

## QCD, Structure Functions, Jets

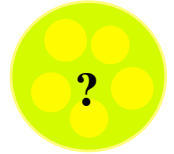
- History of the Strong Interaction
- QCD / QED
- Proton-structure: structure functions
- hadronisation
- factorisation
- hadron jets
- measurement of  $\alpha_s$
- search for new physics (BSM)

# History of Strong Interactions (1)

**1932:** discovery of **neutrons**

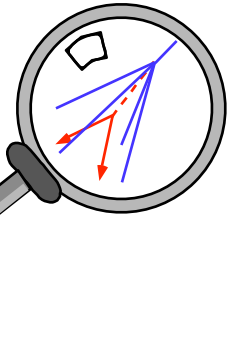


**1933:**  $\vec{\mu} \cong 2.5 \frac{e}{2 m_p} \vec{\sigma} \Rightarrow$  **substructure** of the protons

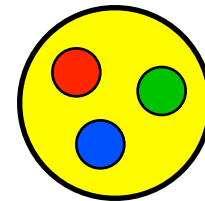


**1947:** discovery of  $\pi$ -mesons and long-living V-particles ( $K^0$ ,  $\Lambda$ ) in **cosmic rays**

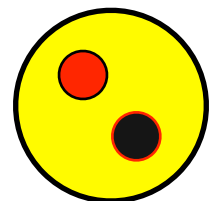
**1953:** V-particles produced at **accelerators**  
new inner quantum number ("**strangeness**").



**1964:** static **quark-model**;  
new inner quantum number: **colour**



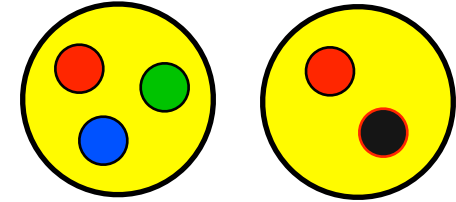
Baryon  
(p,n,  $\Lambda$ ,...)



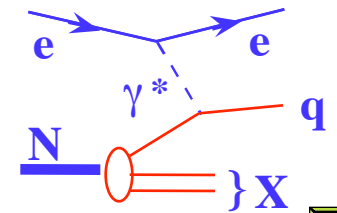
Meson  
( $\pi$ ,K,...)

# History of Strong Interactions (2)

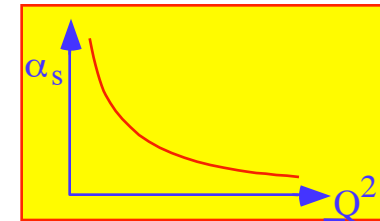
**1964:** static **quark model** ;  
new inner quantum number: **Farbe**.



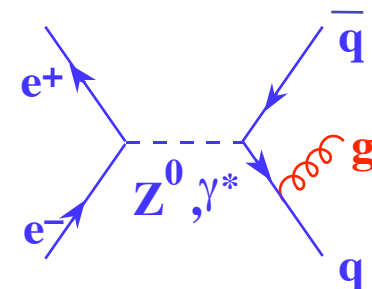
**1969:** dynamic **parton model** :



**1973:** concept of **asymptotic freedom** ;  
**Q**uantum **C**hromo **D**ynamics.



**1975:** **2-Jet structure** in  $e^+ e^-$  - annihilation:  
confirmation of **quark-parton-model**.

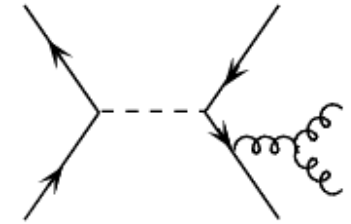
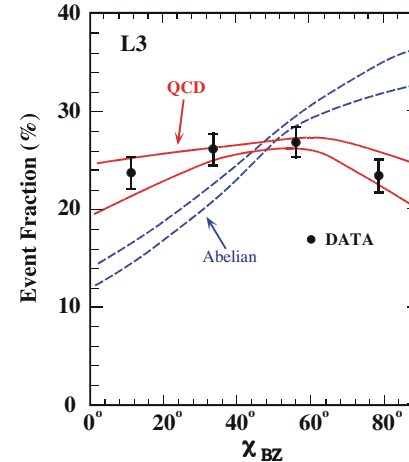


**1979:** discovery of **gluons** in **3-Jet-events**  
of  $e^+ e^-$  -annihilations.



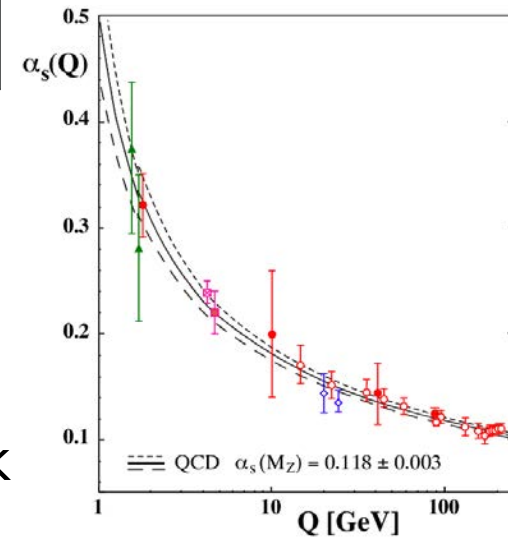
# History of Strong Interactions (3)

**1991:** exp. signature of the  
gluon self coupling



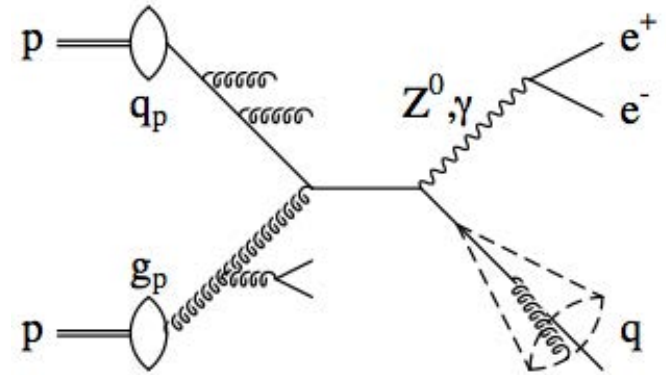
**1990-2000:** confirmation of  
asymptotic freedom

**2004:** Nobel Prize (concept of A.F.) to  
D. Gross, H.D. Politzer und F. Wilczek

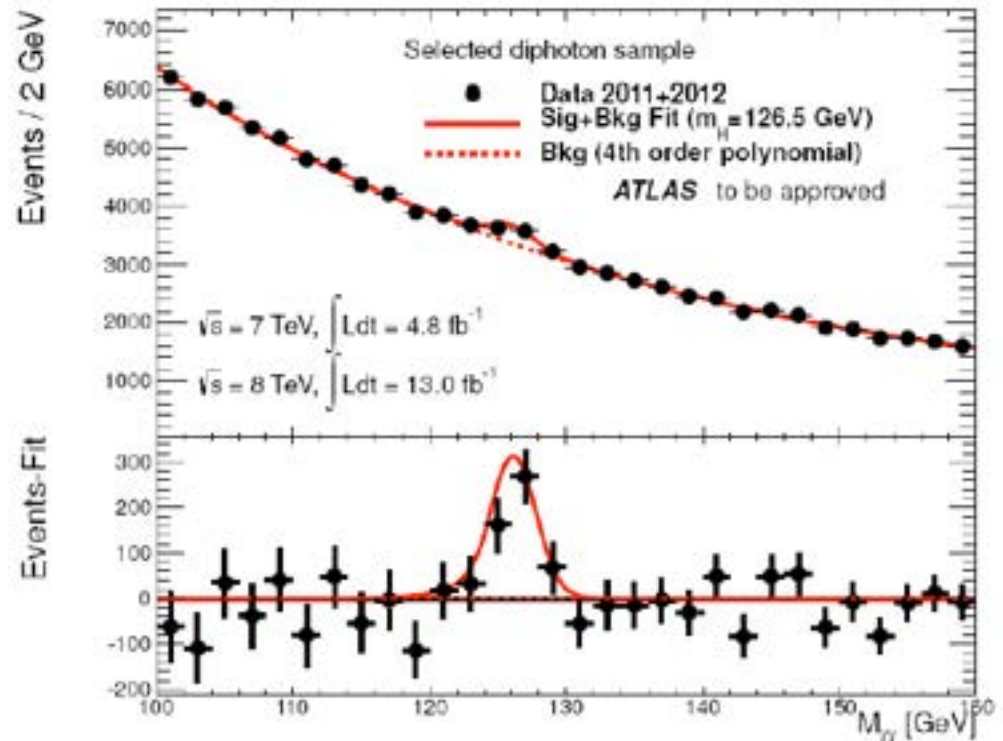
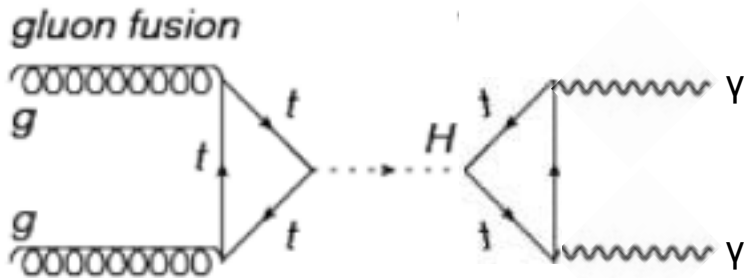


# History of Strong Interactions (4)

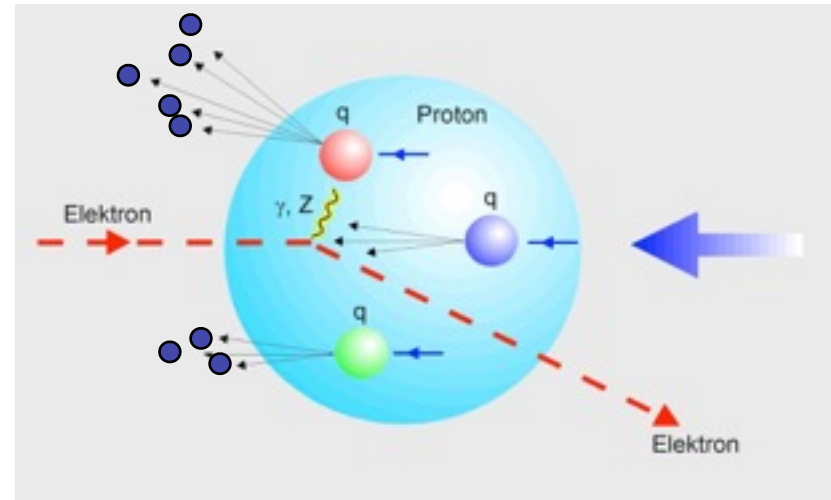
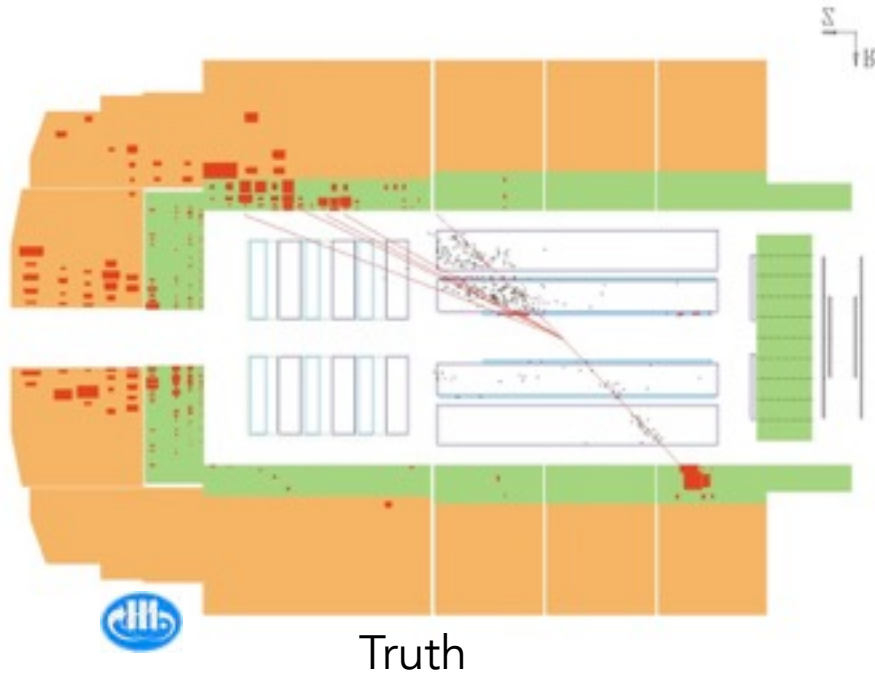
>2004: QCD as background in searches for New Physics (BSM)



example: Higgs search



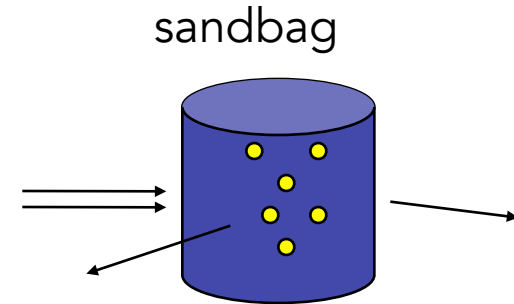
# Quarks in the proton: model and experiment



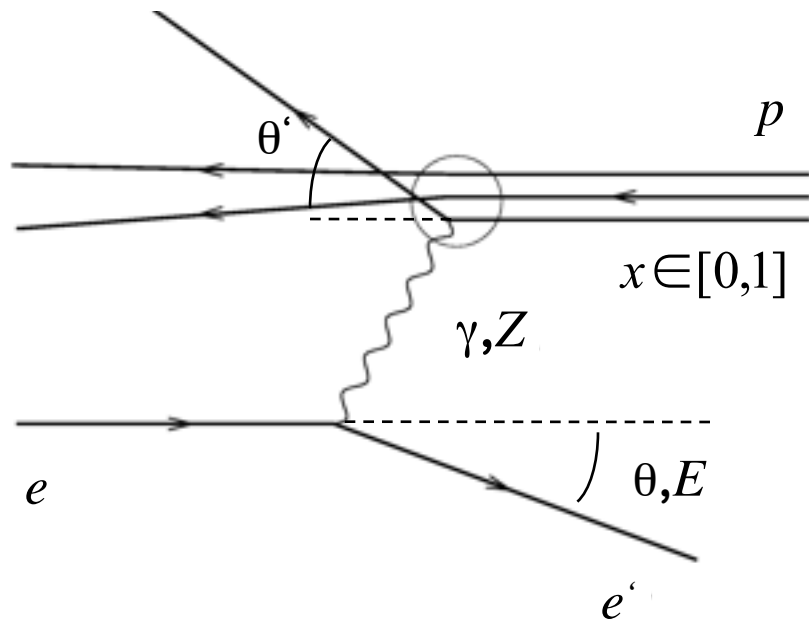
experiment: measurement of scattered electrons

result: too many electrons with large scattering angles (qualitatively similar to experiments of Rutherford, 1911)

explanation: the proton has „hard“ components: **QUARKS**

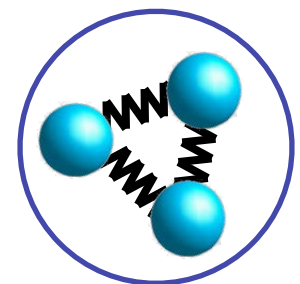
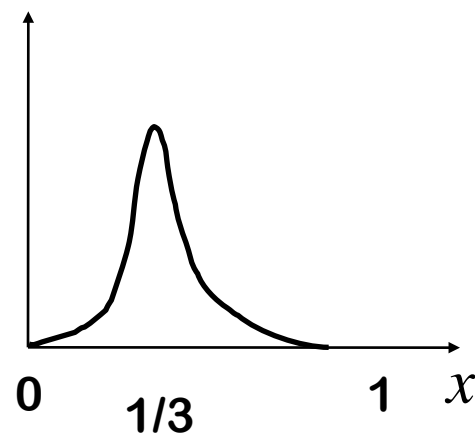
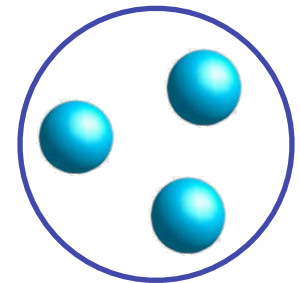
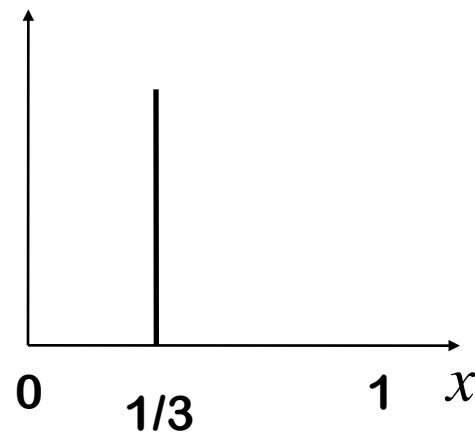
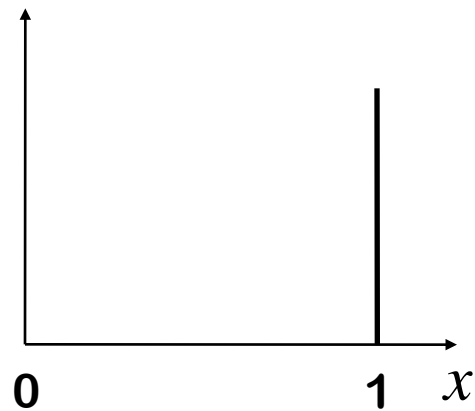


# Quarks in the proton ?



measurement of **scattering angle** and **energy** of electrons  
(2 given entities):

determine **angle** and **momentum fraction  $x$**   
of scattering partner of electron  
(2 unknowns)



