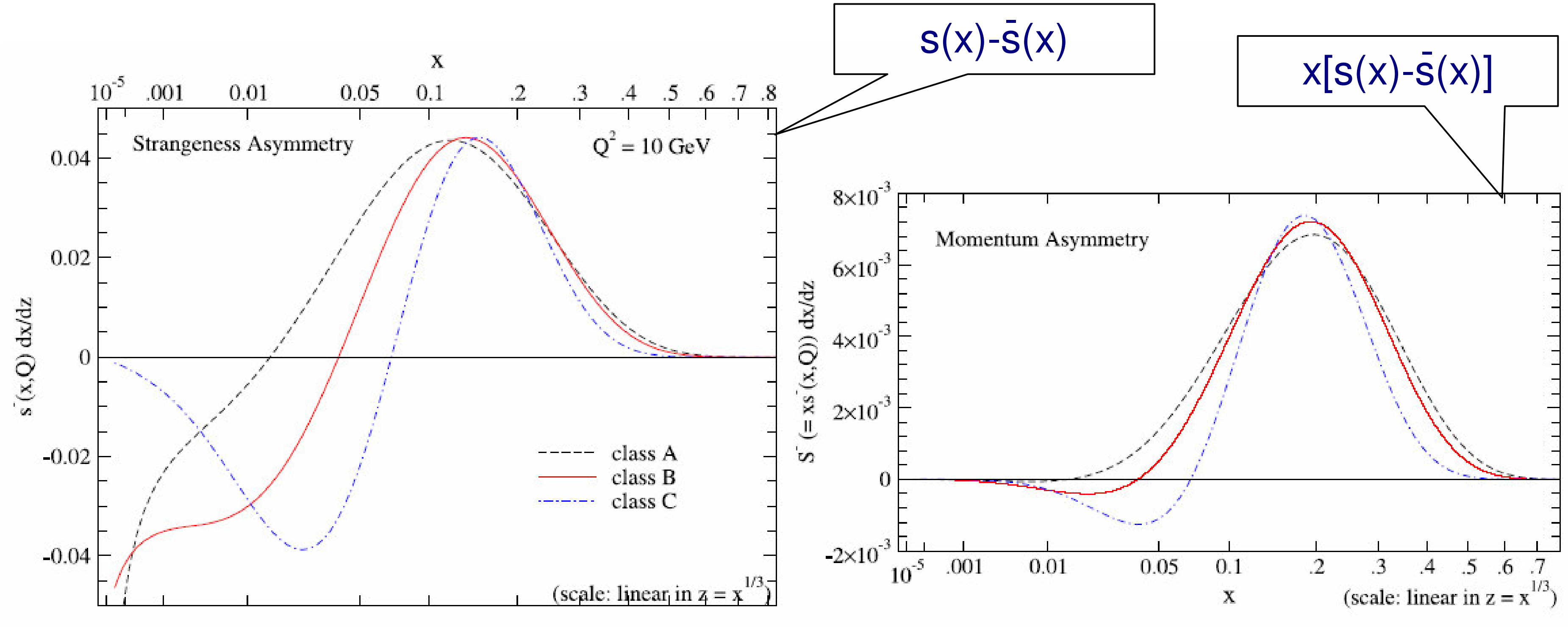
- Models of explicit isospin violation at low $Q^2 \to$ small
- Global fit (MRST) $\Rightarrow \sim$ 0.5% violation in momentum sum
- QED effects in evolution equation $\Rightarrow$ u quarks evolve faster than d quarks
- Next MRST set will include $f_{\gamma/p}$ and hence this source of isospin violation…

$\Rightarrow$ Important to have data on deuterium (isoscalar) targets (see later…)

Strange–Antistrange Asymmetry

- Strange quark distribution best measured from CC charm production, eg $\nu_\mu + s \to \mu^- + c$ (CCFR+NuTeV)
- CTEQ fits (Kretzer et al hep-ph/0312322) allow $s(x) \neq \bar{s}(x)$



