

# Metody eksperymentalne w fizyce wysokich energii

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Zakład Cząstek i Oddziaływań Fundamentalnych IFD

## Wykład XIV

- Pomiar przekroju czynnego
- ⇒ przekrój całkowity
- ⇒ przekrój różniczkowy

# Cross Section: Experimentally

Number of observed events: counted

Background:  
Measured from data /  
calculated from theory

$$\sigma = \frac{N_{\text{obs}} - N_{\text{BG}}}{\int L dt \cdot \epsilon}$$

Cross section  $\sigma$

Luminosity:  
Determined by accelerator,  
trigger prescale, ...

Efficiency:  
optimized by  
experimentalist

Includes acceptance due to kinematics, geometry, cuts etc.

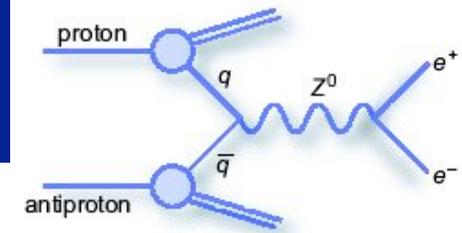
# Acceptance / Efficiency

- Actually rather complex:
  - Many ingredients enter here
  - You need to know:

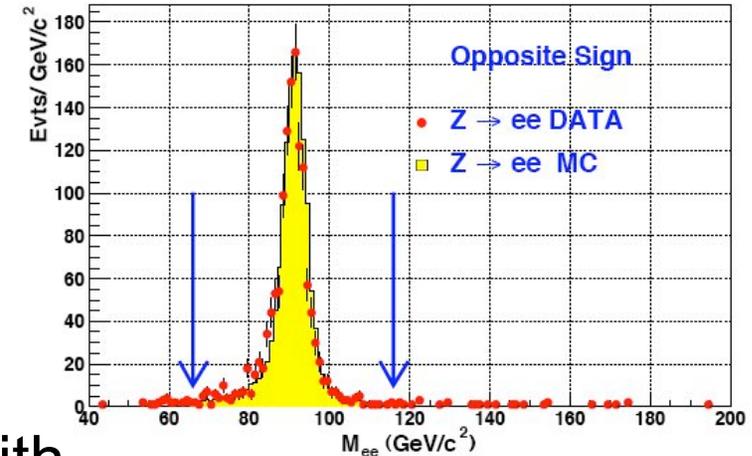
$$\epsilon_{\text{total}} = \frac{\text{Number of Events used in Analysis}}{\text{Number of Events Produced}}$$

- Ingredients:
  - Trigger efficiency
  - Identification efficiency
  - Kinematic acceptance
  - Cut efficiencies
- Using three example measurements for illustration:
  - Z boson, top quark and jet cross sections

# Z Boson Cross Section



- Trigger requires one electron with  $E_T > 20$  GeV
  - Criteria at L1, L2 and L3/EventFilter
- You select two electrons in the analysis
  - With certain quality criteria
  - With an isolation requirement
  - With  $E_T > 25$  GeV and  $|\eta| < 2.5$
  - With oppositely charged tracks with  $p_T > 10$  GeV
- You require the di-electron mass to be near the Z:
  - $66 < M(\text{ll}) < 116$  GeV



$$\Rightarrow \epsilon_{\text{total}} = \epsilon_{\text{trig}} \epsilon_{\text{rec}} \epsilon_{\text{ID}} \epsilon_{\text{kin}} \epsilon_{\text{track}}$$

# Uncertainty on Cross Section

- You will want to minimize the uncertainty:

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{\delta N_{obs}^2 + \delta N_{BG}^2}{(N_{obs} - N_{BG})^2} + \left(\frac{\delta\mathcal{L}}{\mathcal{L}}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

- Thus you need:
  - $N_{obs} - N_{BG}$  large (i.e.  $N_{signal}$  large)
    - Optimize selection for large acceptance and small background
  - Uncertainties on efficiency and background small
    - Hard work you have to do
  - Uncertainty on luminosity small
    - Usually not directly in your power

# Optymalizacja selekcji

Aby uzyskać możliwie najdokładniejszy pomiar przekroju czynnego musimy optymalizować kryteria selekcji (cięcia).

W pierwszym przybliżeniu (dominują błędy statystyczne) optymalizujemy

$$k = S / \sqrt{S+B} \quad \text{znaczoność sygnału} \quad \text{nie } S/B !$$

Najczęstsze podejście: optymalizacja "krok po kroku" (cięcie po cięciu) naogół wymaga kilku iteracji

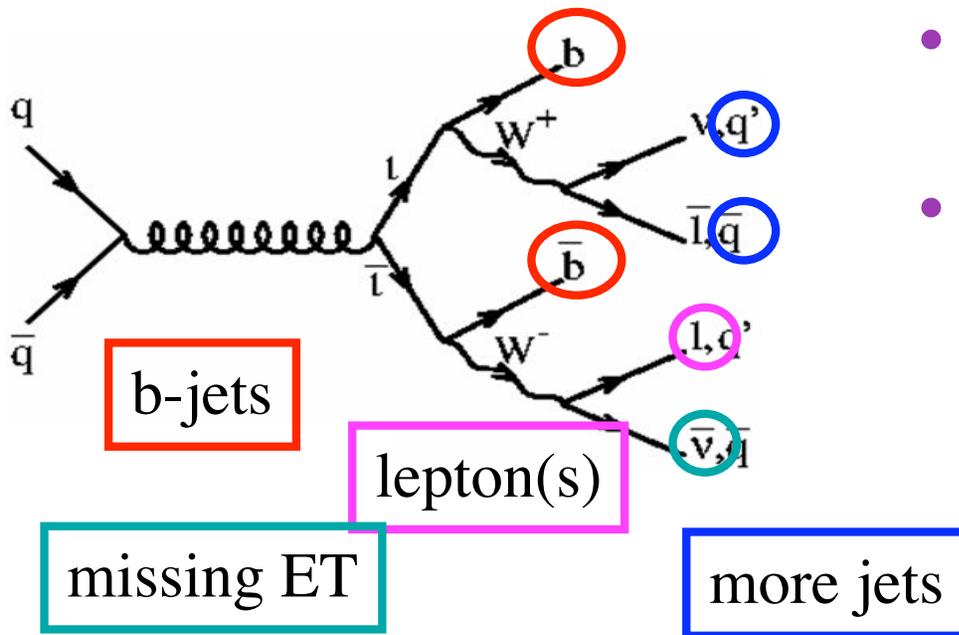
Istnieją też metody uwzględniające jednocześnie całą wiedzę o przypadku (np. sieci neuralne, "boosted decision tree", etc.)

Optymalizacja praktycznie zawsze oparta jest na symulacjach MC!

# Top Quark Cross Section

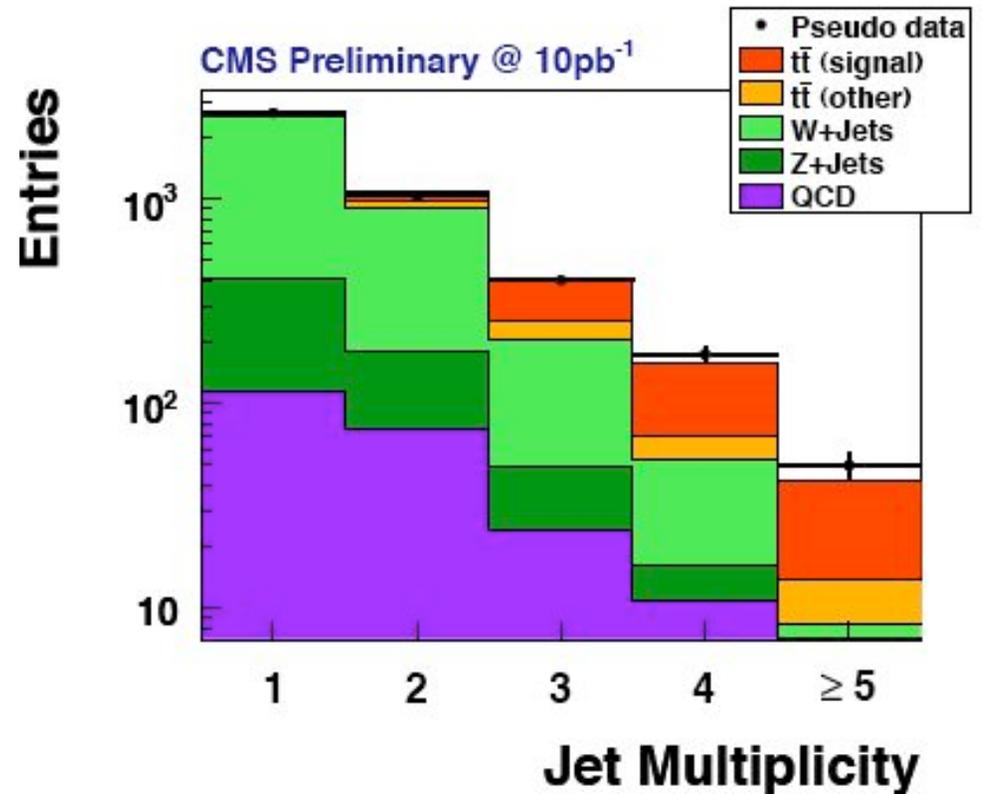
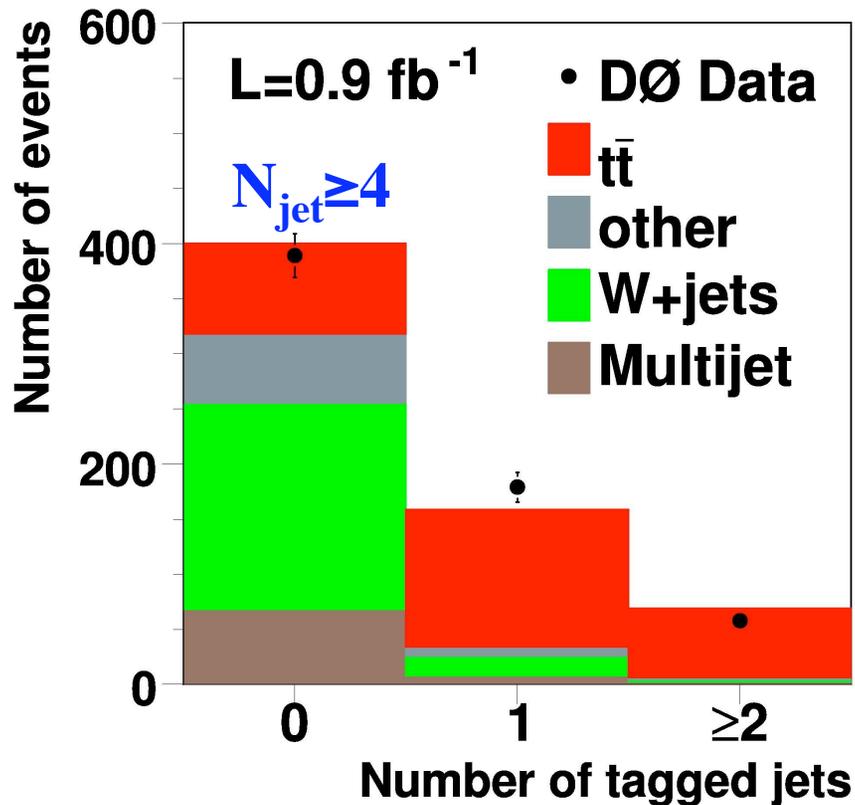
SM:  $t\bar{t}$  pair production,  $\text{Br}(t \rightarrow bW) = 100\%$ ,  $\text{Br}(W \rightarrow l\nu) = 1/9 = 11\%$

dilepton	(4/81)	2 leptons + 2 jets + missing $E_T$
lepton+jets	(24/81)	1 lepton + 4 jets + missing $E_T$
fully hadronic	(36/81)	6 jets



- Trigger on electron/muon
  - Like for Z's
- Analysis cuts:
  - Electron/muon  $p_T > 25$  GeV
  - Missing  $E_T > 25$  GeV
  - 3 or 4 jets with  $E_T > 20-40$  GeV

# Finding the Top Quark

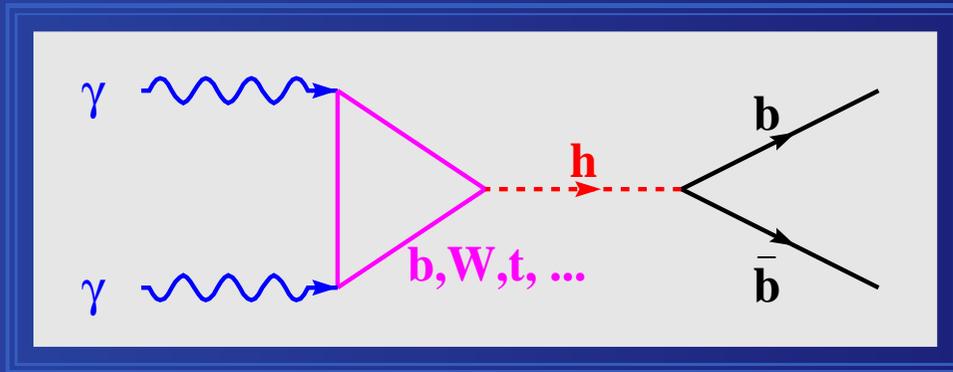


- **Tevatron**
  - Top is overwhelmed by backgrounds:
  - Top fraction is only 10% ( $\geq 3$  jets) or 40% ( $\geq 4$  jets)
  - Use b-jets to purify sample => purity 50% ( $\geq 3$  jets) or 80% ( $\geq 4$  jets)
- **LHC**
  - Purity  $\sim 70\%$  w/o b-tagging (90% w b-tagging)

$$m_h \approx 120 \text{ GeV}$$

Process:  $\gamma + \gamma \rightarrow h \rightarrow b + \bar{b}$

$$J_z = 0$$



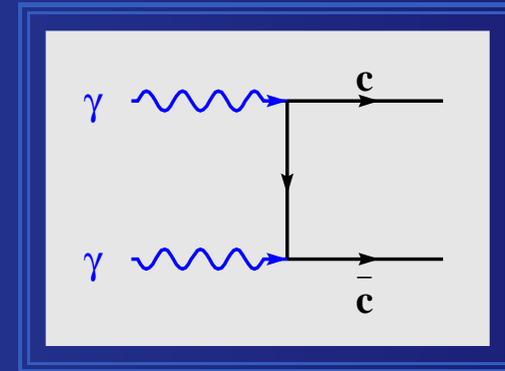
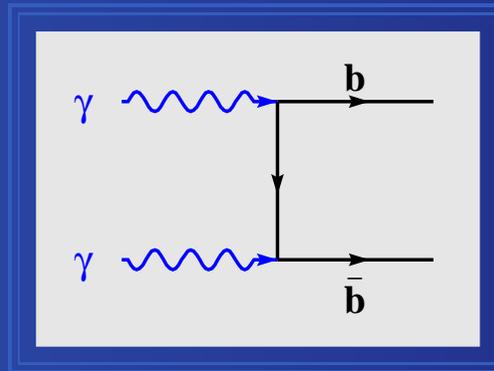
“Hard” background:

- $\gamma + \gamma \rightarrow b + \bar{b}$

- $\gamma + \gamma \rightarrow c + \bar{c}$

$$\sigma \propto Q_q^4$$

$$\sigma^{LO}(|J_z| = 2) \gg \sigma^{LO}(J_z = 0)$$



Other background:

- Resolved photon(s) interactions  $\gamma + \gamma \rightarrow X + Q + \bar{Q}$

- Overlaying events

(high intensity of photon-beams in the low-energy part of the spectrum)

# Generation & Simulation. Selection.

Photon-photon spectrum: CompAZ

Signal: HDECAY, PYTHIA

Background: program by G. Jikia

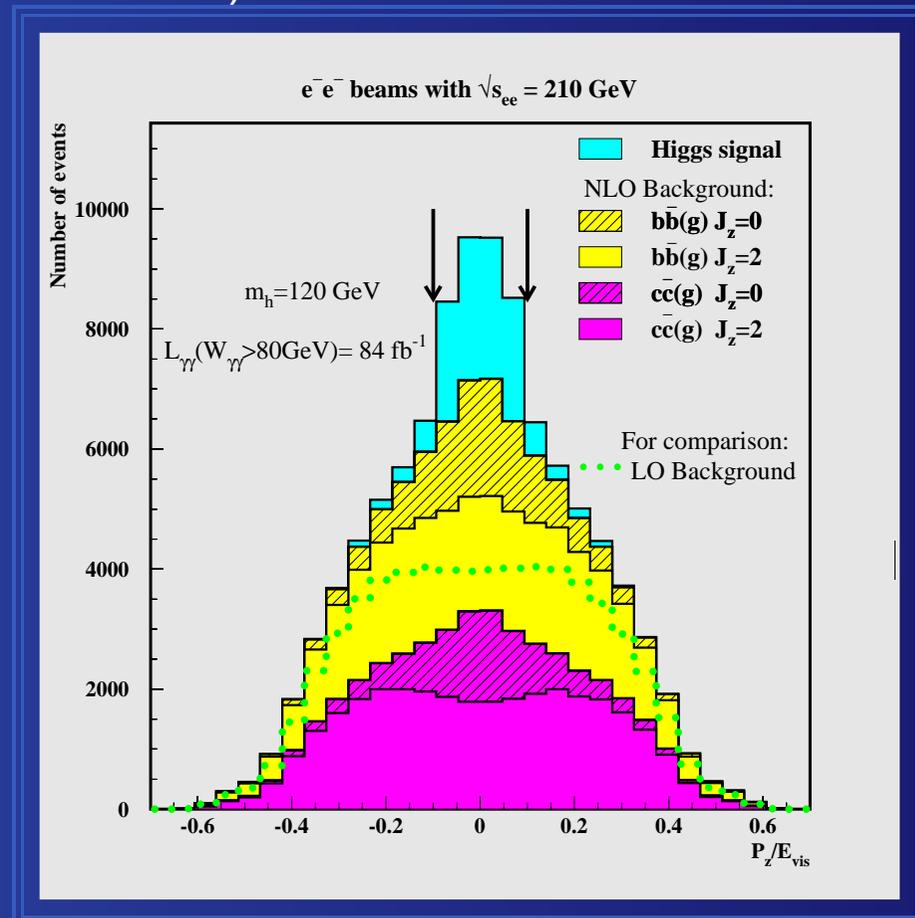
Fragmentation: Lund in PYTHIA

Detector performance: SIMDET (parametric simulation)

Jets: Durham algorithm with  $y_{cut} = 0.02$

## Selection of $b\bar{b}$ events:

- 1) Assumed bb-tagging and mistagging
- 2) Using ZVTOP-B-Hadron-Tagger
- $E_{vis} > 90$  GeV
- $N_{jets} = 2, 3$
- $|P_z|/E_{vis} < 0.1$

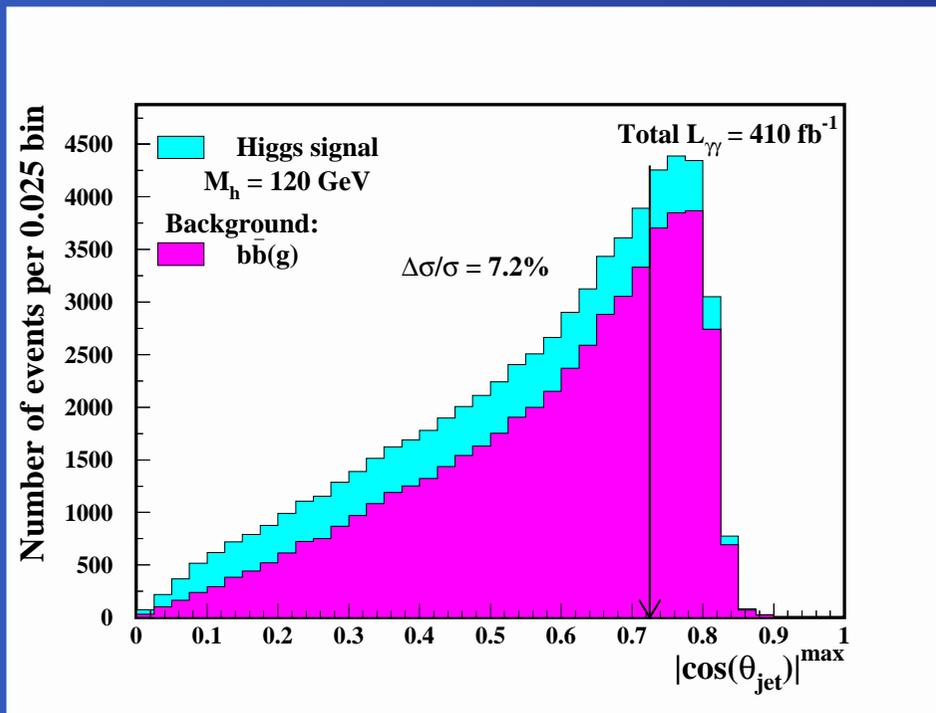


# Cuts

Cuts optimized by minimizing:

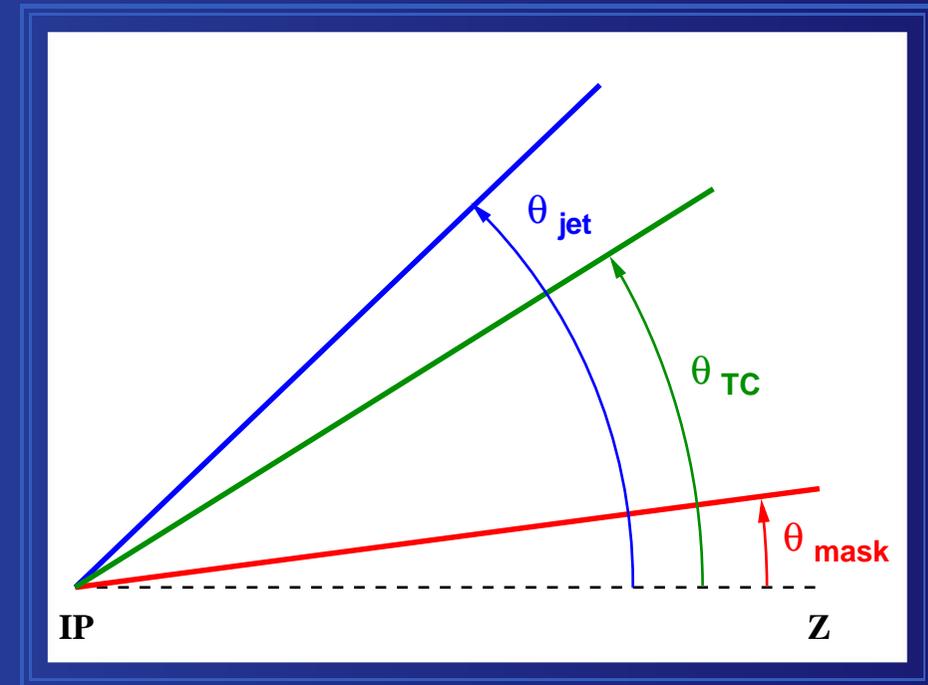
$$\frac{\Delta\sigma(\gamma\gamma \rightarrow h \rightarrow b\bar{b})}{\sigma(\gamma\gamma \rightarrow h \rightarrow b\bar{b})} = \frac{\sqrt{\mu_S + \mu_B}}{\mu_S},$$

For example:



Maximal value of  $|\cos\theta_{jet}|$   
over all jets in the event

All angular cuts



Detector mask

Particles on Pythia level:  $\cos\theta_{mask} \approx 0.99$

OE suppression

Tracks & clusters:  $\cos\theta_{TC} = 0.85$

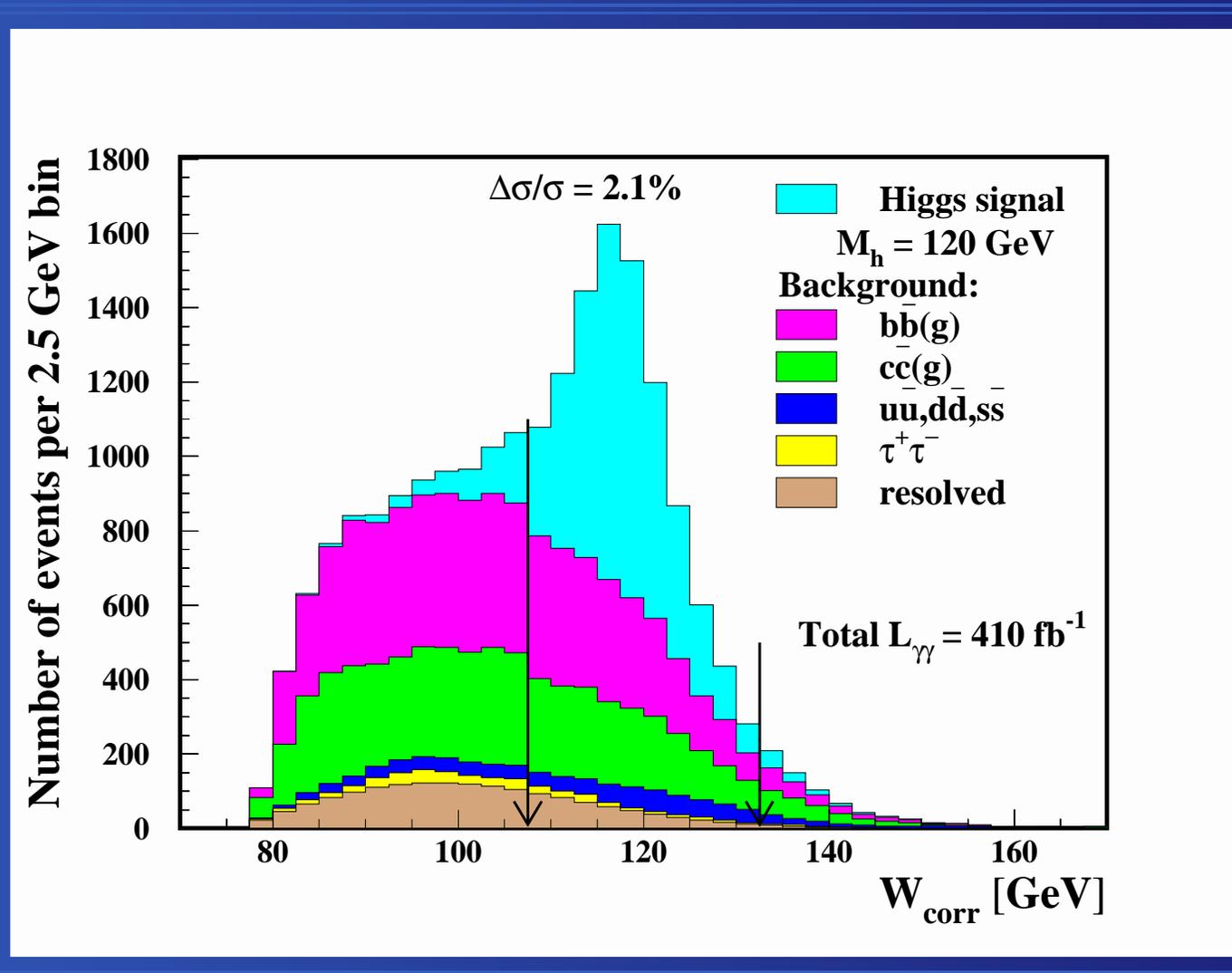
$\gamma\gamma \rightarrow Q\bar{Q}(g)$  suppression

Jets:  $|\cos\theta_{jet}|^{\max} = 0.725$



# SM, $M_h = 120 \text{ GeV}$

Final results



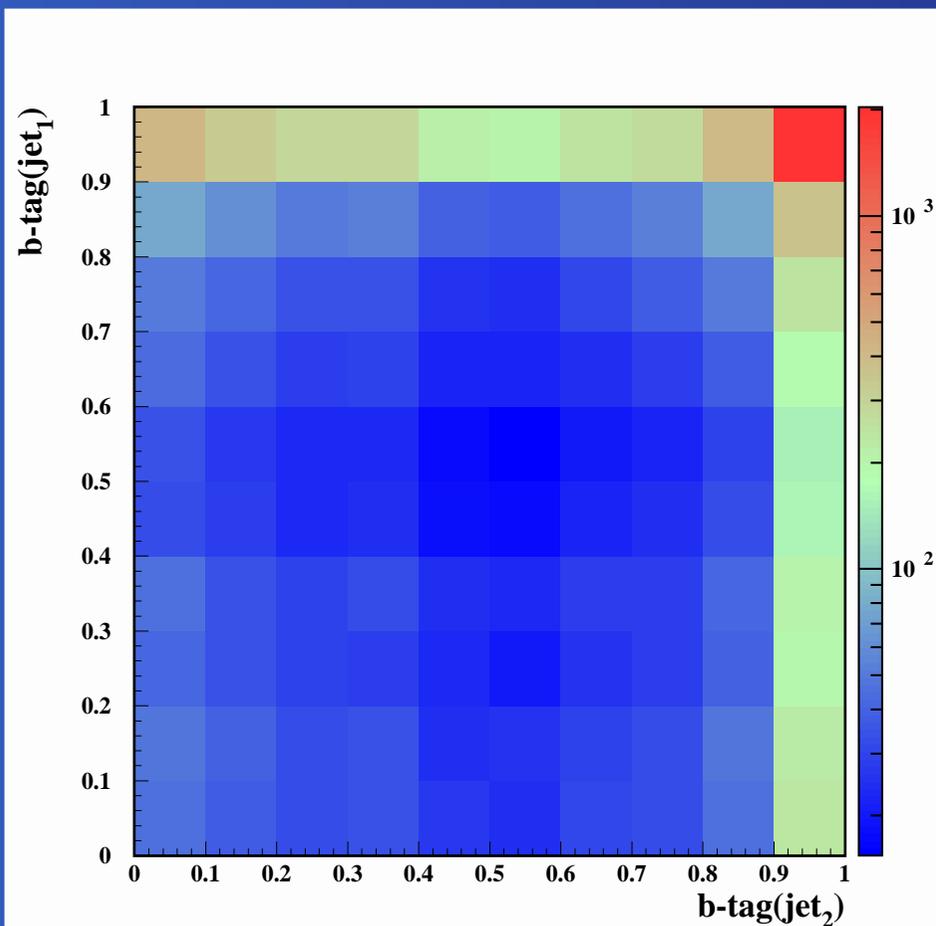
# Optymalizacja selekcji

Zaniedbując błędy systematyczne istnieje przepis na **optymalną** metodę selekcji (**minimalizującą błąd statystyczny**). Można go stosować przy niewielkiej liczbie parametrów opisujących przypadek:

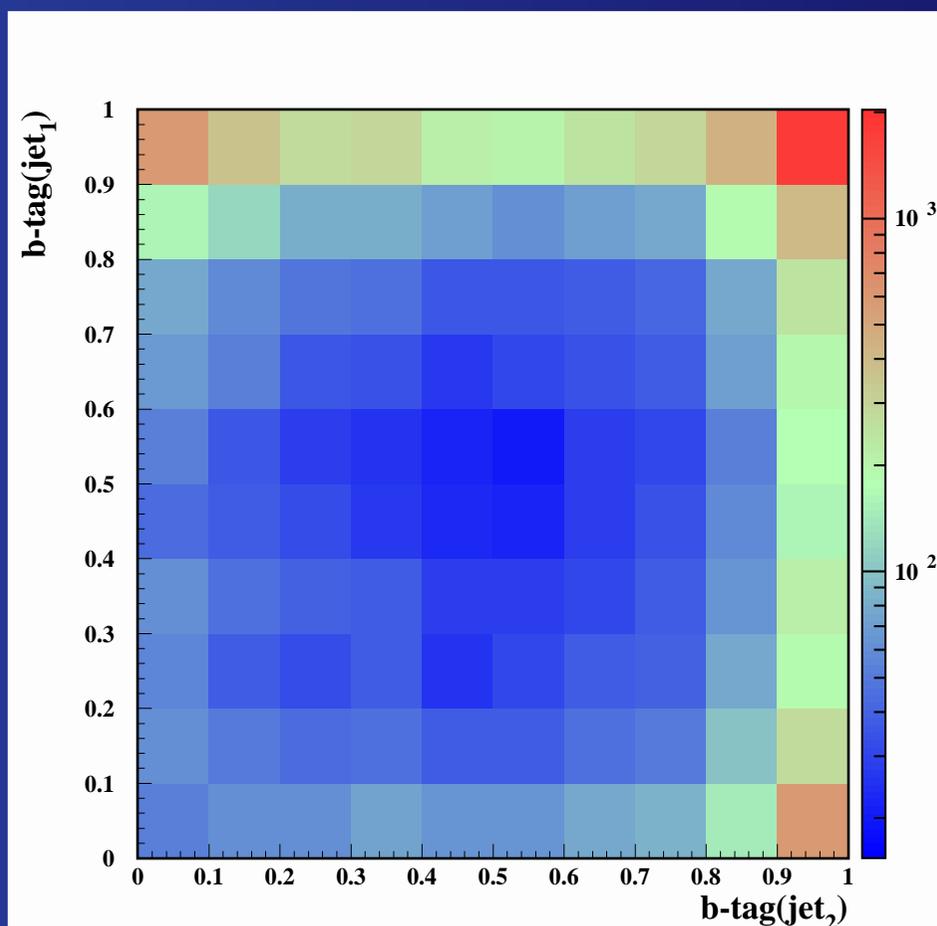
- dzielimy zakresy zmienności **wszystkich parametrów**  $i$  na  $N_i$  binów
- dla każdego zestawu parametrów  $j$  ( $j=1, \dots, \prod N_i$ ) wyznaczamy stosunek sygnału do tła w tym (**wielowymiarowym**) przedziale  $r_j = S_j / B_j$
- dla założonego cięcia  $r_{\min}$  sumujemy sygnał i tło ze wszystkich przedziałów o  $r_j > r_{\min}$  :  $\mathbf{S}^r = \sum_{r_j > r_{\min}} \mathbf{S}_j$        $\mathbf{B}^r = \sum_{r_j > r_{\min}} \mathbf{B}_j$
- wyznaczmy zależność
$$\mathbf{k}(r_{\min}) = \mathbf{S}^r / \sqrt{\mathbf{S}^r + \mathbf{B}^r}$$
- znajdujemy maksimum  $\mathbf{k}(r_{\min})$  w funkcji  $r_{\min}$

# $b\bar{b}$ -tagging

$$\gamma\gamma \rightarrow h \rightarrow b\bar{b}$$



$$\gamma\gamma \rightarrow b\bar{b}(g)$$

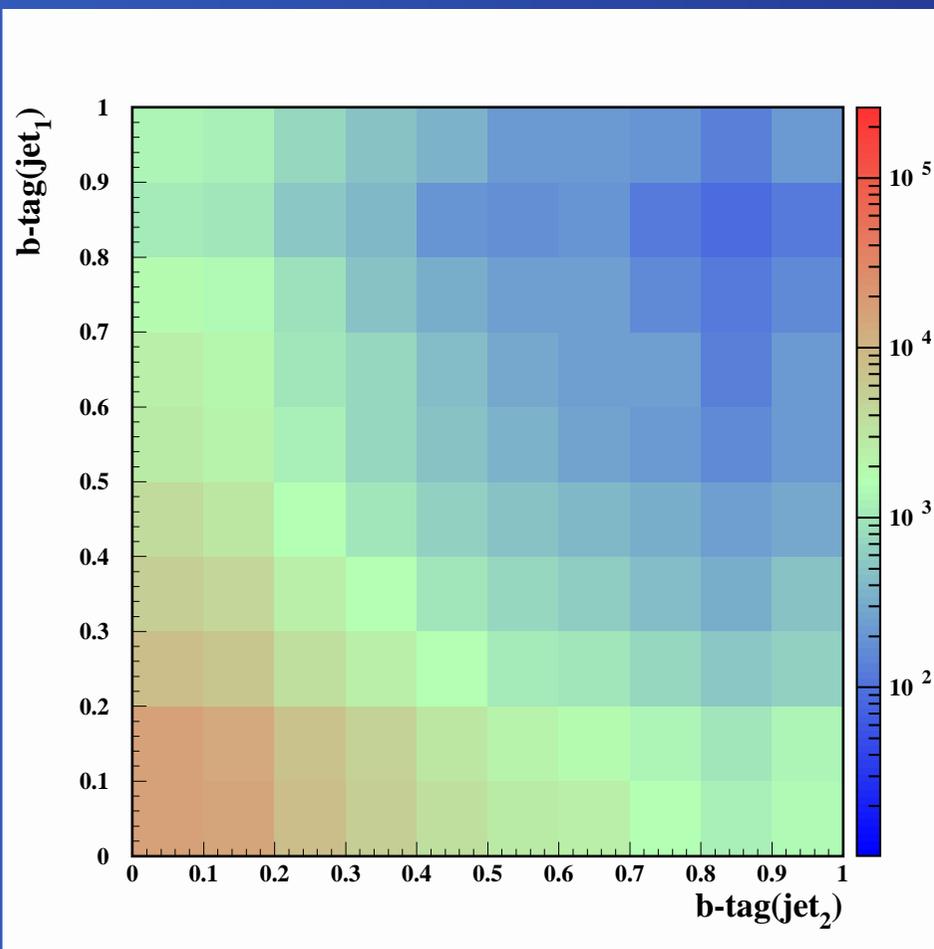


$J_z = 0$  suppressed for  $b\bar{b}$   
 $\Rightarrow$  hard  $g$ -jet with low  $b$ -tag

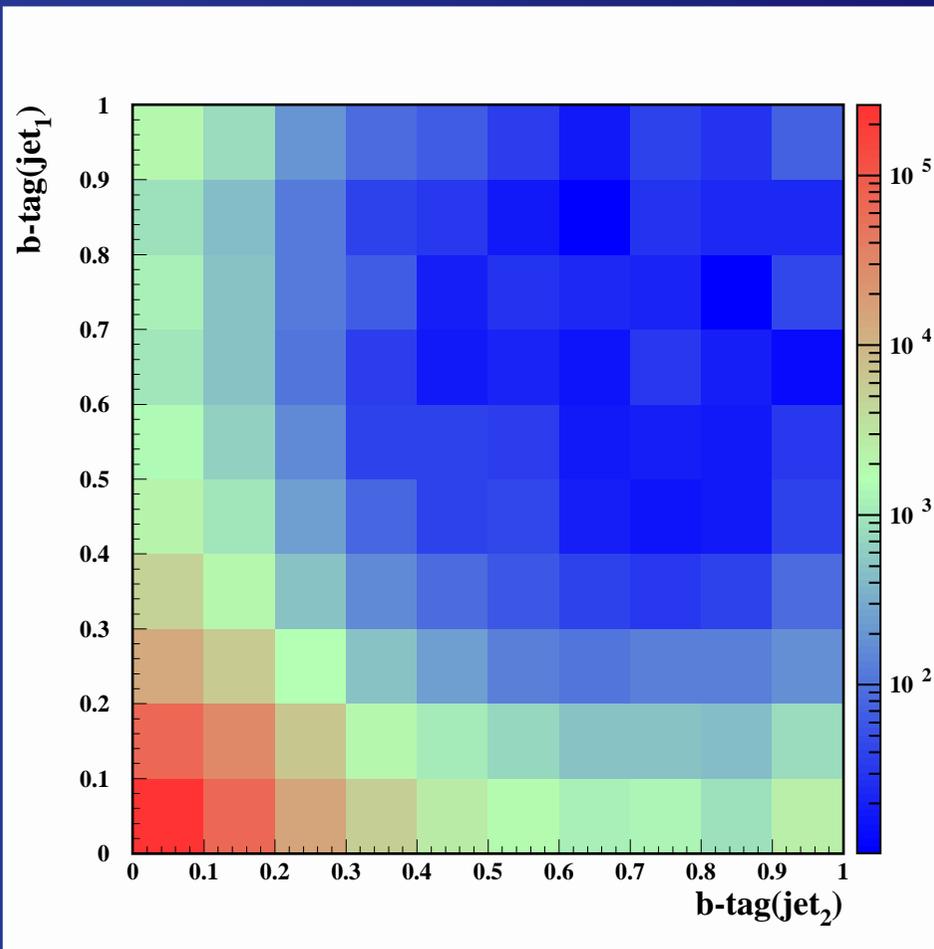


# $b\bar{b}$ -tagging

$$\gamma\gamma \rightarrow c\bar{c}(g)$$



$$\gamma\gamma \rightarrow q\bar{q} \quad (q = u, d, s)$$



Significant fraction mistagged  
 $\Rightarrow$  double  $b$ -tag



# *higgs-tagging* at $M_h = 120 \text{ GeV}$

*higgs-tagging*: a cut on the ratio  
of  $\gamma\gamma \rightarrow h \rightarrow b\bar{b}$

to  $\gamma\gamma \rightarrow b\bar{b}(g), c\bar{c}(g)$  events

$\Rightarrow \varepsilon_{higgs} = 70 \%$

$\varepsilon_{bb} = 66\%, \varepsilon_{cc} = 4\%$

Earlier we used *b*-tagging:

a cut on the ratio

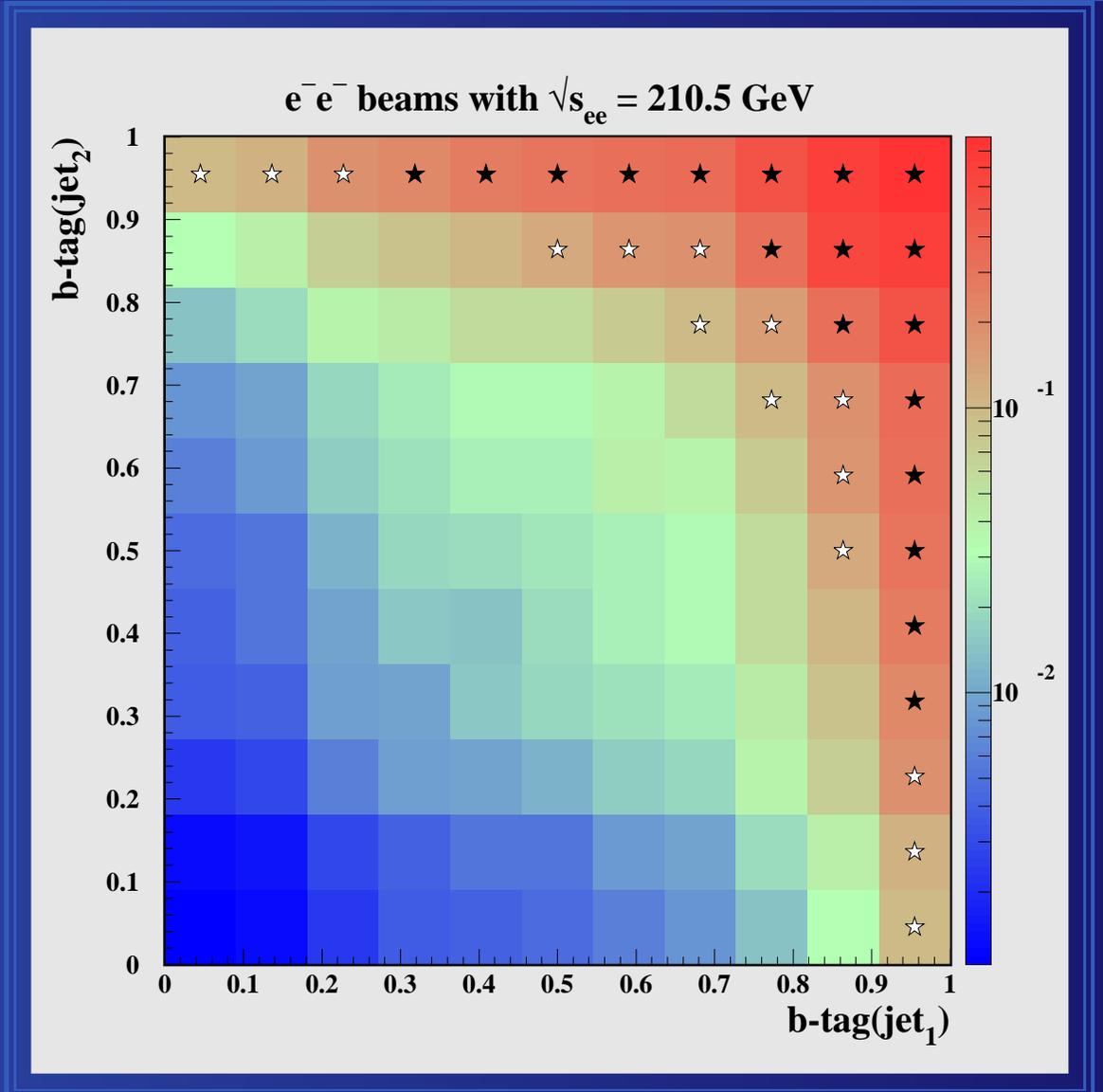
of  $\gamma\gamma \rightarrow b\bar{b}(g)$

to  $\gamma\gamma \rightarrow c\bar{c}(g)$  events

$\Rightarrow \varepsilon_{higgs} = 85 \%$

$\varepsilon_{bb} = 82\%, \varepsilon_{cc} = 2\%$

Tighter cuts are needed  
due to OE contribution

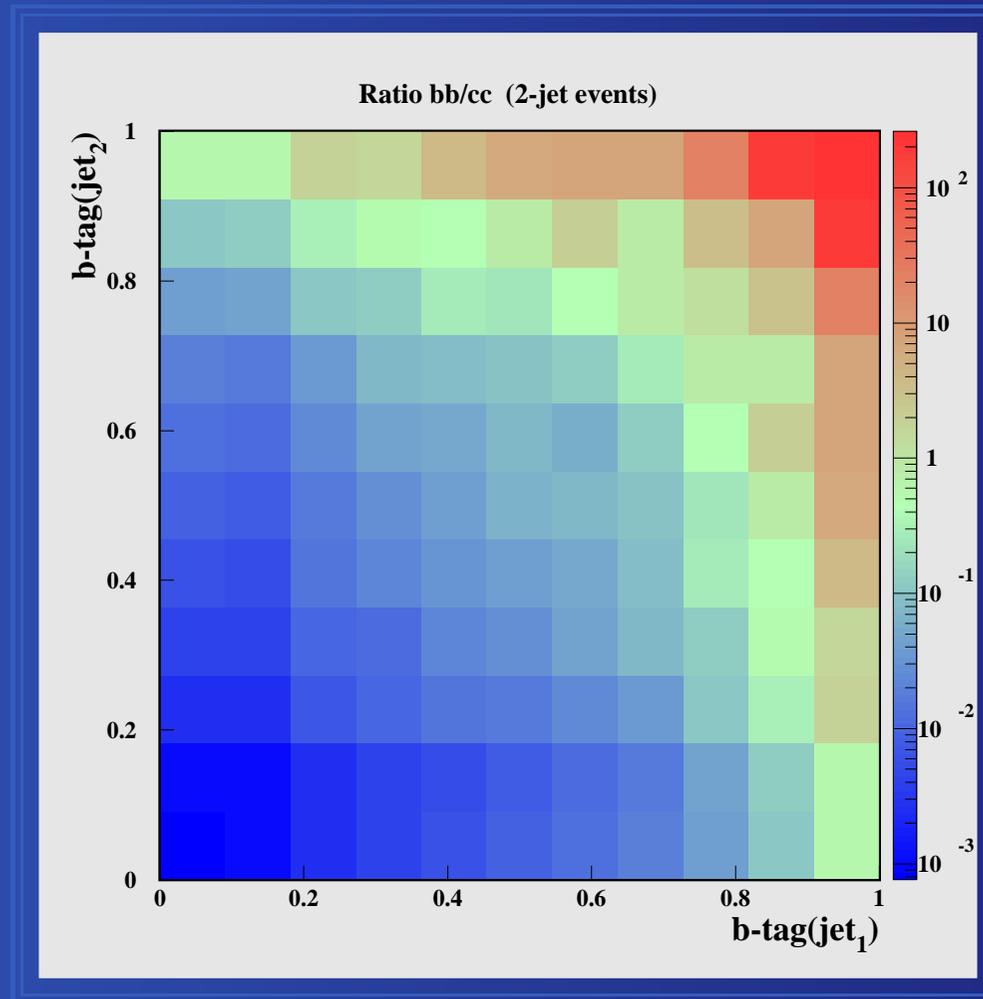


Black stars – optimized selection

Black+white stars – analysis without OE

# B-tagging

## ZVTOP-B-Hadron-Tagger



$$\frac{S}{B} = \frac{\#(\gamma\gamma \rightarrow b\bar{b})}{\#(\gamma\gamma \rightarrow c\bar{c})}$$



