Precision physics at the LHC

HERA-LHC Workshop,
Second plenary meeting
Oct 11-13, CERN

Michelangelo Mangano
TH Division
CERN, Geneva, Switzerland

Theoretical ingredients

- Higher-order matrix elements
  - multiloop computations
  - multilegged LO calculations
  - calculation of differential spectra in presence of cuts at (N)NLO
- Accurate PDFs
  - systematic uncertainties
  - NNLO fits
  - direct use of LHC data?
- Reliable merging with shower MC
  - progress in description of multijet final states
  - merging of NLO and shower (MC@NLO)
- Accurate description of hadronization, underlying event
  - development of new models, with increased realism and more knobs to allow tuning
  - strong efforts to make exp data available for MC tunings

Recent progress in precision tools

- Progress towards fully differential NNLO predictions Atanasiou, Dixon, Melnikov, Petriello
- New NLO parton-level event generators ➪ MCFM (Campbell-Ellis); pp→3jets@NLO (Z.Nagy), ...
- NLO matrix elements in shower MC's (Dobbs (**2001**), Grace (**2002**), MC@NLO, (**2003**)
- New incarnation of old MC codes. Pythia/Herwig=>C++ (**2003**) with
  - new features, better QCD, better hadronization
- New shower MC codes (**Sherpa**: Gleisber, Höche,Krauss, Schälicke, Schumann, Winter, **2003**), with new:
  - shower algorithms
  - hadronization schemes
- Implementation of new techniques for merging of multijet ME's and shower MC's (Catani, Krauss, Kuhn, Webber (**2001**), Lönnblad (**2002**), MLM (**2002**), Mrenna&Richardson (**2003**))
- Continued improving of PDF fits and understanding of their systematics

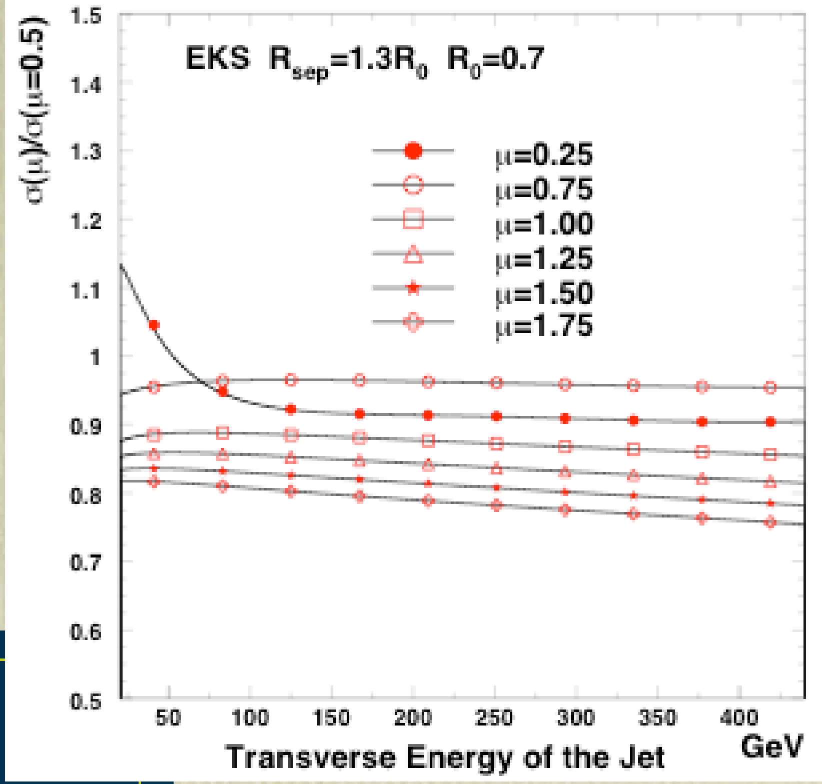
- Progress in all of the above fields has been remarkable in the past few years, and we heard about recent developments during the parallel sessions
- Accurate calculations are not however sufficient:
  - The complexity of the LHC environment is such that tools accuracy must be validated directly on the data
  - The definition and the evaluation of validation strategies will therefore play a very important role in the success of a precision physics programme at the LHC

Contents

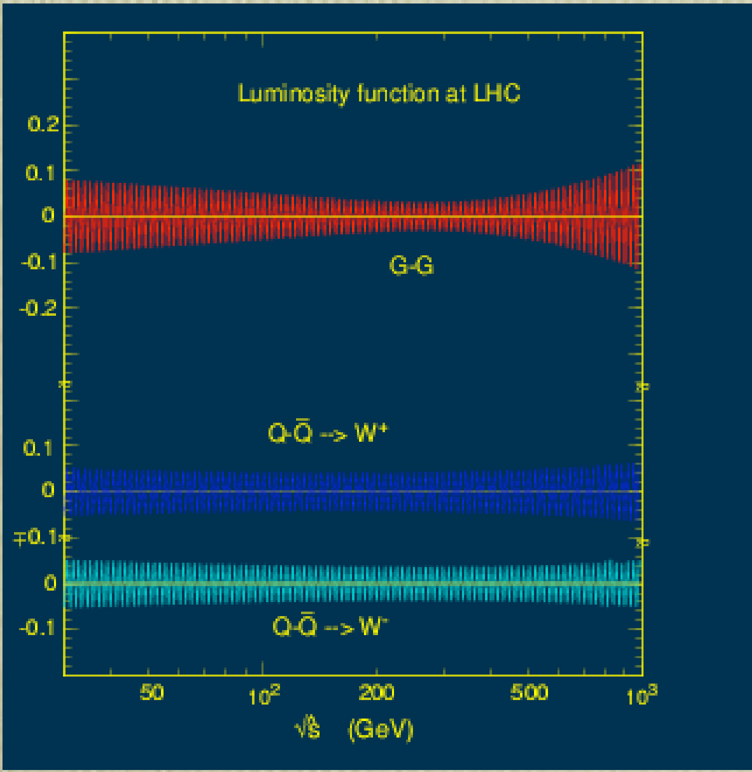
- Jet physics
- W/Drell-Yan physics
- Top physics
- Underlying event

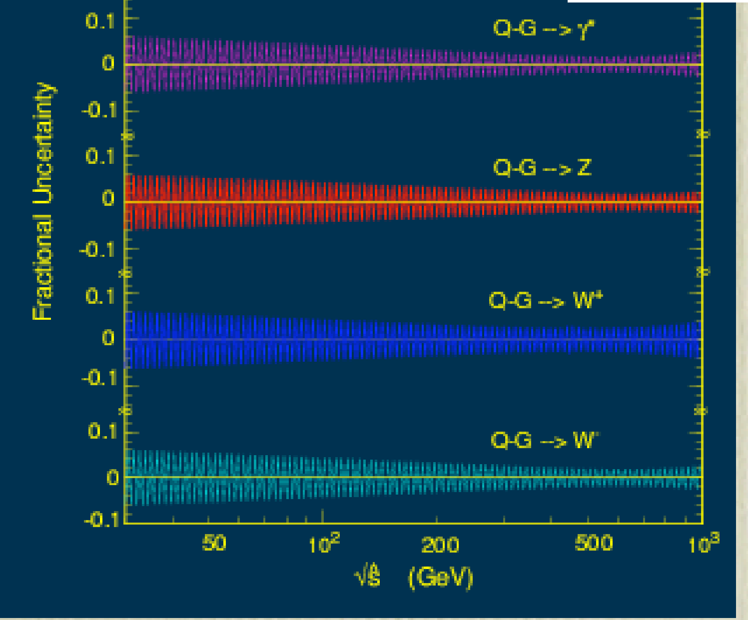
Jet processes

1. Inclusive jets



Theoretical syst uncertainty at NLO
(from scale variation) ~ +-10-20%





PDF uncert
(mostly g(x))
growing at large x

What can the Tevatron data teach us?

DO, run I data

Cone jets (R=0.7)

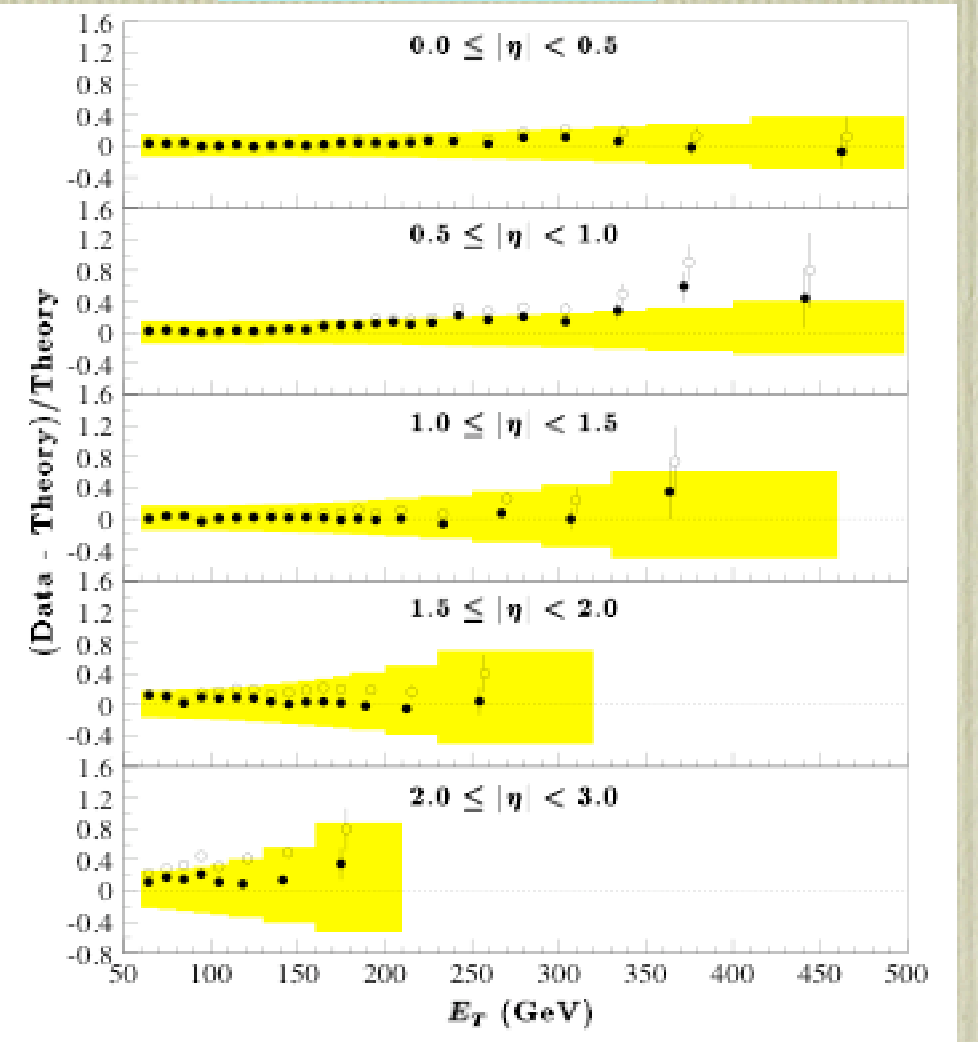


FIG. 3. Comparisons between the D0 single inclusive jet cross sections and the $\mathcal{O}(\alpha_s^3)$ QCD predictions calculated by JETRAD with the CTEQ4HJ (●) and CTEQ4M (○) PDFs. The highest E_T points are offset slightly for CTEQ4M.

k_T jets (D=1)

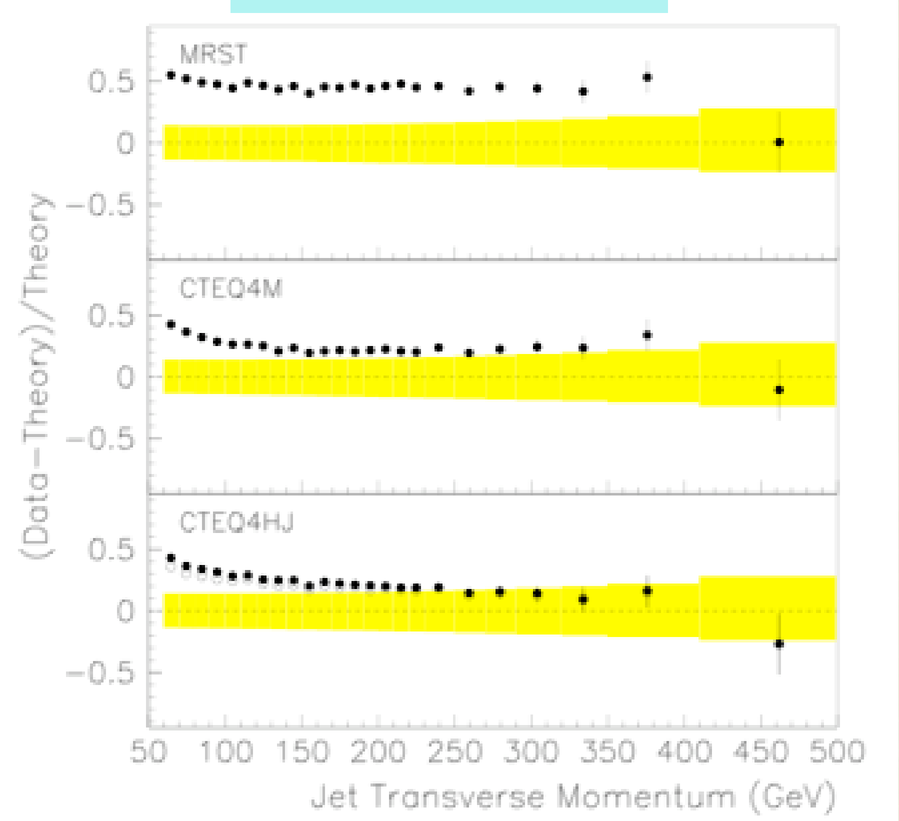
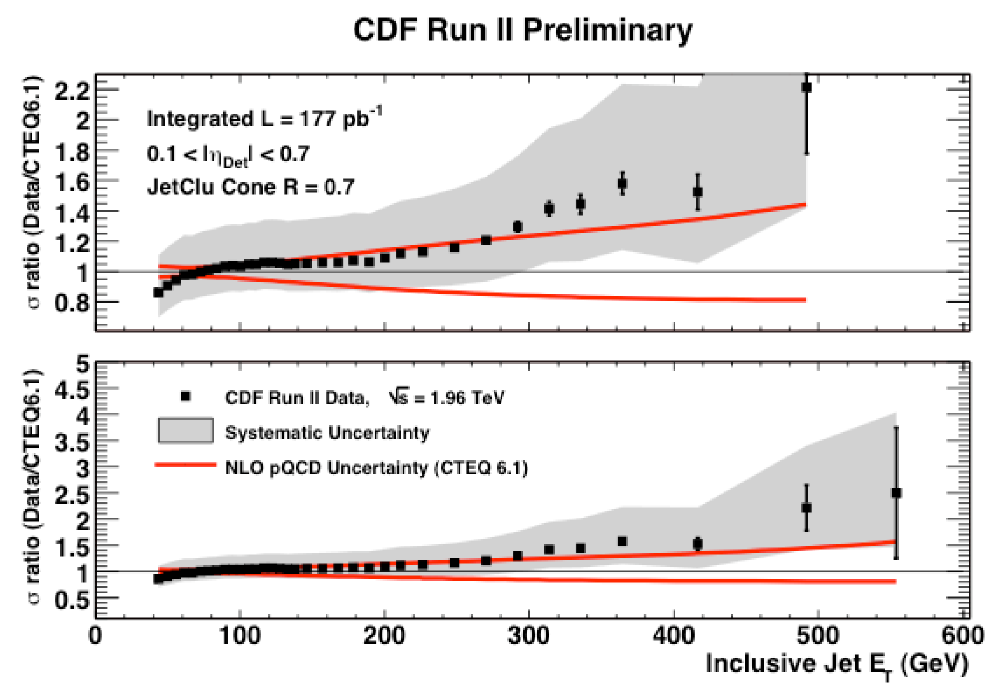


