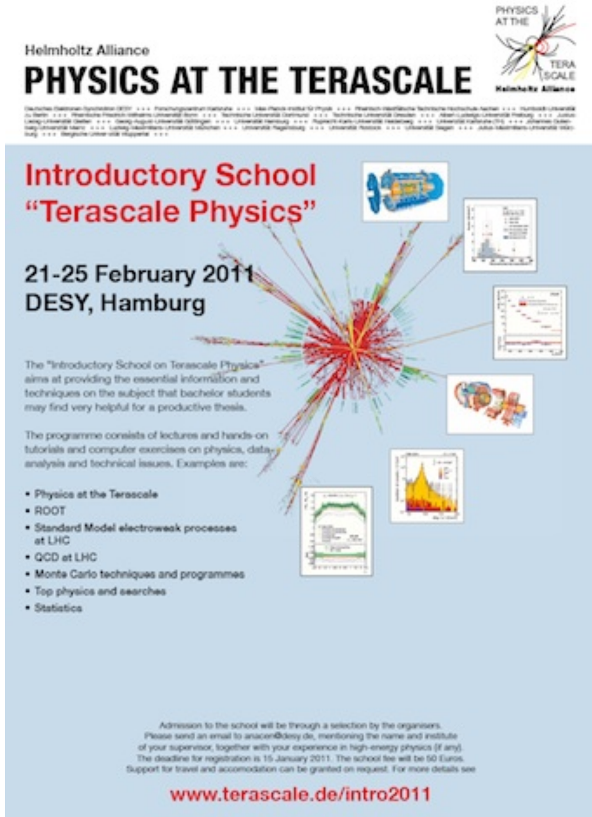
QCD at the LHC …

… and elsewhere.

Thomas Schörner-Sadenius

„Introduction to Terascale Physics“
DESY Hamburg
23 February 2011



OUTLINE

- Why the LHC – why QCD at the LHC?
  - History and basics of QCD
- Soft QCD and minimum bias physics
  - The “Underlying event” (UE)
- Intermezzo: Parton distribution functions
- Hard QCD: Jet physics at the LHC (and elsewhere)
  - Inclusive jet spectra
  - Dijets and trijets, multijets
  - Jet calibration
  - Extractions of the strong coupling constant
  - Jets and searches for new physics
- Not covered: Flavour physics, identified particles, details on jet algos, forward and diffractive physics, photons, trimming, pruning ...

WHY A NEW MACHINE?

The Standard Model (SM) is in excellent agreement with basically all measurements – so why worry?

> We have not yet found the **Higgs boson**!

- Without a Higgs, the SM diverges at 1 TeV!

> The **SM is not really simple** or beautiful!

- Too many free parameters!
  Explanation in fundamental theory?

> No gauge-coupling **unification**!

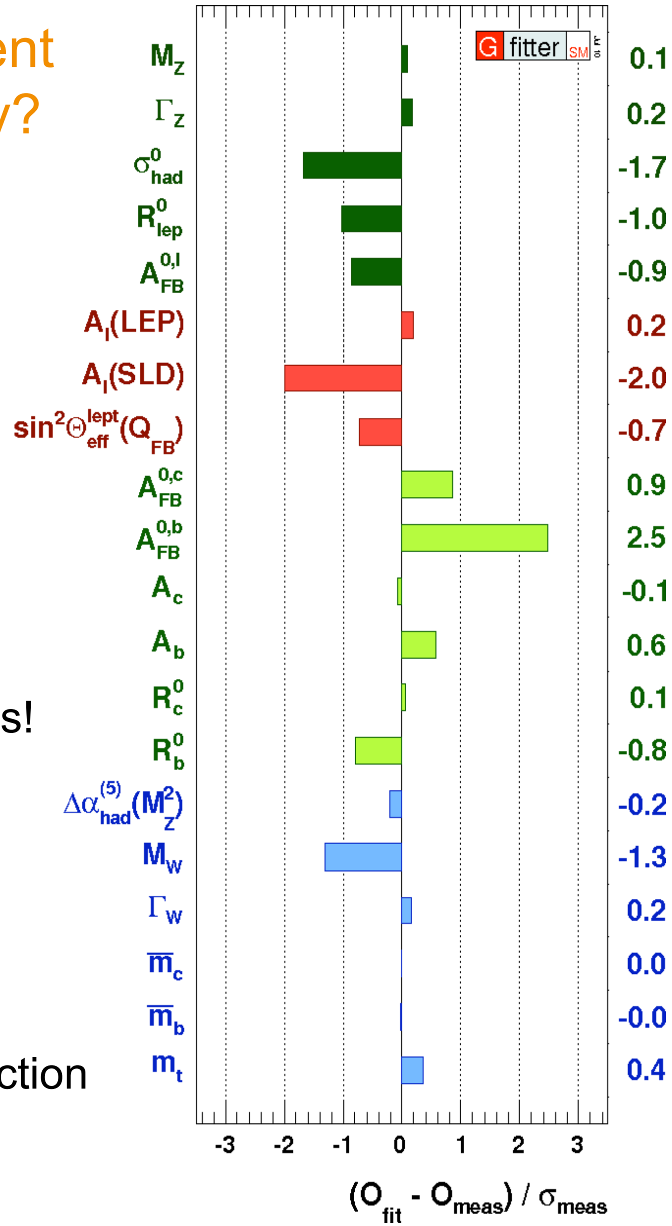
- The three SM couplings do not unify at highest energies!

> No **dark-matter candidate**!

- Galaxy rotation curves, structure formation, etc.!

> More **fundamental questions**!

- Gravity? Gauge structure? Why 3 generations? Connection between leptons and quarks? Hierarchy / fine-tuning problem? Baryon asymmetry? …



WHY A LARGE HADRON COLLIDER?

> $E = mc^2$

- We know that new particles are heavy
  → need **high energy** to produce them!

> $\lambda \approx \hbar / p$

- Because of uncertainty principle, smaller substructures require **higher momentum**.

> But: synchrotron radiation!

- Energy lost per orbit: $W = \frac{e^2}{3\varepsilon_0} \cdot \frac{E^4}{m^4 R}$

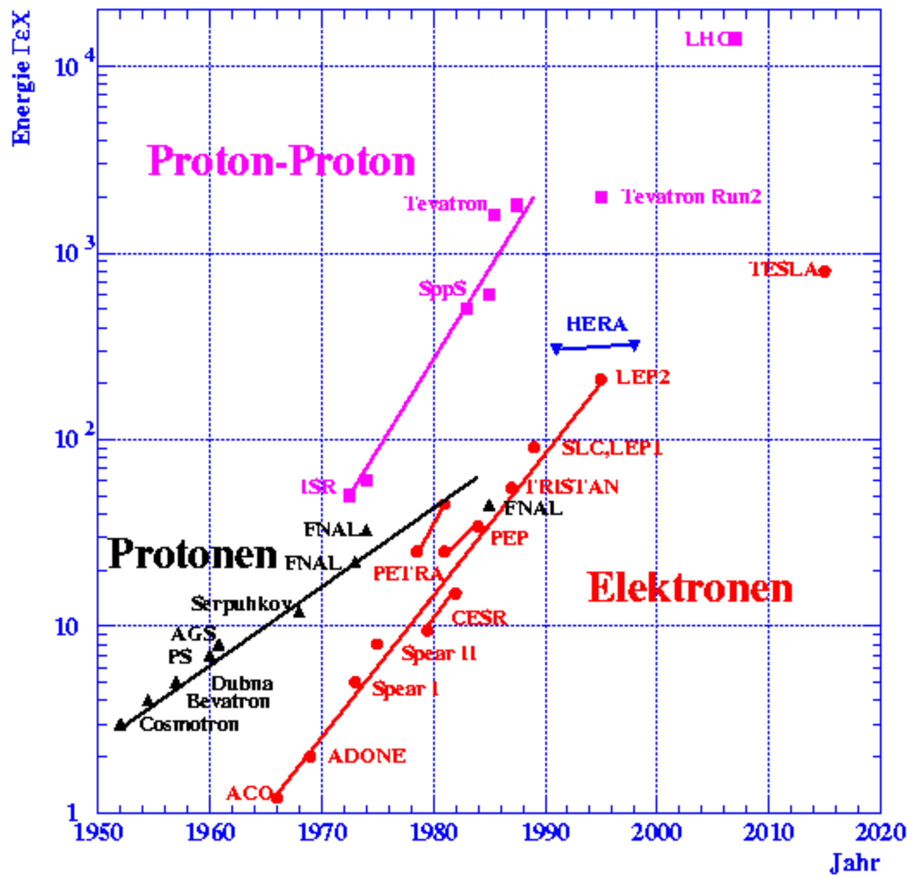
  ➔ **large radius** to minimise losses!

> Discoveries with **hadron machines**!

- Then precision physics at lepton colliders.
- By the way: bosons discovered in Europe!

> **Colliders**: higher energy for same E_{beam}!

$$\sqrt{s} = 2E_{beam} \quad vs \quad \sqrt{s} \cong \sqrt{2mE_{beam}}$$



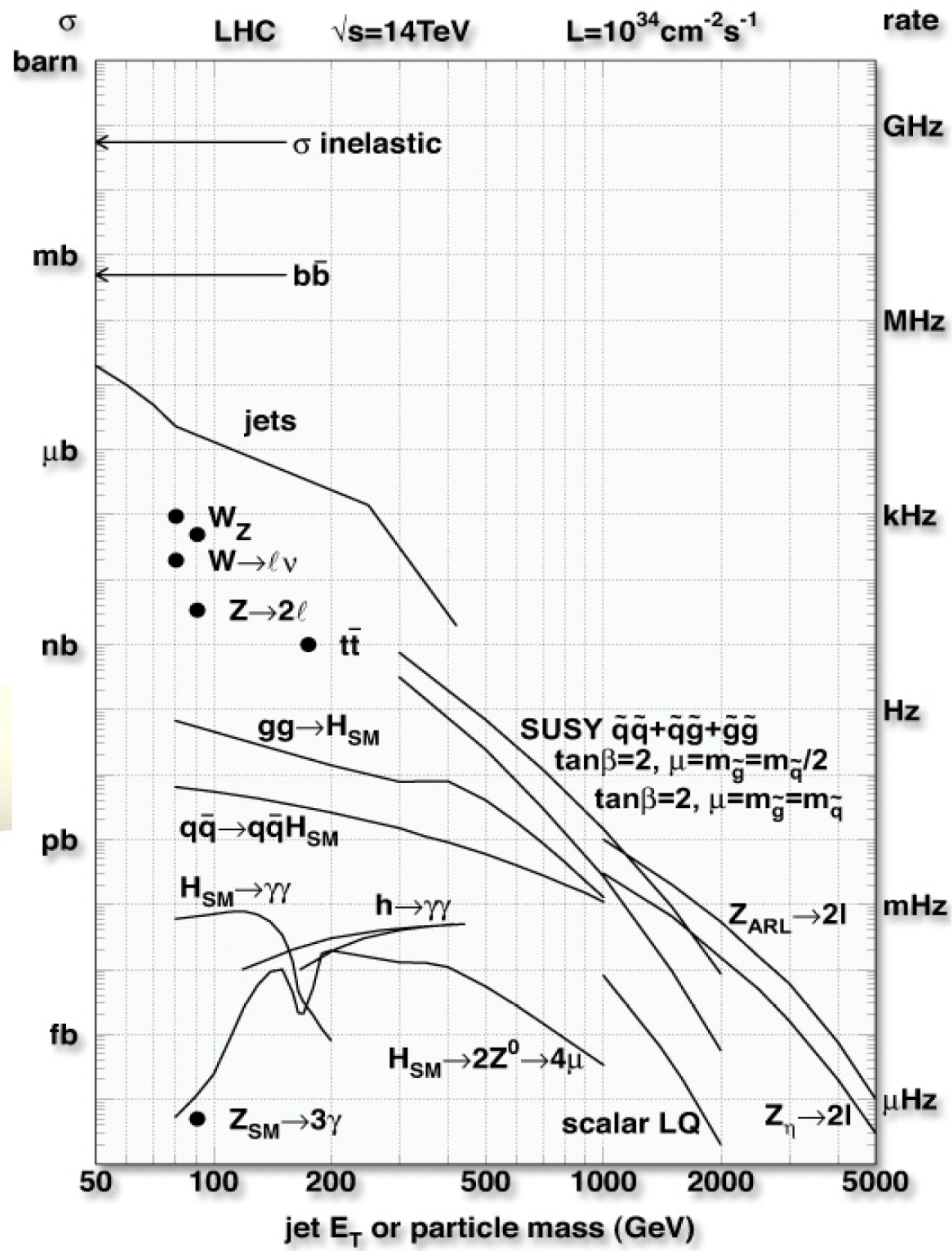
WHY QCD?

The events at the LHC are dominated by QCD!

> Highest rates: inelastic pp collisions (mostly "soft QCD")!
- Protons "barely scraping each other".
- No hard jets, no hard scale.
- Difficult to describe (perturbation theory not applicable)

> Dominating hard processes:
- (Di)jet production (with or without flavour)
- Perturbatively accessible.

> LHC is first of all a QCD machine
- "Bread-and-butter physics"?
- Need to understand backgrounds!



THE PATH TO QCD – HISTORY (1)

> Early classifications of `hadrons' (`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????

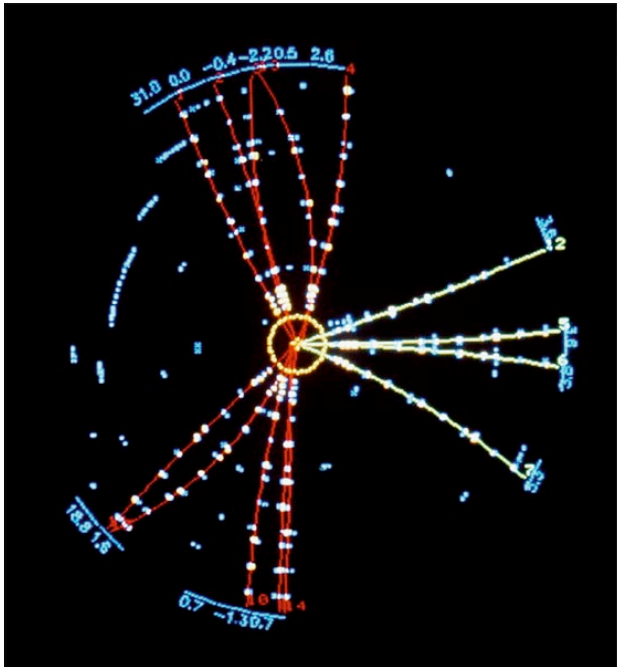
THE PATH TO QCD – HISTORY (2)

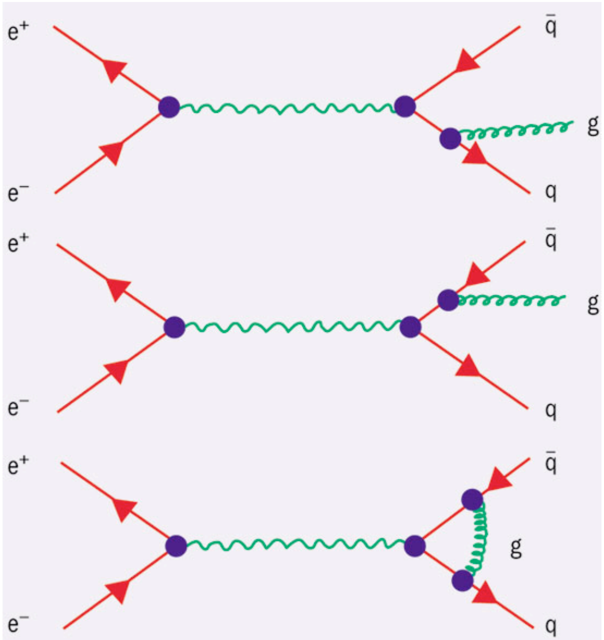
> Solution: QCD

- 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!





3-jet events prouced "… at a rate consistent with gluon radiation and a value of the strong coupling of about 0.15 …"

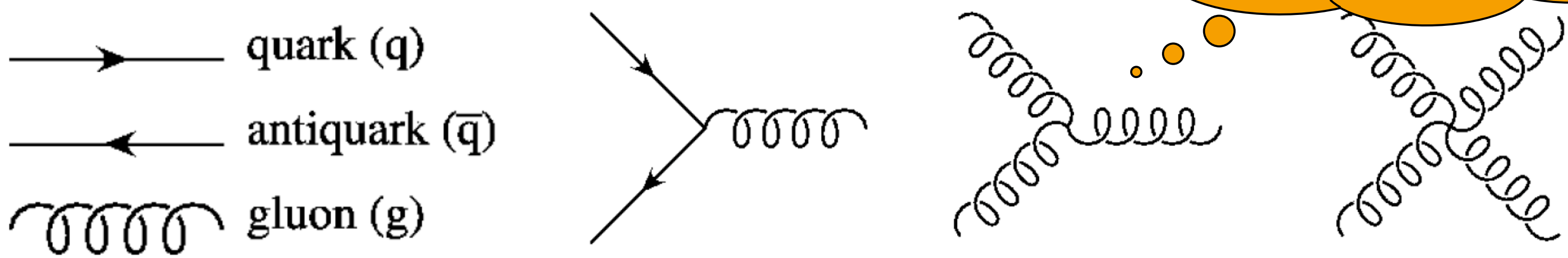
BASICS OF QCD

> 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.

> 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, Wilczek, Politzer)

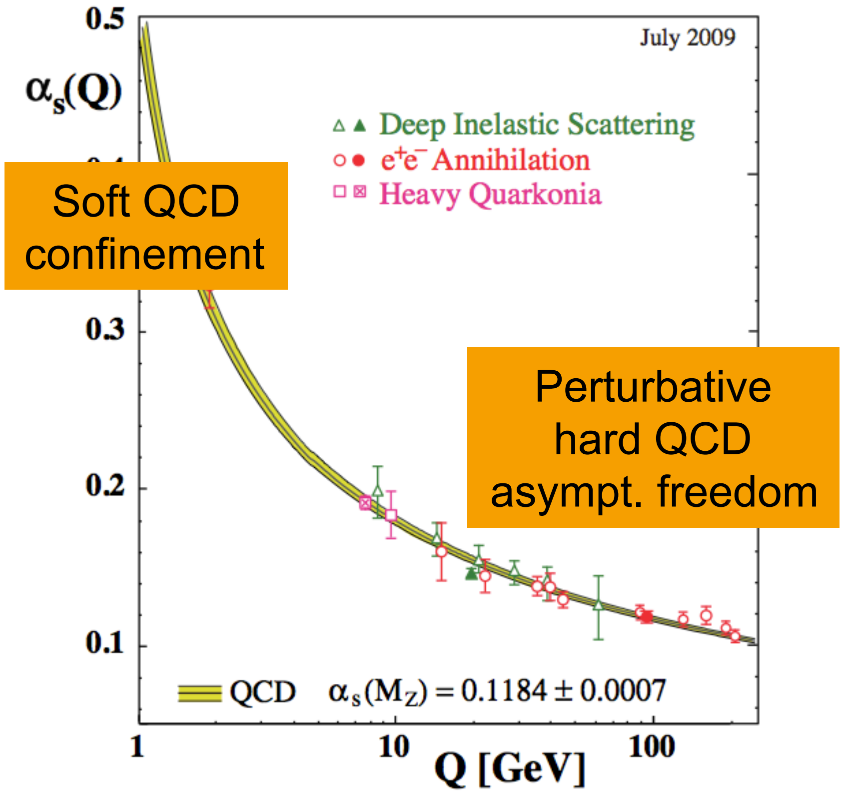
- Relevant parameter: Coupling strength between coloured particles: α_s!

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

- 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).



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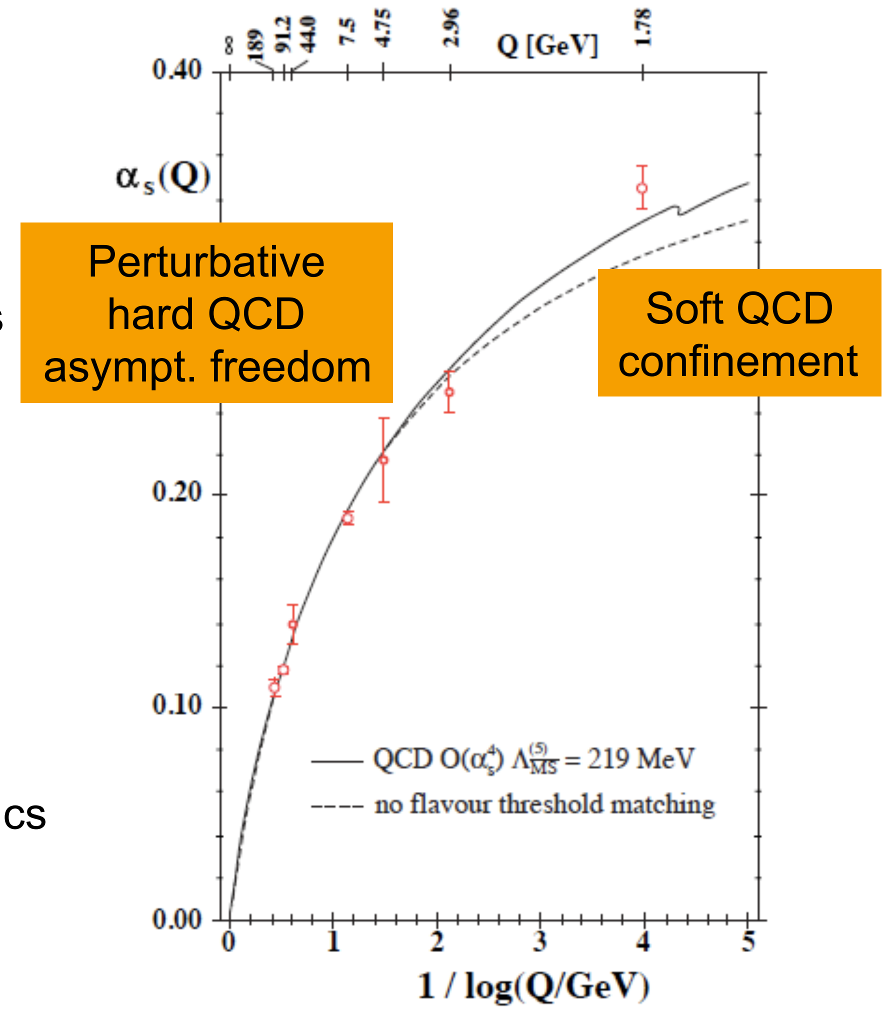


SALIENT FEATURES OF QCD (2)

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

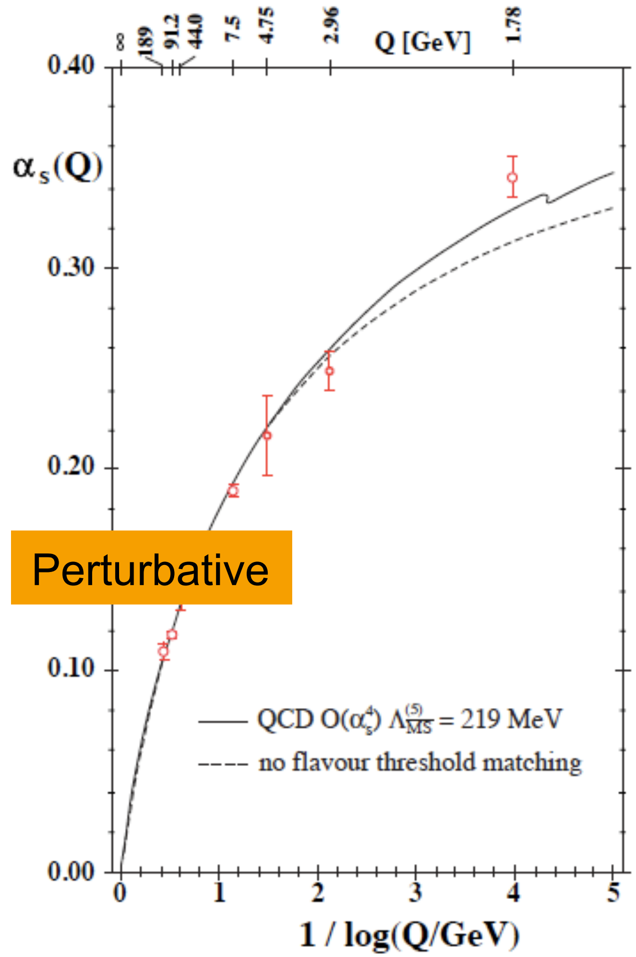
> How to tackle QCD?

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

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

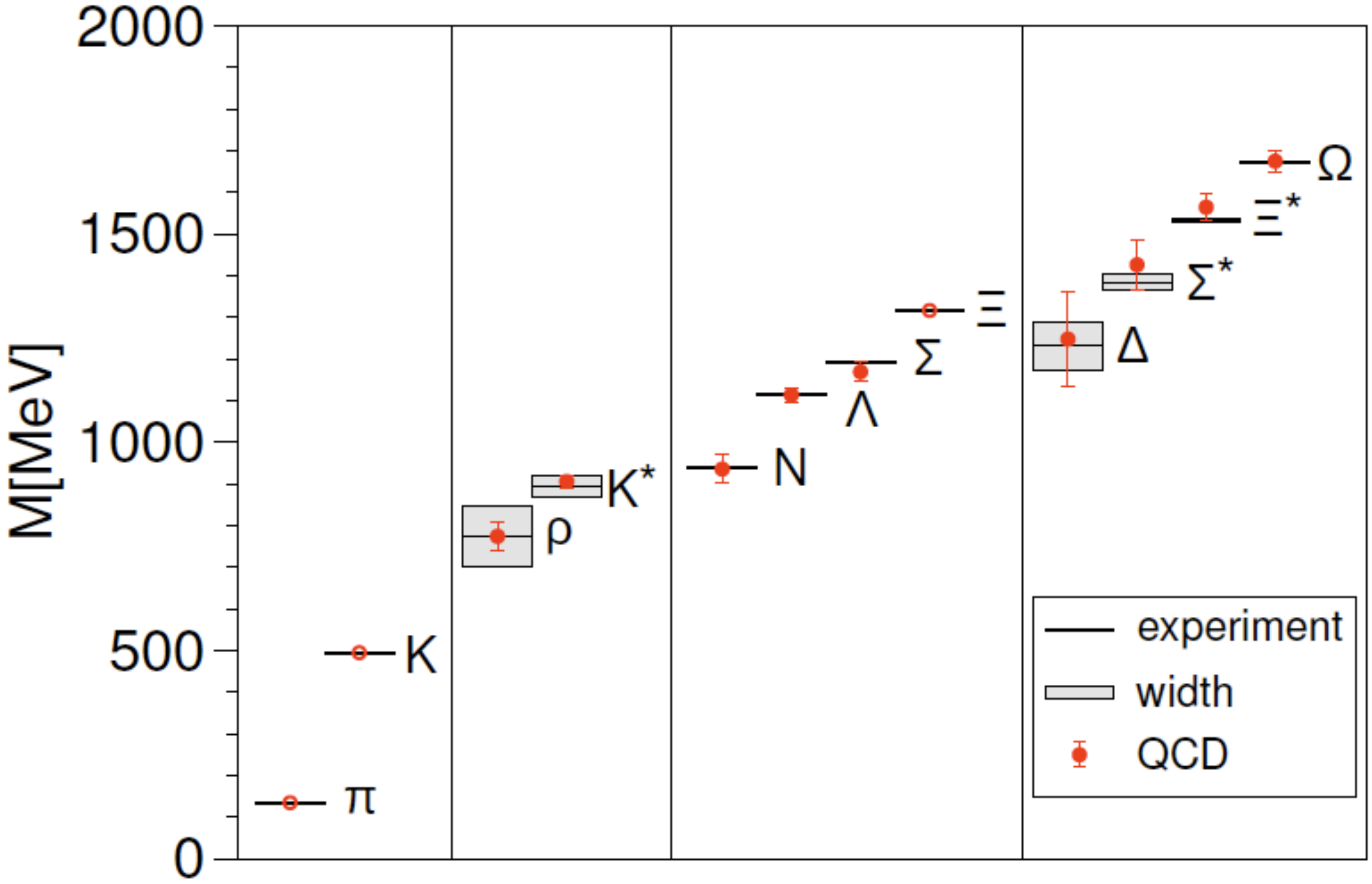
  The coefficients can typically be evaluated to some (small) order: LO, NLO, NNLO
  In addition methods to sum up other large contributing terms (large logs).

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

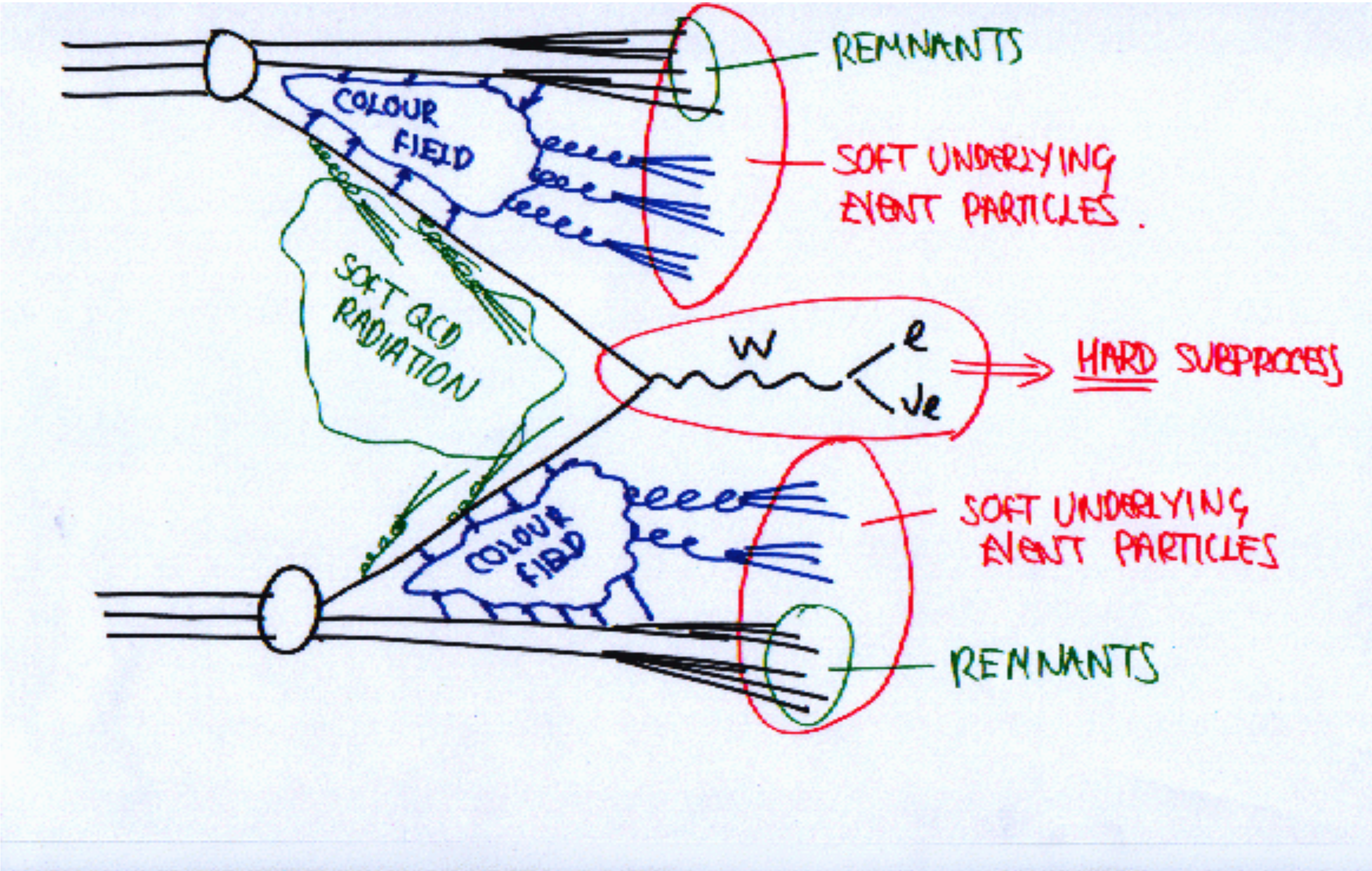


SALIENT FEATURES OF QCD (2)