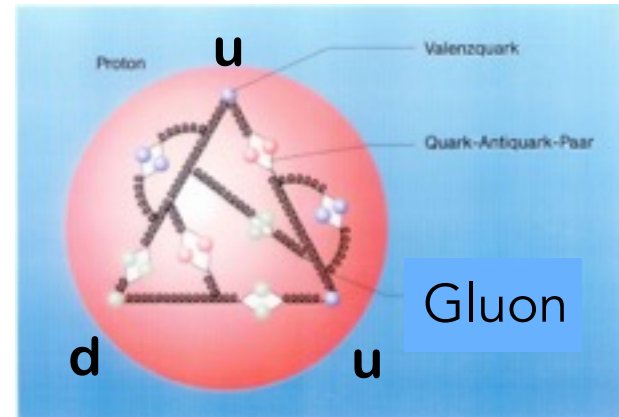
(Ch. Kiesling)



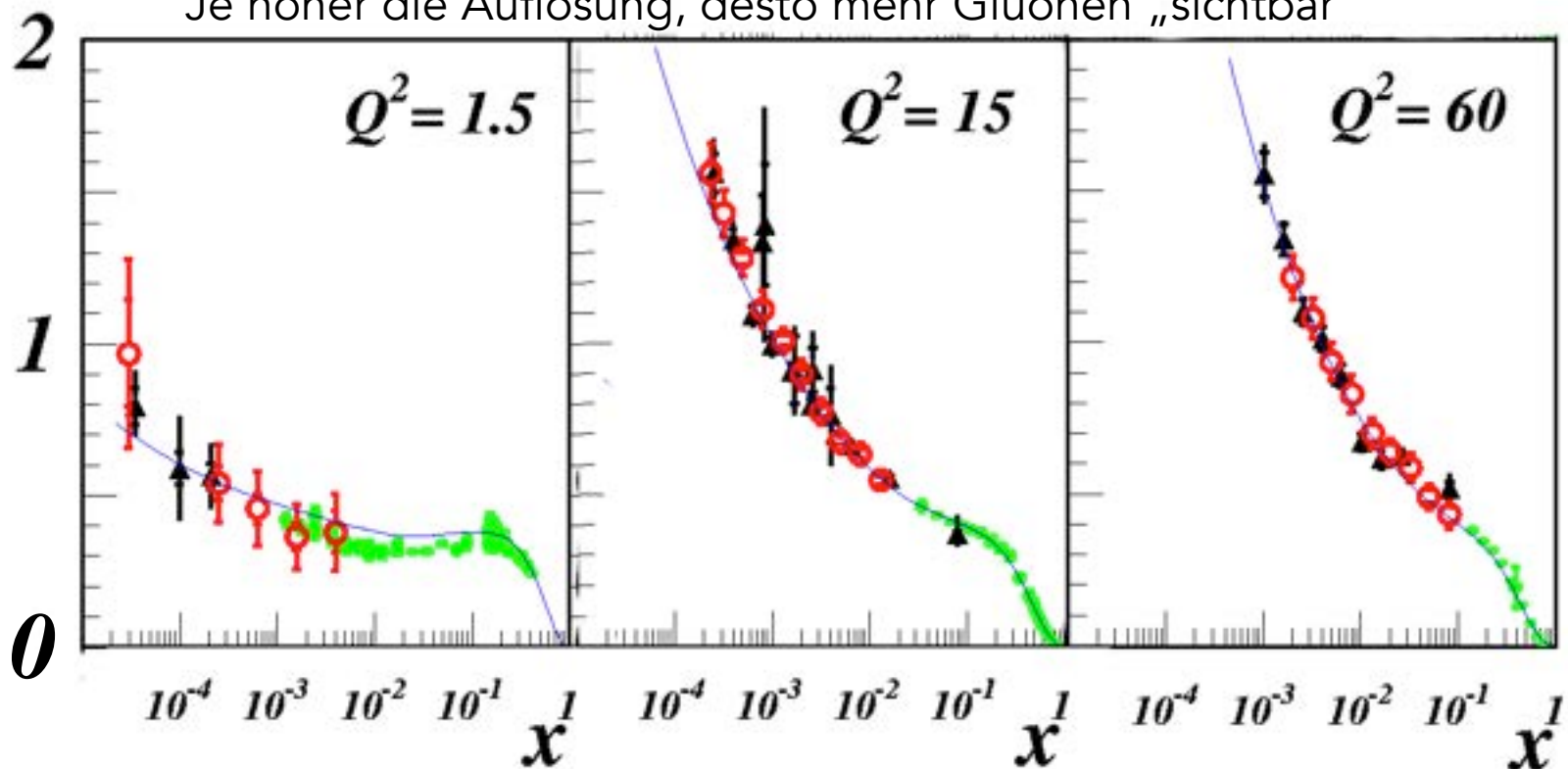
# Quarks and gluons in the proton !

measurement of momentum fraction demonstrates complicated „linner life“ of the protons:

only half of momentum is carried by quarks ;  
the rest is carried by „force carriers“,  
the gluons


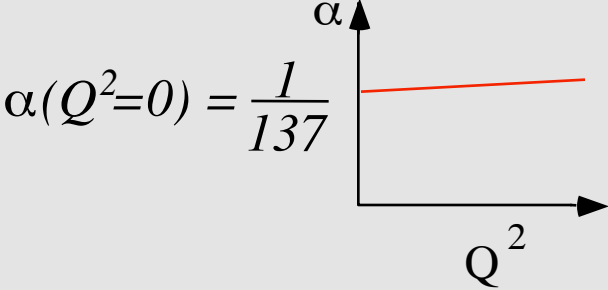
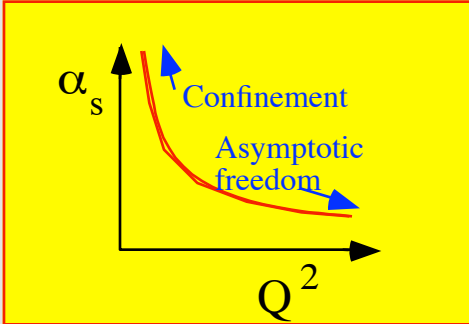


Je höher die Auflösung, desto mehr Gluonen „sichtbar“





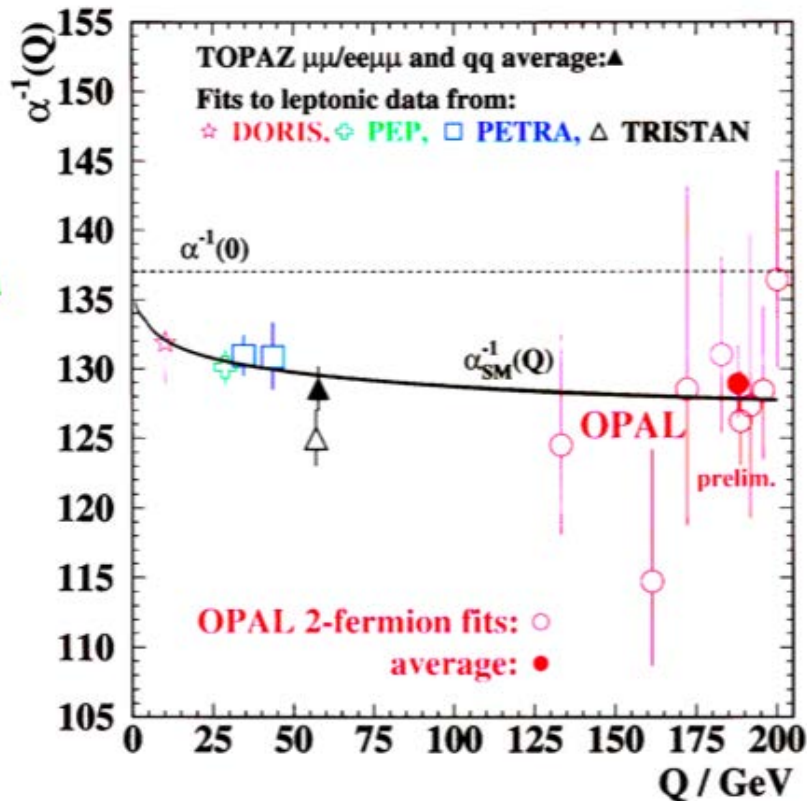
# properties of QED and QCD:

	QED	QCD
<i>fermions</i>	<i>leptons (e, μ, τ)</i>	<i>quarks (u, d, s, c, b, t )</i>
<i>force couples to</i>	<i>electric charge</i>	<b>3 color-charges</b>
<i>exchange quantum</i>	<i>photon (γ) (carries no charge)</i>	<i>gluons (g) (carry 2 color charges)</i> ⇒ 
<i>coupling "constant"</i>	$\alpha(Q^2=0) = \frac{1}{137}$ 	$\alpha_s(Q^2 \approx M_Z^2) \approx 0.12$ 
<i>free particles</i>	<i>leptons (e, μ, τ)</i>	<i>(color neutral bound states of q and q̄)</i> <b>Hadronen</b>
<i>theory</i>	<i>perturbation theory up to O(α<sup>5</sup>)</i>	<i>perturbation theory up to O(α<sub>s</sub><sup>4</sup>)</i>
<i>precision achieved</i>	$10^{-6} \dots 10^{-7}$	$0.1\% \dots 20\%$

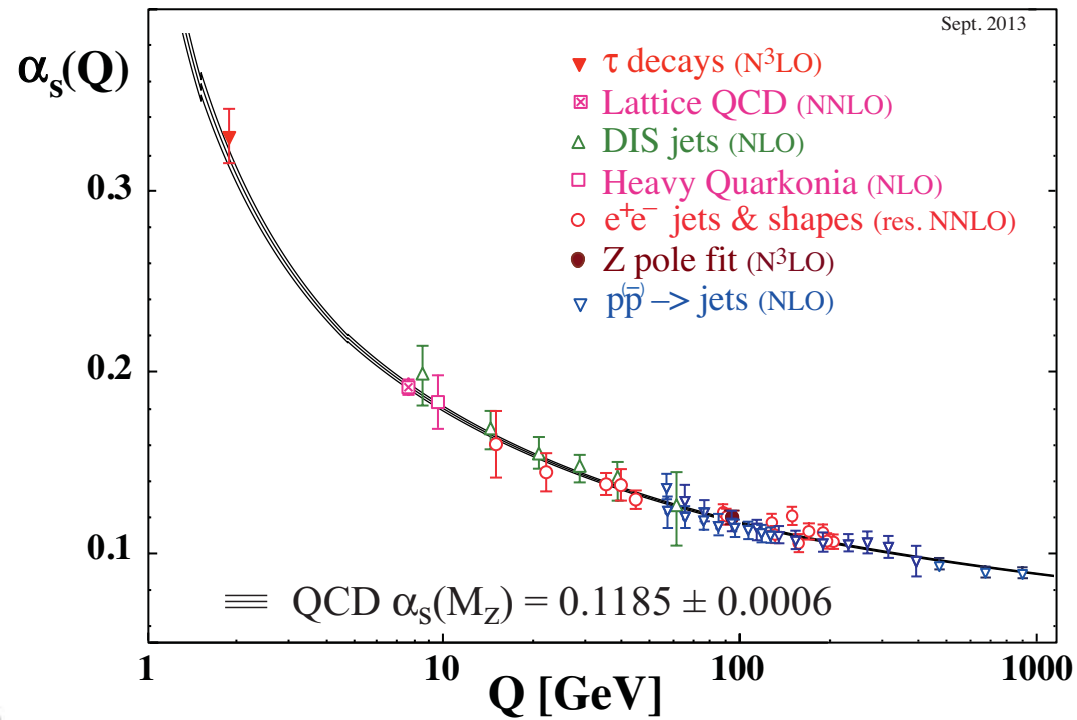
# energy dependence of coupling "constants":

- verified by high precision measurements

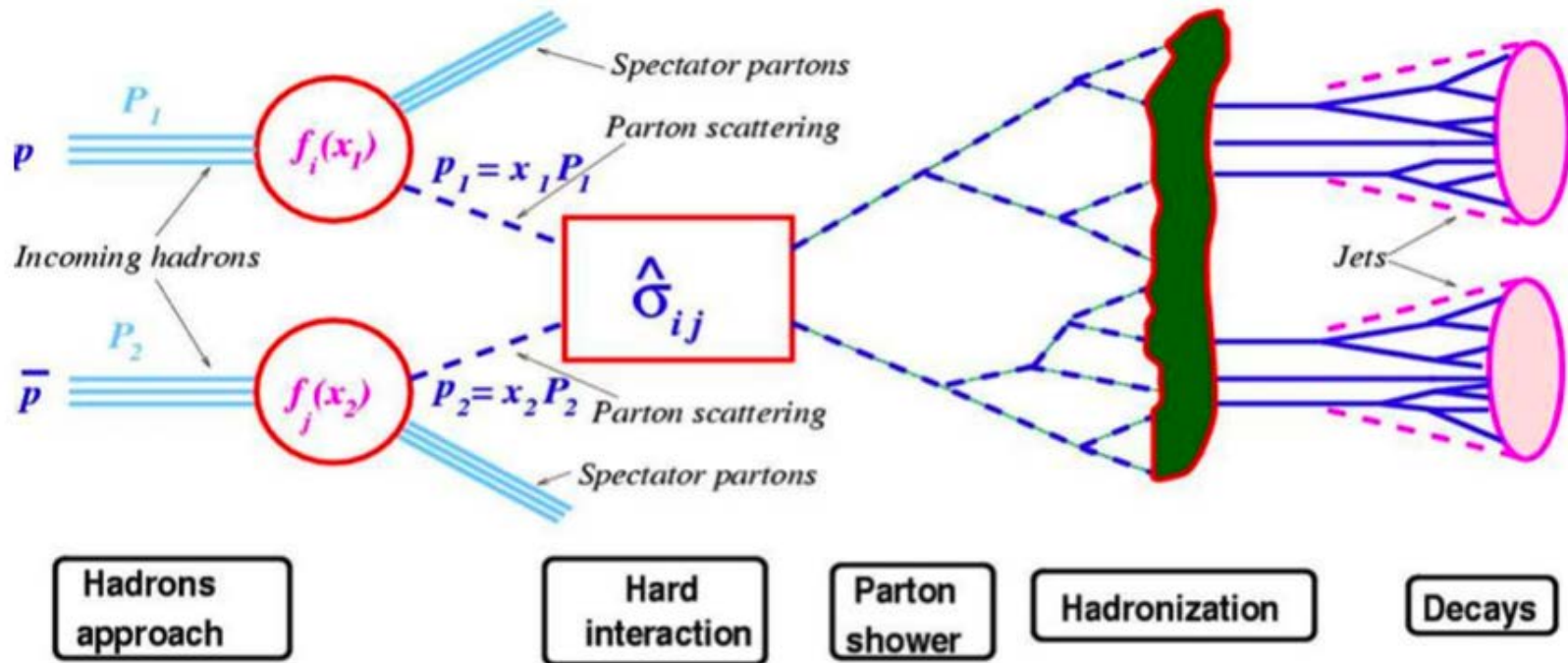
QED



QCD



# Theoretische Beschreibung hadronischer Prozesse

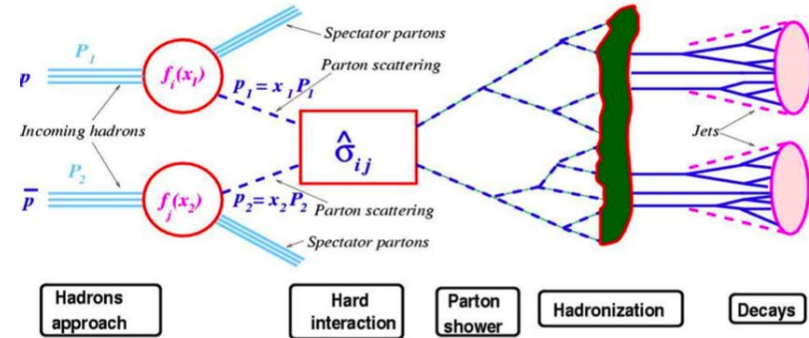


- Beschreibung der einzelnen Unterprozesse :

- $f(x, Q^2)$  : Partonendichte ( $q, g$ ) im Proton [pdf]  
(Wahrscheinlichkeit, daß ein parton Bruchteil  $x$  des  $p$ -Impulses hat)
- $\hat{\sigma}_{ij}(Q^2)$  : "harter" QCD Wirkungsquerschnitt, z.B. von  $qq \rightarrow gg$ ;  $qg \rightarrow q'g'$
- parton shower: QCD Abstrahlung  $q \rightarrow qq$ ,  $g \rightarrow gg$ ,  $g \rightarrow qq$
- Hadronisation: Parametrisierung des Übergangs von  $q, g$  in Hadronen (Modelle!)
- Zerfälle: Parametrisierung nach Messungen und Spin-Statistik

# Faktorisierungstheorem:

$$\sigma_{ij} = f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}_{ij}(Q^2)$$



sowie sequentielle Anwendung der Prozesse "Parton Shower" und "Hadronisierung".

