High-p_T interactions: introduction

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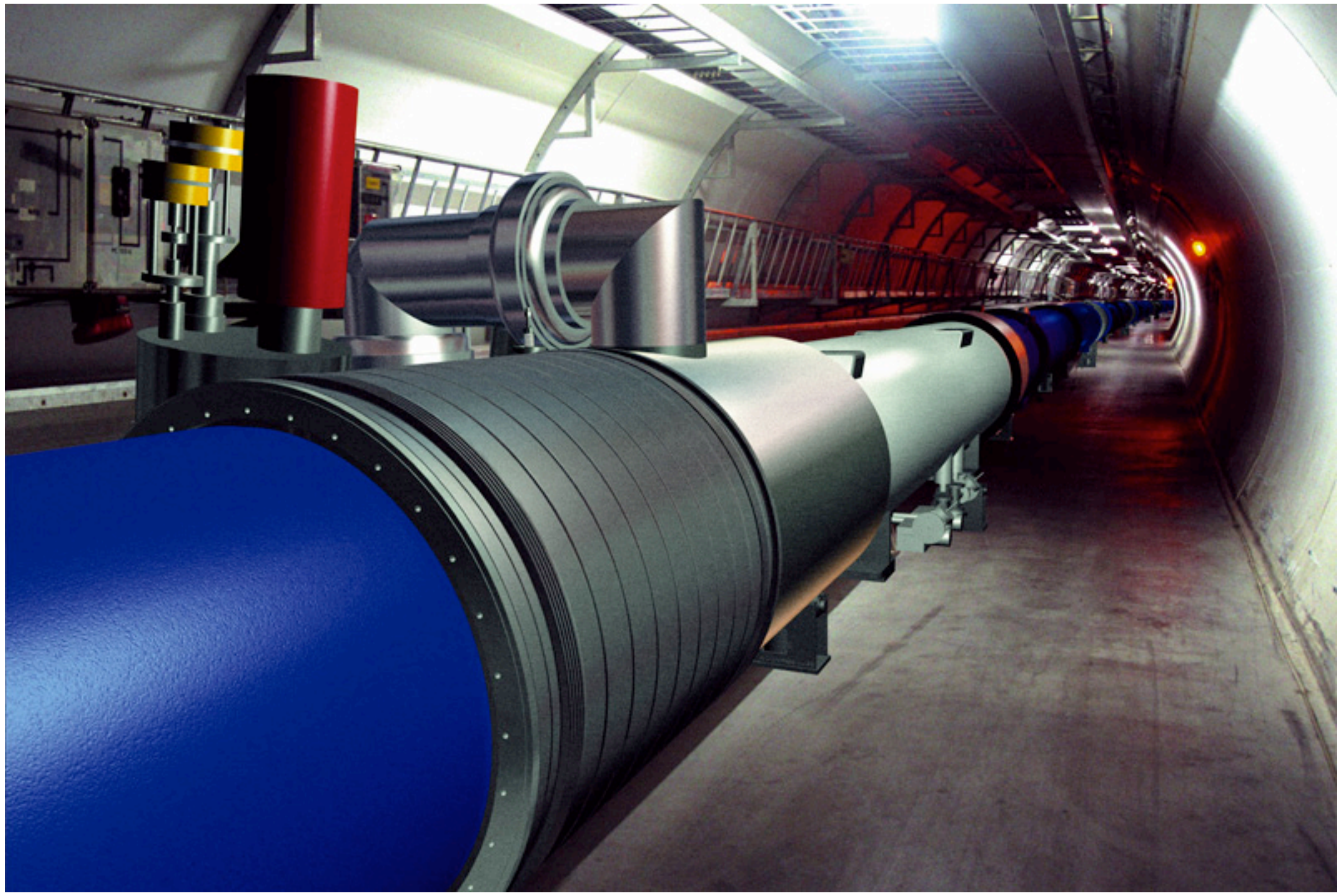
Outline

- Prologue
- Parton distribution functions (PDFs)
- Partonic cross section at NLO
- Benchmark processes at hadron colliders
- Jets
- Monte Carlo parton showers

Prologue

After many years of preparation, the LHC has now started its operations and it is colliding proton beams at 7 TeV in the centre-of-mass



The LHC is expected to shed light on the fundamental questions of high energy physics like the origin of mass, the existence of SUSY and the nature of dark matter

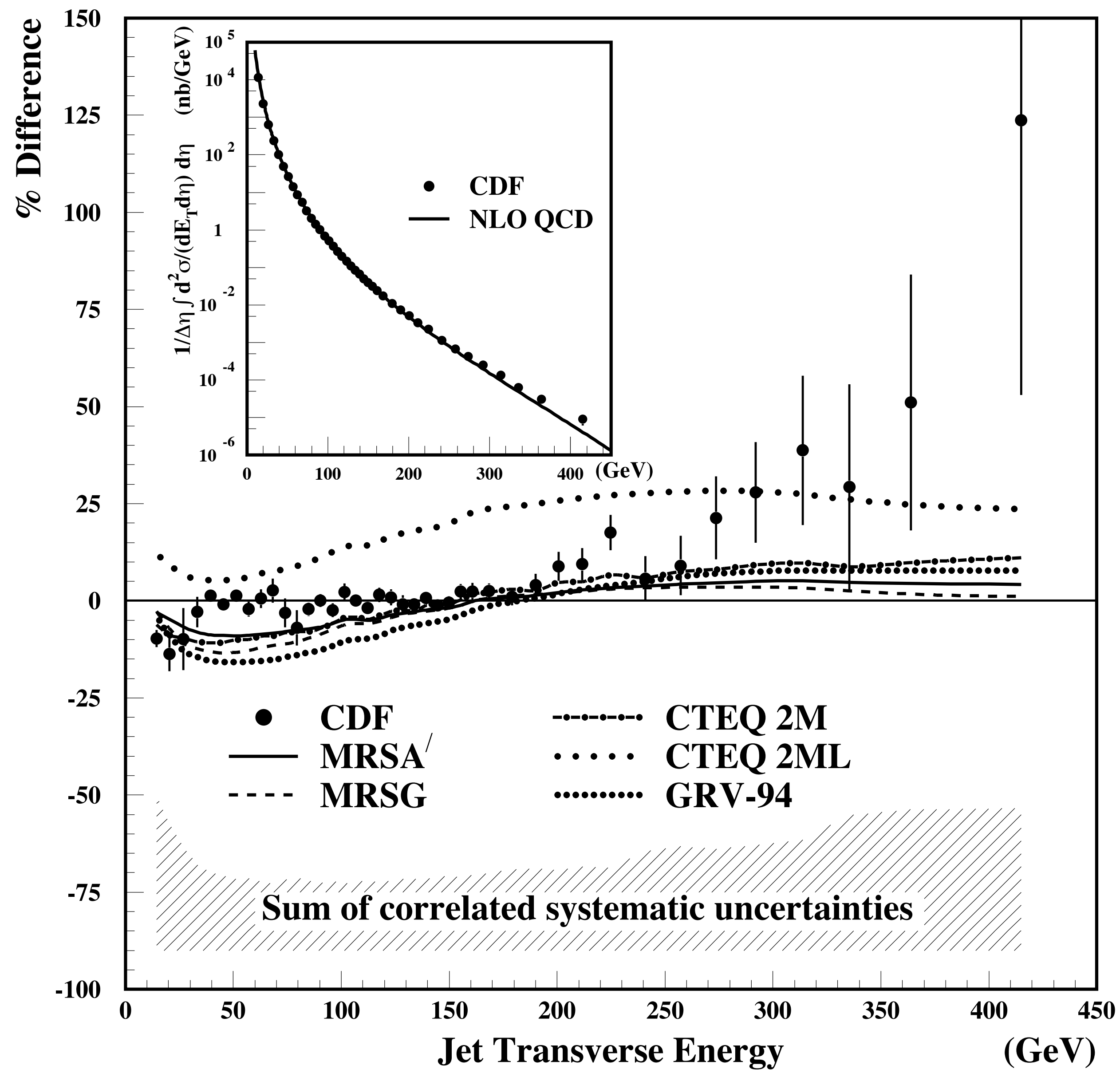
Prologue

What role for high-p_T interactions at the LHC ?

High-p_T events are the most interesting as far as new physics searches are concerned

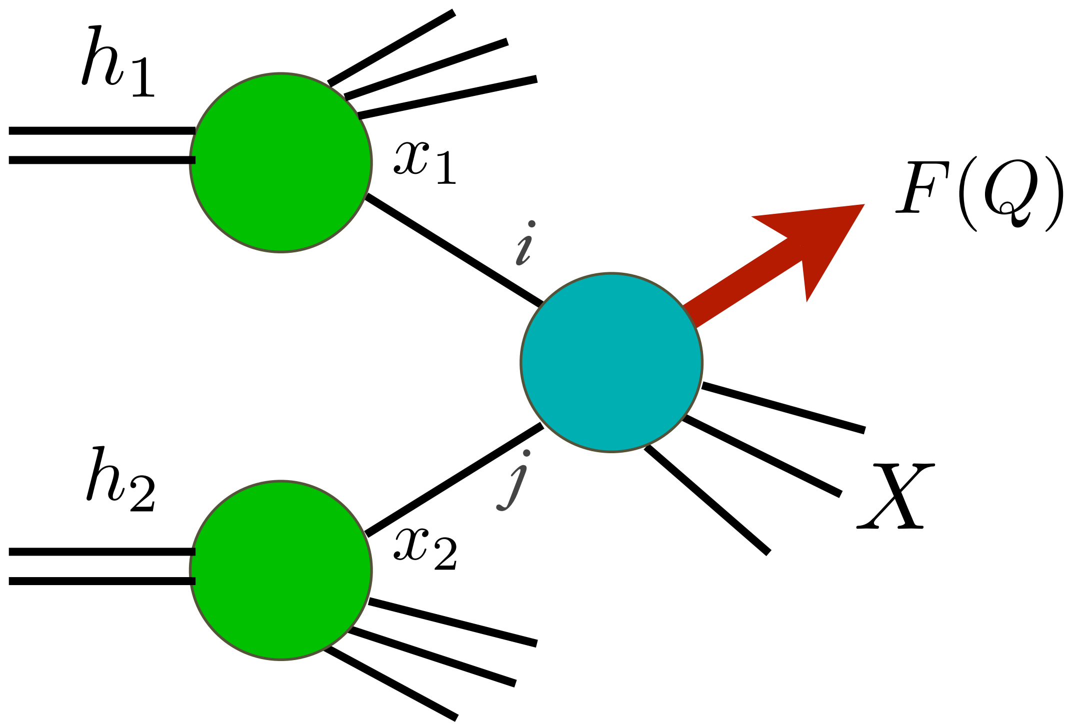
New physics signals could lie in the tail of kinematic distributions

Remember the famous excess in the inclusive jet cross section measured by CDF at high E_T (compositeness ?)



Need good control of signal and background to claim evidence for new physics !