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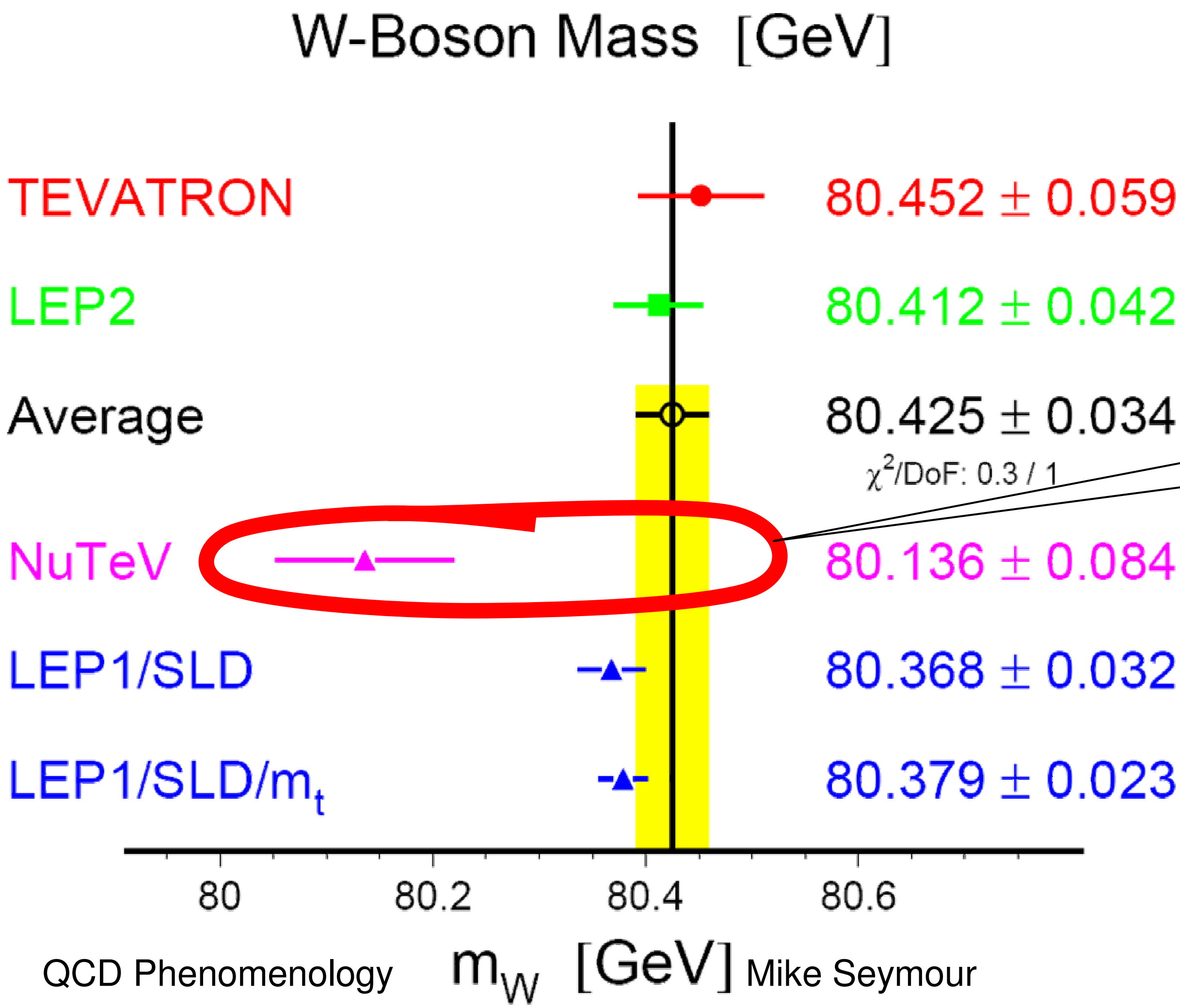
- CTEQ fits (Kretzer et al hep-ph/0312322) allow $s(x) \neq \bar{s}(x)$
- Results on $x[s(x) - \bar{s}(x)]$ stable >0

$\Rightarrow$ important to have sign-selected data

- NuTeV $\sin^2\theta_w$ measurement (from charged/neutral current ν DIS) relies on these effects being small
- $\sin^2\theta_w = (1-m_w^2/m_z^2) \Rightarrow m_w$ measurement



3σ discrepancy ?

