Quantum Chromodynamics

… at the LHC and elsewhere …

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Introductory School to Terascale Physics
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HELMHOLTZ
GEMEINSCHAFT

DESY

OUTLINE

- Basics of Quantum Chromodynamics (QCD)
  - Particles, interactions, Feynman diagrams
  - A bit of history, and some salient features
- Parton Distribution Functions (veeeery briefly)
  - Factorisation, and QCD processes at the LHC (hadron colliders)
- Particle production
  - Spectra, multiplicities, identified particles, etc.
- Jets as probes of hard interactions
  - Jet algorithms
  - Measurements in ee, at HERA,Tevatron and LHC
  - Extractions of α_S
- The Underlying Event
  - … just one slide ….

THE PATH TO QCD – HISTORY (1)

> Early classifications of particles (`particle zoo')

- Based on charge, spin, isospin (Heisenberg et al.: SU(2)-based theories, grouping for example proton and neutron together …)
- `Invention' of `quarks' as building blocks of hadrons by Gell-Man, Zweig: up, down (strange), …

> Parallel: scattering experiments on nuclear/proton substructure:

- Evidence for proton substructure: Partons (Bjorken / Feynman).

→ Invention of the `Quark-Parton Model'

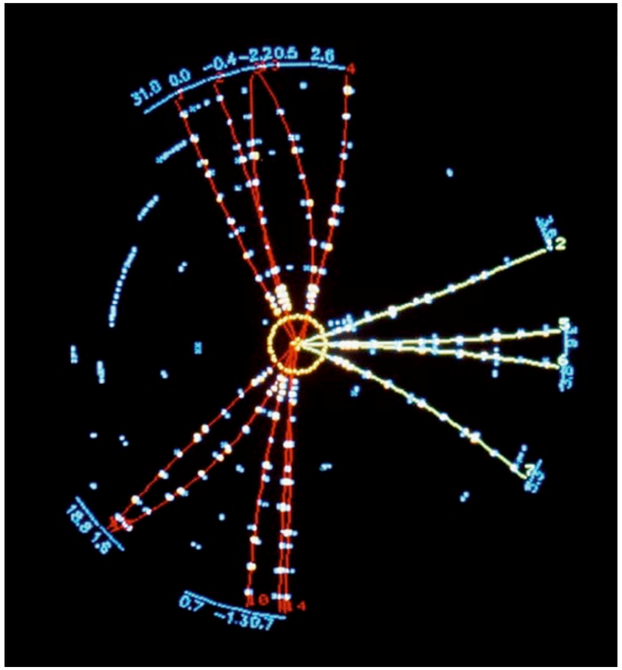
Proton consists of pointlike partons/quarks which carry fractional electric charge and a fraction x of the proton's momentum!

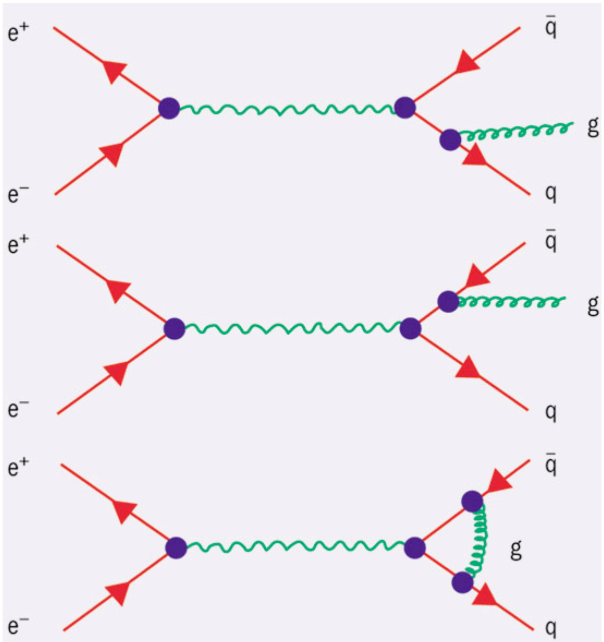
> Problems!!!!

- The Δ^{++}: spin-3/2 particle built from 3 identical up quarks with parallel spins????
- Scaling violations in deep-inelastic scattering experiments!!!
- How do electrically charged particles hold together in the proton????
- Where is the rest of the proton momentum – if not in the quarks????

THE PATH TO QCD – HISTORY (2)

- Solutions: QCD
  - A gauge theory along the lines of what was established for electro-weak interactions!
  - Introduction of a new degree of freedom: colour!
- Experimental evidence: Discovery of gluons (here at PETRA / DESY!)
  - $e^+e^- \rightarrow$ qqg events at the PETRA collider 1979!





"… at a rate consistent with gluon radiation and a value of the strong coupling of about 0.15 …"

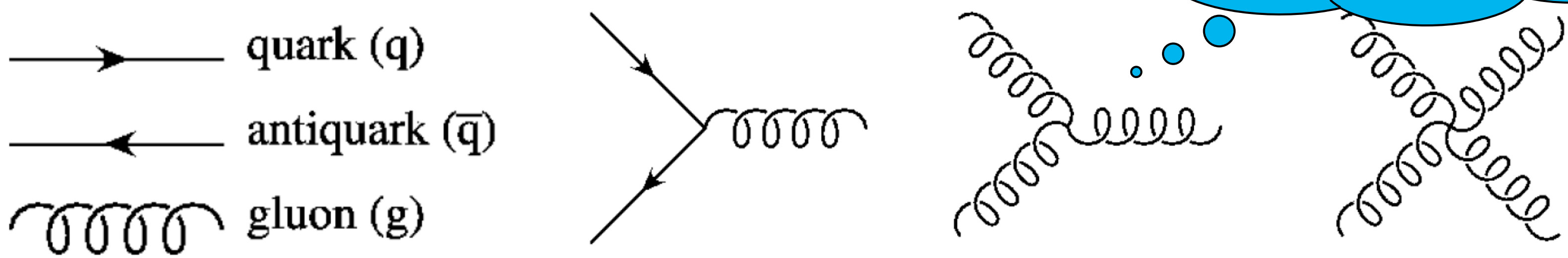
BASICS OF QCD

> Quantum Chromodynamics (QCD) – the theory of strong interactions

- Non-abelian gauge field theory based on an $SU(3)_C$ symmetry.
- QCD describes interactions between coloured particles: quarks and gluons.
- Developed in the 1970es by Fritzsch, Gell-Mann, Leutwyler, Gross, Weinberg, etc. (see a bit on history later).

> Interactions in QCD

Gluons are colour-charged – different (non-abelian) behaviour than QED!



> We have three colour charges (`red’, `blue’, `green’) and coloured gauge bosons

- This leads to 8(+1) gauge bosons (gluons) – in contrast to QED (1 neutral photon)
- … and also to other remarkable features (next slides).

SALIENT FEATURES OF QCD (1)

> Asymptotic Freedom (NP2004 – Gross, Wilzcek, Politzer)

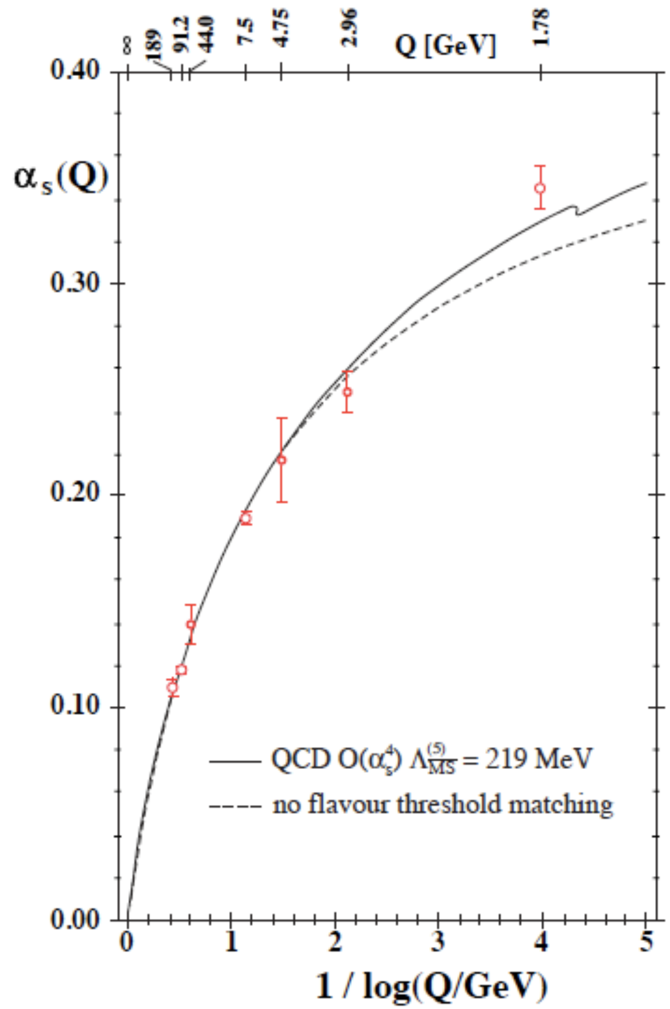
- Relevant parameter: Coupling strength between coloured particles: α_s!

$$\alpha_S(\mu) = \frac{\alpha_S(M_Z)}{1+\alpha_S(M_Z)\cdot b\cdot \ln\left(\mu^2/M_Z^2\right)}$$

- At large energies / small distances, quarks are `free' inside the proton / hadron.

> Confinement:

- At large distances / small energies, the coupling increases and diverges.
- There are no free quarks!
- Solution of confinement is one of the Millenium Prize problems (Clay Mathematics Institute).



SALIENT FEATURES OF QCD (2)

$$\alpha_S(\mu) = \frac{\alpha_S(M_Z)}{1+\alpha_S(M_Z)\cdot b\cdot \ln\left(\mu^2/M_Z^2\right)}$$

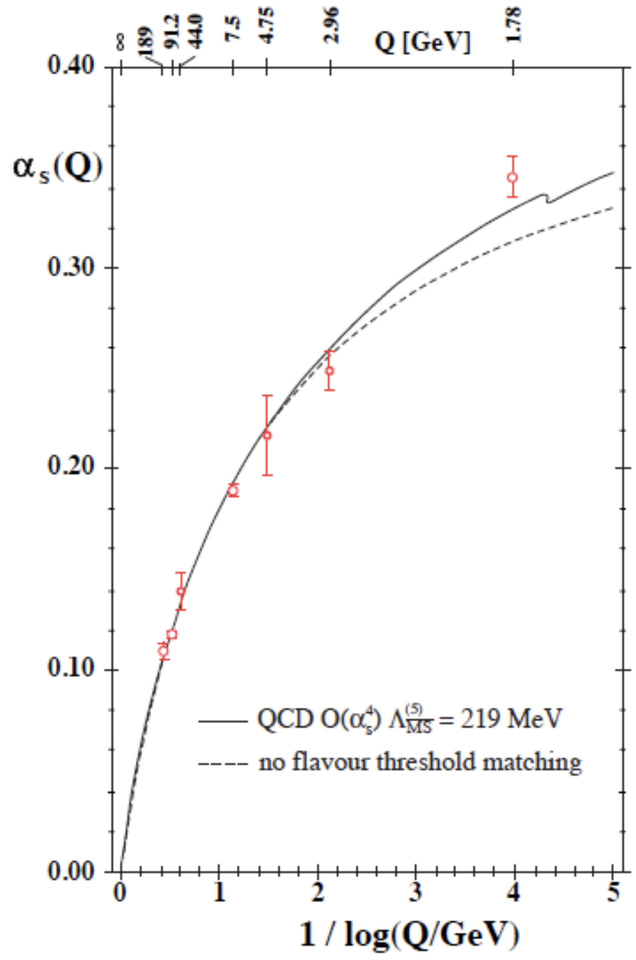
> How to tackle QCD?

- Perturbative QCD: At high energies, the coupling is small and cross sections can be evaluated as power series in α_S:

$$\sigma = C_0 + \alpha_S \cdot C_1 + \alpha_S^2 \cdot C_2 \ldots = \sum_{n=0}^{\infty} \alpha_S^n \cdot C_n$$

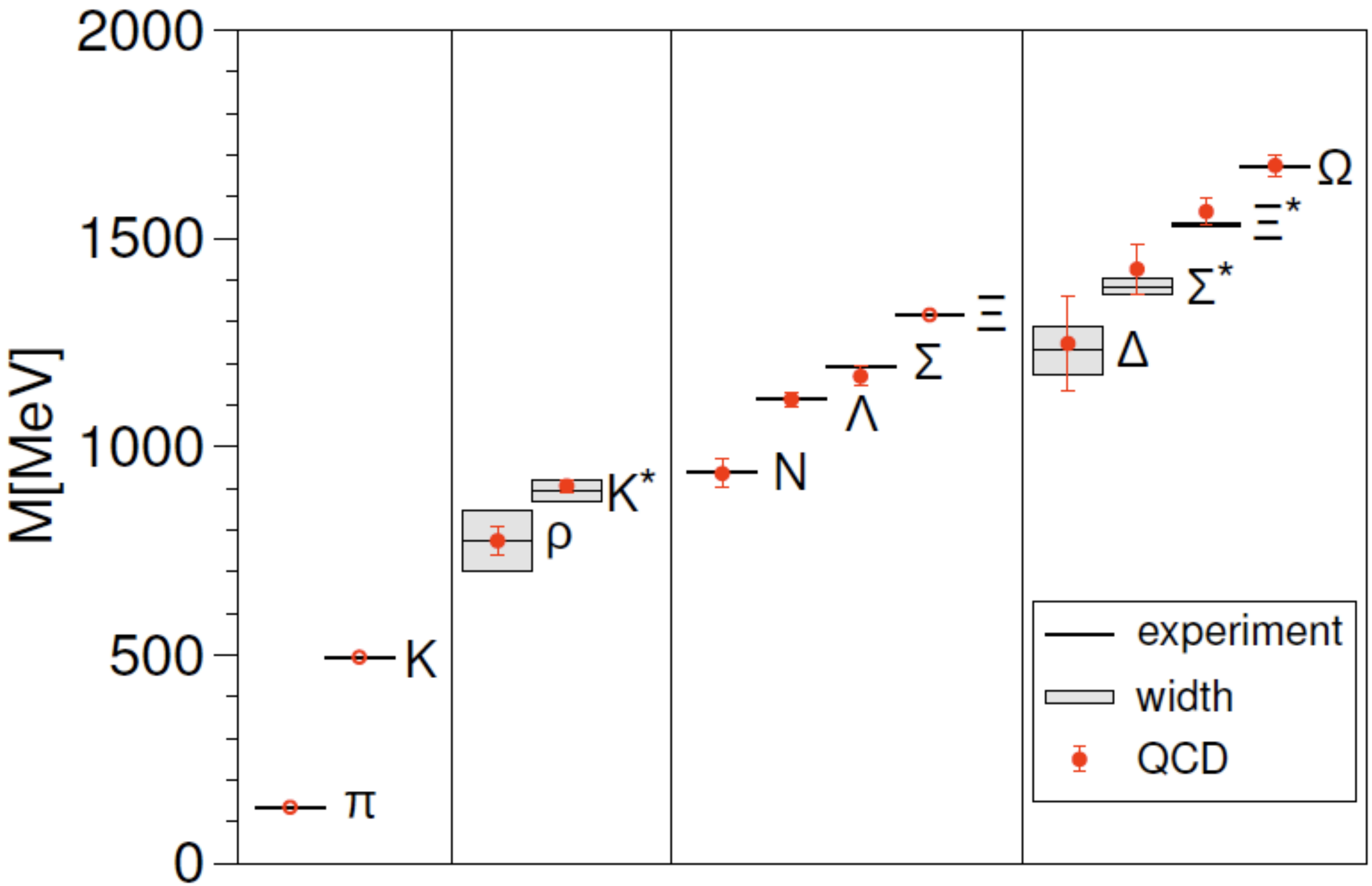
  The coefficients can typically be evaluated to some (small) order: LO, NLO, NNLO
  In addition methods to sum up other large contributing terms (large logs).

- Lattice QCD: can give particle spectra, indications for the value of the coupling, …
- Effective theories
- 1/N expansions
- …



SALIENT FEATURES OF QCD (2)

> Hadron spectroscopy in lattice QCD



PARTON DISTRIBUTION FUNCTIONS

More in I. Brock's lecture tomorrow!

- We are talking about proton-proton collisions …
  - … so we better know what the proton is (in terms of colliding constituents / partons / quarks+gluons).
  - Description in terms of parton distribution functions (PDFs): probability to find a quark / gluon of type a with momentum fraction x in the proton when probed at a scale Q!

$$f_{a/p}(x,Q) \quad a = u, \bar{u}, d, \ldots, g$$

- Why does $f_{a/p}$ depend on Q (dependence on x should be clear)?
  - Virtual processes in the hadron: See more of the inner life when increasing the resolution (the scale / the energy, decreasing the distance, get closer) → change of probabilities to find quarks with certain properties (next slide).
- … the bad thing about PDFs:
  - They cannot be calculated from first principles …
  - … but have to be determined using experimental data and involved mathematical tools (DGLAP evolution, not covered here).

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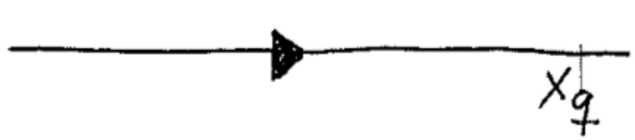

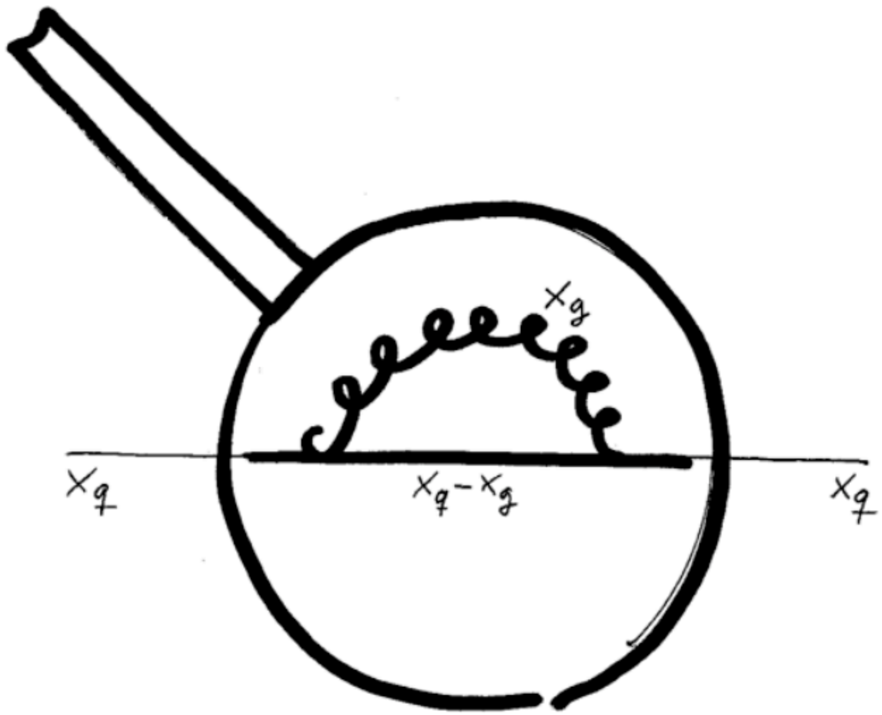

PARTON DISTRIBUTION FUNCTIONS

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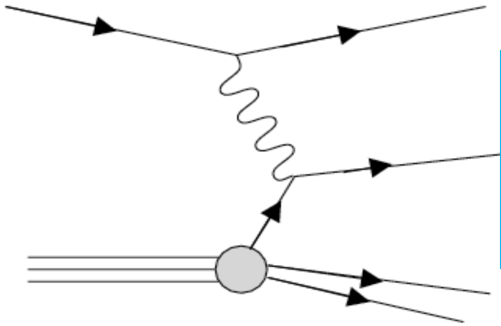
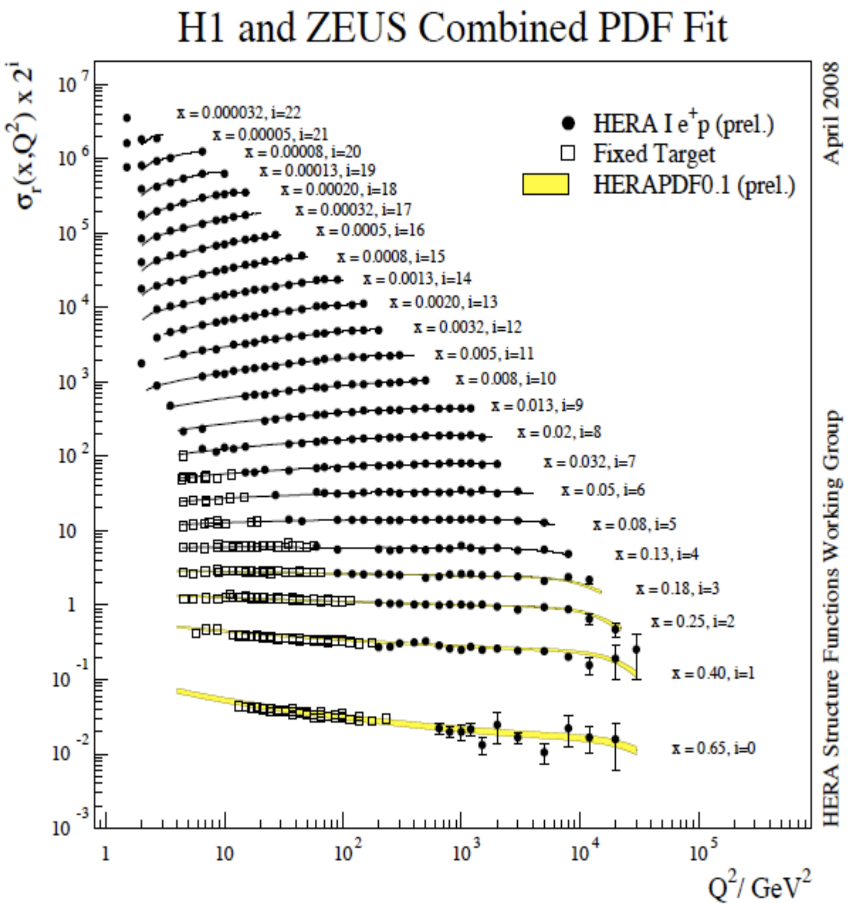
> Extractions rely mainly on deep-inelastic scattering data (HERA)

- Structure function F_2: Related to ep cross section σ_{ep} and parton densities f_i!