Prologue



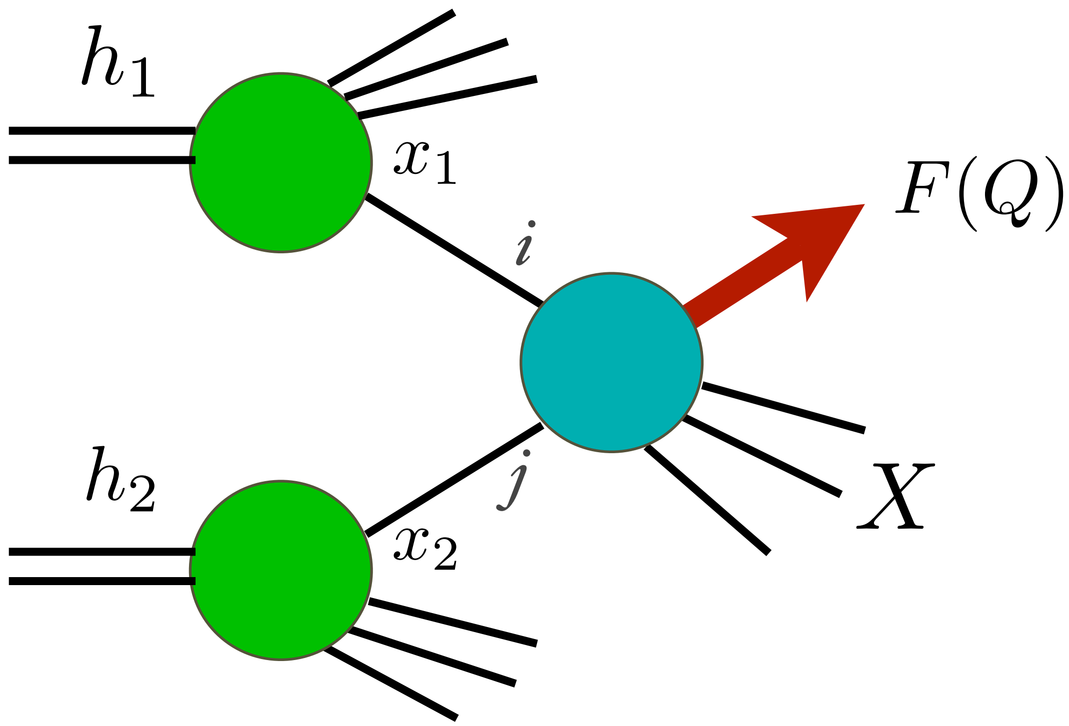
High-p_T interactions are characterized by the presence of a hard scale Q

→ They can be controlled through the factorization theorem

The corresponding cross section can be written as

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_{i/h_1}(x_1, \mu_F^2) f_{j/h_2}(x_2, \mu_F^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2; \mu_F^2, \mu_R^2)$$

Prologue



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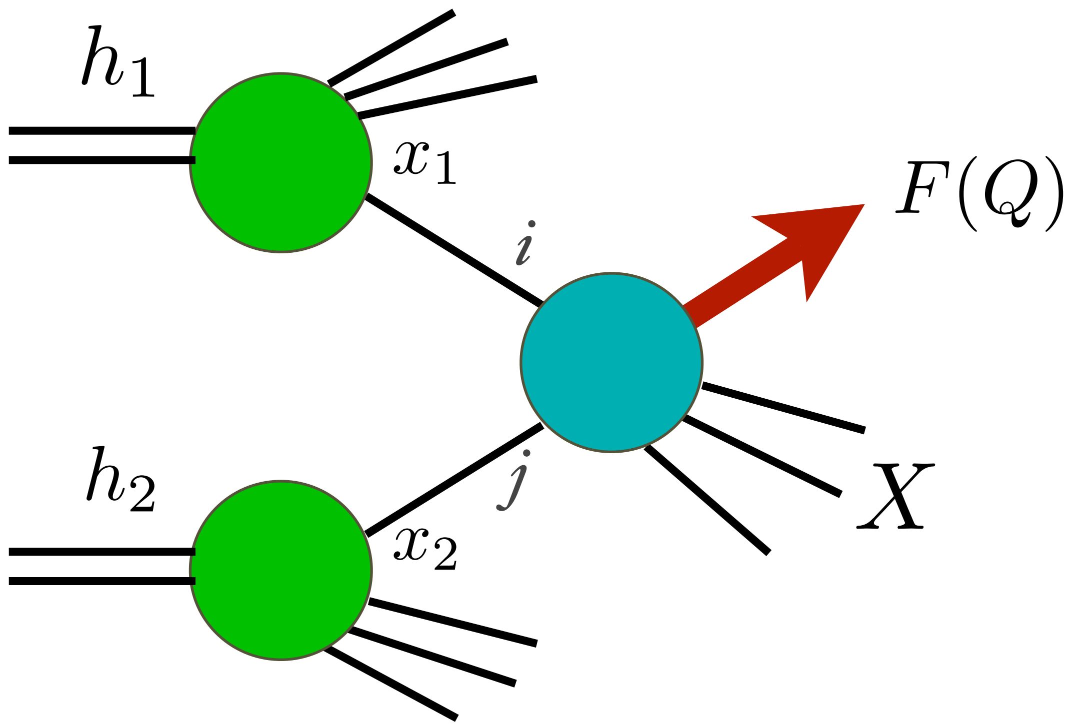
Parton distribution functions (PDFs)

Prologue



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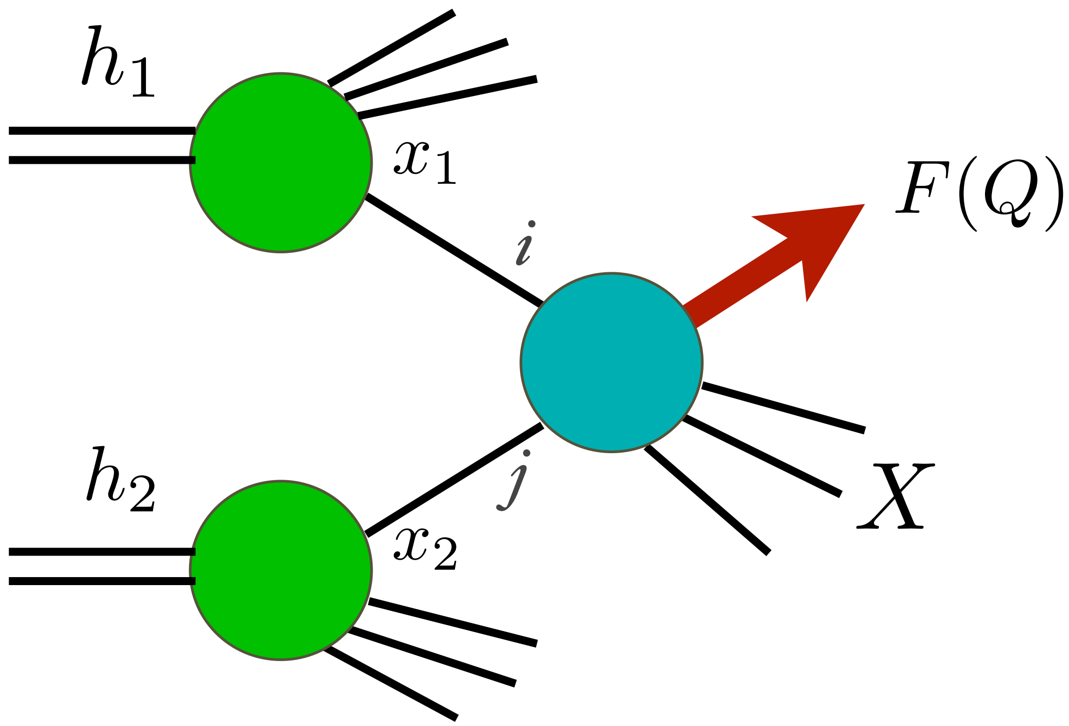

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Parton distribution functions (PDFs)

renormalization scale

Predictions for hadronic cross section depend on knowledge of both $\hat{\sigma}_{ij}$ and $f_{i,h}(x, \mu_F^2)$

factorization scale

PDFs

Determined by global fits to different data sets

Standard procedure:

- Parametrize at input scale $Q_0 = 1 - 4 \text{ GeV}$

$$xf(x, Q_0^2) = Ax^{\alpha}(1-x)^{\beta}(1 + \epsilon\sqrt{x} + \gamma x + ...)$$

- Impose momentum sum rule: $\sum_a \int_0^1 dx x f_a(x, Q_0^2) = 1$

- Evolve to desired Q^2 through DGLAP equation

$$Q^2 \frac{\partial f_a(x, Q^2)}{\partial Q^2} = \int_x^1 \frac{dz}{z} P_{ab}(\alpha_S(Q^2), z) f_b(x/z, Q^2)$$

$$P_{ab}(\alpha_S, z) = \frac{\alpha_S}{2\pi} P_{ab}^{(0)}(z) + \left(\frac{\alpha_S}{2\pi}\right)^2 P_{ab}^{(1)}(z) + \left(\frac{\alpha_S}{2\pi}\right)^3 P_{ab}^{(2)}(z) + ...$$

LO (1974) NLO (1980) NNLO (2004: Moch et al.)

- Compute observables and then fit to data to obtain the parameters

PDFs

Main groups: MRST (now MSTW), CTEQ

Now also: Alekhin, Delgado-Reya, HERAPDF, NNPDF...

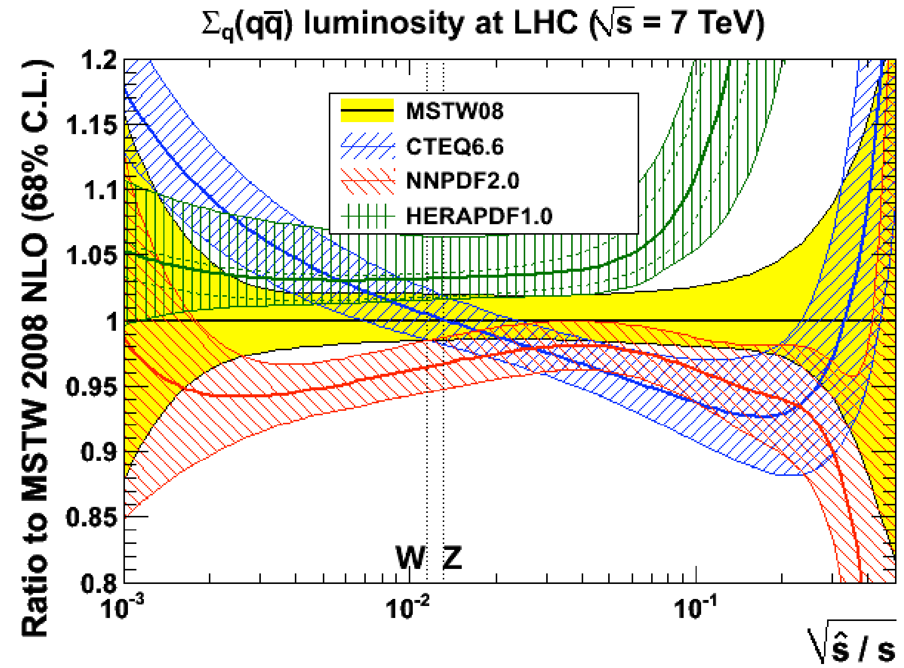
Broad agreement but differences due to:
- choice of data sets
- treatment of errors
- treatment of heavy quarks
- initial parametrization
- theoretical assumptions

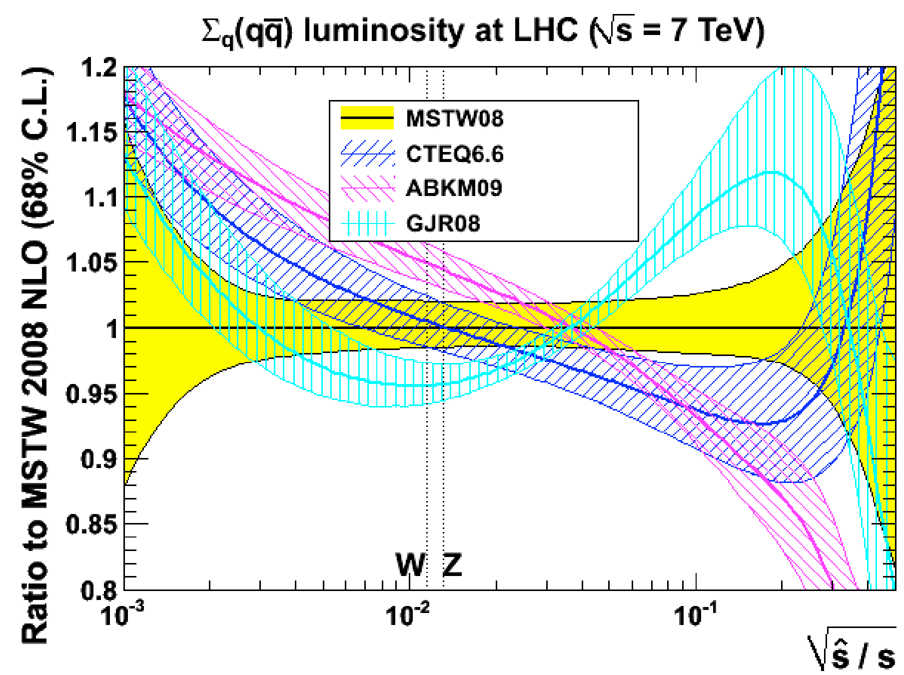
....