> Hadron spectroscopy in lattice QCD



OVERVIEW: A QCD EVENT



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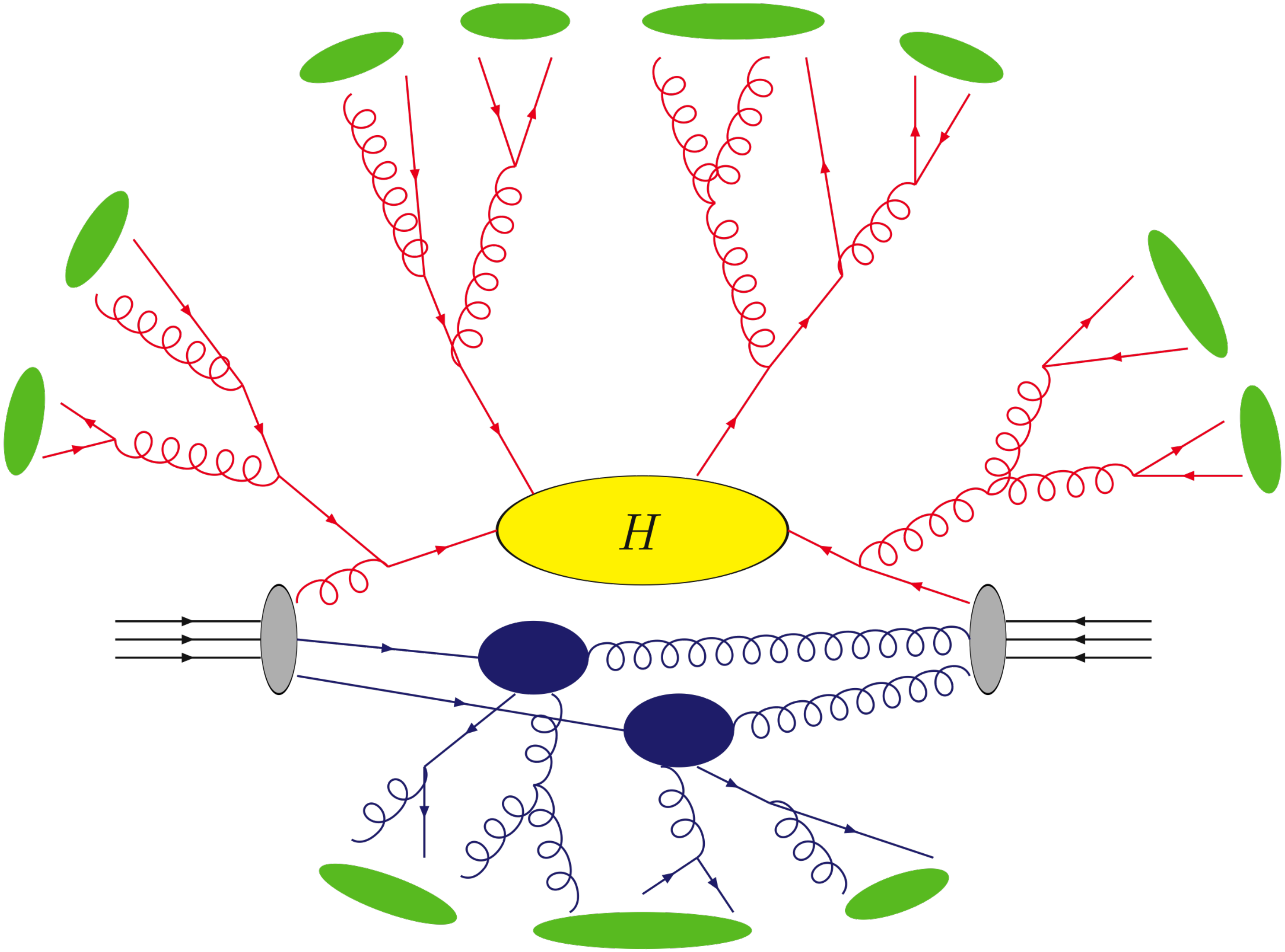
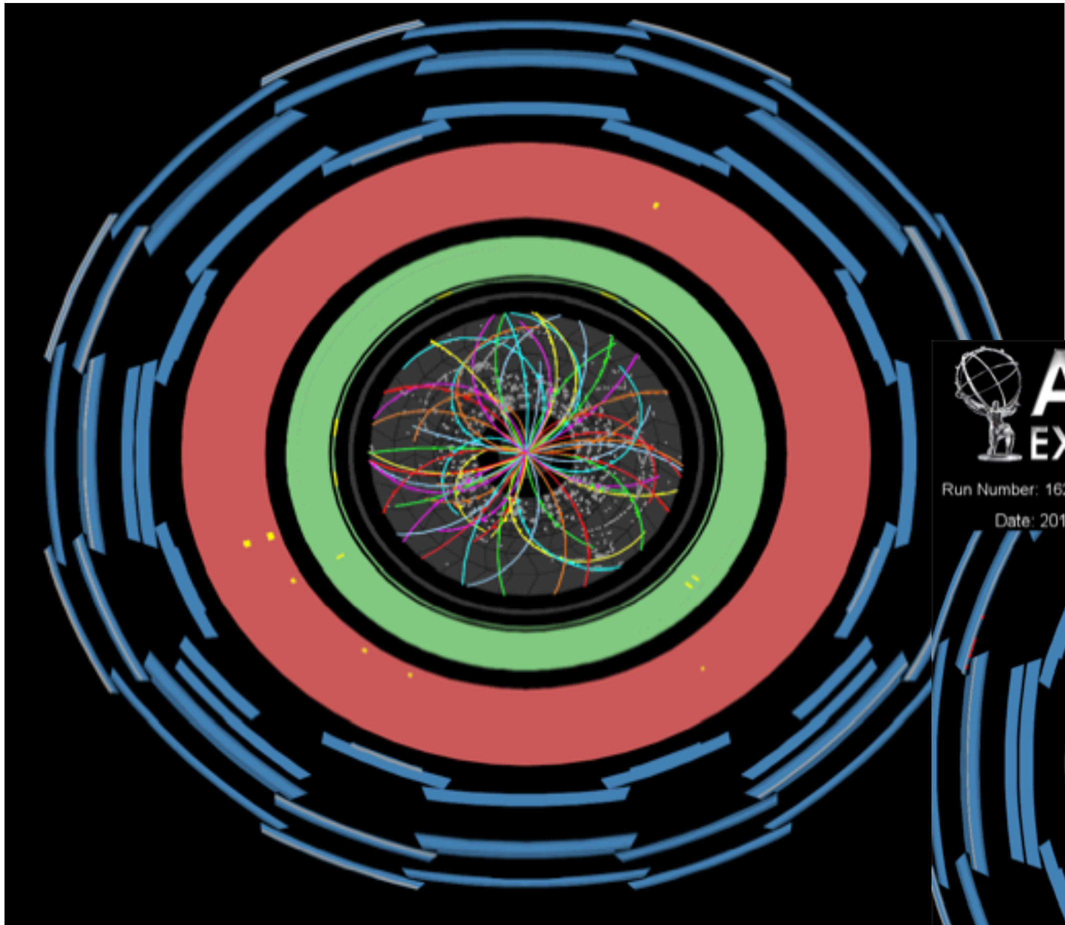
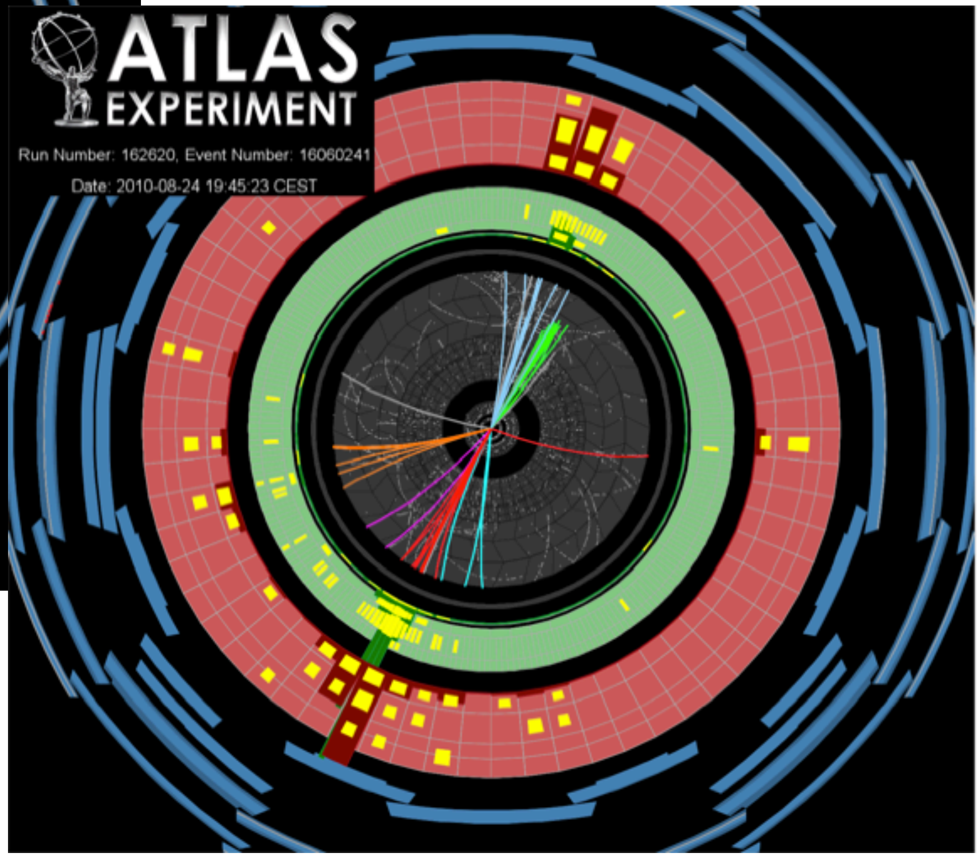


SOFT vs. HARD QCD IN THE EXPERIMENT





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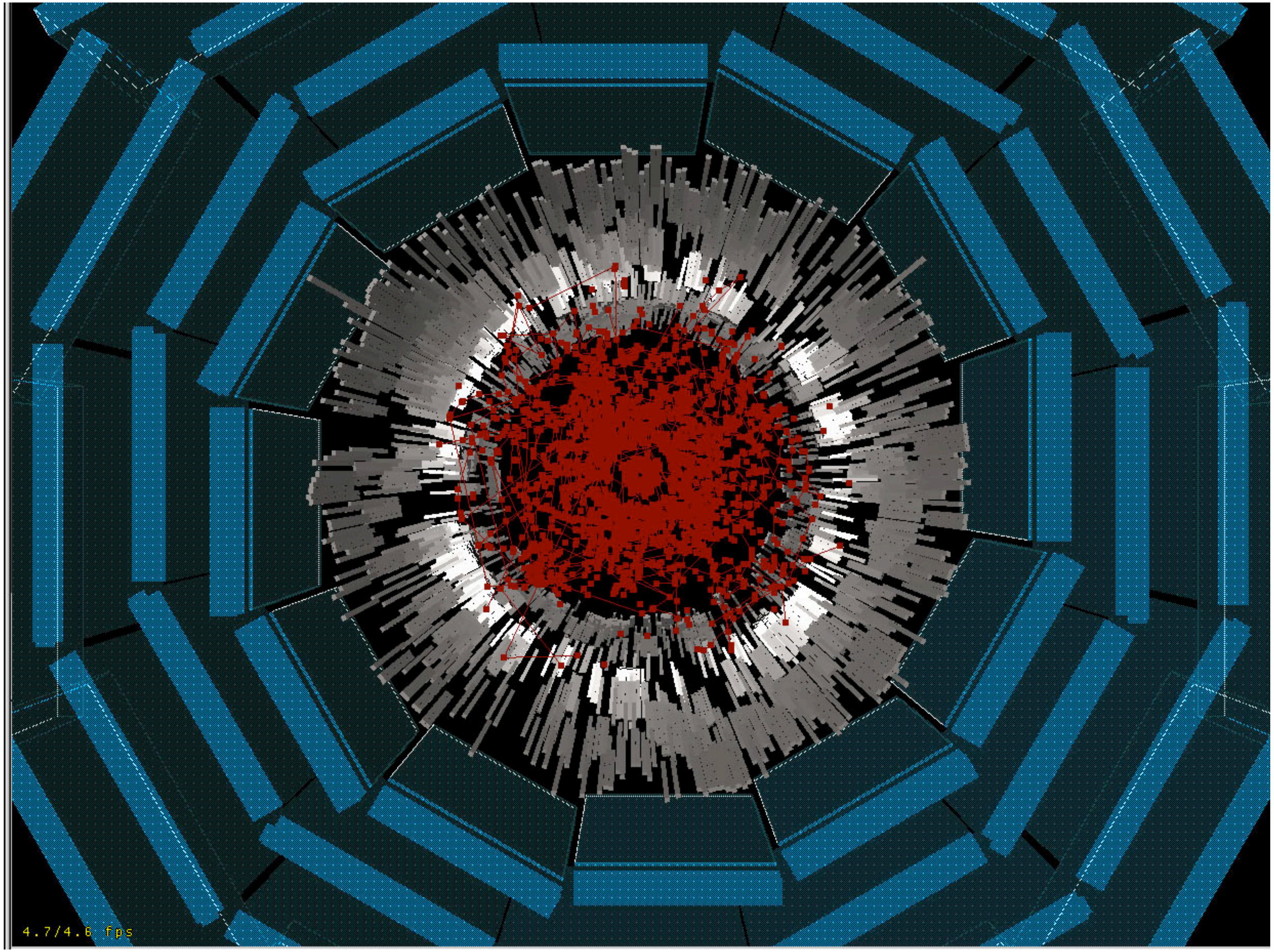


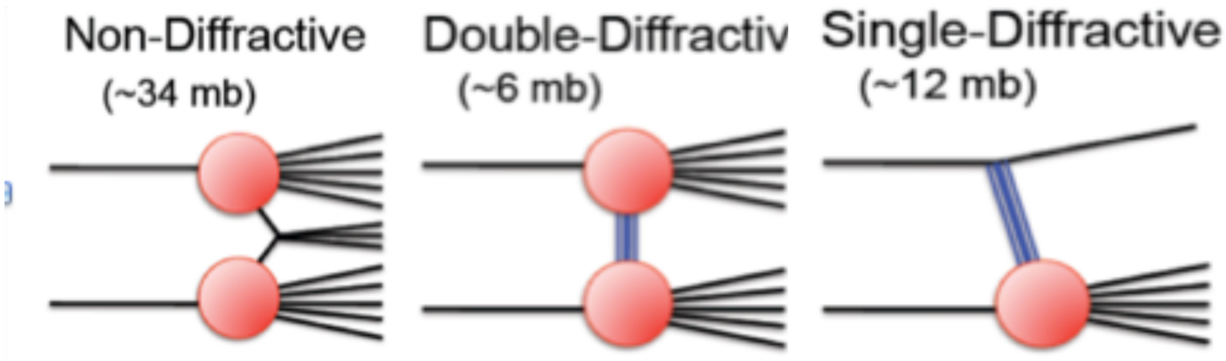
SOFT QCD

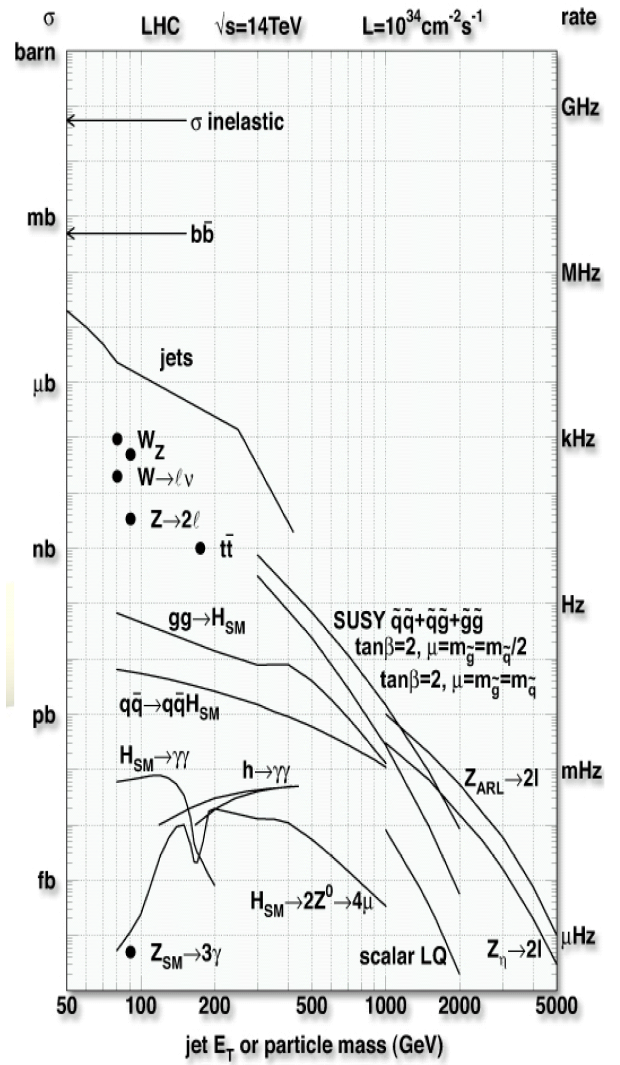

Collision Event at
7 TeV
ATLAS
EXPERIMENT
2010-03-30, 12:58 CEST
Run 152166, Event 316199
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

"MINIMUM BIAS" PHYSICS

> In most pp collision events:

- No hard scale and little activity in the event. Trigger only on small number of tracks or "forward" activity.
- Remember the cross sections: Only very few of these events will have "hard" signatures (jets, heavy particles)
- Resulting data sample: Large admixture of diffractive events with no or little colour flow ("rapidity gaps") → modelling?





> Experimentally difficult to define: E.g. ATLAS and CMS have different definitions (including / excluding parts of the diffractive components)

MINIMUM BIAS, 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.
  - Universality of showering / fragmentation process?

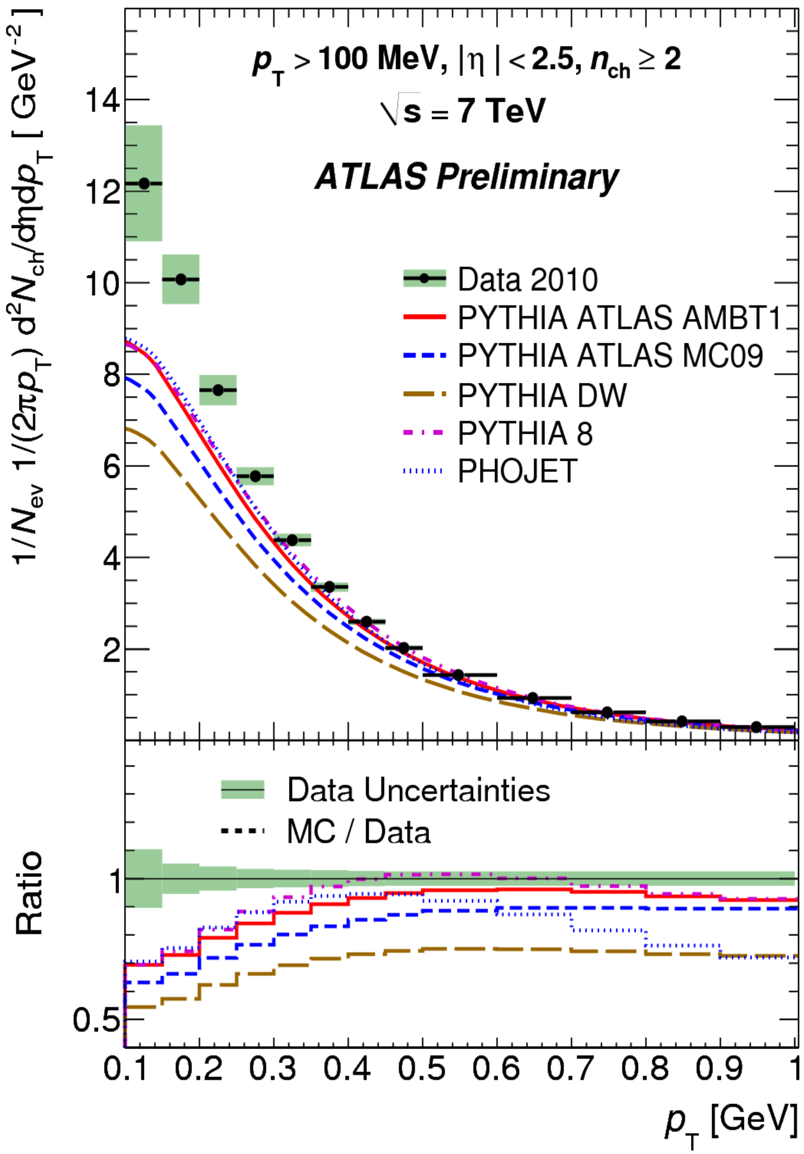
> Note that it is especially interesting to measure the same distributions at different centre-of-mass energies and at different machines in order to

  - 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, HERA, LEP, LHC, RHIC, Tevatron

MINIMUM BIAS, PARTICLE PRODUCTION

- Measurement of p_T, pseudorapidity, number of particles / tracks
  - Treatment of diffractive component in the experiments?
  - Measurement down to 100 MeV possible!
- Measurement difficult!
  - Uncertainties: Tracking/trigger efficiency, modelling, unfolding (few %)
  - Models have problems!
  - “Tuning” of MC models – systematic adaption of model parameters?



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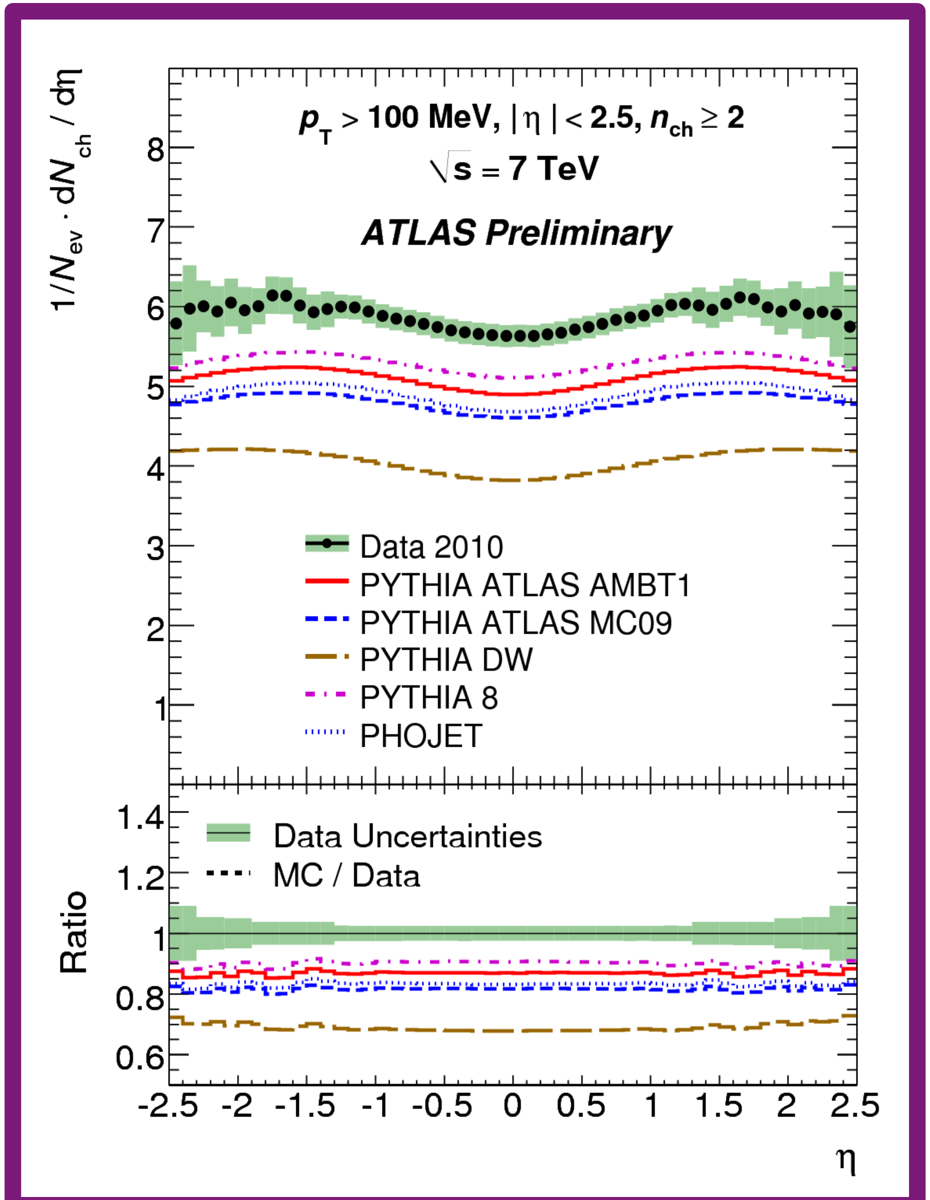

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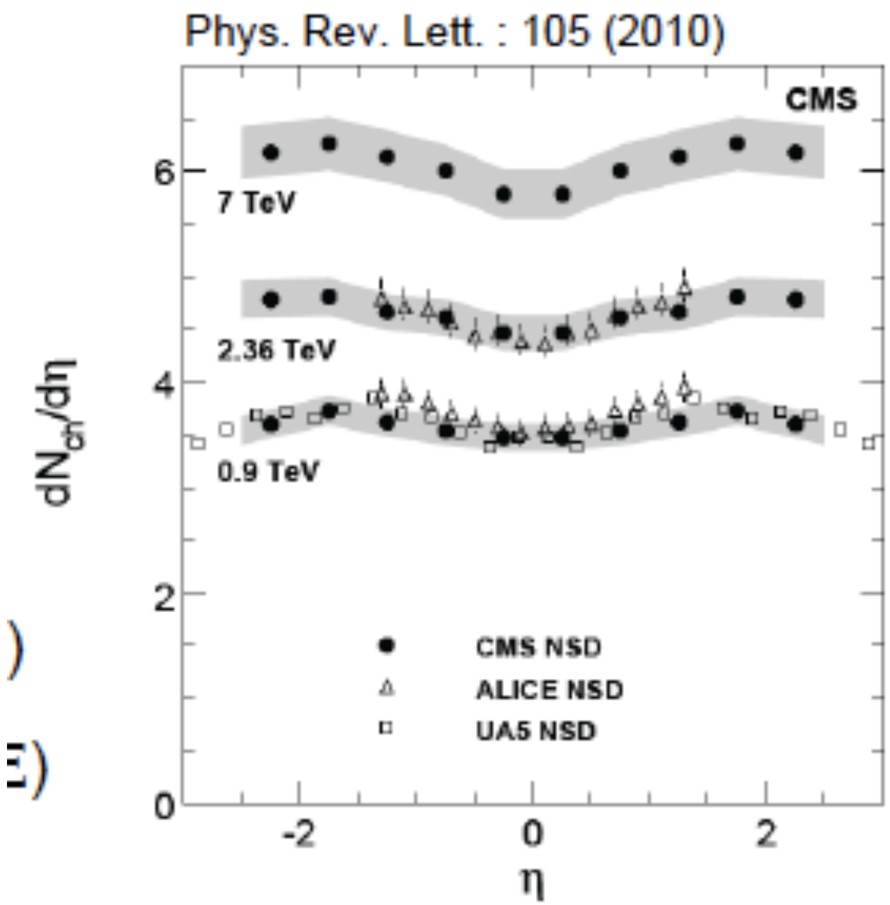
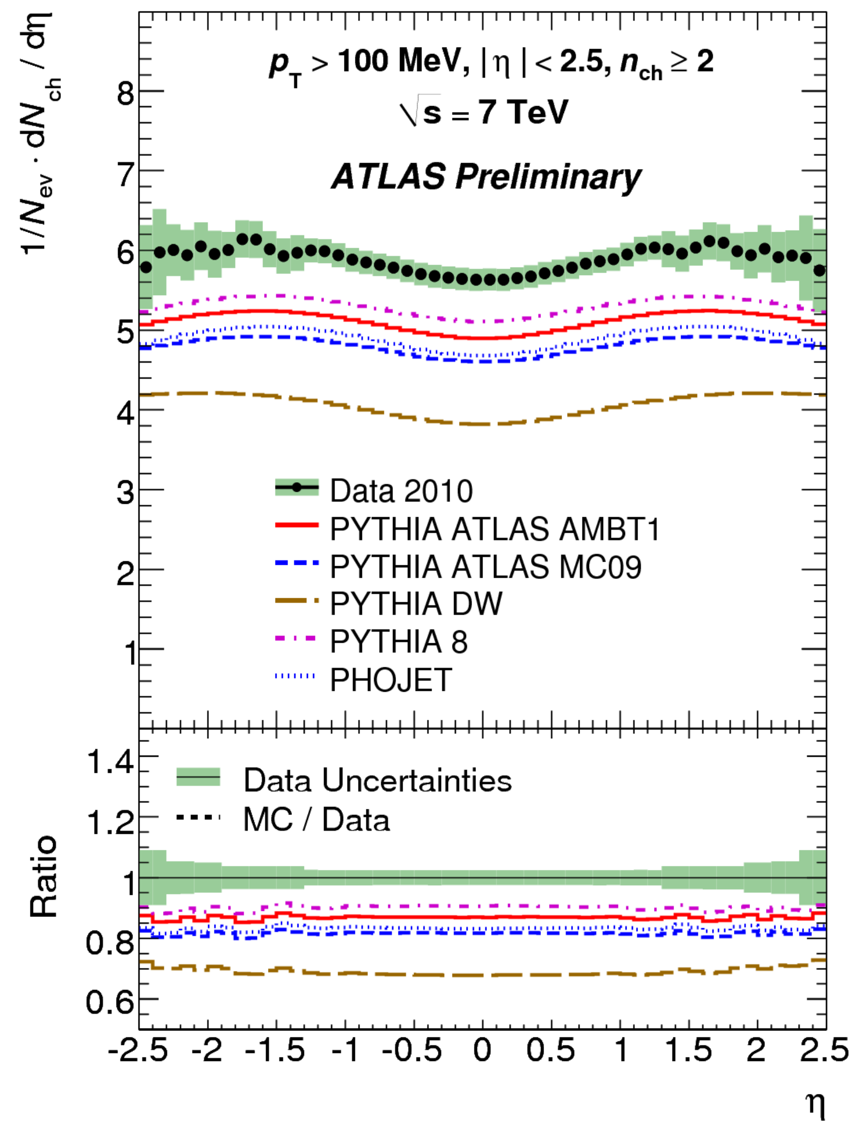
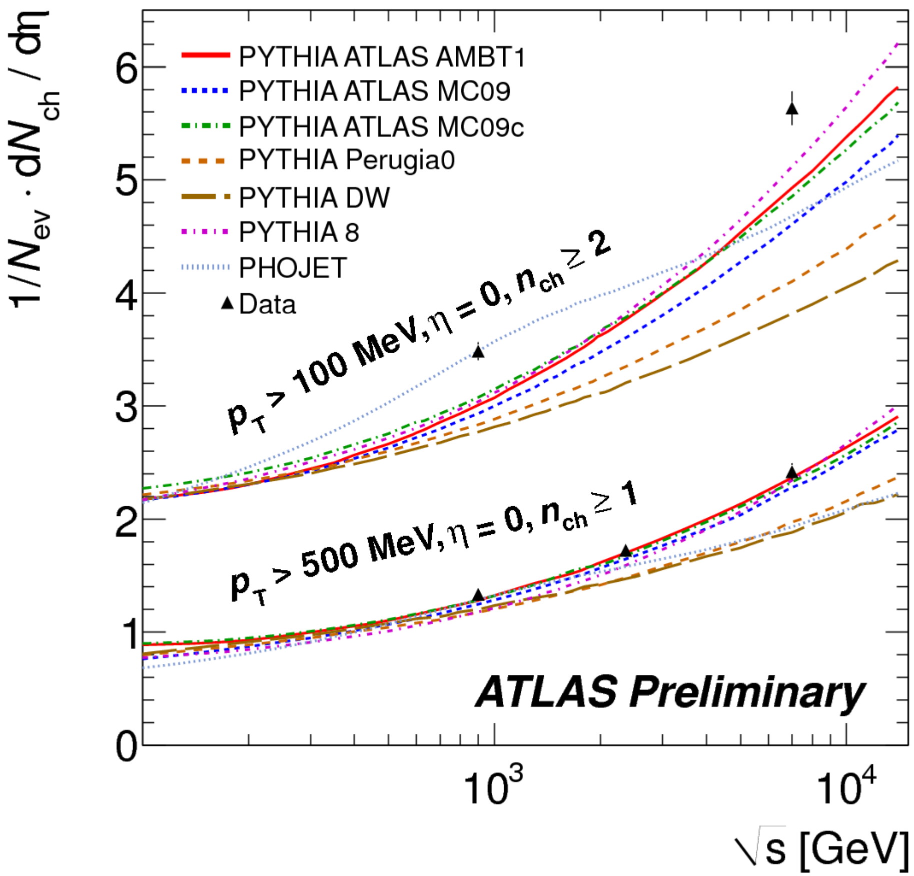


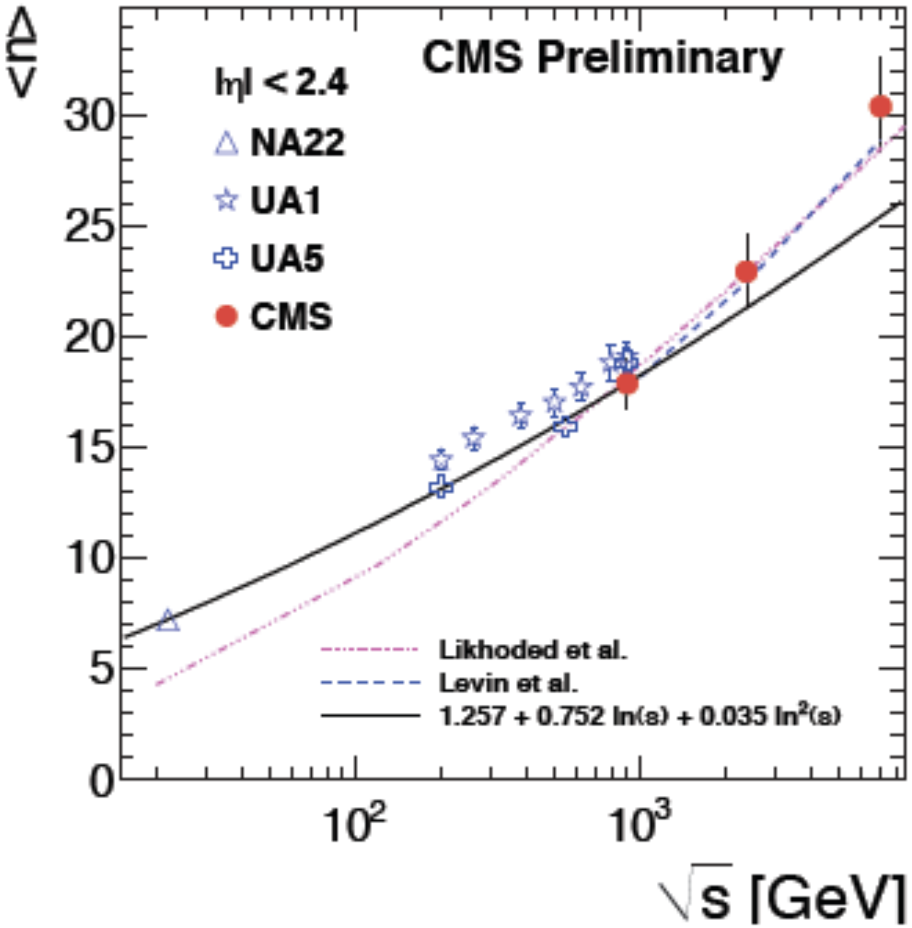


MINIMUM BIAS, PARTICLE PRODUCTION

> Averaged charged particle multiplicity:

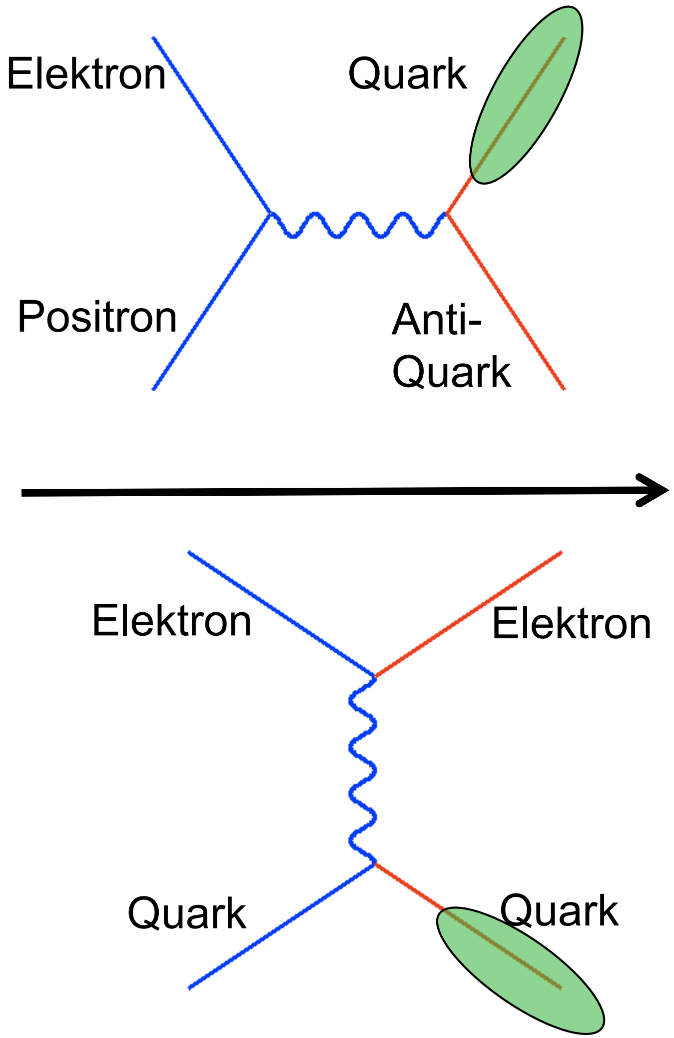
- Models underestimate increase with centre-of-mass energy.
- Possible to find phenomenological parametrisations that describe all data points.

