Physics Program

of the experiments at

Large Hadron Collider

Lecture 4

Starting to explore hard QCD

Latest news!!!

- Machine and data taking:
    - 368 bunches
    - 150ns bunch spacing
    - L ~ 2.1 x 10^{32} → up to 6 pb^{-1} in a fill
    - Bunch intensity: up to 1.2 10^{11}p/bunch; emitance 2 μm (both better than nominal)
    - Max (average) pile-up: 3.8 events /x-ing
    - Stored beam energy: ~ 24MJ
    - Recorded luminosity: > 32 pb^{-1}
- LHC plans: deliver 40pb^{-1} by Thursday, then 5 days with 50ns bunch spacing, then start preparing heavy ion run.

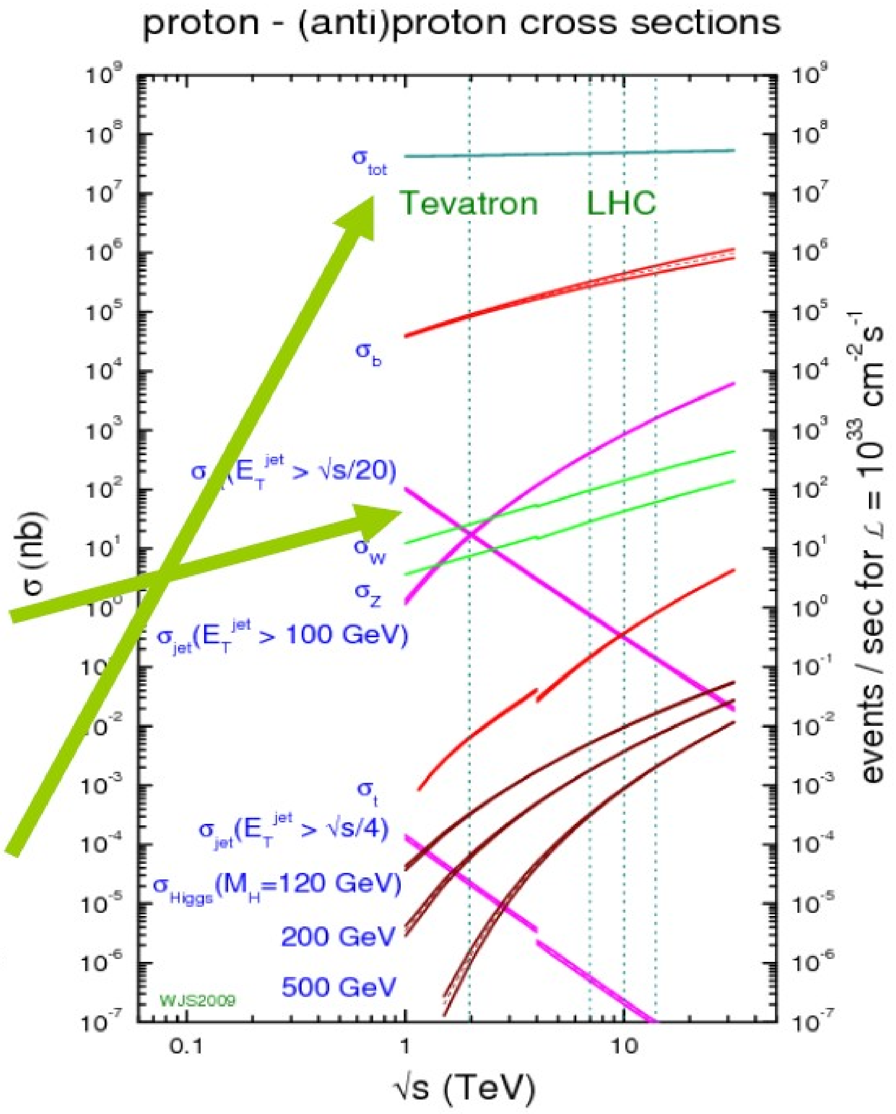
QCD

Scattering processes at high energy hadron colliders can be classified as either HARD or SOFT

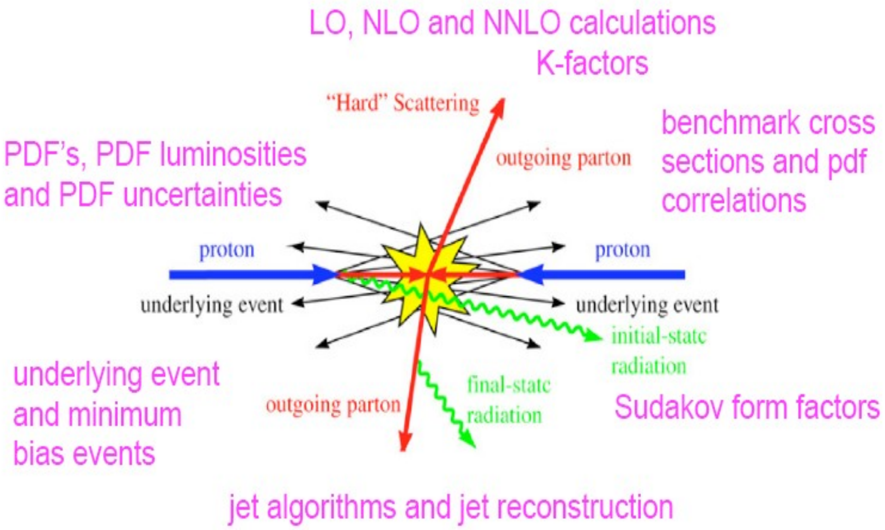
Quantum Chromodynamics (QCD) is the underlying theory for all such processes, but the approach (and the level of understanding) is very different for the two cases

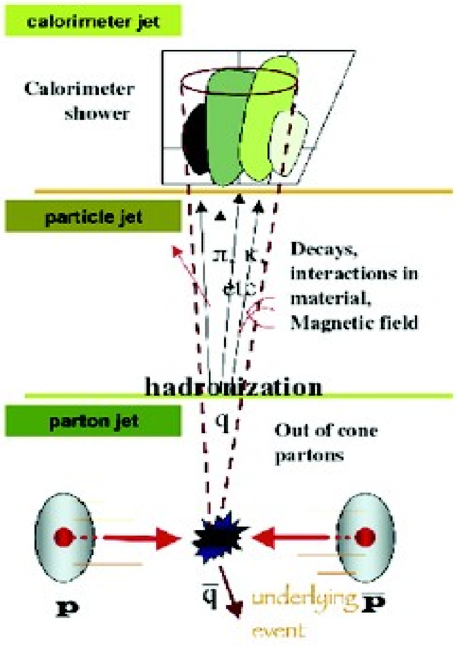
For HARD processes, e.g. W or high-E_T jet production, the rates and event properties can be predicted with some precision using perturbation theory

For SOFT processes, e.g. the total cross section or diffractive processes, the rates and properties are dominated by non-perturbative QCD effects, which are much less well understood

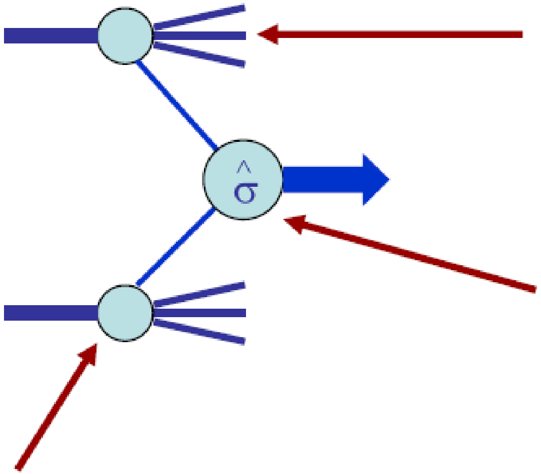


Understanding cross-sections at the LHC





Perturbative QCD in the LHC era



Tuned event simulation
(parton shower + UE) MC
interfaced with LO or NLO
hard scattering MEs

LO, NLO, NNLO, ... supplemented by
resummed N^nLL improvements,
EW corrections

Parton distribution functions

- The QCD factorisation theorem for hard scattering (short distance) inclusive processes

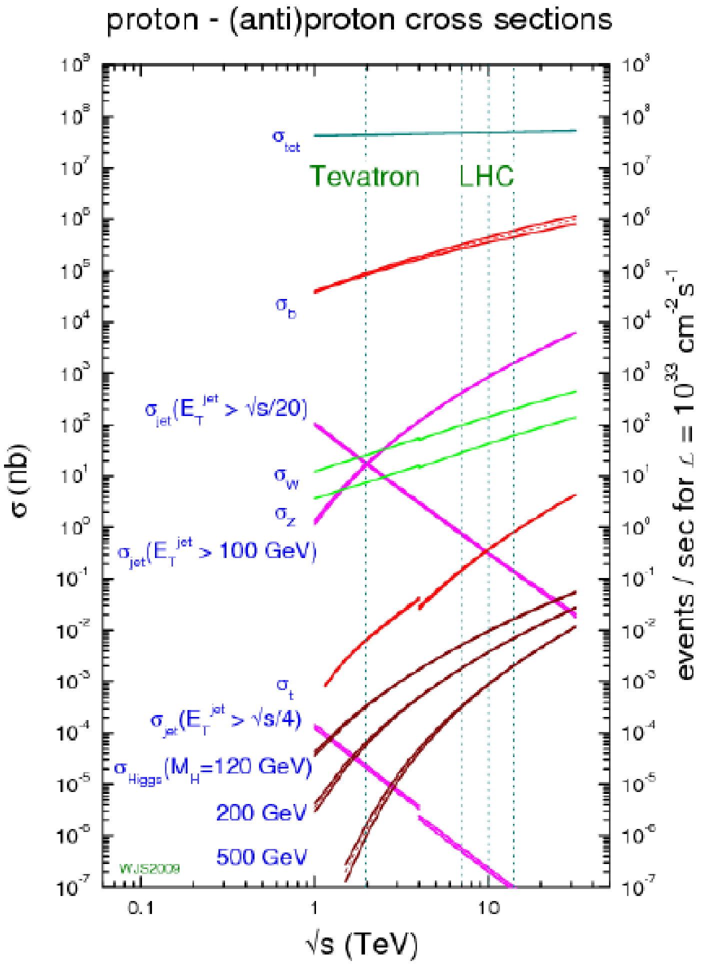
$$\begin{aligned} \sigma_X &= \sum_{a,b}\int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2)\, f_b(x_2,\mu_F^2) \\ &\times\ \hat{\sigma}_{ab\to X}\left(x_1,x_2,\{p_i^\mu\};\alpha_S(\mu_R^2),\alpha(\mu_R^2),\frac{Q^2}{\mu_R^2},\frac{Q^2}{\mu_F^2}\right) \end{aligned}$$

Perturbative processes

- Hard processes are rather well described by QCD
  - Quantitative description for Q^2 scales above ~ 10 GeV^2
  - Decades of earlier work have teach us how to make useful predictions and what questions to ask of the data
- Now we have the possibility to extend measurements into new Q^2 range
  - First we have to gain confidence in the predictions and our ability to confront them with the data
- Hard scattering is the domain of new physics
  - Important we understand the standard model processes if we are to be able to identify new physics

How precise predictions

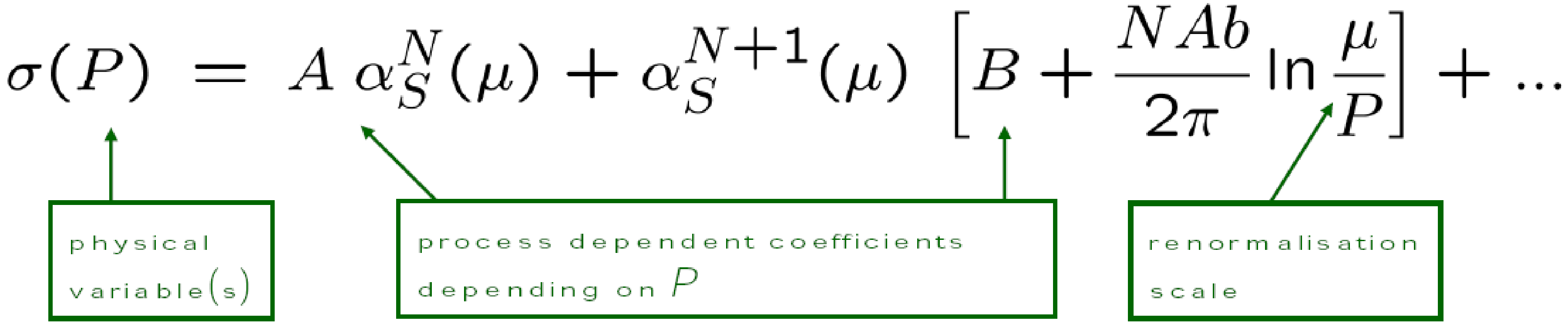
- LO for generic parton-shower MCs, tree level ME's
- NLO for many parton level signal and background processes
- NNLO for limited number of precision observables: W, Z, DY, H



$$\delta\sigma_{th} = \delta\sigma_{UHO} \oplus \delta\sigma_{pdf} \oplus \delta\sigma_{param} \oplus \dots$$

