EWK Cross-sections and Widths

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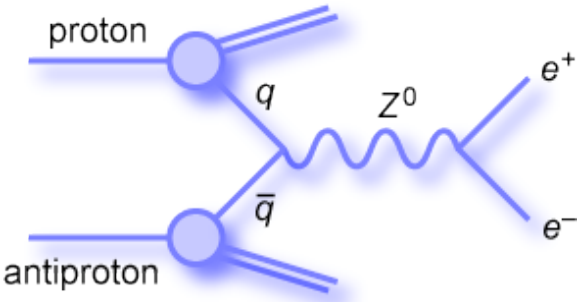
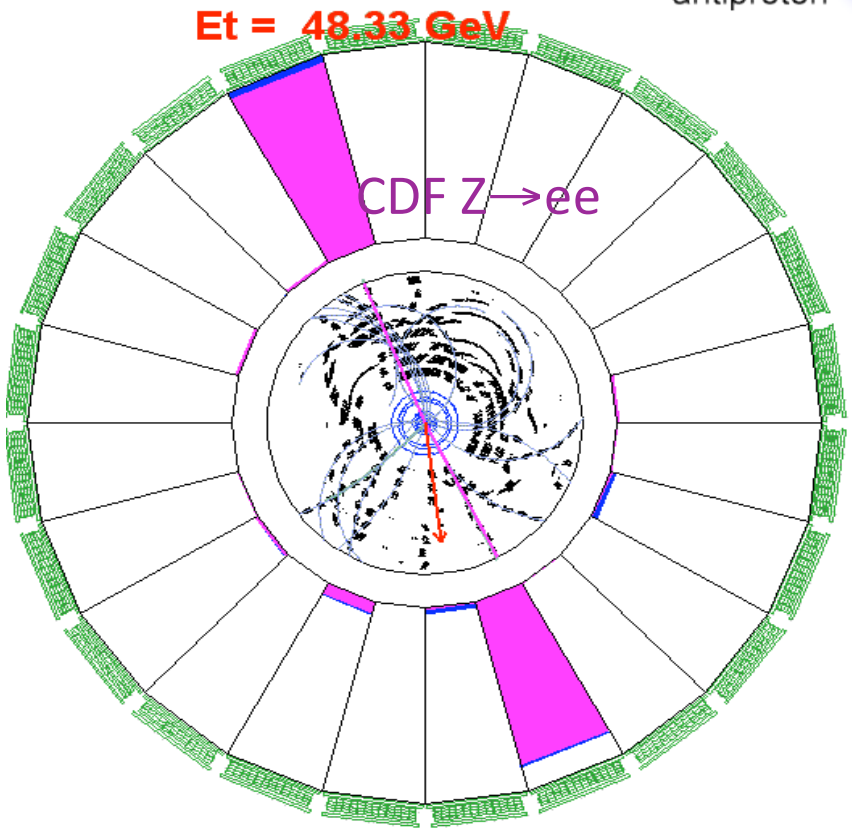
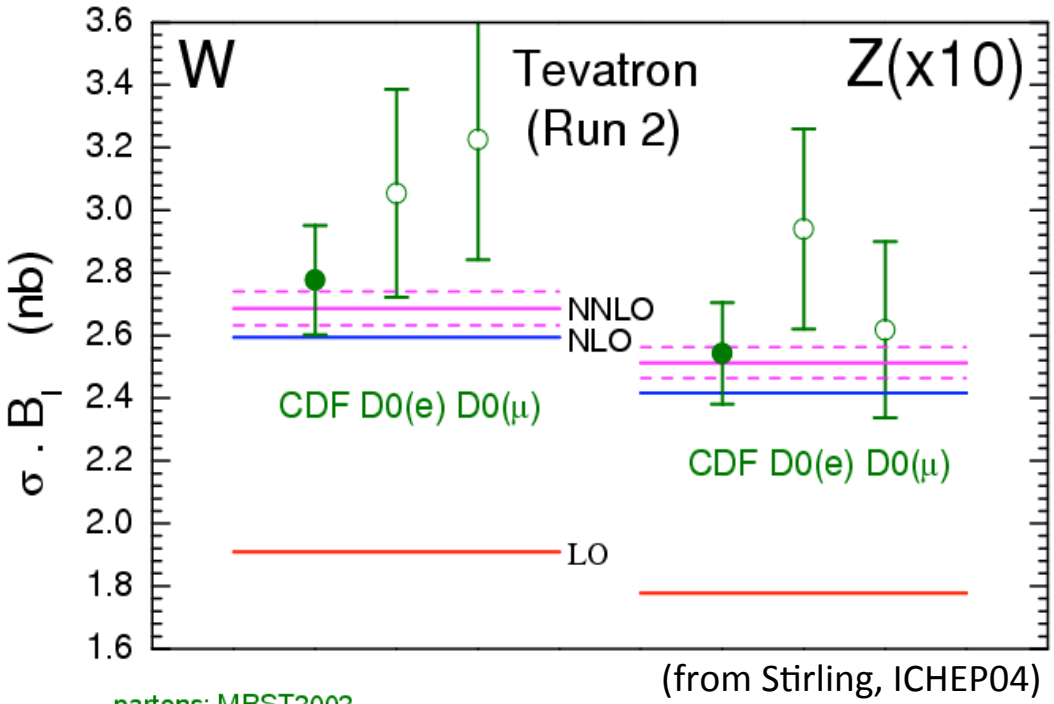
for the CDF and D0 Collaborations

ICHEP, Philadelphia, 30 July 2008





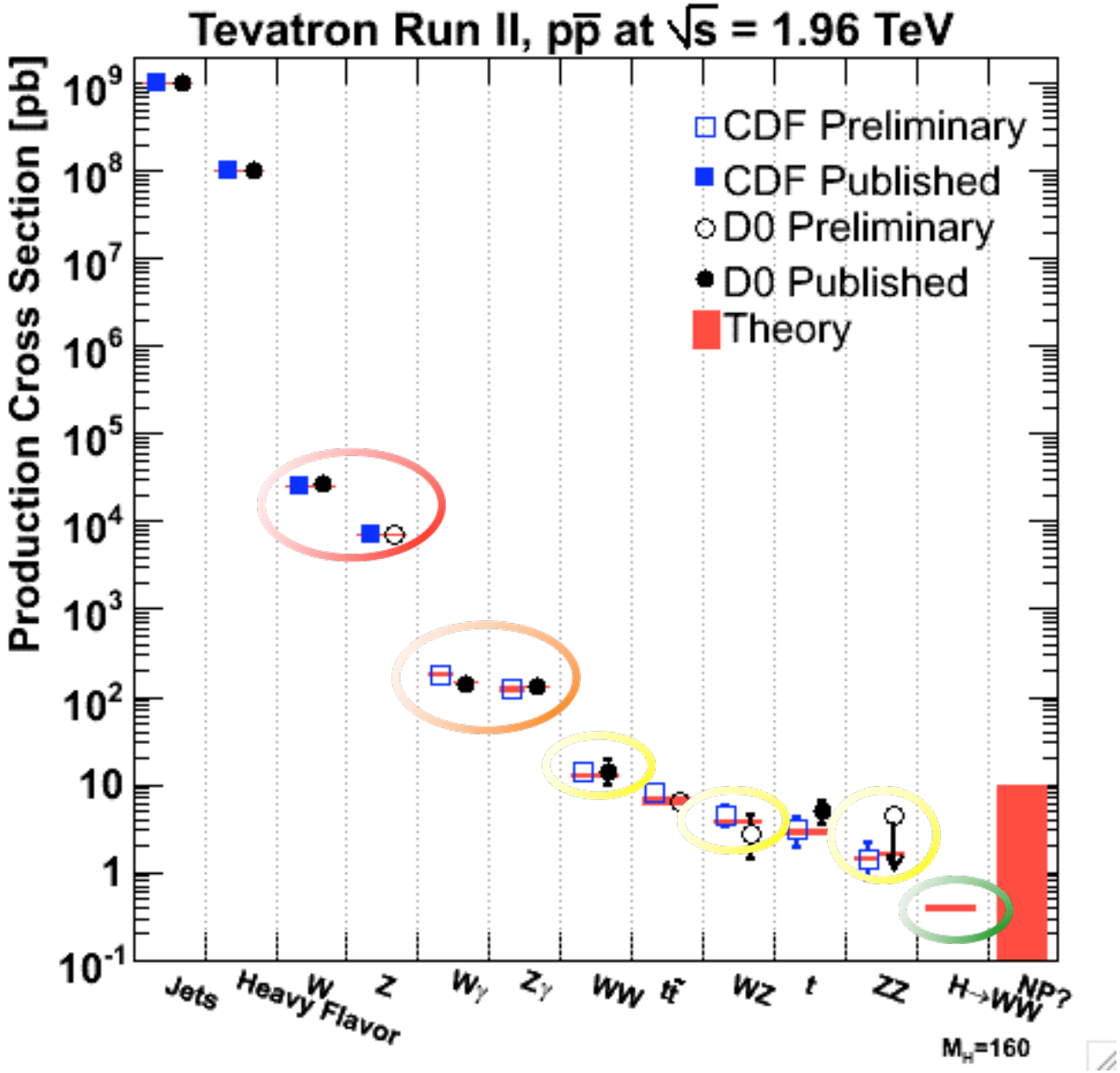


(from Stirling, ICHEP04)

partons: MRST2002
NNLO evolution: Moch, Vermaseren, Vogt
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections

2004, using < 100 pb^{-1}

A high-p_T physics programme



Now:

- More challenging τ channels
- Differential cross-sections
- High-precision measurements of Standard Model parameters

Outline

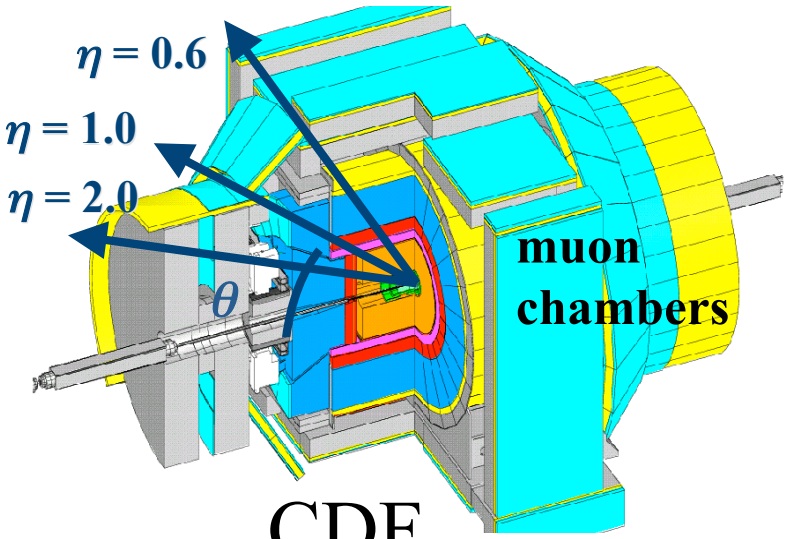
- More challenging τ channels
- Differential cross-sections
- High-precision measurements of Standard Model parameters

$\sigma(p\bar{p} \rightarrow Z) \,.\, Br(Z \rightarrow \tau\tau)$

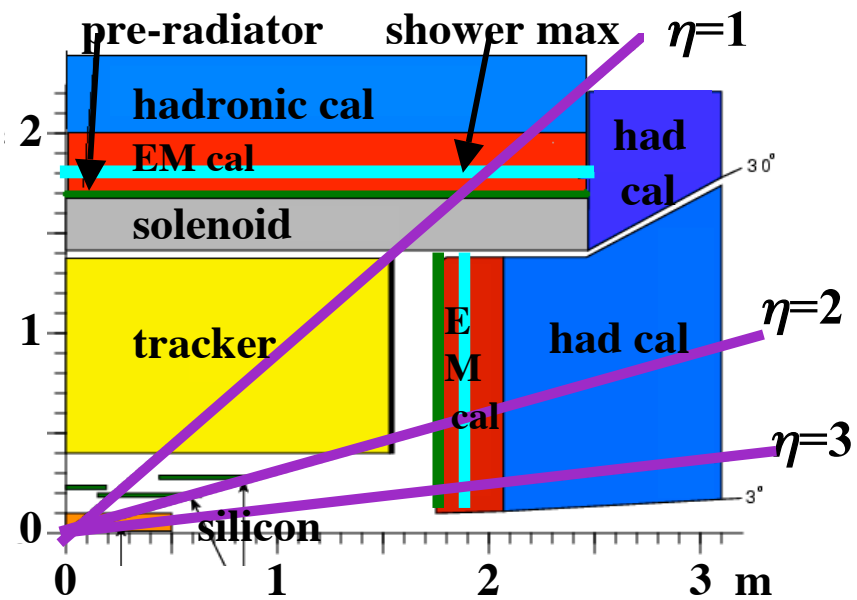
$d\sigma_Z / dy$
$d\sigma_Z / dp_T$

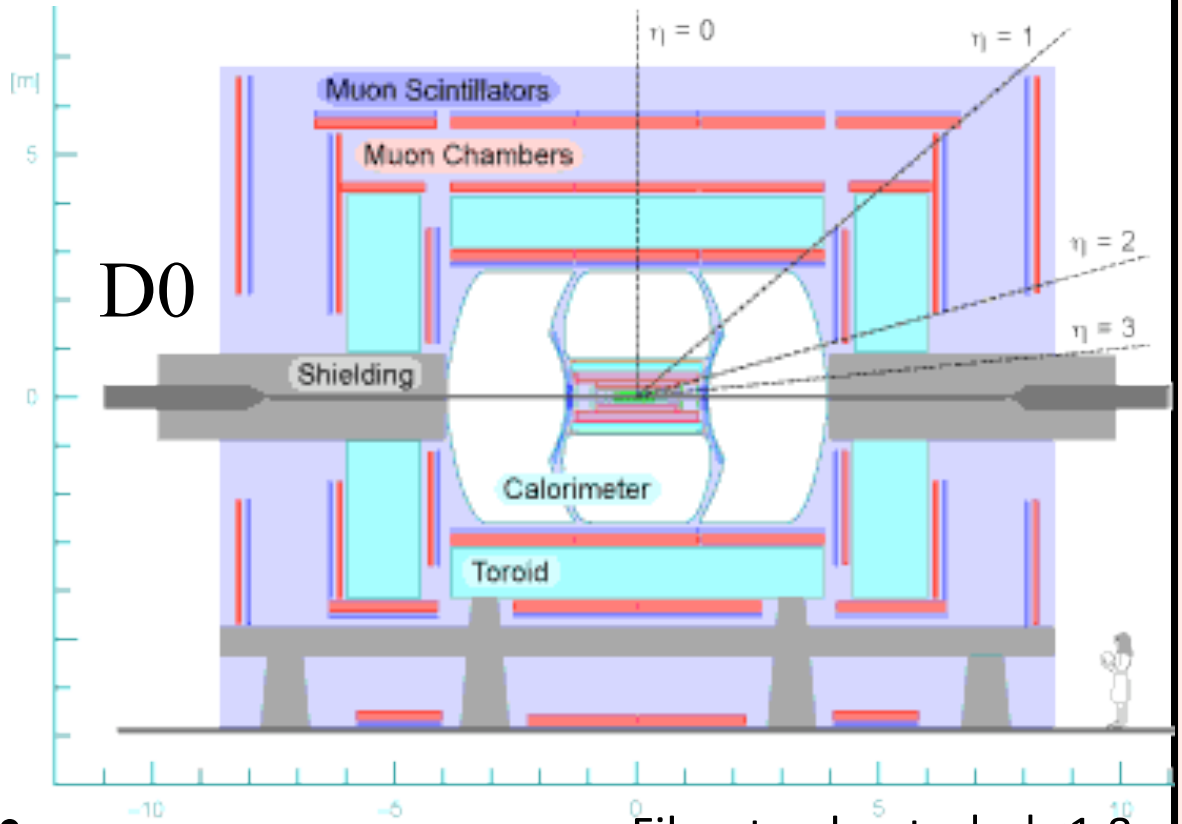
Γ_W
Γ_Z(invisible)

CDF and D0



CDF





D0

Drift chamber to $|\eta|<1$
Further tracking from Si
Calorimeter to $|\eta|<3$
Muon system to $|\eta|<1.5$

Fibre tracker to $|\eta|<1.8$
Calorimeter to $|\eta|<4$
Muon system to $|\eta|<2$