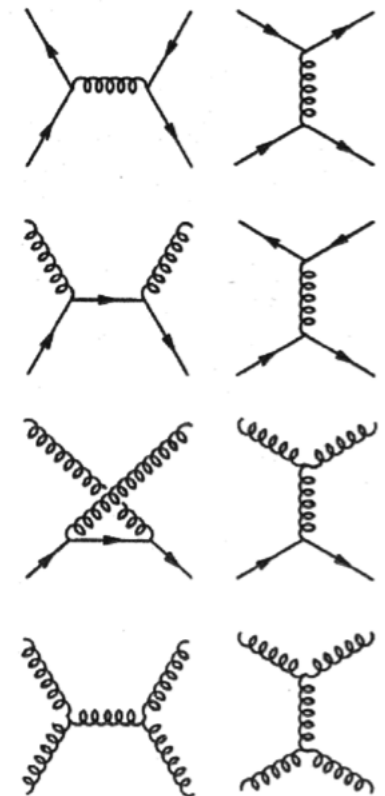
# Strukturfunktionen:

$$F_2(x, Q^2) = \sum e_q^2 x f(x, Q^2)$$

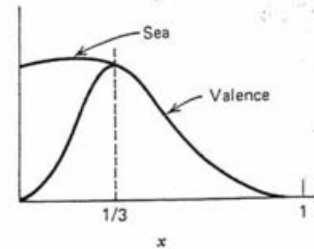
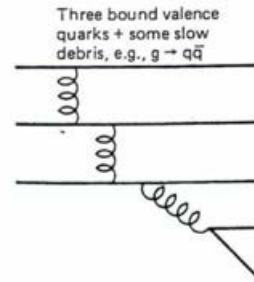
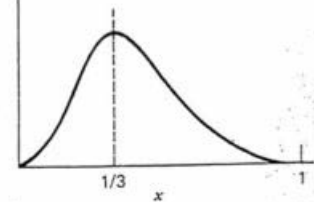
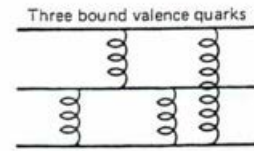
# QCD Störungstheorie:

Leading order (lo) Matrixelemente  
z.B. für 2→2 Prozesse:

(für Präzisionsmessungen sind mind. next-to-leading order (nlo) oder sogar nnlo Rechnungen notwendig!)



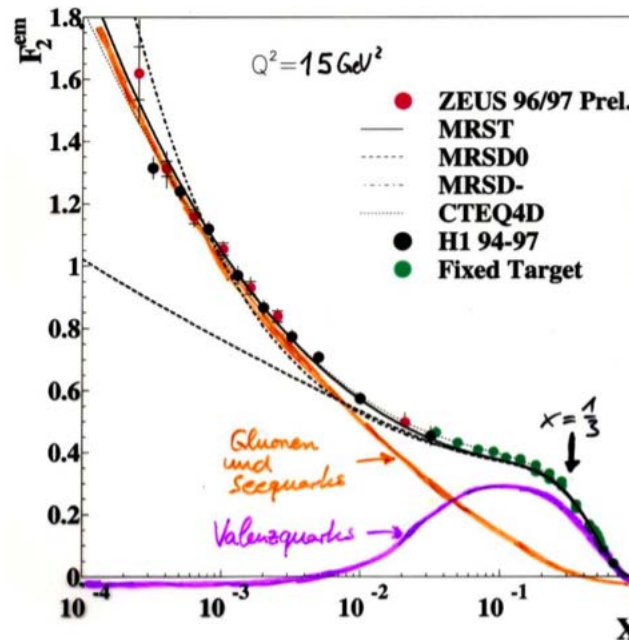
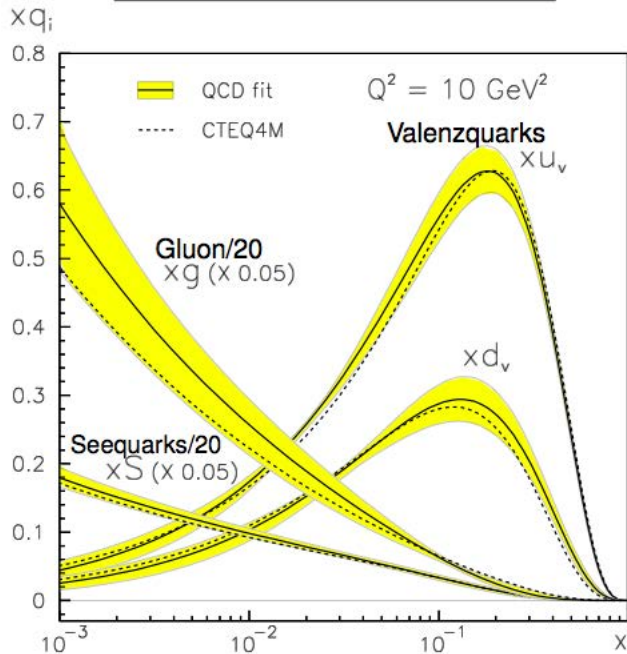
# proton structure



Small x

$$F_2(x) = \sum_{i=\substack{u,d,s,\dots \\ \bar{u},\bar{d},\bar{s},\dots,g}} e_i^2 x \cdot f_i(x)$$

$$F_2(x) = \sum_q e_q^2 x \cdot (q(x) + \bar{q}(x))$$





# proton structure (HERA + LHC)

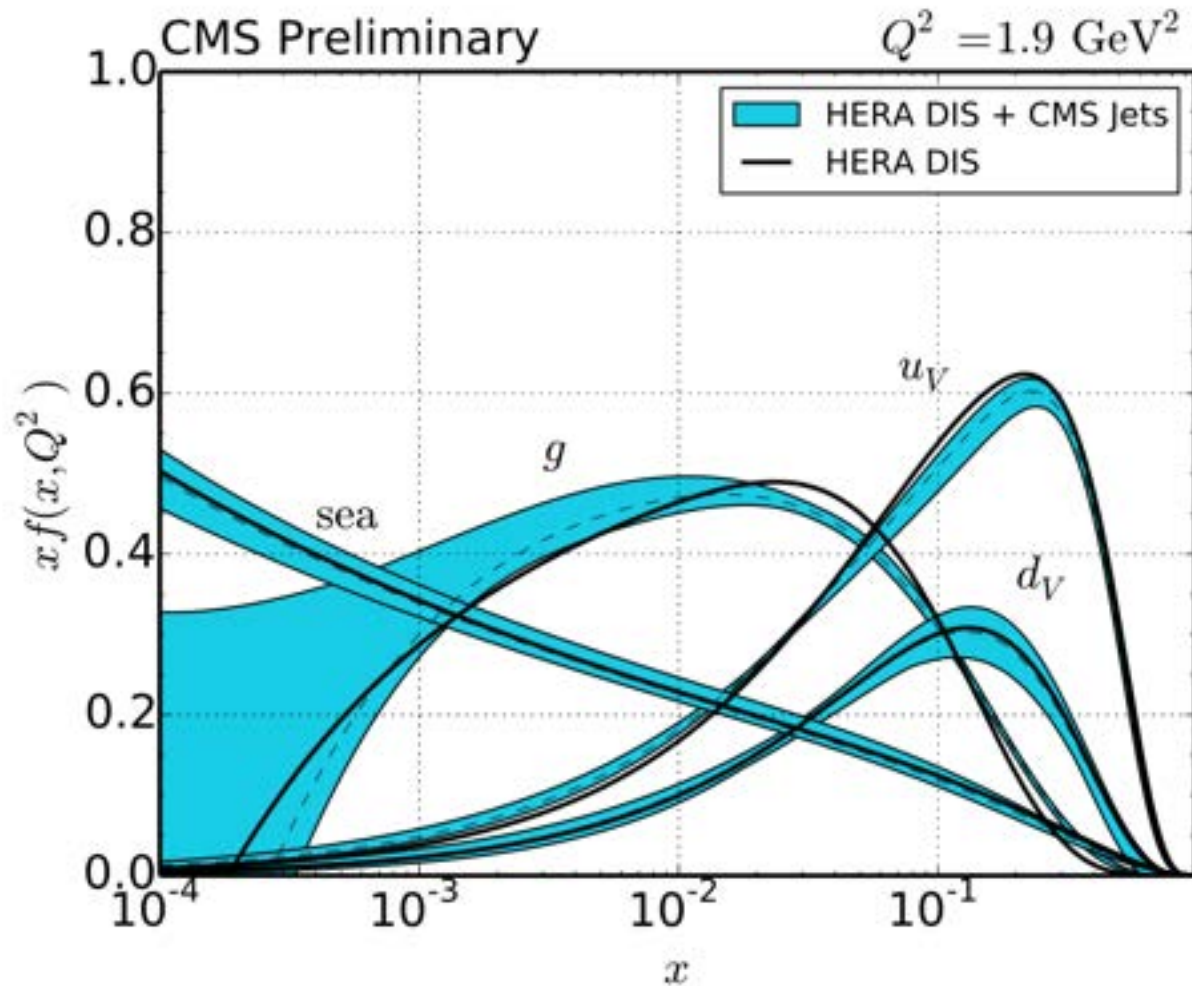
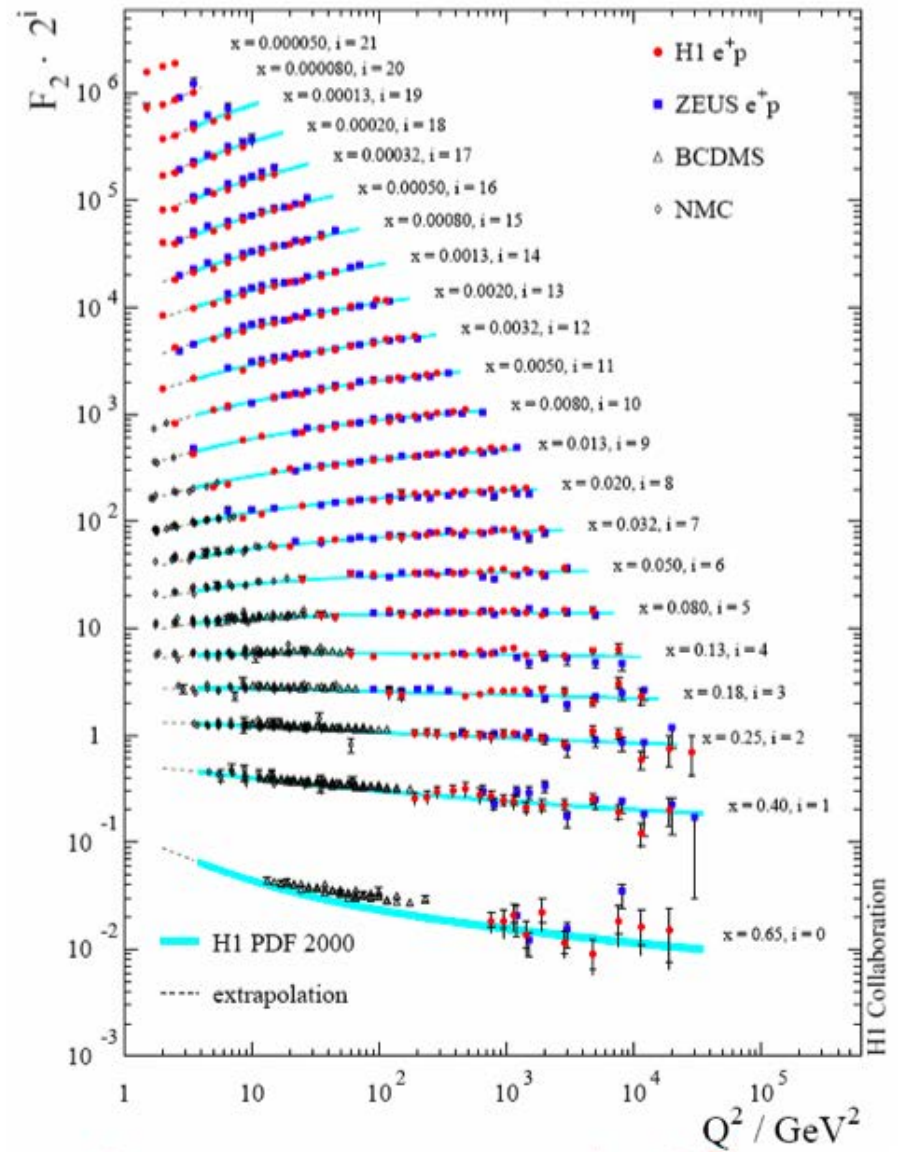
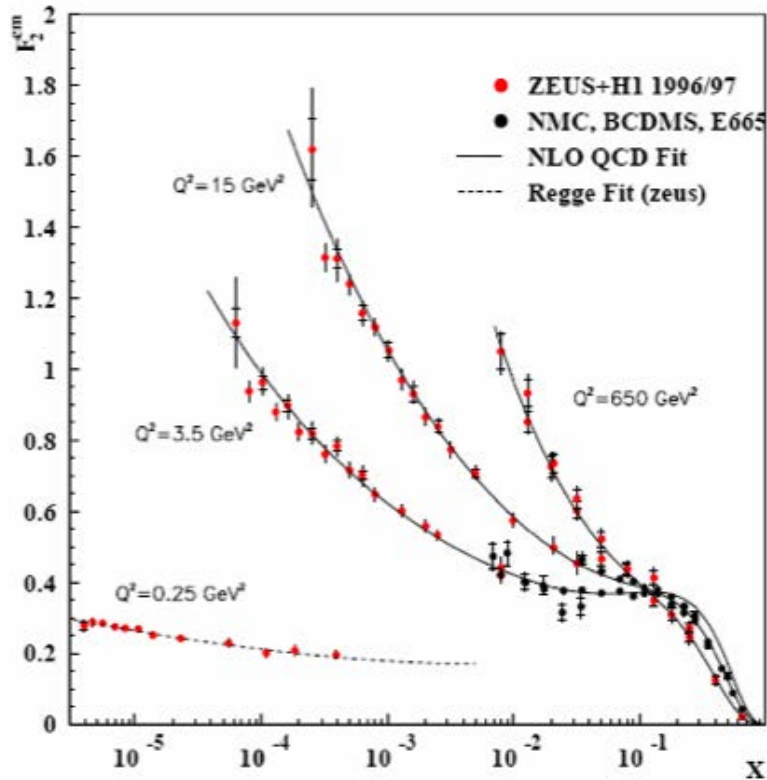


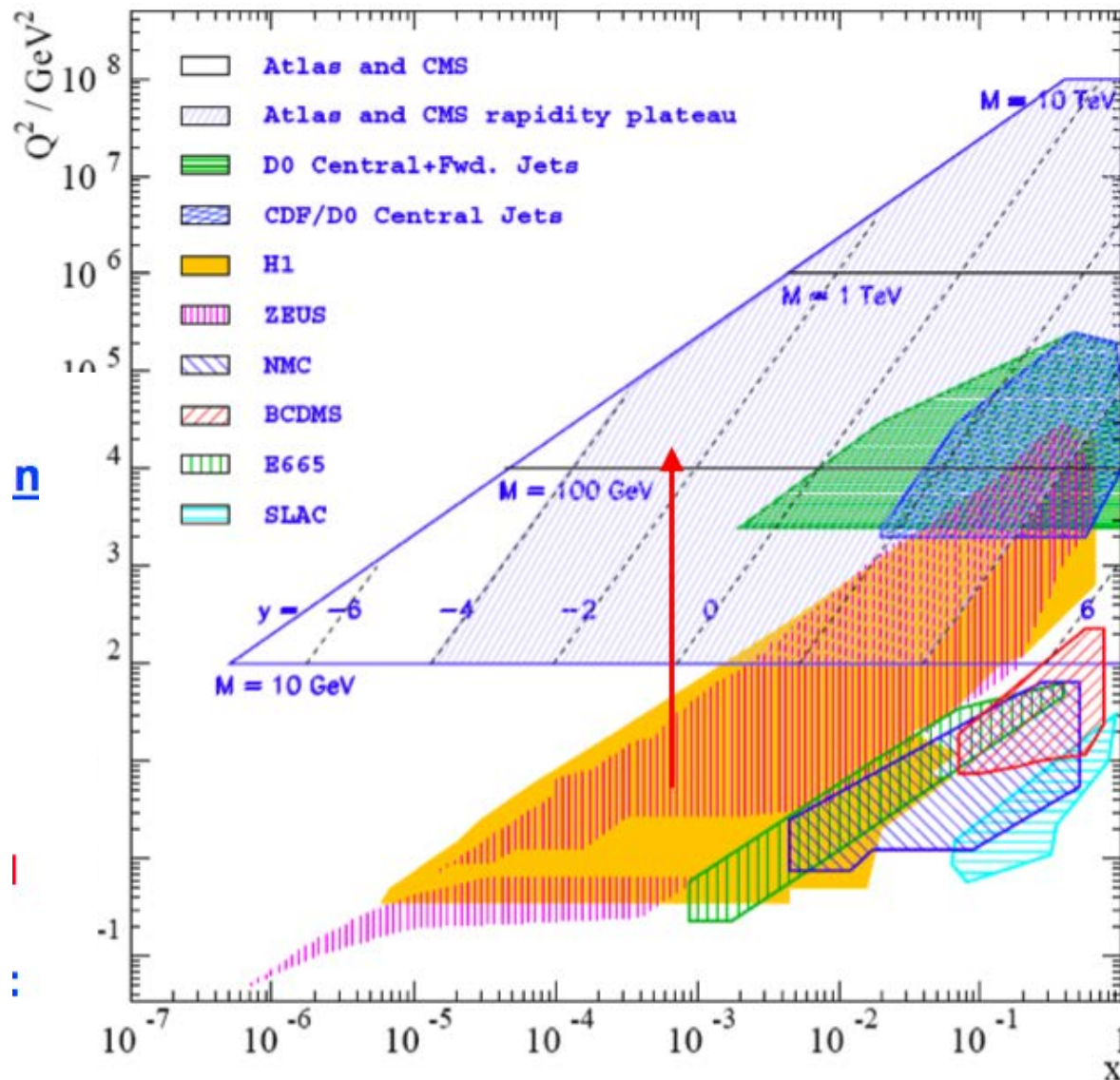
Figure 11: Overview of the gluon, sea, u valence, and d valence PDFs before (full line) and after (dashed line) including the CMS jet data into the fit. The PDFs are shown at the starting scale  $Q^2 = 1.9 \text{ GeV}^2$ . In addition the total uncertainty including the CMS jet data is shown as a band around the central fit.



