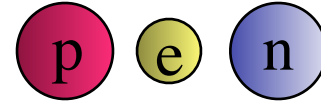


QCD, Structure Functions, Jets

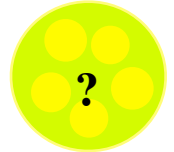
- History of the Strong Interaction
- QCD / QED
- Proton-structure: structure functions
- hadronisation
- factorisation
- hadron jets
- measurement of α_s
- search for new physics (BSM)

History of Strong Interactions (1)

1932: discovery of **neutrons**

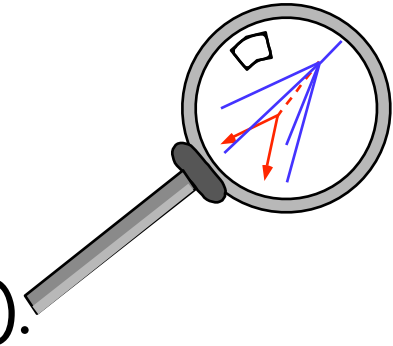


1933: $\vec{\mu} \cong 2.5 \frac{e}{2 m_p} \vec{\sigma} \Rightarrow$ **substructure** of the protons

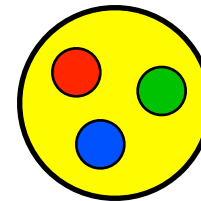


1947: discovery of π -mesons and long-living V-particles (K^0 , Λ) in **cosmic rays**

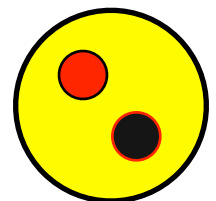
1953: V-particles produced at **accelerators**
new inner quantum number ("**strangeness**").



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



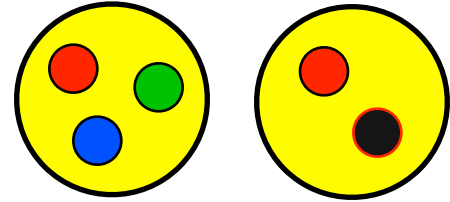
Baryon
(p,n, Λ ,...)



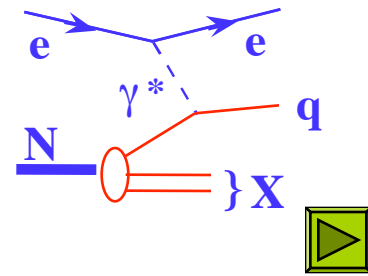
Meson
(π ,K,...)

History of Strong Interactions (2)

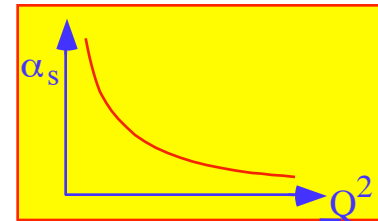
1964: static **quark model** ;
new inner quantum number: **Farbe**.



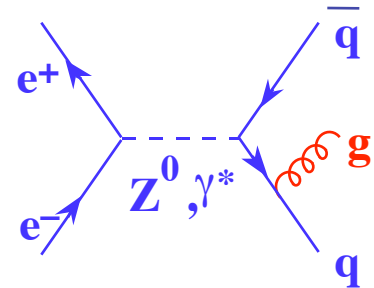
1969: dynamic **parton model** :



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



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

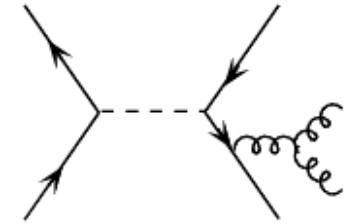
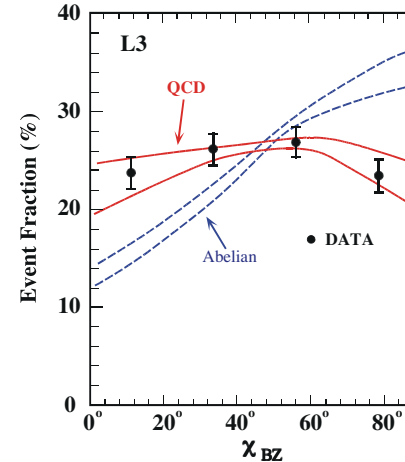


1979: discovery of **gluons** in **3-Jet-events**
of $e^+ e^-$ -annihilations.



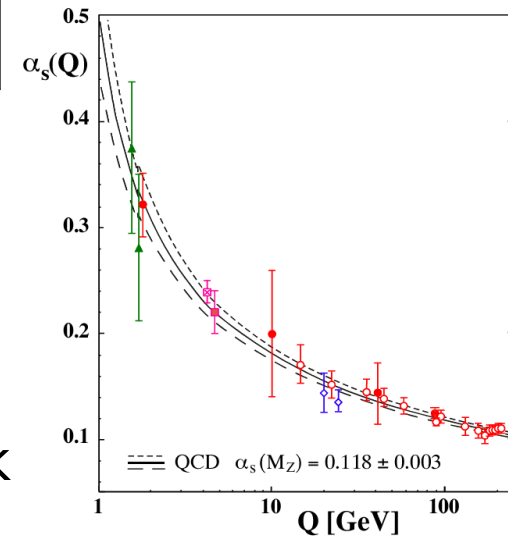
History of Strong Interactions (3)

1991: exp. signature of the
gluon self coupling



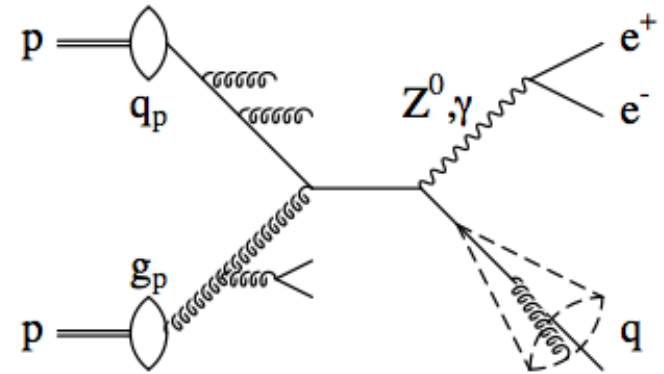
1990-2000: confirmation of
asymptotic freedom

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

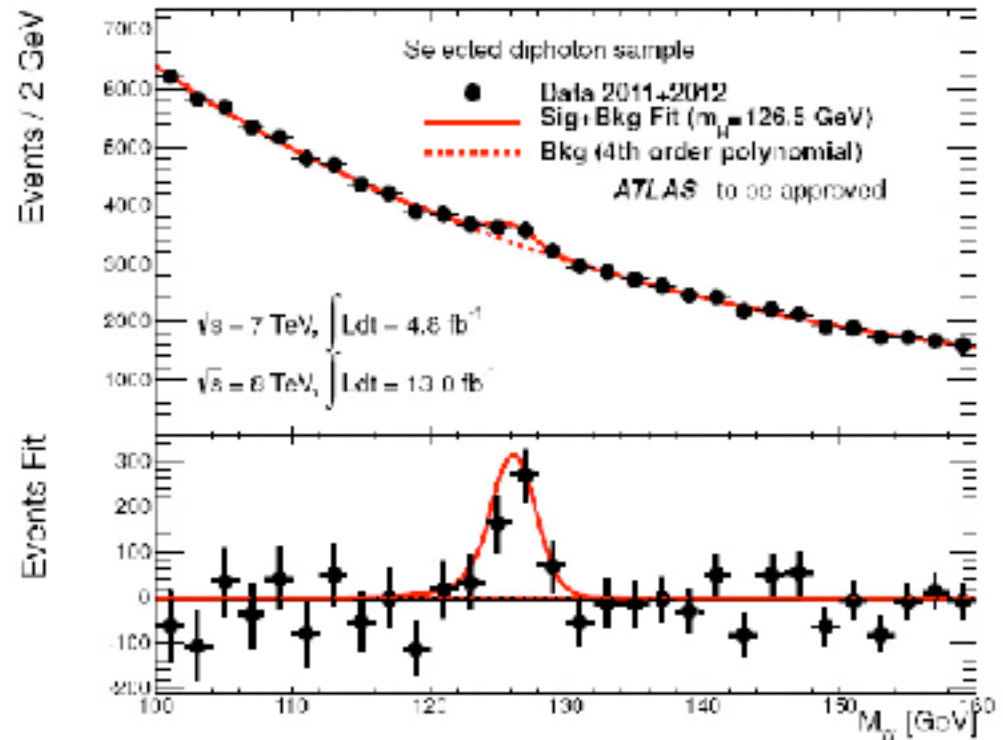
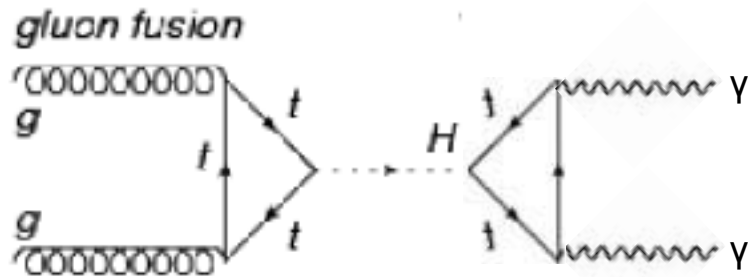


History of Strong Interactions (4)

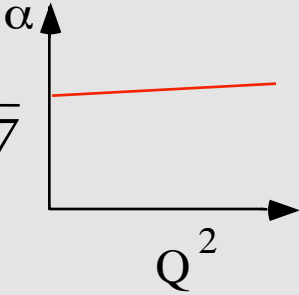
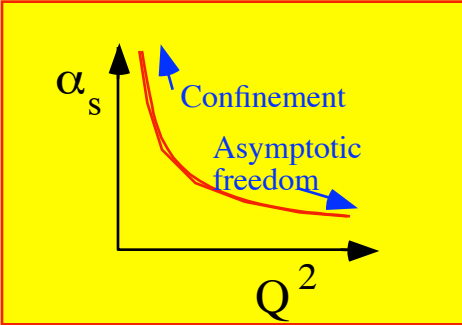
>2004: QCD as background
in searches for
New Physics (BSM)



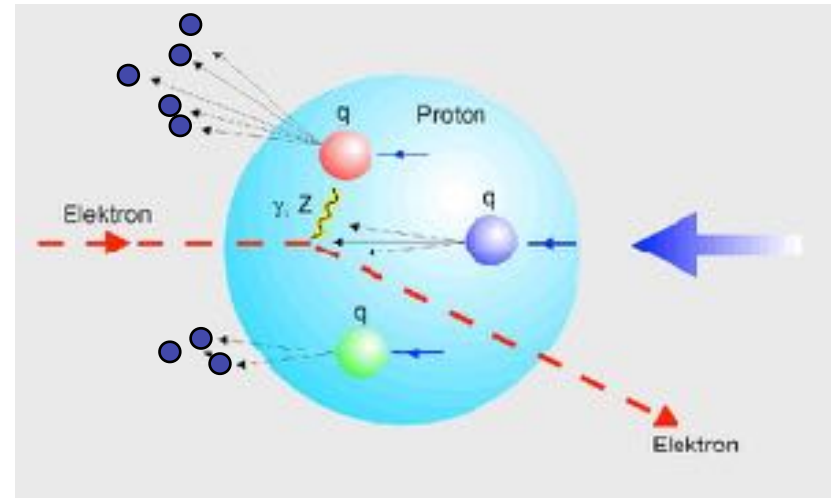
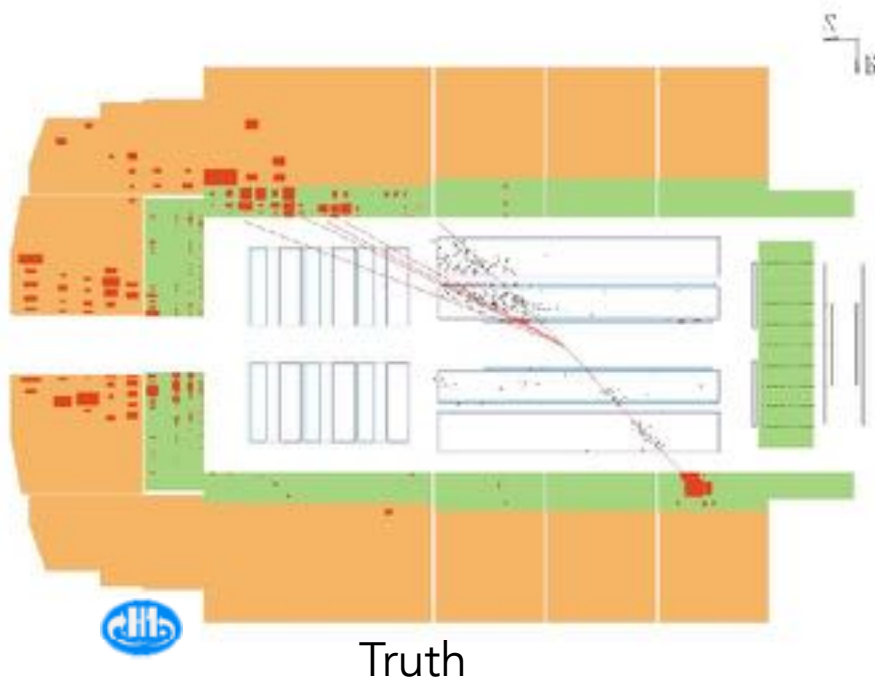
example: Higgs search



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>	3 color-charges
<i>exchange quantum</i>	<i>photon (γ) (carries no charge)</i>	<i>gluons (g) (carry 2 color charges)</i> $\Rightarrow$ 
<i>coupling "constant"</i>	$\alpha(Q^2=0) = \frac{1}{137}$ 	$\alpha_s(Q^2 \simeq M_Z^2) \approx 0.12$ 
<i>free particles</i>	<i>leptons (e, μ, τ)</i>	(color neutral bound states of q and $\bar{q}$) Hadronen
<i>theory</i>	<i>perturbation theory up to $O(\alpha^5)$</i>	<i>perturbation theory up to $O(\alpha_s^4)$</i>
<i>precision achieved</i>	$10^{-6} \dots 10^{-7}$	0.1% ... 20%

Quarks in the proton: model and experiment

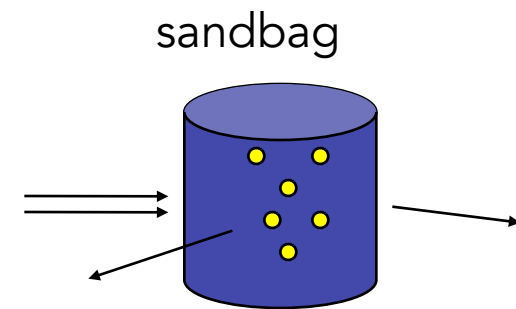


model, theory

experiment: measurement of scattered electrons

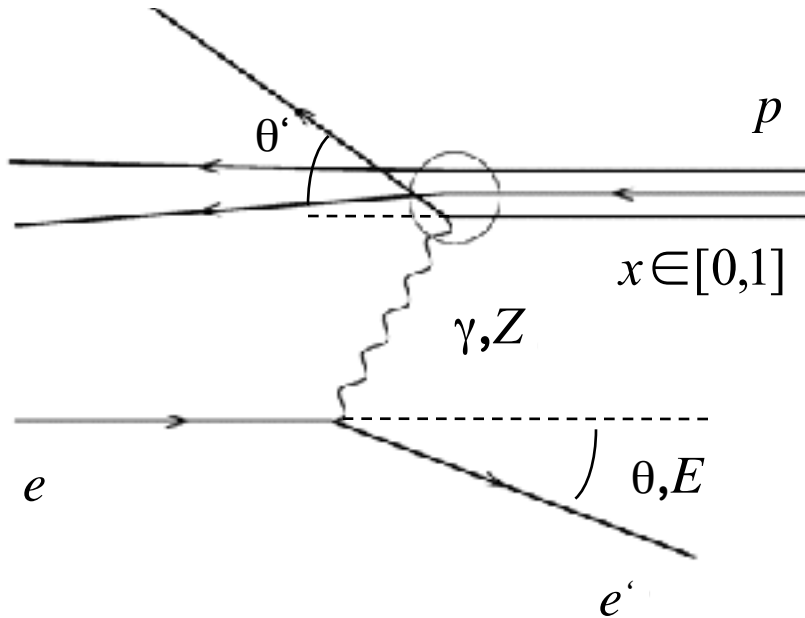
result: too many electrons with large scattering angles (qualitatively similar to experiments of Rutherford, 1911)

