

## *Neue Daten, verbesserte Theorie - ein Ausblick auf erste QCD Analysen am LHC*

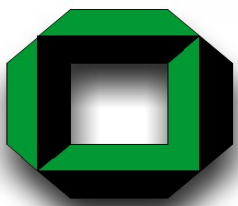
Klaus Rabbertz  
Institut für Experimentelle Kernphysik  
Universität Karlsruhe



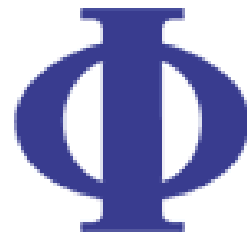
**bmb+f** - Förderschwerpunkt

Elementarteilchenphysik

Großgeräte der physikalischen  
Grundlagenforschung



# Übersicht



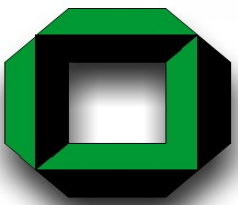
Rückblick ...!

Stand der Dinge

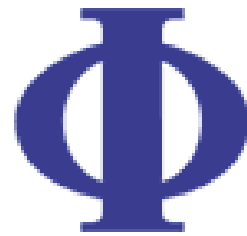
Erste Analysemöglichkeiten

- Underlying Event
- Jets
- PDFs

Ausblick



# Rückblick - SppS



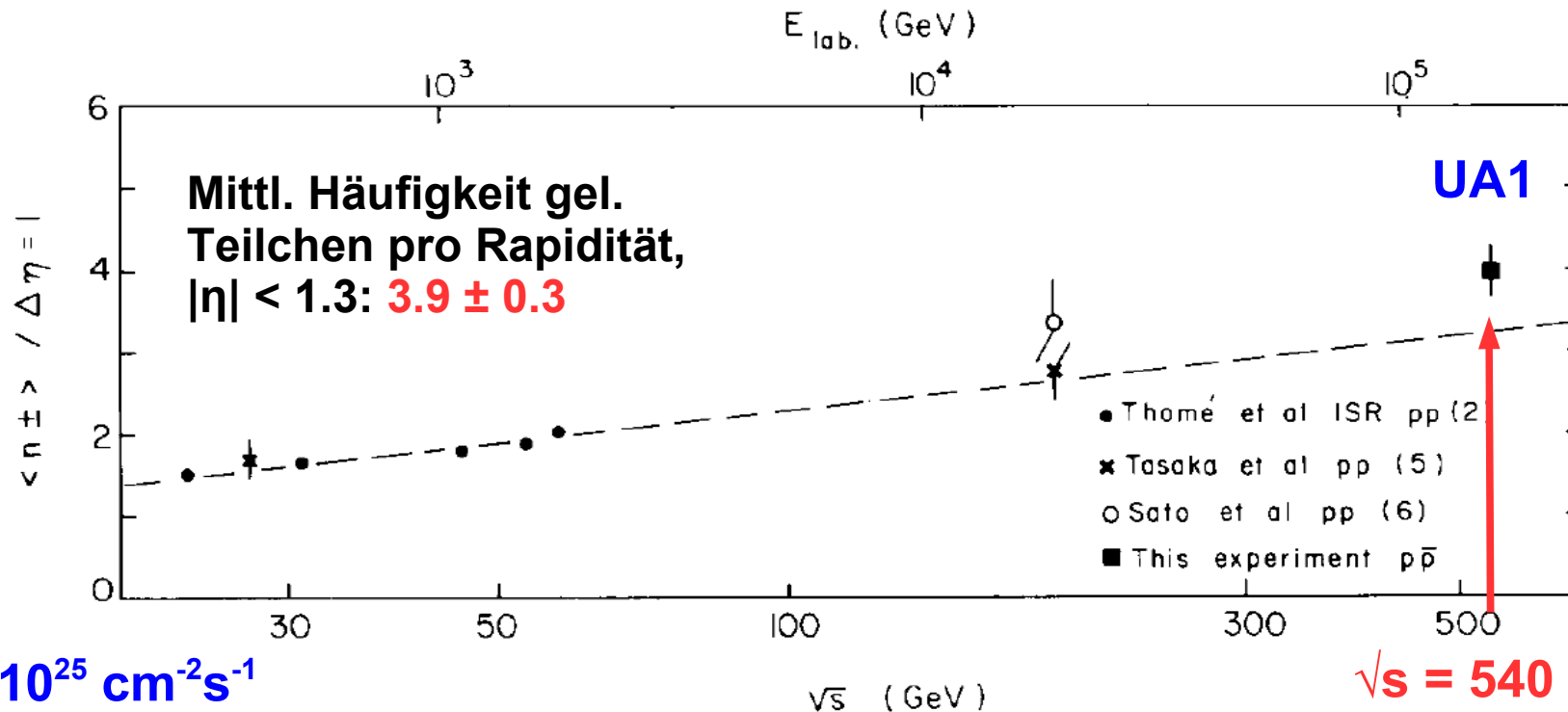
Phys.Lett.Vol.107B, no. 4

Erste UA1 Publikation QCD

17. Dezember 1981

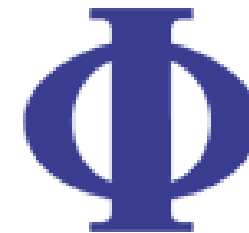
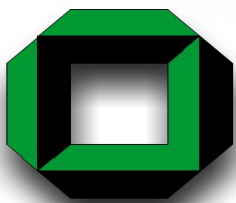
## SOME OBSERVATIONS ON THE FIRST EVENTS SEEN AT THE CERN PROTON-ANTIPROTON COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland



$L_{max} \approx 2 \cdot 10^{25} \text{ cm}^{-2} \text{ s}^{-1}$

$\sqrt{s} = 540 \text{ GeV}$



## ➔ CDF QCD Publikationen:

- 1.  $p_T$  Verteilung gel. Teilchen  
(Phys.Rev.Lett.61:1819,1988.)
- 2. Inkl. Jetwirkungsquerschnitte  
(Phys.Rev.Lett.62:613,1989.)
- 4. Winkelverteilung von Di-Jets  
(Phys.Rev.Lett.62:3020-3023,1989.)

## ➔ D0 QCD Publikationen:

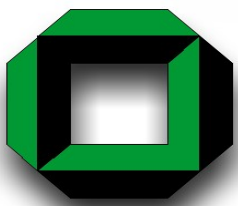
- 3. Rapidity Gaps between Jets  
(Phys.Rev.Lett.72:2332-2336,1994.)
- 42. Di-Jet Winkel  
(Phys.Rev.Lett.80:666-671,1998.)
- 57. Inkl. Jets  
(Phys.Rev.Lett.82:2451-2456,1999. )

## ➔ H1 QCD Publikationen:

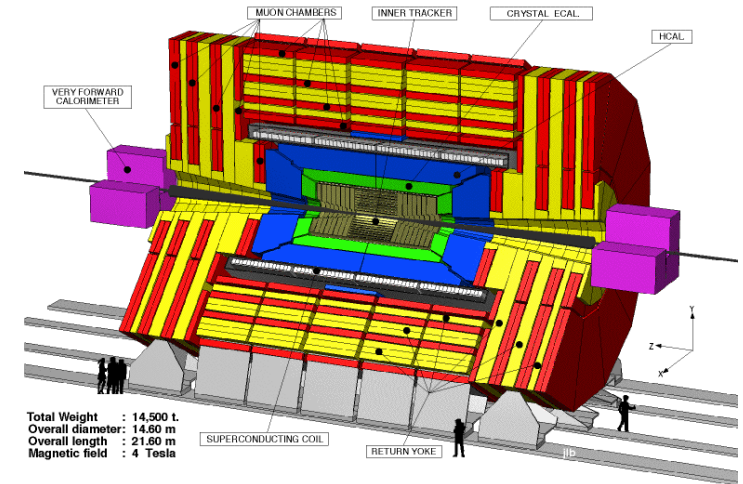
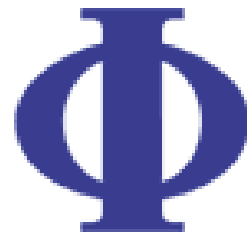
- 1. Photoproduktion  
(Phys.Lett.B297:205-213,1992.)
- 6. Inkl. Jets in Photoprod.  
(Phys.Lett.B314:436-444,1993.)
- 7. Protonstrukturfunktion  
(Nucl.Phys.B407:515-538,1993.)

## ➔ ZEUS QCD Publikationen:

- 1. Photoproduktion  
(Phys.Lett.B293:465-477,1992.)
- 5. Di-Jets in DIS  
(Phys.Lett.B306:158-172,1993.)
- 9. Protonstrukturfunktion  
(Phys.Lett.B316:412-426,1993.)



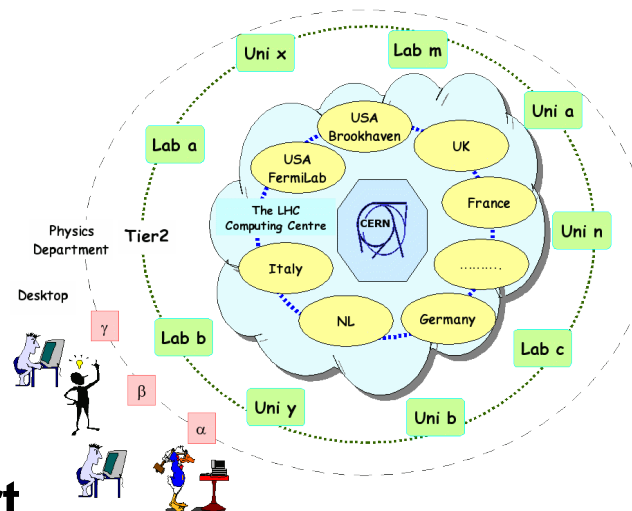
# Die ersten Daten werden ...



- mit einem neu einzustellenden Beschleuniger erzeugt

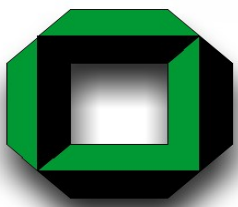
- mit einem noch unverstandenen Detektor aufgenommen

- auf dem Grid analysiert

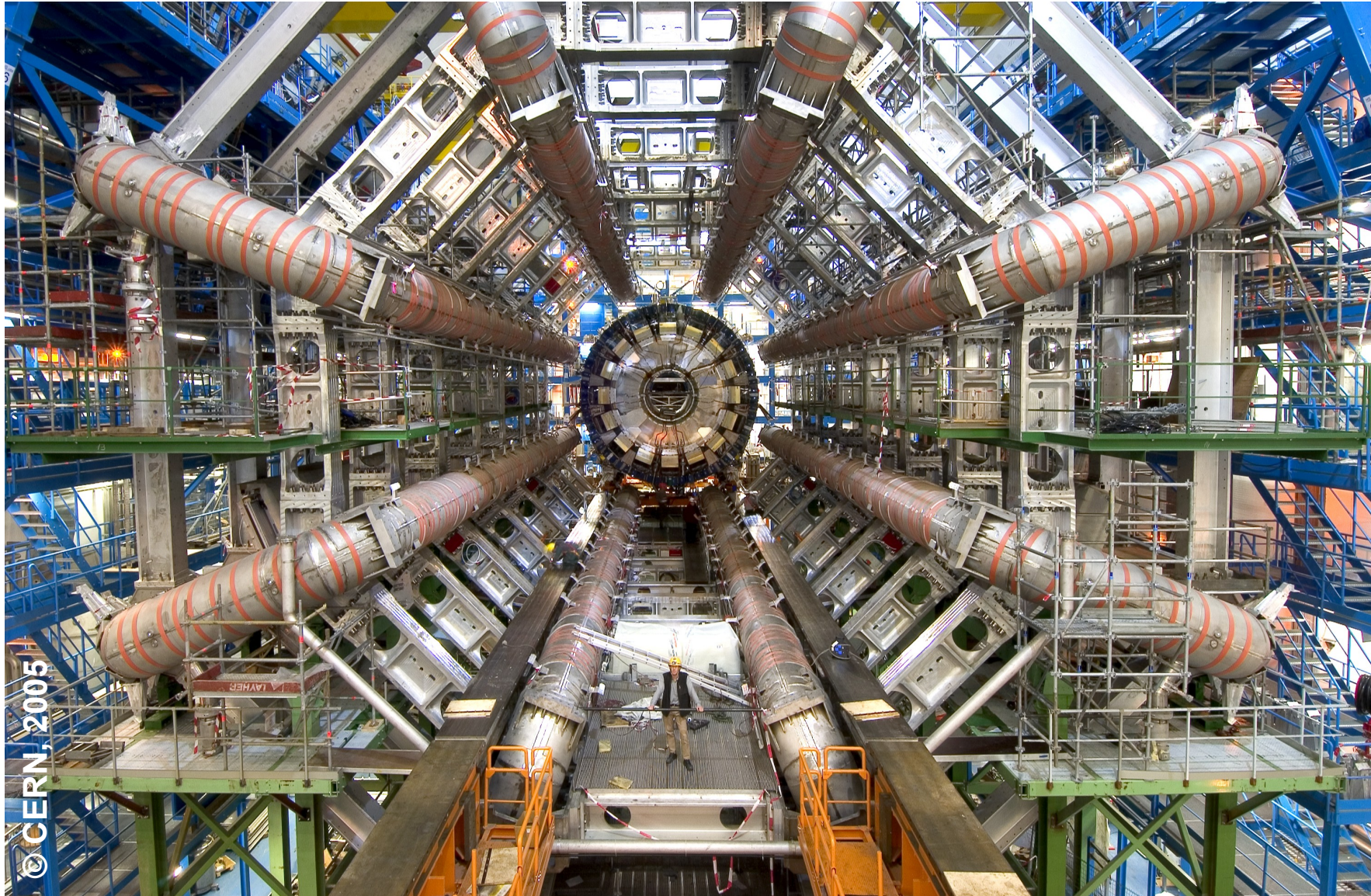
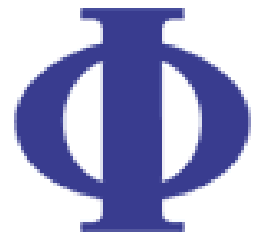


- und wahrscheinlich als erstes als QCD Analysen publiziert ...





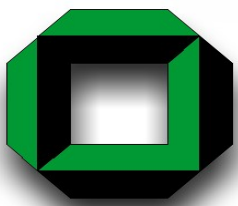
# ATLAS Toroidmagnet



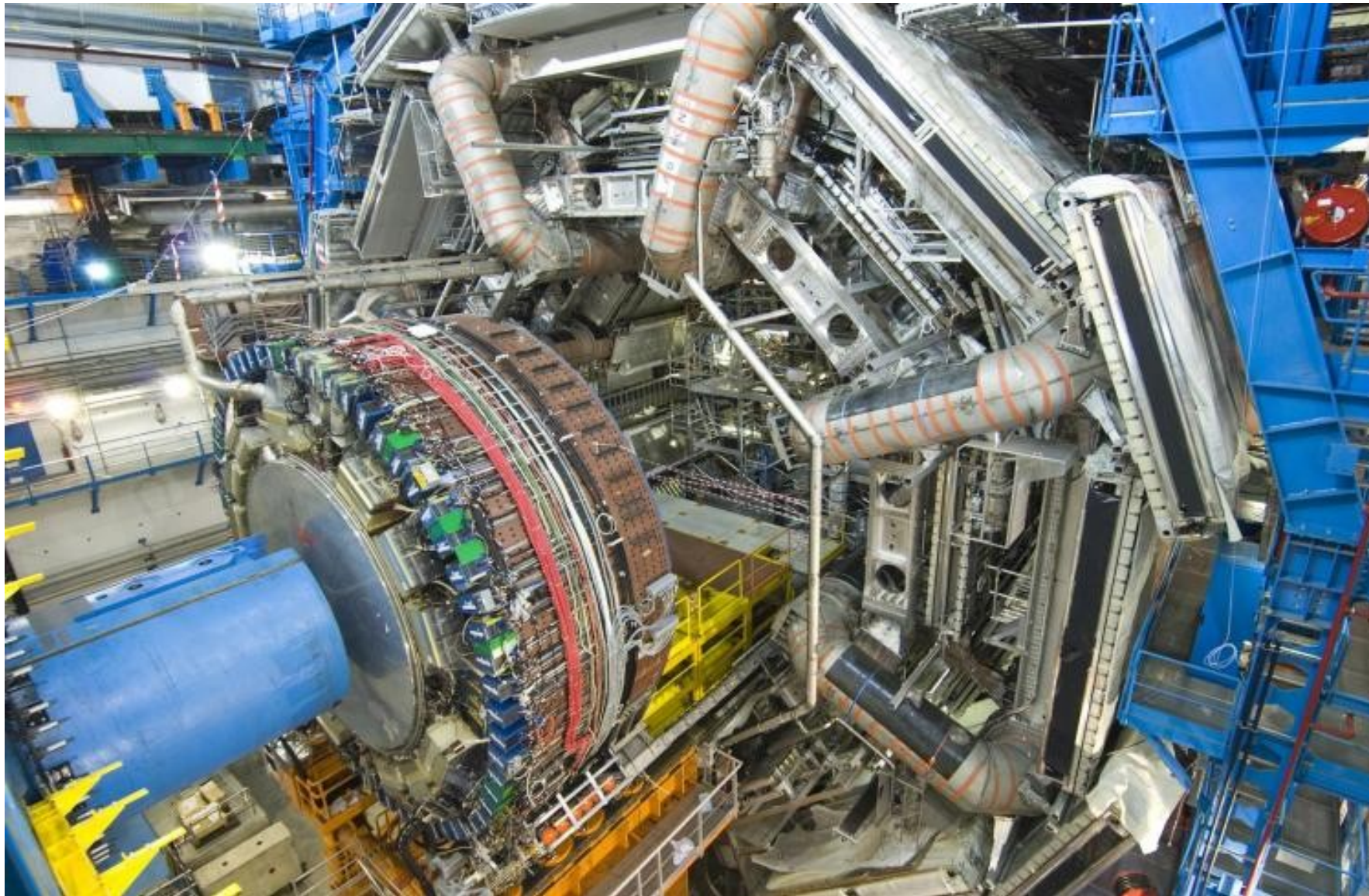
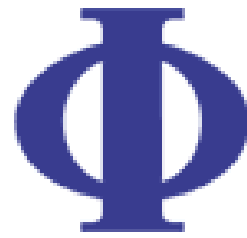
04.11.2005