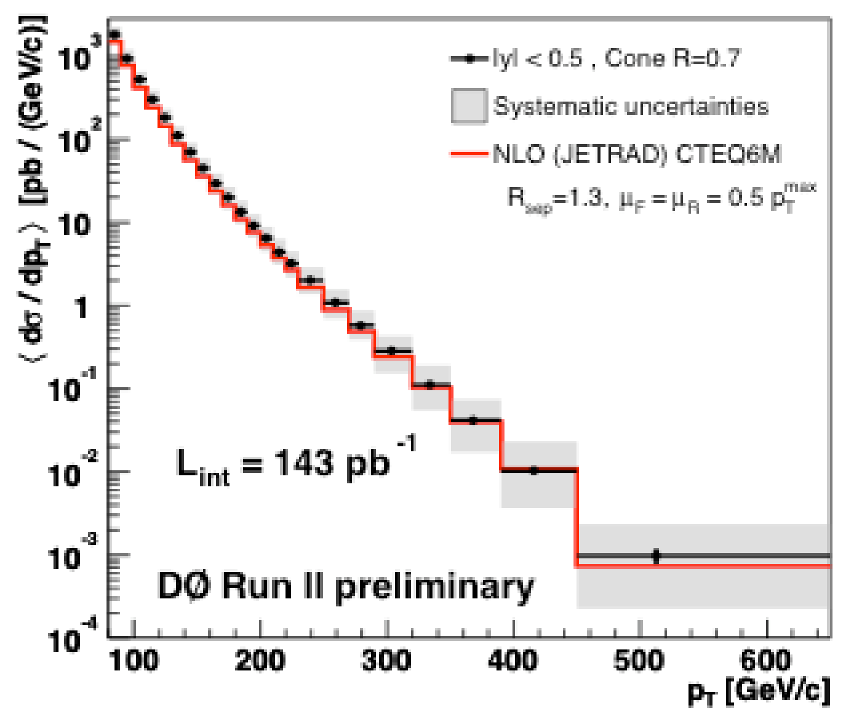
FIG. 3. Difference between data and JETRAD pQCD, normalized to the predictions. The shaded bands represent the total systematic uncertainty. In the bottom plot a HERWIG hadronization contribution has been added to the prediction (open circles).

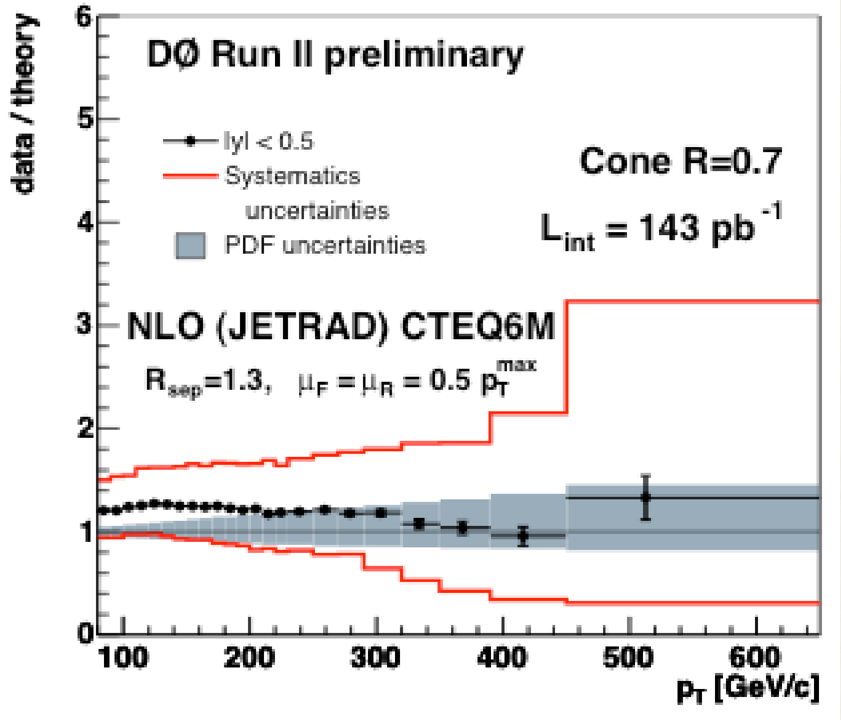
Puzzling discrepancy, in view of the fact that at NLO rates for cone-jets with R=0.7 and k_T jets with D=1 are equal to within 1%

At Run II the Exp syst (mostly energy scale) is still too big to draw conclusions



still large E-scale systematics ⇒ a bit premature to feed these data into new PDF fits



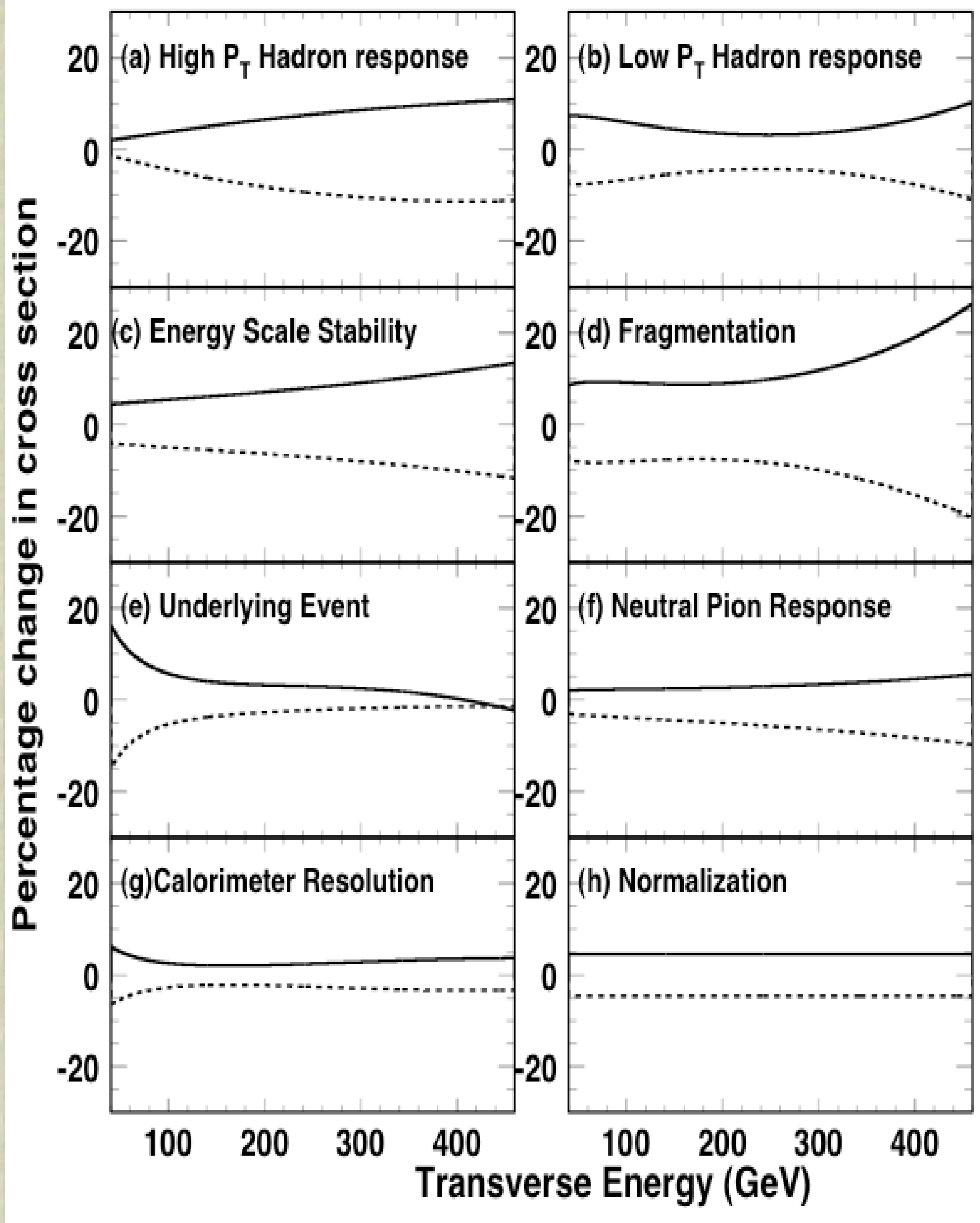


Main sources of syst uncertainties (CDF, run I)

At high E_T the syst is dominated by the response to high p_T hadrons (beyond the test beam p_T range) and fragmentation uncertanties

Out to which E_T will the systematics allow precise cross-section measurements at the LHC?

Out to which E_T can we probe the jet structure (multiplicity, fragm function)?



Bandurin and Skachkov, hep-ex/0209039, hep-ex/0207028

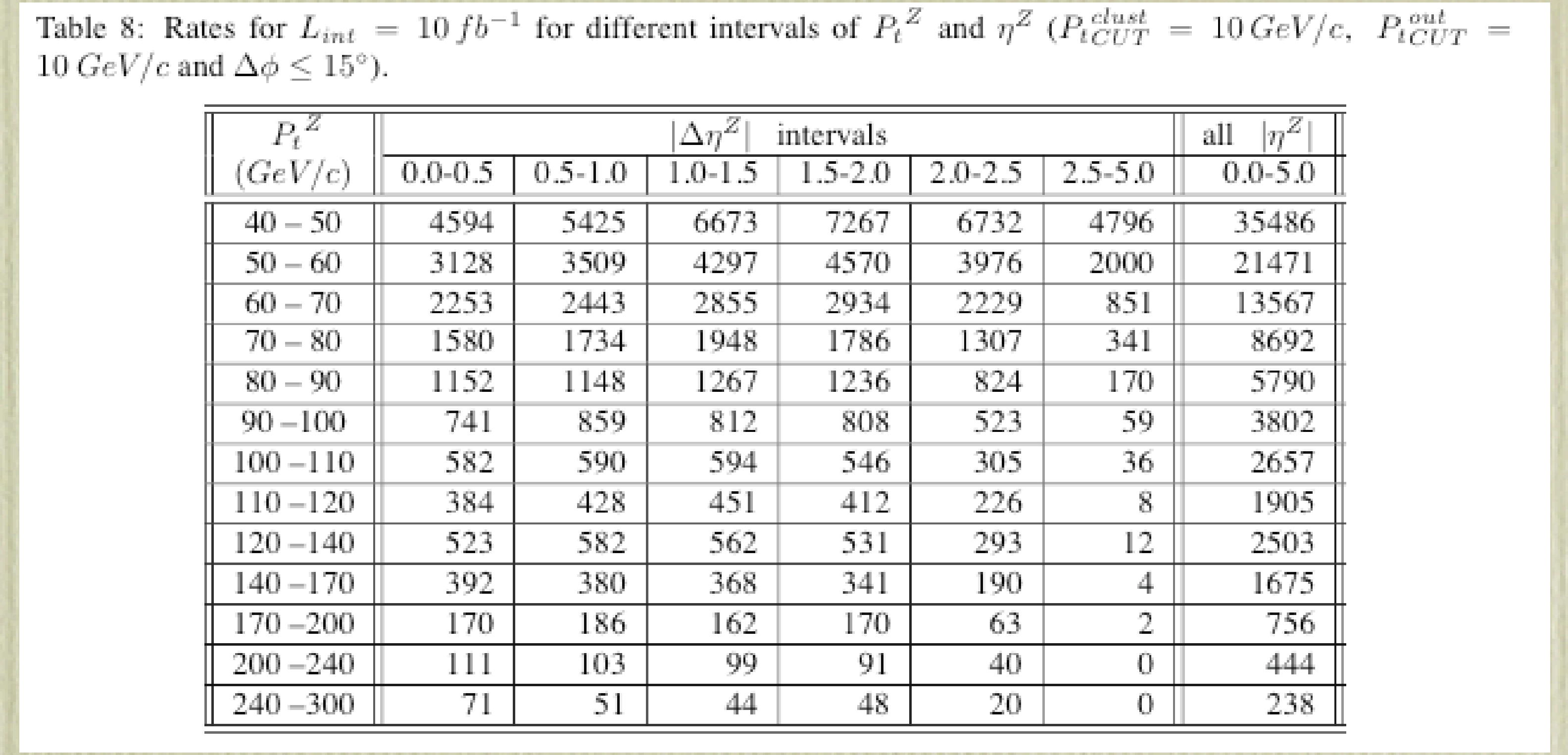


Table 8: Rates for $L_{int} = 10\,fb^{-1}$ for different intervals of P_t^Z and η^Z ($P_{tCUT}^{clust} = 10\,GeV/c$, $P_{tCUT}^{out} = 10\,GeV/c$ and $\Delta\phi \le 15^\circ$).