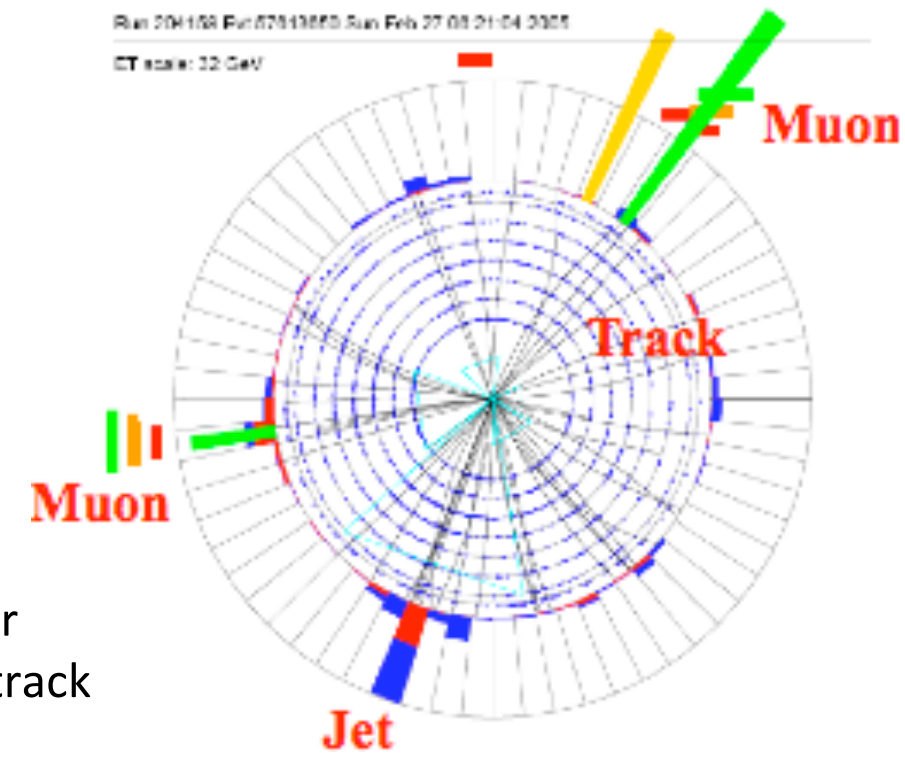
W and Z selection

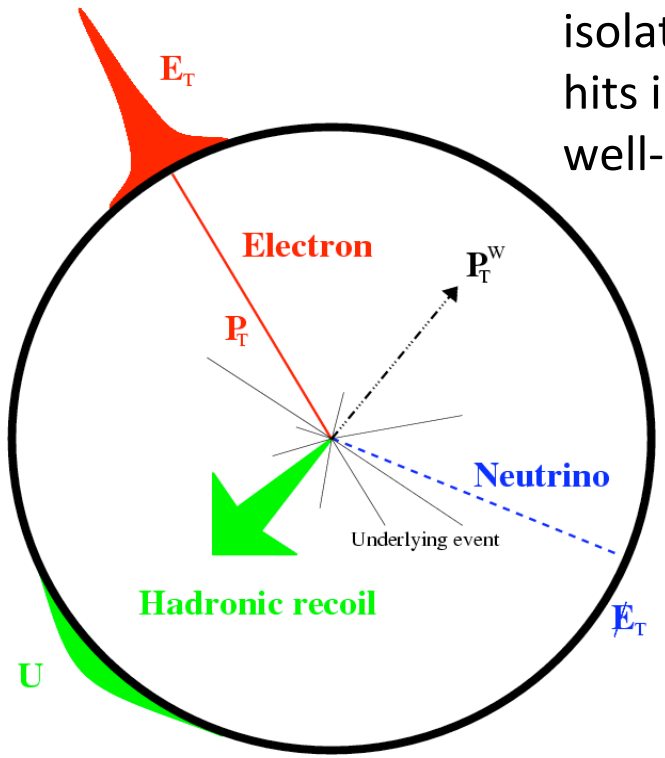
Electrons:

good EM shower shape
small hadronic energy
isolated in calorimeter
well-matching good track
(except far forward)

Muons:

MIP in calorimeter
isolated
hits in muon chamber
well-matching good track





Z selection:

2 oppositely-charged electrons or muons
invariant mass consistent with m_Z

W selection:

exactly one electron or muon
energy imbalance in reconstructed event, associated with neutrino

Taus at D0

The elements:

- calorimeter cluster (cone R<0.5)
- energy concentrated in inner cone R<0.3
- tracks in inner cone, mass<1.8GeV
- EM sub-clusters in finely segmented shower-max layer of calorimeter

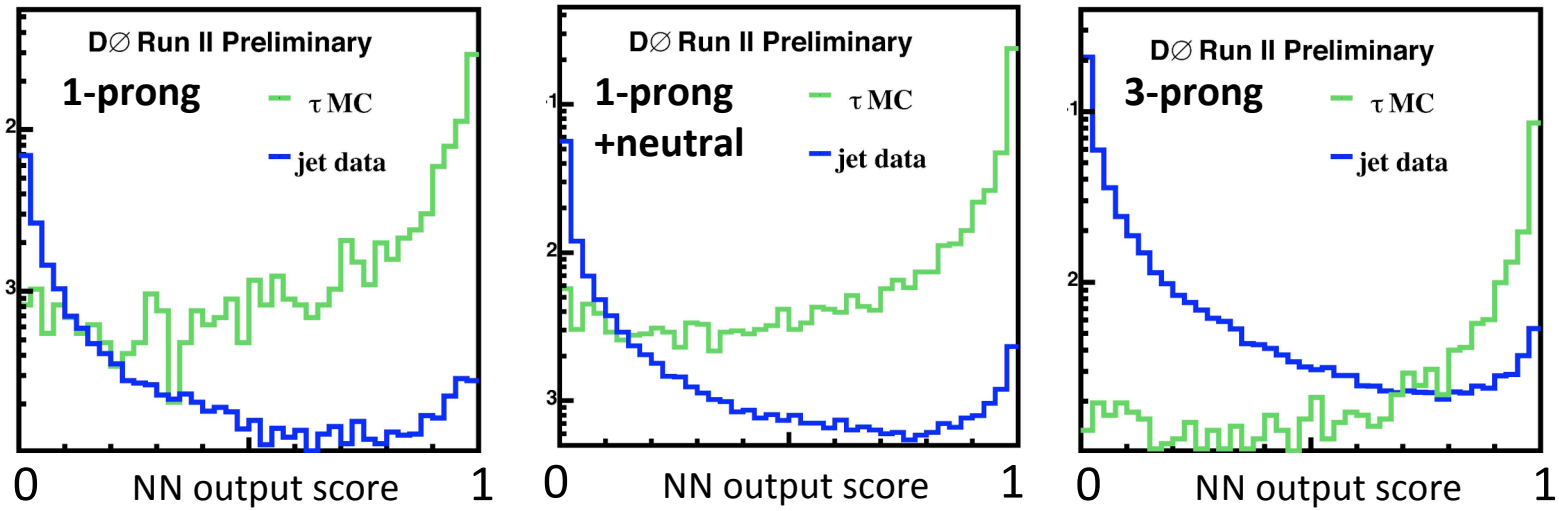
New: improved tau E_T measurement

Neural net separator trained on variables measuring:

- isolation
- shower shape
- calorimeter–track correlations

Three D0 tau categories:

1-prong: 1 track, no EM sub-cluster
1-prong + neutral: 1 track, ≥1 EM sub-clusters
3-prong: ≥2 tracks, ≥0 EM sub-clusters



$Z \rightarrow \tau\tau$

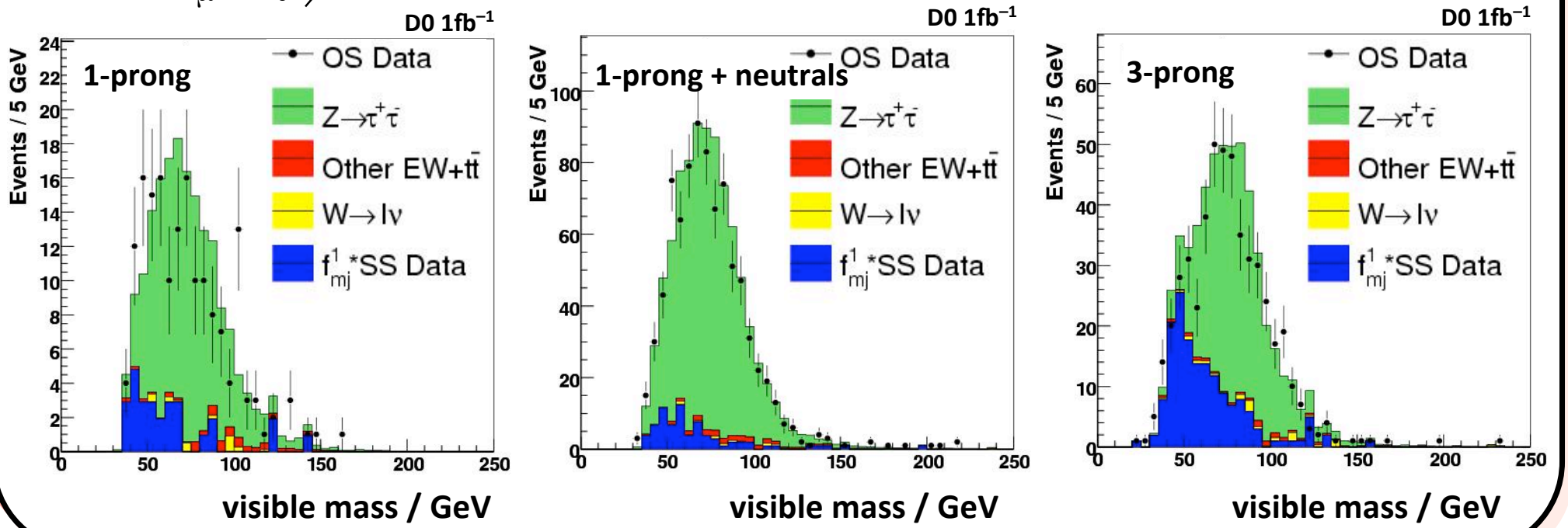
Select $Z \rightarrow \tau_\mu \tau_h$ from inclusive muon trigger. Additionally:

- $p_T^\mu > 15$ GeV
- $p_T^\tau > 15$ GeV
- opposite charge
- scalar sum p_T of τ tracks > 15GeV or 5 GeV
- NN > 0.9 or 0.95

Backgrounds:

- QCD ($b\bar{b}$) data-driven from same-sign events → corrected for SS–OS ratio in QCD-enhanced sample
- EWK backgrounds from MC → W+jets corrected for component accounted for in same-sign events

$$m_{vis} = \sqrt{(P_\mu + P_\tau + \not{P}_T)^2}$$



$Z \to \tau\tau$

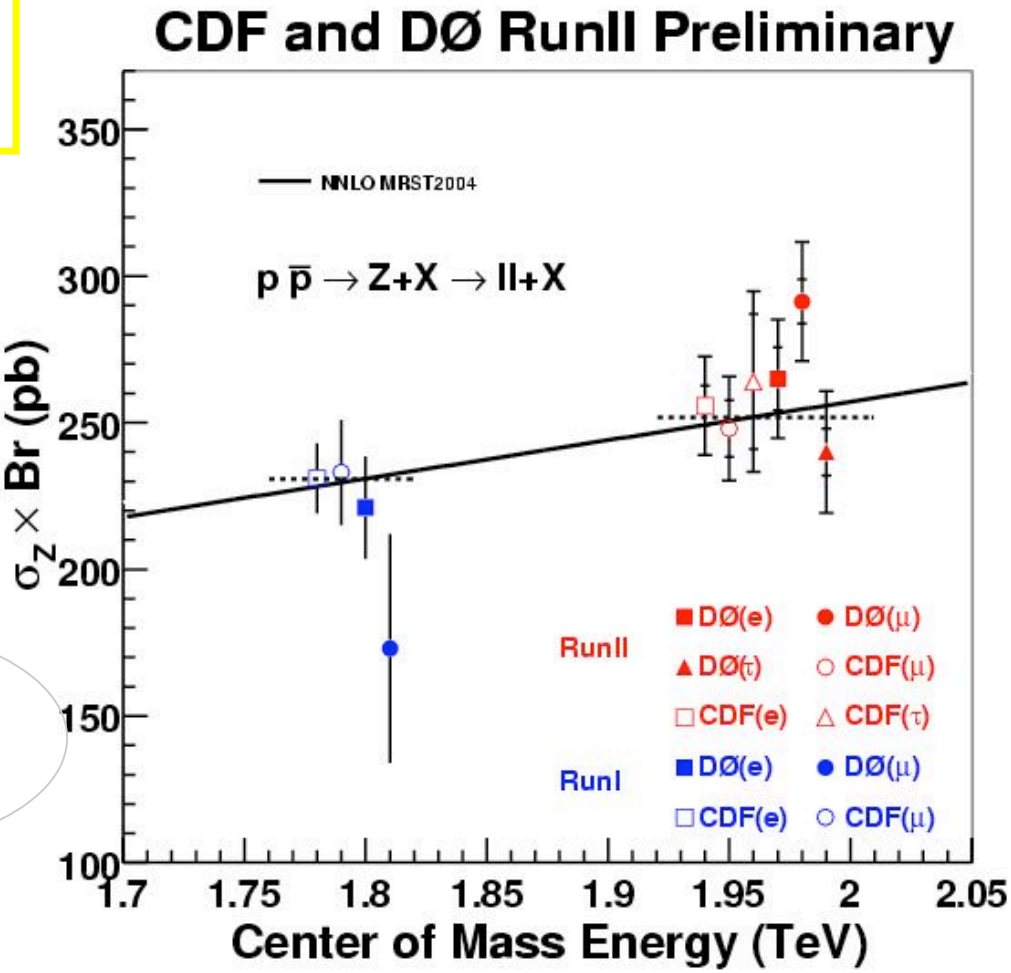
Total 1511 events observed, ~20% background

$\sigma(p\bar{p} \to Z) \,.\, Br(Z \to \tau\tau)$
$= 240 \pm 8(\text{stat}) \pm 13(\text{sys}) \pm 15(\text{lumi})$ pb

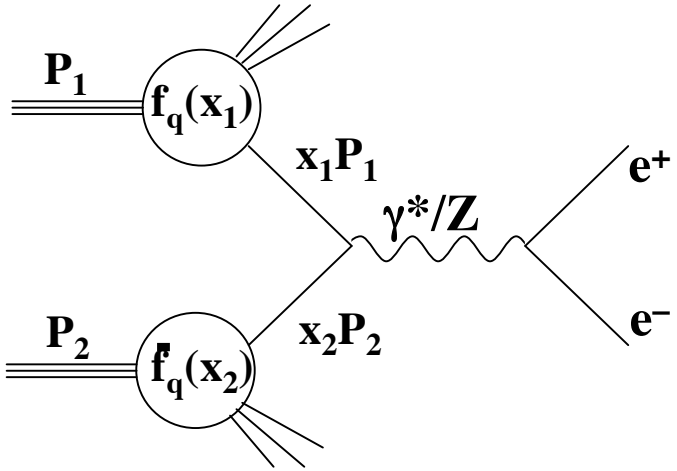
Systematic source	Value
Tau Energy Scale	1.0%
Tau ID	2.7%
Tau track reco	1.6%
QCD background	1.6%
$W \to \mu\nu$ background	0.5%
Trigger	2.7%
Muon track match	0.8%
Muon identification	0.6%
Charge misid	1.0%
PDF	2.0%
Total (excl lumi)	5.2%
Luminosity	6.2%

← 2.5%
← 3.5%
← 2.3%

Values from previous published analysis (PRD **71** 072004 (200

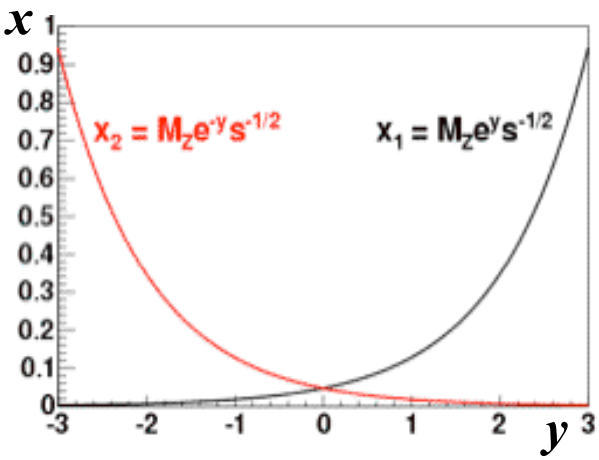


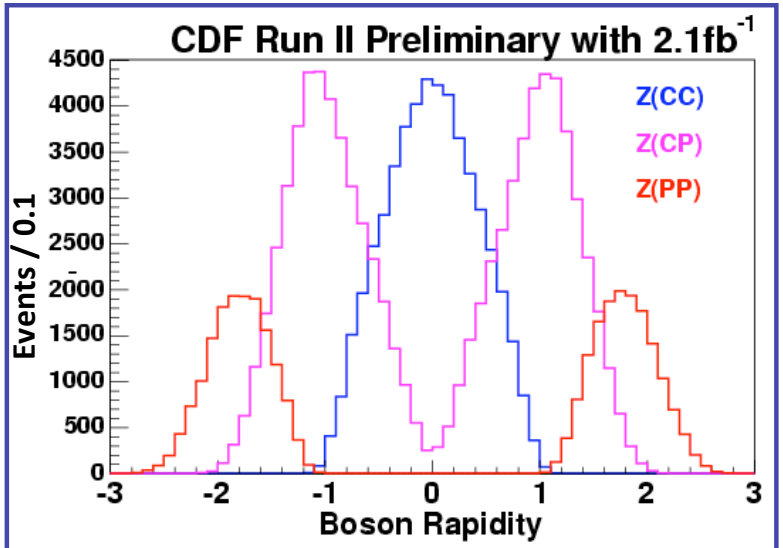
Z rapidity



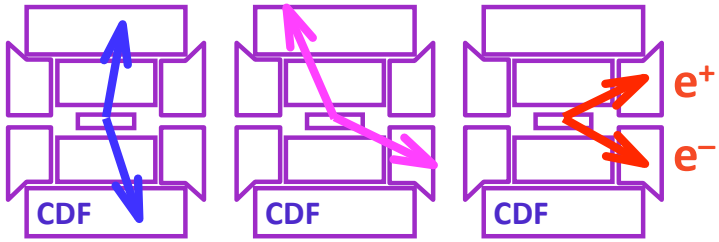
Z production: rapidity $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$

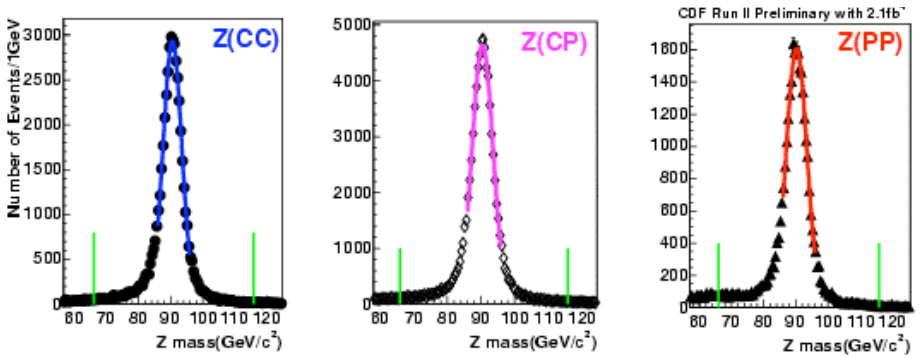
closely related to parton x: $x_{1,2} = \frac{m}{\sqrt{s}} e^{\pm y}$ (LO)