Could be solved by ~0.5% isospin violation and/or strange asymmetry

Tools of the Trade

- Fixed-order perturbation theory
- All-order perturbation theory
- ‘Best of both’
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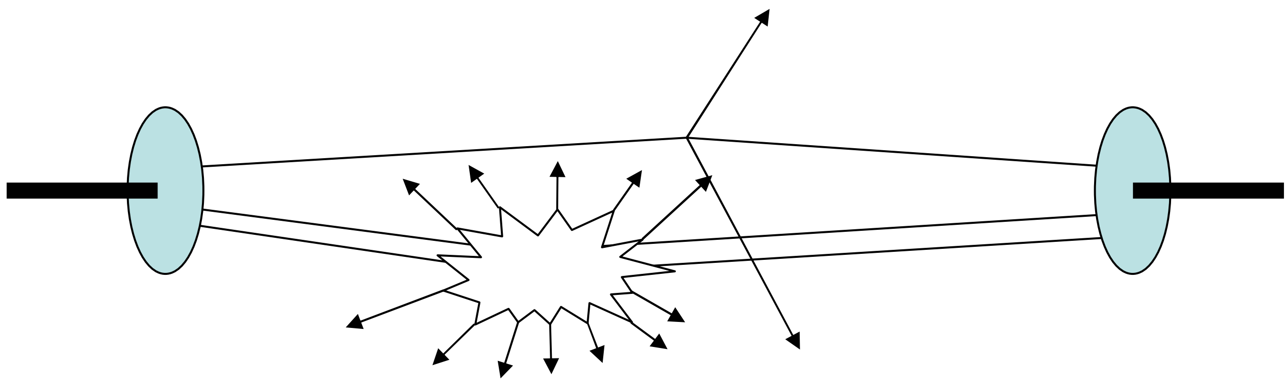
  - Underlying event models
- Analysis tools

What do we mean by the Underlying Event?

“Everything except the hard process”



but…

- initial state radiation
- factorization scale
- parton distribution functions
- parton evolution

→ underlying event model integral part of event model

Why should we be interested?

1. QCD

Connection with:

diffraction

saturation

confinement

total cross section

Can we predict/understand the properties of hadrons?

2. Experiments

Occupancy

Pile-up

Backgrounds

Why should we be interested?

2. Experiments
   - Occupancy
   - Pile-up
   - Backgrounds

3. Physics
   - Jet cross sections
   - Mass reconstruction
   - Rapidity gaps/jet vetoes
   - E_{miss} reconstruction
   - Photon/lepton isolation
   - ⋮

"Don't worry, we will measure and subtract it"

But… fluctuations and correlations crucial

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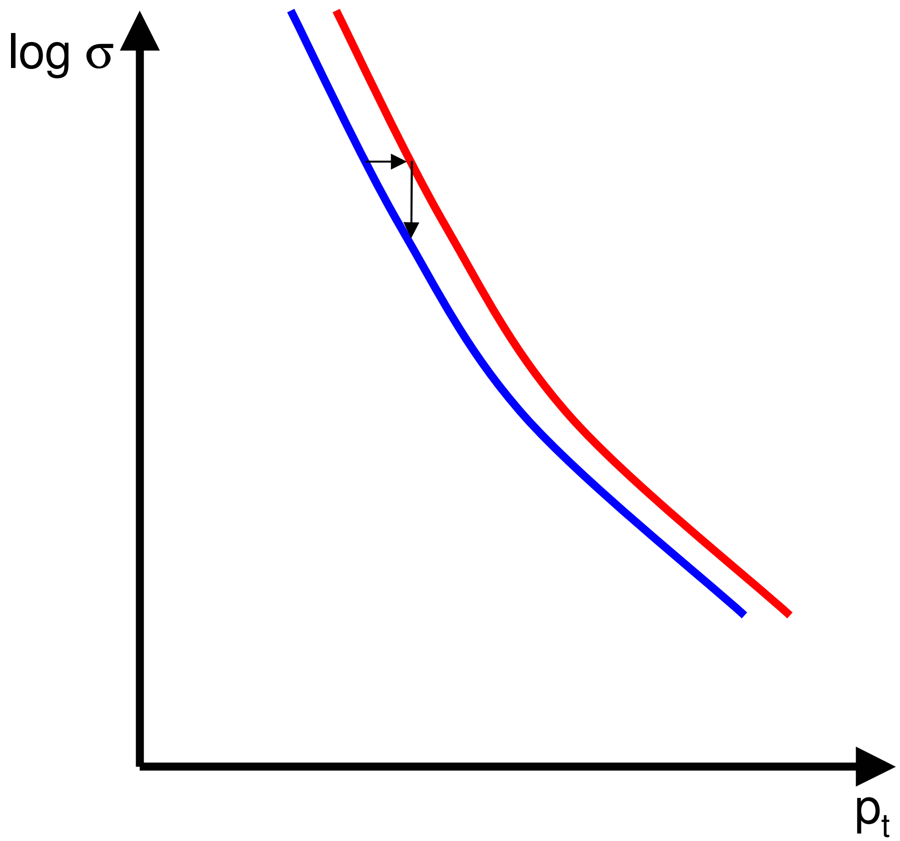
Fluctuations and correlations