Gewicht:  
830 t

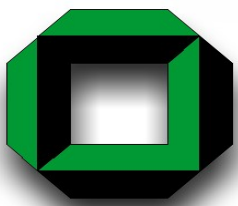
Maße:  
26x20x20m<sup>3</sup>



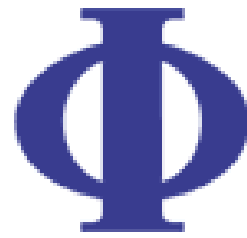
# *ATLAS Toroidmagnet*



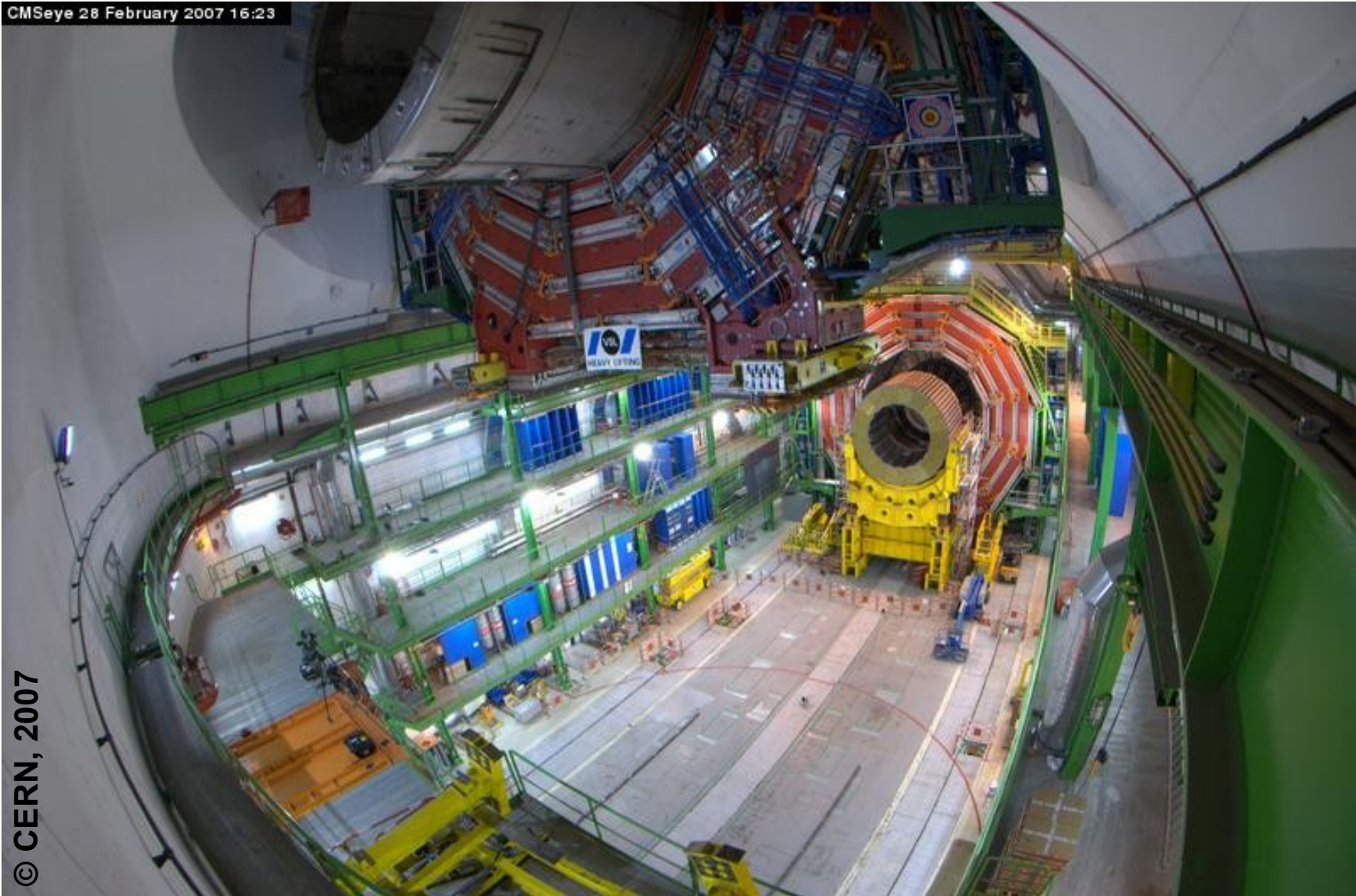
Feb. 2007



# Ankunft von YB0 (CMS)



CMSeye 28 February 2007 16:23



© CERN, 2007

**28.02.2007**

**Gewicht:**  
**1920 t**

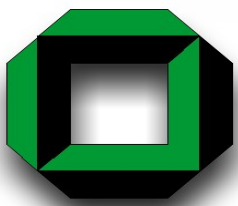
**Maße:**  
**16x17x13m<sup>3</sup>**

**Abstieg:**  
**100 m**

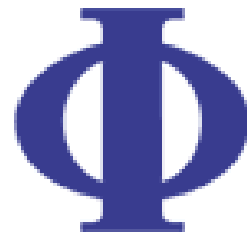
**Spielraum:**  
**20 cm**

**Dauer:**  
**10 h**

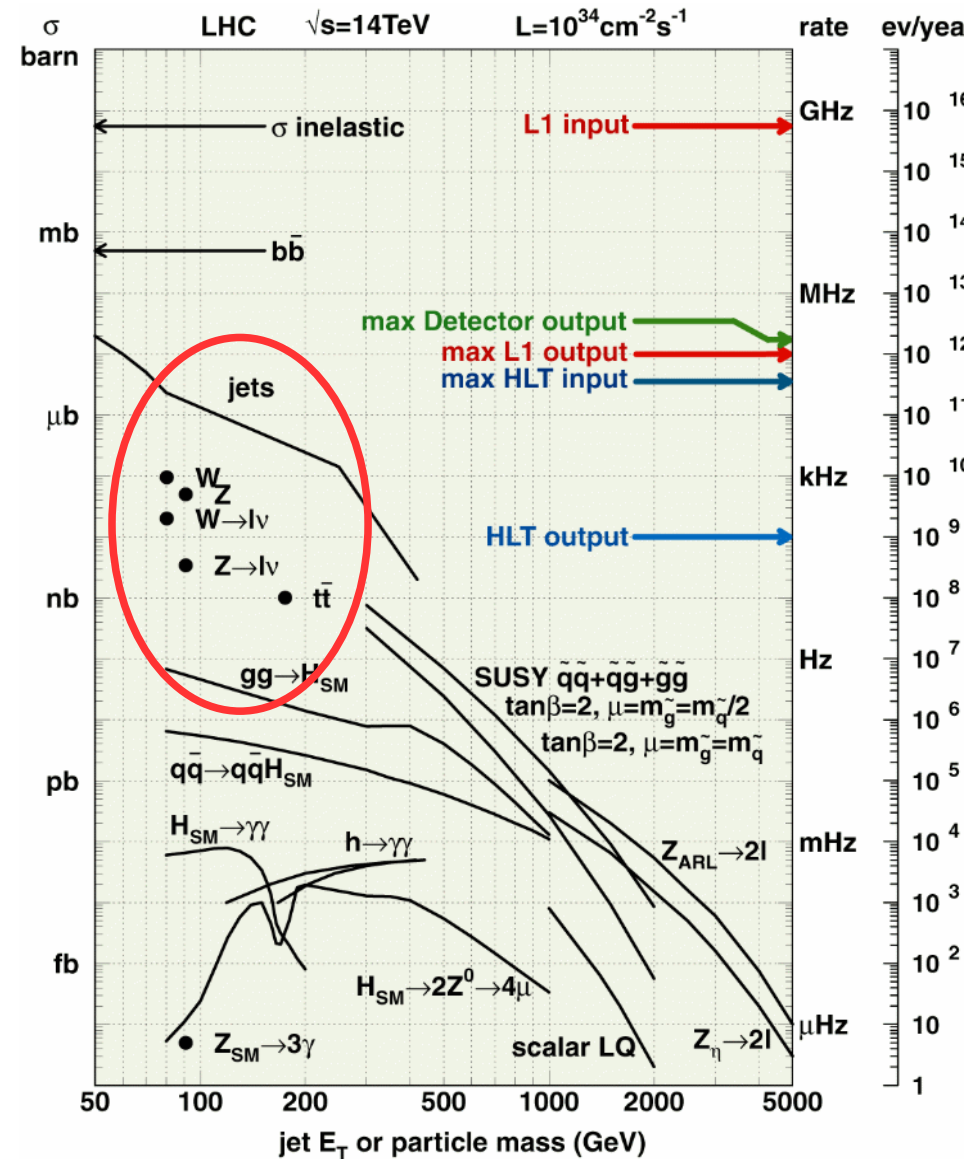


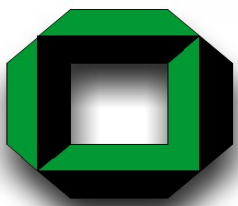


# Erstes Jahr LHC

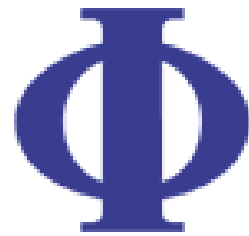


- Was geht mit  $1 \text{ fb}^{-1}$  ?
- Im Falle von QCD besser: Wie weit kommt man ?
- Für eine int. Luminosität von  $1 \text{ fb}^{-1}$  blieben grob  $10/\text{GeV}$  Ereignisse übrig bei:
  - ➔ Jet  $p_t$ :  $\approx 2.5 \text{ TeV}$
  - ➔ Zweijetmassen:  $\approx 5.0 \text{ TeV}$
  - ➔ Prompt Photon  $p_t$ :  $\approx 0.5 \text{ TeV}$
- Aber: Große syst. Unsicherheiten (Jetenergieskala, ...)



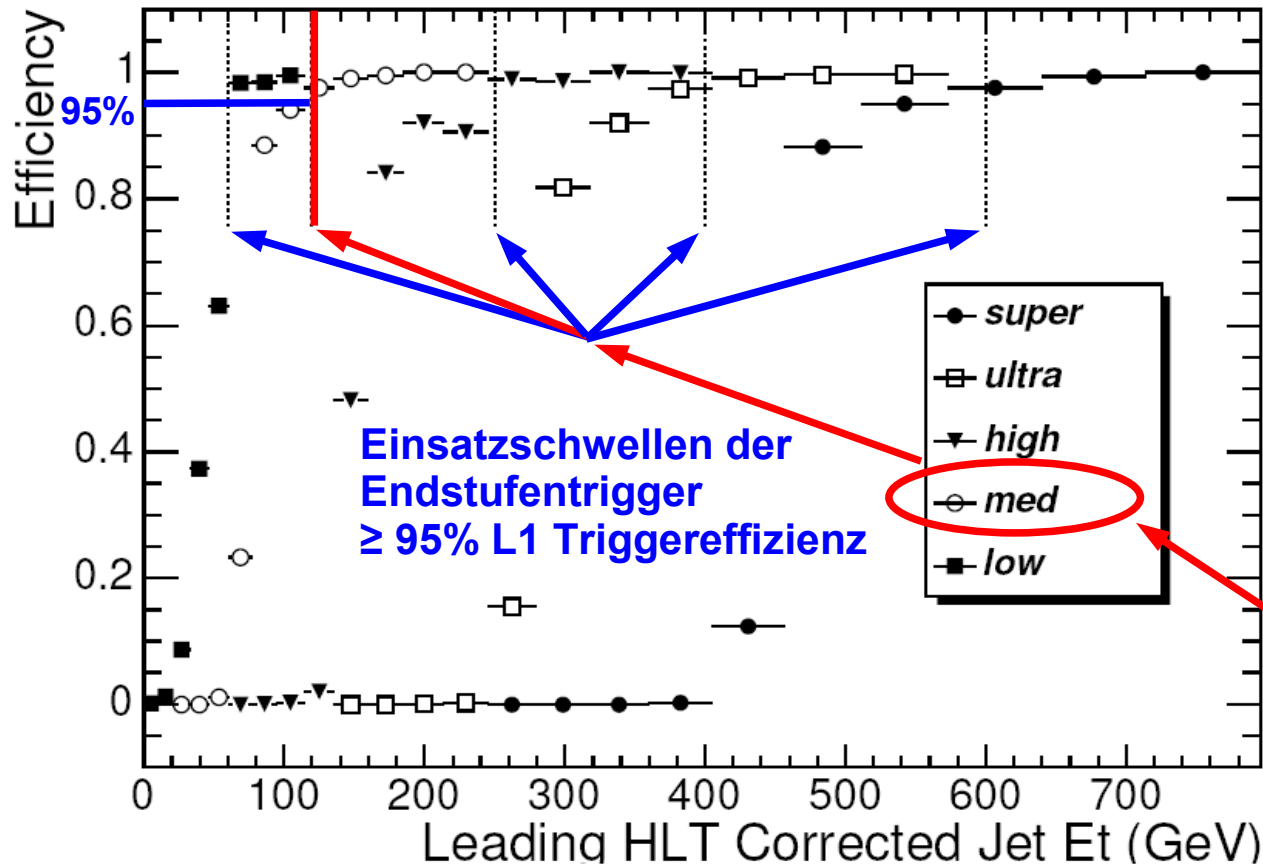


# “QCD Trigger”



## Beispiel: (Phys. TDR Vol. 2, CMS)

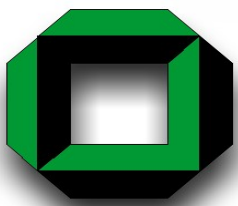
- Effizienz des L1 Jet-Triggers in Abh. der Jet  $E_t$
- Bis zu 5 **Trigger-Pfade** (Vorskalierung abh. von instantaner Luminosität → **Rate je 2.5 Hz**)



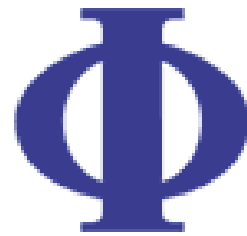
## ➔ Weitere wichtige Triggerung für QCD Analysen:

- Multijet-Trigger ( → top ...)
- Trigger auf einzelne Photonen, Staffelung ähnlich Jets (Achtung: Isolation)
- Zweiphotontrigger ( Untergrund Higgs →  $\gamma\gamma$ )
- Minimum Bias
- Diffraktive Prozesse

L1 Schwelle: 60 GeV  
HLT Schwelle: 120 GeV



# Trigger und neue Jets



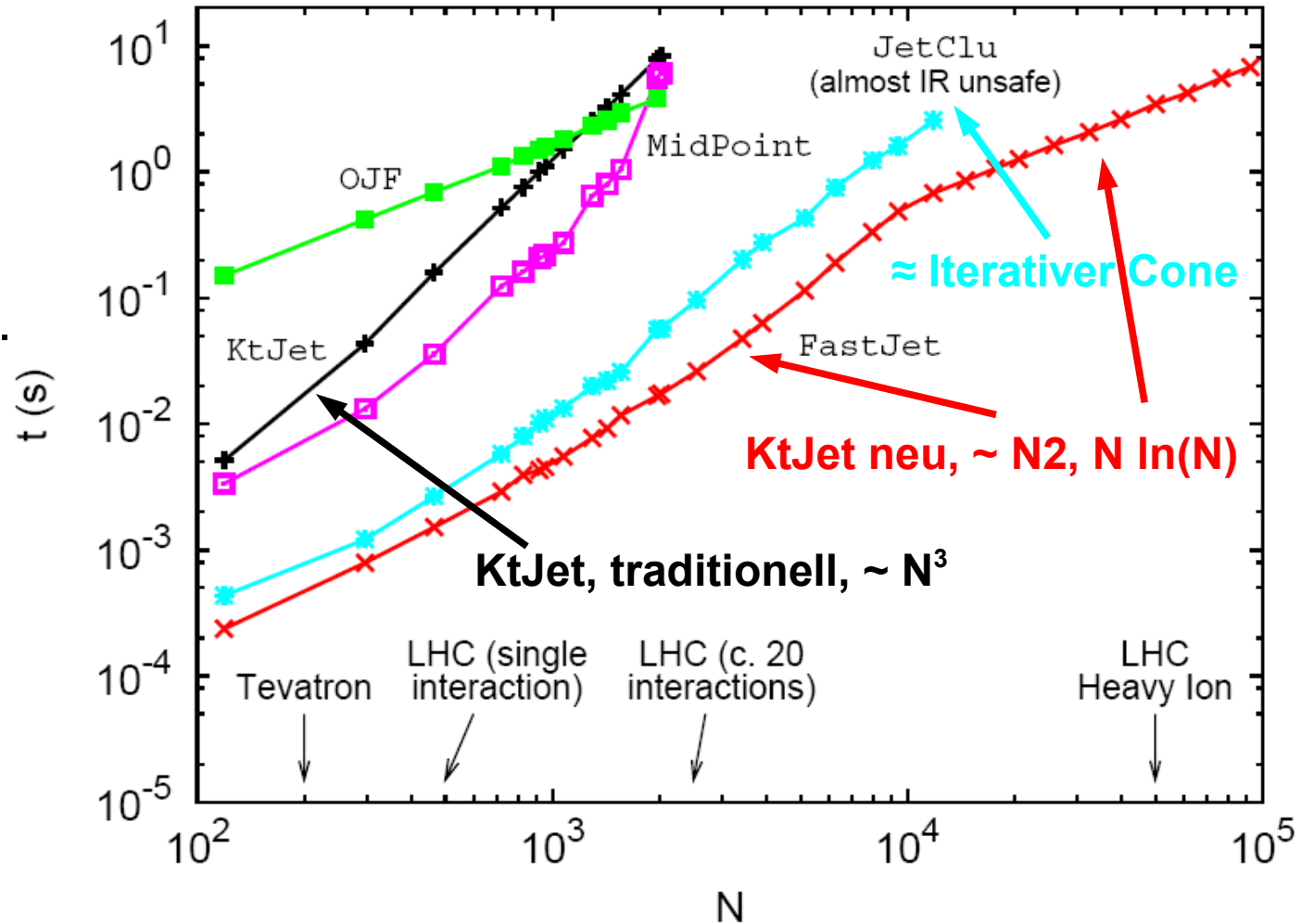
## ➤ Bisher:

- Nur einfachste, weil schnellste Algorithmen im Trigger verwendet
- Iterativer Cone-Alg. o.ä.
- Unvorteilhaft f. Theorie
- Inkonsistent mit finaler Analyse

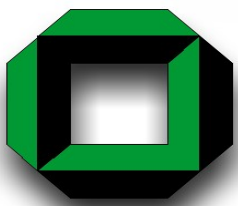
## ➤ Jetzt:

- Kt Jetalgorithmus im Trigger möglich

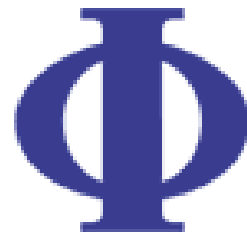
## Geschwindigkeitsvergleich Jetalgorithmen