General structure of a QCD perturbation series

- Choose a renormalisation scale (e.g. MSbar)
- Calculate cross-section to some order (e.g. NLO)



$$\sigma(P) = A\,\alpha_S^{N}(\mu) + \alpha_S^{N+1}(\mu)\left[B + \frac{NAb}{2\pi}\ln\frac{\mu}{P}\right] + \ldots$$

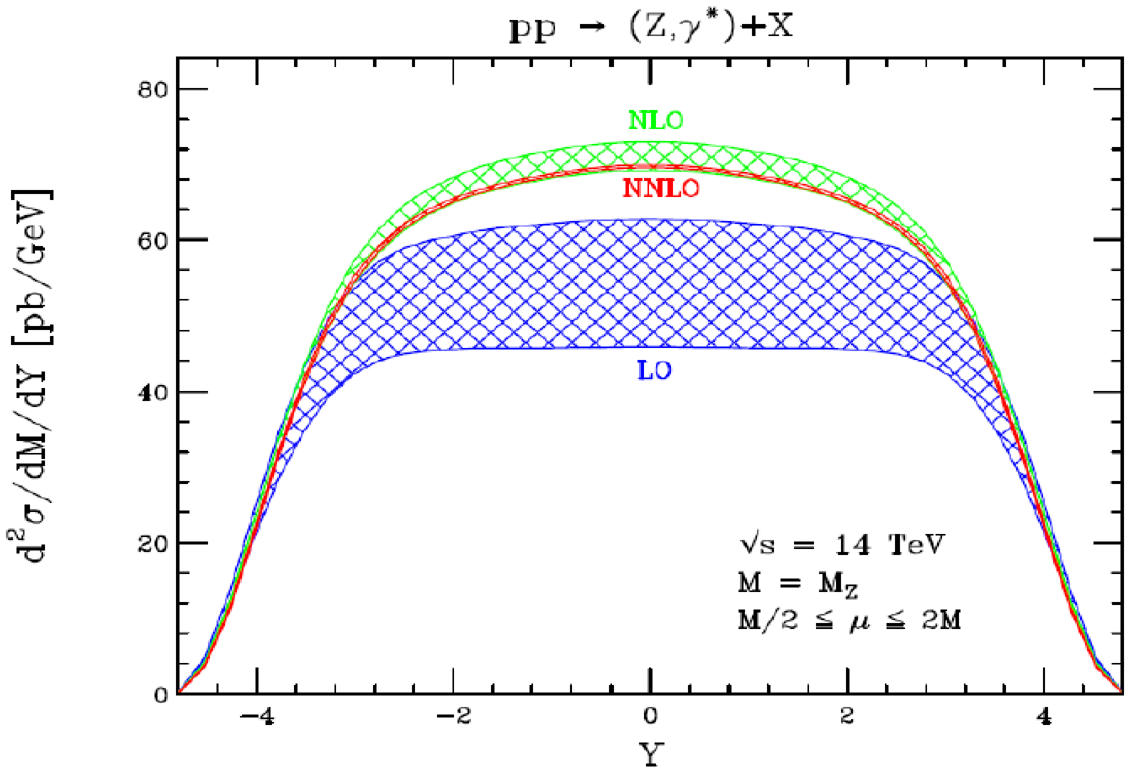
physical variable(s)

process dependent coefficients depending on P

renormalisation scale

- Can help to converge by using a physical scale choise e.g. $\mu = M_Z$ or $\mu = E_T^{jet}$

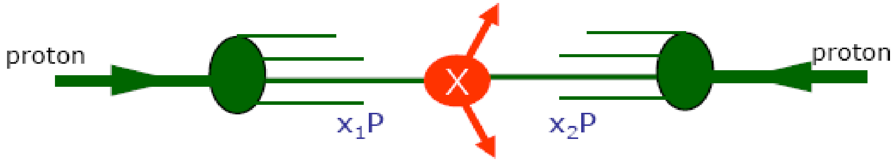
The impact of NLO



Anastasiou, Dixon, Melnikov, Petriello, 2004

- Shown only scale variation μ_R and μ_F

Parton distribution functions

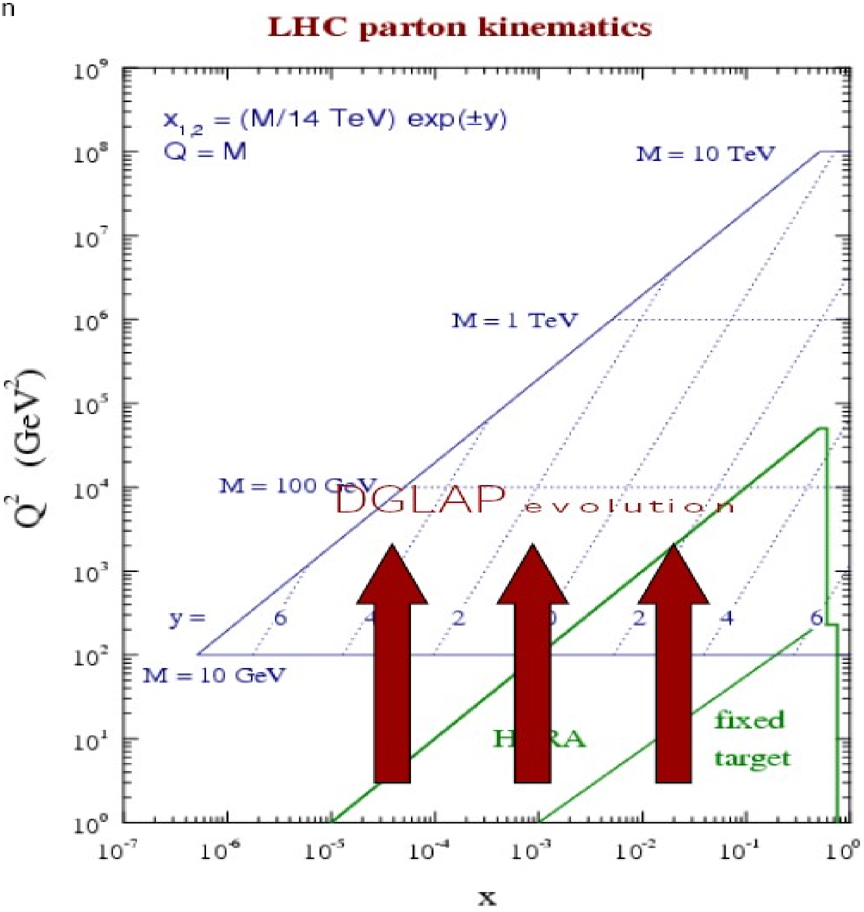


Momentum fraction x_1, x_2 determined by mass and rapidity of X.

- x dependence of $f_i(x,Q^2)$ determined by “global fit” to deep inelastic scattering and other data, Q^2 dependence determined by DGLAP equations:

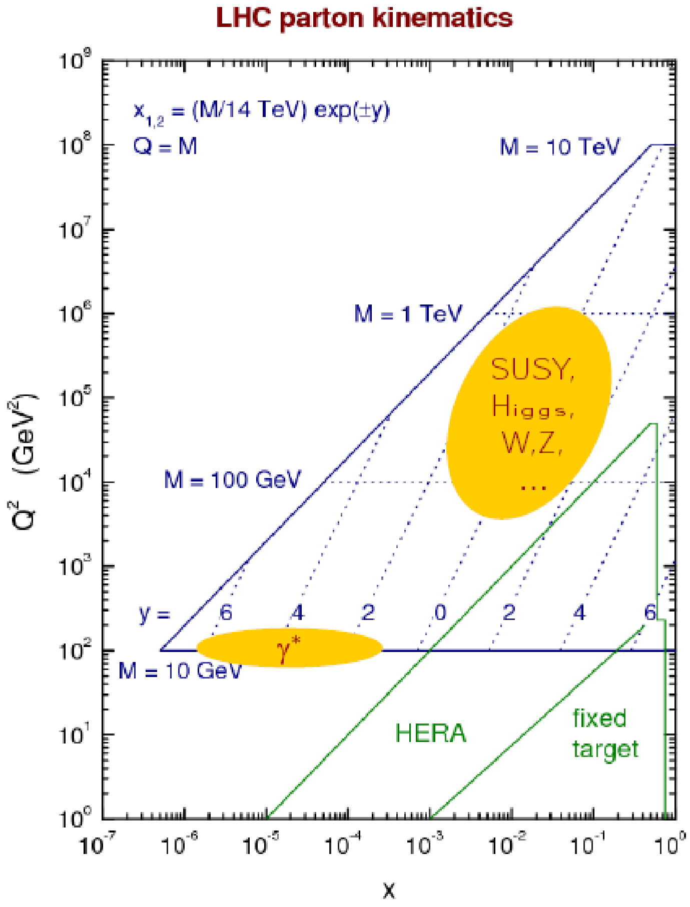
$$\frac{\partial q_i(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{q_iq_j}(y,\alpha_S)\, q_j\big(\frac{x}{y},Q^2\big) + P_{q_ig}(y,\alpha_S)\, g\big(\frac{x}{y},Q^2\big)\Big\}$$

$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{gq_j}(y,\alpha_S)\, q_j\big(\frac{x}{y},Q^2\big) + P_{gg}(y,\alpha_S)\, g\big(\frac{x}{y},Q^2\big)\Big\}$$



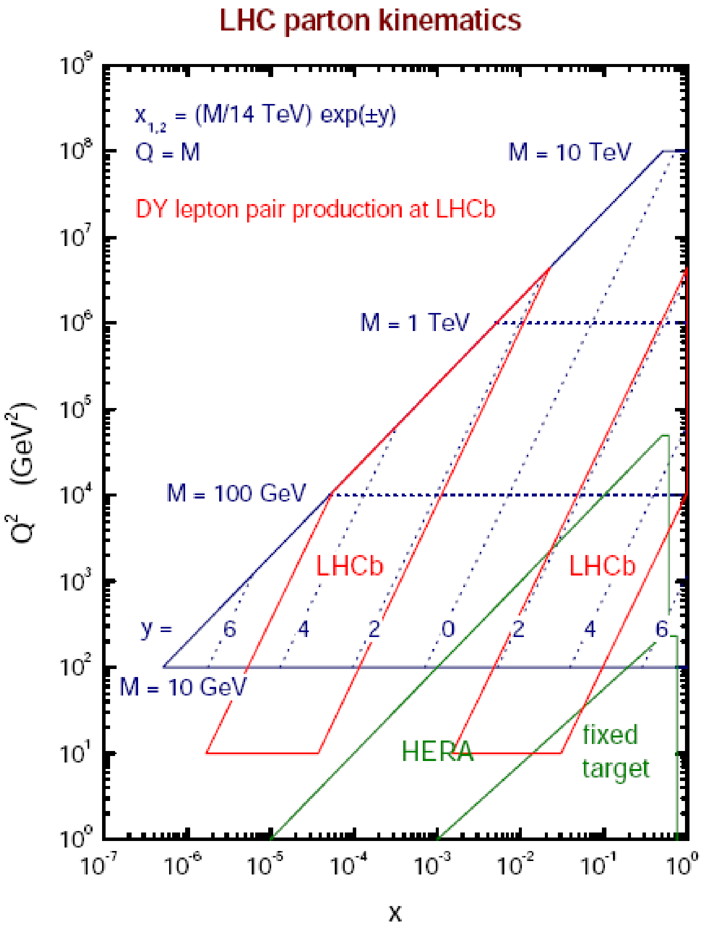
PDF's at LHC

- Most SM and new physics sample pdf's in the region of where they are already well known
- Current pdf uncertainties provide benchmark for whether LHC can add new information
- Low-mass forward production (e.g. b quarks, Drell-yan) might provide new information on small-x partons



Extending even further

- To probe very small x at LHC we need to produce relatively light objects at forward rapidity
  - $x \sim (M/\sqrt{s}) \cdot e^{-y} << 1$
- The simplest process is Drell-Yan production, it requires good detection of lepton with low p_T in the forward region.
- Studies underway at the LHCb to cover this region.



How PDF's are obtained

- Choose a factorisation scheme (e.g. MSbar), and an order of perturbation theory (LO, NLO, NNLO) and a starting scale Q_0 where pQCD applies (e.g. 1-2 GeV).
- Parametrise quark and gluon distributions at Q_0, e.g.