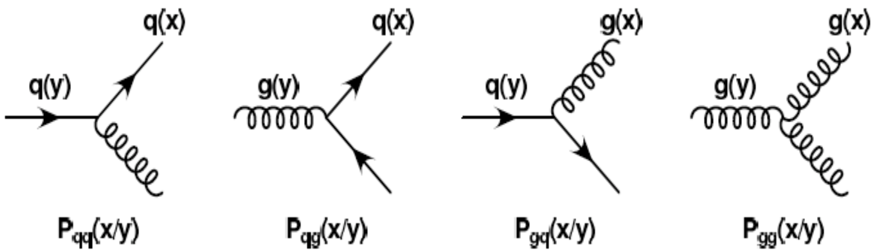
$$\sigma_{ep} \propto F_2\left(x,Q^2\right) \approx x \sum_{i=q,\bar{q}} f_i\left(x,Q^2\right) \cdot q_i^2$$



> QCD predicts behaviour of $F_2(Q^2)$

$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto -\alpha_S P_{qq} F_2 + \alpha_S P_{qg}\, g$$

- Use to extract PDF f_i and α_S.



PARTON DISTRIBUTION FUNCTIONS

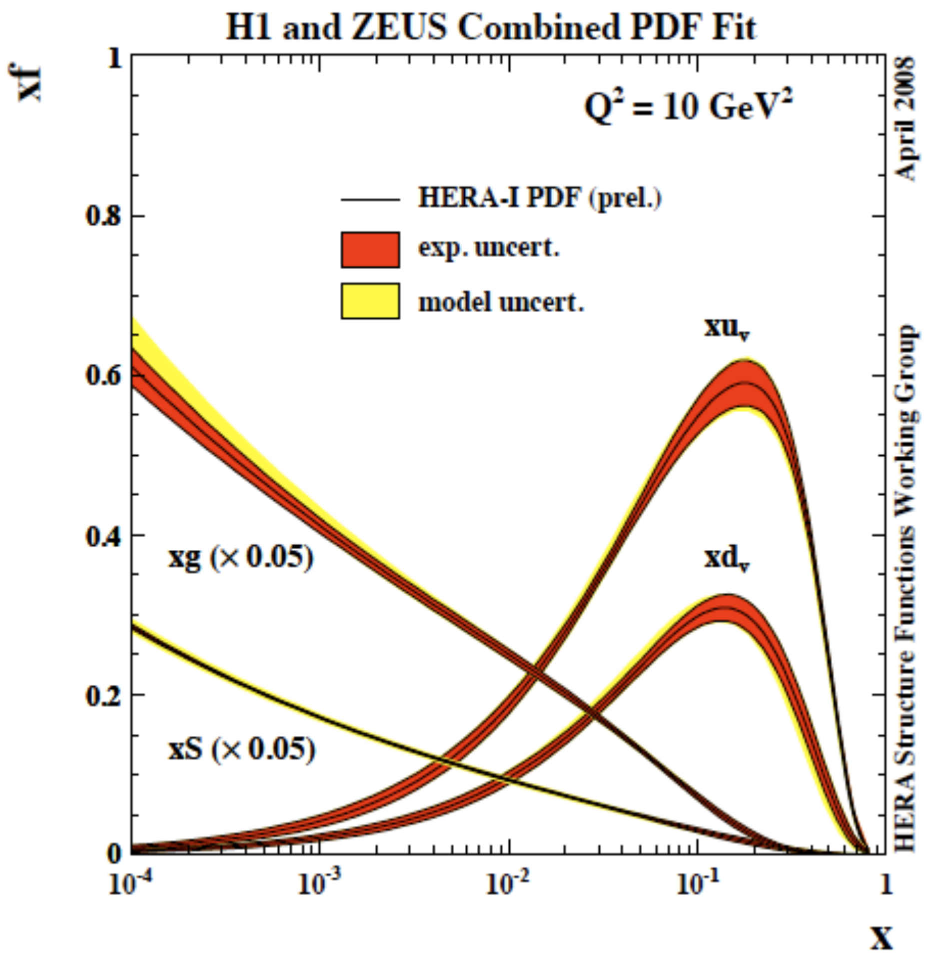
More in I. Brock's lecture!

> Current state-of-the art: PDF efforts from different groups like CTEQ, MSTW, HERA, etc. (and hopes to improve with LHC data):

$$f_{a/p}(x,Q) \quad a = u,\bar{u},d,\ldots,g$$

> Use existing libraries to access given PDF sets for usage in your analysis

- LHAPDF
- OOPDF
- …
- Interfaced to experiment-specific software!



PARTON DISTRIBUTION FUNCTIONS

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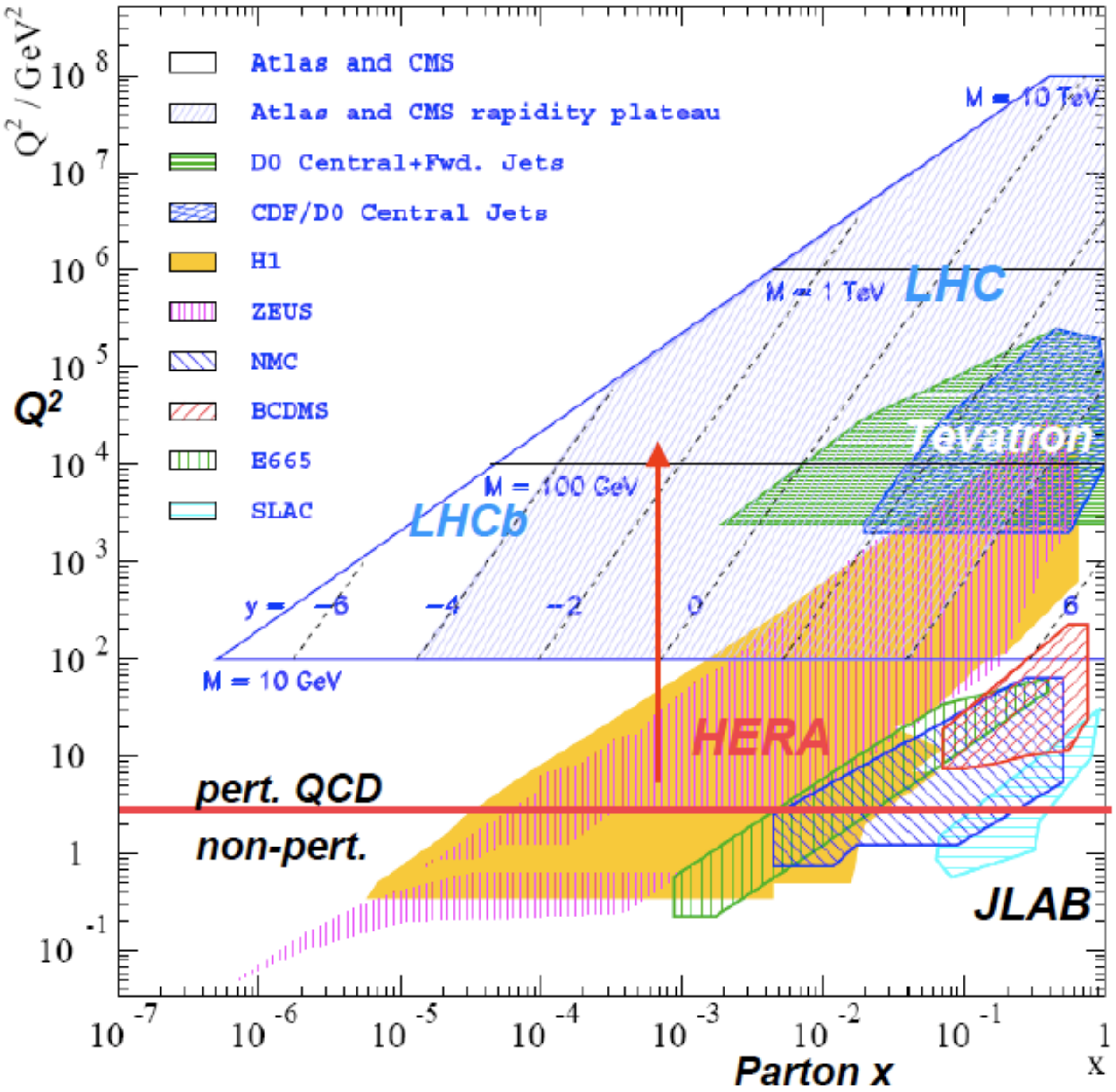


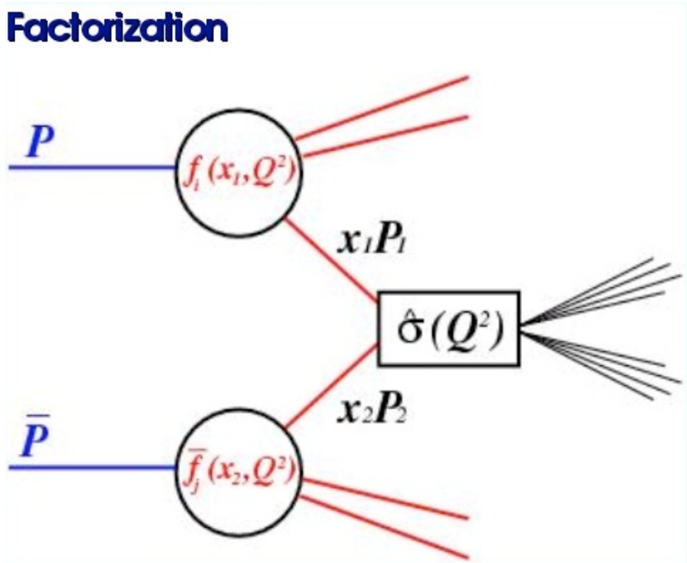
PDFs AND FACTORISATION

> How to get from the PDFs to the physics? Convolution of PDFs with matrix elements describing the underlying scattering process.

$$\sigma = \sum_{a=q,\bar{q},g} f_{a/p}(x_a, Q) \otimes \hat{\sigma}_{ab} \otimes f_{b/p}(x_b, Q)$$

$$= \sum_n \sum_{a,b=q,\bar{q},g} f_{a/p} \otimes \hat{\sigma}_{ab,n} \otimes f_{b/p}$$

$$= \sum_n \alpha_S^n \cdot \sum_{a,b=q,\bar{q},g} f_{a/p} \otimes C_{ab,n} \otimes f_{b/p}$$

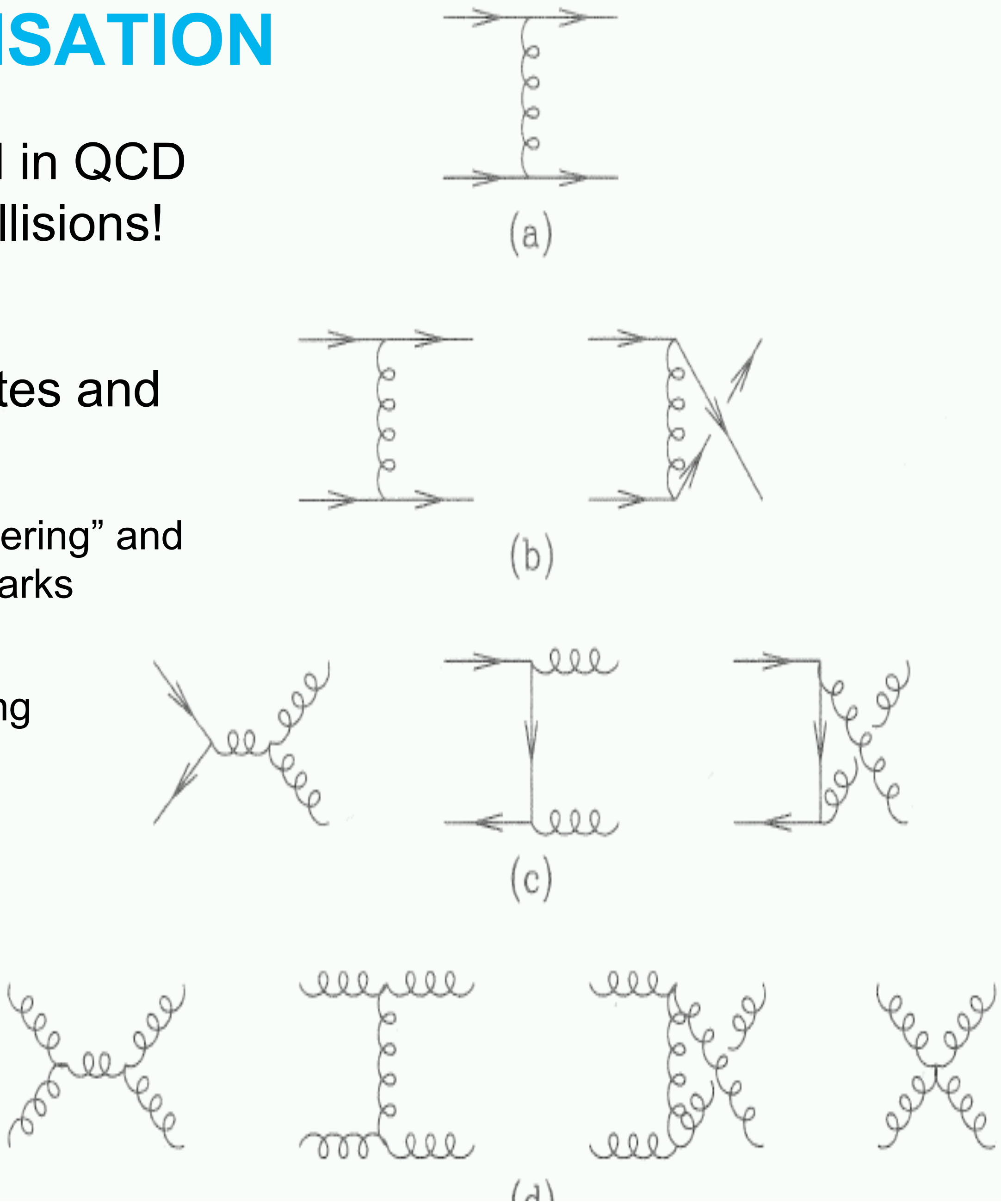


> So the problem reduces to having the PDFs and calculating, using pQCD, the matrix elements or coefficients C_n.

➔ Although that statement is a bit over-simplifying … see next slides!

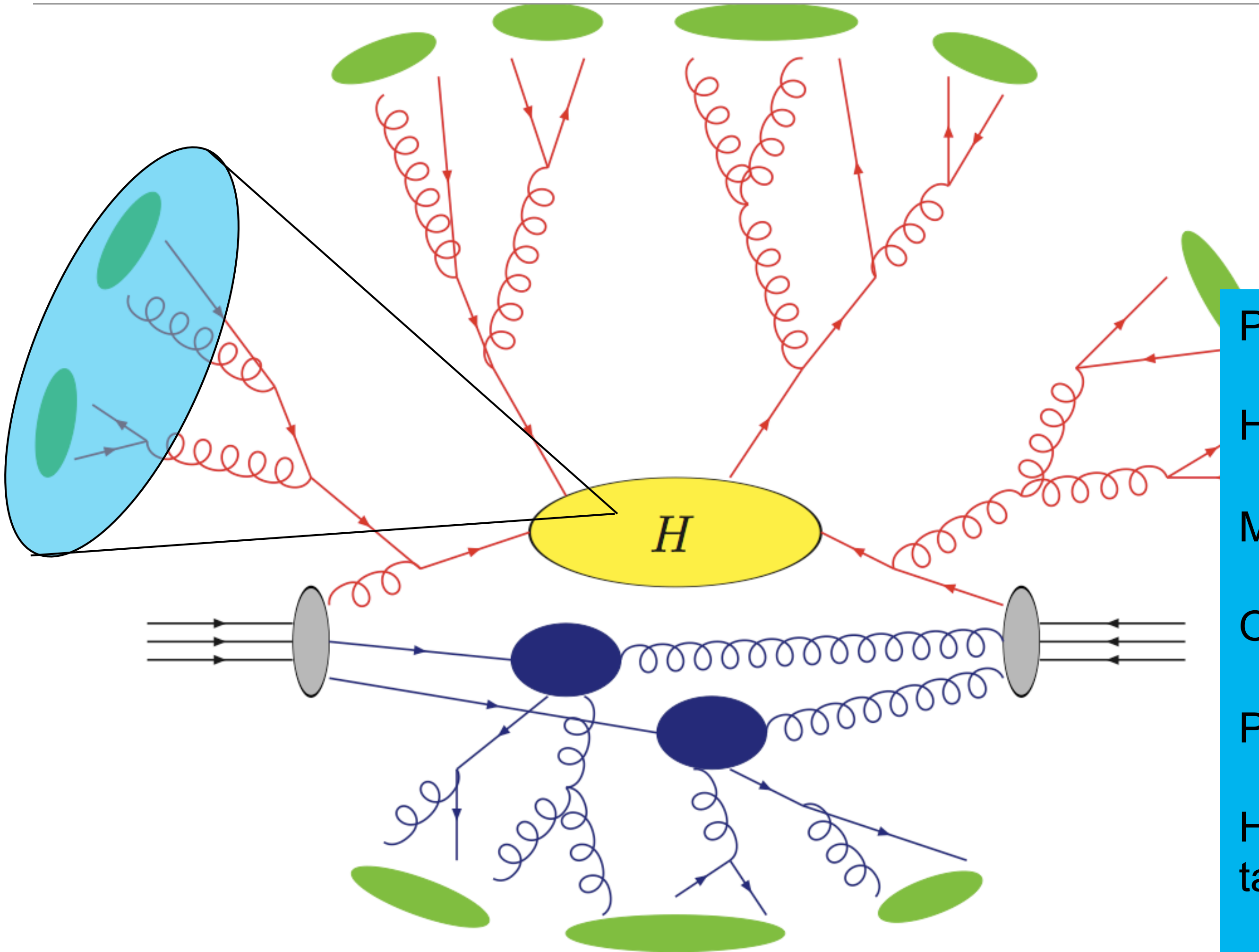
PDFs AND FACTORISATION

- Processes to be considered in QCD events in hadron-hadron collisions!
  - … just a few examples …
- Important: different final states and different physics questions.
  - Particle production from “showering” and “fragmentation” of outgoing quarks and gluons.
  - Jets as “fingerprints” of outgoing quarks and gluons.
  - Cross-sections / rates of these processes → background for searches and new physics (QCD as “bread-and-butter physics”)



PDFs AND FACTORISATION

> … there's more to events in hadron-hadron collisions!