M. Cacciari, G. Salam, (Phys.Lett.B641:57-61,2006.)

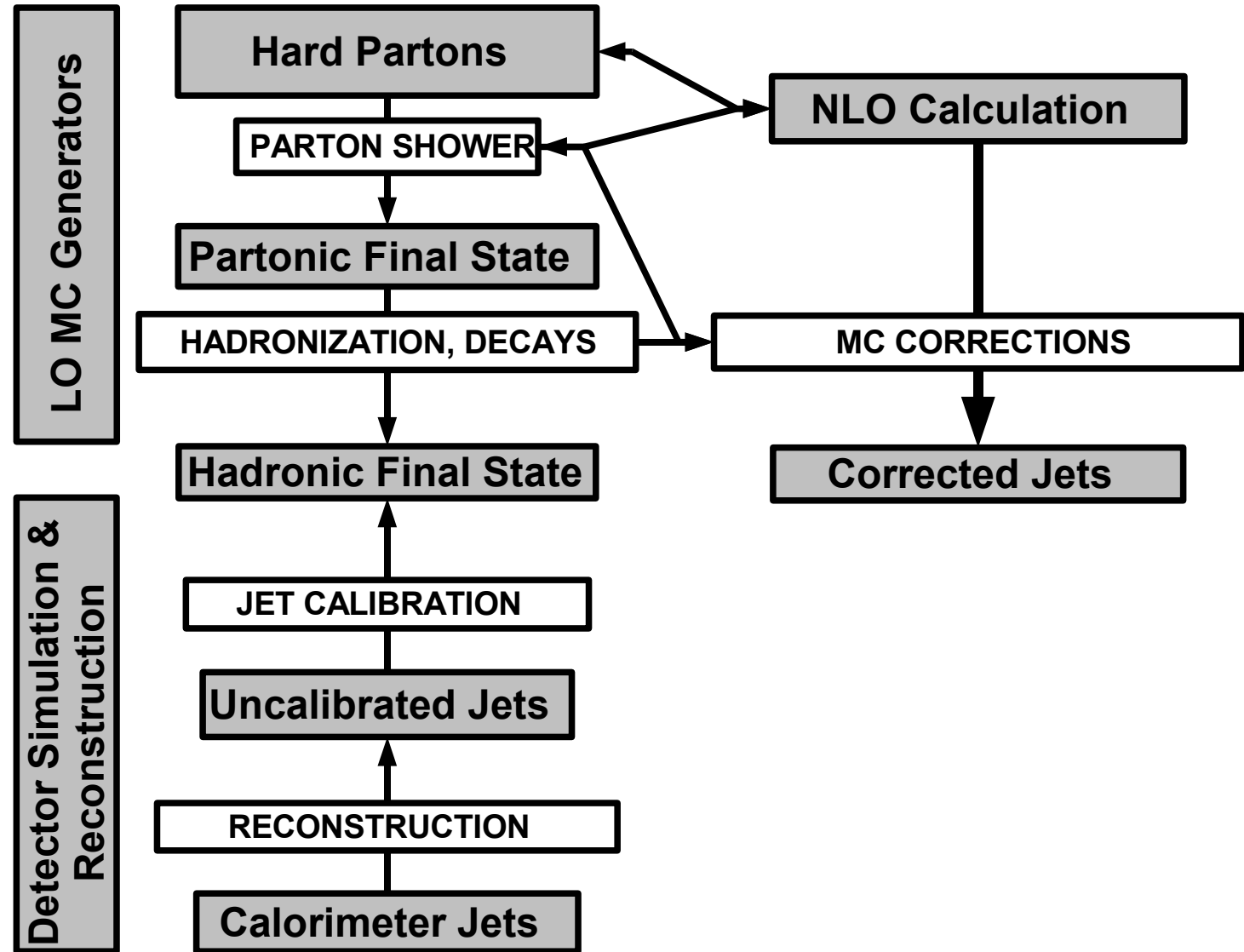


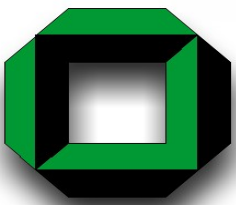
# Generische Jetanalyse 1



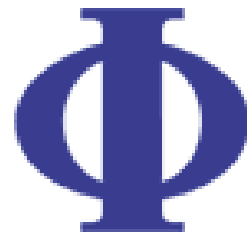
## Benötigt:

- + PDFs
- + LO & NLO MC
- + Det.-Simulation
- + Jetenergieskala/  
Korrektur
- + Jetalgorithmen
- + Kalorimeter-  
kalibration
- + Jettrigger
- + und ...  
Daten natürlich!





# Generische hh Kollision



Zu messendes oder simulierendes Ereignis

Zus. hh Kollisionen  
Minimum Bias (MB)  
→ Pile-up (PU)

Zus. Parton-Parton Ww.,  
Abstr. im Anfangszust.  
MPI, ISR → UE

Harte Ww.  
ME (LO, NLO)

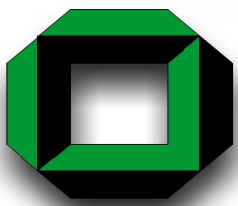
Partonschauer  
(perturbativ, QCD)  
+  
Hadronisierung  
(nicht-pert., Modell)

Bzgl. Jets:  
“splash in”

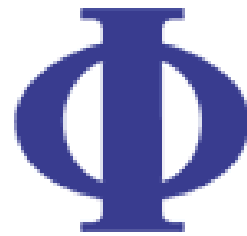
Partonschauer  
(perturbativ, QCD)  
+  
Hadronisierung  
(nicht-pert., Modell)

Bzgl. Jets:  
“splash out”

Hadronischer Endzustand, farblose Teilchen



# Generische Jetanalyse 2

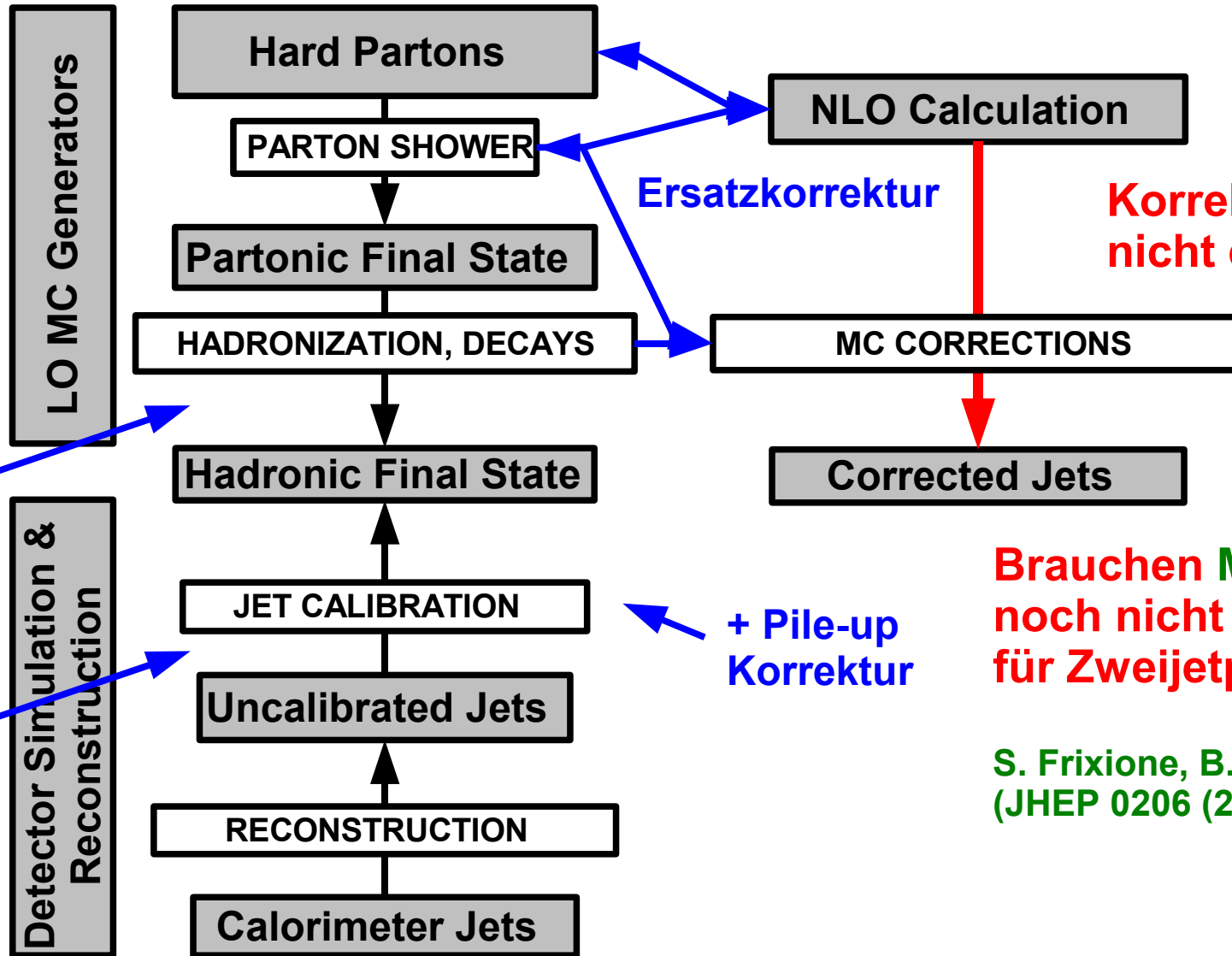


**Frage:**

Wo findet die Korrektur aufs unterliegende Ereignis (UE) statt?

Mit MC? (Pythia Tunes)

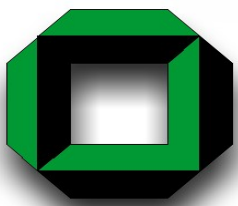
Mit Daten? (UE Messung!)



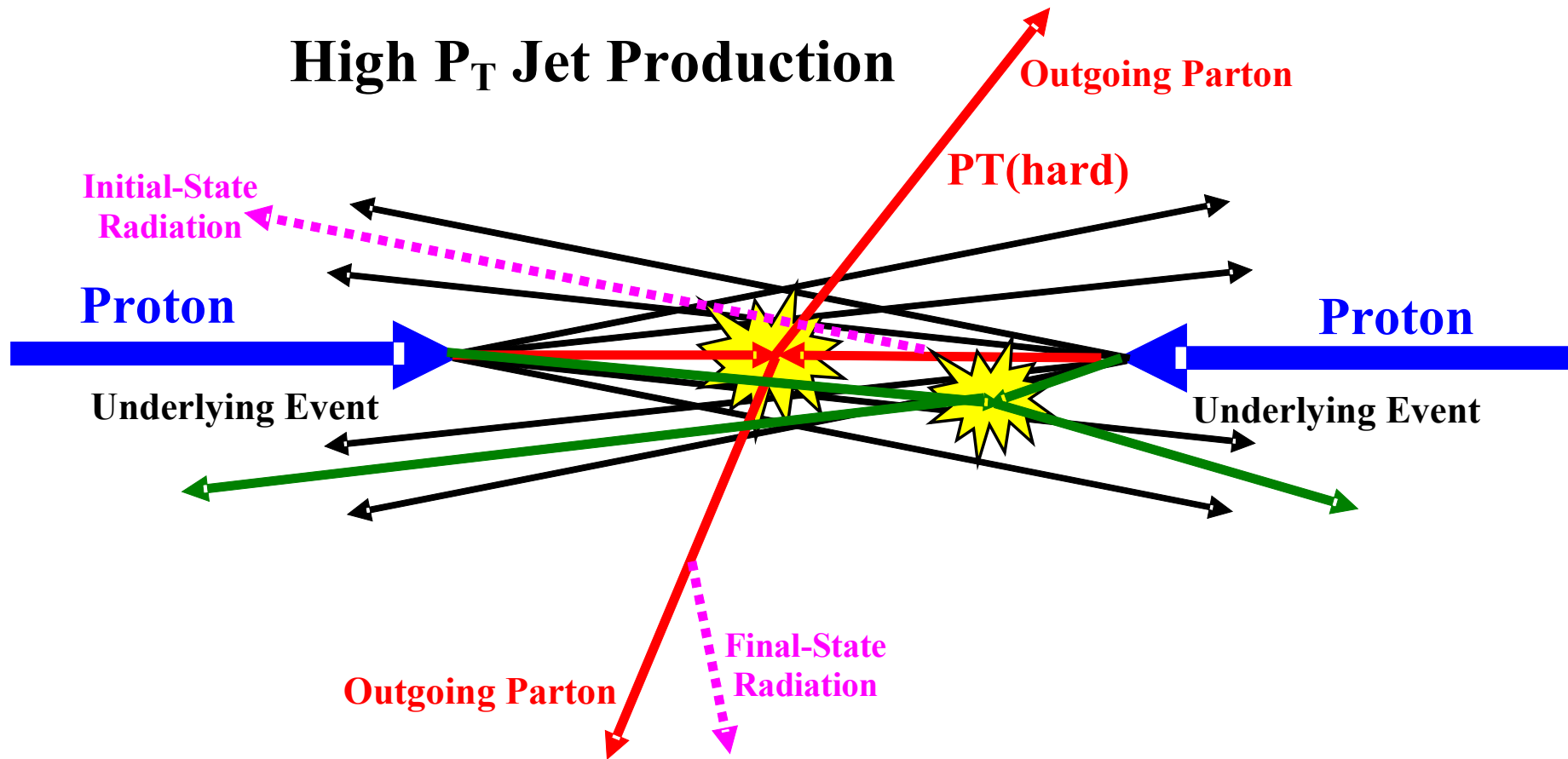
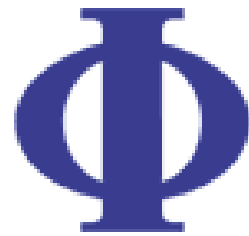
Korrektur bisher nicht ermittelbar!

Brauchen MC@NLO, noch nicht verfügbar für Zweijetproduktion!

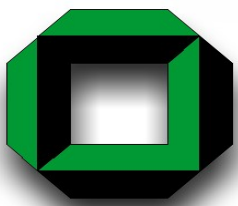
S. Frixione, B.R. Webber (JHEP 0206 (2002) 029)



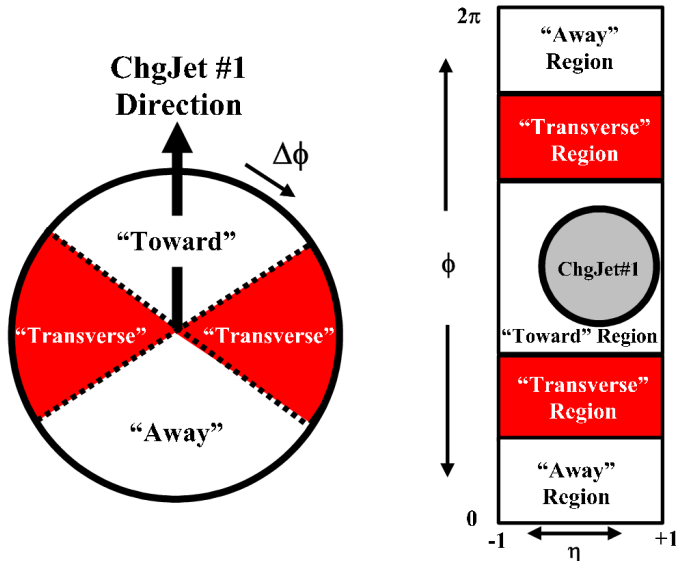
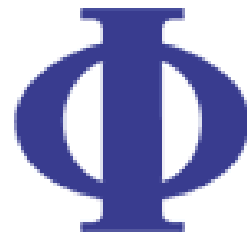
# Sketch einer $hh$ Kollision



à la R. Field

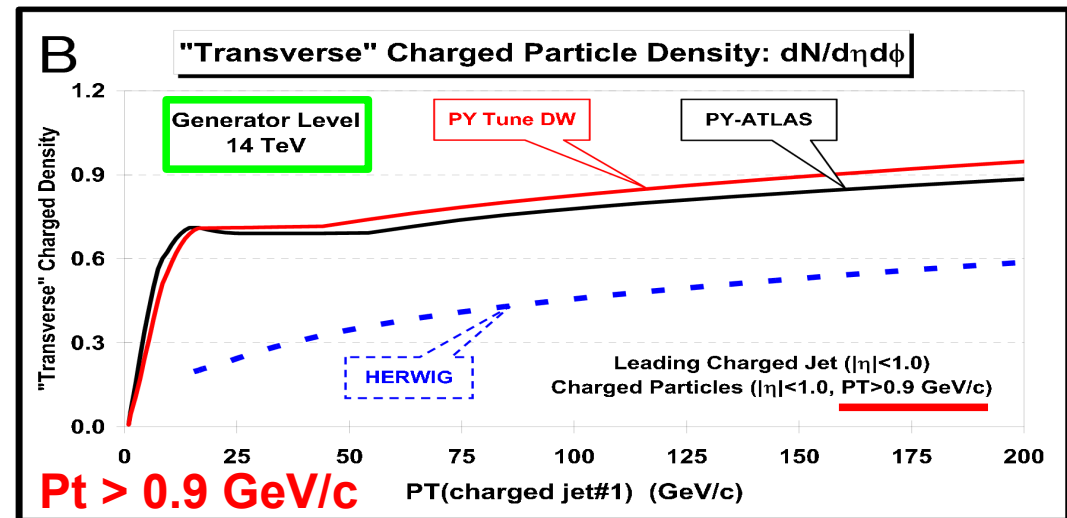
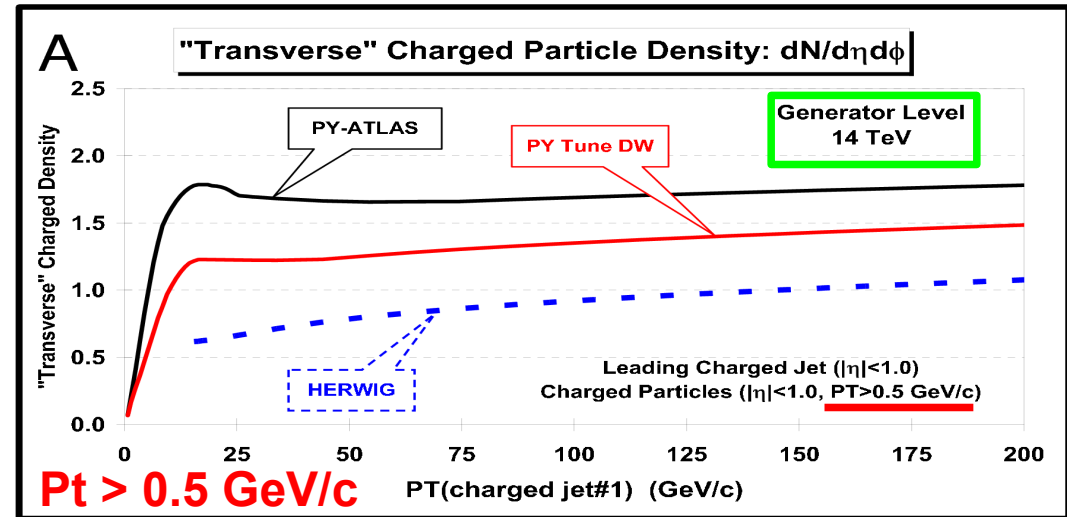