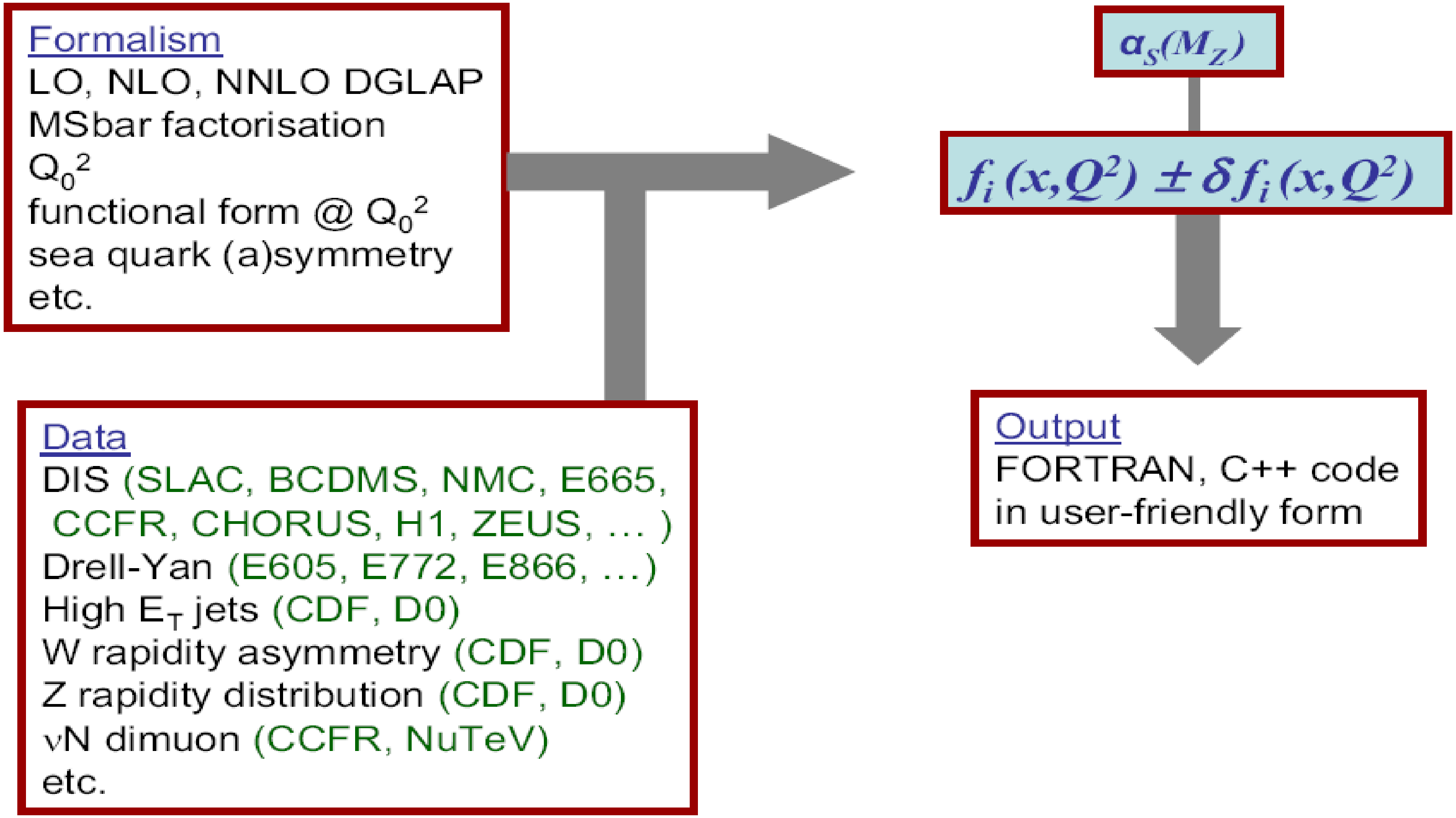
$$f_i(x, Q_0^2) = A_i x^{a_i} [1 + b_i \sqrt{x} + c_i x] (1 - x)^{d_i}$$

- Solve DGLAP equations to obtain the pdfs at any x and $Q>Q_0$; fit data for parameters (A_i, a_i, ...α_s)
- Approximate the exact solutions (e.g. interpolation grids, expansions in polynomials etc), just output “global fit” is available for users

```
SUBROUTINE PDF(X,Q,U,UBAR,D,DBAR,…,BBAR,GLU)
```

input | output

Anatomy of global PDF fit



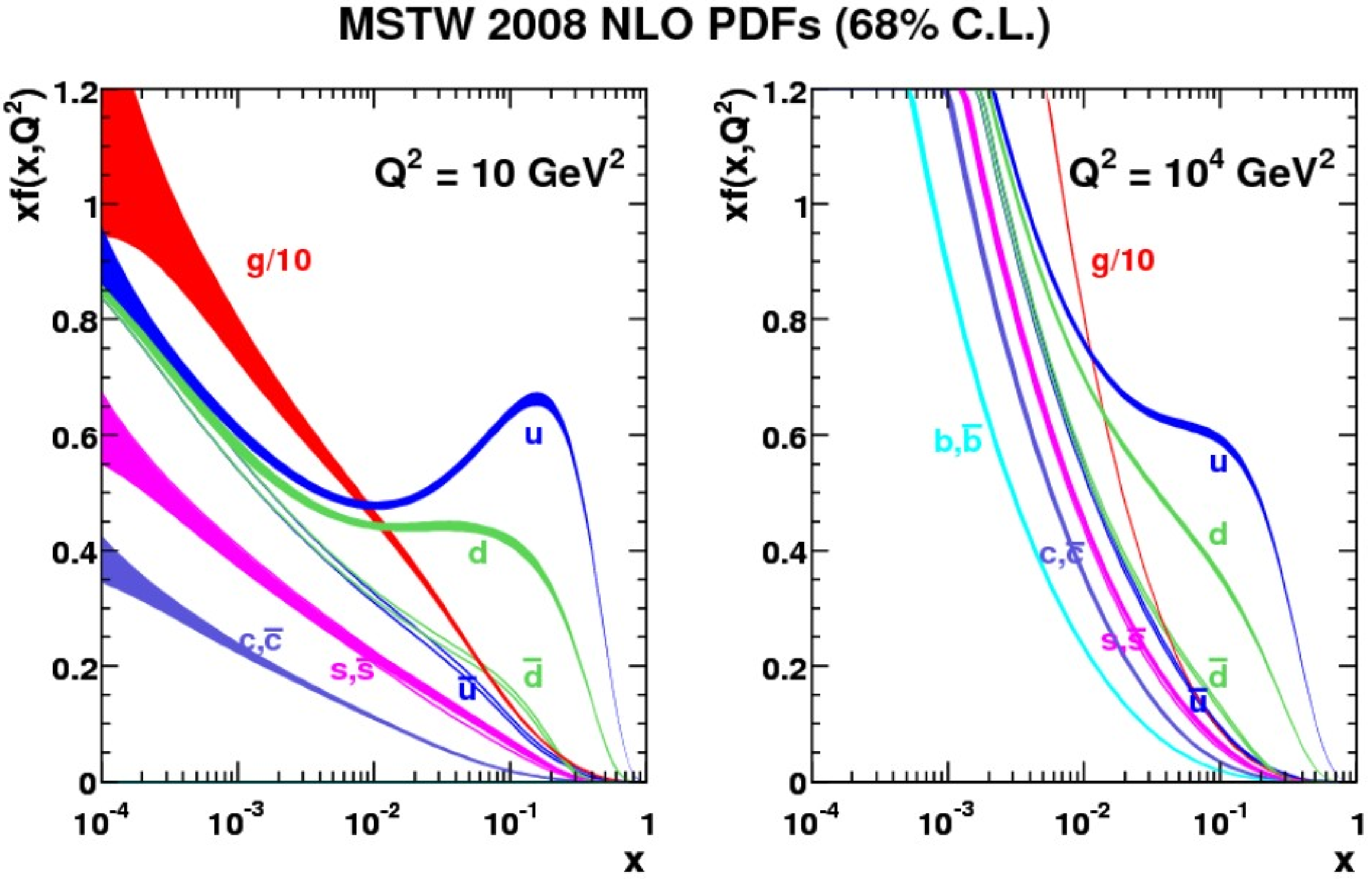
Formalism
LO, NLO, NNLO DGLAP
MSbar factorisation
Q_0^2
functional form @ Q_0^2
sea quark (a)symmetry
etc.

Data
DIS (SLAC, BCDMS, NMC, E665, CCFR, CHORUS, H1, ZEUS, …)
Drell-Yan (E605, E772, E866, …)
High E_T jets (CDF, D0)
W rapidity asymmetry (CDF, D0)
Z rapidity distribution (CDF, D0)
νN dimuon (CCFR, NuTeV)
etc.

$\alpha_S(M_Z)$

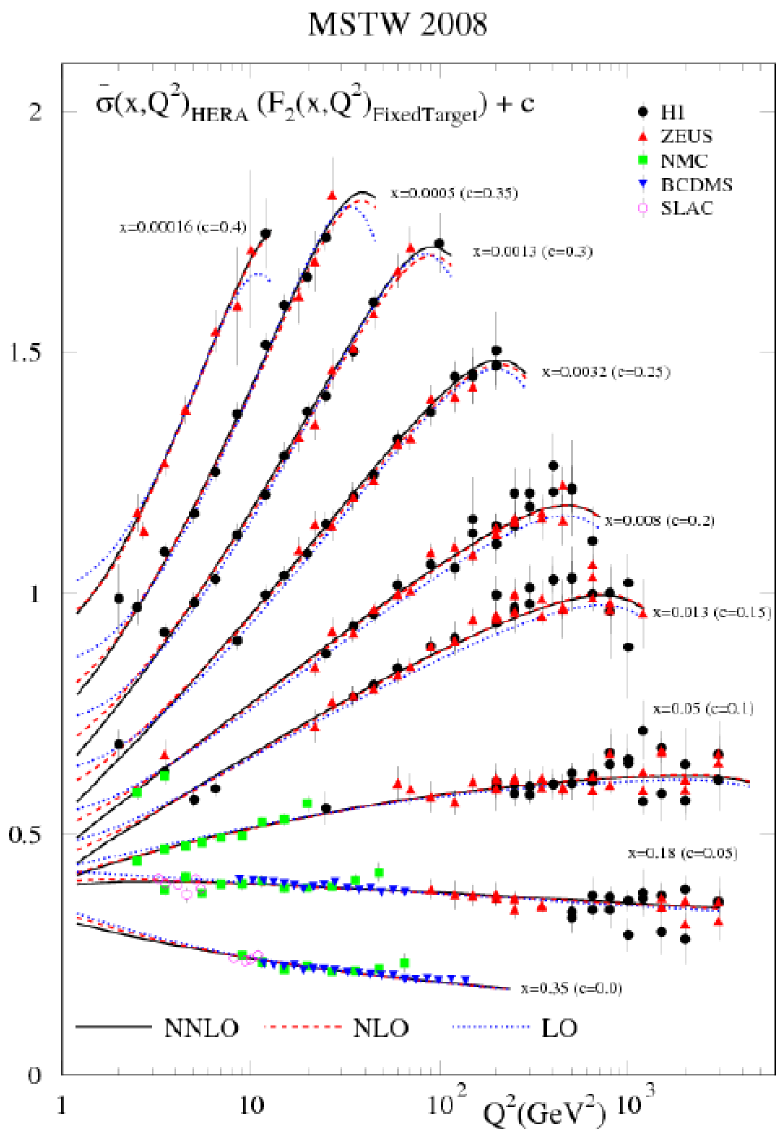
$f_i(x,Q^2) \pm \delta f_i(x,Q^2)$

Output
FORTRAN, C++ code
in user-friendly form

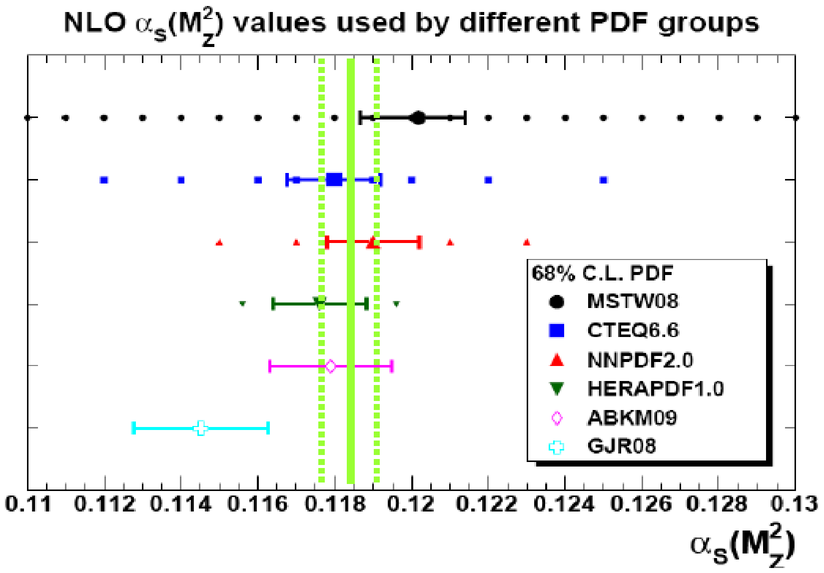

MSTW 2008 NLO PDFs (68% C.L.)
$Q^2 = 10\ \mathrm{GeV}^2$
$Q^2 = 10^4\ \mathrm{GeV}^2$
$xf(x,Q^2)$
x
g/10
u
d
$\bar{u}$
$\bar{d}$
$s,\bar{s}$
$c,\bar{c}$
$b,\bar{b}$
0
0.2
0.4
0.6
0.8
1
1.2
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

LO vs NLO vs NNLO

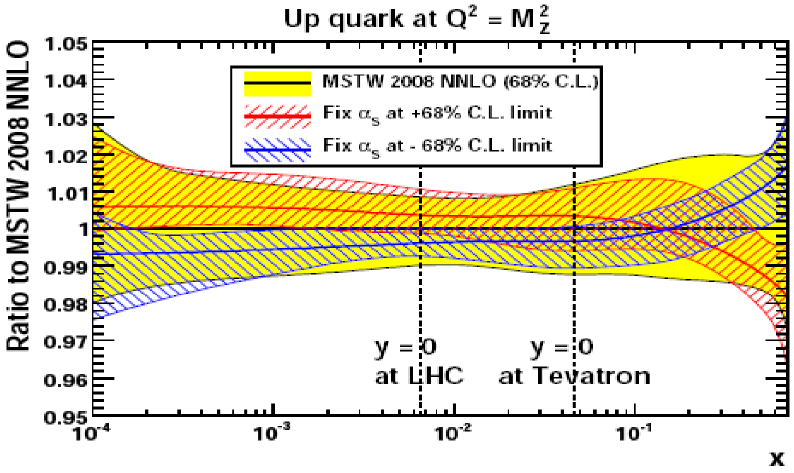
- LO evolution too slow at small x
- NNLO fit maginally better than NLO
- LO can be improved (e.g. LO*)for MC's by adding K-factors, relaxing momentum conservation, etc.