P_t^Z (GeV/c)	$\lvert\Delta\eta^Z\rvert$ intervals 0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-5.0	all $\lvert\eta^Z\rvert$ 0.0-5.0
40 – 50	4594	5425	6673	7267	6732	4796	35486
50 – 60	3128	3509	4297	4570	3976	2000	21471
60 – 70	2253	2443	2855	2934	2229	851	13567
70 – 80	1580	1734	1948	1786	1307	341	8692
80 – 90	1152	1148	1267	1236	824	170	5790
90 –100	741	859	812	808	523	59	3802
100 –110	582	590	594	546	305	36	2657
110 –120	384	428	451	412	226	8	1905
120 –140	523	582	562	531	293	12	2503
140 –170	392	380	368	341	190	4	1675
170 –200	170	186	162	170	63	2	756
200 –240	111	103	99	91	40	0	444
240 –300	71	51	44	48	20	0	238

(Z→ee)+jet

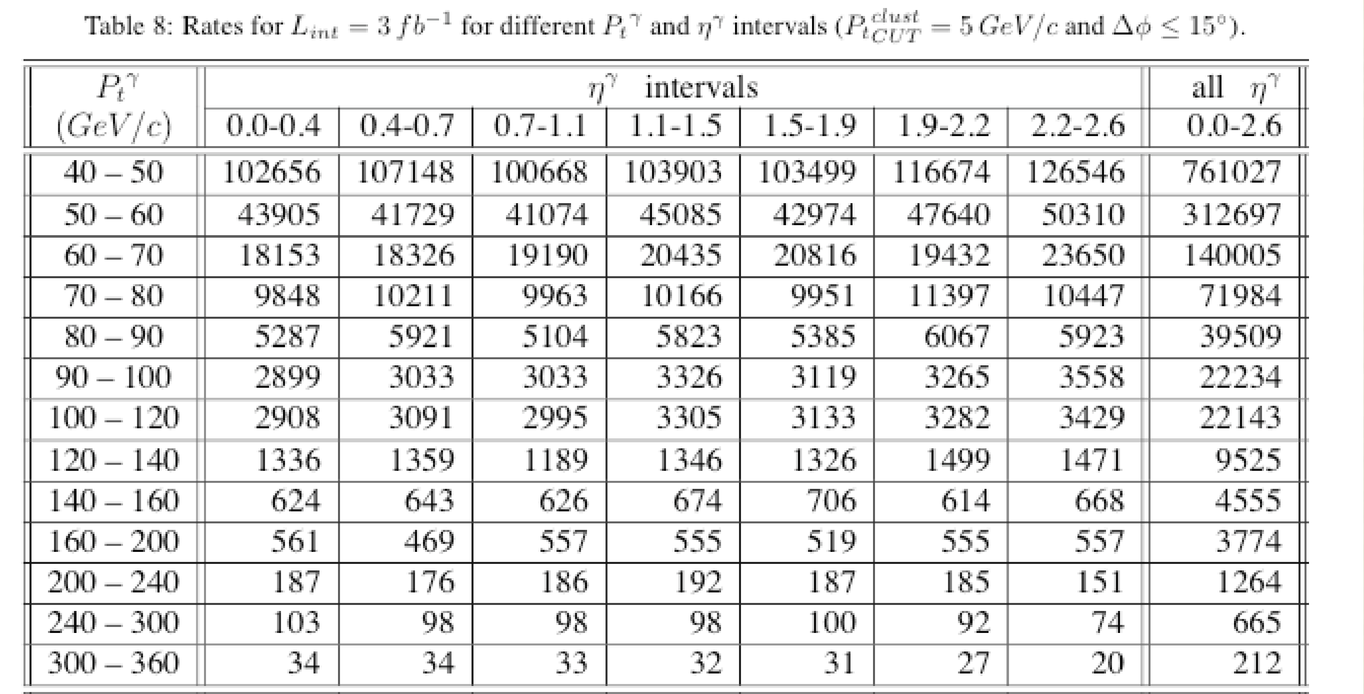


Table 8: Rates for $L_{int} = 3\,fb^{-1}$ for different P_t^γ and η^γ intervals ($P_{tCUT}^{clust} = 5\,GeV/c$ and $\Delta\phi \le 15^\circ$).

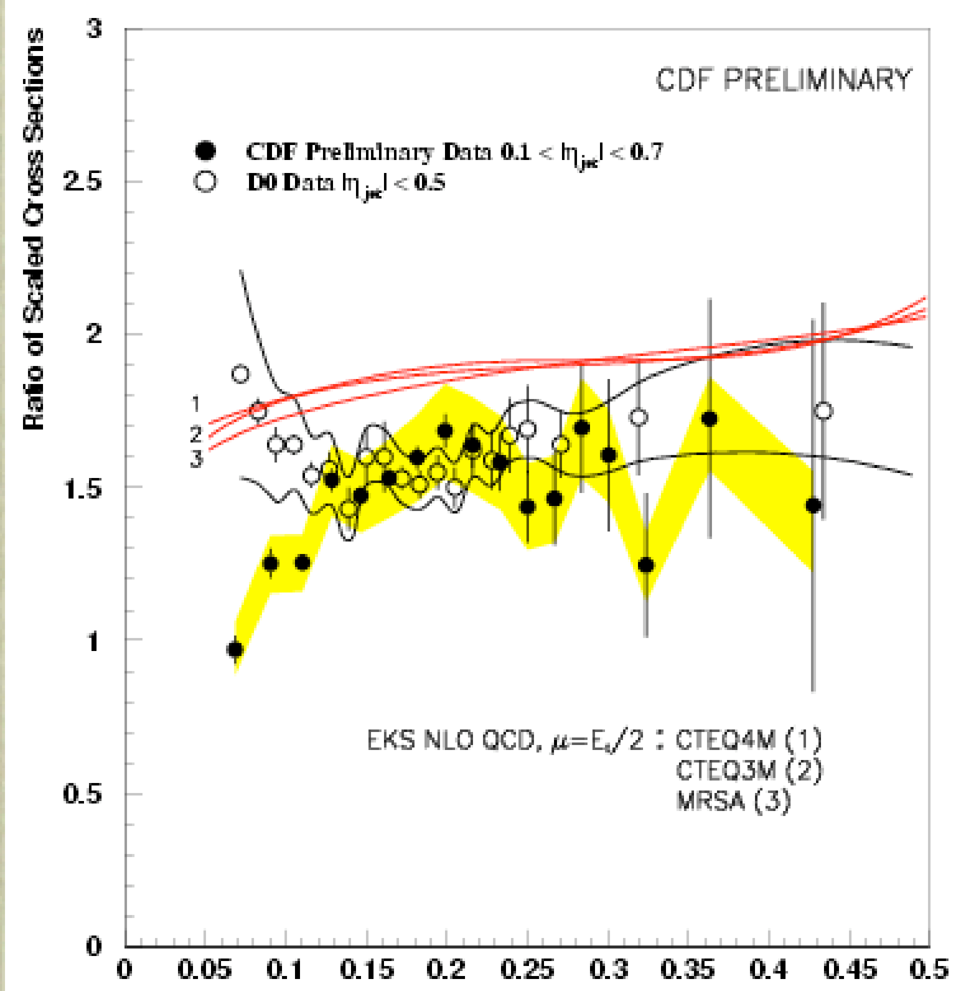
P_t^γ (GeV/c)	η^γ intervals 0.0-0.4	0.4-0.7	0.7-1.1	1.1-1.5	1.5-1.9	1.9-2.2	2.2-2.6	all η^γ 0.0-2.6
40 – 50	102656	107148	100668	103903	103499	116674	126546	761027
50 – 60	43905	41729	41074	45085	42974	47640	50310	312697
60 – 70	18153	18326	19190	20435	20816	19432	23650	140005
70 – 80	9848	10211	9963	10166	9951	11397	10447	71984
80 – 90	5287	5921	5104	5823	5385	6067	5923	39509
90 – 100	2899	3033	3033	3326	3119	3265	3558	22234
100 – 120	2908	3091	2995	3305	3133	3282	3429	22143
120 – 140	1336	1359	1189	1346	1326	1499	1471	9525
140 – 160	624	643	626	674	706	614	668	4555
160 – 200	561	469	557	555	519	555	557	3774
200 – 240	187	176	186	192	187	185	151	1264
240 – 300	103	98	98	98	100	92	74	665
300 – 360	34	34	33	32	31	27	20	212

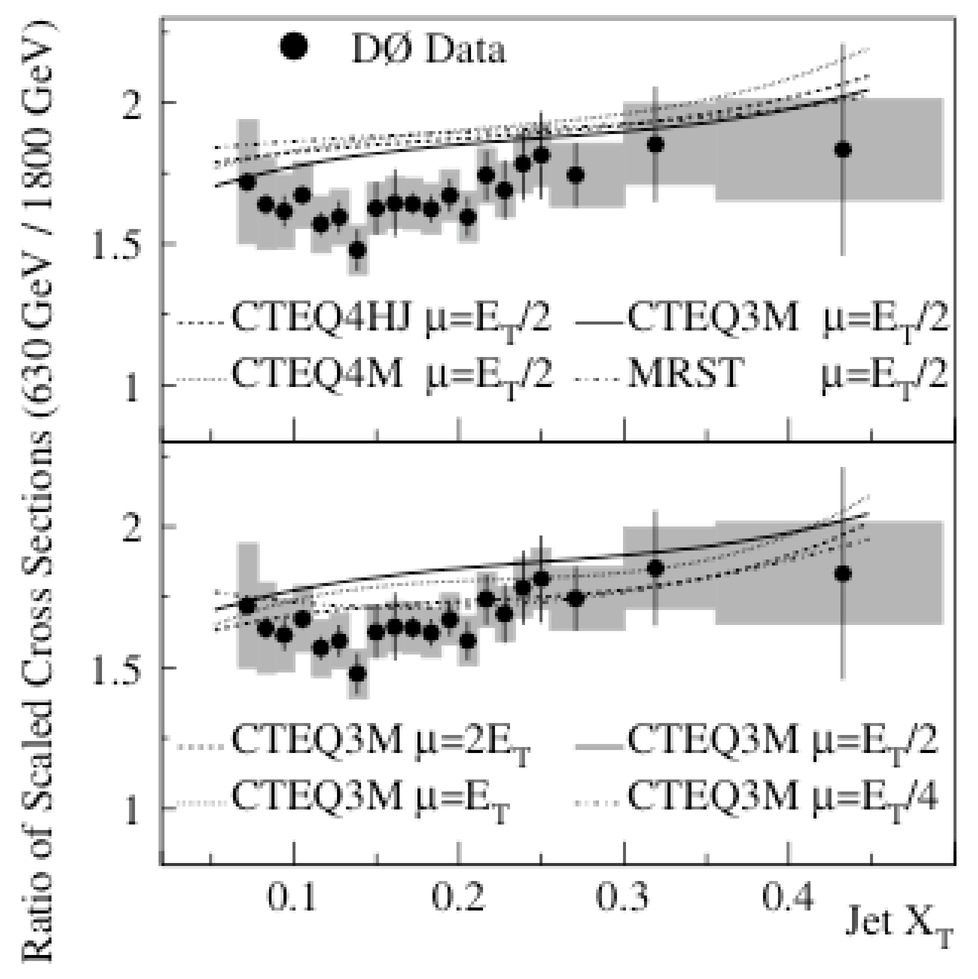
γ+jet

⇒ not enough to probe the E_T~TeV region

2: One more puzzle from run I: x_T ratios

$x_T = E_T / E_{beam}$

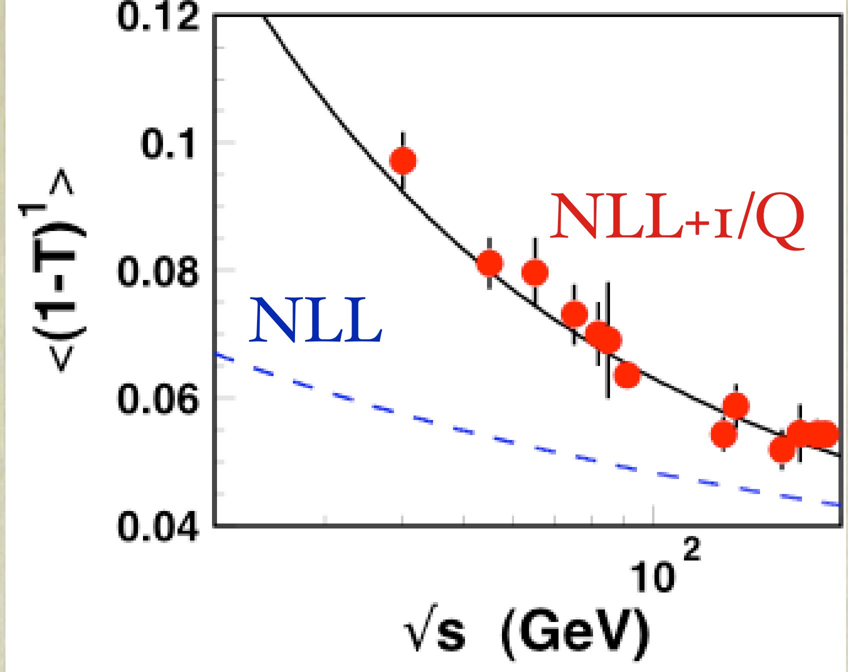


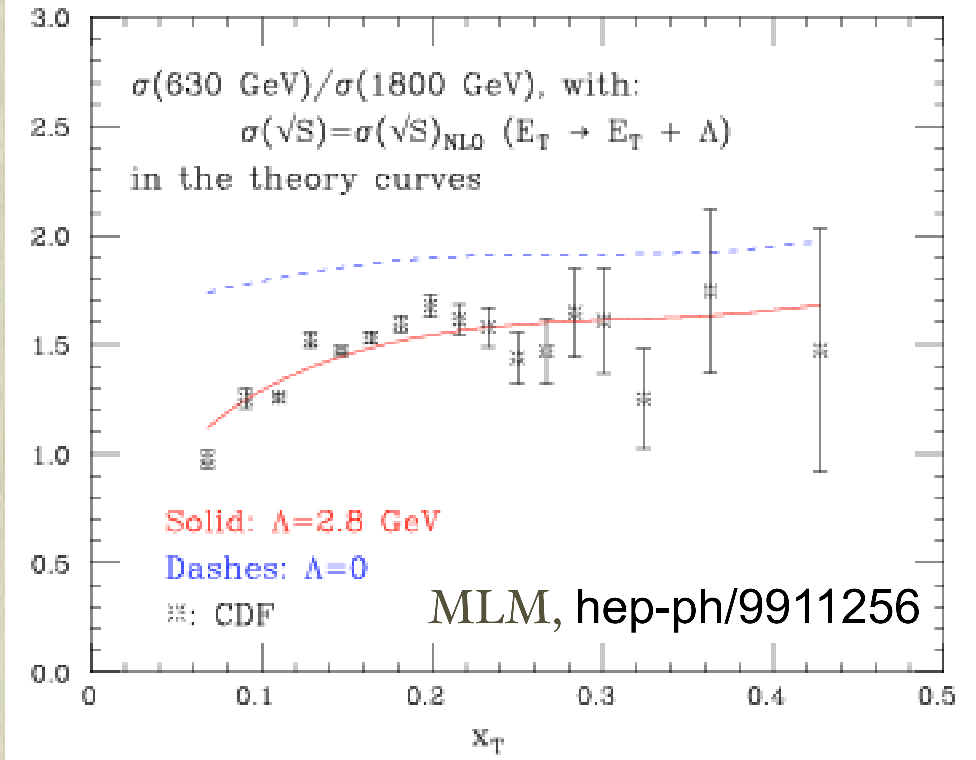


Agreement marginal even at high E_T : pity, since x_T is a powerful observable to tell new physics from PDF effects!

Need for power corrections?