# Underlying Event mit Jets



## MC Vergleich zweier verschiedener Pythia Anpassungen:

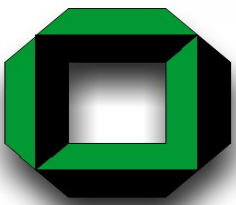
- PY ATLAS
- PY Tune DW von R. Field fitting CDF Run 1 und 2 UE Daten sowie HERWIG
- MI Parameter für **Energieabhängigkeit**:  $PARP(90) = 0.16$  (ATLAS),  $0.25$  (DW)
- Weicheres Spektrum gel. Teilchen für ATLAS Anpassung



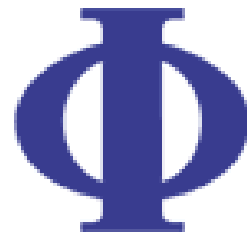
(Phys. TDR Vol. 2, CMS)

**Was werden wir bei LHC sehen/messen?** Siehe auch F. Bechtel T 512.9

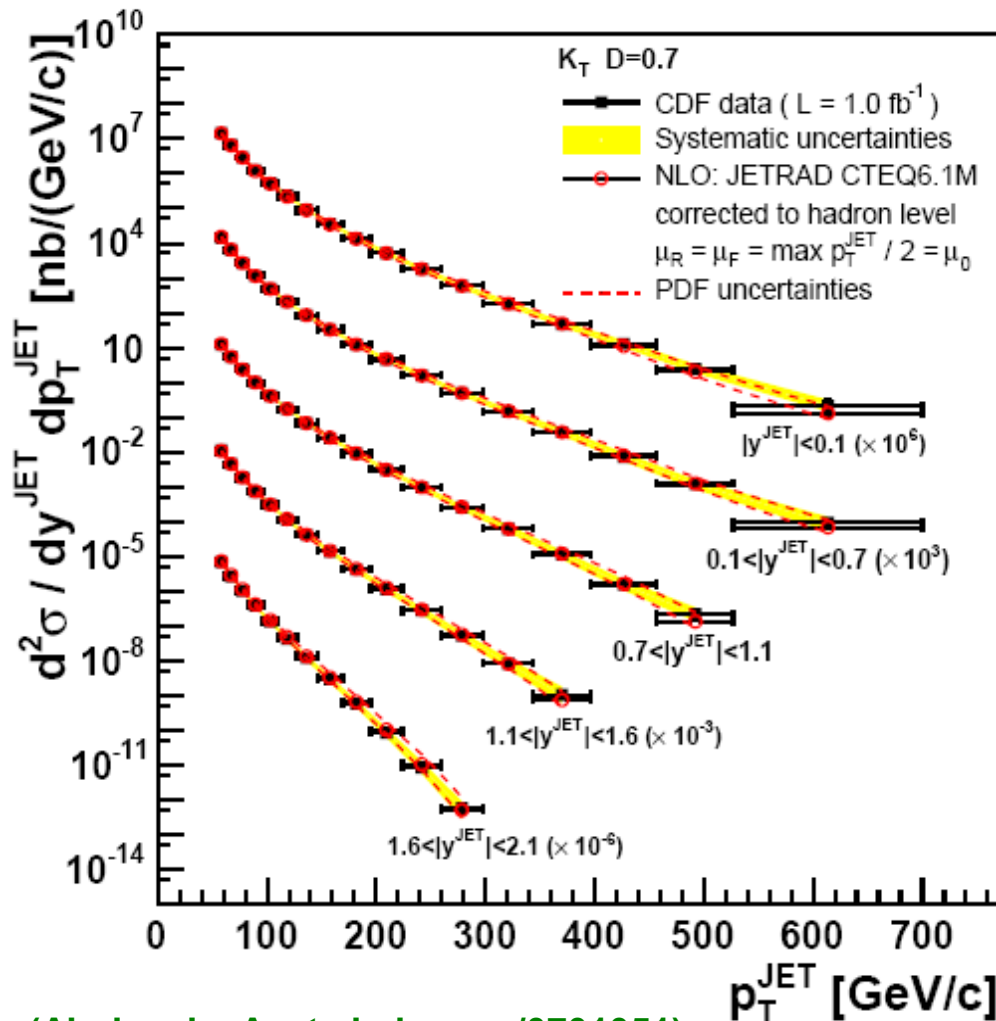




# Inklusive Jets 1

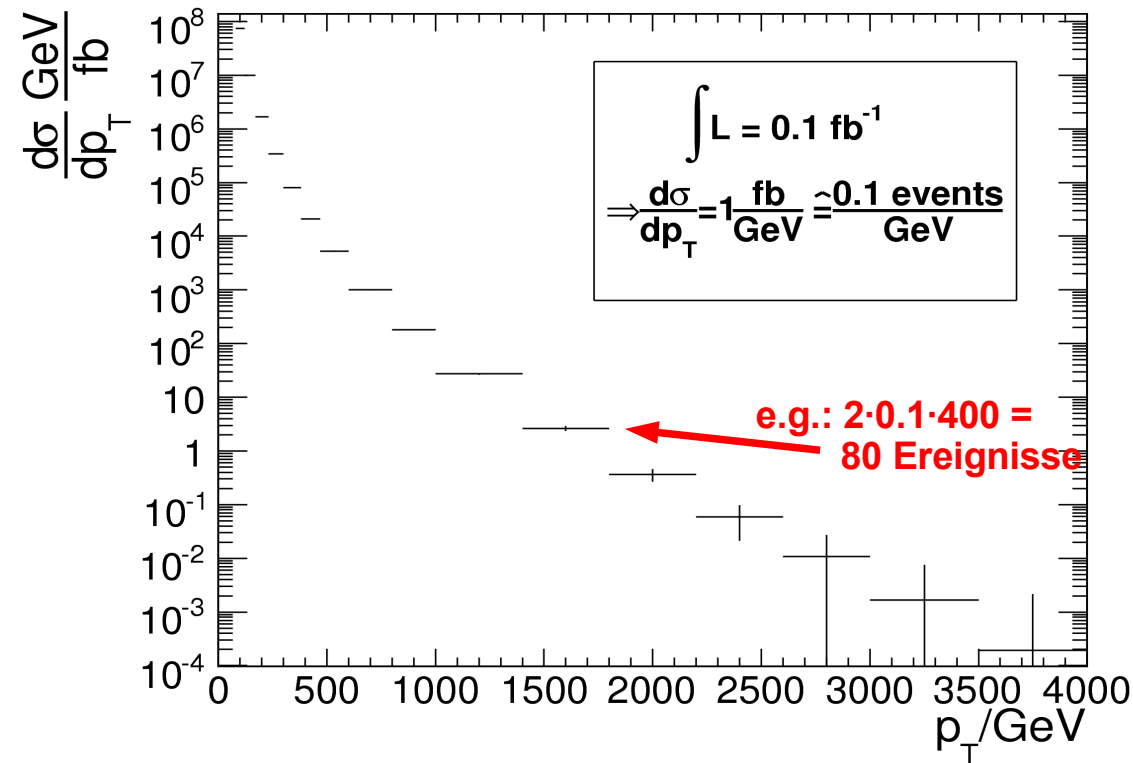


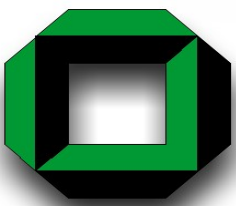
## Neueste Ergebnisse zu $K_T$ Jets von CDF



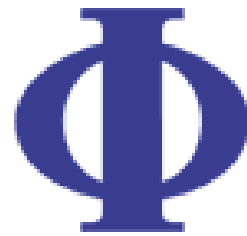
(Abulencia, A. et al.: hep-ex/0701051)

Zu erwartende Statistik bei LHC für  $L_{\text{int}} = 0.1 \text{ fb}^{-1}$  (LO Pythia, alle Rap. y)



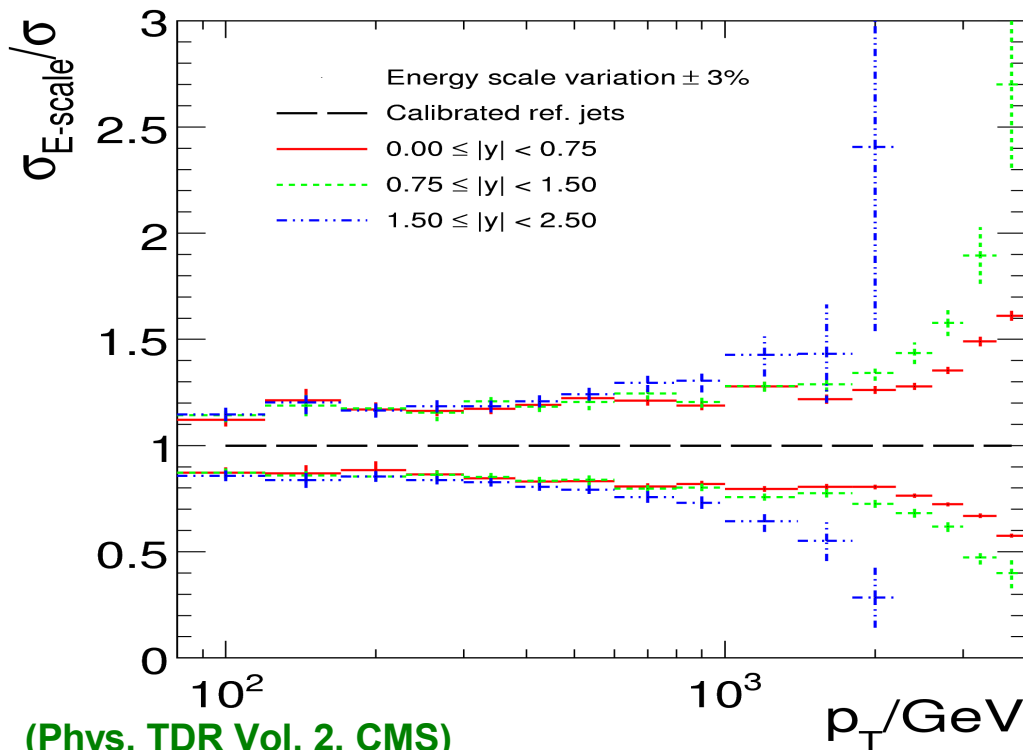


# Inklusive Jets 2

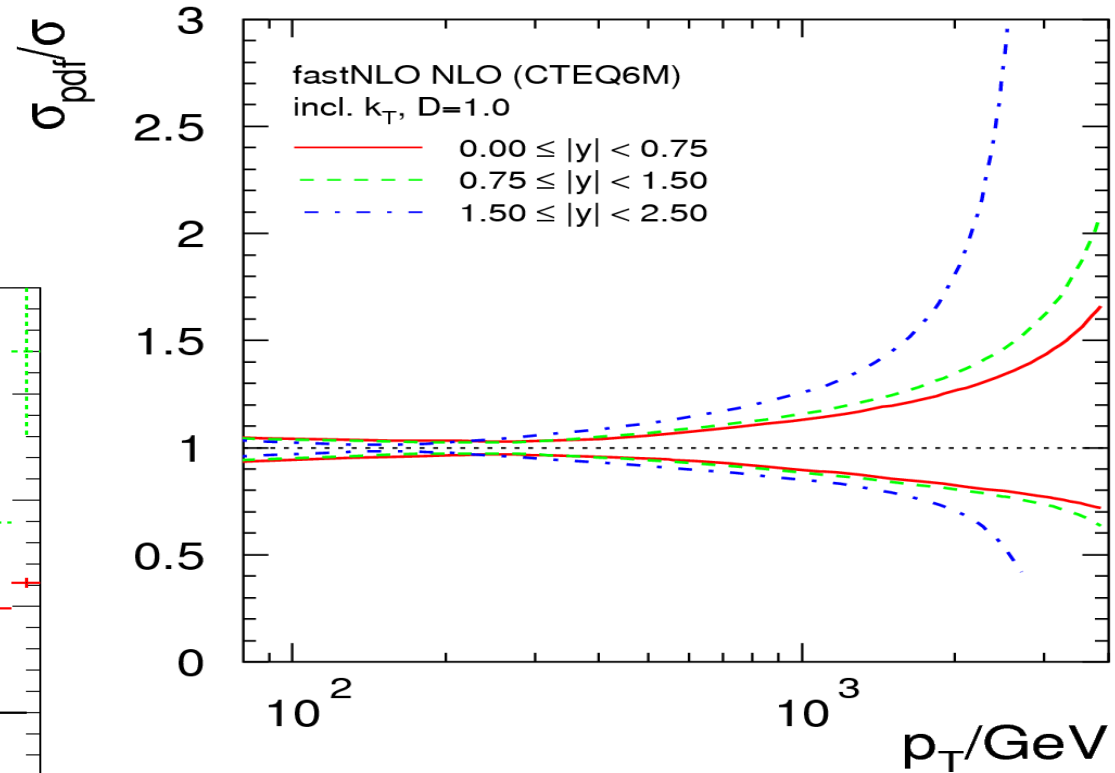


Dominante systematische Unsicherheiten in 3 Rapiditätsbereichen:  
 $0.00 \leq |y| < 0.75$ ,  $0.75 \leq |y| < 1.50$ ,  $1.50 \leq |y| < 2.00$

Abs. Jet-Energieskala ( $\pm 3\%$ )

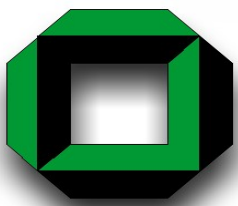


(Phys. TDR Vol. 2, CMS)

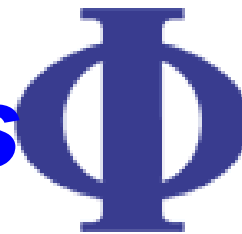


PDFs (CTEQ6.1) in NLO

Siehe auch A. Oehler T 512.8

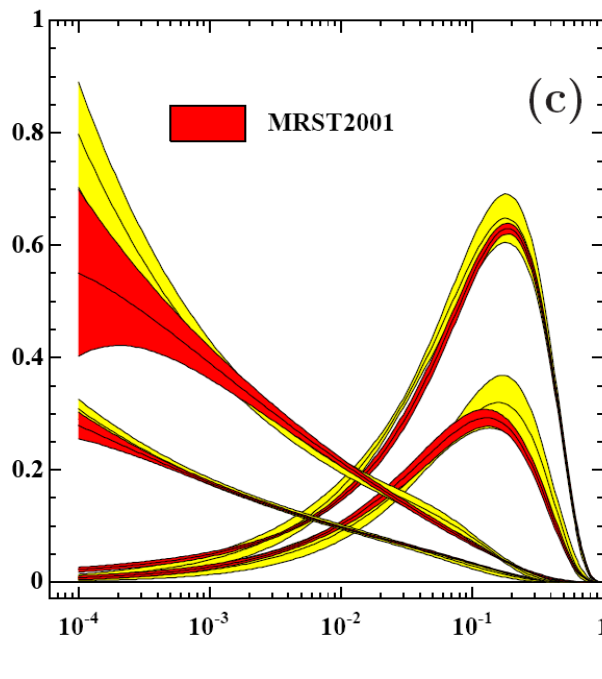


# NLO Anpassungen der PDFs

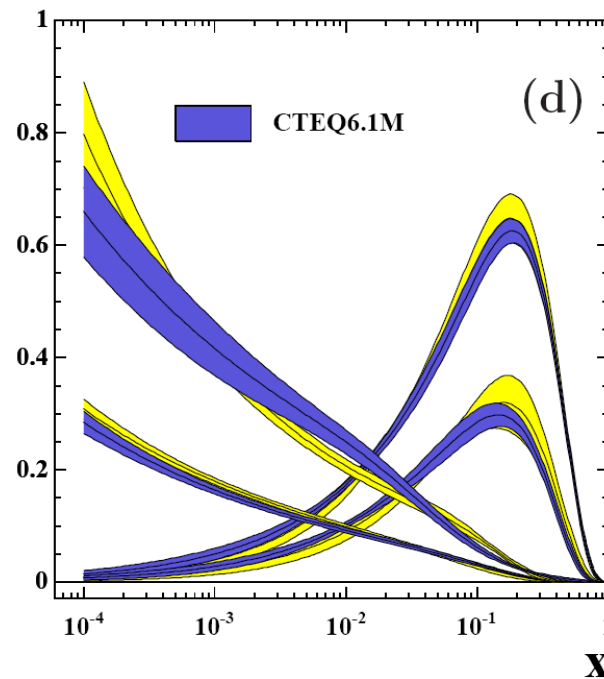


Vergleich einer **NLO** Anpassung der PDFs aus ZEUS-Daten allein (Inklusiv NC/CC + DIS Jets + Dijet-Photoproduktion)