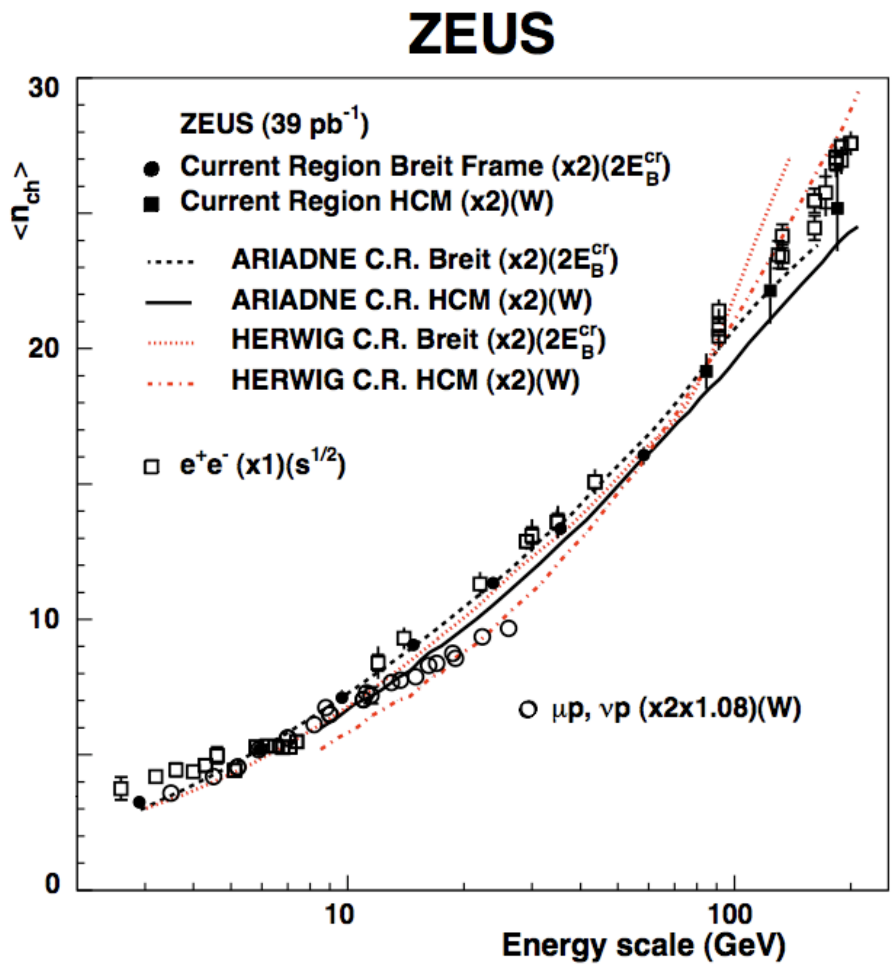




PARTICLE PRODUCTION

- … energy dependence of charged hadron multiplicity:

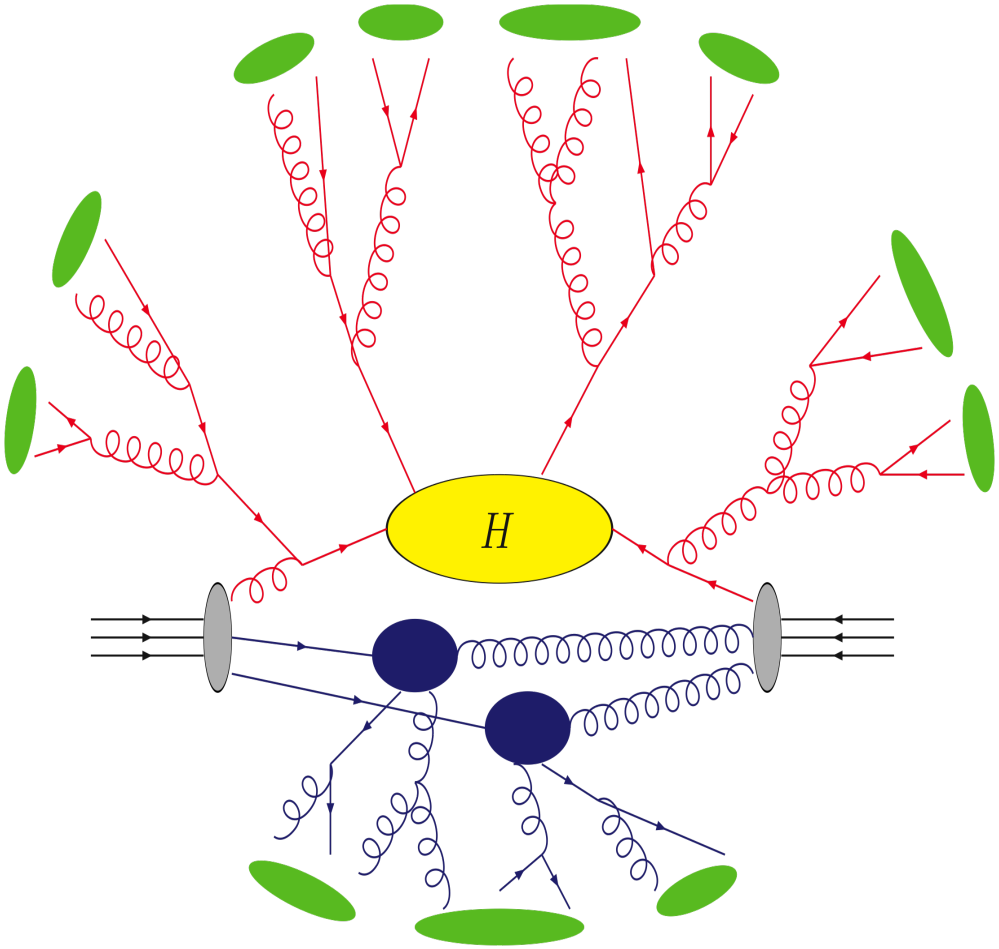




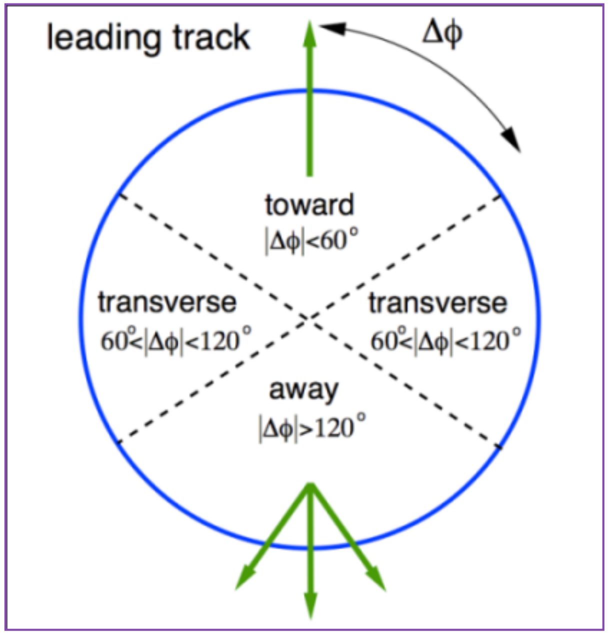
Fragmentation is ~ universal!

FEW SLIDES: THE UNDERLYING EVENT

> "Everything except the hardest 2→2 interaction in the event"



- Pile-up – several pp collisions
- Multi-parton interactions.
- Beam remnants, other soft stuff
- Potential impact on all analyses!
- Study using, for example, energy flow in different regions.



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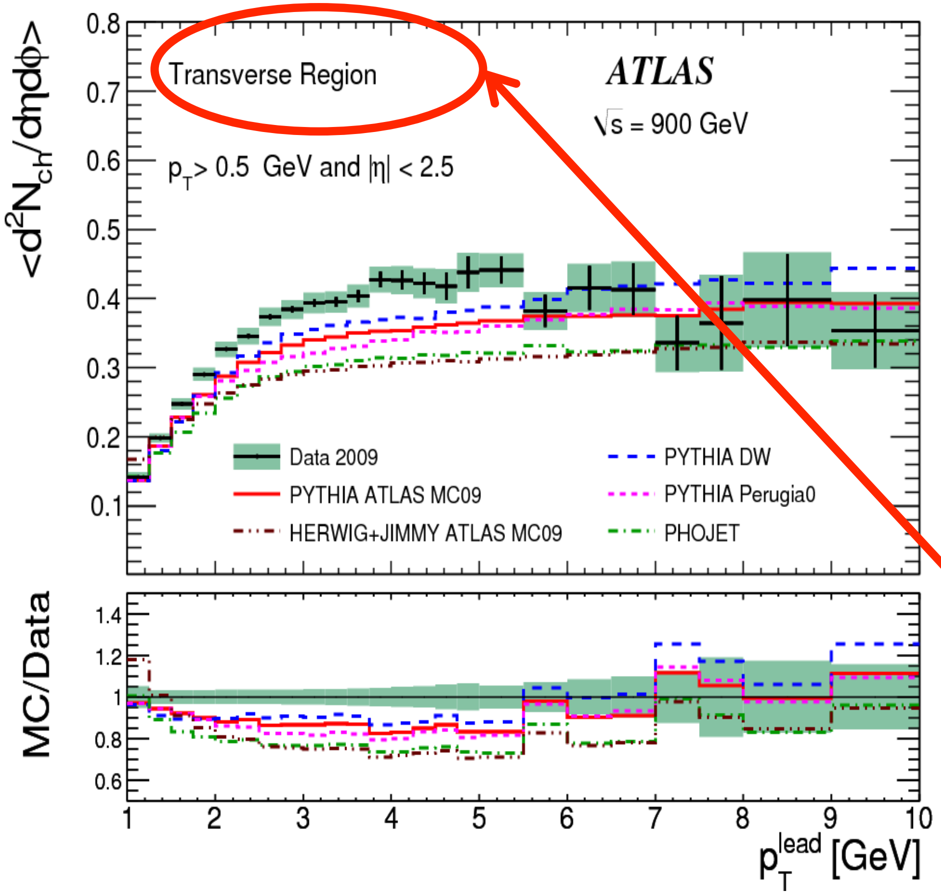

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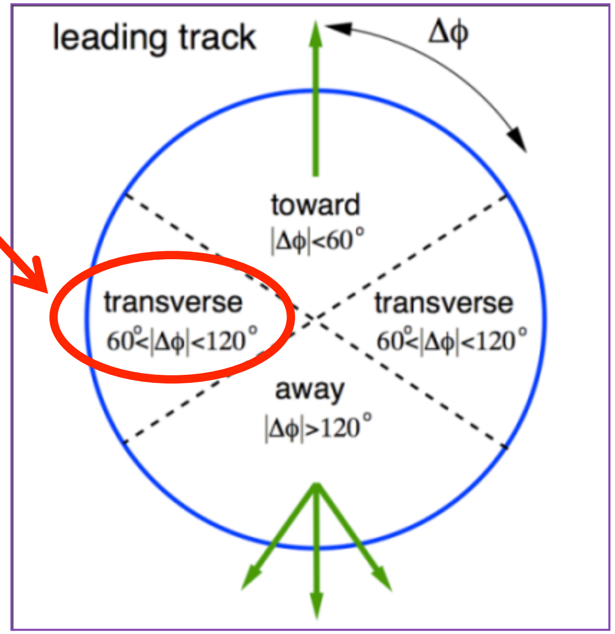
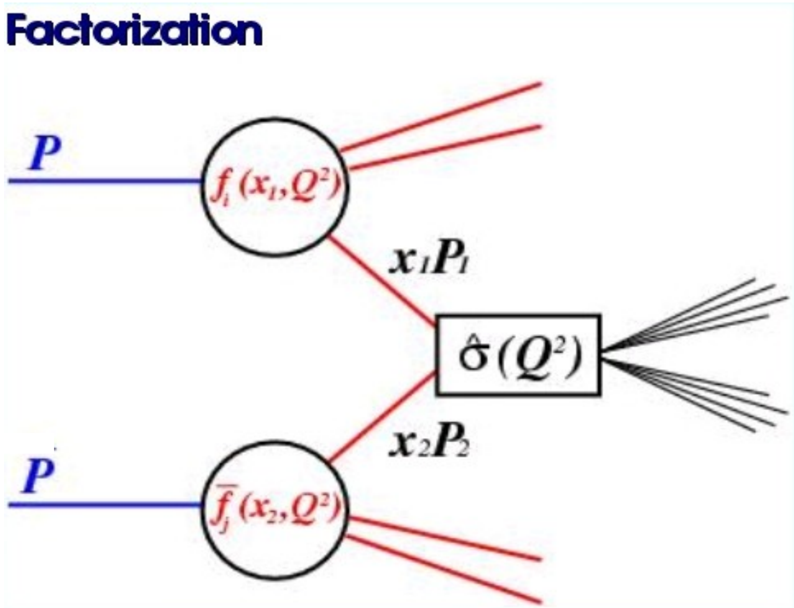


- Behaviour with CMS energy?
- Modelling?

INTERMEZZO: PDFs (and factorisation)

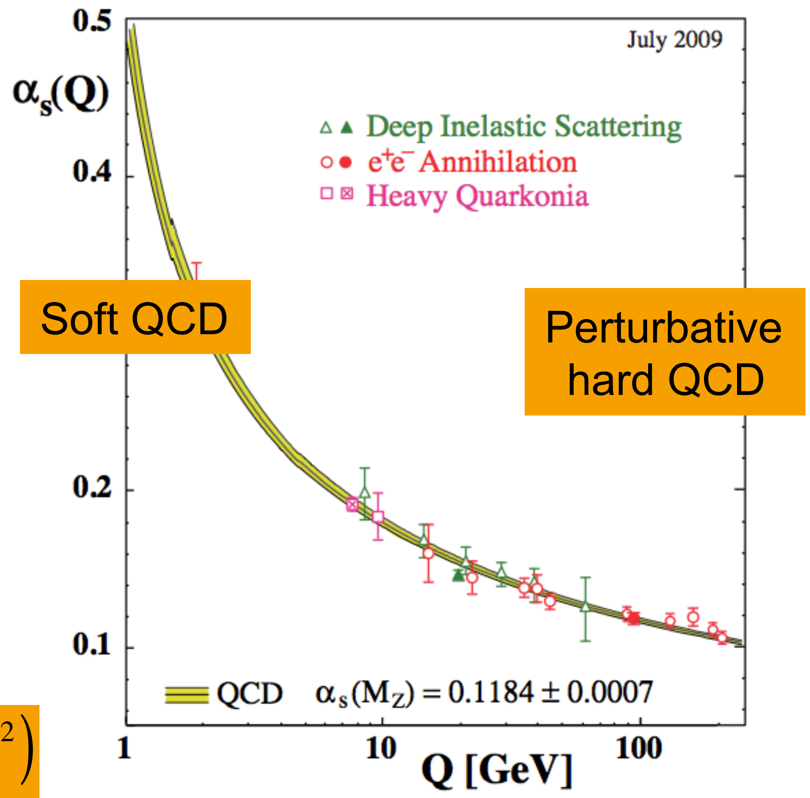
- Factorisation of cross section into soft and hard (or long- and short range contributions)



$$\sigma(s) = \sum_{ij} \iint dx_1 dx_2 f_{i/p}(x_1,Q^2) f_{j/p}(x_2,Q^2) \hat{\sigma}_{ij}(x_1,x_2,Q^2)$$

- Functions $f_{i/p}$: parton distribution functions; need to be obtained from experiment!

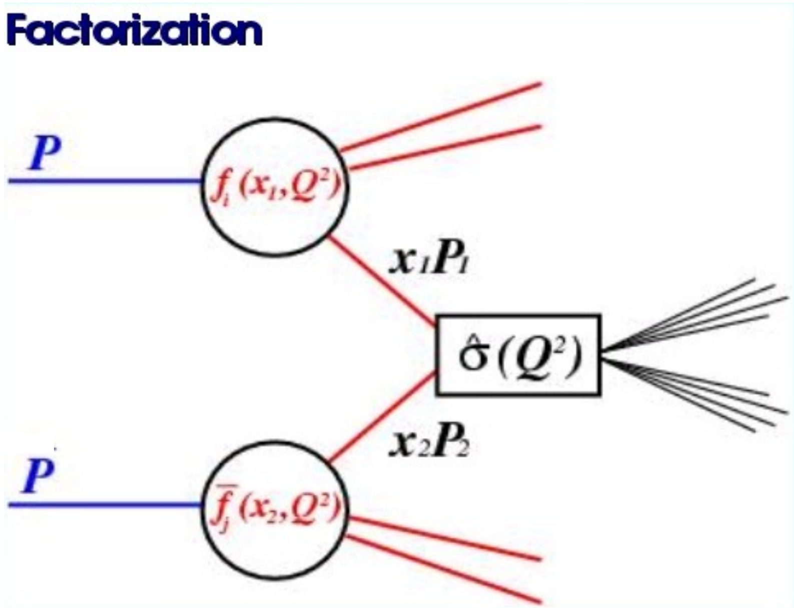
- Hard scales, small α_S: expand "hard scattering" into powers of α_S.



$$\hat{\sigma}_{ij} = \sum_n \alpha_S^n(Q^2) C_{ij,n}(\ldots)$$
$$= C_{ij,0} + \alpha_S \cdot C_{ij,1} + \alpha_S^2 \cdot C_{ij,2} + \ldots$$

INTERMEZZO: PDFs (and factorisation)

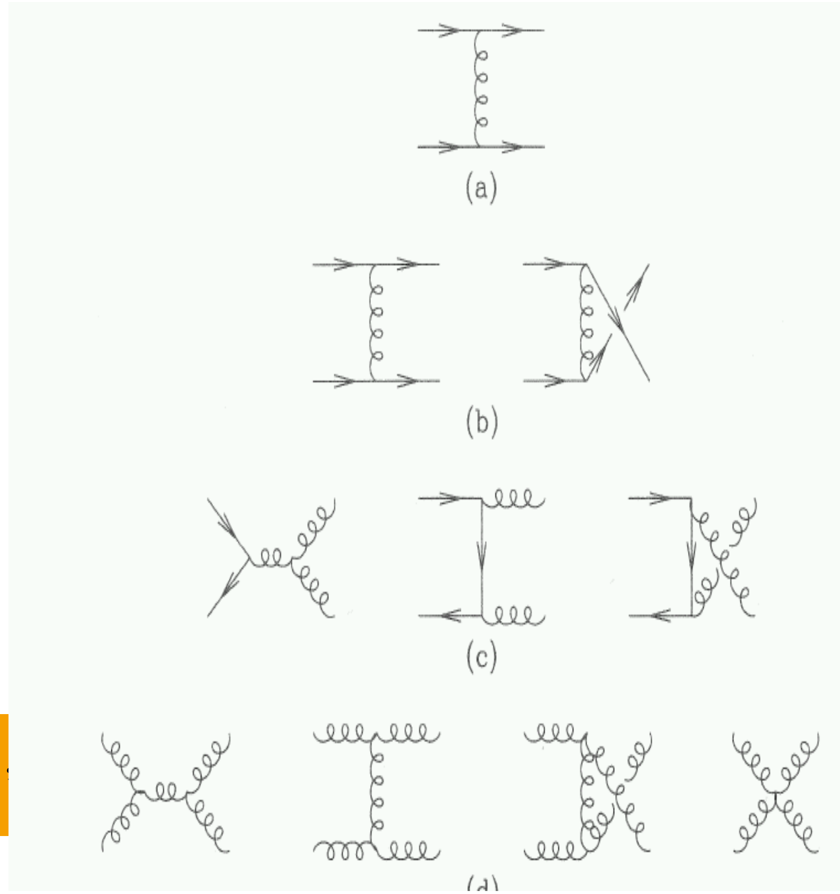
- Factorisation of cross section into soft and hard (or long- and short range contributions)



$$\sigma(s) = \sum_{ij} \iint dx_1 dx_2 f_{i/p}\left(x_1, Q^2\right) f_{j/p}\left(x_2, Q^2\right) \hat{\sigma}_{ij}\left(x_1, x_2 \ldots\right.$$

- Functions $f_{i/p}$: parton distribution functions; need to be obtained from experiment!

- Plug in any hard matrix element you are interested in!

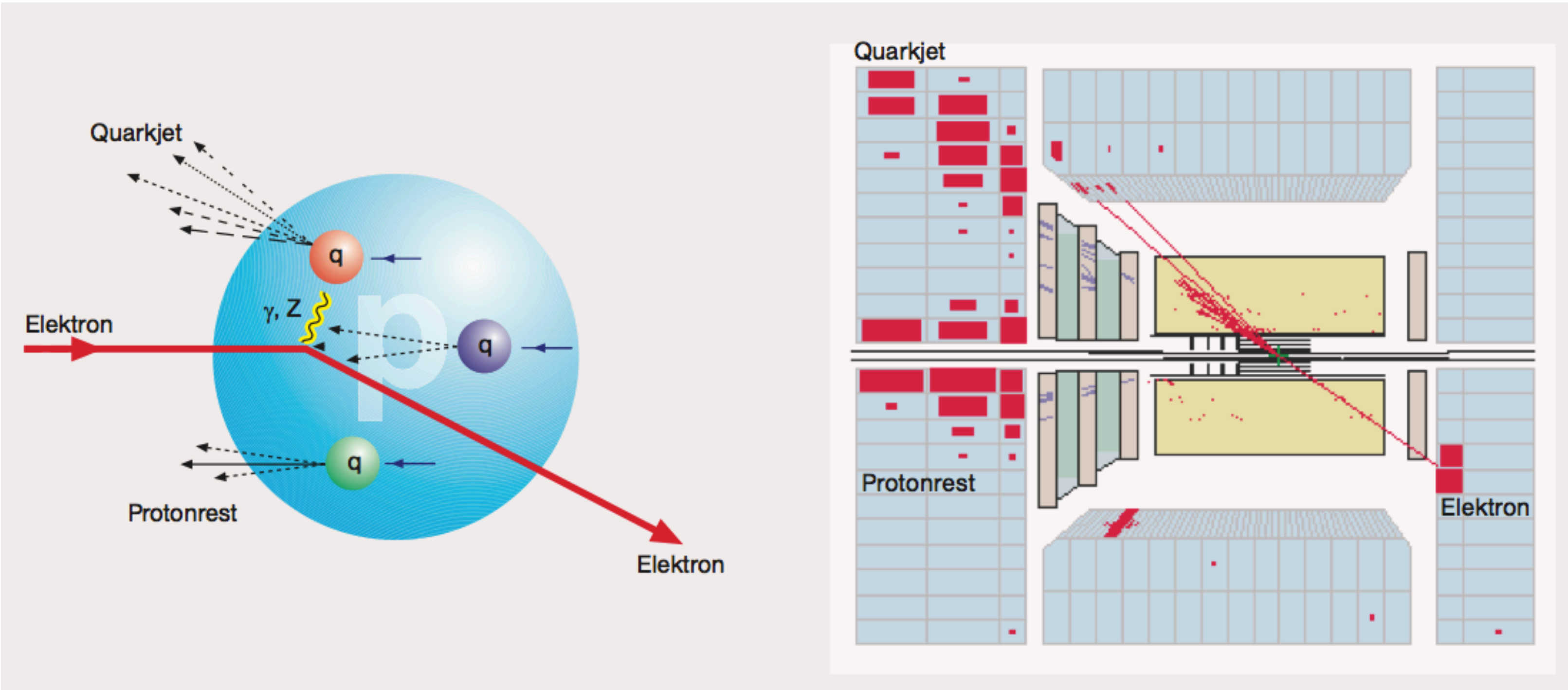


- Shown: ME for 2→2 QCD events.

INTERMEZZO: PDFs

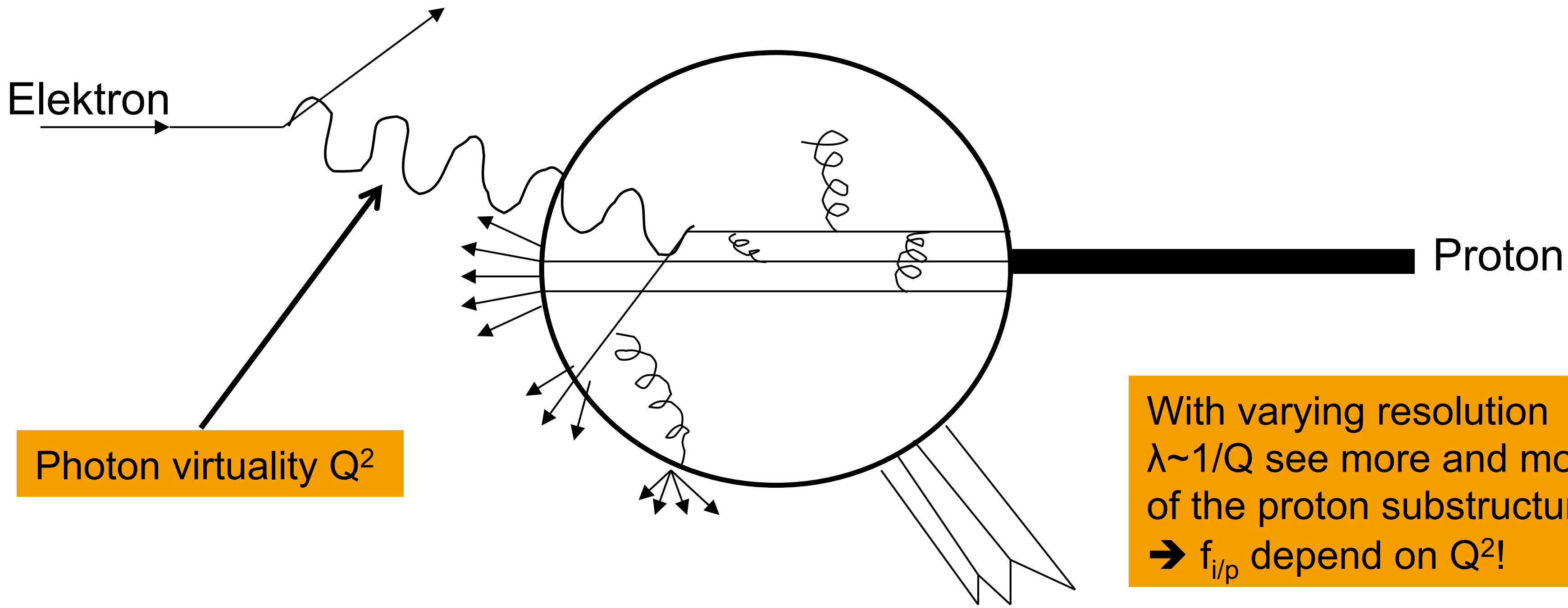
> Remember factorisation: $\sigma(s) = \sum_{ij} \iint dx_1 dx_2 f_{i/p}(x_1, Q^2) f_{j/p}(x_2, Q^2) \hat{\sigma}_{ij}(x_1, x_2, Q^2)$

- Functions $f_{i/p}$ describe structure of the proton – probability to find parton of type i (quark, antiquark, gluon) with momentum fraction x_1 if looking with resolution Q^2.
- Problem: Parton distributions not calculable from first principles – need precision data to derive them → HERA electron-proton collider!



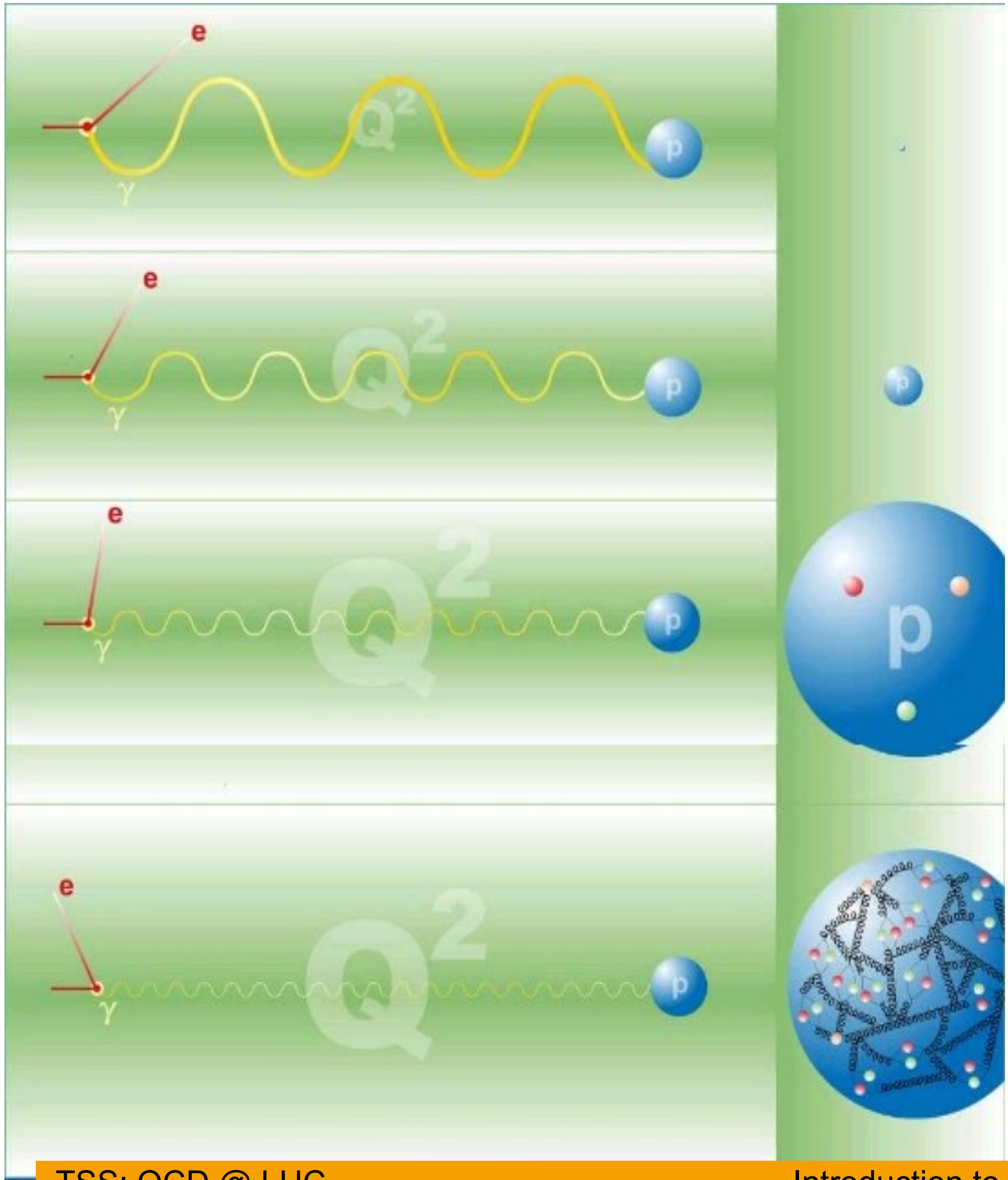
INTERMEZZO: PDFs

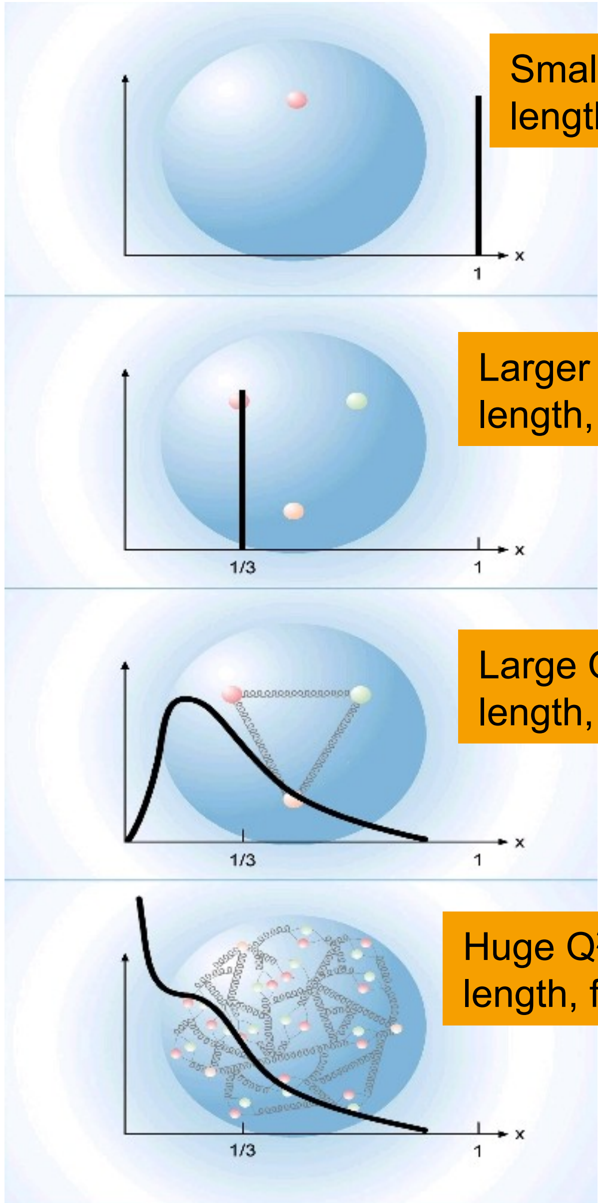
- Proton parton distribution functions – the structure of the proton
- Remember factorisation: $\sigma(s) = \sum_{ij} \iint dx_1 dx_2 f_{i/p}\left(x_1, Q^2\right) f_{j/p}\left(x_2, Q^2\right) \hat{\sigma}_{ij}\left(x_1, x_2, Q^2\right)$
  - Functions $f_{i/p}$, $f_{j/p}$ describe structure of the proton – probability to find parton of type I (quark, antiquark, gluon) with momentum fraction x_1 if looking with resolution Q^2.
  - Problem: Parton distributions not calculable from first principles – need precision data to derive them → HERA electron-proton collider!
  - Electron / photon acts as magnifying glass for proton structure; resolution ~1/Q !!!



With varying resolution λ~1/Q see more and more of the proton substructure
➔ $f_{i/p}$ depend on Q^2!

INCREASING RESOLUTION $\boxed{\lambda \propto 1/Q}$





Small Q^2, large wave length, proton as such

Larger Q^2, smaller wave length, resolve 3 partons

Large Q^2, small wave length, see fluctuations

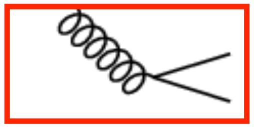
Huge Q^2, tiny wave length, full proton beauty!

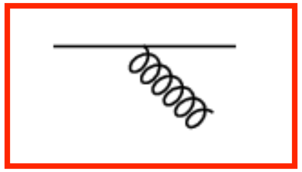
HERA INPUT

$$\frac{d^2\sigma}{dxdQ^2} \propto \frac{4\pi\alpha}{xQ^4} F_2\left(x,Q^2\right)$$

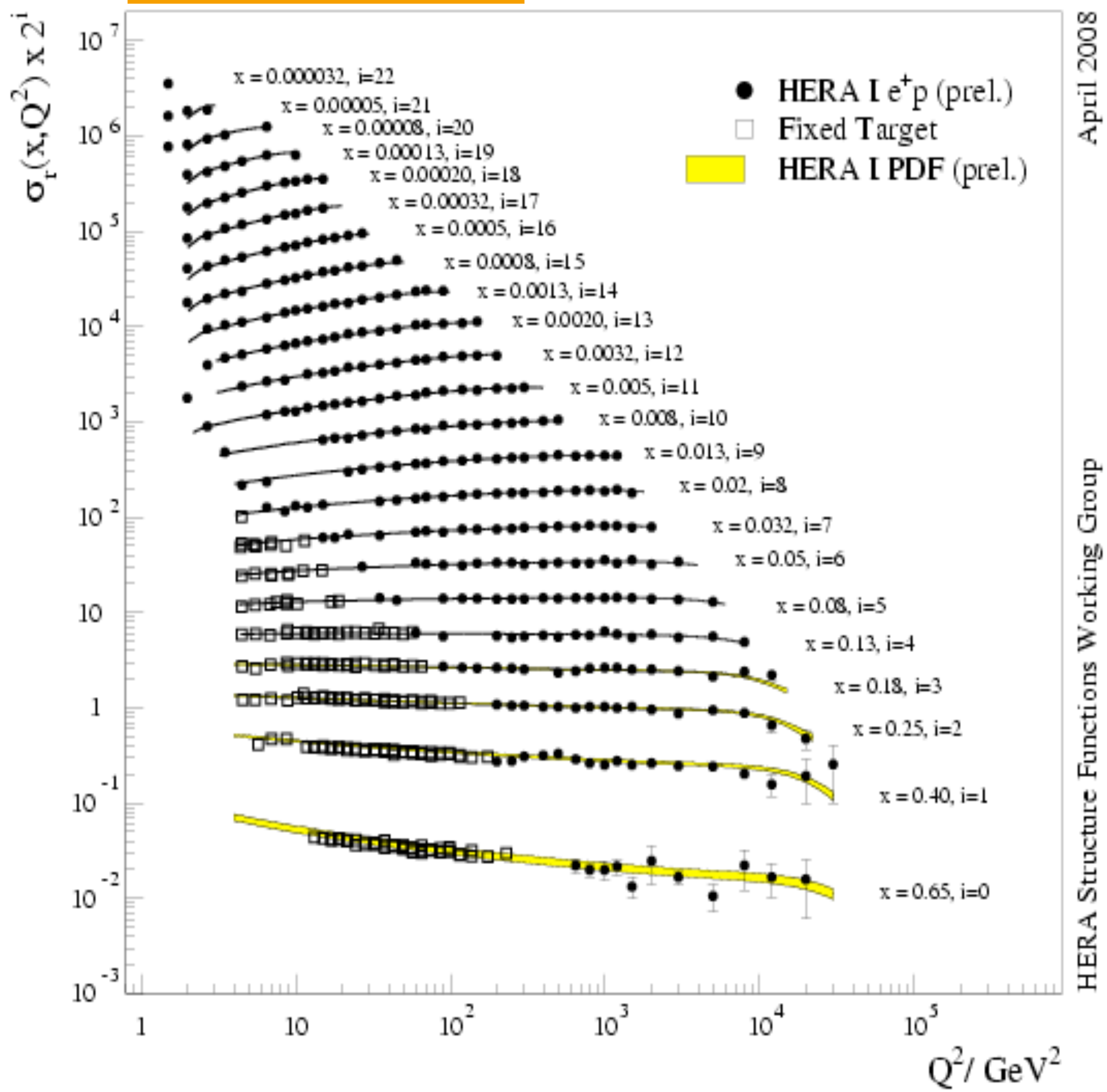
$$F_2 = F_2(x,Q^2) = \sum_i e_i^2 x f_{i/p}(x,Q^2)$$

Low x: With increasing Q^2 (resolution), more radiated gluons and quark pairs from g→ qq are seen!





