Highlights of QCD measurements at the LHC

Precision QCD @ 2020; IIT Hyderabad

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February 3, 2020

The Large Hadron Collider (LHC) at CERN

- Marvel of technology.
  Operates at the very boundaries of scientific knowledge.
- Collides proton-on-proton (p-p), heavy ions (p-Pb, Pb-Pb, Xe-Xe) at 4 collision points.
- ATLAS and CMS are the major multipurpose experiments.
- India participates in ALICE & CMS experiments.
- The performance of the experiments have crossed the design expectations.
  They also demand high precision theoretical predictions.
- Measurement of precision observables based on Standard Model (SM) can shed light into possible BSM physics.
- **Will cover only few results from pp collision with bias towards CMS.**

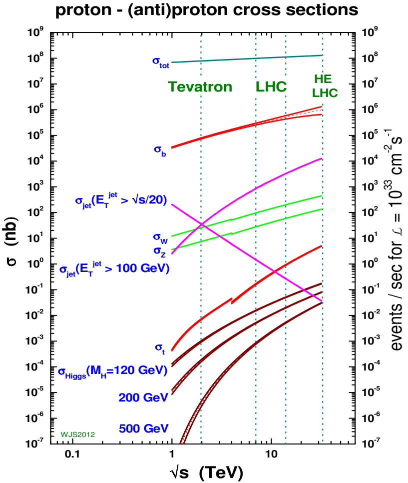
LHC data and physics terrain

collision system	collision energy	integrated luminosity
pp	13 TeV	150/fb
	8 TeV	20/fb
	7 TeV	5/fb
	2.76 TeV	5/pb
p-Pb	8 TeV/nucl.	180 /nb
	5 TeV/nucl.	35 /nb
Pb-Pb	5 TeV /nucl.	25 /nb
	2.76 TeV/nucl.	150 /μb
Xe-Xe	5.44 TeV/nucleon	13 /mb

- Standard Model
- Direct and indirect signatures of physics beyond SM
- Heavy flavour
- Low-x and forward physics
- Quark-gluon plasma

- Humongous effort by theory and experiment communities

What we measure at LHC



- Total cross section at $\sqrt{s} = 7$ TeV

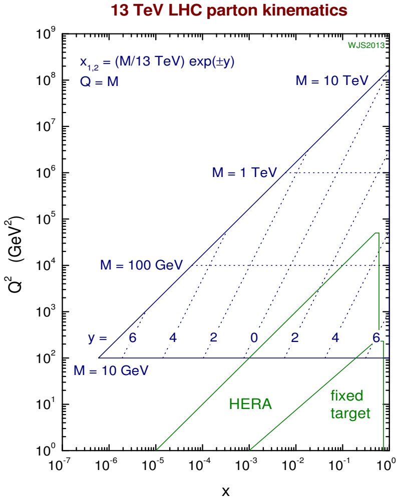
$$\sigma_{\rm inel}(\rm mb) = 73.2^{+2.0}_{-4.6}(\rm mod.) \pm 2.6(\rm lumi)$$

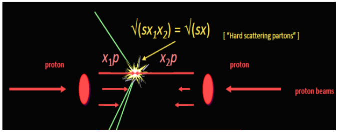
Rates at $L = 10^{34}/\mathrm{cm}^2/\mathrm{s}$, $\sqrt{s} = 8$ TeV

inelastic reaction	10^9/s
$\mathrm{b\bar{b}}$ pairs	5×10^6/s
$\mathrm{t\bar{t}}$ pairs	8/s
$W \to e\nu$	150/s
$Z \to e^+e^-$	15/s
Higgs (125 GeV)	0.2 /s
Gluino, squark (1TeV)	0.03/s

- at $\sqrt{s} = 13$ TeV, the relative increase in rates is more for gluon initiated processes.

