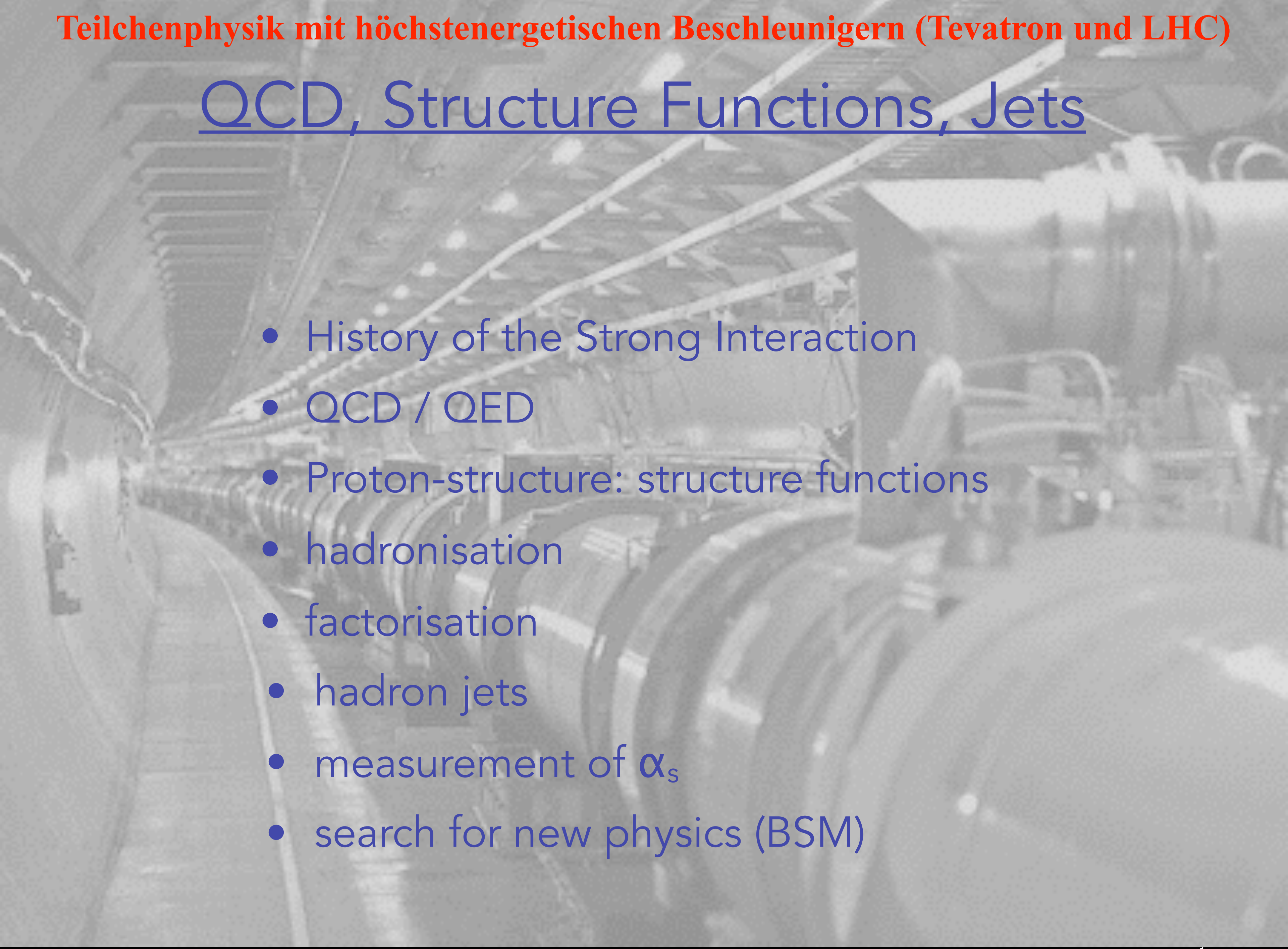
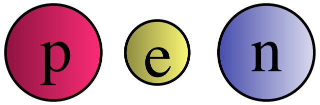
QCD, Structure Functions, Jets



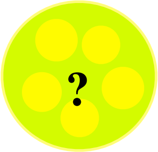
- History of the Strong Interaction
- QCD / QED
- Proton-structure: structure functions
- hadronisation
- factorisation
- hadron jets
- measurement of α_s
- search for new physics (BSM)

History of Strong Interactions (1)

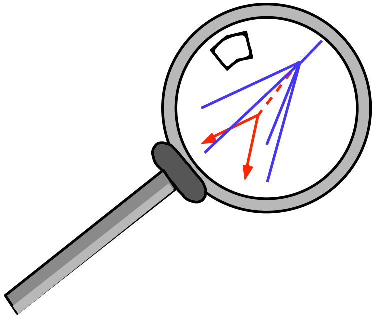
1932: discovery of neutrons



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

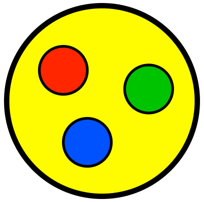


1947: discovery of π-mesons and long-living V-particles (K^0, Λ) in cosmic rays

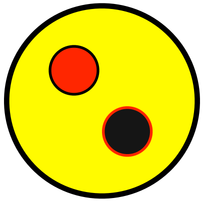


1953: V-particles produced at accelerators
new inner quantum number ("strangeness").

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

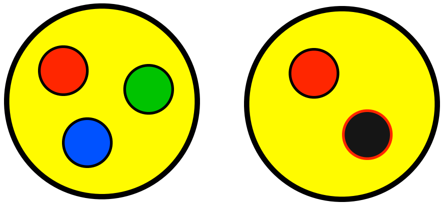


Baryon
(p,n, Λ,...)

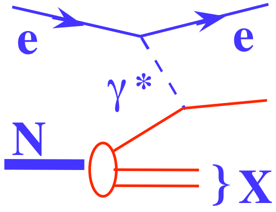


Meson
(π,K,...)

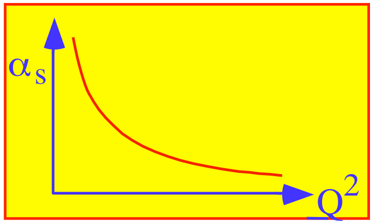
History of Strong Interactions (2)



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

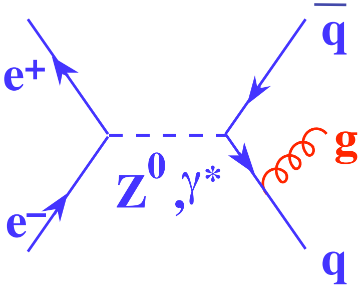


1969: dynamic parton model :



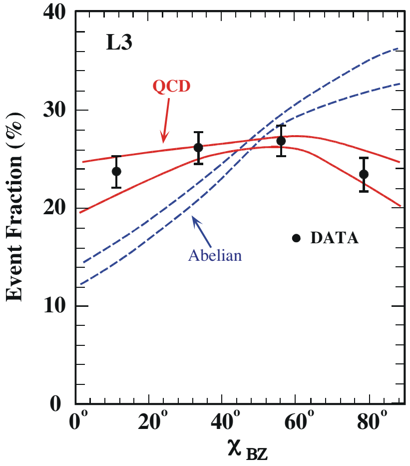
1973: concept of asymptotic freedom ;
Quantum Chromo Dynamics.

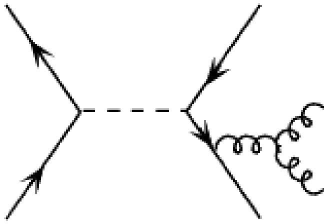
1975: 2-Jet structure in $e^+ e^-$ - annihilation:
confirmation of quark-parton-model.



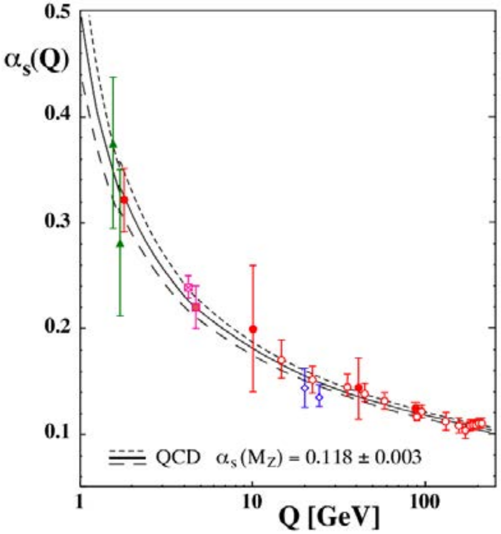
1979: discovery of gluons in 3-Jet-events
of $e^+ e^-$ -annihilations.

History of Strong Interactions (3)



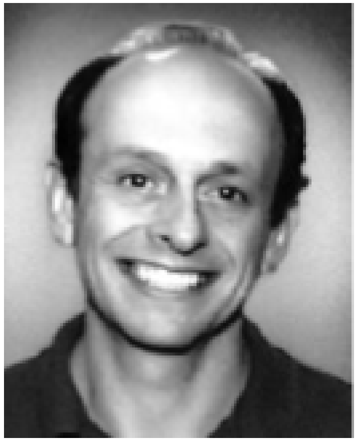
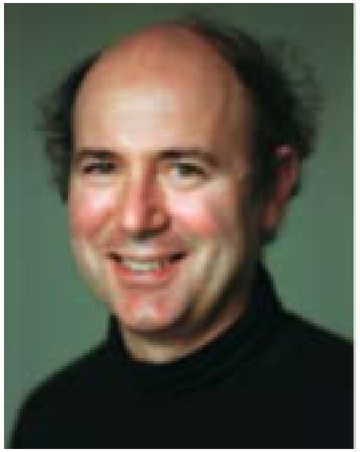


1991: exp. signature of the
gluon self coupling



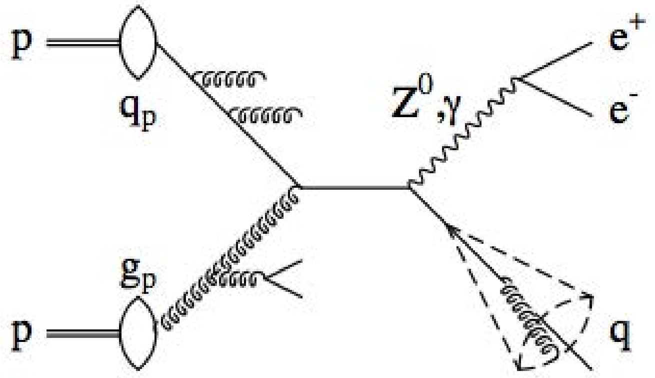
1990-2000: confirmation of
asymptotic freedom

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

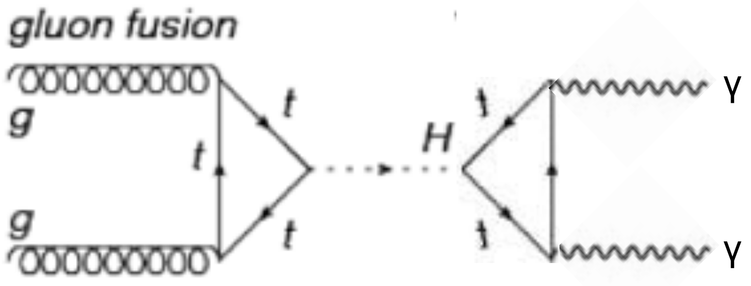




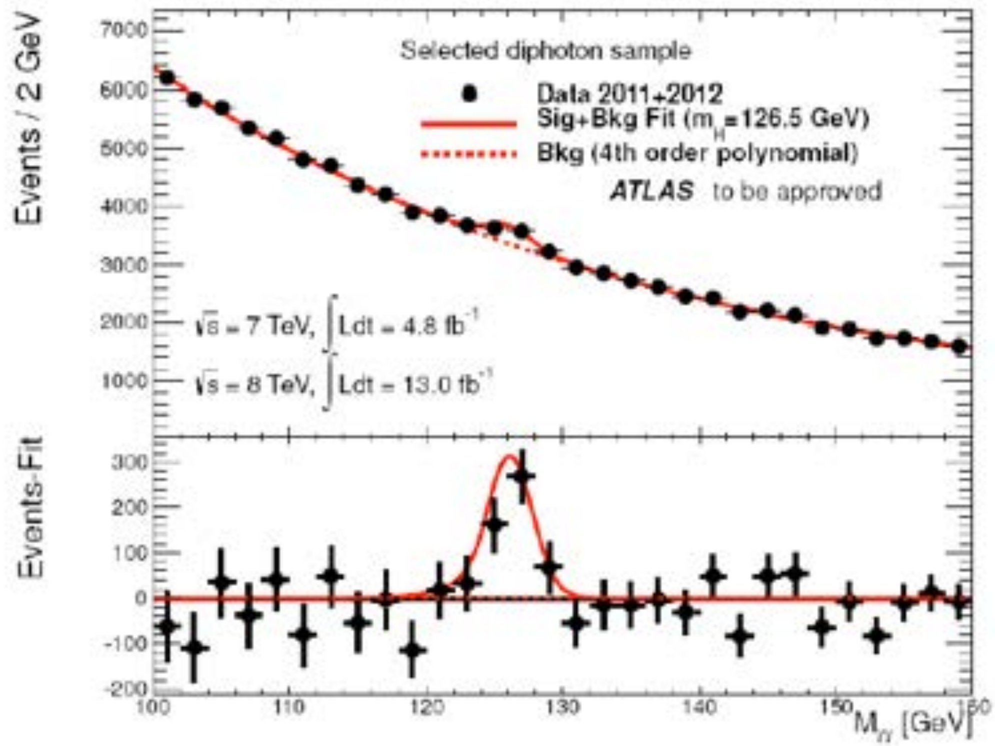
History of Strong Interactions (4)