Most groups provide PDFs with 'errors'

Such errors come from the experimental uncertainties in the data used in the fit

Theoretical assumptions in the way the fit is set up and performed are more difficult to assess





J.Stirling

talk by A.Cooper-Sarkar

Partonic cross section

The partonic cross section for high-p_T processes can be computed as a series expansion in the QCD coupling α_S

$$\hat{\sigma} = \hat{\sigma}^{(0)} + \frac{\alpha_S}{\pi}\,\hat{\sigma}^{(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \hat{\sigma}^{(2)} + \ldots$$

LO NLO NNLO

Leading order (LO) calculations typically give only the order of magnitude of cross sections and distributions: to obtain reliable predictions next-to leading order (NLO) is needed

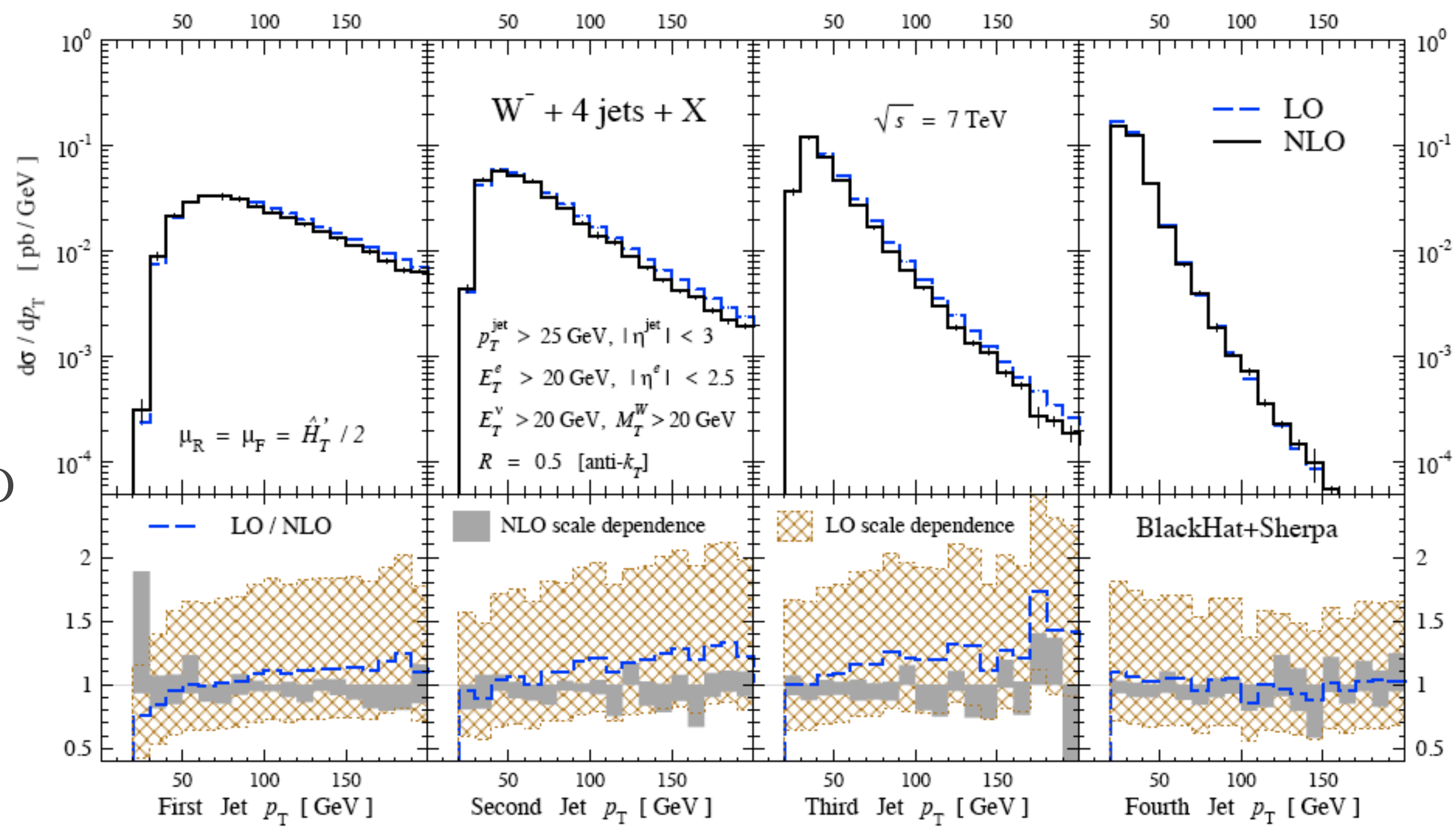
Example: W(Z)+jets → background for new physics searches

The bottleneck has been for many years the evaluation of the 1 loop correction

This is a field that has seen the most significant advances in the last few years

The traditional approach based on Feynman diagrams is now complemented with new powerful methods based on recursion relations and unitarity

Blackhat coll.:
W+4 jets at NLO



Shape difference between LO and NLO results for the first three leading jets

C.F.Berger et al. (2010)

First (almost) complete 2->5 NLO computation

(leading color approximation for the virtual terms)

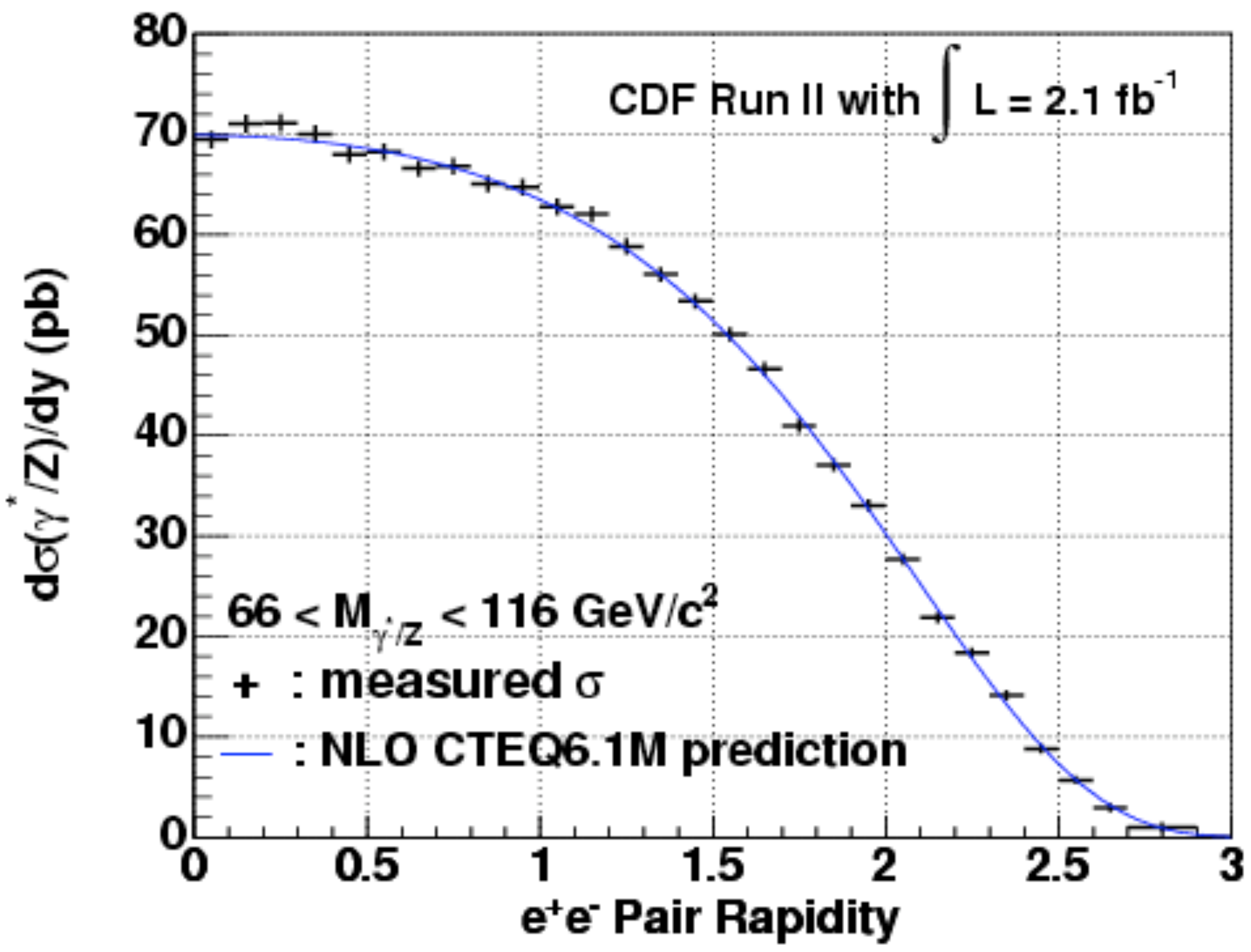
talk by M.Worek

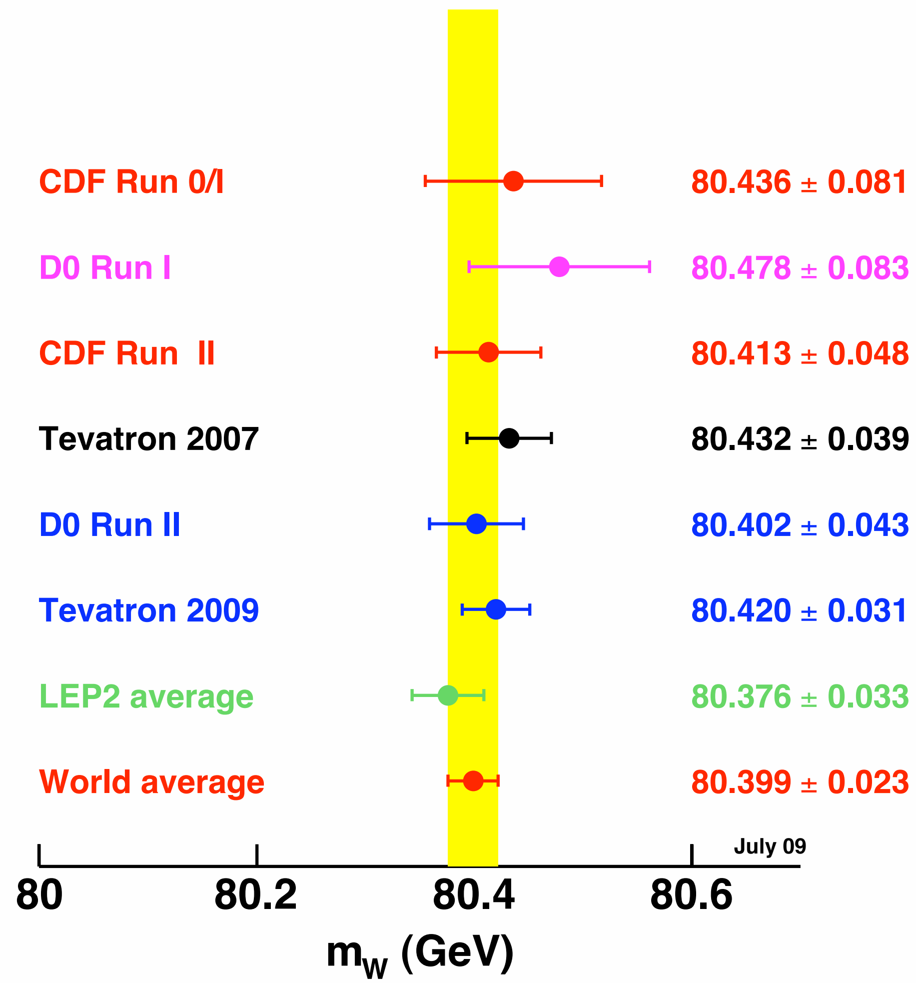
Benchmarks: W, Z

W and Z production are benchmarks processes at hadron colliders

- large production rates and clean signatures
- standard candles for detector calibration
- stringent constraints for PDFs extraction
- W mass

....