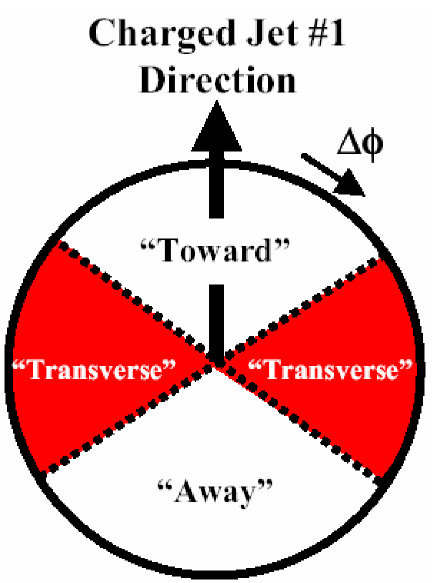
Steep distribution ⇒ small sideways shift = large vertical

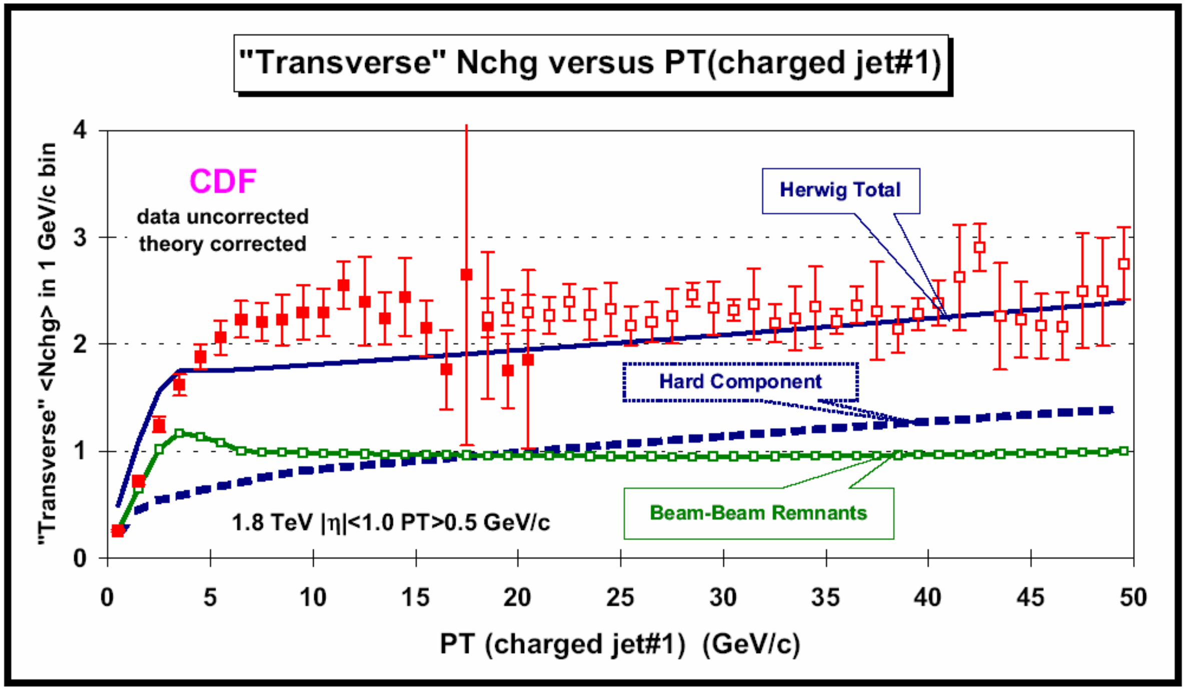
Rare fluctuations can have a huge influence

