QCD at LHC.

- Relevance of QCD for LHC and vice versa.

  a Issues of importance in QCD studies for the LHC.
  b Introductory comments on the theoretical developments in accurate predictions for LHC.
  c Discussions of issues where knowledge of QCD in the saturation and/or small x regime is relevant for LHC and vice versa.

- Important but will not discuss **at all**
  - Diffractive Physics and the LHC.

Some references:

Talk by M. Mangano: available from home page
http://home.cern.ch/mlm/talks/nikhef.ps.gz

Review by S. Catani : hep-ph/0005233 Working group report of the LHC QCD workshop: hep-ph/0005025.

QCD and SM Working group reports of the Les Houches workshop: hep-ph/0005114, hep-ph/0204316,hep-ph/0403100

HERA and the LHC: A Workshop on the implications of HERA for LHC physics: Proceedings of a year long workshop, hep-ph/0601012, hep-ph/0601013.

1)Rohit Hegde, R.G., G. Pancheri,...et al.: ''Total cross-sections at the large hadron collider,'' Pramana **66**, 657

2)A. Achilli, R. Hegde, R. M. Godbole, A. Grau, G. Pancheri and Y. Srivastava "Total cross-section and rapidity gap survival probability at the LHC" arXiv:0708.3626 (PLB)

Two aspects of this discussion: QCD at LHC: **QCD for LHC and LHC for QCD!**

SM: $SU(3)_C \times SU(2)_L \times U(1)$

1 QCD for LHC: relevant for the study of Physics of and beyond the (**the aspects of electroweak physics** SM) (BSM) at the LHC

2 LHC for QCD: study aspects of QCD itself at the LHC. Of course the Heavy ion mode will do this in a big way..but so will the pp mode.

Some possible pointers:

1 Theoretical explanation of Mass hierarchy: neutrino masses in eV and top mass in GeV : Understanding the flavour sector.

2 Coupling unification?

3 'Naturally' light, weakly coupled Higgs:

- Higgs sector beyond the SM?
- Supersymmetry?
- Little Higgs models?
- Higgsless theories?
- Extra Dimensions?

Why bother about QCD?

- Because it is ubiquitious –ever present- at a hadronic Collider. QCD describes gluons and quarks. Colliding objects are hadrons and detected objects are also hadrons. QCD required to give information about quark/gluon content in the initial state and fragmentation of quark/gluon in the final state.
- Because it has the beauty. What does this mean? b quarks important part of the signal for almost ALL new physics processes AND B-mesons a big part of the LHC_b program which will again probe new physics through B-studies.
- To appreicate this more let us analyse goals of LHC and see what role QCD plays.

- Goals
  - Discovery of Higgs Boson and SUSY.
  - Search and discovery beyond the expected : eg. extra dimensions, extra gauge bosons of Little Higgs Models...
  - Accurate measurements of the constants in and beyond the SM. Find (in)consistencies with the SM.

Ingredients of Discovery

- Anomaly or excess over the SM expectation: Counting Experiment eg. the search for 'invisible' higgs in Zh production channel. Accurate predictions of SM cross-sections. Era of precision QCD.

- Resonance, Asymmetries.Abs. rates not important. Even then hadronic environment $\longrightarrow$ QCD predicitons of various baclground SM processes necessary .

- Determination of new physics needs good control over absolute backgrounds.

- To set limits on new physics control over absolute values of the expected cross-sections is a must.

QCD measurements at LHC

- Parton luminosity measurements to reduce the systematic uncertainty in the prediction of normalisation of cross-sections.

- Classic QCD measurements such as α_s, determination of Parton Density Functions, measurement of processes involving γ for run time calibration of the bakground to (say) $\gamma\gamma$ signal to the h.

- Knowledge of (and/or QCD predictions) of underlying event necessary to make sure the cuts being made are appropriate.

- High luminosity at LHC $\Rightarrow$ multiple interactions $\Rightarrow$ overlapping events.

- High energies at the LHC $\Rightarrow$ multi parton interactions increase in number $\Rightarrow$ minijet activity can increase.

- Need to fine tune the current Monte Carlos to describe this accuartely for LHC as cuts on hadronic activity used quite often to fish signals above background: the 'invisible' higgs in VV fusion or WW scattering.

- Large extrapolations from Tevatron/HERA to LHC will be required here. Of course will need to use LHC studies to fine tune them further.