ZEUS vs. MRST2001

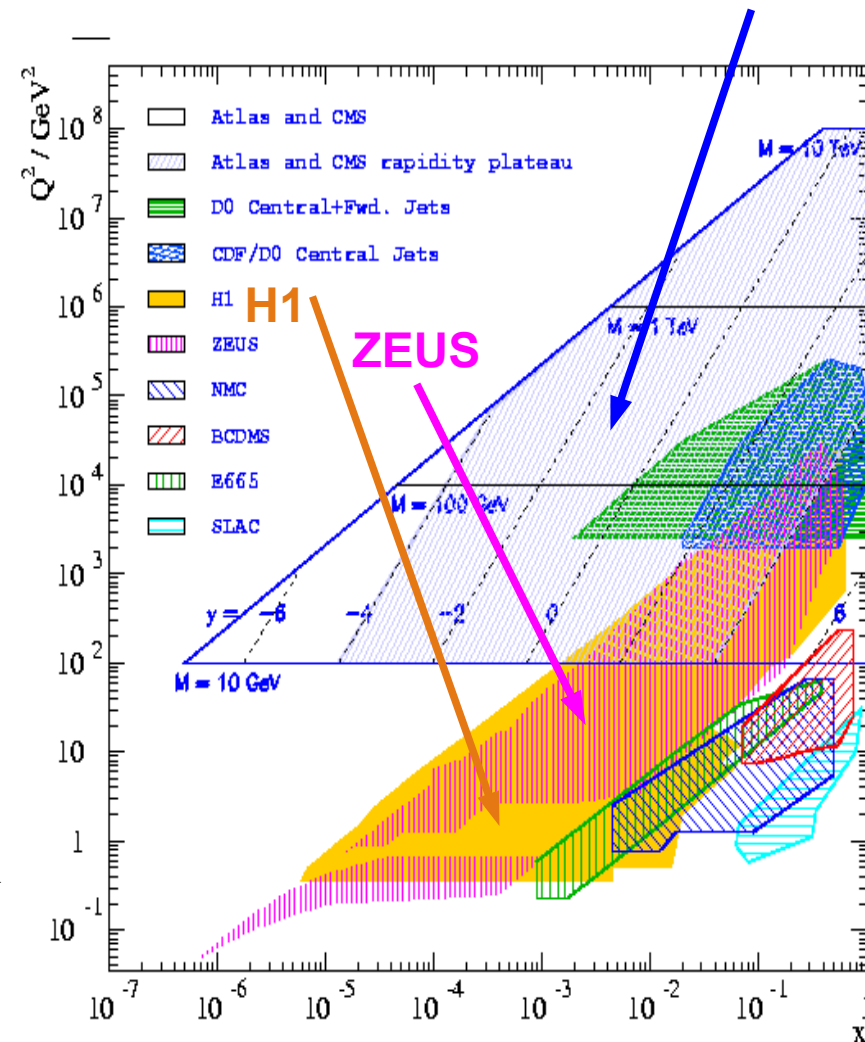


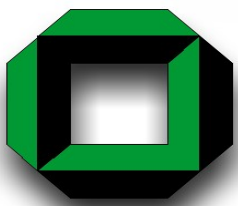
ZEUS vs. CTEQ6.1



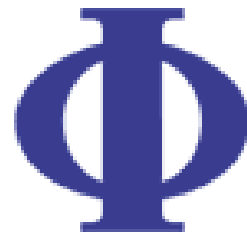
ZEUS (Eur.Phys.J. C42 (2005) 1-16)

Kinematische Ebene mit LHC

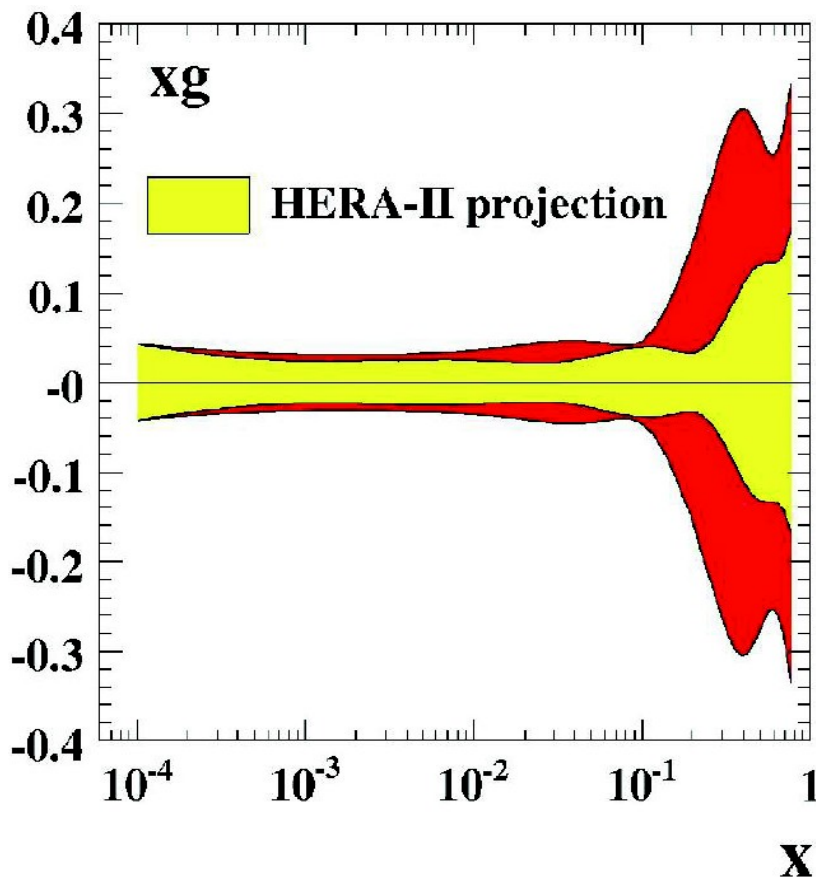




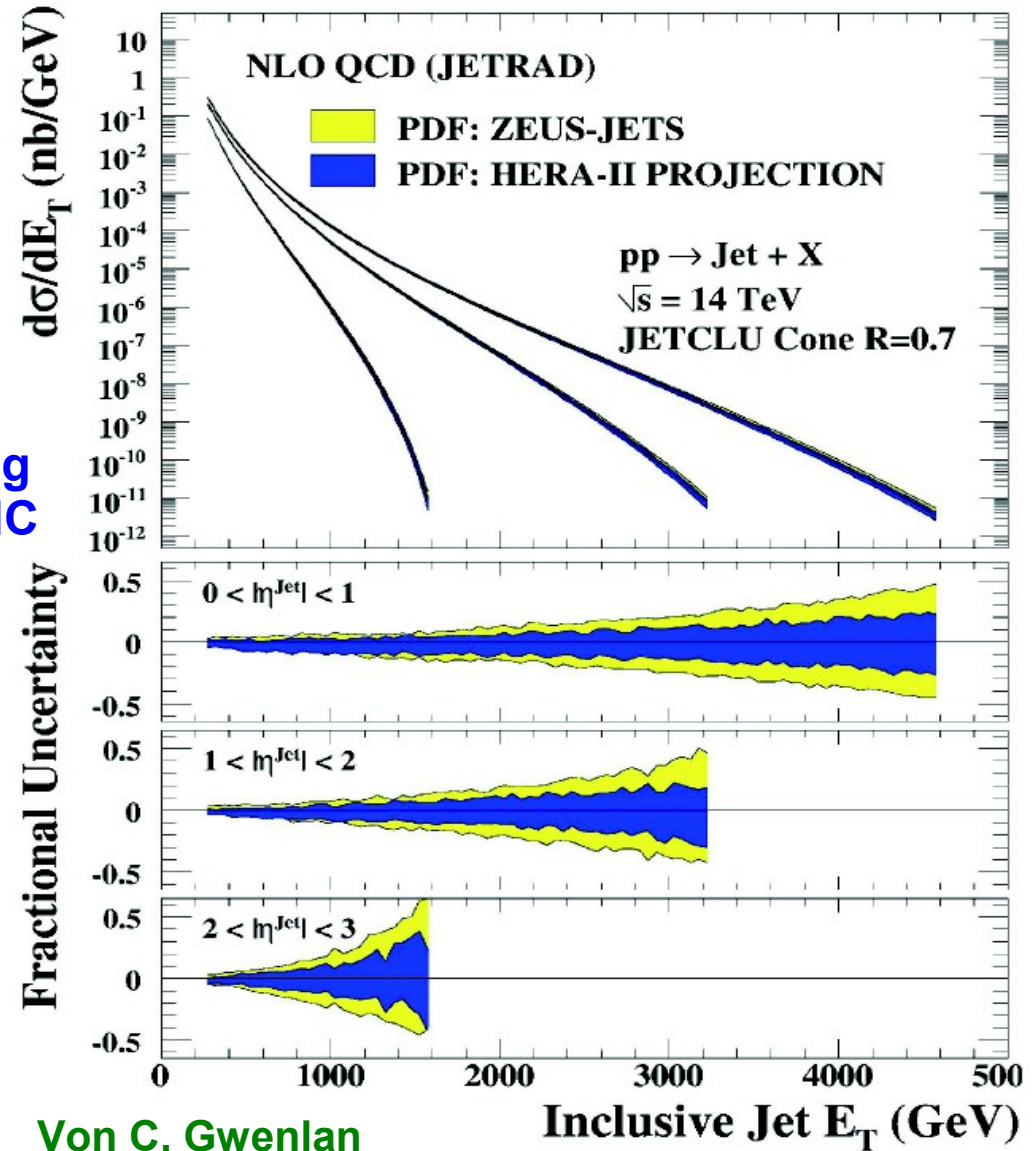
# Kenntnis der PDFs



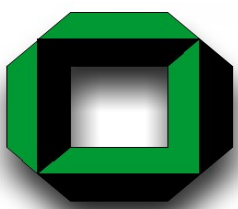
Voraussichtliche Reduzierung der PDF-  
Unsicherheit, hier das gluon, in Anpassungen  
von ZEUS (F2 + Jets) bei HERA II



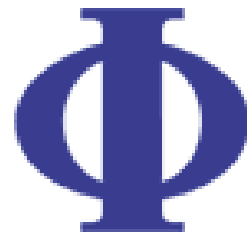
Auswirkung  
auf den LHC



Von C. Gwenlan



# Jetwirkungsquerschnitt in Hadron-Hadron Kollisionen

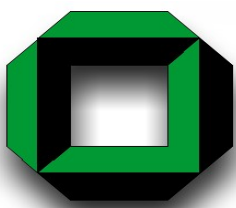


## Genereller Wirkungsquerschnitt:

$$\sigma_{hh} = \sum_n \alpha_s^n(\mu_r) \sum_{flavour i} \sum_{flavour j} c_{i,j,n}(\mu_r, \mu_f) \times f_i(x_1, \mu_f) \times f_j(x_2, \mu_f)$$

abhängig von:

- Starker Kopplungskonstanten  $\alpha_s$  zur Potenz  $n$
  - Perturbativen Koeffizienten  $c_{i,j,n}$
  - Partondichtefunktionen (PDFs) der Hadronen  $f_i(x)$ ,  $f_j(x)$
  - Renormierungs-  $\mu_r$  und Faktorisierungsskala  $\mu_f$
  - Impulsanteil  $x$
- ➔ Standardprozedur: Integration über Phasenraum in  $(x_1, x_2)$   
(normalerweise MC Methode) => **Abhängigkeit von PDFs!**
- ➔ Alternativ: Interpolation zwischen festen Stützpunkten in  $x$  für die PDFs => **Auswertung a posteriori** möglich



# Partonische Subprozesse $hh$

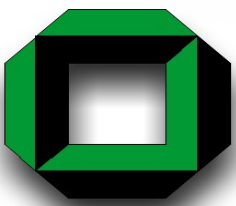


➔ Statt naiv  $13 \times 13 = 169$  PDF Kombinationen ...

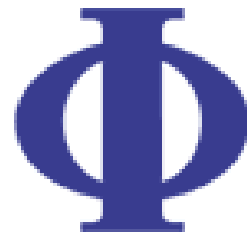
➔ Für  $hh \rightarrow$  jets **sieben** relevante part. Subprozesse:

- 1)  $gg \Rightarrow$  jets  $\propto H_1(x_1, x_2)$
- 2)  $qg, \bar{q}g \Rightarrow$  jets  $\propto H_2(x_1, x_2)$
- 3)  $gq, g\bar{q} \Rightarrow$  jets  $\propto H_3(x_1, x_2)$
- 4)  $q_i q_j, \bar{q}_i \bar{q}_j \Rightarrow$  jets  $\propto H_4(x_1, x_2)$
- 5)  $q_i q_i, \bar{q}_i \bar{q}_i \Rightarrow$  jets  $\propto H_5(x_1, x_2)$
- 6)  $q_i \bar{q}_i, \bar{q}_i q_i \Rightarrow$  jets  $\propto H_6(x_1, x_2)$
- 7)  $q_i \bar{q}_j, \bar{q}_i q_j \Rightarrow$  jets  $\propto H_7(x_1, x_2)$

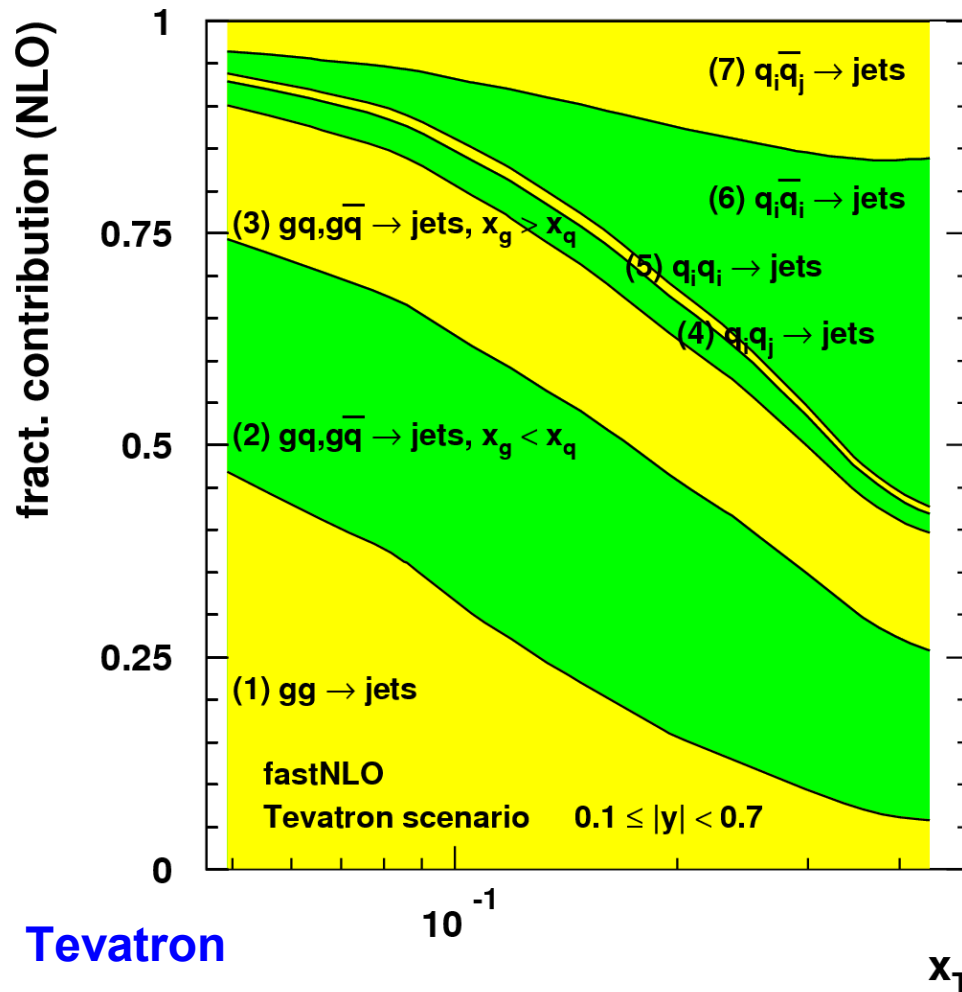
➔ Nur sieben Linearkombinationen  $H_i$  von PDFs



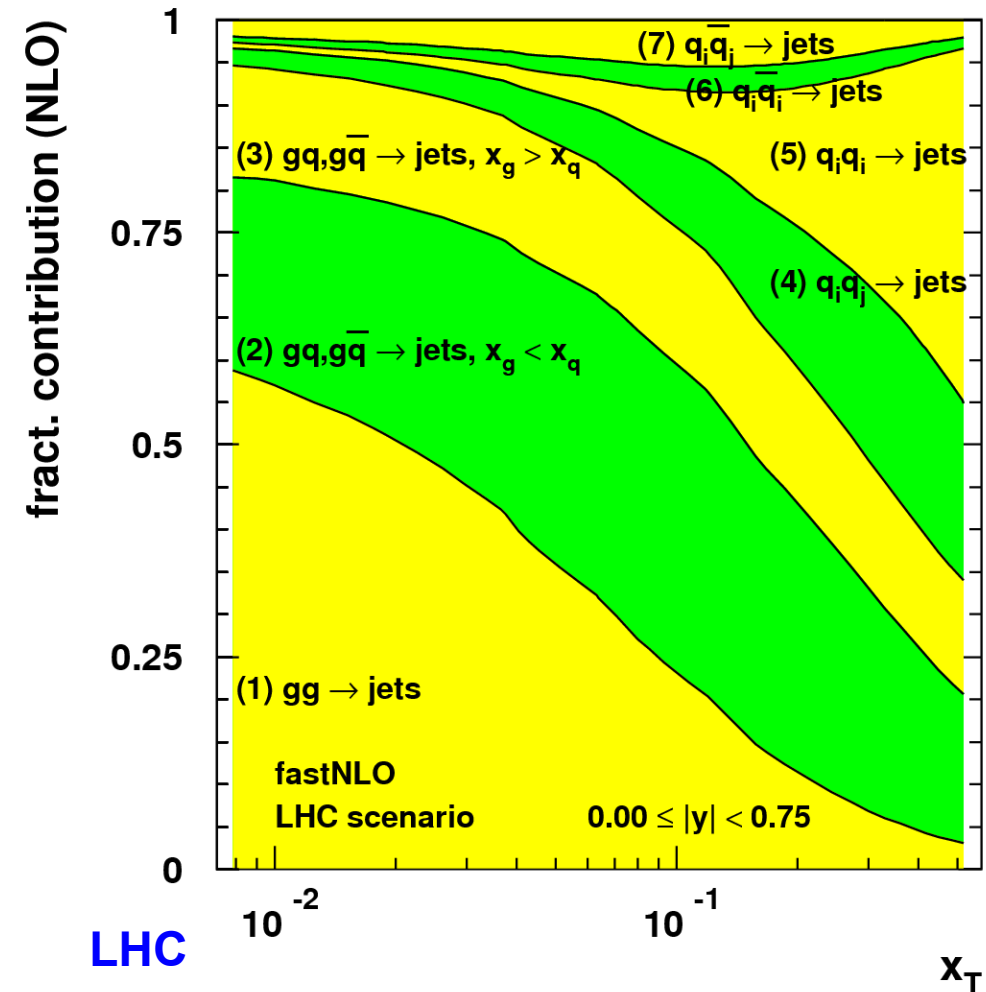
# Zerlegung in Subprozesse



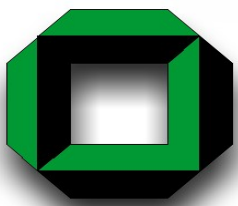
Zerlegung des Gesamtquerschnitts in Subprozesse im zentralen Rapiditätsbereich gegen SkalenvARIABLE  $x_T = 2p_T/\sqrt{s}$