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

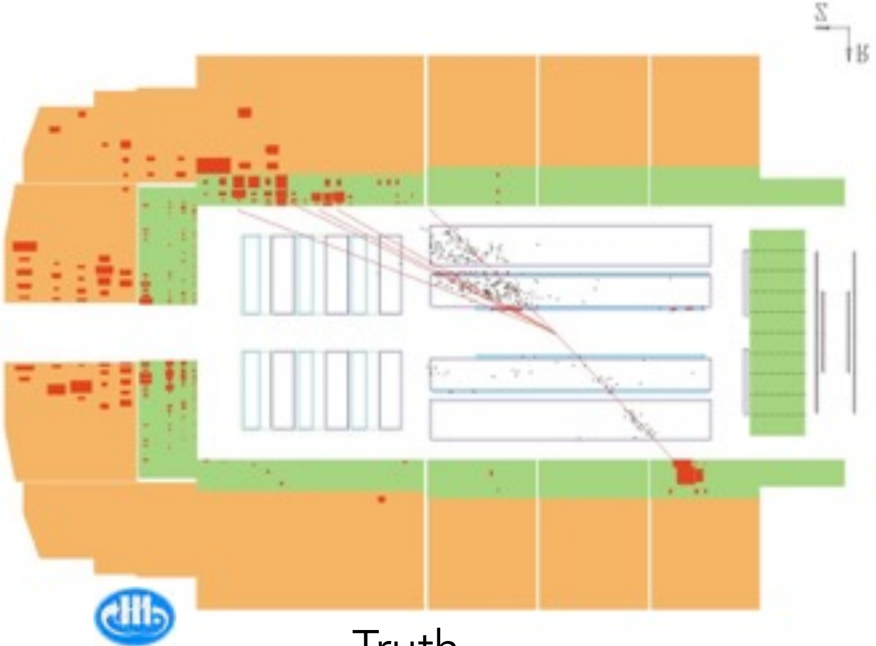


example: Higgs search

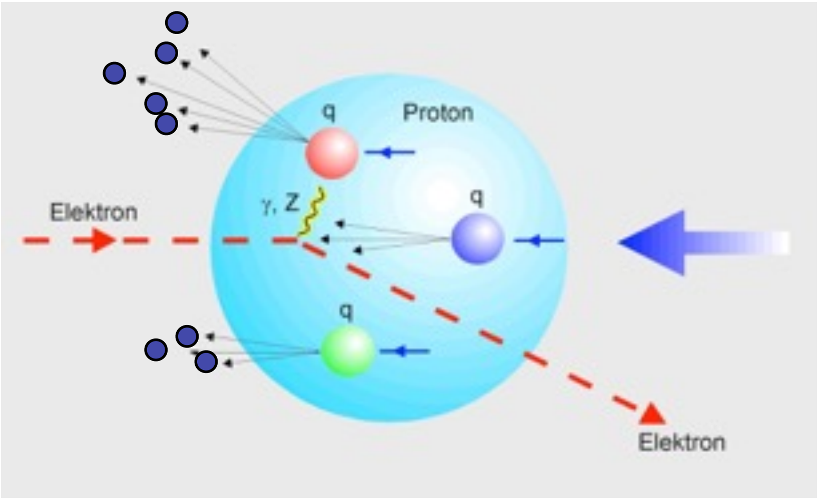




Quarks in the proton: model and experiment



Truth

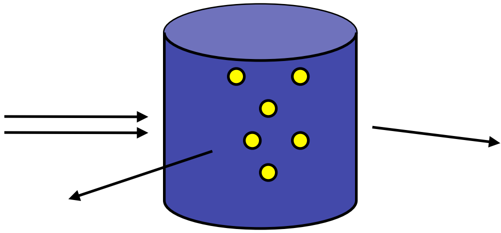


model, theory

experiment: measurement of scattered electrons

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

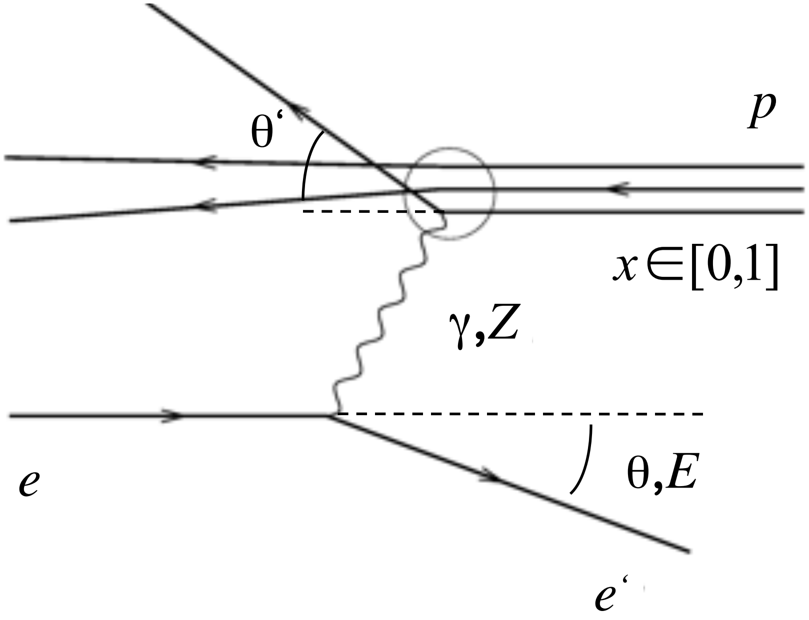
sandbag



explanation: the proton has „hard“ components: QUARKS

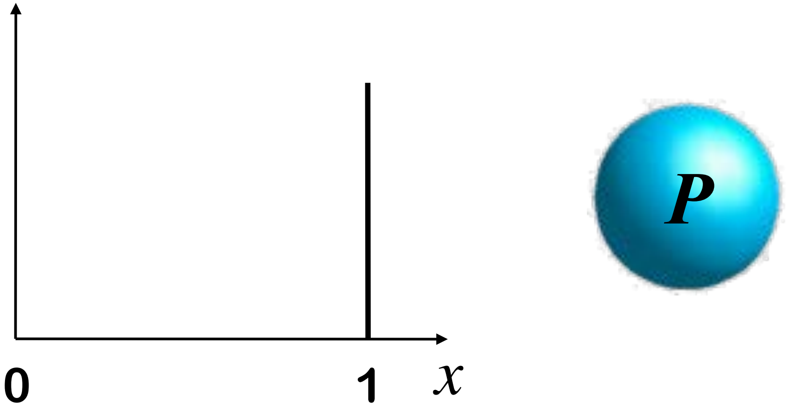
(Ch. Kiesling)

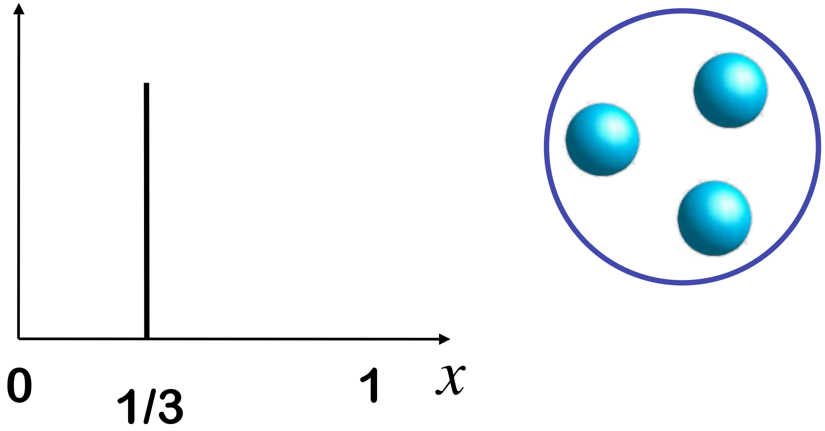
Quarks in the proton ?

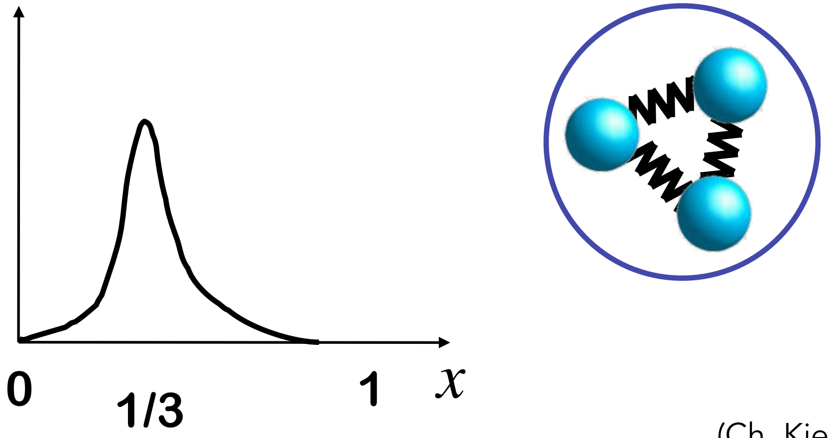


measurement of scattering angle
and energy of electrons
(2 given entities):

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





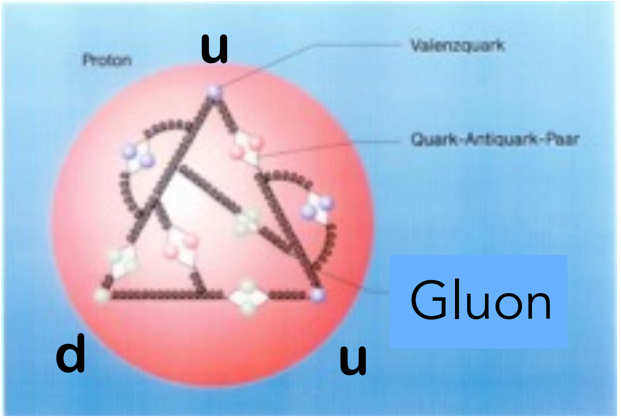


(Ch. Kiesling)

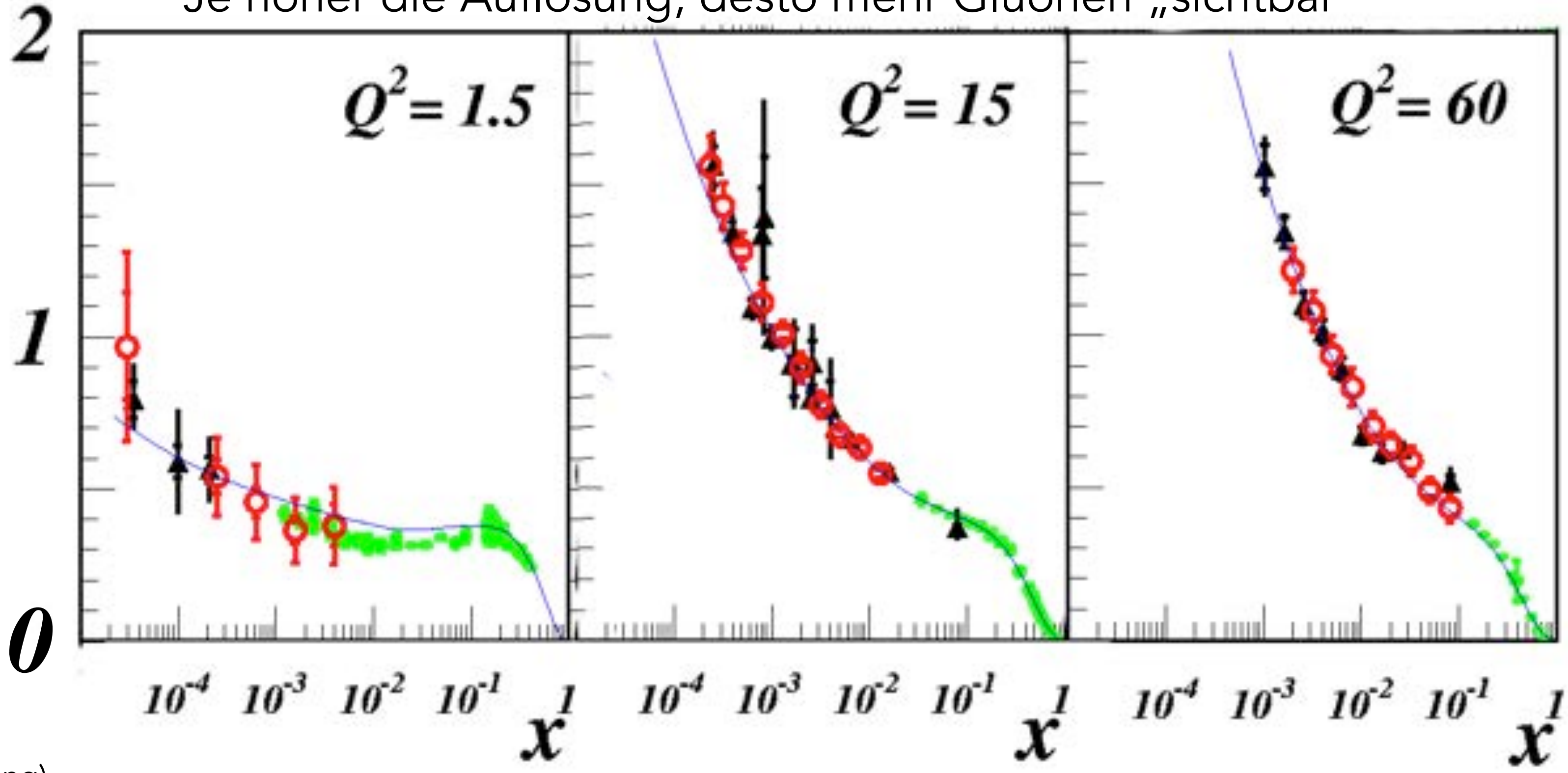
Quarks and gluons in the proton !

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

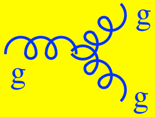
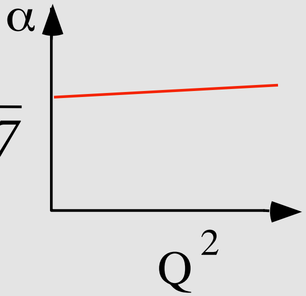
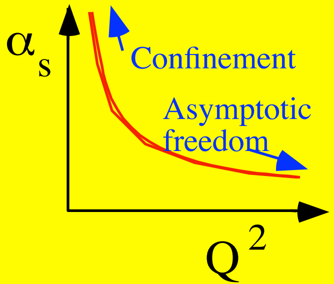


Je höher die Auflösung, desto mehr Gluonen „sichtbar“



(Ch. Kiesling)

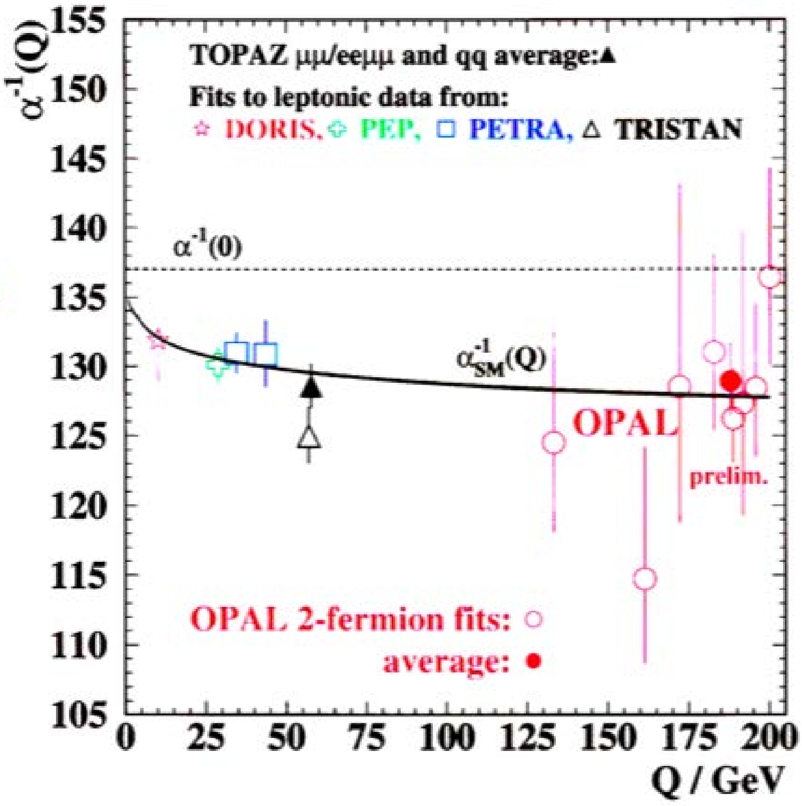
properties of QED and QCD:

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

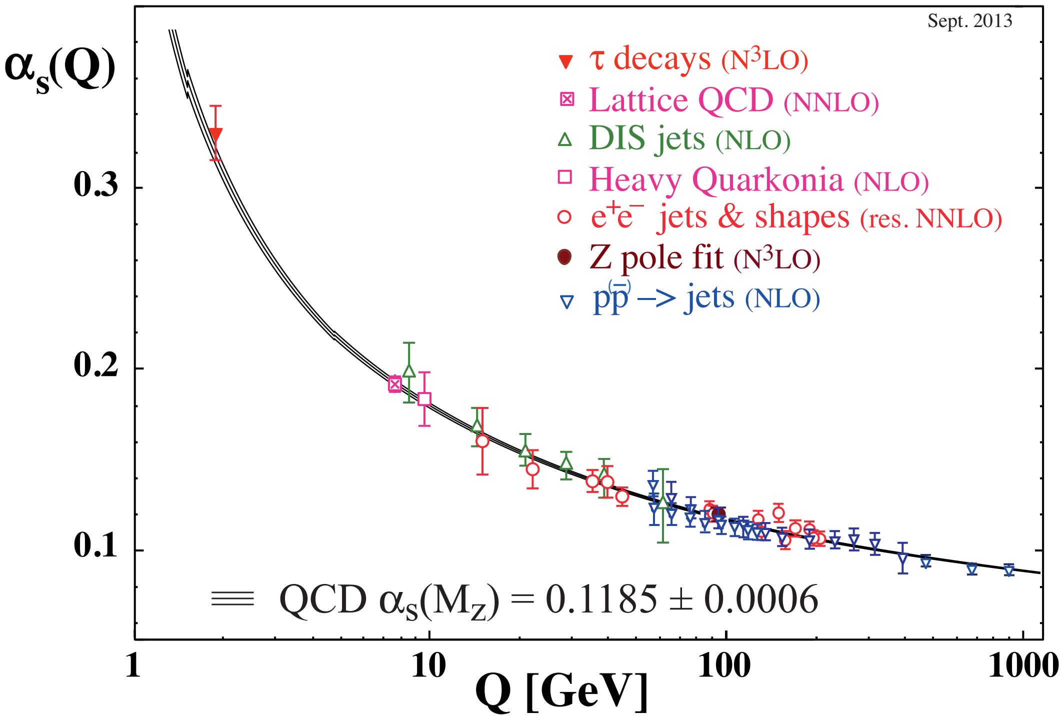
energy dependence of coupling "constants":