⇒ corrections depend on physics process

How do we Measure Underlying Event?

- “Transverse” region of two-jet events



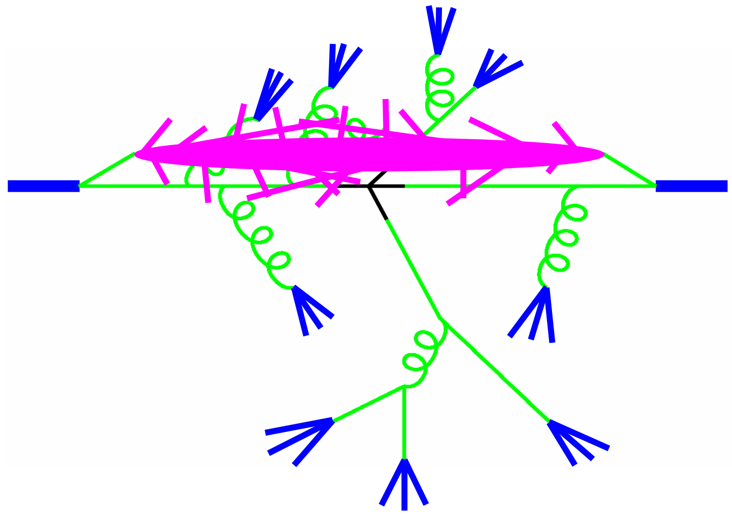


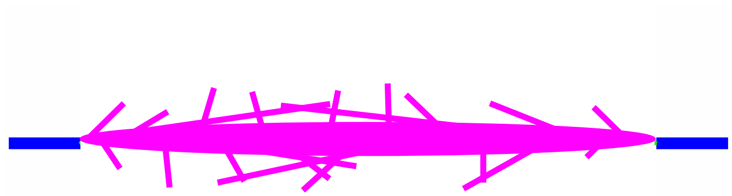
http://www.phys.ufl.edu/~rfield/cdf/chgjet/chgjet_intro.html