PDF's and $\alpha_s(Q^2)$

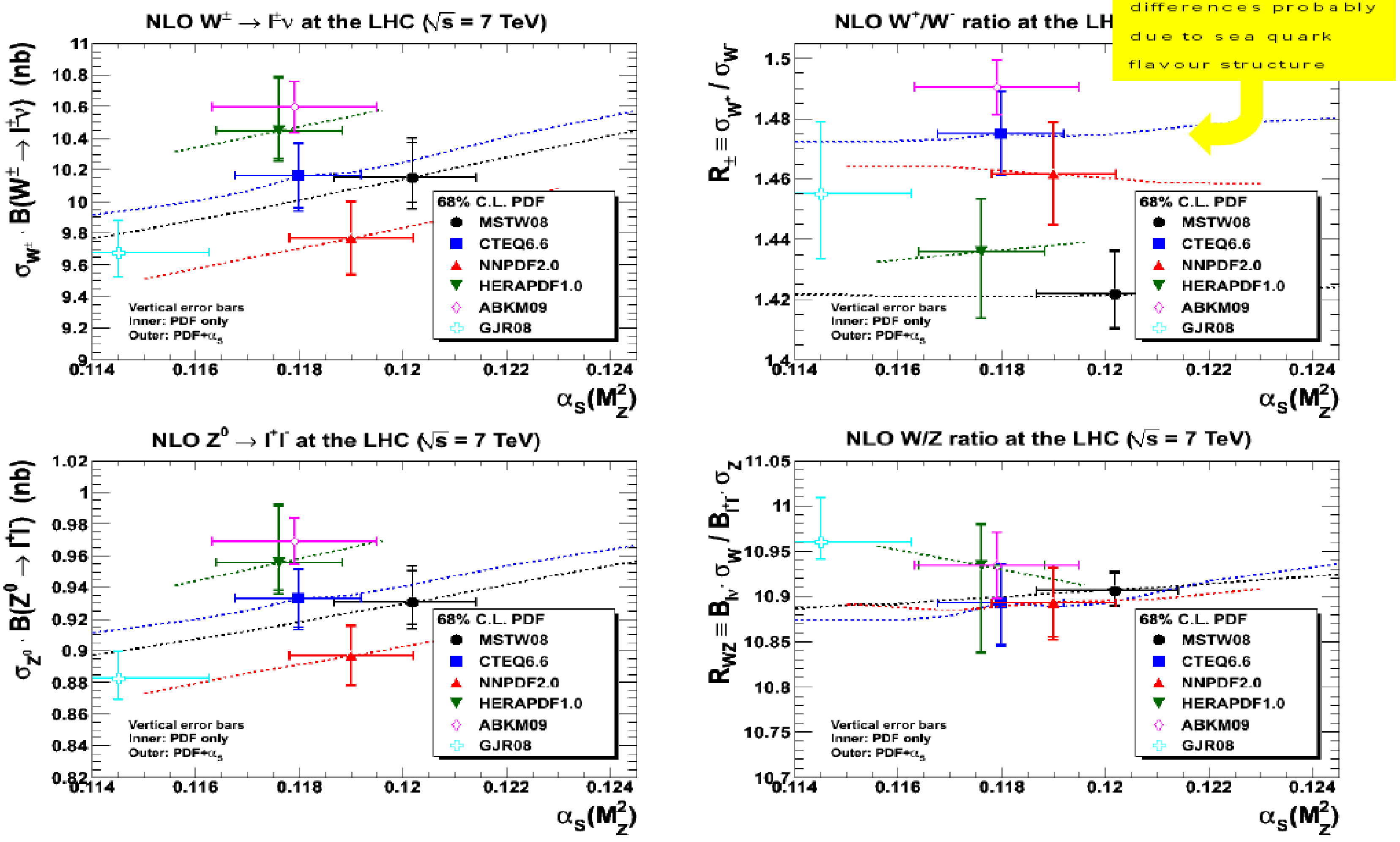


- PDF's and $\alpha_s(Q^2)$ are correlated
- With new approach it can be accounted for simultaneusly in calculations of the cross-sections
  - Eigenvectors of PDF's with different fixed as values provided



NNLO quark up distribution, ratio to central value

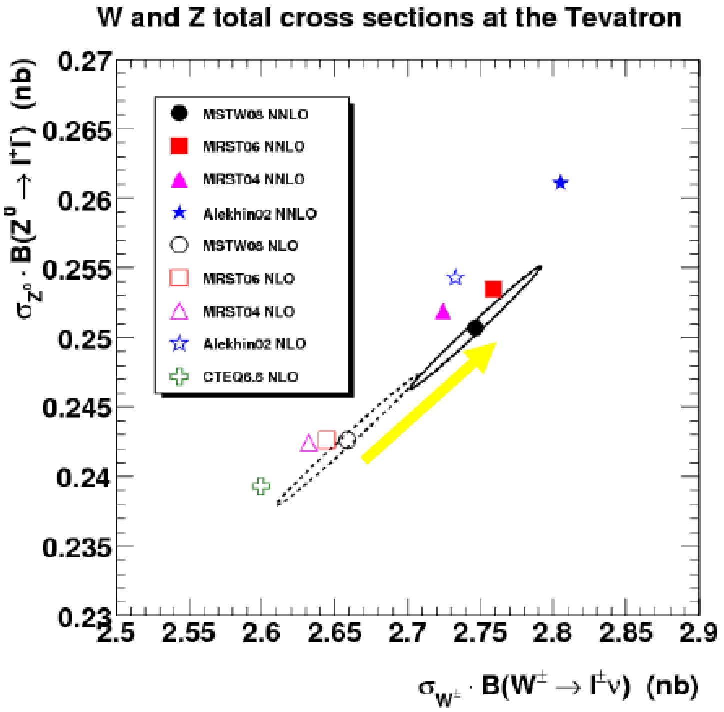
Benchmark W,Z cross-sections

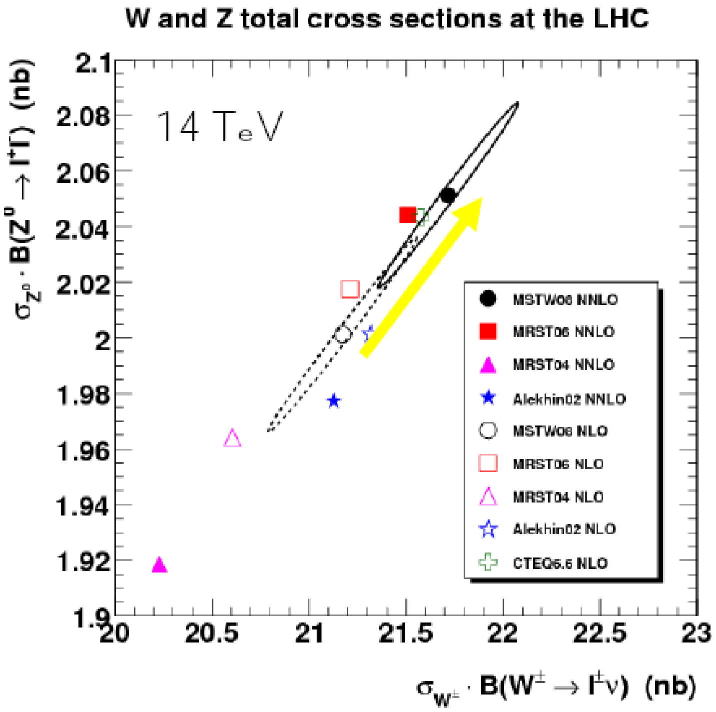


differences probably due to sea quark flavour structure

Predictions for σ (W,Z)

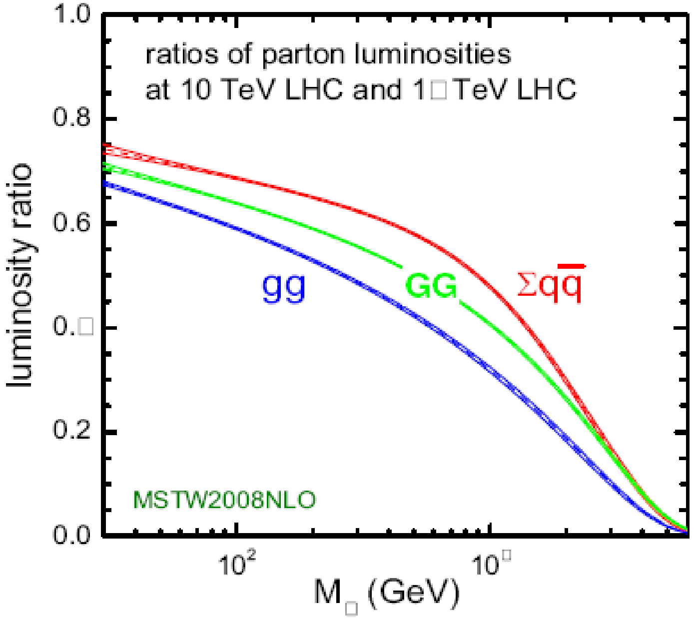
- NLO vs NNLO



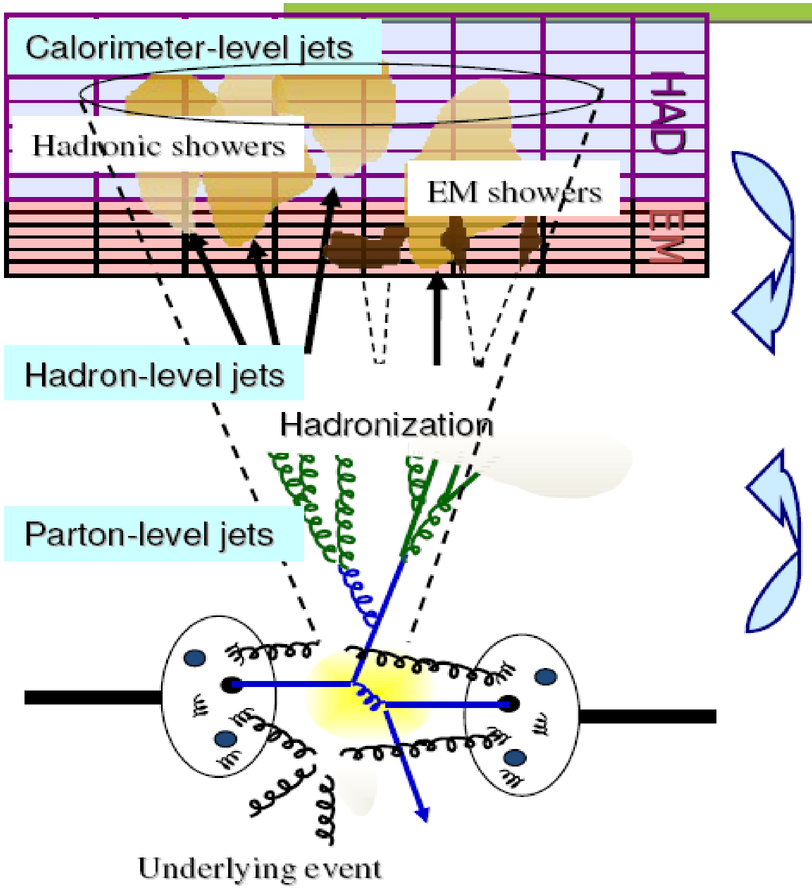


Parton luminosities: 10 TeV vs 14 TeV

- Ratio of parton luminosities and 10 TeV and 14 TeV for
  - Σqqbar (W,Z production)
  - gg (Higgs, ttbar)
  - G=g+4/9Σ (q+qbar) (high ET dijet production)
- In case of W and Z cross-sections are not that much smaller



Inclusive jet production



Unfold measurements to
the hadron (particle) level

Correct parton-level theory
for non-perturbative effects
(hadronization & underlying event)