PDFs: incoming particles

Hard interaction

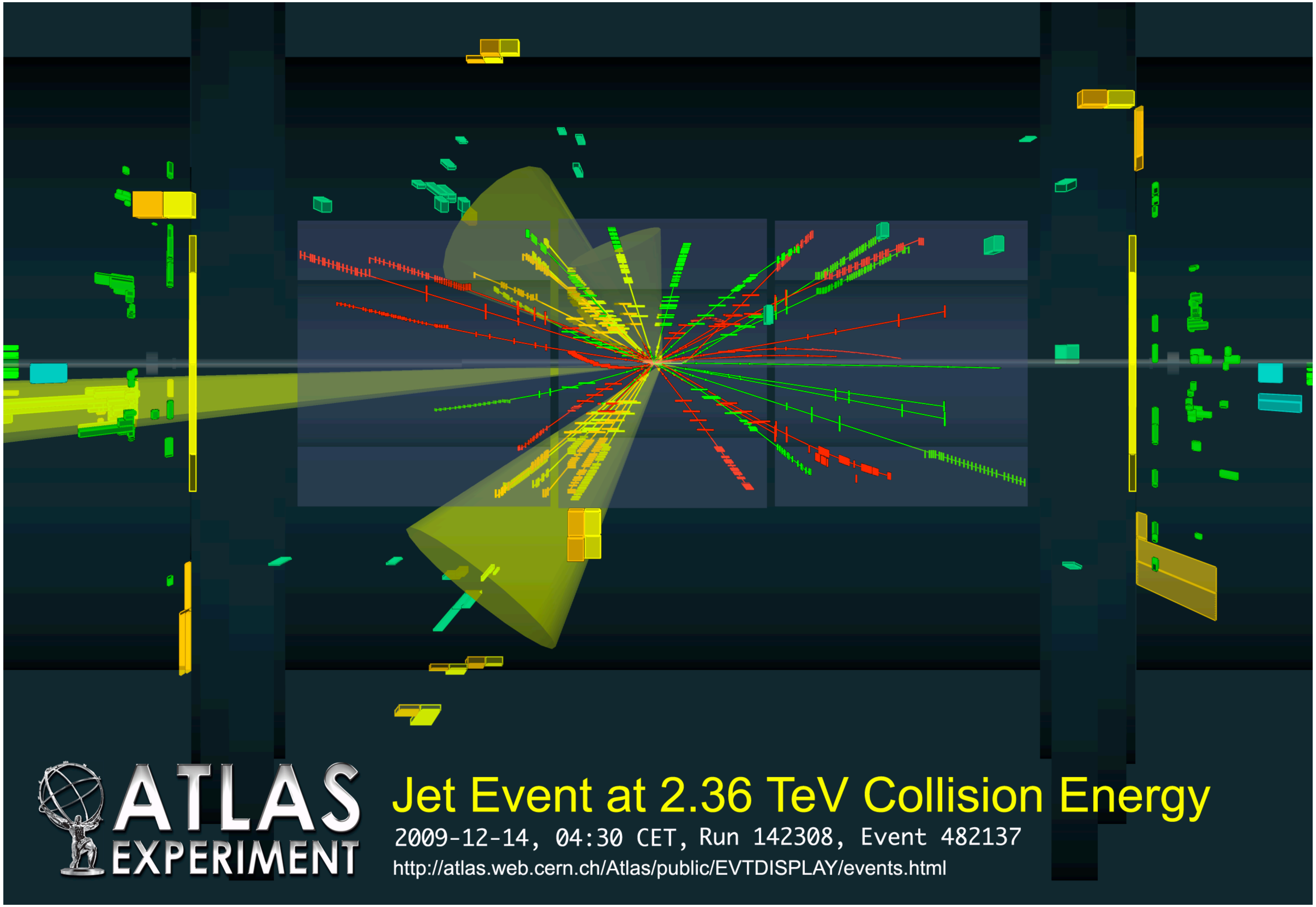
Multiple interactions

Outgoing partons

Parton showering

Hadronisation (fragmen-tation), decay

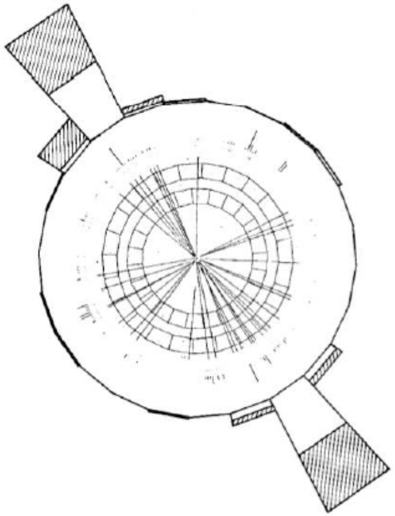
Jets

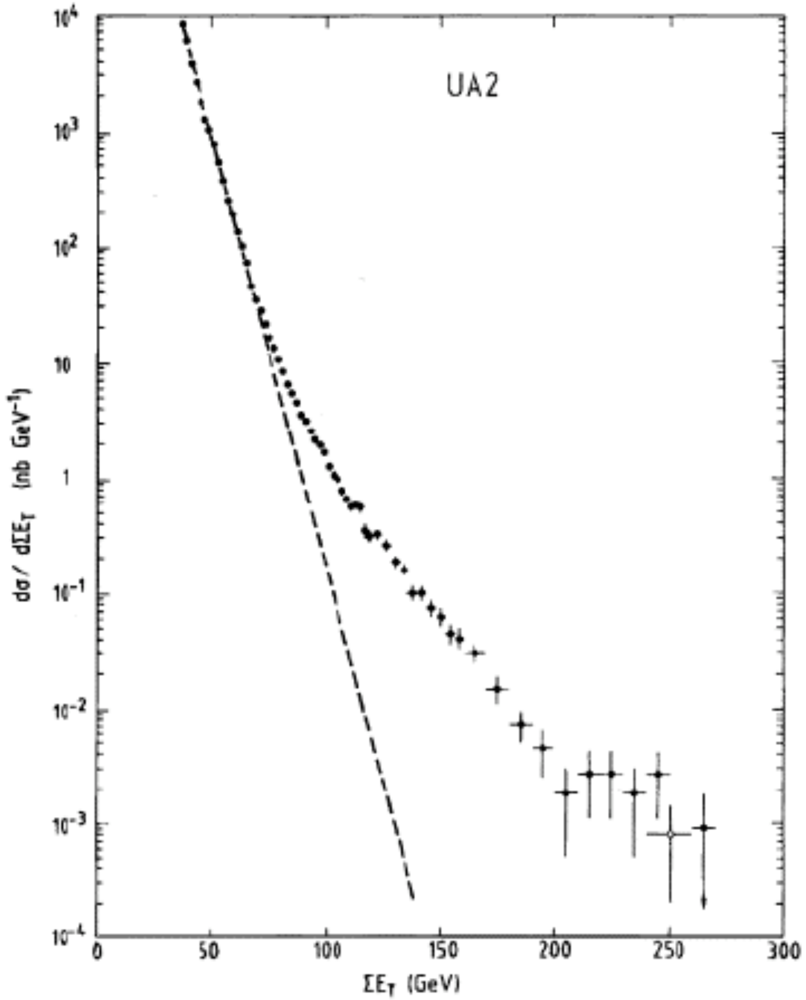

ATLAS
EXPERIMENT
Jet Event at 2.36 TeV Collision Energy
2009-12-14, 04:30 CET, Run 142308, Event 482137
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

PARTICLE PRODUCTION: HISTORY

> In the 1960es, 70es observables describing events were measured in hadron collisions – for example total transverse energy (here UA2 at SppS).

- Low E_T: exponential fall-off, higher E_T: power law: E_T^{-n}.
- Indication for hard proton constituents!
- Furthermore: "jet-like" structures observed: indication of hard 2→2 scattering, with final-state clustered around initial partons.



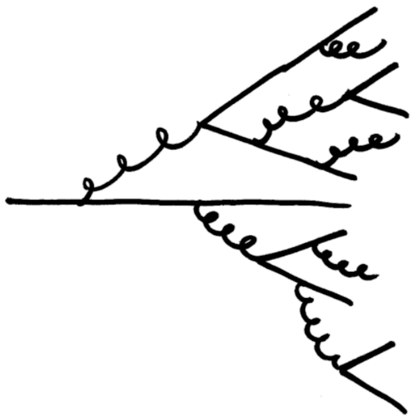


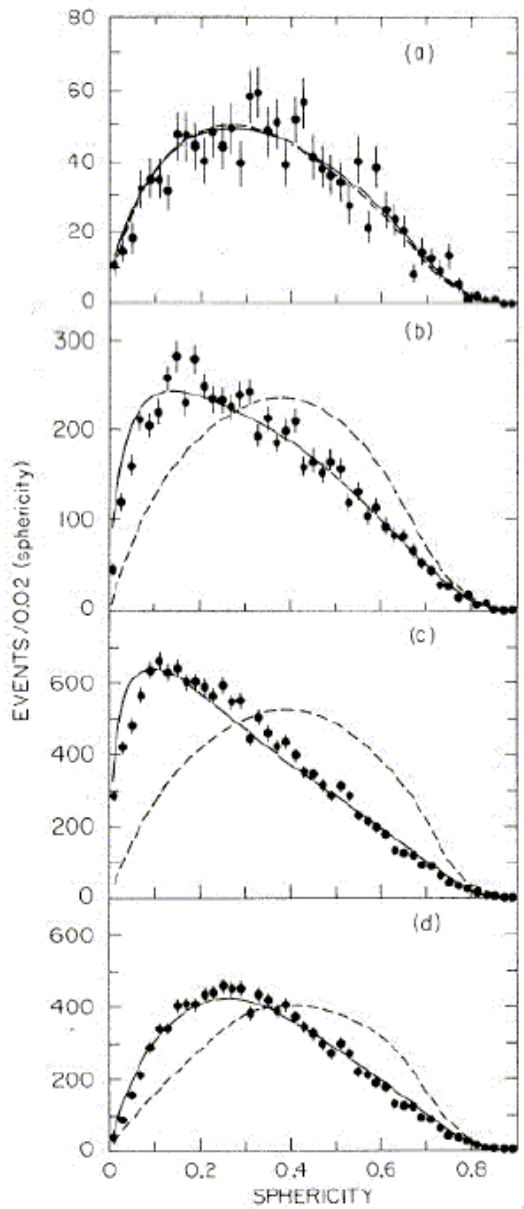
PARTICLE PRODUCTION: HISTORY

- Question: Are particles produced spherically symmetrically (in transverse plane) or is there a structure?
  - Studied in hadron-hadron / ee collisions.
  - Example: Sphericity S (Mark-I at SPEAR):

$$S = \frac{3\left(\sum_i p_{T,i}^2\right)}{2\left(\sum_i \vec{p}_i^{\,2}\right)},$$

  - Evidence for jet-like structure
    → fragmentation / showering models.





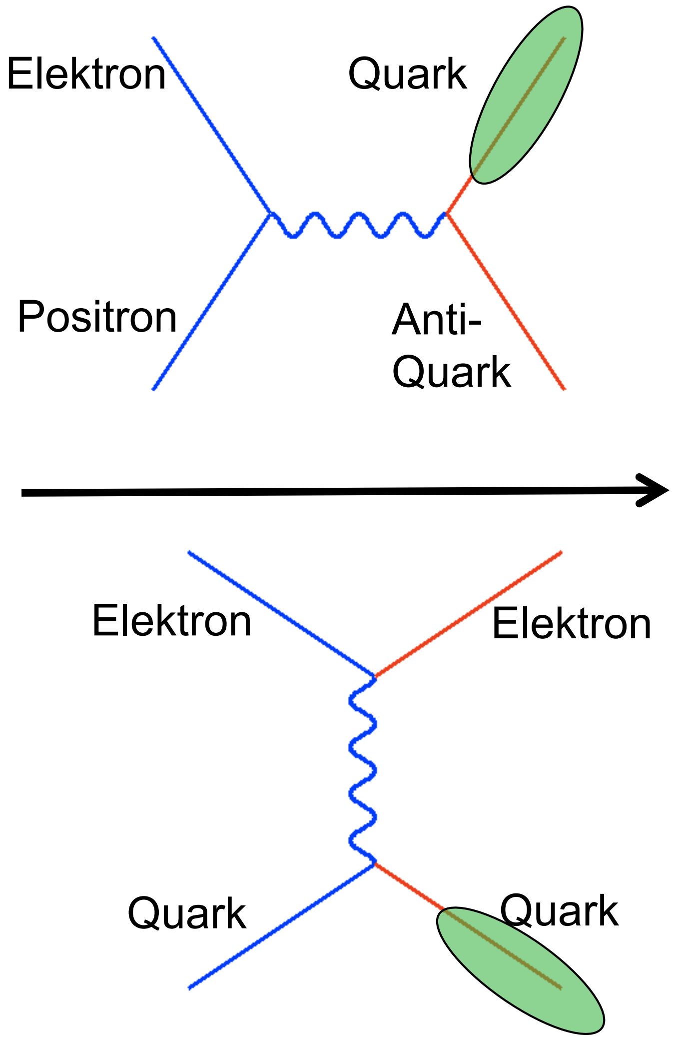
PARTICLE PRODUCTION

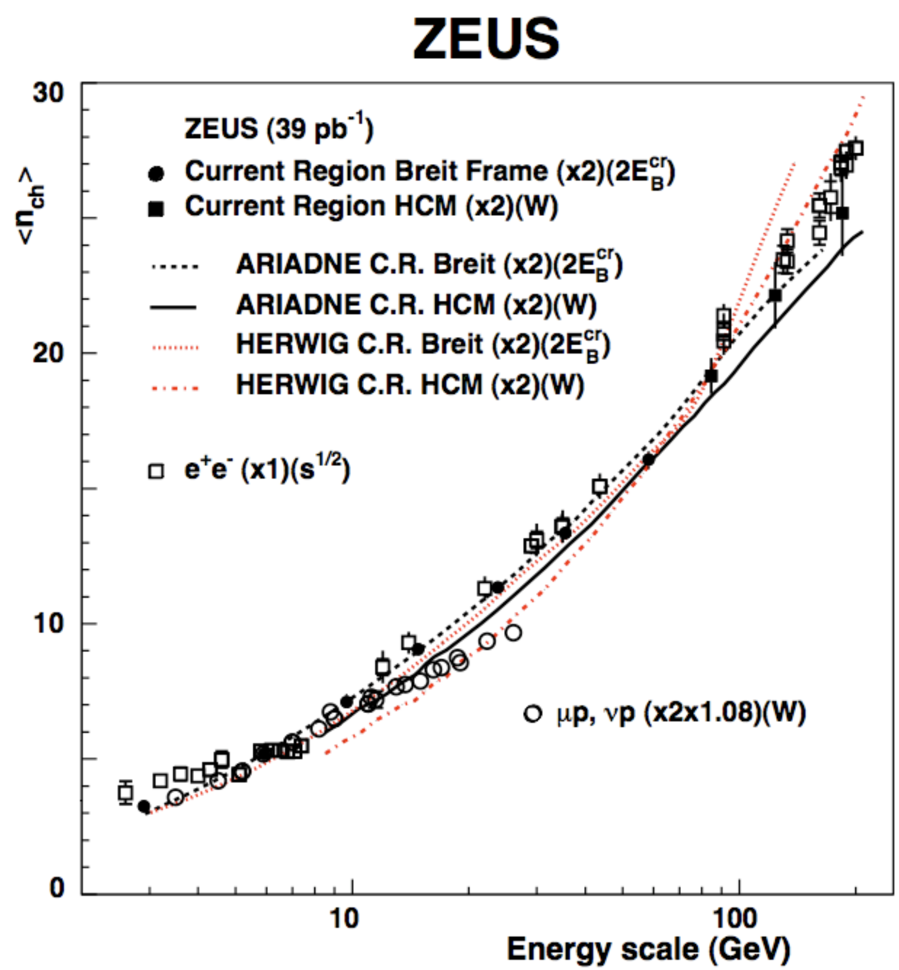
- In the processes of parton showering and fragmentation of the final-state quarks, numerous stable particles (pions, protons, …) are produced.
  - Measure the number of charged particles as functions of transverse momentum p_T and pseudorapidity η and test models.
  - Measure energy dependence of average transverse momentum and average charged particle multiplicity.
  - Measure individual particles, for example K, Λ, J/Ψ, and ratios of these.
  - Measure …
- Note that it is especially interesting to measure the same distributions at different centre-of-mass energies and at different machines in order to
  - Be able to compare / verify different measurements and
  - To learn about the behaviour of distributions and average values with energy.
  - To adjust ("tune") the models we have.