HERWIG's Soft Underlying Event model

G.Marchesini & B.R.Webber, PRD38(1988)3419

Compare underlying event with 'minimum bias' collision

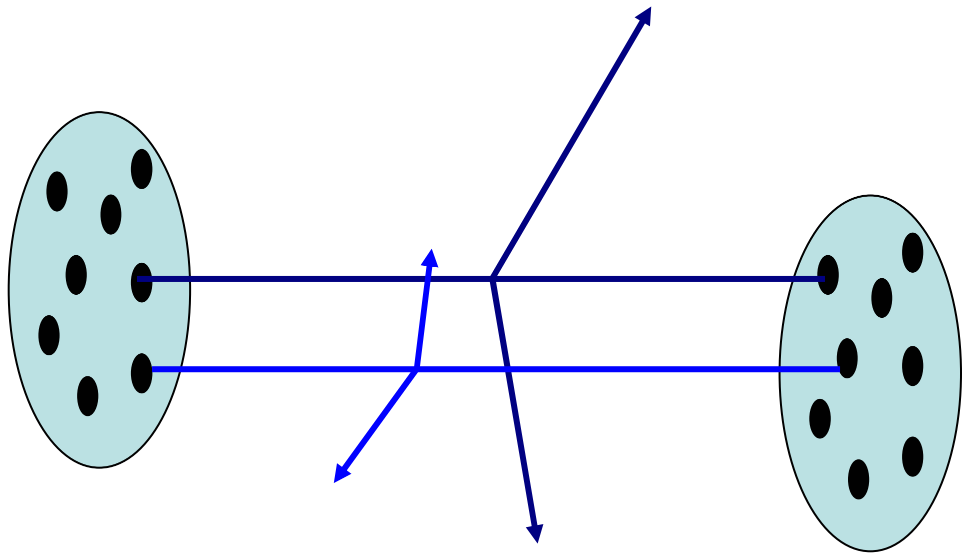




Parameterization of (UA5) data

+ model of energy-dependence

Multiparton Interactions



- Assume p–p collision ≈ local instantaneous sampling of two disks of partons

→ Can have several perturbative scatters within one event

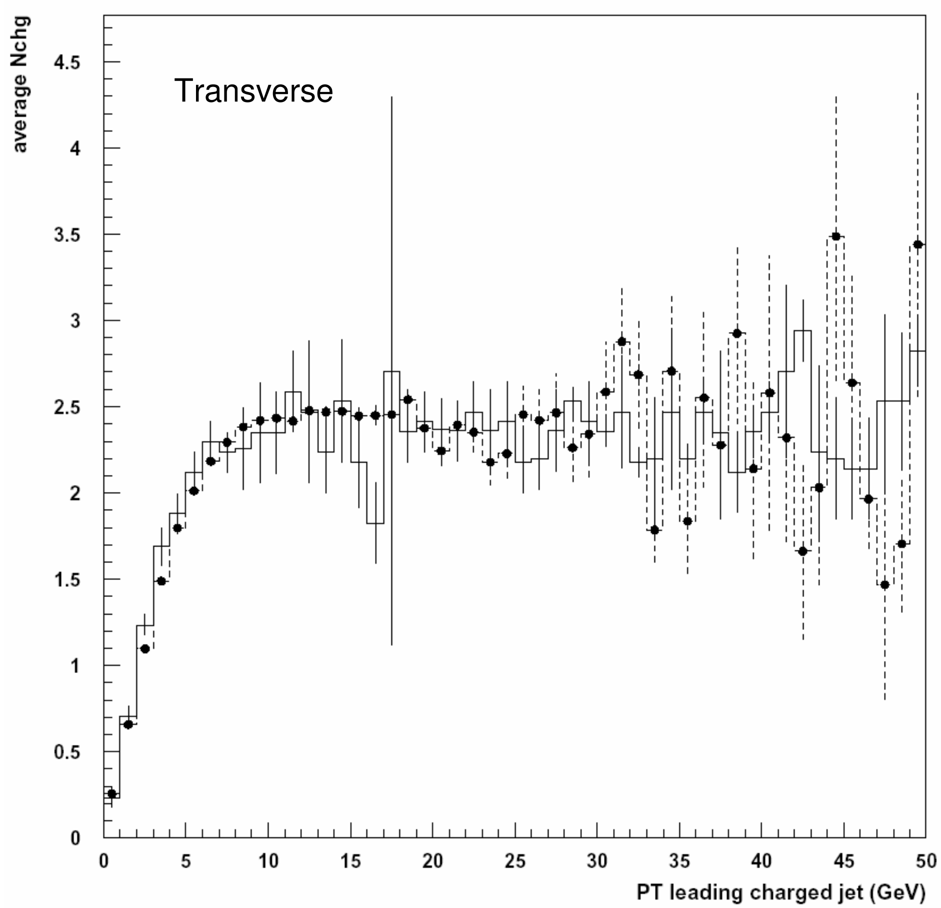
- PYTHIA and Jimmy (add-on for HERWIG)
- Low p_t scatters → underlying event