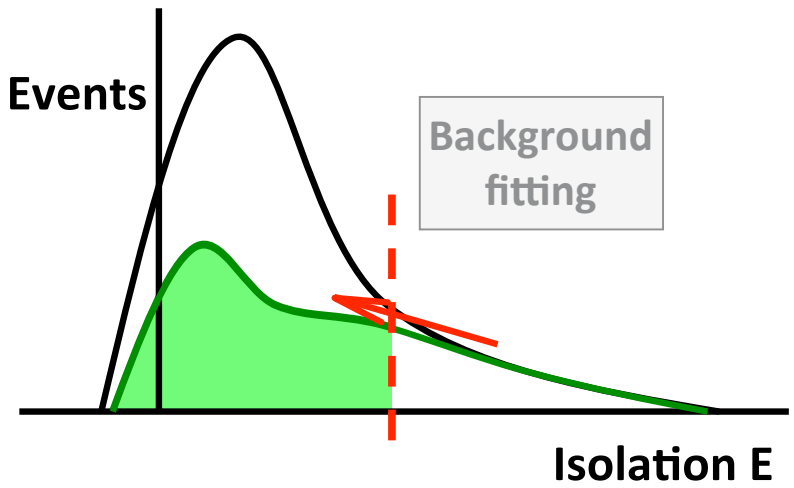


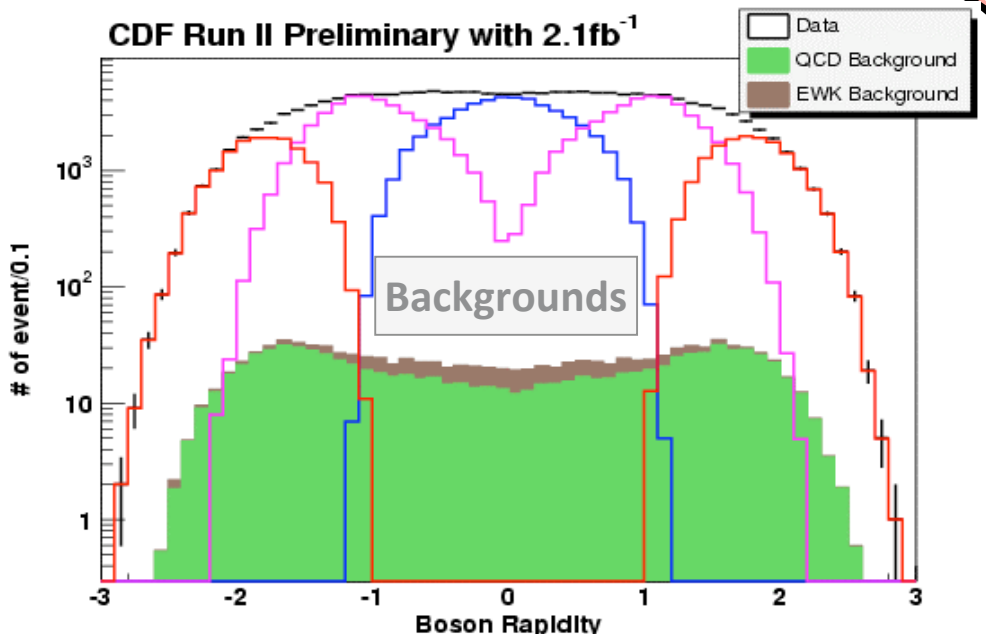
observe complete kinematic range

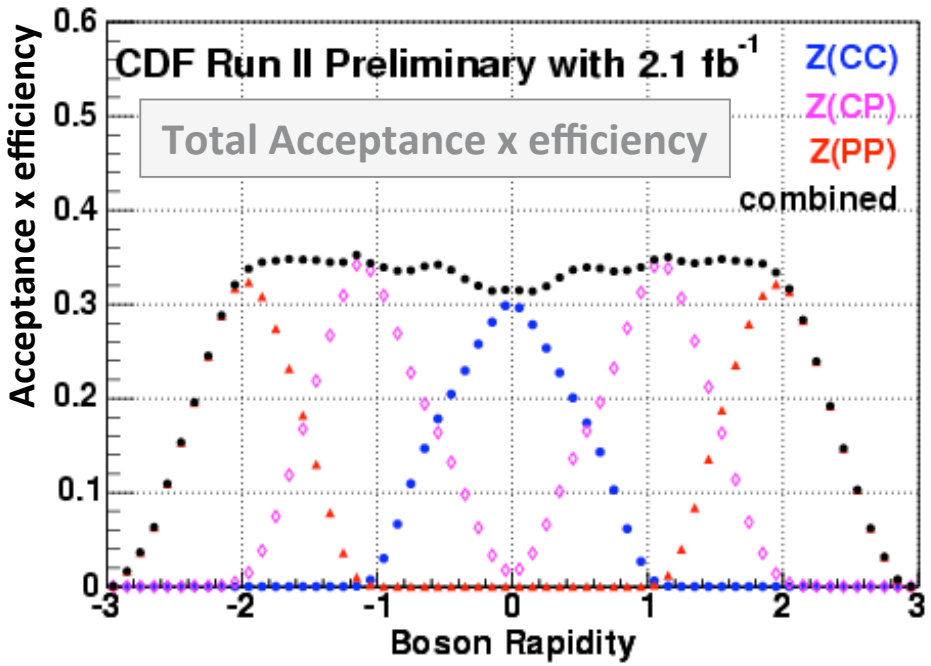




Z rapidity



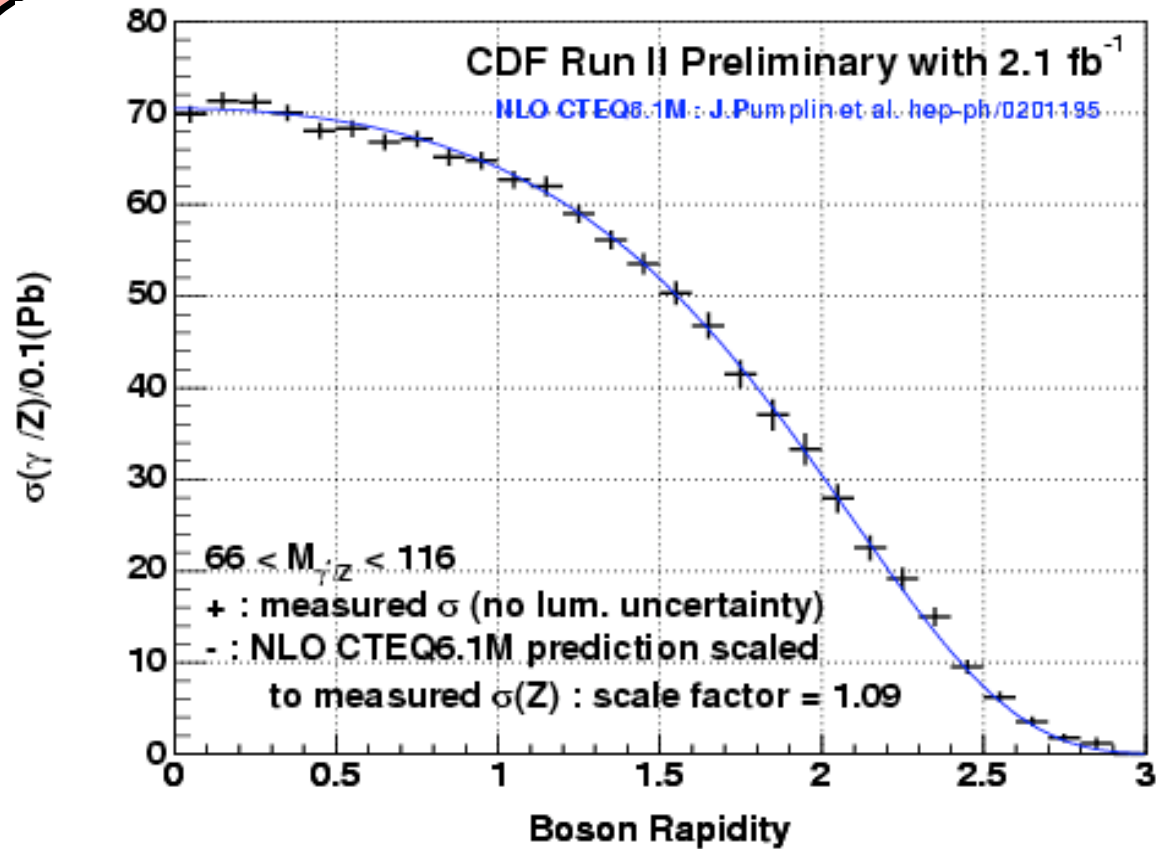


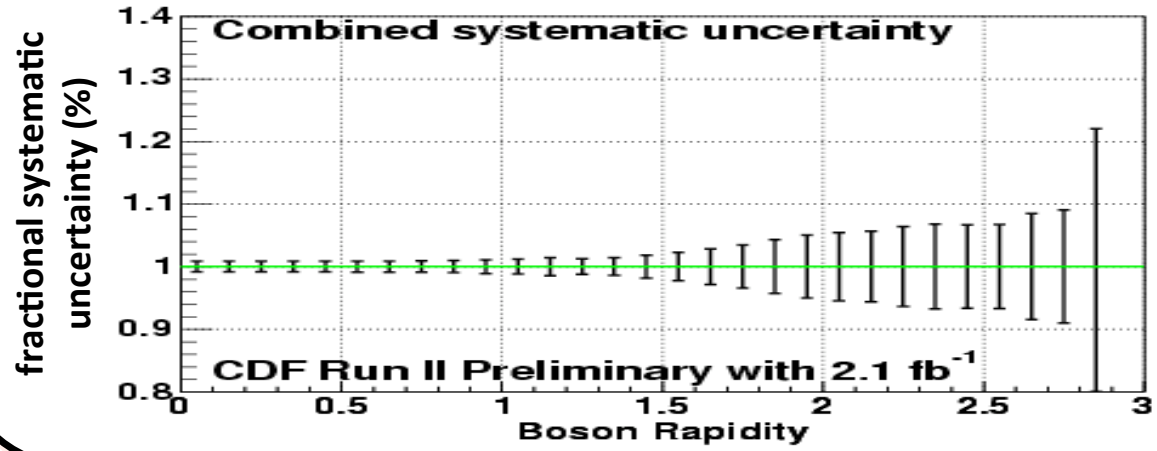


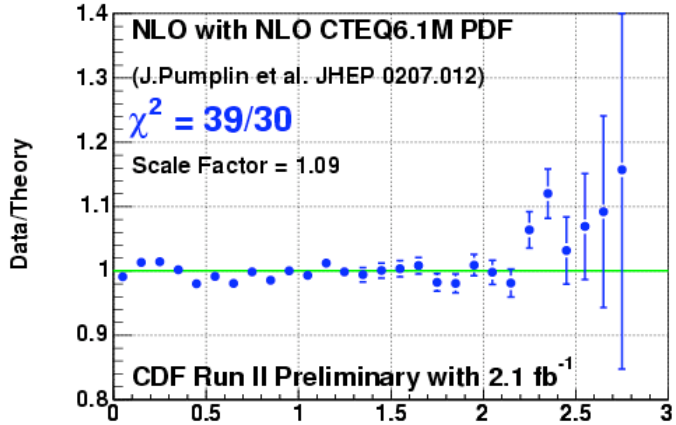
Systematics:

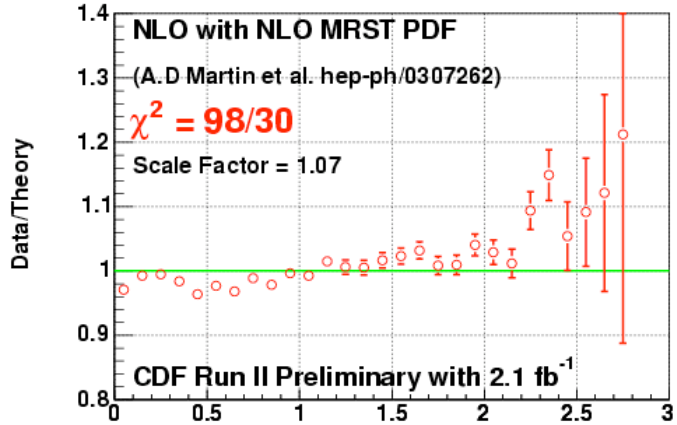
Detector material modeling
Background estimates
Electron identification efficiencies
Silicon tracking efficiency
Acceptance

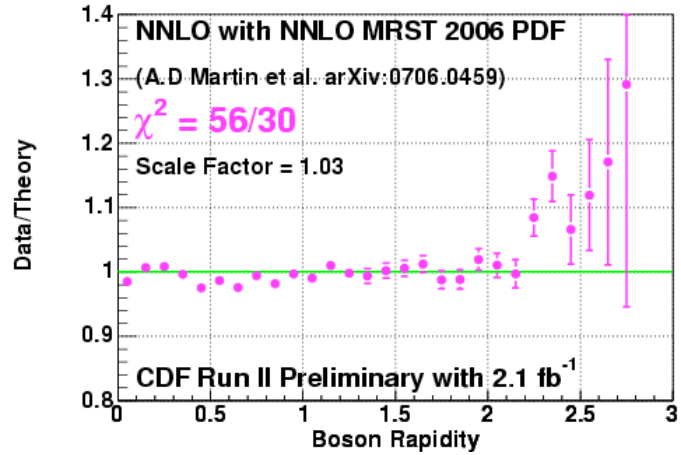
Z rapidity


CDF Run II Preliminary with 2.1 fb^{-1}
NLO CTEQ6.1M : J.Pumplin et al. hep-ph/0201195
$\sigma(\gamma/Z)/0.1$(Pb)
$66 < M_{\gamma/Z} < 116$
+ : measured σ (no lum. uncertainty)
- : NLO CTEQ6.1M prediction scaled
to measured σ(Z) : scale factor = 1.09
Boson Rapidity


Combined systematic uncertainty
fractional systematic uncertainty (%)
CDF Run II Preliminary with 2.1 fb^{-1}
Boson Rapidity

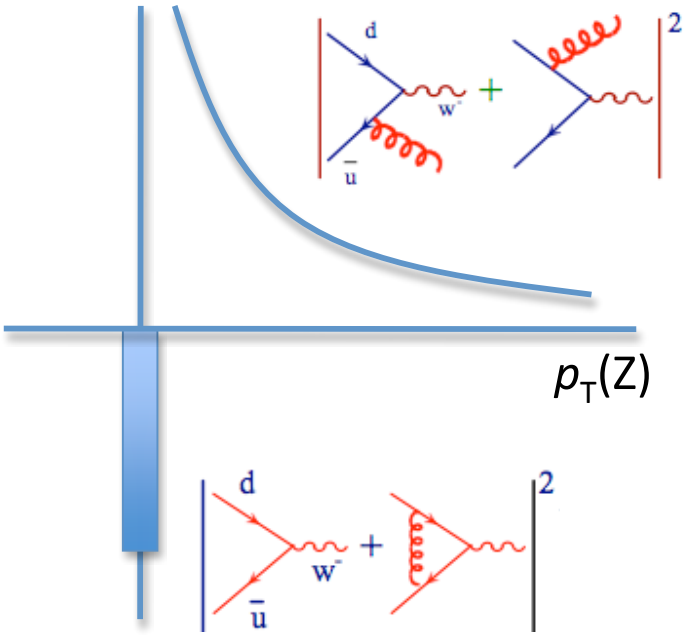

NLO with NLO CTEQ6.1M PDF
(J.Pumplin et al. JHEP 0207.012)
χ^2 = 39/30
Scale Factor = 1.09
Data/Theory
CDF Run II Preliminary with 2.1 fb^{-1}


NLO with NLO MRST PDF
(A.D Martin et al. hep-ph/0307262)
χ^2 = 98/30
Scale Factor = 1.07
Data/Theory
CDF Run II Preliminary with 2.1 fb^{-1}

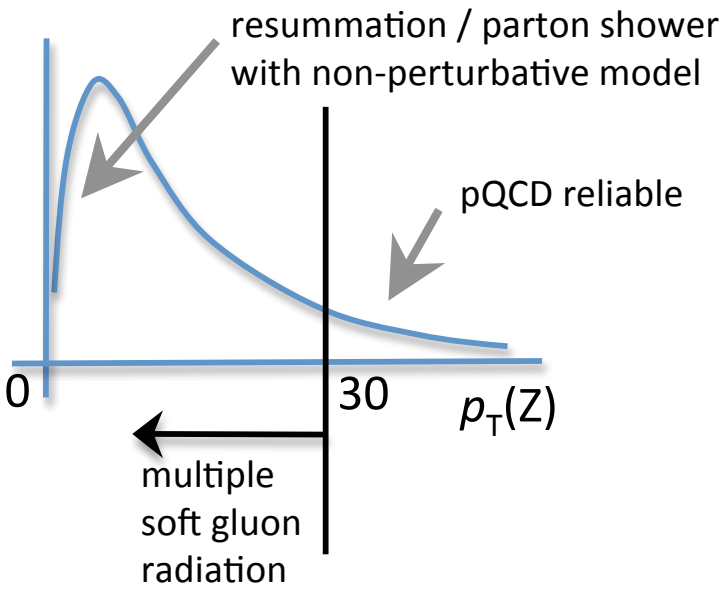

NNLO with NNLO MRST 2006 PDF
(A.D Martin et al. arXiv:0706.0459)
χ^2 = 56/30
Scale Factor = 1.03
Data/Theory
CDF Run II Preliminary with 2.1 fb^{-1}
Boson Rapidity