  ➔ Compare experimental results from ISR, SppS, LHC, RHIC, Tevatron

PARTICLE PRODUCTION

> … energy dependence of charged hadron multiplicity:

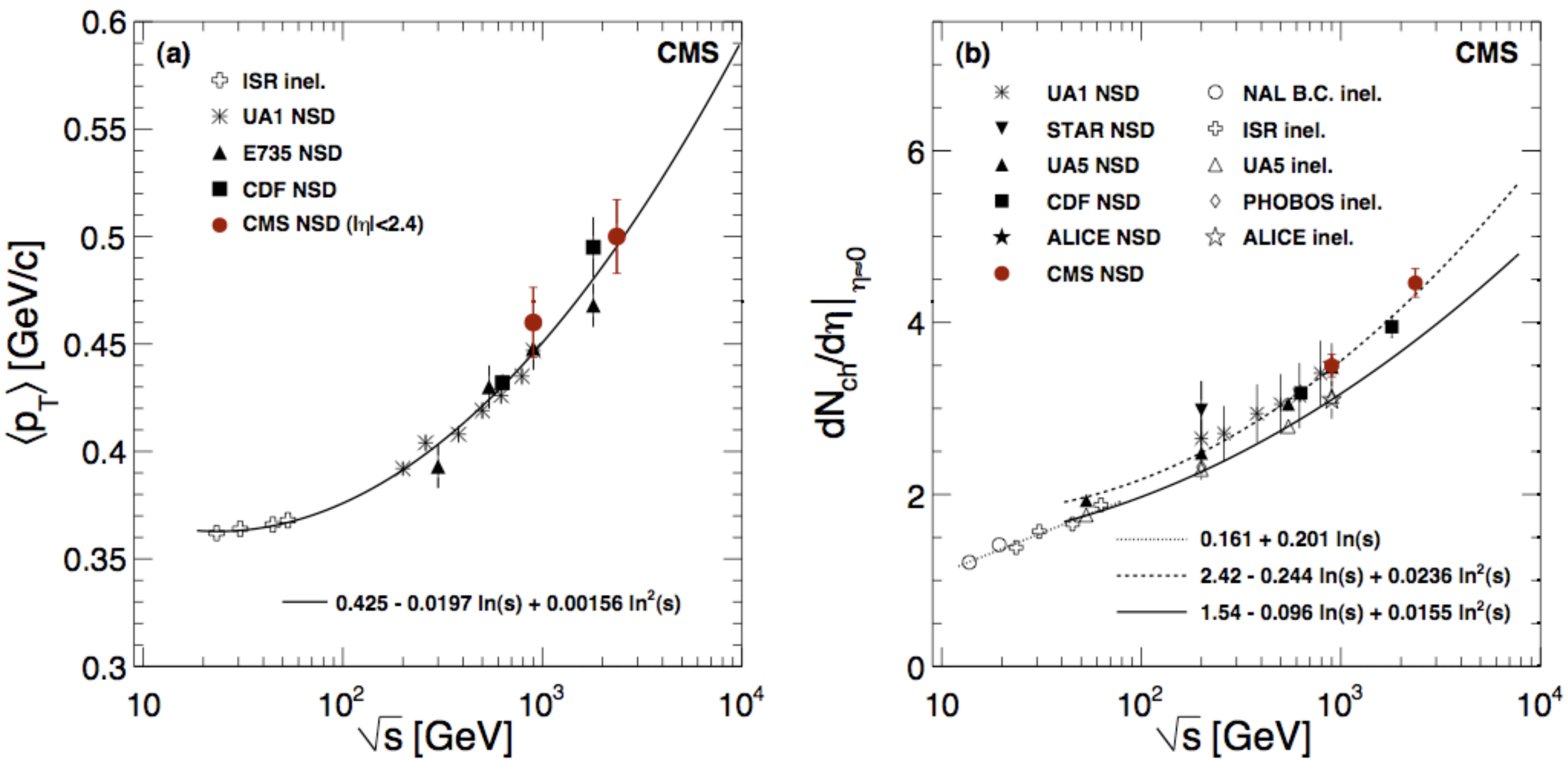




Fragmentation is ~ universal!

PARTICLE PRODUCTION

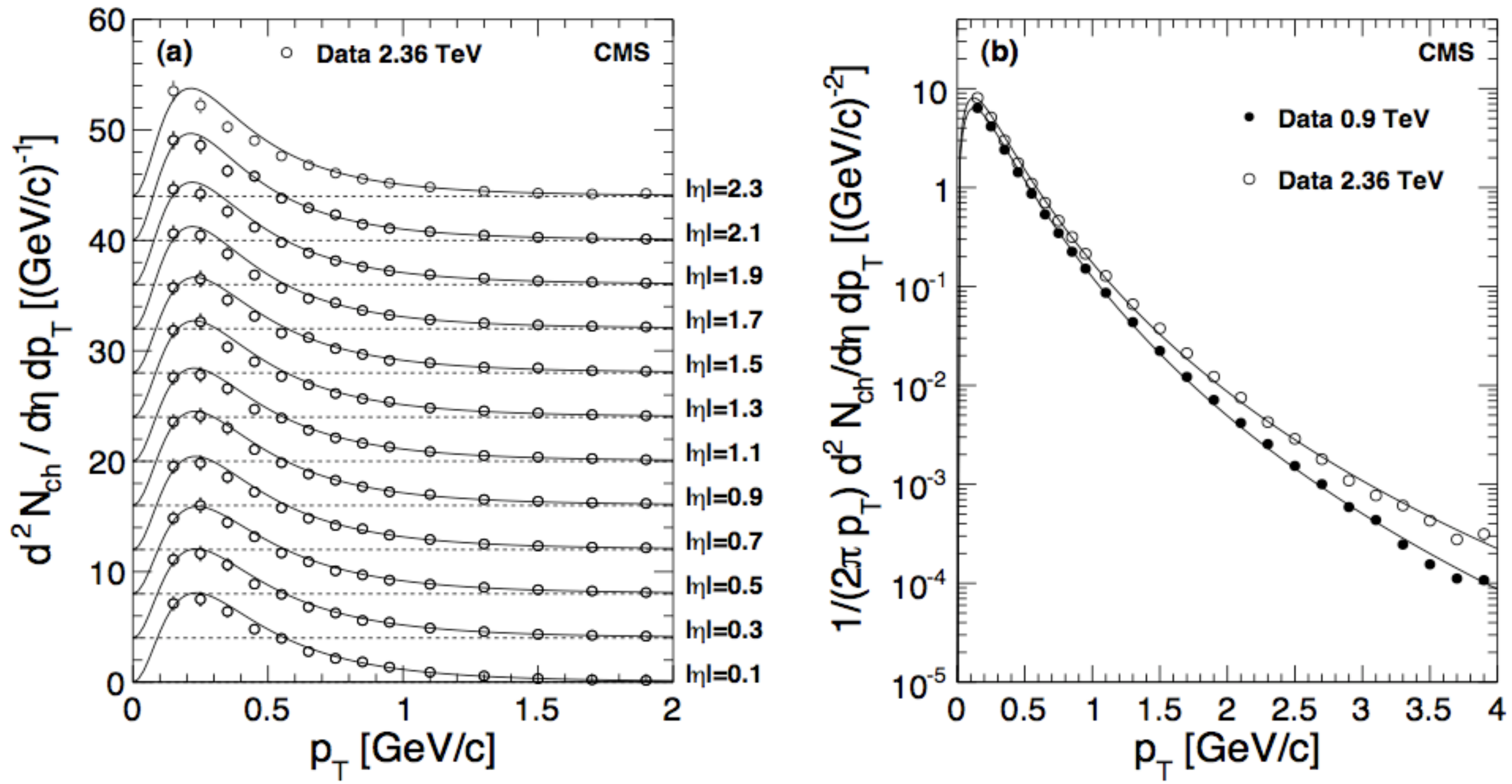
> … recent results from CMS, and some comparisons.



CMS result fits in nicely with skimple parametrisation of behaviour with CMS energy!

PARTICLE PRODUCTION

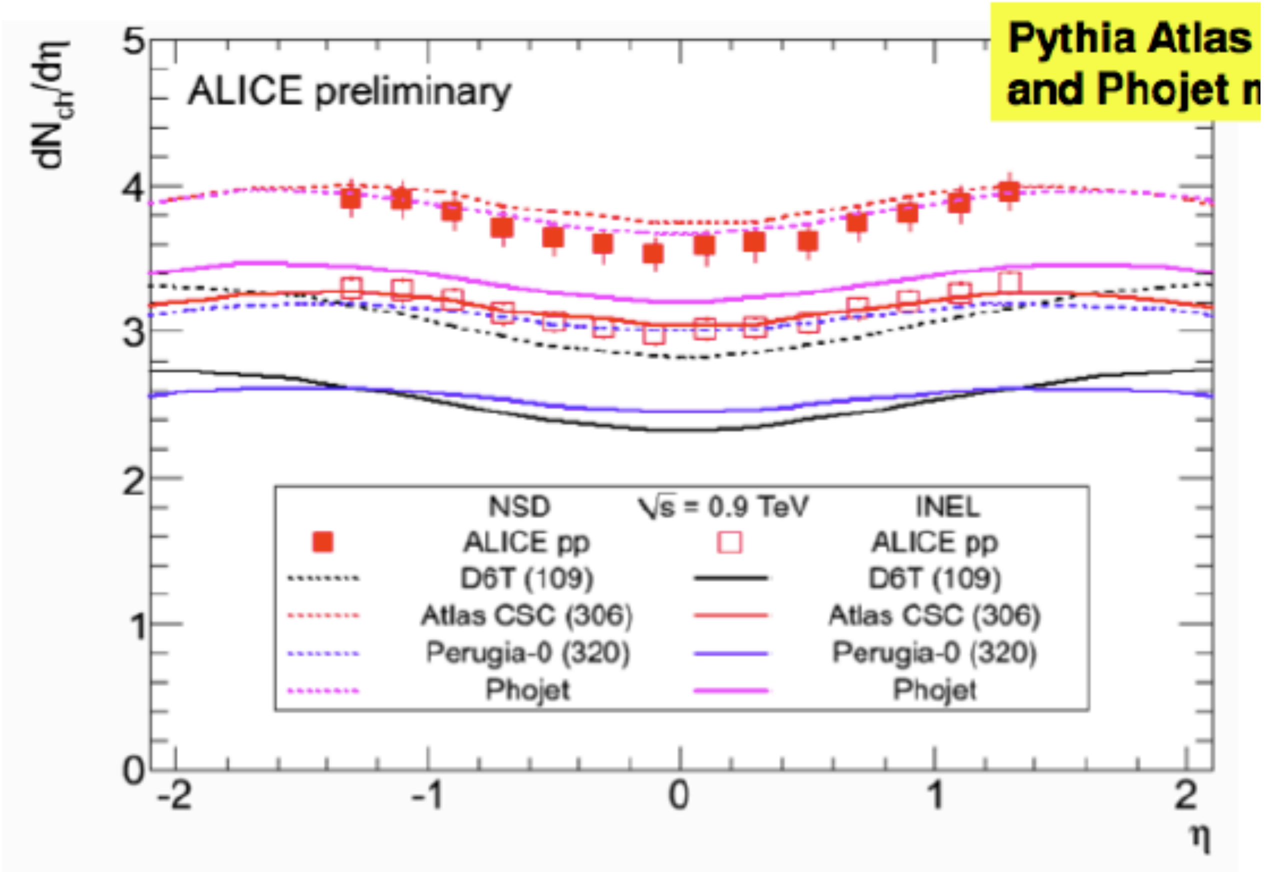
> … recent results from CMS, and some comparisons.



$$E\frac{d^3N_{\rm ch}}{dp^3} = \frac{1}{2\pi p_T}\frac{E}{p}\frac{d^2N_{\rm ch}}{d\eta dp_T} = C(n,T,m)\frac{dN_{\rm ch}}{dy}\left(1+\frac{E_T}{nT}\right)^{-n},$$

PARTICLE PRODUCTION

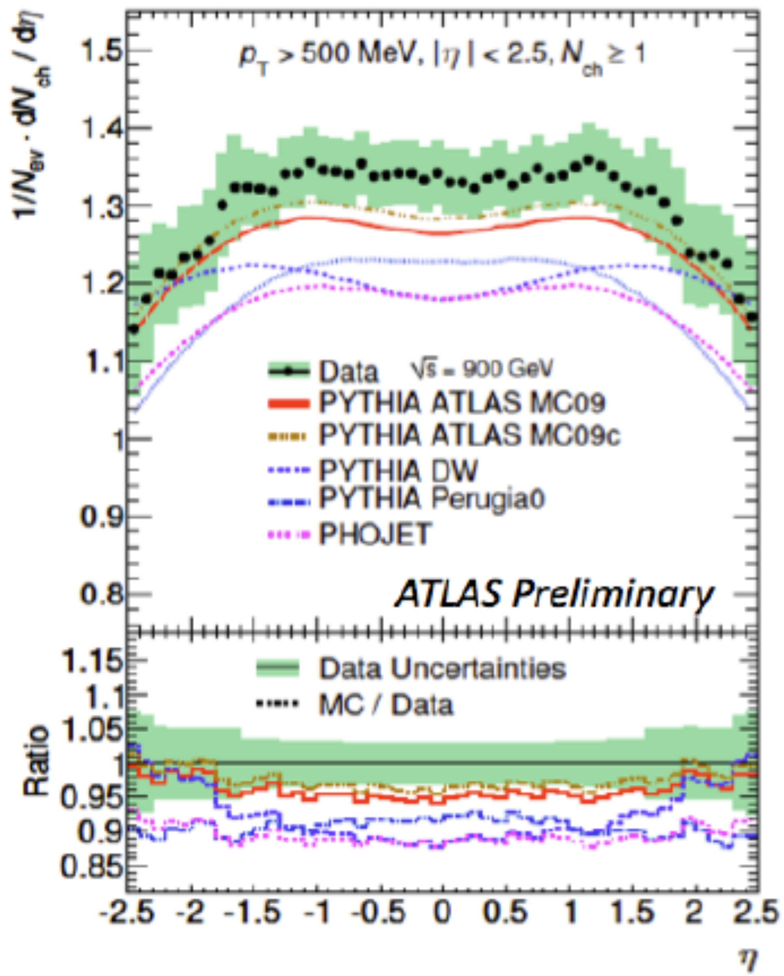
> … recent results from LHC, and some comparisons.



PARTICLE PRODUCTION

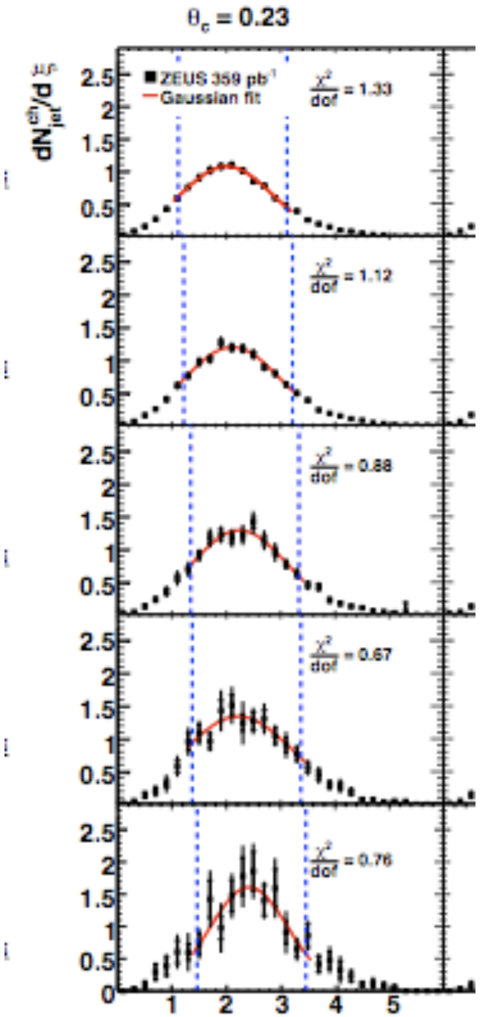
- … recent results from LHC, and some comparisons.

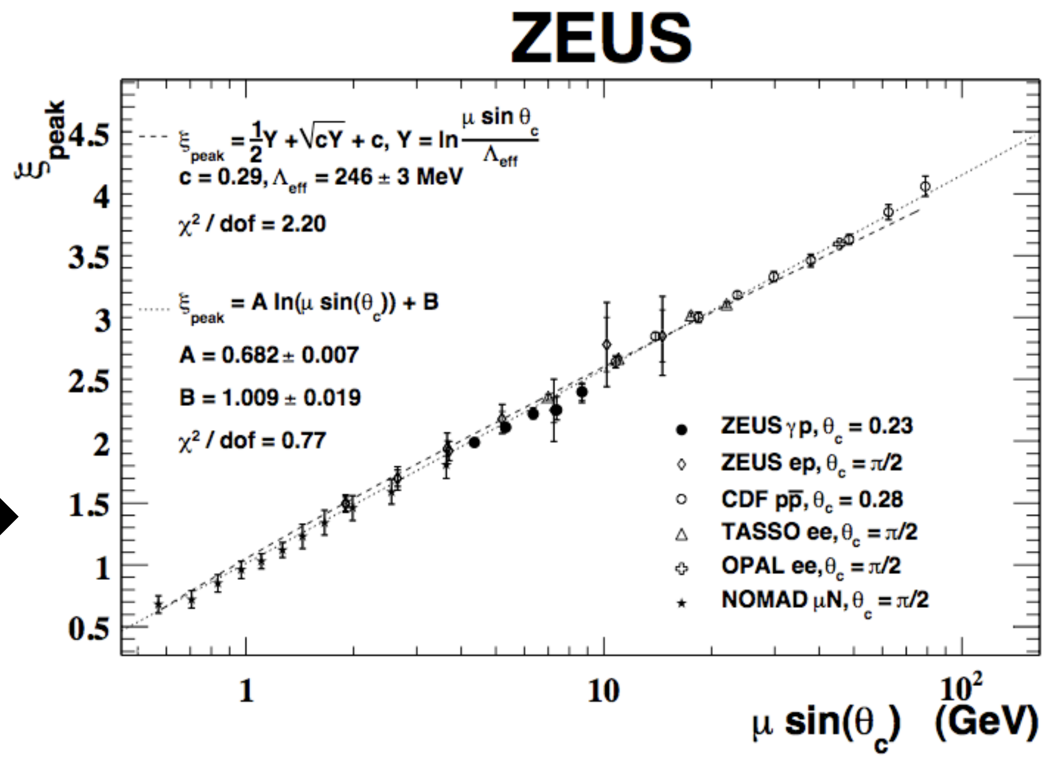
$dN_{ch}/d\eta$



PARTICLE PRODUCTION

> … Mean energy fraction of particles in jets as function of opening angle!





$$\bar{D}^{\mathrm{lim,pl}}_{\mathrm{g-jet}} = F_{\mathrm{nMLLA}}\frac{4n_c}{b}\Gamma(B)\int_{-\pi/2}^{\pi/2} e^{-B\alpha}\left[\frac{\cosh\alpha+(1-2\zeta)\sinh\alpha}{\frac{4n_c}{b}Y\frac{\alpha}{\sinh\alpha}}\right]^{B/2} \cdot I_B\left(\sqrt{\frac{16n_c}{b}Y\frac{\alpha}{\sinh\alpha}[\cosh\alpha+(1-2\zeta)\sinh\alpha]}\right)\frac{d\tau}{\pi},$$

Nice agreement between results from different machines !

JET PHYSICS

> … there's more to events in hadron-hadron collisions …

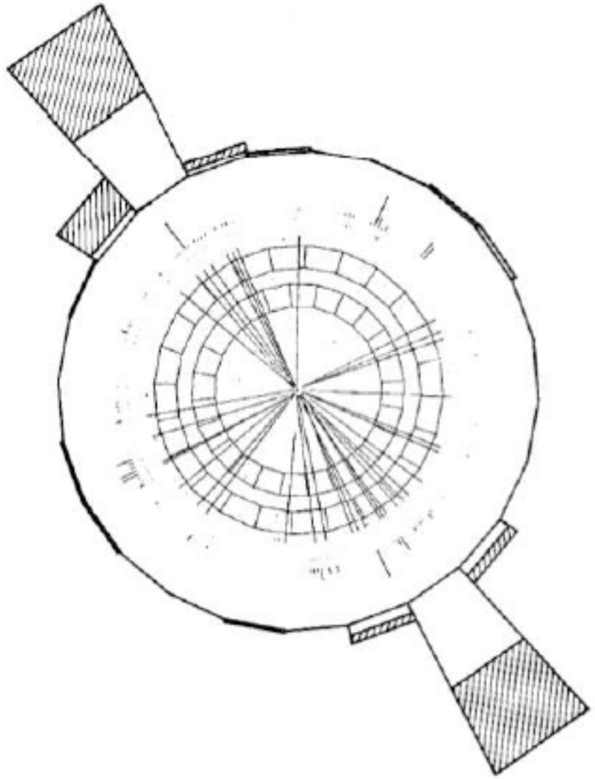
- … than "just" produced particles!

> Already mentioned: "Jets" structures underlying the distribution of the produced particles (example from UA2)

- Two back-to-back "jets" (word inherited from cosmic-ray experiments)???
- Polar-angular distribution of jets following

$$1+\alpha\cos^2\theta$$

→2→2 scattering with spin-1/2 particles?