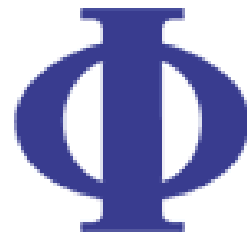
Tevatron



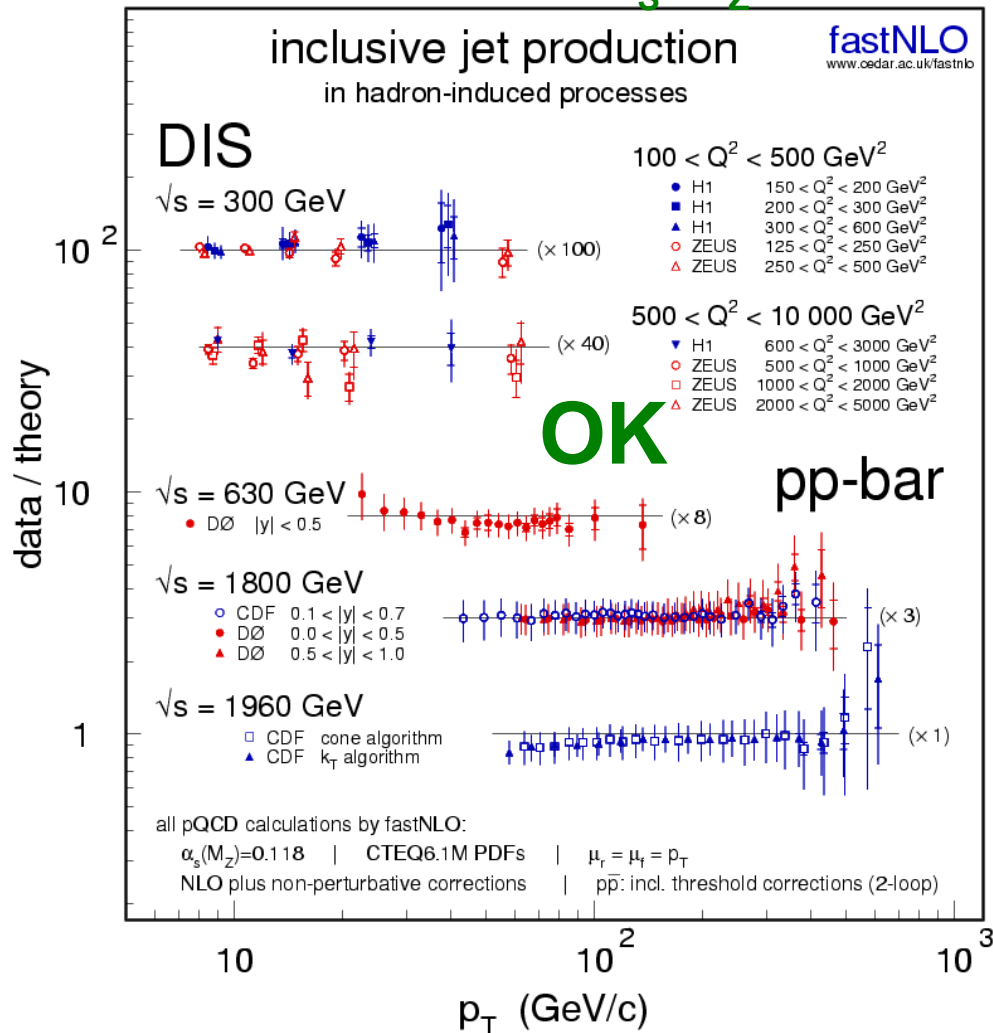
LHC



# fastNLO Anwendung

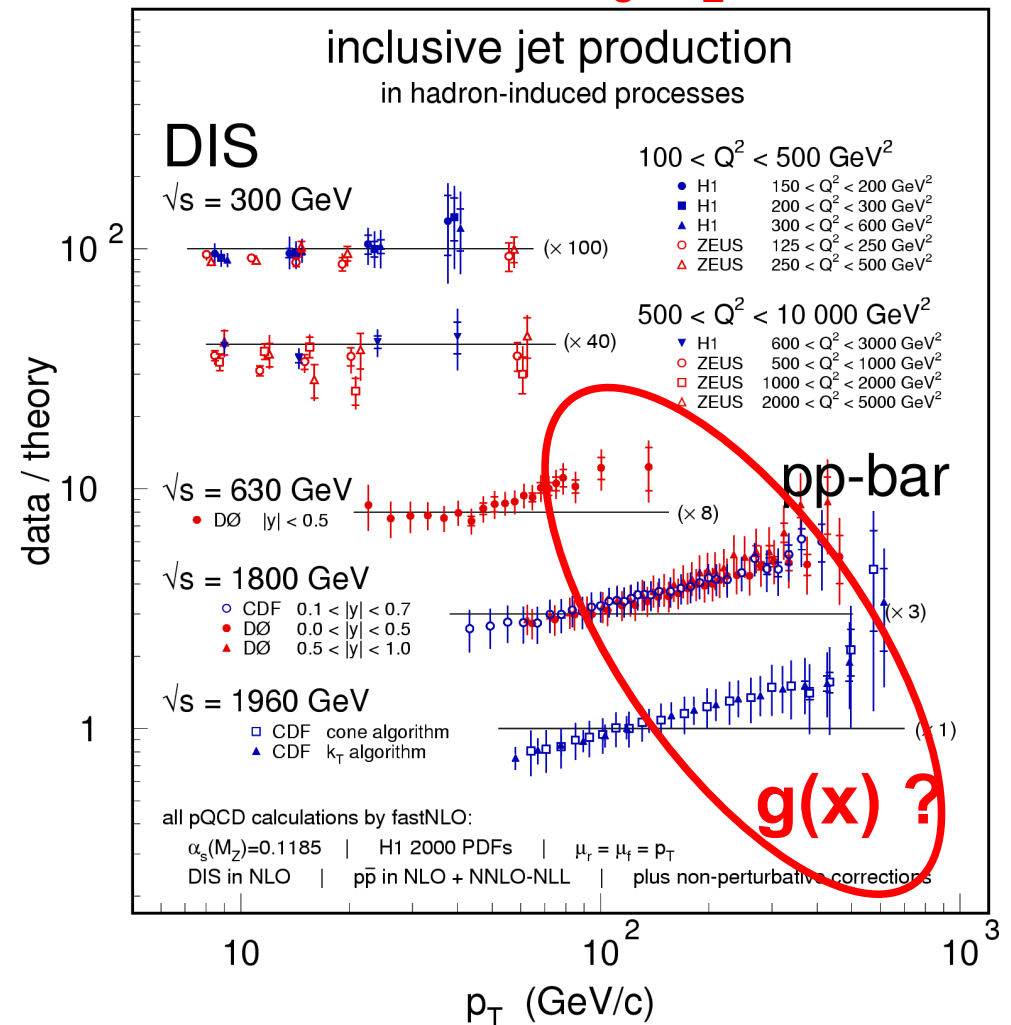


## CTEQ6.1 PDFs, $\alpha_s(M_Z) = 0.118$

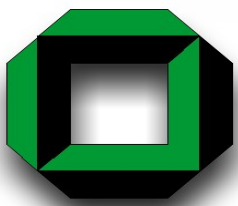


## Keine Jetdaten in H1 PDF Anpassungen

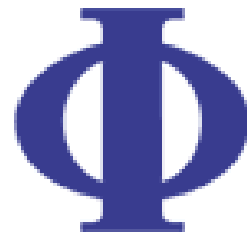
## H1 2000 PDFs, $\alpha_s(M_Z) = 0.118$







# Produktion von Eichbosonen



Erinnerung: Ereignisraten schon bei  $L = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

$pp \rightarrow W + X \rightarrow e\nu + X: 2.0 / \text{s} = 7200 / \text{Stunde}$

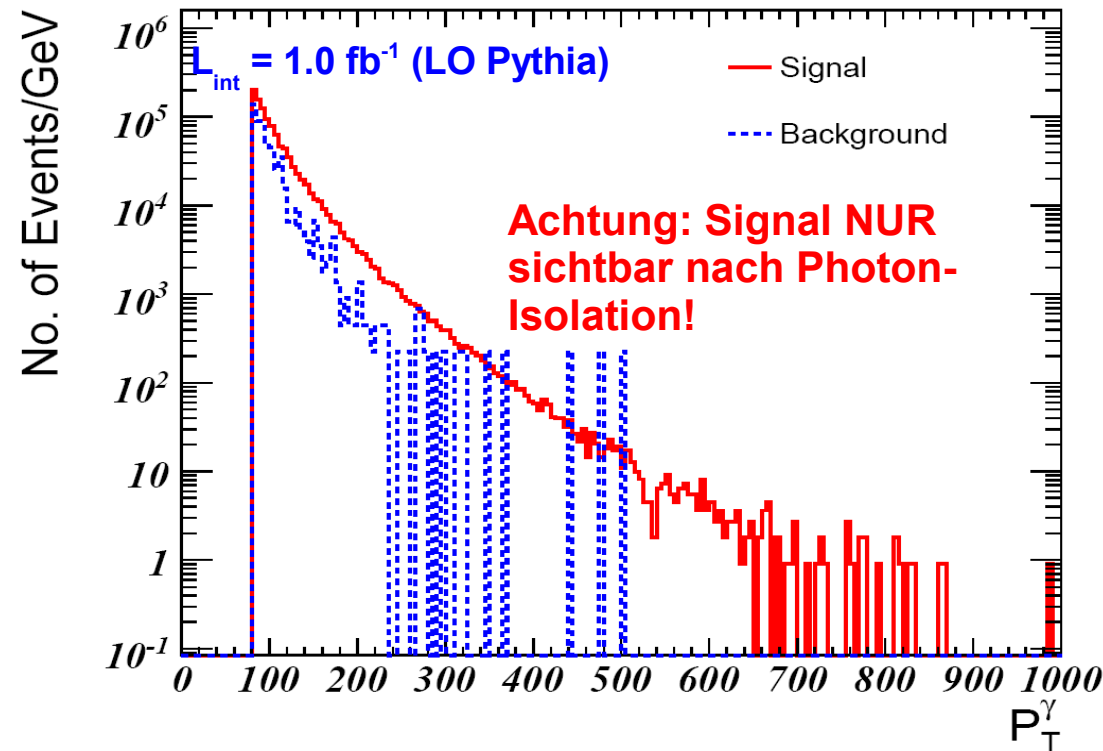
$pp \rightarrow Z + X \rightarrow ee + X: 0.2 / \text{s} = 720 / \text{Stunde}$

Eine Größenordnung mehr als am Tevatron!

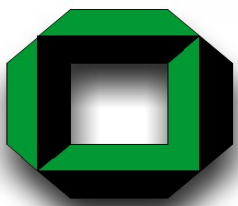
➔ Eichbosonproduktion liefert wichtige Zusatzinformationen:

- Detektorkalibration
- Luminositätsmessung
- PDFs

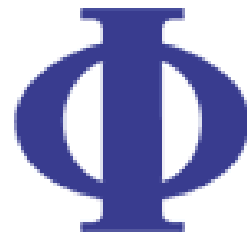
## Photon + Jet schwieriger



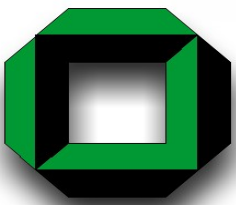
CMS NOTE 2007/004



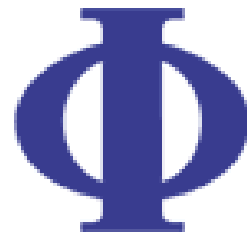
# Ausblick 1



- Natürlich warten alle gespannt darauf, die sprichwörtliche “Nadel im Heuhaufen” zu finden ...
- Higgs, SUSY,  $Z'$ , ... ?
- Aber wie sieht das Heu aus?



# Ausblick 2



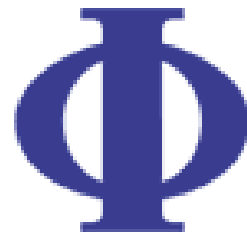
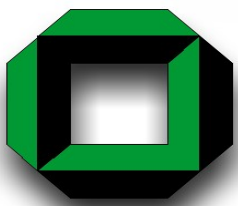
## + Zum LHC-Start stehen viele neue Werkzeuge bereit:

- Schnellere Jetalgorithmen
- Verbesserte/-bare Modelle für UE Unsicherheit
- MC Generatoren in NLO (demnächst für Jets?)
- MC Generatoren mit Verbesserungen bei Multijets (CKKW, MLM)
- Präzisere Theorierechnungen (NLO, NNLO, ...)

## + Mit neuen Daten vom LHC werden

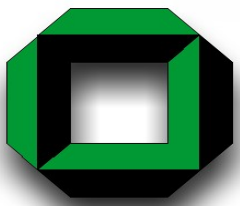
- Erste “einfache” Messungen und Vergleiche vorgenommen
- Die Detektorkalibration, Luminositätsmessung, ... verbessert
- Kombinierte Anpassungen der PDFs vorgenommen

## + Wir müssen nur das Puzzle zusammensetzen.

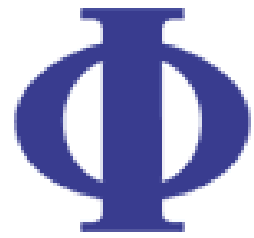


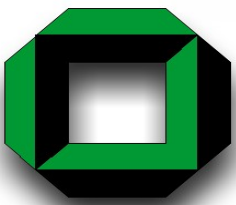
## ➔ Einige Zitate aus Phys. Lett. Vol. 107B, no. 4:

- ... dipole magnet which produces a field of **0.7 T** over a volume of 7m x 3.5m x 3.5m ...
- ... yields space points at **centimetre** intervals on the detected tracks
- ... two short accelerator development periods in October and November 1981 ...
- The events were **scanned by physicists** on a Megatek display.
- ... was examined independently by all physicists who participated in the scanning. The combined effect of the **scanner variations** ...

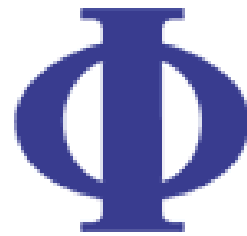


# *Reserve*





# PDF Approximation



- ➔ Stützpunkte  $x^{(i)}$  with  $x^{(n)} < .. < x^{(i)} < .. < x^{(0)} = 1$
- ➔ Um jeden Stützpunkt  $x^{(i)}$  definiere Eigenfunktion  $E^{(i)}(x)$  mit:  
 $E^{(i)}(x^{(i)}) = 1, E^{(i)}(x^{(j)}) = 0 (i \neq j), \sum_i E^{(i)}(x) = 1$  für alle  $x$
- ➔ Setze PDF  $f(x)$  aus lin. Kombinationen der Eigenfunktionen zusammen mit Koeffizienten gegeben durch PDF Werte **an diskreten Punkten**:  
 $f(x) = \sum_i f(x^{(i)}) E^{(i)}(x) \Rightarrow$  **Integration nur über  $E^{(i)}(x)$ , nicht  $f(x)$ !**

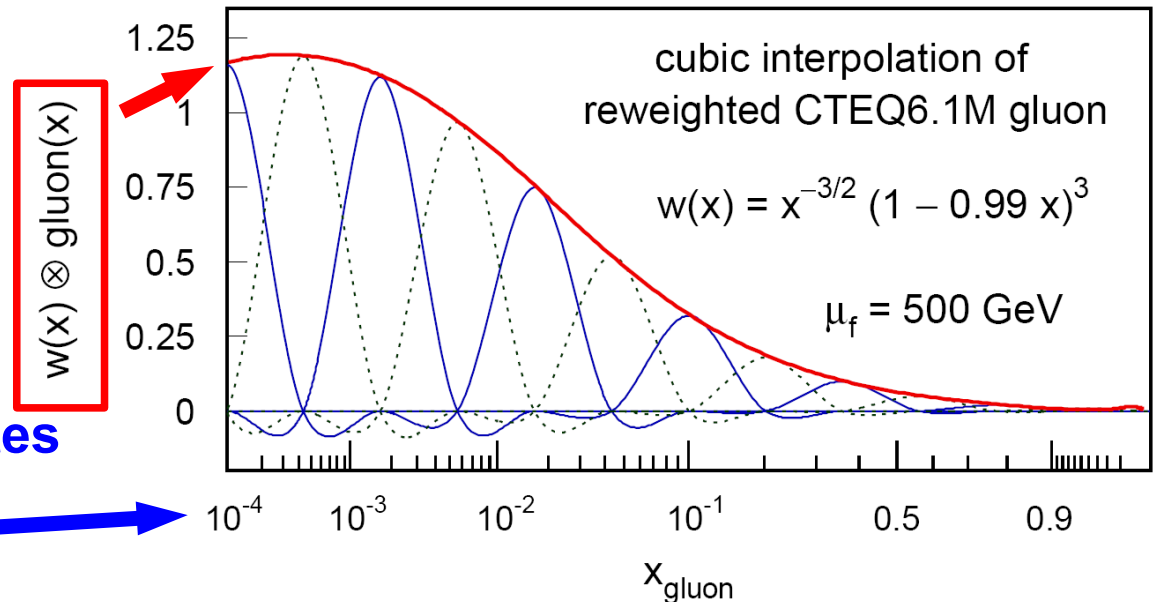
**Mehr dazu:**  
 (T.Kluge, M.Wobisch, KR)