- verified by high precision measurements

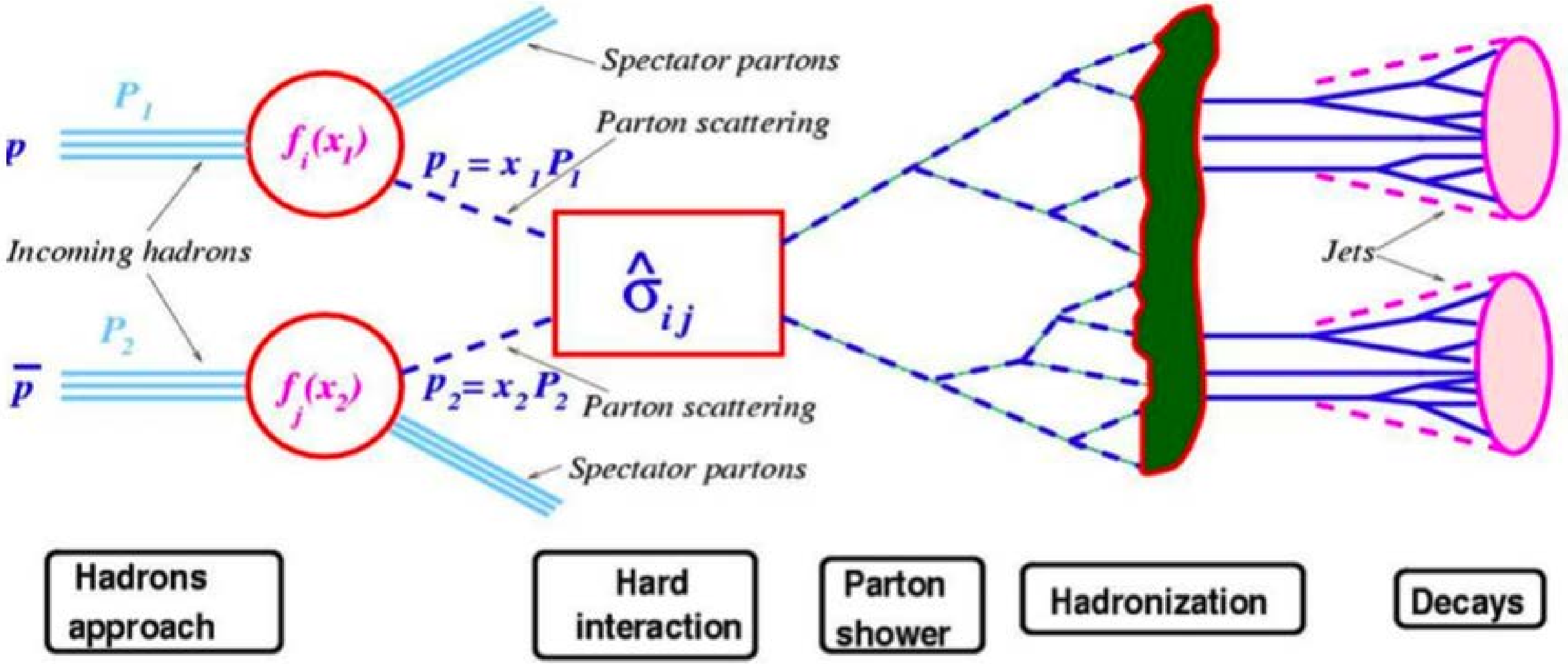
QED



QCD

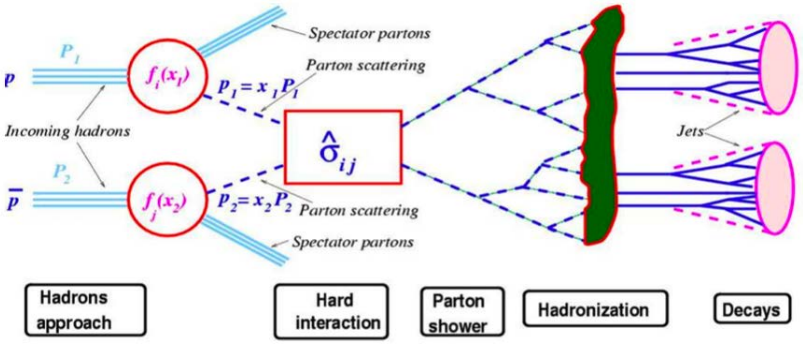


theoretical description of hadronic processes



- description of sub-processes :
  - $f(x,Q^2)$: parton density functions for q and g inside the proton [pdf]
    (probability of a parton having a fraction of x of the proton momentum)
  - $\hat{\sigma}_{ij}(Q^2)$: "hard" QCD cross section, e.g. for qq –> gg; qg –> $q'g'$
  - parton shower: QCD radiation processes q–>qg, g–>gg, g–>qq
  - Hadronization: parametrization of transition of q,g into hadrons
  - Decays: parametrization following measurements and spin-statistics

factorization theorem:

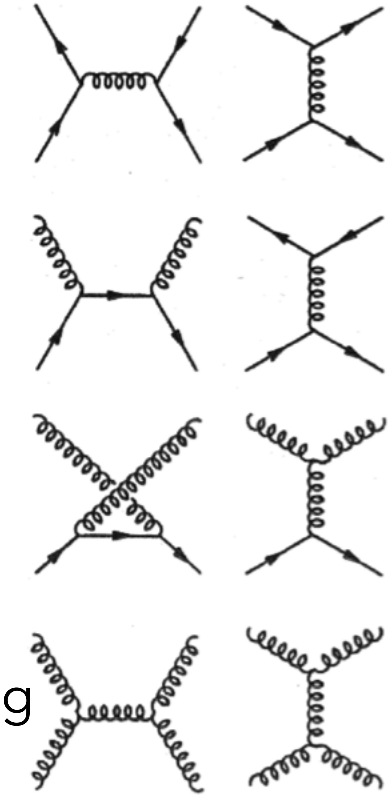


$$\sigma_{ij} = f_i(x_1,Q^2)f_j(x_2,Q^2)\hat{\sigma}_{ij}(Q^2)$$

plus sequential application of“Parton Shower” and “Hadronization” .

structure functions:

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

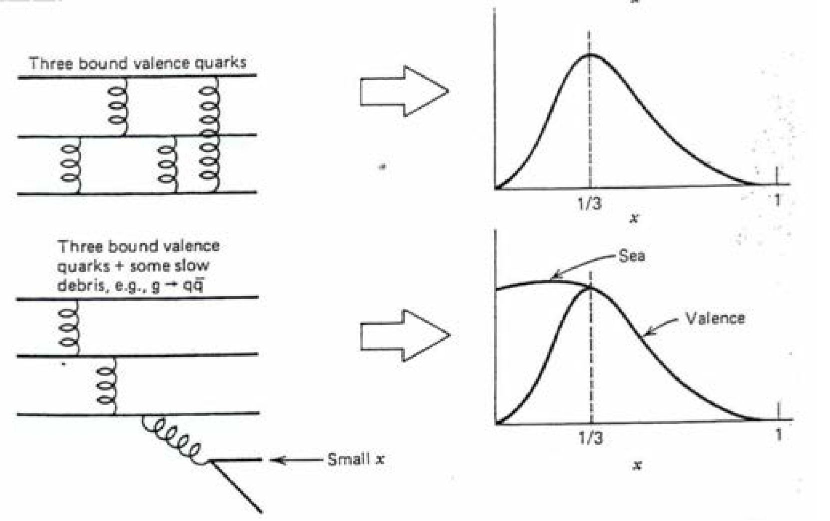


QCD perturbation theory:

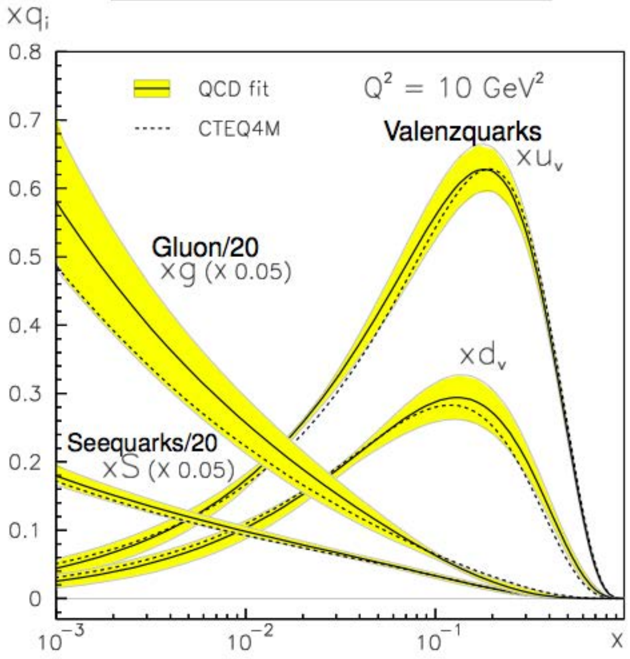
Leading order (lo) matrix elements e.g. for 2–>2 processes:

(for precision measurements, need at least next-to-leading order (nlo) or even nnlo calculations!)

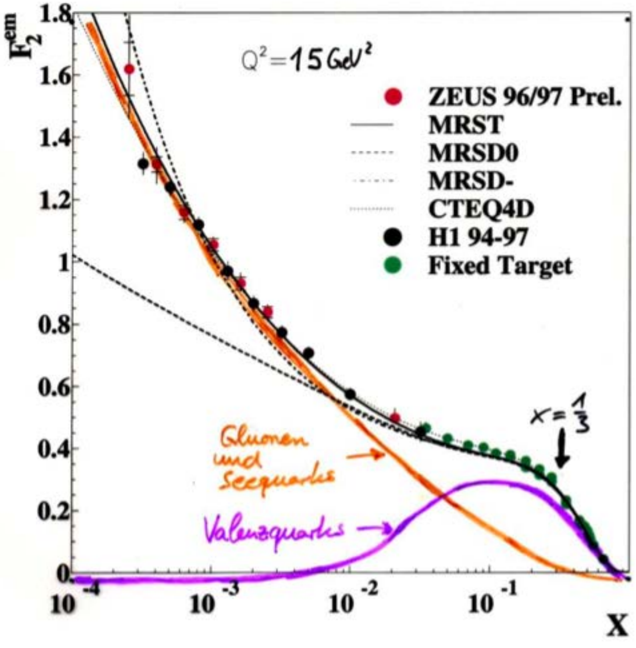
proton structure



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



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



proton structure (HERA + LHC)

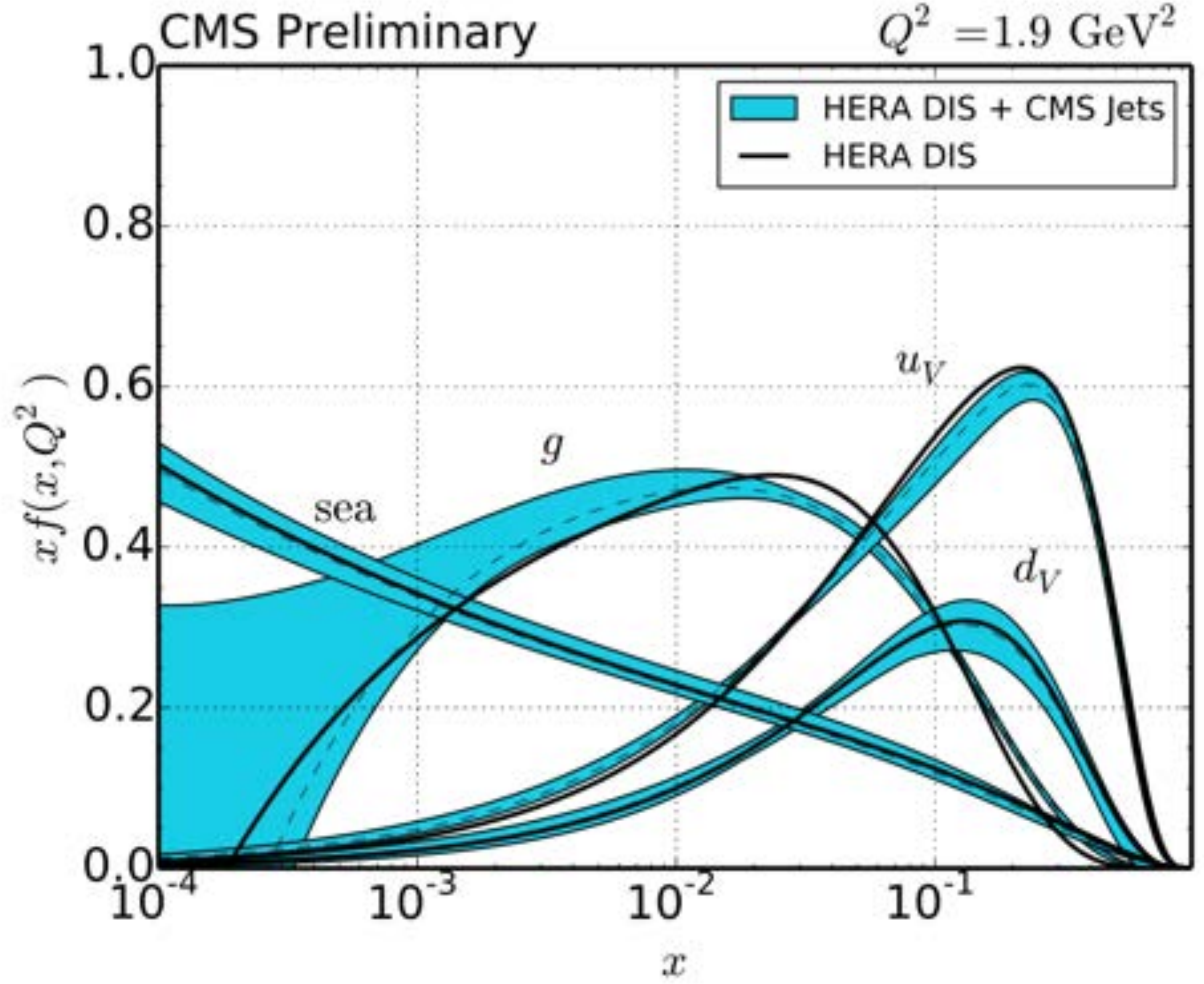
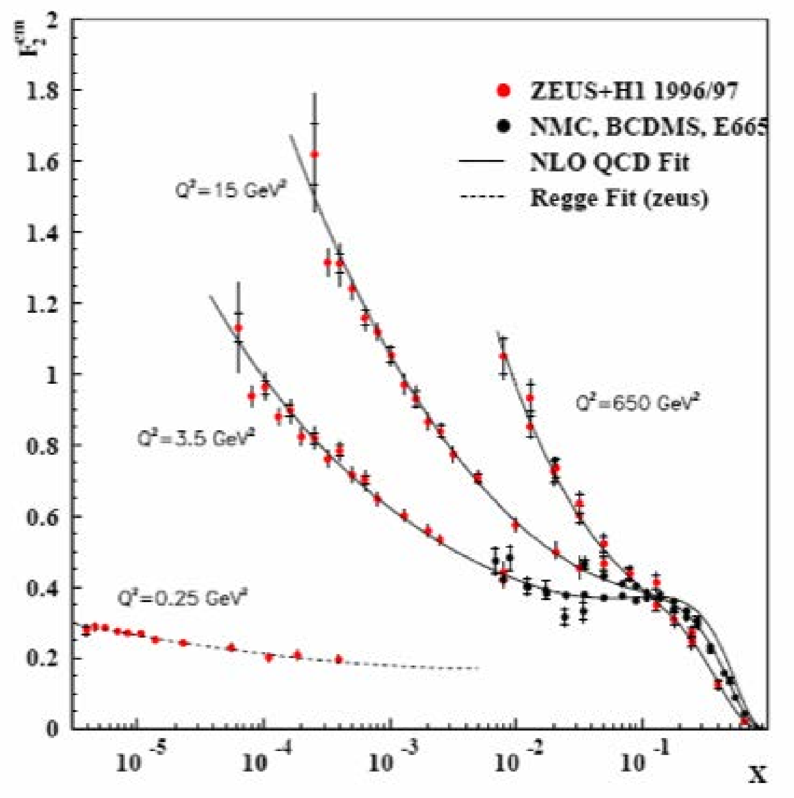
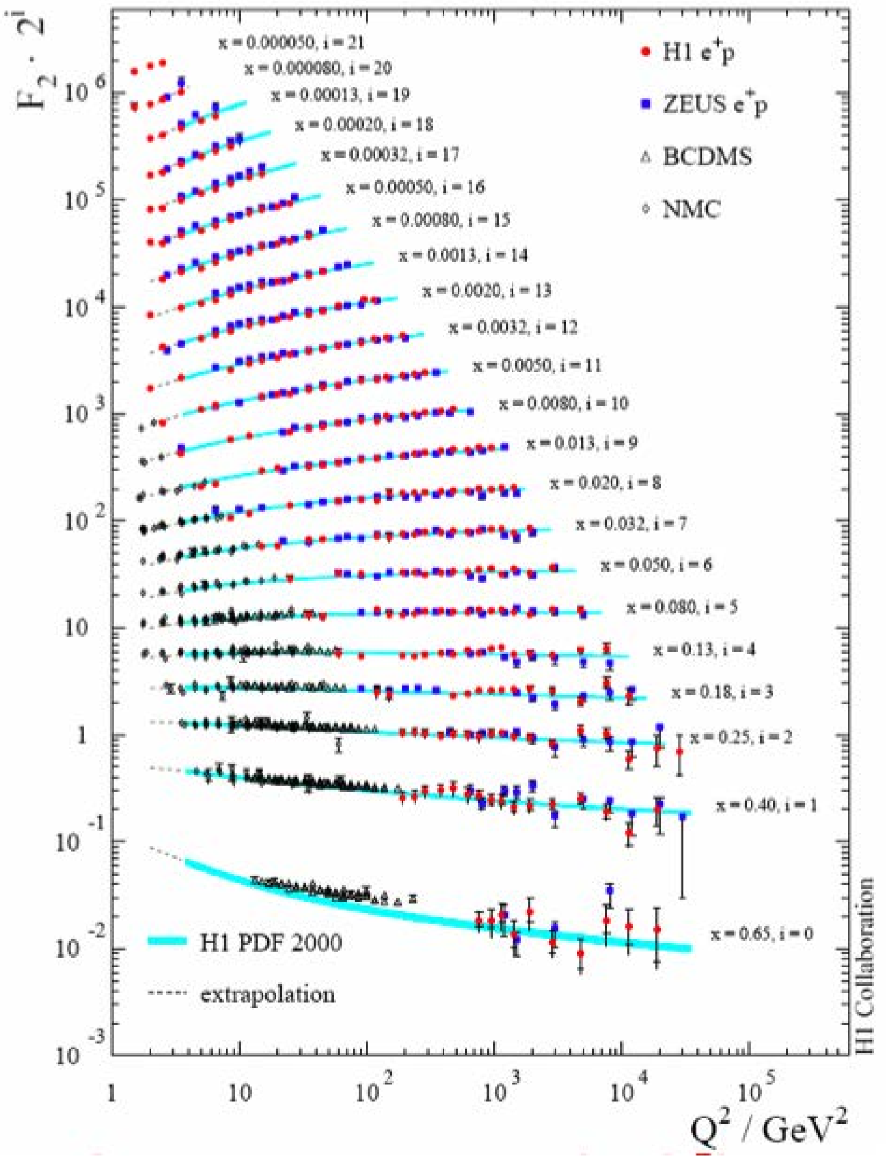