# Uncertainty on Cross Section

- You will want to minimize the uncertainty:

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{\delta N_{obs}^2 + \delta N_{BG}^2}{(N_{obs} - N_{BG})^2} + \left(\frac{\delta\mathcal{L}}{\mathcal{L}}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

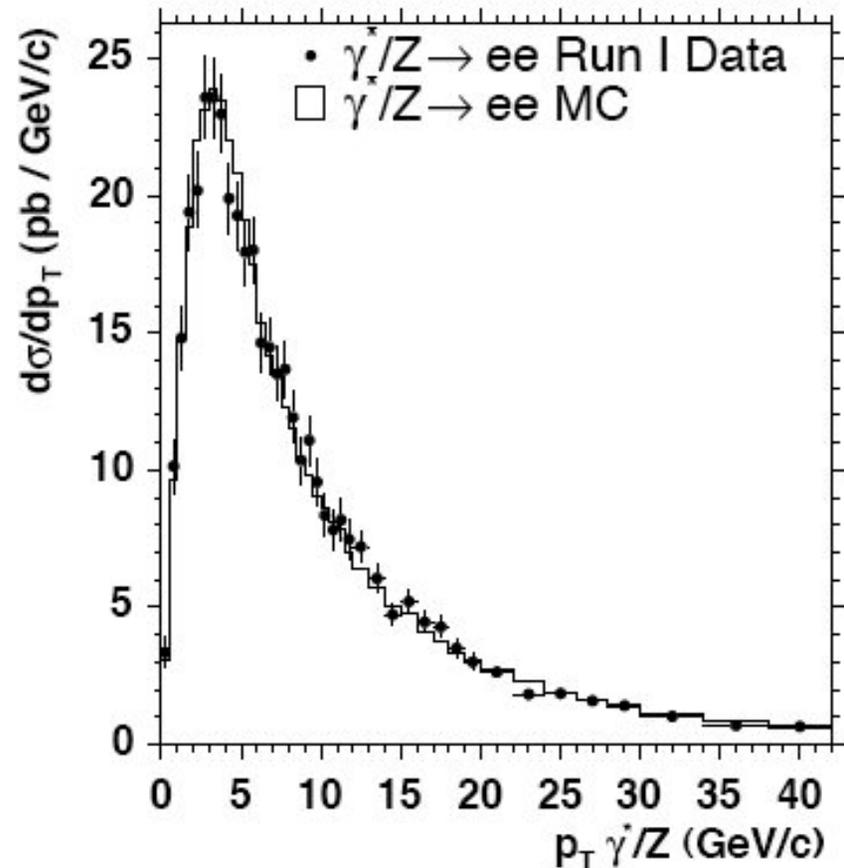
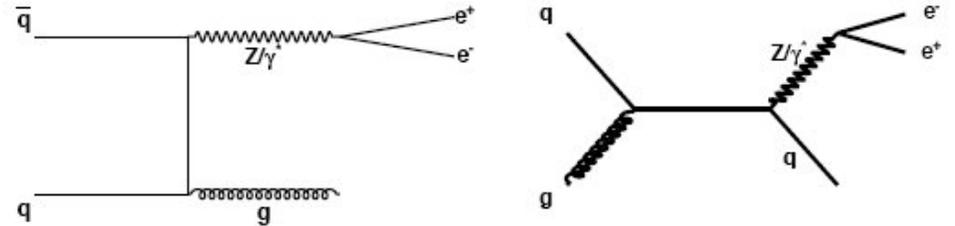
- Thus you need:
  - $N_{obs} - N_{BG}$  large (i.e.  $N_{signal}$  large)
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# Systematic uncertainties

- This will likely be  $>90\%$  of the work
- **Systematic errors cover our lack of knowledge**
  - need to be determined on every aspect of measurement by varying assumptions *within sensible reasoning*
  - Thus there is no “correct way”:
    - But there are good ways and bad ways
    - You will need to develop a feeling and discuss with colleagues / conveners / theorists
    - There is a lot of room for creativity here!
- What’s better? Overestimate or underestimate
  - Find New Physics:
    - it’s fine to be generous with the systematics
    - You want to be really sure you found new physics and not that “Pythia doesn’t work”
  - Precision measurement
    - Need to make best effort to neither overestimate nor underestimate!

# QCD Modeling of Process

- Kinematics affected by  $p_T$  of Z boson
  - Determined by soft and hard QCD radiation
    - tune MC to describe data
- Limitations of Leading Order Monte Carlo
  - Compare to NNLO calculation



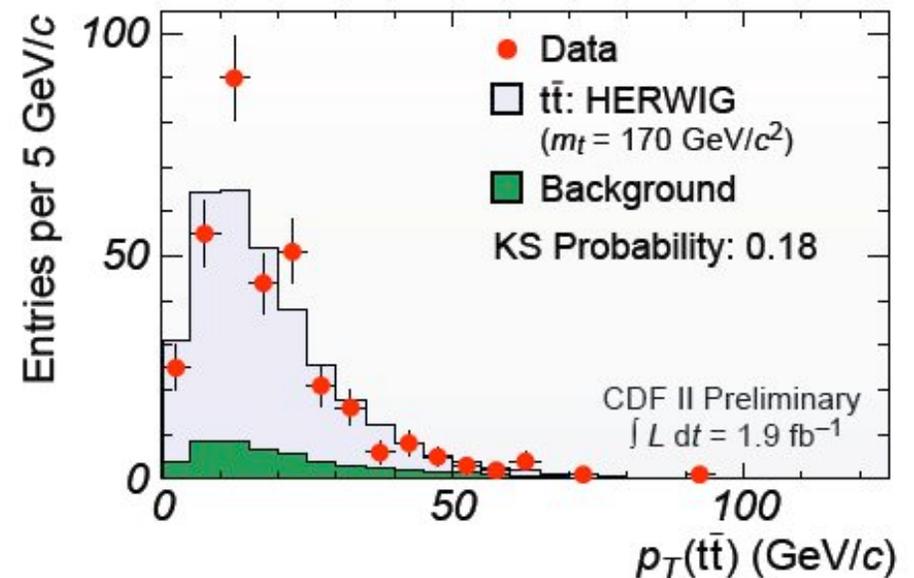
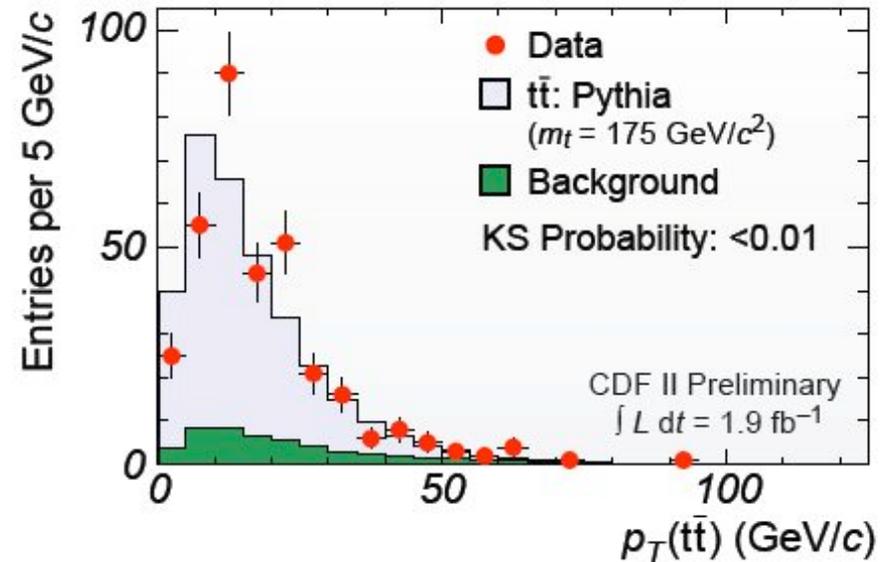
CDF

TABLE XII: Central acceptance values for our candidate samples based on  $d\sigma/dy$  distributions obtained from both NNLO and PYTHIA simulation.

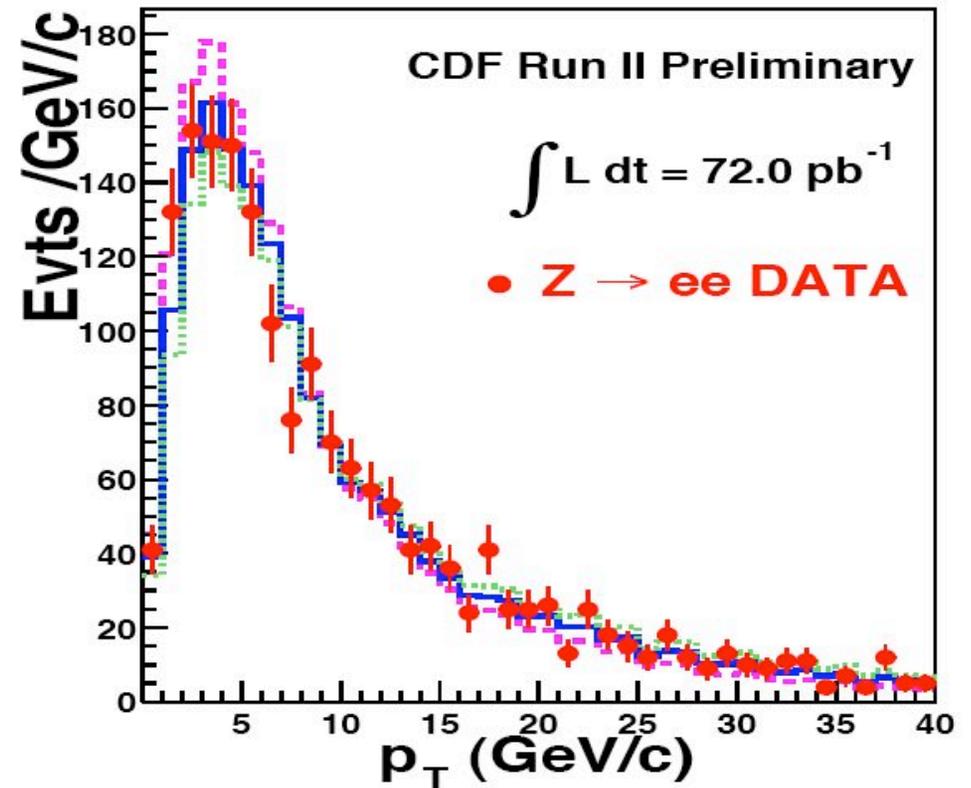
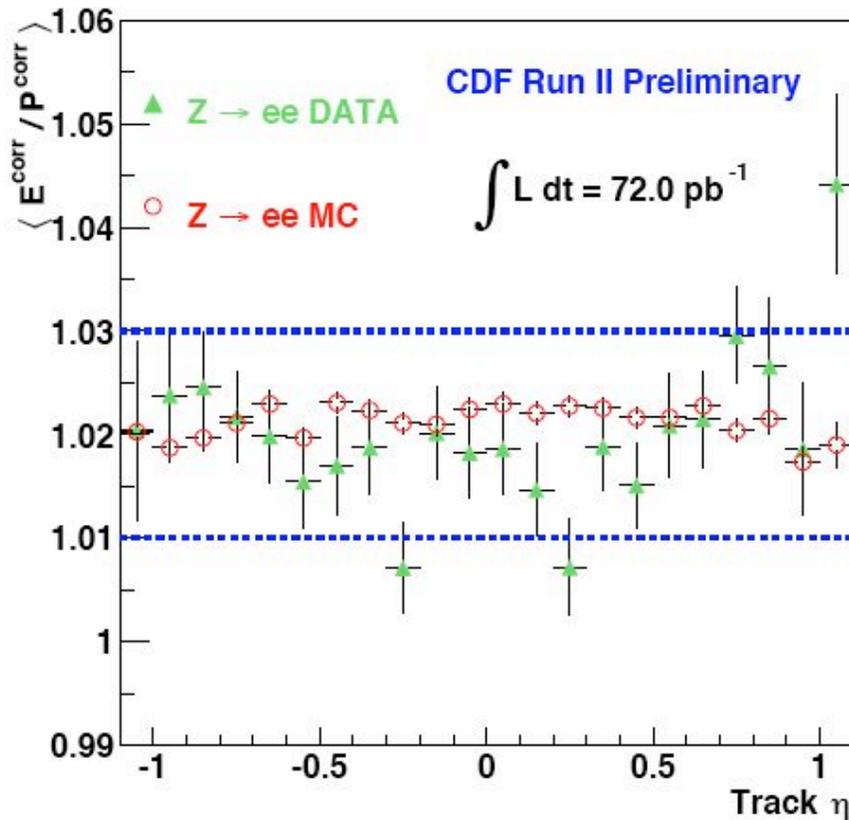
Acceptance	NNLO Calc.	PYTHIA	Difference (%)
$A_{W \rightarrow \mu\nu}$	0.1970	0.1967	+0.15
$A_{W \rightarrow e\nu}$	0.2397	0.2395	+0.08
$A_{Z \rightarrow \mu\mu}$	0.1392	0.1387	+0.36
$A_{Z \rightarrow ee}$	0.3182	0.3185	-0.09
$A_{Z \rightarrow \mu\mu} / A_{W \rightarrow \mu\nu}$	0.7066	0.7054	+0.17
$A_{Z \rightarrow ee} / A_{W \rightarrow e\nu}$	1.3272	1.3299	-0.20

# MC Modeling of top

- Use different MC generators
  - Pythia
  - Herwig
  - Alpgen
  - MC @ NLO
  - ...
- Different tunes
  - Underlying event
  - Initial/final state QCD radiation
  - ...
- Make many plots
  - Check if data are modelled well



# Examples for Systematic Errors



- Mostly driven by comparison of data and MC
  - Systematic uncertainty determined by (dis)agreement and statistical uncertainties on data

# Systematic Uncertainties: Z and top

## top cross section

### Z cross section (not all systematics)

source	variation	$\Delta A_Z$	$\Delta A_Z / A_Z$
$E_T^e$ scale	1% variation	0.03%	0.3%
$E_T^e$ resolution	2% extra smearing	0.02%	0.2%
$p_T^e$ scale	1% variation	0.01%	0.1%
$p_T$ modelling		0.01%	0.1%
Material	5.5 % $X_0$	0.54%	4.7%
PDFs	reweighting of y	0.34%	2.9%
<b>overall</b>		0.64%	5.5%

Systematic	Inclusive (Tight)	Double (Loose)
Lepton ID	1.8	
ISR	0.5	0.2
FSR	0.6	0.6
PDFs	0.9	
Pythia vs. Herwig	2.2	1.1
Luminosity	6.2	
JES	6.1	4.1
<i>b</i> -Tagging	5.8	12.1
<i>c</i> -Tagging	1.1	2.1
<i>l</i> -Tagging	0.3	0.7
Non- <i>W</i>	1.7	1.3
<i>W</i> +HF Fractions	3.3	2.0
Mistag Matrix	1.0	0.3
<b>Total</b>	11.5	14.8

- Relative importance and evaluation methods of systematic uncertainties are very, very analysis dependent

# Final Result: Z cross section

- Now we have everything to calculate the final cross section

TABLE XXXVII: Summary of the input parameters to the  $\gamma^*/Z \rightarrow \ell\ell$  cross section calculations for the electron and muon candidate samples.

	$\gamma^*/Z \rightarrow ee$	$\gamma^*/Z \rightarrow \mu\mu$
$N_Z^{\text{obs}}$	4242	1785
$N_Z^{\text{bck}}$	$62 \pm 18$	$13 \pm 13$
$A_Z$	$0.3182^{+0.0039}_{-0.0041}$	$0.1392^{+0.0027}_{-0.0033}$
$\epsilon_Z$	$0.713 \pm 0.012$	$0.713 \pm 0.015$
$\int \mathcal{L} dt \text{ (pb}^{-1}\text{)}$	$72.0 \pm 4.3$	$72.0 \pm 4.3$

$$\sigma_{\gamma^*/Z} \cdot Br(\gamma^*/Z \rightarrow ee) = 255.8 \pm 3.9(\text{stat.})$$

$$\pm 5.5(\text{syst.})$$

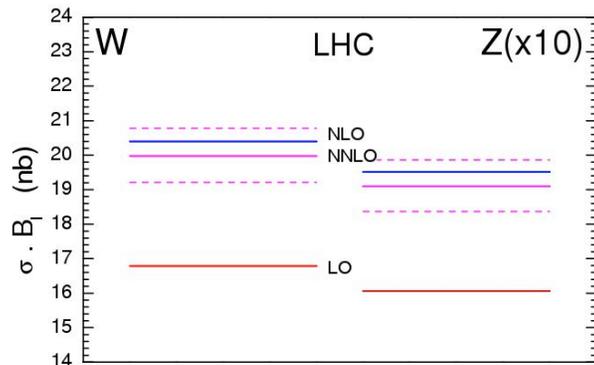
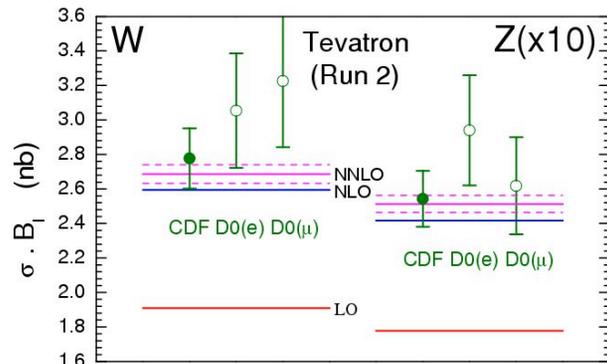
$$\pm 15.3(\text{lum.}) \text{ pb}$$

Measurement gets quickly systematically limited

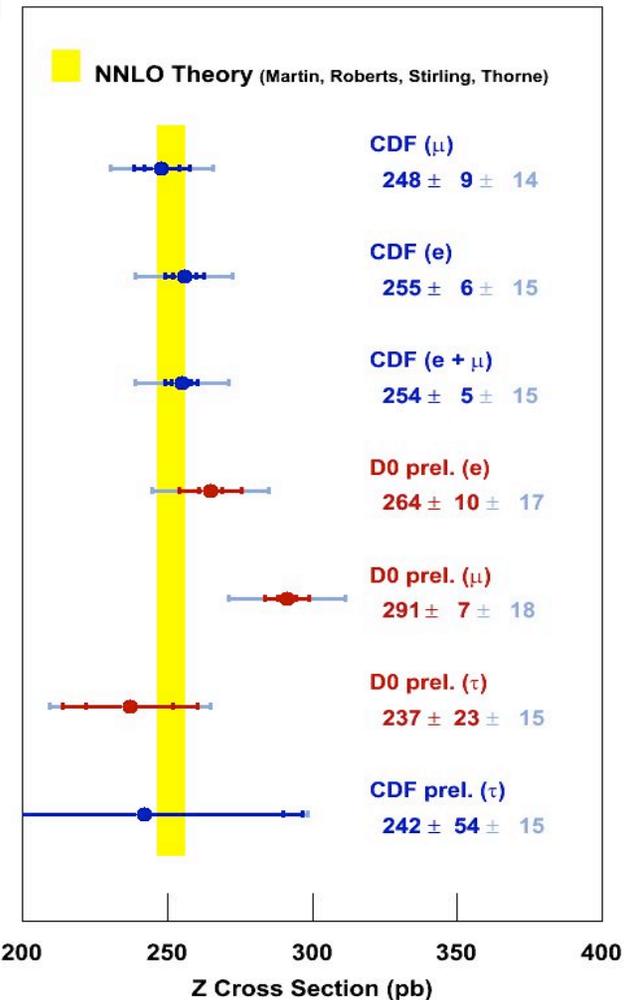
# Comparison to Theory

- Experimental uncertainty:  $\sim 2\%$
- Luminosity uncertainty:  $\sim 6\%$
- Theoretical uncertainty:  $\sim 2\%$

$\sigma_{\text{Th,NNLO}} = 251.3 \pm 5.0 \text{ pb}$   
(Martin, Roberts, Stirling, Thorne)

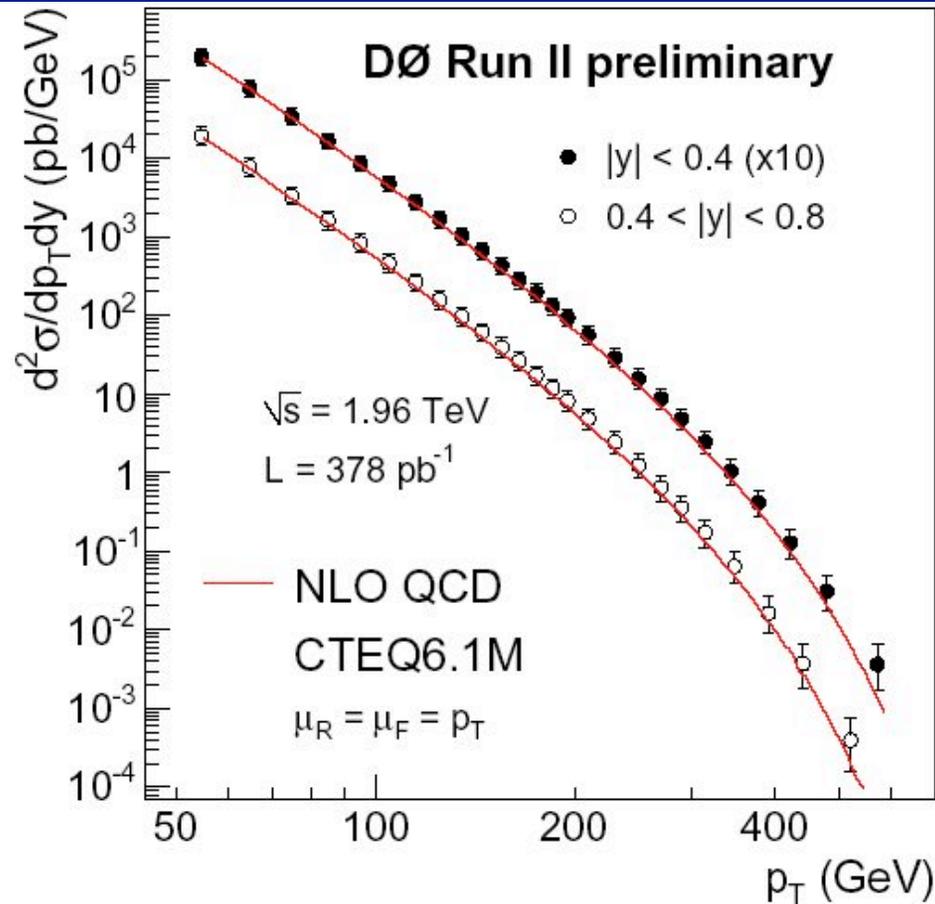


partons: MRST2002  
NNLO evolution: Moch, Vermaseren, Vogt  
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections



- Can use these processes to normalize luminosity absolutely
  - However, theory uncertainty larger at LHC and theorists don't agree (yet)<sup>47</sup>

# Differential Cross Section



- Measure jet spectra differentially in  $E_T$  and  $\eta$
- Cross section in bin  $i$ : 
$$\sigma(\mathbf{i}) = \frac{N_{\text{obs}}(\mathbf{i}) - N_{\text{BG}}(\mathbf{i})}{\int L dt \epsilon(\mathbf{i})}$$

# Differential Cross Section: Unfolding

- “Unfolding” critical for jet cross sections
- Measure:
  - Cross section for calorimeter jets
- Want:
  - Cross section for hadron-jets

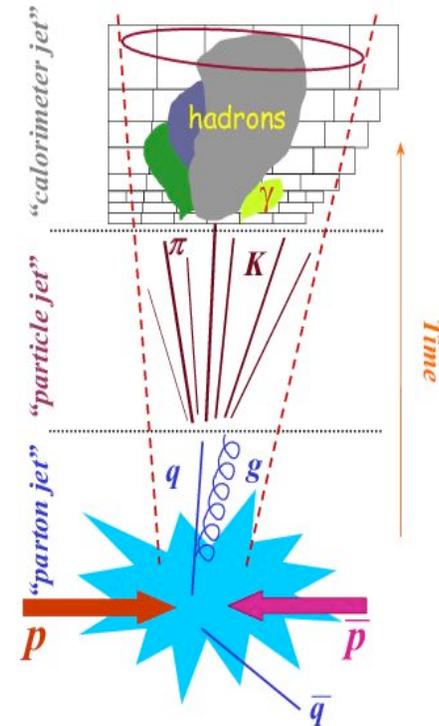
Unfolding factor (bin by bin):

$$C_i = \frac{N_{JET\ i}^{HAD}}{N_{JET\ i}^{CAL}}$$

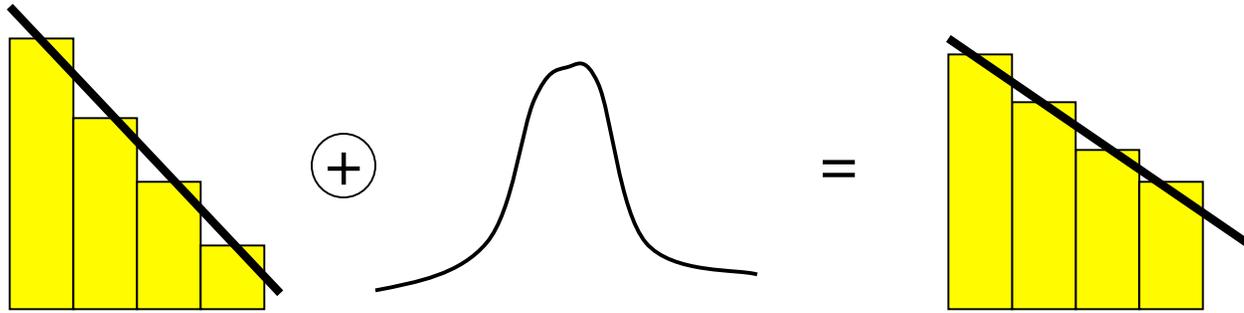
Then:

$$N_{JET\ i}^{DATA\ UNFOLDED} = C_i \cdot N_{JET\ i}^{DATA\ NOT\ UNFOLDED}$$

- But, unfolding factors depend on MC  
 $E_T$  spectrum - **depend on the measured cross section !!!**



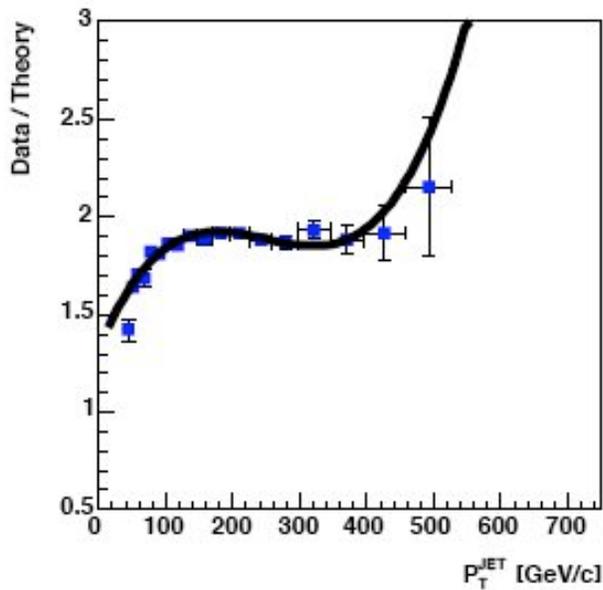
# Differential Cross Section: Unfolding



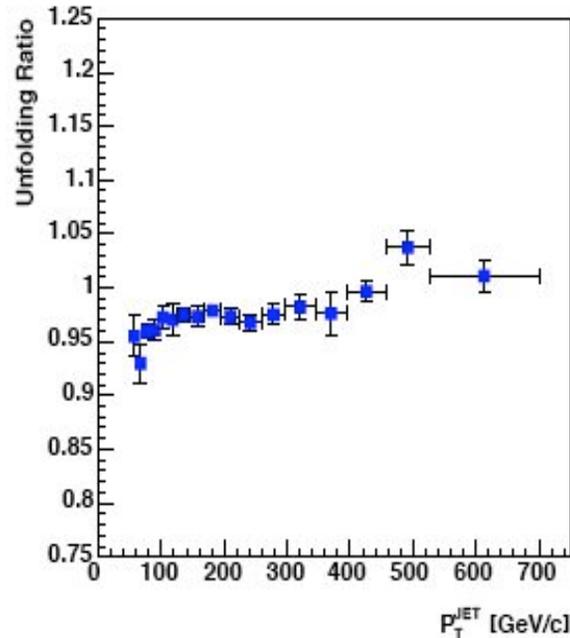
- **Problem:**
  - Steeply falling spectrum causes migrations to go from low to high  $p_T$ 
    - Measured spectrum “flatter” than true spectrum
  - Size of migration depends on input spectrum
- **Requires iterative procedure** (bin-by-bin unfolding):
  1. Measure using spectrum from MC
  2. Fit measurement
  3. Reweight MC to reflect data measurement => go back to 1.

# Example for Bin-by-Bin Unfolding

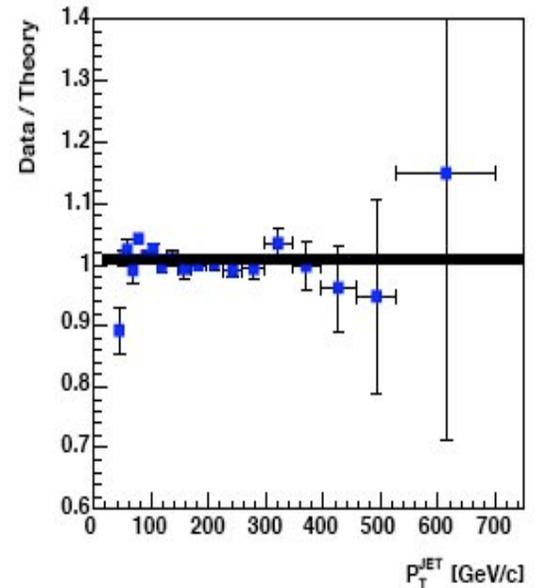
Data / Unweighted Herwig (D=0.7)



Weighted Herwig / Weighted Pythia (D=0.7)



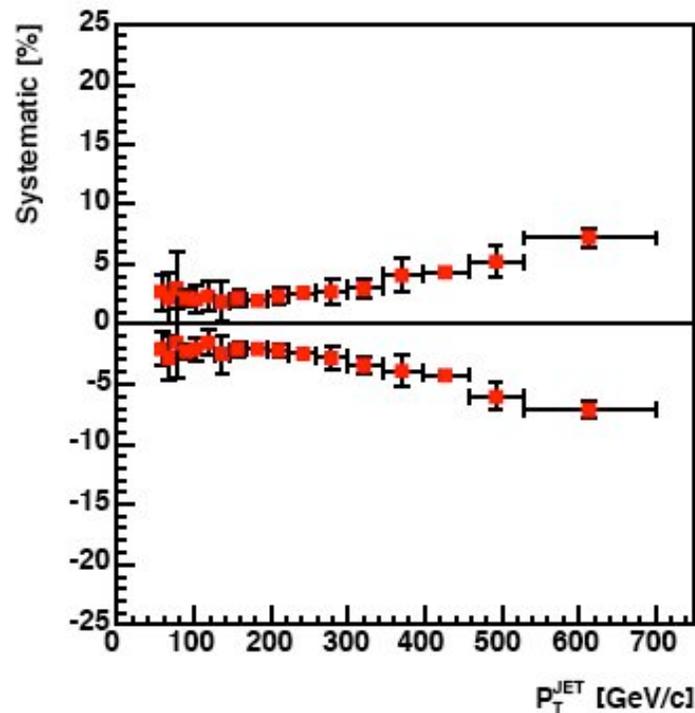
Data / Weighted Herwig (D=0.7)



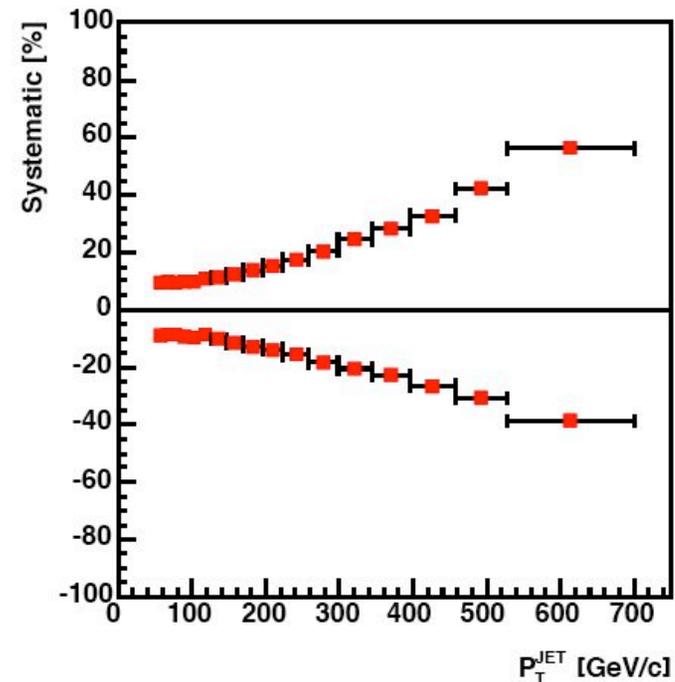
- Correction to unfolding factors <10%
  - One iteration sufficient in this example
  - Starting spectrum was already quite close to data

# Systematic Uncertainties: Jet Cross Section

8% uncertainty on resolution (D=0.5)

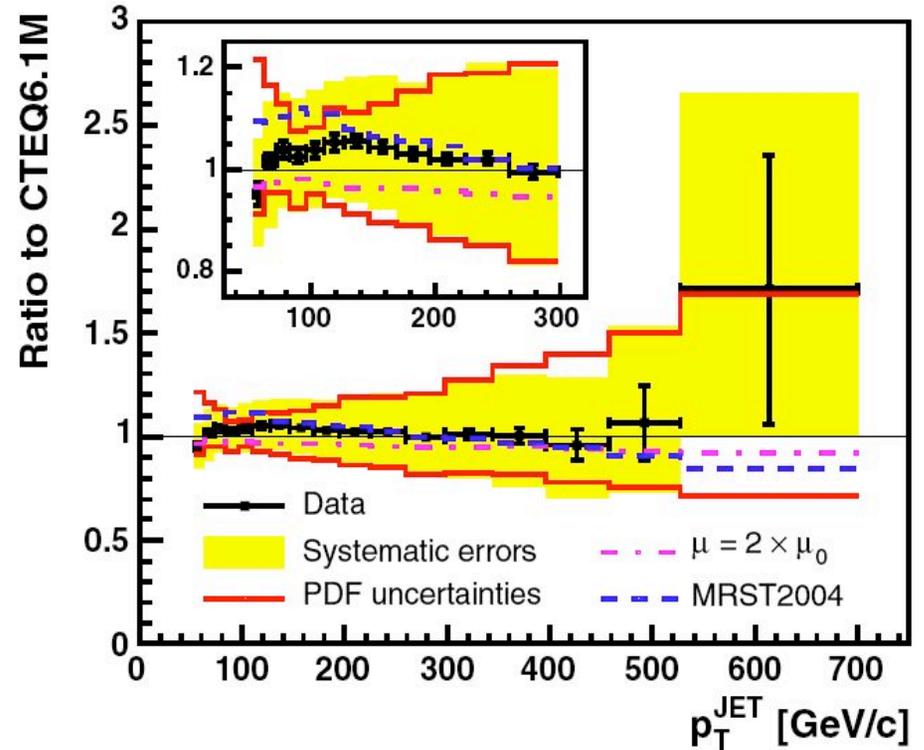
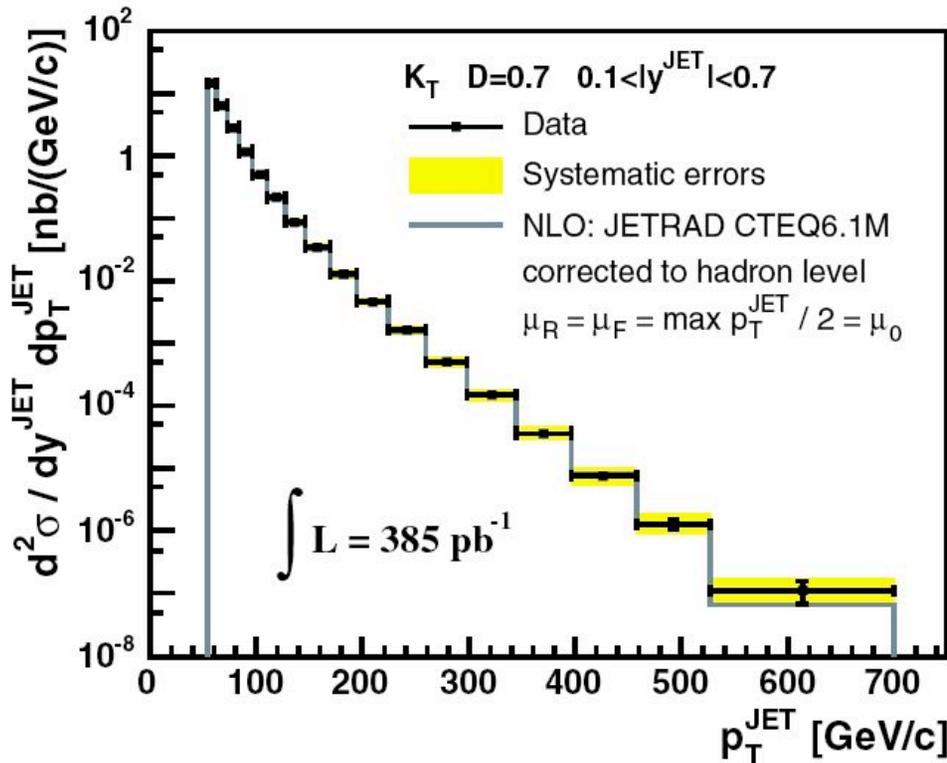


Jet Energy Scale Uncertainty (D=0.5)



- For Jet Cross Section the Jet Energy Scale (JES) uncertainty is dominant systematic error
  - 3% uncertainty on JES results in up to 60% uncertainty on cross section
  - 8% uncertainty on JE resolution causes <10% uncertainty on cross section

# Jet Cross Section Result



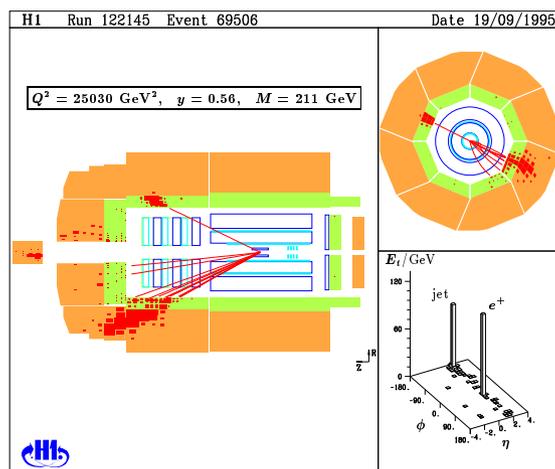
- Cross section falls by 8 orders of magnitude in measured  $E_T$  range
- Data in good agreement with QCD prediction
  - Experimental and theoretical errors comparable

# Deep Inelastic $e^\pm p$ Scattering

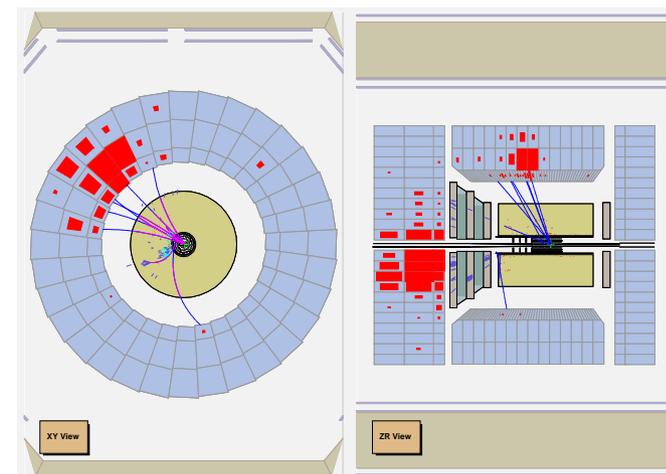


Main process studied at H1 and ZEUS

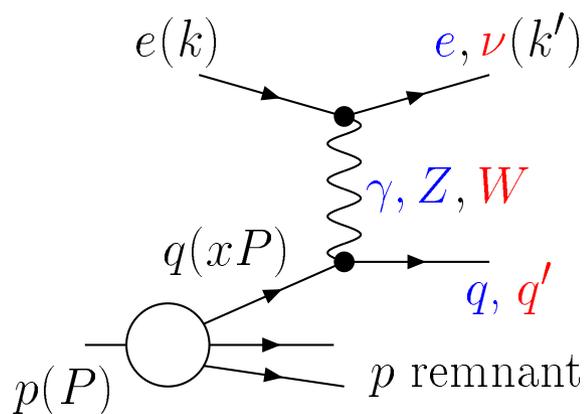
NC DIS



CC DIS



Kinematic variables:



$$Q^2 = -(k - k')^2$$

[virtuality] of the exchanged boson

⇒ spatial resolution  $\lambda \sim 1/Q$

$$x = \frac{Q^2}{2P \cdot (k - k')}$$

⇒ sensitivity to mass scales  $\Lambda \sim Q$

$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

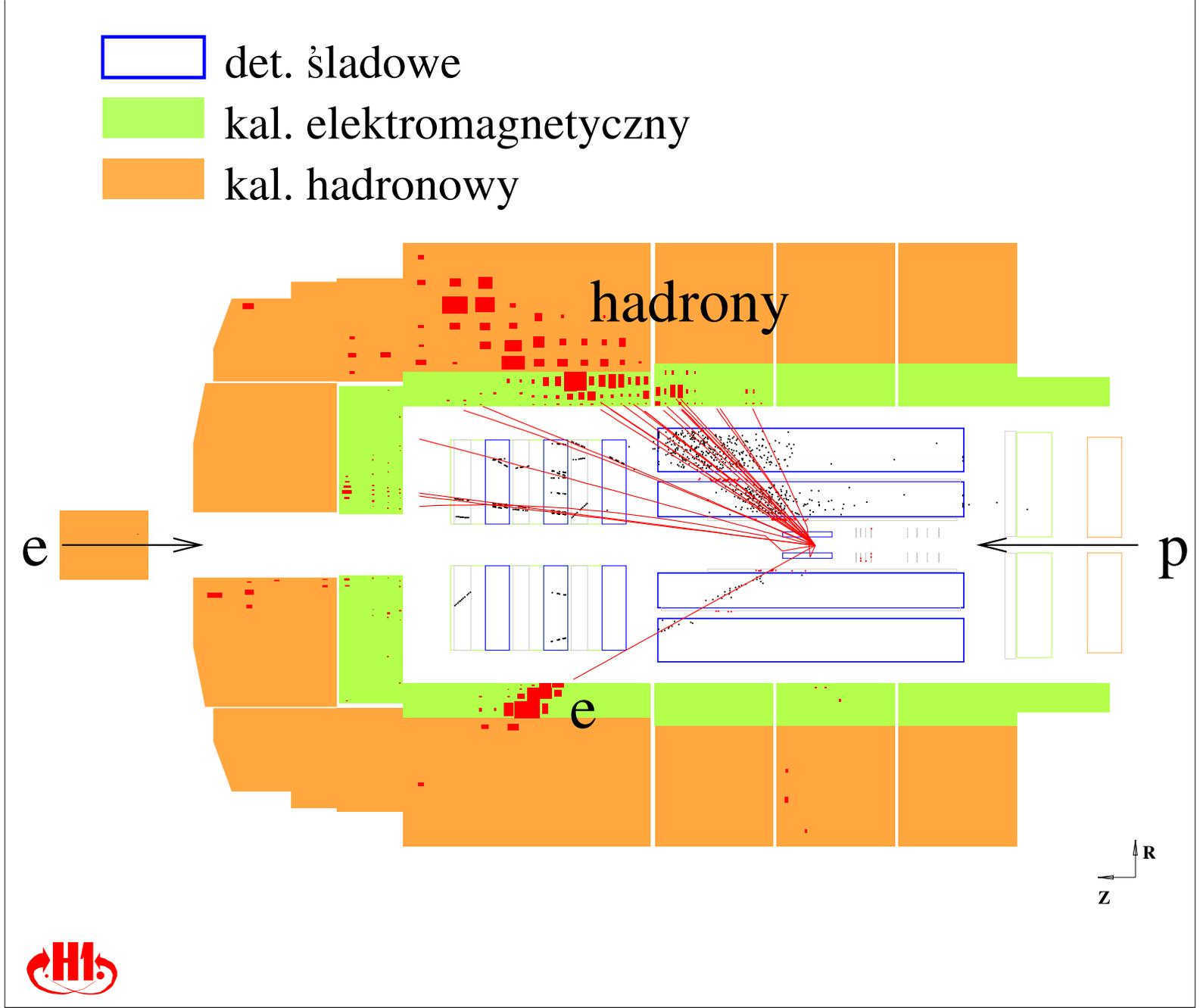


Przypadek  
NC DIS

**Ekspertment H1**

mierzymy **energie**  
i **kąt** rozproszenia  
elektronu  
 $\Rightarrow x, Q^2$

można też mierzyć  
stan hadronowy...