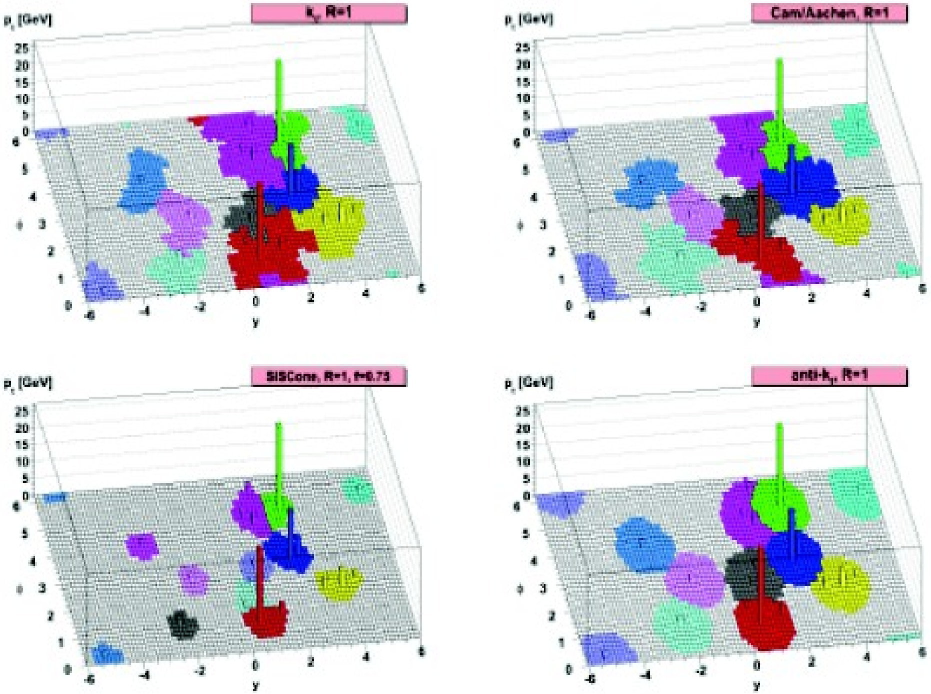
Jets are collimated spray of particles
originating from parton fragmentation.
→ To be defined by an algorithm

Jet clustering algorithms

- Infra-red and collinear safe
  - Resultant jets stable under these effects
- Two general classes
  - Cone algorithms around seeds
    - Require split-merge if overlapping cones
  - Clustering algorithms
    - May give irregular shapes with complicated background corrections
- Anti-k_t is a clustering algorithm
  - p=1 for k_t clustering, p=0 for Cambridge/Aachen, p=-1 for anti-k_t
  - Cluster smallest distance and recompute

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \qquad \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = k_{ti}^{2p}$$



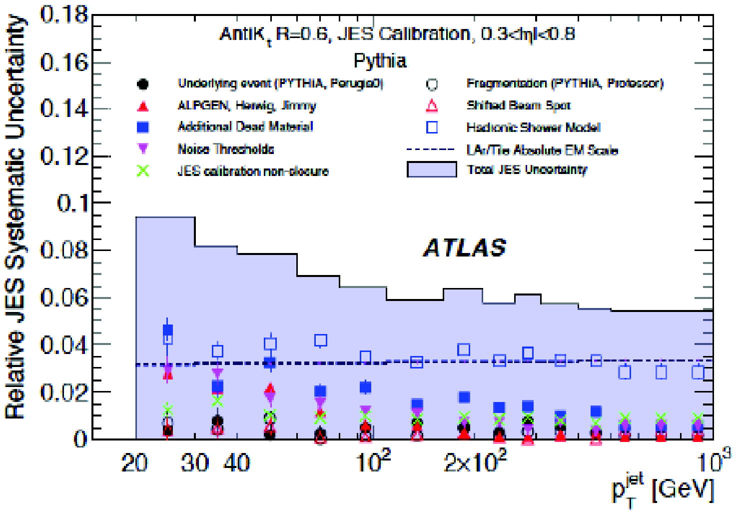
arXiv:0802.1189v2

Jet energy scale (JES)

- Jet energy scale is critical
  - Based on the test-beam calibration of production detector elements with monochromatic beams of electrons and hadrons
  - Extra complications with the final detector
    - More dead material (supports, cables, pipes, etc.)
    - Hadrons are in jets rather than isolated single particles
      - Spectrum of hadron energies
      - Mixture of EM ($\pi^{0} \rightarrow \gamma\gamma$) and hadronic energy deposition
  - These complications are captured in Geant4 simulation MC
    - Used for both test beam and final detector
    - Detector response fully simulated for final states (different MC: Pythia, Herwig, Alpgen)

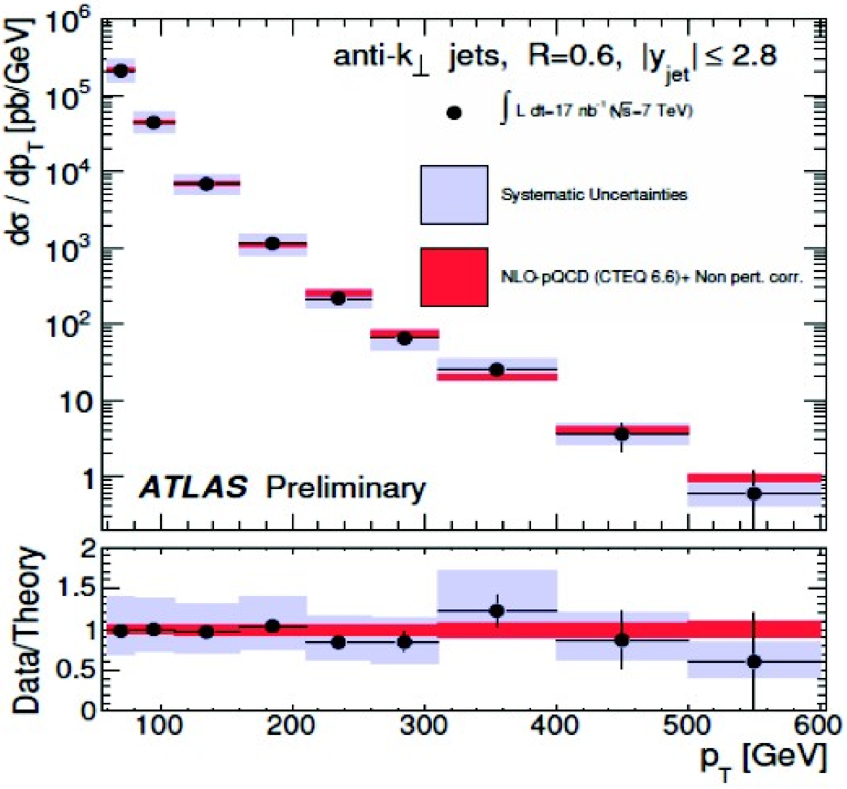
Jet energy scale (JES)

- Jet energy scale is critical
  - In-situ cross-checks done with data
    - Calorimetr response for isolated hadrons
    - p_T balance for dijet final states
    - p_T balance for γ-jet final states
- Current jet energy scale uncertaintity (ATLAS)
  - A mild function of p_T and η
  - With $17 nb^{-1}$ data ~ 7-8%
  - Ultimate goal is 1%



Inclusive jet production

- Inclusive single jet cross-section measured to p_T of 550GeV
- Excellent agreement with NLO prediction over 5 orders of magnitude
- The dominant systematic uncertainty for the data is the JES

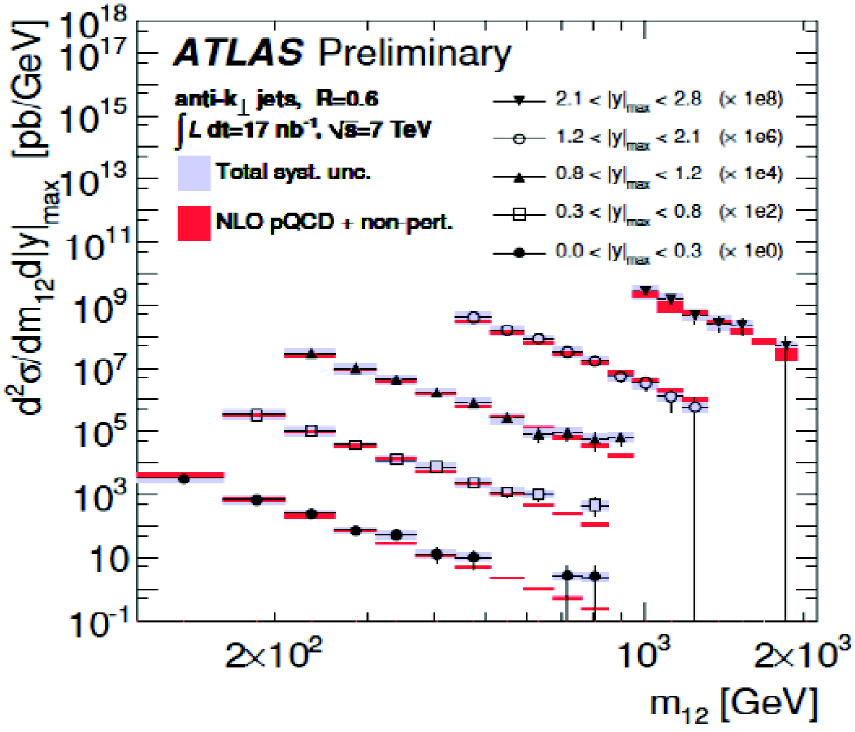


Emerging "precision" phenomenology at LHC

Inclusive dijet production

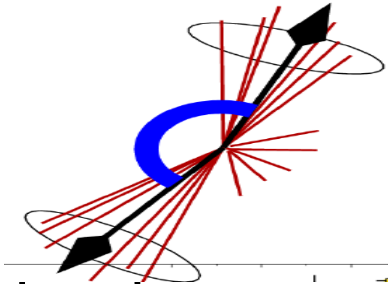
- Inclusive dijet cross-section measured to

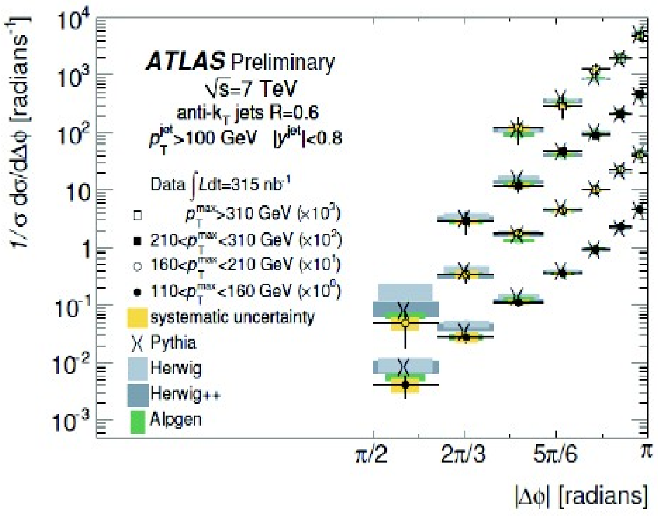
  M~ 2 TeV
  - Leading jet p_T > 60 GeV
  - Subleading jet p_T > 30 GeV
  - $|\eta| < 2.8$
- Excellent agreement with NLO predictions



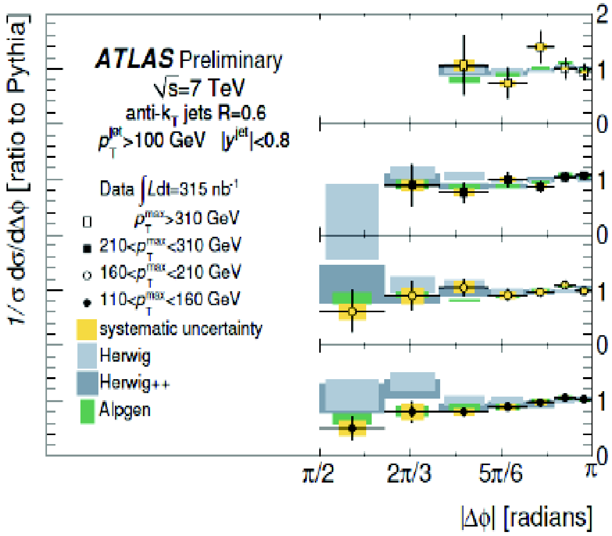
Emerging “precision” phenomenology at LHC

Azimuthal decorrelation in dijet events



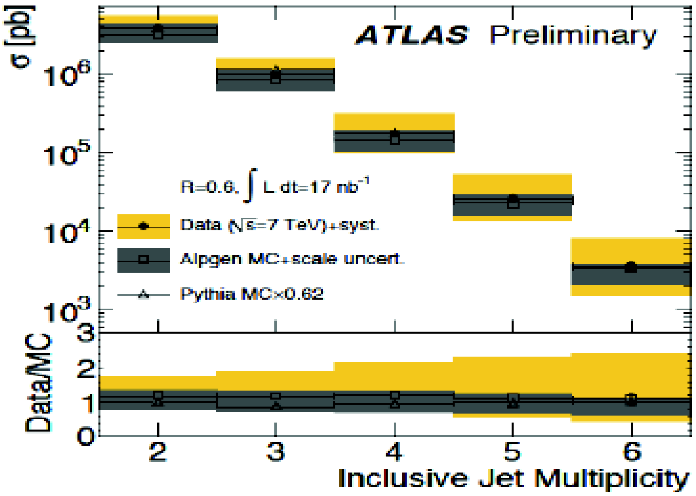


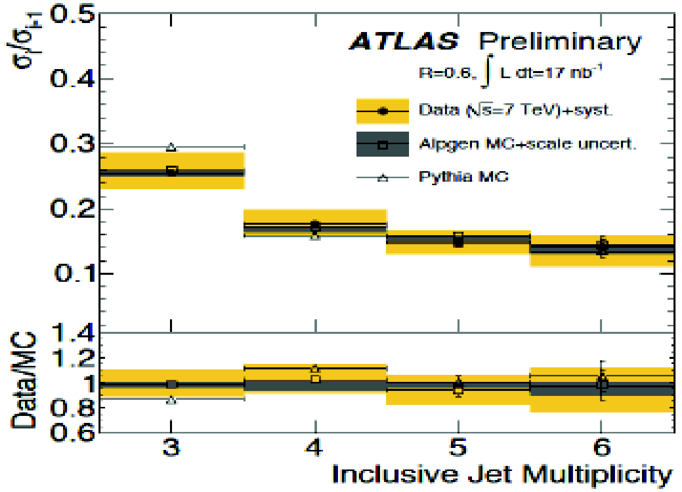
- Inclusive jets are no back-to-back
  - Additional jets in the final state
  - How large is effect?
  - Do MC models describe it properly?
    - Alpgen works very well over 3 orders of magnitude
    - Data are well described