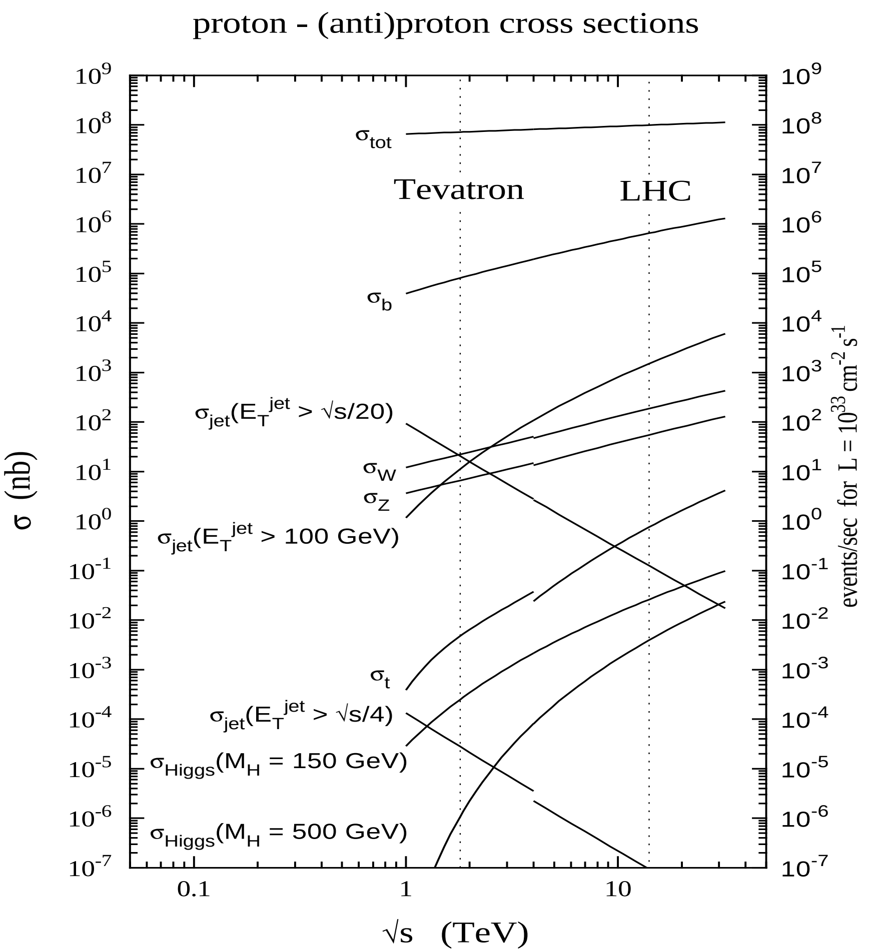
- Measurements of total cross-sections etc at LHC might ADD to our knowledge of QCD in these issues and NP regime.

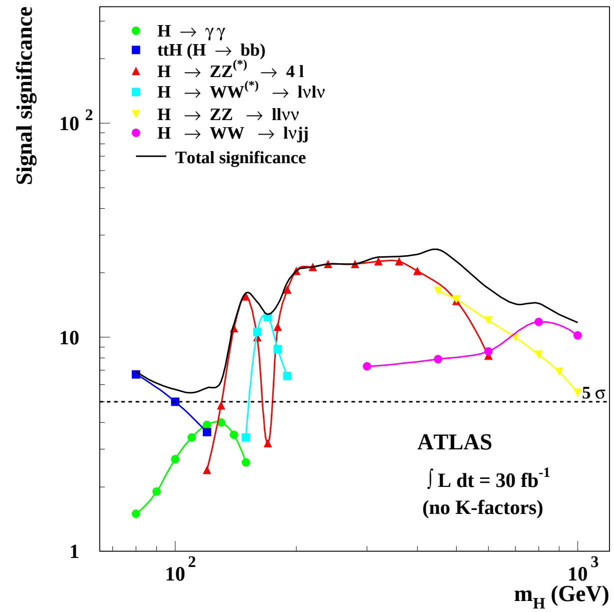
No. of events $= \mathcal{L} \times \sigma$

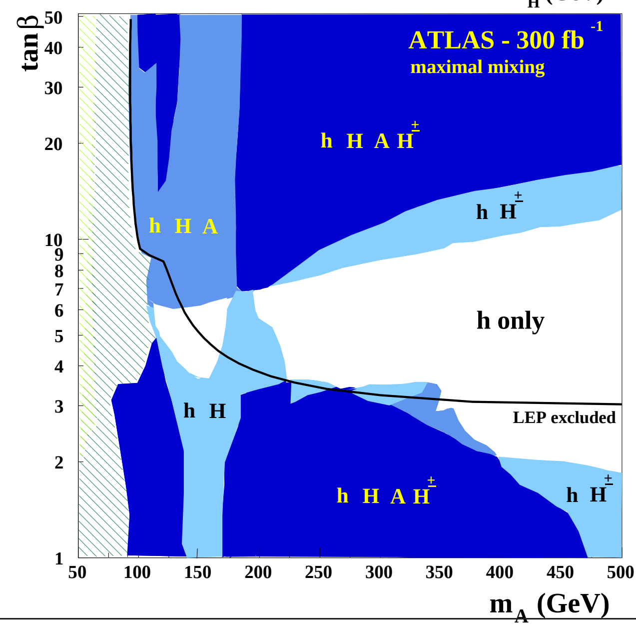
$\mathcal{L} = 10^{33} cm^{-2} sec{-}1 = 1 nb^{-1} sec^{-1} \rightarrow 10 fb^{-1}/yr$

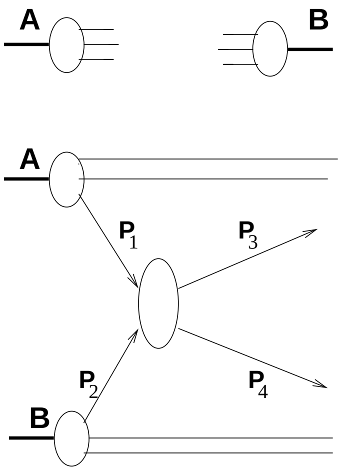
We expect to measure signals which have cross-section of $\sim$ 1 pb or so, giving 1000 events/yr.