# proton structure



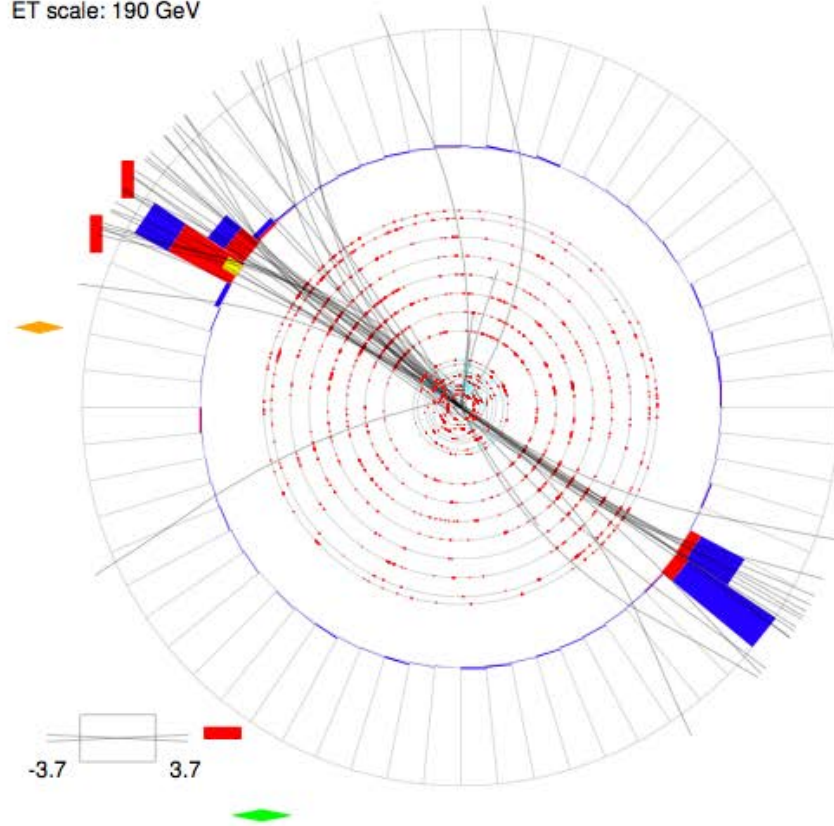
# kinematic regions accessible to experiments



# 2-Jet final state in proton-antiproton collision (Tevatron; D0 detector)

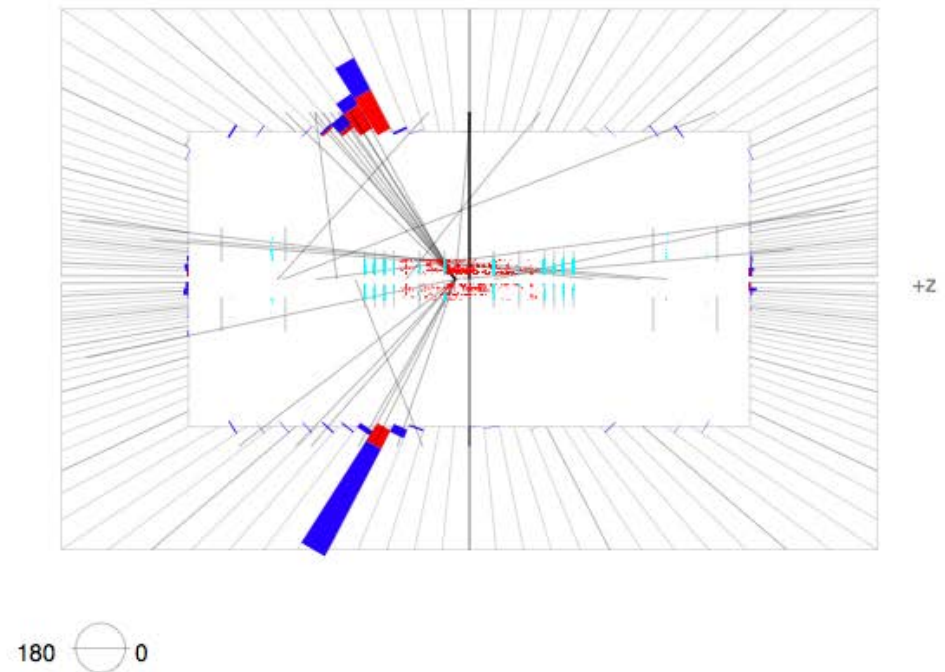
Run 162592 Event 5490755 Fri Oct 25 11:57:39 2002

ET scale: 190 GeV



Run 162592 Event 5490755 Thu Oct 24 13:54:27 2002

E scale: 303 GeV

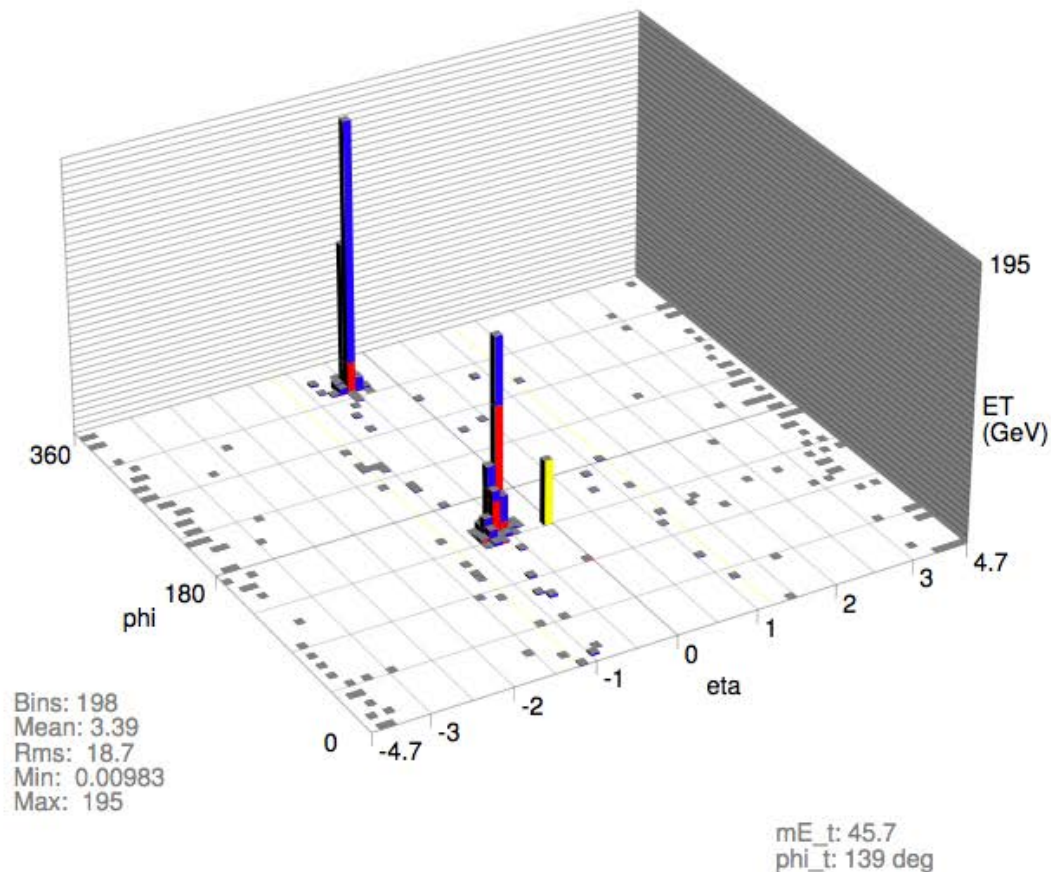


# 2-Jet final state in proton-antiproton collision (Tevatron; D0 detector)

Darstellung in

$\varphi$ - $\eta$ -Ebene:

Run 162592 Event 5490755 Thu Oct 24 13:54:25 2002



Azimutwinkel  $\varphi$ , Pseudorapidität  $\eta = -\tan(\vartheta/2)$ , Polarwinkel  $\vartheta$ , transversale Energie  $E_T = E \sin \vartheta$



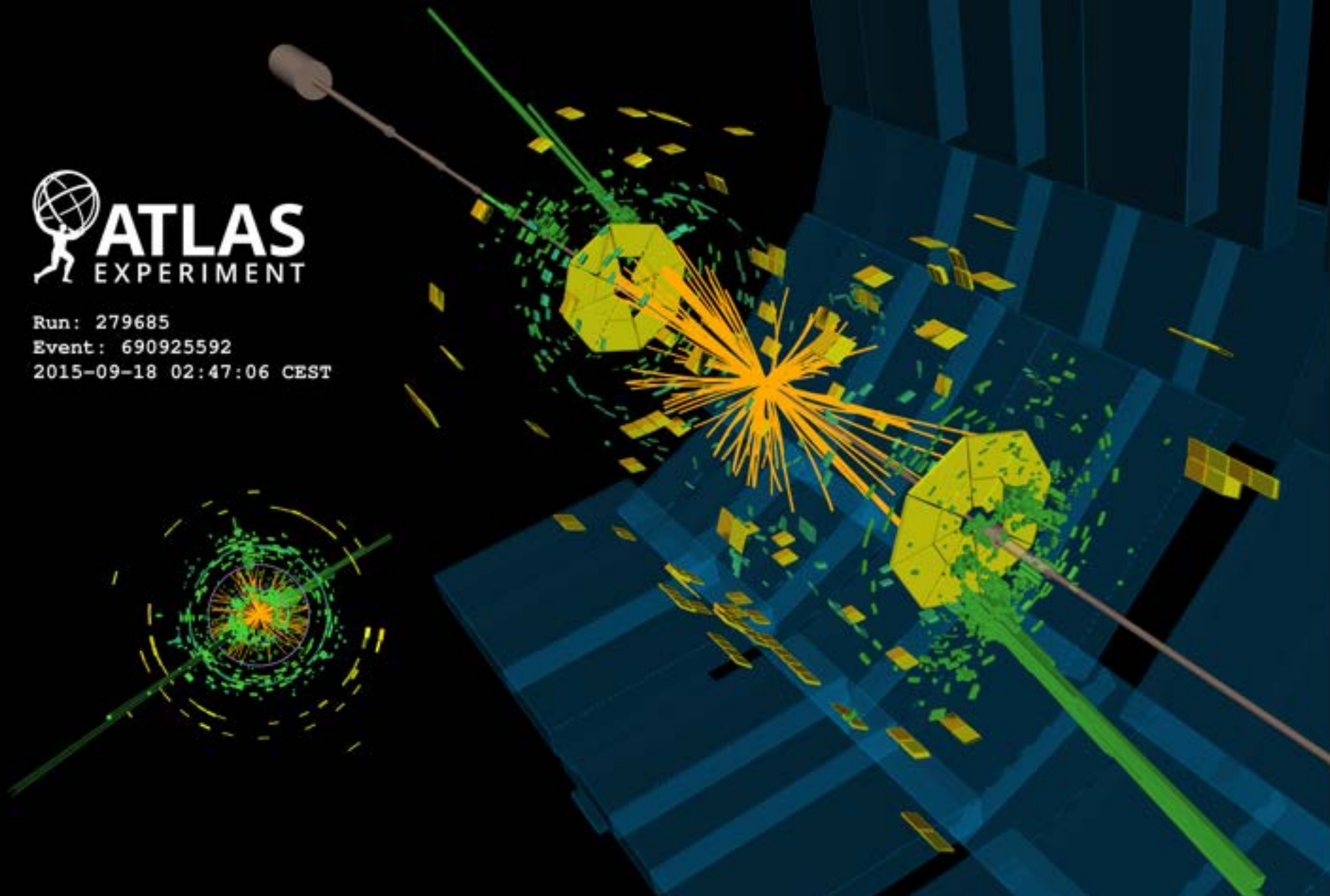
# high-mass (9 TeV) di-jet event at LHC (13 TeV)

 **ATLAS**  
EXPERIMENT

Run: 279685

Event: 690925592

2015-09-18 02:47:06 CEST

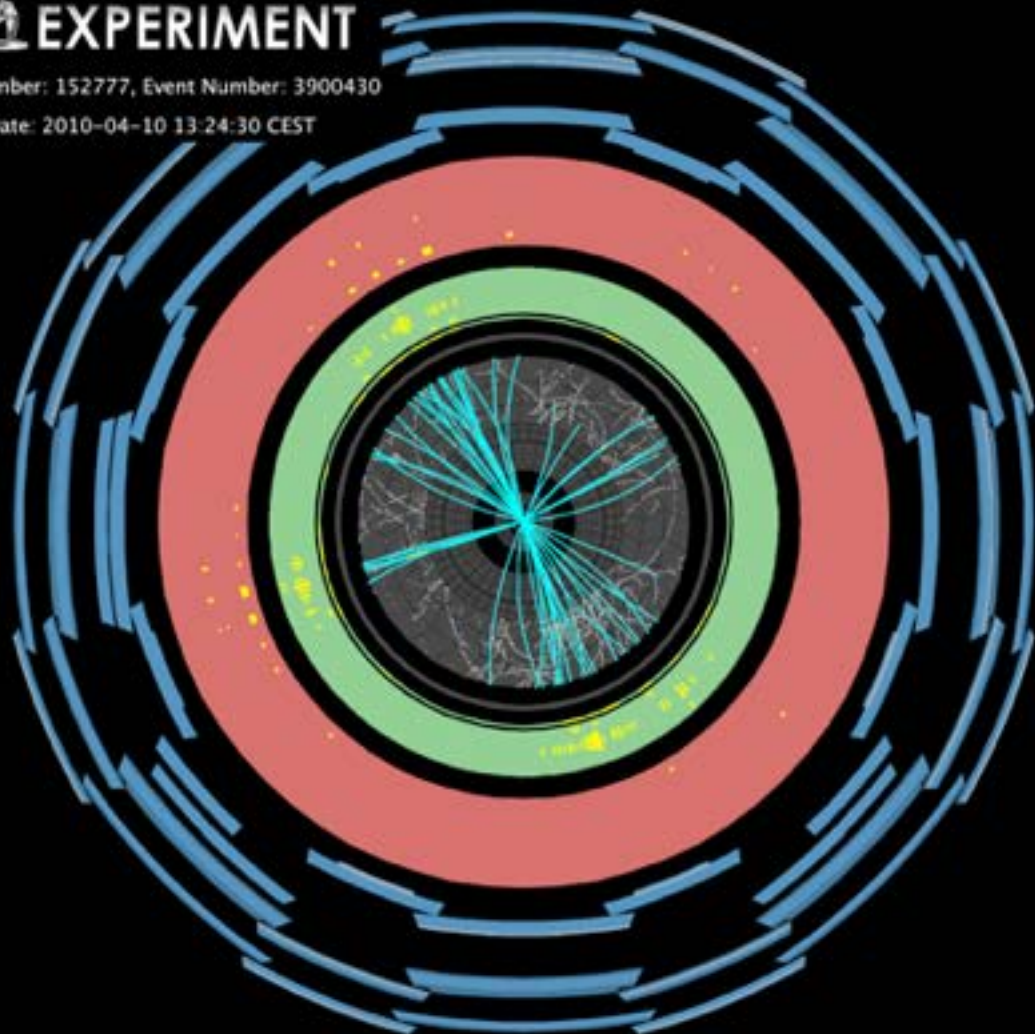


Event with four reconstructed hadronic jets. The four jets have a calibrated  $p_T > 50$  GeV, and are found with the anti-kt algorithm with  $R=0.6$ . The highest  $p_T$  jet has a calibrated jet  $p_T$  of 144 GeV. Event collected on 10 April 2010.