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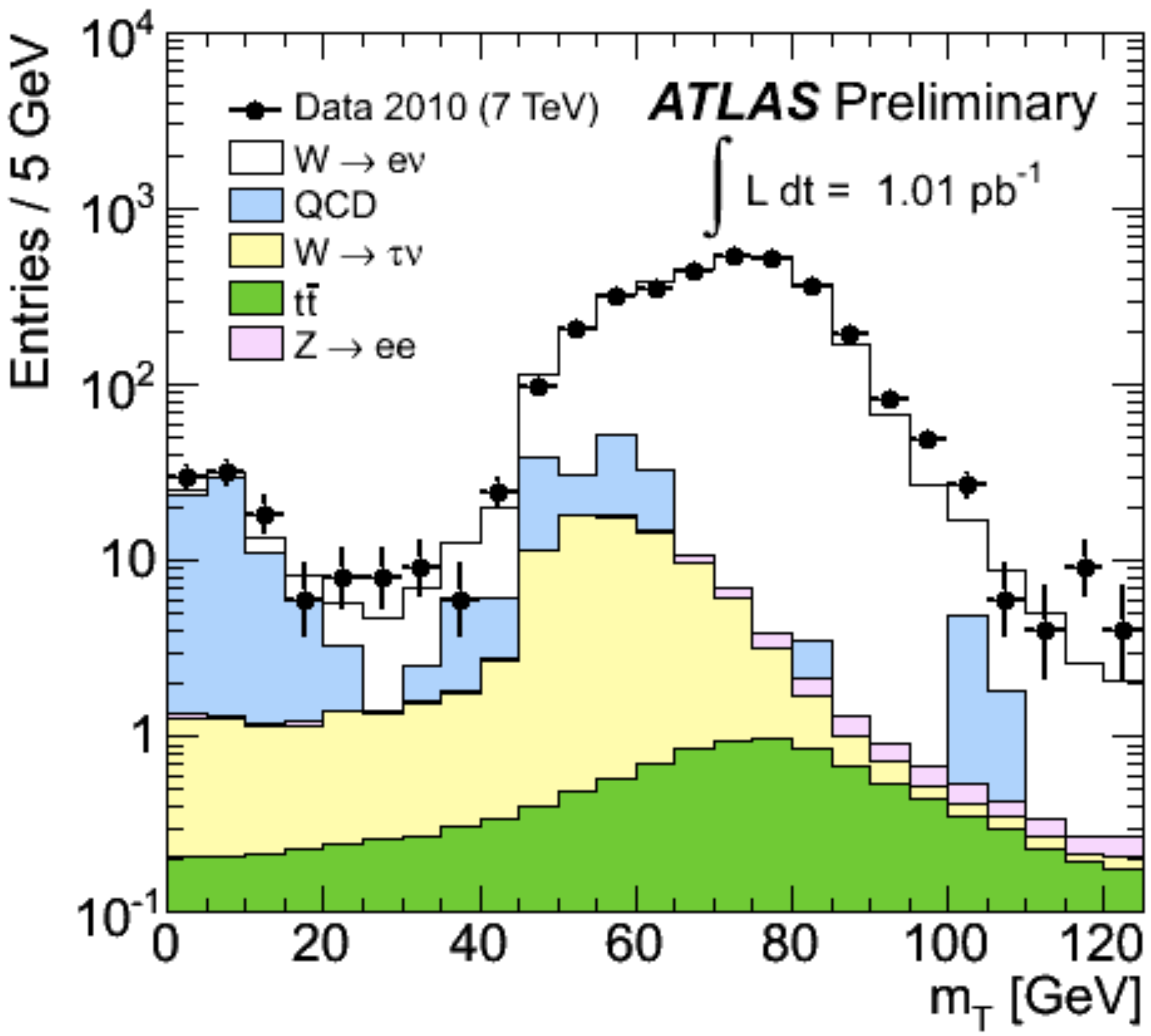
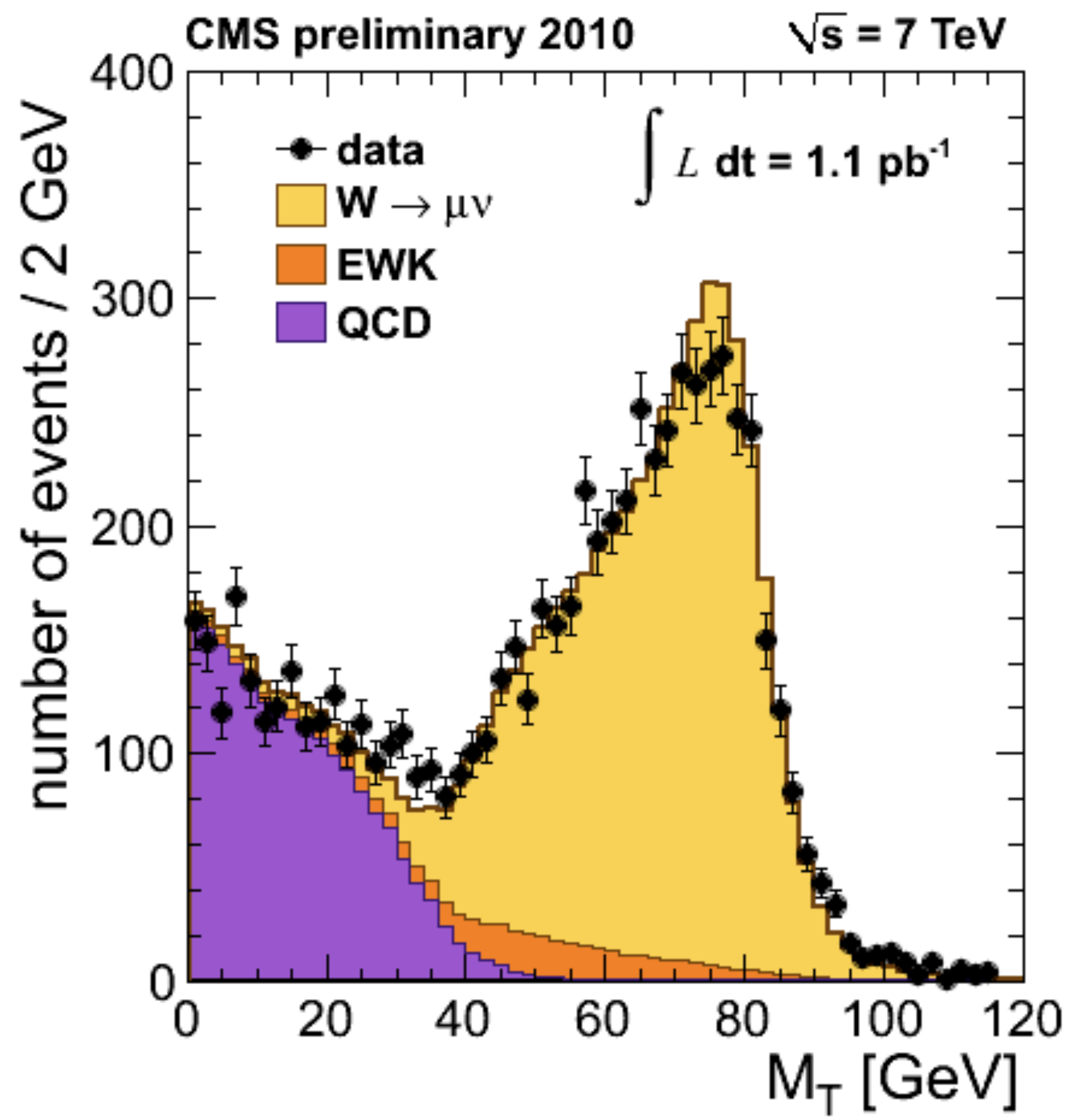
Nice data from LHC@7 TeV





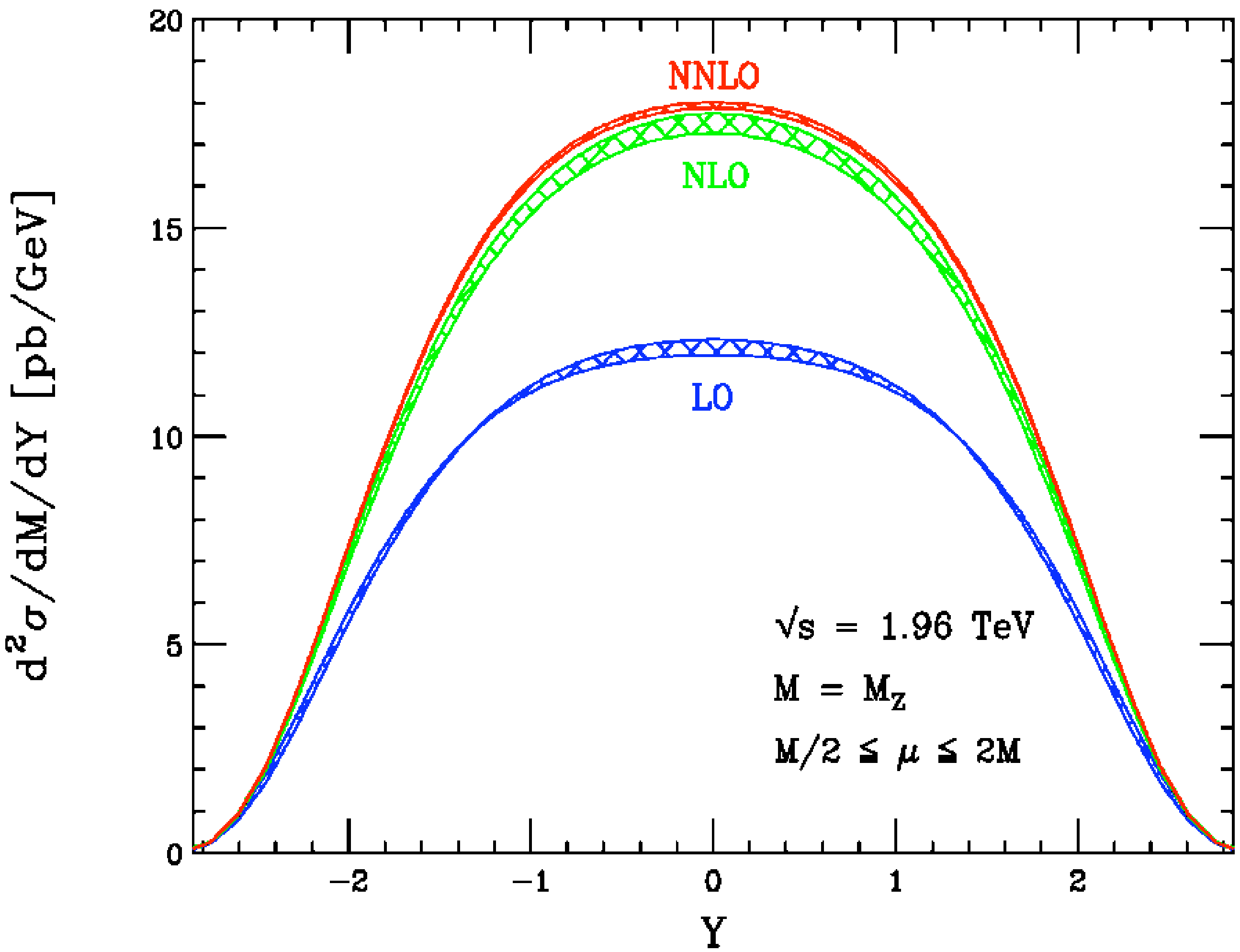
talks by A.Alonso, A.Magnan

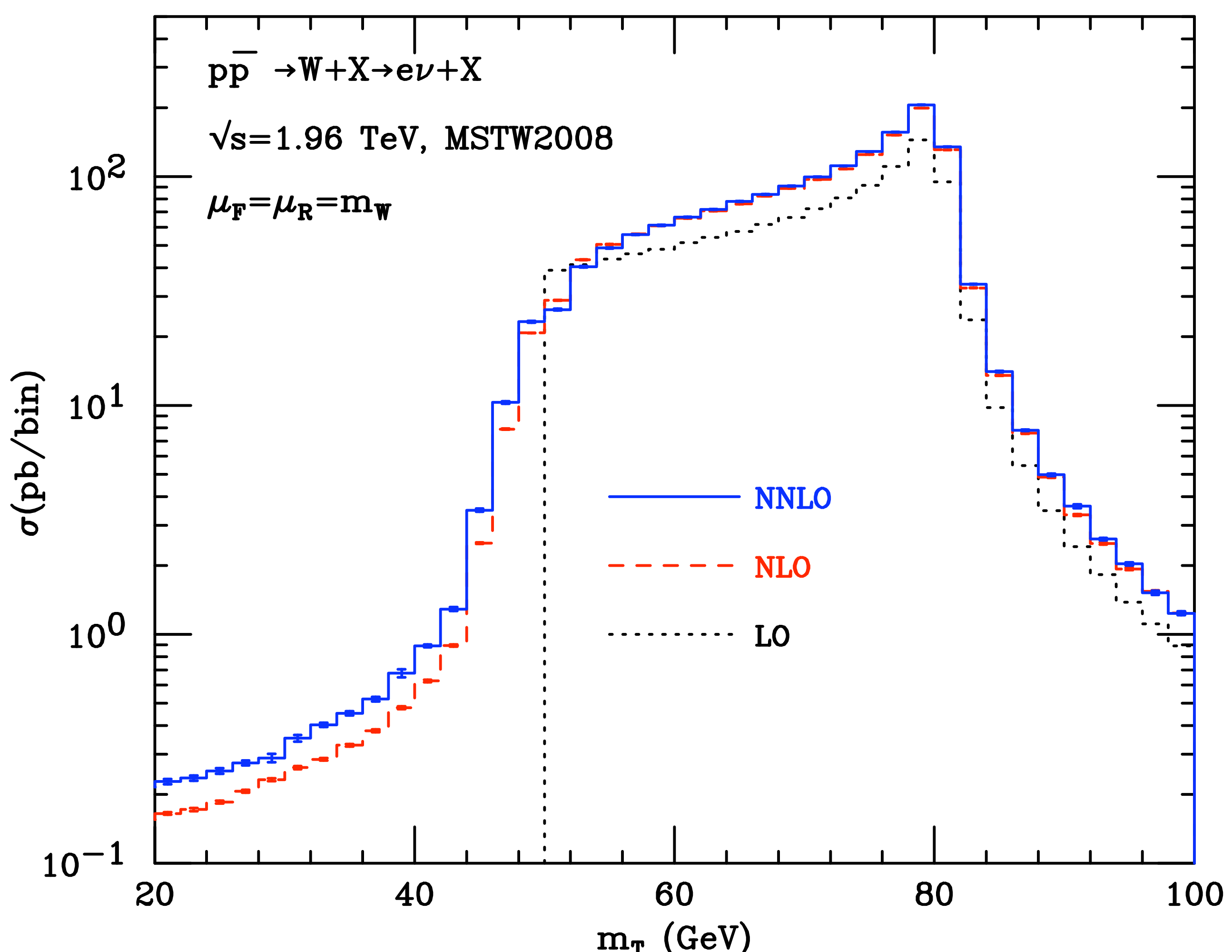
Benchmarks: W, Z

Here theory has done well !