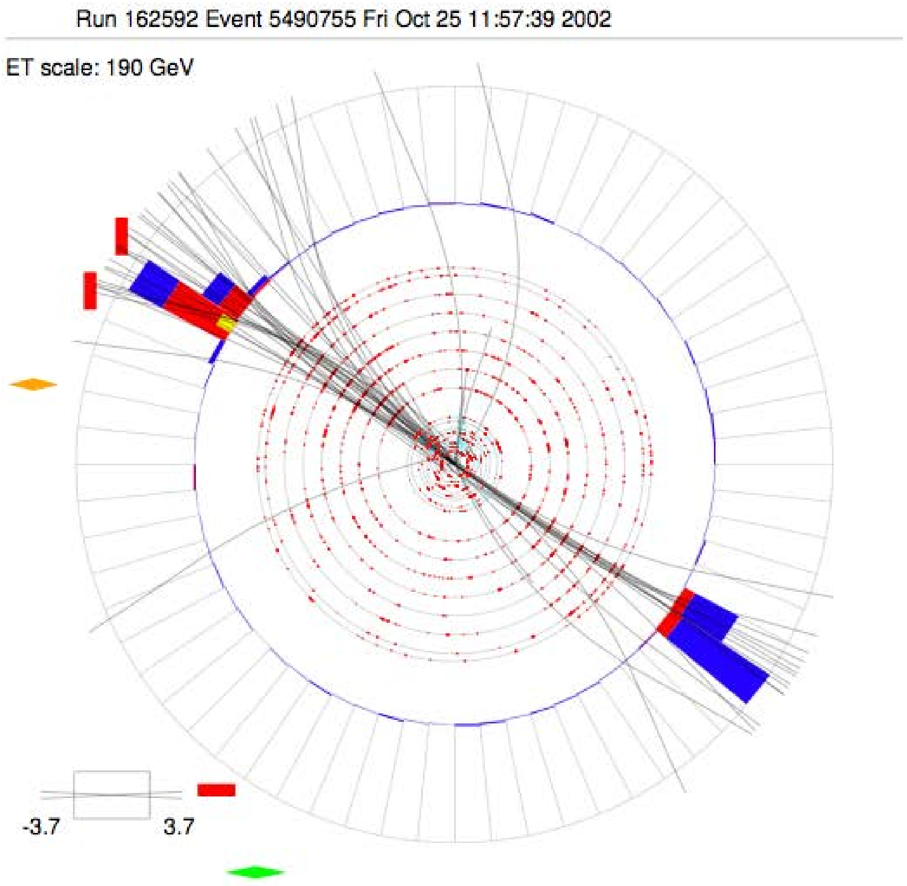
Figure 11: Overview of the gluon, sea, u valence, and d valence PDFs before (full line) and after (dashed line) including the CMS jet data into the fit. The PDFs are shown at the starting scale $Q^2 = 1.9\,\mathrm{GeV}^2$. In addition the total uncertainty including the CMS jet data is shown as a band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

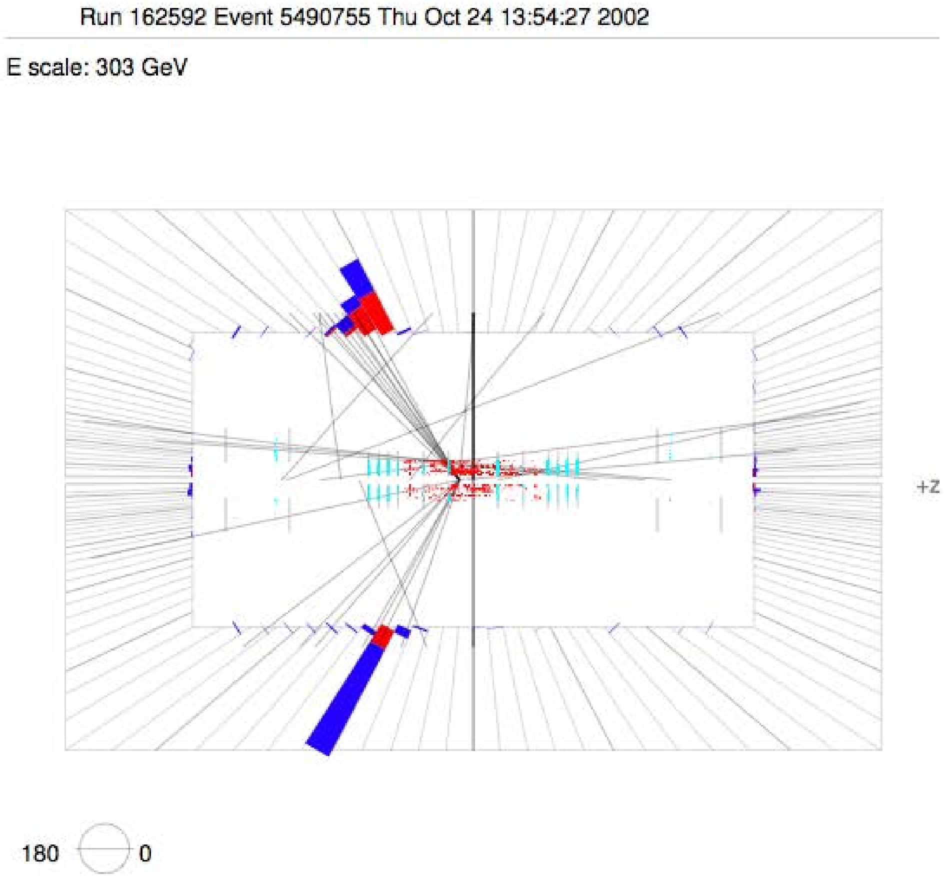
proton structure





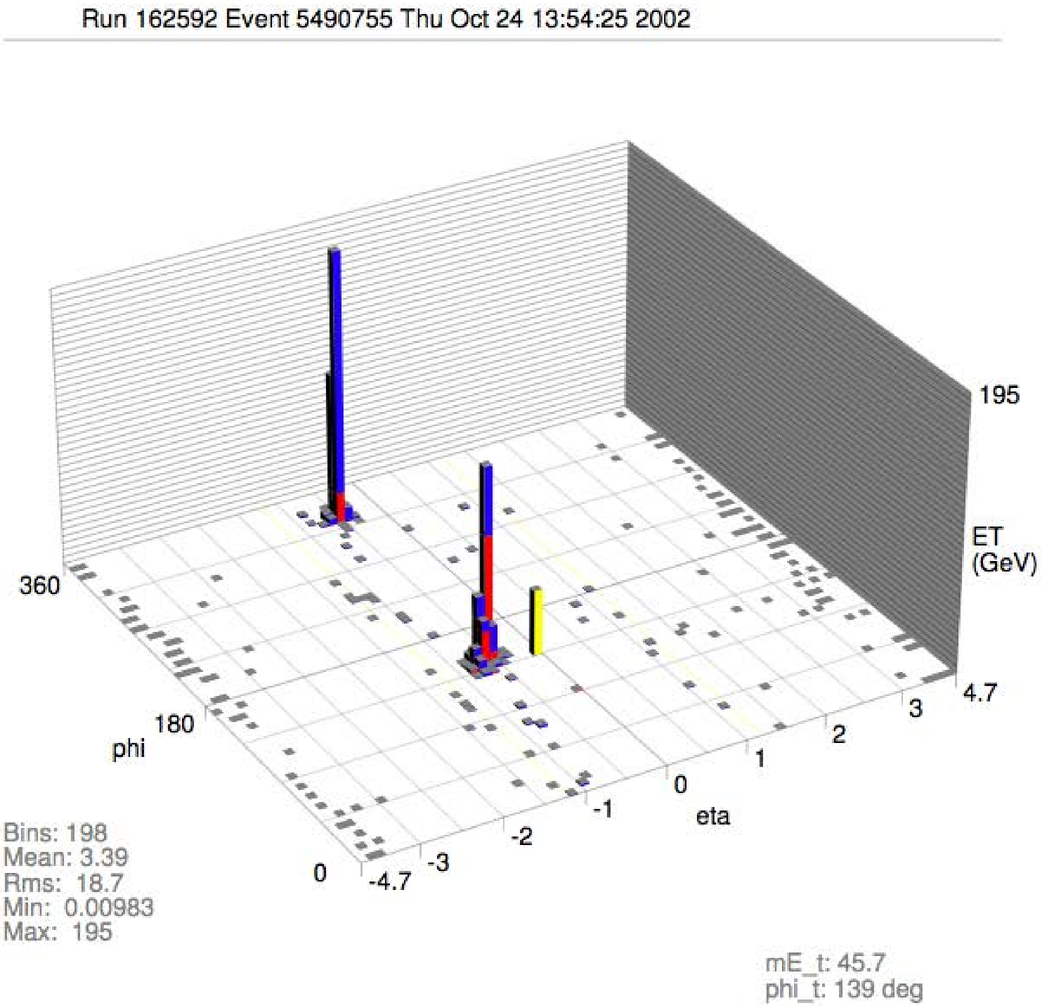
2-Jet final state in proton-antiproton collision (Tevatron; D0 detector)





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

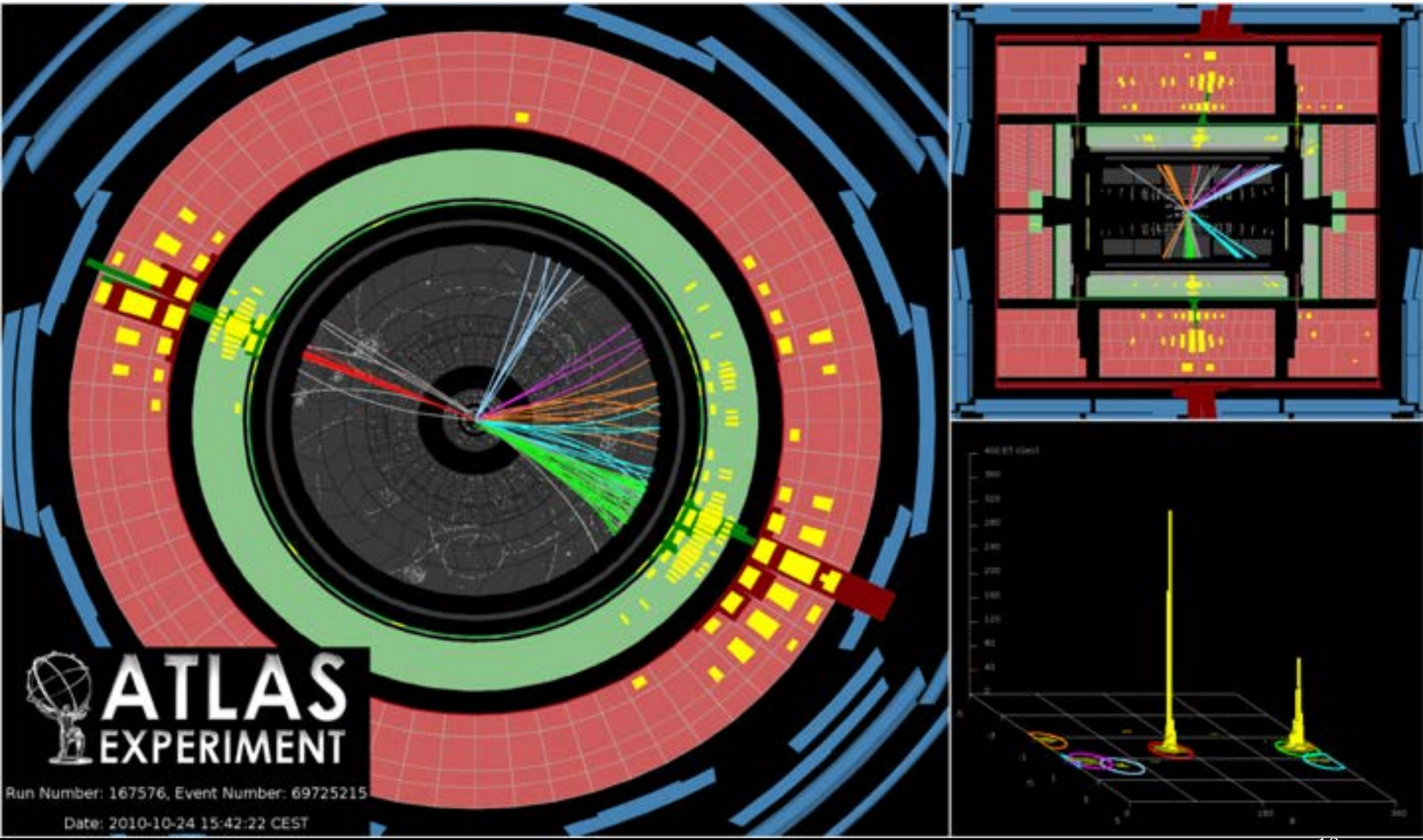
Darstellung in φ-η-Ebene:



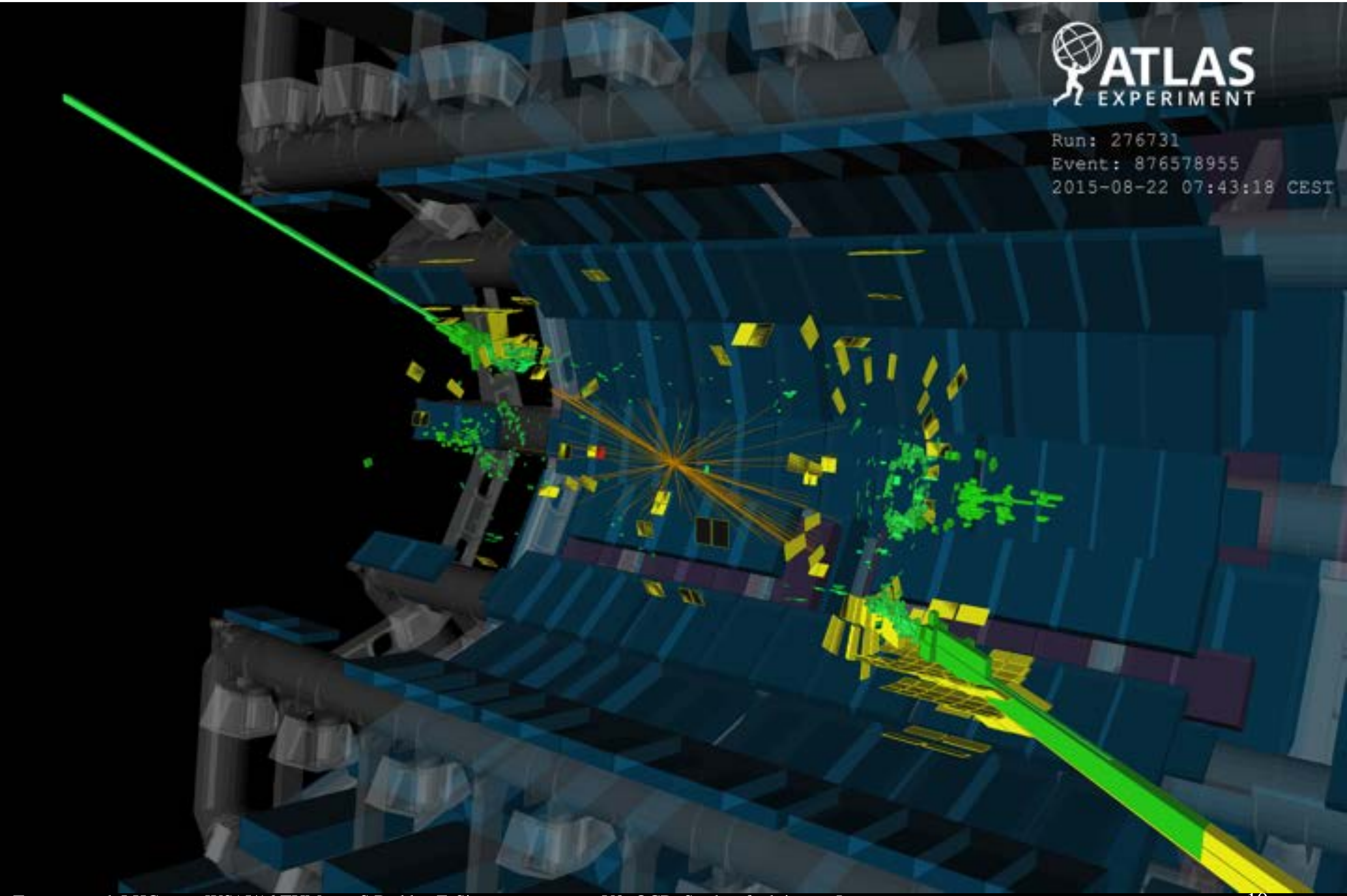
Azimutwinkel φ, Pseudorapidität $\eta = -\tan(\vartheta/2)$, Polarwinkel ϑ, transversale Energie $E_T = E\sin\vartheta$

The highest mass central dijet event and the highest-p_T jet collected by the end of October 2010: two central high-p_T jets have an invariant mass of 2.6 TeV and the highest p_T jet has p_T of 1.3 TeV.

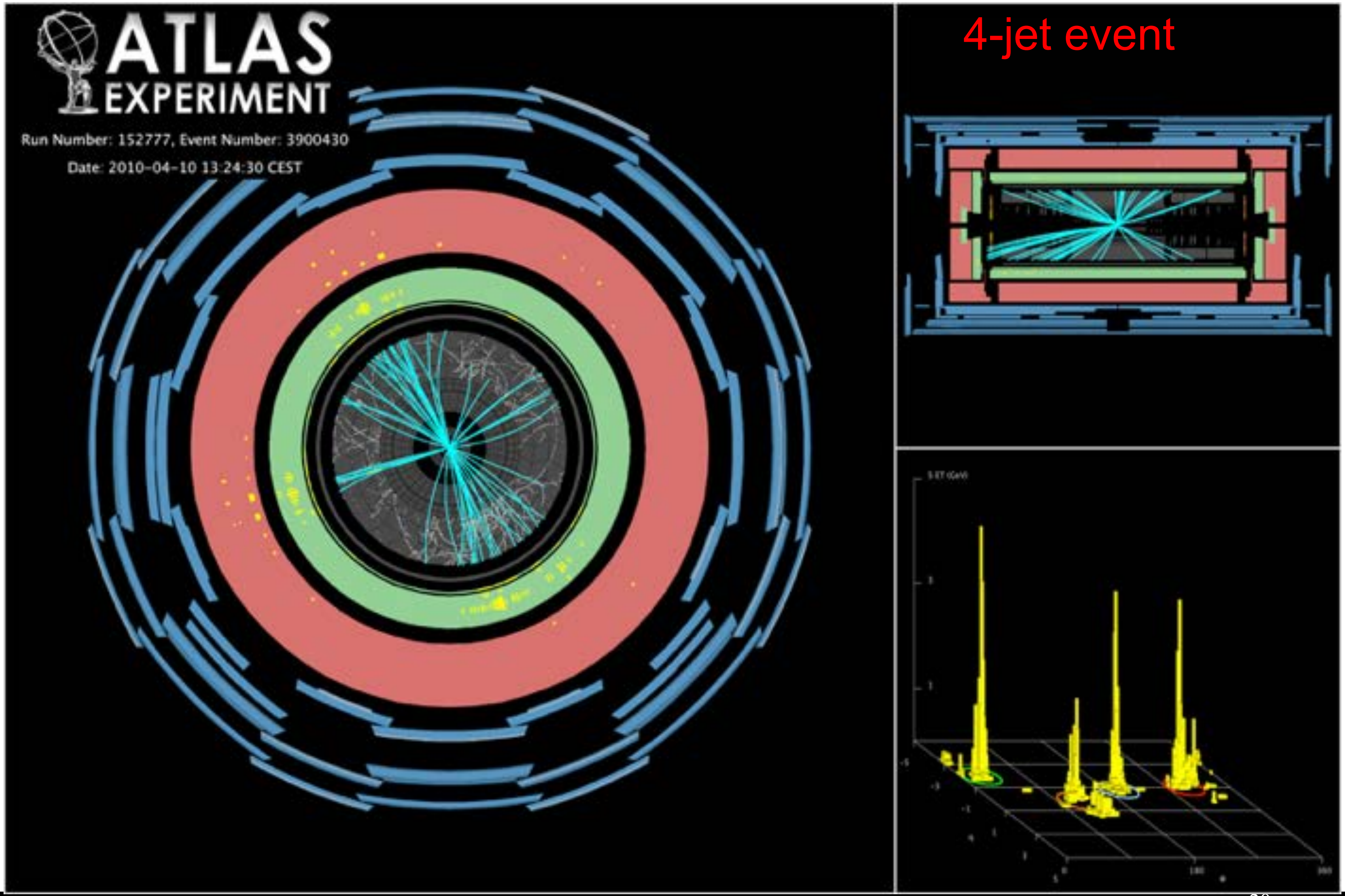
- 1st jet (ordered by p_T): $p_T = 1.3$ TeV, $\eta = 0.2$, $\varphi = 2.8$
- 2nd jet: $p_T = 1.2$ TeV, $\eta = 0.0$, $\varphi = -0.5$
- Missing $E_T = 42$ GeV, $\varphi = 1.5$
- Sum $E_T = 2.2$ TeV



one of the highest-mass di-jet events at $\sqrt{s}$ = 13 TeV: m_{ij} = 6.9 TeV



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.

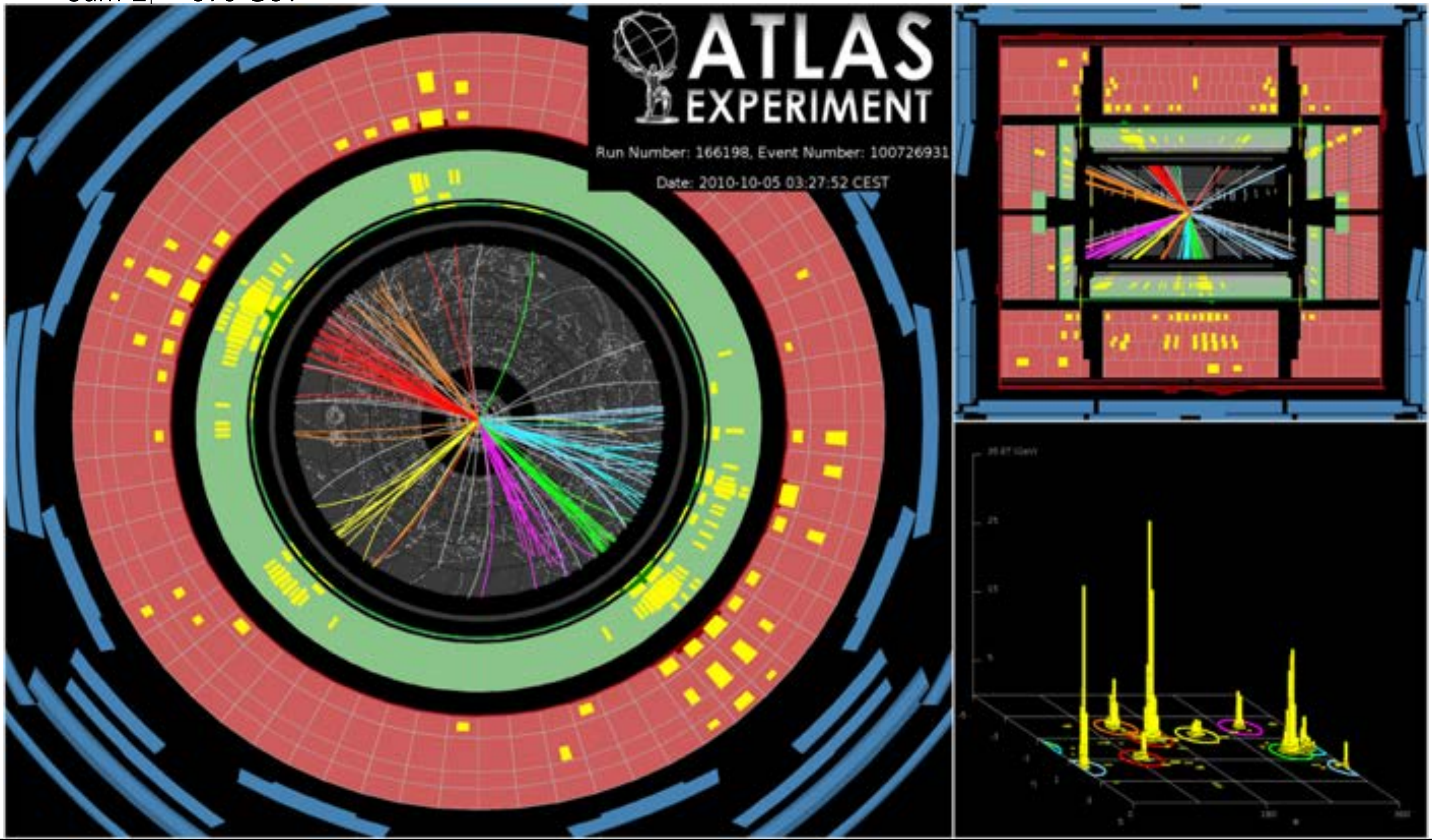


4-jet event

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.

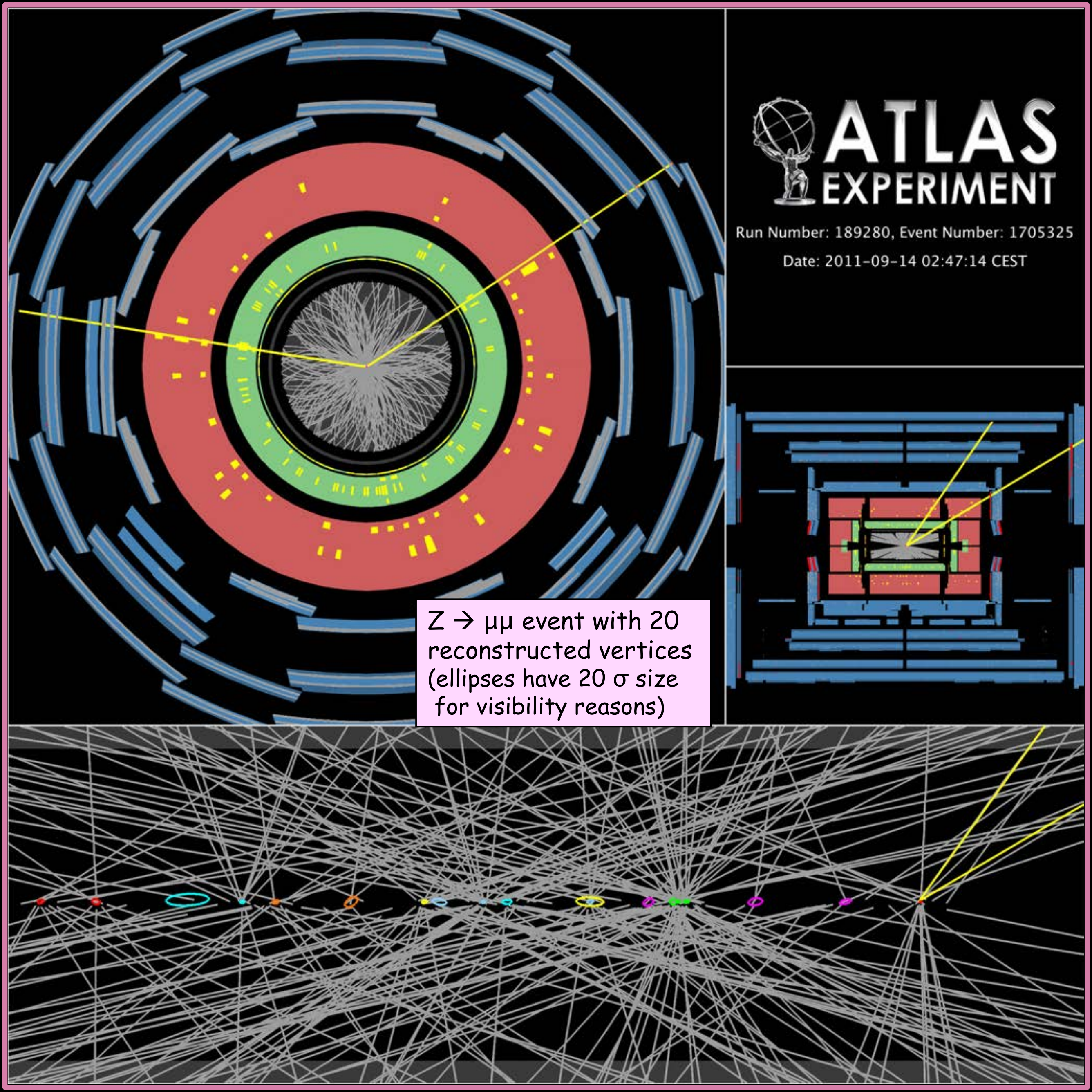
- 1st jet (ordered by p_T): p_T = 290 GeV, η = -0.9, φ = 2.7
- 2nd jet: p_T = 220 GeV, η = 0.3, φ = -0.7
- Missing E_T = 21 GeV, φ = -1.9
- Sum E_T = 890 GeV