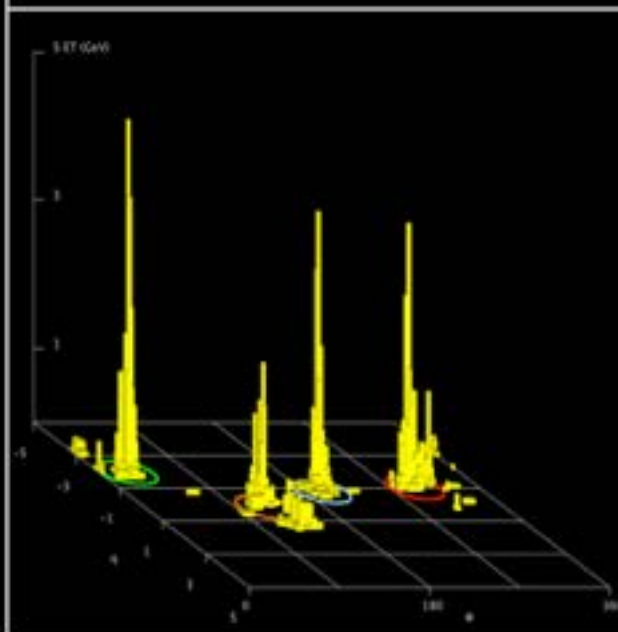
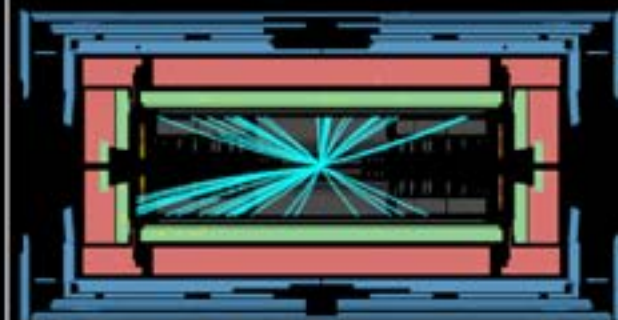
**ATLAS**  
EXPERIMENT

Run Number: 152777, Event Number: 3900430

Date: 2010-04-10 13:24:30 CEST



4-jet event

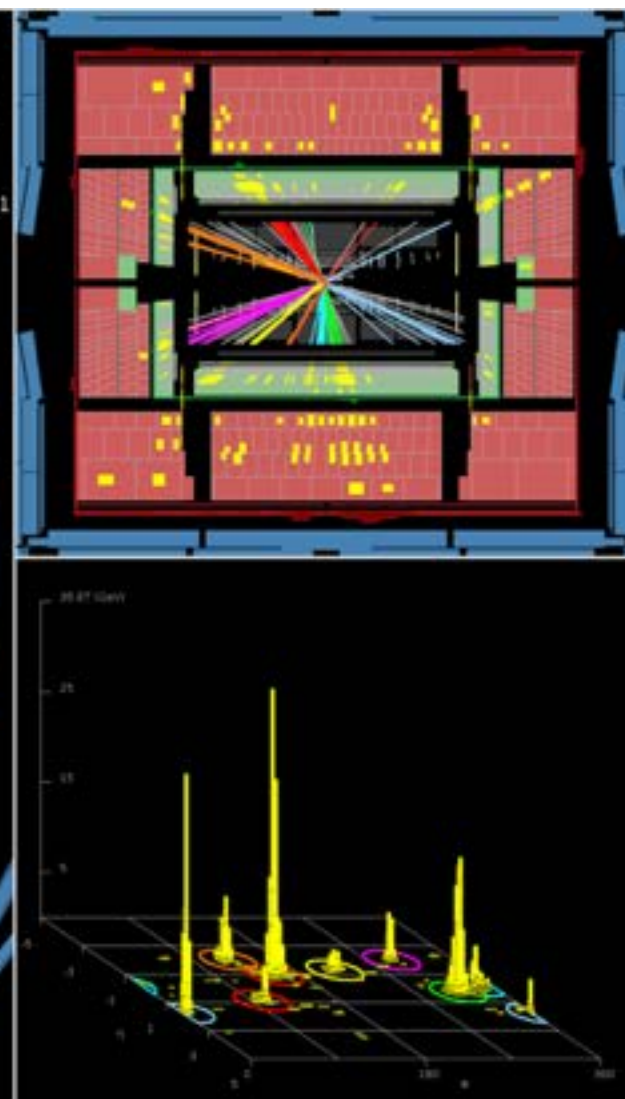
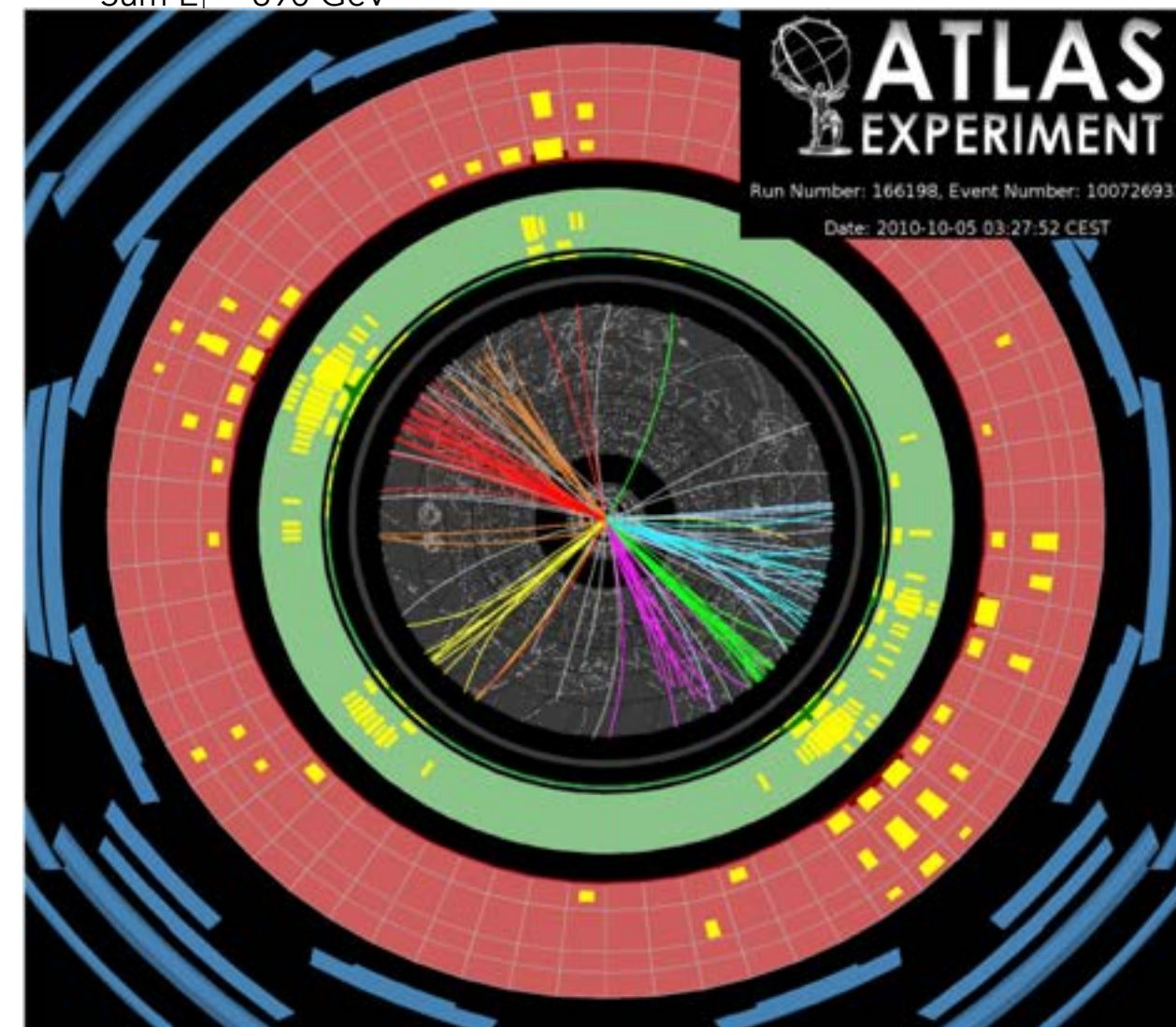




Jet momenta are calibrated according to the "EM+JES" scheme. Event collected on 8 October 2010. The highest jet multiplicity event collected by the end of October 2010, counting jets with  $p_T$  greater than 60 GeV: this event has eight.

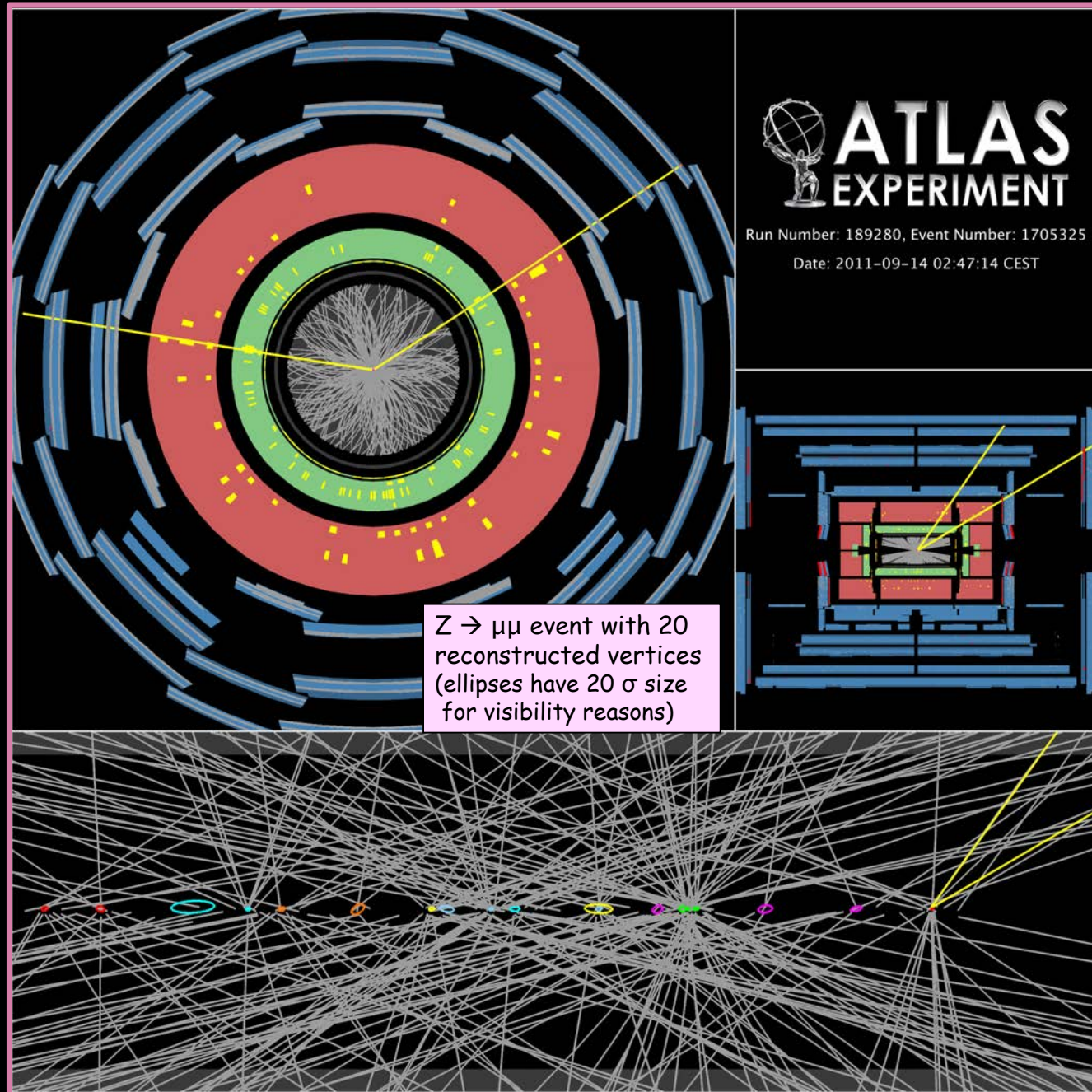
- 1st jet (ordered by  $p_T$ ):  $p_T = 290$  GeV,  $\eta = -0.9$ ,  $\phi = 2.7$
- 2nd jet:  $p_T = 220$  GeV,  $\eta = 0.3$ ,  $\phi = -0.7$
- Missing  $E_T = 21$  GeV,  $\phi = -1.9$
- Sum  $E_T = 890$  GeV

## 8-jet event



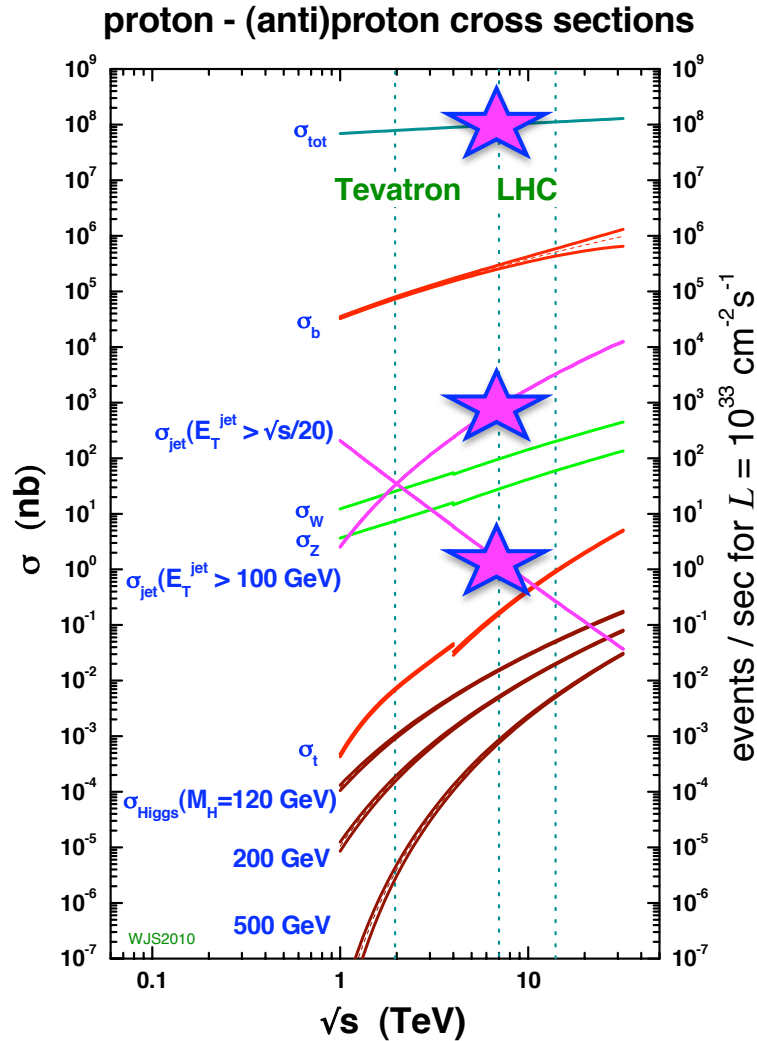
# „pile-up“:

- 10-40 collisions per beam crossing
- detectors and electronics must cope with huge amounts of data
- physics analyses must cope with extremely high background rates





# QCD- / Jet- production cross sections



total QCD cross section

Jet cross section  $E_T^{\text{jet}} > 100 \text{ GeV}$

Jet cross section  $E_T^{\text{jet}} > \sqrt{s}/20$

# Physik der Hadronen-Jets

Zum Vergleich von Hadronen-Jets mit analytischen QCD -Rechnungen (Quark- und Gluondynamik) muß man **auflösbare Teilchenjets** Theorie und Praxis definieren.

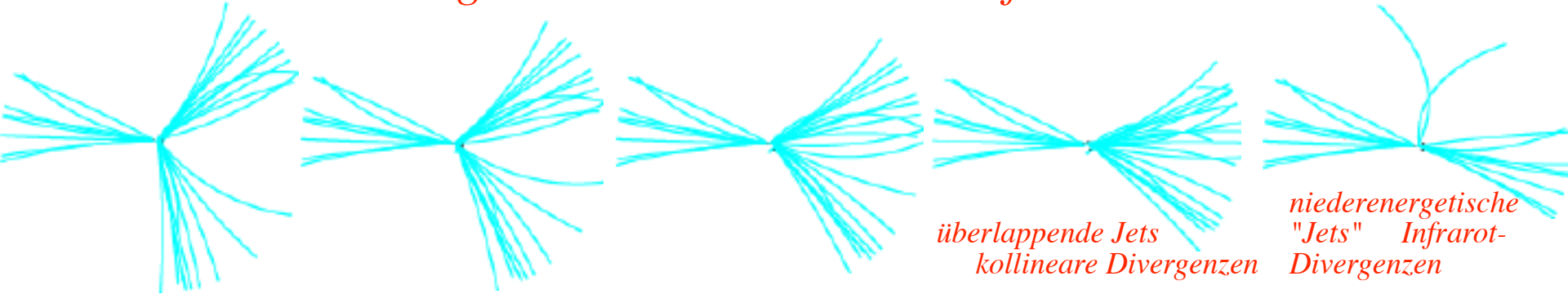


Dazu benötigt man:

- Definition eines **Auflösungskriteriums** (z.B. minimale invariante Paarmasse, minimale Winkel, minimale Energien ..)
- Vorschrift, wie man nichtauflösbare Jets **rekombiniert**.

allerdings:

*Es gibt keine "natürliche" Definition von Jets !*



*überlappende Jets  
kollineare Divergenzen*

*niederenergetische  
"Jets" Infrarot-  
Divergenzen*

$k_T$  - Algorithmus und Jetdefinition:

(meistbenutzt in  $e^+e^-$ -Vernichtung; seit LHC auch in Hadron-Kollisionen)

## $k_T$ - Algorithmus und Jetdefinition:

für jedes Objekt eines Ereignisses (Parton, Teilchen, Energie-Cluster) wird berechnet:

$$d_{ij} = \min(k_{t,i}^2, k_{t,j}^2) \frac{(\Delta R)_{ij}^2}{R^2};$$

$$d_{iB} = k_{t,i}^2$$

$$\text{mit } (\Delta R)_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$k_{t,i}$  : transversaler Impuls bezügl. Strahlachse

$\phi_i$  : azimuthaler Winkel

$y$  : Rapidität; =  $1/2 \ln [ (E+p_z) / (E-p_z) ]$

$d_{ij}$  : Abstandsmass zwischen zwei Objekten  $i, j$

$d_{iB}$  : Abstandsmass zwischen Objekt und Strahlachse

eine Liste aller  $d_{ij}$  und  $d_{iB}$  wird erstellt. Falls der kleinste Eintrag  $d_{ij}$  ist, werden Objekte  $i$  und  $j$  kombiniert (Addition der 4er-Vektoren); falls  $d_{iB}$  der kleinste ist, wird Objekt  $i$  als „Jet“ definiert und aus der Liste entfernt.

$R$  : „Auflösungsparameter“, bei dem Objekte  $i$  und  $j$  noch getrennt werden können.