- QCD physics at LEP taught us that the concept of IR and collinear safety, while essential to justify the use of fixed-order perturbative calculations, does not guarantee the accuracy of such calculations.
- The impact of power corrections, as well as of the resummation of large logs, is crucial for a faithful description of the data. This is true even at high-Q
- **A balance between perturbative accuracy and realism in the description of the physical observables (e.g. in the description of the structure of an experimental jet) is mandatory**



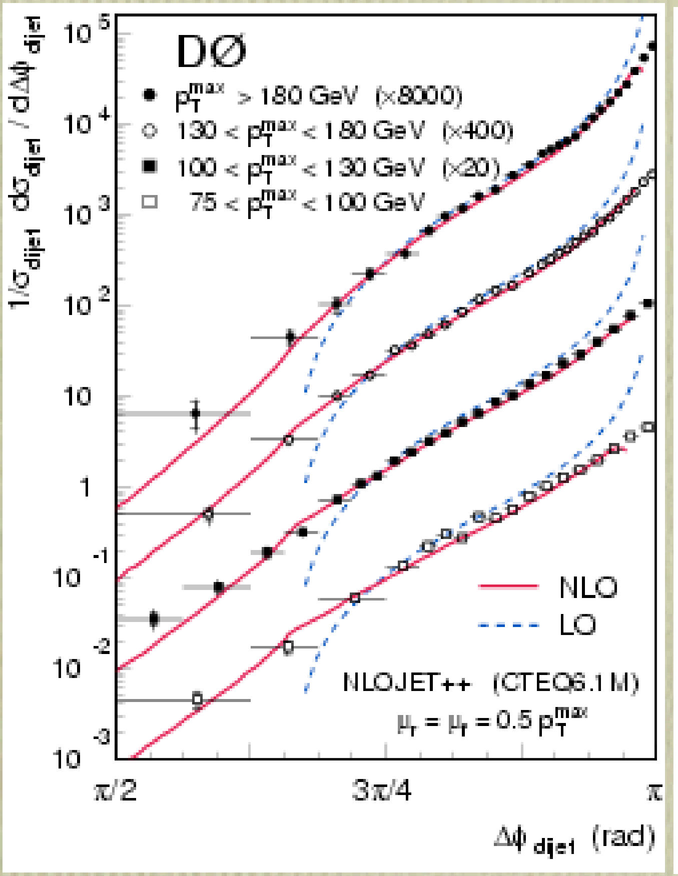


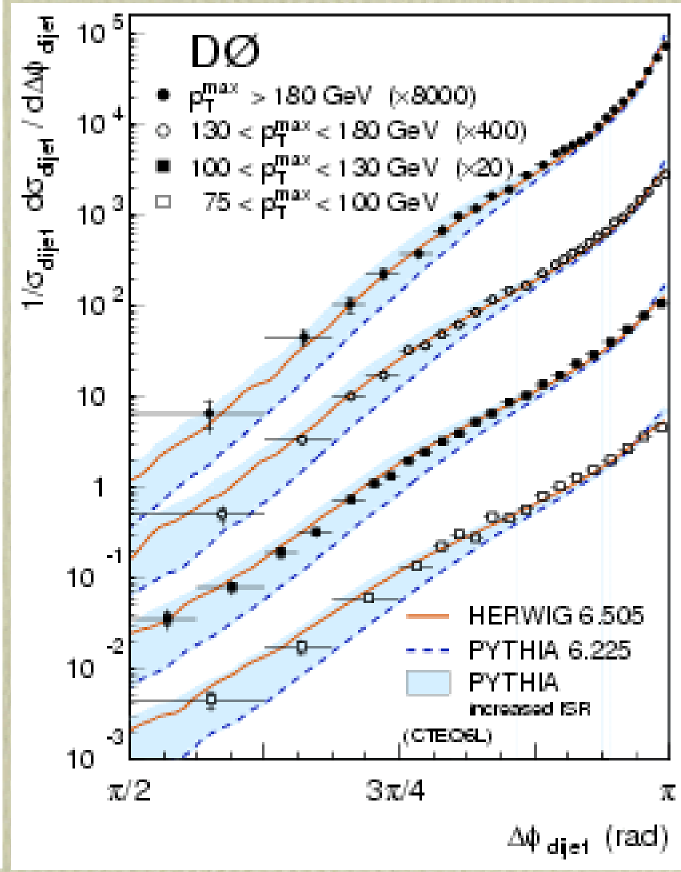
MLM, hep-ph/9911256

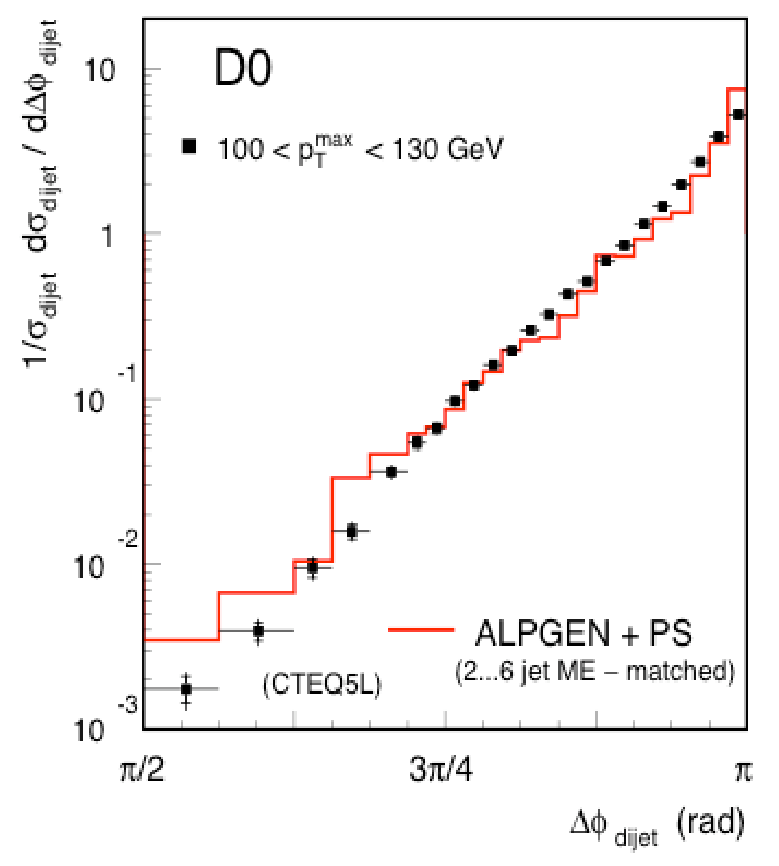
- Studies have started to address the issue of resummation and power corrections in hadronic collisions, e.g.:
  - **RESUMMED EVENT SHAPES AT HADRON - HADRON COLLIDERS.** By Andrea Banfi (NIKHEF, Amsterdam), Gavin P. Salam (Paris, LPTHE), Giulia Zanderighi (Fermilab), **JHEP 0408:062,2004** e-Print Archive: **hep-ph/0407287**
- There is however so far not a single concrete analysis of inclusive jet production at the Tevatron going beyond parton-level NLO:
  - lack an understanding of the connection among power corrections to various observables (jet E_T rates, jet shapes, event shapes, etc), similar to the one we had in e^+e^- and ep.
  - inclusion and estimate of the impact of power-corrections is in my view, at this stage, more important than having a NNLO parton-level calculation
  - **inclusion of jet processes in MC@NLO will be an essential step for any quantitative study (PDF fits, α_s extraction, etc) of jets in hadronic collisions**
- Use of jets for precision physics will require the consistency of the complete picture of jet properties: jet shapes, jet correlations, fragmentation functions, heavy quark content, ...

3. Extending NLO accuracy to 3-parton final states: dijet azimuthal correlations at NLO

Z.Nagy







Shape $\leftrightarrow \alpha_s \Rightarrow$ good observable to extract α_s ?

see T.Carli, // session

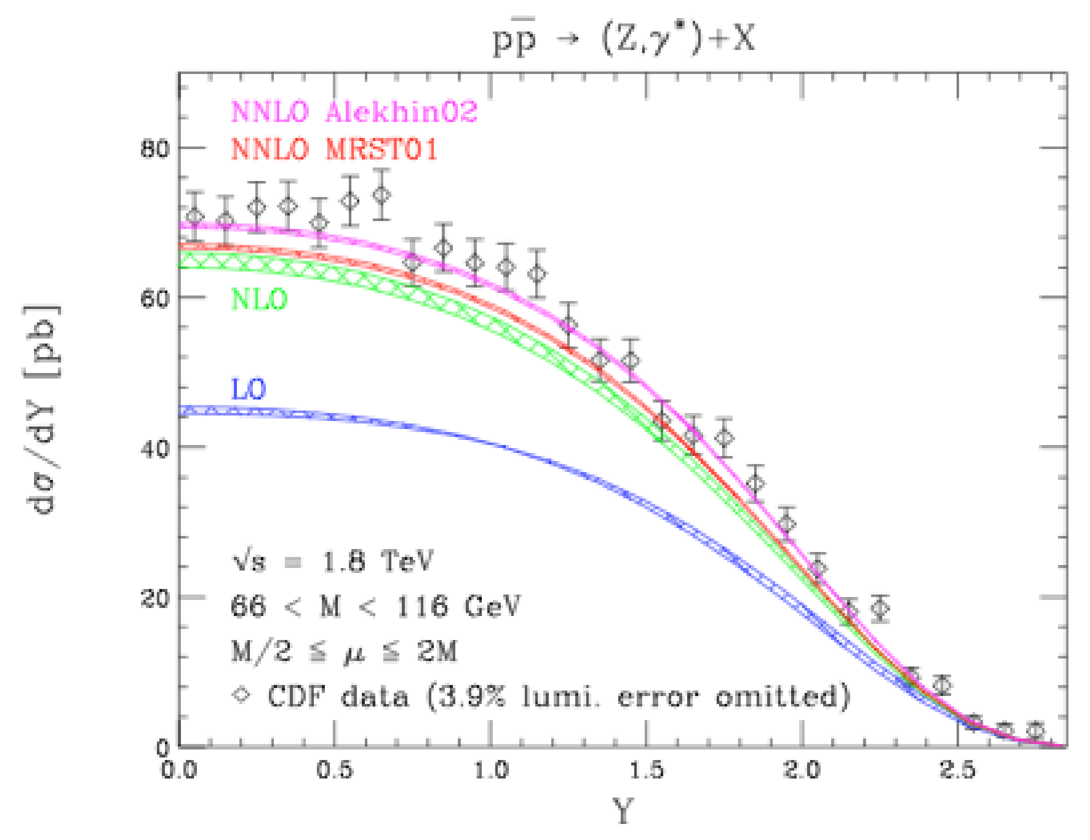
W/Z cross-sections

- Test of QCD to NNLO: potential accuracy ~ 2% on σ_{tot}
- Luminosity monitor
- Probe of PDF's

=> In view of incomplete detector coverage, need to ensure that the potential NNLO accuracy is reflected in the calculation of acceptancies. The realization of a QCD NNLO event generator, however, will still take some time, especially if a merging with the shower (MC@NNLO) is desired. **Is it required?**

How the measurement will be done

- Count events N(e) within some cuts, e.g.
  - E_T(e)>20 GeV, |η(e)|<2.5, MissE_T>20 GeV
- Compare against a theoretical simulation subject to the same cuts, or
- Take a MC and evaluate the acceptance A of the cuts, to extract the total cross-section:
  - σ = 1/A N(e)/Lum
- Same if one is interested in a cross-section defined by the kinematics of the W boson (e.g. $d\sigma/dy_W$)

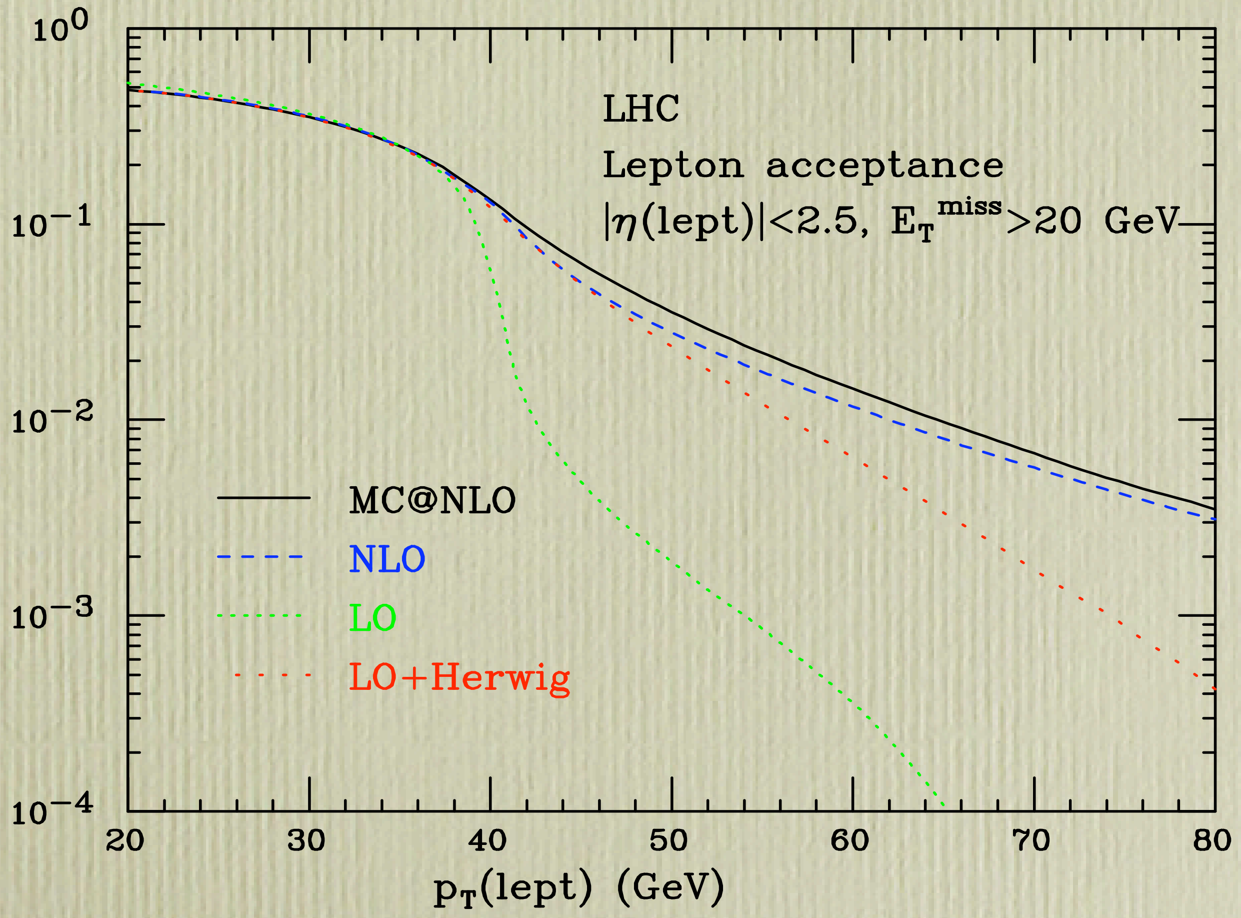


Anastasiou, Dixon, Melnikov, Petriello

The accuracy of the extraction of the cross-section is therefore related to the accuracy of the acceptance calculation

Study of acceptance systematics

(MLM and S.Frixione, **hep-ph/0405130**)



LO: leading order ME, parton level

LO+Herwig: leading order ME, plus parton shower

NLO: next-to-leading order ME, parton level

MC@NLO: next-to-leading order ME, plus parton shower

Cuts A $\longrightarrow$ $|\eta^{(e)}| < 2.5$, $p_T^{(e)} > 20$ GeV, $p_T^{(\nu)} > 20$ GeV

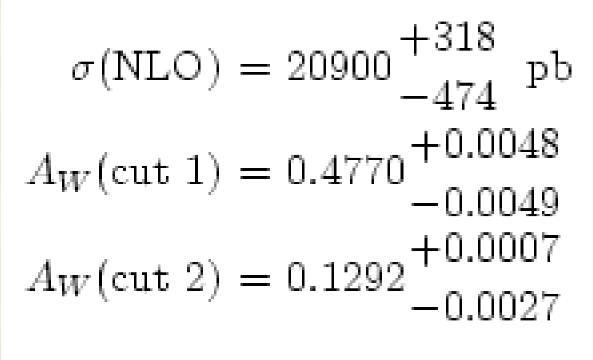
Cuts B $\longrightarrow$ $|\eta^{(e)}| < 2.5$, $p_T^{(e)} > 40$ GeV, $p_T^{(\nu)} > 20$ GeV

	LO		LO+HW	NLO		MC@NLO
Cuts A	0.5249	$\xrightarrow{-7.7\%}$	0.4843	0.4771	$\xrightarrow{+1.5\%}$	0.4845
	↓5.4%			↓7.0%		↓6.3%
Cuts A, no spin	0.5535			0.5104		0.5151
Cuts B	0.0585	$\xrightarrow{+208\%}$	0.1218	0.1292	$\xrightarrow{+2.9\%}$	0.1329
	↓29%			↓16%		↓18%
Cuts B, no spin	0.0752			0.1504		0.1570

- Large differences between LO and NLO. In large part absorbed improving LO with the parton shower
- Effect of parton shower strongly reduced after NLO effects are included in ME
- Difference between LO+HW and MC@NLO smaller than between NLO/MC@NLO
- Large impact of spin correlations

$\Longrightarrow$ A MC implementation of NNLO corrections is likely not needed with a 1-2% accuracy goal, provided p_T thresholds are loose enough. Before it is of any use, however, spin correlations must be included.