High x: With increasing Q^2, less and less un-radiated partons are left here!



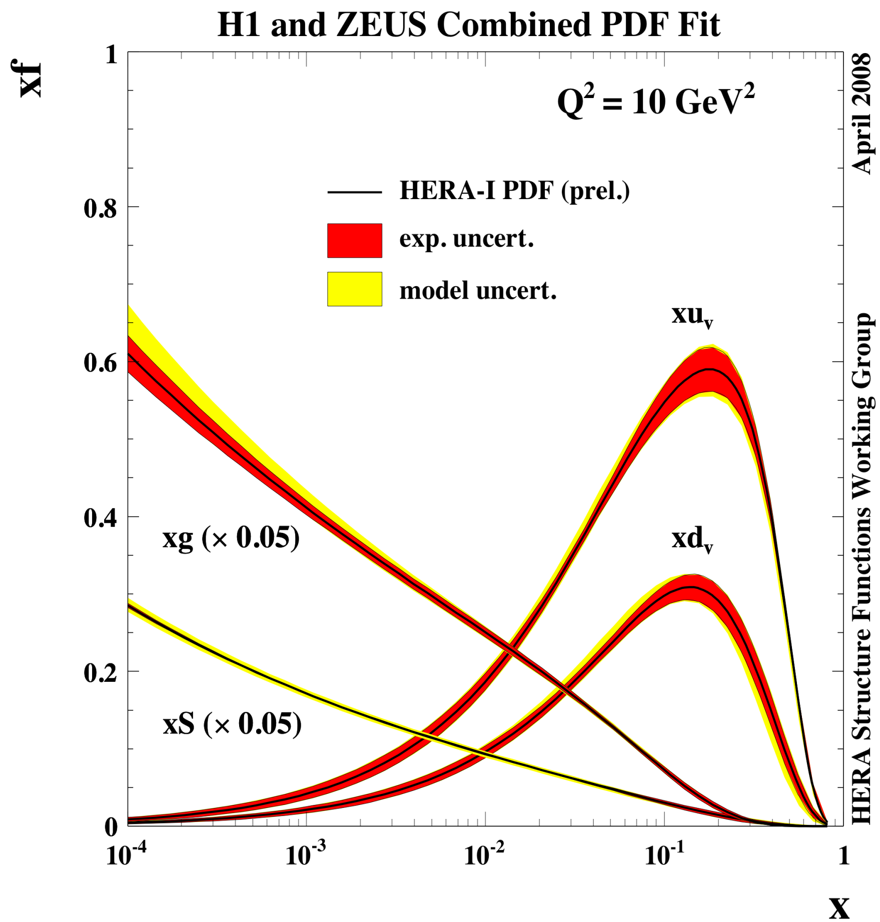
FROM STRUCTURE FUNCTIONS TO PDFs

- By means of "DGLAP evolution"
  - Connection F_2 to $f_{i/p}$:

$$\boxed{F_2 = F_2(x,Q^2) = \sum_i e_i^2 x f_{i/p}(x,Q^2)}$$

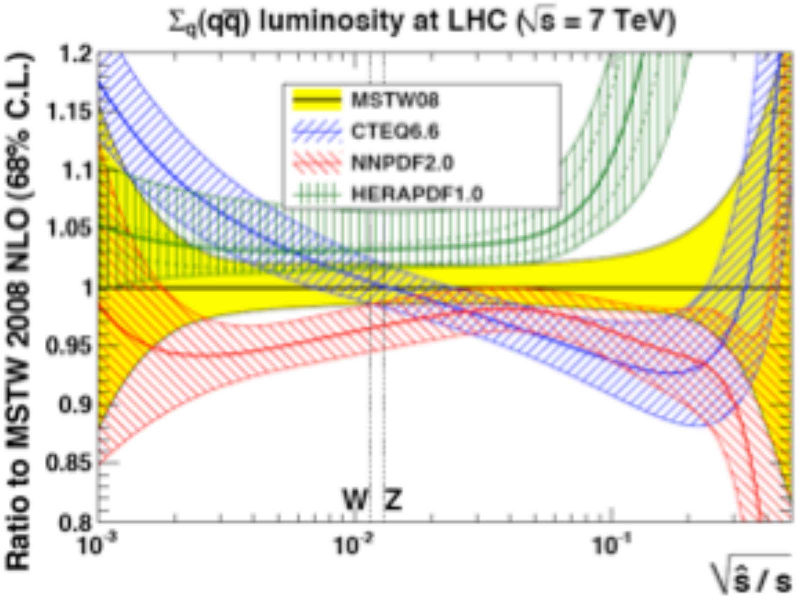
$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi} \cdot \int_x^1 \frac{dz}{z}\frac{x}{z}\left[P_{qq}\left(\frac{x}{z}\right)F_2(z,Q^2) + 2zP_{qg}\left(\frac{x}{z}\right)g(z,Q^2)\sum_i Q_i^2\right]$$

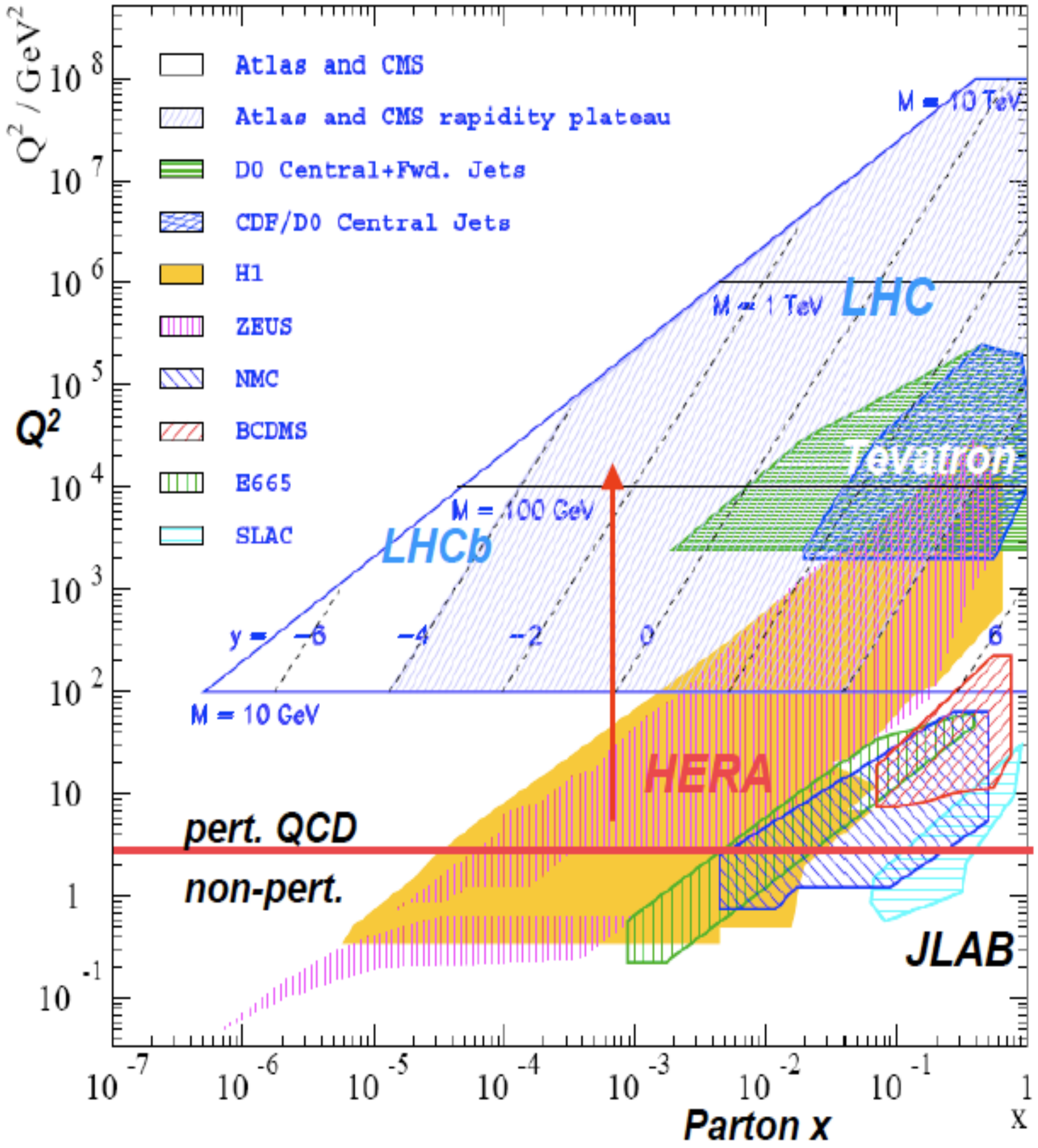
- Done by several groups, with slightly different concepts:
  - HERA-PDF, CTEQ, MSTW, AB(K)M, JR, NNPDF
- Strong rise of gluon density one of the important results of HERA!!!
- PDFs available via different libraries:
  - PDFLIB
  - LHAPDF
  - Interfaced to experiment-specific softwar



PDFs AT THE LHC

- Currently LHC experiments use the existing PDFs based on HERA and other data.
- Soon: crucial tests of PDFs using “candle” processes like W/Z production:
  - Input data from LHC!





PDFs AT THE LHC

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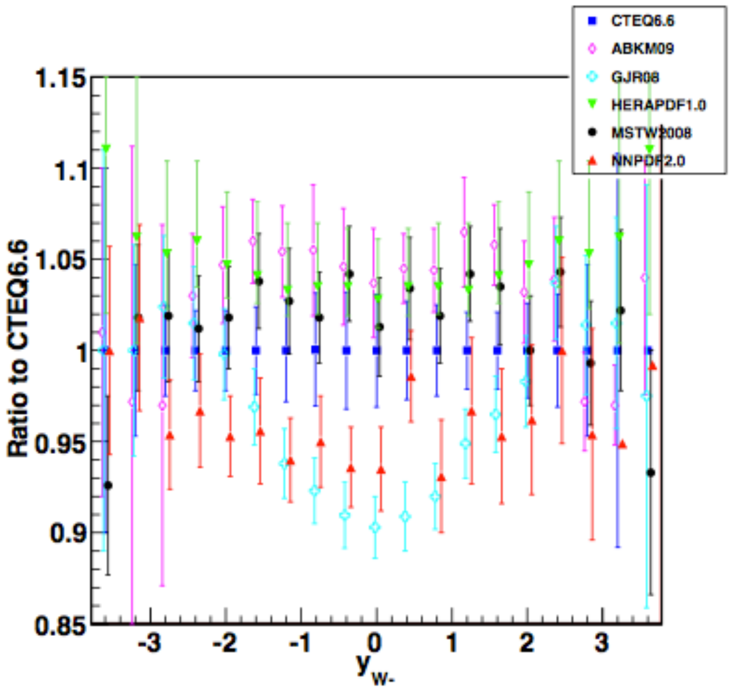
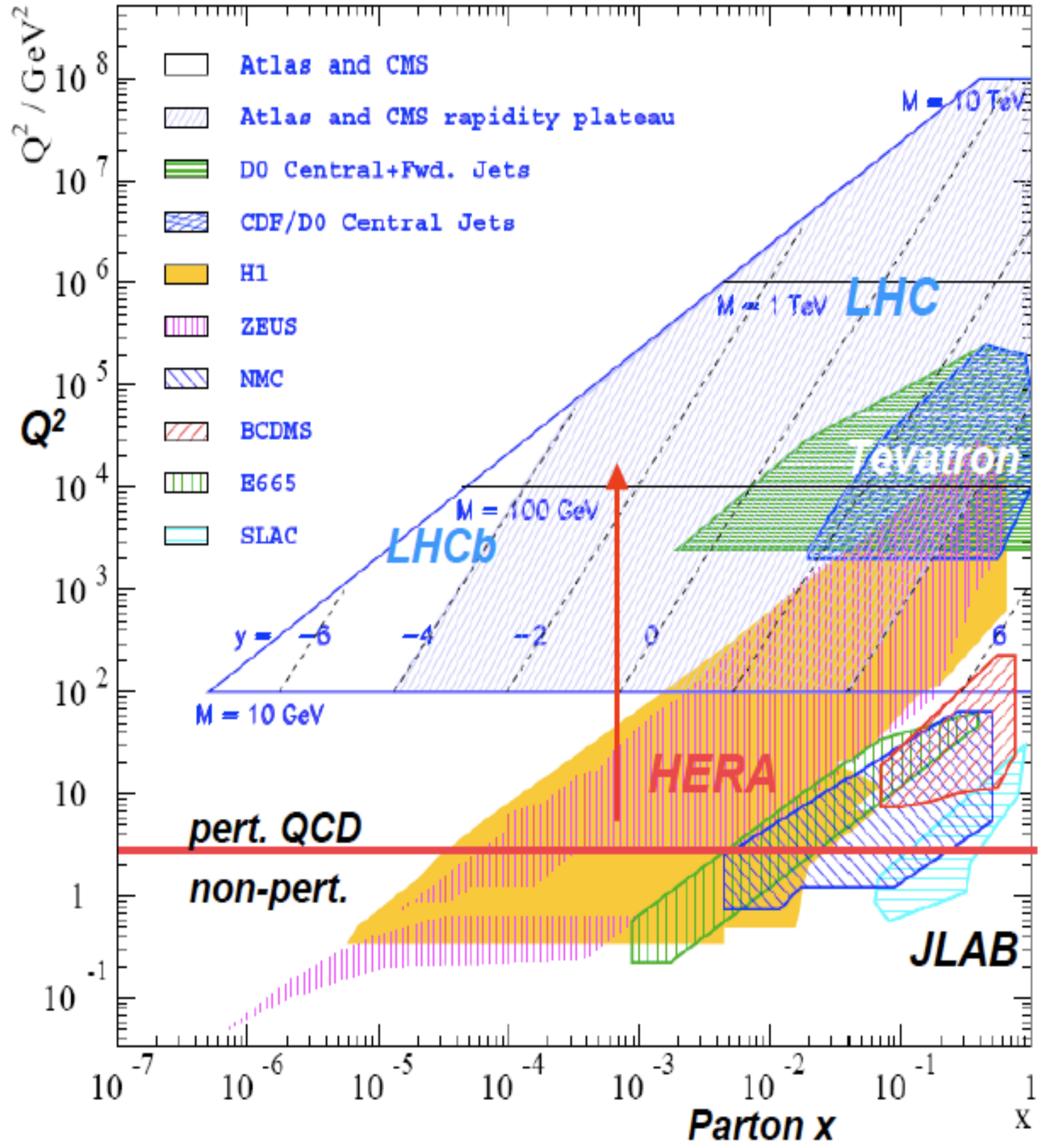
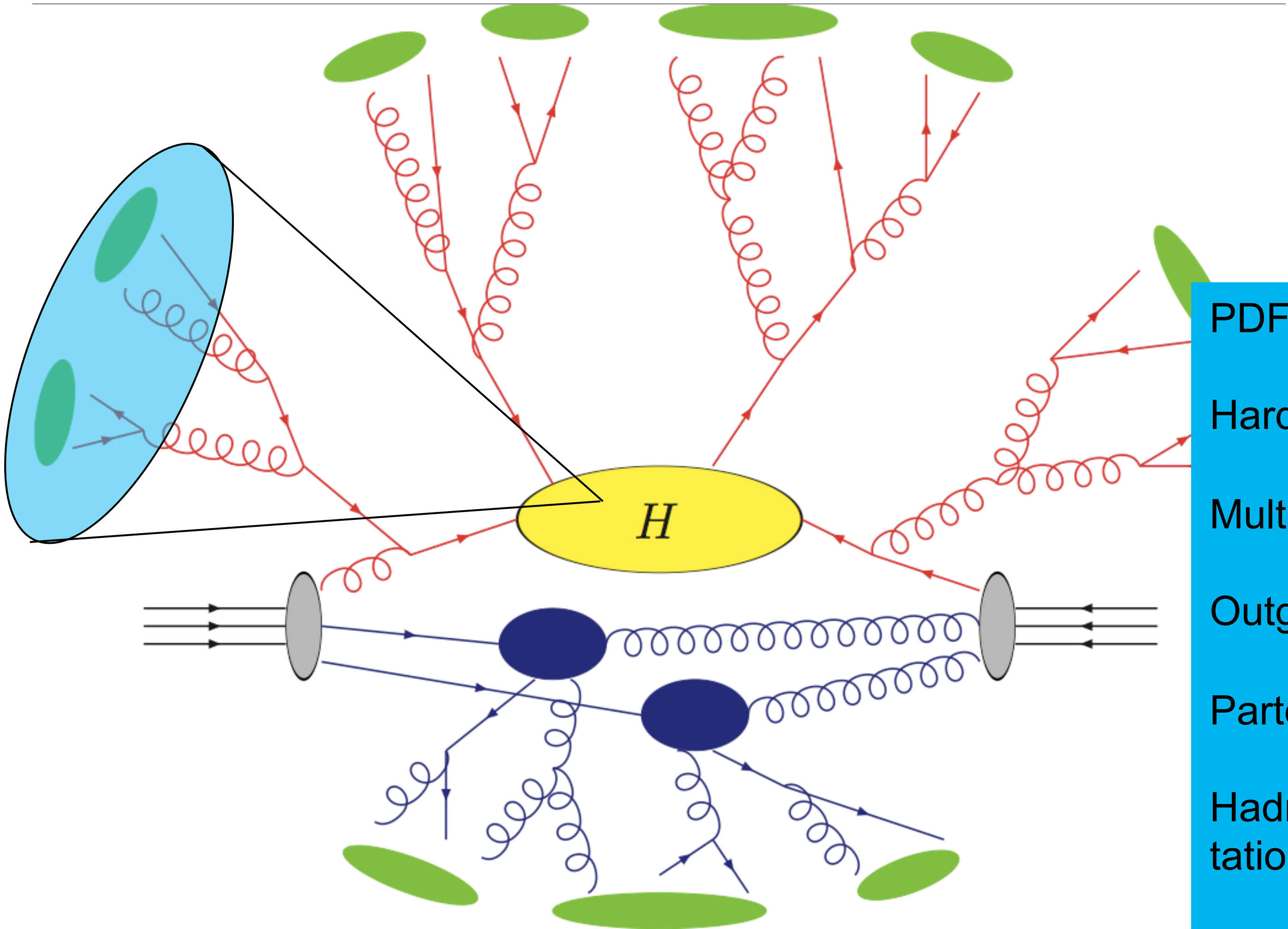
- Soon: crucial tests of PDFs using "candle" processes like W/Z production:





HARD QCD AND JETS

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



PDFs: incoming particles

Hard interaction

Multiple interactions

Outgoing partons

Parton showering

Hadronisation (fragmen-tation), decay

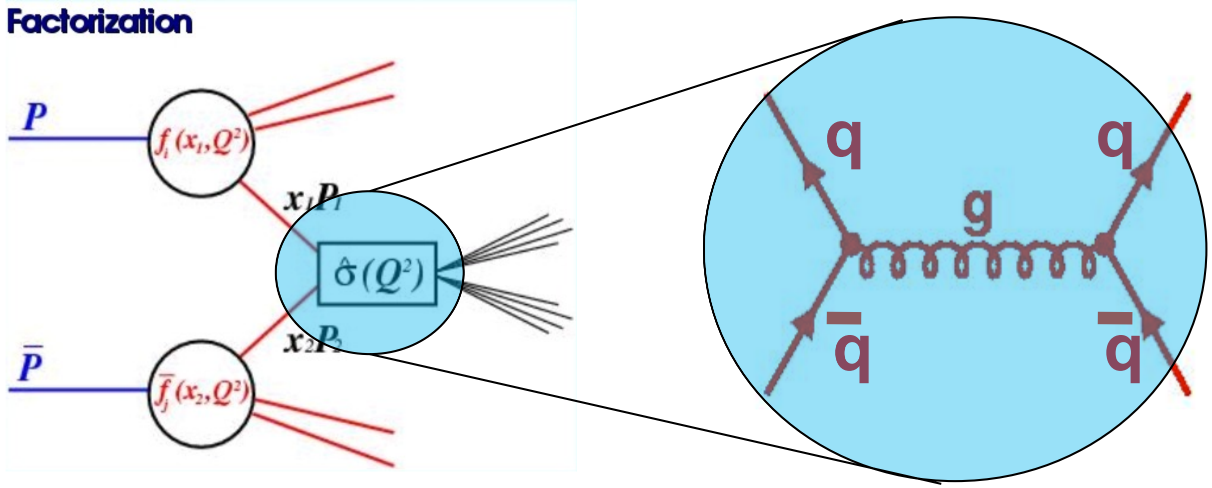
Jets

JETS IN HADRON COLLISIONS

> Remember factorisation:

$$\sigma = \sum_{ij} f_{i/p} \otimes \hat{\sigma}_{ij} \otimes f_{j/p}$$

- Simplest 2→2 process with incoming partons:
  - qq→qq, qg→qg, gg→gg, gg→qq



> Final-state quarks and gluons cannot exist freely → parton shower and hadronisation → bunches of hadrons → "hadronic jets".

- Simplest QCD signature: (balanced) pair of jets.
- Need "jet algorithm" to reconstruct jet (four-momentum) from hadrons / energy deposits in the detector.
- Then measure jet properties like transverse energy and momentum, (pseudo) rapidity, multiplicity, substructure, mass, dijet mass, angular correlations, …
- Compare to QCD theory!

JETS IN HADRON COLLISIONS

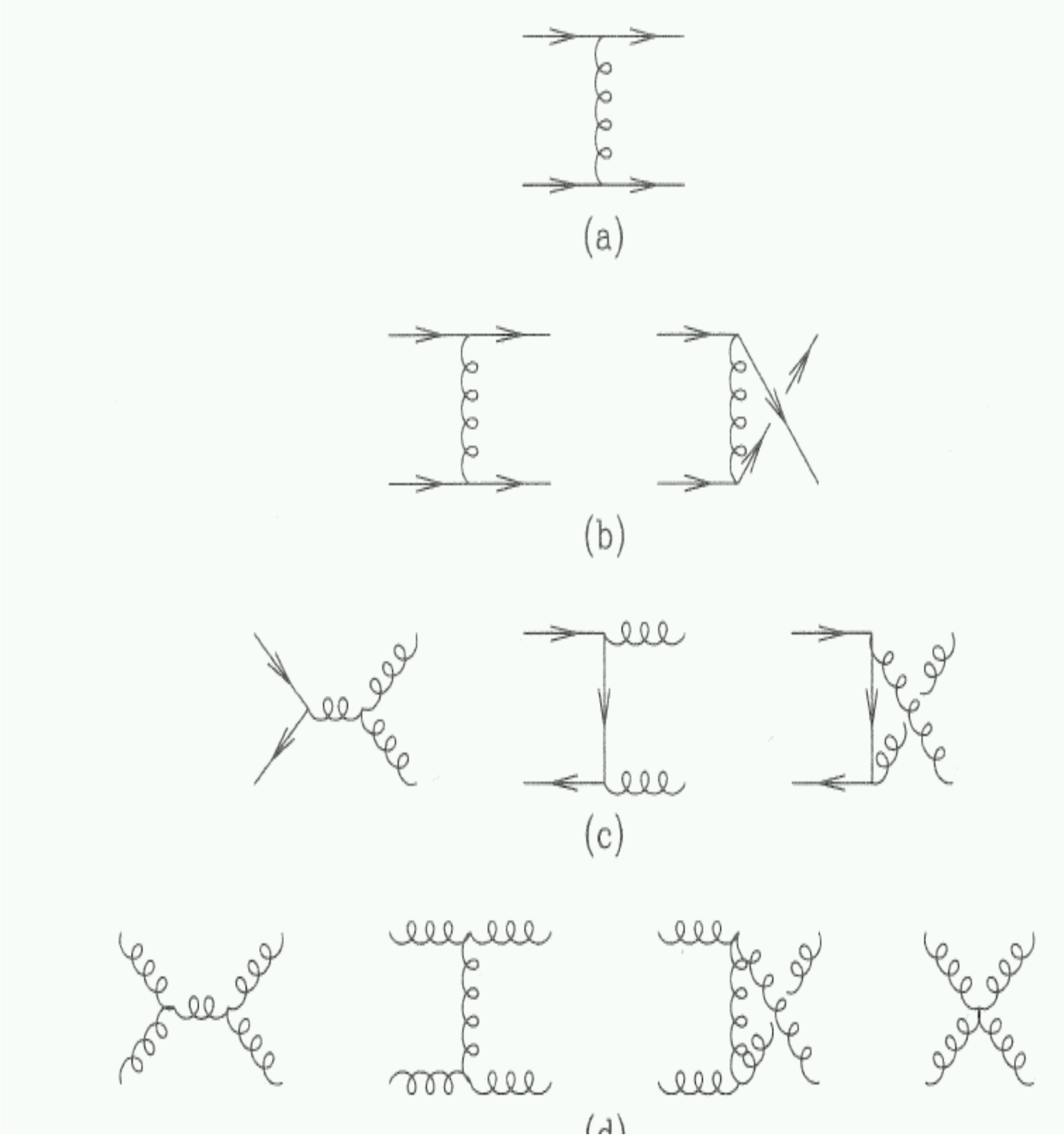
> Remember factorisation:

$$\sigma = \sum_{ij} f_{i/p} \otimes \hat{\sigma}_{ij} \otimes f_{j/p}$$

- Simplest 2→2 process with incoming partons:
  - qq→qq, qg→qg, gg→gg, gg→qq

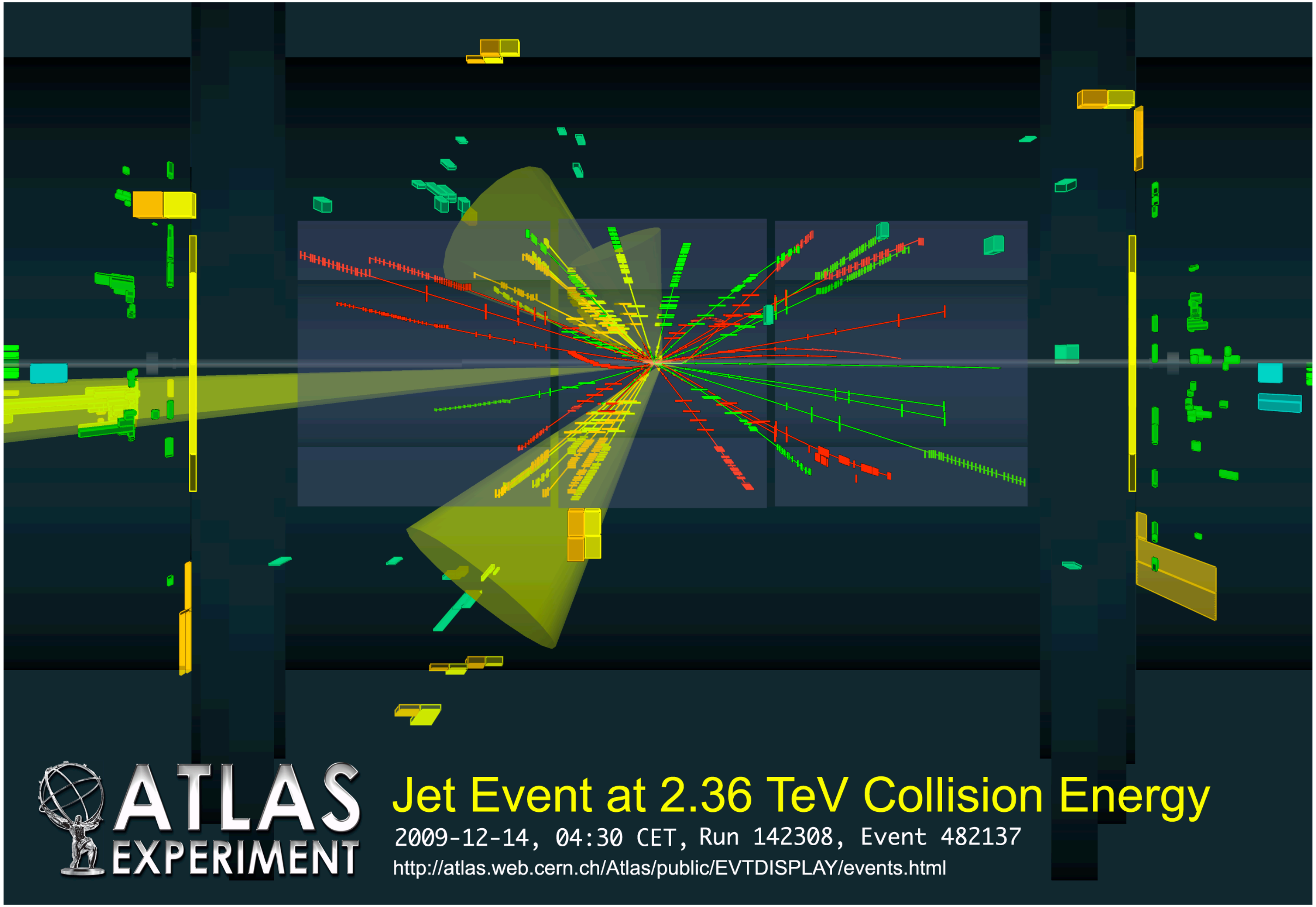
> All 2→2 processes.

  - All in current calculations, plus virtual+real corrections (everything up to "next-to-leading" order (NLO).



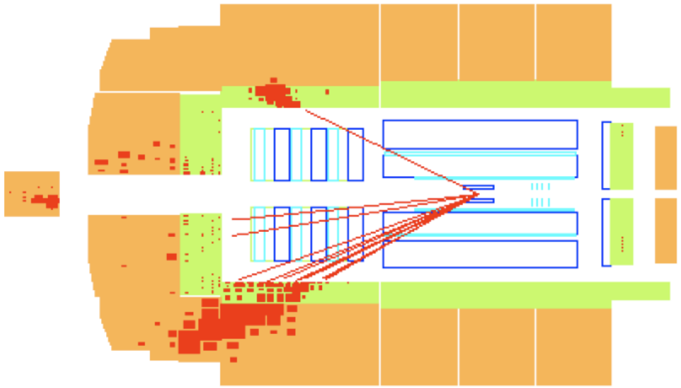
JET PHYSICS

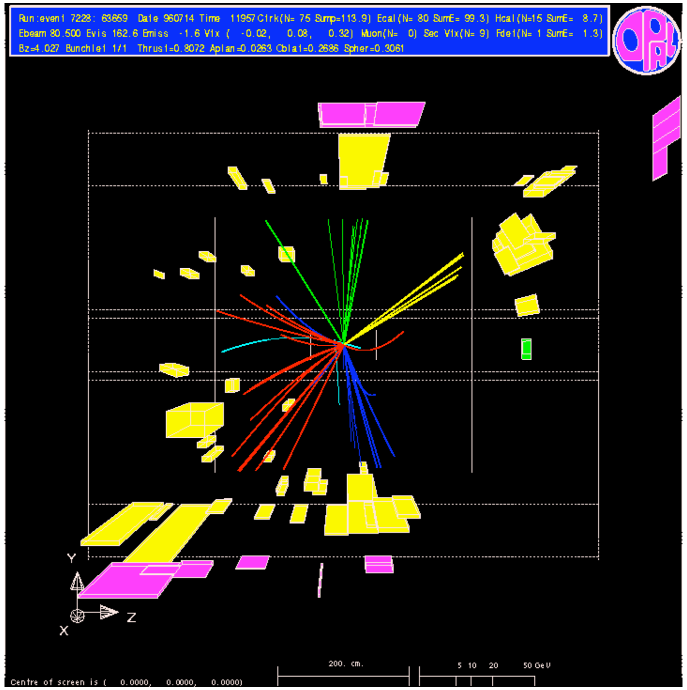
- … at different experiments:

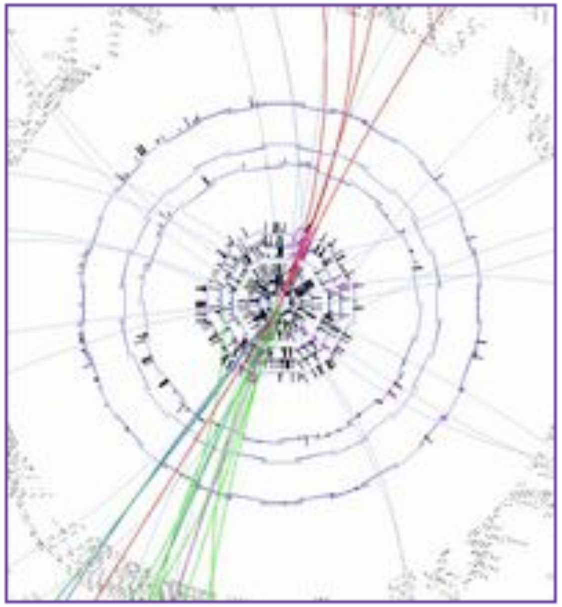


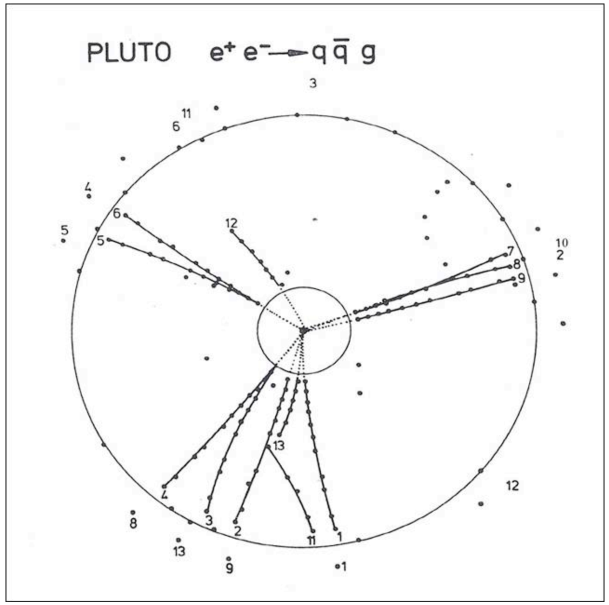
JET PHYSICS

> … at different experiments:



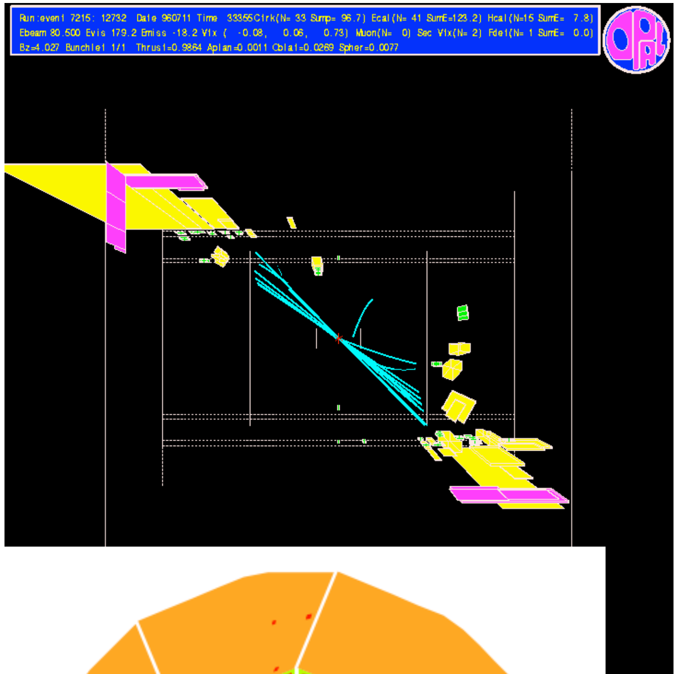


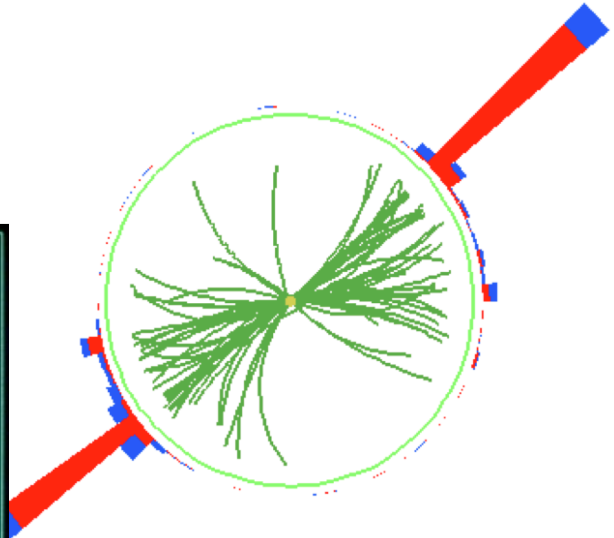


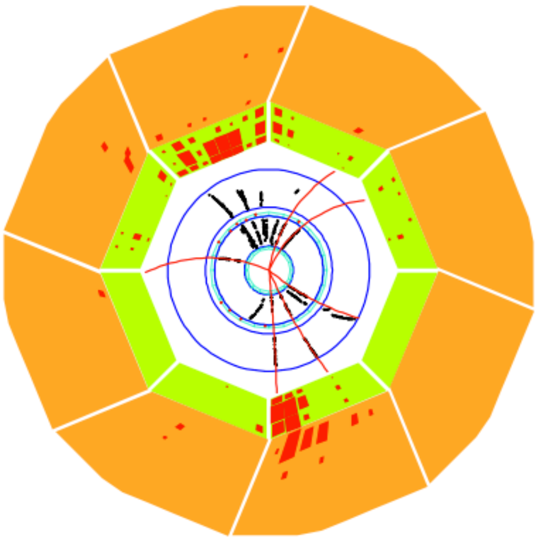


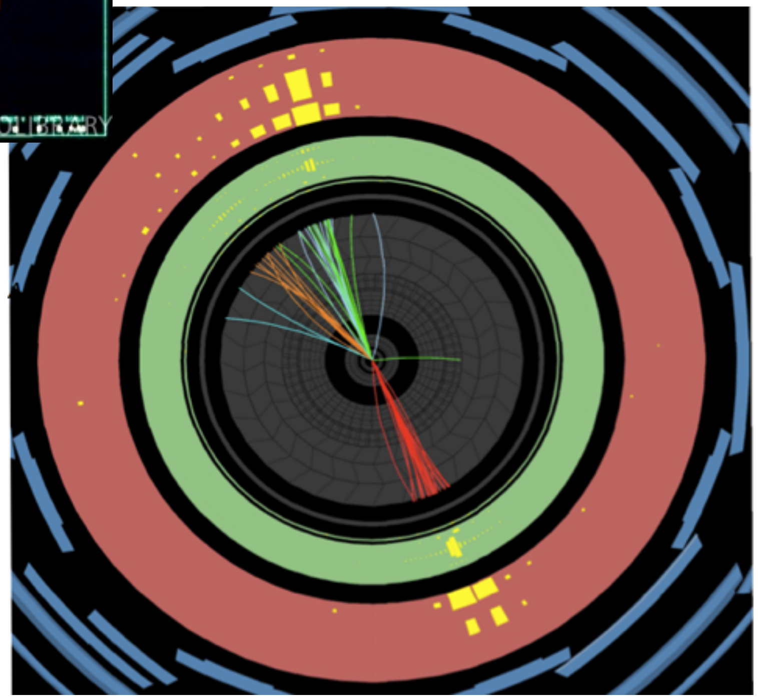
JETS IN HADRON COLLISIONS

- p_T balance of dijets in various 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!