## anti- $k_T$ - Algorithmus und Jetdefinition:

$$d_{ij} = \min(k_{t,i}^{-2}, k_{t,j}^{-2}) \frac{(\Delta R)_{ij}^2}{R^2}$$

$$d_{iB} = k_{t,i}^{-2}$$

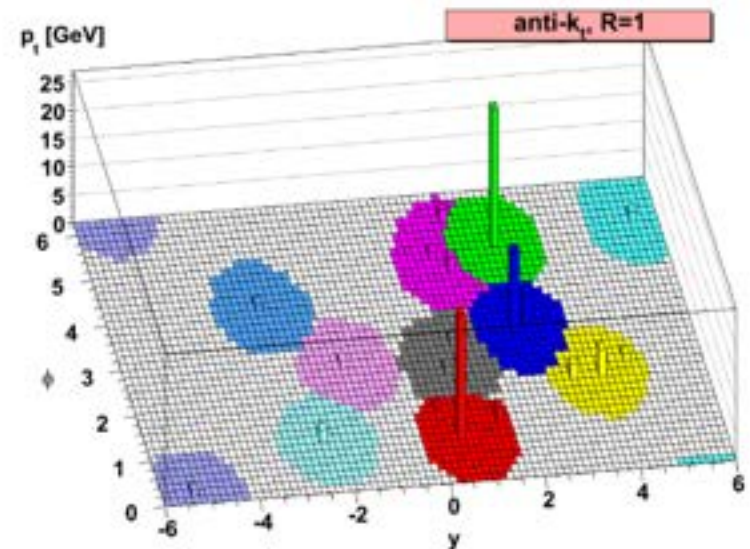
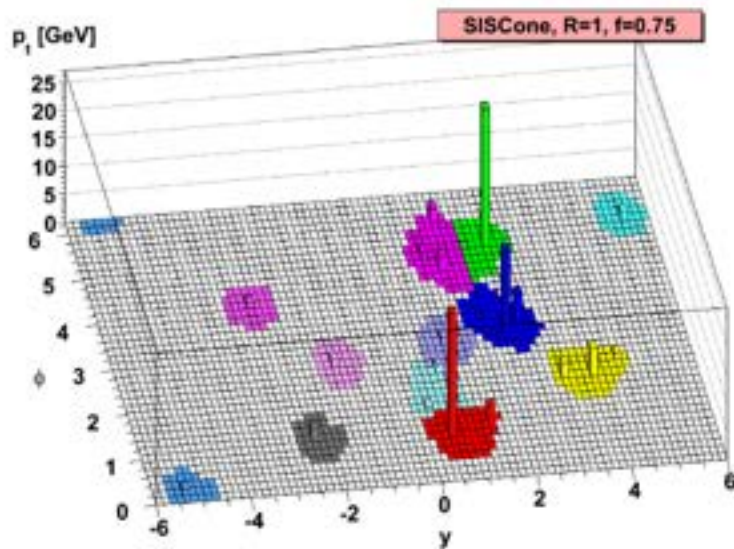
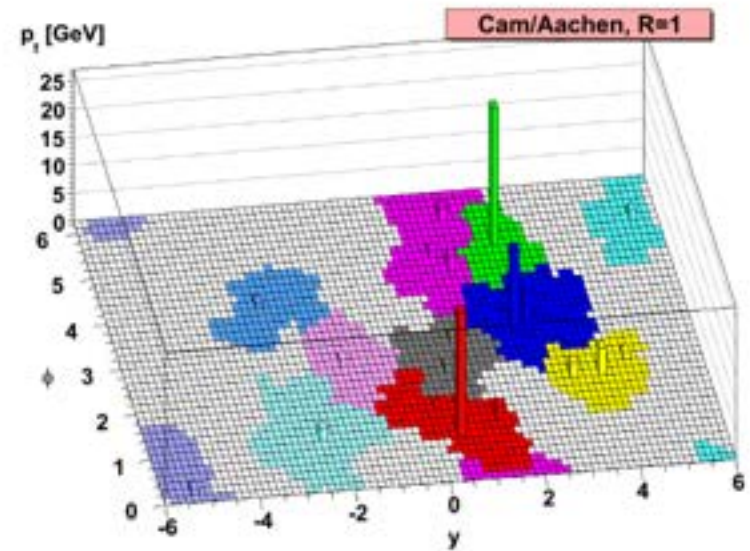
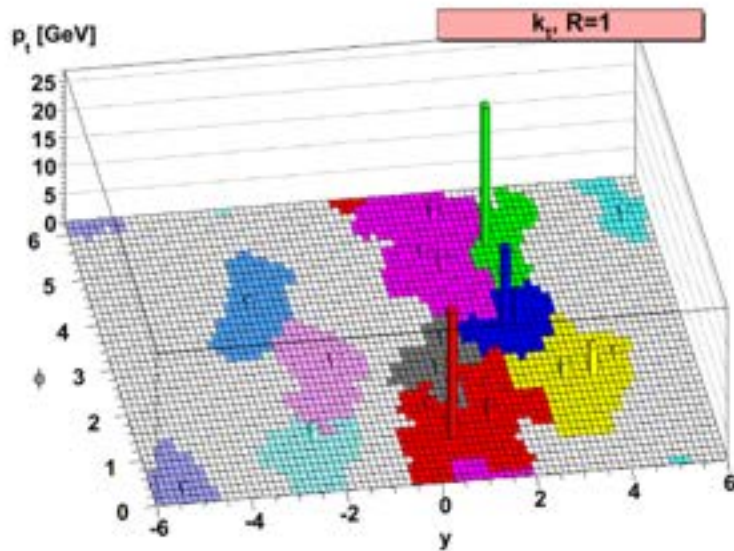
(derzeit meist gebräuchlich am LHC, mit  $R \sim 0.4 \dots 0.7$ )



# Anmerkungen zum $k_T$ - Jetalgorithmus

- die Jetdefinition über den Auflösungsparameter  $d_{ij} = 1/2 \min(E_i^2, E_j^2) (1 - \cos \theta_{ij})$  ist eine Abwandlung der Formel für die invariante Paarmasse zweier masselose Teilchen:  $M_{ij}^2 = E_i E_j (1 - \cos \theta_{ij})$  --- die historisch vor Einführung des  $k_T$  Algorithmus verwendet wurde (unter dem Namen “JADE” Algorithmus).
- die  $k_T$  Jetdefinition ist infrarot und kollinear sicher, d.h. Berechnungen in QCD Störungstheorie sind möglich und verfügbar. Die Benutzung von  $d_{ij}$  anstelle der mehr intuitiven Paarmasse hat Vorteile bei der theoretischen Berechnung; u.a. können durch einen mathematischen Trick führende Beiträge zu höheren Ordnungen aufsummiert werden, was bei der JADE Definition nicht möglich war.
- der  $k_T$  Algorithmus hat sich besonders in der Analyse von Jets in der  $e^+e^-$  Vernichtung (zB bei LEP) als sehr erfolgreich erwiesen, sowohl in experimenteller wie in theoretischer Sicht.
- am Hadron Collider muss bei Adaption des  $k_T$  Algorithmus besondere Rücksicht auf die durch die weiterfliegenden Proton-Reste verursachten “remnant jets” bzw. das “underlying event” in Vorwärts-/Rückwärts-Richtung genommen werden -- geschieht über die Definition von  $d_{iB}$

# clustering performance of $k_T$ - type Jet algorithms

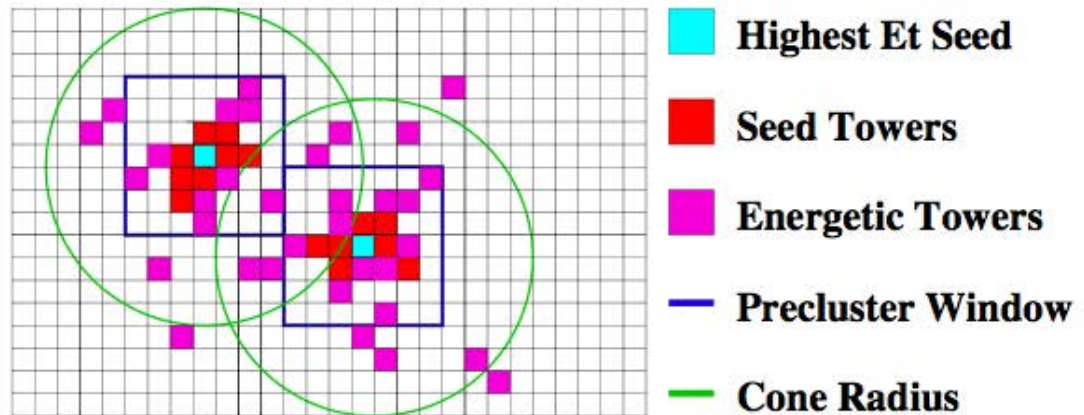


# Cone-Jet algorithm:

- **JetClu:** CDF's Run I algorithm

- Create  $E_T$ -ordered list of calorimeter towers (seed towers:  $E_T > 1$  GeV).
- Build **pre-clusters** from adjacent seed towers beginning with the highest  $E_T$  tower.
- For each pre-cluster: Calculate centroid;  
**iterate** cone using all towers above 100 MeV  
( $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < R_{\text{cone}}$ ).
- **“Ratcheting”**: During the iteration no seed tower of the original pre-cluster ever leaves the cone! (Pre-clusters remain connected to cones.)
- Two overlapping stable cones are **merged** if more than 75% of the transverse energy of one of the cones is shared by the other one.  
Otherwise the cones are **split** by distributing the shared energy among the cones.  
(CDF-specific, iterative)

- JetClu is neither infrared safe nor collinear safe.
- Yet, JetClu is being used in CDF's Run II Level 3 trigger and for some analyses (backward compatibility).

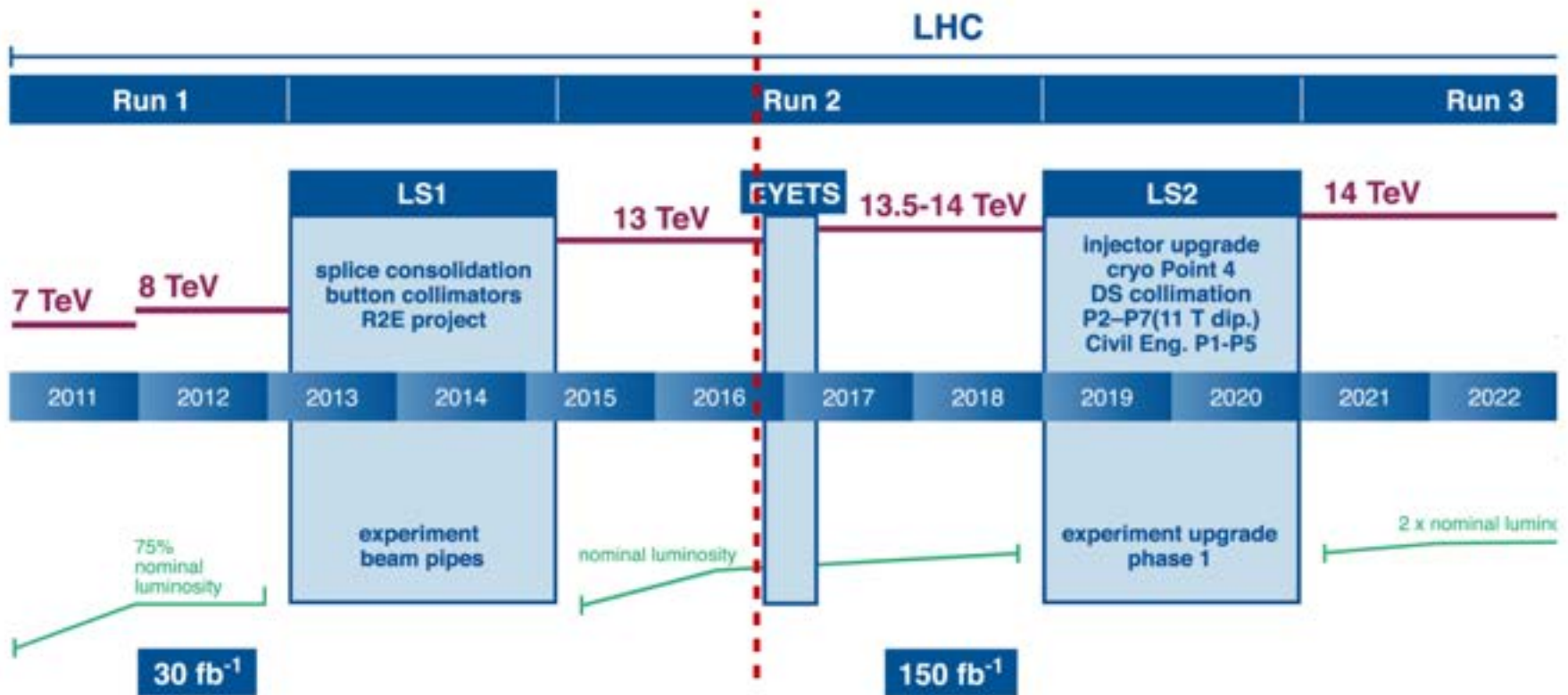


# Anmerkungen zum Cone - Jetalgorithmus

- der Cone-Algorithmus ist historisch der am längsten und meist benutzte Jetalgorithmus in der Analyse von Hadron Kollisionen (Tevatron).
- seine Definition und Anwendung ist i.w. durch experimentelle Randbedingungen (Zellgrösse hadronischer Kalorimeter) und technischer Details bestimmt; in der Vergangenheit hat daher auch jedes Experiment (zB CDF und D0 am Tevatron) leicht verschiedene Variationen des Cone-Algorithmus benutzt.
- der Cone-Algorithmus ist weder infrarot noch kollinear sicher, kann daher nicht für QCD Präzisionsstudien verwendet werden.
- wegen der langen exp. Erfahrung mit dem Cone-Algorithmus wird dieser auch weiterhin am Tevatron dominant (und zT auch am LHC) benutzt; hier besonders für technische Studien (z.B. Isolation von Leptonen, Ereignisklassifizierung, jet tagging etc).