QCD corrections to the total cross section and rapidity distribution known up to NNLO

R.Hamberg, W.Van Neerven, T.Matsuura (1991)
C.Anastasiou, K.Melnikov, L.Dixon,F.Petriello (2003)





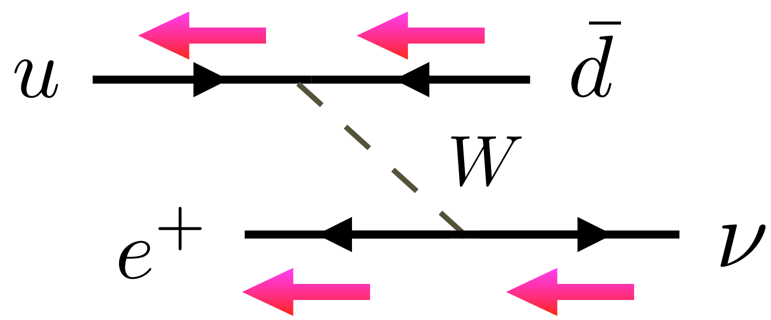
Now also fully exclusive NNLO computation available

K.Melnikov, F.Petriello (2004)
S. Catani et al. (2009)

One application: first NNLO computation of the lepton charge asymmetry

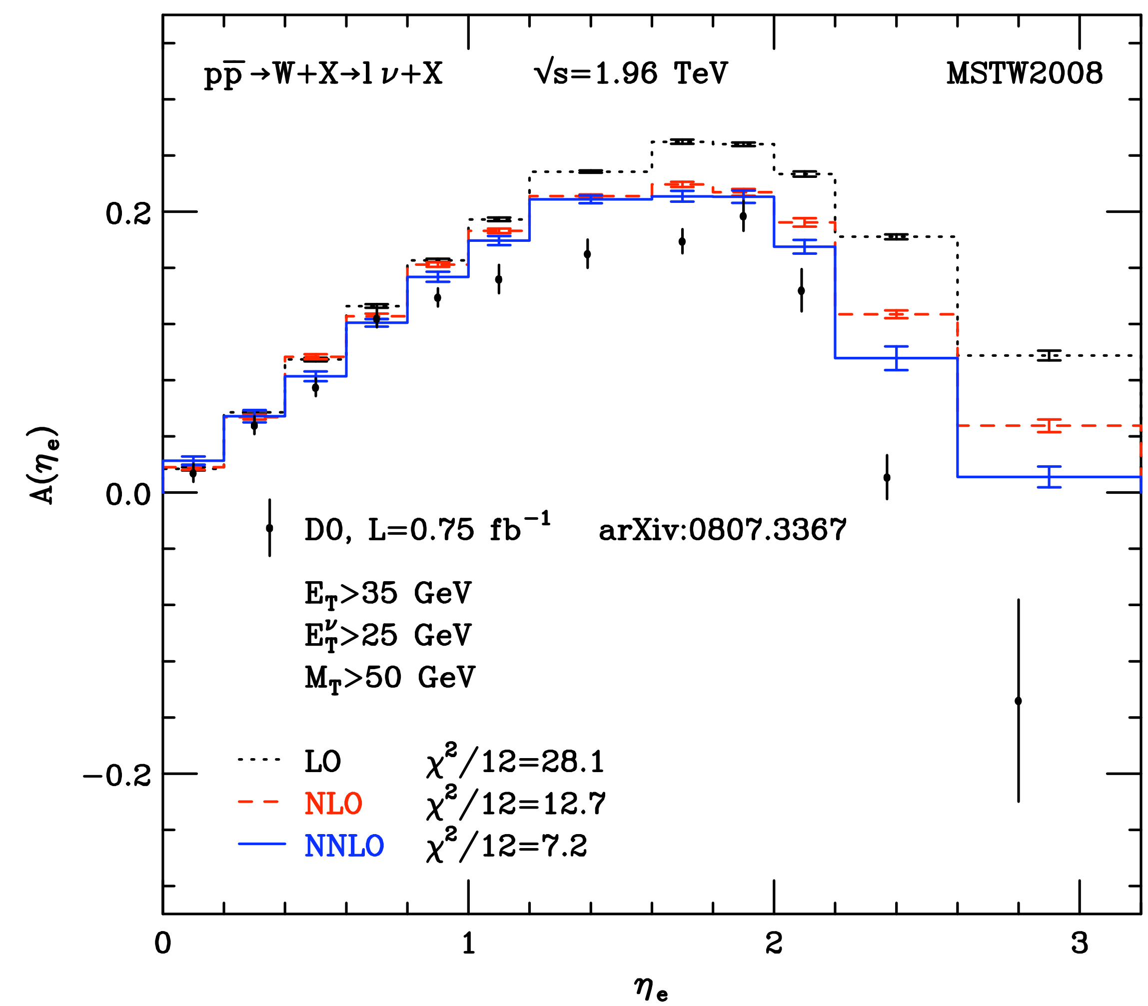
W asymmetry gives important information on u and d quarks in the proton

(u carries more momentum than d)



W production and decay mechanisms are correlated

Angular momentum conservation: the charged lepton is mainly produced in the direction of the down quark



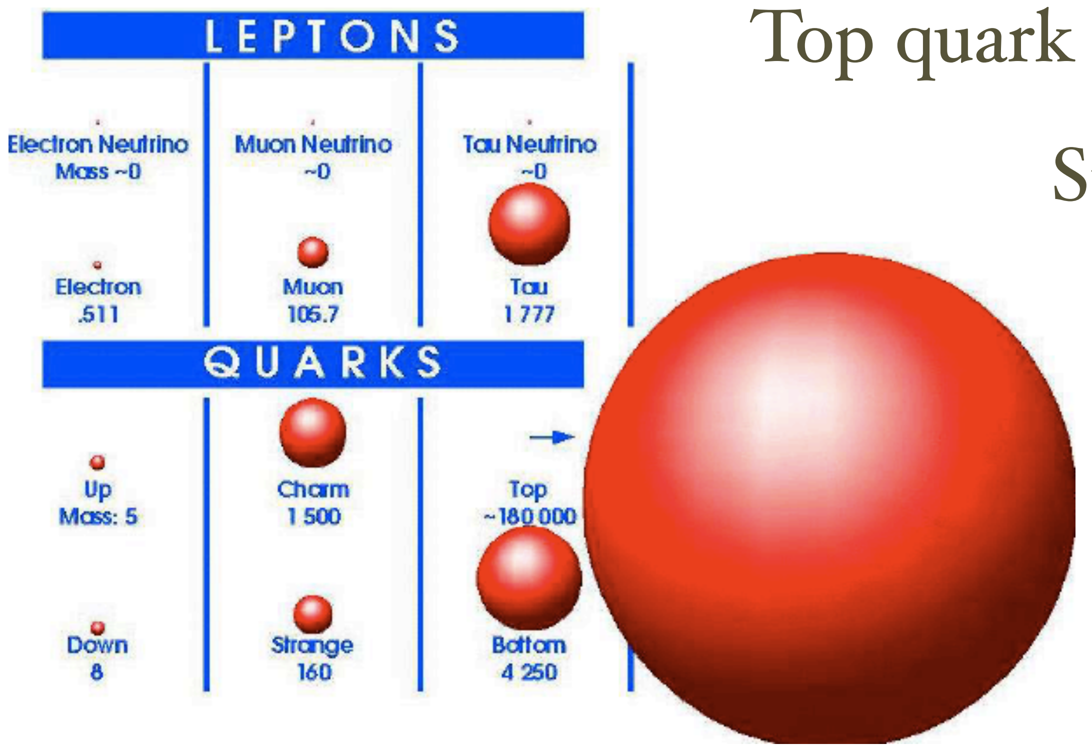
The calculation takes into account all cuts used in the analysis

Recent DØ data difficult to fit

NNLO effect goes in the right direction

S. Catani, G.Ferrera, MG (2010)

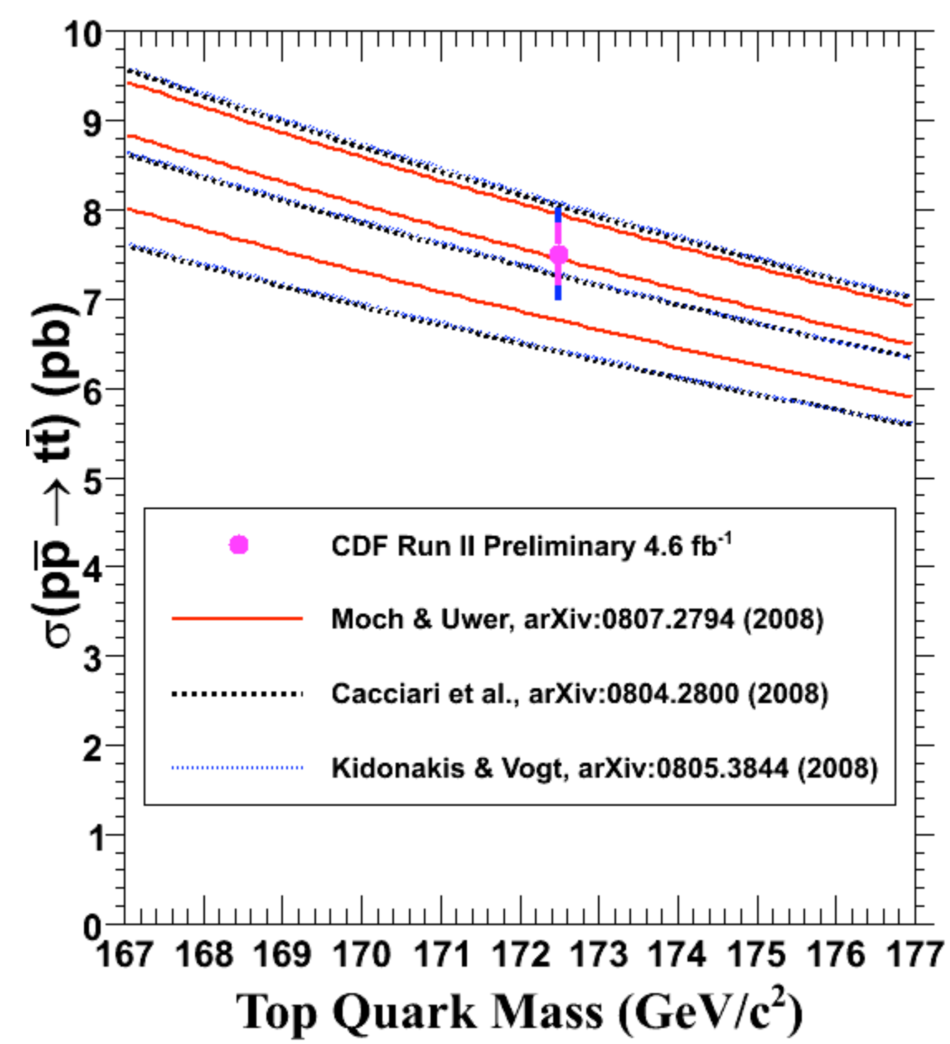
Benchmarks: top



Top quark is the heaviest fundamental particle we know

Strongly coupled to the Higgs sector $m_t \sim \lambda_t v$

→ The Yukawa coupling λ_t must be large !