Process	$\sigma(nb) \equiv$ # of events/sec	events/yr
Total cross-sections	10^8	10^{15}
$W^{\pm} \rightarrow e\nu$	20	2×10^8
$Z \rightarrow e^+e^-$	2	2×10^7
$t\bar{t}$	0.8	8×10^6
$b\bar{b}$	5×10^5	5×10^{12}
central jets ($P_T > 10 GeV$)	2.5×10^6	2.4×10^{13}
central jets ($P_T > 100 GeV$)	10^3	10^{10}
central jets ($P_T > 1000 GeV$)	1.5×10^{-3}	1.5×10^5

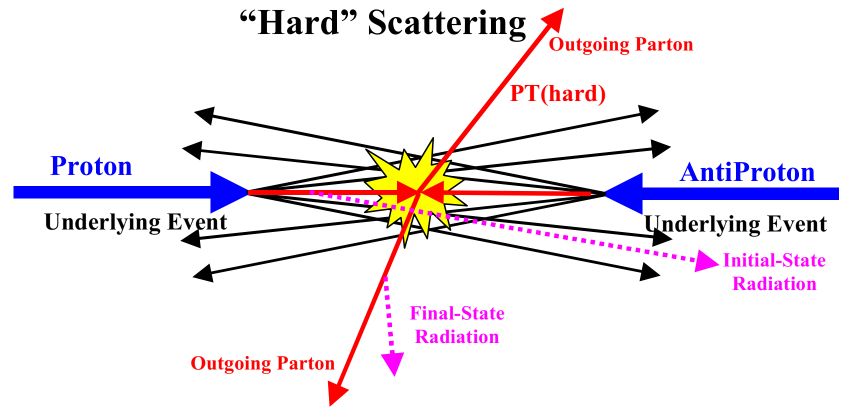

proton - (anti)proton cross sections
Tevatron
LHC
σ_tot
σ_b
σ_jet(E_T^jet > √s/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_t
σ_jet(E_T^jet > √s/4)
σ_Higgs(M_H = 150 GeV)
σ_Higgs(M_H = 500 GeV)
σ (nb)
events/sec for L = 10^33 cm^-2 s^-1
√s (TeV)


H → γγ
ttH (H → bb)
H → ZZ(*) → 4 l
H → WW(*) → lνlν
H → ZZ → llνν
H → WW → lνjj
Total significance
ATLAS
∫ L dt = 30 fb^-1
(no K-factors)
5 σ
Signal significance
m_H (GeV)


ATLAS - 300 fb^-1
maximal mixing
h H A H±
h H±
h H A
h only
h H
LEP excluded
h H A H±
h H±
tanβ
m_A (GeV)



A + B → jet + jet + X



QCD factorisation theorem for short distance, inlcusive processes:

$$\sigma(pp \to X + ..) \qquad = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2)$$

$$\times \sigma(a + b \to X) \left(x_1, x_2, \mu_R^2, \alpha_s(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2} \right)$$

Theoretical prediction:

Initial State	subprocess	final state
parton density distributions PDF	$\sigma(a + b \to X)$	Fragmentation Functions.

Underlying Event

Different definitions possible:

- Everything except the LO process of interest : Wrong in principle.
- All particles produced in a single particle collision except the process of interest: most commonly used.

Essentially implies a distinction between coherent radiation and other HO corrections (parton showers...) and inchoherent “remnant-remnant” interactions.

- Can be a hard scatter or soft.
- Is NOT equivalent to just adding a mimimum bias event to the process of interest as **correlations** are significant.
- Related to minimum bias events and a study of minimum bias events can giv information on the underlying event.
- Related to multiple parton scattering, rescattering models..
- Has implications for rapidity gaps, as incoherent remnant interactions fill the gap.
- Tevatron/HERA data important. Equally important are the models of the multiple parton scattering, transverse overlap functions for the protons.

LHC requires from QCD theory:

- Precise inputs
  - α_s
  - Parton Density Functions (PDF's)
- Accurate calculations of subprocess cross-sections
  - NLO, NNLO calculations of cross-sections.
  - Resummation of large logarithms.
- New physics $\rightarrow$ large masses $\rightarrow$ long decay chains Discussions of SUSY signals $\rightarrow$ Multijet final states $\rightarrow$ high order tree level matrix elements
- PT-NonPT interface
  - parton-hadron transistion fragmentation functions
  - underlying event.
  - multiple hard scattering.
  - low p_T interactions(minimum bias interactions).

Cross-sections in QCD

Calculated by truncating perturbative expansion to a fixed order (FO).

$$\hat{\sigma}(p_1, p_2; Q, \{Q_1, \ldots\}; \mu_F^2) = \alpha_s^k(\mu_R^2) \Big\{ \hat{\sigma}^{(LO)}(p_1, p_2; Q, \{Q_1, \ldots\}) + \alpha_s(\mu_R^2)\, \hat{\sigma}^{(NLO)}(p_1, p_2; Q, \{Q_1, \ldots\}; \mu_R^2; \mu_F^2) + \alpha_s^2(\mu_R^2)\, \hat{\sigma}^{(NNLO)}(p_1, p_2; Q, \{Q_1, \ldots\}; \mu_R^2; \mu_F^2) + \ldots \Big\} .$$

The LO (tree level) calculation hasa strong dependence on the choice of scale Q^2. The scale dependence is reduced by going to NLO. To get a reliable esitmate of error on theoretical calculation, a NLLO calculation is necessary.

DGLAP sums large logs in Q^2/Q_0^2.

When $\sqrt{s} >> Q$ ln(S/Q^2) are large as well. They need to be resummed.

Third type of logs which need to be resummed are soft gluon bremsstrahlung logs.

• NNLO calculation a must for all the processes for which the NLO corrections change the LO cross-sections by large K-factor.

