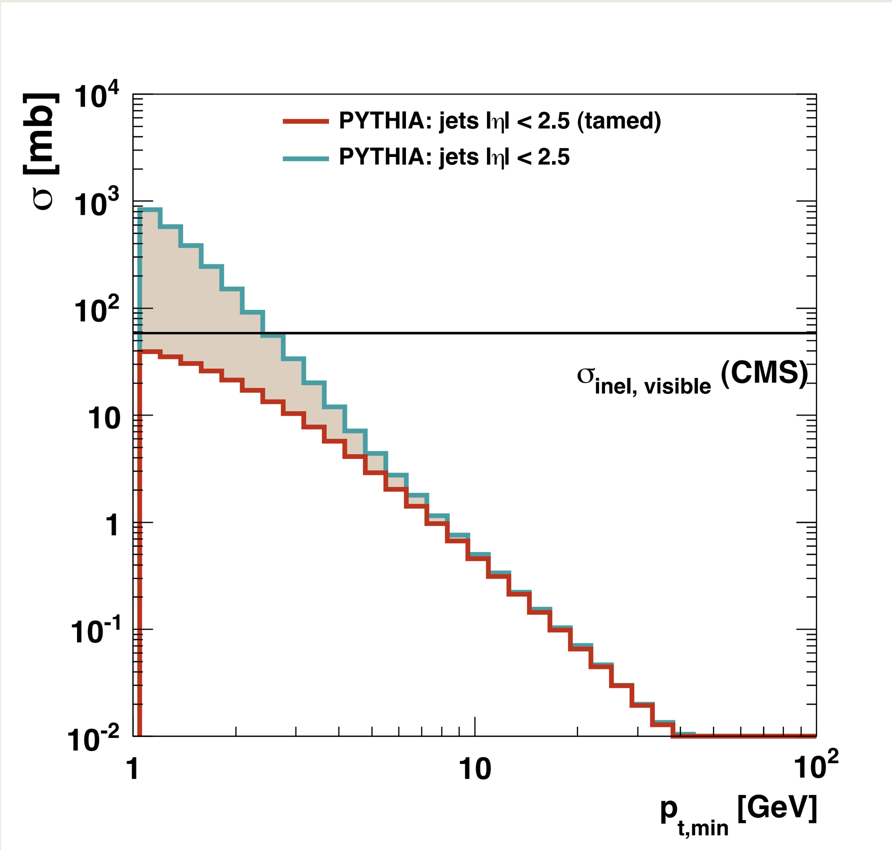
QCD at the Extremes

CMS contribution to the update of the European Strategy for Particle Physics

Physics at highest center-of-mass Energies

The dynamics of the high energy limit of QCD is driven by the increasingly higher gluon densities at low parton fractional momentum $x \sim p_T/\sqrt{s} \cdot e^{-y}$. At increasingly higher energies, the jet cross section rises and eventually overshoots the total inelastic pp cross section. At which transverse momentum this happens depends on the parton density and the centre-of-mass energy, but already at $\sqrt{s}$ = 14 TeV this occurs in the perturbative regime $\mathcal{O}$(10 GeV). This diverging cross section is supposed to be tamed by a combination of multi-parton interactions and gluon saturation effects which are maximal around a perturbative "saturation scale" of a few GeV. However, fundamental details of these processes are not yet well known, and especially the $\sqrt{s}$ evolution of the saturation scale is not known. The understanding of the high-energy behaviour of QCD is of similar importance as the understanding of the high-energy behaviour of the electroweak (longitudinal WW) cross sections, which is also diverging and only the introduction of the Higgs boson restores unitarity in the theory.

In the right figure the integrated 2 $\rightarrow$ 2 cross section $\int_{p_T^{min}} dp_T \hat{\sigma}(p_T)$ is shown as a function of the cut of the minimum transverse momentum p_T^{min} calculated with PYTHIA6 [1]. The integrated cross section becomes larger than the total inelastic cross section $\sigma_{inel} =$ 70 - 80 mb at p_T^{min} of the order of a few GeV and violates therefore unitarity. This unitarity violation is an argument to introduce the concept of multi-parton interaction, where the number of interactions per pp collision is $\langle n \rangle \sim \int dp_T \hat{\sigma}(p_T)/\sigma_{inel}$, and thus one interprets $\hat{\sigma}(p_T)$ as the jet cross section but not an event cross section.
In the region where $\int_{p_T^{min}} dp_T \hat{\sigma}(p_T) > \sigma_{inel}$ is predicted, multi-parton interaction as well as saturation and colour screening effects are needed to prevent a violation of unitarity. This can be measured with the mini-jet cross section as a function of p_T at the highest $\sqrt{s}$.
The luminosity required for this measurement is small, since the cross section is very large, but the pileup has to be minimum (PU = 1) in order to be able to measure jets down to the minimum p_T reachable. In order to have a range in p_T, where at large p_T the measurement should agree with pQCD calculations, a short dedicated low-PU run with integrated luminosity of the order of 0.1 pb^{-1} would be sufficient.