PDF syst (MRST2001) for absolute rate and acceptances:



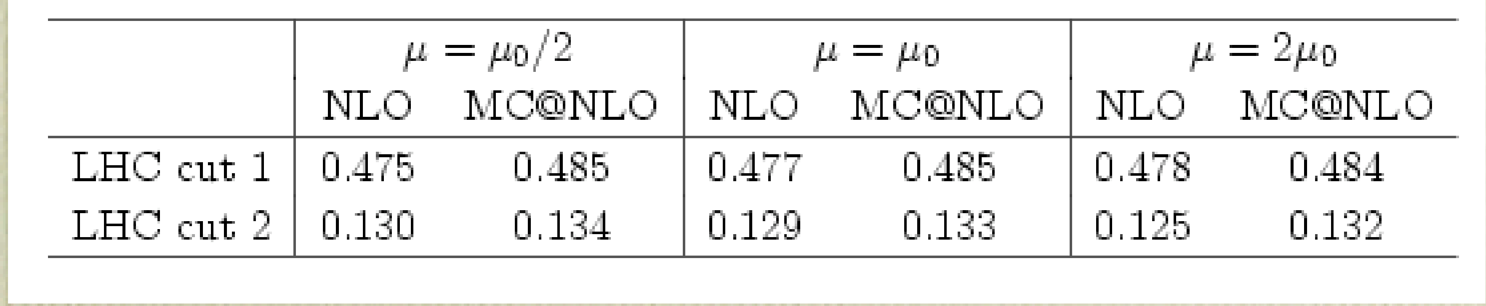
$$\sigma(\mathrm{NLO}) = 20900^{+318}_{-474}\ \mathrm{pb}$$

$$A_W(\mathrm{cut}\ 1) = 0.4770^{+0.0048}_{-0.0049}$$

$$A_W(\mathrm{cut}\ 2) = 0.1292^{+0.0007}_{-0.0027}$$

Uncertainty on acceptance ~
1/2 uncertainty on full rate

Scale dependence of acceptances at NLO and MC@NLO

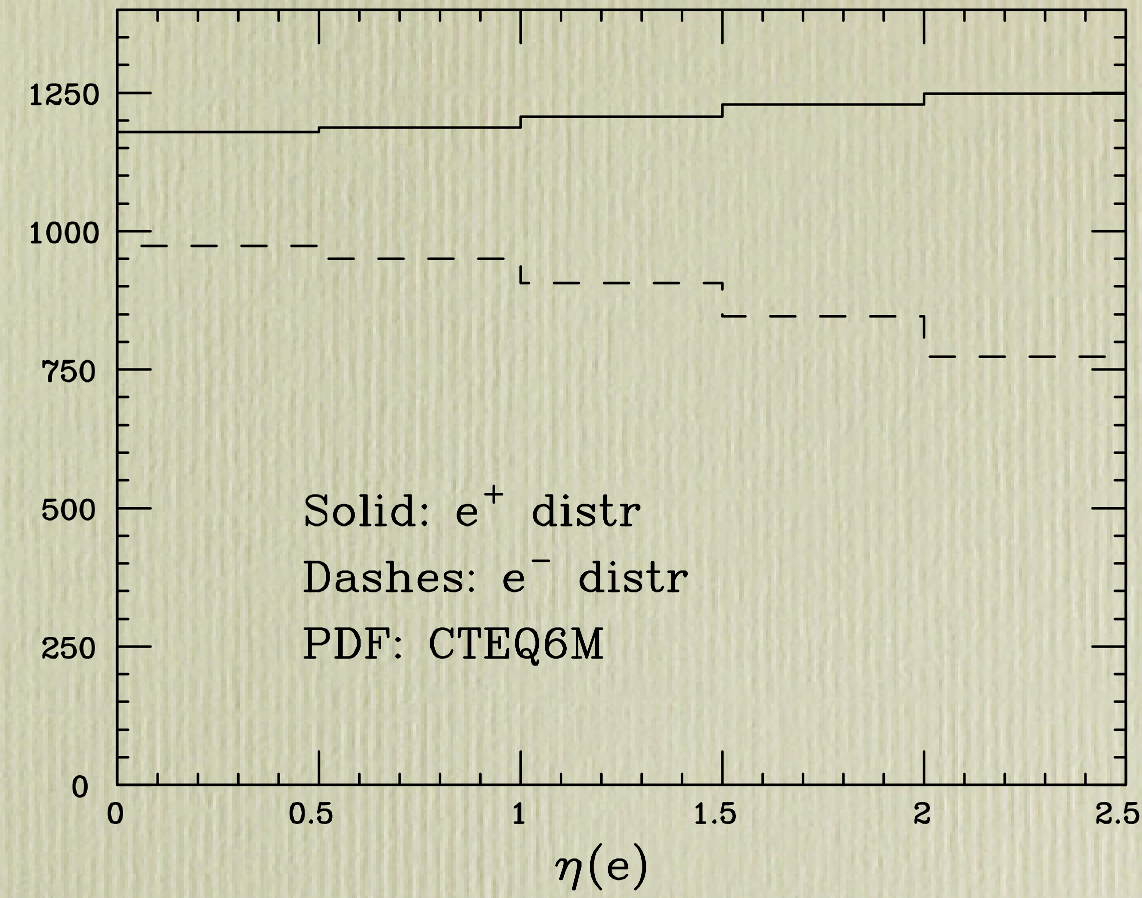


	$\mu = \mu_0/2$		$\mu = \mu_0$		$\mu = 2\mu_0$	
	NLO	MC@NLO	NLO	MC@NLO	NLO	MC@NLO
LHC cut 1	0.475	0.485	0.477	0.485	0.478	0.484
LHC cut 2	0.130	0.134	0.129	0.133	0.125	0.132

Smaller dependence with MC@NLO !!

PDF correlations in W→eν

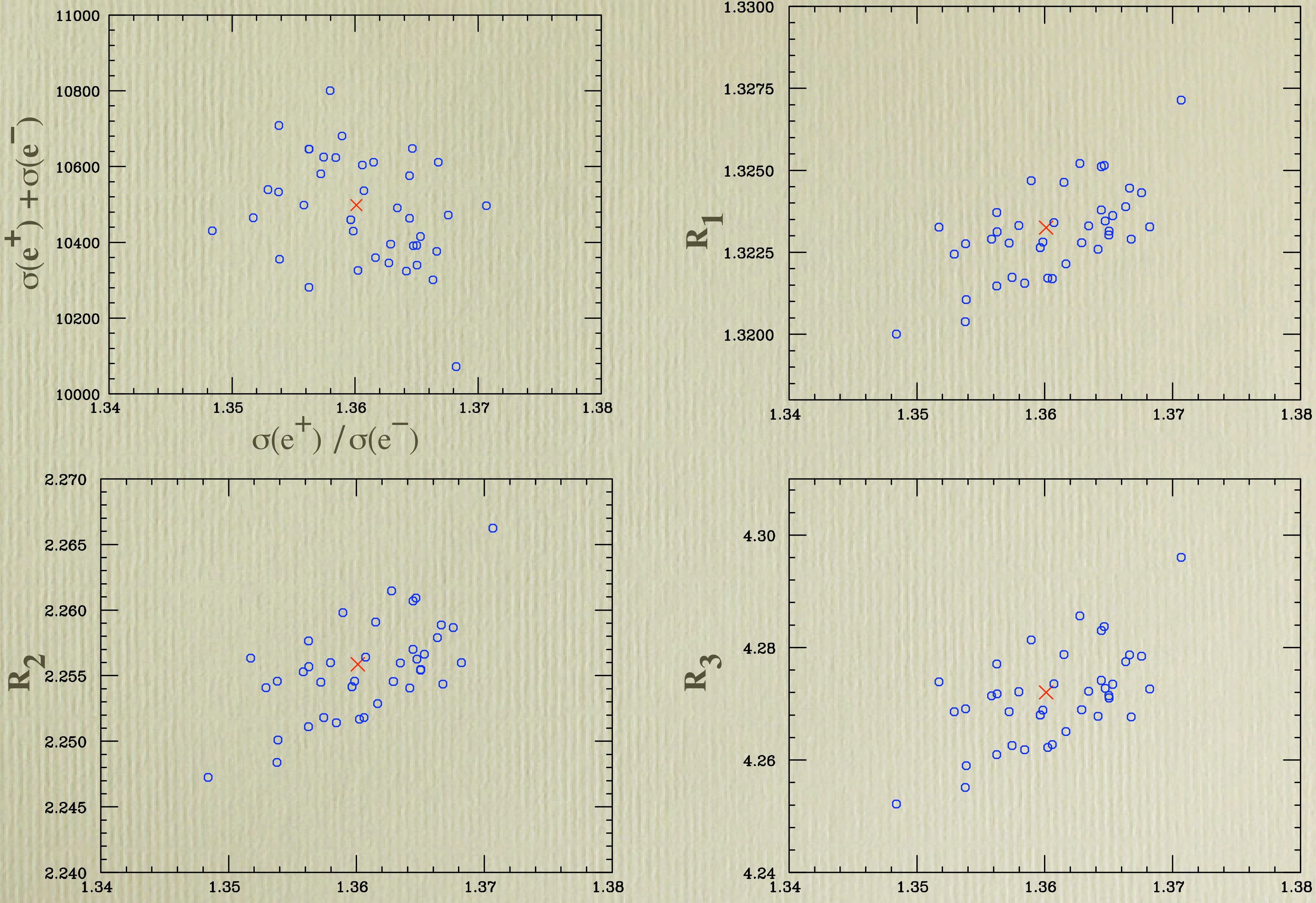
$p_T(e)>20$, $|\eta_e|<2.5$, MET>20



Study moments of the ratio: $$\frac{\sigma(e^-)}{\sigma(e^+)}\ \frac{d\sigma/d\eta(e^+)}{d\sigma/d\eta(e^-)}$$

$$R_n = \int \frac{\sigma(e^-)}{\sigma(e^+)}\ \frac{d\sigma/d\eta(e^+)}{d\sigma/d\eta(e^-)}\ \eta^n\, d\eta$$

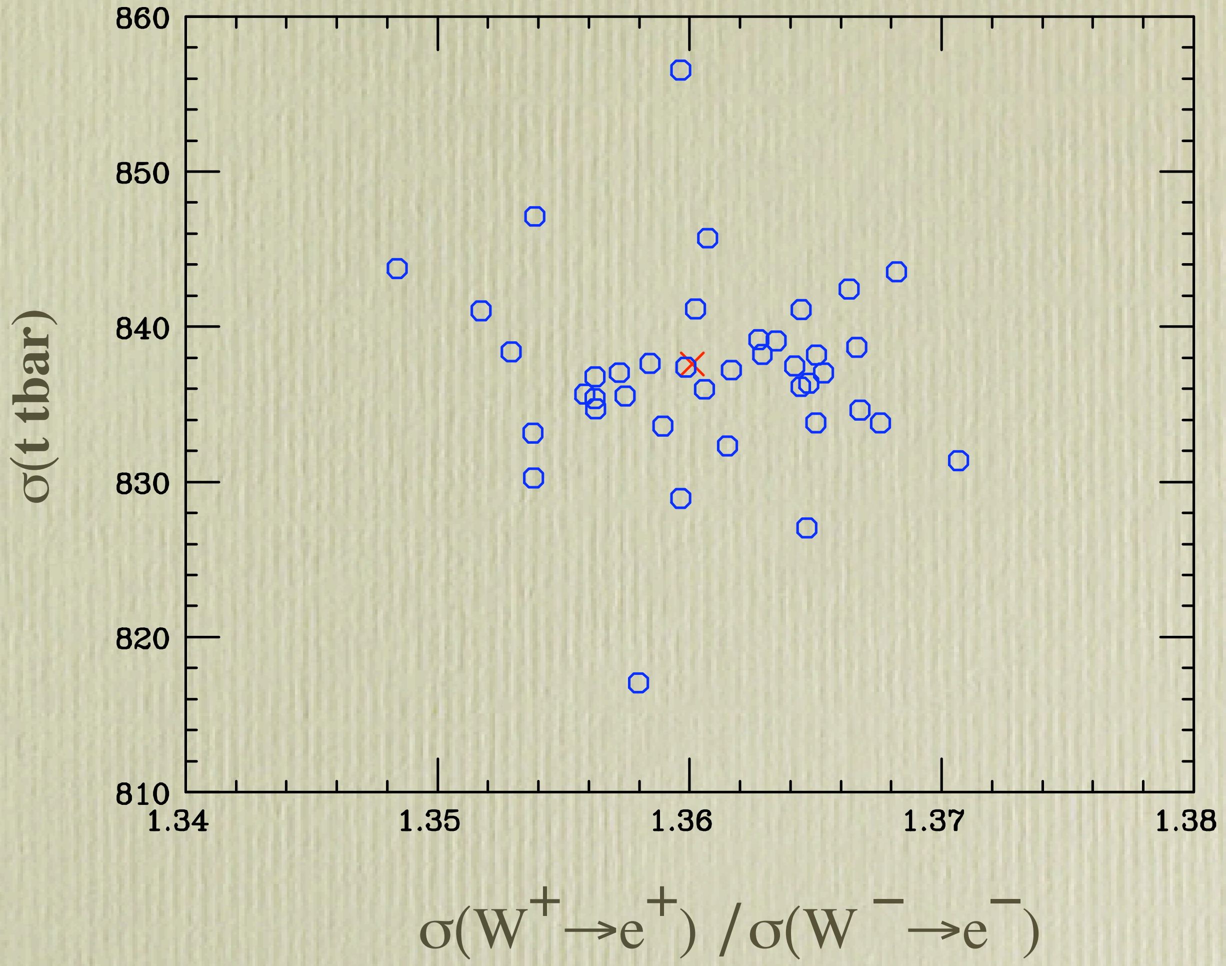
NB: below the ∫ is approximated with a discrete sum over bins