8-jet event



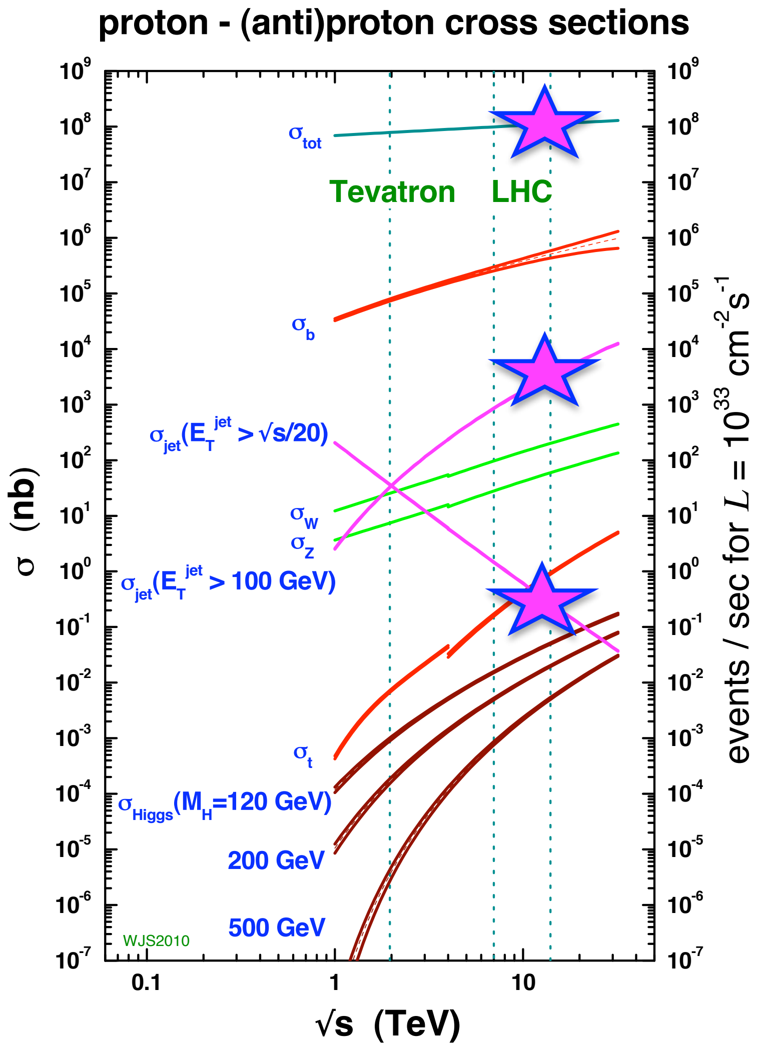
„pile-up“:

- 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



Z → μμ event with 20 reconstructed vertices (ellipses have 20 σ size for visibility reasons)

QCD- / Jet- production cross sections



total QCD cross section

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

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

Physik der Hadronen-Jets

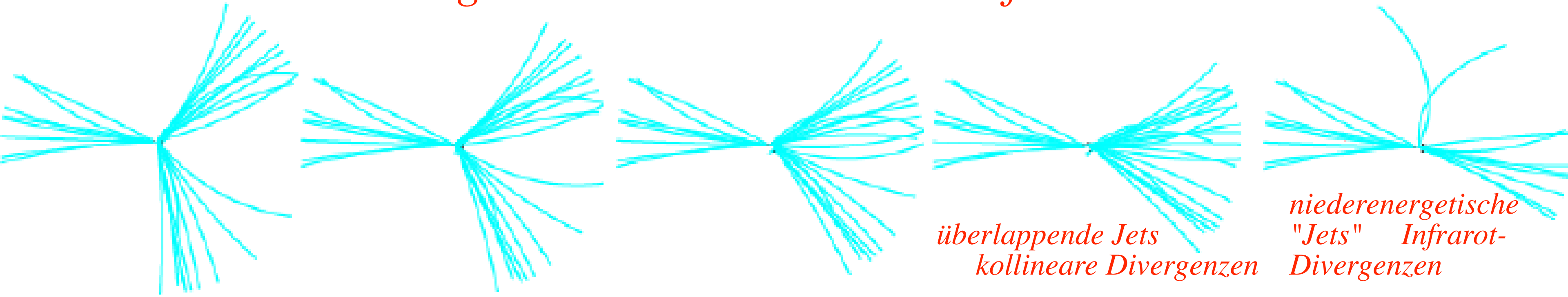
Zum Vergleich von Hadronen-Jets
mit analytischen QCD -Rechnungen
(Quark- und Gluonendynamik)
muß man
auflösbare Teilchenjets
Theorie und Praxis definieren.

→

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:

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

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

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

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

ϕ_i : azimutaler 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-Verktoren); 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 ~ 0.4 … 0.7)

Anmerkungen zum k_T - Jetalgorithmus

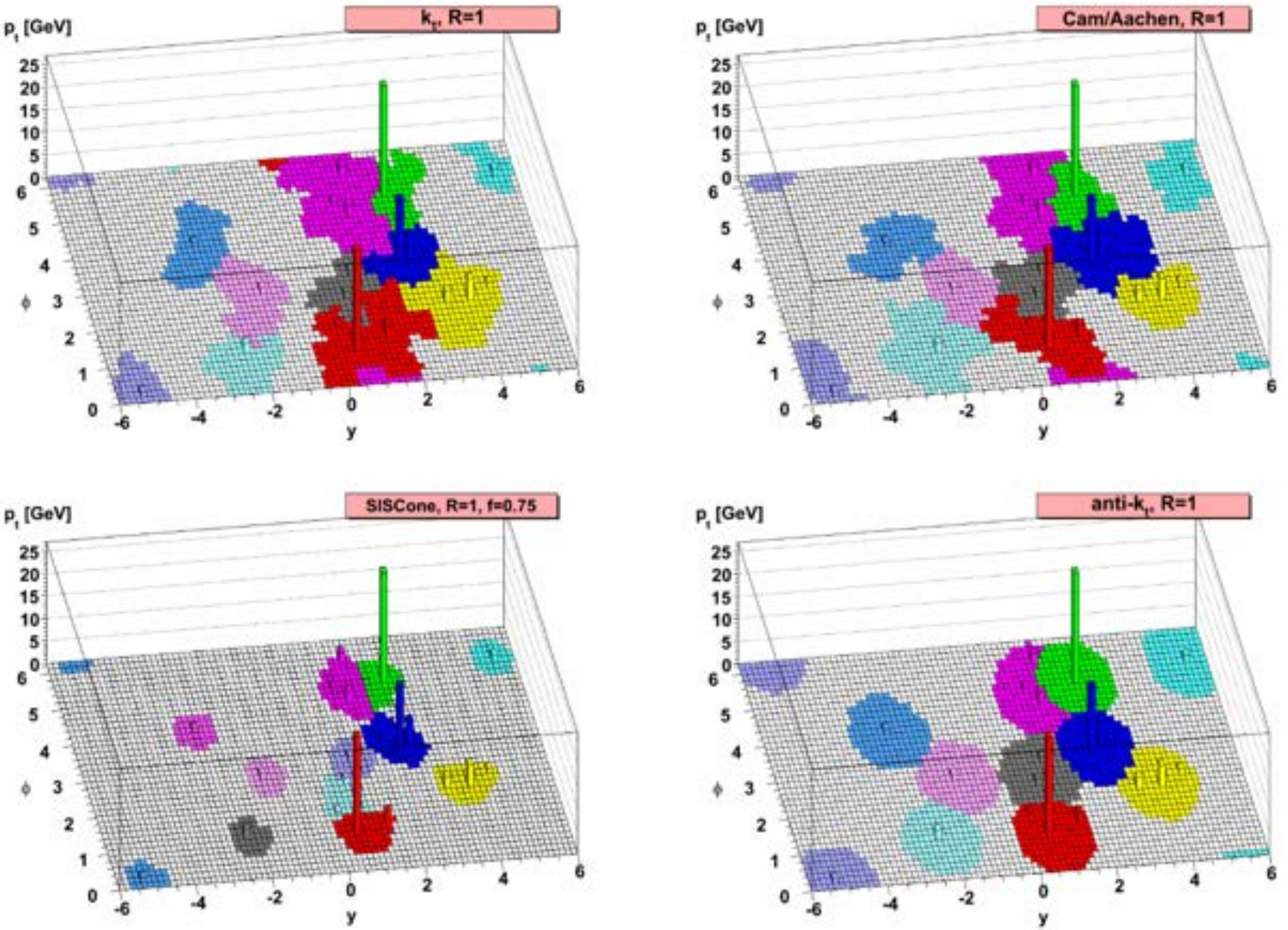
- die Jetdefinition über den Auflösungsparameter $d_{ij} = \min(E_i^2, E_j^2)\, \Delta R^2_{ij} / \Delta R^2$ ist eine Abwandlung der Formel für die invariante Paarmasse zweier masselose Teilchen: $M_{ij}^2 = E_i E_j\, (1 - \cos\theta_{ij})$ --- die historisch vor Einführung des k_T Algorithmus verwendet 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.

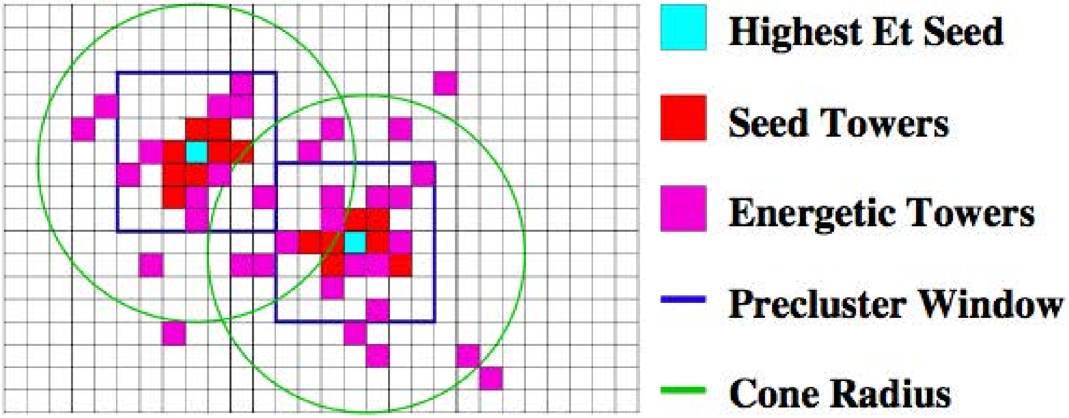
- am Hadron Collider muss bei Adaption des k_T Algorithmus besondere Rücksicht auf die durch die weiterfliegenden Proton-Reste verursachten “remnant jets” bzw. das “underlying event” in Vorwärts-/Rückwärts-Richtung genommen werden -- geschieht über die Definition von d_{iB}

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).



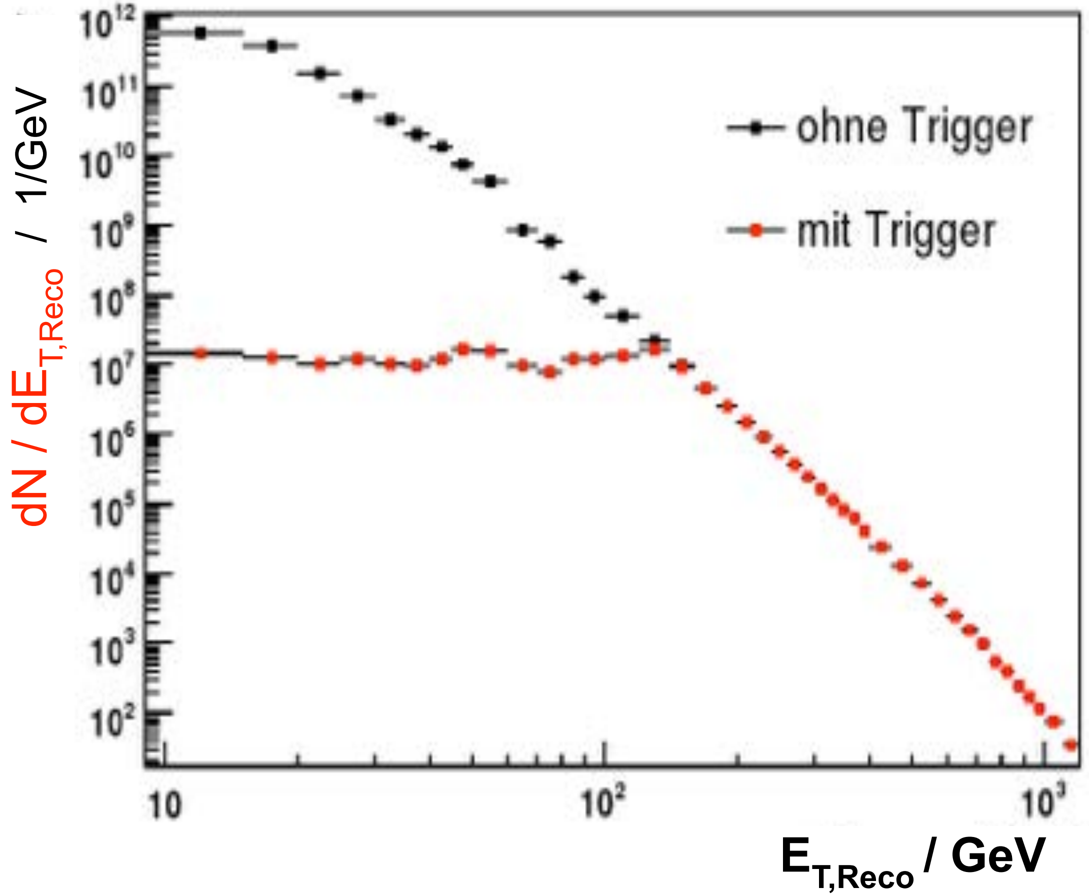
Anmerkungen zum Cone - Jetalgorithmus

- 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).

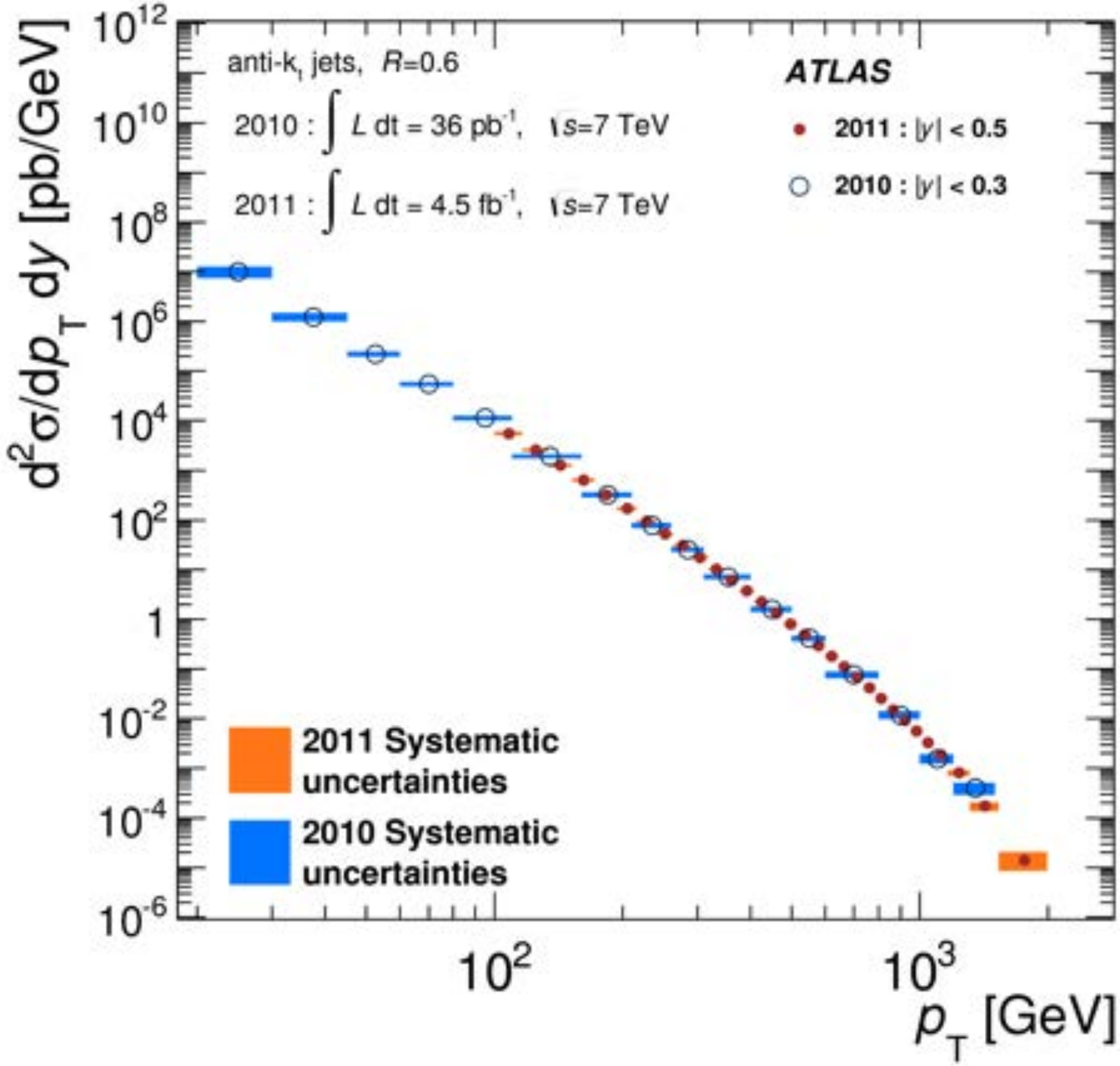
Jet-Wirkungsquerschnitt am LHC

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

- ○ Messung bis 1 TeV sehr früh möglich
- ○ Unsicherheiten:
  - Jet-Energieskala
  - Energieauflösung
  - Triggereffizienzen
  - Luminosität