Huge effort to calculate cross section accurately

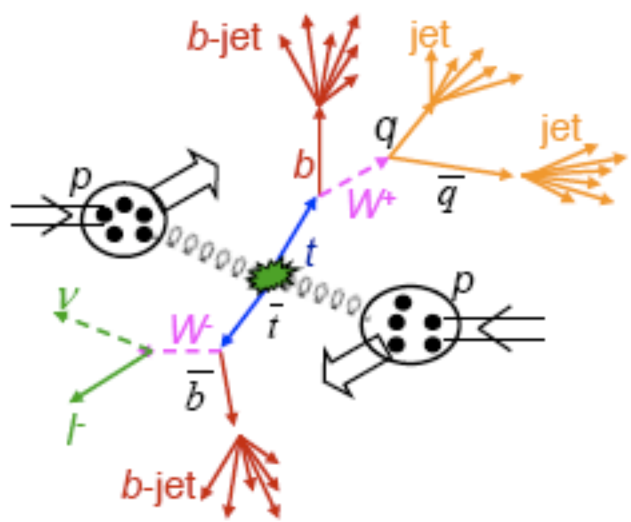
Single top: recently observed at the Tevatron

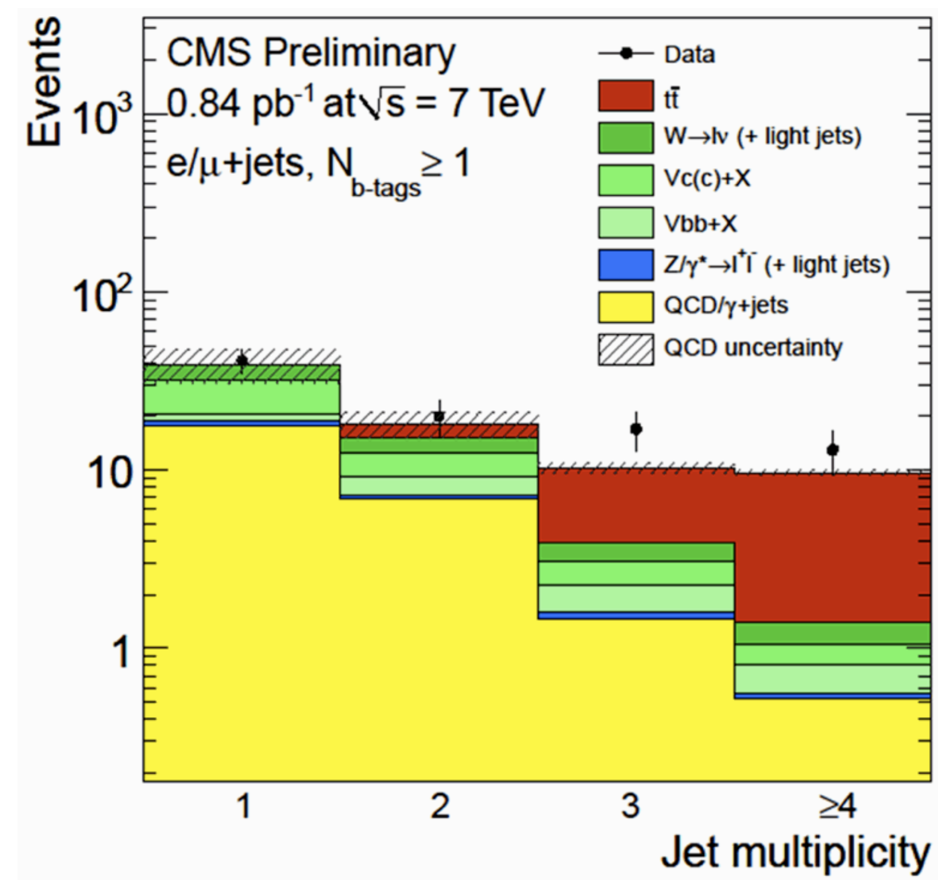
talk by R.Frederix

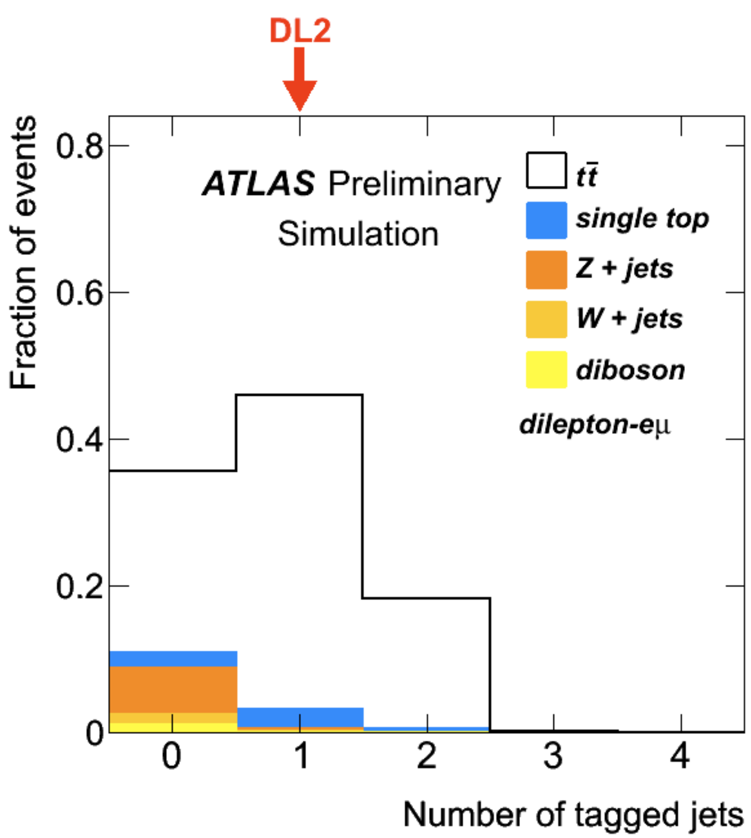
Benchmarks: top

LHC@7 TeV: integrated luminosity allows to observe the first ttbar candidates

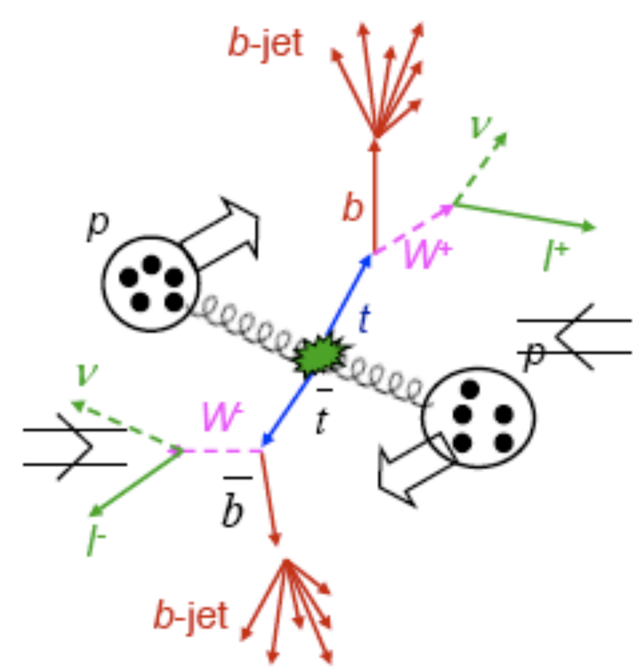
lepton+jets channel







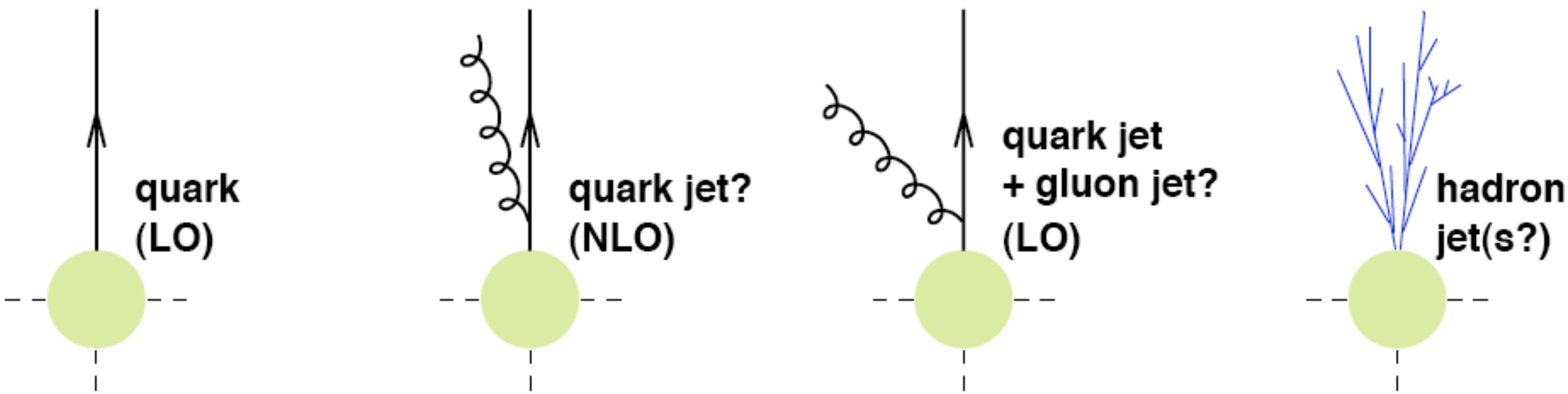
dilepton channel



Jets

It is common to discuss QCD at high-energy in terms of partons

But quarks and gluons are never really visible since, immediately after being produced they fragment and hadronize



A jet is a collimated spray of energetic hadrons and is one of the most typical manifestation of QCD at high energy

By measuring its energy and direction one can get a handle on the the original parton

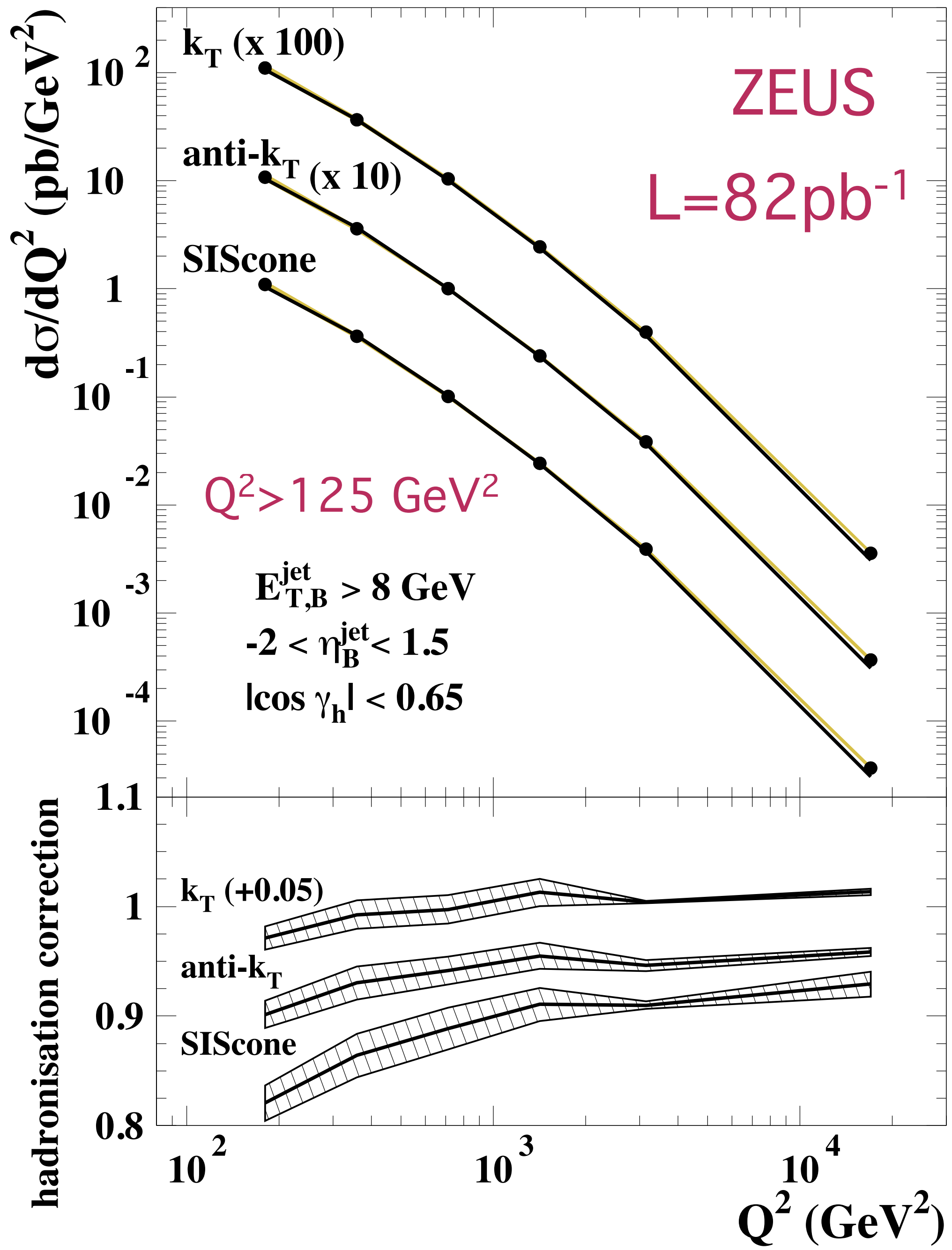
Jets

Problem: the traditional (cone) algorithms used at hadron colliders are often IR unsafe