x: CTEQ6M

o: CTEQ6Mxx

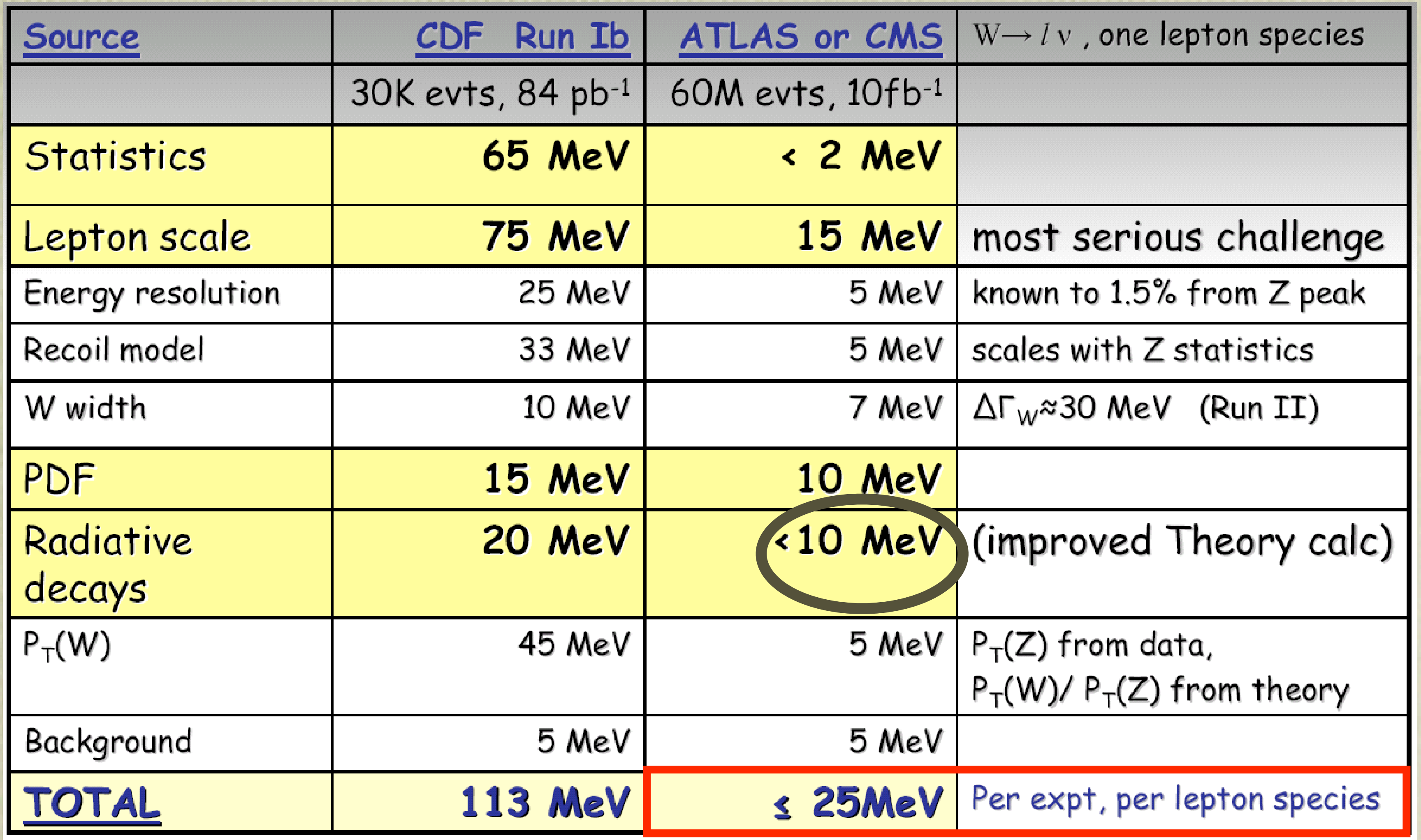
=> correlation between spectrum and W^+/W^- rate



No correlation with the top cross-section (clearly different combinations of flavours)

QED effects

W mass determination:



Source	CDF Run Ib	ATLAS or CMS	W→ $l\,\nu$, one lepton species
	30K evts, 84 pb^{-1}	60M evts, 10fb^{-1}	
Statistics	**65 MeV**	**< 2 MeV**	
Lepton scale	**75 MeV**	**15 MeV**	most serious challenge
Energy resolution	25 MeV	5 MeV	known to 1.5% from Z peak
Recoil model	33 MeV	5 MeV	scales with Z statistics
W width	10 MeV	7 MeV	$\Delta\Gamma_W \approx 30$ MeV (Run II)
PDF	**15 MeV**	**10 MeV**	
Radiative decays	**20 MeV**	**<10 MeV**	(improved Theory calc)
$P_T(W)$	45 MeV	5 MeV	$P_T(Z)$ from data, $P_T(W)/\,P_T(Z)$ from theory
Background	5 MeV	5 MeV	
TOTAL	**113 MeV**	**≤ 25MeV**	Per expt, per lepton species

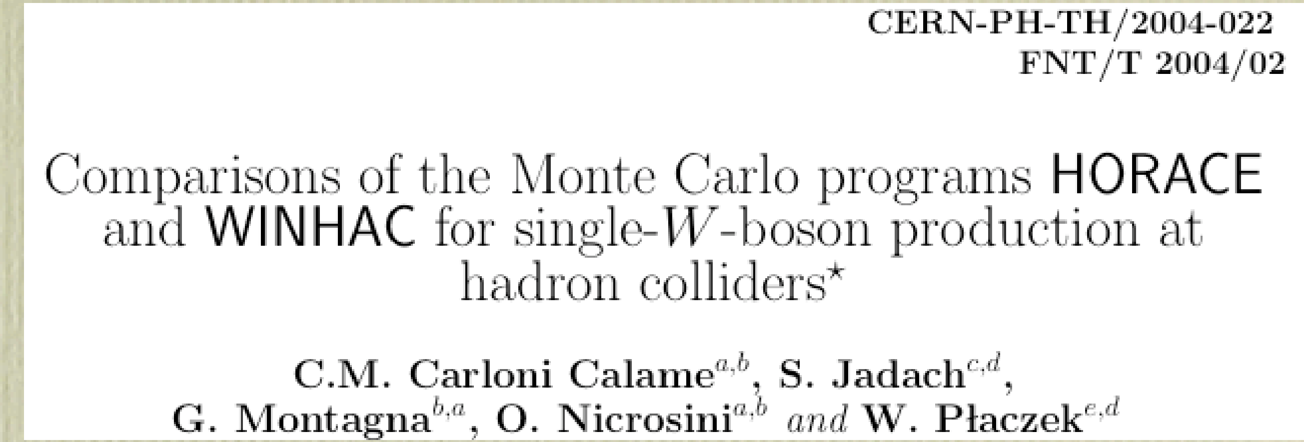
QED effects

With the level of accuracy reached in the QCD part of the W cross-section calculations, EW effects start becoming important.

Full inclusion of EW effects will require inclusion of QED effects in the PDF (see J.Stirling, // session).

Does HERA have any sensitivity to these effects? => see J.Stirling talk, ep->eγX data

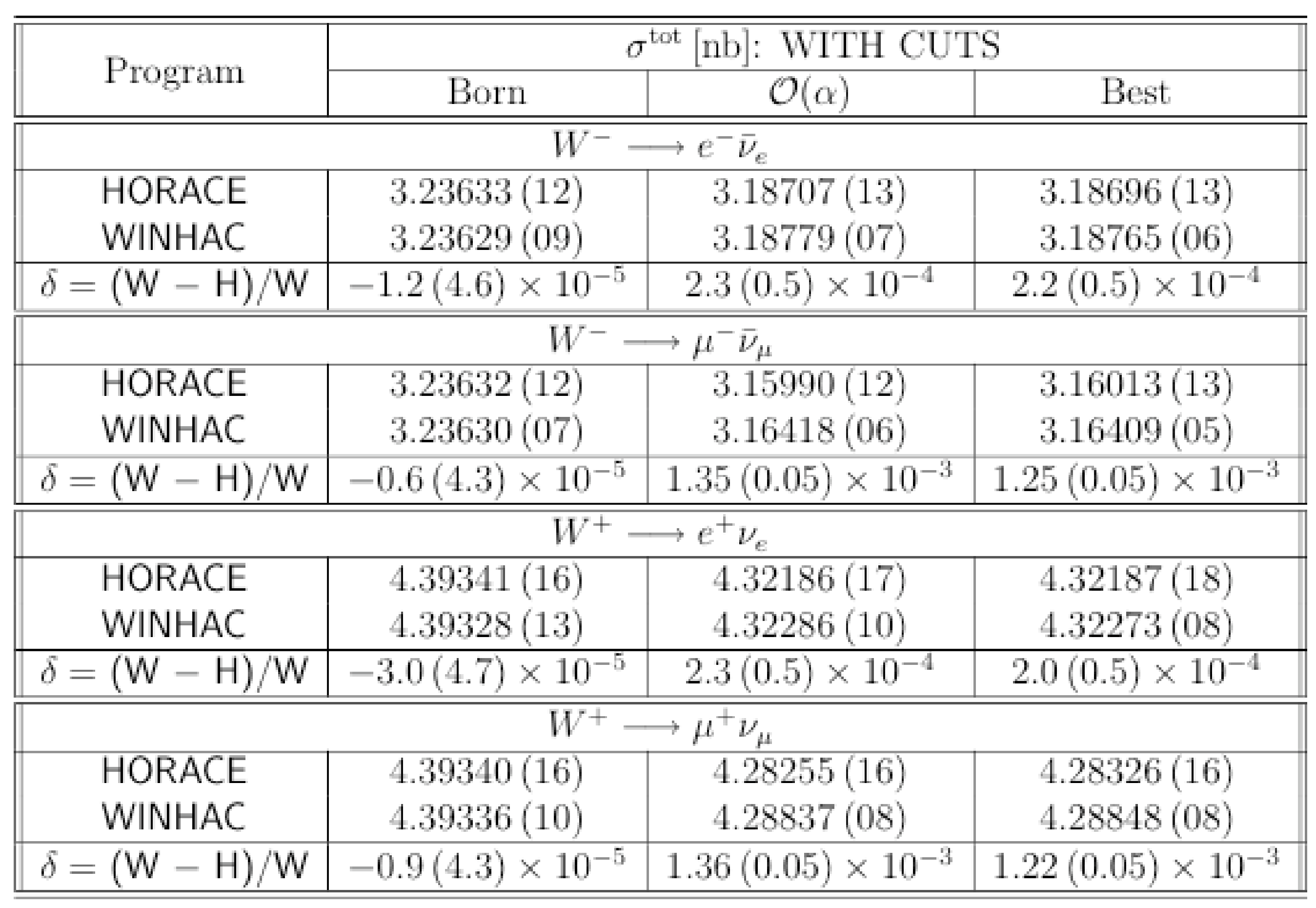
How do we validate these calculations with LHC data?



CERN-PH-TH/2004-022
FNT/T 2004/02

Comparisons of the Monte Carlo programs HORACE and WINHAC for single-W-boson production at hadron colliders*

C.M. Carloni Calame[a,b], S. Jadach[c,d],
G. Montagna[b,a], O. Nicrosini[a,b] *and* W. Płaczek[e,d]



Program	σ^{tot} [nb]: WITH CUTS		
	Born	$\mathcal{O}(\alpha)$	Best
	$W^- \longrightarrow e^-\bar{\nu}_e$		
HORACE	3.23633 (12)	3.18707 (13)	3.18696 (13)
WINHAC	3.23629 (09)	3.18779 (07)	3.18765 (06)
$\delta = (W - H)/W$	$-1.2\,(4.6) \times 10^{-5}$	$2.3\,(0.5) \times 10^{-4}$	$2.2\,(0.5) \times 10^{-4}$
	$W^- \longrightarrow \mu^-\bar{\nu}_\mu$		
HORACE	3.23632 (12)	3.15990 (12)	3.16013 (13)
WINHAC	3.23630 (07)	3.16418 (06)	3.16409 (05)
$\delta = (W - H)/W$	$-0.6\,(4.3) \times 10^{-5}$	$1.35\,(0.05) \times 10^{-3}$	$1.25\,(0.05) \times 10^{-3}$
	$W^+ \longrightarrow e^+\nu_e$		
HORACE	4.39341 (16)	4.32186 (17)	4.32187 (18)
WINHAC	4.39328 (13)	4.32286 (10)	4.32273 (08)
$\delta = (W - H)/W$	$-3.0\,(4.7) \times 10^{-5}$	$2.3\,(0.5) \times 10^{-4}$	$2.0\,(0.5) \times 10^{-4}$
	$W^+ \longrightarrow \mu^+\nu_\mu$		
HORACE	4.39340 (16)	4.28255 (16)	4.28326 (16)
WINHAC	4.39336 (10)	4.28837 (08)	4.28848 (08)
$\delta = (W - H)/W$	$-0.9\,(4.3) \times 10^{-5}$	$1.36\,(0.05) \times 10^{-3}$	$1.22\,(0.05) \times 10^{-3}$

What is the sequence of steps that will lead to the certification of a W cross-section measurement to the 1-2% level, and of m_W to 20 MeV or less??

These levels of accuracies will be crucial to extract measurements of EW parameters (e.g. $\sin^2\theta_W$).