Multijet production

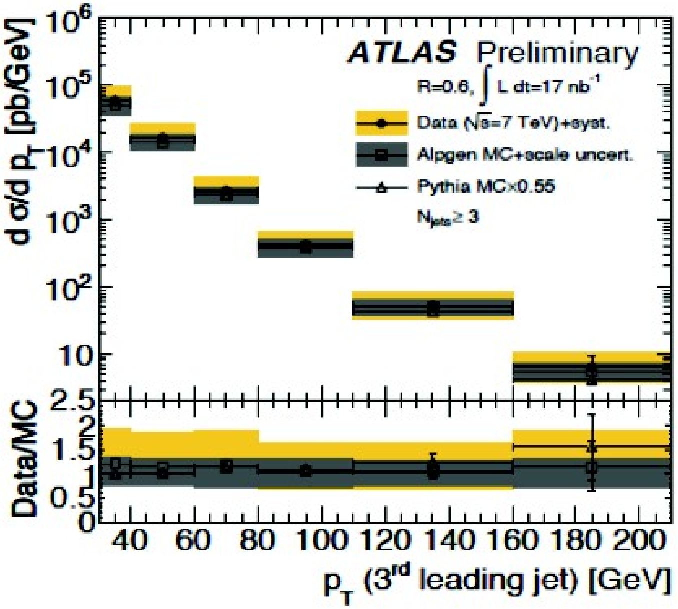
- Can we count and characterize the additional jets?
  - Essential to understand for new-particle searches
  - Prediction requires higher order QCD corrections
- Count jets with $p_T>30$ GeV, $|y|<2.8$
  - JES crucial because of steeply falling spectrum
- Plot ratio of cross-sections for successive multiplicities
  - Many systematic errors cancel

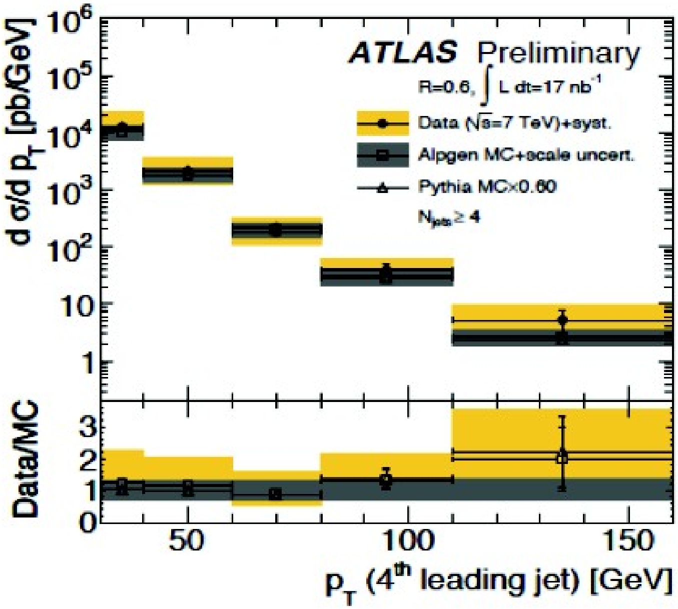




Multijet production

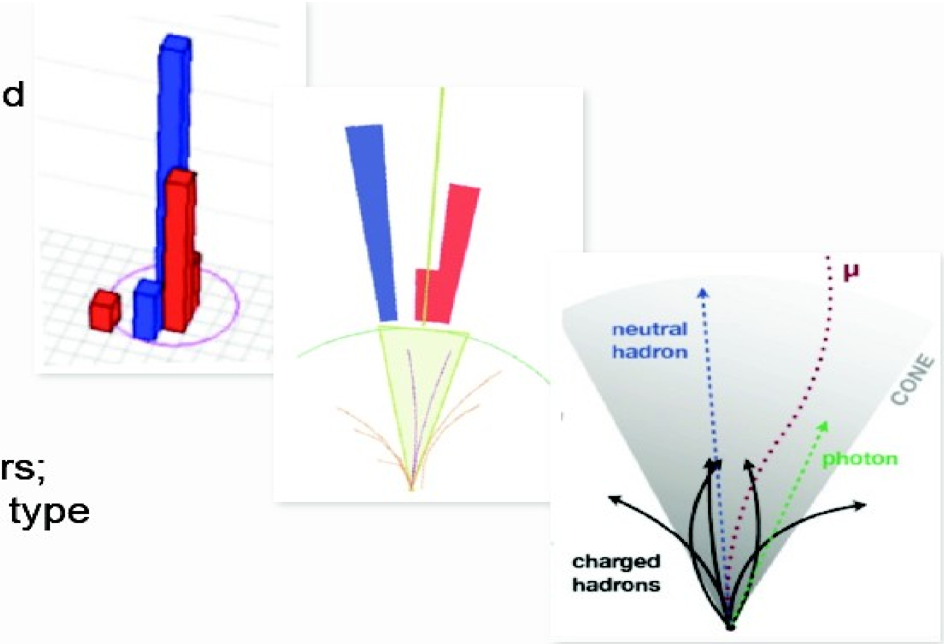
- Do we understand the p_T spectrum of the extra jets?
  - Pythia spectrum renormalised to data for each jet multiplicity
  - Results in good agreement with Alpgen





Jet reconstruction in CMS

- CalorimeterJet (calojet)
  - from energy depositions grouped HCAL & ECAL
- Jet Plus Tracks (JPT)
  - Calorimeters jets corrected with tracker momentum
- Particle Flow Jets (PFJ):
  - Reconstructed particles using information from all sub-detectors; separate calibration per particle type
- TrackJets
  - from tracks only



- Jet Algorithms:
  - Default for p+p collisions is anti-K_T with R = 0.5
  - Also implemented: K_T, SiSCone

Using different inputs allows CMS to study and constrain experimental systematics for good understanding of jet identification, resolutions and energy scale

Inclusive jet cross-section

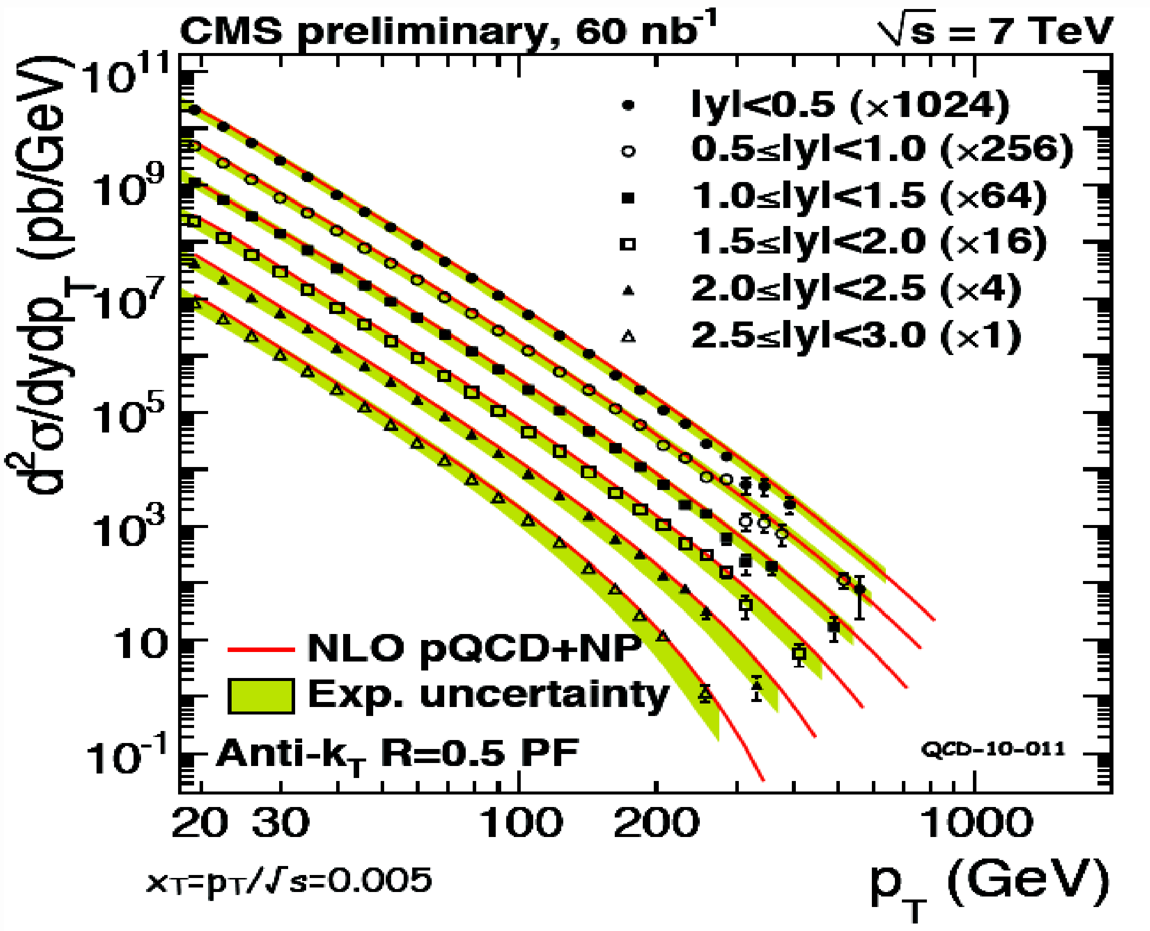
Inclusive jet p_T spectra are in **good agreement with NLO** theory for all reconstruction types

Extending to very low p_T thanks to novel reconstruction methods (Particle Flow)

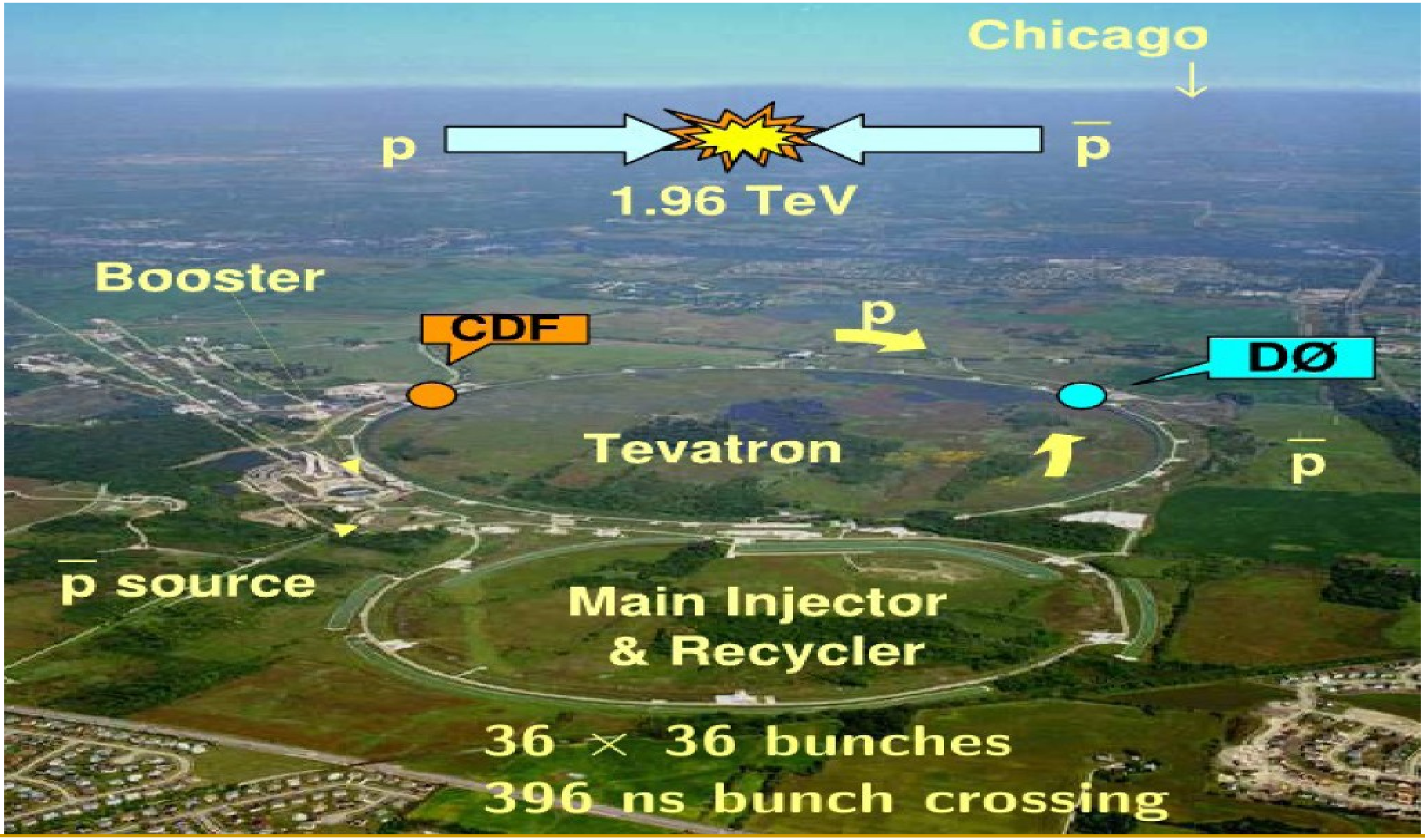
Low p_T reach limited from theory side by non-perturbative corrections