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



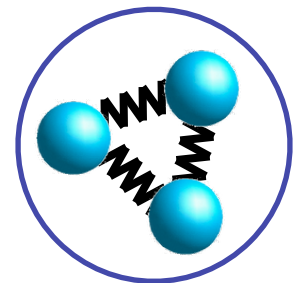
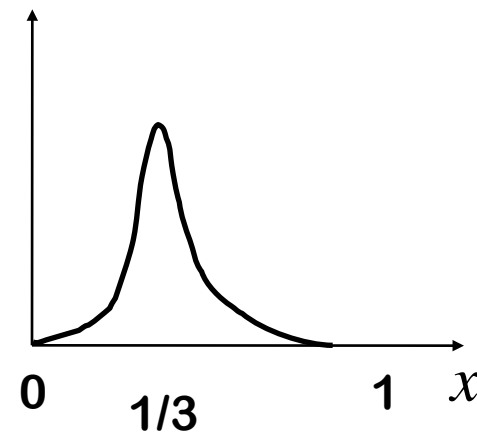
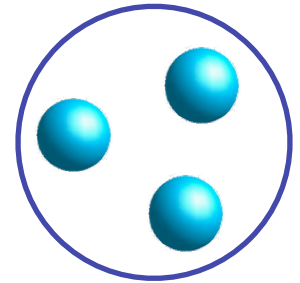
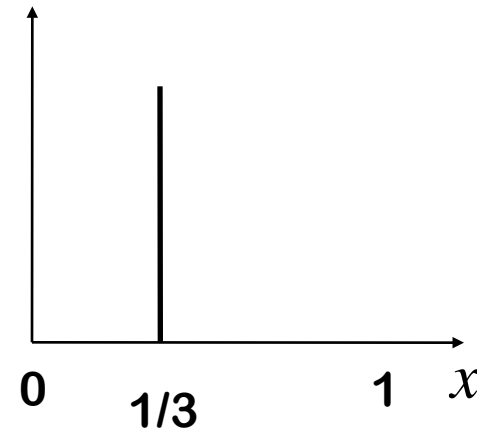
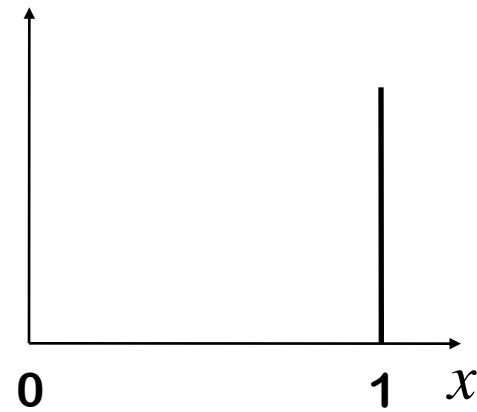
(Ch. Kiesling)

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)

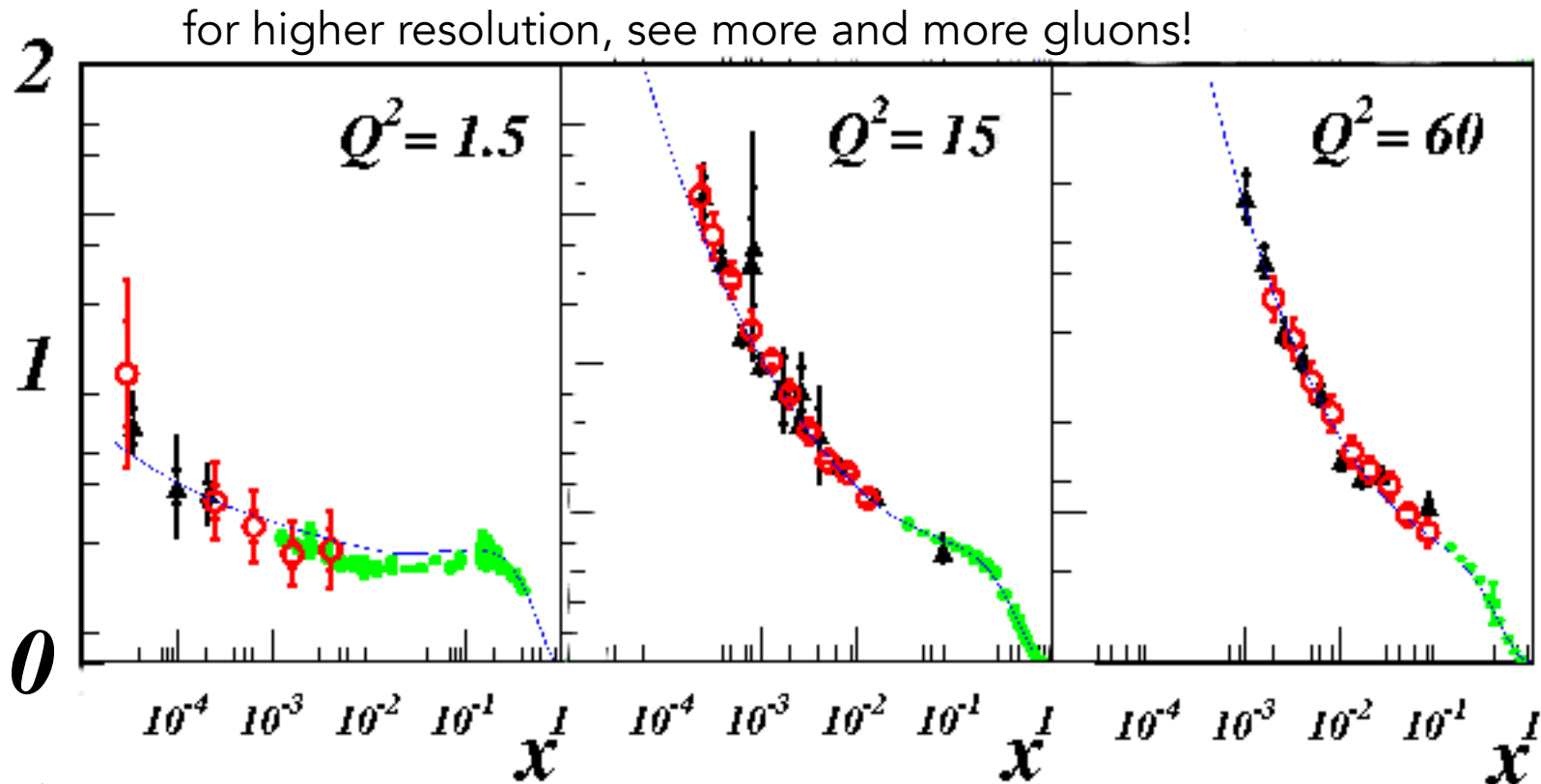
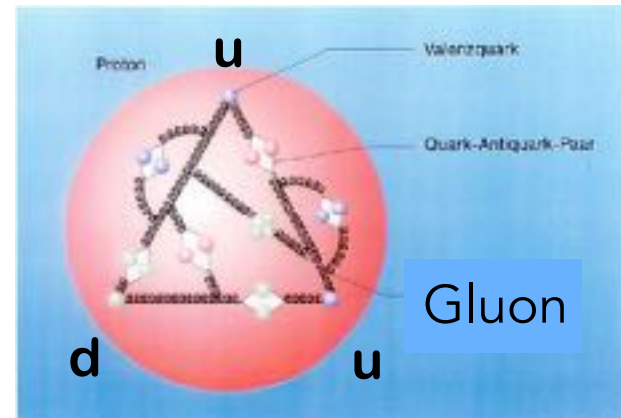


(Ch. Kiesling)

Quarks and gluons in the proton !

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

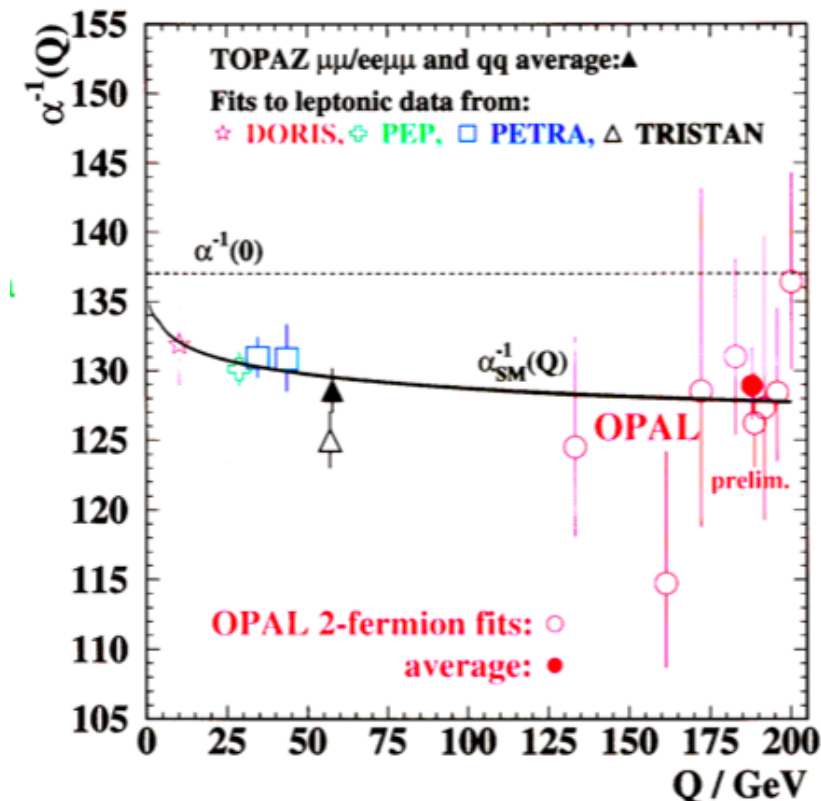
only half of momentum is carried by quarks ;
the rest is carried by „force carriers“,
the gluons



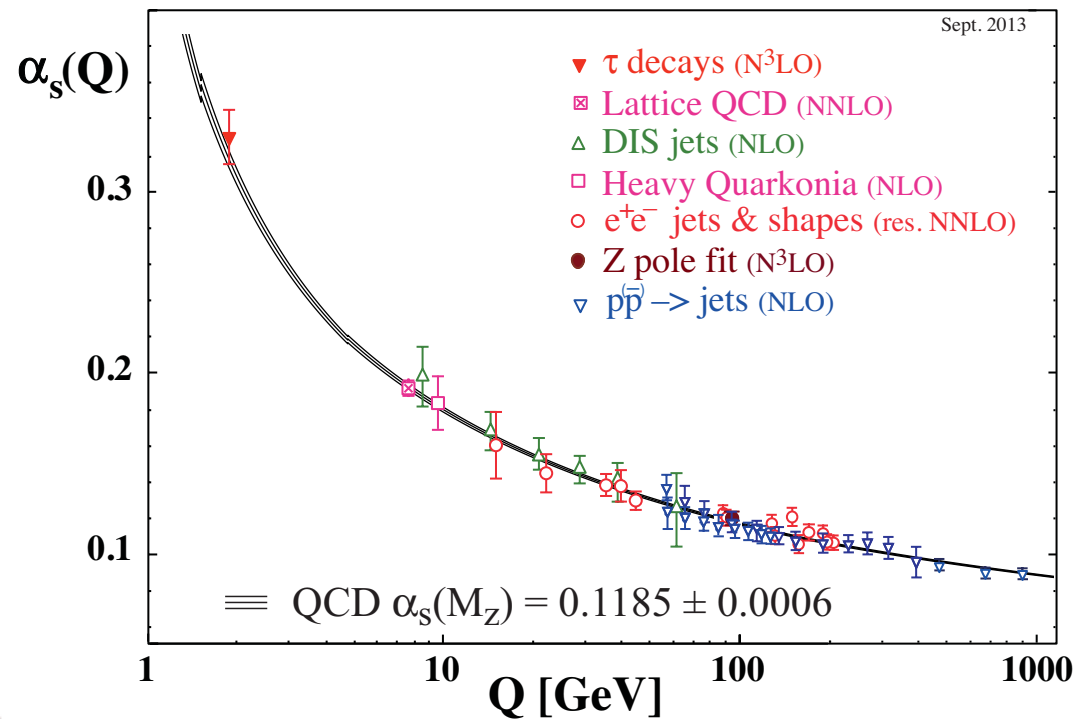
energy dependence of coupling “constants”:

- verified by high precision measurements

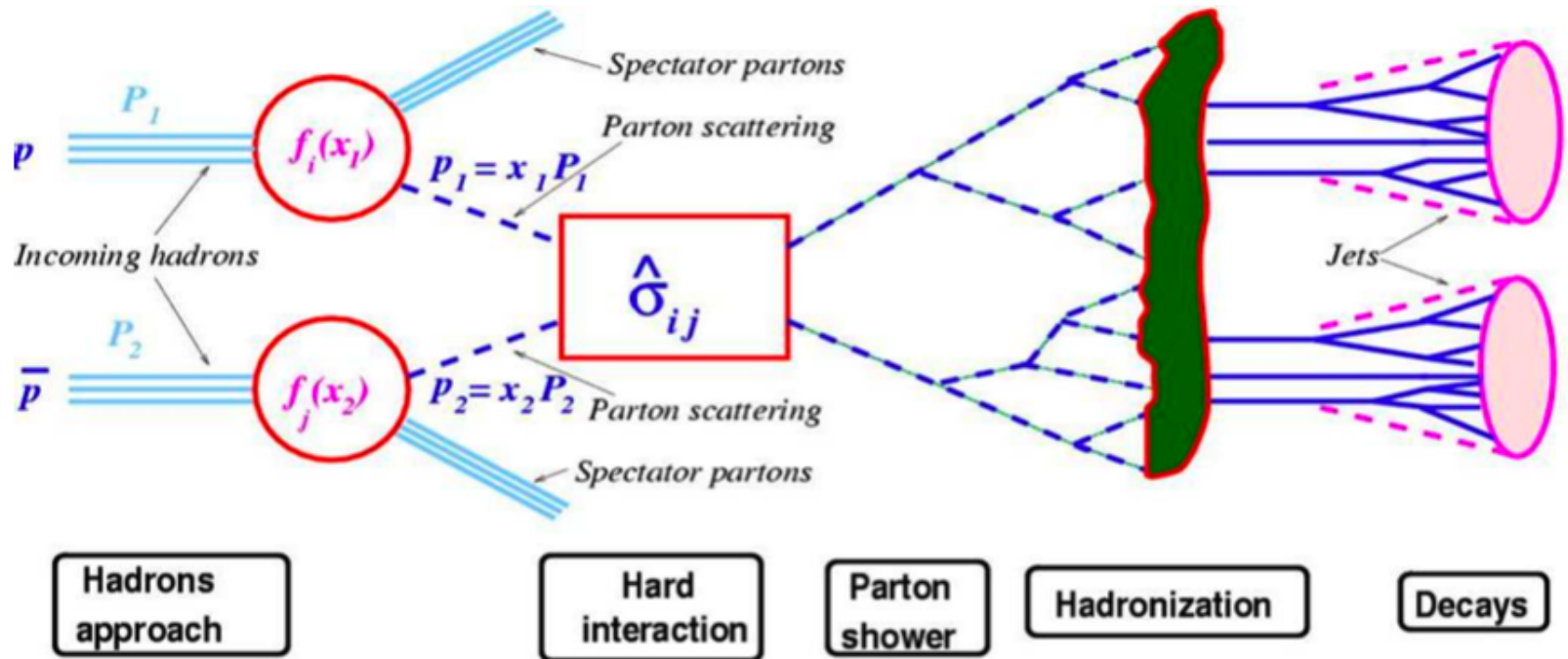
QED



QCD



theoretical description of hadronisation process

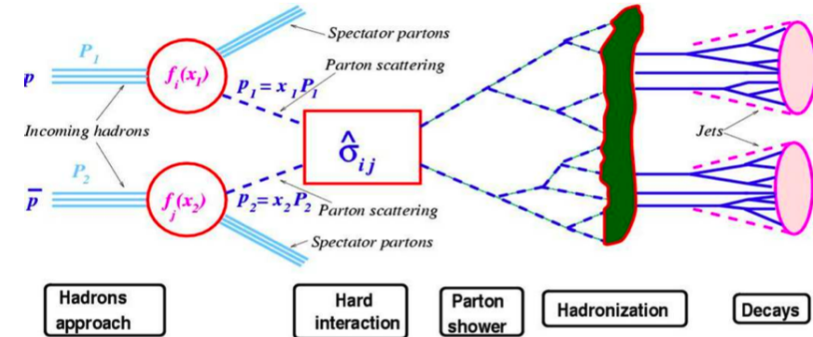


- parametrisation of individual subprocesses :
 - $f(x, Q^2)$: parton density (q, g) in Proton [pdf]
(probability for a parton with fraction x of proton momentum)
 - $\hat{\sigma}_{ij}(Q^2)$: "hard" QCD cross section, e.g. for $qq \rightarrow gg$; $qg \rightarrow q'g'$
 - parton shower: QCD radiation / splitting $q \rightarrow qg$, $g \rightarrow gg$, $g \rightarrow qq$
 - hadronisation: parametrisation of transition of q, g to hadrons (models!)
 - decays: parametrisation according to exp. data and spin-statistics

factorisation (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 "hadronisation" .processes