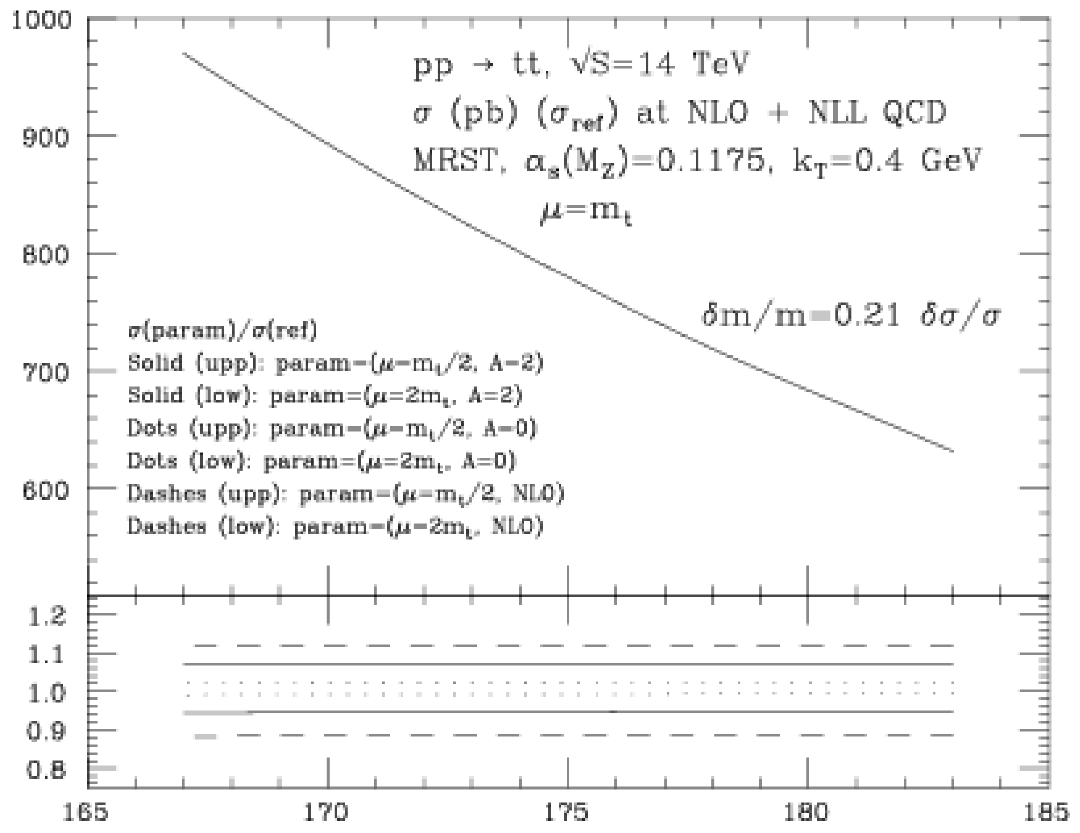
Low luminosity can play an important role, reducing backgrounds, allowing for lower trigger thresholds, better MissE$_T$ resolution, etc.

Top cross-section

Gluon better
known at LHC in
the relevant x range

$\sigma_{tt}^{\mathrm{LHC}} = 840\mathrm{pb}\ (1 \pm 5\%_{\mathrm{scale}} \pm 3\%_{\mathrm{PDF}})$

cfr $\sigma_{tt}^{\mathrm{FNAL}} = 6.5\mathrm{pb}\ (1 \pm 5\%_{\mathrm{scale}} \pm 7\%_{\mathrm{PDF}})$



Scale unc: ± 12%$_{\mathrm{NLO}}$ => ± 5%$_{\mathrm{NLO+NLL}}$

=> ± 3%$_{\mathrm{NLO+NLL}}$ with “aggressive” assumptions about $1/N_{\mathrm{mellin}}$ terms

Δσ= ± 6% ⇔ Δm= ± 2 GeV, comparable to $\Delta m_{\mathrm{direct}}$

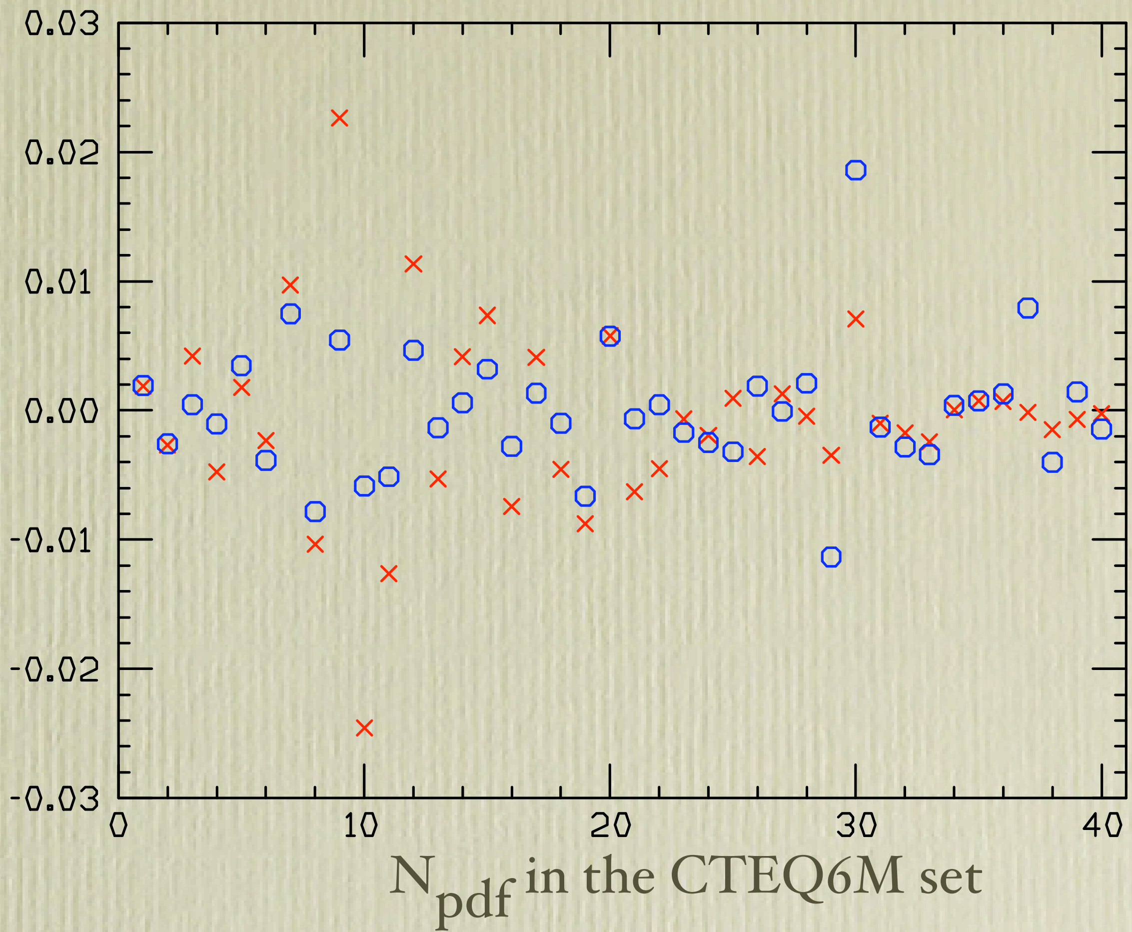
Looking for PDF correlations with the *inclusive jet sample:*

σ_{jet}= rate of events with

E_{Tjet}>175 GeV

X: $\frac{\sigma_{tt}(N_{pdf})}{\sigma_{tt}(6M)} - 1$

O: $\frac{\sigma_{tt}(N_{pdf})/\sigma_{jet}(N_{pdf})}{\sigma_{tt}(6M)/\sigma_{jet}(6M)} - 1$



A correlation exists, but it is not perfect. Likely due to the fact that the initial state is not precisely the same:

$$\sigma_{gg}(tt) : \sigma_{qg}(tt) : \sigma_{qq}(tt) = 90\% : 1\% : 10\%$$

$$\sigma_{gg}(jet) : \sigma_{qg}(jet) : \sigma_{qq}(jet) = 45\% : 45\% : 10\%$$

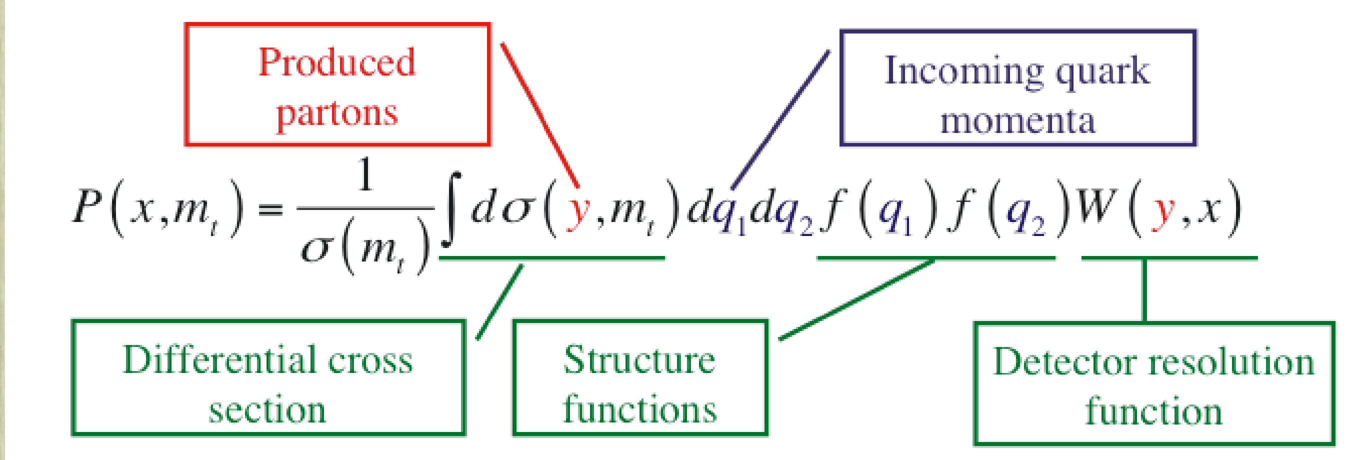
m(top)

Latest average from Tevatron:

$$m_t=178.0\pm4.3 \Rightarrow m_H = 117^{+45}_{-68}$$

mostly driven by the new run I DO measurement:

$$m_t = 180.1 \pm 3.6\,(\text{stat.}) \pm 4.0\,(\text{syst.})\ \text{GeV}$$



Produced partons

Incoming quark momenta

$$P(x,m_t) = \frac{1}{\sigma(m_t)}\int d\sigma(y,m_t)\,dq_1 dq_2\, f(q_1)\, f(q_2)\, W(y,x)$$

Differential cross section

Structure functions

Detector resolution function

Rely on tree-level tt→lν+4q ME. We know however that ~50% of tt →4j events have 4th jet from ISR, not from top: systematics??

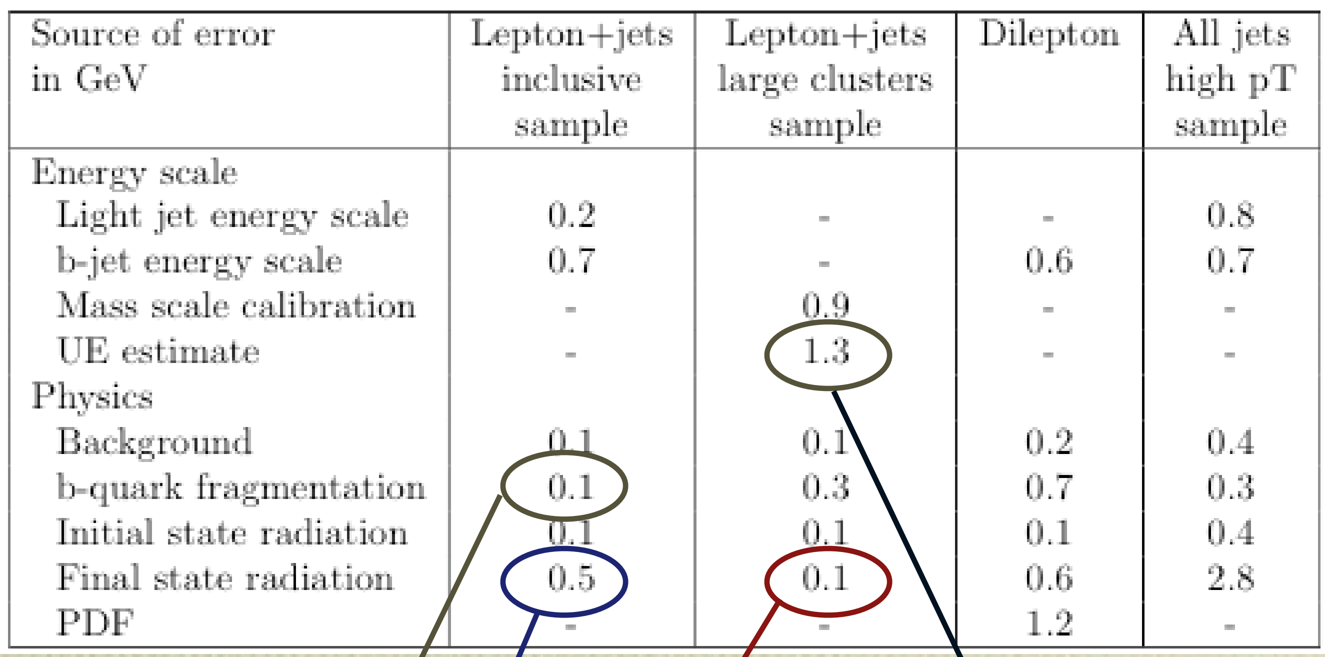
Validation of these "probabilistic" approaches is needed: require more data than available today at the Tevatron

m_{top} at the LHC:Δm_{top} ~ 1 GeV ?

Recent overview of ATLAS strategy and results for m_{top}: hep-ph/0403021

Channels considered:

- + $(W \rightarrow l\nu)$+4 jets, with 2 b tags
- + high-pT top, $t \rightarrow 3$ jets
- + $(W \rightarrow l\nu)\ (W \rightarrow l\nu)$ + bb
- + $m_{l\psi}$ in events with $B \rightarrow \psi X$



Source of error in GeV	Lepton+jets inclusive sample	Lepton+jets large clusters sample	Dilepton	All jets high pT sample
Energy scale				
Light jet energy scale	0.2	-	-	0.8
b-jet energy scale	0.7	-	0.6	0.7
Mass scale calibration	-	0.9	-	-
UE estimate	-	1.3	-	-
Physics				
Background	0.1	0.1	0.2	0.4
b-quark fragmentation	0.1	0.3	0.7	0.3
Initial state radiation	0.1	0.1	0.1	0.4
Final state radiation	0.5	0.1	0.6	2.8
PDF	-	-	1.2	-

Need a strategy for validation of the MC input models:

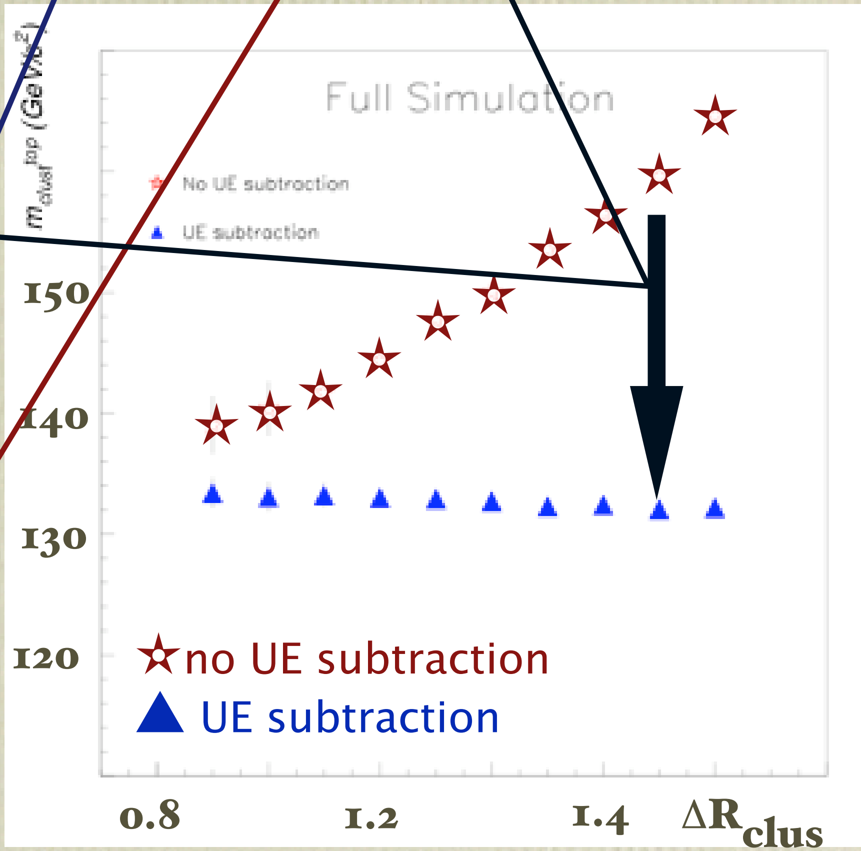
+ UE modeling and subtraction

+ validation of FSR effects:

✶ jet fragmentation properties, jet energy profiles

✶ how do we validate emission off the top quark in the high-pt top sample?