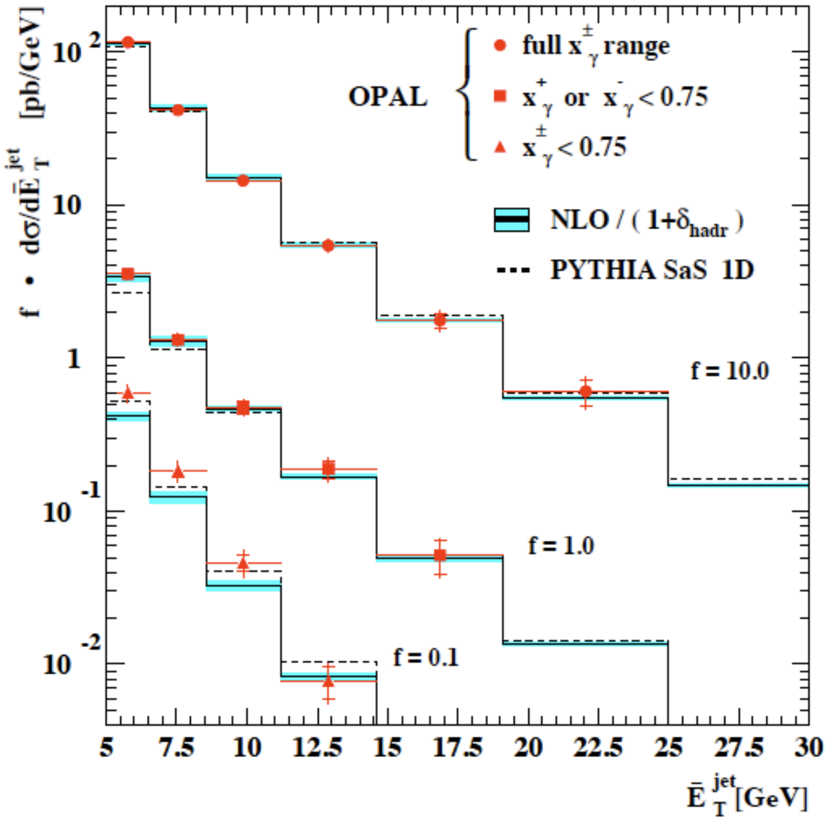
- A jet algorithm is a mathematical prescription for clustering the objects of the final state (if possible both in the experiment and for theoretical predictions and models).
- Different classes of algorithms, different fields of applications (hadron colliders, lepton colliders, HERA, …), different 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, …

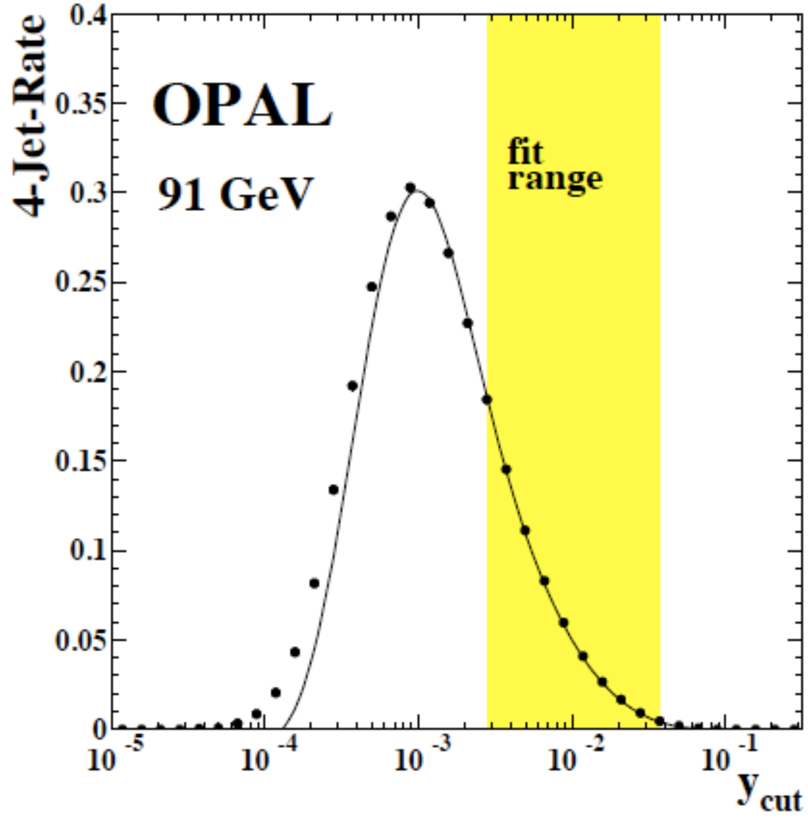
> Currently two classes of algorithms used: cluster algorithms and cone-based algorithms

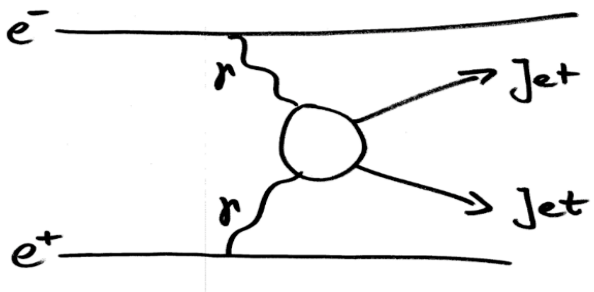
- Historically, the Tevatron experiments tended to cone-based algorithms, e+e- and HERA to clustering algorithms;
- At LHC, both collaborations study a multitude of different algorithms.

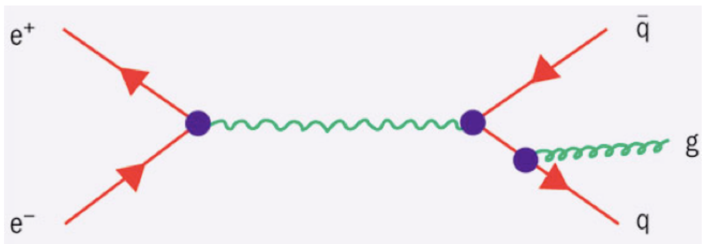
JET PHYSICS: RESULTS FROM LEP

- In ee→qq(q,q) or in γγ collisions:



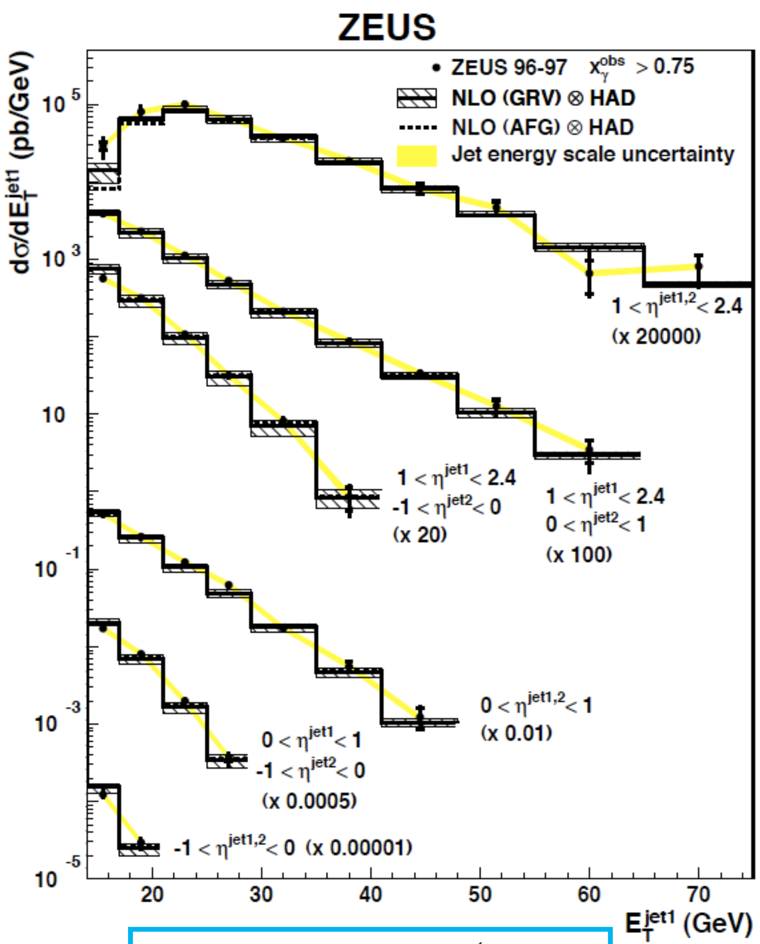


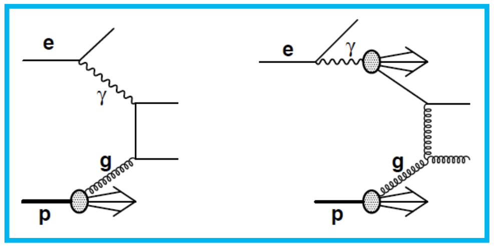


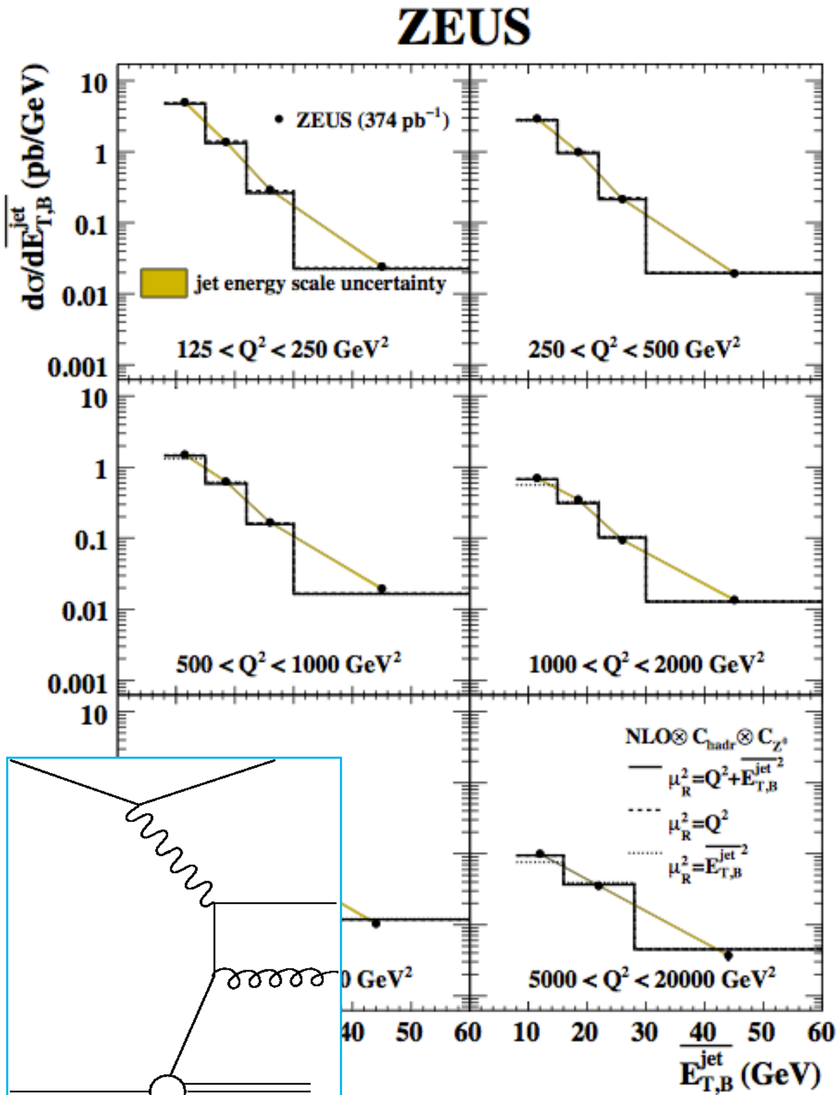


JET PHYSICS: RESULTS FROM HERA (1)

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







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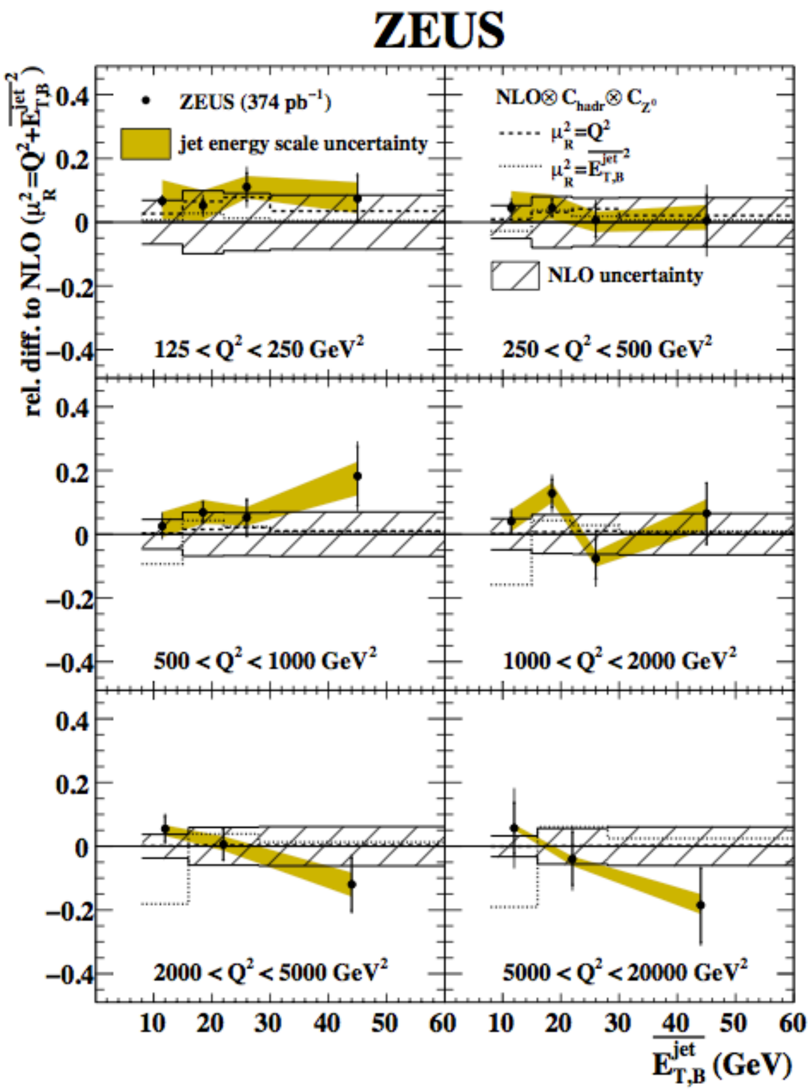
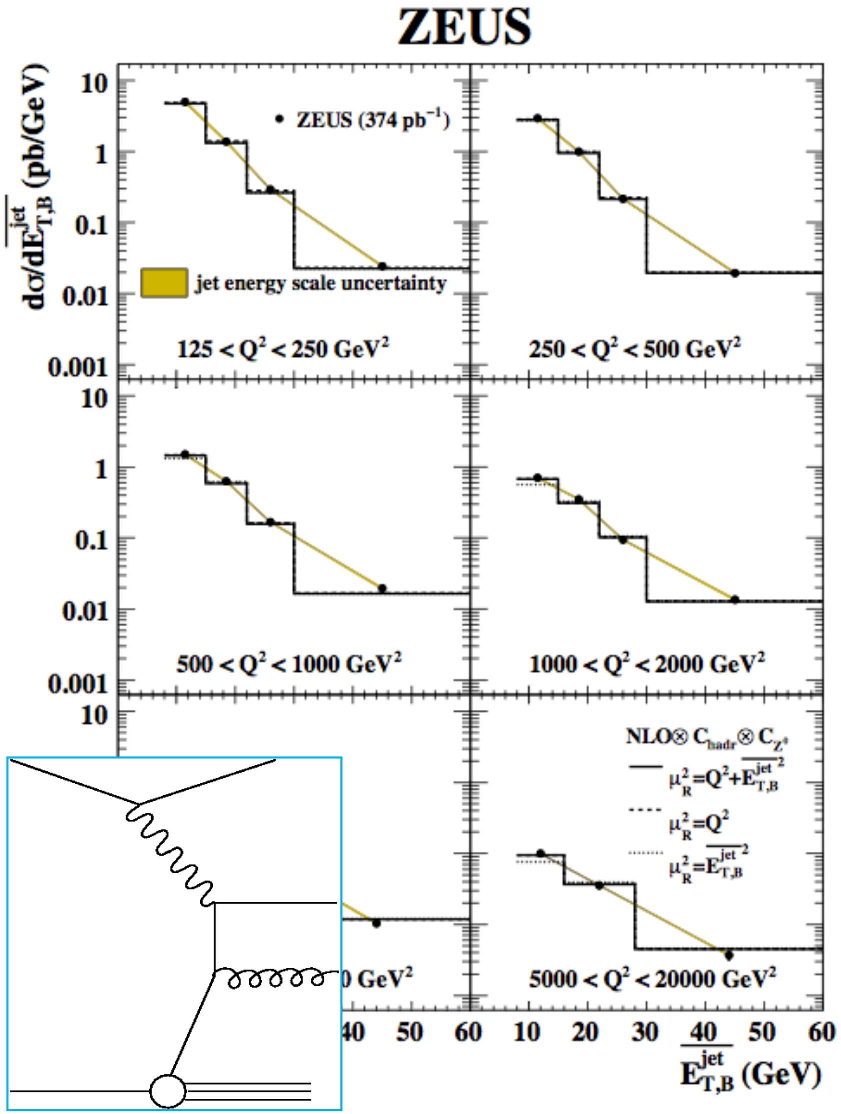
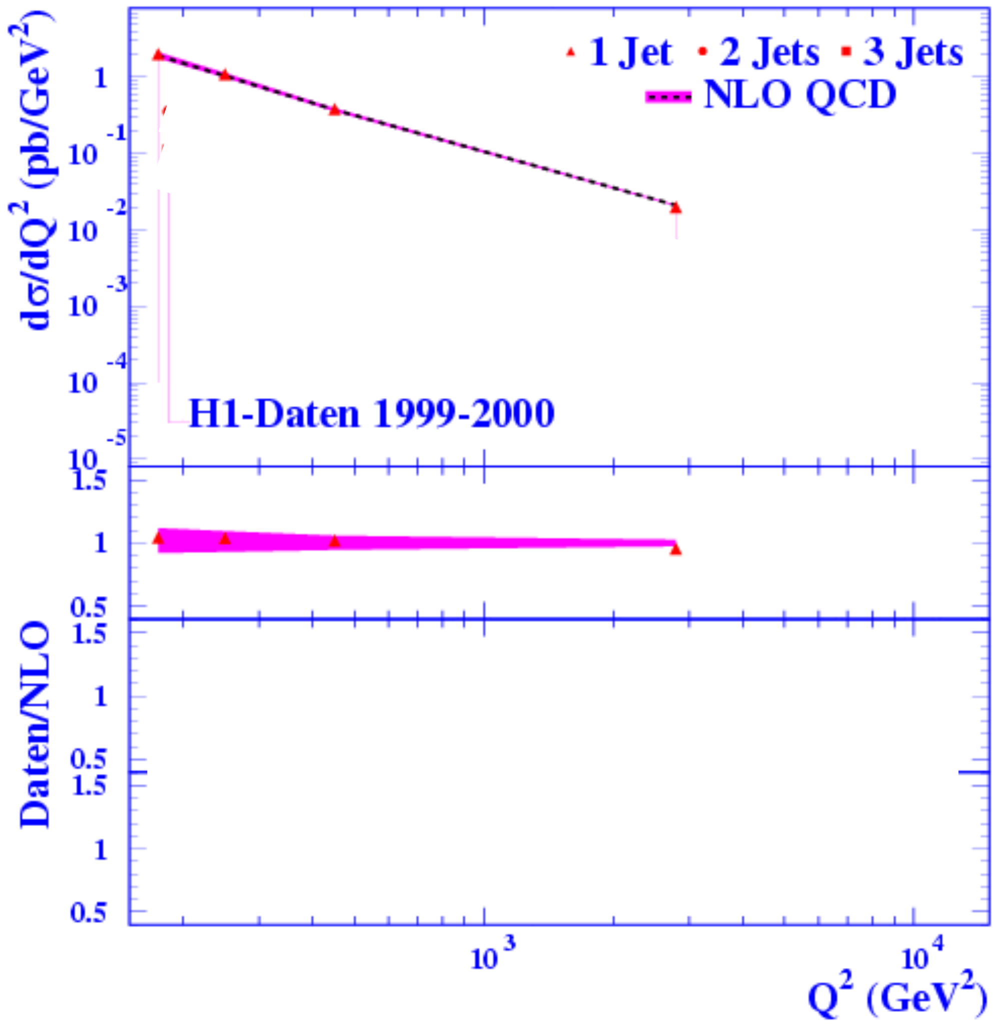


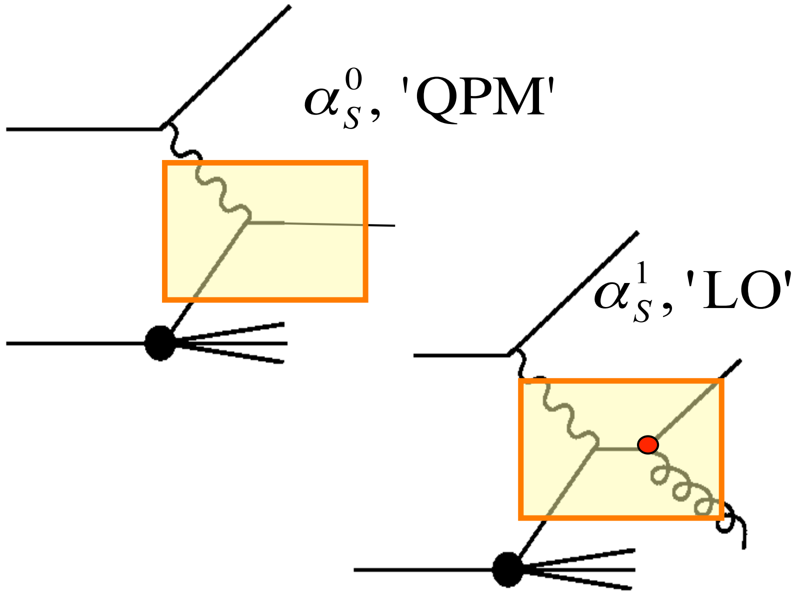


JET PHYSICS: RESULTS FROM HERA (2)

> Comparison of 1,2,3 jet production!

- Clearly visible: Effect of α_S for each additional radiation (plus phase space)





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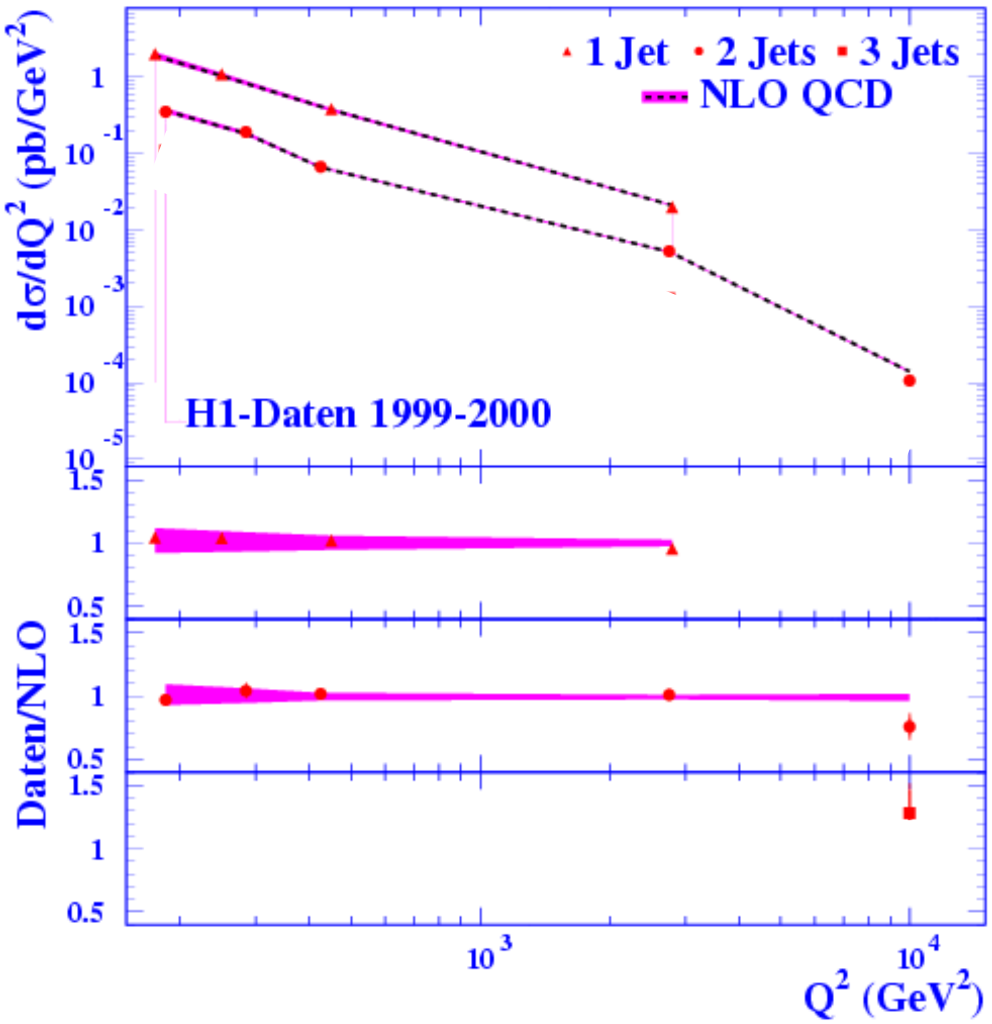

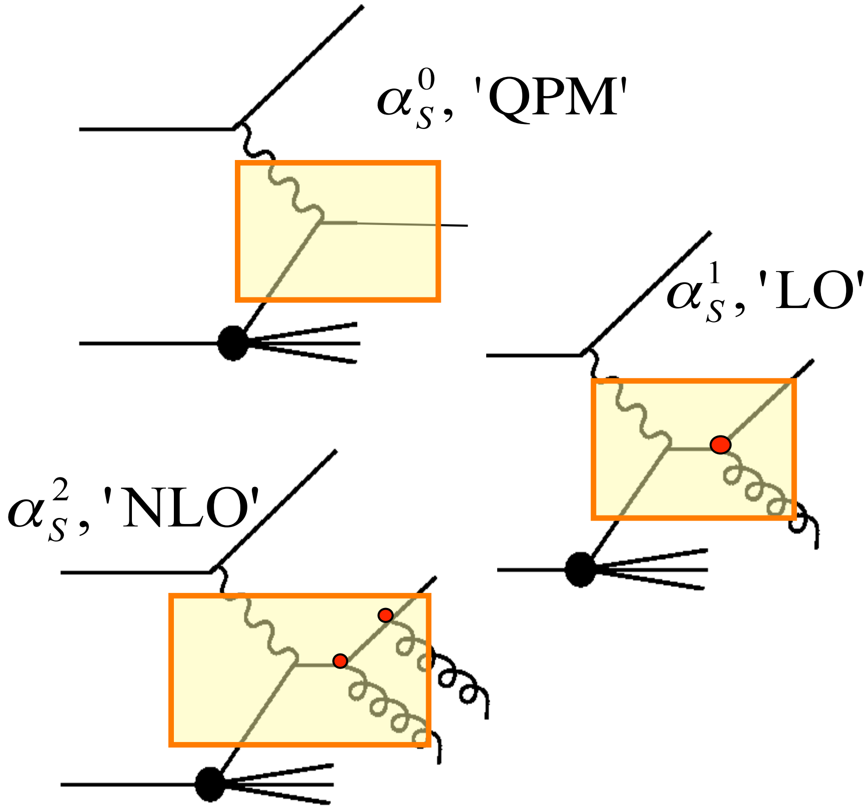

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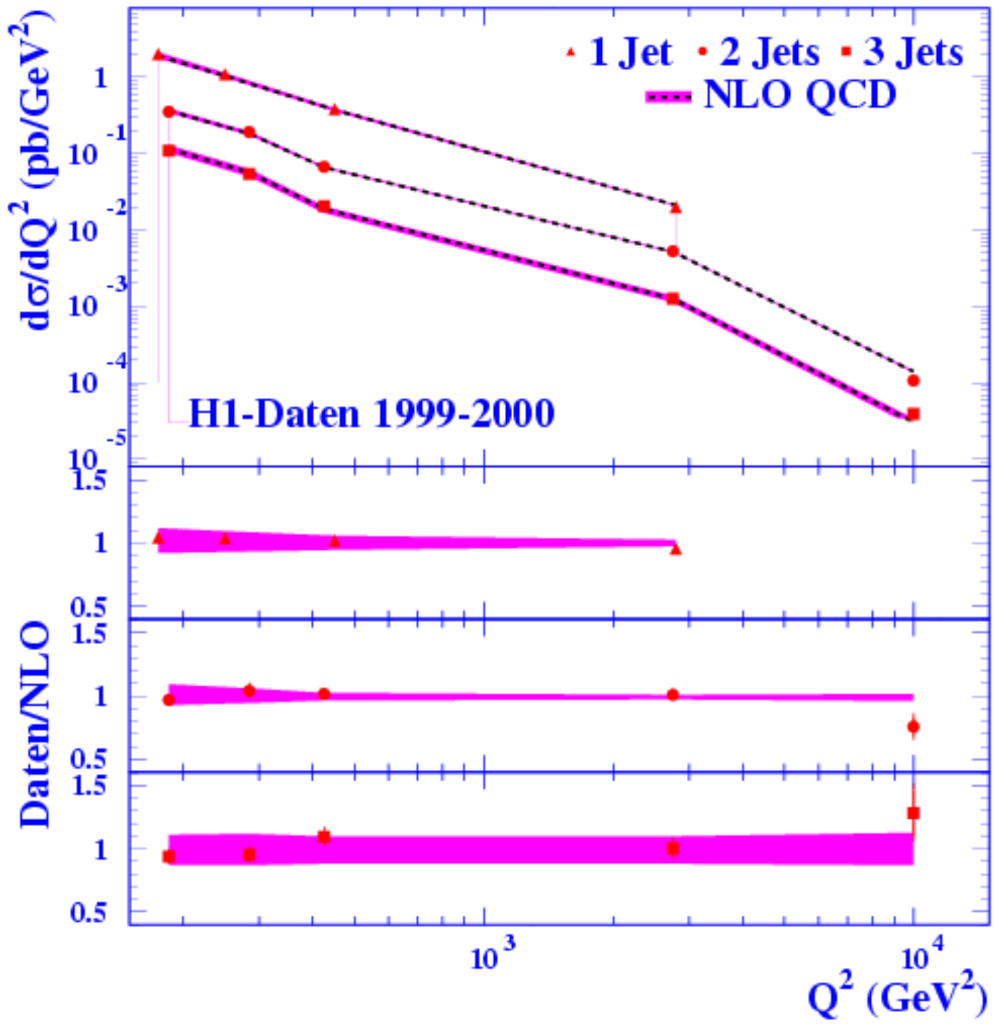
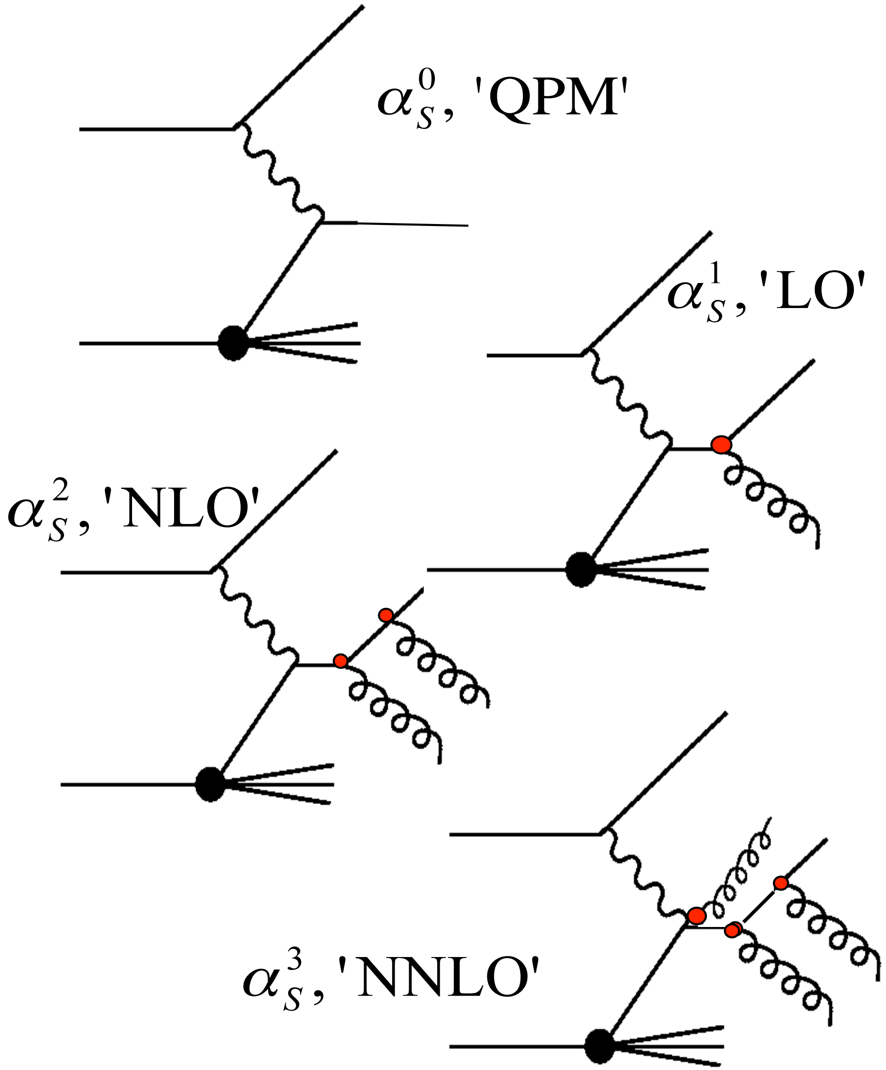
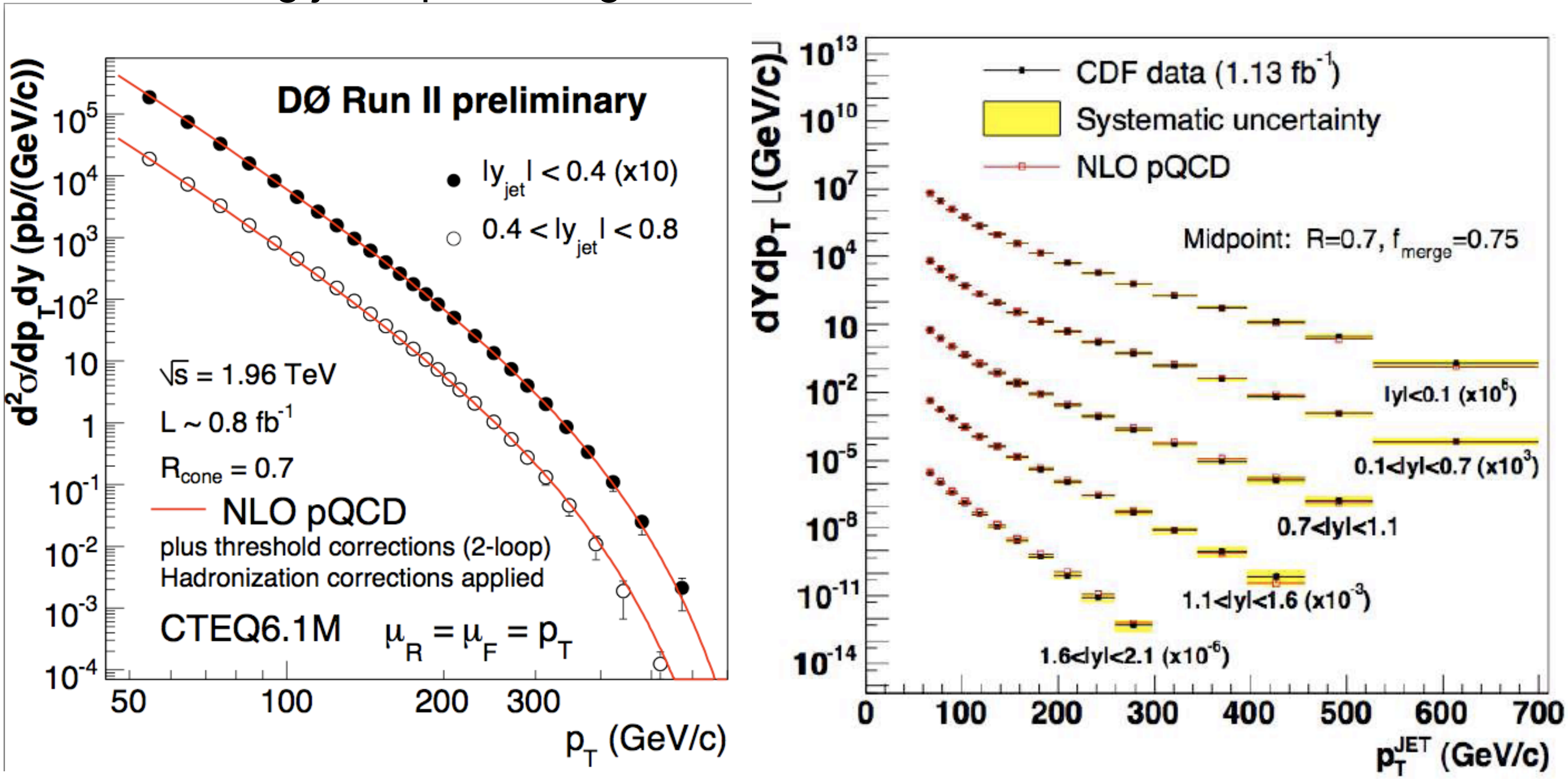