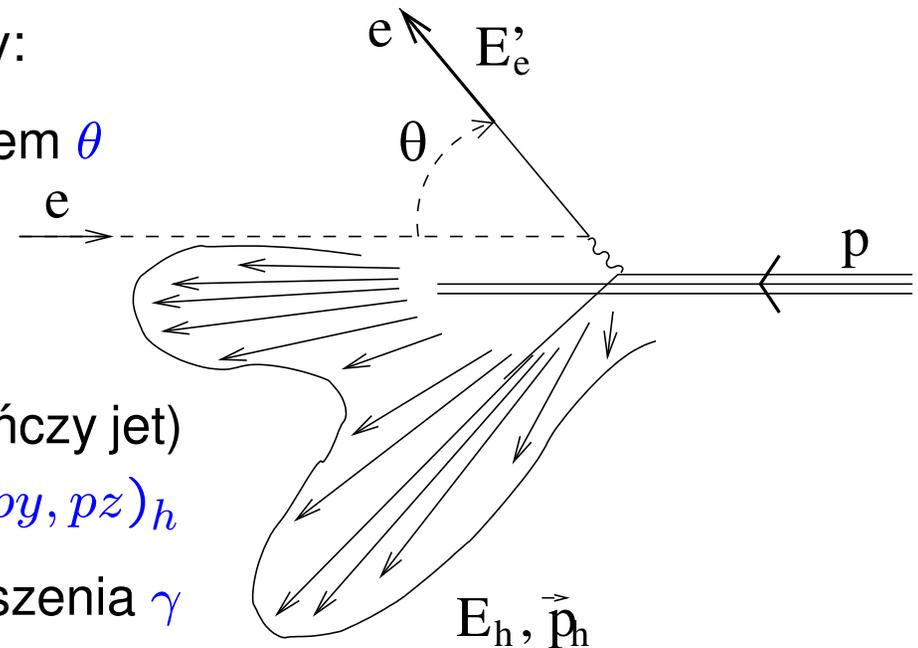


# Rekonstrukcja przypadków

## Pomiar w detektorze

W przypadkach **NC DIS** w detektorze mierzymy:

- **elektron** o energii  $E'_e$  rozproszony pod kątem  $\theta$
  - stan **hadronowy** (na ogół nie jest to pojedynczy jet) o całkowitej energii  $E_h$  i pędzie  $\vec{p}_h = (p_x, p_y, p_z)_h$
- ⇒ możemy wyznaczyć **efektywny kąt** rozproszenia  $\gamma$  i **energię**  $E_q$  jetu ⇒ partonu



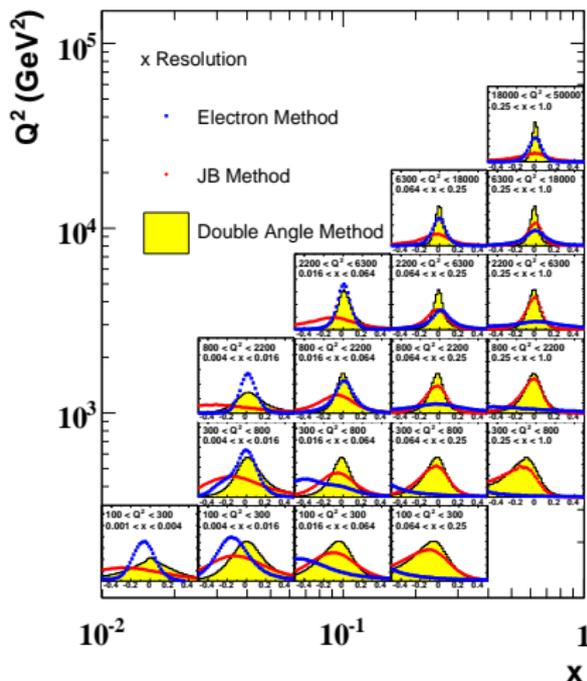
Chcemy wyznaczyć **dwie** zmienne, np.  $x$  i  $Q^2$  (trzecią zmienną mamy z relacji:  $Q^2 = xys$ )

Mamy **cztery** wielkości mierzone:  $E'_e$ ,  $\theta$ ,  $E_q$  i  $\gamma$  ⇒ **mamy dużą swobodę wyboru metody**

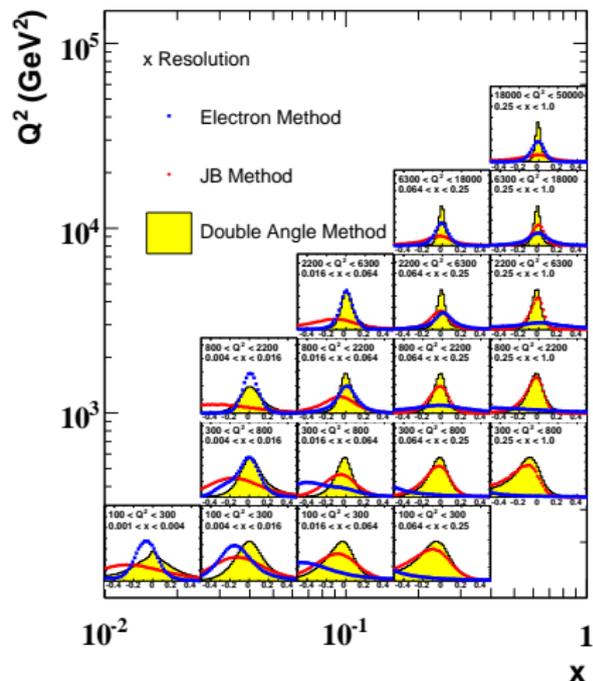
**Teoretycznie** (nieskończenie dokładny pomiar) wszystkie metody są **równoważne**.

**Efekty doświadczalne** (**błędy pomiarowe**) powodują jednak znaczne **różnice w dokładności** wyznaczenia  $x$ ,  $y$  i  $Q^2$  różnymi metodami ⇒ wybór zależy od eksperymentu...

## Nominal



## Using MEPS



# Wyznaczanie funkcji struktury

## Przekrój czynny

Funkcję struktury  $F_2(x, Q^2)$  wyznaczamy bezpośrednio z pomiaru różniczkowego **przekroju czynnego** na **NC DIS**:

$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) (1 + \delta_L + \delta_Z + \delta_{rad})$$

Wyznaczane **teoretycznie poprawki** pochodzą od:

- $\delta_L$  – tzw. podłużnej funkcji struktury  $F_L$   
( wkład gluonów powoduje, że  $F_L \equiv F_2 - 2xF_1 \neq 0$  )
- $\delta_Z$  – wymiany bozonu  $Z^0$   
(istotne tylko dla bardzo dużych  $Q^2$ )
- $\delta_{rad}$  – procesów radiacyjnych  
(poprawki radiacyjne; emisja  $\gamma$  przez elektron przed lub po zderzeniu)

# Wyznaczanie funkcji struktury

## Przekrój czynny

Różniczkowy przekrój czynny wyznaczamy mierząc liczbę przypadków zrekonstruowanych w przedziałach  $x$  i  $Q^2$ :

$$\Delta N(x \pm \frac{\Delta x}{2}, Q^2 \pm \frac{\Delta Q^2}{2}) = \frac{d^2 \sigma}{dx dQ^2} \cdot \Delta x \cdot \Delta Q^2 \cdot \mathcal{L}_{int} \cdot \mathcal{E} \cdot \mathcal{A}$$

gdzie:

- $\mathcal{L}_{int}$  – scałkowana świetlność
- $\mathcal{E}$  – efektywność selekcji przypadków
- $\mathcal{A}$  – poprawka związana z niedokładnością pomiaru (“przesypywanie” przypadków pomiędzy przedziałami)

### 5.1.3 Acceptances, purities, efficiencies

Samples of Monte Carlo events processed through the entire detector simulation chain were used to calculate the acceptances, the purities and efficiencies of the fragmentation variables. In the presented analysis the definitions were used as follows:

- the acceptance for bin  $i$  is defined as

$$A_i = \frac{\text{No. of events reconstructed in bin } i}{\text{No. of events generated in bin } i}$$

- the purity for bin  $i$  is defined as

$$P_i = \frac{\text{No. of events generated and reconstructed in bin } i}{\text{No. of events reconstructed in bin } i}$$

- the efficiency for bin  $i$  is defined as

$$\epsilon_i = \frac{\text{No. of events generated and reconstructed in bin } i}{\text{No. of events generated in bin } i}$$

# Optymalizacja selekcji

W przypadku różniczkowych przekrojów czynnych istotny jest nie tylko wybór cięć, ale też **dobór przedziałów** w których wyznaczamy  $d\sigma$

Do wyznaczenia **wartości**  $d\sigma$  wchodzi tylko poprawka na akceptację  $A_i$

Ale efektywność  $\varepsilon_i$  i czystość  $P_i$  mają znaczenie dla **systematyki**.

Dla **rzetelnego pomiaru** oczekujemy, żeby czystość przypadków w każdym binie

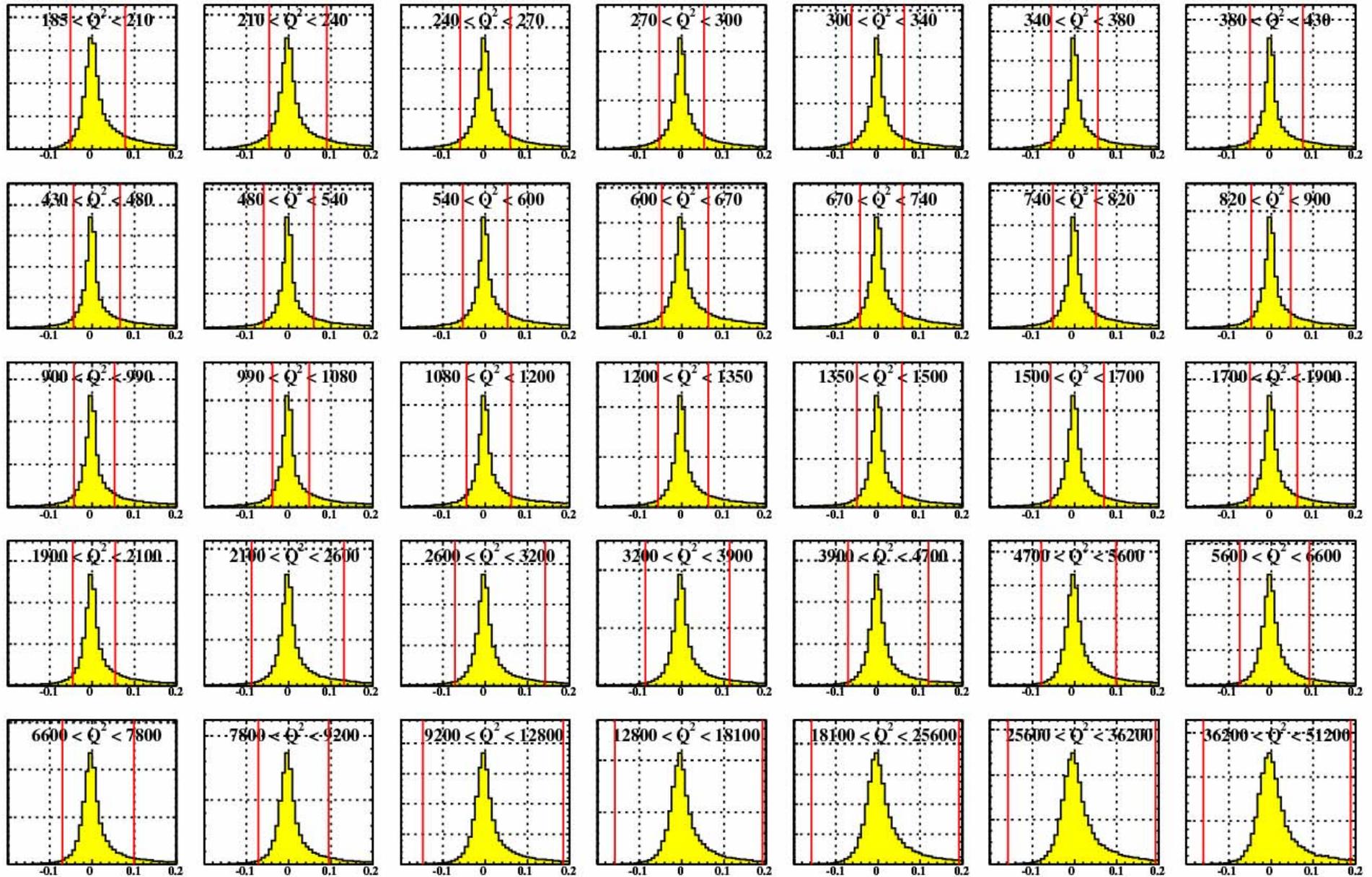
$$P_i > \sim 50\%$$

inaczej uzyskiwany po poprawkach kształt bardziej odzwierciedla wyniki symulacji Monte Carlo niż dane!

**Rozmiary binów nie mogą być mniejsze niż dokładność pomiaru!**

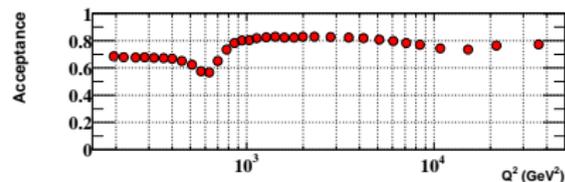
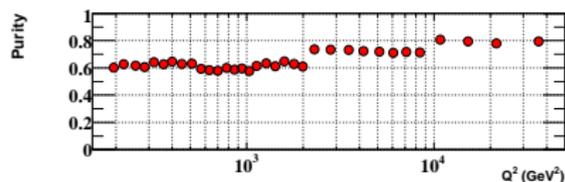
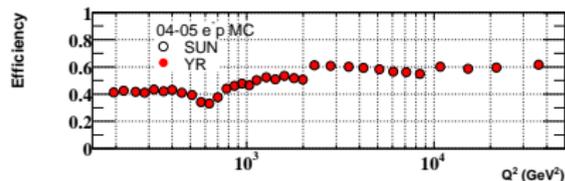
**Zwiększając rozmiary binów zwiększamy  $\varepsilon_i$  i  $P_i$**

# $d\sigma/dQ^2$ : Bias and Resolution



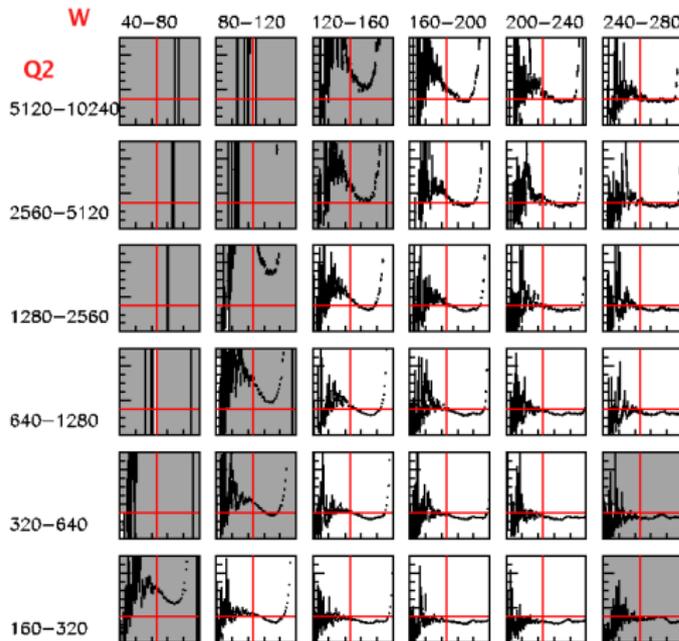
$$(Q^2_{DA} - Q^2_{true})/Q^2_{true}$$

# Efficiency and Purity for $d\sigma/dQ^2$



- Efficiency =  $\frac{\text{Generated \& Accepted}}{\text{Generated}}$
- Purity =  $\frac{\text{Generated \& Accepted}}{\text{Accepted}}$
- Acceptance =  $\frac{\text{Efficiency}}{\text{Purity}}$

# Correction factor for limited fragmentation



$$\text{corr. factor} = \frac{\eta(\text{true level})}{\eta(\text{detector level})}$$

first rejections for correction factor bigger than 1.5

horizontal red line – corr. factor equal 1.5  
 vertical red line – the value of  $\eta$ , where the slope starts

# Wyznaczanie funkcji struktury

Rozkład mierzonych przypadków **NC DIS** w zmiennych  $x, Q^2$ .

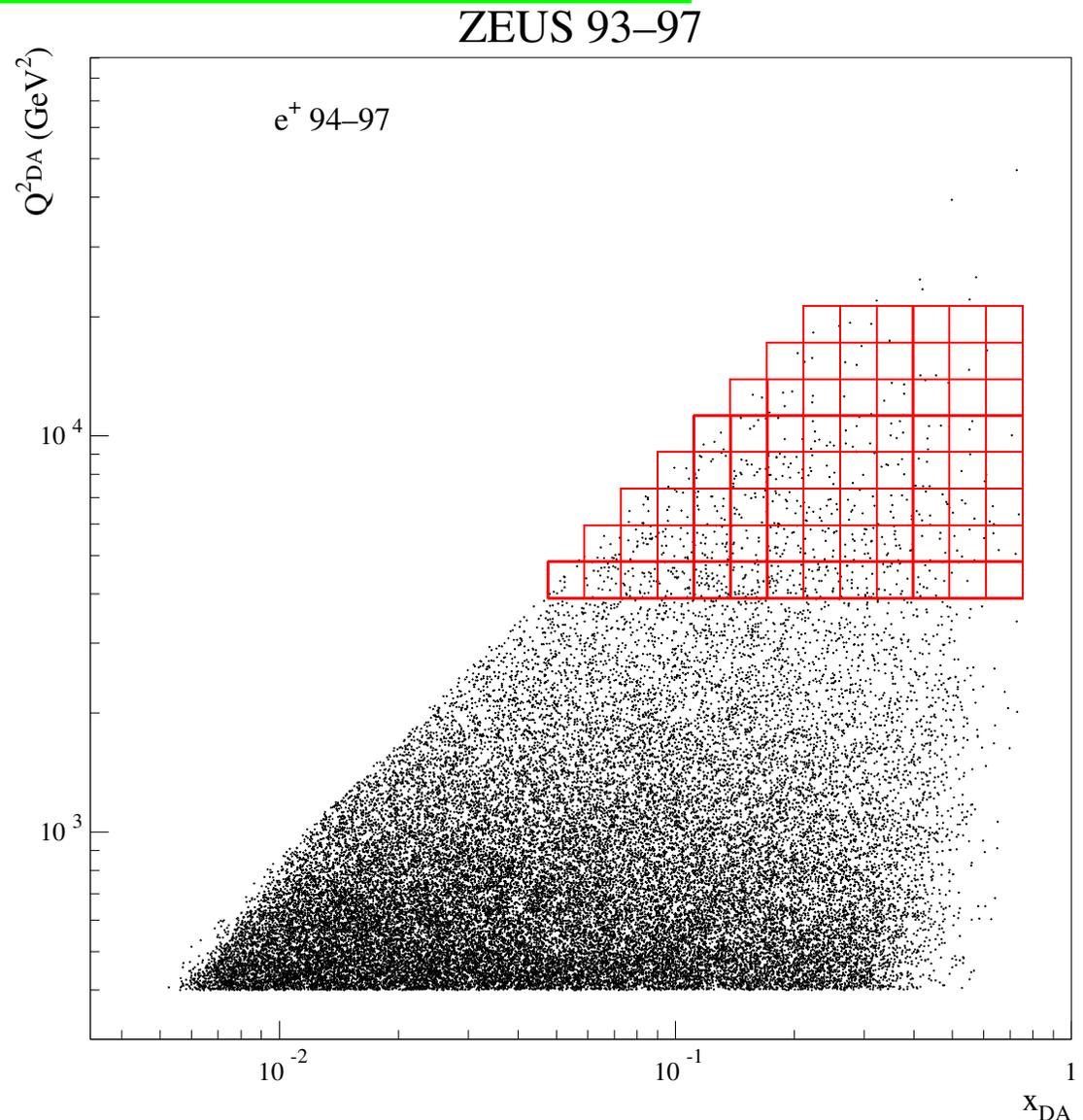
Dane współpracy **ZEUS**  $\Rightarrow$

Liczba przypadków w binach maleje szybko z  $Q^2$

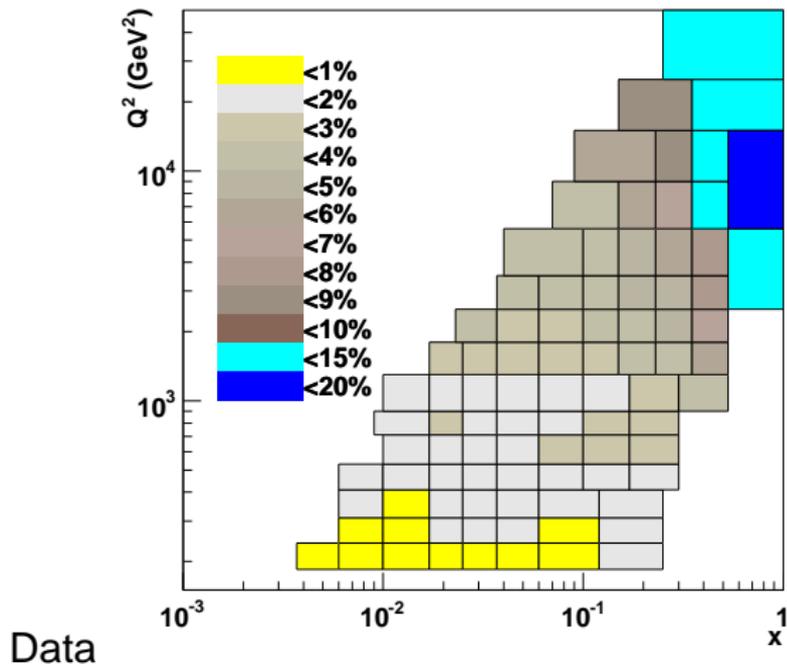
$$\Delta N \sim \frac{1}{Q^4}$$

$\Rightarrow$  pomiar ograniczony do

$$Q^2 \leq 2 \cdot 10^4 \text{ GeV}^2$$



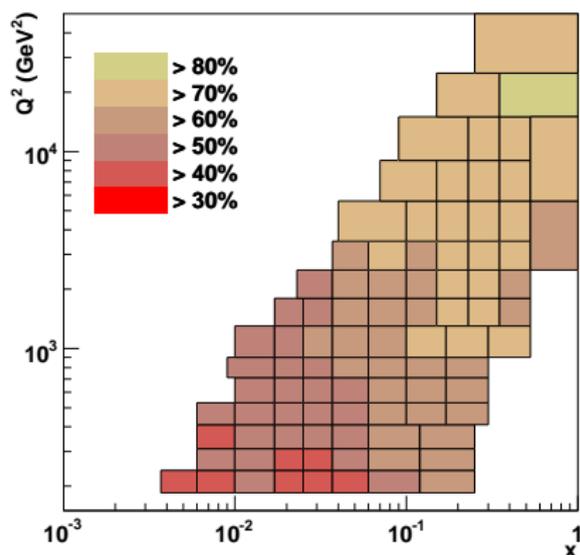
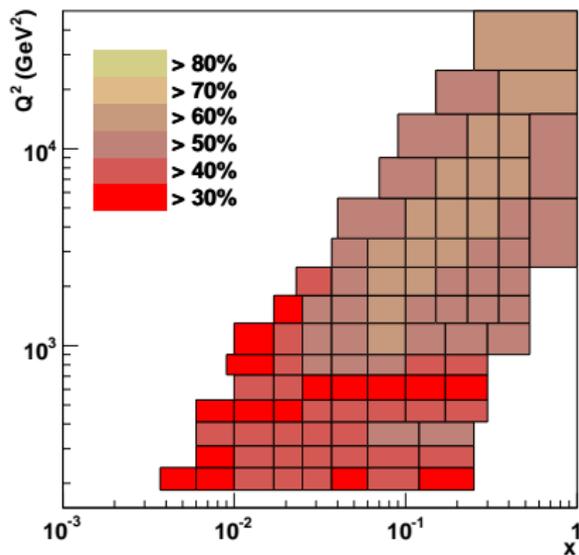
# Statistical Error in Bins used for $d^2\sigma/dxdQ^2$