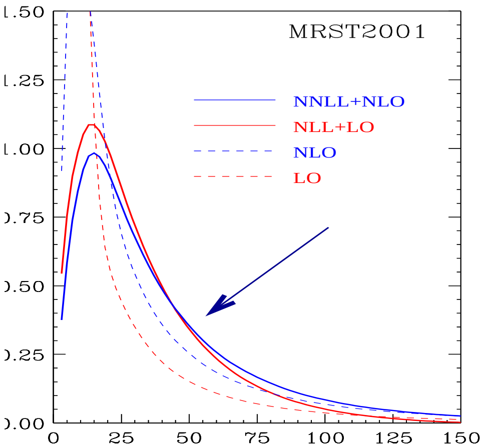
• $|\mathcal{M}|^2$ is to be calculated for diagrams with $m \geq 0$ loops and $n \geq 2$ legs, eg. potential background for Higgs pair production, to be used for studying higgs self coupling λ directly, will need calculation of $b\bar{b}b\bar{b} + n$ jets.

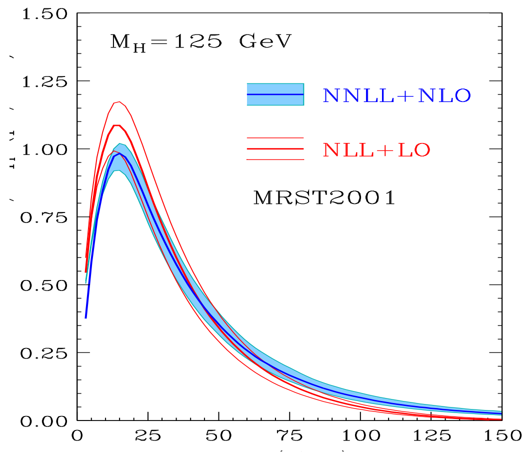
• The number of diagrams to be computed increases *very* quickly with number of increasing legs. For $gg \to g_1..g_n$ for $n = 7$ is 559405.

• Therefore one requires very intelligent autmoated computation.

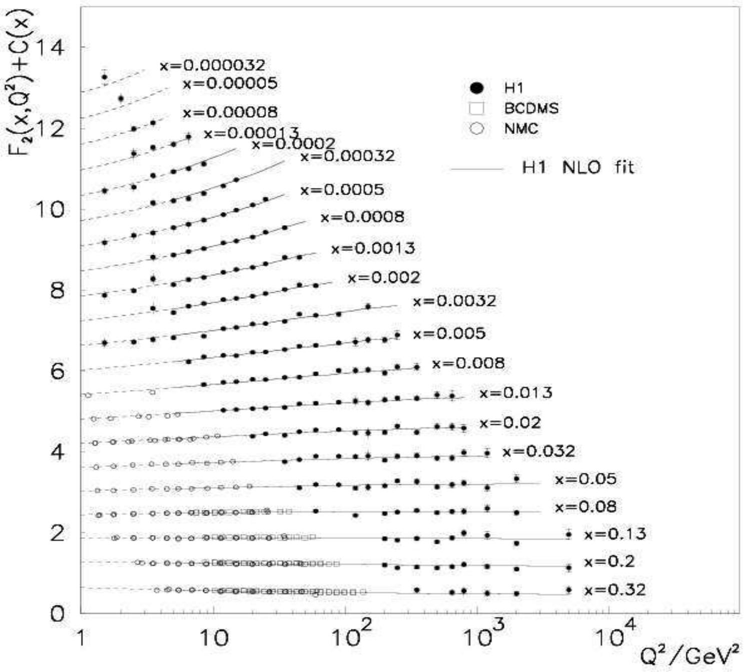
• There are techniques based on helicity amplitudes, string theory techniques and SUSY.

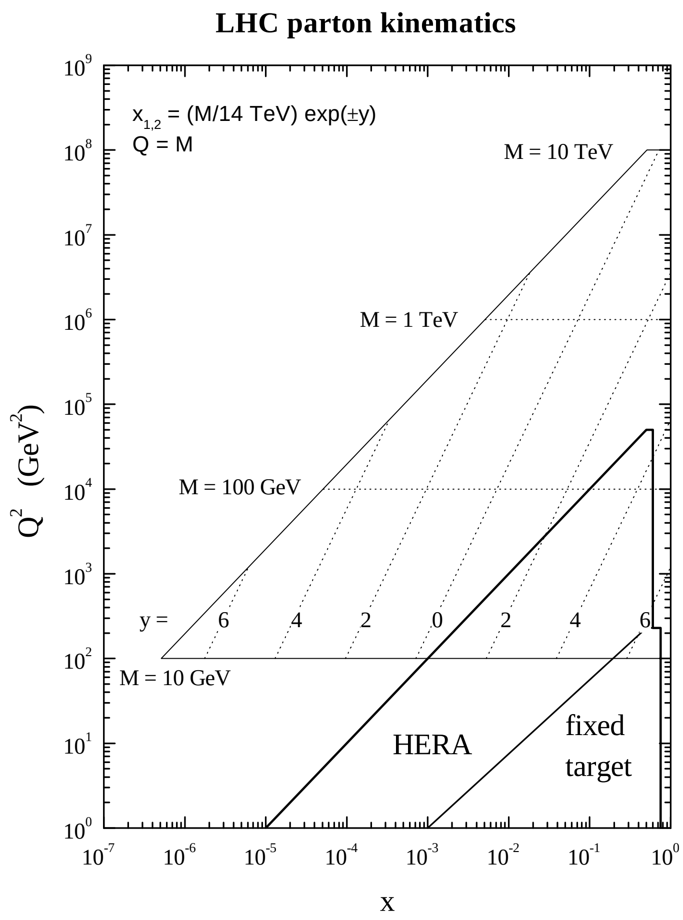
- Berends, Kuijf, Giele, Mangano, Kleiss, Bernd, Kosower, Dixon...
- Many different programs: CompHEP, MADGRAPH, GRACE, ALPGEN...
- NLO/NNLO calculations sometimes necessary also for some proecesse which are not present in LO.
- The intricate part is cancellation of infrared and collinear singularities between the real emissions and virtual contribution.
- Enormous progress in calculation of loop amplitudes.
- New technical breakthroughs (Remmidi, Gehrmann, Binoth, Catani, Grazzini .....]
- One loop calculations for $2 \to 3$ even some $2 \to 4$ processes now available
- n-loop Matrix Element requires AP kernel at $(n+1)$ loop level and has to be used with Str. fucntions evaluated at the same level (3-loop splitting function: Vermaseren et al)