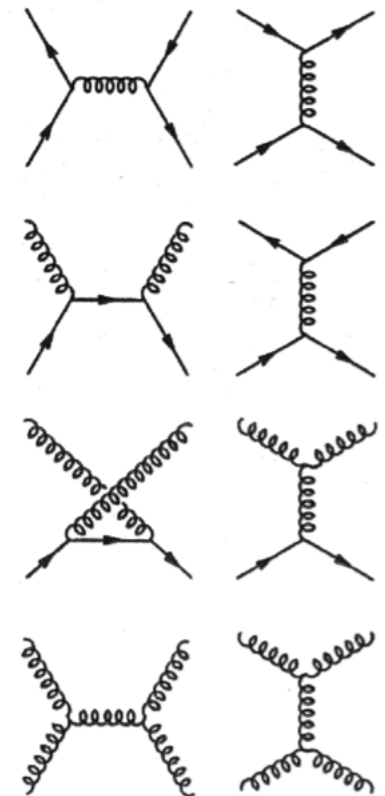
structure functions:

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

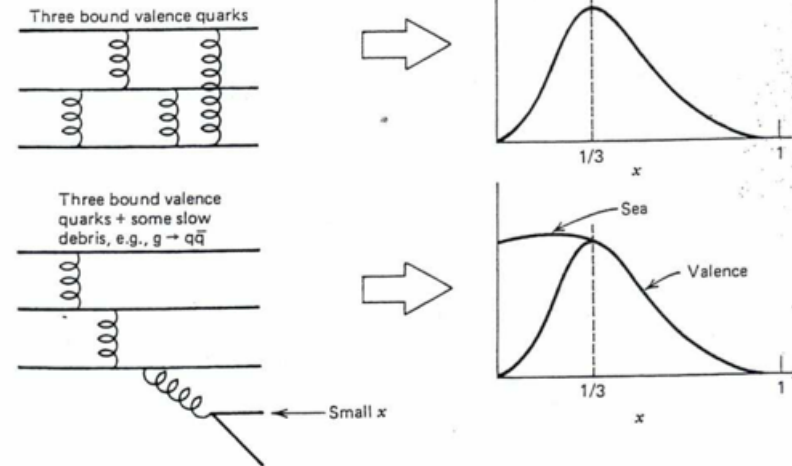
QCD perturbation theory:

Leading order (LO) matrix elements
e.g. for 2→2 processes:

(for precision measurements, at least next-to-leading
order (NLO) or even NNLO calculations required!)

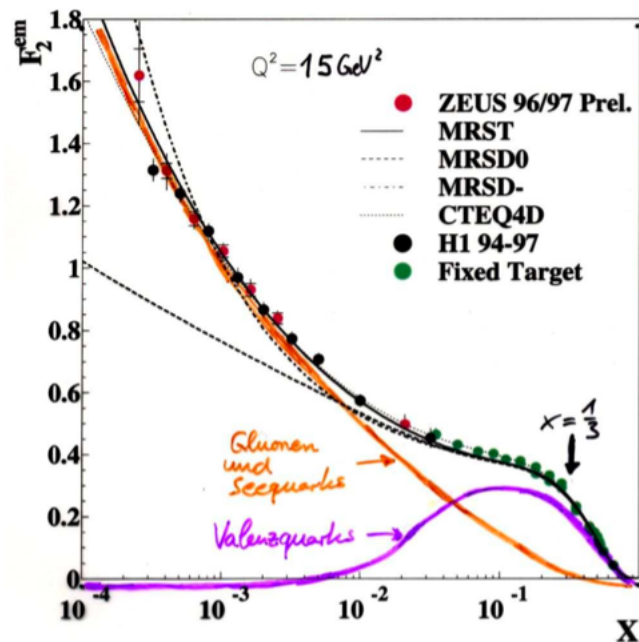
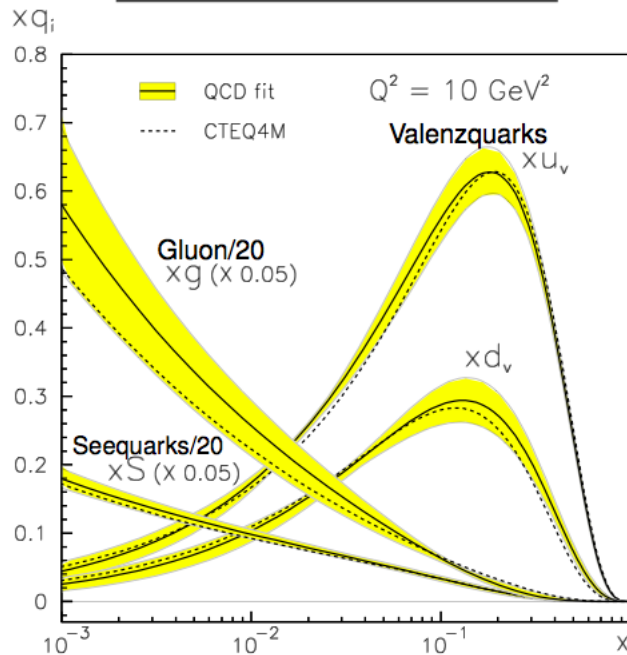


proton structure



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

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



proton structure (HERA + LHC)

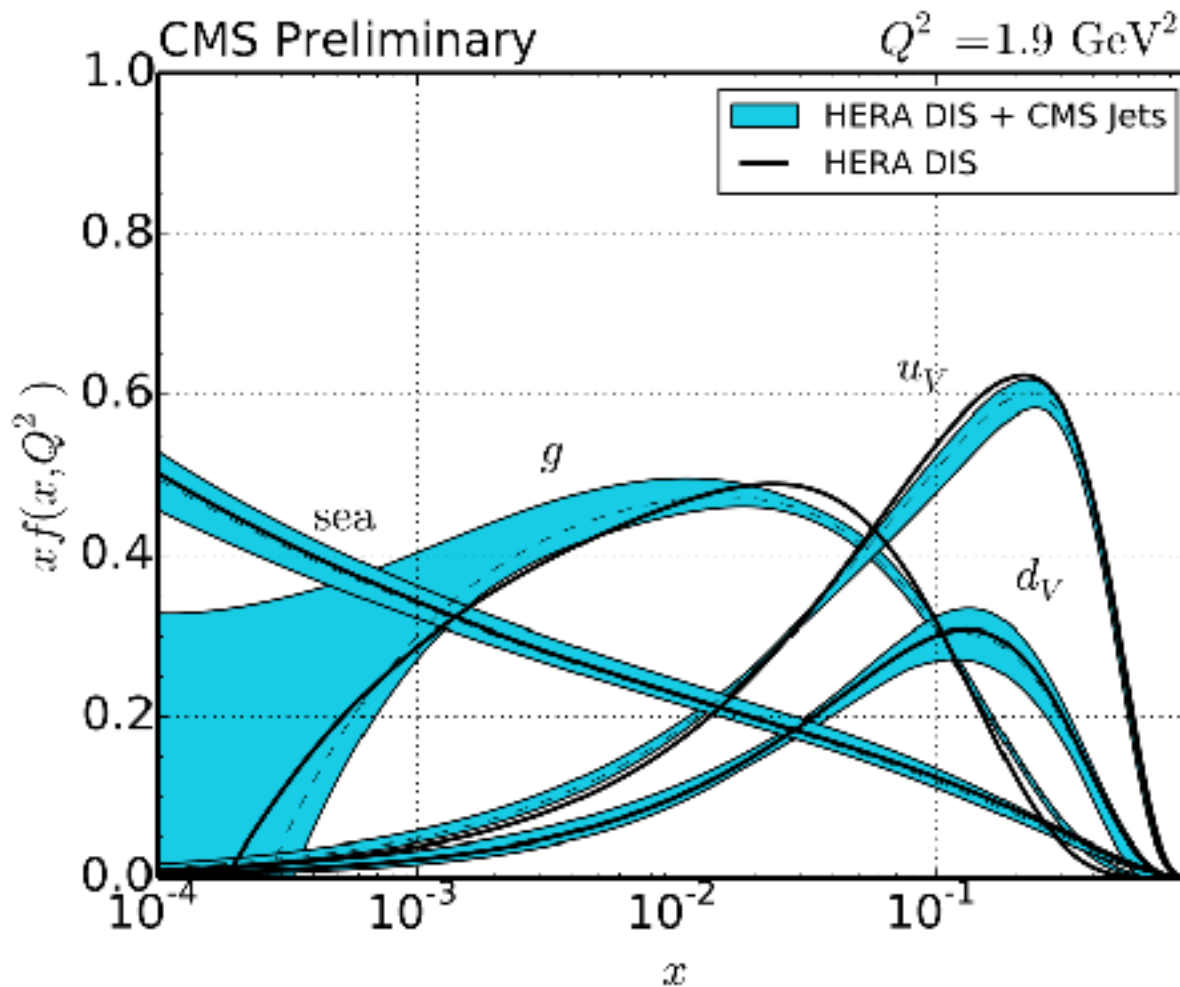
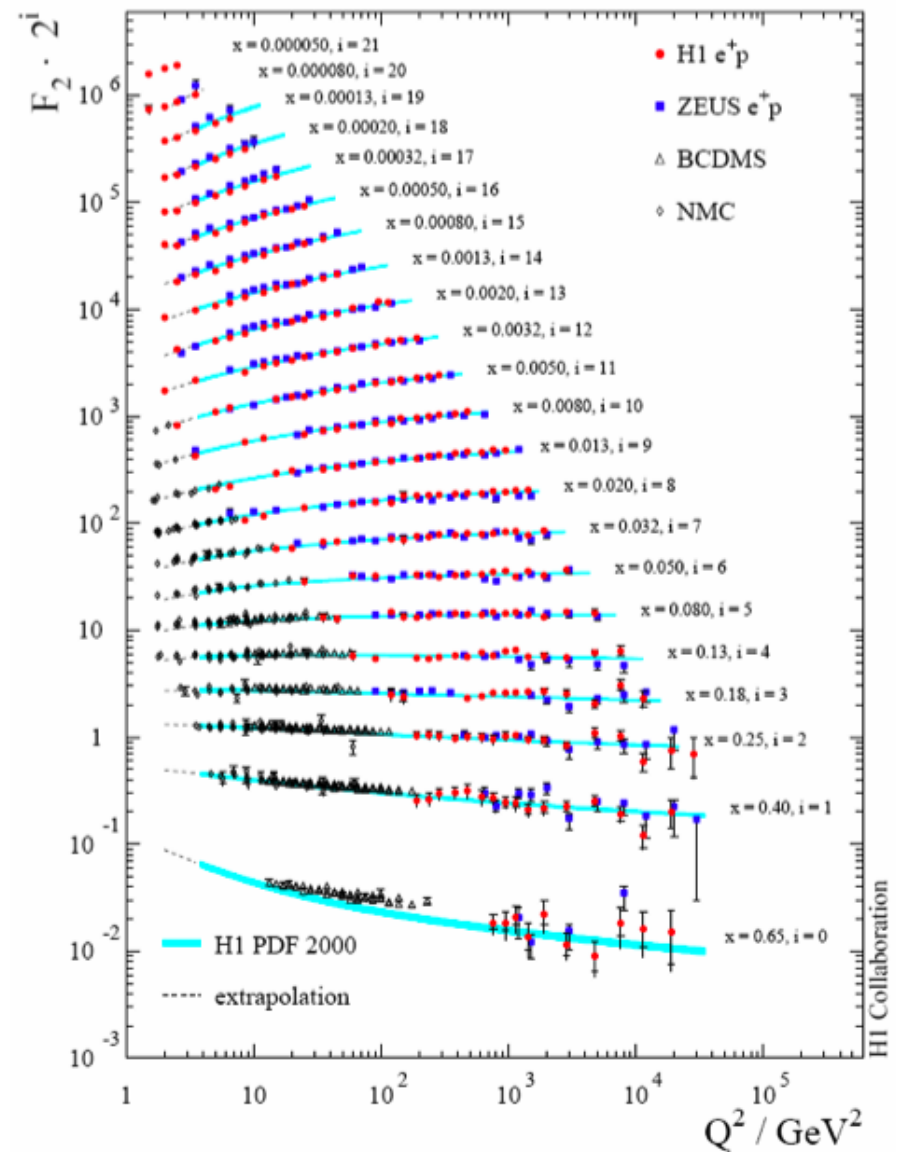
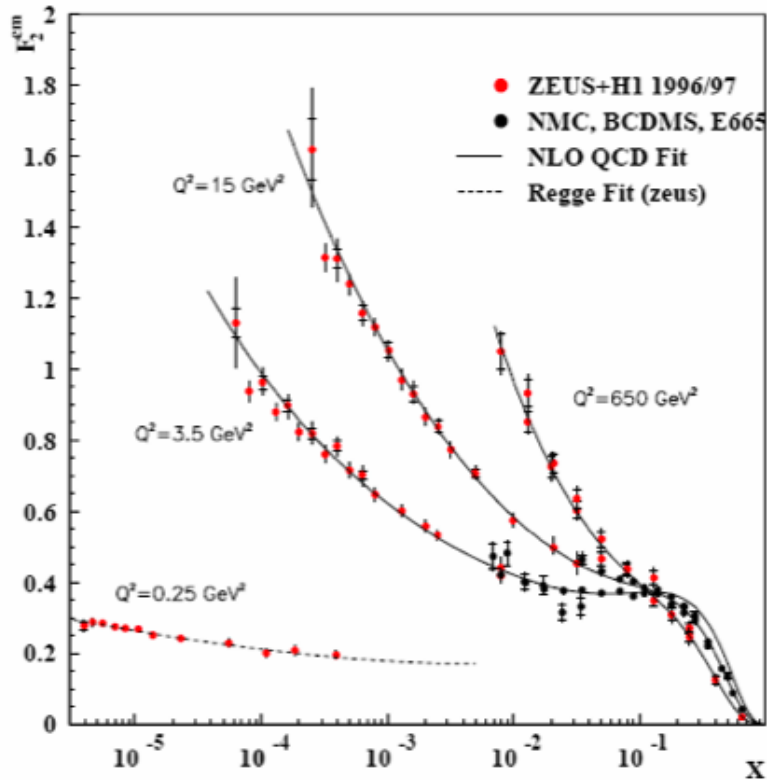
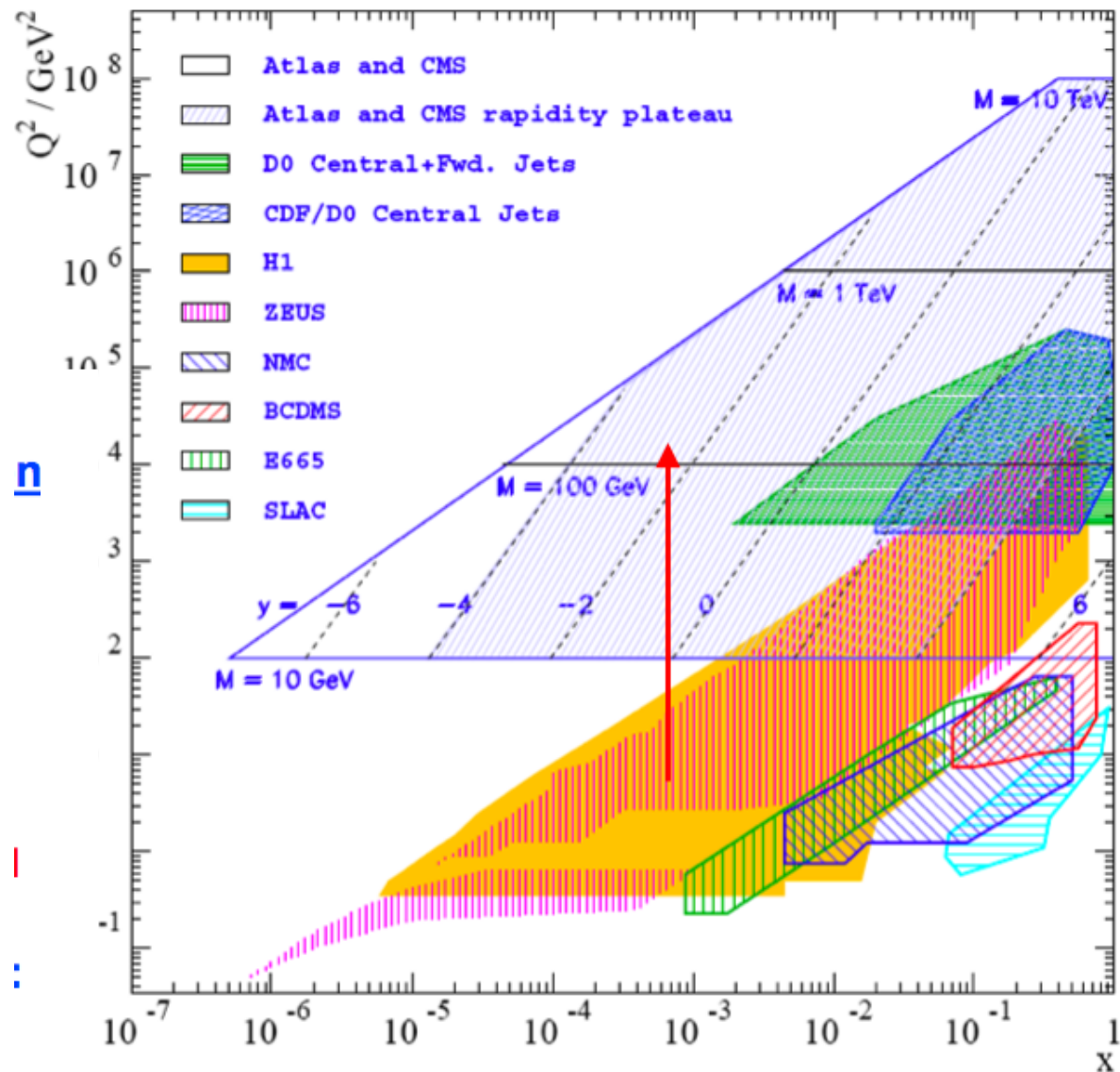