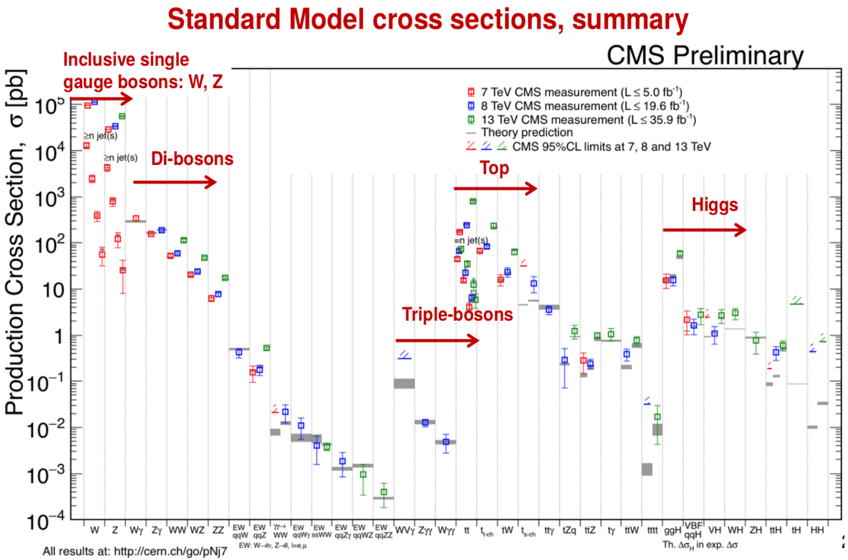
LHC Kinematics





- Reach: x up to $\sim 10^{-6}$

No phenomenon is a phenomenon, until it is observed!



Hard scattering cross section

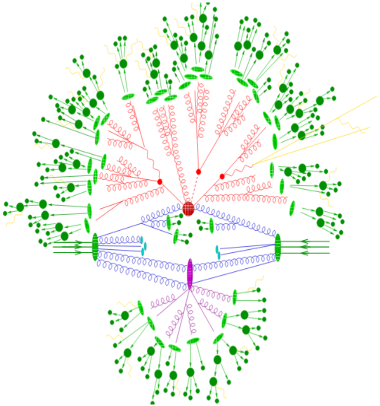
$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\text{FS}}\, f_a(x_1,\mu_F) f_b(x_2,\mu_F)\, \hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$$

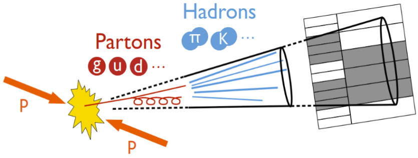
Phase-space integral — Parton density functions — Parton-level cross section

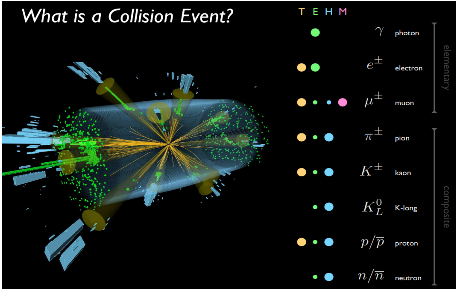
$$\hat{\sigma} = \sigma^{\text{Born}}\left(1 + \frac{\alpha_s}{2\pi}\sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2\sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3\sigma^{(3)} + \dots\right)$$

- This factorisation picture can be improved systematically, until the power-sppressed contributions become quantitatively relevant.
- Subprocess cross section: depends on the process, calculable with perturbative QCD; short-distance coefficients as an expansion in α_s.
- Parton density functions (PDFs): non-perturbative.
  $\Rightarrow$ Fit from experimental data and theoretical evolution with DGLAP eqns (Q^2-ordered).
- Final state hadronization ($q \to \pi, K, p, D, B$) or bound state formation use universal form factors extracted from data + DGLAP.

LHC event: simulation, visualization, display

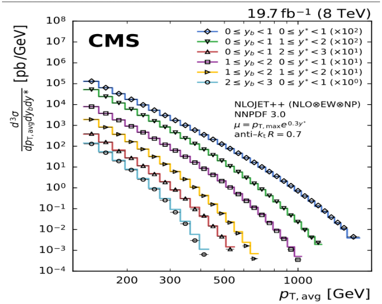


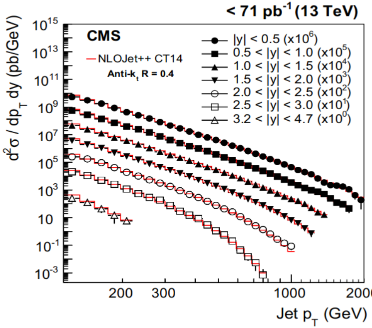




- Reconstructed jets in data are from hadrons; theory predictions are for parton level jets.