- SM Higgs production at the NNLO has been computed. Haarlander, Kilgore, Catani, Grazzini, Van Neerven, Ravindran, Anastasiou, Melinkov....
- Different authors have used different techniques and hence cross-checks.
- K-factor for Higgs production between 2.1 to 2.5 as mass changes from 10 GeV to 300 GeV.
- Beyond fixed order, soft gluon resummation for calculating Higgs q_T distribtuion has also been done.





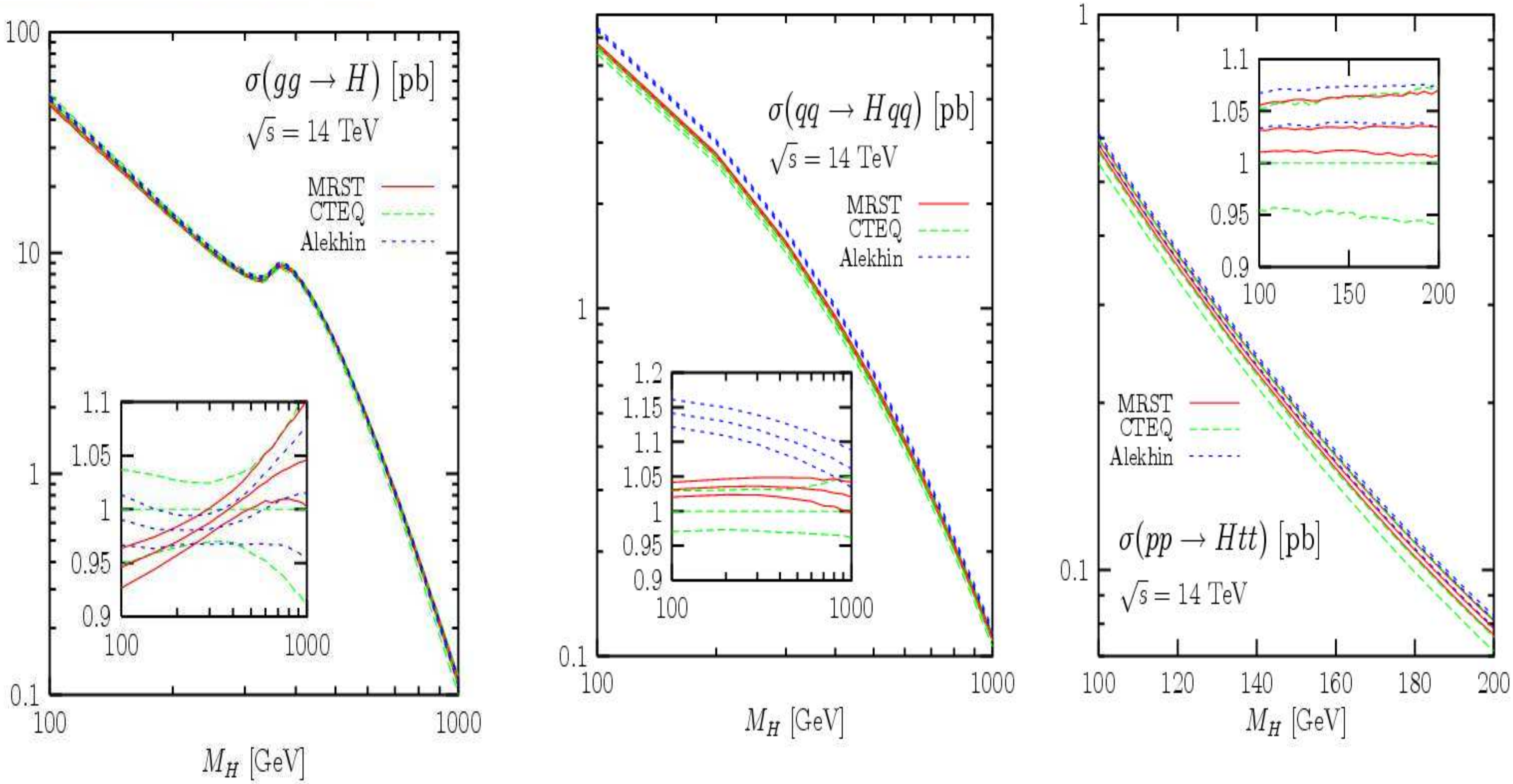
LHC sensitive to PDF's in new kinematic region. Extrapolations from HERA to LHC region required. Only DGLAP fits (NLO/NNLO). Is that enough?