Figure 11: Overview of the gluon, sea, u valence, and d valence PDFs before (full line) and after (dashed line) including the CMS jet data into the fit. The PDFs are shown at the starting scale $Q^2 = 1.9 \text{ GeV}^2$. In addition the total uncertainty including the CMS jet data is shown as a band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

proton structure



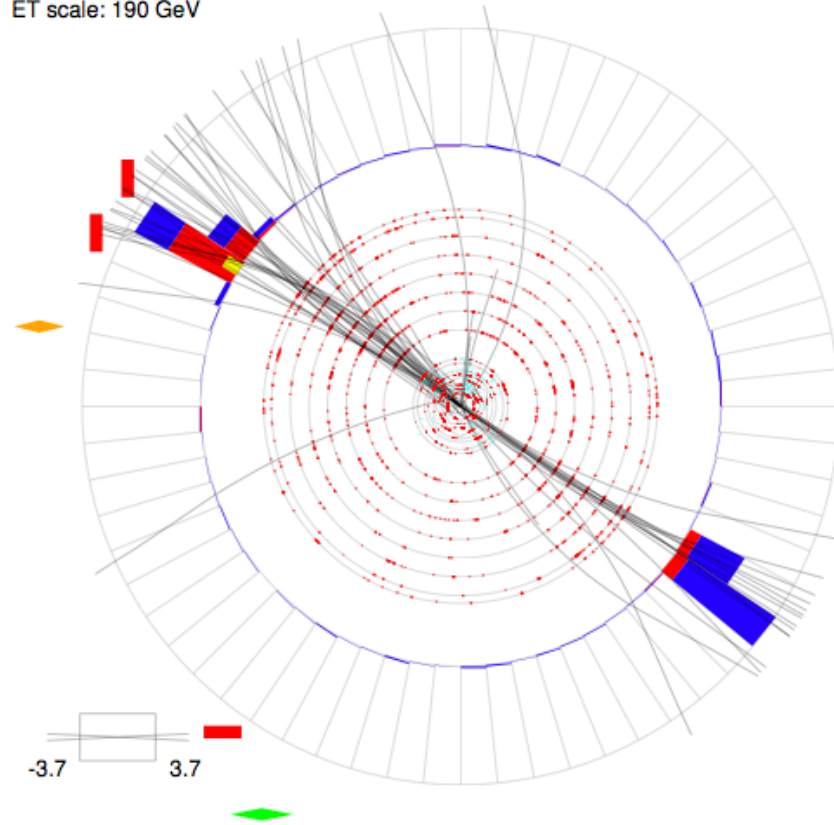
kinematic regions accessible to experiments



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

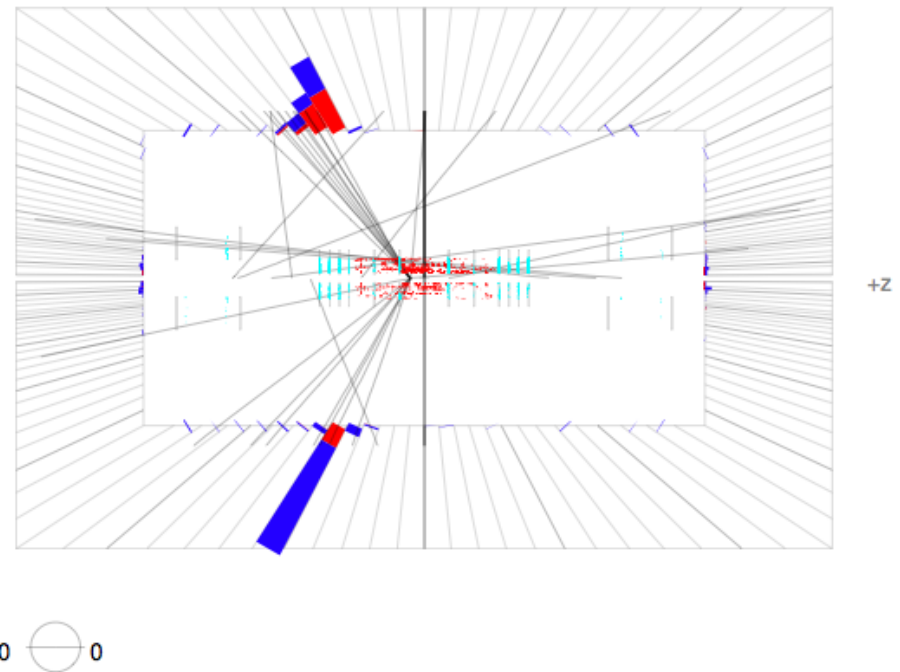
Run 162592 Event 5490755 Fri Oct 25 11:57:39 2002

ET scale: 190 GeV



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

E scale: 303 GeV

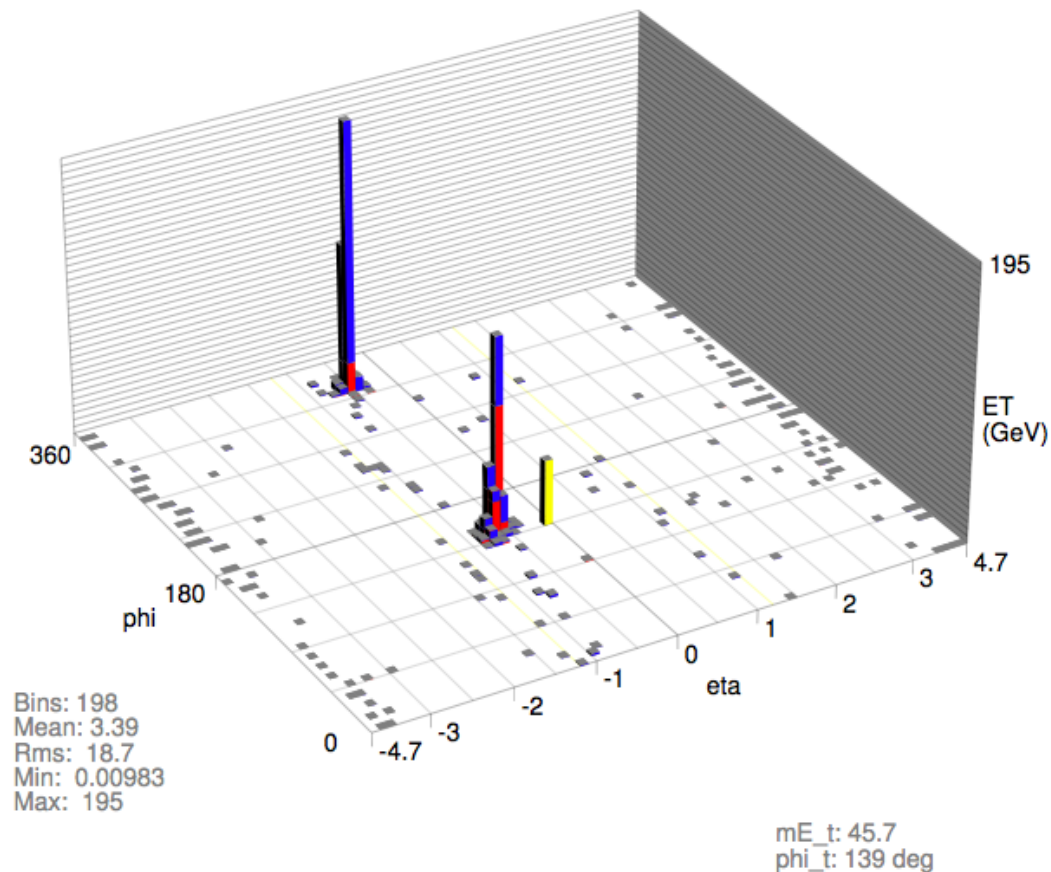


2-Jet final state in proton-antiproton collision (Tevatron; D0 detector)

Darstellung in

φ - η -Ebene:

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

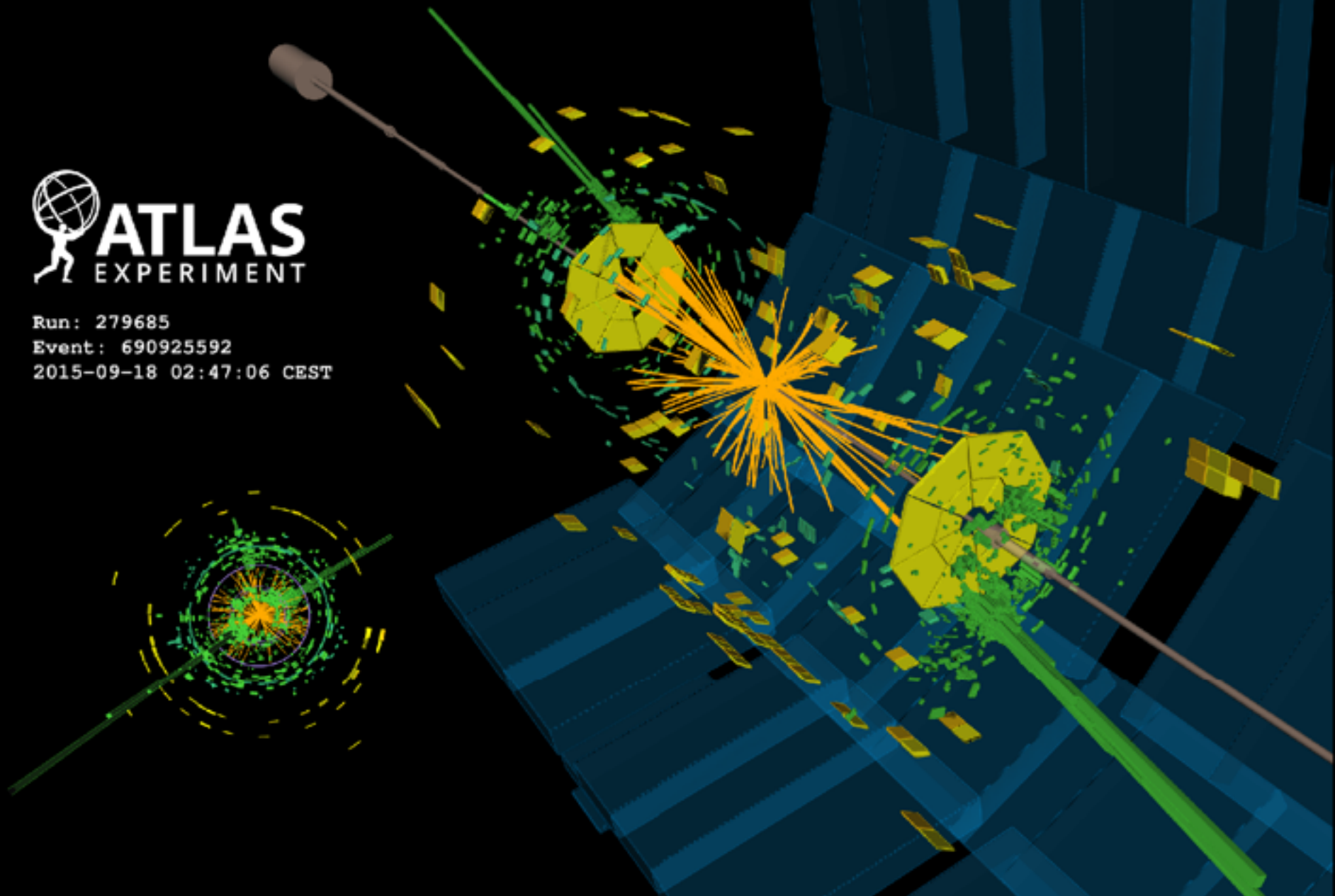


Azimutwinkel φ , Pseudorapidität $\eta = -\tan(\vartheta/2)$, Polarwinkel ϑ , transversale Energie $E_T = E \sin \vartheta$

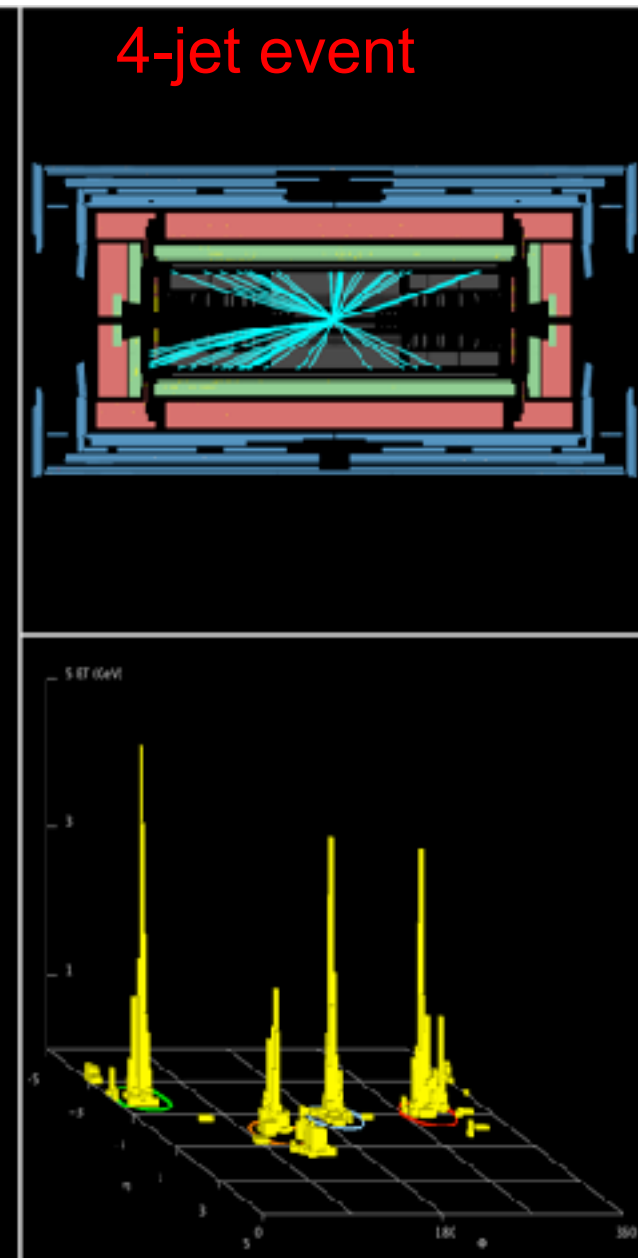
high-mass (9 TeV) di-jet event at LHC (13 TeV)