Jet production cross section



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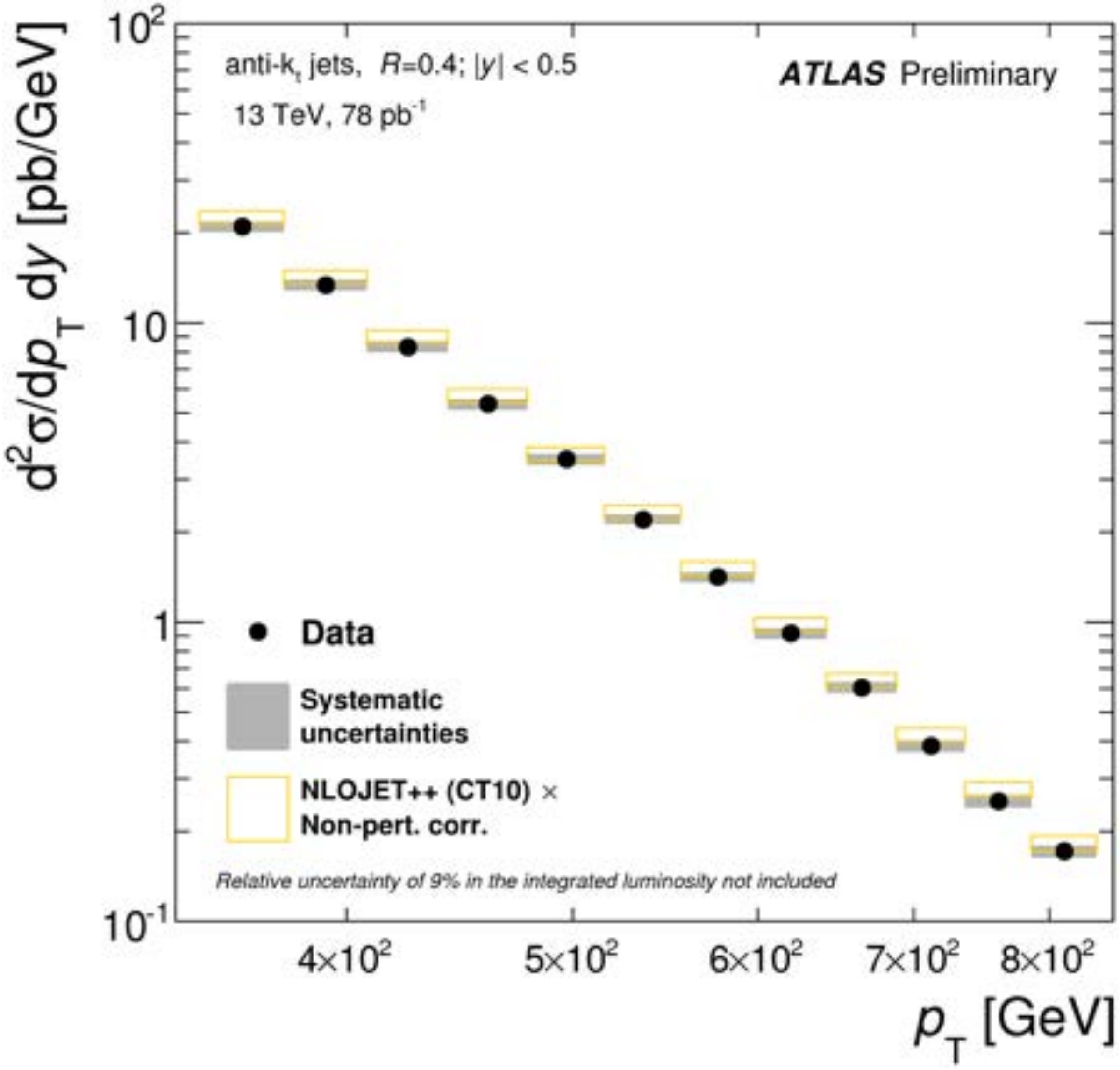
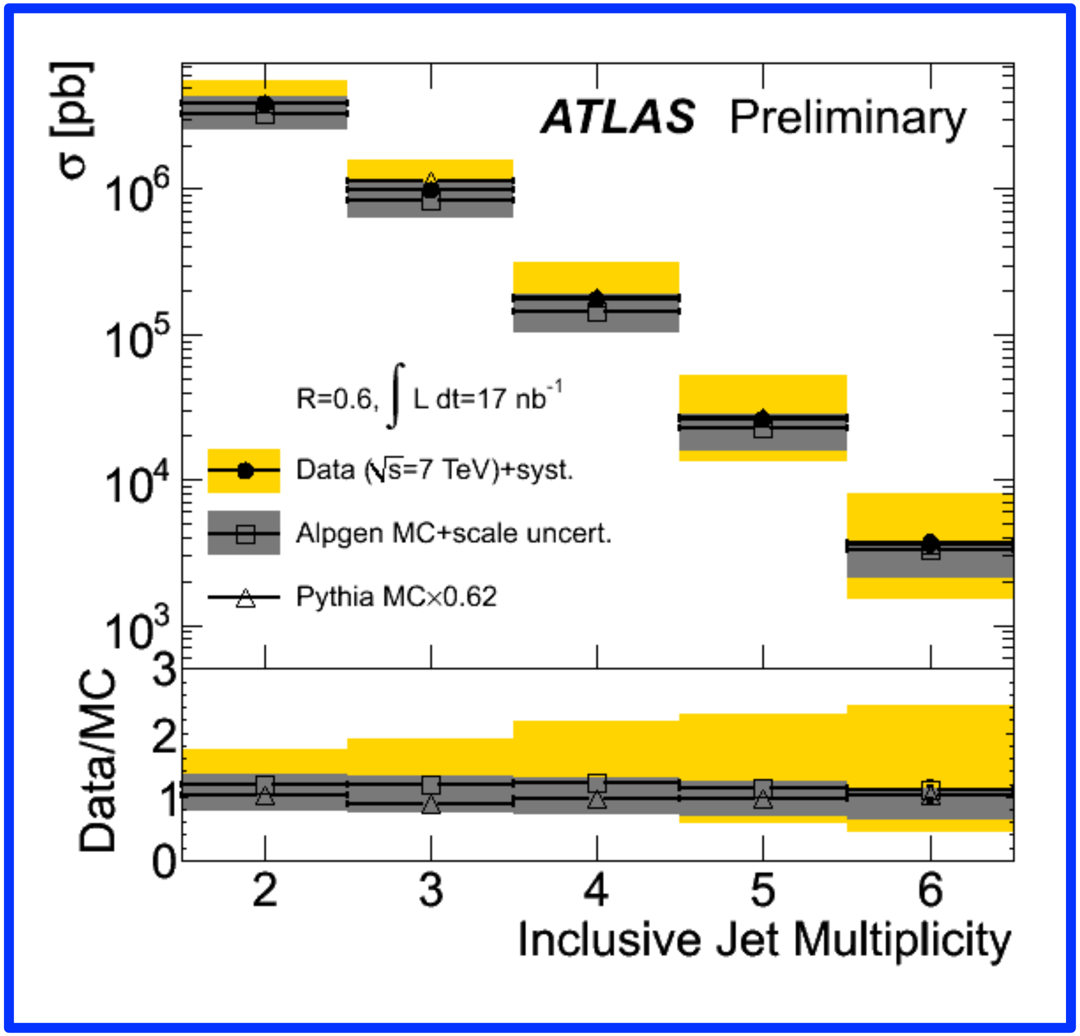
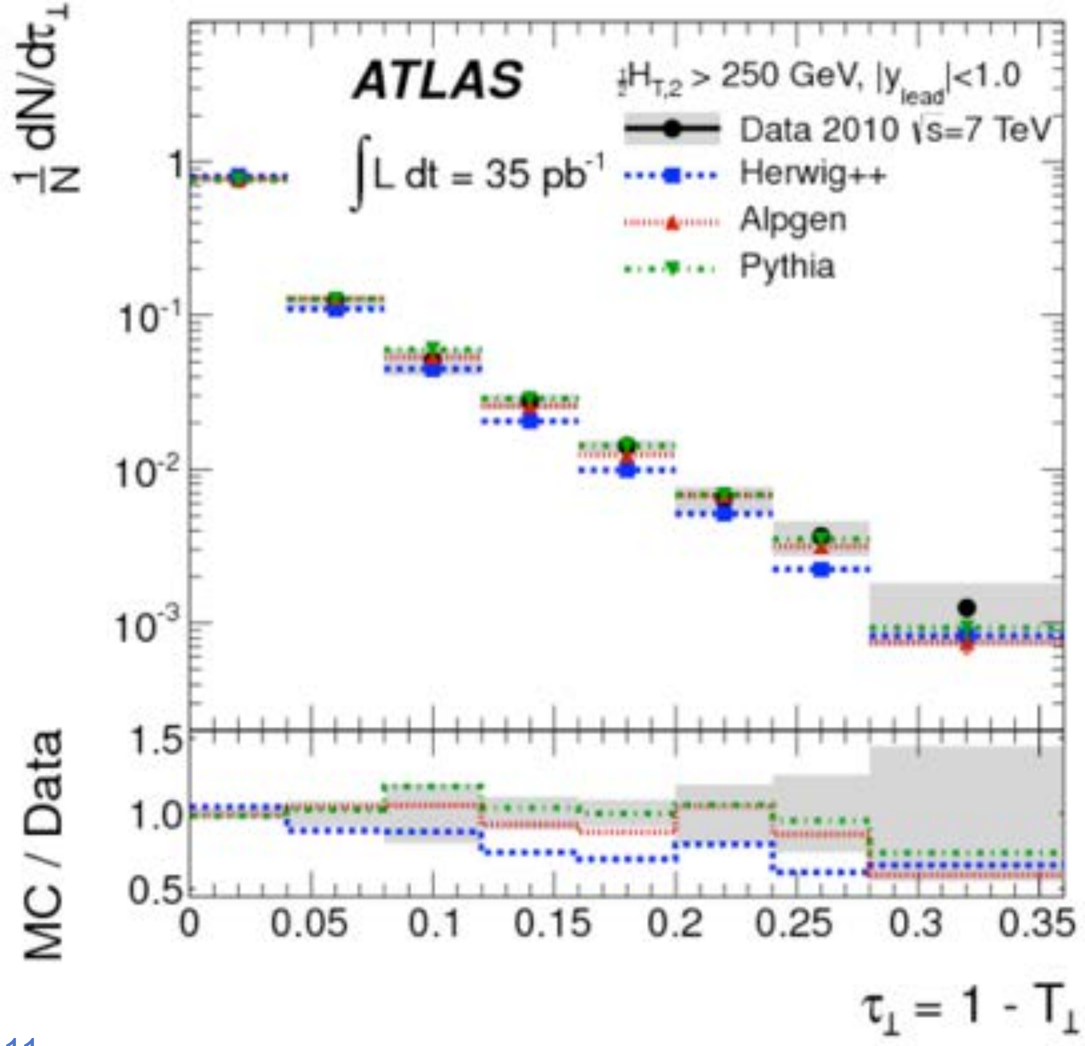
Jet production cross section



Jet multiplicities



Measurement of event shapes at large momentum transfer



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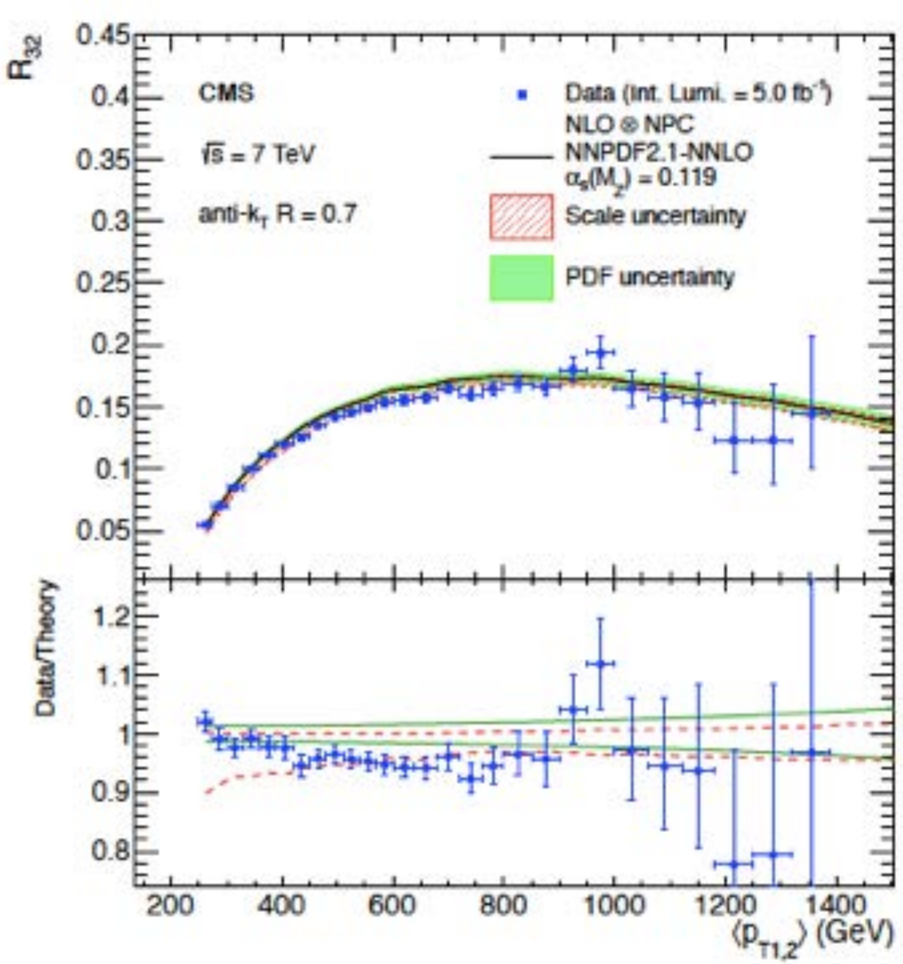
Measurement of the ratio of the inclusive 3-jet and 2-jet cross sections