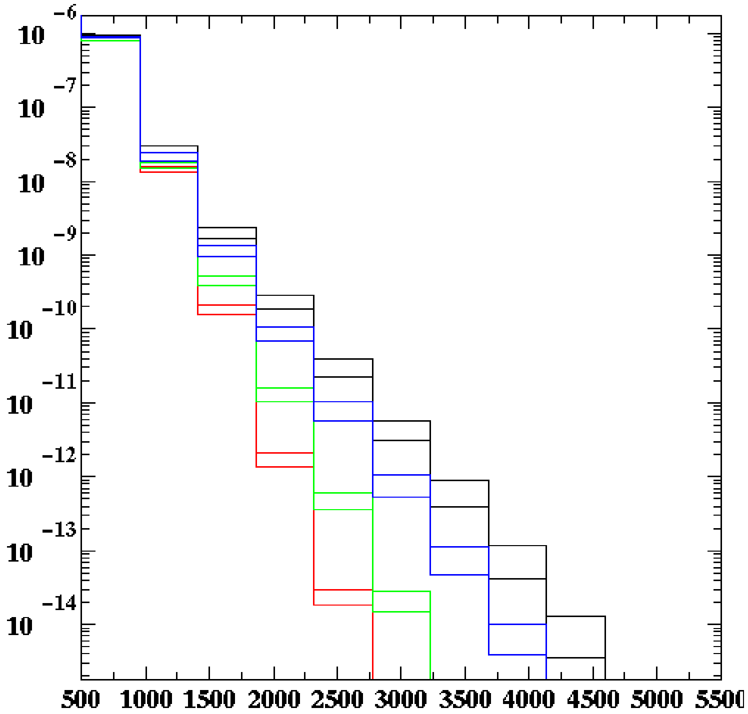
Global fits use different data

- DIS data from HERA,BCDMS,CCFR,SLAC,NMC covering a wide range in x and Q^2.
- low mass DY data: determine $\bar{u} - \bar{d}$ asymmetry.
- CCFR/NuTev data: determine strange quark density using muon/dimuon data
- Use Tevatron W rapidity data to determin u/d ratio.
- jet cross-sections at Tevatron for $g(x, Q^2)$.

Information on fits available from

http://durpdg.dur.ac.uk/hepdata/pdf.html


$\sigma(gg \to H)$ [pb]
$\sqrt{s} = 14$ TeV
MRST
CTEQ
Alekhin
M_H [GeV]
$\sigma(qq \to Hqq)$ [pb]
$\sqrt{s} = 14$ TeV
MRST
CTEQ
Alekhin
M_H [GeV]
$\sigma(pp \to Htt)$ [pb]
$\sqrt{s} = 14$ TeV
MRST
CTEQ
Alekhin
M_H [GeV]



The uncertainty on the PDF's certainly will affect the conclusions on the whether one has seen the Extra Dimensions or not!

- Prompt γ production in hadron collisions at fixed target and colliders. Even the different data are not consistent with each other. NNLO calculations available.

- Large E_T jet data from CDF, particularly ratio of data from 630 and 1800 GeV, as a function of scaled variable $X_T = 2 * E_T/\sqrt{s}$

- These two contribute to the uncertainty in the knowledge of large x gluon and hence deteriorate somewhat predication accuracy at LHC for gluon initated processes and processes with γ in the final state.

- Improved understanding of the PT− NPT interplay, power corrections etc. should help in fixing the large x gluon further.

- Description of $b(B)$ cross-section at Tevatron. Used to be a problem area. seems to be now solved.

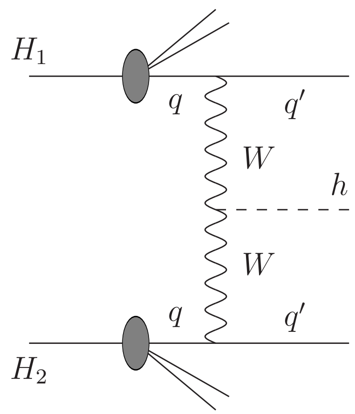
Consider Higgs production via WW fusion processes.

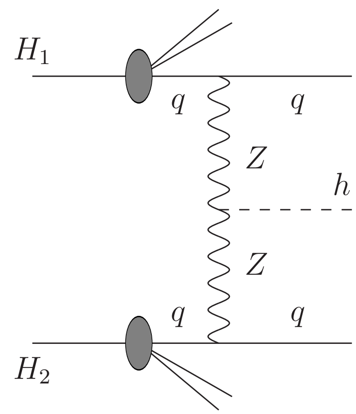
Usually one demands that the the two jets 'forward' jets have very little hadronic activity among them.

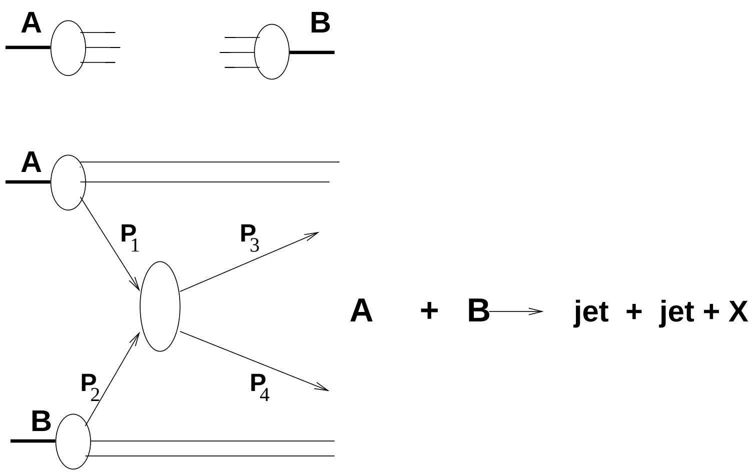
These are called 'large rapidity gap' events.