# Efficiency and Purity in $d^2\sigma/dxdQ^2$

$$\text{Efficiency} = \frac{\text{Generated \& Accepted}}{\text{Generated}}$$

$$\text{Purity} = \frac{\text{Generated \& Accepted}}{\text{Accepted}}$$

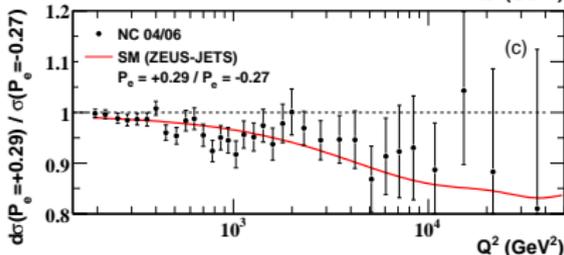
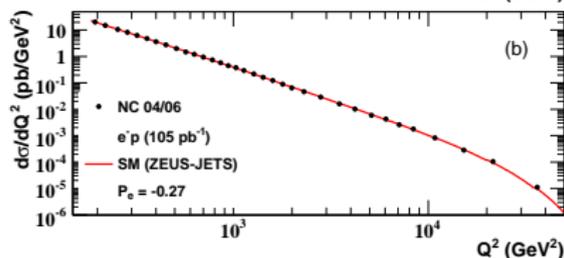
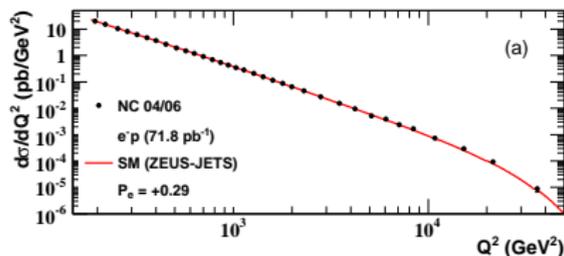


# Unfolding Cross Sections

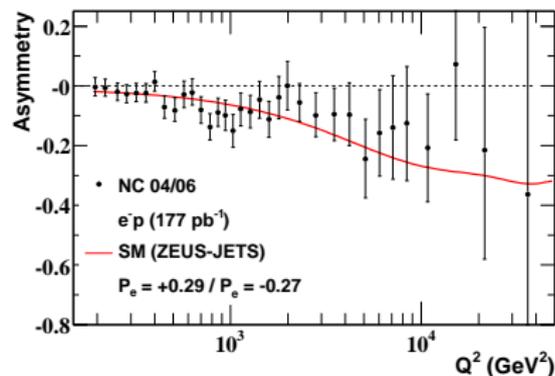
Cross sections extracted using:

- $\frac{d\sigma}{dQ^2} \Big|_{Q_0^2} = \frac{(N_{DATA} - N_{BG})}{N_{MC}} \frac{d\sigma}{dQ^2} \Big|_{Q_0^2}^{theory}$
- With Born-level unpolarised MC and theory values
- See backup for bin selection (based on HERA I binning)
  - Finer in  $d\sigma/dQ^2$
  - Higher/lower bins in  $d\sigma/dx$ ,  $d\sigma/dy$
  - Keep same for reduced cross sections

$$d\sigma/dQ^2$$



- $\chi^2$  test for all ratio points:
- +ve  $P_e$  / -ve  $P_e = 1$  case
  - $\chi^2 / \text{ndf} = 83 / 34$
- +ve  $P_e$  / -ve  $P_e = \text{SM}$  case
  - $\chi^2 / \text{ndf} = 28 / 34$



# Wyznaczanie funkcji struktury

Liczba mierzonych przypadków decyduje o błędzie statystycznym wyznaczonych wartości  $F_2(x, Q^2)$ :

$$\frac{\sigma_{F_2}^{stat}}{F_2} = \frac{1}{\sqrt{\Delta N}}$$

Błędy statystyczne dominują przy dużych  $Q^2$ , przy małych  $Q^2$  są zaniedbywalne.

Błąd systematyczny pomiaru wynika z **niepewności**:

- poprawek teoretycznych  $\delta_L$ ,  $\delta_Z$  i  $\delta_{rad}$
- pomiaru świetności  $\mathcal{L}_{int}$
- wyznaczenia poprawek  $\mathcal{E}$  i  $\mathcal{A}$   
(niepewności związane z symulacją Monte Carlo badanego procesu i działania detektora)

Błędy systematyczne dominują przy małych  $Q^2$ .

Na ogół są na poziomie kilku % (obecne pomiary w HERA)

# Błędy systematyczne

Ocena błędów systematycznych jest często bardzo trudna.

Nie ma jednoznacznego, uniwersalnego przepisu.

Powszechnie stosowane podejścia:

- zmiana parametrów detektora w symulacji (skala energii, rezolucja)
- zmiana cięć (w symulacji i w danych)

jeśli MC jest poprawne wynik nie powinien się zmienić

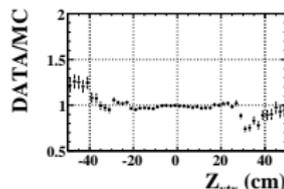
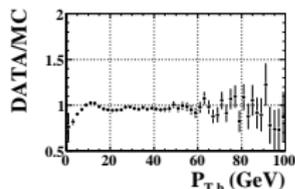
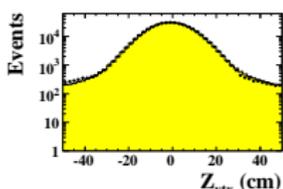
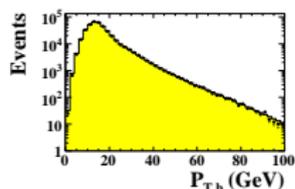
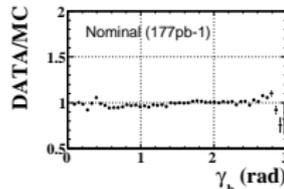
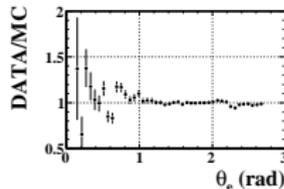
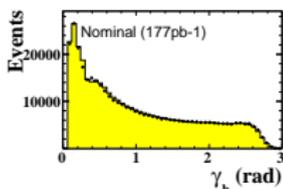
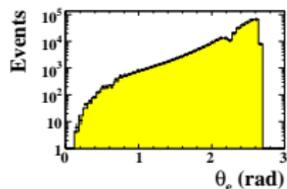
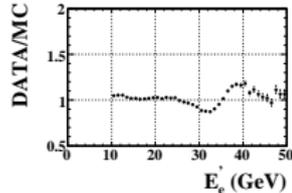
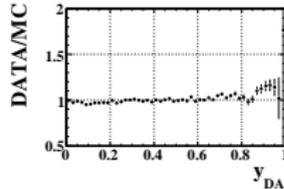
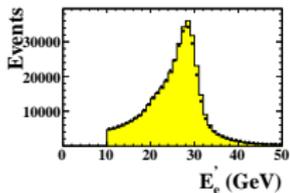
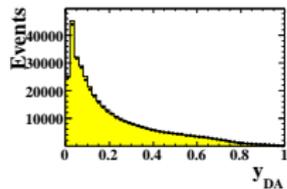
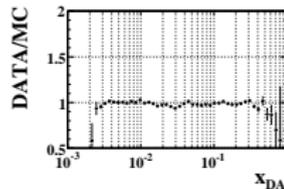
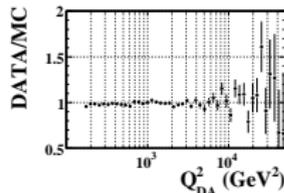
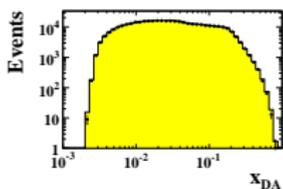
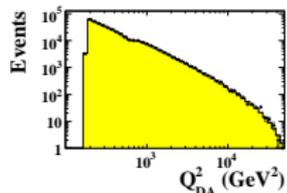
- zmiana parametrów/modelu symulacji (np. rozwoju kaskad czy kaskady partonowej czy fragmentacji; tylko symulacja)
- poszukiwanie rozbieżności między danymi i symulacją (ich wielkość można przyjąć jako oszacowanie błędu systematycznego symulacji)

Błędy systematyczne w danym binie dodajemy "w kwadratach".

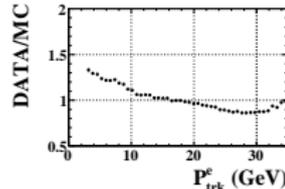
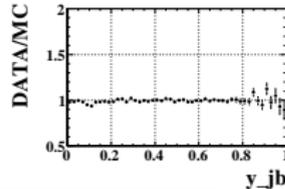
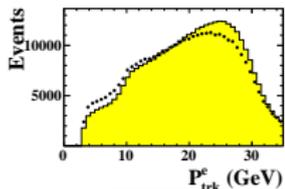
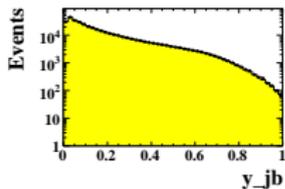
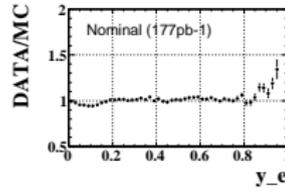
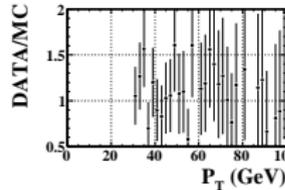
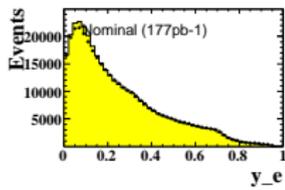
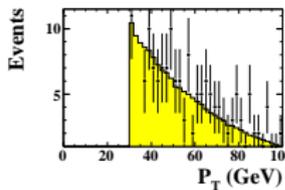
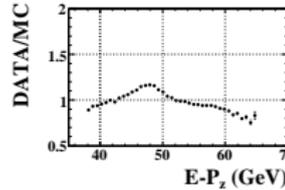
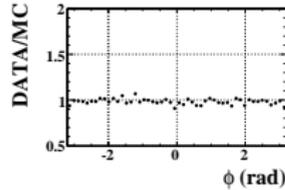
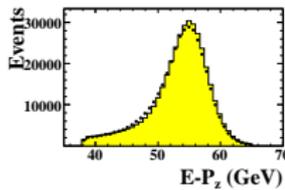
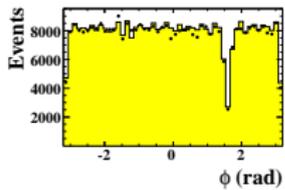
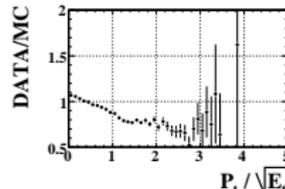
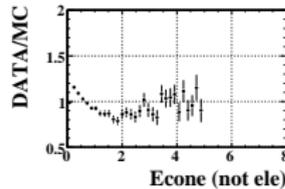
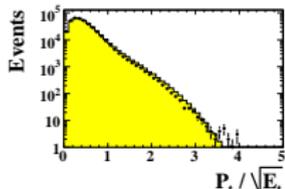
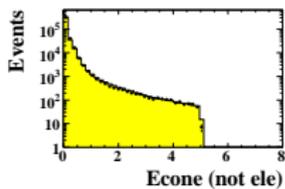
Zwiększając liczbę przyczynków możemy je dowolnie zwiększyć, trzeba zachować umiar !

Pomiędzy binami są skorelowane (czasami silnie).

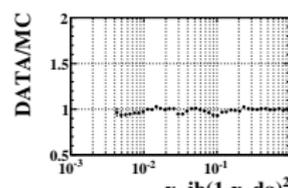
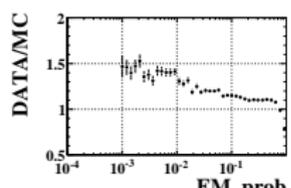
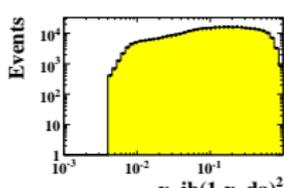
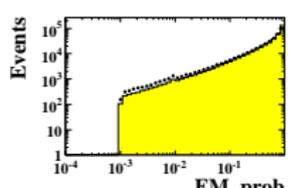
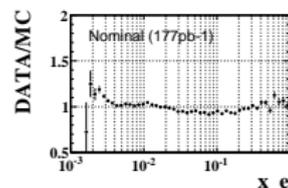
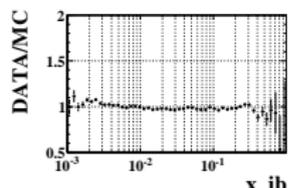
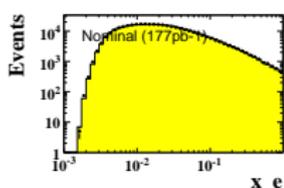
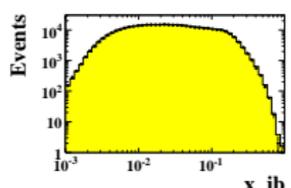
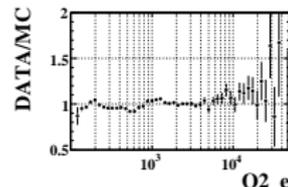
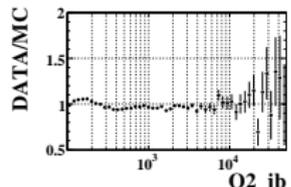
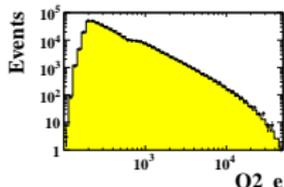
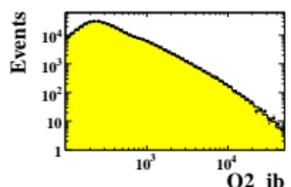
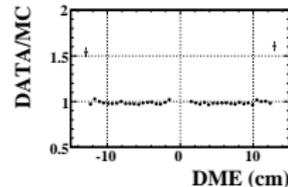
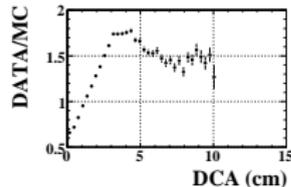
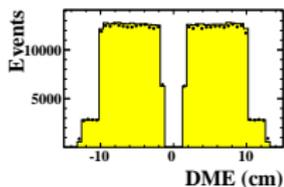
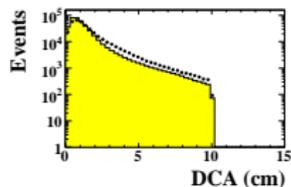
# Control Plots



# Control Plots



# Control Plots

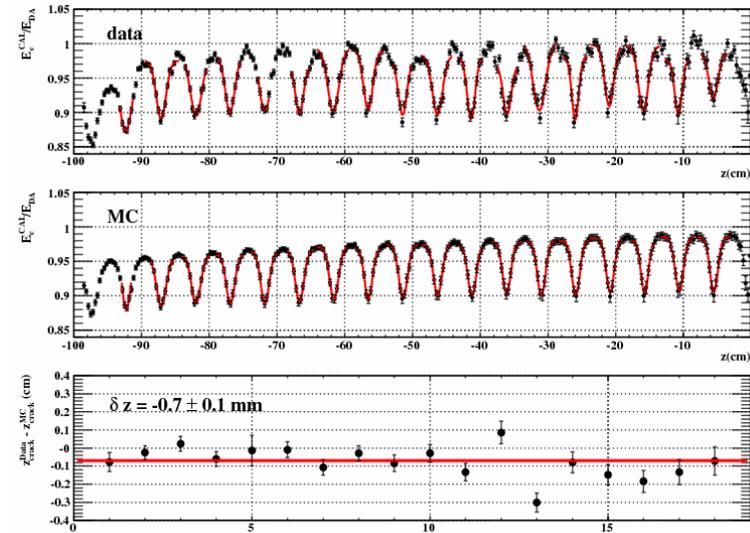


# CAL alignment with respect to CTD

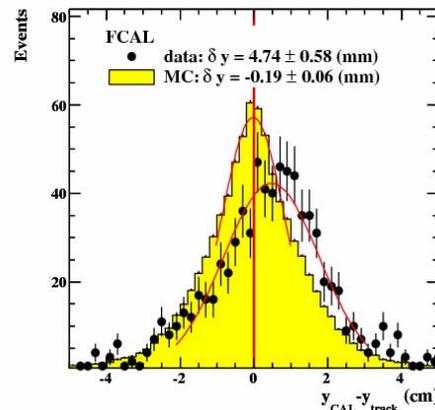
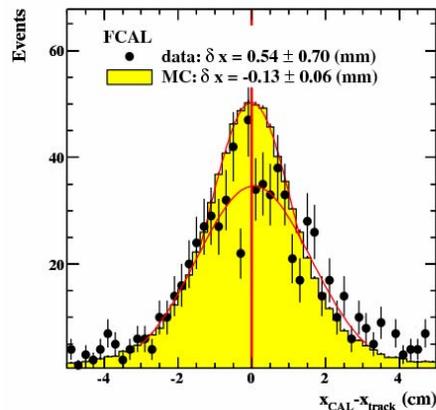
Stat error only.

	RHES left	RHES right
$\delta \phi$	$+1.6 \pm 0.1 \text{ mrad}$	$+0.9 \pm 0.1 \text{ mrad}$
$\delta z$	$+2.0 \pm 0.2 \text{ mm}$	$-0.9 \pm 0.2 \text{ mm}$
$\delta x$	<u><math>+1.9 \pm 0.1 \text{ mm}</math></u>	<u><math>-1.7 \pm 0.1 \text{ mm}</math></u>
$\delta y$	<u><math>+1.4 \pm 0.1 \text{ mm}</math></u>	<u><math>-1.0 \pm 0.1 \text{ mm}</math></u>

**RCAL** is aligned within **2.0mm** in x and y direction.



**BCAL** is aligned within **1.0mm**.  
(Only z shift is checked.)



FCAL position correction : Shift the e position with -4mm in y for data. (Hadronic system is neglected.)

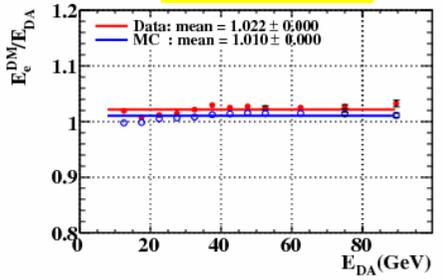
**FCAL** is aligned within **2.0mm**.

For more details, see talk at  $F_L$  review meeting on 09/Feb/2007.

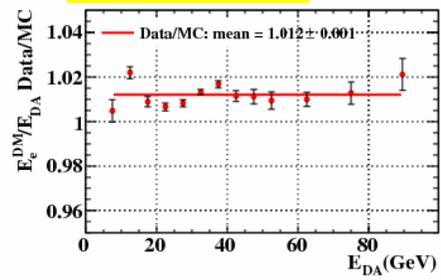
# BCAL electron energy

$E_e$  is corrected by dead-material map and non-uniformity.