→ Sensitive to the emission of additional soft particles or to the splitting in two collinear particles

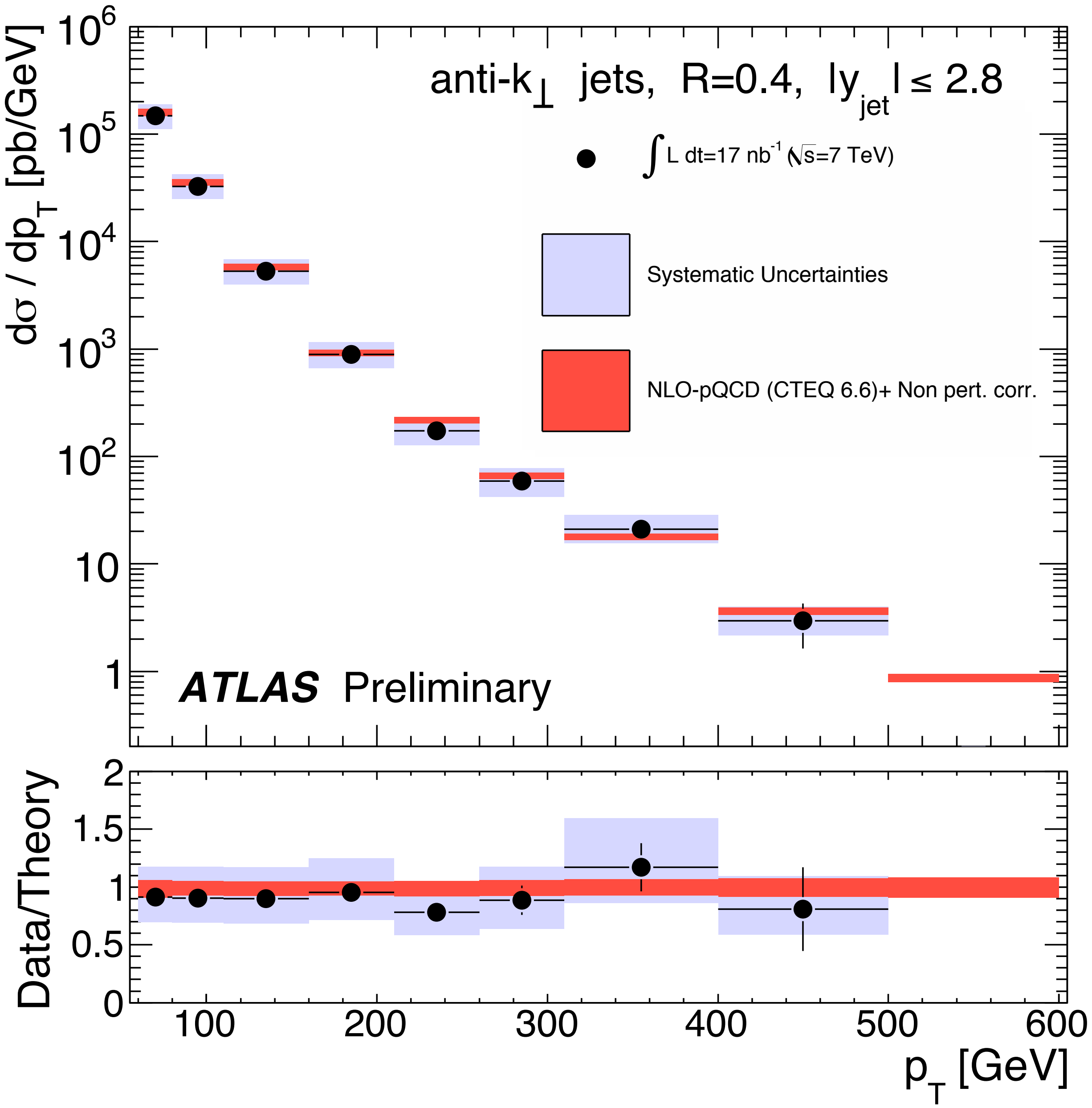
Sequential recombination algorithms (e.g. k_T) solve this problem (clustering sequence closely follows QCD soft and collinear splitting)

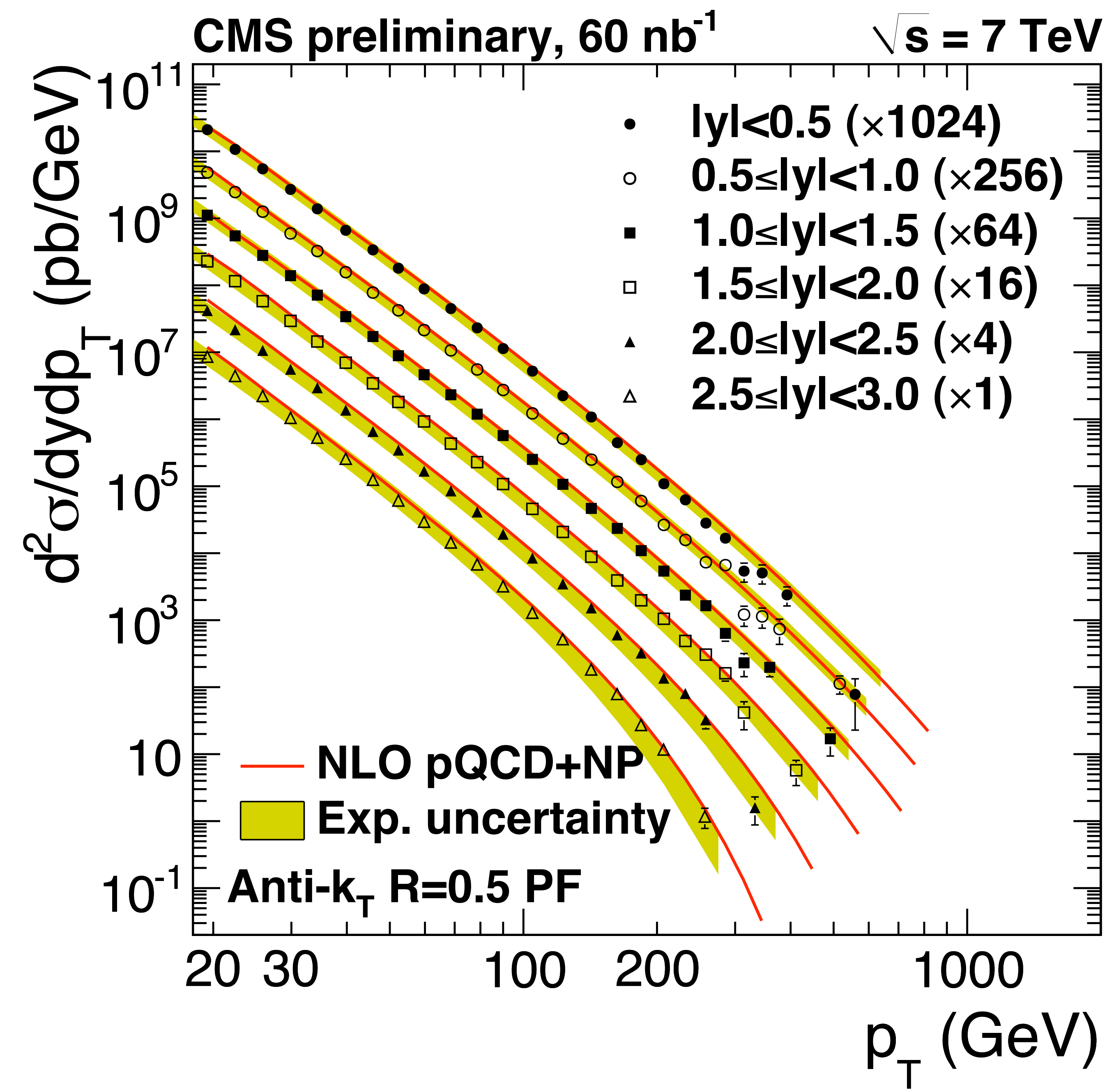
Recent important developments: SIScone, anti-k_T



talk by M.Brinkmann

Jets





anti-k_T: repeatedly combine pairs with smallest $d_{ij}=\Delta R^2/\max(k^2_{Ti}, k^2_{Tj})$

Cone-like jets but through a sequential (IR safe) algorithm

talks by A.Alonso, A.Magnan

M.Cacciari, G.Salam, G.Soyez (2008)

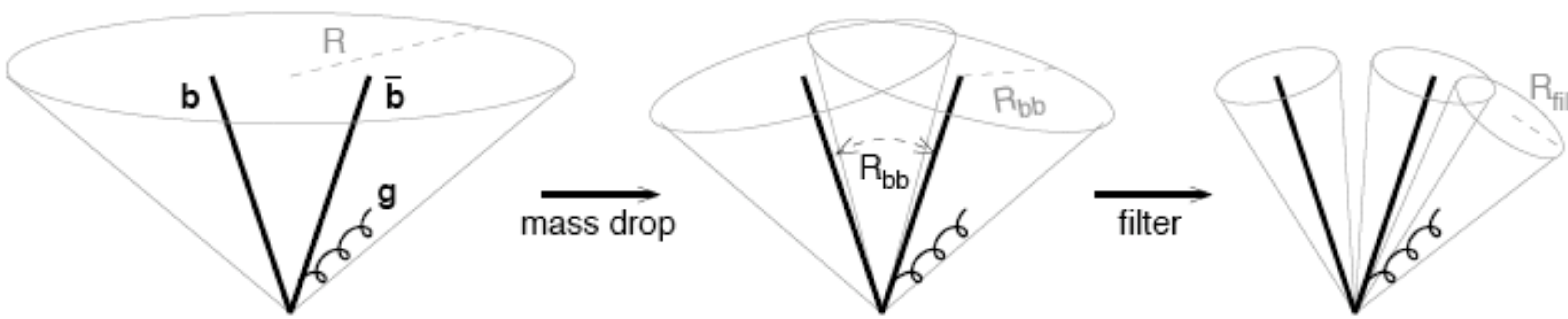
Jets as discovery tools

Associated production of the Higgs boson with a W (or a Z) is not promising at the LHC:

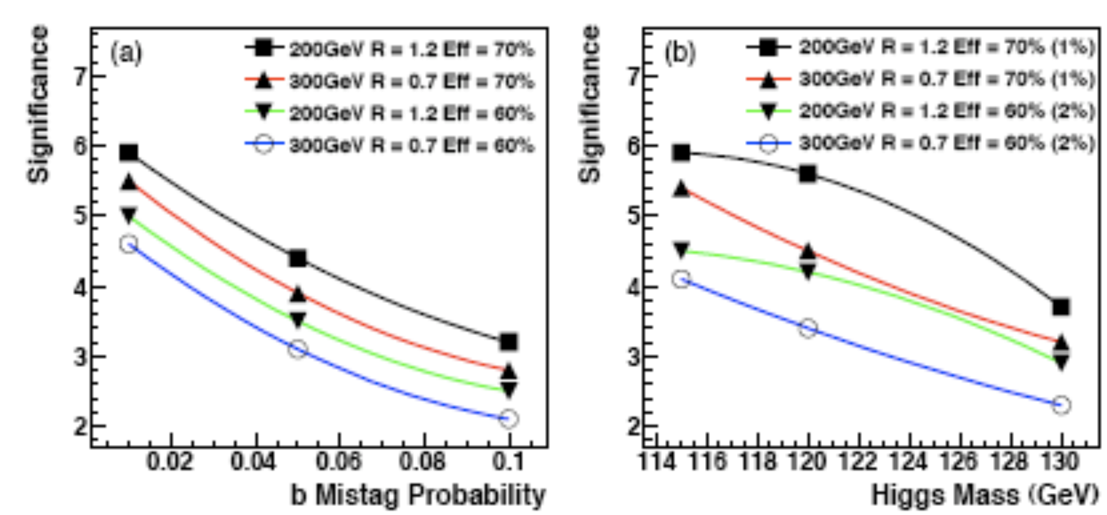
- HV produced at rapidities often beyond the detector acceptance
- presence of large background with scales close to the Higgs mass (eg b from top decays has energy about 65 GeV)

Recently a new analysis strategy has been proposed

J.Butterworth, A.Davison, M.Rubin, G.Salam, (2008)



- Look for events where the Higgs and the vector are back to back
- Cluster into "fat jets" and then undo the last clustering
- Look for two b-tagged smaller jets and filter UE with a smaller jet parameter



Monte Carlo generators

Monte Carlos are ubiquitous in high-energy physics
Every physics analysis involves a QCD based Monte Carlo parton shower to

- simulate signal
- simulate background(s)
- simulate detector response

....