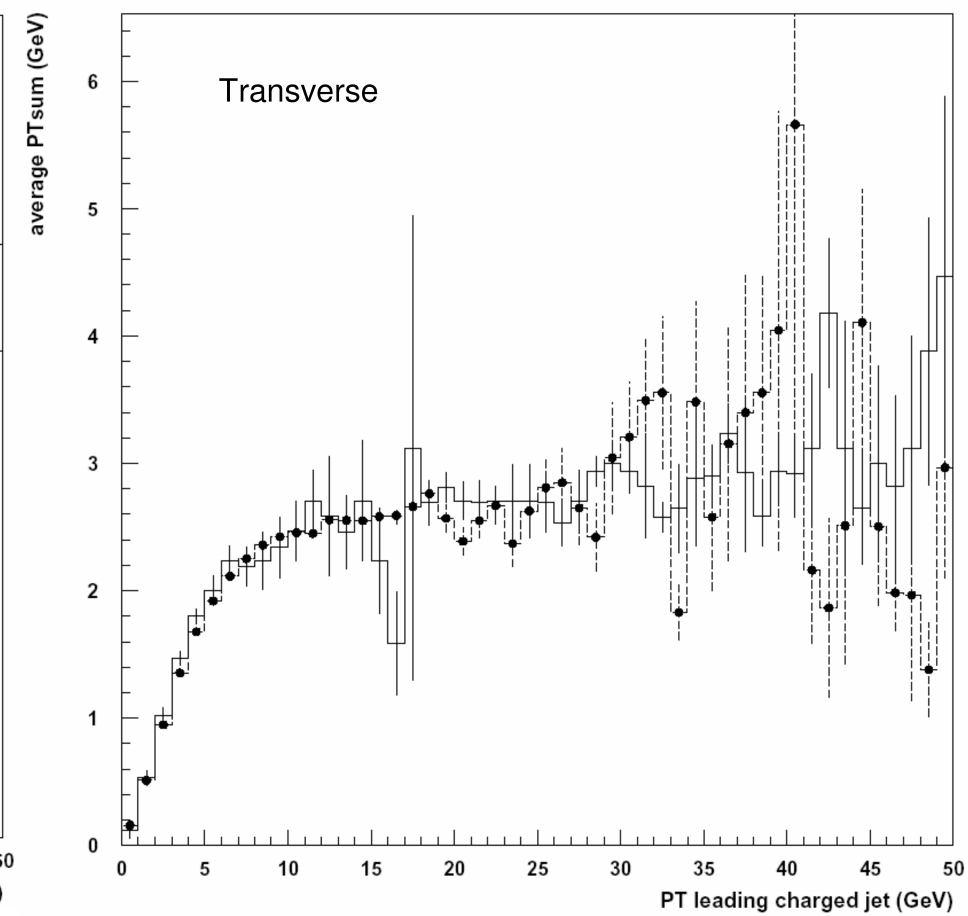
Proton Radius parameter within Jimmy

I.Borozan, PhD thesis, unpublished

- Increasing μ^2 to 2 GeV^2 (i.e. decreasing proton radius by 40%) with ptmin=3 GeV gives

~ perfect description of Tevatron data…



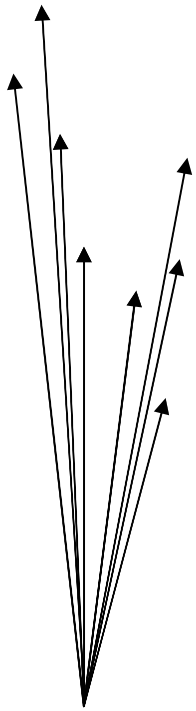


Tools of the Trade

- Fixed-order perturbation theory
- All-order perturbation theory
- ‘Best of both’
- Non-perturbative fits and models
- Analysis tools
  - Event shapes
  - Jet algorithms
  - ‘Event definitions’

Jet Algorithms

- Leading order: a parton is a jet
- But…

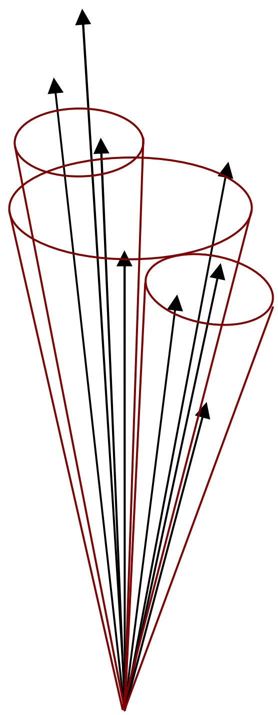


one jet or two?