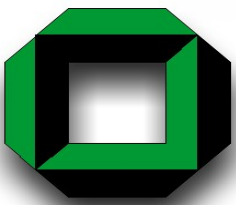
<http://hepforge.cedar.ac.uk/fastnlo>

**Ähnliches Projekt: NLO-GRID**  
 (D.Clements, C.Gwenlan,  
 C.Buttar, G.Salam, T.Carli,  
 A.Cooper-Sarkar, M.Sutton)

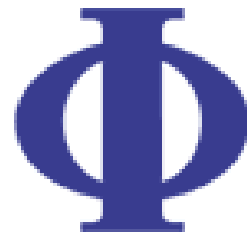
**Äquidistantes Binning in:**

$\sqrt{\log(1/x)}$





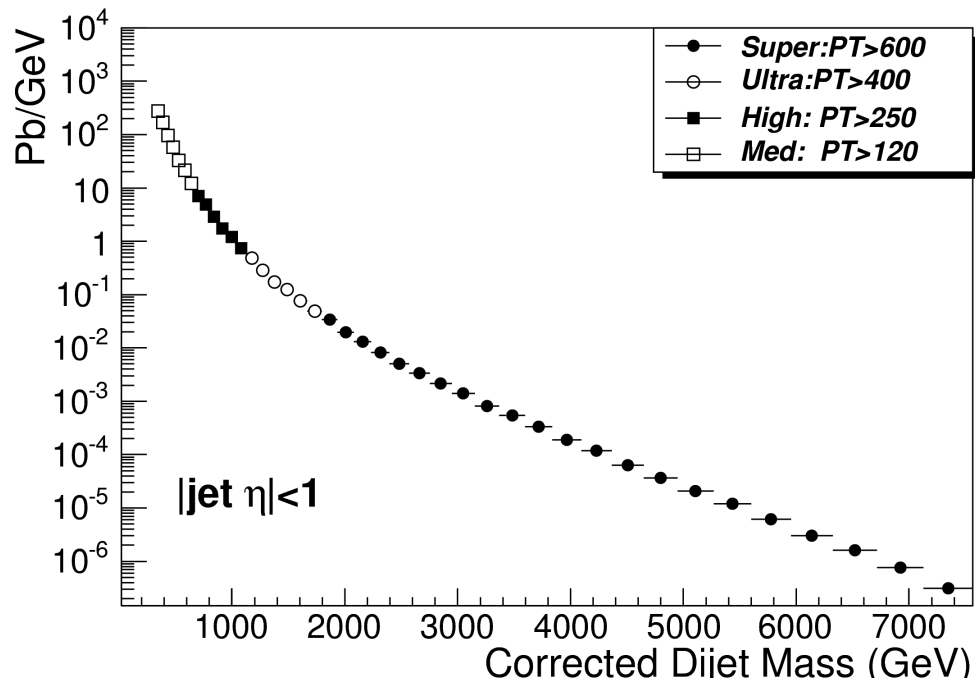
# Zweijetmassen



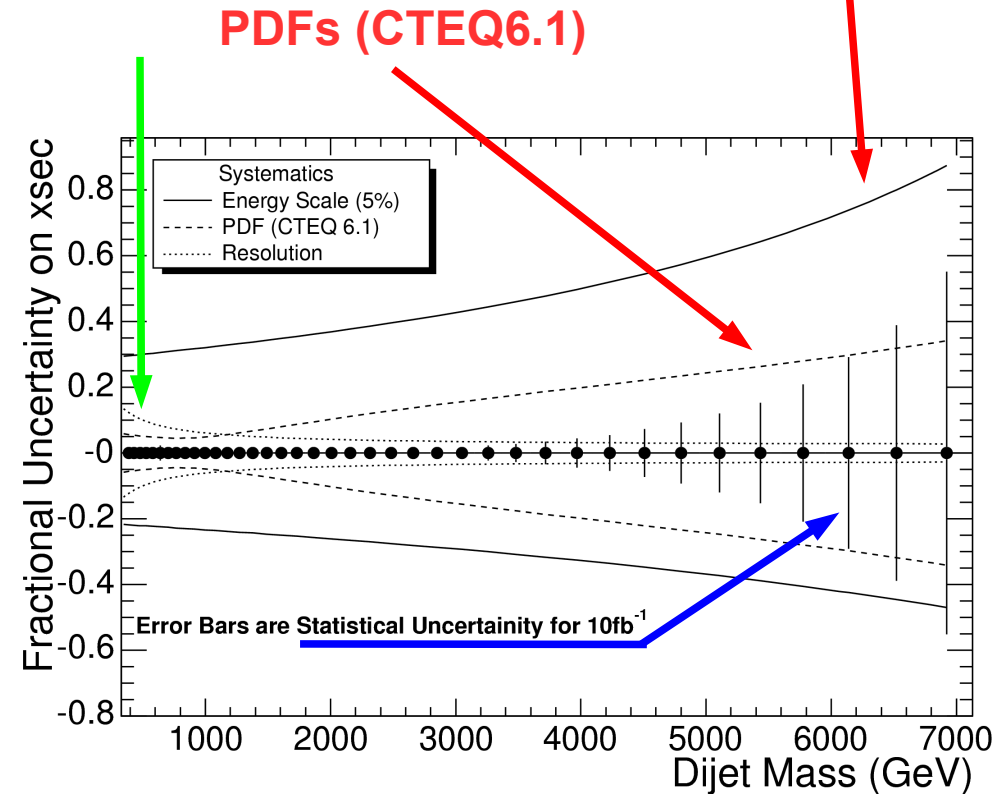
Vergleiche messbaren Wirkungsquerschnitt mit Modellen neuer Physik  
Besser noch (Energieskala ...): Winkel zwischen den Jets

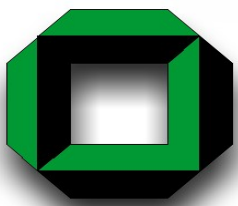
Calorimeter smearing (resolution) Abs. jet energy scale ( $\pm 5\%$ )

## Zweijetmassenquerschnitt

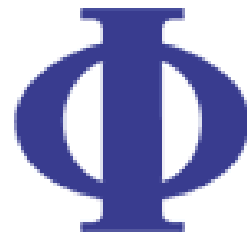


(Phys. TDR Vol. 2, CMS)





# *Produktion von Eichbosonen*

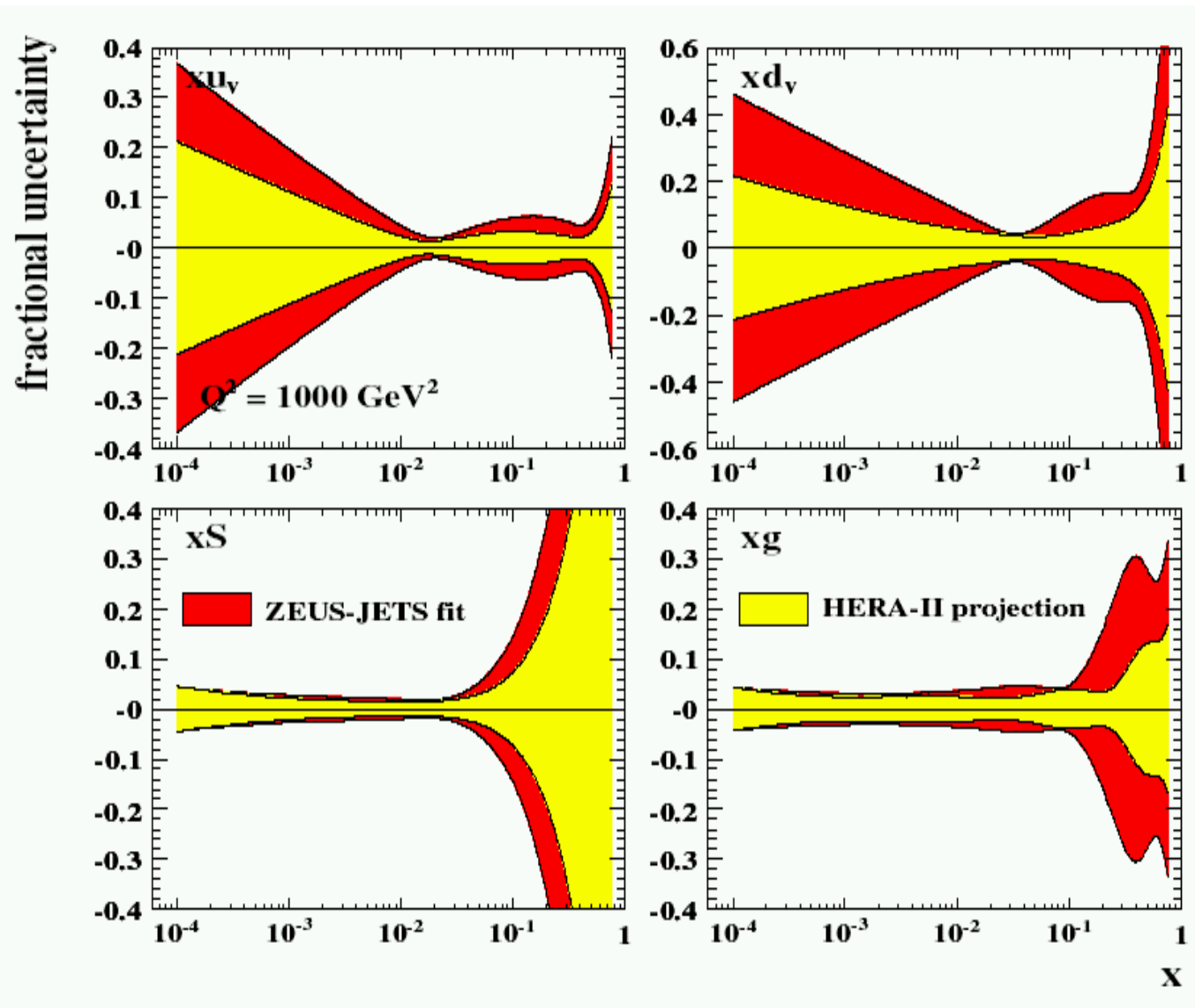
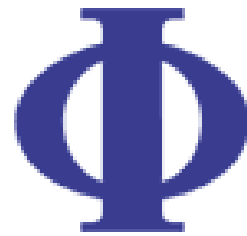
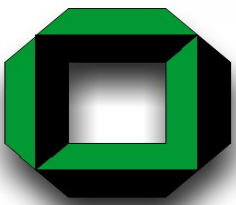


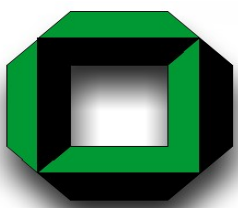
**Ausserdem Dijets Sherpa,  
Herwig++ (JIMMY)**

## Verfügbare Rechnungen, e.g.:

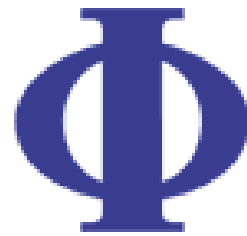
- LO MEPS: Pythia
- Mod. MEPS (MLM): ALPGEN
- NLO: PHOX



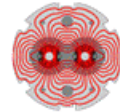




# LHC Fortschritt



28.02.2007

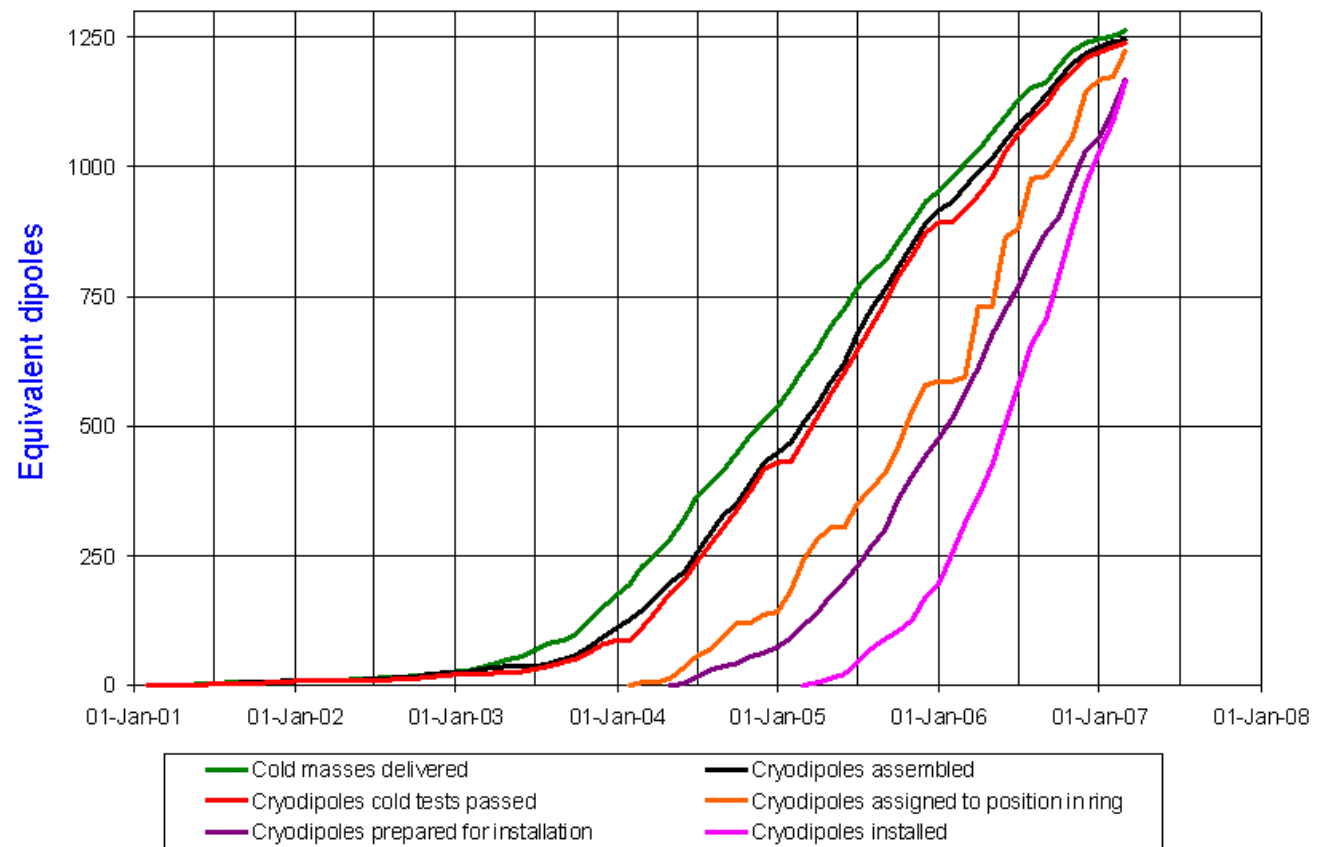


LHC Progress Dashboard



**Die letzten Dipole sollten bald installiert sein.**

Cryodipole overview



**Anzahl: 1232**

**Gewicht: je 35 t**

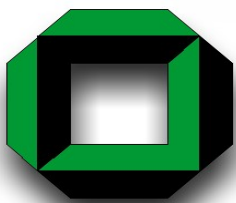
**Länge: 14.3 m**

**Magnetfeld: 8.4 T**

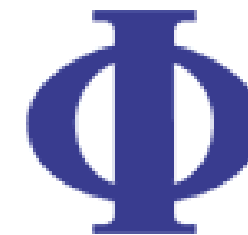
**Strom: 11700 A**

Updated 28 Feb 2007

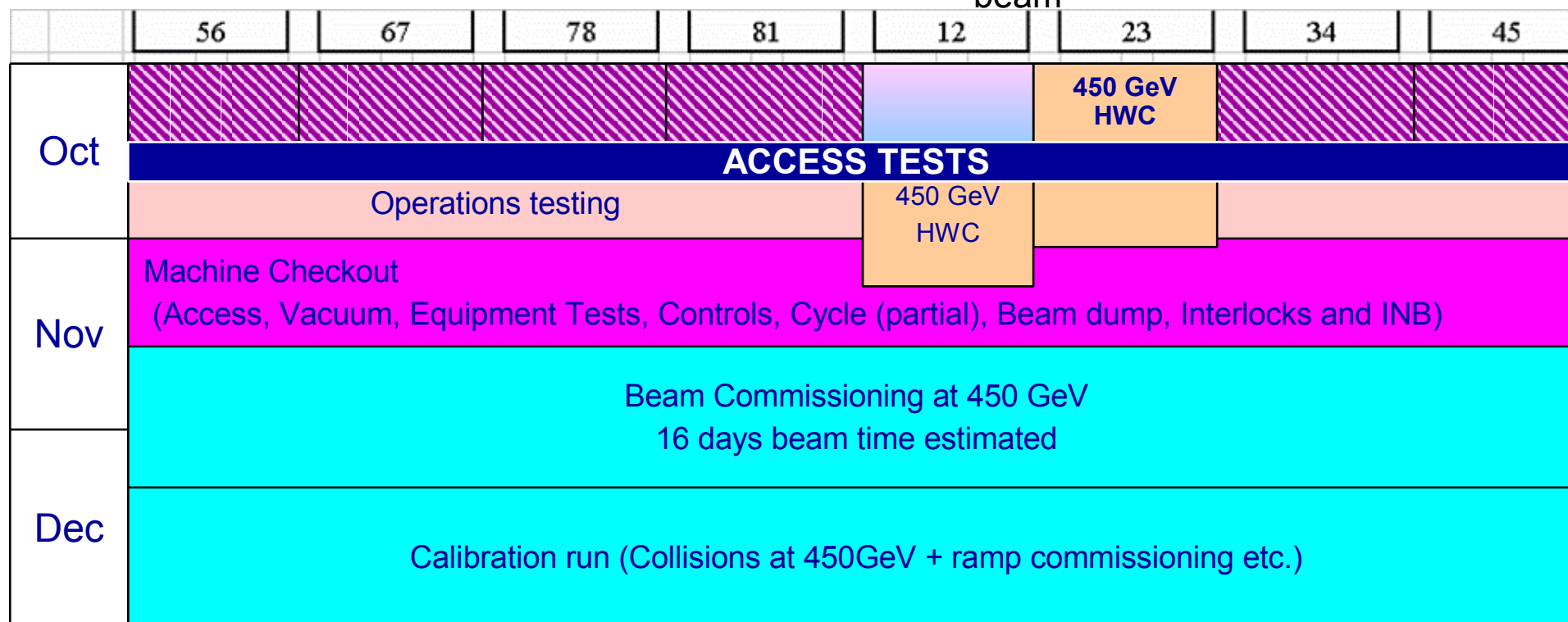
Data provided by D. Tommasini AT-MCS, L. Bottura AT-MTM

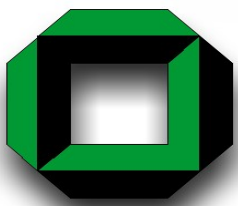


# LHC Start-up, 2007

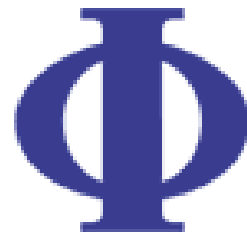


- M. Lamont, September 2006:
  - ➔ Calibration run 2007: 3 weeks collisions with:
  - ➔  $L \approx 1.2 \cdot 10^{28} - 2.6 \cdot 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ ,  $E_{\text{beam}} = 450 \text{ GeV}$



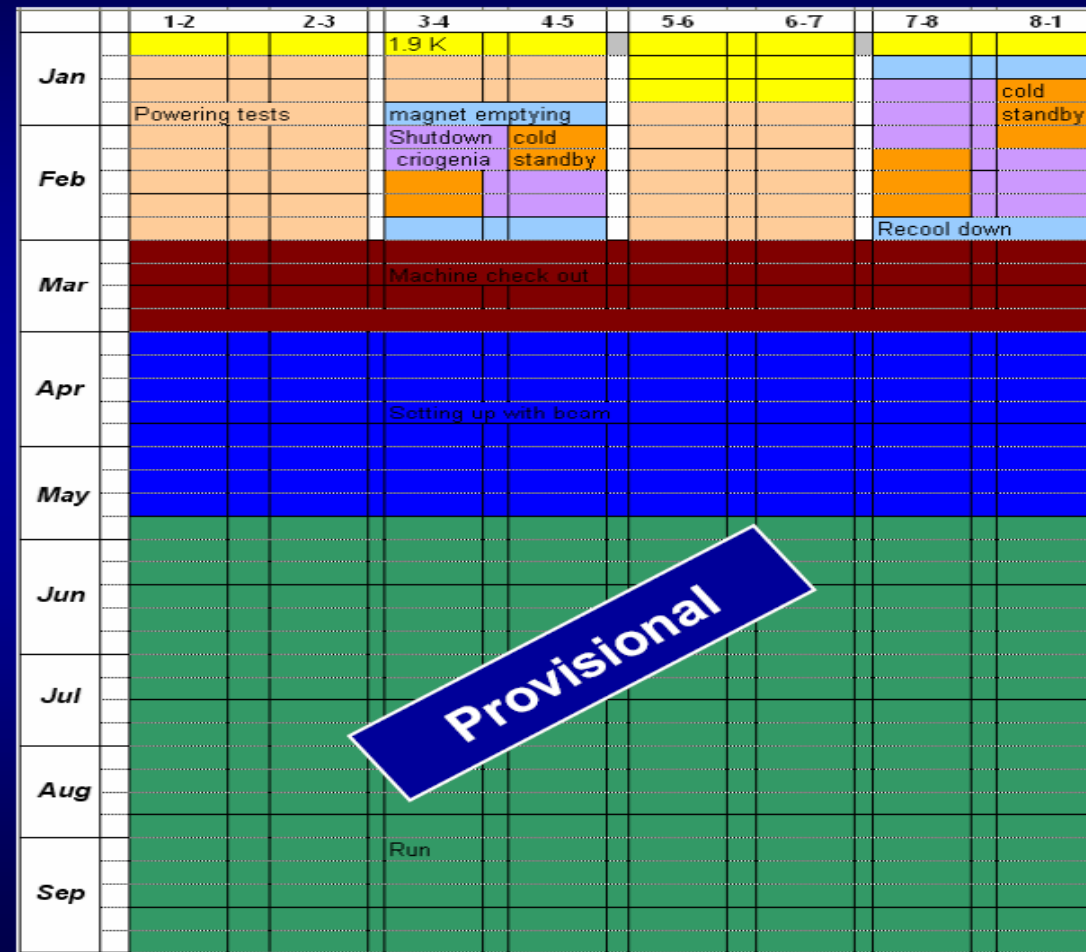


# LHC Start-up, 2008



M. Lamont, September 2006

Should look something like...