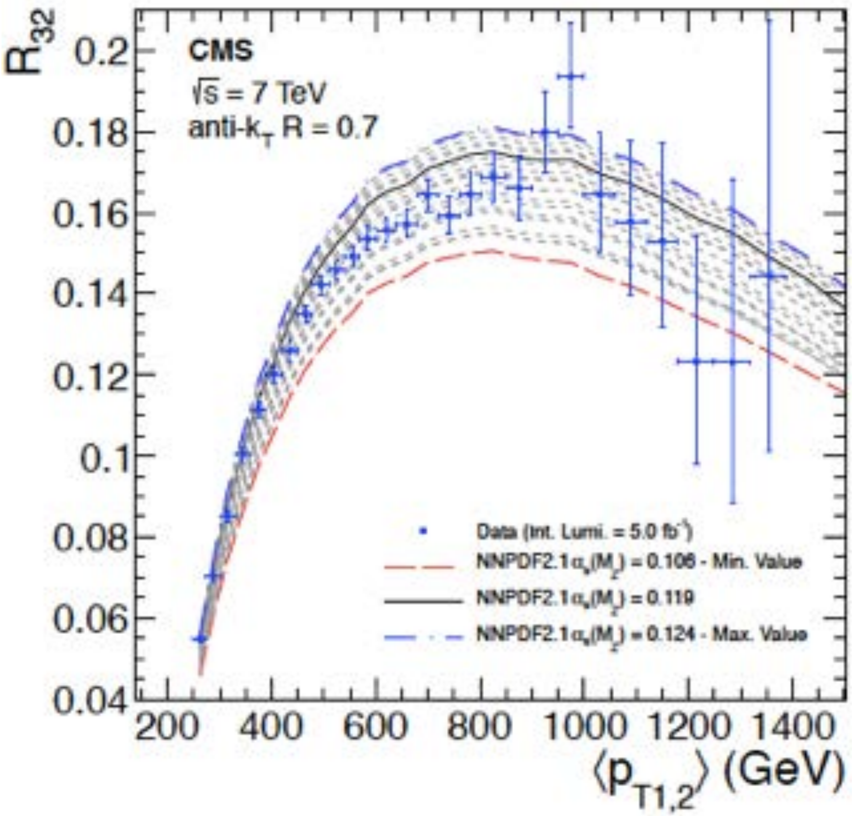
and

first determination of the strong coupling constant α_s in the TeV range

- measurement of $R_{32} = R_{3jet}/R_{2\text{-}jet}$ 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 $p_{T1,2}$

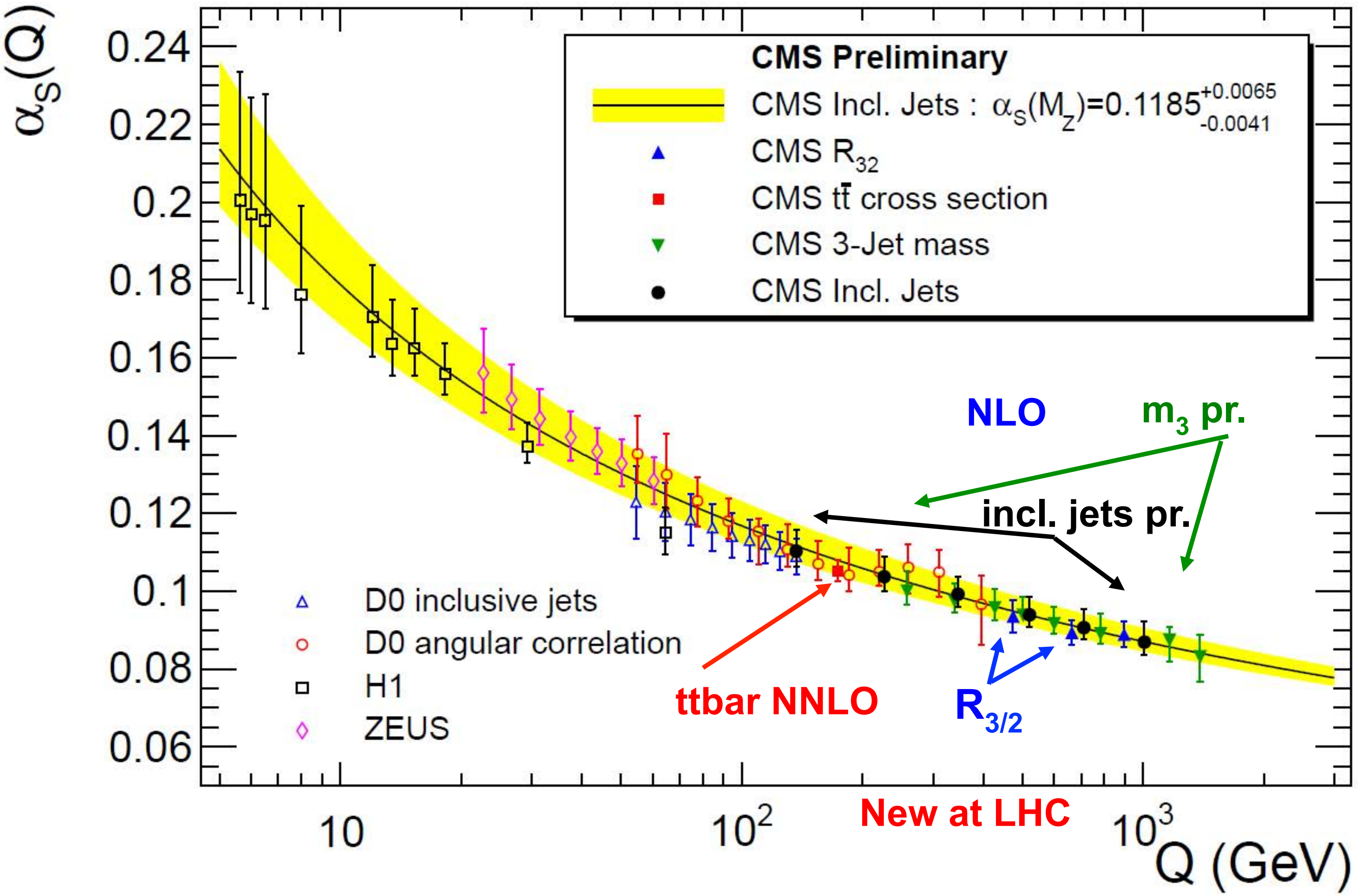




arXiv:1304.7498

summary of α_s measurements

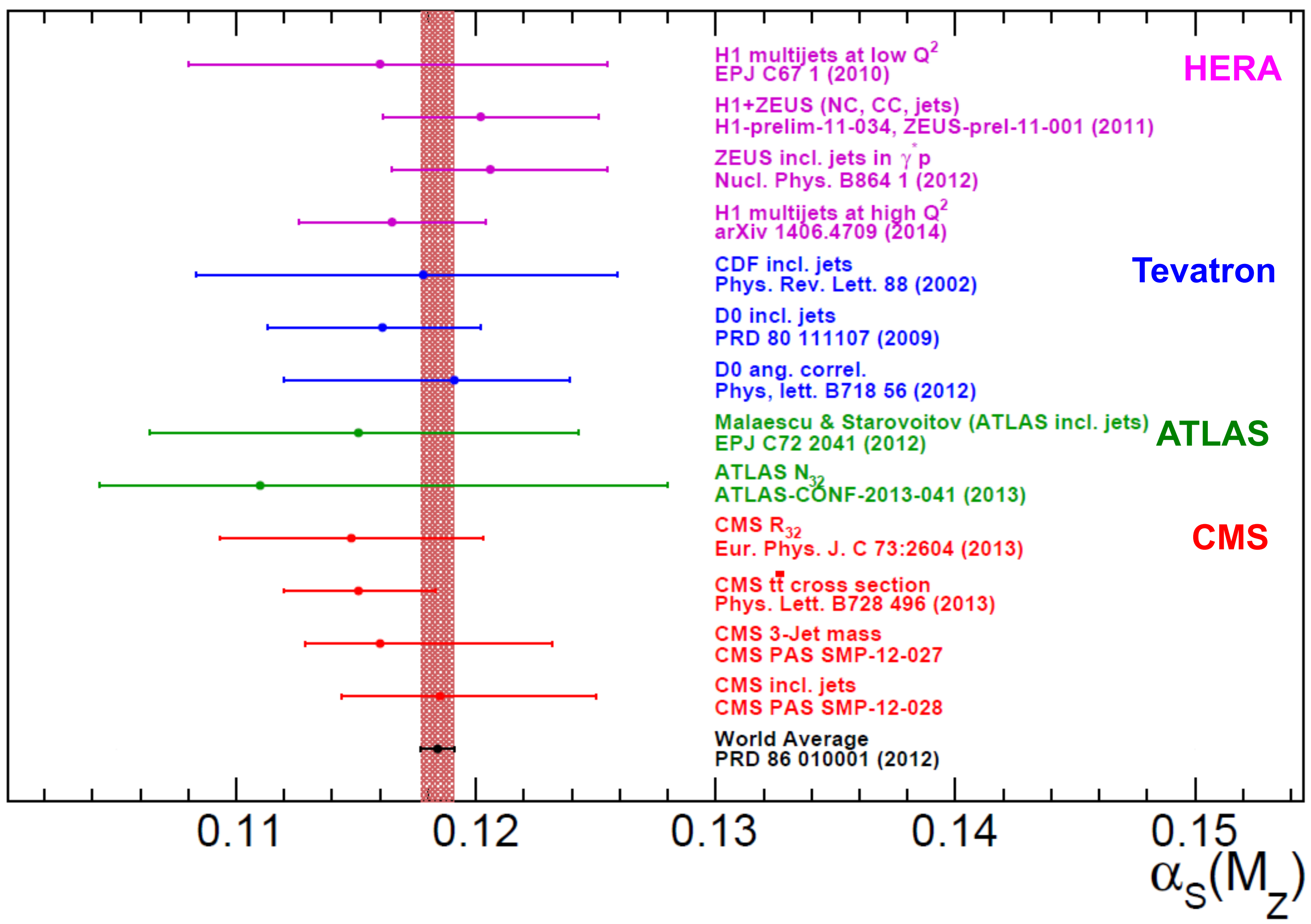
at hadron colliders (ep, pp, ppbar)



K.Rabbertz, ICFA Beijing 2014

summary of α_s measurements

at hadron colliders (ep, pp, ppbar)



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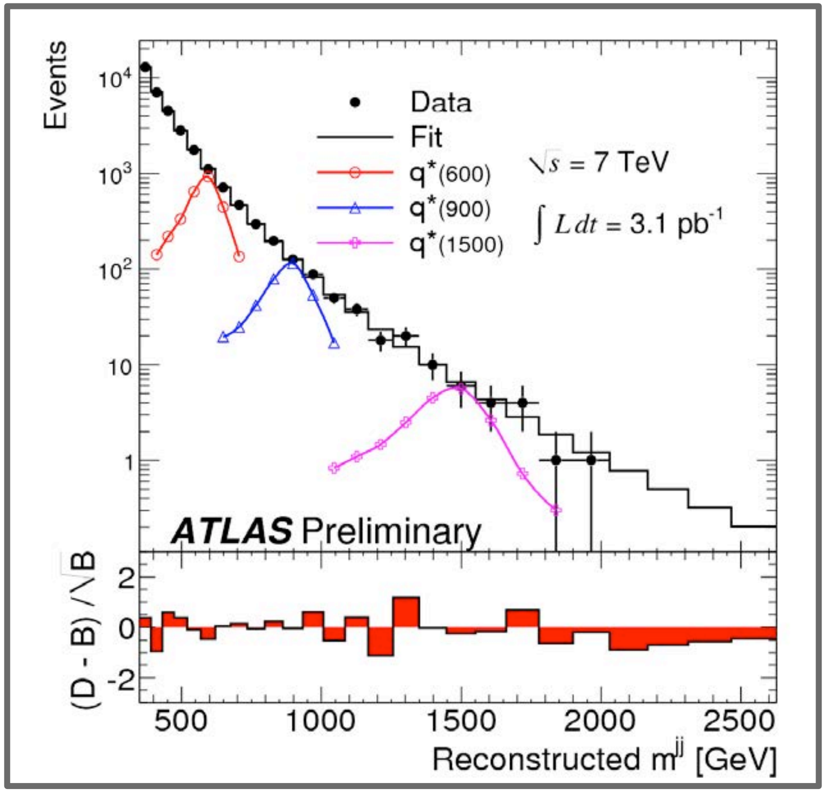
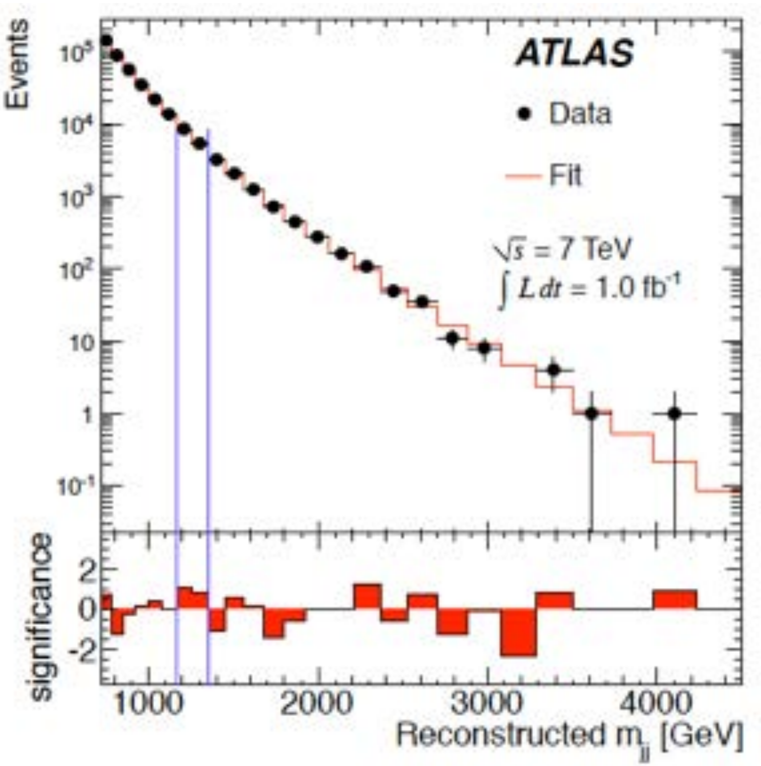
Jet Paar-Massen und Suche nach neuen schweren Teilchen: excited Quarks





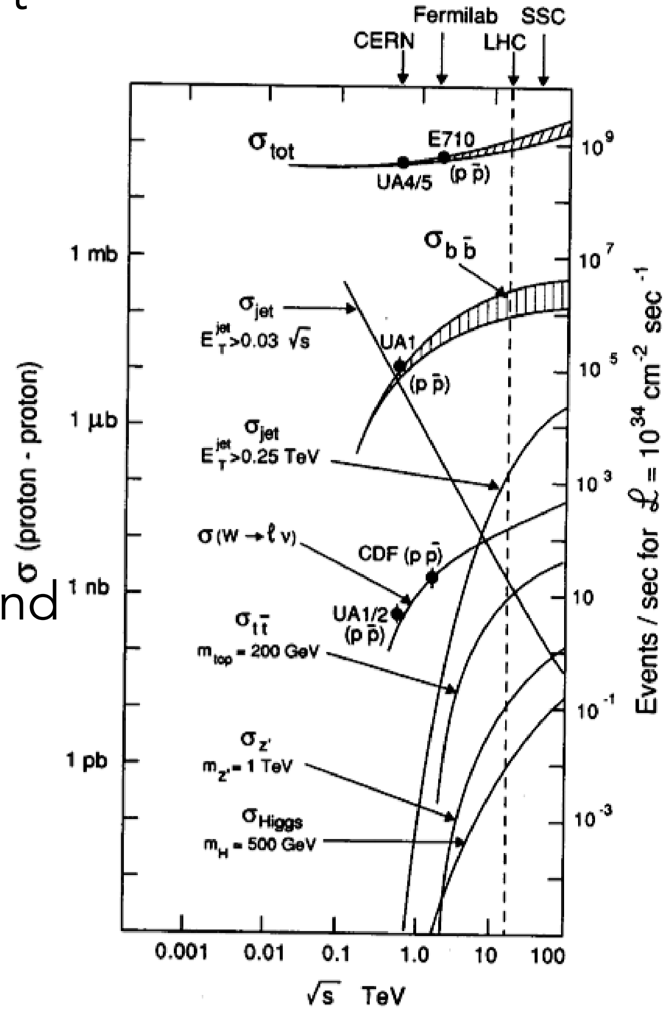
Produktion angeregter Quarks ausgeschlossen

im Massen-Intervall $0.3 < m < 3$ TeV

(Tevatron limit: 0.8 TeV)

Zusammenfassung

- QCD (d.h. die Starke Wechselwirkung) dominiert bei weitem die Reaktionsraten an Tevatron und LHC (σ_{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 α_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).



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- 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:

07.12.2014:	Higgs Physik (I)
14.12.2014:	Higgs Physik (II)
21.12.2014:	*– keine Vorlesung –*