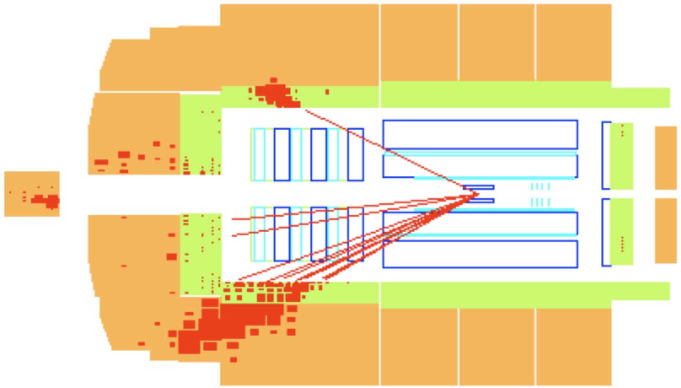
> In parallel: jet structures in e+e- collisions at different experiments; identification as

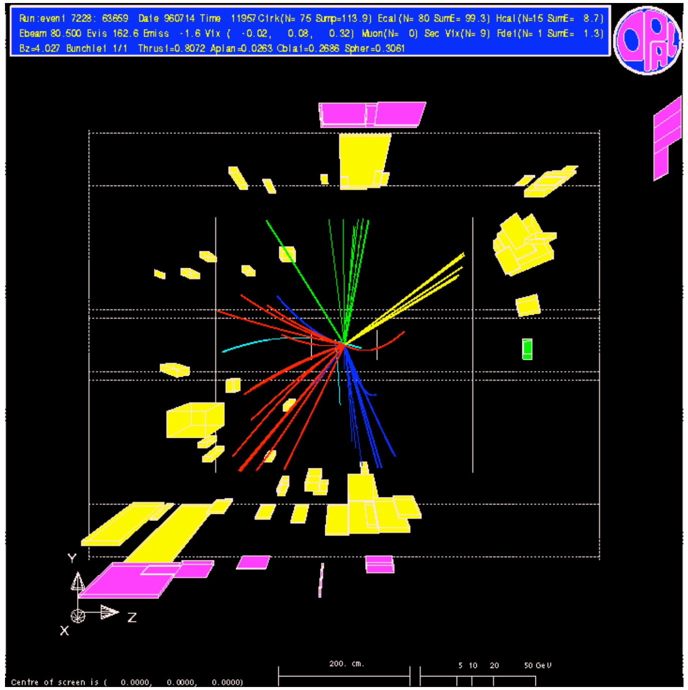
$$e^+e^- \to q\bar{q}$$

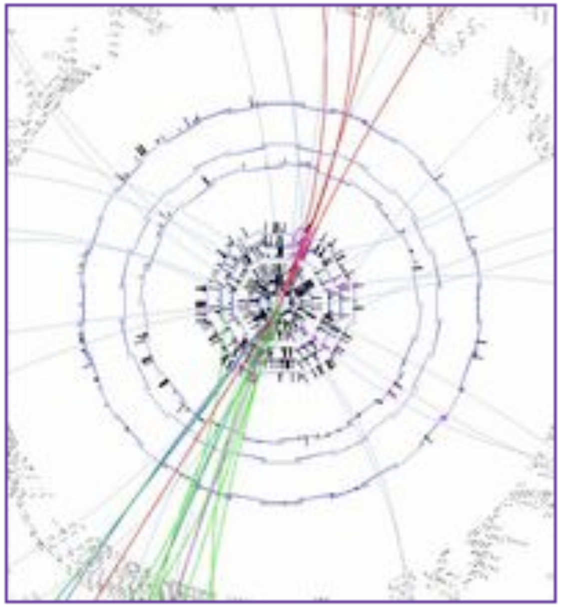
> Historically not a trivial story to identify the partons in the proton with the results of ee!

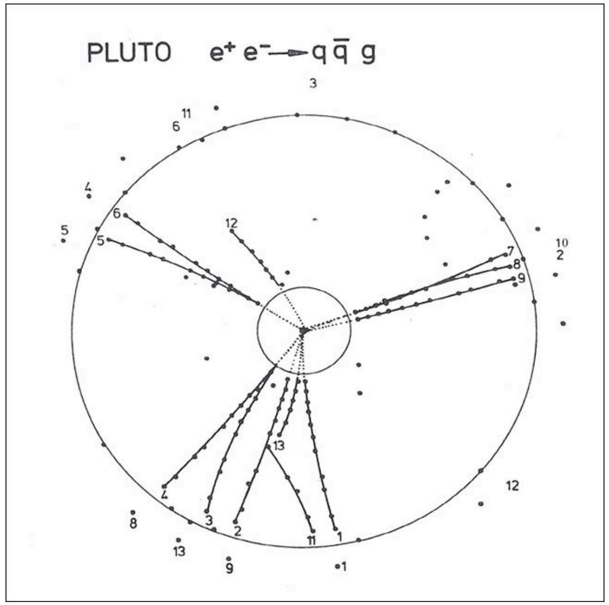
JET PHYSICS

> … at different experiments:



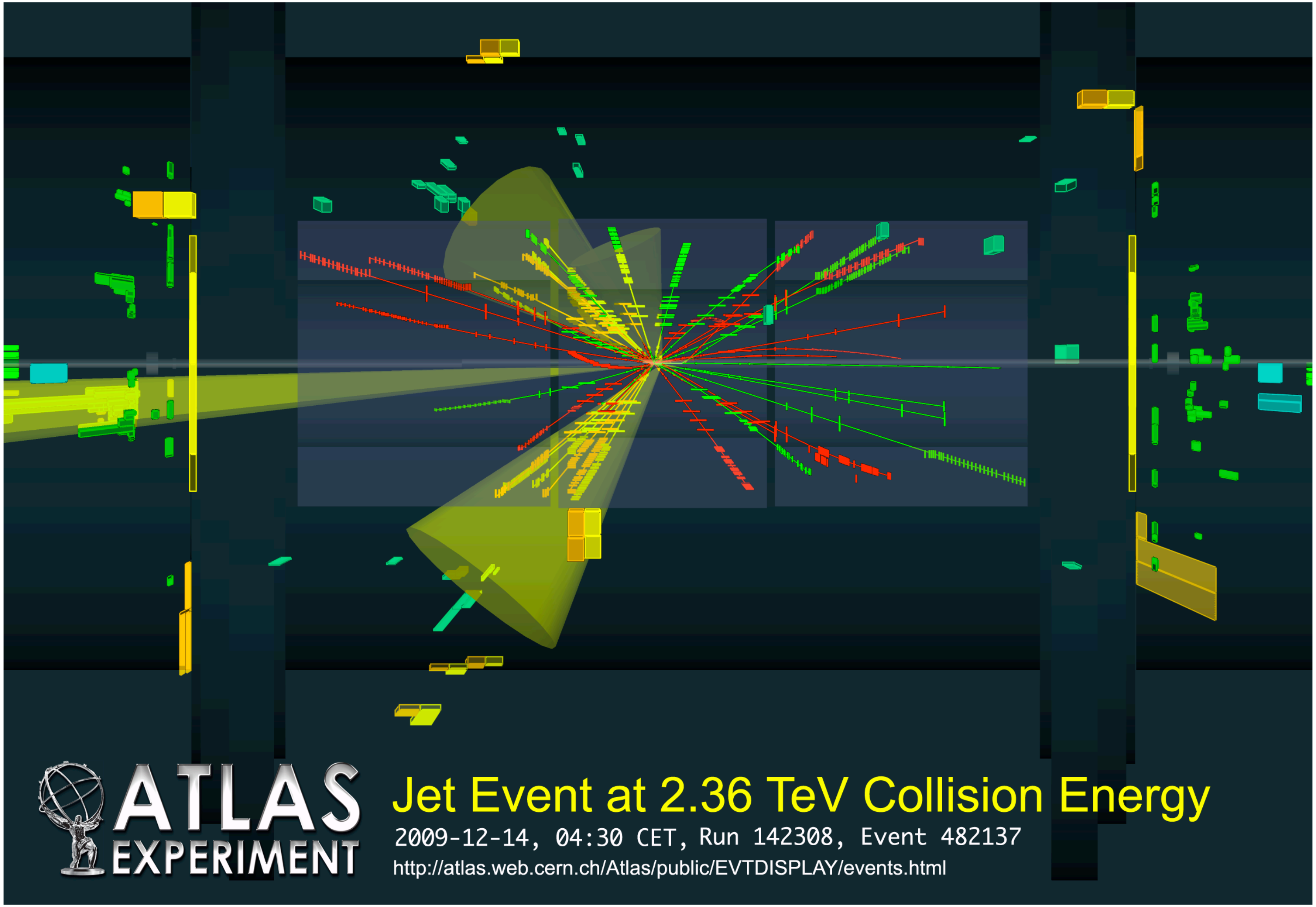






JET PHYSICS

> … at different experiments:



JET PHYSICS: BASICS

> Jets: two-fold purpose in high-energy physics

- Tool for studying (hard QCD) interactions
- Object of study in itself: Fragmentation etc.

> Jets – although clearly visible to the naked, untrained eye – are neither a simple nor a well-defined concept!

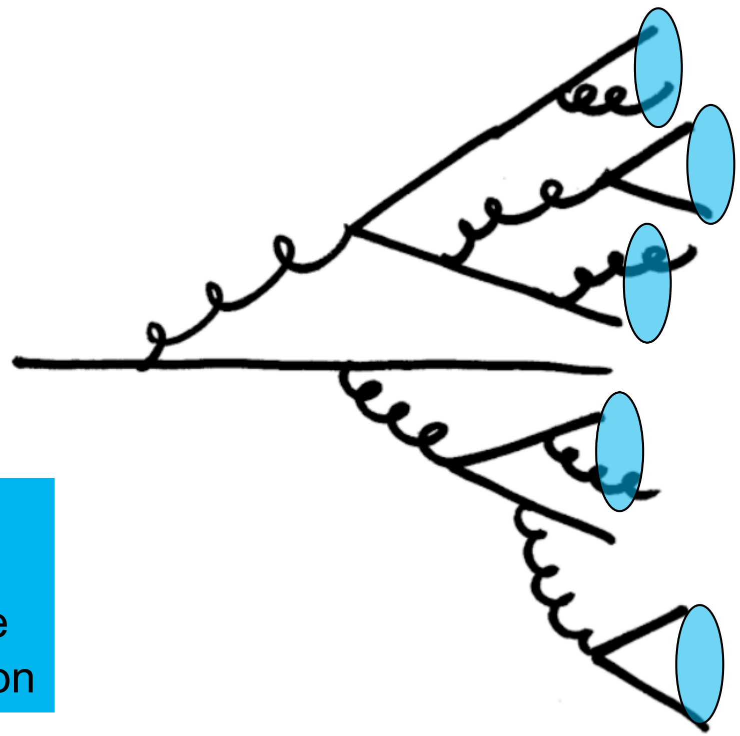
- A jet algorithm is a mathematical prescription for clustering the objects of the final state (if possible both in the experiment and for theoretical predictions and models).
- Different classes of algorithms, different fields of applications (hadron colliders, lepton colliders, HERA, …), different physics questions → jet physics is a science in itself!
- Jet algorithms shall fulfill a number of requirements (without completeness): theoretically safe, easy to handle, small hadronisation corrections, unbiased, …

> Currently two classes of algorithms used: cluster algorithms and cone-based algorithms

- Historically, the Tevatron experiments tended to cone-based algorithms, e+e- and HERA to clustering algorithms;
- At LHC, both collaborations study a multitude of different algorithms.

JET PHYSICS: ALGORITHMS

- Cone algorithms: Aim at minimising the relative transverse momentum in cones of fixed sizes (directions of largest energy flow in the event).
- Clustering algorithms: “Resumming” the parton showering / fragmentation process, using some distance criteron:



All particles clustered to a number of jets !!!

Possible criteria:
- invariant mass
- distance in angle
- some combination

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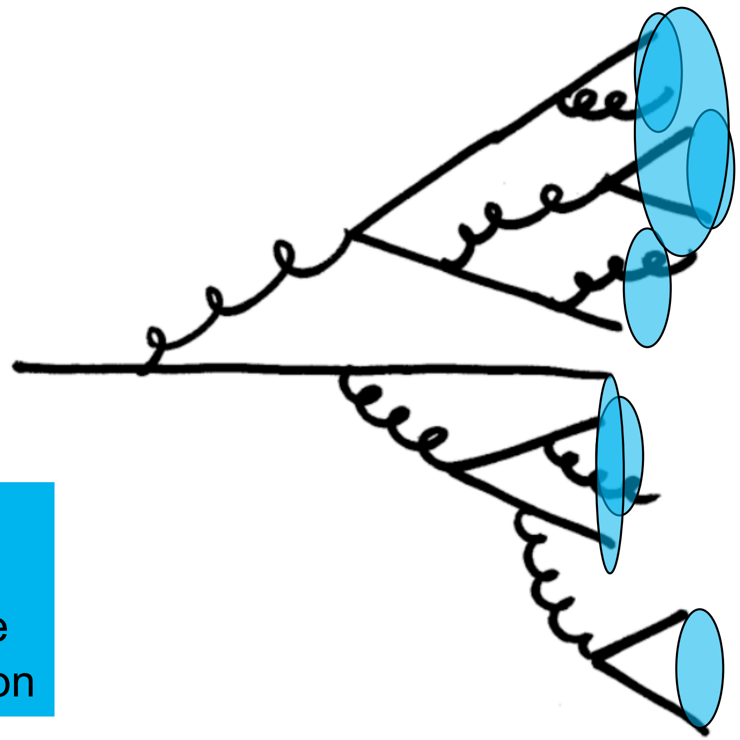

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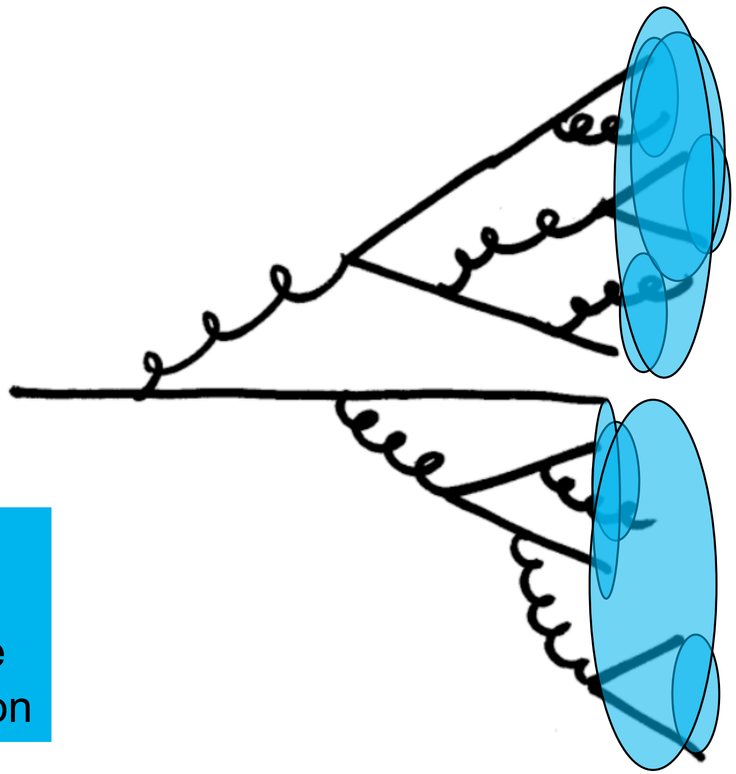

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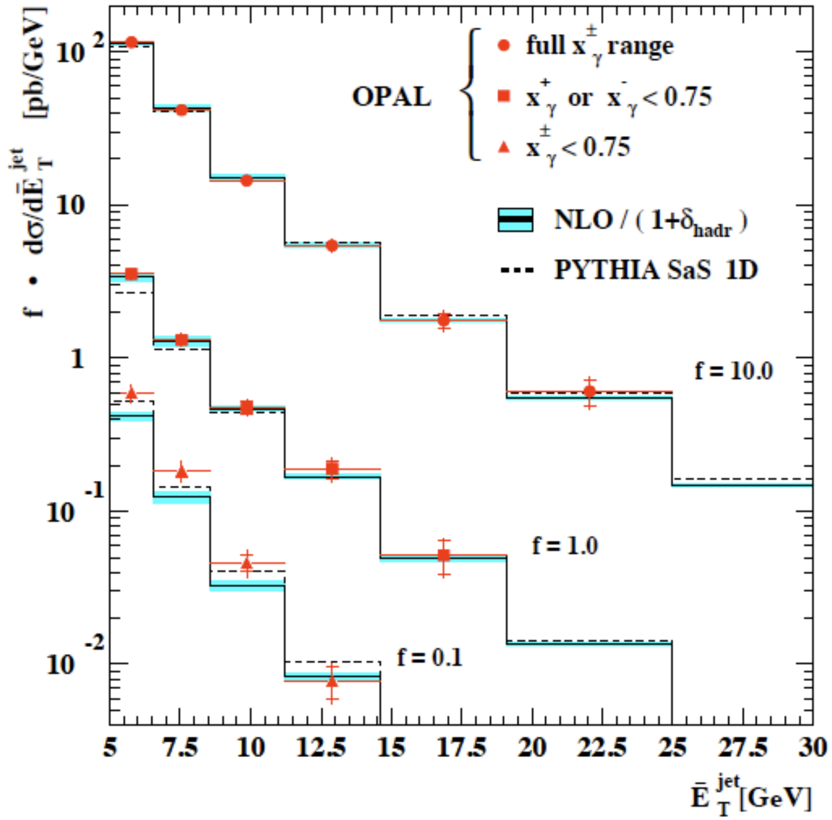
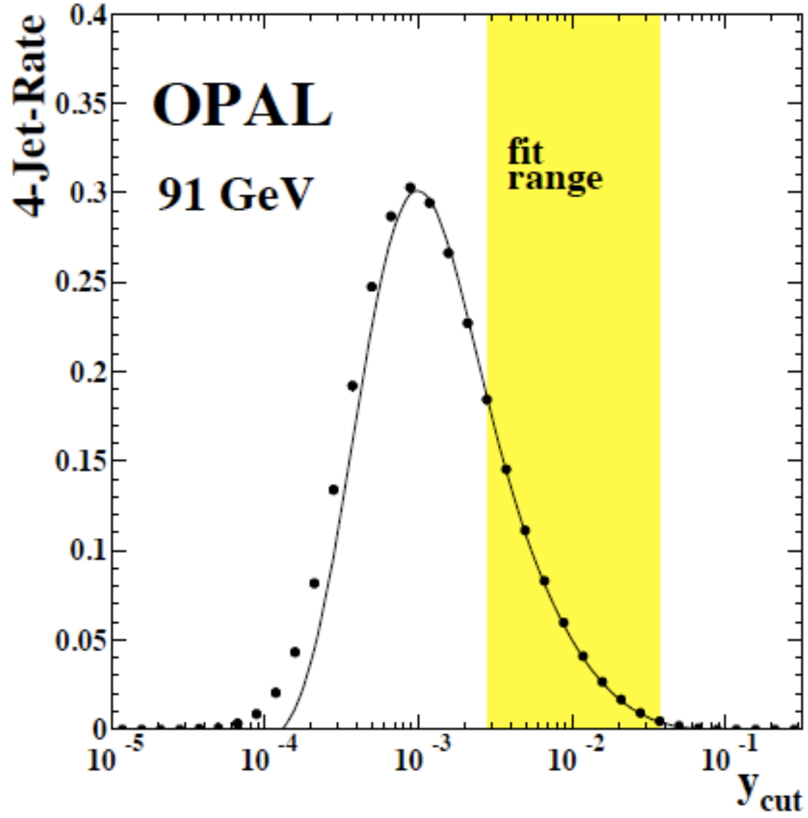
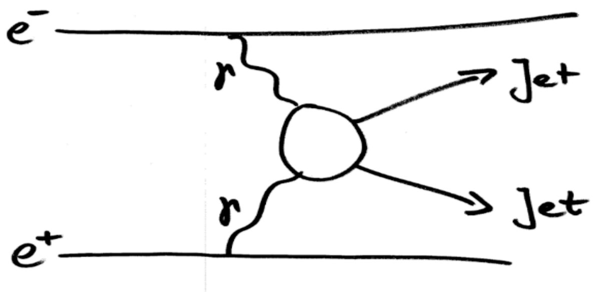
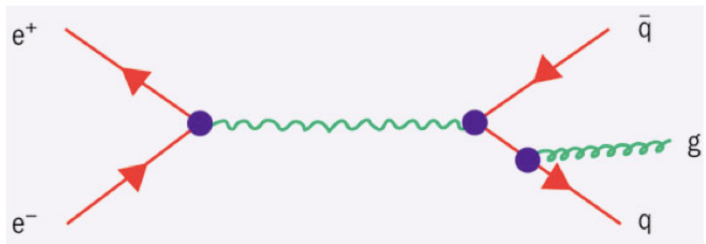
JET PHYSICS: RESULTS FROM LEP