Test of perturbative QCD predictions

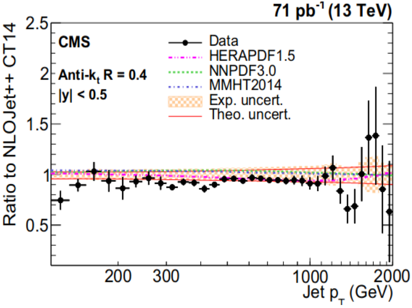


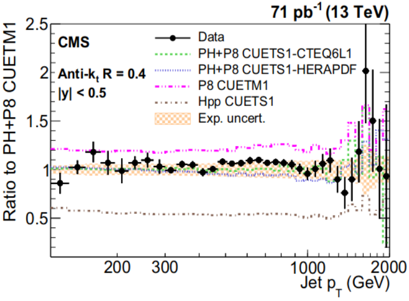


- There is discrepancy with CMS data at higb p_T, using large radius jet.
- Use of p_T^{jet} as the QCD scale brings better agreement of CMS 13 TeV results with prediction including nonperturbative QCD and Electroweak corrections.
- Non-perturbative corrections account for parton shower, hadronization and multiparton interactions.

Jet measurements & fixed order calculations

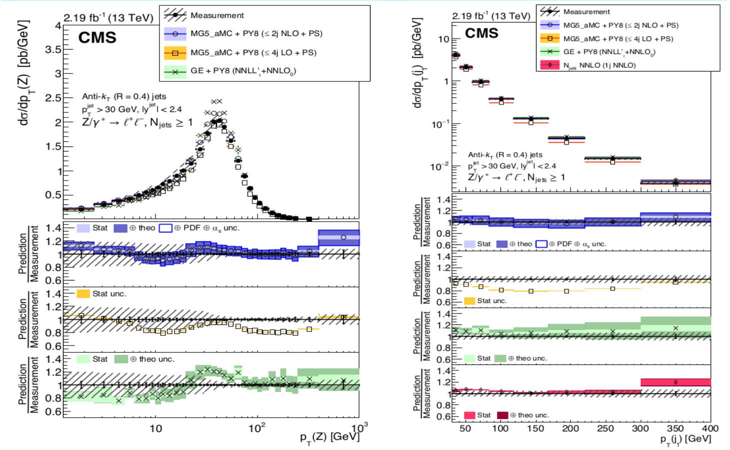
- Data matches batter with NLO predictions matched to parton shower (POWHEG+ PYTHIA8)
- Fixed-order NLO prediction combined with non-perturbative and electroweak corrections (NLOJet++) does not account for parton shower and resummation contributions $\Longrightarrow$ overestimates cross section for $R = 0.4$.





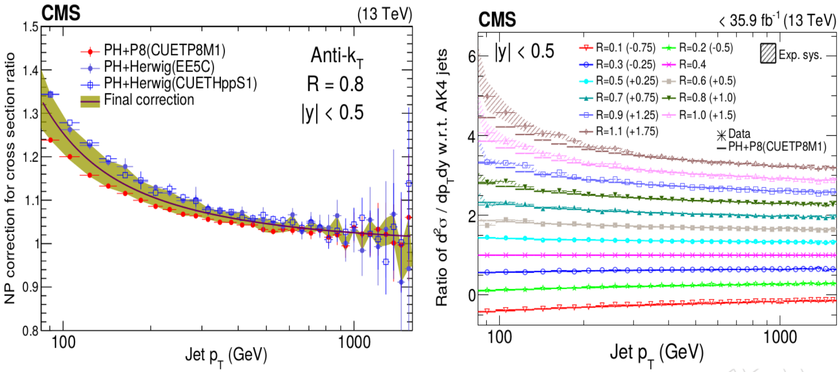
- CMS dijet data reduces uncertainty in gluon PDF at high x

Z+jets at 13 TeV



- Z+X cross sections compared to generators & corrections for NP effects.
- Measurements are in good agreement with NLO+PS mutli-parton calculations including kinematic variables sensitive to soft-gluon radiation.