Run: 279685
Event: 690925592
2015-09-18 02:47:06 CEST



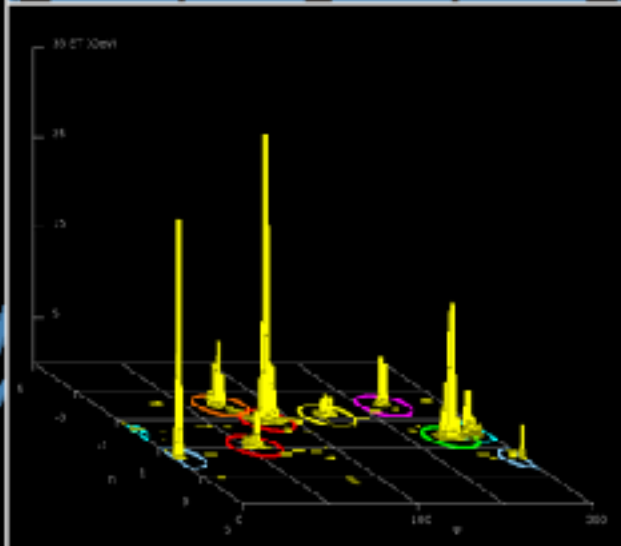
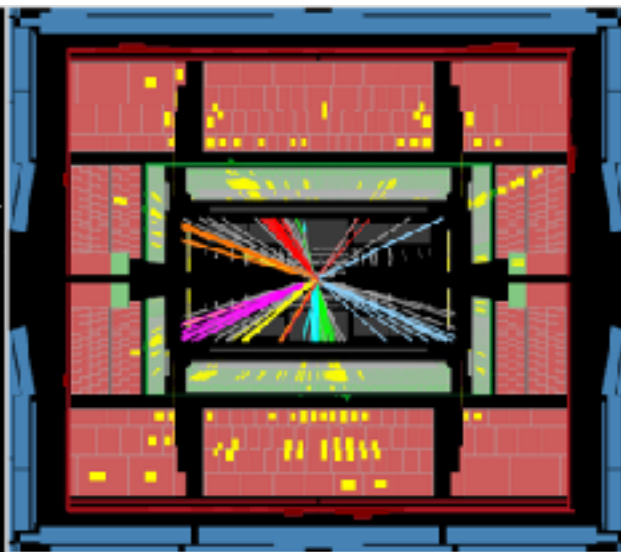
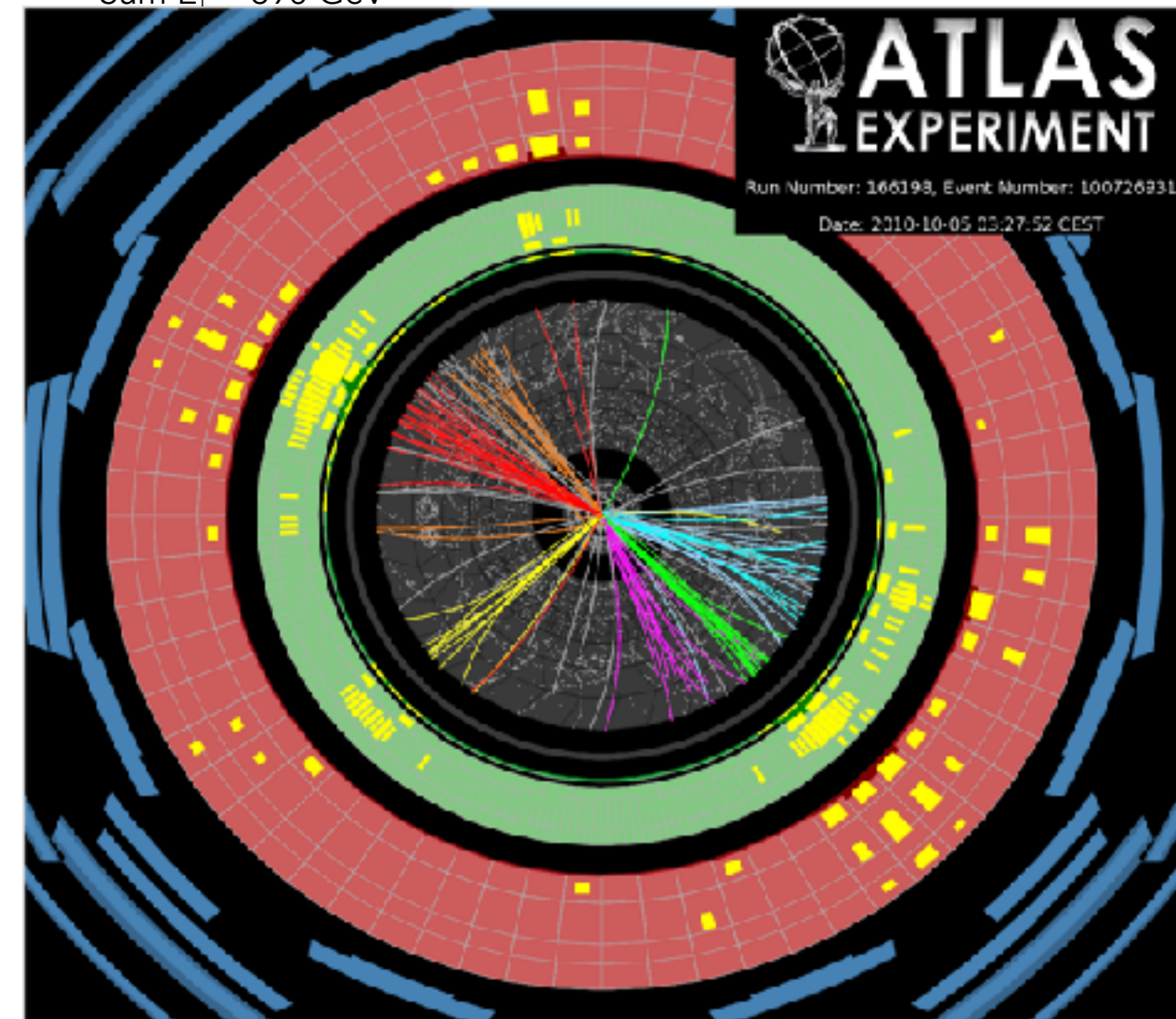
Event with four reconstructed hadronic jets. The four jets have a calibrated $p_T > 50$ GeV, and are found with the anti-kt algorithm with $R=0.6$. The highest p_T jet has a calibrated jet p_T of 144 GeV. Event collected on 10 April 2010.



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.

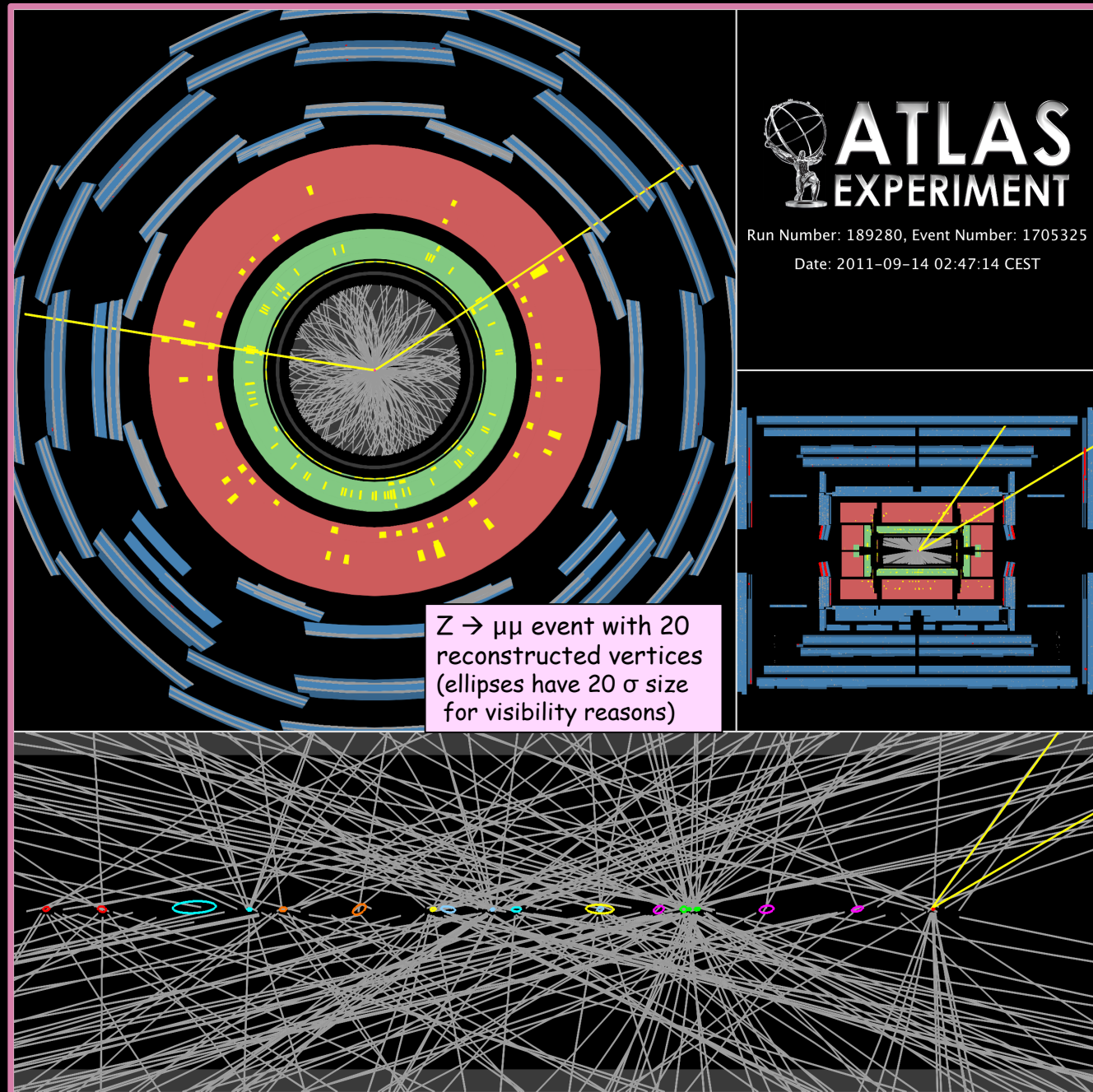
- 1st jet (ordered by p_T): $p_T = 290$ GeV, $\eta = -0.9$, $\phi = 2.7$
- 2nd jet: $p_T = 220$ GeV, $\eta = 0.3$, $\phi = -0.7$
- Missing $E_T = 21$ GeV, $\phi = -1.9$
- Sum $E_T = 890$ GeV

8-jet event

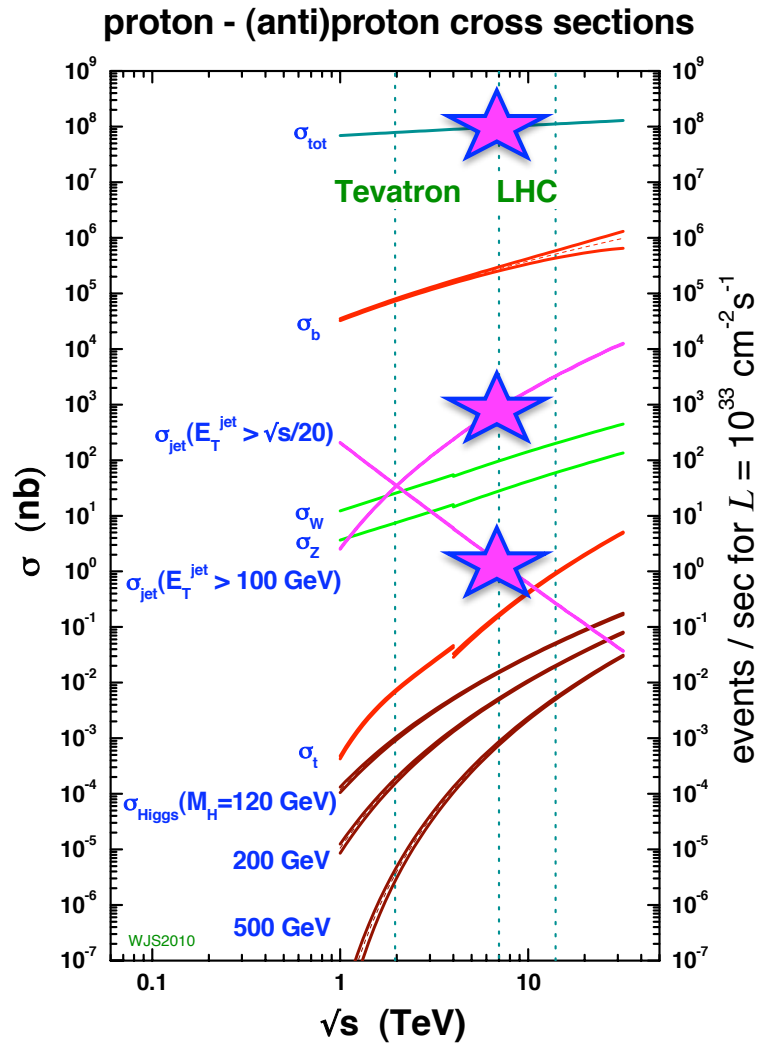


„pile-up“:

- 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.

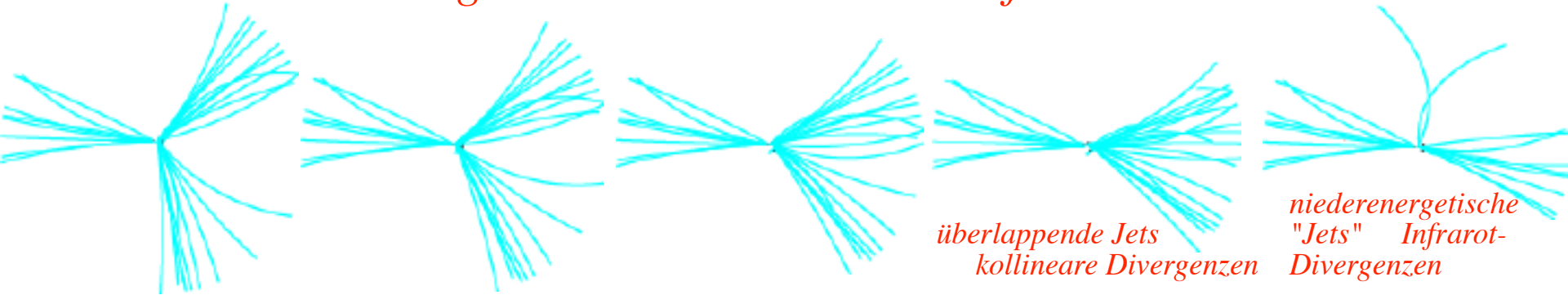


Dazu benötigt man:

- 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 !