- In ee→qq(q,q) or in γγ collisions:



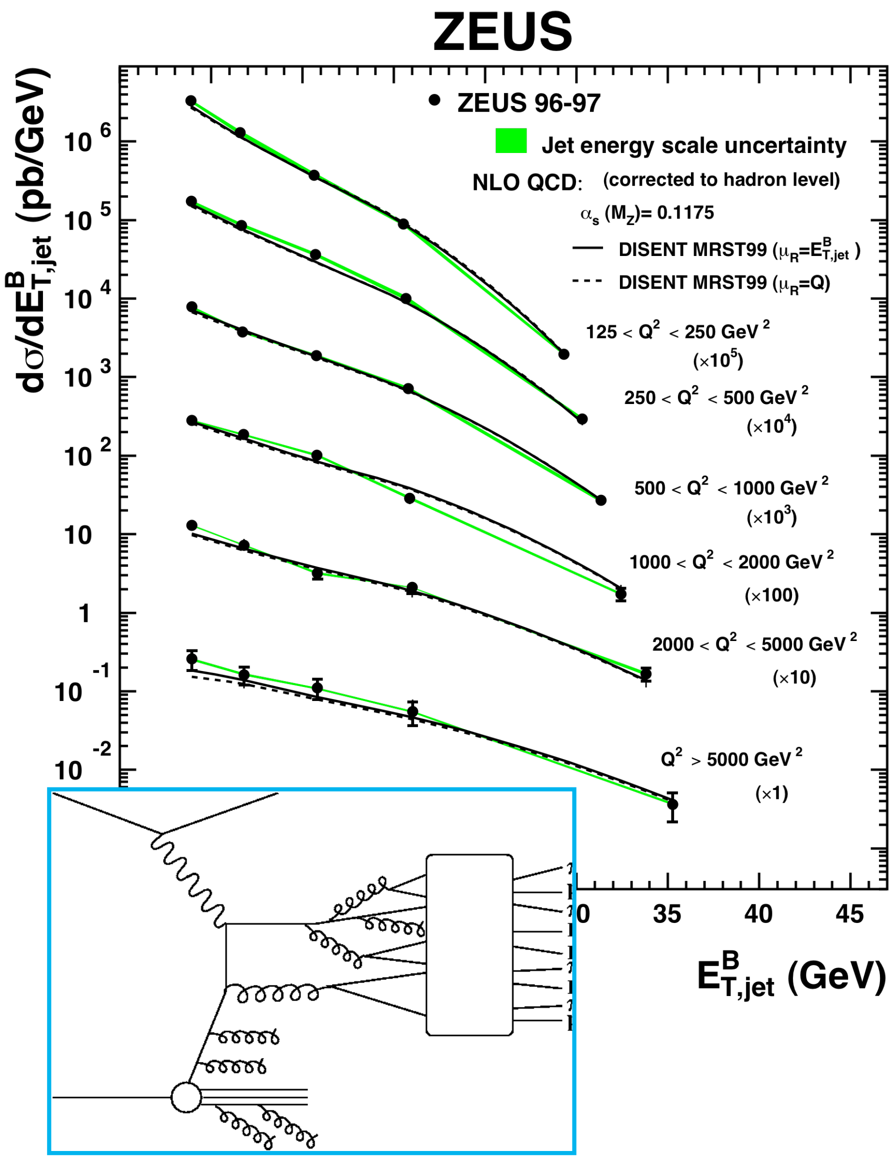


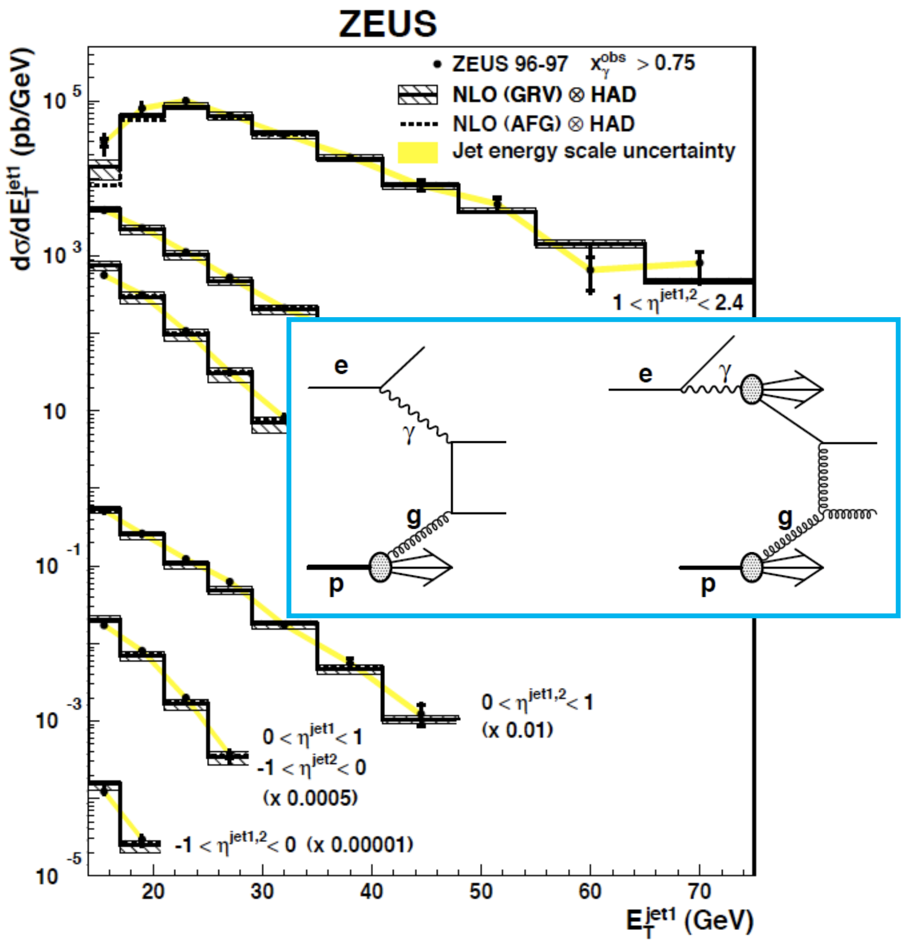




JET PHYSICS: RESULTS FROM HERA (1)

- In photoproduction, in deep-inelastic scattering, in diffraction

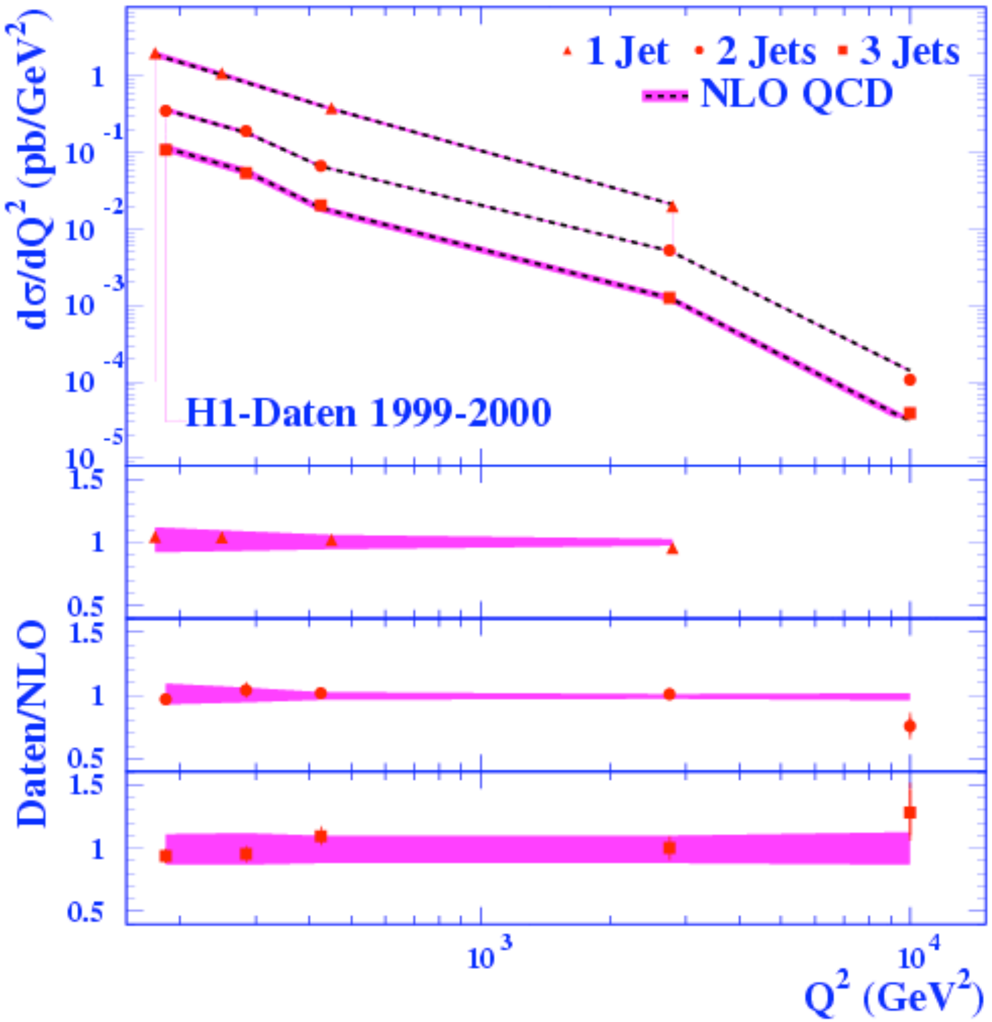




QCD at NLO works beautifully in most phase-space regions !!!

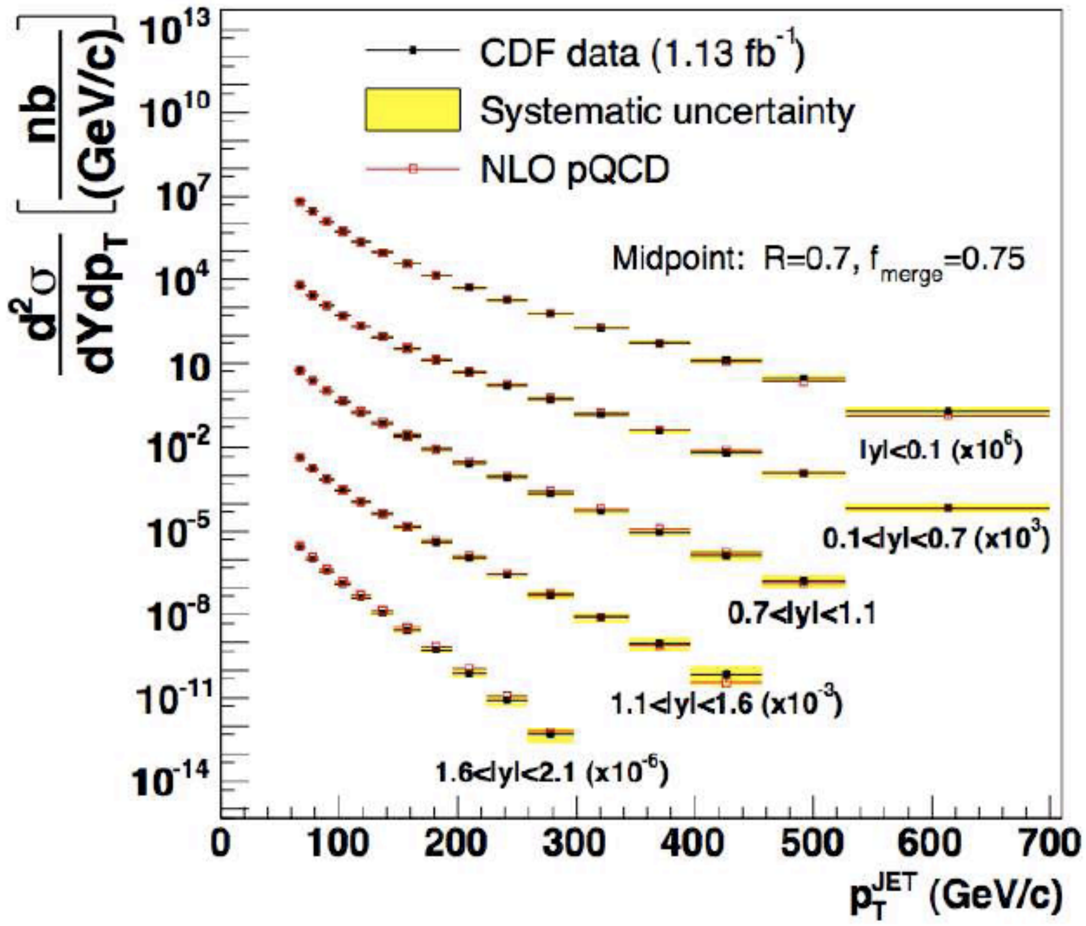
JET PHYSICS: RESULTS FROM HERA (2)

> Comparison of 1,2,3 jet production!



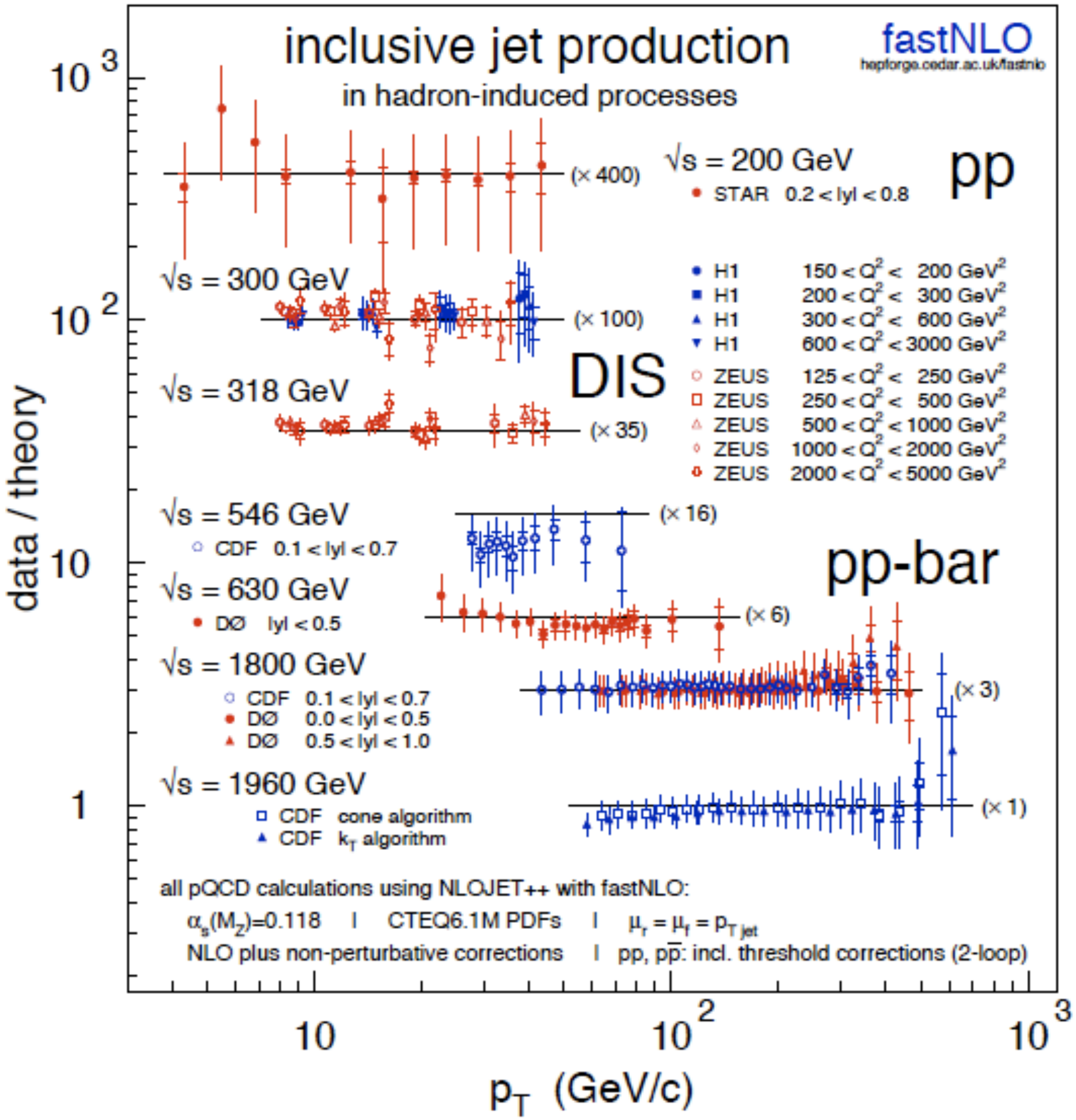
JET PHYSICS: RESULTS FROM TEVATRON

> Measuring jets up to energies of 600 GeV!!!!



> Nice description by NLO QCD calculations! In contrast to HERA, often experimentally limited.

JET PHYSICS: RESULTS OVERVIEW

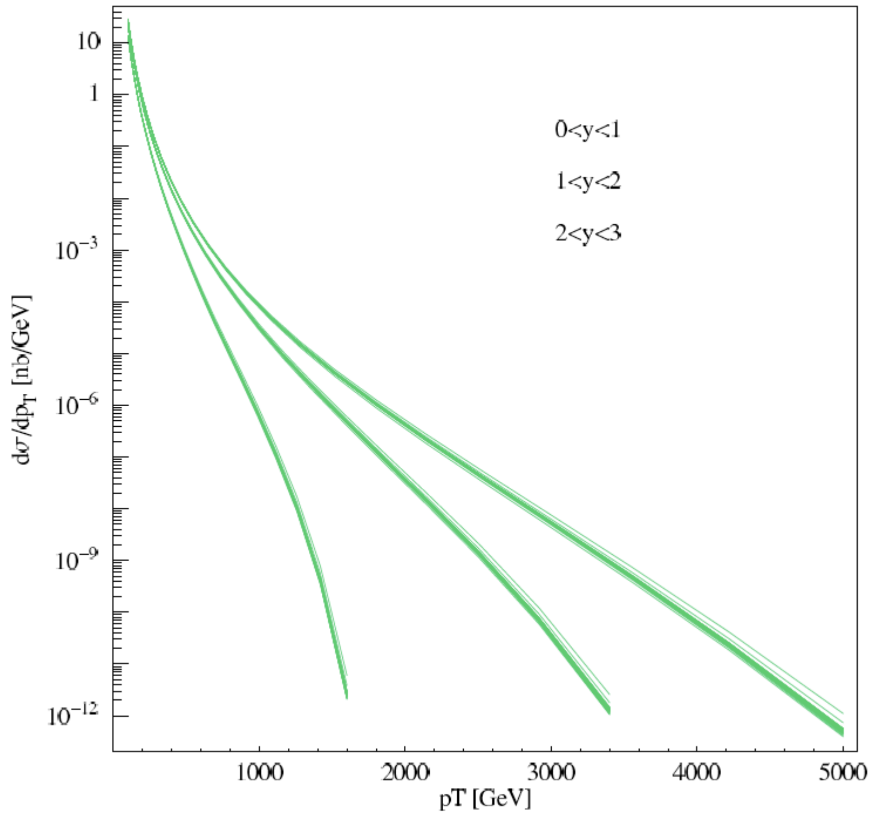


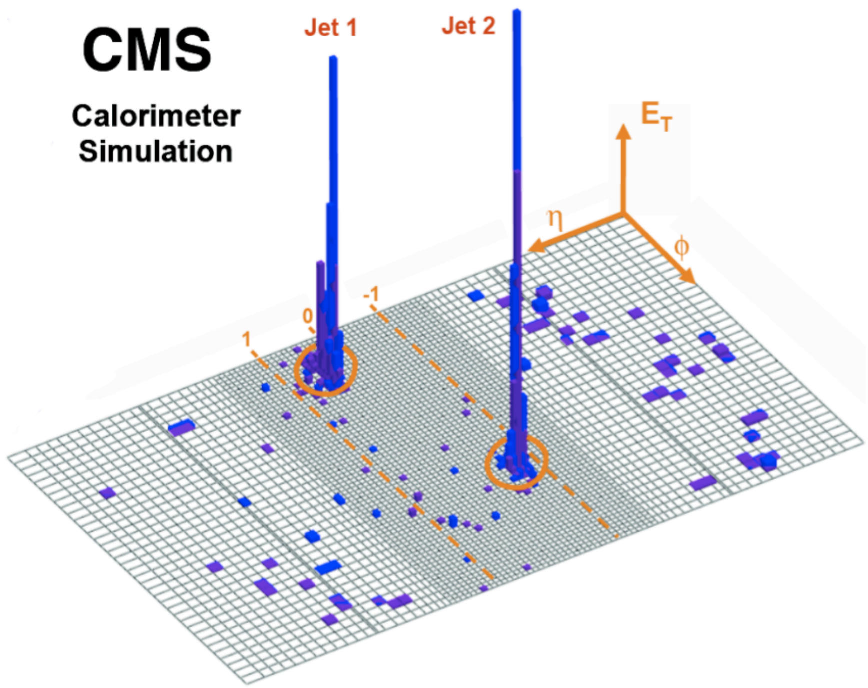
- Jet physics is a well-established and well-understood field.
- Excellent basis for QCD studies at the LHC.
  - Some difficult phase space regions.
- Note that jets are of more importance than “only” for QCD studies.