JET PHYSICS: RESULTS TEVATRON

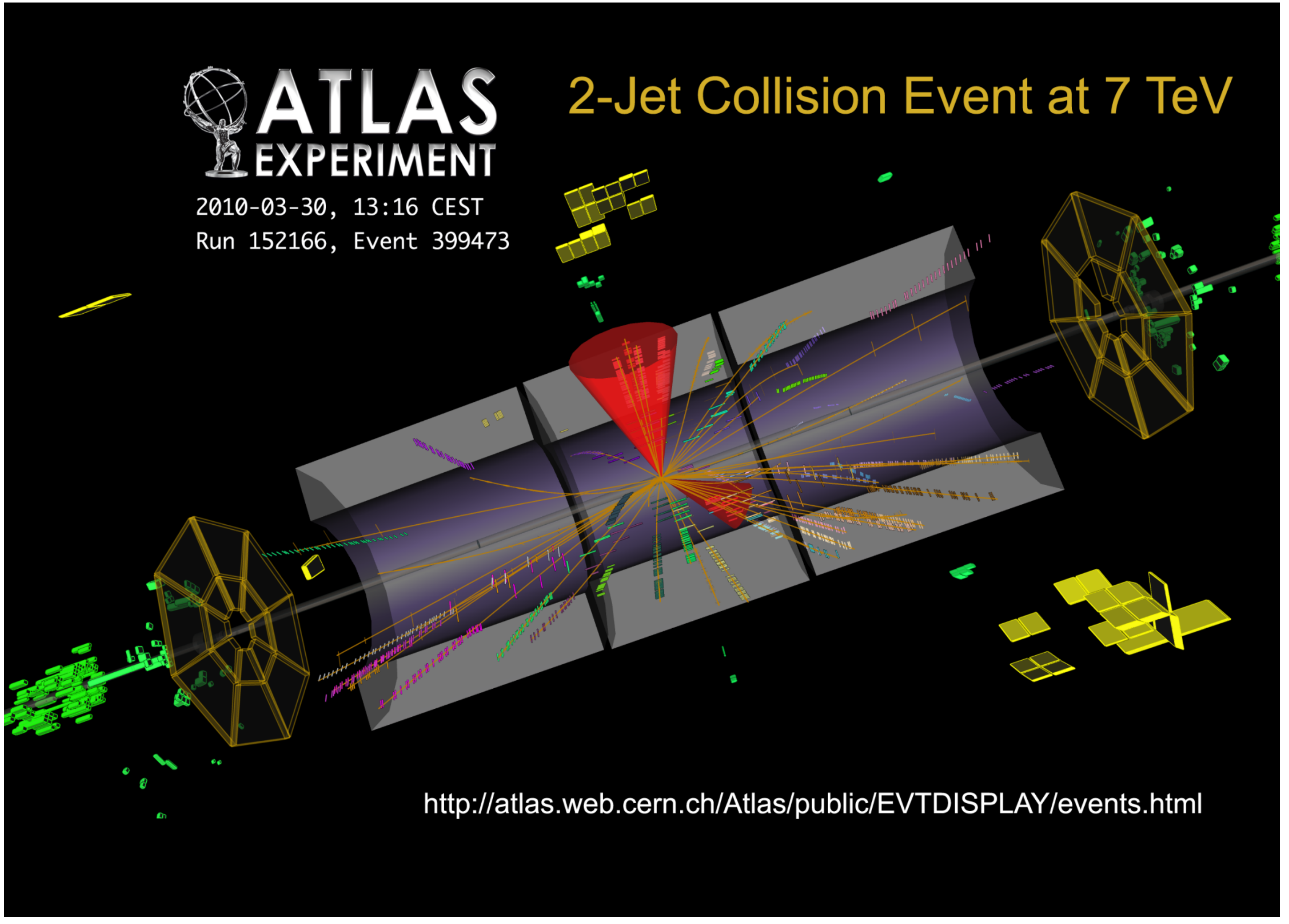
- Measuring jets up to energies of 600 GeV!!!!



- Nice description by NLO QCD calculations! In contrast to HERA, rather experimentally limited (jet energy scale uncertainty).

JET PHYSICS AT THE LHC

> Tests of hard QCD, and discovery potential (e.g.dijet resonances, later)



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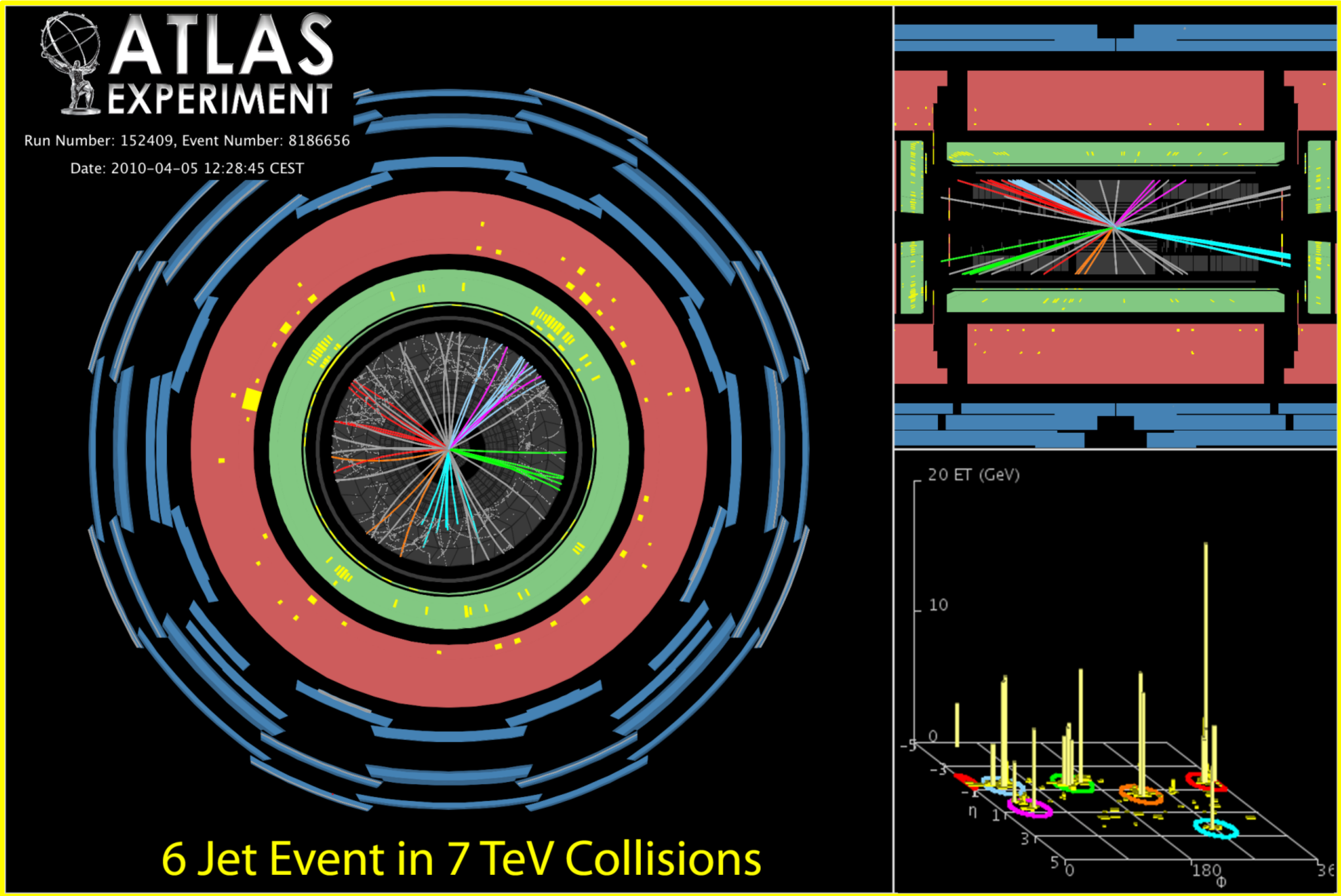
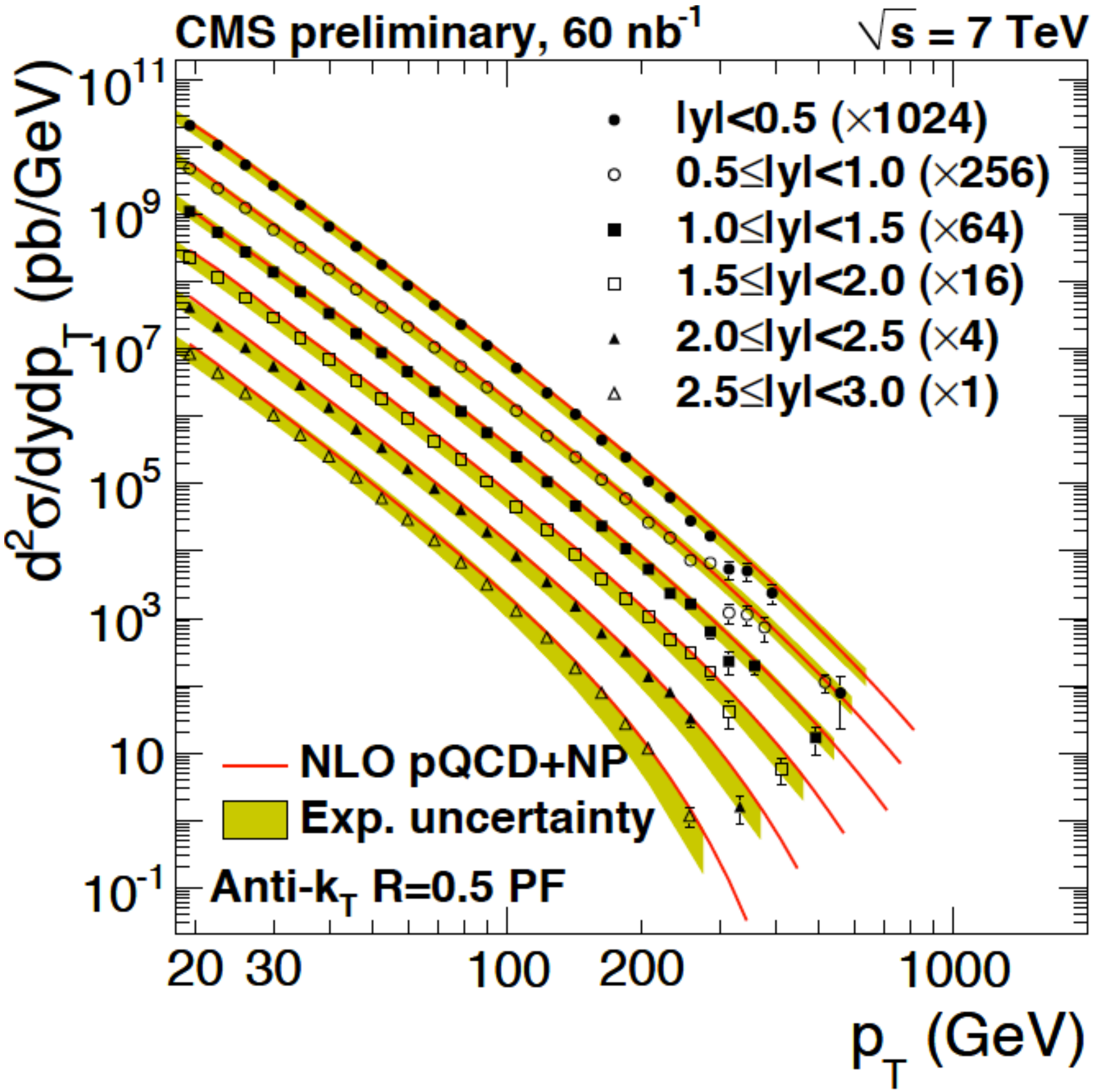


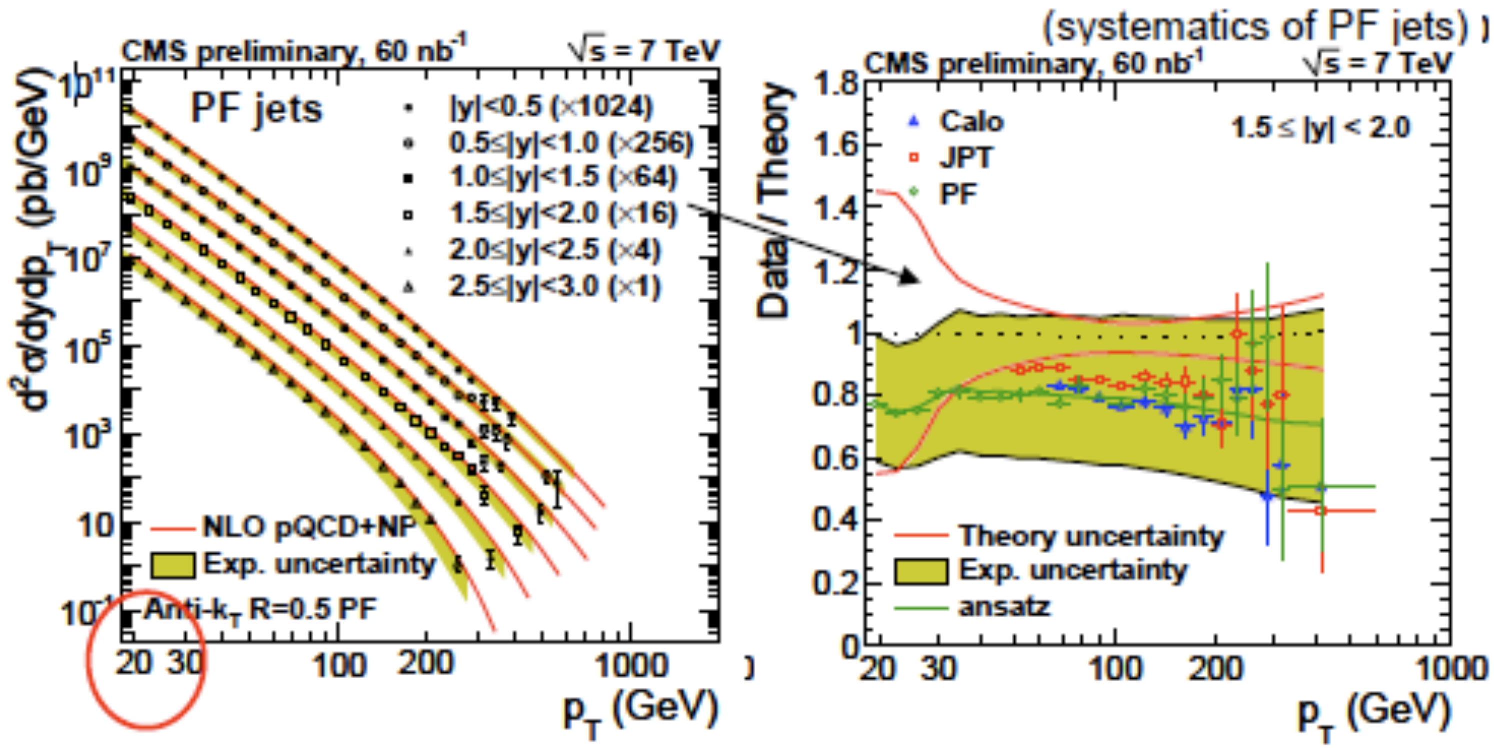
JETS IN HADRON COLLISIONS

- Inclusive jet cross section, CMS



JET PHYSICS

> Inclusive jets measured by CMS compared to NLO calculations corrected for non-perturbative effects.

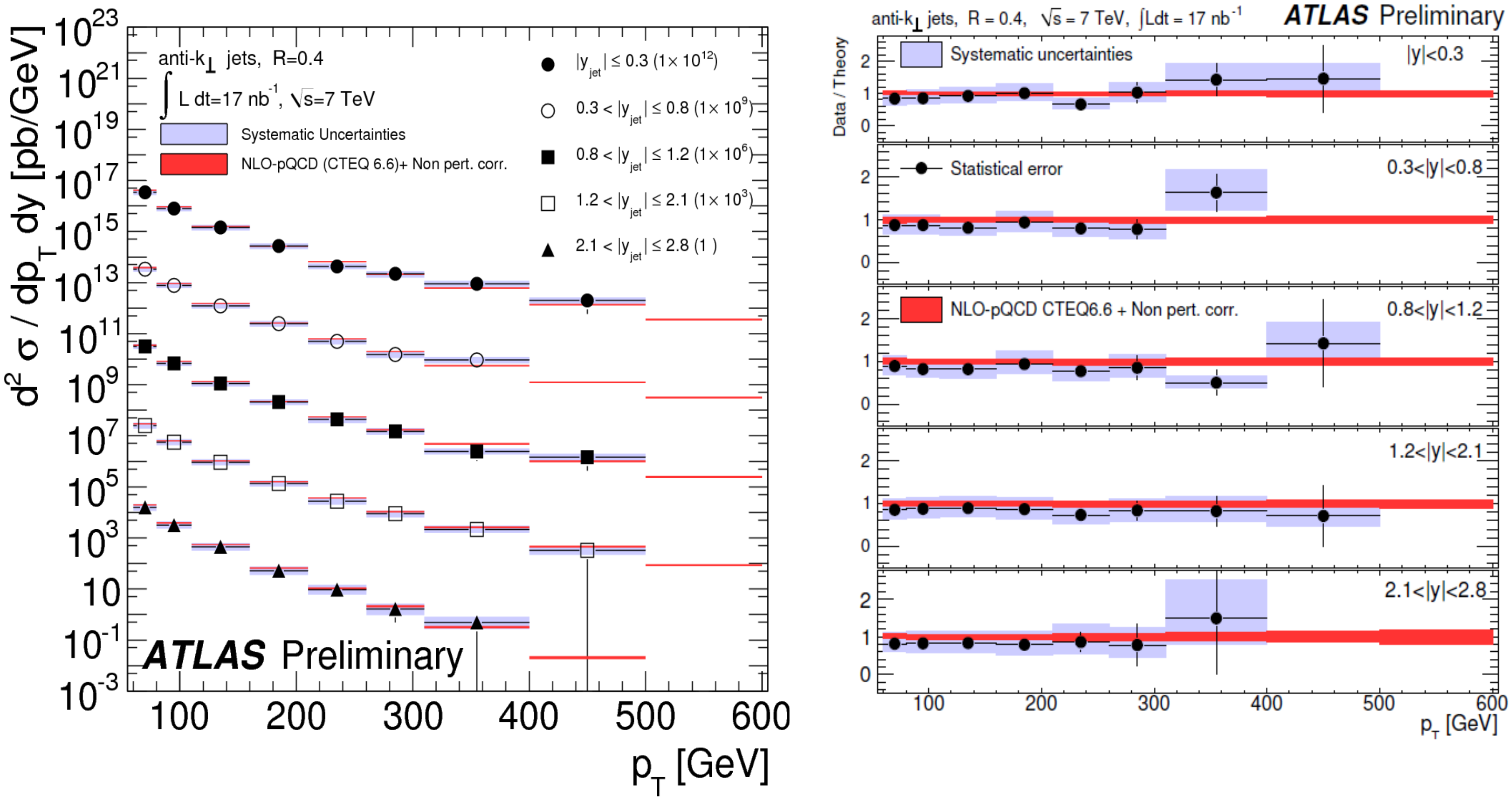


- Few % difference in JES between algos → 10% on the xsec

> Good description by QCD calculations. Uncertainties depend a lot on eta and p_T, room for improvement!

JET PHYSICS

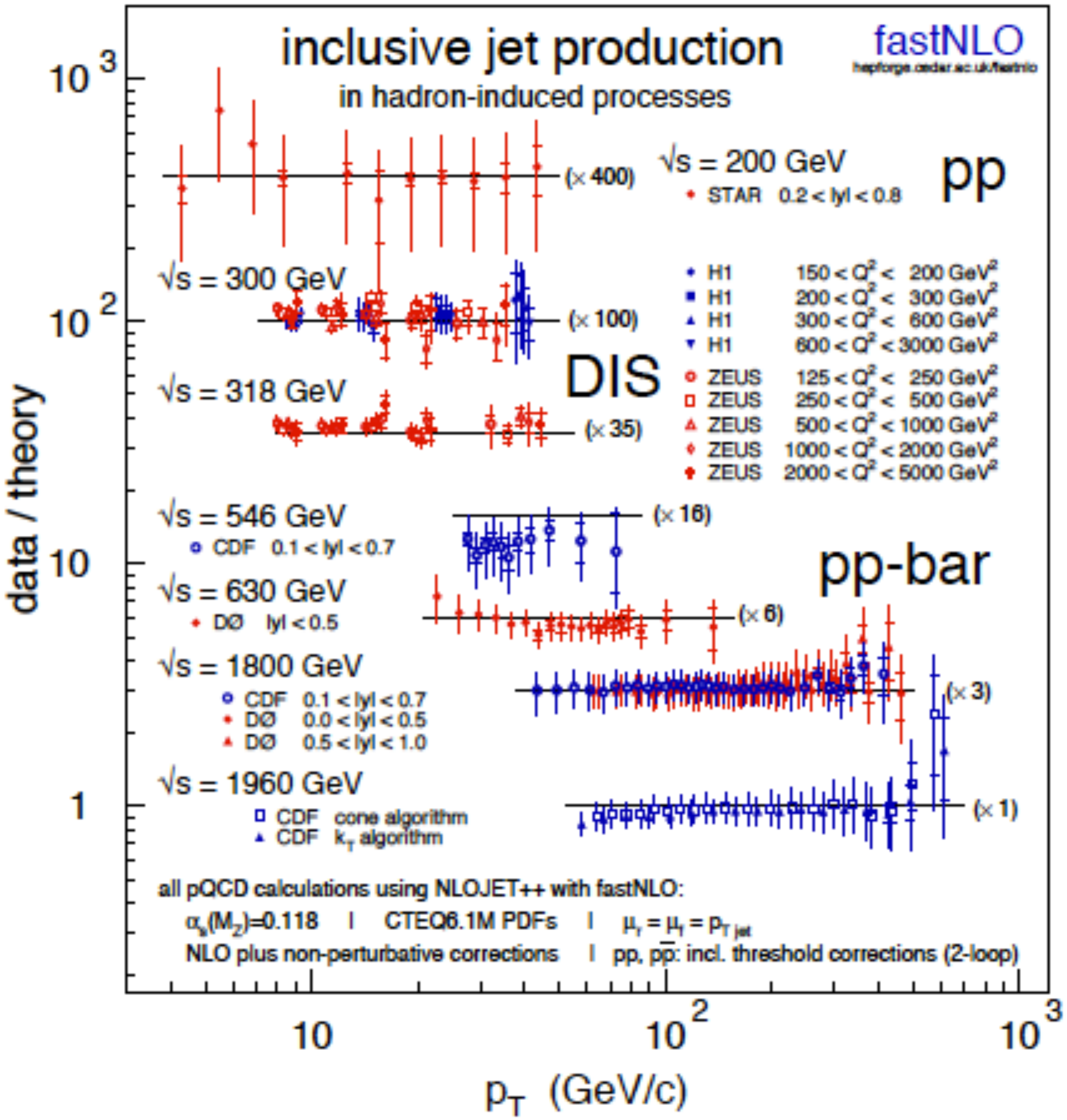
> Inclusive jets measured by ATLAS compared to NLO calculations corrected for non-perturbative effects.



> Good description by QCD calculations.

INCLUSIVE JETS - WORLD DATA

- Overview of jet production data from various colliders and experiments.
- Excellent agreement of data with NLO QCD calculations
- QCD as a "precision theory"!!!
- Important input to the understanding of back-grounds to searches.



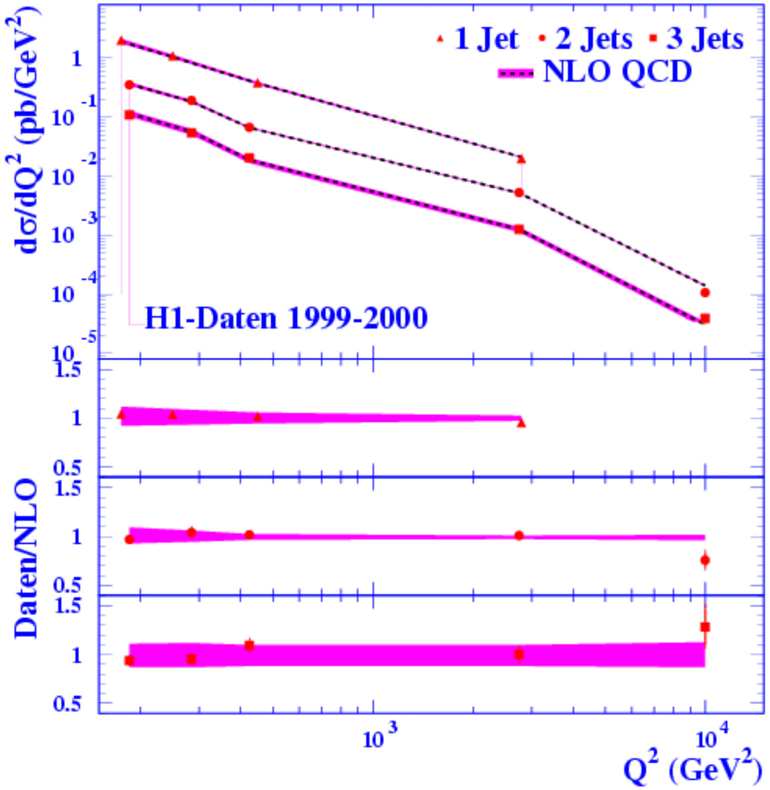
DI/TRIJETS/MULTIJETS

> Remember factorisation: Each additional jet suppressed by α_S.

> More jets / final-state particles
→ more complex QCD dynamics!

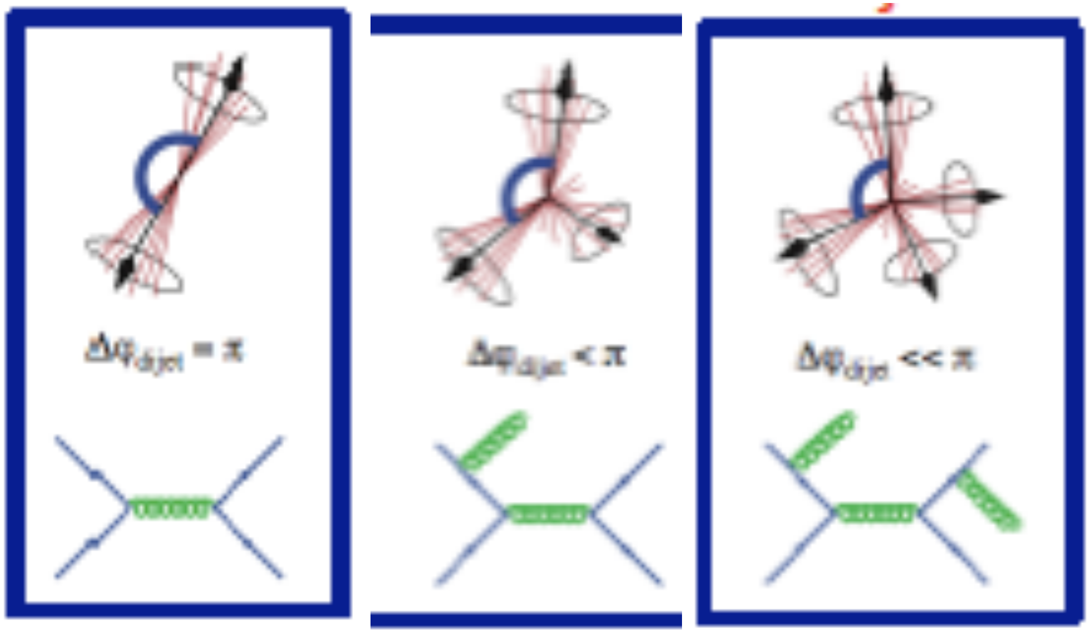
> Many interesting studies:

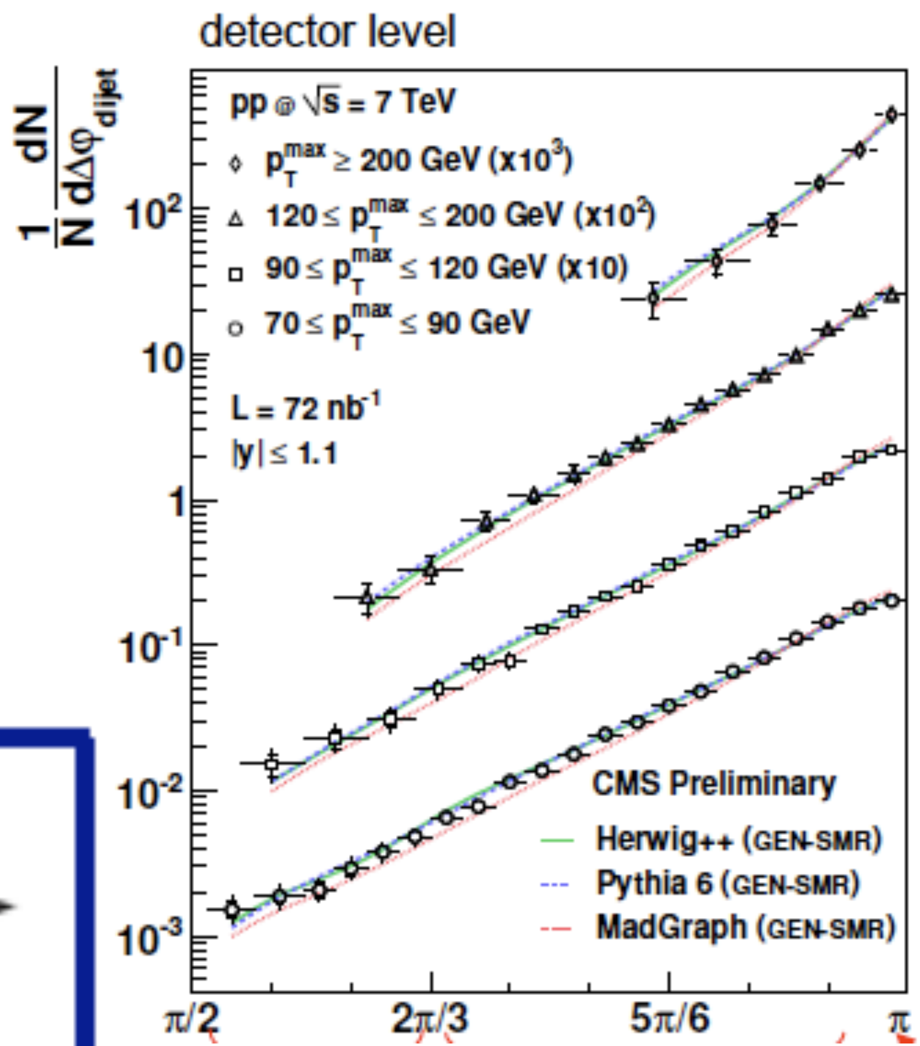
- Measurements of strong coupling – in ratios often uncertainties cancel (later)!



DI/TRIJETS/MULTIJETS

- Remember factorisation: Each additional jet suppressed by α_S.
- More jets / final-state particles → more complex QCD dynamics!
- Many interesting studies:
  - Angular correlations – e.g. $\Delta\phi$, angle between two hardest jets.