Extending the high-p_T reach beyond Tevatron's

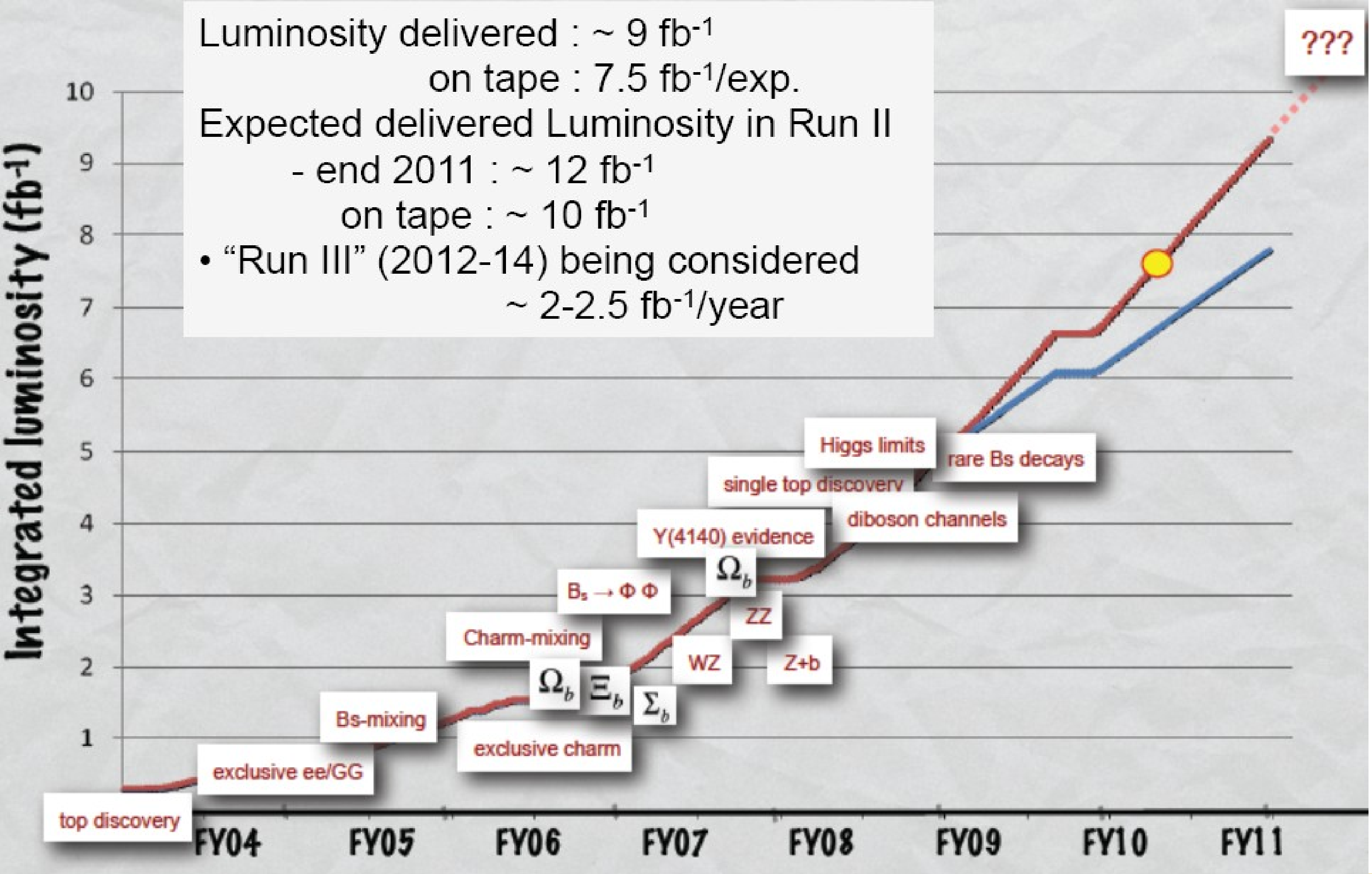
Large rapidity coverage up to |y|<3



Tevatron: recorded about 8-9 fb^{-1}/exp.

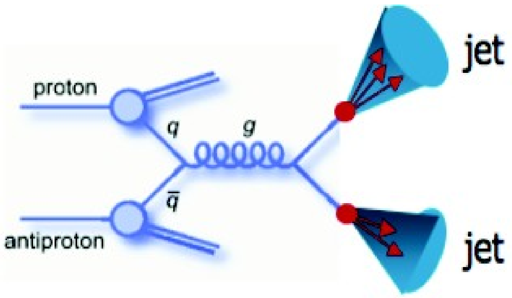


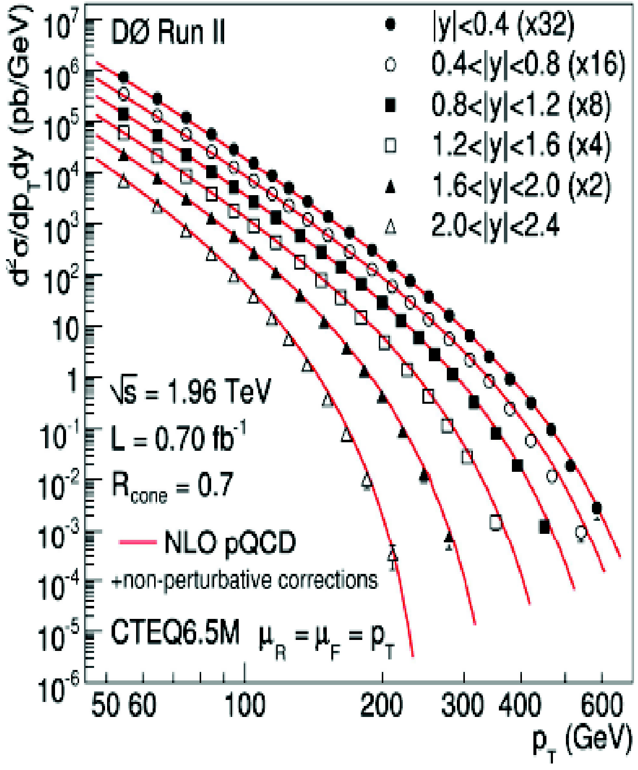
Tevatron a “SM” discovery machine

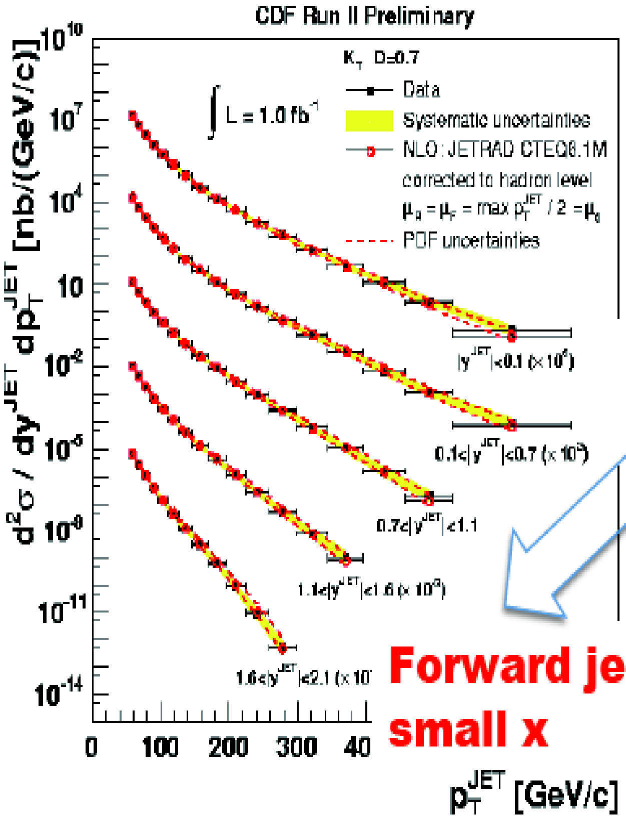


Luminosity delivered : ~ 9 fb^{-1}
on tape : 7.5 fb^{-1}/exp.
Expected delivered Luminosity in Run II
- end 2011 : ~ 12 fb^{-1}
on tape : ~ 10 fb^{-1}
- “Run III” (2012-14) being considered
~ 2-2.5 fb^{-1}/year

Jet physics







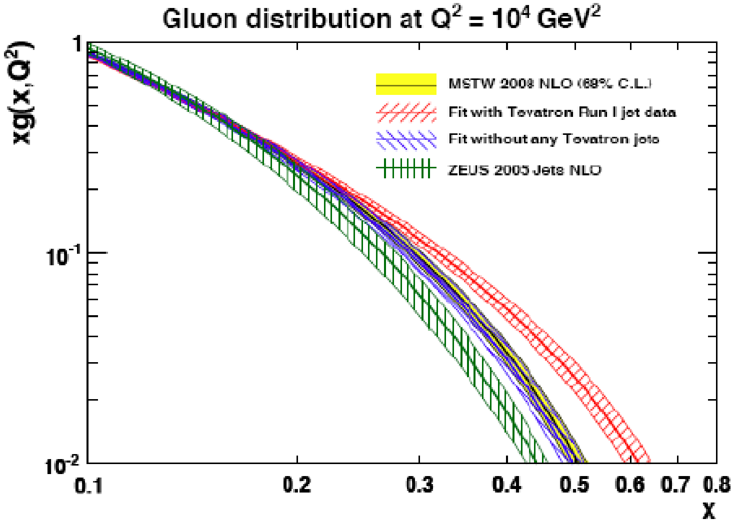
Jet reconstruction : cone based algorithms (CDF,DØ), k_T algorithm (CDF)

Central jets : high x

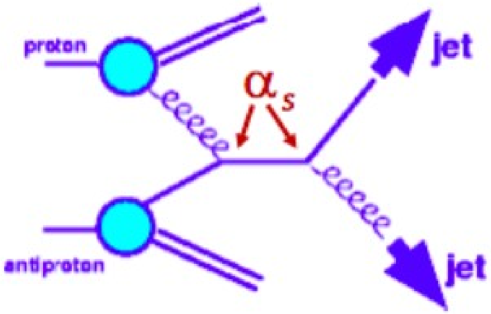
Forward jets : small x

Glun density at high x

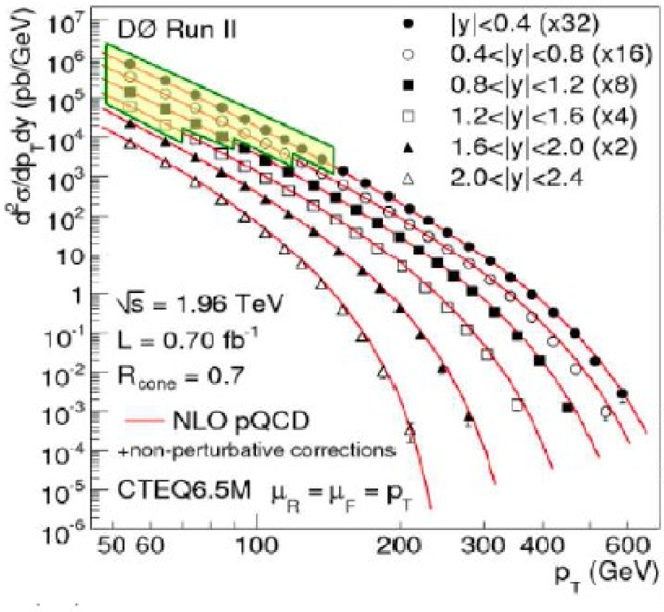
- Tevatron jet measurements complement HERA measurements.
  - Unique constrain on gluon density at high x in MSTW08-fit: lower gluon density from Run II data compared with Run I