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

ϕ_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:

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

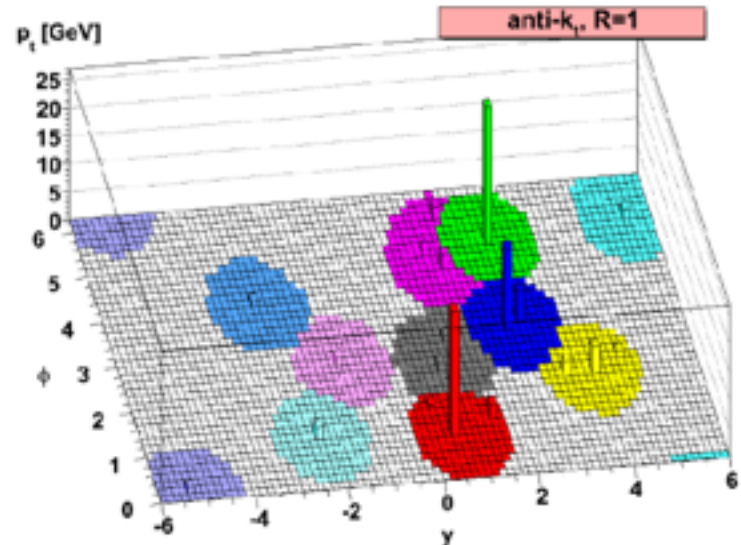
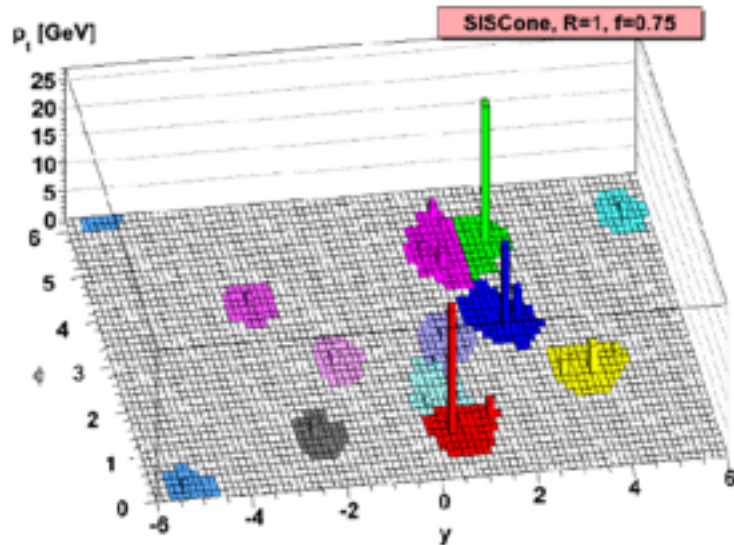
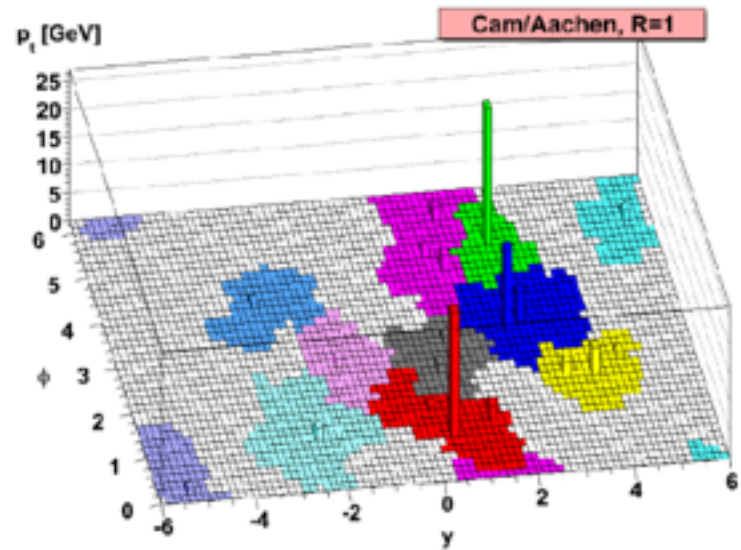
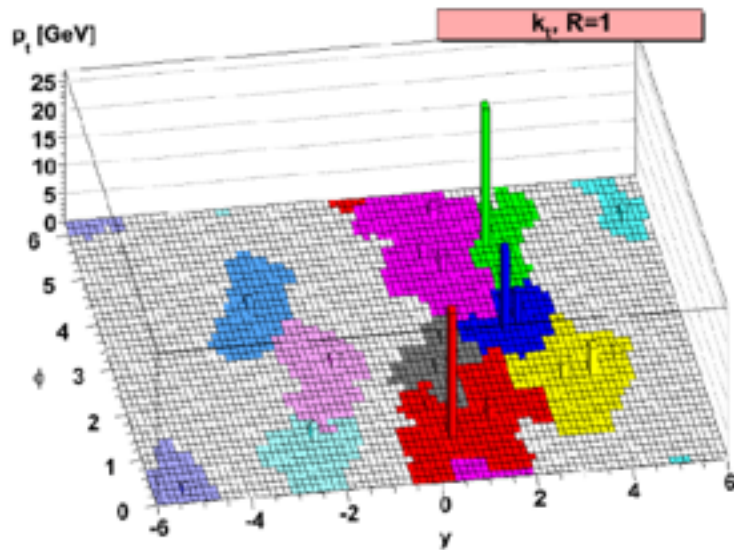
$$d_{iB} = k_{t,i}^{-2}$$

(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}

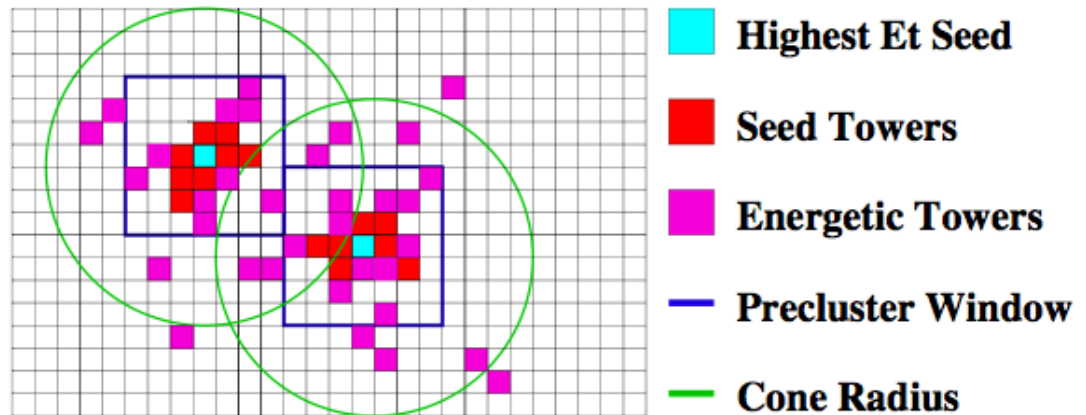
clustering performance of k_T - type Jet algorithms



Cone-Jet algorithm:

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

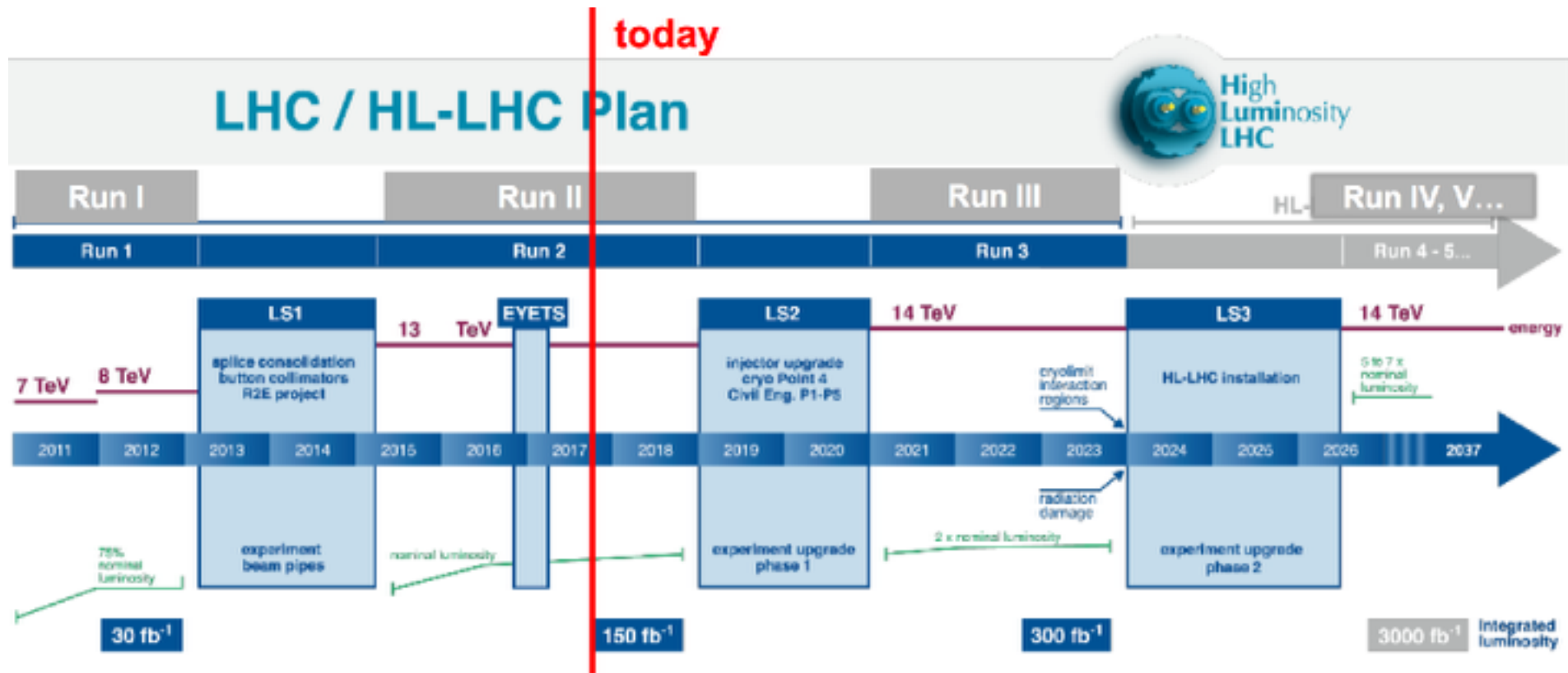
- Create E_T -ordered list of calorimeter towers (seed towers: $E_T > 1$ GeV).
- Build **pre-clusters** from adjacent seed towers beginning with the highest E_T tower.
- For each pre-cluster: Calculate centroid;
iterate cone using all towers above 100 MeV
($\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < R_{\text{cone}}$).
- **“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

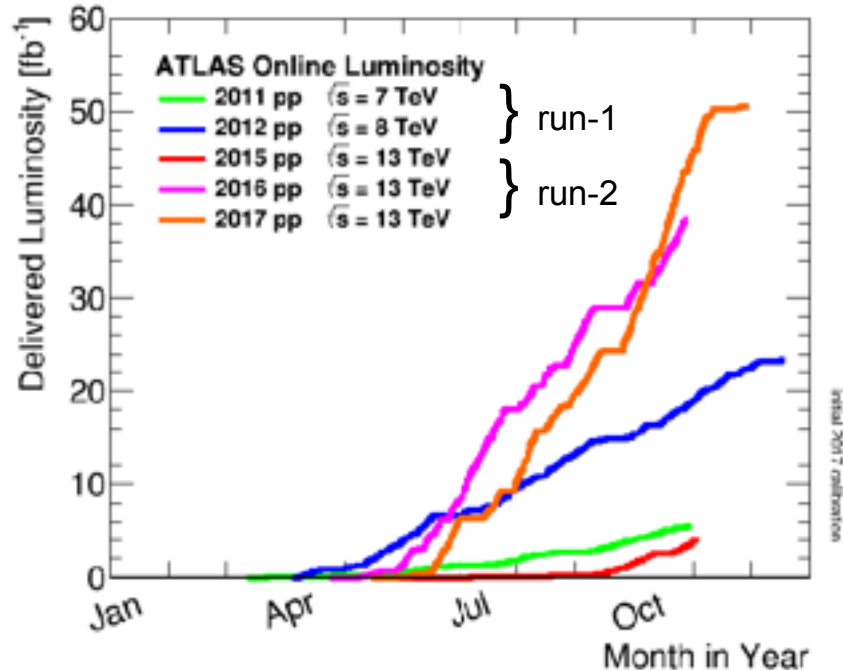
- der Cone-Algorithmus ist historisch der am längsten und meist benutzte Jetalgorithmus in der Analyse von Hadron Kollisionen (Tevatron).
- seine Definition und Anwendung ist i.w. durch experimentelle Randbedingungen (Zellgrösse hadronischer Kalorimeter) und technischer Details bestimmt; in der Vergangenheit 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

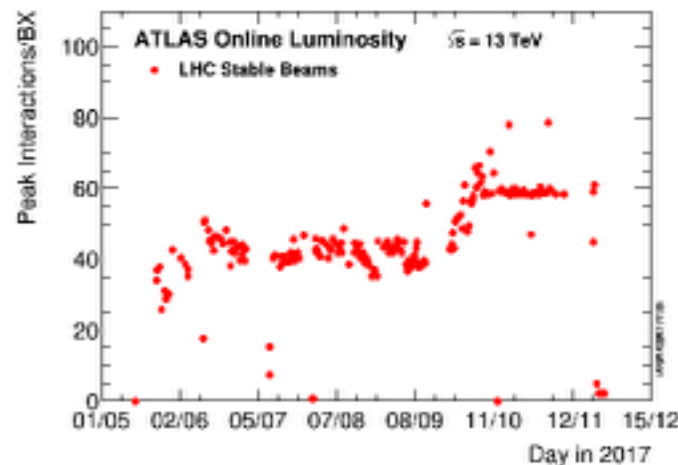
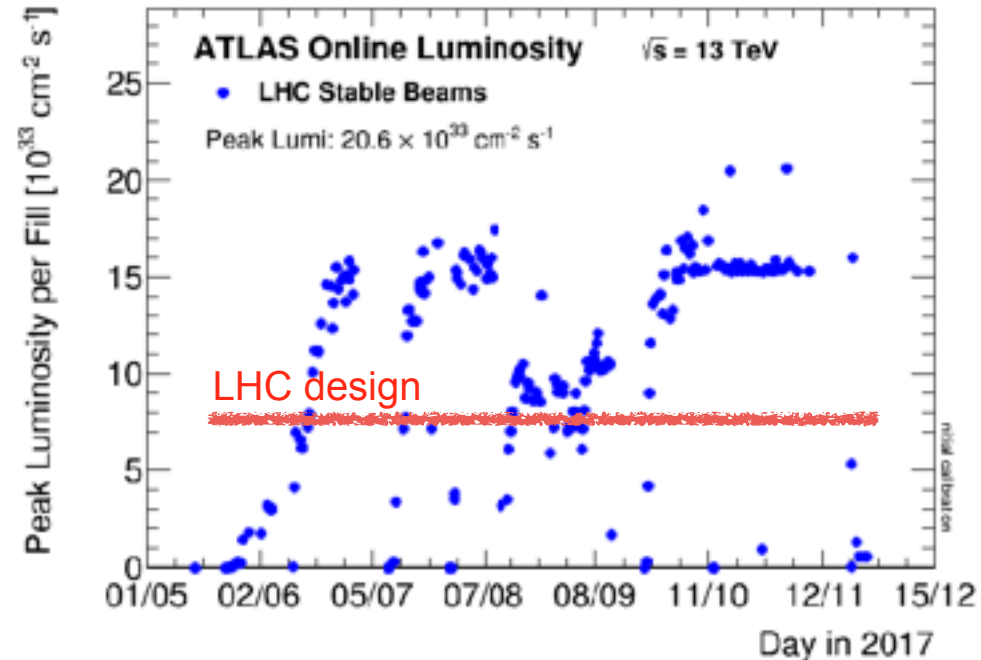