Z p_T

Measurement of Z p_T tests QCD predictions for initial state gluon radiation



resummation required

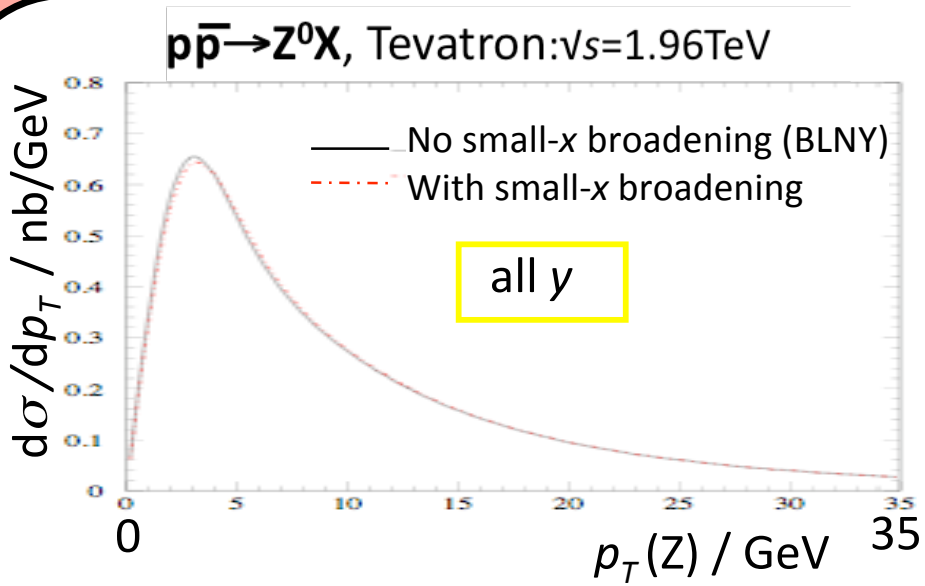


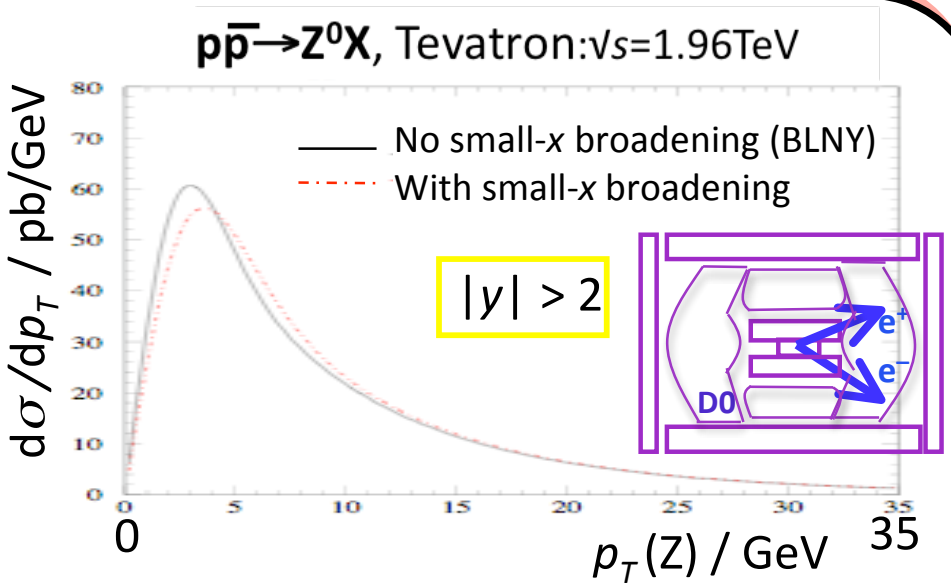
RESBOS event generator implements NLO QCD and CSS resummation (with BNLY form-factor)

3-parameter function, global data fit

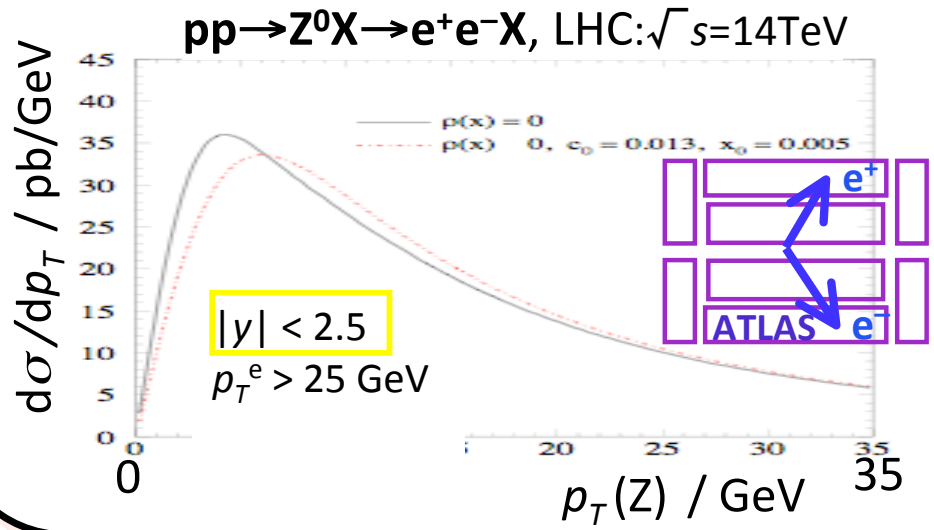
Recent global fits suggest extra small-x form-factor

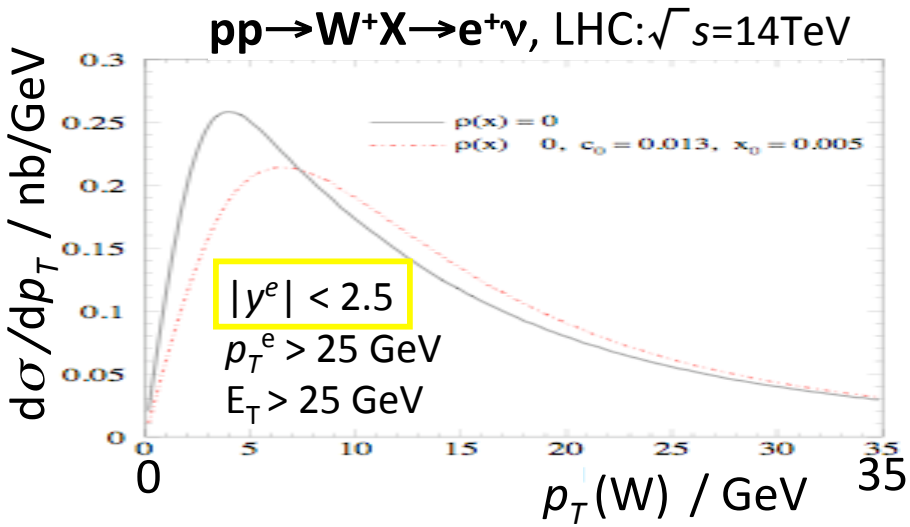
Z p_T





- Recent global fits suggest extra small-x form-factor
  – implies p_T(Z) broadened at high y





Z p_T

Selection:

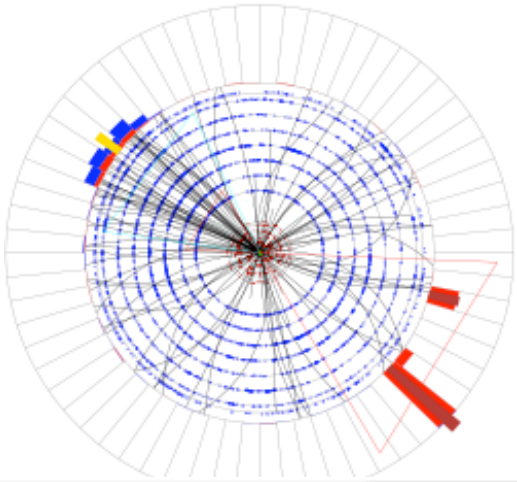
$p_T(e_1)$, $p_T(e_2)$ > 25 GeV
$|\eta|$<1.1 or 1.5<$|\eta|$<3.2
70 < m_{ee} < 110

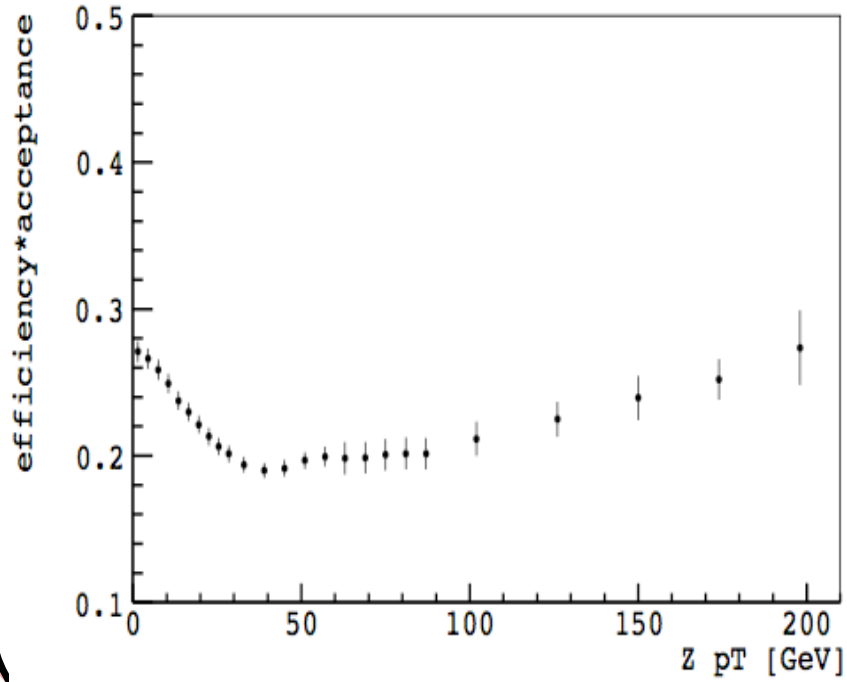
} 64k events, > 5k for $|y_Z|$>2

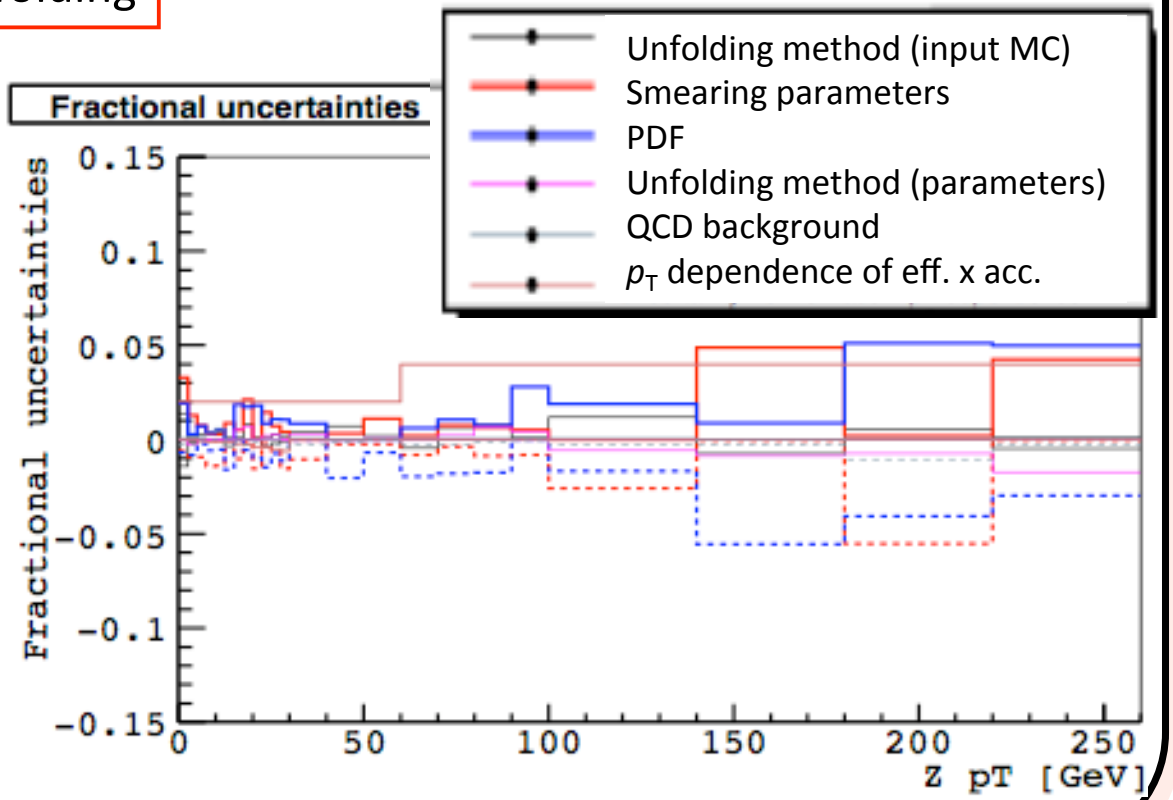
Backgrounds: fit m_{ee} with templates

1.3–8.5%

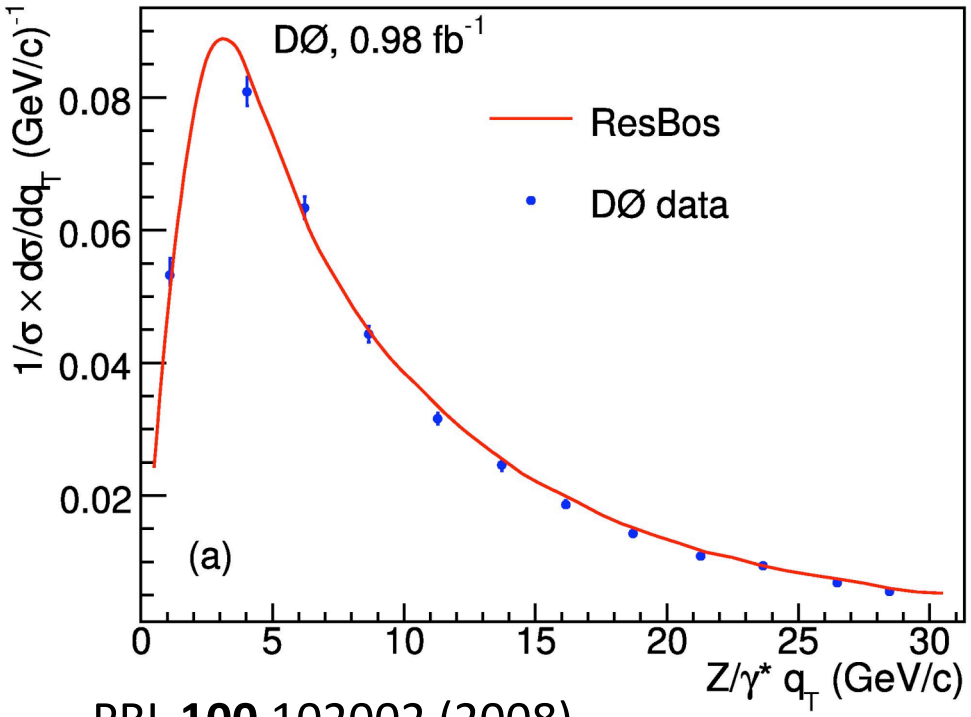
Regularized unfolding



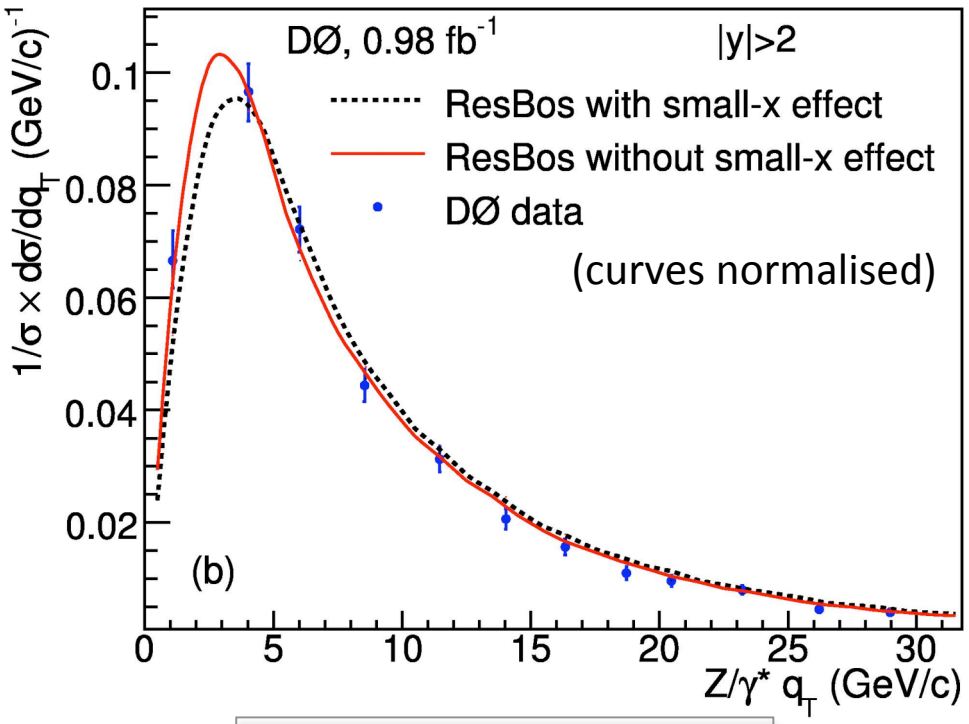




Z p_T



PRL **100** 102002 (2008)