- General-purpose tools
- Complete exclusive description of the event: hard scattering, showering and hadronization

Inclusion of small-x effects

talk by M.Deak

Most famous: PYTHIA, HERWIG, SHERPA

How do they compare with standard (theory driven) perturbative approach ?

Monte Carlo generators

Theory way:

- For low multiplicity include higher-order terms when possible

$$\hat{\sigma} = \hat{\sigma}^{(0)} + \frac{\alpha_S}{\pi}\hat{\sigma}^{(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \hat{\sigma}^{(2)} + \dots$$

- For high multiplicity use tree-level matrix elements

- Pure theoretical view
- Quantum interferences are exactly accounted for
- Final description only in terms of partons: not directly useful for realistic simulations

Experimental way

- Use parton shower to describe both low multiplicity ad high-multiplicity final states starting from 2->1 and 2->2

- Fully realistic simulation of final states
- Big uncertainties in normalization
- Very crude description of multijet final states

Monte Carlo generators

Is there a way to merge the two approaches ?

Difficulty: avoid double counting

Two directions:

- Obtain fully exclusive description of multiparton events correct at LO(+LL) in all phase space

  ME+PS

  CKKW, MLM

- Obtain fully exclusive description of events at NLO both in the normalization and in the distributions

  NLO+PS

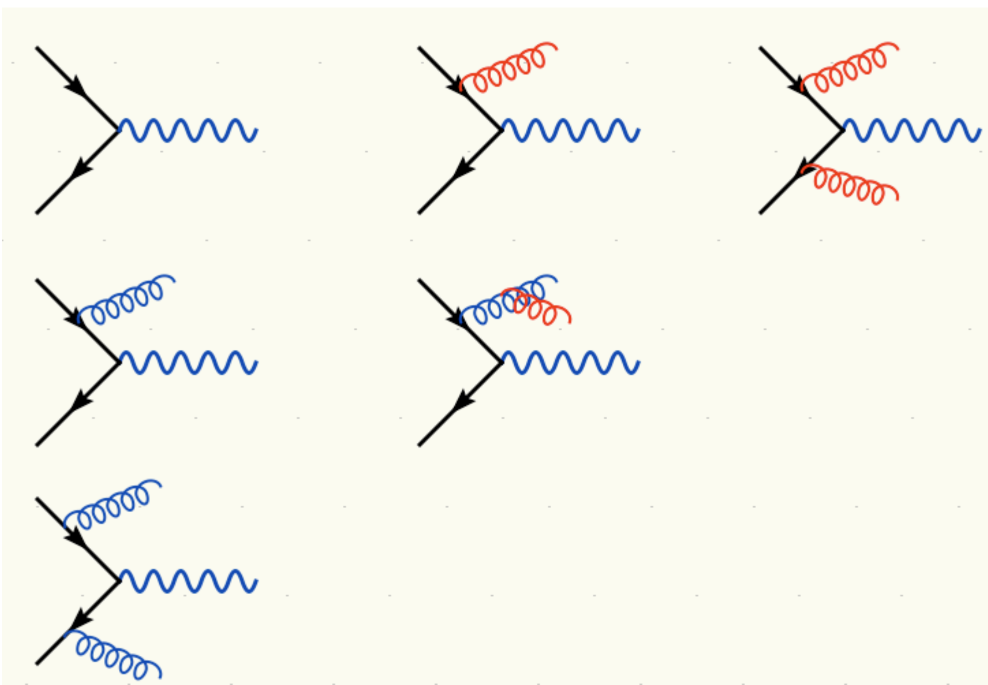
  MC@NLO, POWEG

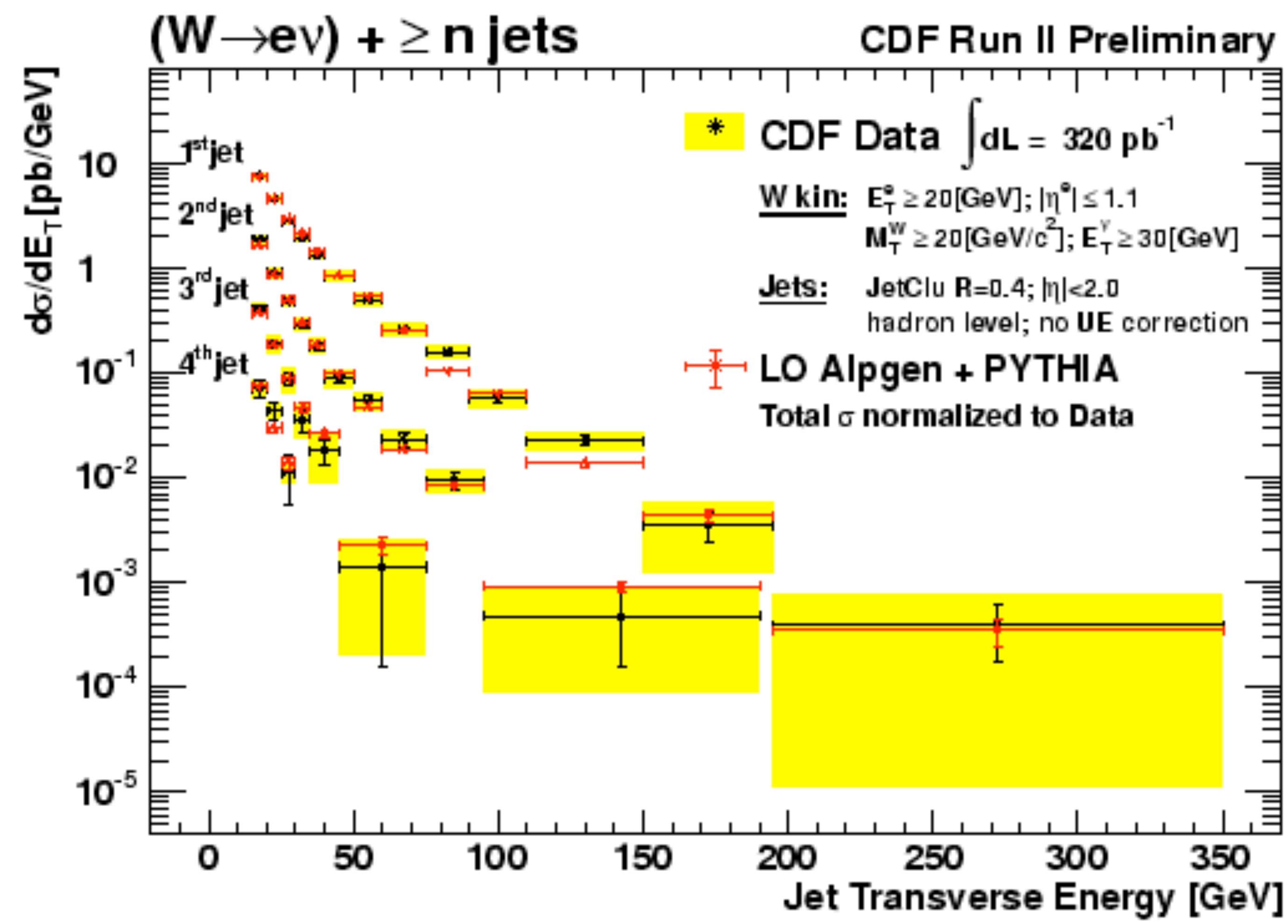
Monte Carlo generators

ME+PS

PS→

ME ↓





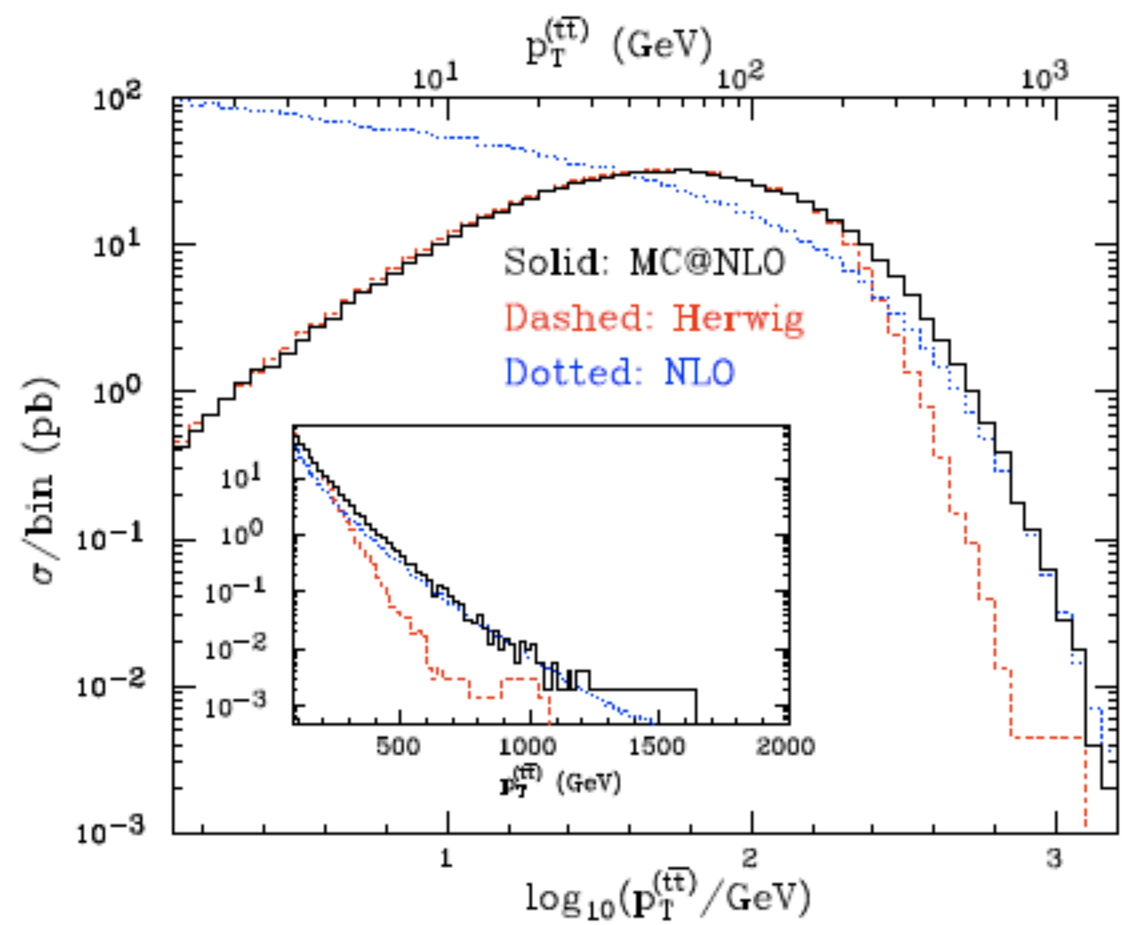
Double counting of configurations that can be obtained in different ways
Matching algorithms (CKKW, MLM,...) apply criteria to select only one possibility based on the hardness of the partons.

Monte Carlo generators

NLOwPS

Two approaches:

- MC@NLO (Frixione, Webber)
  - Matches NLO to HERWIG
  - Requires some work to interface a new NLO calculation to HERWIG
  - Some negative weights
- POWEG (Oleari, Nason)
  - Independent on the PS
  - Can use existing NLO results
  - Exponentiate full real matrix element



OUTLOOK: Exclusive (hadron-level) quality of Monte Carlo and NLO accuracy together

Enjoy the session !