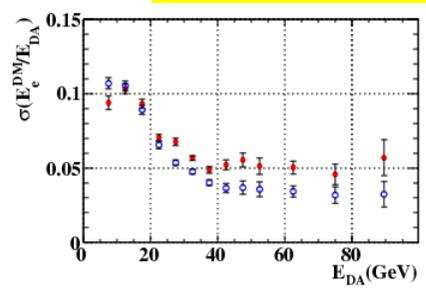
$E_e/E_{DA}$



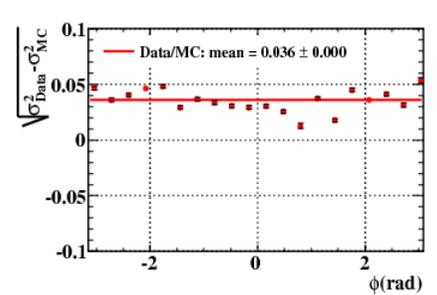
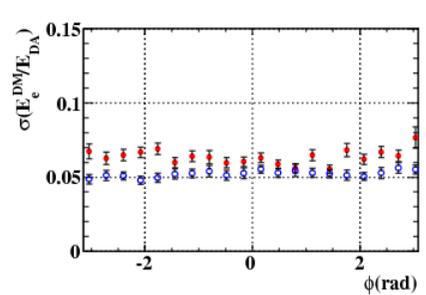
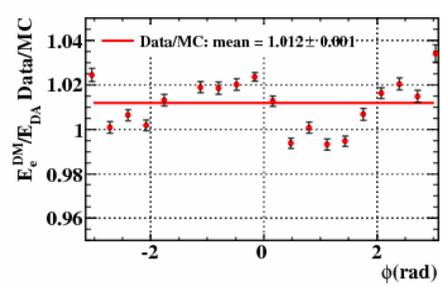
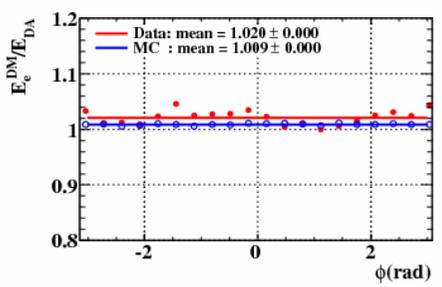
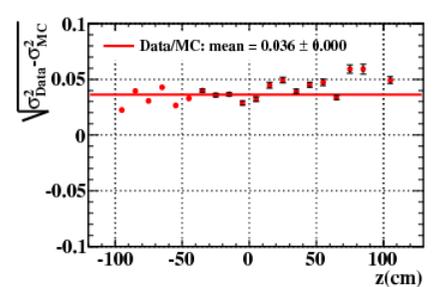
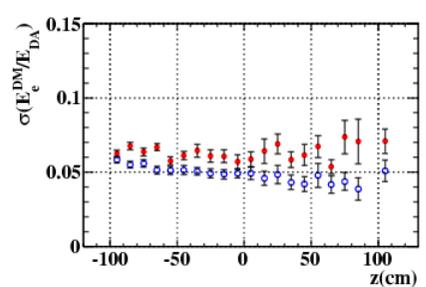
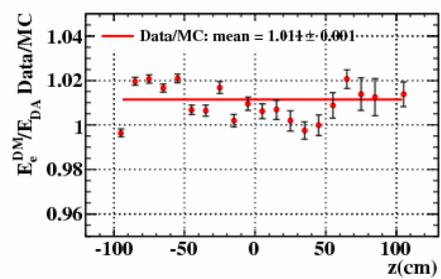
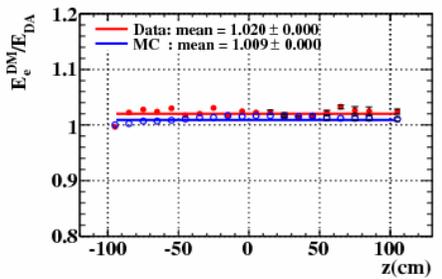
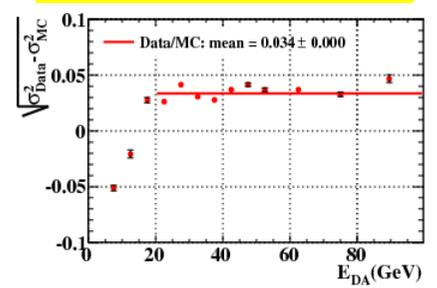
Data/MC



$\sigma(E_e/E_{DA})$



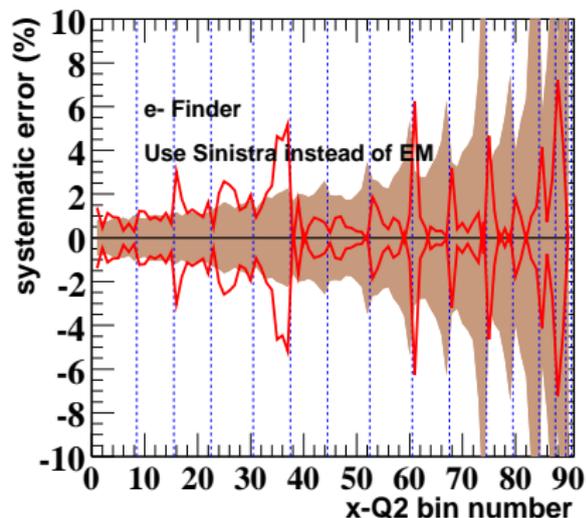
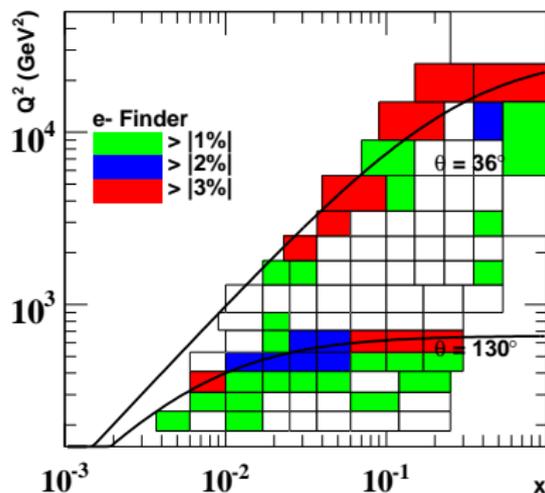
$\sqrt{\sigma_{Data}^2 - \sigma_{MC}^2}$



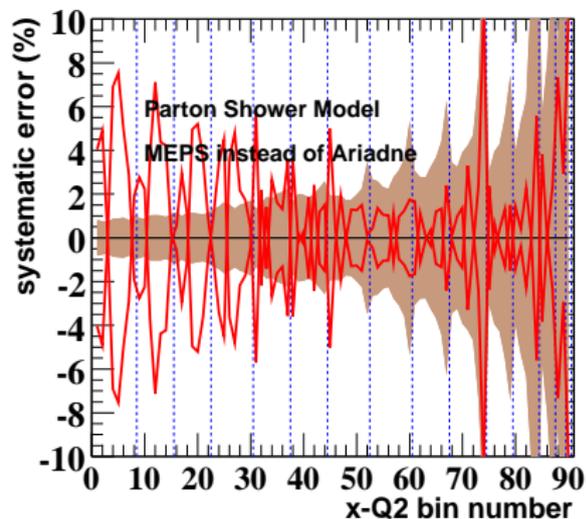
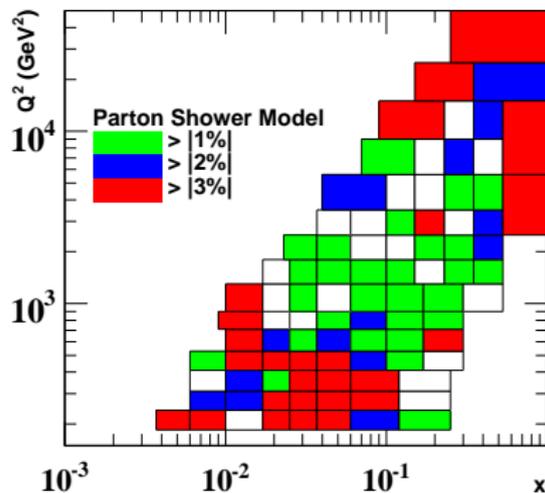
Scale uncertainty is 2%.

Smearing factor is 3.4%.

# Systematics in $d^2\sigma/dx dQ^2$ for EM $\rightarrow$ SINISTRA

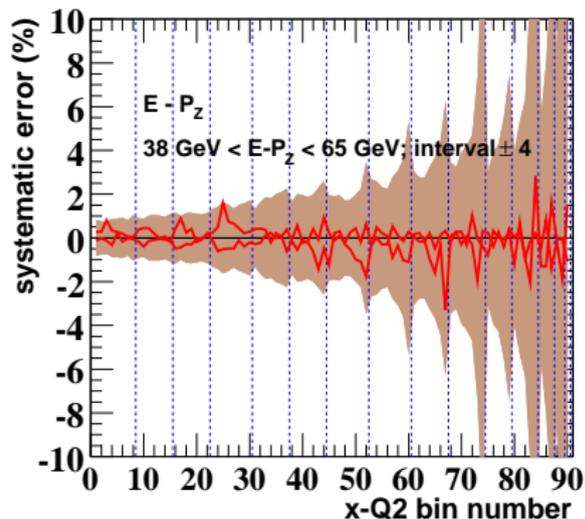
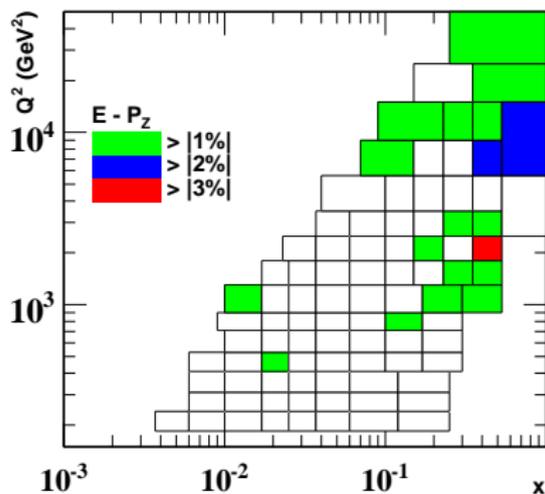


# Largest Systematics in Dbl Diff bins - MEPS

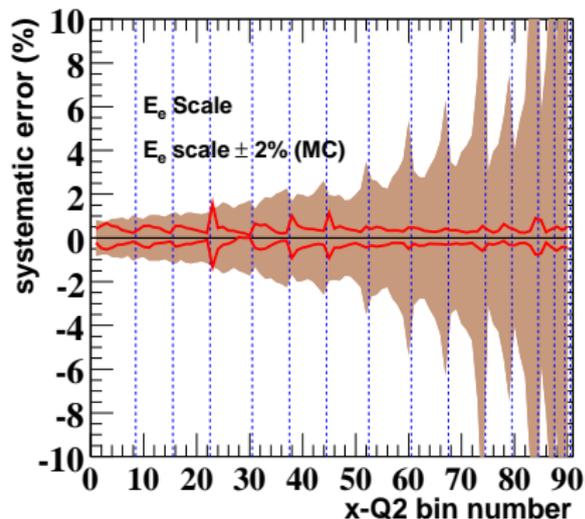
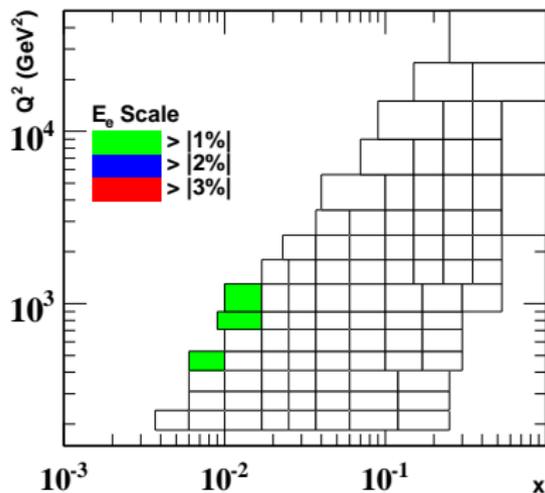


■ Dominates low  $Q^2$  region

# Largest Systematics in Dbl Diff bins - $E - P_Z$



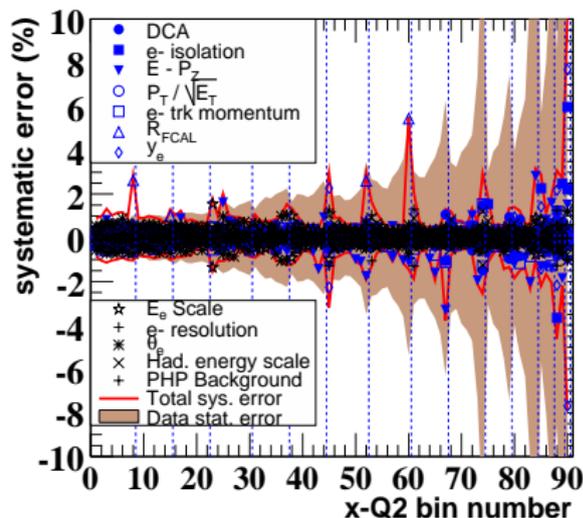
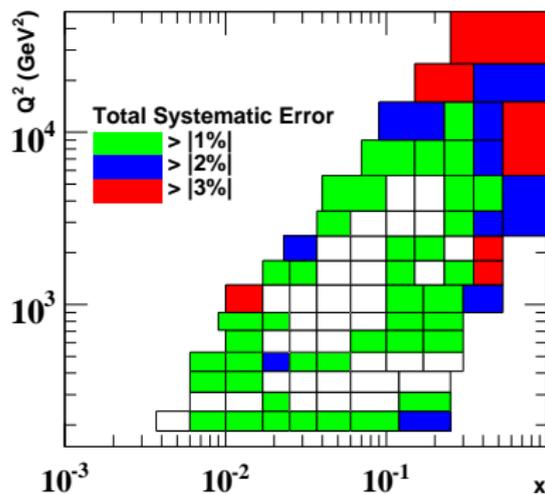
# Largest Systematics in Dbl Diff bins - $E_e$ scale



# Systematic Checks

- $DCA > 10 \text{ cm}; 8\text{cm}$
- $E_{note}^{cone} < 5 \text{ GeV}; \pm 2 \text{ GeV}$
- $38 \text{ GeV} < E - P_Z < 65 \text{ GeV};$   
interval  $\pm 4 \text{ GeV}$
- $P_T / \sqrt{E_T} < 4\sqrt{\text{GeV}}; \pm 1\sqrt{\text{GeV}}$
- $P_{trk}^e > 3 \text{ GeV}; \pm 1 \text{ GeV}$
- $R_{FCAL} > 18 \text{ cm}; \pm 3 \text{ cm}$
- $y_e < 0.95; 0.9$
- $E_e \text{ scale } \pm 2\% \text{ (MC)}$
- $E_e \text{ smeared } \pm 1\% \text{ (MC)}$
- $\theta_e \pm 1\text{mrad (MC)}$
- $E_h \text{ scale } \pm 3\% \text{ (MC)}$
- PHP MC normalization  $\pm 100\%$
- Checks not used in error calculations:
  - ARIADNE  $\rightarrow$  MEPS
  - EM  $\rightarrow$  Sinistra
  - CorAndCut  $\rightarrow$  ZUFOs

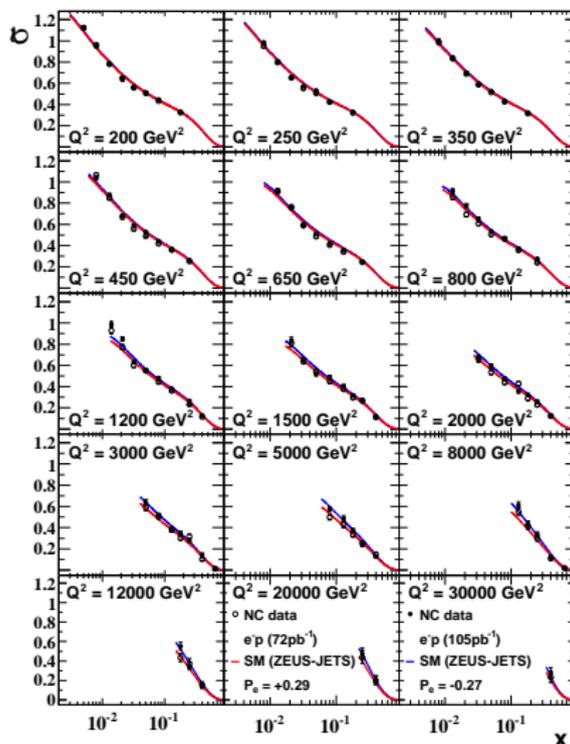
# Systematics in $d^2\sigma/dxdQ^2$



# Reduced Cross Sections

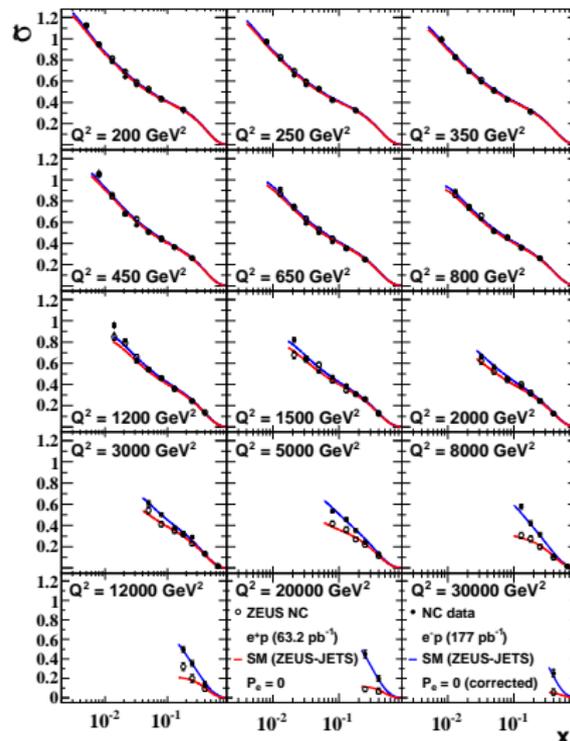
LH and RH separate

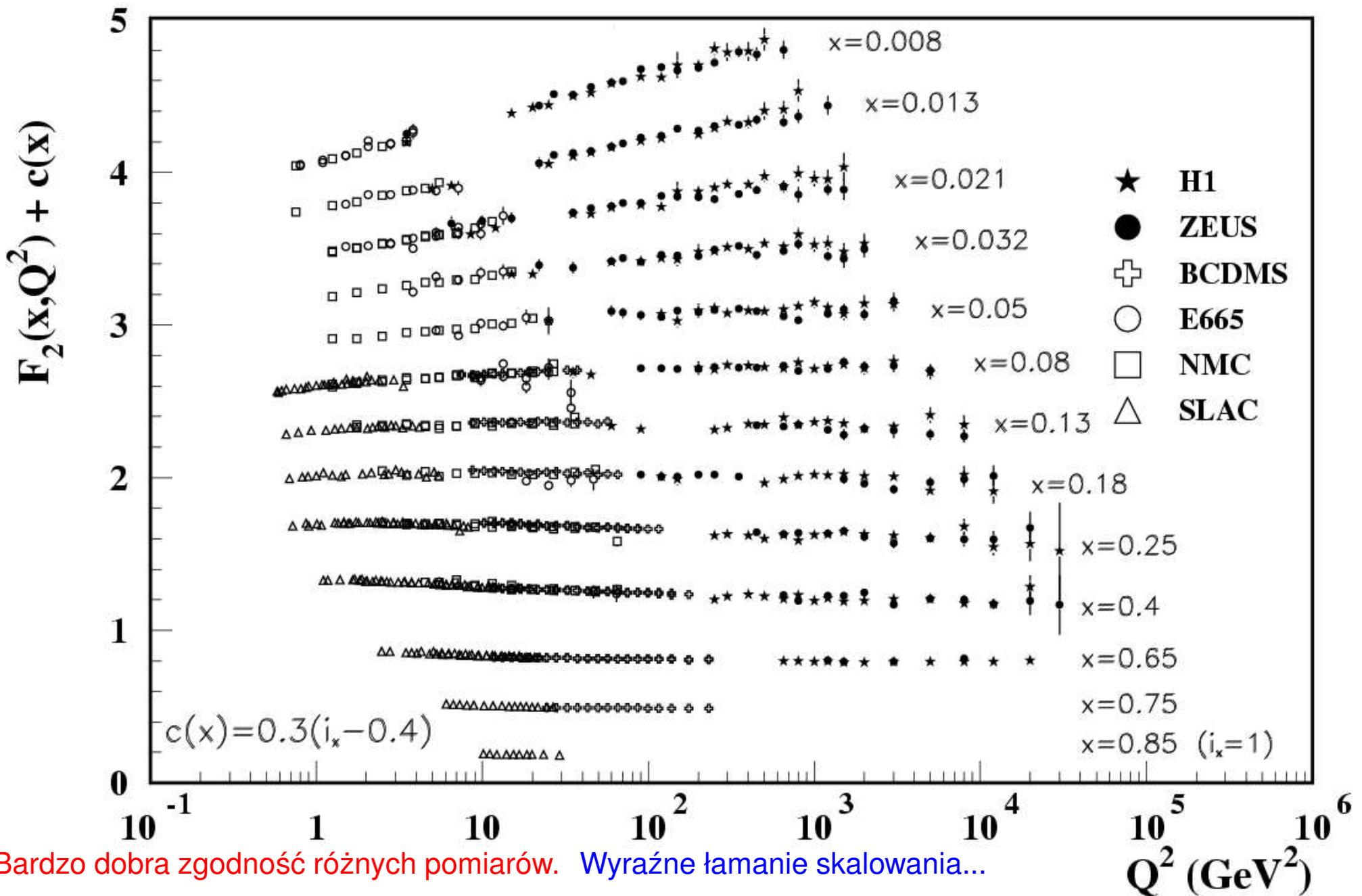
ZEUS



Entire data set

ZEUS



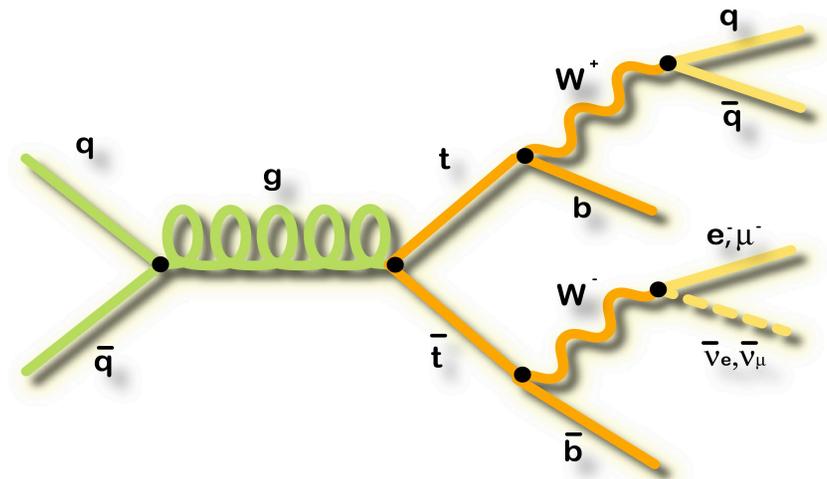
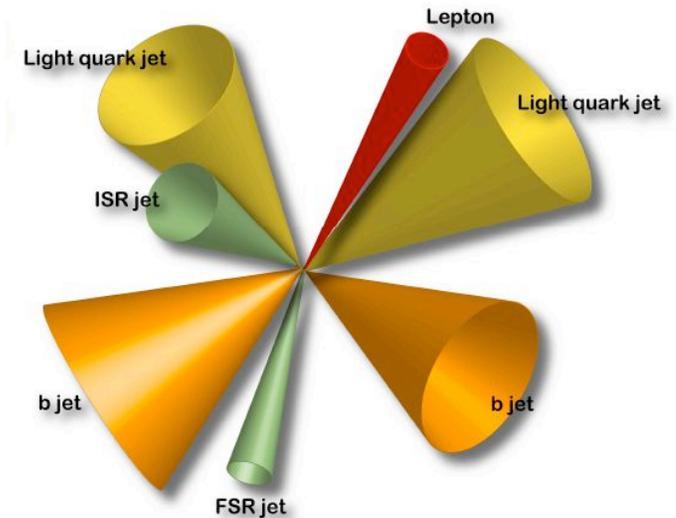


Bardzo dobra zgodność różnych pomiarów. Wyraźne łamanie skalowania...