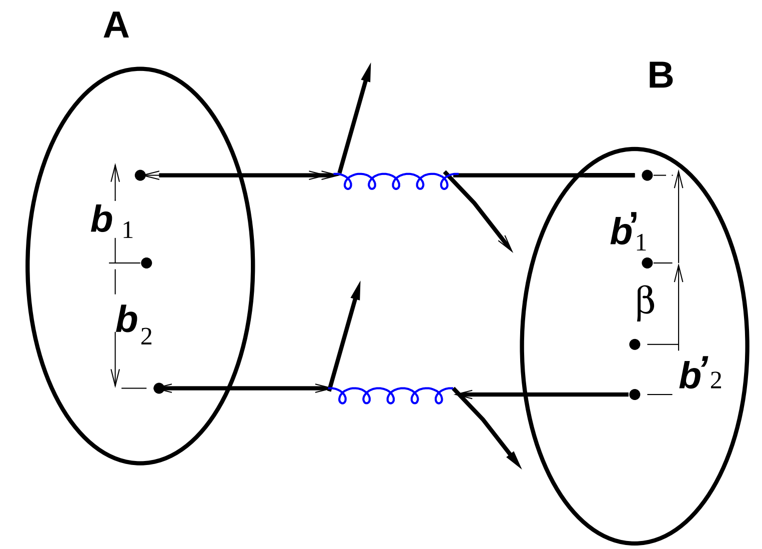
Question: How do we decide that the the underlying event does not fill the fap?

This depends on the models for multiparton interactions in a given collision.









Transverse Overlap of the hadrons

Bjorken pointed out that the gap survival probablity could be computed if one knew this overlap.

The same overlap function is also needed to calculate the total cross section as a function of energy in QCD based models using eikonal picture.

Eikonal picture per se was pioneered by Tjostrand is tested at Tevatron/HERA.

The description and the overlap integral depends on parametrisation of nonperturbative physics and the models used.

Gap Survivial probability:

$$< |S|^2 >= \frac{\int d^2\vec{b} A^{AB}(\vec{b},s)|S(\vec{b})|^2 \sigma(b,s)}{\int d^2\vec{b} A^{AB}(\vec{b},s)\sigma(b,s)}.$$

Here $|S(\vec{b})|^2$ is the probability that the two hadrons A,B go through each other without an inelastic interactioni, which will also be different in different models of calculation of total cross-section.

$$\sigma_{tot}^{AB} = 2\int d^2\vec{b}[1 - e^{-n(b,s)}]$$

$n(b,s)$ is the average number of multiple collisions at an impact parameter b and energy $\sqrt{s}$.

In our model:

$$n(b,s) = A_{BN}(b, q_{max}^{soft})\sigma_{soft}^{pp,\bar{p}} + A_{BN}(b, q_{max}^{jet})\sigma_{jet}(s; p_{tmin})$$

Parameters fixed by fits to total c.section, make prediction for GSP.

- $\sigma^{\text{inel}}_{pp(\bar{p})} = 2\int d^2\vec{b}[1 - e^{-n(b,s)}]$

- Build n(b,s) for σ^{inel} and use it for

- $\sigma^{\text{tot}}_{pp(\bar{p})} = 2\int d^2\vec{b}[1 - e^{-n(b,s)/2} cos(\chi_R)],\ \chi_R = 0$ in EMM

Approximations:

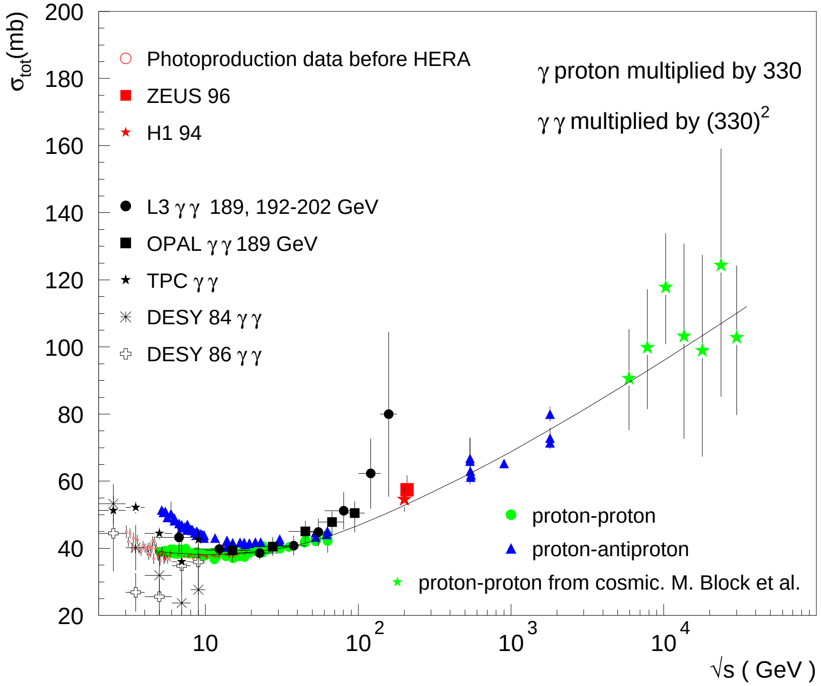
$$n(b,s) = n_{NP}(b,s) + n_P(b,s)$$

Further factorisation:

$$n(b,s) = A(b)[\sigma_{soft} + \sigma_{jet}]$$

- Model for A(b).
- σ_{soft} parametrized
- σ_{jet} LO QCD jet x-sections
- Eikonal model not restricted to calculate ONLY c.sections also used to calculate properties of hadronic events. pioneering: T. Sjostrand , More recent : M. Seymore + Borozan JHEP (2002).