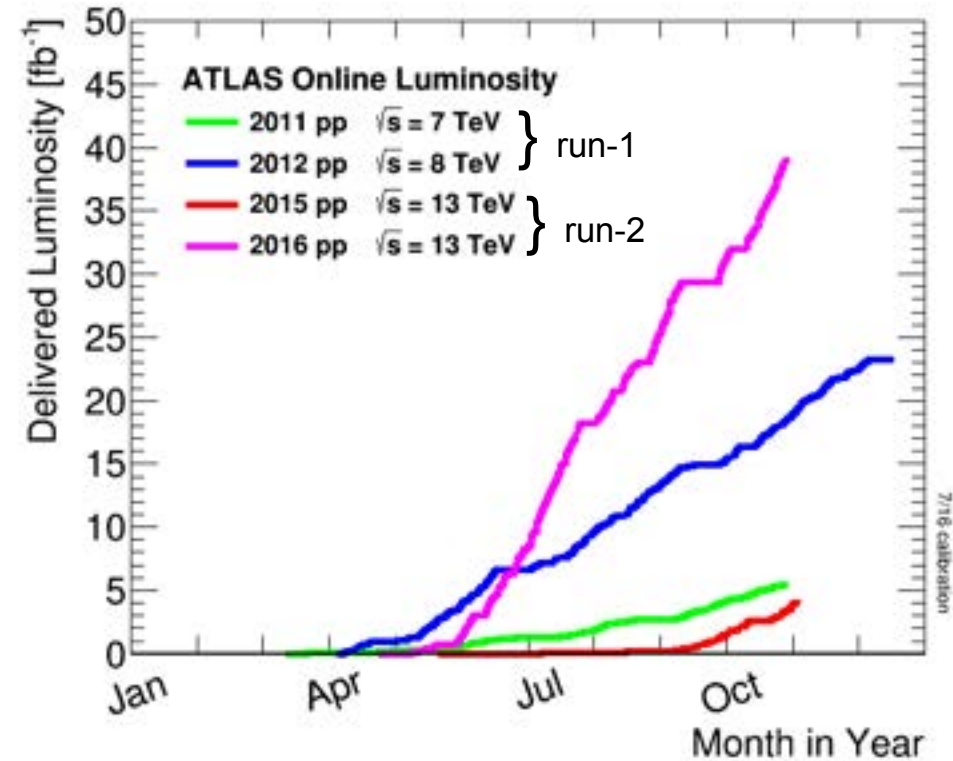


# LHC Run-1 and Run-2

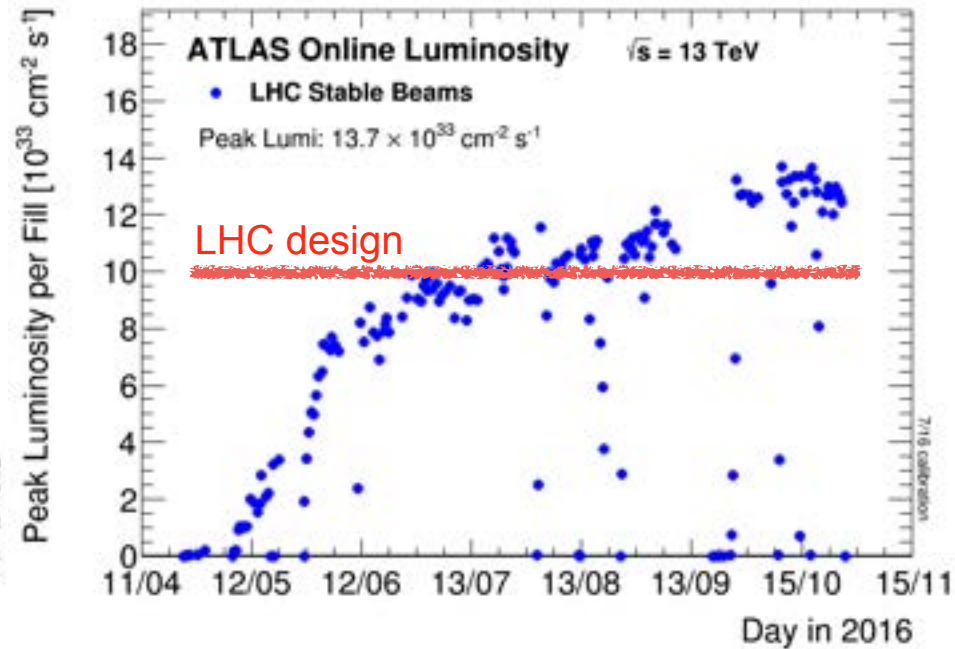


# LHC performance

## integrated Luminosity



## peak Luminosity





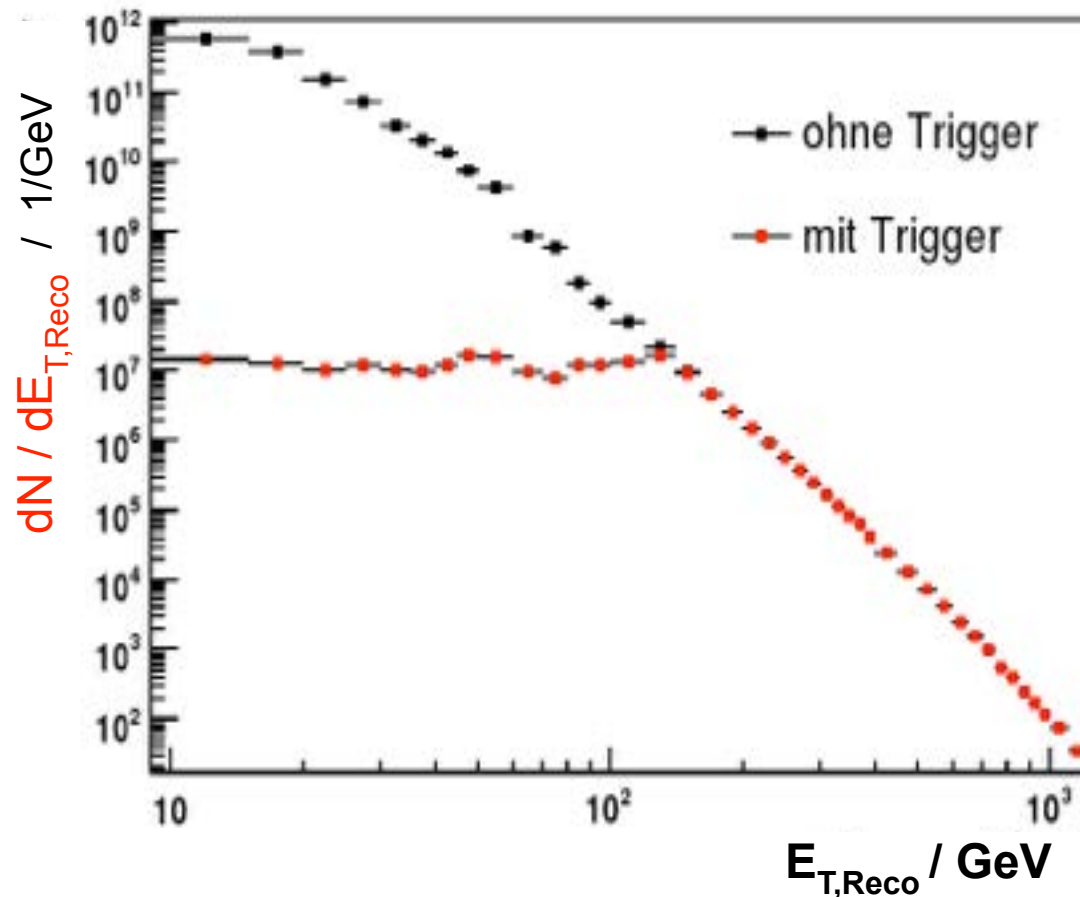
# Jet-Wirkungsquerschnitt am LHC

- Studie: Single-Jet-Spektrum nach einer Laufzeit von etwa 1 Jahr ( $10^7$ s), bei niedriger Luminosität ( $L = 10^{32} \text{cm}^{-2}\text{s}^{-1}$ ):  $\int L dt = 1 \text{ fb}^{-1}$

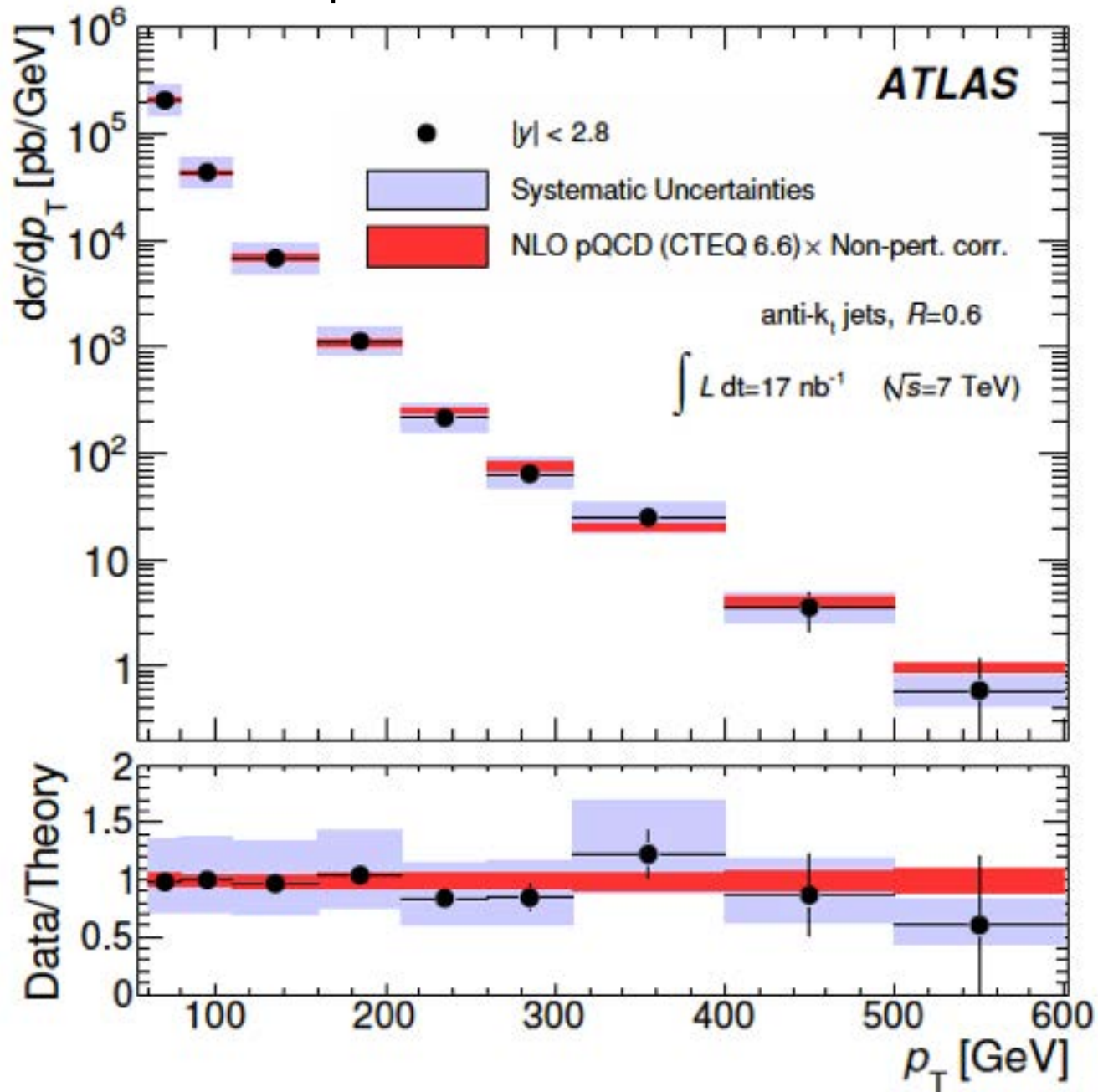
- Messung bis 1 TeV sehr früh möglich

- Unsicherheiten:

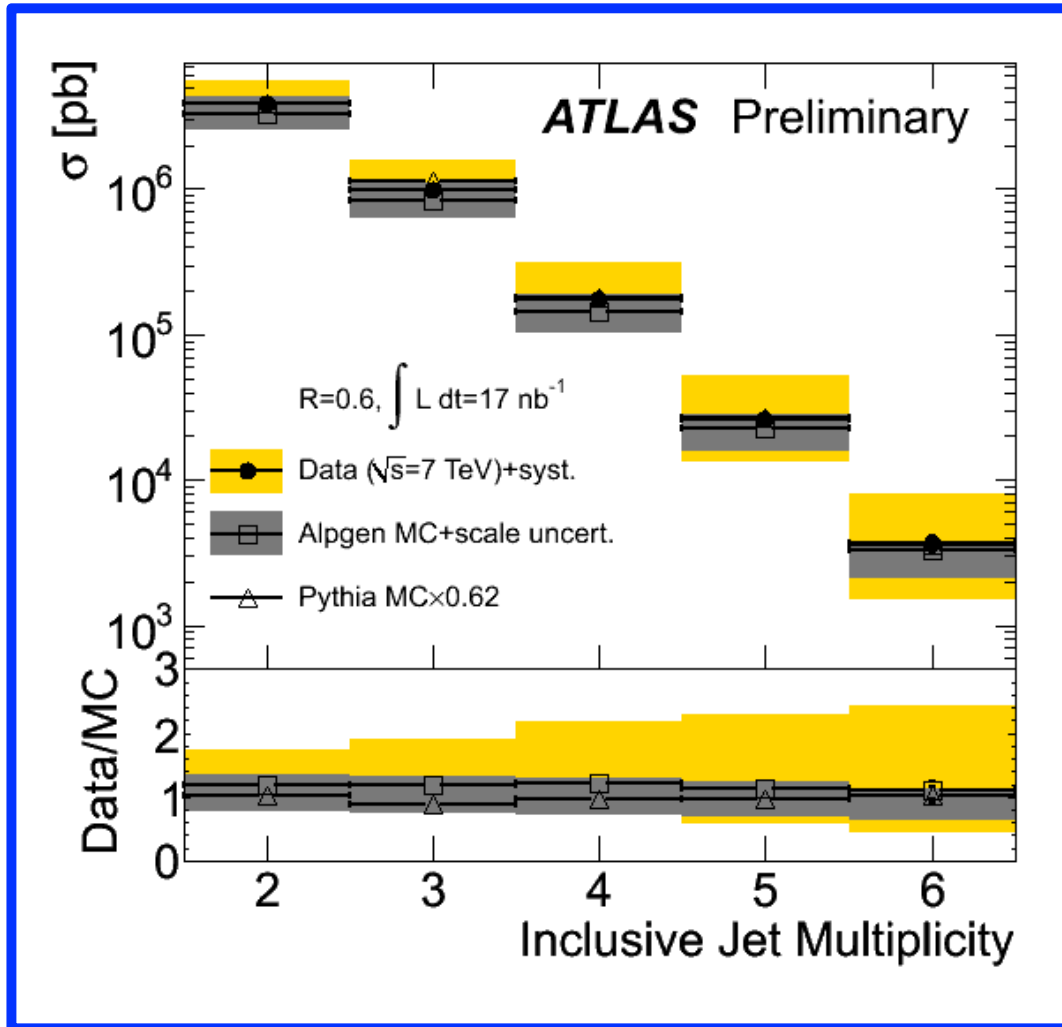
- Jet-Energieskala
- Energieauflösung
- Triggereffizienzen
- Luminosität



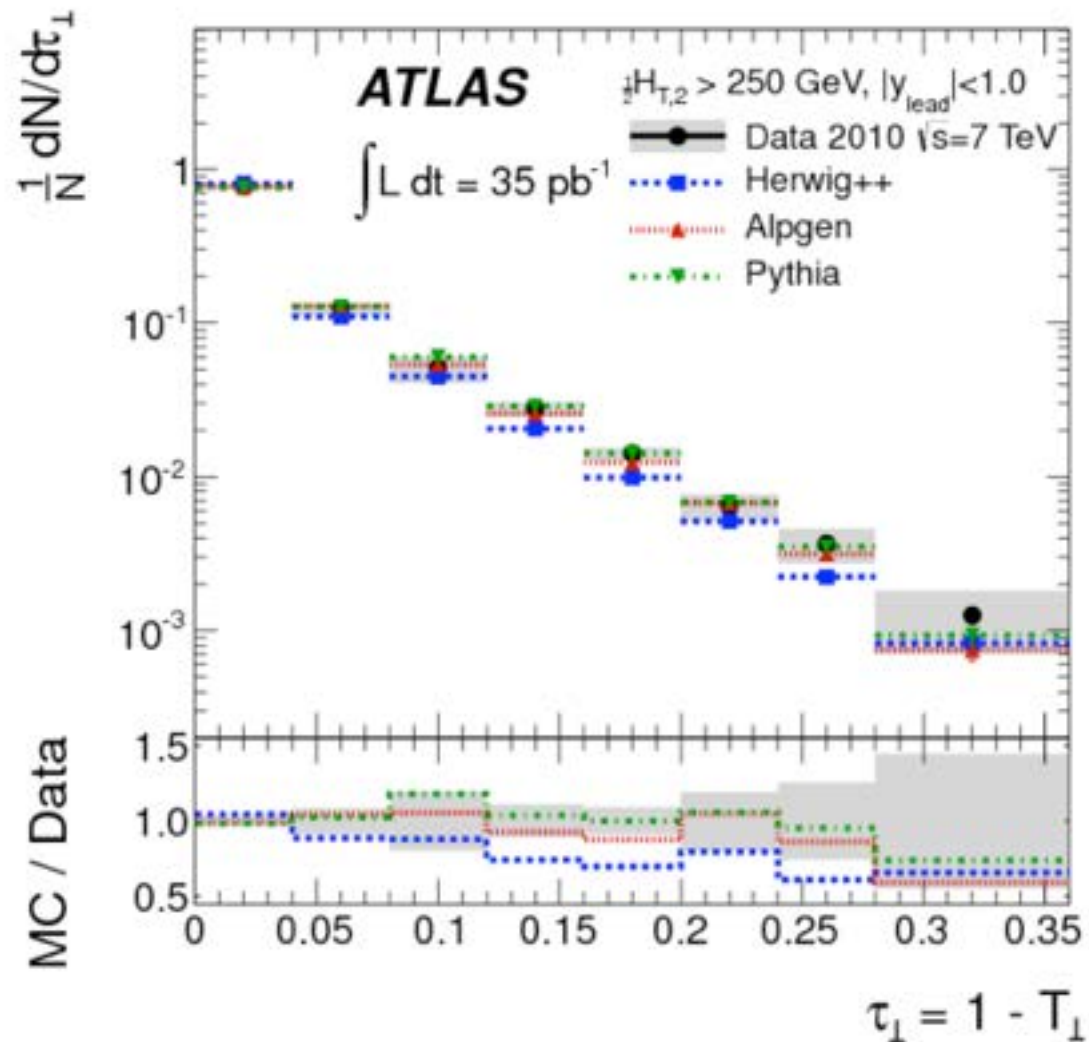
# Jet production cross section



# Jet multiplicities



# Measurement of event shapes at large momentum transfer



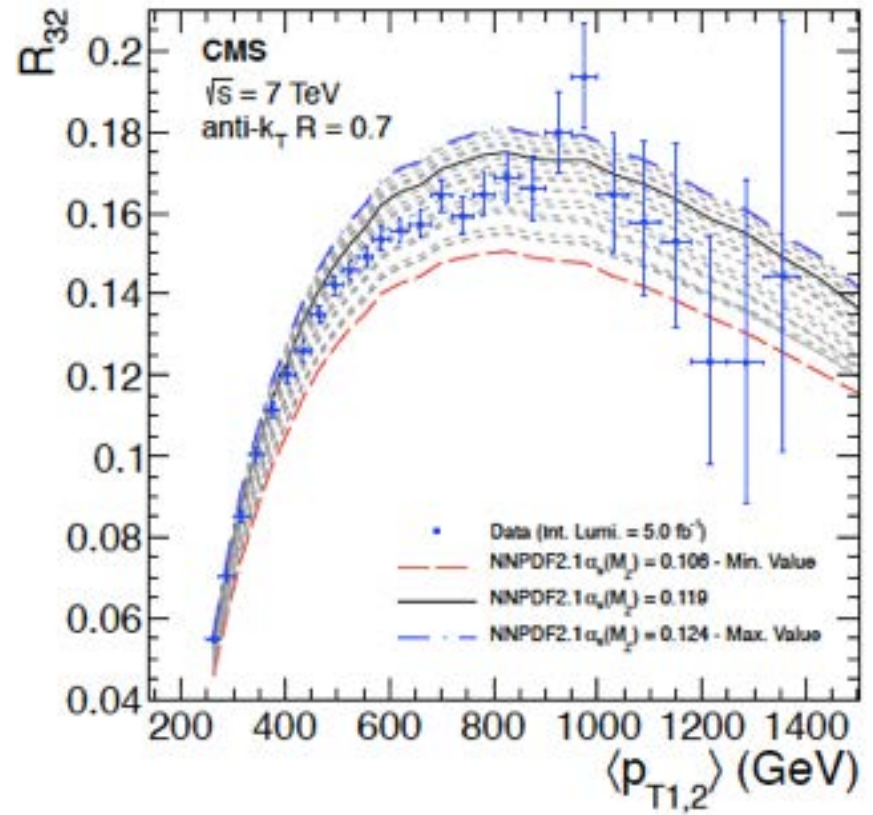
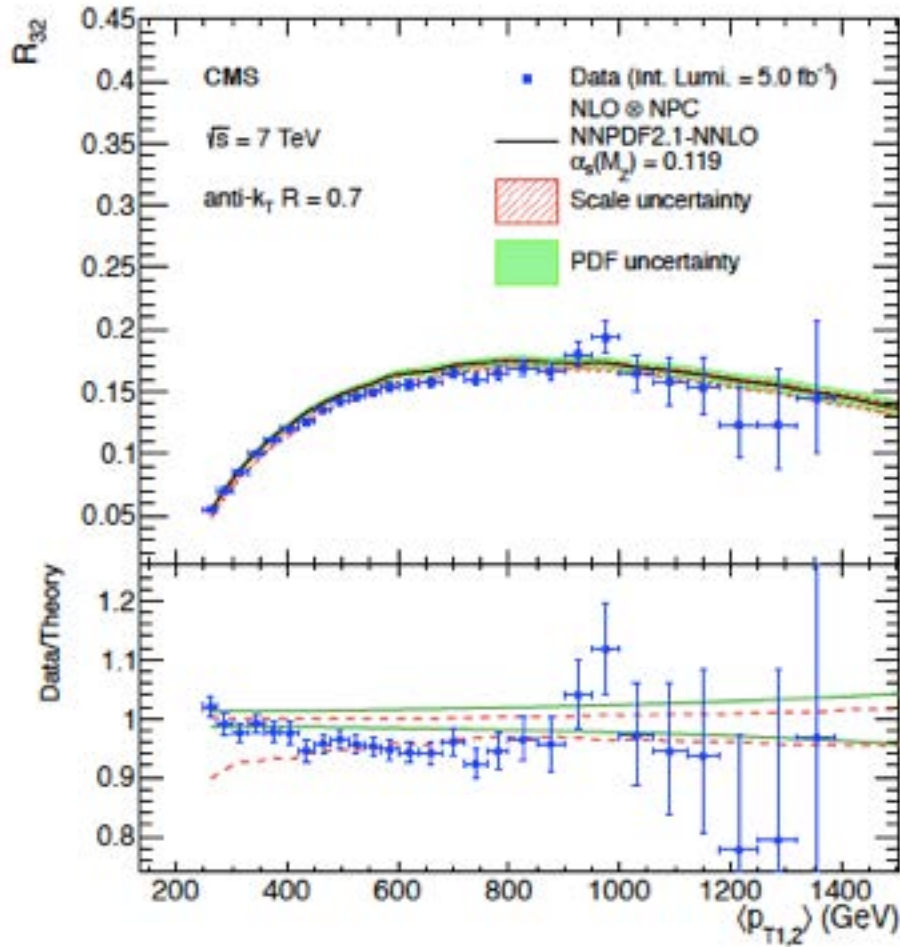
[Eur. Phys. J. C \(2012\) 72: 2211](https://arxiv.org/abs/1112.5749)