# Top Mass Measurement:

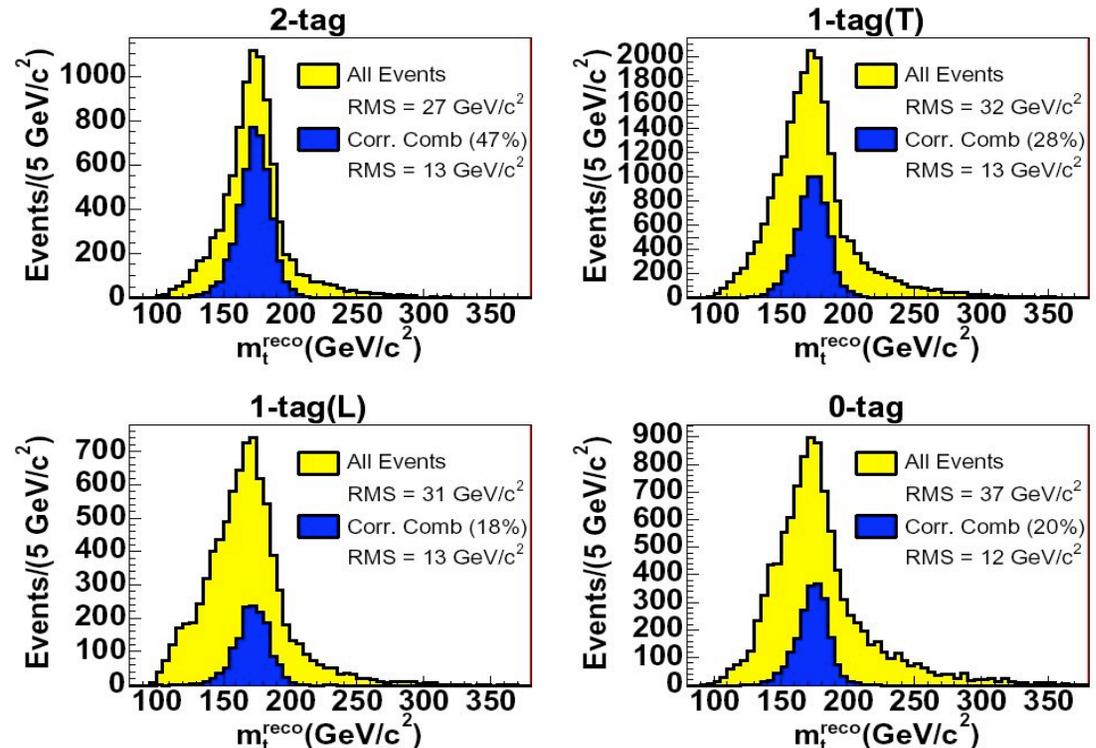
## $t\bar{t} \rightarrow (b\ell\nu)(bqq)$

- 4 jets, 1 lepton and missing  $E_T$ 
  - Which jet belongs to what?
  - Combinatorics!
- B-tagging helps:
  - 2 b-tags  $\Rightarrow$  2 combinations
  - 1 b-tag  $\Rightarrow$  6 combinations
  - 0 b-tags  $\Rightarrow$  12 combinations
- Two Strategies:
  - Template method:
    - Uses “best” combination
    - Chi2 fit requires  $m(t) = m(\bar{t})$
  - Matrix Element method:
    - Uses all combinations
    - Assign probability depending on kinematic consistency with top



# Top Mass Determination

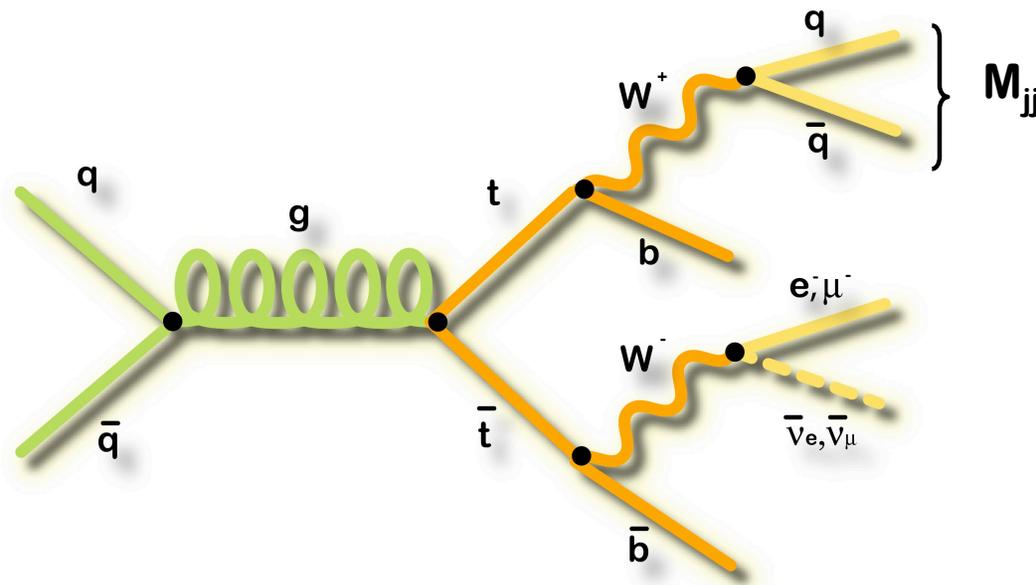
- Inputs:
  - Jet 4-vectors
  - Lepton 4-vector
  - Remaining transverse energy,  $p_{T,UE}$ :
    - $p_{T,v} = -(p_{T,l} + p_{T,UE} + \sum p_{T,jet})$
- Constraints:
  - $M(l\nu) = M_W$
  - $M(qq) = M_W$
  - $M(t) = M(\bar{t})$
- Unknown:
  - Neutrino  $p_z$
- 1 unknown, 3 constraints:
  - Overconstrained
  - Can measure  $M(t)$  for each event:  $m_t^{reco}$



Selecting correct combination  
20-50% of the time

# *In-situ* Measurement of JES

- Additionally, use  $W \rightarrow jj$  mass resonance ( $M_{jj}$ ) to measure the jet energy scale (JES) uncertainty

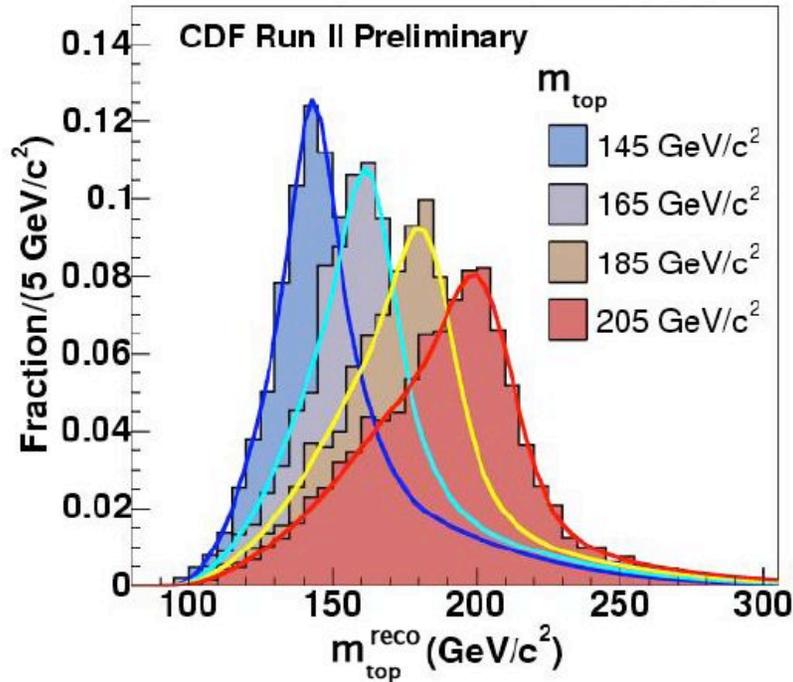


2D fit of the invariant mass of the non-b-jets and the top mass:

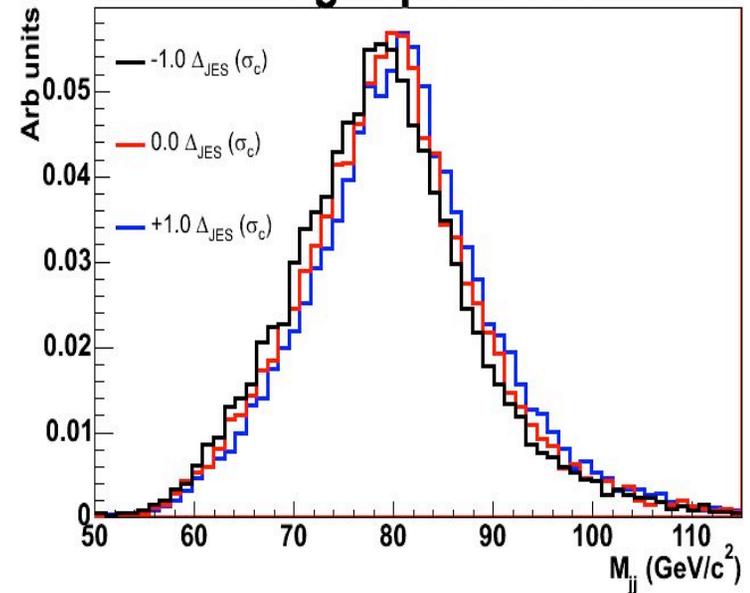
$$\text{JES} \propto M(jj) - 80.4 \text{ GeV}/c^2$$

Measurement of JES scales directly with data statistics

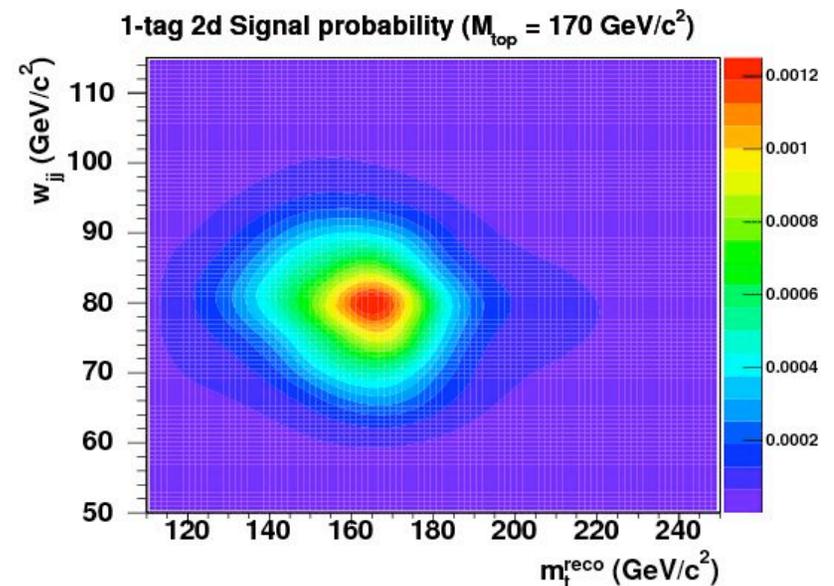
# Top Mass Templates



## 1-tag Lepton+Jets

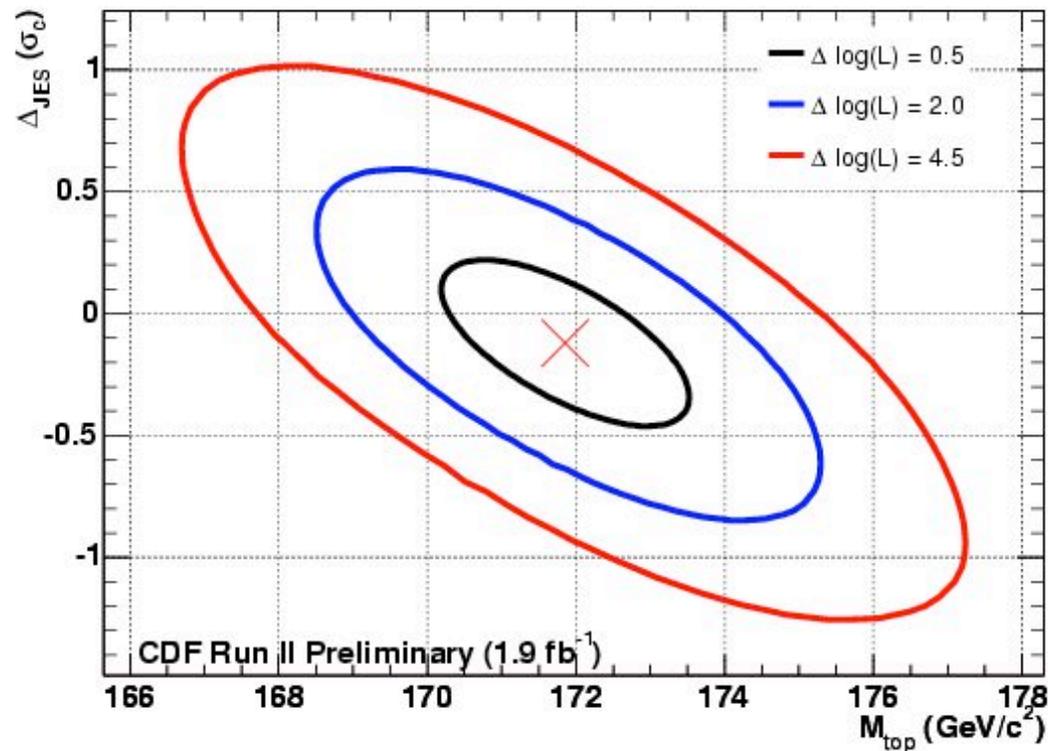


- Fit to those templates for
  - Top mass
  - Jet Energy Scale



# Template Analysis Results on $m_{\text{top}}$

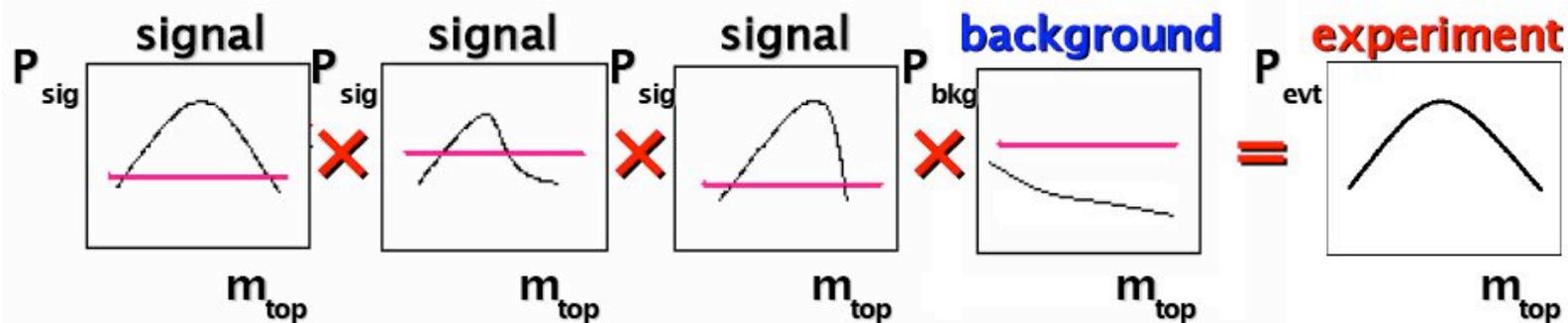
- Using 344 lepton+jets and 144 dilepton candidate events in  $1.9 \text{ fb}^{-1}$
- Using in-situ JES calibration results in factor four improvement on JES



$$m_{\text{top}} = 171.9 \pm 1.7 \text{ (stat.+JES)} \pm 1.0 = 171.6 \pm 2.0 \text{ GeV}/c^2$$

# “Matrix Element Method”

- Construct probability density function as function of  $m_{\text{top}}$  for each event
- Multiply those probabilities of all events

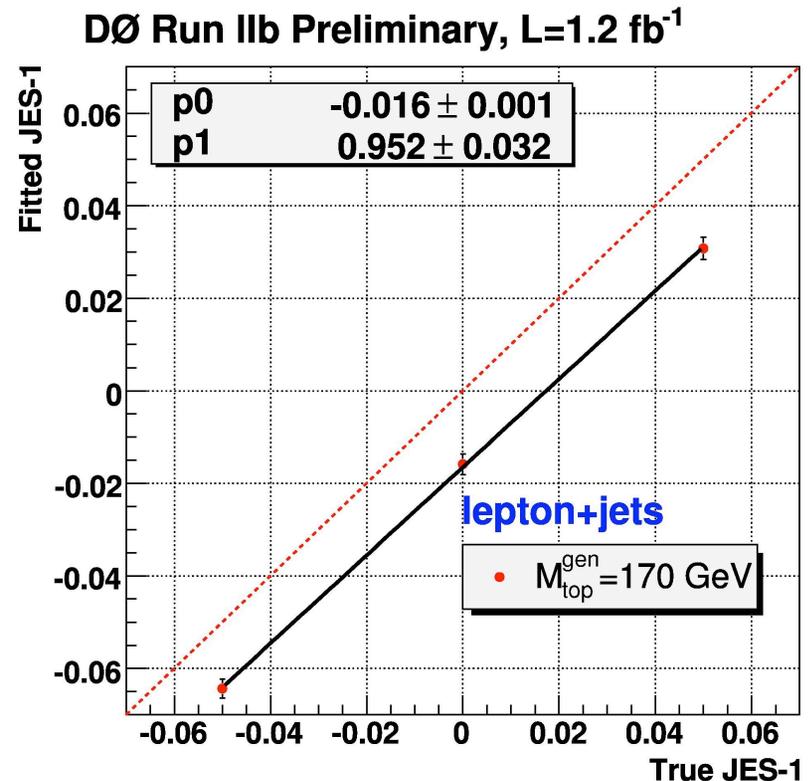
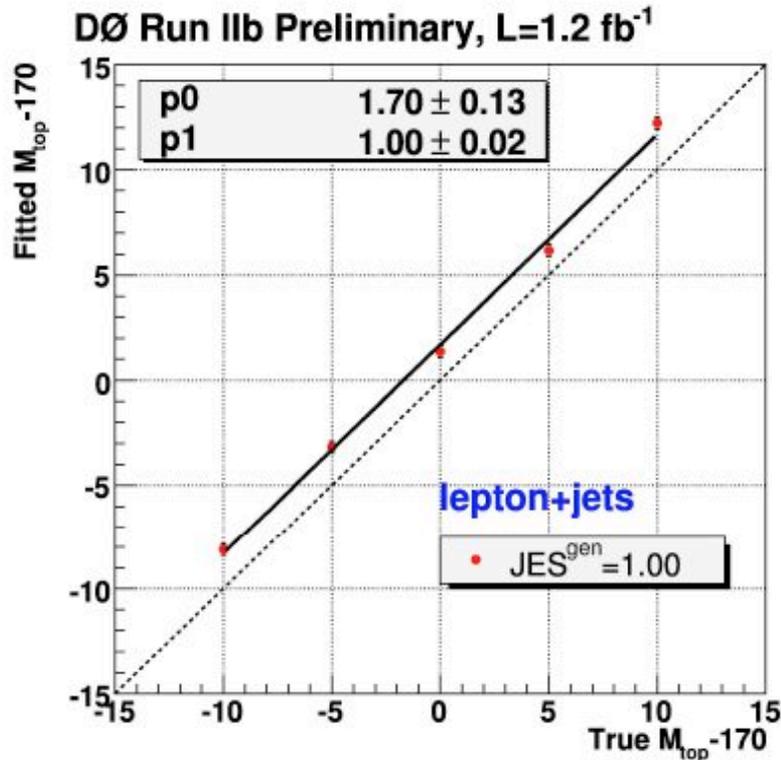


$$P_{\text{sig}}(x; m_{\text{top}}, JES) = \underbrace{Acc(x)}_{\text{Acceptance (selection, trigger,...)}} \times \frac{1}{\sigma} \int d^n \underbrace{\sigma(y; m_{\text{top}})}_{\text{LO-Matrix element x phase space}} \underbrace{dq_1 dq_2 f(q_1) f(q_2)}_{\text{PDF's}} \underbrace{W(x, y; JES)}_{\text{Transfer Functions (Probability to measure x when y was produced)}}$$

- **maximum Likelihood fit:**

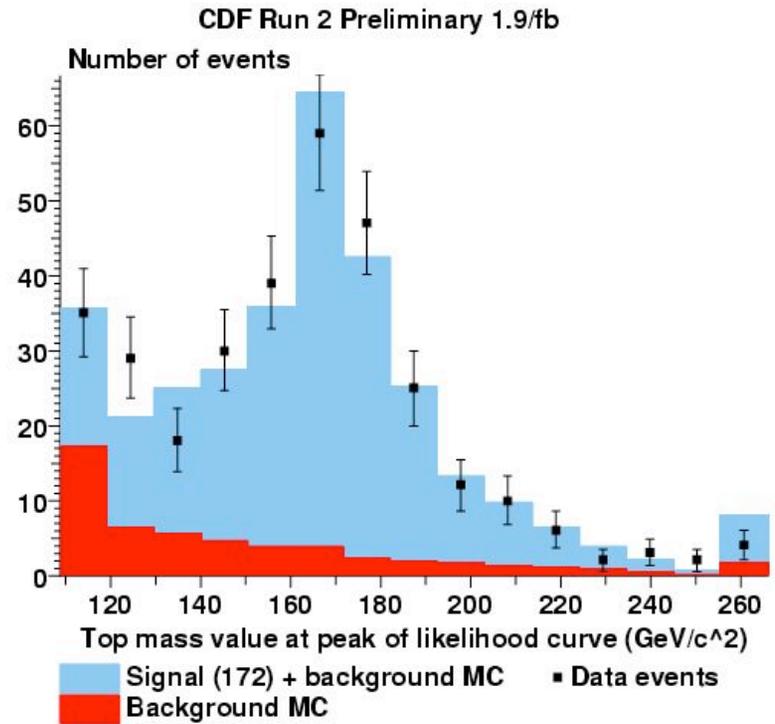
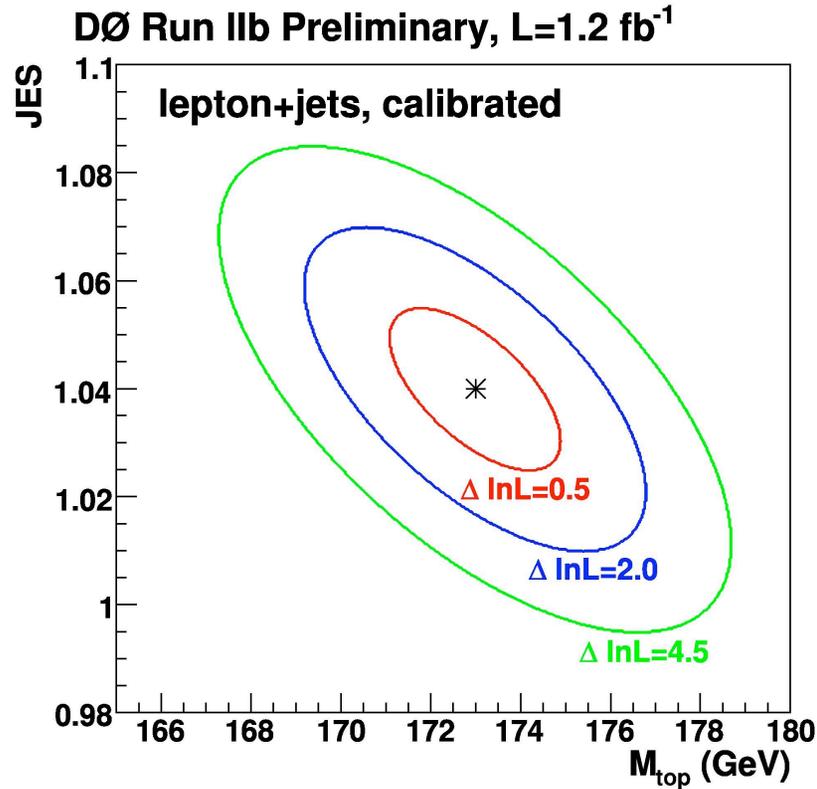
$$L(x_1, \dots, x_n; m_{\text{top}}, JES, f_{\text{top}}) = \prod_{i=1}^n P_{\text{evt}}(x_i; m_{\text{top}}, JES, f_{\text{top}})$$

# Check you get the right answer



- Run “Pseudo-Experiments” on Monte Carlo to see if you get out the mass that was put in
  - Pretend MC is data and run analysis on it N times
- Non-trivial cross check given the complexity of the method
  - If not: derive “calibration curve” from slope and offset

# Matrix Element Top Mass Results



DØ: 2.2 fb<sup>-1</sup>

$$m_{top} = 172.2 \pm 1.0 \text{ (stat)} \pm 1.4 \text{ (syst)} \text{ GeV}$$

**±1.0%**

CDF: 2.9 fb<sup>-1</sup>

$$m_{top} = 172.2 \pm 1.0 \text{ (stat)} \pm 1.3 \text{ (syst)} \text{ GeV}$$

**±1.0%**

# Combining $M_{\text{top}}$ Results

- Excellent results in each channel
  - Dilepton
  - Lepton+jets
  - All-hadronic
- Combine them to improve precision
  - Include Run-I results
  - Account for correlations
- Uncertainty: **1.2 GeV**
  - Dominated by systematic uncertainties