JET PHYSICS: LHC

> Will have jets up to several TeV!

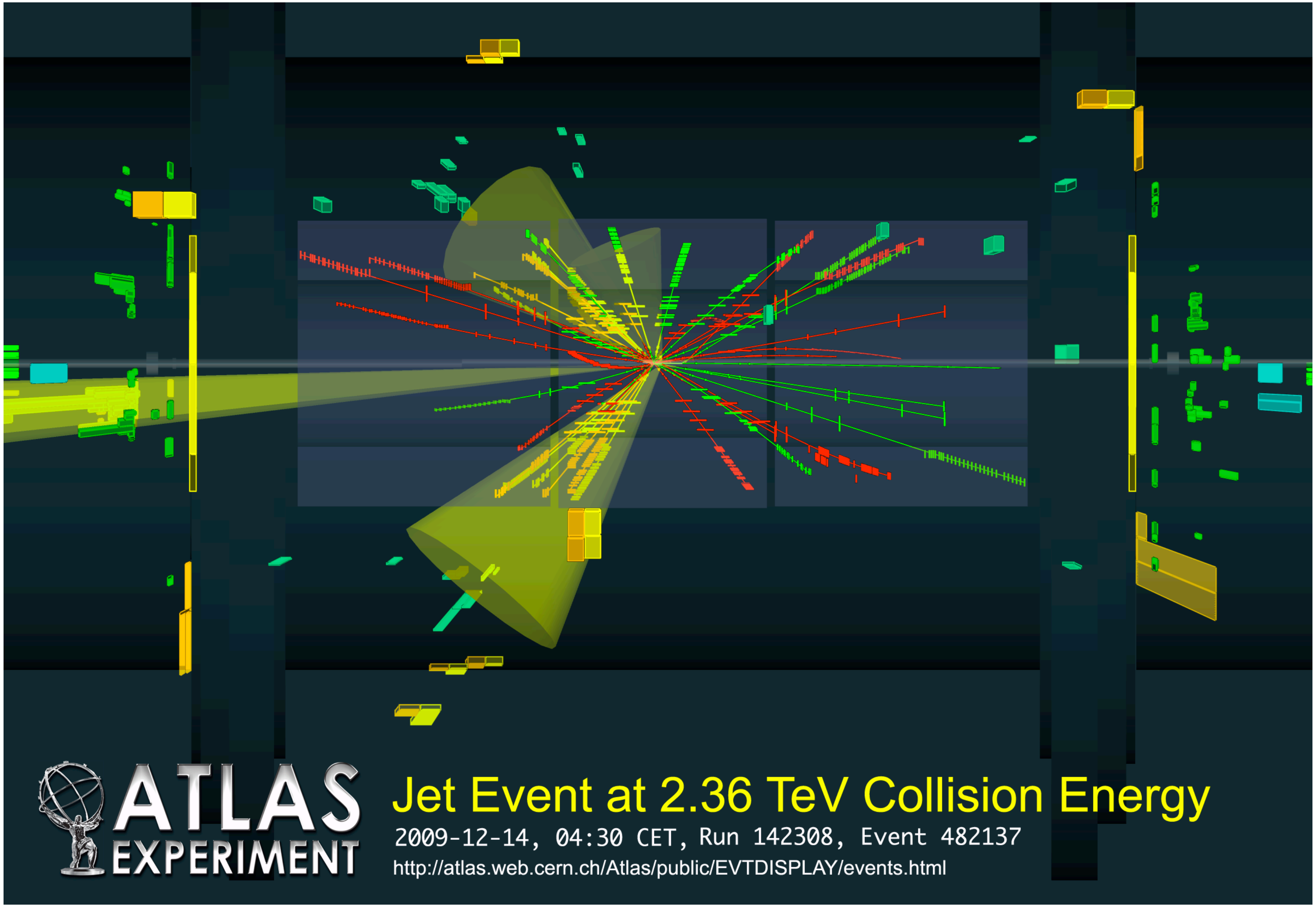
- Factor 10 higher energies than at the Tevatron!
- Massive reach for QCD studies and …





JET PHYSICS

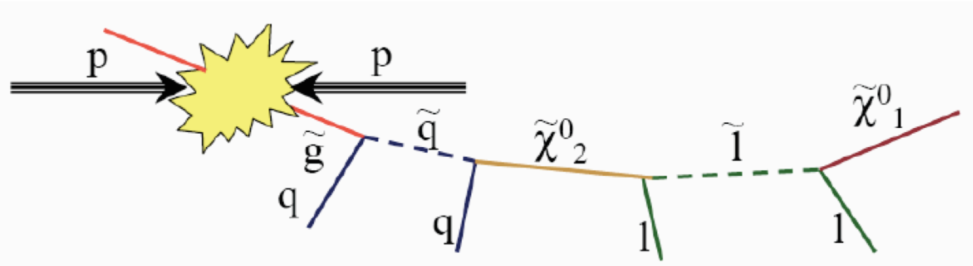
> … at different experiments:

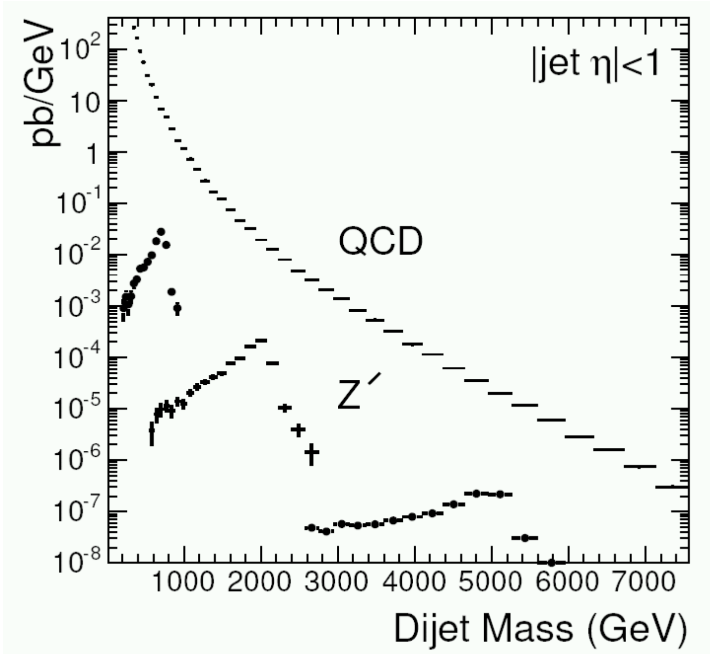


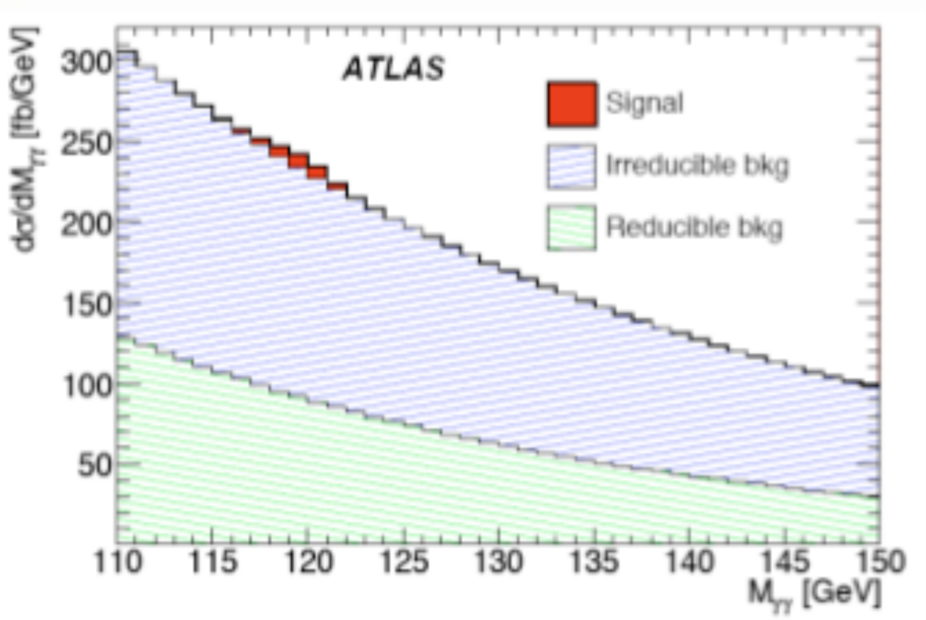
JET PHYSICS: LHC

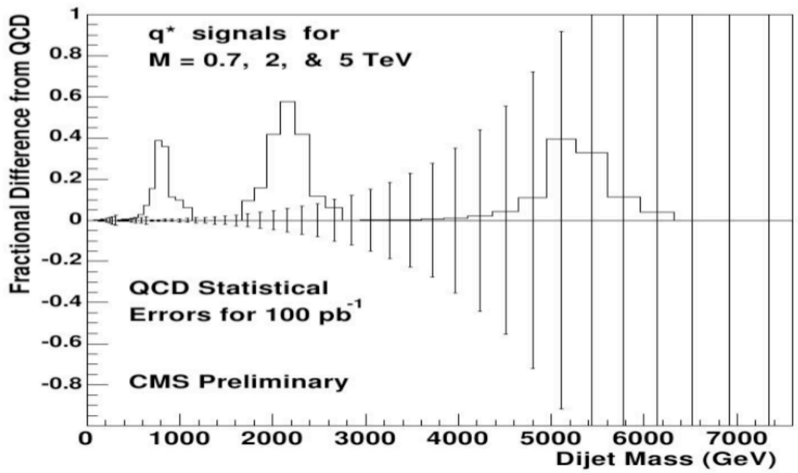
> Jets play crucial role in many new physics scenarios

- Often QCD rates for similar signatures higher!
- Need to understand QCD!!!





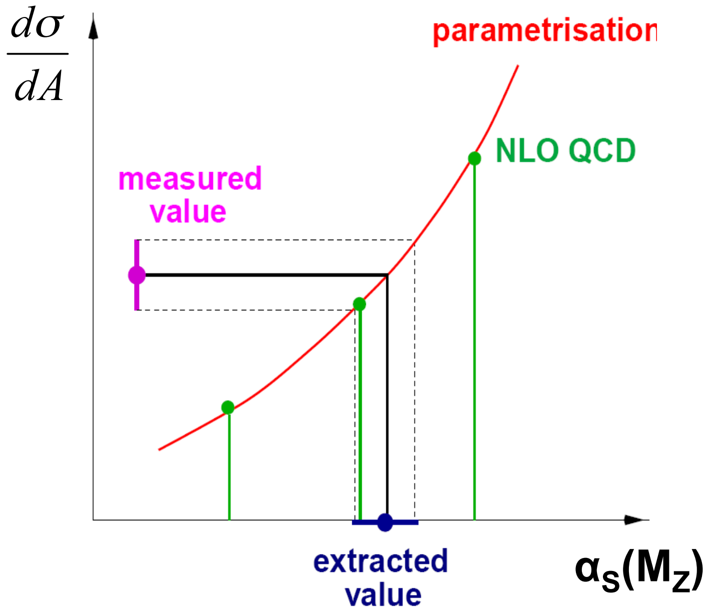


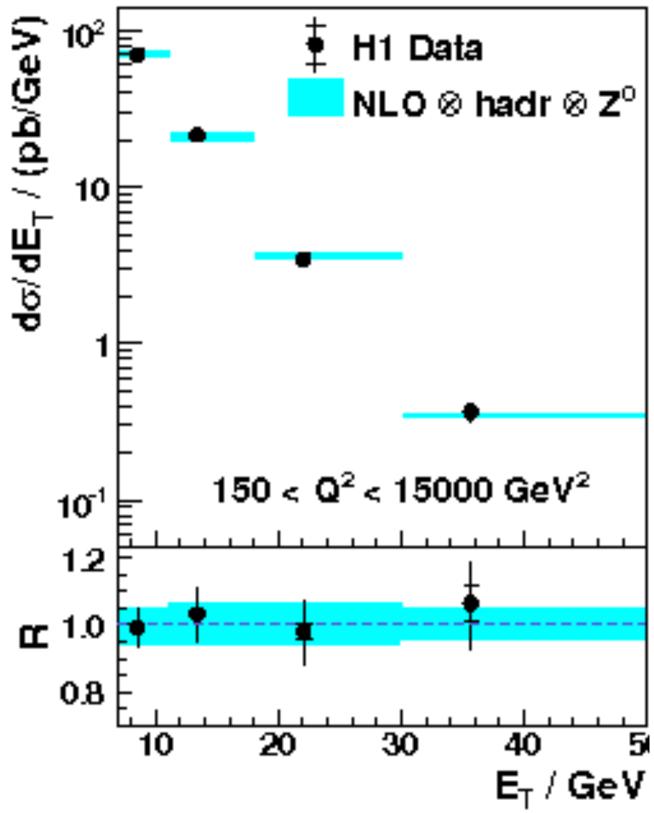


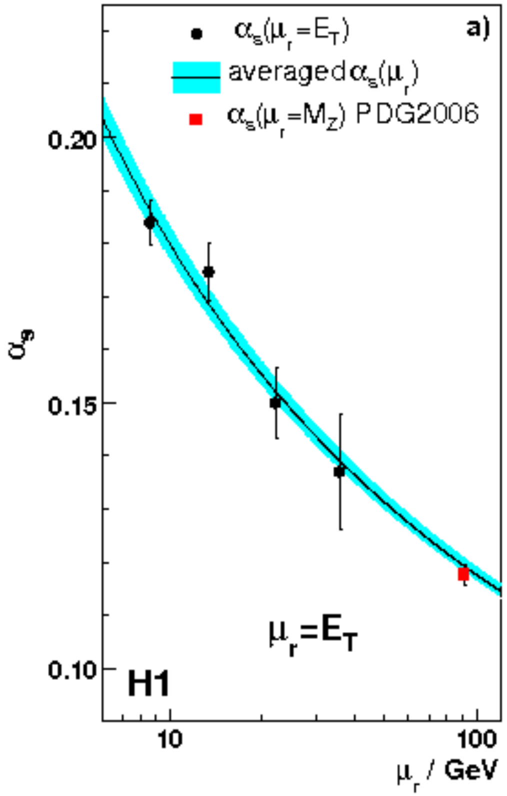
JETS AND THE STRONG COUPLING

> One example: HERA jet data ….

$$\left.\frac{d\sigma(\alpha_S(M_Z))}{dA}\right|_{NLO} = C_1\alpha_S(M_Z) + C_2\alpha_S^2(M_Z)$$

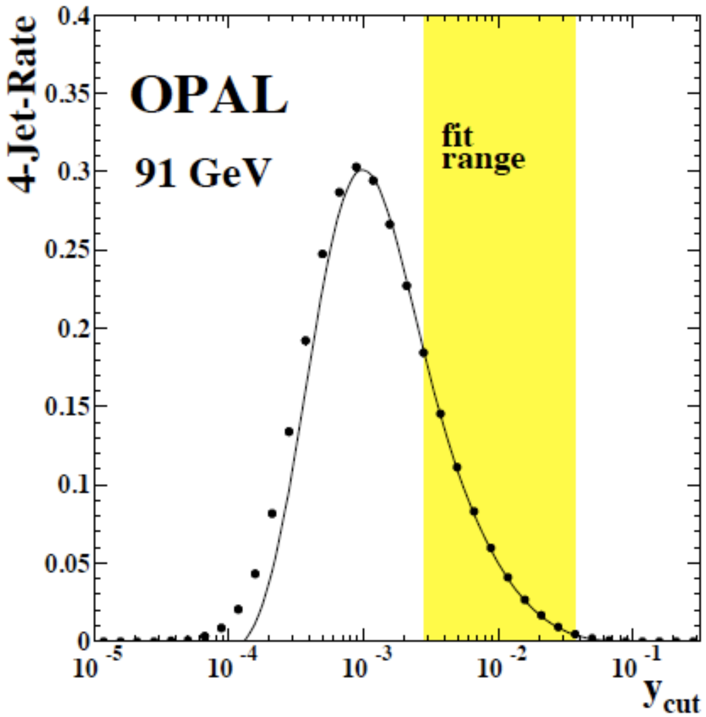




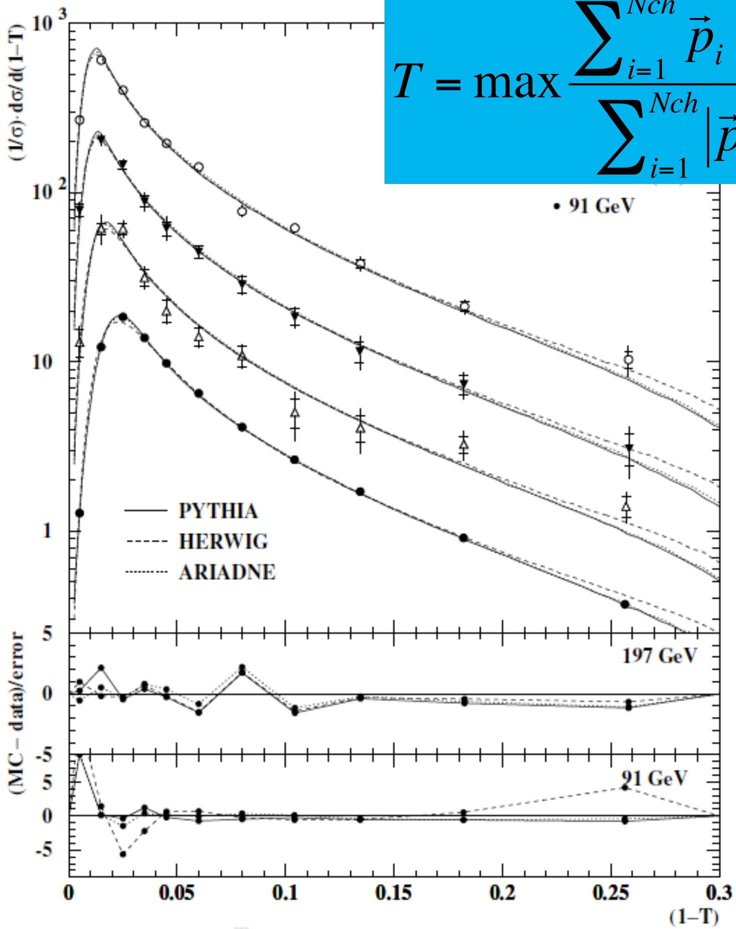


THE STRONG COUPLING: e+e- EXAMPLES

> Thrust, and the four-jet rate



$$T = \max \frac{\sum_{i=1}^{Nch} \vec{p}_i \cdot \vec{n}}{\sum_{i=1}^{Nch} |\vec{p}_i|}$$