LHC performance

integrated Luminosity

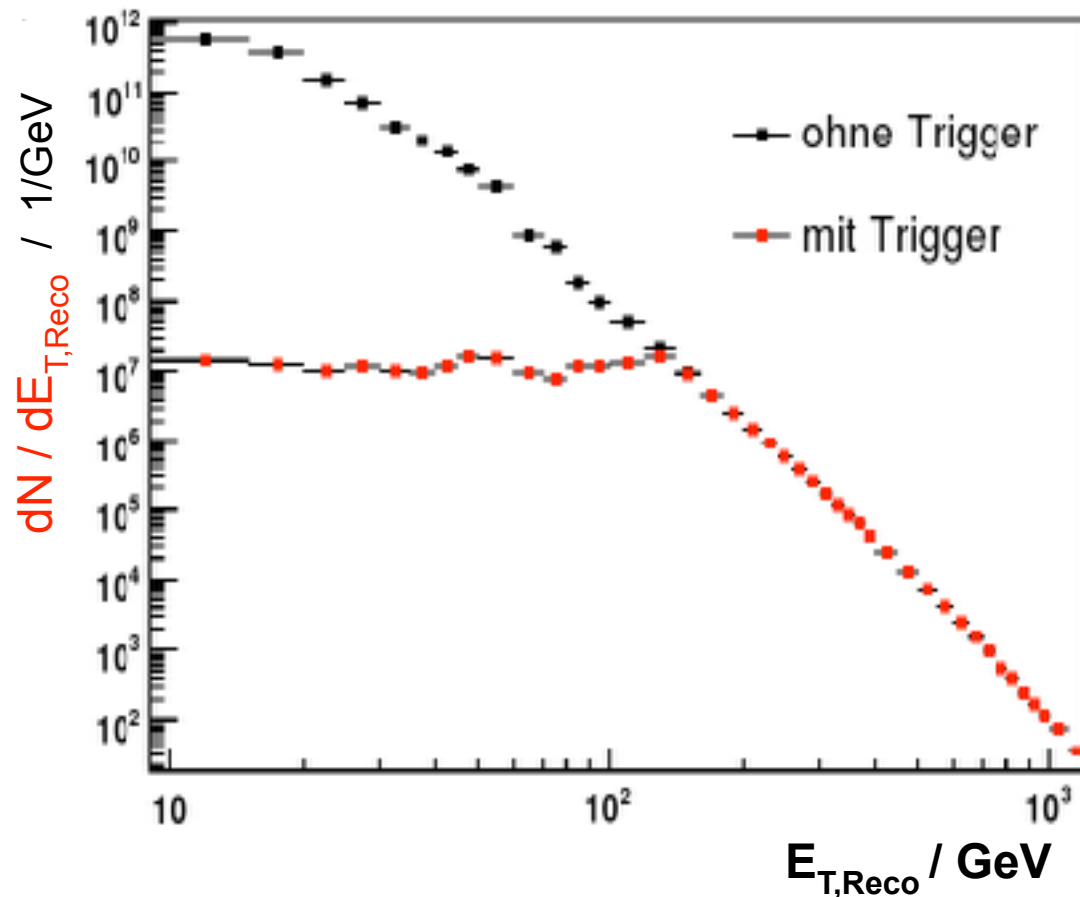


peak Luminosity

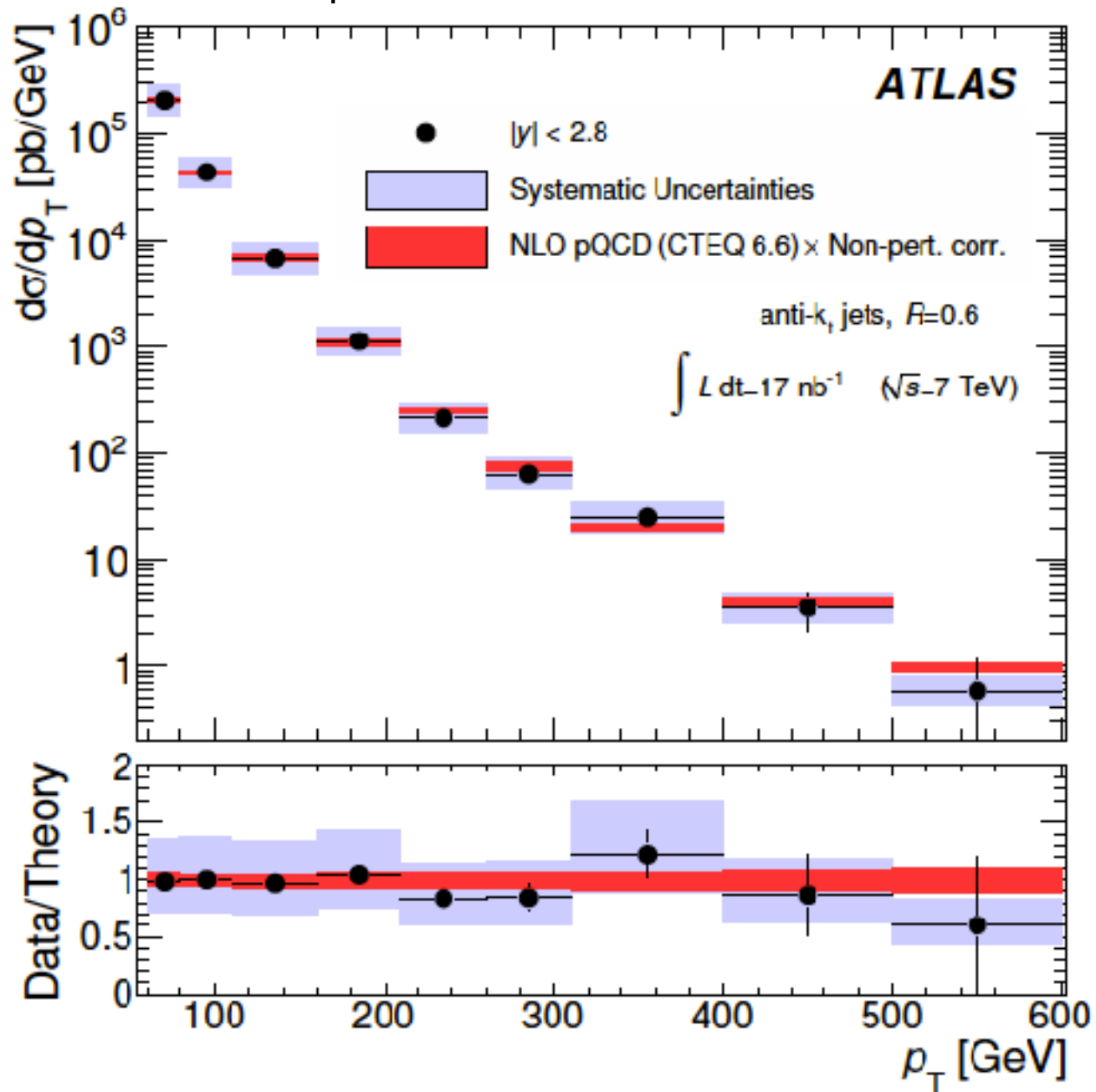


Jet-Wirkungsquerschnitt am LHC

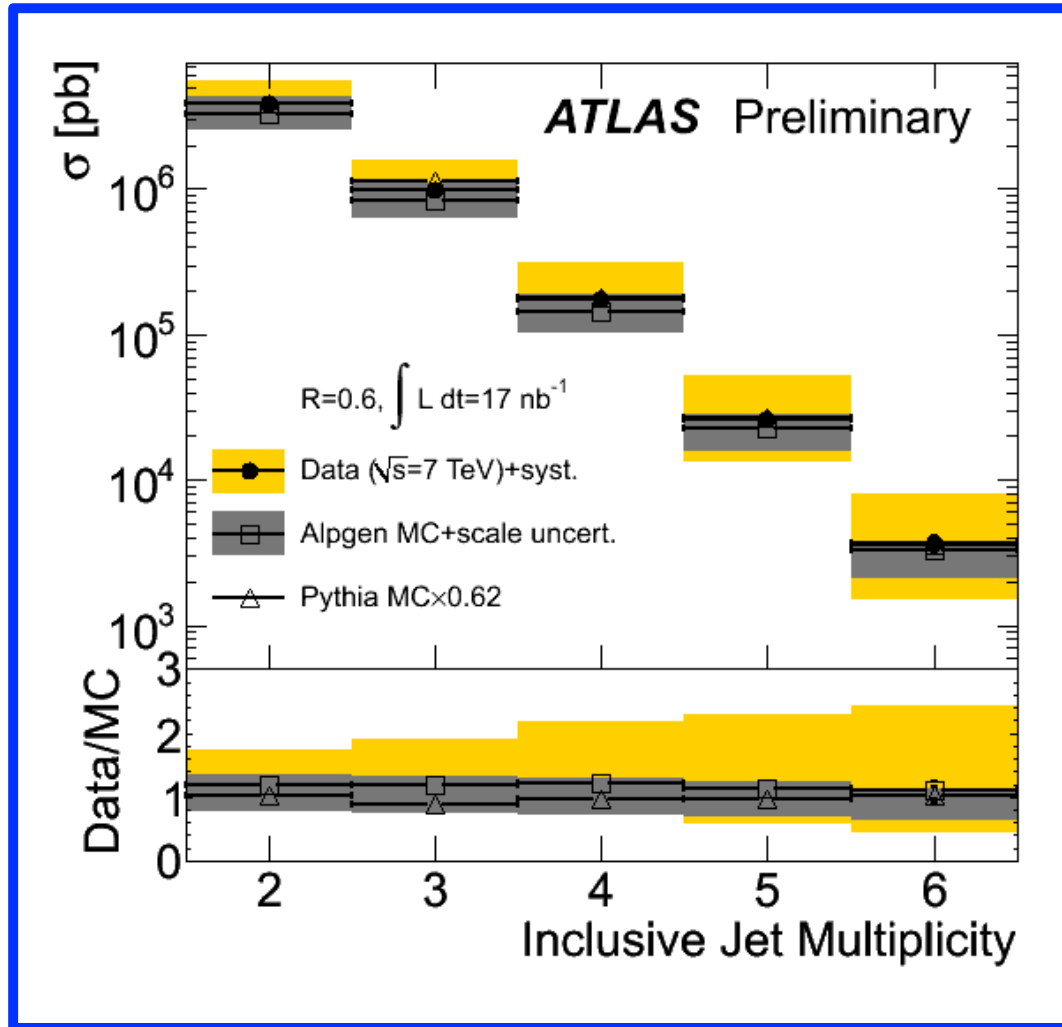
- Studie: Single-Jet-Spektrum nach einer Laufzeit von etwa 1 Jahr (10^7s), bei niedriger Luminosität ($L = 10^{32}\text{cm}^{-2}\text{s}^{-1}$): $\int L dt = 1 \text{ fb}^{-1}$
- Messung bis 1 TeV sehr früh möglich
- Unsicherheiten:
 - Jet-Energieskala
 - Energieauflösung
 - Triggereffizienzen
 - Luminosität



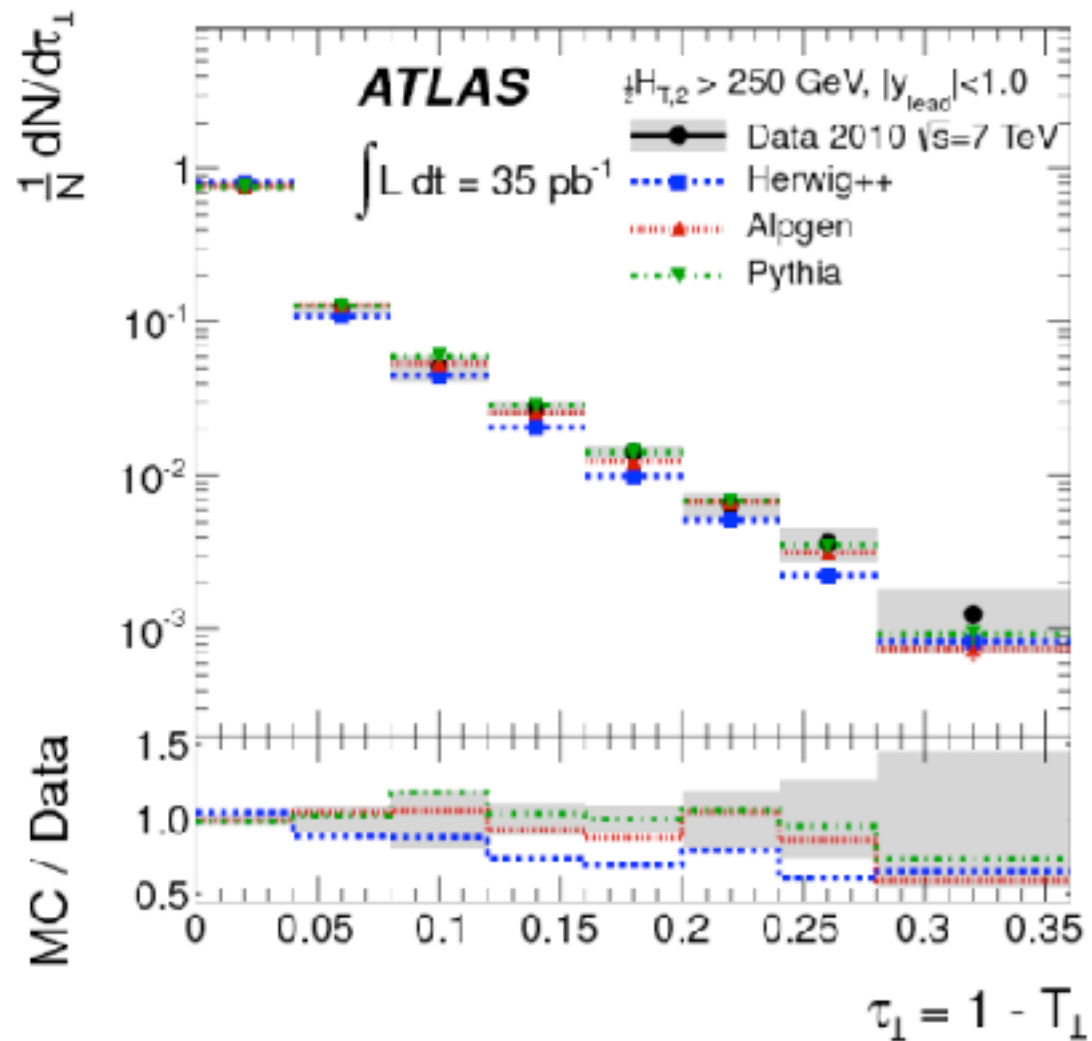
Jet production cross section



Jet multiplicities



Measurement of event shapes at large momentum transfer



[Eur. Phys. J. C \(2012\) 72: 2211](#)

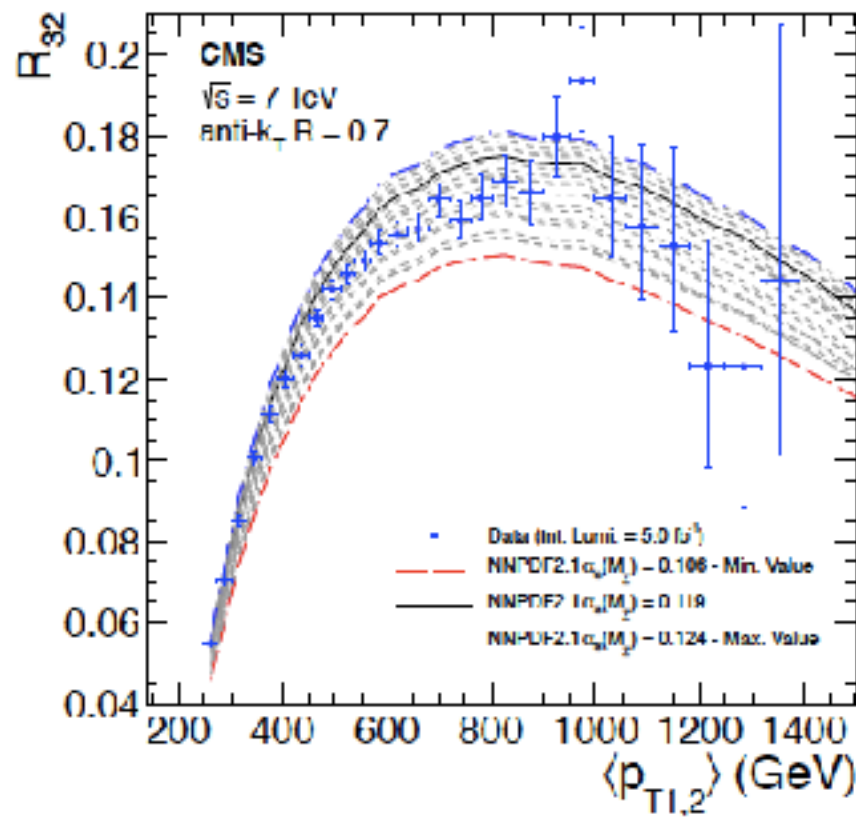
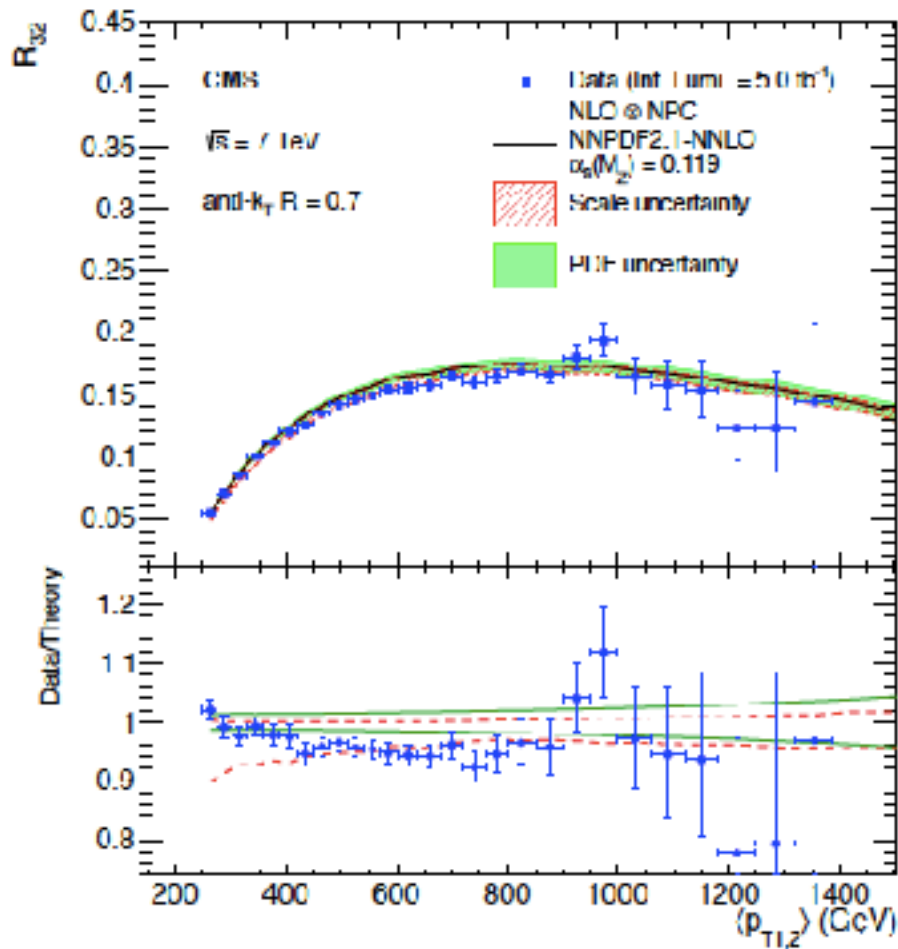
Measurement of the ratio
of the inclusive 3-jet and 2-jet cross sections
and

first determination

of the strong coupling constant α_s in the TeV range

- measurement of $R_{32} = R_{3\text{jet}}/R_{2\text{-jet}}$ 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 $\alpha_s(Q)$