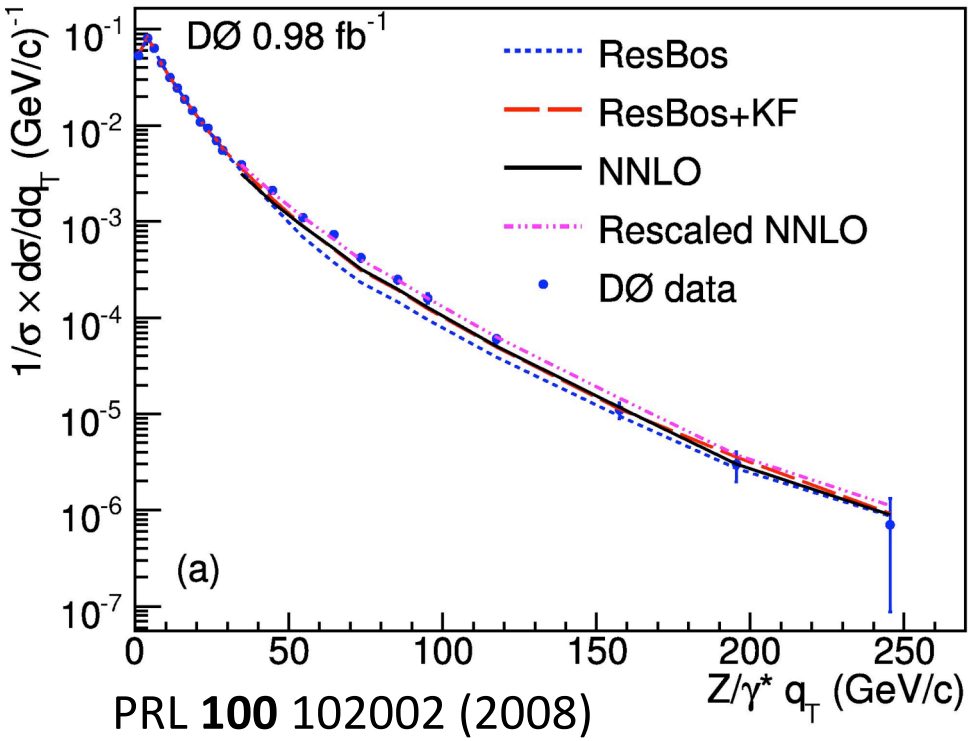
without small-*x* effect:
χ^2/dof = 11.1/11

including small-*x* effect:
χ^2/dof = 31.9/11

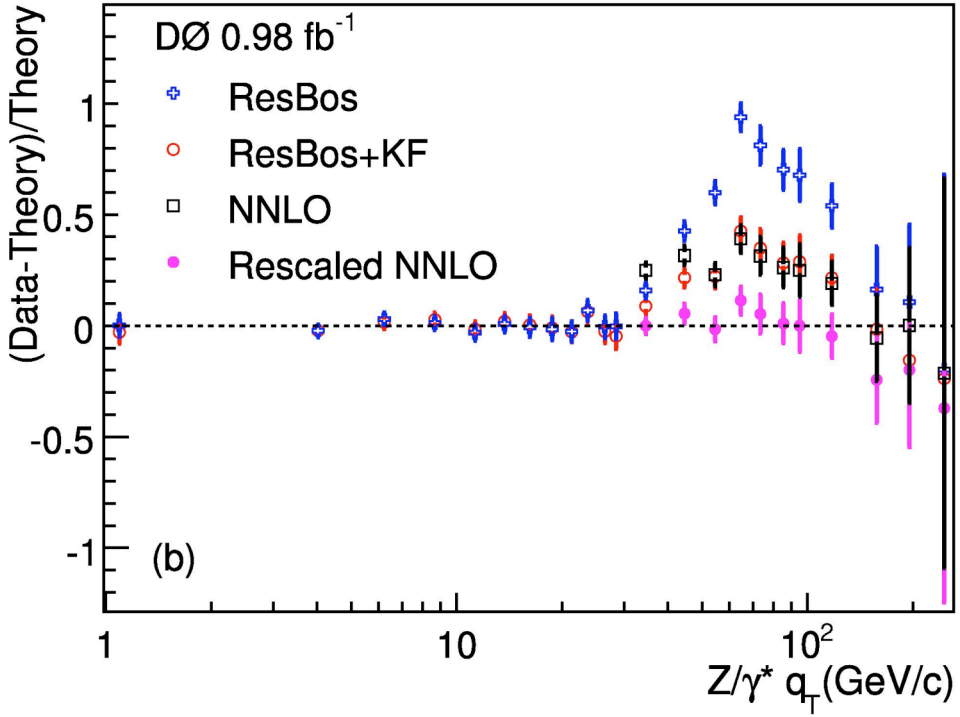
Data does not favour small-x broadening

Z p_T

The complete spectrum:



PRL **100** 102002 (2008)



Compare 4 models:

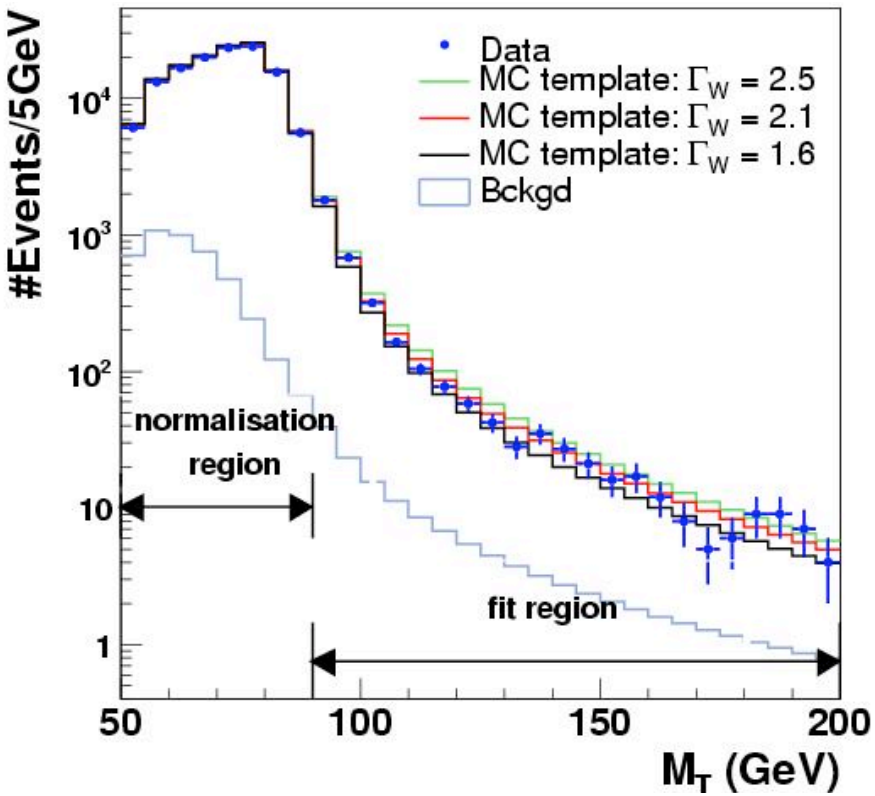
- Resbos with default parameters
- Resbos with additional NLO–NNLO K-factor
- NNLO (Melnikov and Petriello)
- NNLO rescaled at to data at 30GeV/*c*

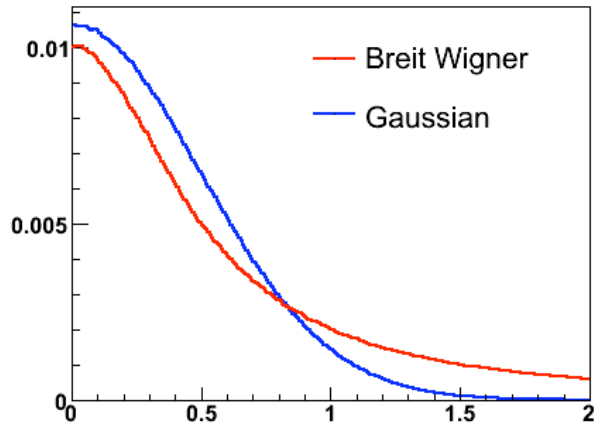
W width

Γ_W predicted in Standard Model: Γ_W^{SM} = 2093±2 MeV (Renton, hep-ph/0804.4779)

Experimentally have access to transverse quantities:

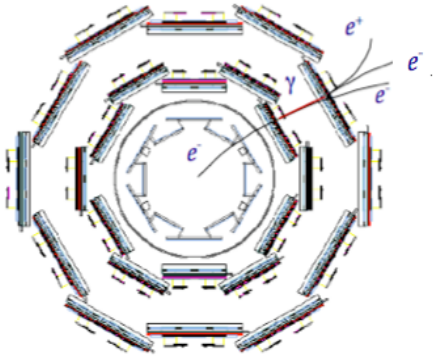
$$m_T = \sqrt{2 p_T^{\,l} p_T^{\,\nu} (1 - \cos\phi_{l\nu})}$$



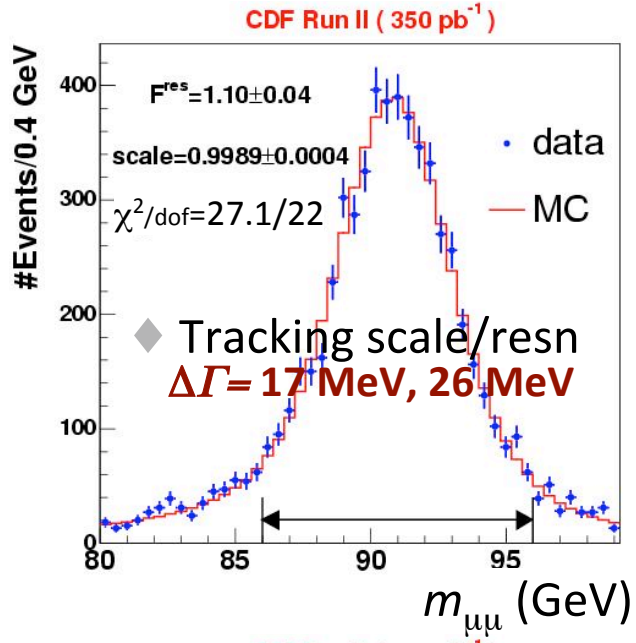


W width

- Generator:
  LO MC
  matched with Resbos (QCD ISR)
  and Berends/Kleiss (QED FSR)

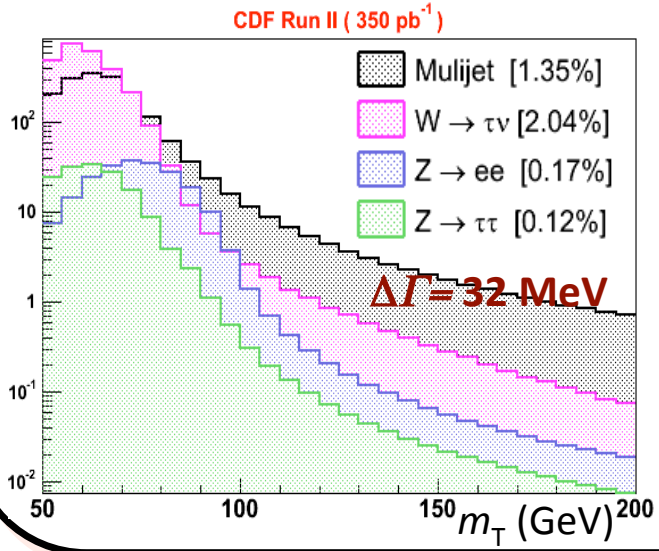


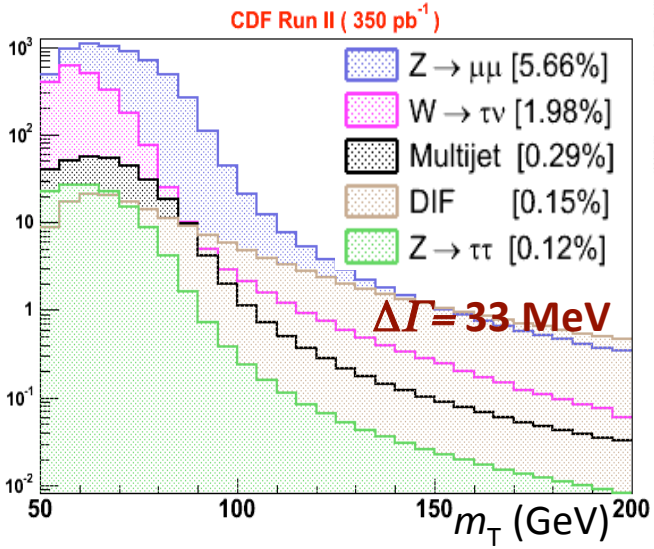
- Fast simulation for templates:
  electron conversions + showering
  muon energy loss
  parametric model of recoil energy
  (QCD, underlying event + brem)
  $\Delta\Gamma$= 54 MeV (ele), 49 MeV (mu)

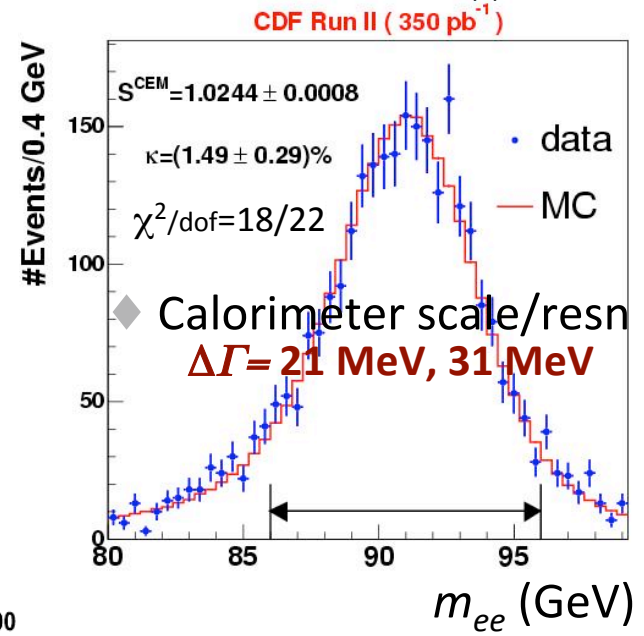


- Tracking scale/resn
  $\Delta\Gamma$= 17 MeV, 26 MeV

- Backgrounds

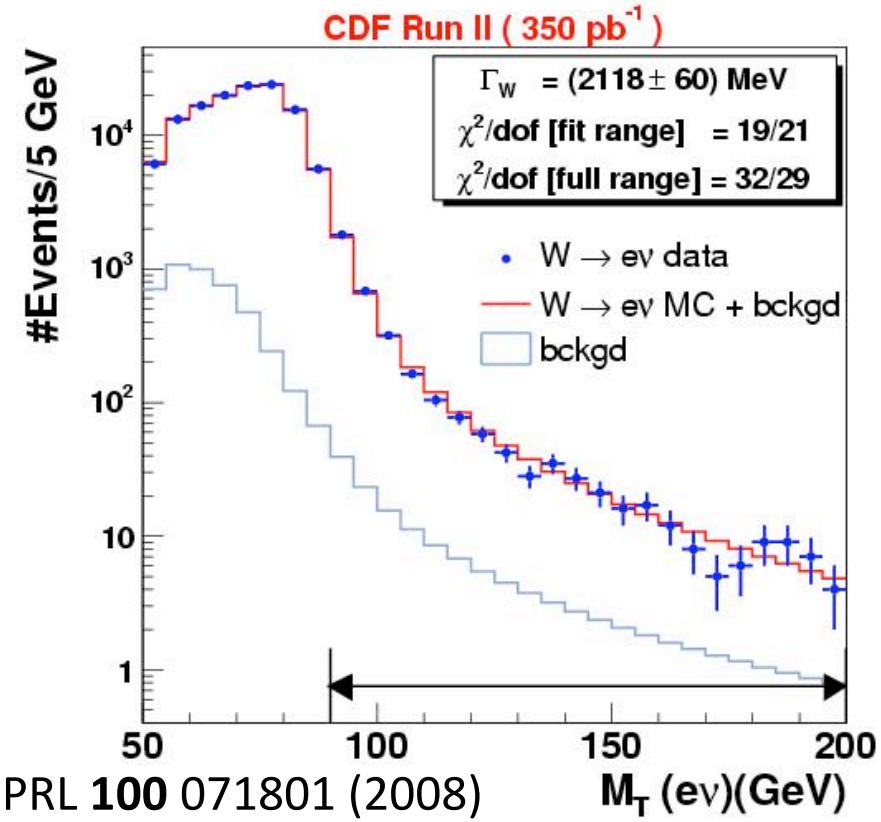




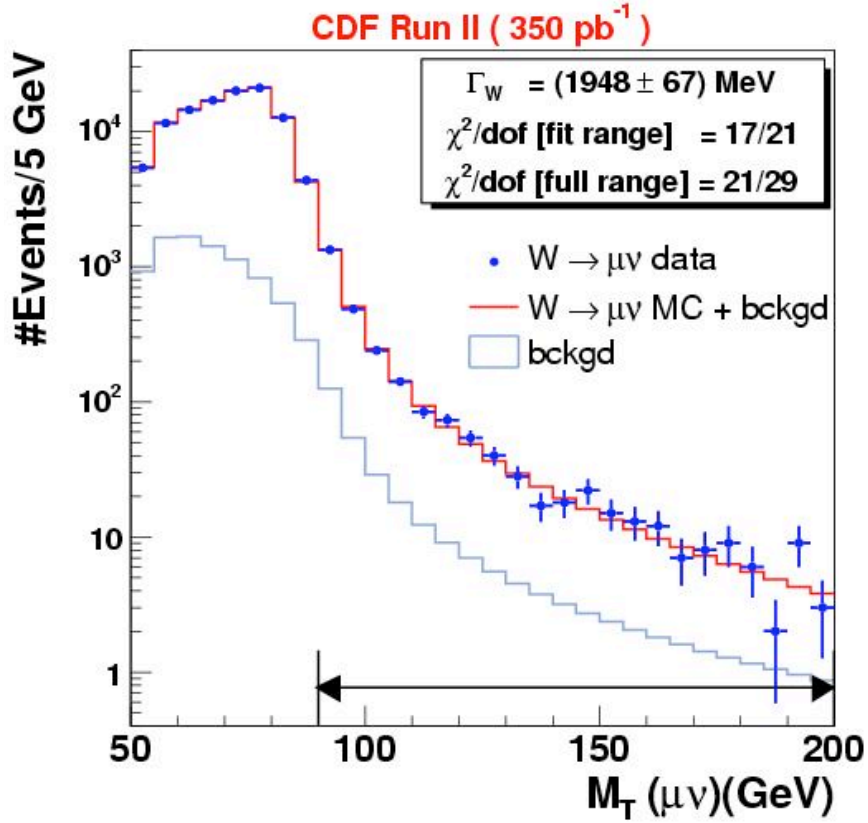


- Calorimeter scale/resn
  $\Delta\Gamma$= 21 MeV, 31 MeV

W width



PRL **100** 071801 (2008)