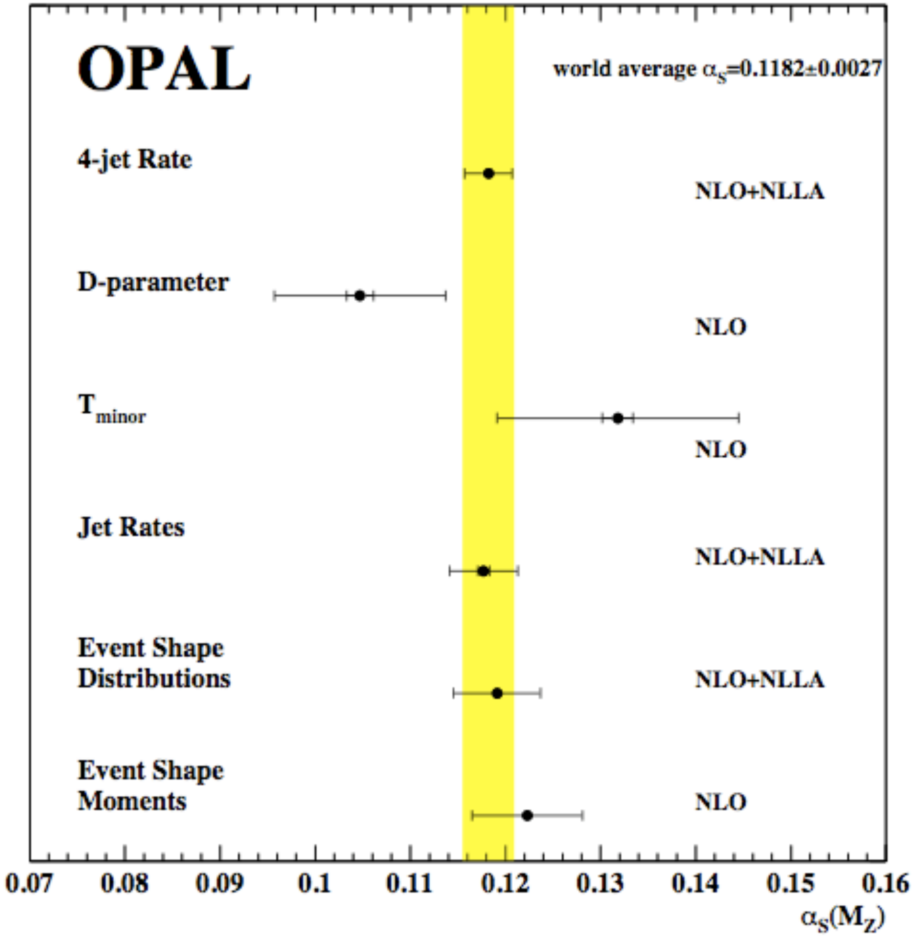


$$\ln R_{\mathcal{O}(\alpha_s^2)}(y) = \mathcal{A}(y)\overline{\alpha}_s + \left[\mathcal{B}(y) - \frac{1}{2}\mathcal{A}(y)^2\right]\overline{\alpha}_s^2 + \mathcal{O}(\alpha_s^3)$$

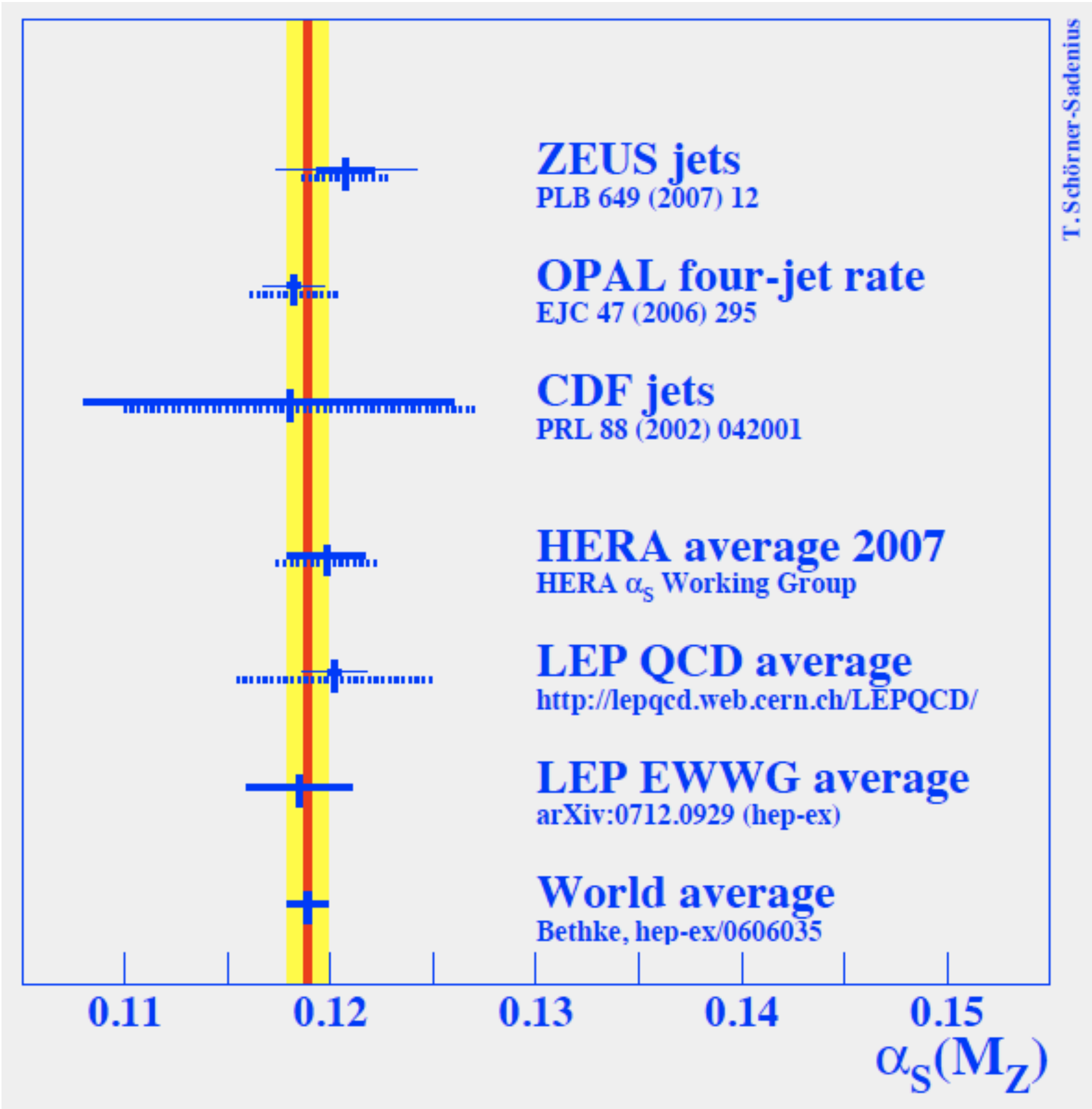
$$\ln R_{\mathrm{NLLA}}(y) = Lg_1(\alpha_s L) + g_2(\alpha_s L) + C_1\overline{\alpha}_s + [C_2 - \frac{1}{2}C_1^2]\overline{\alpha}_s^2 + \mathcal{O}(\alpha_s^3)$$

THE STRONG COUPLING: e+e- EXAMPLES

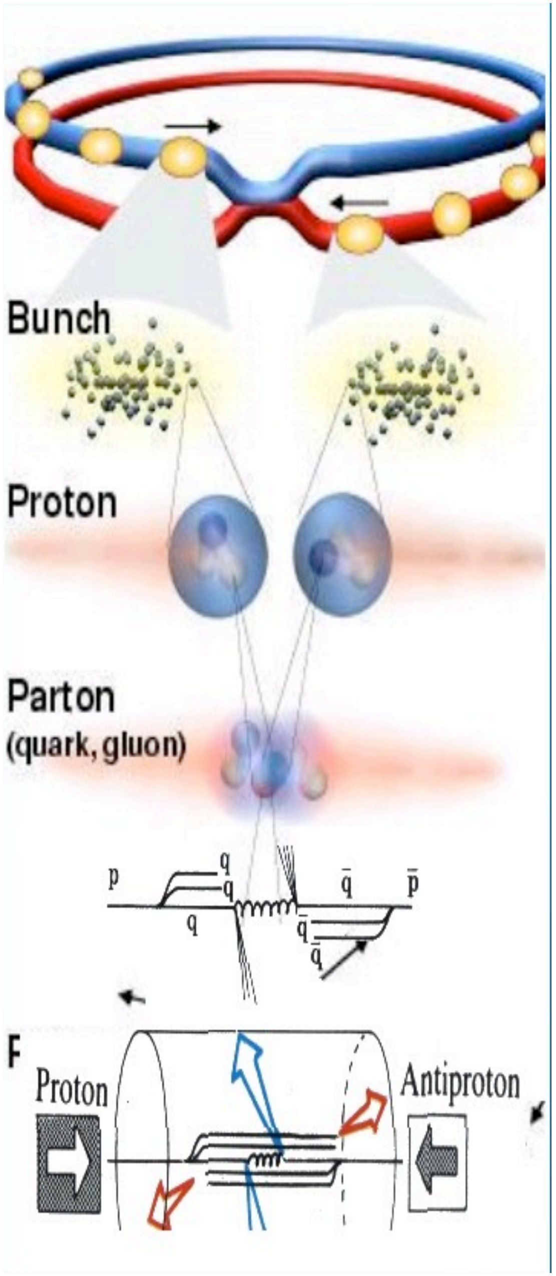
> Extracted values of the strong coupling:



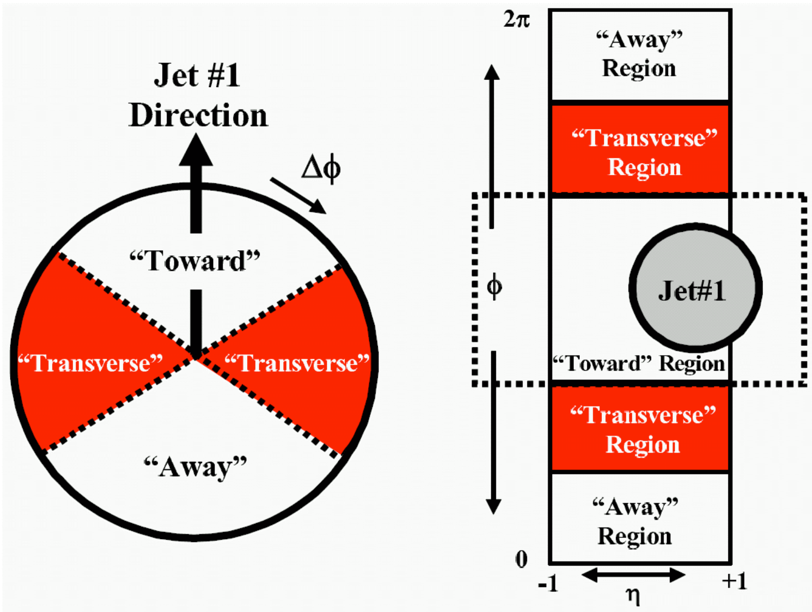
THE STRONG COUPLING: SUMMARY



FEW SLIDES: THE UNDERLYING EVENT

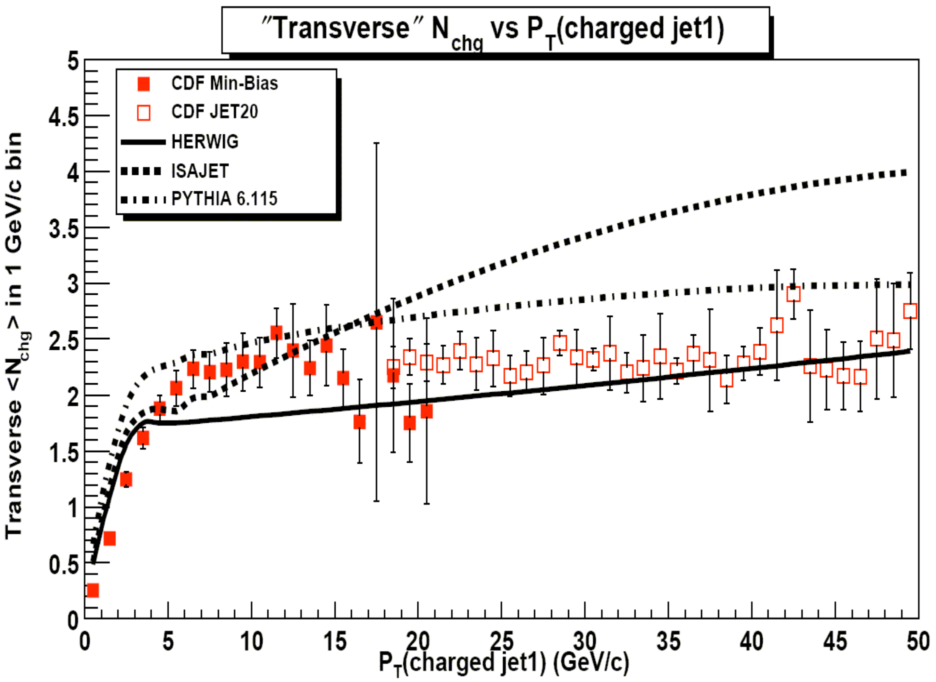


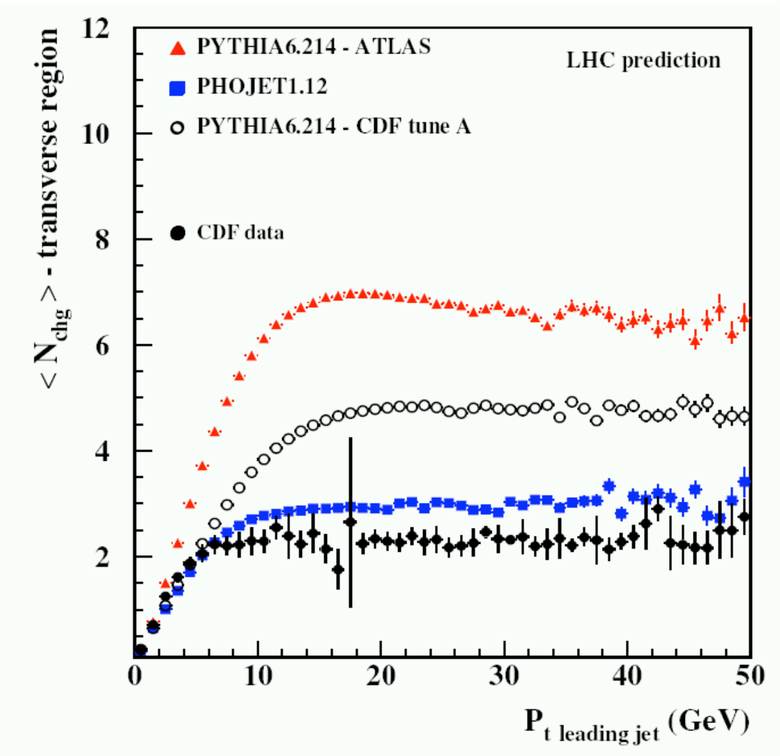
- Possibility of multi-parton interactions (and also pile-up)
  - Potentially large impact on analyses!
  - Study using for example energy flow in different regions.



FEW SLIDES: THE UNDERLYING EVENT

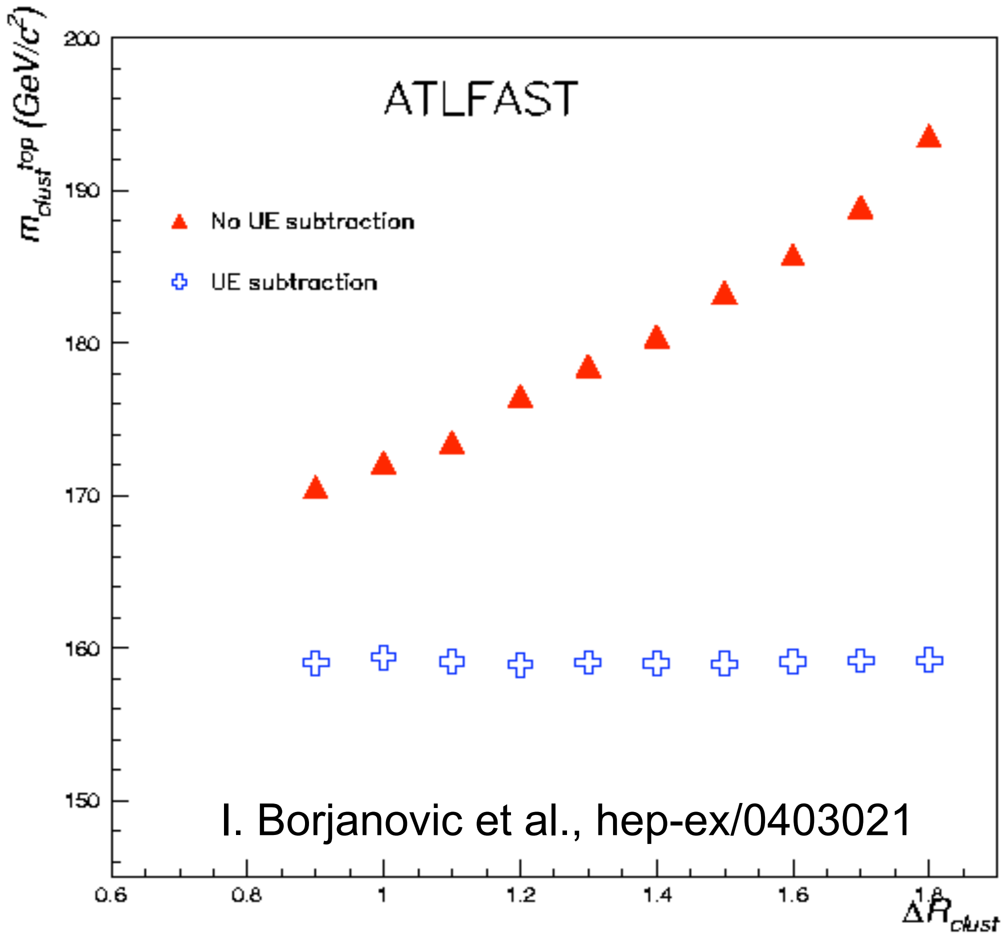
- Studies at the Tevatron (and also at HERA)!
  - Models can describe data …
  - … but fail in interpolation to LHC energies!





FEW SLIDES: THE UNDERLYING EVENT

> Impact on top mass reconstruction!



I. Borjanovic et al., hep-ex/0403021

SUMMARY

- QCD was a major topic at all previous and running hgh-energy colliders – and continues to be important at the LHC
  - Signal
  - Background
- QCD has many different aspects:
  - Particle production
  - Jet physics
  - Determination of QCD parameters like strong coupling α_S.
- Jet physics is a very interesting topic
  - QCD at highest scales
  - Discovery potential for new physics
  - Question of algorithms, calibration, uncertainties, ….
- Many other aspects of QCD (at the LHC) not covered here …
- Now enjoy the QCD/jets tutorial!