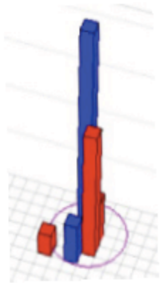


JET RECO AND JET ALGOS (SHOOOORT)

Calorimeter Jets

Jets clustered from ECAL and HCAL deposits (Calo Towers)
Accordingly:

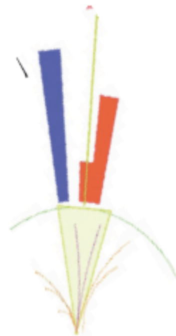
Calo MET



Jet-Plus-Track Jets (JPT)

Subtract average calorimeter response from CaloJet and replace it with the track measurement
Accordingly:

Tc MET

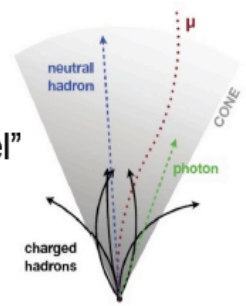


Particle Flow Jets (PF)

Cluster Particle Flow objects:
Unique list of calibrated particles "a la Generator Level"
Accordingly:

PF MET

F. Beaudette
01/22.7 17:15



Track Jets

Reconstructed from tracks of charged particles, independent from calorimetric jet measurements

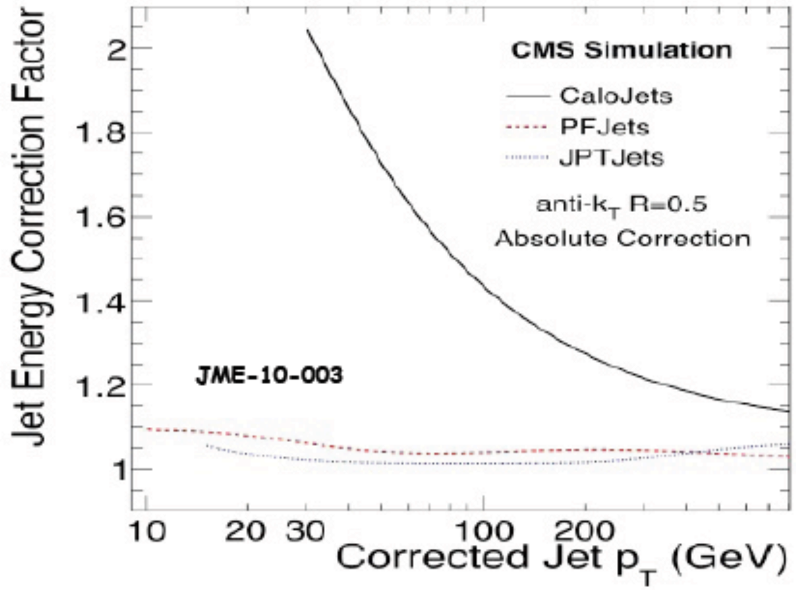
Jet algorithms – a field of its own!
-"Cone" vs "clustering" algorithms!
- New developments since the times of LEP, HERA and the Tevatron, active field.
- Seedless safe cone algorithms (SISCone)
- Jet trimming and pruning …
- …

CMS JET SCALE CALIBRATION

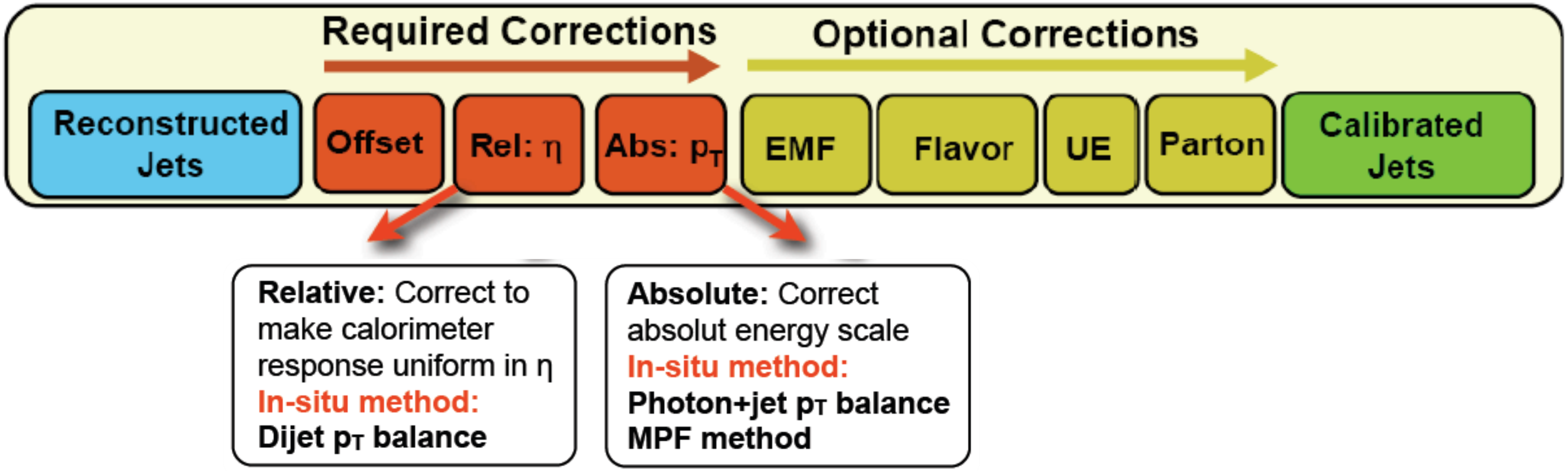
Two Strategies:

MC-truth JEC and In-situ JEC

- Majority of CMS physics analyses currently use **MC-truth** JEC
- MC corrections are derived from PYTHIA QCD dijet MC events
- **In-situ JEC** sub-corrections will replace **MC-truth** corrections when available



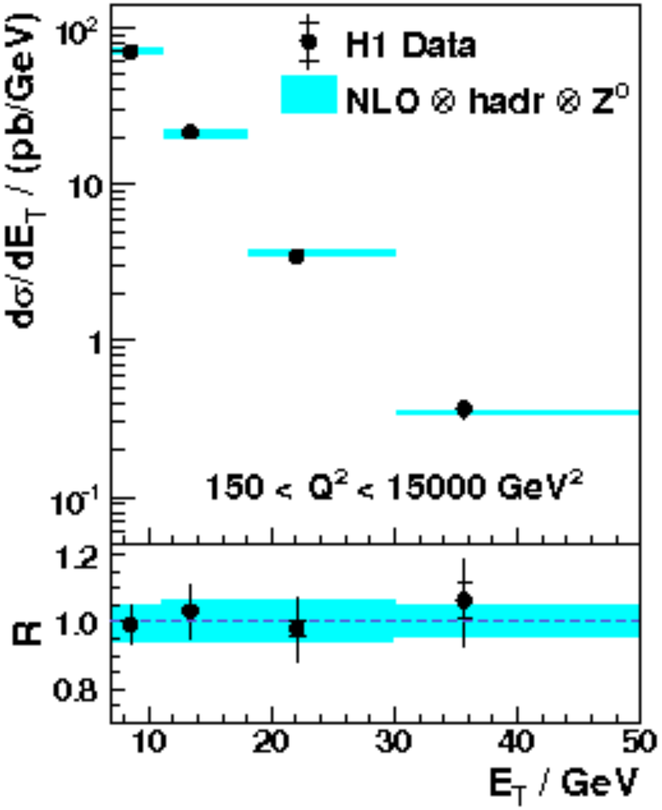
Factorized approach:

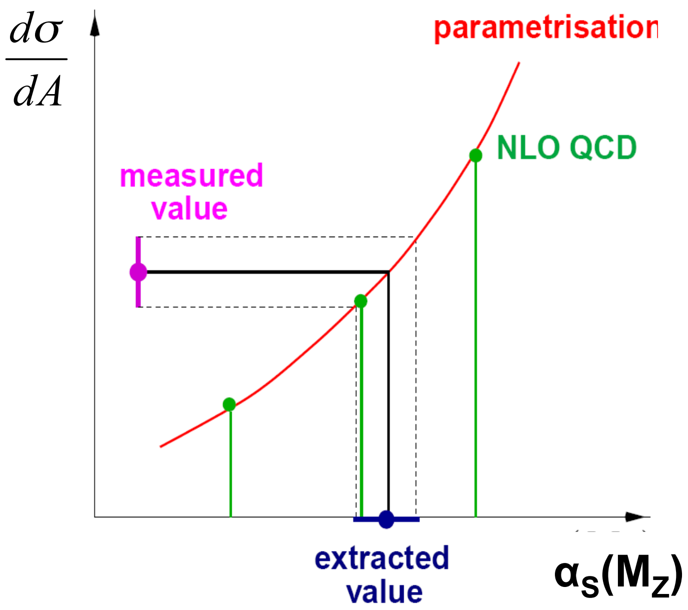


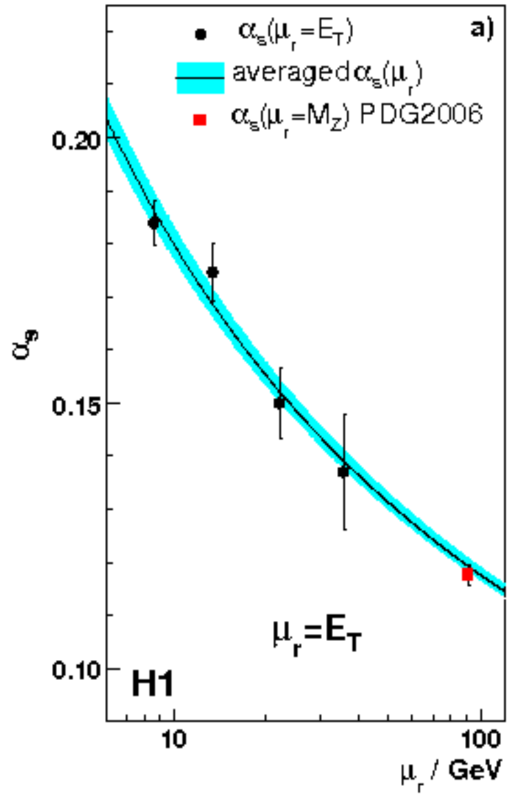
JETS AND THE STRONG COUPLING

> One example: HERA jet data ….

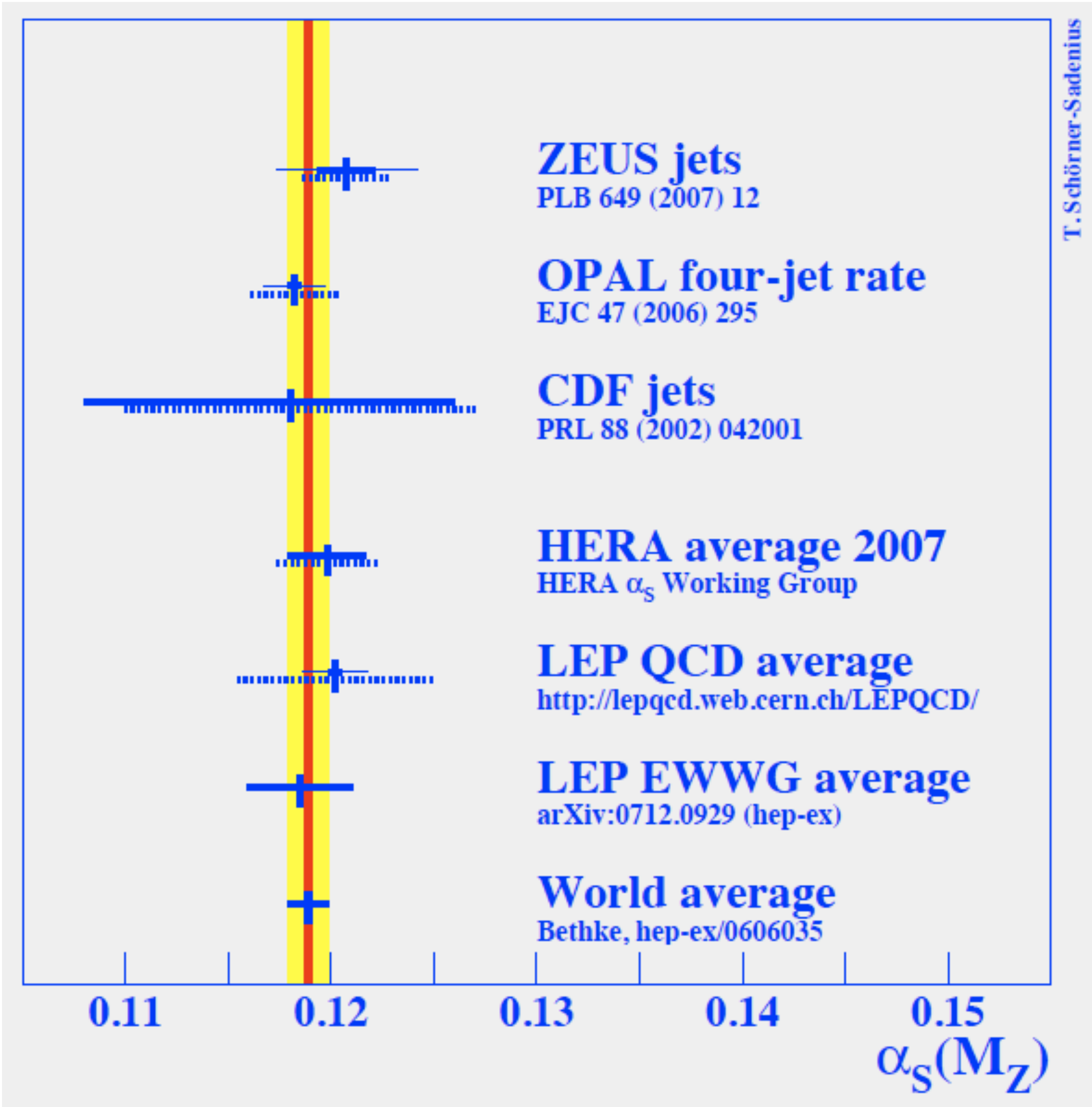
$$\left.\frac{d\sigma(\alpha_S(M_Z))}{dA}\right|_{NLO} = C_1\alpha_S(M_Z) + C_2\alpha_S^2(M_Z)$$







THE STRONG COUPLING: SUMMARY



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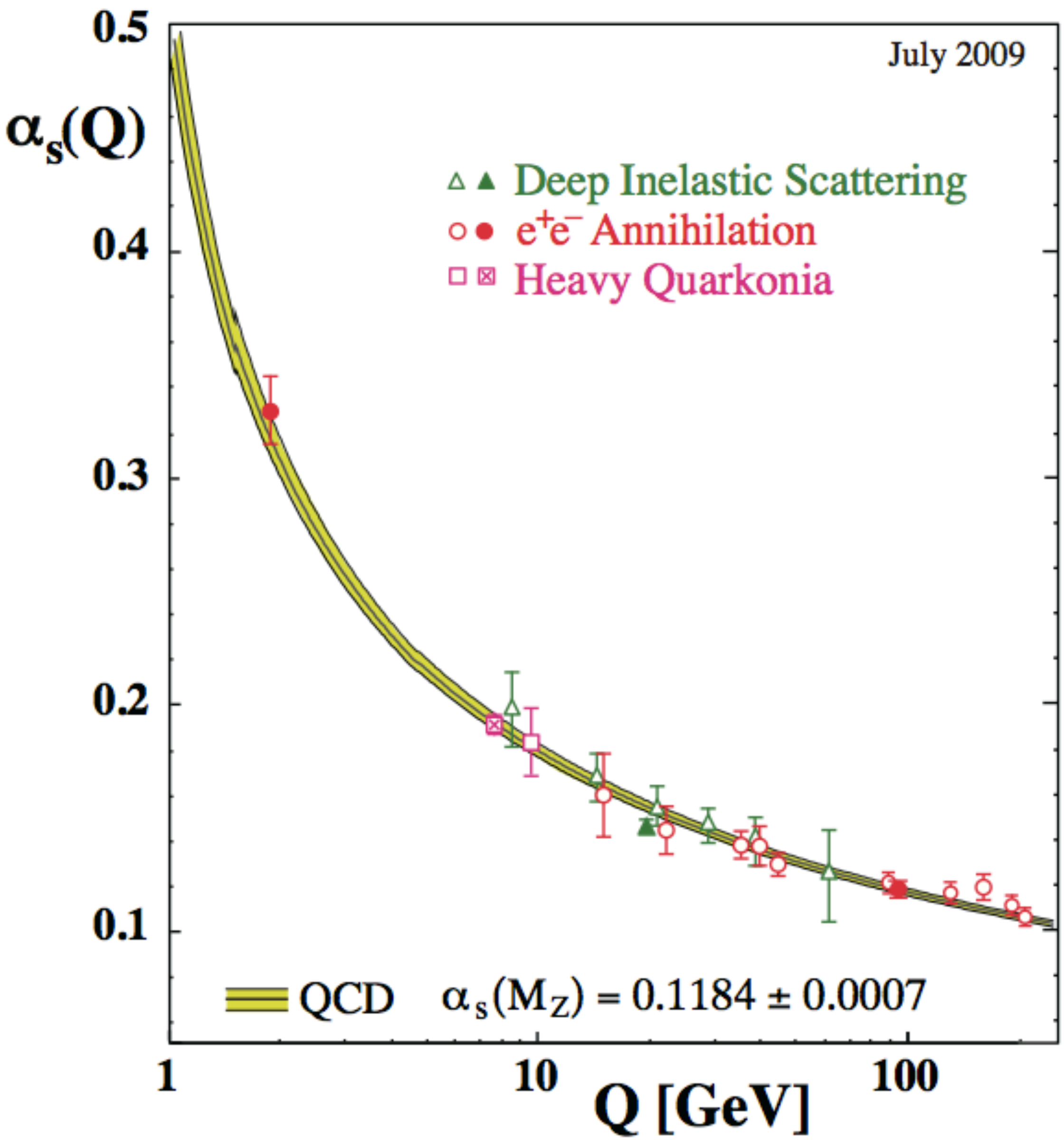
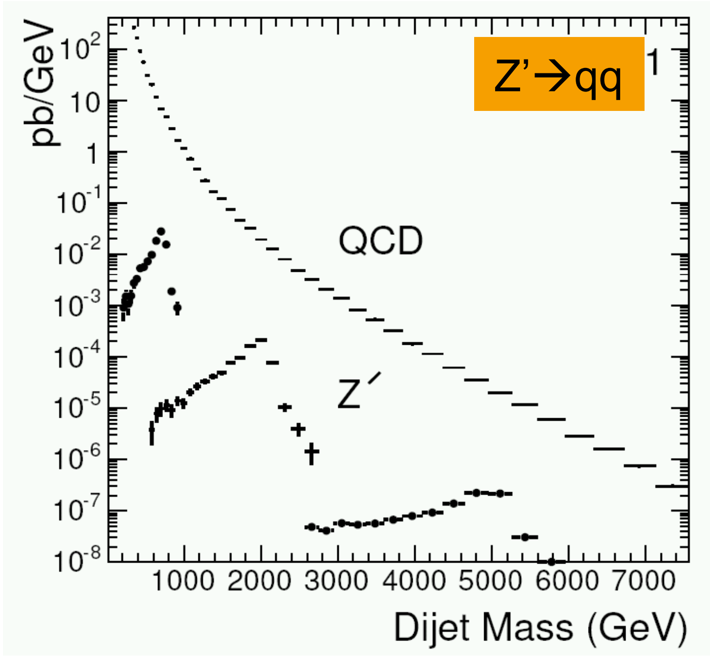
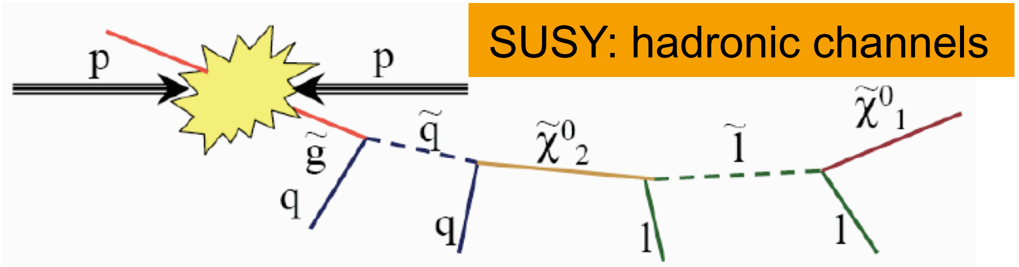
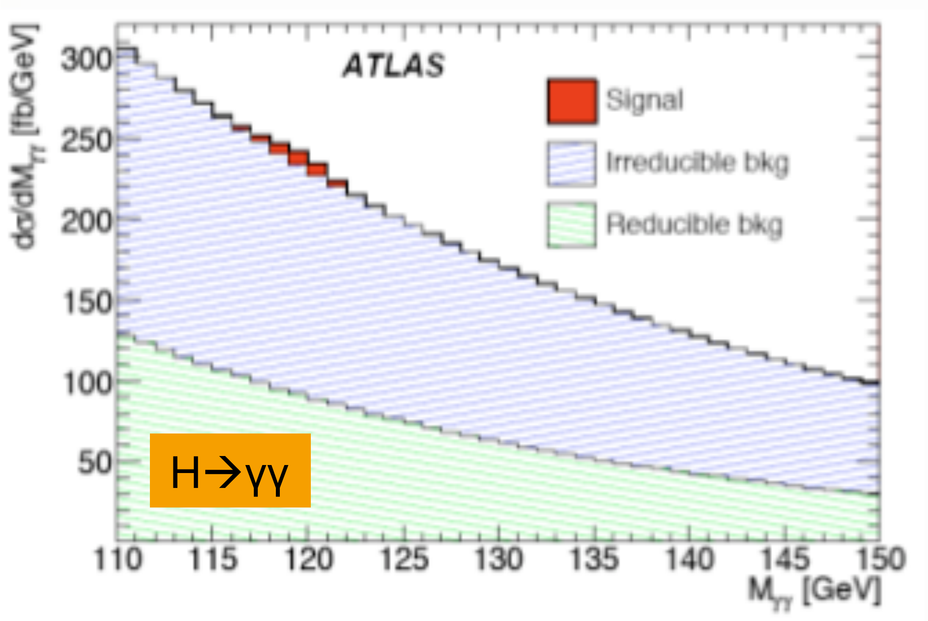


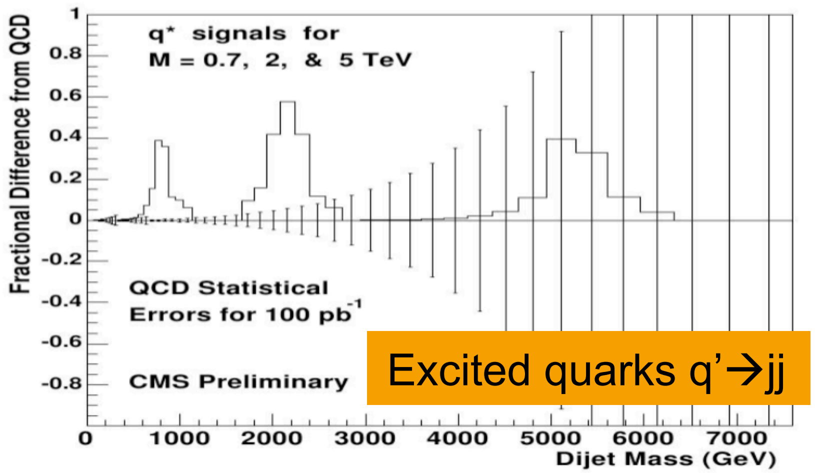
JETS AND NEW PHYSICS

- Jets play crucial role in many new physics scenarios
  - Often QCD rates for similar signatures higher!
  - Need to understand QCD!!!



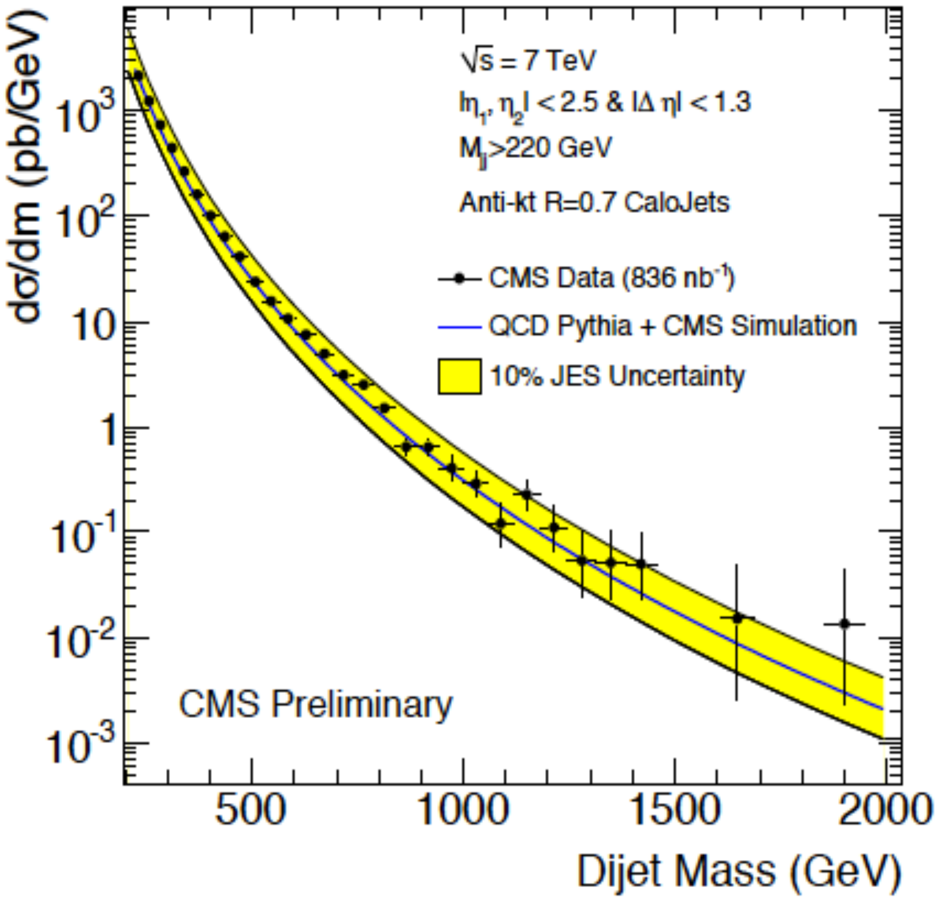




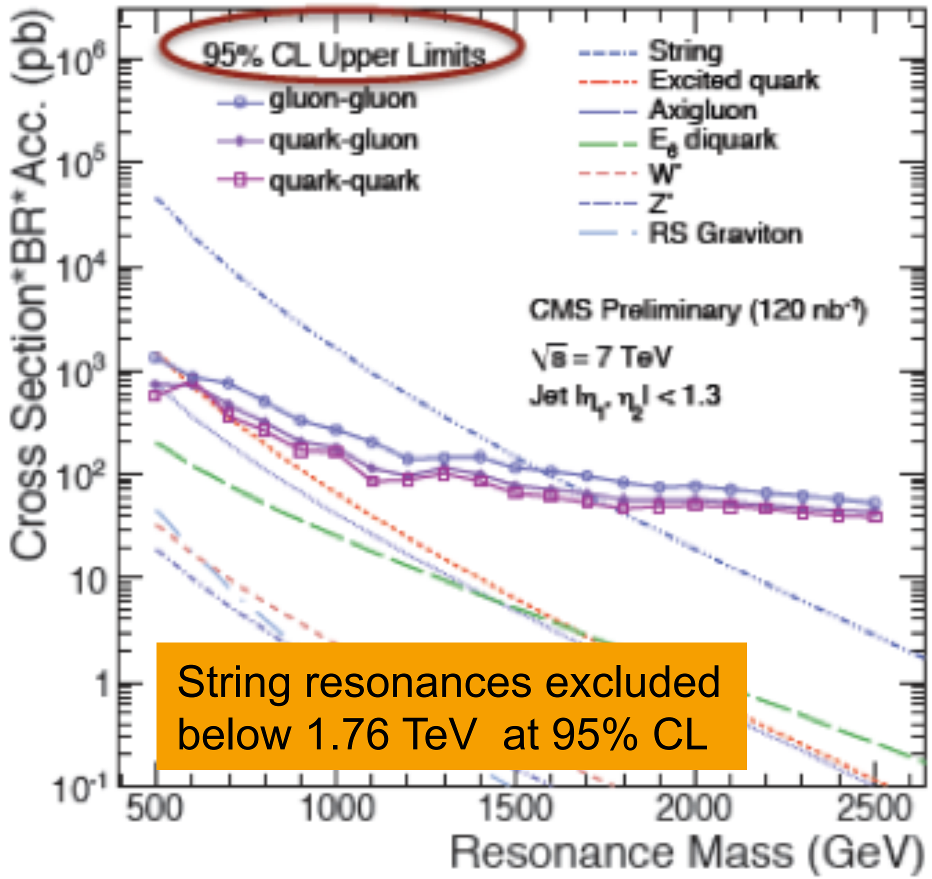


DIJETS AND NEW PHYSICS

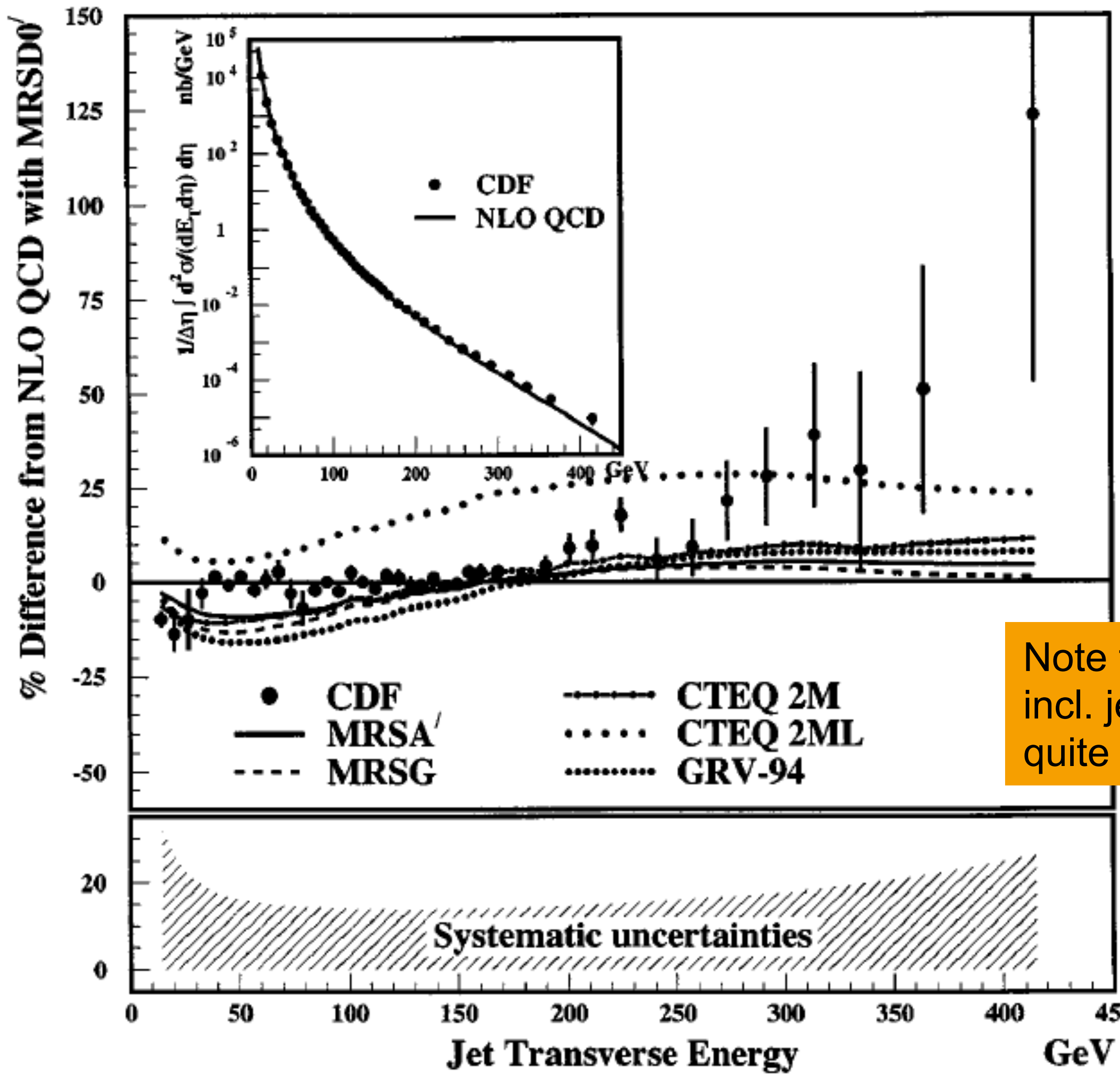
- In principle already in LO two jets.
- Looking for correct description of QCD radiation and new physics.
  - Smooth curves, no bumps → limits!



- For example in decays of heavy gauge bosons Z' or excited quarks q*→qq.
- New limits by LHC already now!!!



JET PHYSICS: DISCOVERY POTENTIAL?



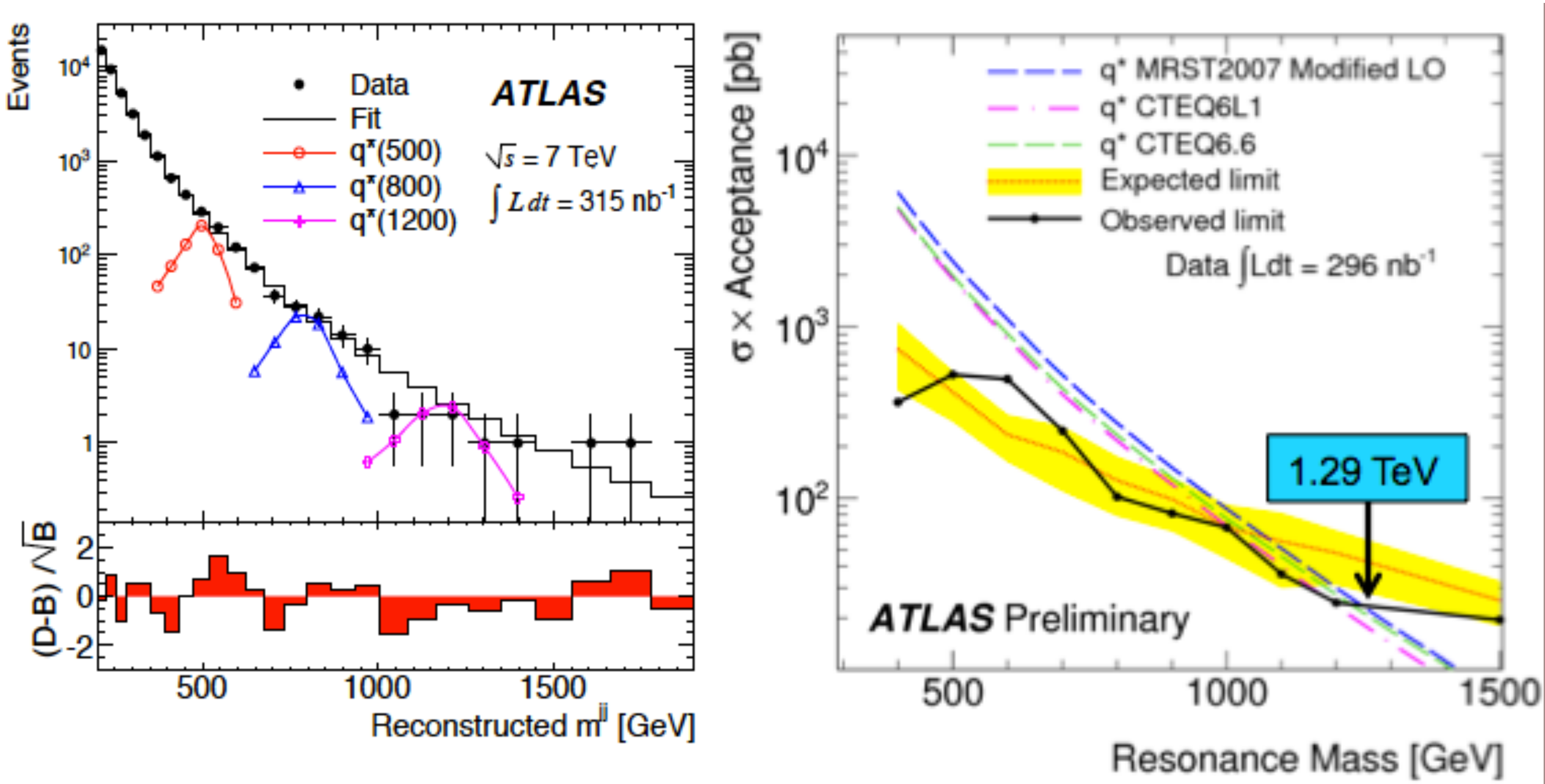
Note that some 10 years ago incl. jets from CDF caused quite some excitement!