- Need an algorithmic jet definition

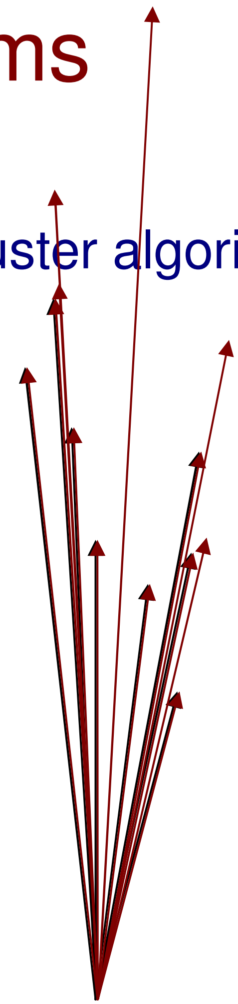
Jet Algorithms

- Cone algorithm



Depends on energy flow relative to cone radius R

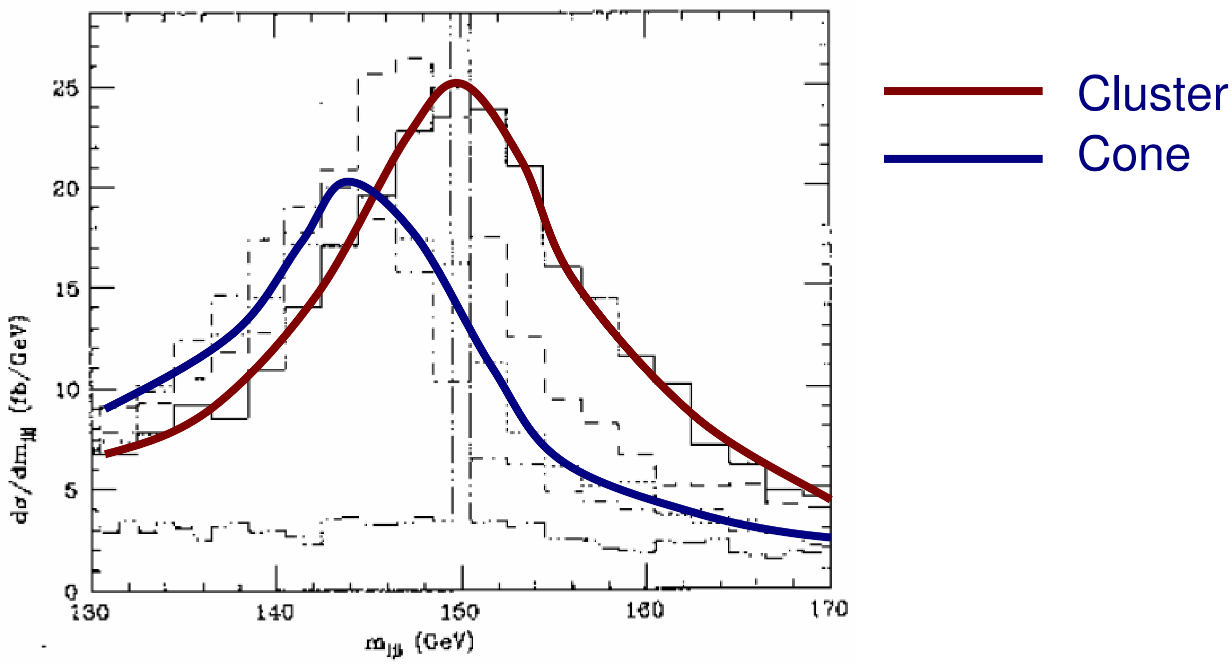
- Cluster algorithm



Depends on separation of subjets relative to cutoff R

Jet Algorithms

- Cone vs cluster algorithm MHS, Z.Phys.C62(1994)127
- Top mass reconstruction as a test case



- Update in progress (Chris Tevlin, ATLAS student)

Summary

- Every measurement in a hadron collider involves doing QCD phenomenology!
- Most involve a long chain of corrections
  - higher orders
  - parton distribution functions
  - jet algorithm
  - hadronization
  - underlying event

  to connect measurement to physics
- Always ask how well these corrections are known:
  - how much am I relying on QCD phenomenology?
  - how well understood is it?