Γ_W = 2032 ± 73 (stat+sys) MeV

World most precise single measurement

Compare to CDF indirect measurement:

(Γ_W^{SM} = 2093 ± 2 MeV)
hep-ph/0804.4779

$$R = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \cdot \frac{\Gamma(Z)}{\Gamma(Z \to \ell\ell)} \cdot \frac{\Gamma(W \to \ell\nu)}{\Gamma(W)}$$

NNLO calc — From LEP — SM value

→ Γ_W (indirect) = 2092 ± 42 MeV

J Phys G **34** 2457

Z invisible width

Γ_Z(invisible) measured very precisely indirectly from LEP: Γ_Z(invis) = 500.8 ± 2.6 MeV

However combined direct LEP measurement:
Γ_Z(invis) = 503 ± 16 MeV

Tevatron measurement uncorrelated

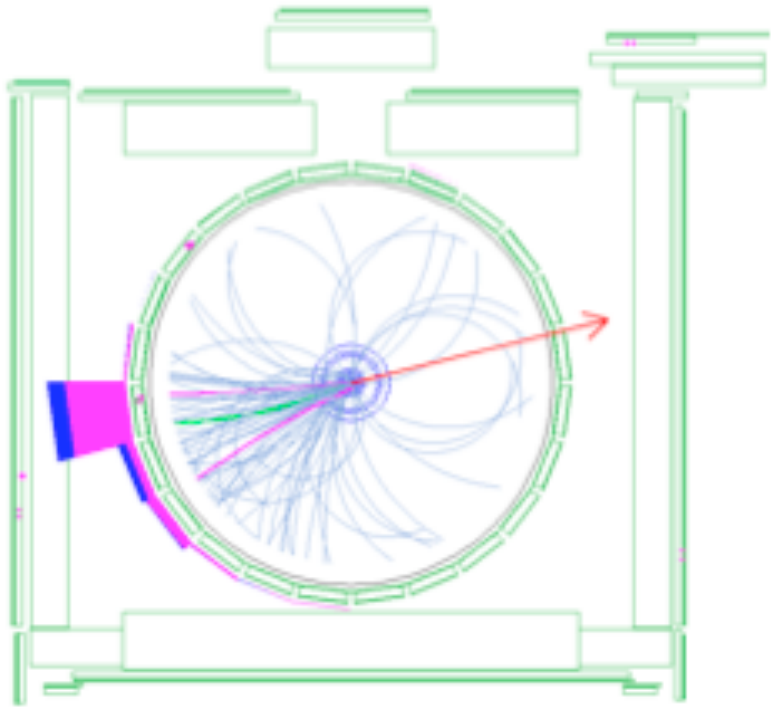
$\not{E}_T$ + single jet channel

Select single-jet events ($\not{E}_T$ trigger)
Independently measure σ(Z+1jet) . Br (Z → ll)
from high-p_T lepton trigger

$$\frac{\Gamma_Z(\text{inv})}{\Gamma_Z(\text{ll})} = \frac{\sigma(\text{Z+1jet}) \,.\, Br\,(\text{Z} \rightarrow \text{inv})}{\sigma(\text{Z+1jet}) \,.\, Br\,(\text{Z} \rightarrow \text{ll})}$$

$$= \frac{N_{obs} - N_{bck}}{\sigma(\text{Z}\rightarrow\text{ll+1jet}) \,.\, L}$$

Must be corrected for different acceptance of '1-jet' selection in Z→νν versus Z→ll (applied after lepton removal)

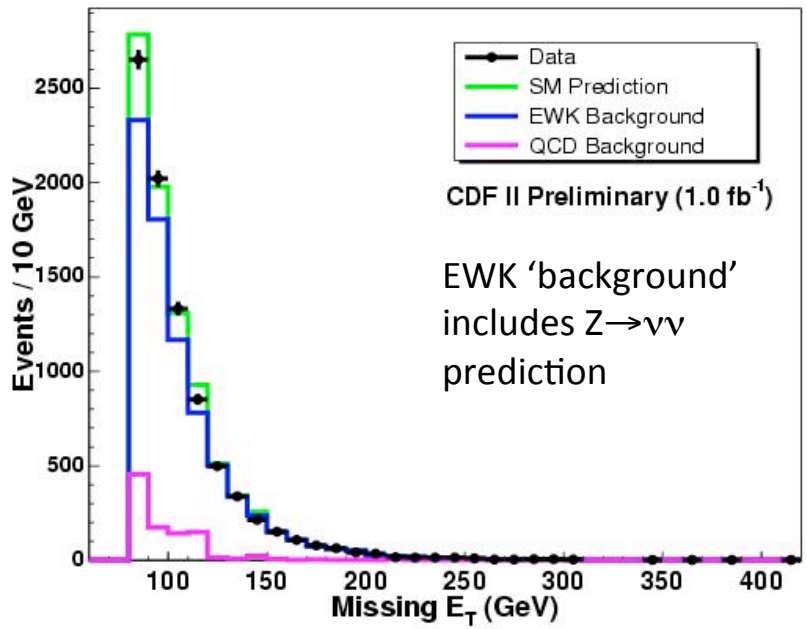


Selection:

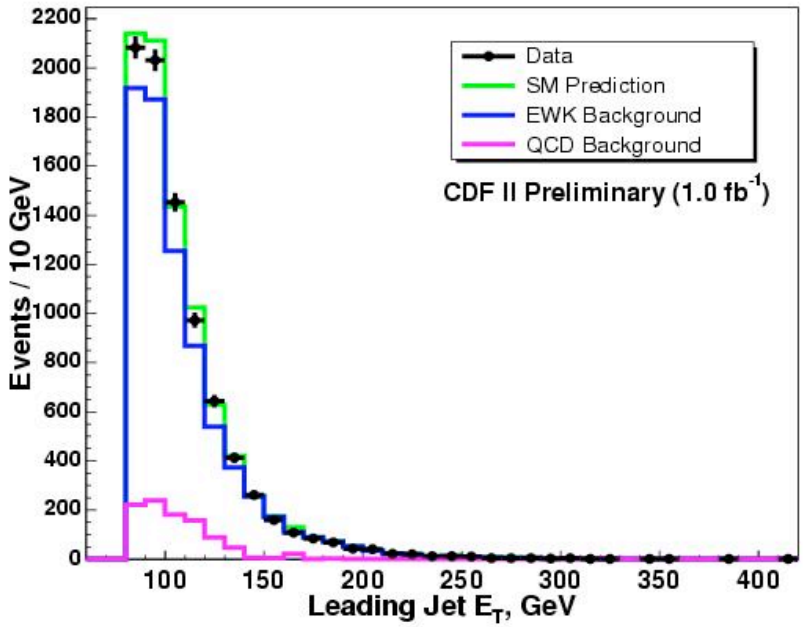
- $\not{E}_T$ > 80 GeV
- E_T^{jet} > 80 GeV

second jet E_T<30 allowed
but ≥ 3 jets E_T>20 rejected

Z invisible width



EWK 'background' includes $Z \to \nu\nu$ prediction



$W \to \tau\nu$	2010 ± 69
$W \to \mu\nu$	1570 ± 54
$W \to e\nu$	824 ± 28
$Z \to ll$	87 ± 3
QCD	708 ± 146
γ+jet	209 ± 41
non-collision	52 ± 52
$Z \to \nu\nu$	3203 ± 137
Total predicted	8663 ± 332
Data observed	8449

Measured $\sigma(Z \to ll+1jet) = 0.555 \pm 0.024$ pb

$$\frac{\Gamma_Z(inv)}{\Gamma_Z(ll)} = 5.546 \pm 0.506$$

$$\Gamma_Z(inv) = 466 \pm 42 \text{ MeV}$$

~ equal contributions from EWK bck, QCD bck and $\sigma(Z \to ll+1jet)$

can interpret as $N_\nu = 2.79 \pm 0.25$

Summary

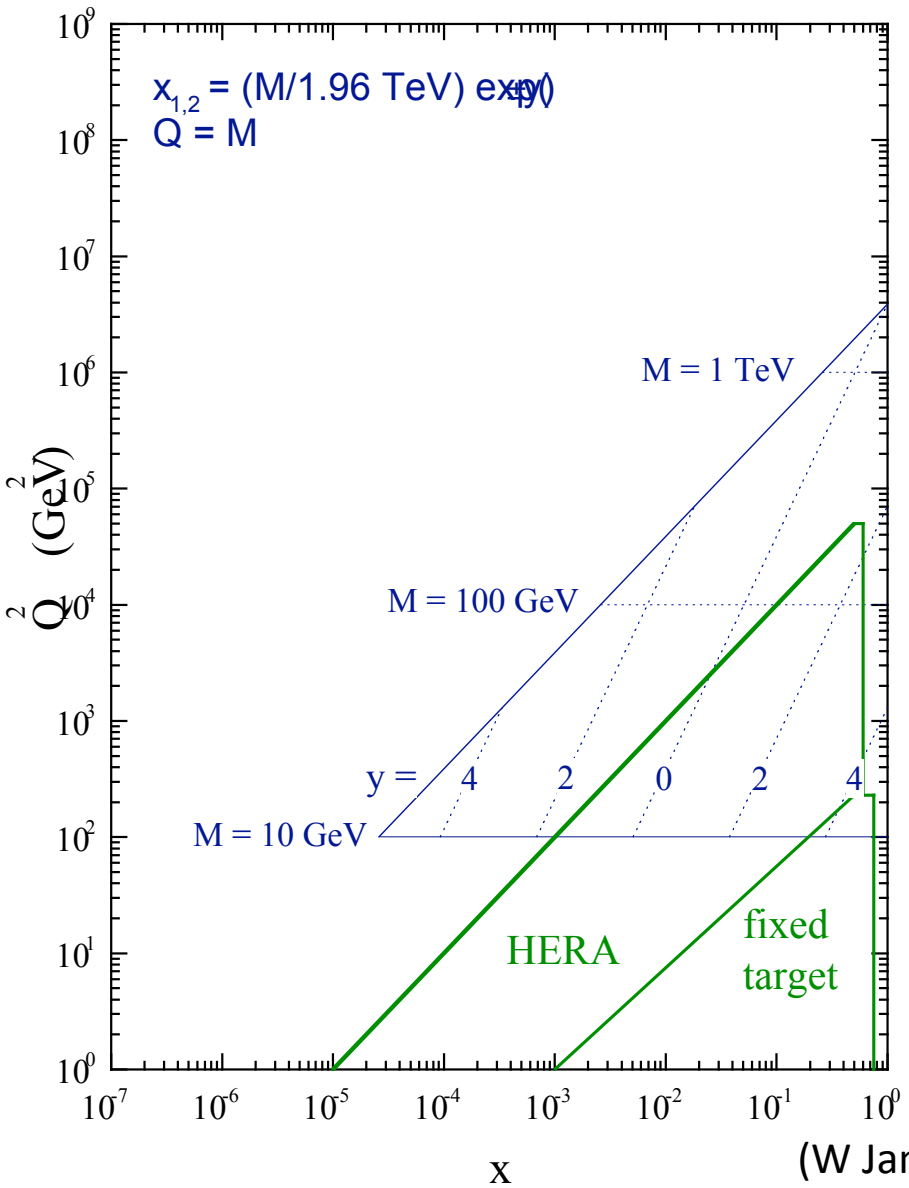
W and Z cross-section measurements underpin the Tevatron high-p_T physics programme

Dedicated measurements are harnessing the high statistics datasets:

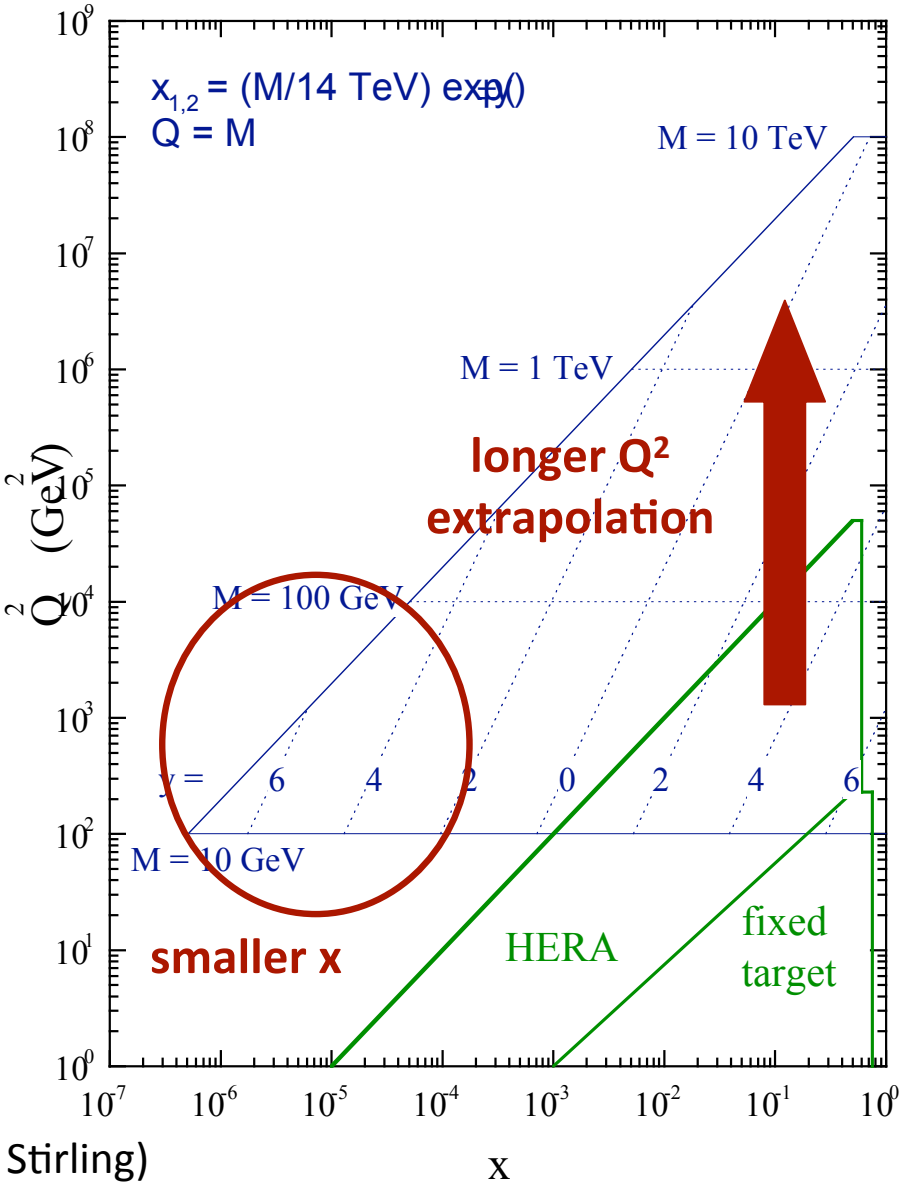
- improving tau identification
- testing higher-order calculations and PDFs and probing QCD
- making precision measurements of SM parameters

Backup

Tevatron parton kinematics



LHC parton kinematics



(W James Stirling)

Taus at D0

The elements:

- calorimeter cluster (cone R<0.5)
- energy concentrated in inner cone R<0.3
- tracks in cone R<0.3, mass<1.8GeV
- EM sub-clusters in finely segmented shower-max layer of calorimeter

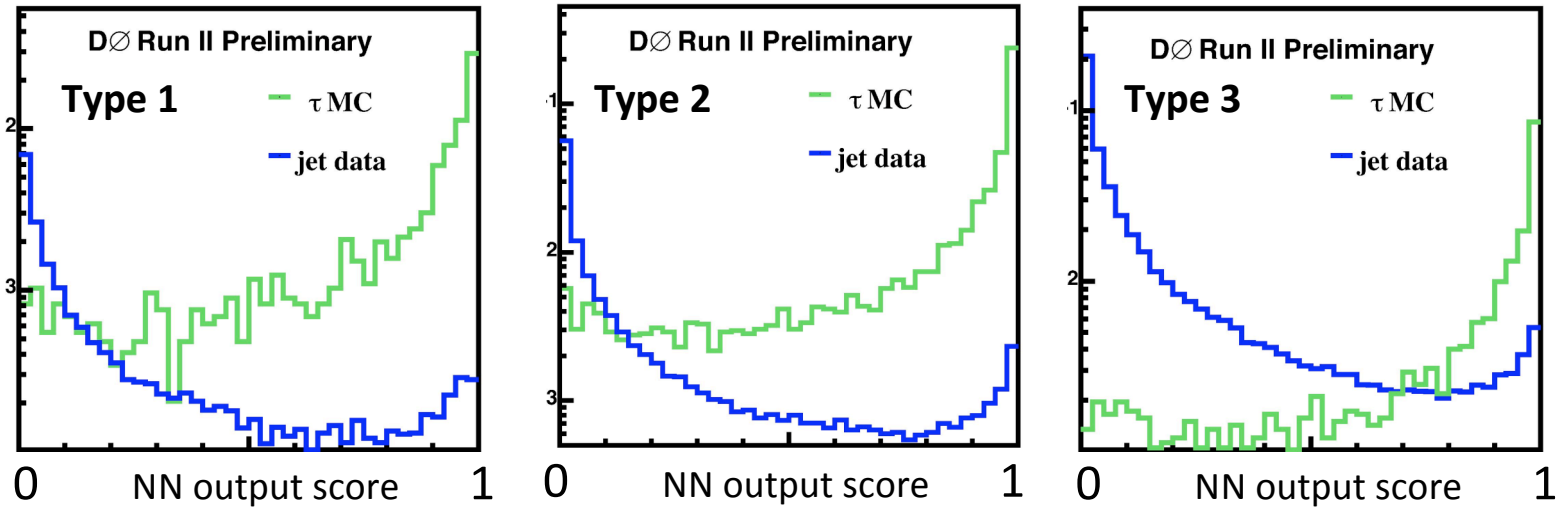
E_T measurement:
For E<100GeV, track p_T & calorimeter E_T are combined for Types 2&3, and single $\pi^{\pm}$ energy corrections derived from special hadronic calorimeter simulation.
Otherwise track p_T used.