DIJETS AND NEW PHYSICS

> ATLAS on excited quarks Q'→ jj:

0.4 < M (q*) < 1.29 TeV excluded at 95% C.L.

Latest published limit:
CDF: 260 < M (q*) < 870 GeV



SUMMARY

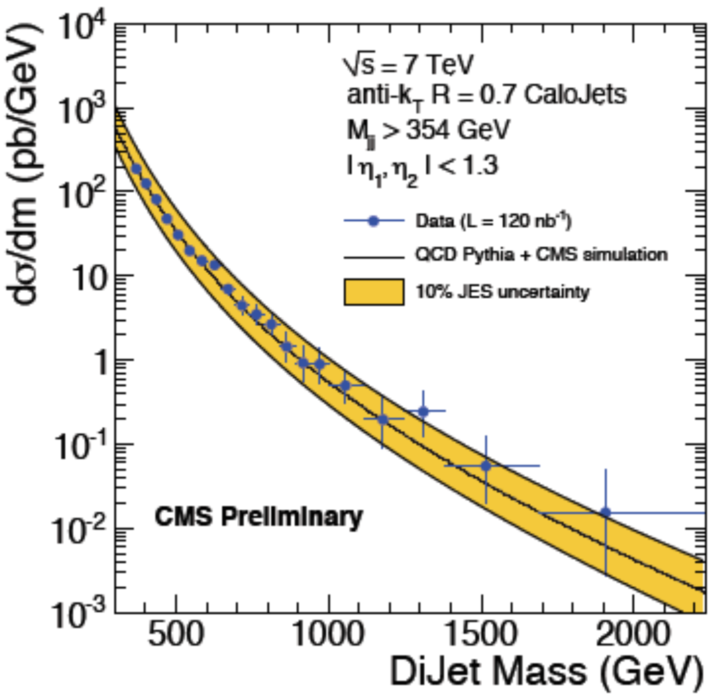
- Covered a few basics and some history of Quantum Chromodynamics
- Soft physics:
  - Difficult to model, perfect to “tune” the MC models
- Jets as an important tool for
  - QCD studies
  - Background studies for new physics searches
  - Jets as active field of research in themselves
- PDFs, and extractions of strong coupling constant, …
- Jets and new physics –
  - … for example in dijet mass spectra.
  - (But there is much more to it …)

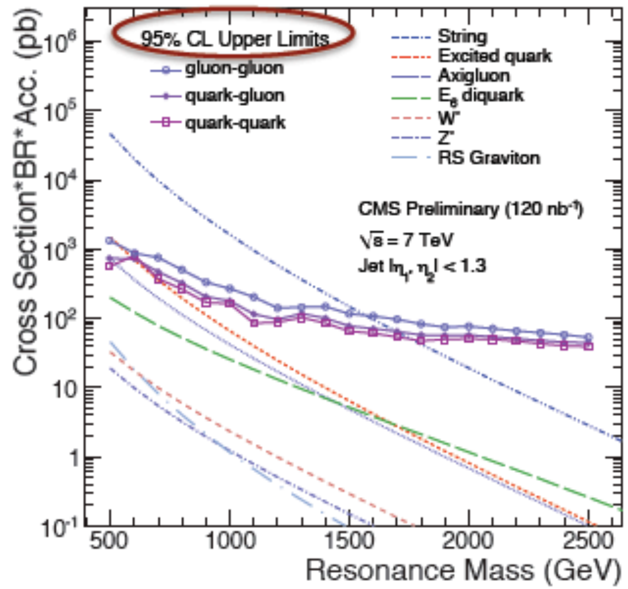
Searches for Di-Jet Resonances

CMS PAS EXO-10-001

Model Name	X	Color	J^P	$\Gamma/(2M)$	Final-state Partons
String	S	mixed	mixed	0.003-0.037	$q\bar{q}$, qq, gg and qg
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
Excited Quark	q^*	Triplet	$1/2^+$	0.02	qg
E_6 Diquark	D	Triplet	0^+	0.004	qq
RS Graviton	G	Singlet	2^+	0.01	$q\bar{q}$, gg
Heavy W	W′	Singlet	1^-	0.01	$q\bar{q}$
Heavy Z	Z′	Singlet	1^-	0.01	$q\bar{q}$

Properties of new particles expected to have significant BF for the decay into di-quark, di-gluons,quark-gluon



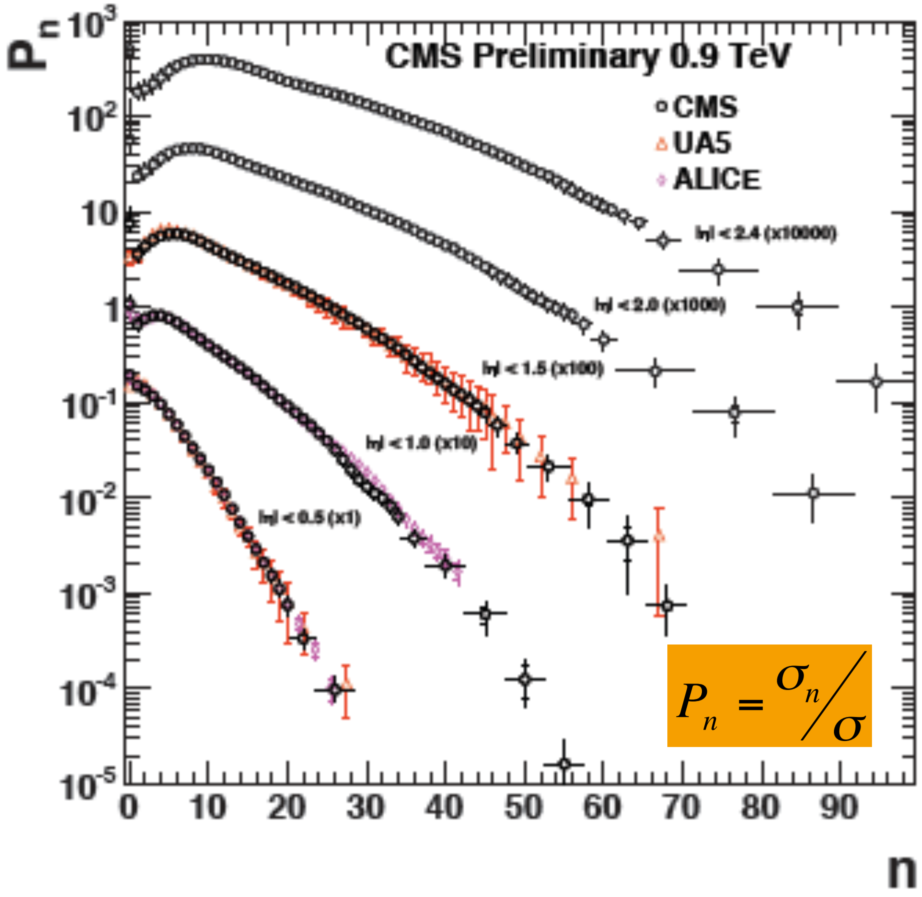


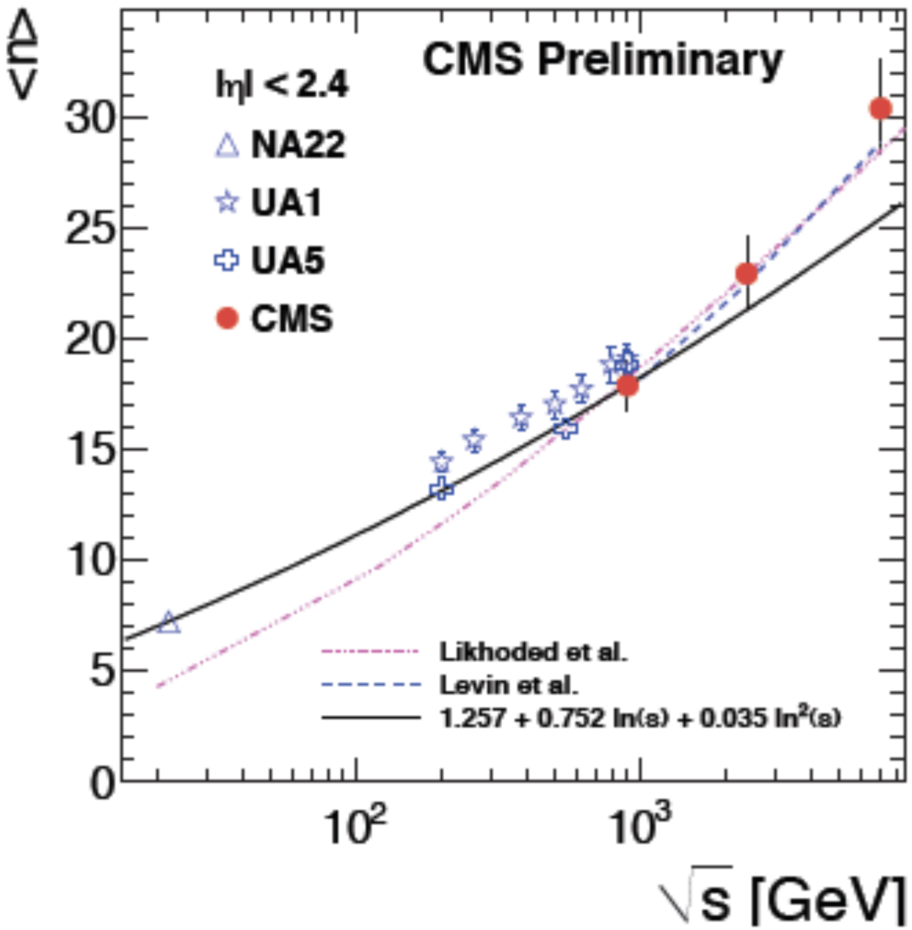
95% Exclusion limits: String resonances with mass<1.67TeV

MINIMUM BIAS, PARTICLE PRODUCTION

> Averaged charged particle multiplicity:

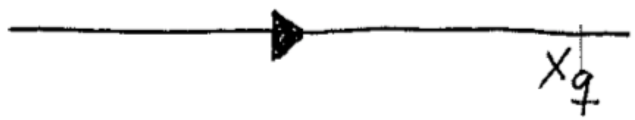
- Models underestimate increase with centre-of-mass energy.

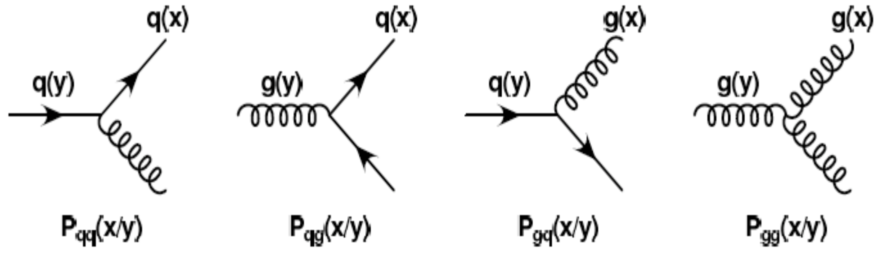


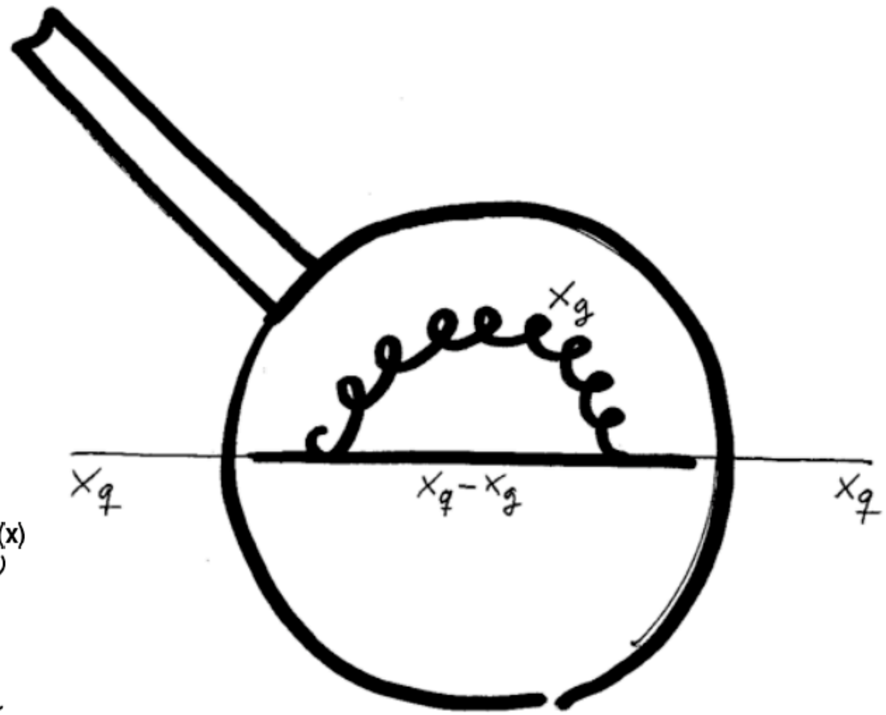


PARTON DISTRIBUTION FUNCTIONS

- Why does $f_{i/p}$ depend on Q^2? $\boxed{f_{i/p} = f_{i/p}\left(x, Q^2\right)}$
  - 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.

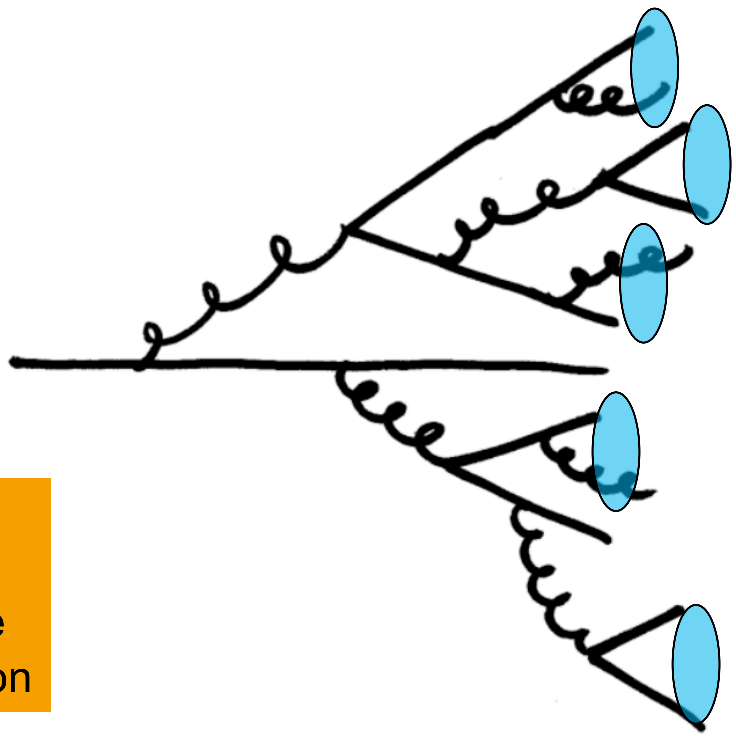






JET PHYSICS: ALGORITHMS

- 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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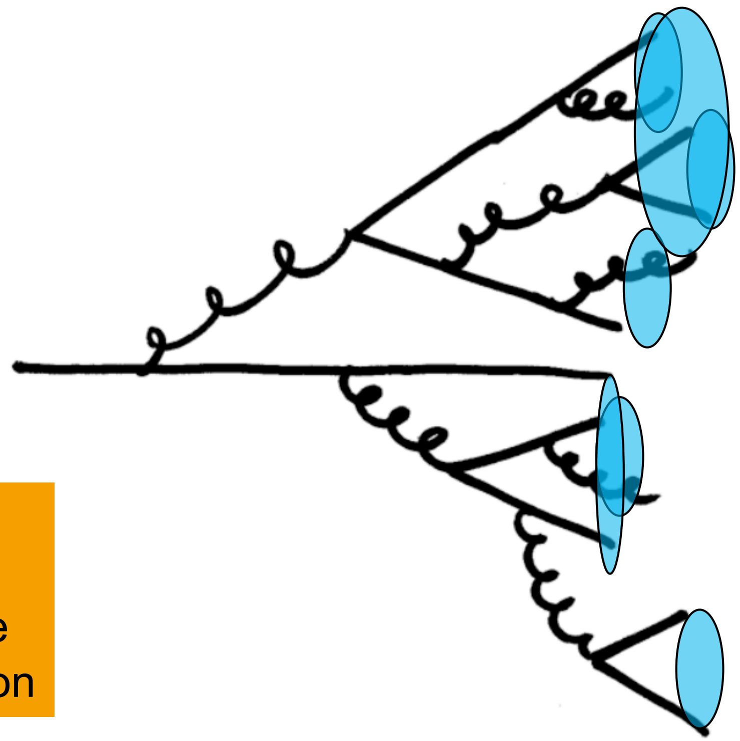

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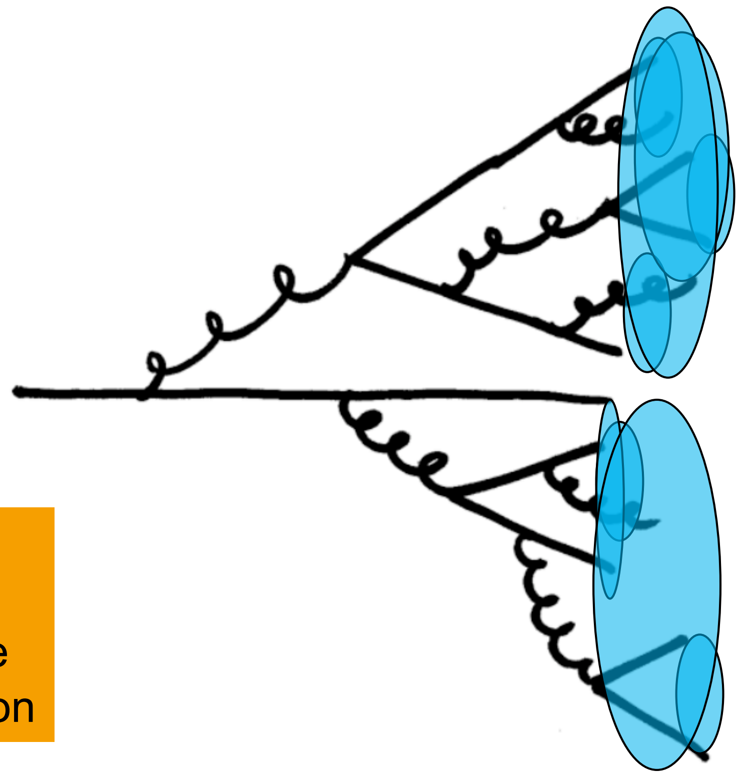

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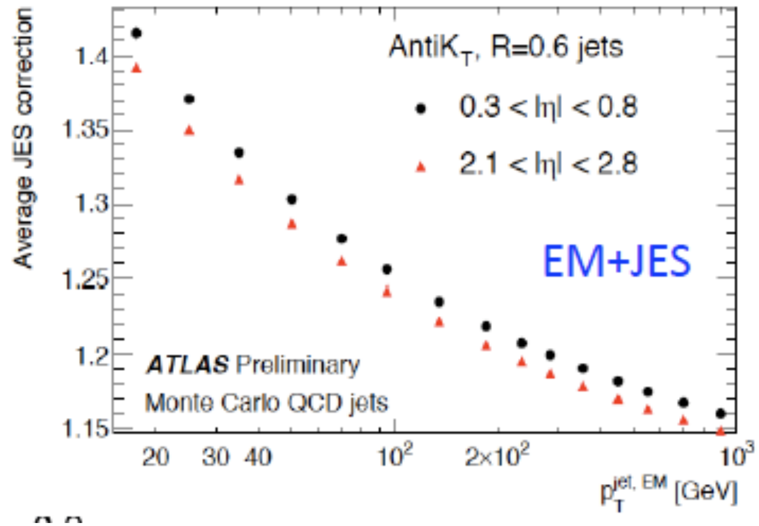
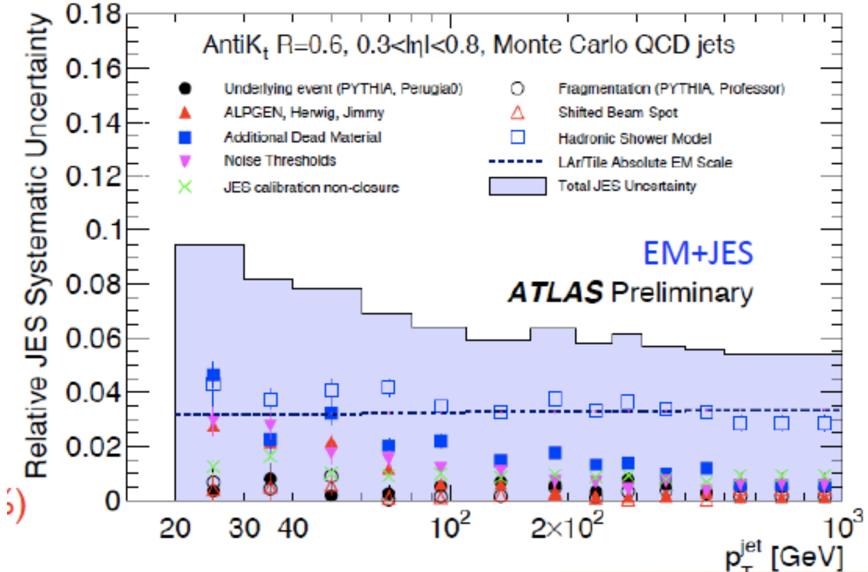
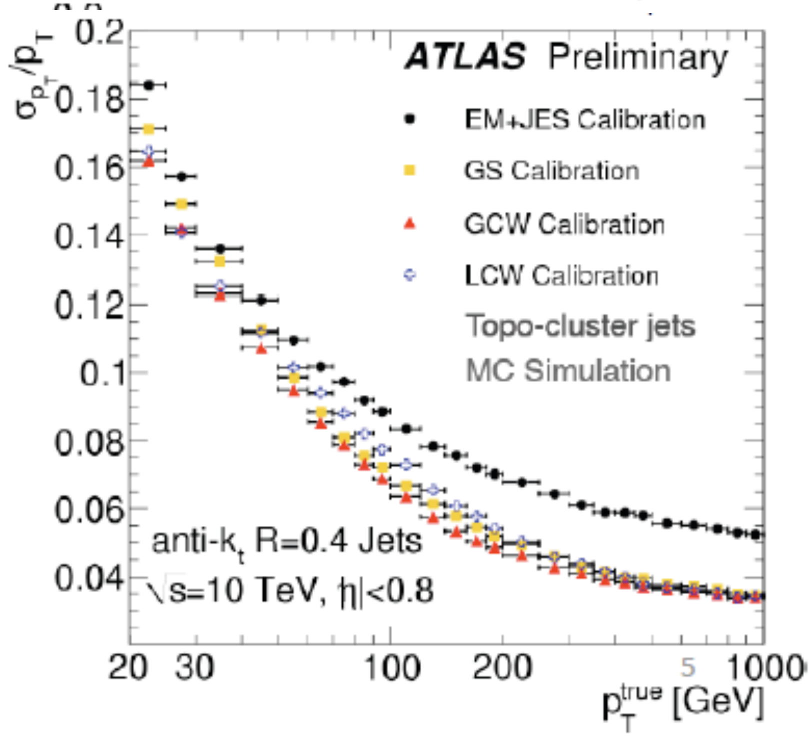
ATLAS JET SCALE CALIBRATION

> Sequential correction procedure to aid the calibration (non-uniformity, energy loss, leakage, pile-up, non-compensation)

- EM+JES: bring jets from EM scale to had scale
- GS: jet-by-jet info about properties of jet
- GCW: correct individual cells for different response to had and EM depositions.
- LCW: cluster correction with MW
- Result: 7% scale uncertainty above 100 GeV!



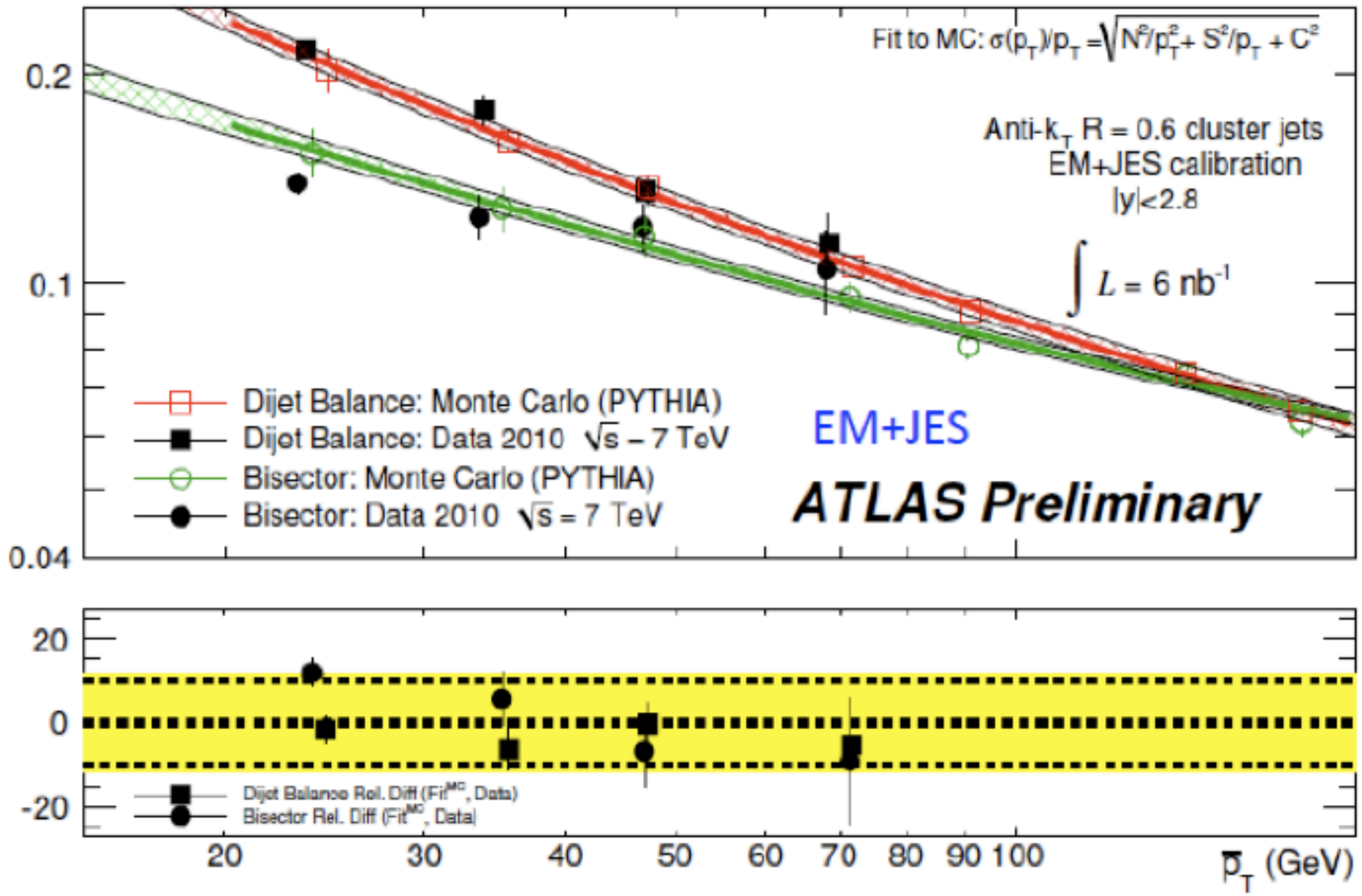




ATLAS JET ENERGY RESOLUTION

$$A = \frac{p_T^1 - p_T^2}{p_T^1 + p_T^2}$$

$$\frac{\sigma(p_T)}{p_T} = \sqrt{2}\sigma_A$$



> Jet energy resolution measured in situ using dijet asymmetry or "bisector" technique.

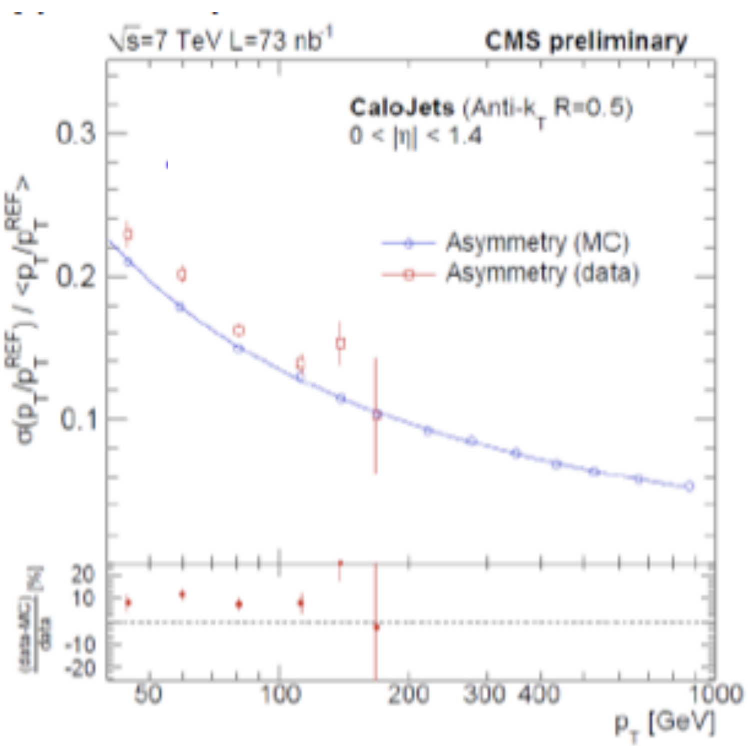
> MC describes data resolution within 14% for jets with 20 < p_T < 80 GeV.

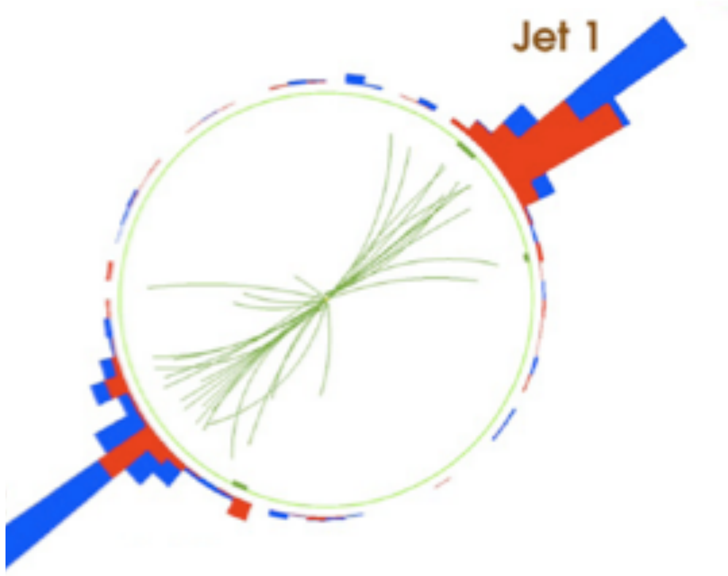
TRIMMING, TUNING, PRUNING

- In

CALORIMETERS: JETS

- Hadronic jets one of the main tasks of calorimeters. Very simple application (but very important for early data taking, confirmation of SM, etc.): incklusive and di-jet distributions.
- Large field: different algorithms (k_T, anti-k_T, SisCone, …) with different radii running on a variety of objects.





Use asymmetric dijet method to estimate jet p_T resolution: Difference in p_T (partly) due to resolution!
➔ Already now better than design value of 100%/sqrt(E)!

Searches for excited quarks: q*→ jj

Full data sample analysed

Looked for di-jet resonance in the measured M(jj) distribution
→ spectrum compatible with a smooth monotonic function → no bumps

➡ 0.4 < M (q*) < 1.29 TeV excluded at 95% C.L.

Latest published limit:
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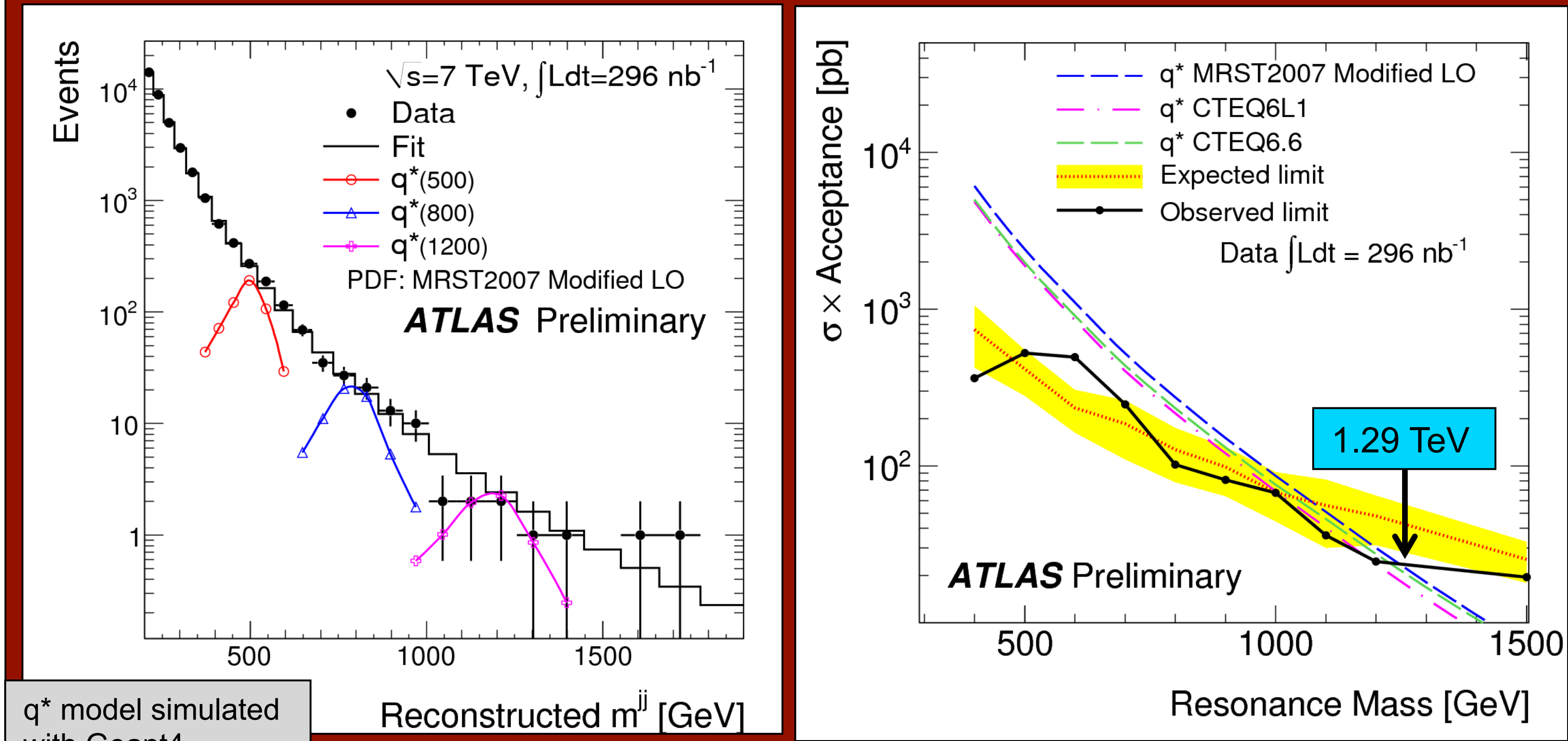

q* model simulated
with Geant4

- ❑ Experimental systematic uncertainties included: luminosity, JES (dominant), background fit, ..
- ❑ Impact of different PDF sets studied → with CTEQ6L1: 0.4 < M (q*) < 1.18 TeV