Non-perturbative corrections



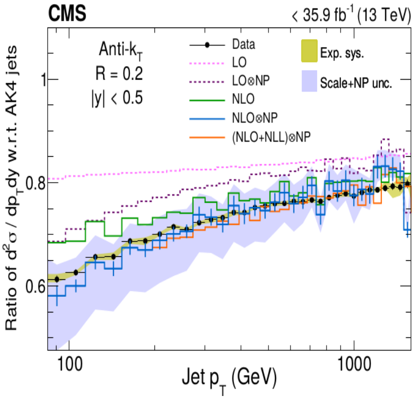
- Dependence of correction on reconstructed jet parameter.

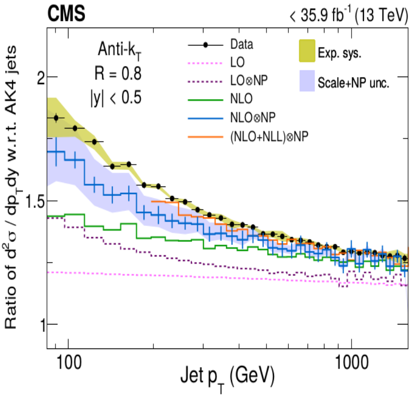
$\Longrightarrow$ based on Monte Carlo predictions from hadronization models & tunes for multi-parton interactions (MPI) in parton shower.

- hadronization correction is larger for jets of smaller size.
- MPI correction has significant size for large jet radius.

Dependence of correction on reconstructed jet parameter

Measurements using different anti-k_{T} distance parameter: R=0.2, 0.8





Ratio of data to next-to-leading-order (NLO) with CUETP8M1 tune for underlying events

QCD analysis with top-pair events in CMS at 13 TeV

- triple differential cross section: $\mathrm{N_{jet}}$, $M(\mathrm{t\bar{t}}), y(\mathrm{t\bar{t}})$

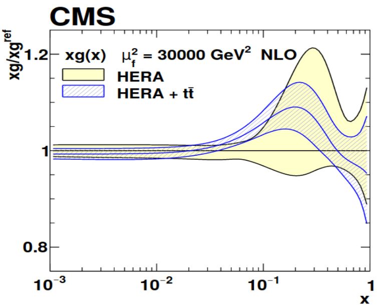
$\mathrm{N_{jet}} \rightarrow$ jets are not part of $\mathrm{t\bar{t}}$ system.

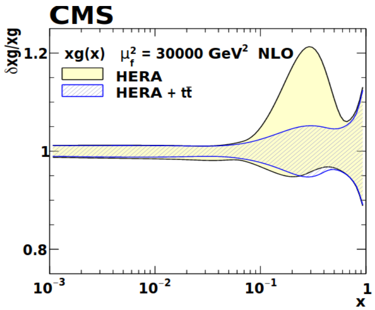
- Use fixed order NLO calculation to extract α_s & m_t, constrain gluon PDF.

$$\alpha_S(m_Z) = 0.1135 \pm 0.0016(\mathrm{fit})^{+0.0002}_{-0.0004}(\mathrm{model})^{+0.0008}_{-0.0001}(\mathrm{param})^{+0.0011}_{-0.0005}(\mathrm{scale}) = 0.1135^{+0.0021}_{-0.0017}(\mathrm{total}).$$

$$m_{\mathrm{t}}^{\mathrm{pole}} = 170.5 \pm 0.7(\mathrm{fit}) \pm 0.1(\mathrm{model})^{+0.0}_{-0.1}(\mathrm{param}) \pm 0.3(\mathrm{scale})\,\mathrm{GeV} = 170.5 \pm 0.8(\mathrm{total})\,\mathrm{GeV}.$$

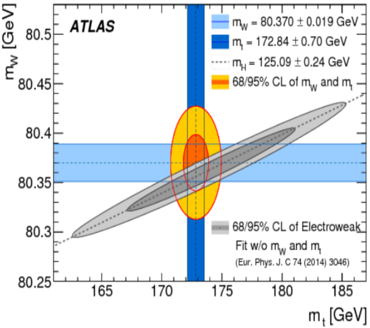
$$x = \frac{M(\mathrm{t\bar{t}})}{\sqrt{s e^{\pm y(\mathrm{t\bar{t}})}}}$$





Parton distribution functions

- Precision on PDF determines the accuracy of current knowledge SM in most cases and hence the sensitivity for beyond SM.
- The limiting factor for predictions of some the SM input parameters: $\mathrm{m_W}$, $\sin^2\theta_\mathrm{w}$, $\mathrm{m_t}$
- At N^{3}LO, the theoretical accuracy in the prediction for cross section of $gg \rightarrow H + X$ is limited by PDF.