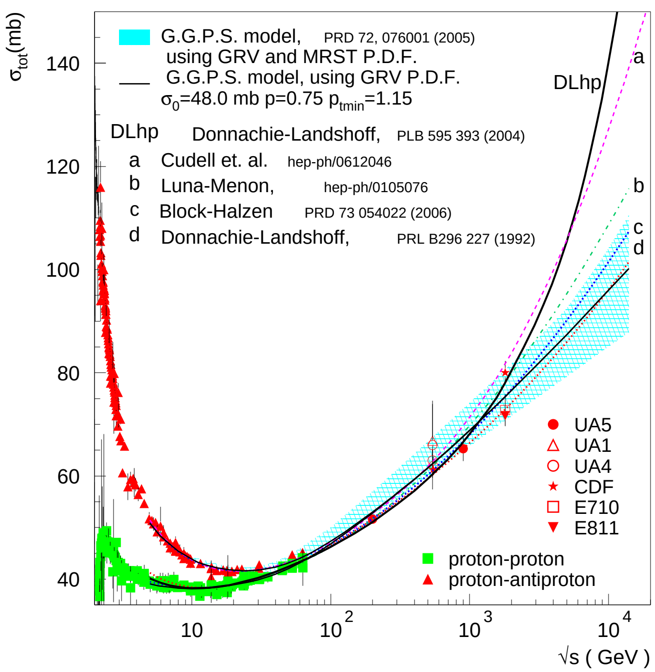
All total cross-sections rise with energy.

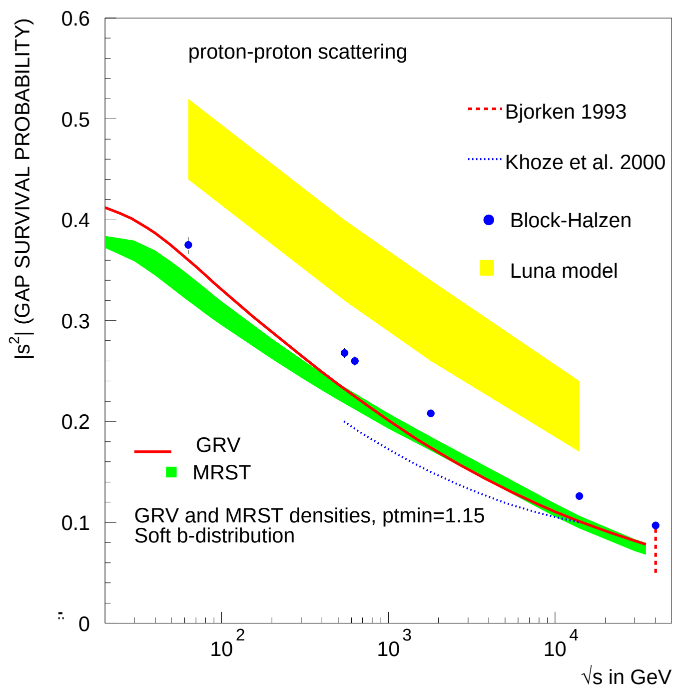


Solid line: Eikonal model improved with soft gluon resummation (Pancheri, Grau Srivastava, Godbole)

Charge to models; Explain

1) The normalisation, 2) The rise **and** 3) the initial fall with energy.


G.G.P.S. model, PRD 72, 076001 (2005)
using GRV and MRST P.D.F.
G.G.P.S. model, using GRV P.D.F.
σ0=48.0 mb p=0.75 ptmin=1.15
DLhp Donnachie-Landshoff, PLB 595 393 (2004)
a Cudell et. al. hep-ph/0612046
b Luna-Menon, hep-ph/0105076
c Block-Halzen PRD 73 054022 (2006)
d Donnachie-Landshoff, PRL B296 227 (1992)
DLhp
a
b
c
d
UA5
UA1
UA4
CDF
E710
E811
proton-proton
proton-antiproton
σtot(mb)
√s (GeV)


proton-proton scattering
Bjorken 1993
Khoze et al. 2000
Block-Halzen
Luna model
GRV
MRST
GRV and MRST densities, ptmin=1.15
Soft b-distribution
|s2| (GAP SURVIVAL PROBABILITY)
√s in GeV

Conclusions:

- PDF uncertainties on the cross-sections are being reduced due to interaction between Tevatron data and HERA data. $\alpha_s(M_Z)$ extracted from these data now agree with that from LEP
- The $b-$ production at hadronic colliders understood in terms of NNLO QCD. Same is not yet the case of photoproduction and $\gamma\gamma$ production.
- NLO calculations available for almost all processes of interest
- NNLO calculation for SM higgs and inclusive jet is available.
- Progress on multi-jet calculations allowing background computation for multiparticle final state.
- One loop calculation for $2 \to 3$ amplitude available.
- Formalism to construct Monte Carlos at NLO are now available.
- QCD tools for LHC are getting ready; data at HERA and Tevatron also helps there.
- Underlying event physics issues are relevant for new physics searches as well.
- Models and LHC data together can help develop this understanding further.