Measurement of the ratio  
of the inclusive 3-jet and 2-jet cross sections  
and  
first determination

of the strong coupling constant  $\alpha_s$  in the TeV range

- measurement of  $R_{32} = R_{3\text{jet}}/R_{2\text{jet}}$  as function of  $Q = p_{T1,2} = (p_{T,1} + p_{T,2})/2$
- use anti- $k_T$  algorithm with  $R=0.7$
- most exp. uncertainties cancel in ratio
- comparison to QCD predictions (NLO) as function of coupling strength  $\alpha_s(Q)$

# $R_{32}$ as function of $p_{T1,2}$

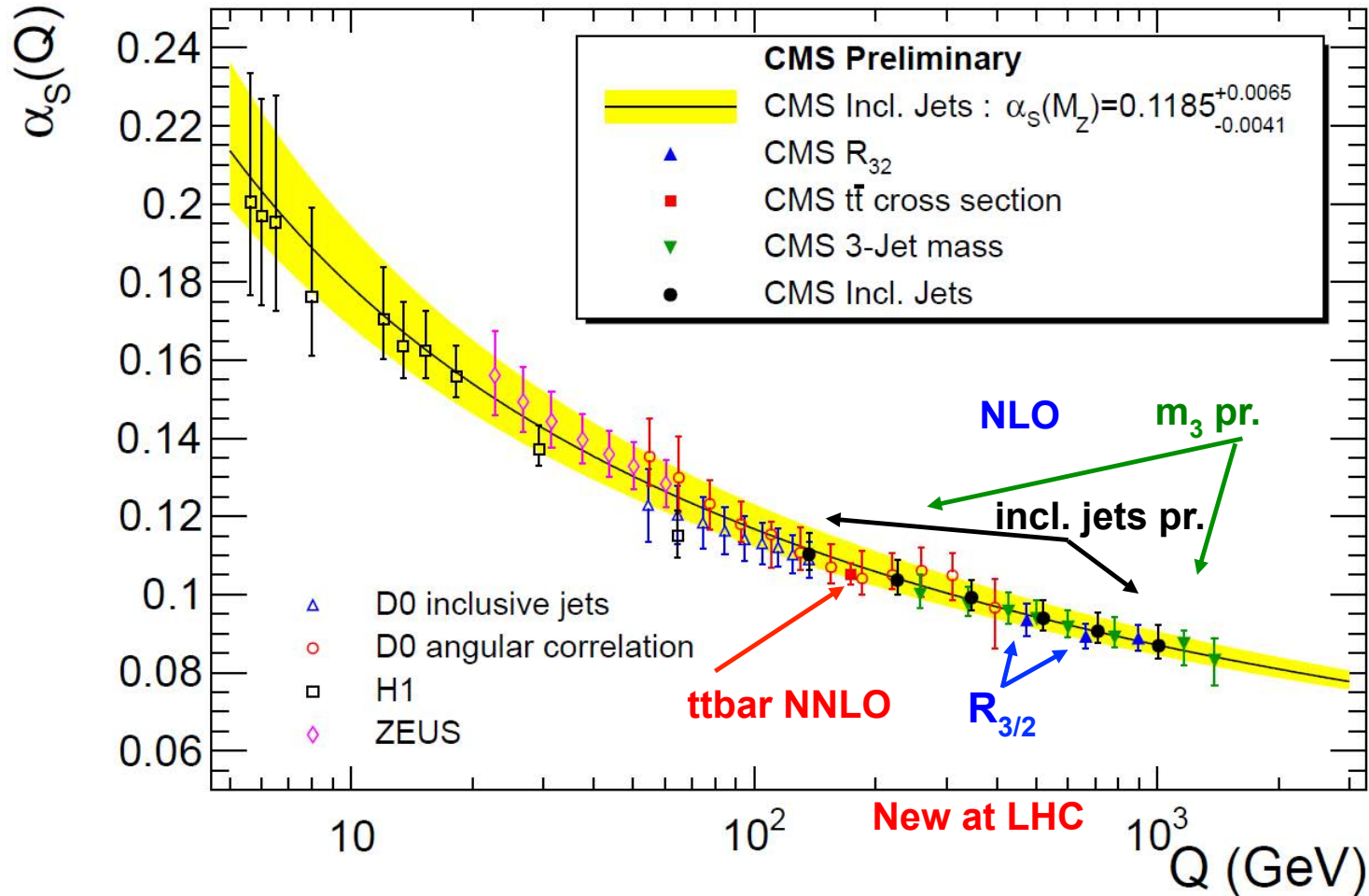


arXiv:1304.7498



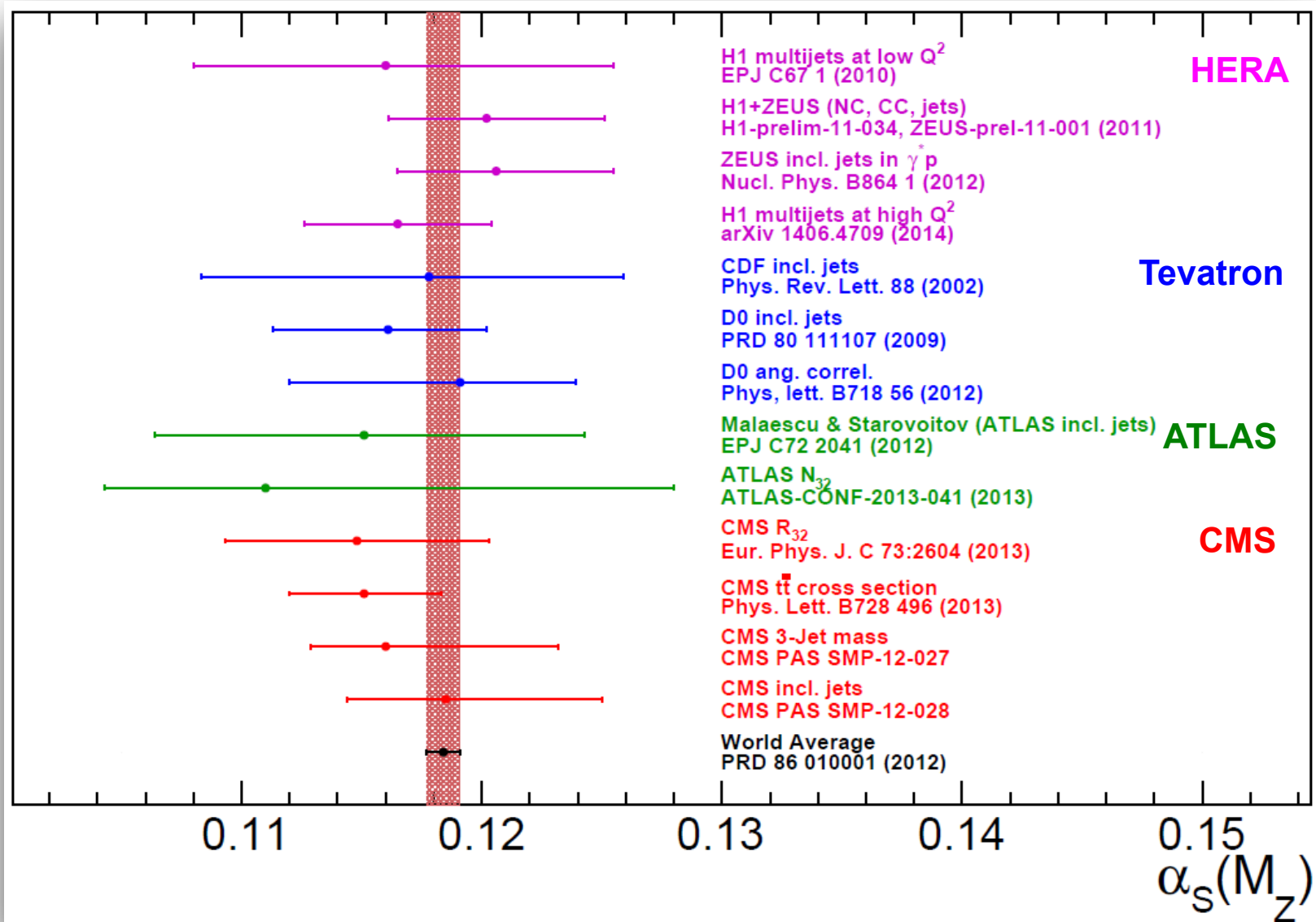
# summary of $\alpha_s$ measurements

at hadron colliders (ep, pp, ppbar)

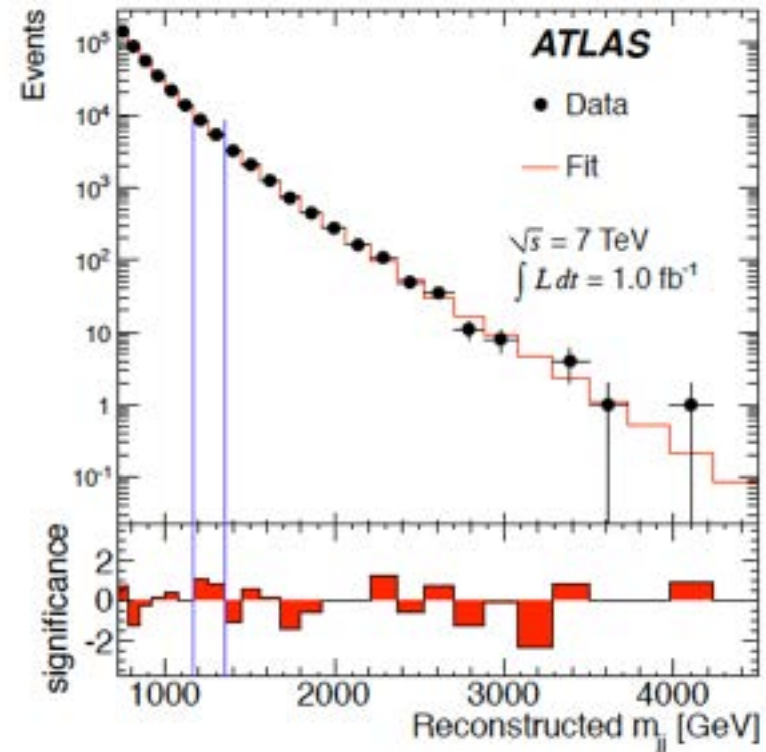
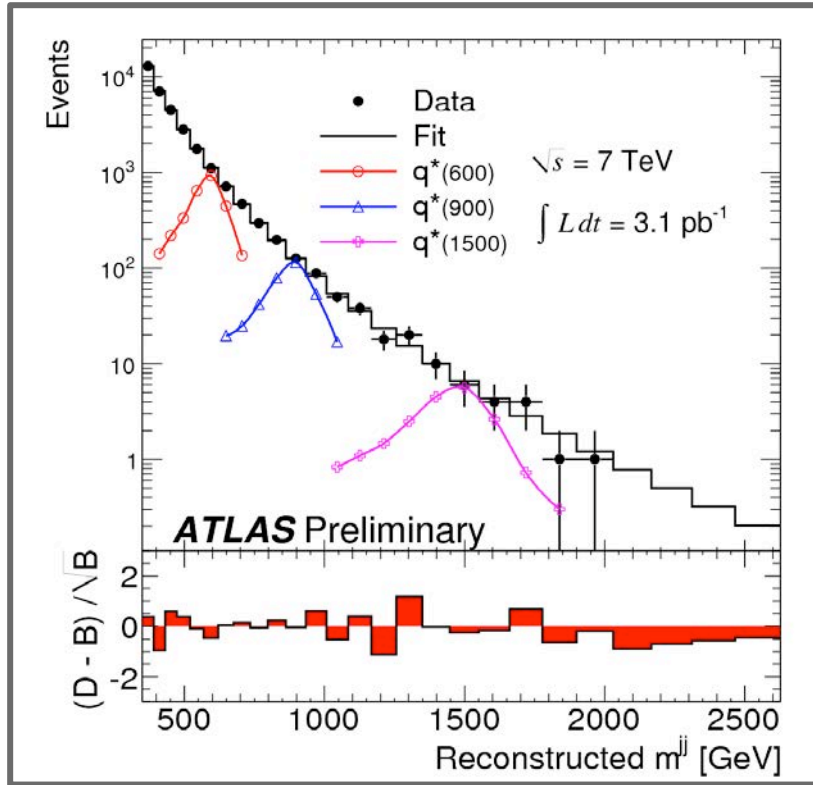


# summary of $\alpha_s$ measurements

at hadron colliders (ep, pp, ppbar)



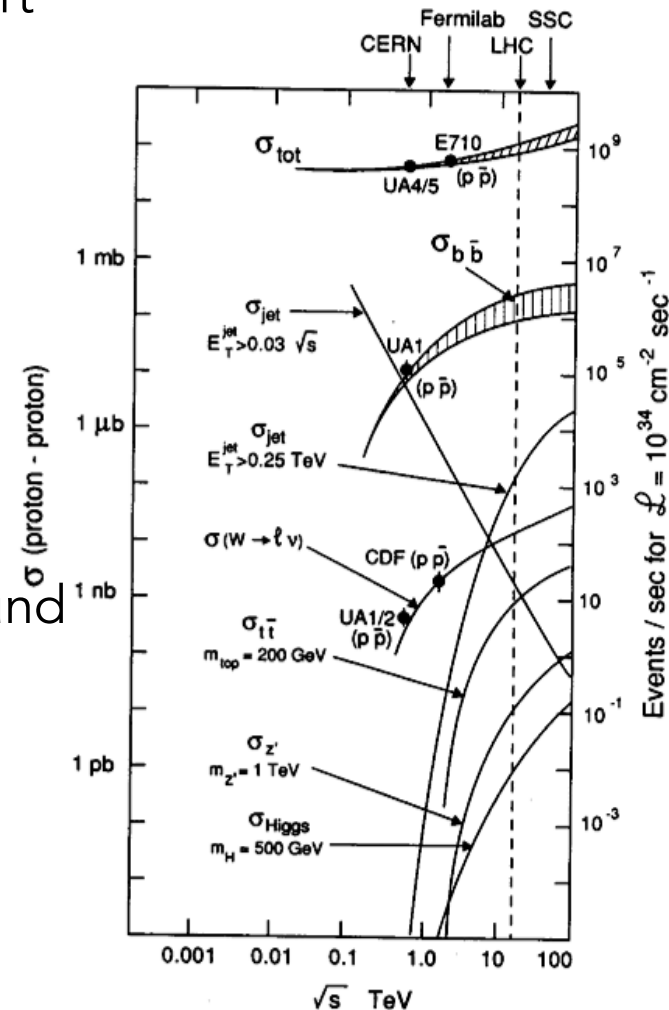
# Jet Paar-Massen und Suche nach neuen schweren Teilchen: excited Quarks



Produktion angeregter Quarks ausgeschlossen  
im Massen-Intervall  $0.3 < m < 3 \text{ TeV}$   
(Tevatron limit:  $0.8 \text{ TeV}$ )

# Zusammenfassung

- QCD (d.h. die Starke Wechselwirkung) dominiert bei weitem die Reaktionsraten an Tevatron und LHC ( $\sigma_{\text{tot}}$  in nebenstehender Graphik)
- QCD beschreibt die Dynamik von Quarks und Gluonen. Die Beschreibung von Hadronen ist nur durch Zuhilfenahme von Hadronisierungsmodellen möglich.
- alternativ werden Hadronenjets definiert und analysiert; Jets können theoretisch mit Quarks und Gluonen assoziiert und berechnet werden.
- neben dezidierten QCD Studien wie der Bestimmung von  $\alpha_s$  ist die genaue Kenntnis der QCD Prozesse unabdingbar für das Finden und die Vermessung neuer physikalischer Effekte am LHC (e.g. Higgs, SUSY, large extra dimensions).



# Literaturempfehlungen

- Ellis, Stirling, Webber: "QCD and Collider Physics", Cambridge Monographs,
- A QCD primer, G. Altarelli, CERN School 2001, <https://cdsweb.cern.ch/record/619179/files/p65.pdf>
- Quantum Chromodynamics, M.H.Seymour, 2004 European School of High-Energy Physics, hep-ph/0505192
- Measurement of inclusive jet and dijet cross sections ..., ATLAS Collaboration, arXiv:1009.5908v2, [Eur.Phys.J. C71 \(2011\) 1512](#)
- Measurement of the ratio of the inclusive 3-jet cross section to the inclusive 2-jet cross section ...; CMS collab., arXiv:1304.7498, [Eur.Phys.J. C73 \(2013\) 2604](#)

## nächste Vorlesungen:

- 12.12.2016: Standard Modell Tests  
19.12.2016: Top Quark Physik  
09.01.2017 Higgs Physik I