[1] T. Sjostrand, S. Mrenna, and P. Skands, JHEP 05, 026 (2006). hep-ph/0603175.

Physics at highest Scales

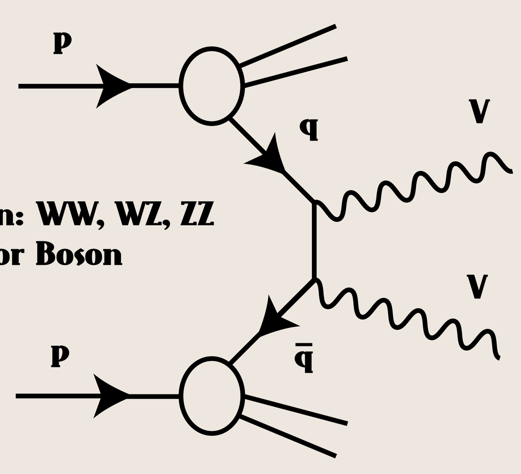
Another unexplored region of phase space is the very high x (x$\rightarrow$1) regime, the region of parton scatterings at very high virtualities Q^2 leading to jets with transverse momentum close to the kinematic threshold $p_T^{max} = \sqrt{s}/2$ and/or Drell-Yan (DY) and di-boson production at large invariant masses ($m_{inv}^{max} = \sqrt{s}/2$). In this region, the parton flux goes asymptotically to zero and the cross sections are very small, but interesting QCD effects are expected. When a large-mass system is produced, there is little phase space left for initial-state parton radiation or parton evolution. Due to the absence of initial-state radiation, the jet multiplicity will drop at variance with the naive expectation of a rise of jet multiplicities with increasing virtualities.

Jet production at largest available transverse momentum is needed for a determination of the parton densities at high scales. At present, events with jets with p_T > 3 TeV have been observed, the cross section has been measured up to $p_T \sim$ 2 TeV. In the table on the left the expected cross sections for different jet- p_T ranges for different $\sqrt{s}$ are given. The cross section falls like $1/p_T^4$, so even for the same $\bar{x} = 2p_T/\sqrt{s}$ the cross section is expected to be different. Even with highest integrated luminosity of $\int \mathcal{L}dt = 3000\ \mathrm{fb}^{-1}$ at most $\bar{x} \sim$ 0.6 can be reached in central jet production. Measurements of processes like di-jet, DY or di-boson production at large invariant masses constitute a very interesting and unexplored class of processes: since they happen at large x and at large scales, the initial-state parton evolves from the soft scale to the hard scale without (or with very few) real parton emission. In the extreme limit for x$\rightarrow$1 there is no phase-space left for any real parton emission.

	$\sigma(pp \to j+j+X)[fb]$	
$\bar{x} = 2p_T/\sqrt{s}$	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 33$ TeV
0.5	$2 \cdot 10^{-1}$	$1 \cdot 10^{-2}$
0.6	$4 \cdot 10^{-3}$	$5 \cdot 10^{-4}$
0.7	$7 \cdot 10^{-5}$	$9 \cdot 10^{-6}$
0.8	$4 \cdot 10^{-7}$	$4 \cdot 10^{-8}$
0.9	$7 \cdot 10^{-11}$	$8 \cdot 10^{-12}$

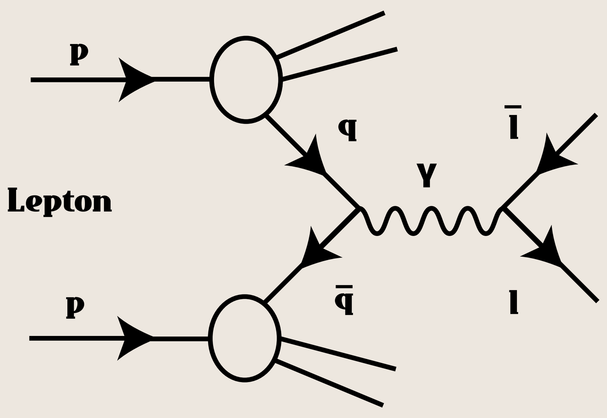
Di-Boson Production

Di-Boson: WW, WZ, ZZ
V: Vector Boson

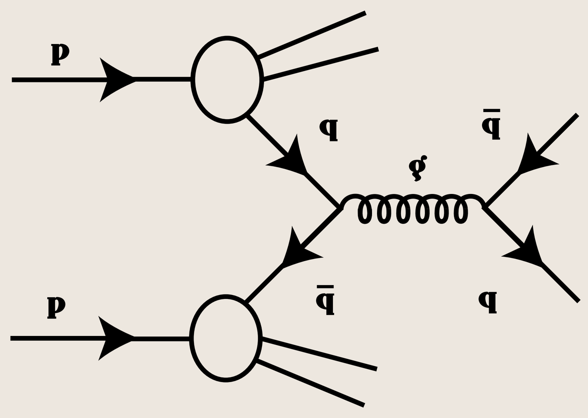


Drell-Yan Process

l: Lepton



Di-Jet Production



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