Three D0 tau categories:

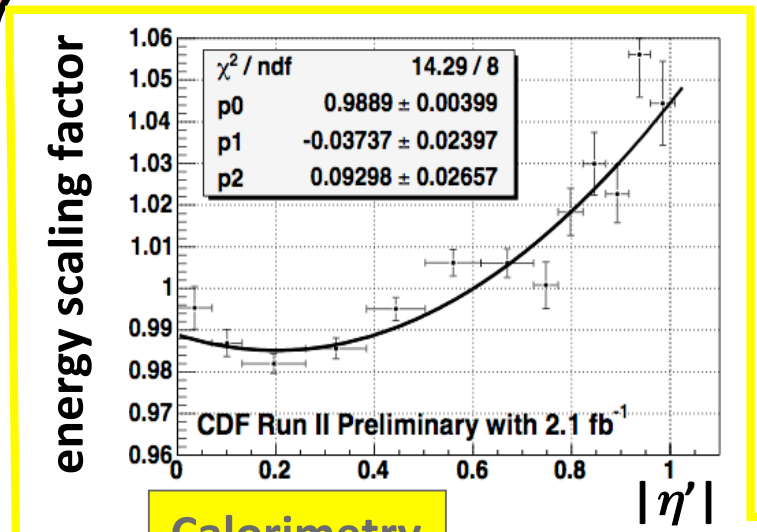
Type 1: 1 track, no EM sub-cluster
Type 2: 1 track, ≥1 EM sub-clusters
Type 3: ≥2 tracks, ≥0 EM sub-clusters

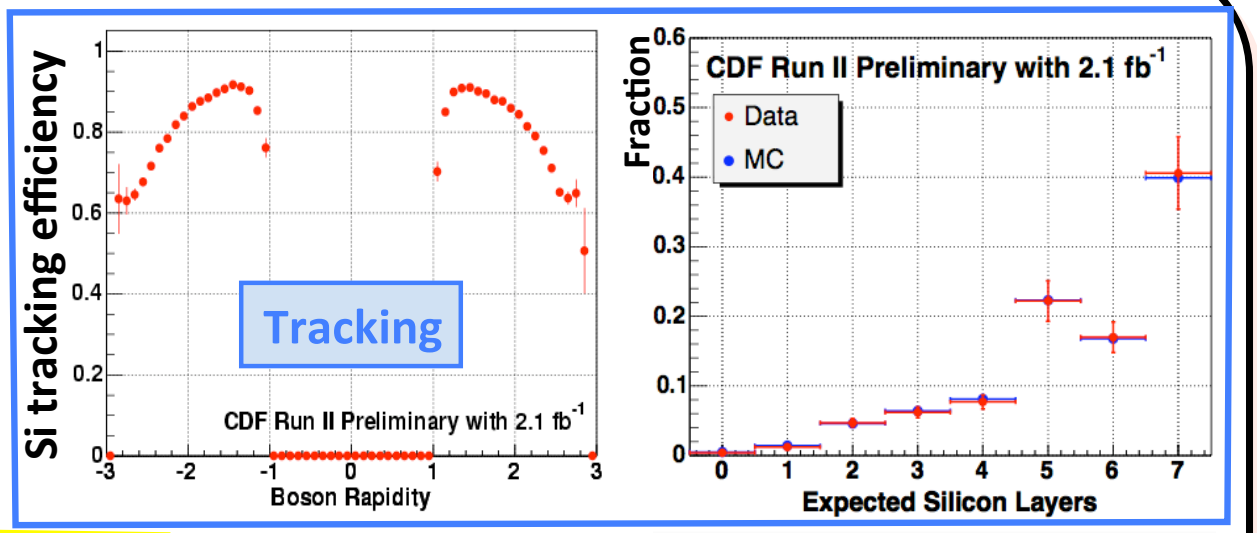
Neural net separator trained on variables measuring:

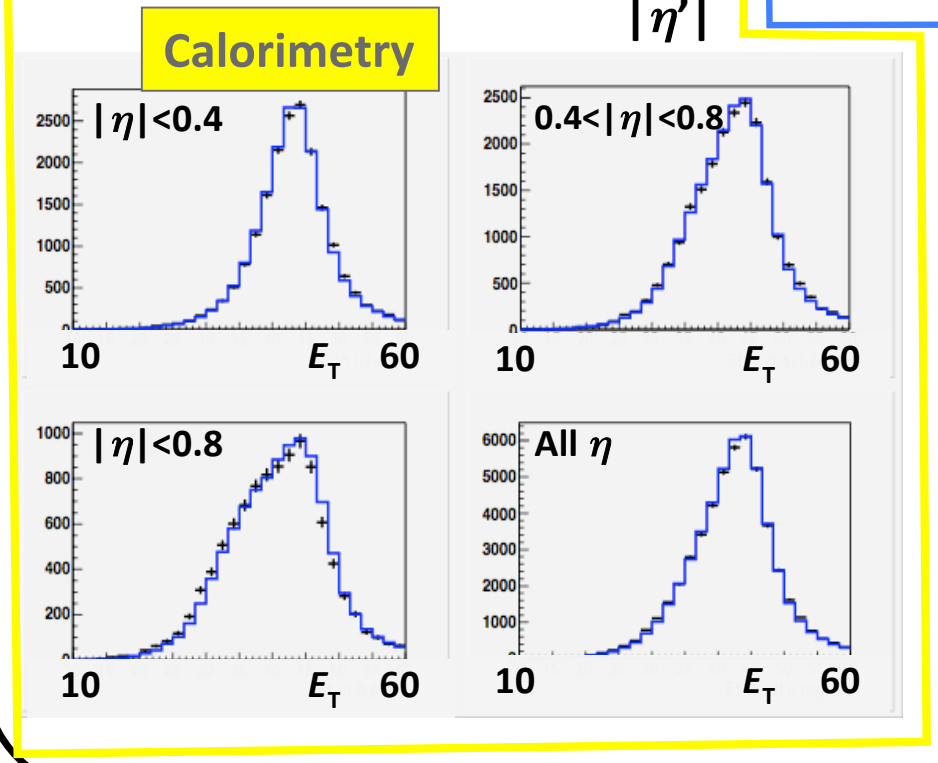
isolation
shower shape
calorimeter–track correlations