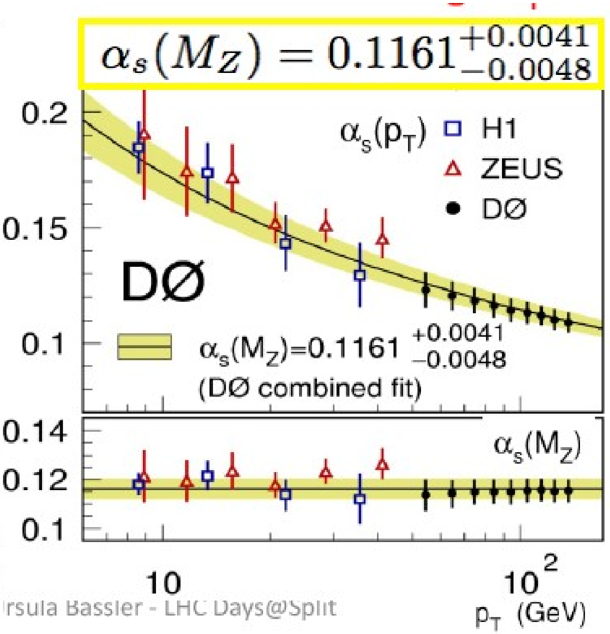


Alpha$_s$ from jets



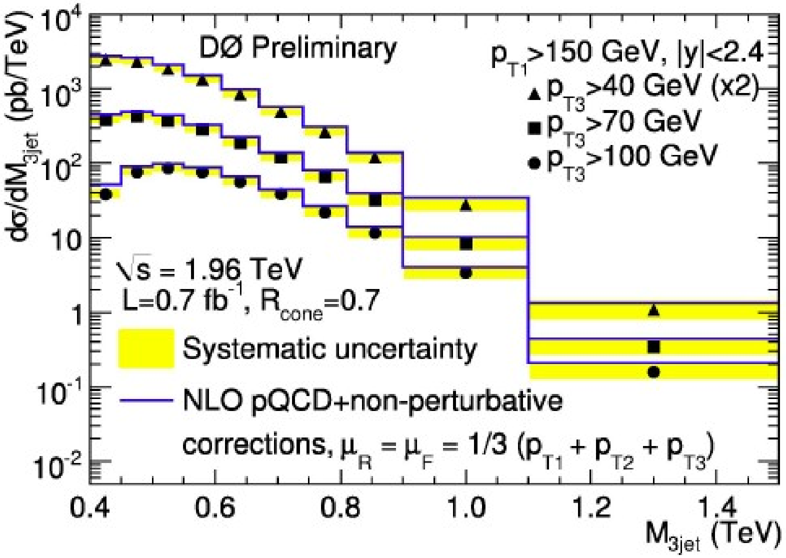
- Uses the p_T dependence of the jet x-section; medium region x= 0.2-0.3
- Highest precision from hadron collider

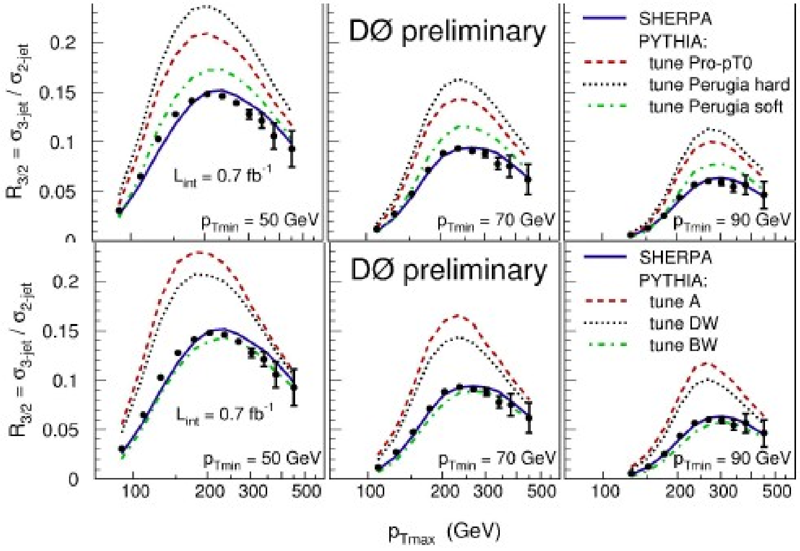




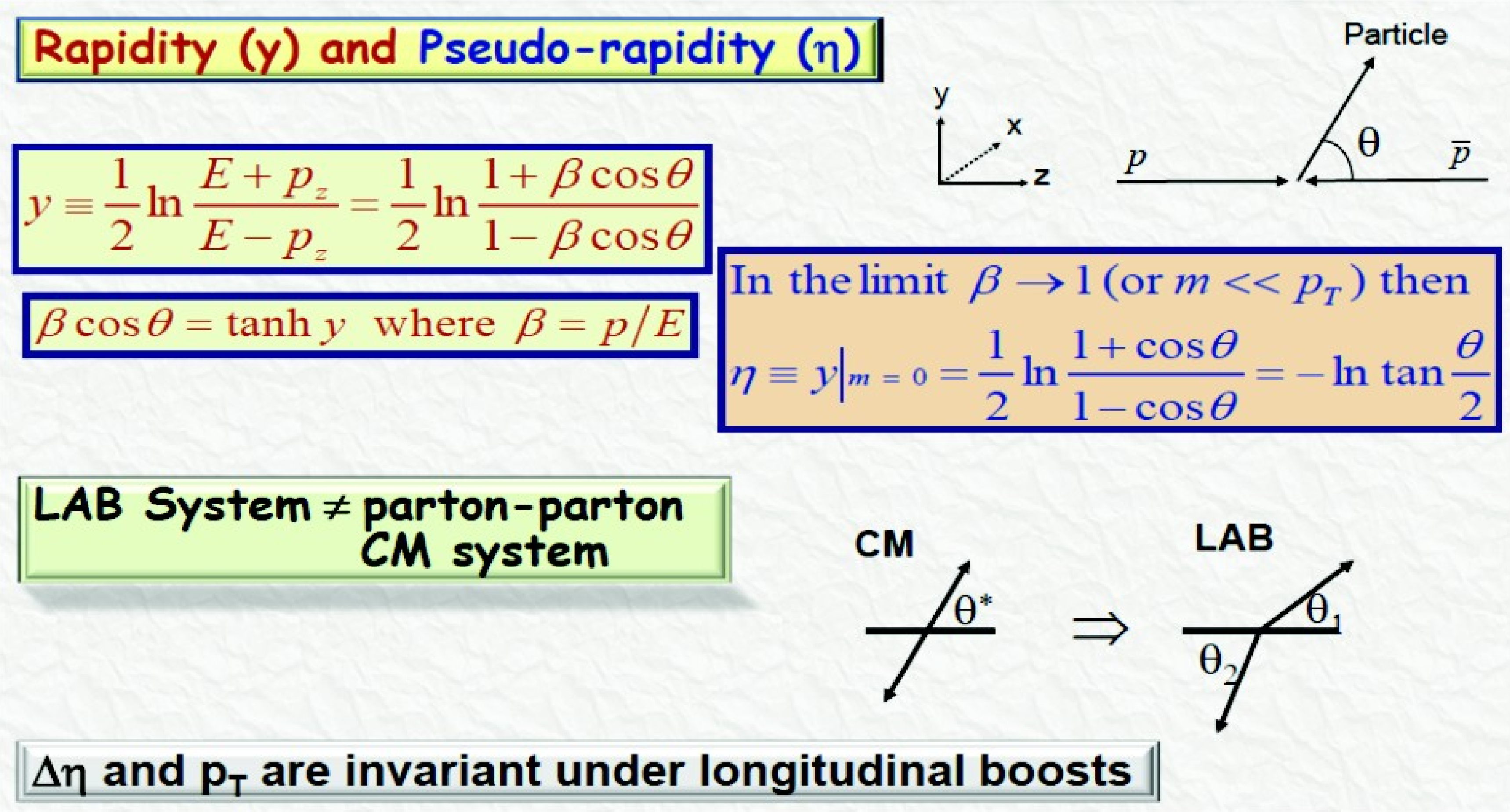
Multi-jet production

- Sensitive to QCD radiation: test of MC models at NLO
- Three-jet mass cross-section and Ratio: 3jets/2jets versus p_T





Some kinematic distributions



Rapidity (y) and Pseudo-rapidity (η)

$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

$$\beta\cos\theta = \tanh y \quad \text{where} \quad \beta = p/E$$

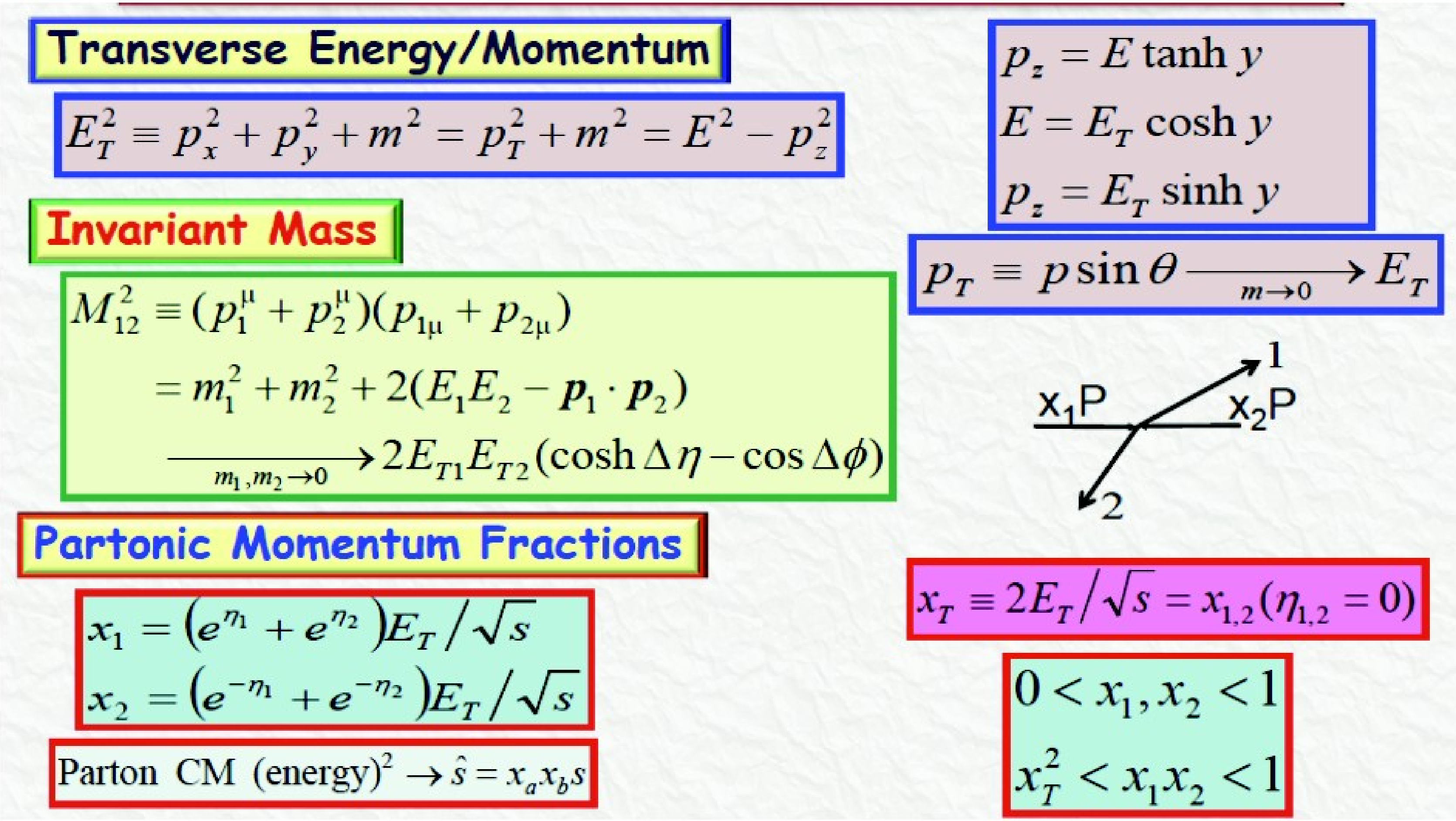
In the limit $\beta \to 1$ (or $m << p_T$) then

$$\eta \equiv y\big|_{m=0} = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\tan\frac{\theta}{2}$$

LAB System ≠ parton-parton CM system

Δη and p_T are invariant under longitudinal boosts

Some kinematic definitions



Transverse Energy/Momentum

$$E_T^2 \equiv p_x^2 + p_y^2 + m^2 = p_T^2 + m^2 = E^2 - p_z^2$$

$$p_z = E \tanh y$$

$$E = E_T \cosh y$$

$$p_z = E_T \sinh y$$

$$p_T \equiv p \sin\theta \xrightarrow[m \to 0]{} E_T$$

Invariant Mass

$$M_{12}^2 \equiv (p_1^\mu + p_2^\mu)(p_{1\mu} + p_{2\mu})$$

$$= m_1^2 + m_2^2 + 2(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)$$

$$\xrightarrow[m_1, m_2 \to 0]{} 2 E_{T1} E_{T2} (\cosh \Delta\eta - \cos \Delta\phi)$$

Partonic Momentum Fractions

$$x_1 = \left(e^{\eta_1} + e^{\eta_2}\right) E_T / \sqrt{s}$$

$$x_2 = \left(e^{-\eta_1} + e^{-\eta_2}\right) E_T / \sqrt{s}$$

Parton CM (energy)$^2 \to \hat{s} = x_a x_b s$

$$x_T \equiv 2E_T / \sqrt{s} = x_{1,2}(\eta_{1,2} = 0)$$

$$0 < x_1, x_2 < 1$$

$$x_T^2 < x_1 x_2 < 1$$

Next topics

- 3.11 - W,Z bosons:
  - cross-sections (incl. differential), W/Z+jets
  - asymmetry
- 10.11 - W,Z bosons:
  - precise measurements
- 17.11 – Top: xsection, mass
- 24.11 – Hot topics: new exclusion limits
- 1.12, 8.12, 15.12 – Higgs