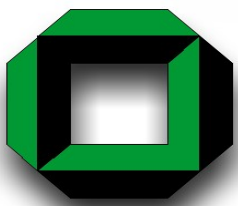


Hardware commissioning to 7 TeV

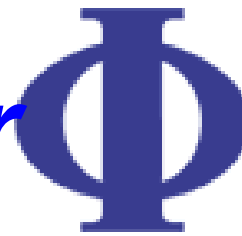
Machine Checkout ≈ 1 month

Commissioning with beam ≈ 2 months

Pilot Physics ≈ 1 month

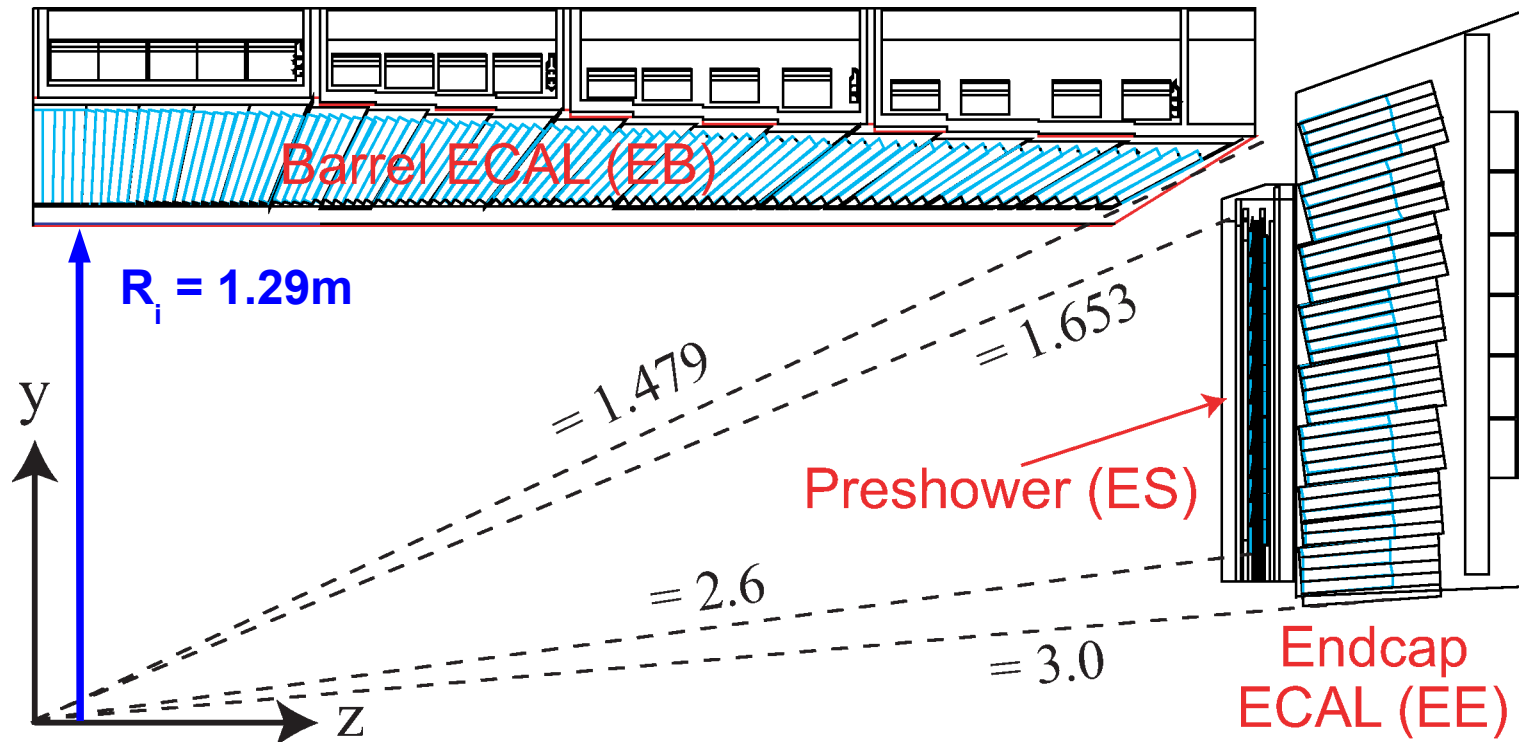


# Electromagnetic Calorimeter



## Barrel (EB):

- $\eta$  segments:  $2 \times 85$
- $\phi$  segments: 360
- 61200 crystals ( $\text{PbWO}_4$ ,  $26 X_0$ )
- $\Delta\eta \times \Delta\phi \approx 0.0174 \times 0.0174$



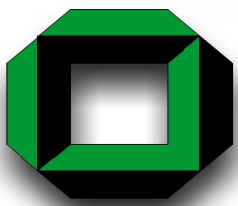
## Energy resolution from test beam:

$S = 3.63\%$ ,  $N = 124 \text{ MeV}$ ,  $C = 0.26\%$

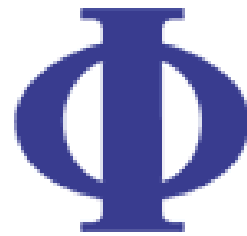
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2$$

## Endcaps (EE):

- (x,y) grid on two halves
- front face  $28 \times 28 \text{ mm}^2$
- $2 \times 2 \times 3662$  crystals = 14648 ( $\text{PbWO}_4$ ,  $25 X_0$ )



# Hadronic Calorimeter



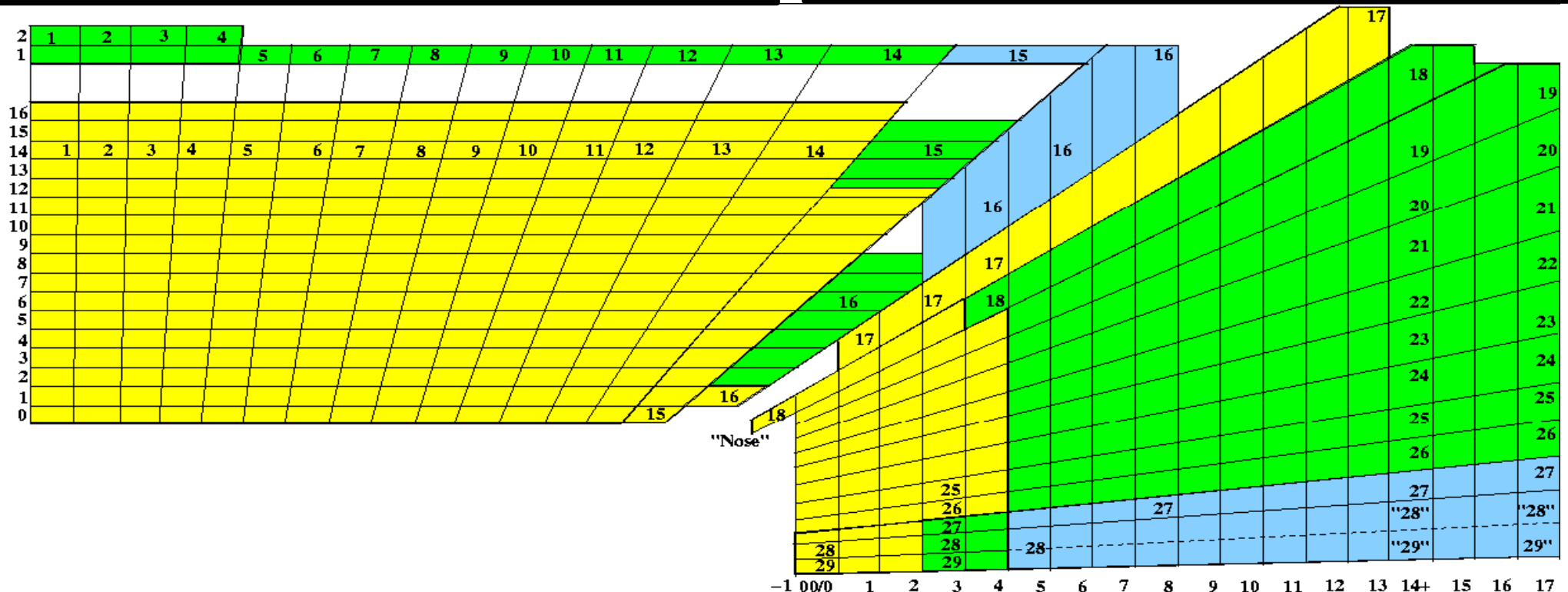
## HCAL (tower structure):

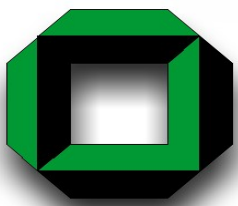
- Barrel (HB):  $|\eta| < 1.4$ , 2304 towers
- Endcaps (HE):  $1.3 < |\eta| < 3.0$ , „ towers
- Outside coil (HO):  $|\eta| < 1.26$  (tail catcher)  
→ 4608 towers (Plastic scintillator tiles,  $\approx 10 \lambda_N$ )
- $\Delta\eta \times \Delta\phi \approx 0.087 \times 0.087 \rightarrow 0.350 \times 0.175$

- Forward (HF):  $2.9 < |\eta| < 5.0$  (not shown)  
→ 2 x 900 towers (Quartz fibers,  $\approx 10 \lambda_N$ )  
→  $\Delta\eta \times \Delta\phi \approx 0.111 \times 0.175 \rightarrow 0.302 \times 0.350$

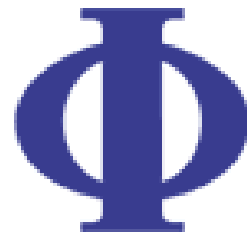
## CASTOR calorimeter (not shown):

- $5.1 < |\eta| < 6.5$ ,  $\approx 22 X_0$ ,  $\approx 10 \lambda_N$

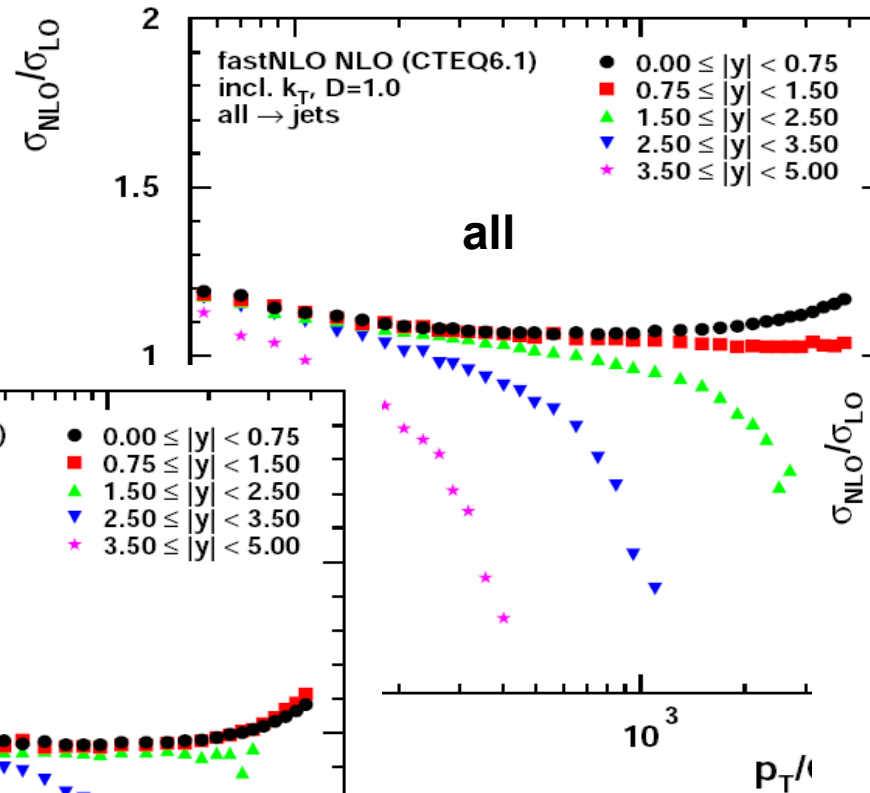
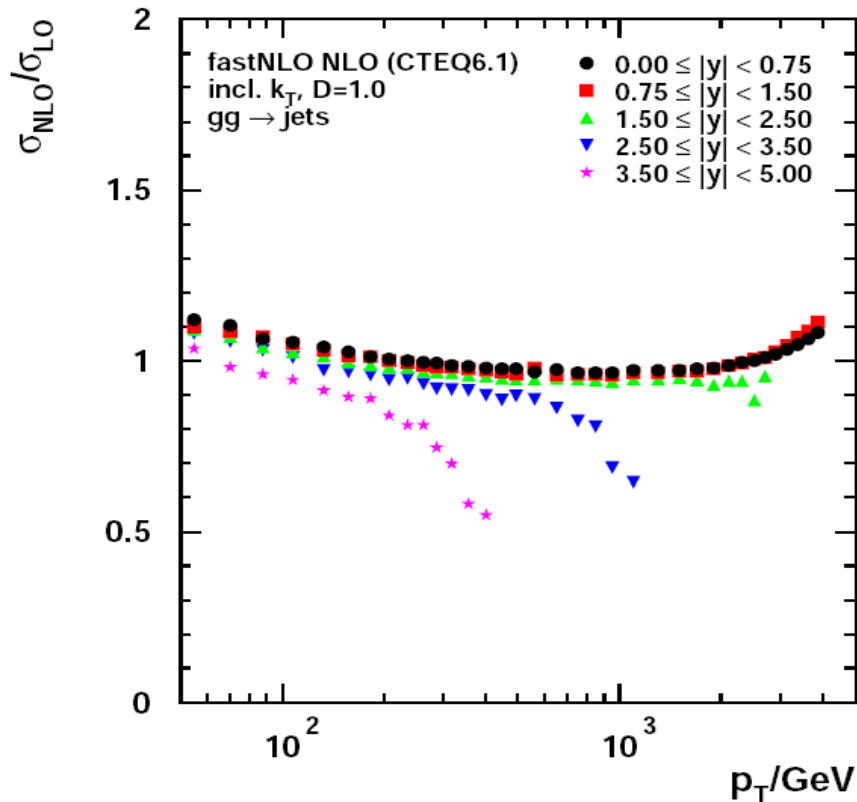




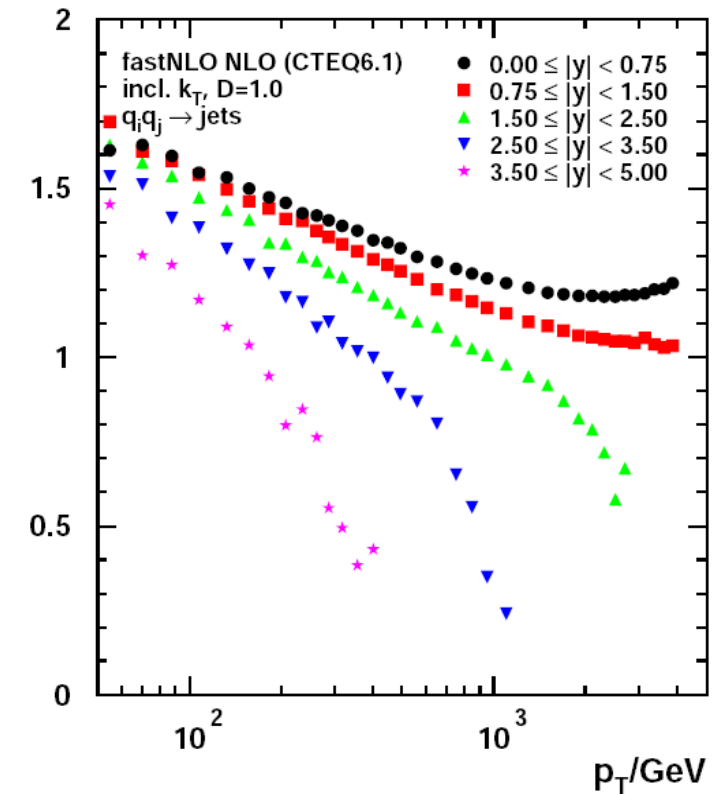
# K Factors

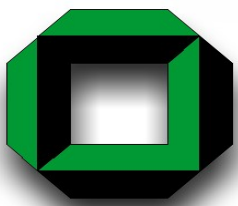


gg subprocess  
dominant at low  $p_T$

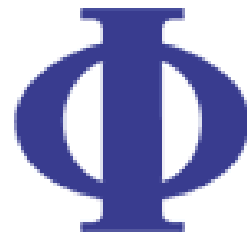


$q_i q_j$  subprocess  
dominant at high  $p_T$





# PDF Table



| Prozess       | Theorie                | PDF          |
|---------------|------------------------|--------------|
| Jets          | JETRAD, NLOJET++ (NLO) | High x gluon |
| Photon + Jets | PHOX (NLO)             |              |
| W + Jets      | MCFM (NLO)             |              |
| Z + Jets      | MCFM (NLO)             |              |
| Drell-Yan     |                        | Quarks       |
| DIS           | NLOJET++ (NLO)         | Quarks       |