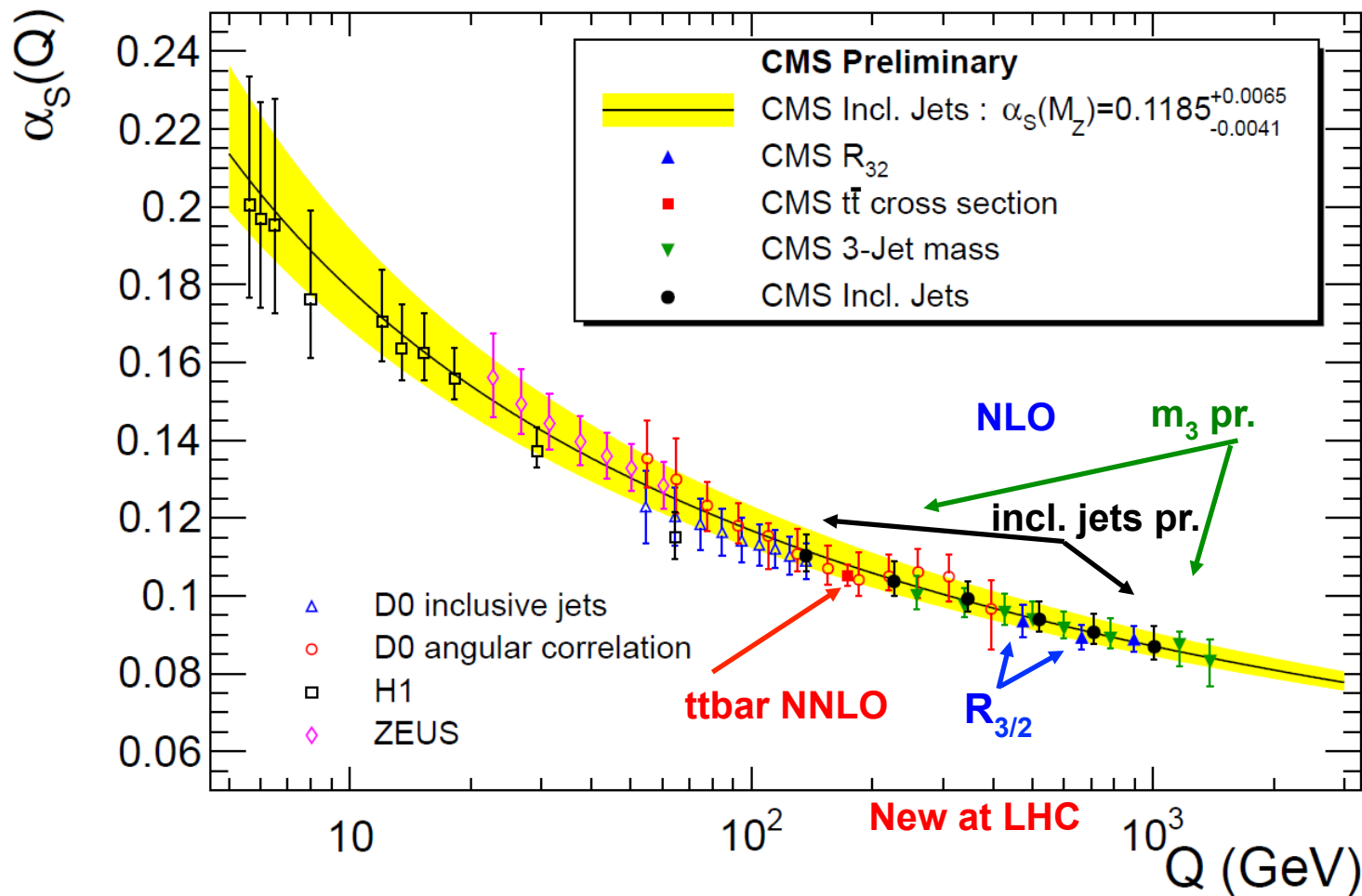
R_{32} as function of $p_{T1,2}$



arXiv:1304.7498

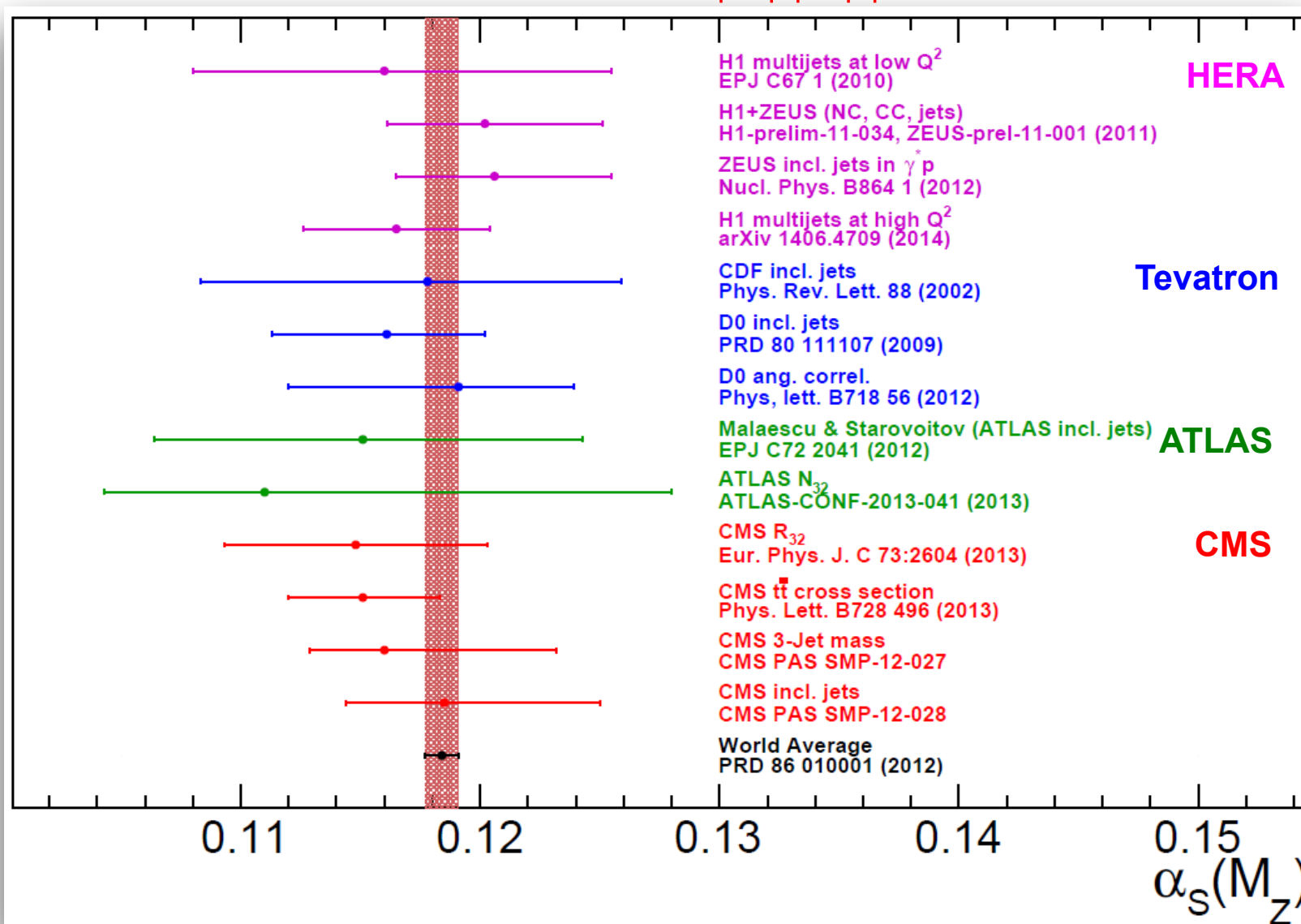
summary of α_s measurements

at hadron colliders (ep, pp, ppbar)

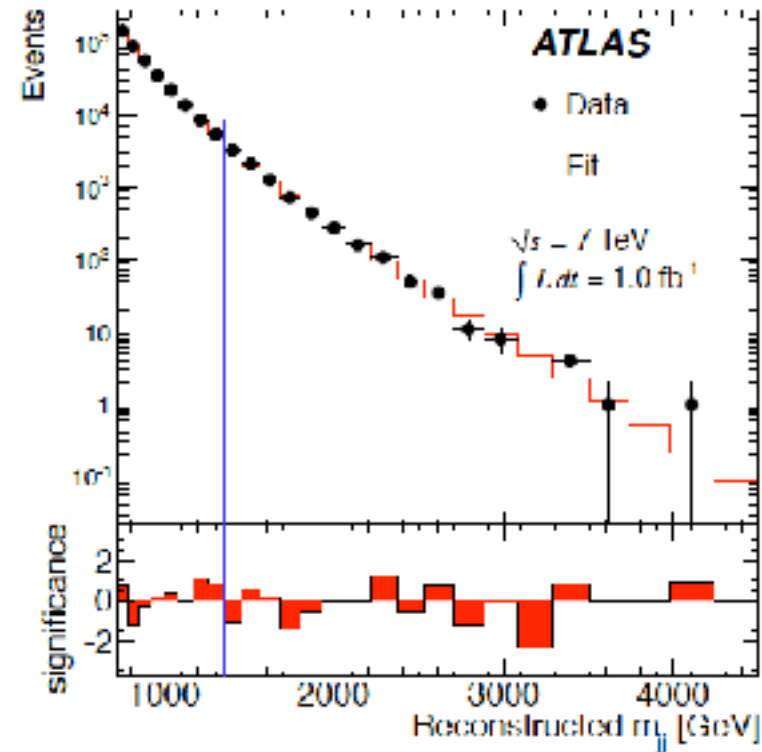
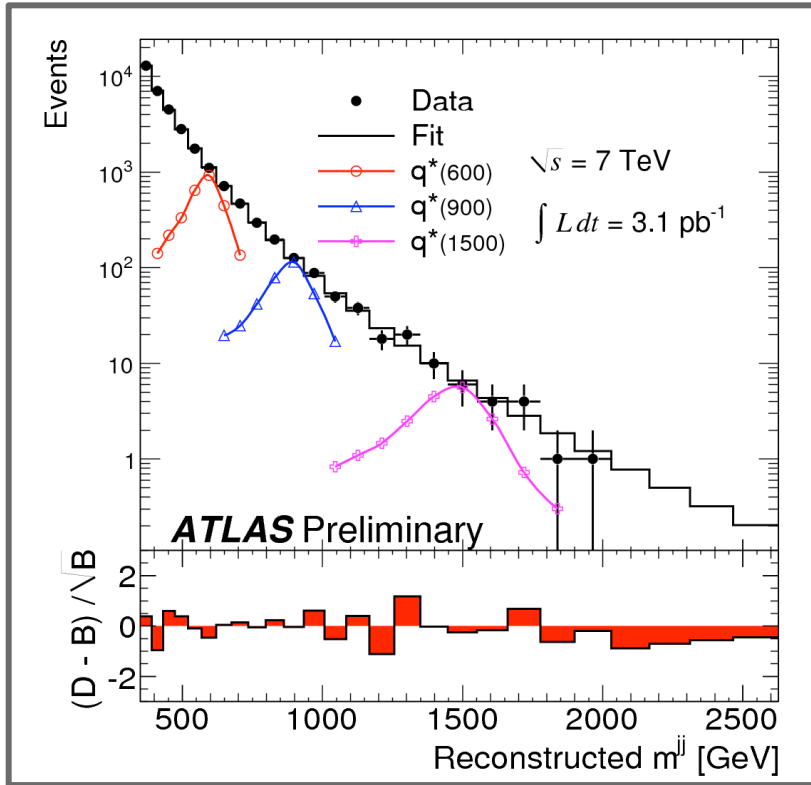


summary of α_s measurements

at hadron colliders (ep, pp, ppbar)



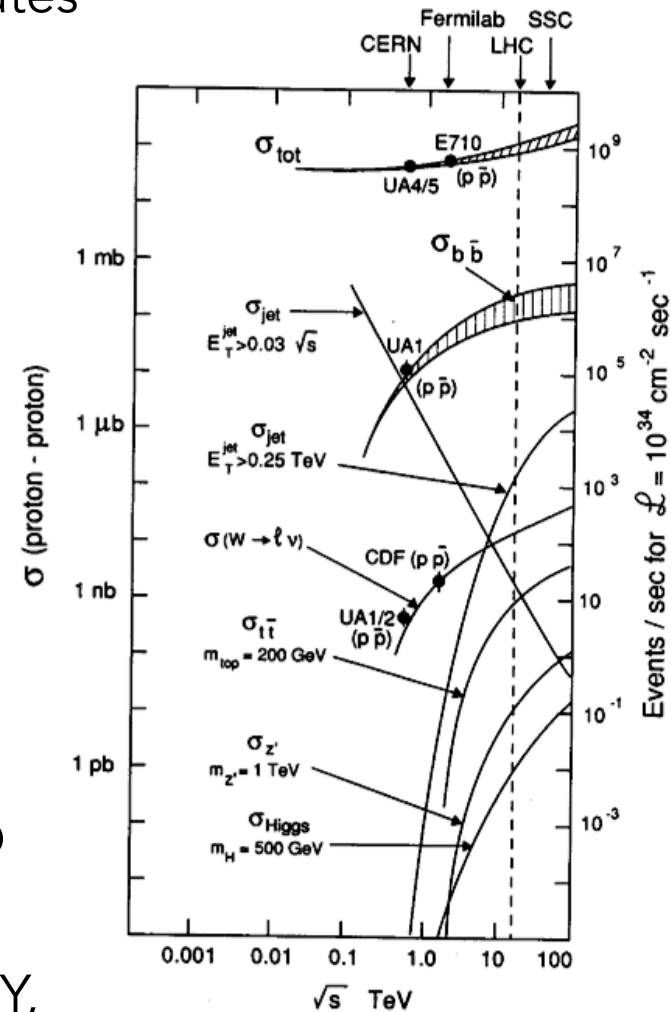
Jet pair masses and search for new heavy particles: excited quarks



production of excited quarks excluded
 in mass interval $0.3 < m < 3 \text{ TeV}$
 (Tevatron limit: 0.8 TeV)

Summary

- QCD (i.e. the strong interaction) largely dominates interaction rates at Tevatron and at LHC (σ_{tot})
- QCD describes the dynamics of quarks and gluons. Description of hadrons only possible through hadronisation models
- alternatively, define and analyse hadron jets; theoretically, jets can be associated with quarks and gluons.
- apart from dedicated QCD studies like the determination of α_s , precise knowledge of QCD processes is indispensable for searches of new effects beyond SM at LHC (e.g. Higgs, SUSY, large extra dimensions).



Literature

- 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](#)

next lectures:

- | | |
|-------------|-------------------------------------|
| 11.12.2017: | Top Quark Physics |
| 18.12.2017: | Standard Model Tests |
| 08.01.2018: | Physics Beyond Standard Model (BSM) |
| 15.01.2018: | Higgs Boson (I) |