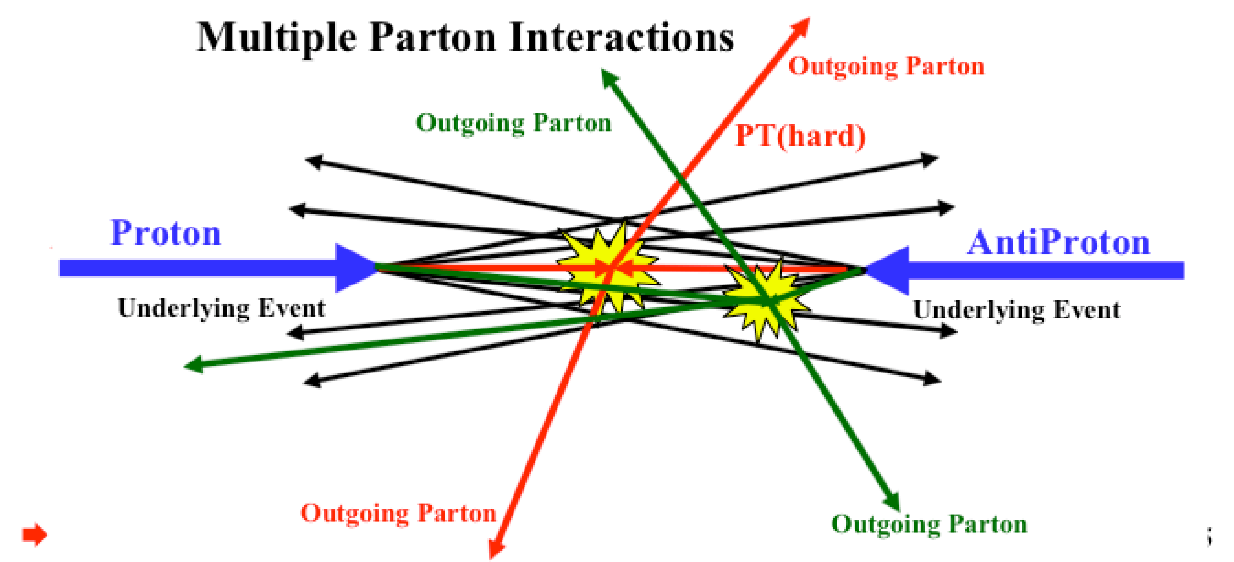
✶ b fragmentation function

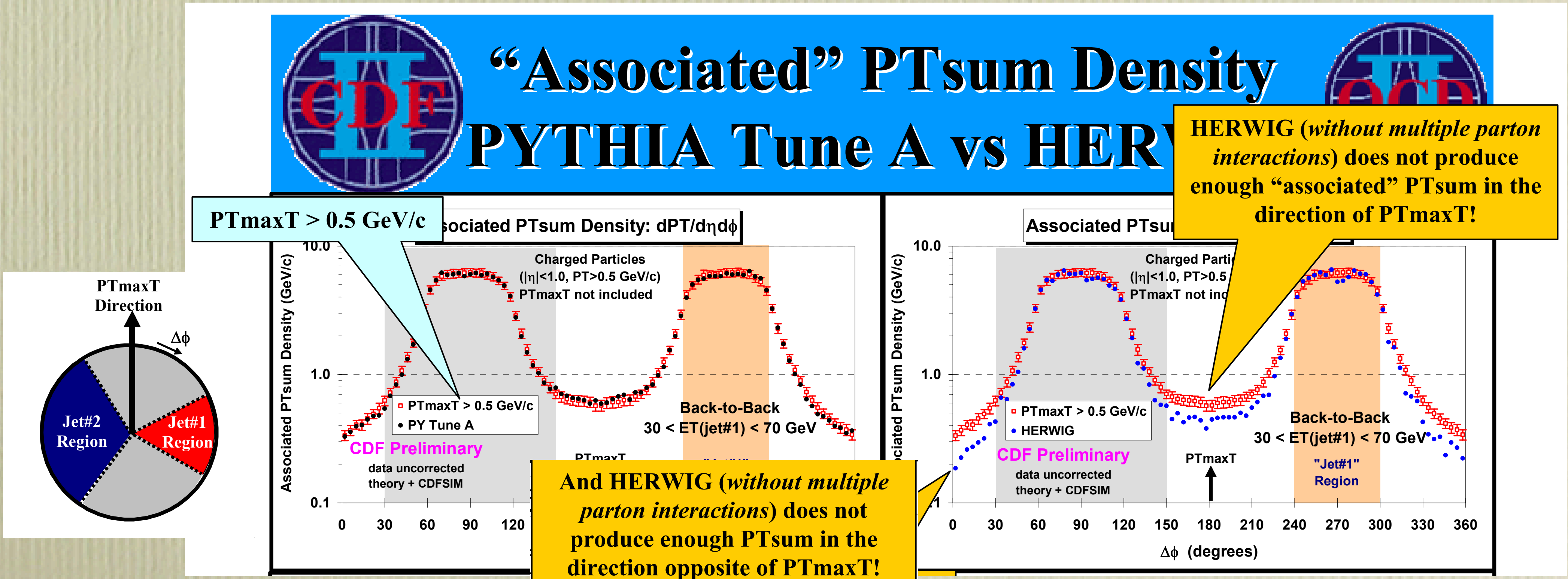


The structure of the underlying event

Mounting experimental evidence (CDF, R.Field in the // sessions) that the UE is the result of **multiple semi-hard (minijet-like) interactions**

R.Field/CDF: **hep-ph/0201192, Phys.Rev.D65:092002,2002**





“Associated” PTsum Density

PYTHIA Tune A vs HER

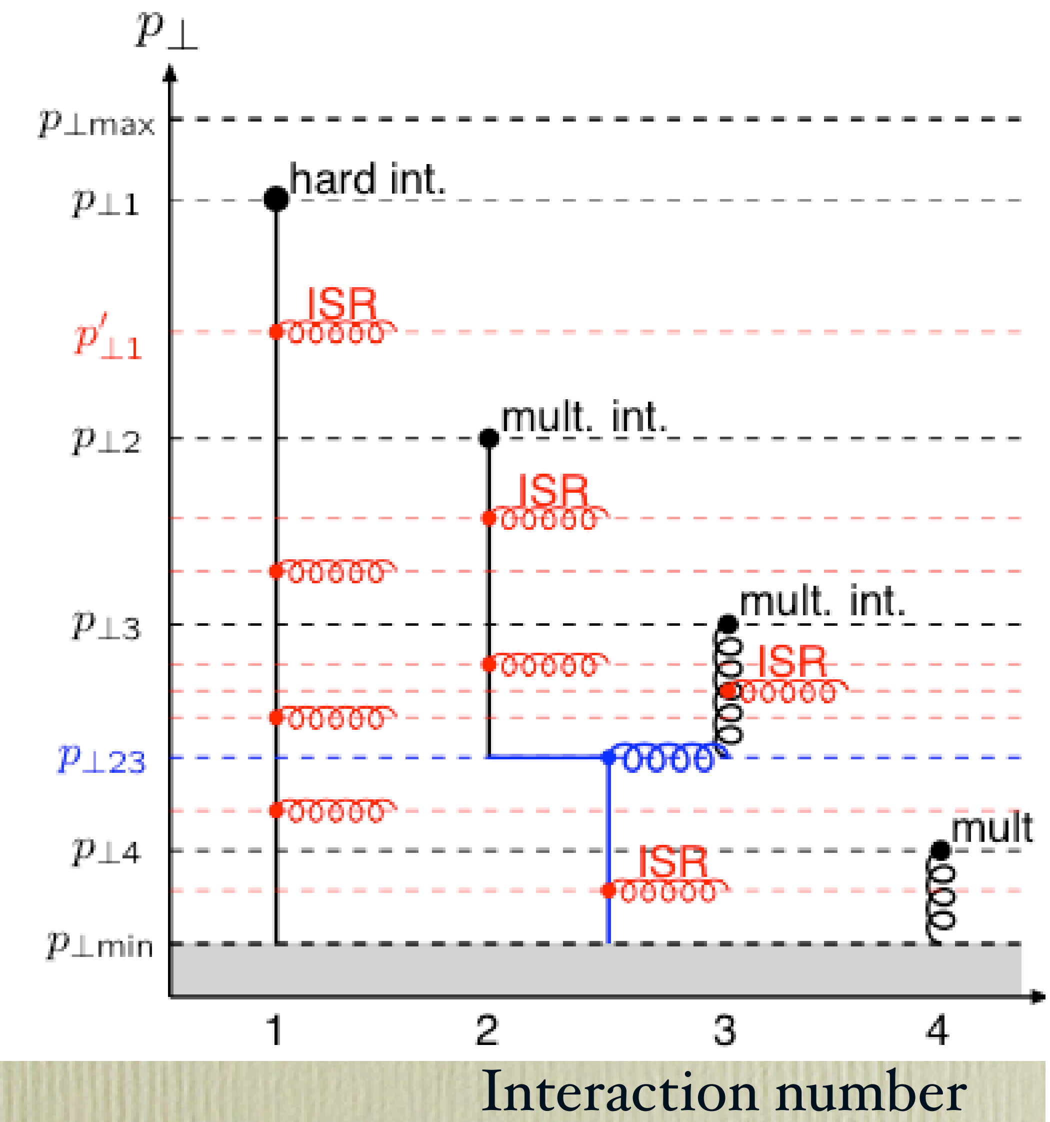
PTmaxT > 0.5 GeV/c

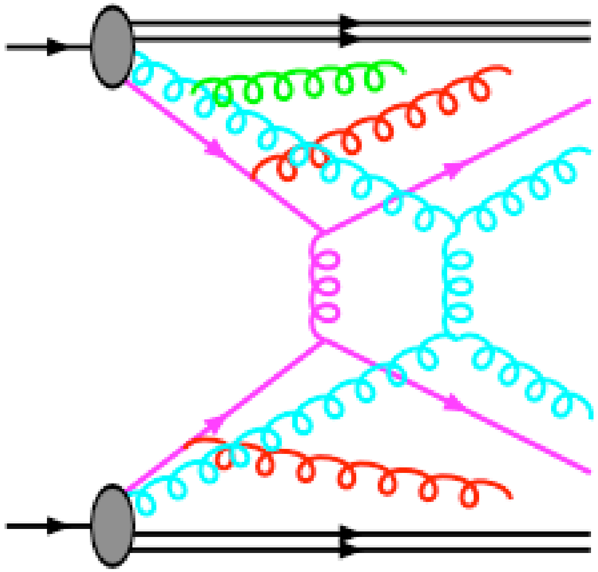
HERWIG (*without multiple parton interactions*) does not produce enough “associated” PTsum in the direction of PTmaxT!

And HERWIG (*without multiple parton interactions*) does not produce enough PTsum in the direction opposite of PTmaxT!

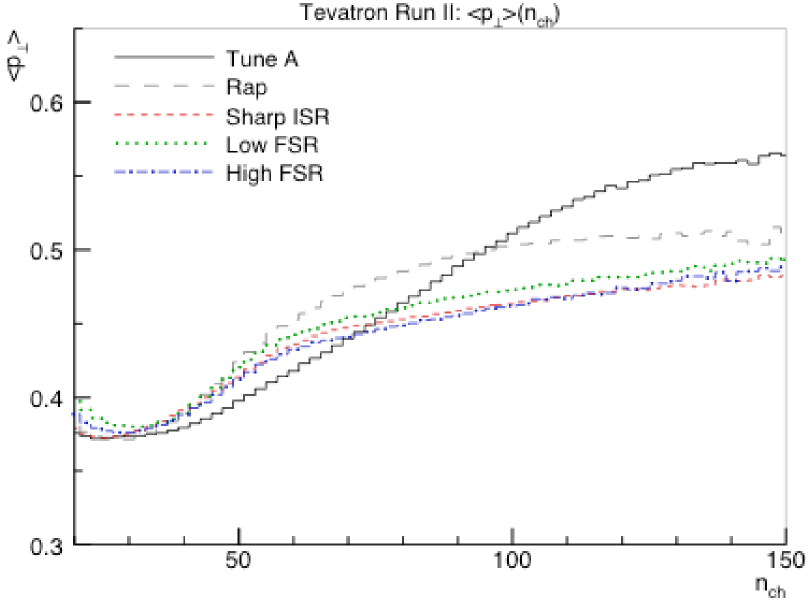
Interleaved Multiple Interactions

P.Skands and T. Sjöstrand, **hep-ph/0408302, hep-ph/0402078**





$\ldots\langle p_\perp\rangle(n_{\mathrm{ch}})$ problematical



⇒ how are final-state colours correlated?

- The fact that the UE is described by multiple semi-hard interactions implies that the tuning of the UE parameters depends on the input PDF.
- Use of UE-sensitive quantities (e.g. jets) in the PDF fits will couple the PDF fitting and PDF-dependent UE tuning!
- The mini-jet nature of the UE implies that the particle and energy flows are not uniformly distributed within a given event:
    - can one do better than the standard uniform, constant, UE energy subtraction?
- Studies of MB and UE should be done early on, at very low luminosity, to remove the effect of overlapping pp events:
    - MB triggers
    - low-E_T jet triggers

Final remarks

- Our tools have significantly improved over the last 2-3 years:
  - inclusion of higher order matrix elements in shower MC's
  - inclusion of NLO corrections in shower MC's
  - differential NNLO spectra
  - better models for the underlying event, and for hadronization
- Proper use of these tools will require validation and tuning against data. The Tevatron experiments are only now developing a culture of MC tuning, along the lines of LEP and HERA. As a result, the control over the theoretical systematic uncertainties in several crucial measurements at the Tevatron and at the LHC is still weak.
- Improvement of our tools, via **theoretical developments** and especially via the development of experimental strategies for the **validation of the theoretical systematics** will be essential to complete a "**precision measurement**" programme at the LHC. The collaboration between MC developers and experimentalists will be fundamental!
- Future progress in the accuracy of MCs may be limited by some intrinsic theoretical difficulty (breaking of factorization, inadequacy of the Markovian evolution, etc)
- Very interesting and rewarding work ahead!