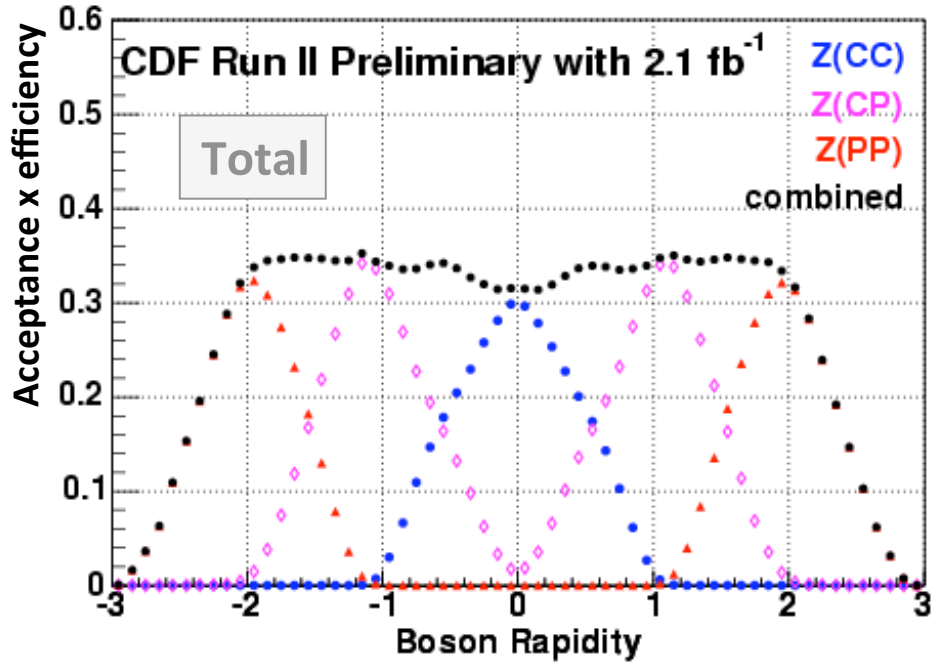


Z rapidity: shapes

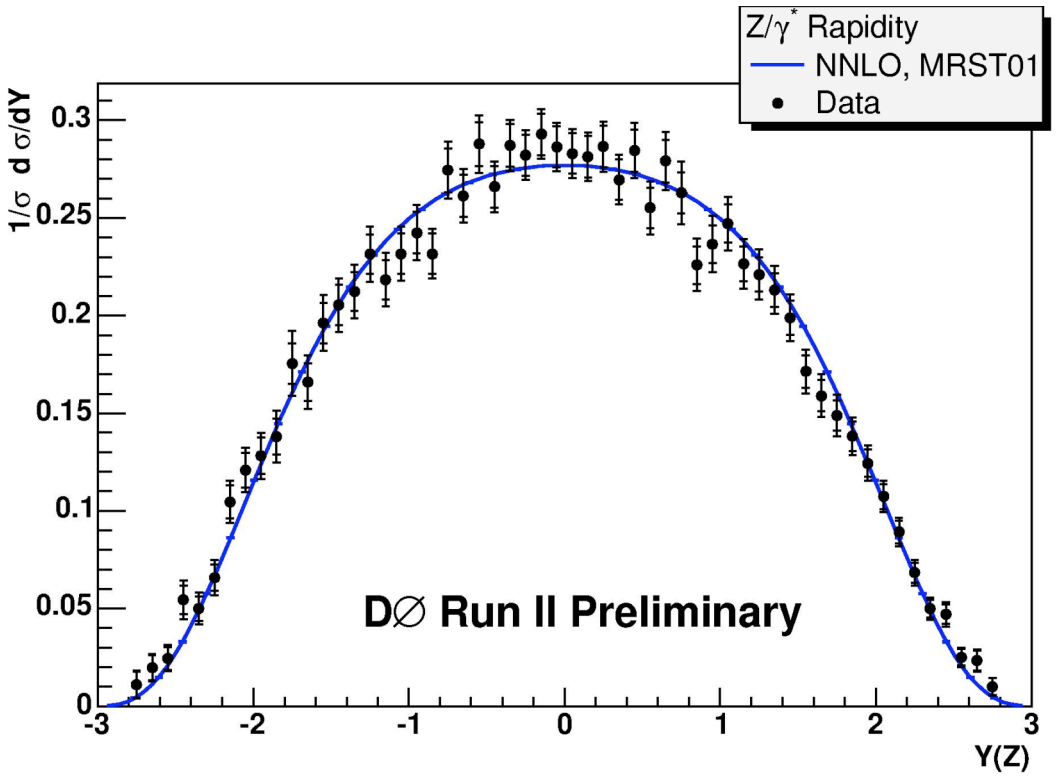


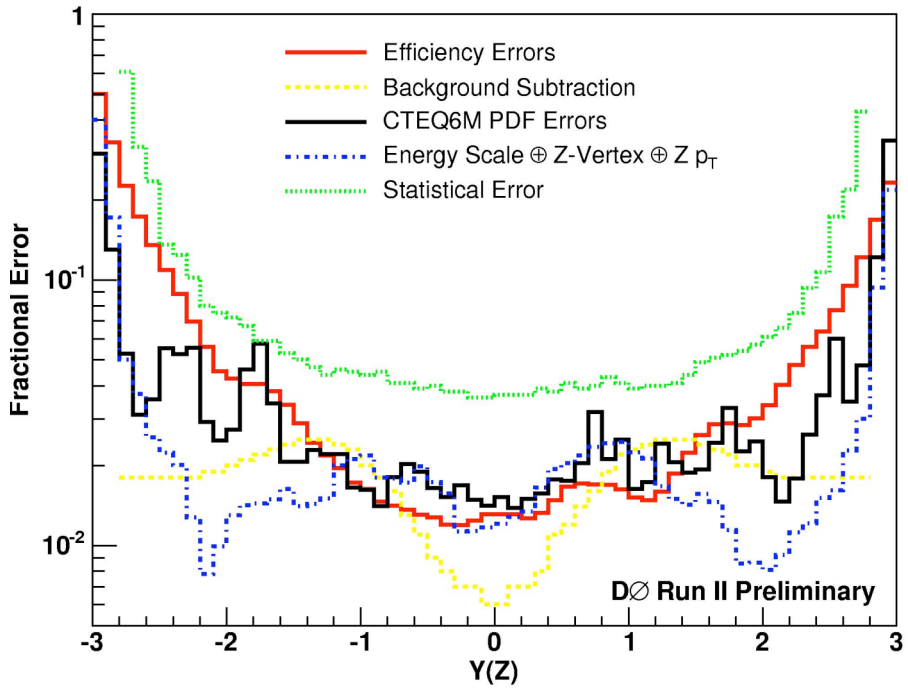






D0 Z rapidity

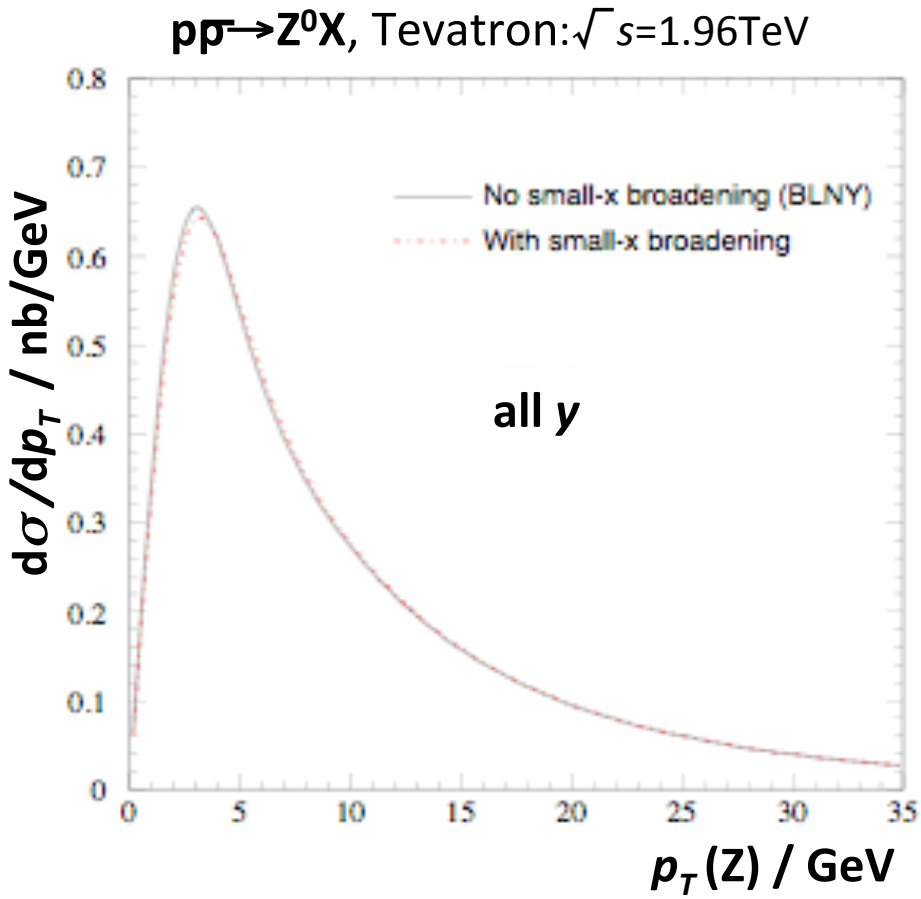


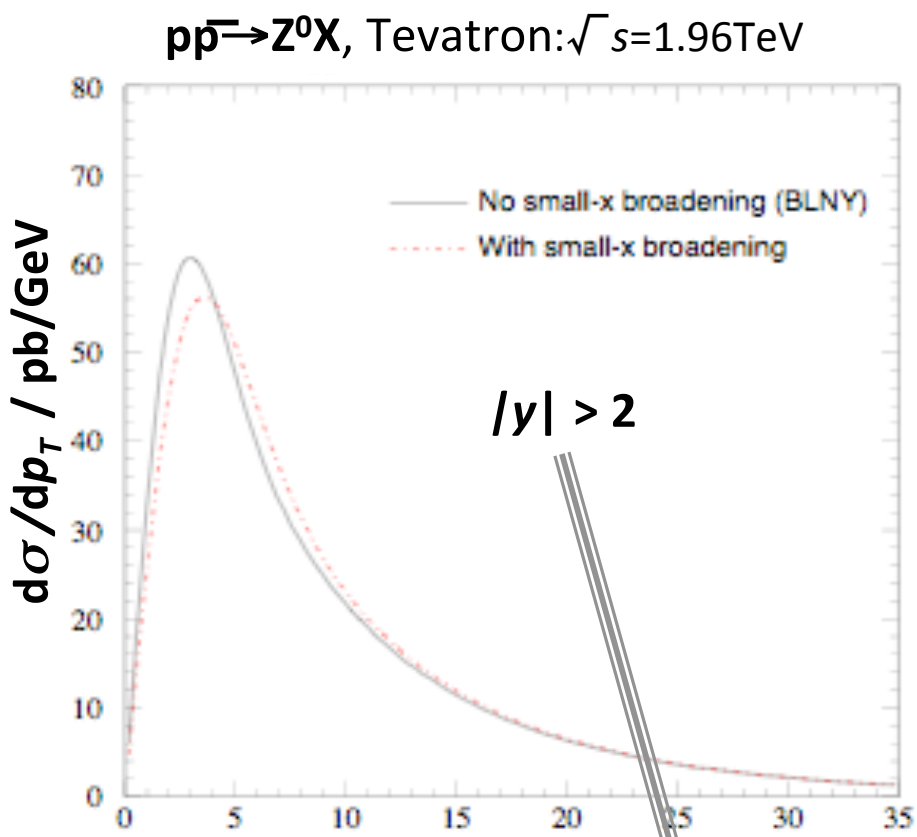


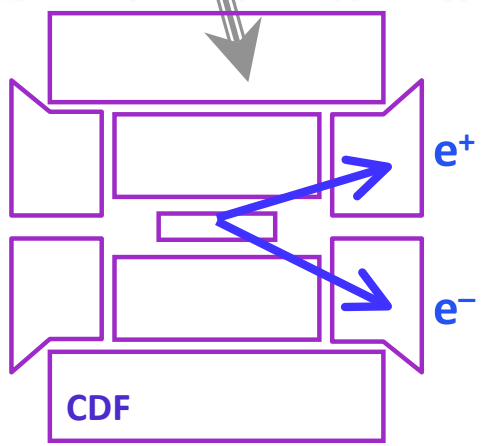
CDF dσ/dy

y	σ	*stat.* δ	*sys.* δ	material	BKG	tracking	ID	zvtx	calib
0.05	69.84	0.74	0.59	0.13	0.06	0.00	0.57	0.00	0.09
0.15	71.31	0.74	0.58	0.12	0.06	0.00	0.57	0.00	0.04
0.25	71.18	0.74	0.59	0.11	0.06	0.00	0.57	0.00	0.03
0.35	69.99	0.72	0.59	0.10	0.07	0.00	0.58	0.00	0.00
0.45	68.06	0.70	0.58	0.08	0.06	0.00	0.57	0.00	0.01
0.55	68.29	0.70	0.61	0.07	0.07	0.00	0.59	0.00	0.06
0.65	66.79	0.69	0.60	0.06	0.07	0.00	0.59	0.00	0.01
0.75	67.13	0.70	0.61	0.06	0.07	0.00	0.60	0.00	0.00
0.85	65.15	0.69	0.65	0.05	0.08	0.00	0.63	0.00	0.10
0.95	64.79	0.68	0.71	0.05	0.08	0.00	0.71	0.00	0.01
1.05	62.72	0.67	0.75	0.12	0.08	0.00	0.73	0.00	0.01
1.15	61.99	0.66	0.88	0.11	0.09	0.00	0.74	0.01	0.45
1.25	58.97	0.65	0.74	0.09	0.10	0.01	0.72	0.03	0.06
1.35	56.12	0.64	0.80	0.08	0.12	0.02	0.79	0.06	0.03
1.45	53.55	0.63	0.98	0.07	0.12	0.05	0.94	0.10	0.20
1.55	50.32	0.62	1.14	0.05	0.14	0.03	1.12	0.13	0.11
1.65	46.79	0.60	1.32	0.04	0.14	0.02	1.30	0.15	0.14
1.75	41.50	0.58	1.46	0.03	0.14	0.14	1.42	0.16	0.22
1.85	37.03	0.56	1.62	0.03	0.13	0.14	1.59	0.16	0.11
1.95	33.26	0.54	1.65	0.02	0.11	0.20	1.63	0.16	0.04
2.05	27.89	0.52	1.53	0.05	0.10	0.24	1.49	0.14	0.02
2.15	22.48	0.50	1.29	0.04	0.08	0.22	1.26	0.12	0.07
2.25	19.09	0.51	1.14	0.03	0.07	0.21	1.12	0.10	0.01
2.35	14.91	0.51	0.90	0.02	0.04	0.18	0.88	0.07	0.02
2.45	9.47	0.48	0.61	0.01	0.03	0.13	0.60	0.04	0.00
2.55	6.16	0.48	0.39	0.01	0.01	0.02	0.39	0.03	0.00
2.65	3.47	0.47	0.27	0.00	0.01	0.03	0.27	0.02	0.00
2.75	1.69	0.45	0.13	0.00	0.00	0.01	0.13	0.01	0.00
2.85	1.11	0.64	0.11	0.00	0.00	0.04	0.11	0.01	0.00
2.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	258.21	0.67	4.77	0.33	0.44	0.33	4.64	0.30	0.37

Z p_T



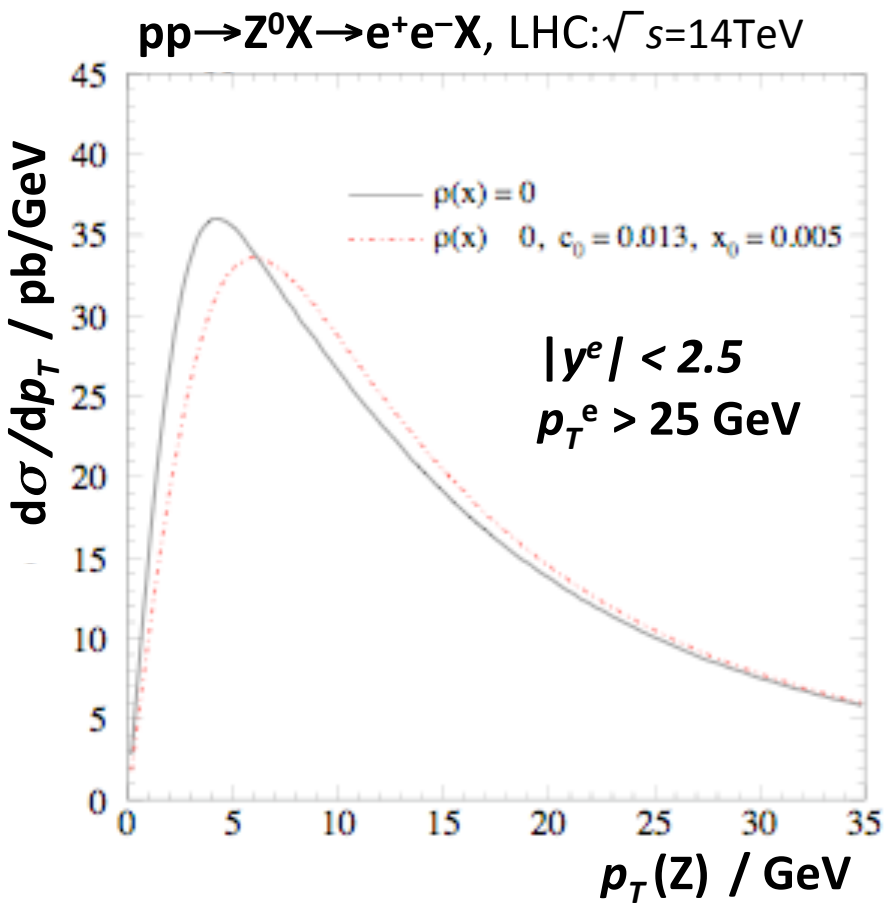


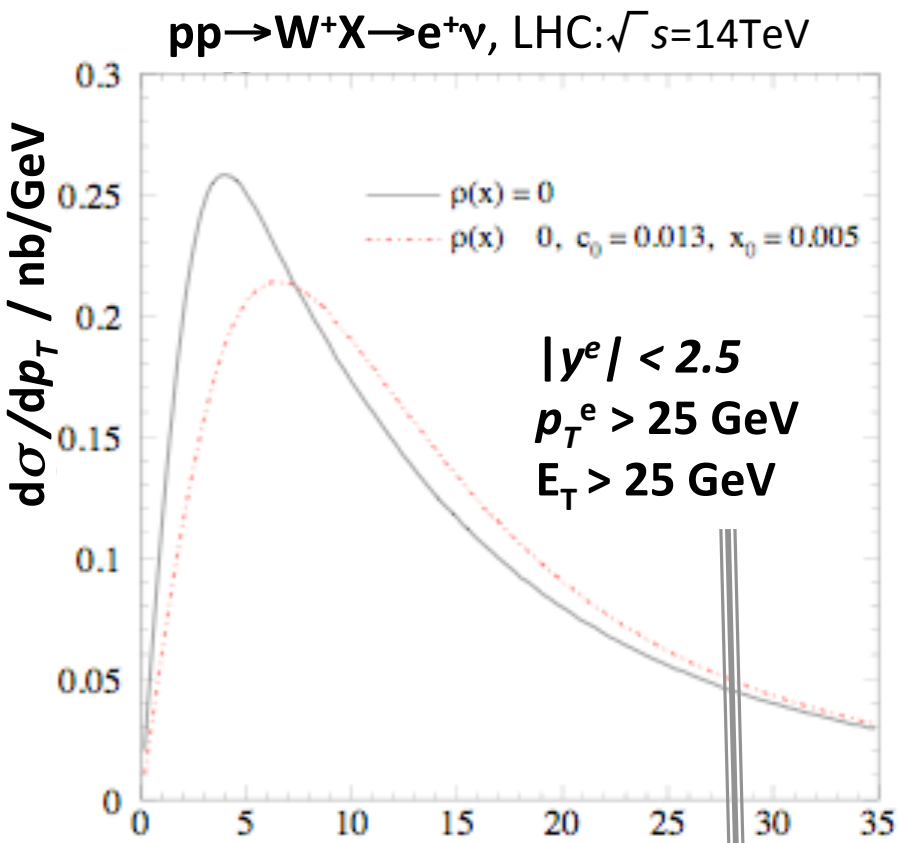


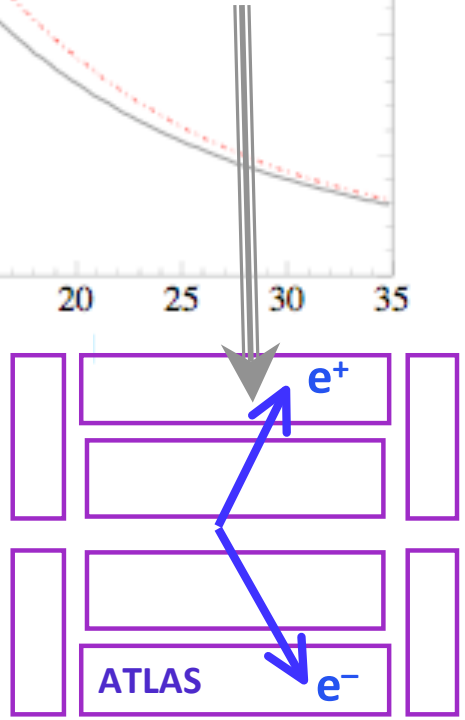
Nadolsky et al:

- global fits to HERA and fixed-target data suggest increased intrinsic p_T carried by proton constituents, for interactions involving only a small fraction of proton's momentum
  - ⇒ they insert extra factor in differential cross-section ; p_T(Z) broadened at high y

Z p_T

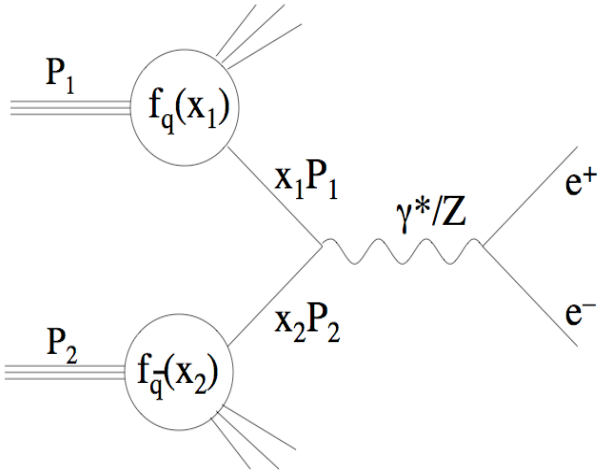






- LHC: beam energies ~7x higher than Tevatron
- Probing new part of phase space
- Tevatron forward detectors map on to LHC central detectors

Problem! W/Z production is a benchmark



Leading order cross-section for Z production from quarks:

$$\hat{\sigma}(q\bar{q} \to Z) = \frac{\pi}{3}\sqrt{2}\, G_F\, m_Z^2\, (g_V^2 + g_A^2)\, \delta(\hat{s} - m_Z^2) \tag{1}$$

The total cross-section is obtained by convolution with parton density functions (PDFs) f_q:

$$\sigma_{\rm tot}(\hat{s}) = \int dx_1 dx_2\, \hat{\sigma}_Z \sum_q \{f_q(x_1) f_{\bar{q}}(x_2) + (q \leftrightarrow \bar{q})\} \ . \tag{2}$$

Interested in higher-orders and in non-perturbative small p_T region; write (in impact parameter b space):

$$\frac{d\sigma}{dy\, dp_T^2} \sim \frac{\sigma_0}{s} \int d^2b\, e^{i\mathbf{p_t}\cdot\mathbf{b}}\, \tilde{W}(b, Q, x_1, x_2) \ \ + Y \tag{3}$$

where Y is the regular part of the fixed order cross-section (small for $p_T \to 0$), and:

$$\tilde{W}(b, Q, x_1, x_2) \sim \frac{\pi}{s} \sum_{\rm partons} \sigma_{1,2}\, e^{-S(b,Q)}\, f_q(x_1, b) f_{\bar{q}}(x_2, b) \tag{4}$$

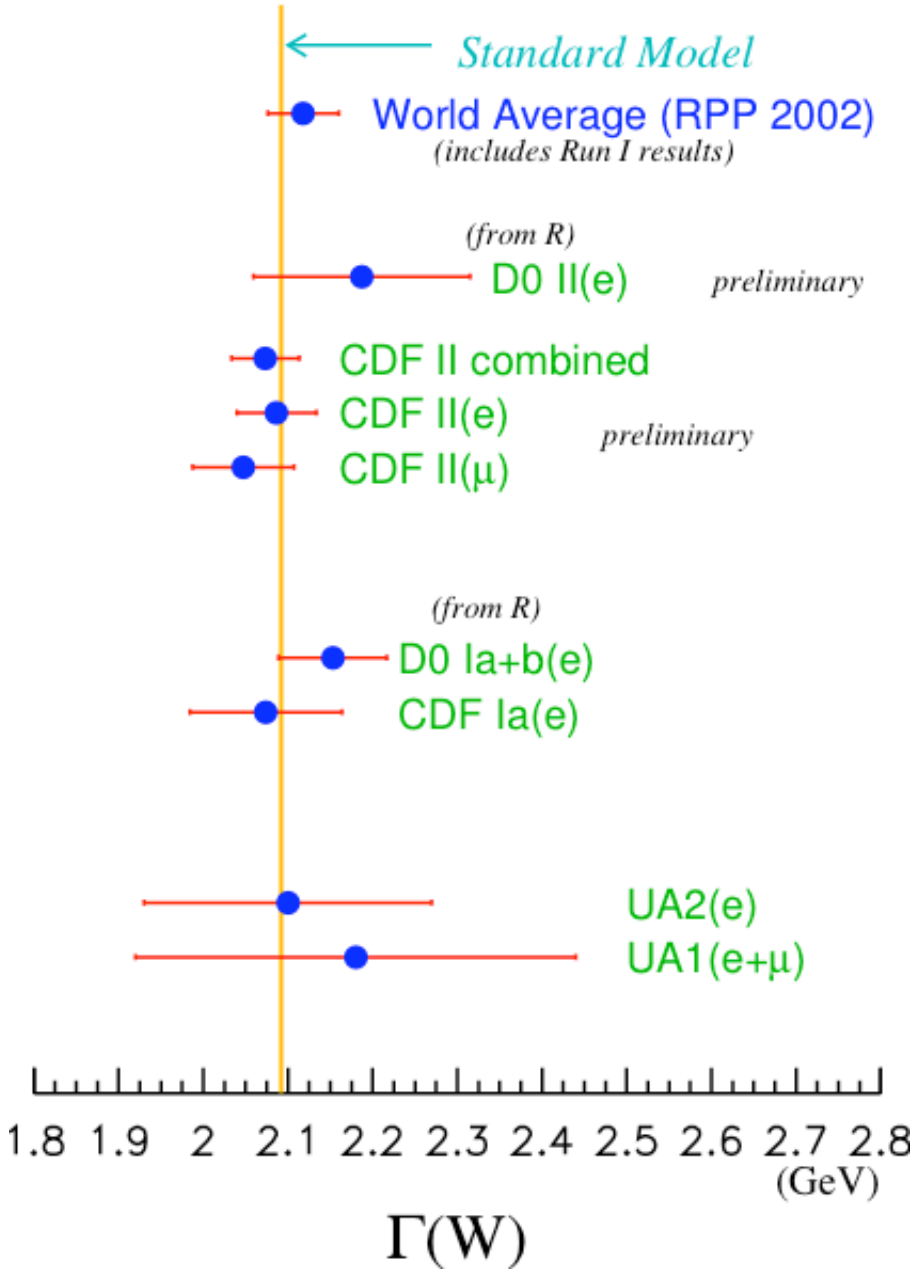
This work was done in the 1980s. S is a Sudakov factor that is fitted to data.
Now Nadolsky et al. suggest using f_q' where

$$f_q' \sim f_q e^{-\rho(x) b^2} \tag{5}$$

and

$$\rho(x) = c_0 \left(\sqrt{\frac{1}{x^2} + \frac{1}{x_0^2}} - \frac{1}{x_0^2} \right) \tag{6}$$

without small-x effect:
$p_T < 5\text{GeV}/c$: $\chi^2/\text{dof} = 0.8/1$
$p_T < 30\text{GeV}/c$: $\chi^2/\text{dof} = 11.1/11$

including small-x effect:
$p_T < 5\text{GeV}/c$: $\chi^2/\text{dof} = 5.7/1$
$p_T < 30\text{GeV}/c$: $\chi^2/\text{dof} = 31.9/11$

Indirect Γ_W