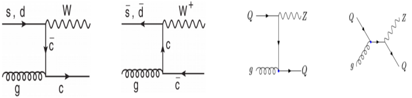
• LHC data potentially disentangles the flavour composition in sea PDF, determine gluon PDF and improve valnce PDF.

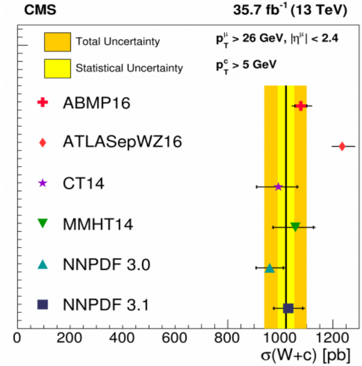
• Different measurements constrain PDFs of various partons

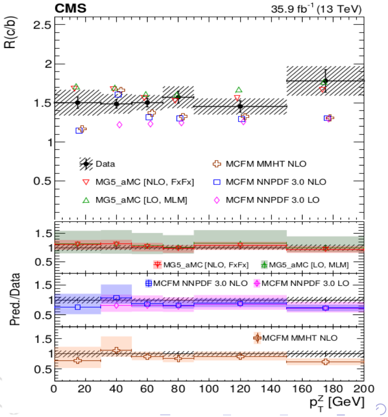
Heavy quark PDFs

Challenging measurements with small production rates and difficulties in identification of heavy flavour jets.

- Estimation of strange quark PDF improves with W + c data.
- Z + c/b measurements test the perturbative and intrinsic parton components in hadrons

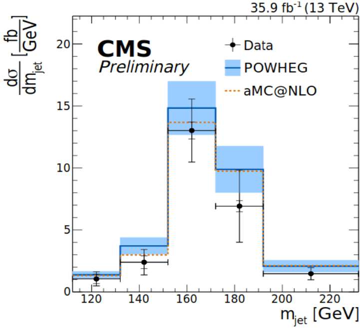




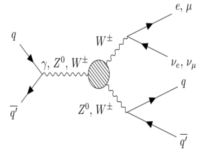


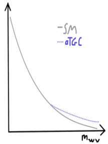
Jet substructure in top physics & electroweak physics

- Mesurement of jet mass in boosted top quark decays using fat jet of $p_T > 400$ GeV



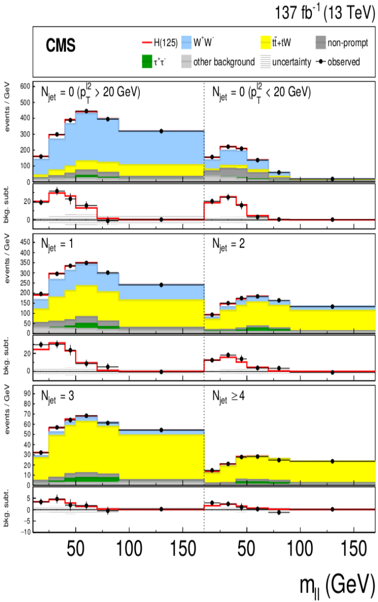
- Using substructure in search for anomalous gauge coupling. Hadronic decays of boosted W, Z results in a single fat jet, to be identified with τ_{21} and soft drop mass.
- Constrain parameters of Effective Field Theory Lagrangian as well as anomalous triple gauge and anomalous quartic gauge couplings.





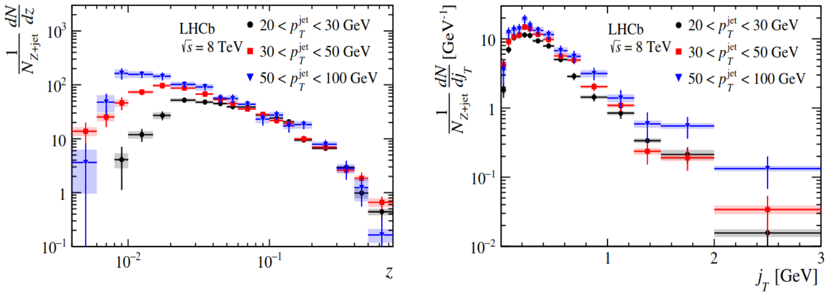
Impact of QCD precision on Higgs physics

- The discovery of the Higgs boson in 2012 has brought Higgs physics of age.
  Precision predictions from theory made the discovery possible within a very short time of LHC start-up.
- Higgs characterization is the current mandate of the community.
  → being carried out via multiple measurements ⇒ crucially depends on accurate theoretical prediction of the observables.
- QCD plays a very significant role. Any deviation from prediction would indicate beyond SM effect.



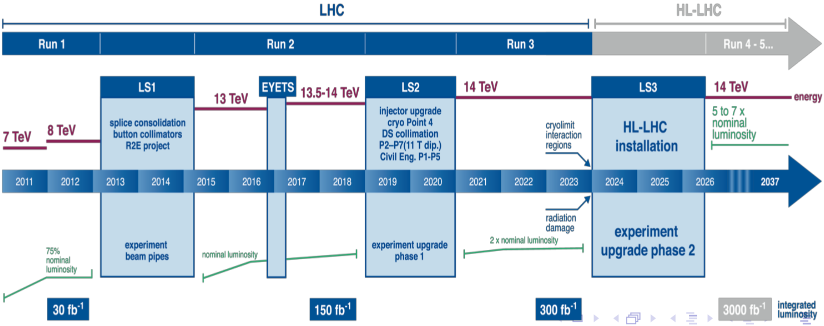
Production of charged hadrons inside a jet

- Typically central and mid rapidity jets are mostly gluon jets.
- Study for forward jets provides opportunity to study production of light quark vs. gluon jets
- LHCb measurement probes: hadronization dynamics, jet properties,...

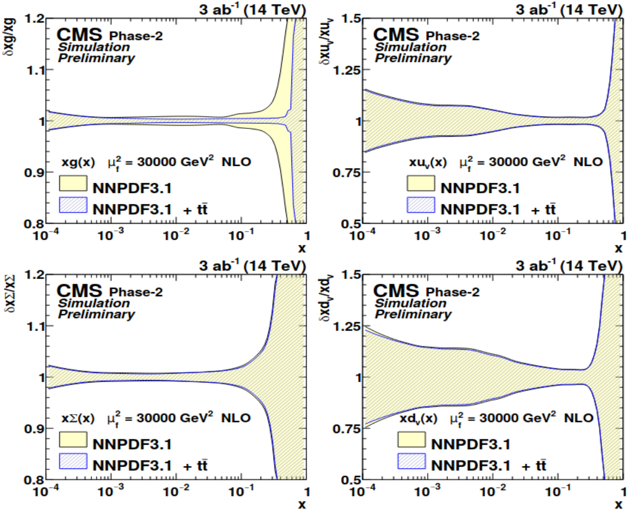


LHC timeline

- Long term facility, has delivered till now only a few % of total data volume expected.
- High luminosity phase of LHC (HL-LHC) is the only approved HEP collider facility for future as of today.
- Design/nominal instantaneous luminosity: 10^{34} /cm^2/s
  At HL-LHC: 7.5×10^{34} /cm^2/s



PDF prospects at the HL-LHC!



Conclusion

- LHC experiments demand high precision predictions.
- Precision observables can shed light onto possible BSM physics.
- Jet physics becomes even more interesting with the availablity of predictions of NNLO accuracy, new variables useful for experiment (like subjettiness), new identifiers/taggers (like TopTagger), as well as ample applications of Machine Learning.
- Recent improvements in theoretical techniques will provide, within small time scale, predictions at N^3LO or at higher accuracy for the most important Standard Model processes.
- These, when combined with better parton density functions (eg., highly desired N^3LO PDF), will be the match for the statistical accuracy achievable with high luminosity LHC.

THANK YOU!