QCD results at LHC
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Outline

talk presents recent results on production of

- jets
- isolated photons
- top
- vector bosons

does not cover

- multibosons
- heavy ion
- Higgs
- diffraction
- ...

ATLAS high mass central dijet event – M= 6.9 TeV
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Collisions
Coverage of LHC detectors

- **ATLAS and CMS:**
  precision tracking and muon identification in central region
  forward calorimetry - measurements of electrons and jets for |\(\eta| < 5\)

- **LHCb:**
  coverage for \(\eta > 2\) – excellent tracking and particle identification
  low \(p_T\), low mass triggers
  → complementary measurements

- **standard candles**
  background for New Physics and Higgs
  → important validation of ME+PS MC Generators

- **sensitive to parton density functions (PDFs)**
  → constrain PDFs

- **precision tests of pQCD**
Jets
the experimental signatures of quarks and gluons
What can we do with jets?

jets result from fragmentation of quarks and gluons in a short-distance scattering process

are powerful probes of QCD:
- explore pQCD in brand new energy regions
- yield information on structure of the proton
- probe and measure $\alpha_s$
- access to dynamics of heavy flavors
- compare to NLO/NNLO predictions
- tune Monte Carlo Generators

there is more than QCD:
- extensive test of the Standard Model: V+Jets, H+Jets, V+heavy flavors…
- jets are background for most of the searches
- beyond the Standard Model:
  - dijet resonances
  - monojet & dark matter
  - new strongly produced states
  - hadronic resonances

CMS multijet event: 12 jets with $p_T > 50$ GeV, and the mass of the system is 6.4 TeV
http://cms.web.cern.ch/news
Inclusive jets and dijets @ 13 TeV

\[ p_T(\text{jet}) > 75 \text{ GeV}, \text{anti-}\kappa_T R=0.4, \text{modified Bayesian unfolding} \]

double differential x-section: inclusive \((p_T,y)\), di-jet \((m_{jj},\Delta y)\)

dominant syst. uncertainty: jet energy scale

compared to: NLOJet++ using CT14, MMHT, NNPDF3.0

overall good agreement for di-jets

slight underestimation at high \(p_T\) and high \(y\)


measurement with \(R=0.4\) and \(0.7\)
Inclusive jets @ 13 TeV

\[ p_T^{(\text{jet})} > 114 \text{ GeV}, \text{anti-}k_T \text{ R=0.4 and R=0.7} \]

\[ \frac{d^2\sigma}{dp_T dy} \]

NLO predictions (NLOJet++)

R=0.7

R=0.4

comparison to MC generators

0.5<|y|<1.0

2.0<|y|<2.5

POWHEG+Pythia

good agreement

HERWIG++:

good in shape, poor in scale

Pythia 8

does describe shape for y<2.0

- R = 0.4 x-section overestimated by about 5–10%
- R=0.7: better description → PS and soft-gluon resummation contributions, which are missing in fixed-order calculations are more relevant for smaller jet cone sizes
Jet charge $Q$

$Q$: estimator for charge of parton initiating the jet

\[ Q^\kappa = \frac{1}{p_T(jet)} \sum_i Q^i(p_T^i)^\kappa \]

$\kappa$ controls relative weight of low and high $p_T$ particles

gluon initiated jets dominant at low $p_T$,
quark initiated more at high $p_T$ \( \rightarrow Q \) increases with $p_T$
predictions tend to underestimate $Q$
Jet charge

unfolded jet charge, $p_T > 400$ GeV
compared to (N)LO predictions
Powheg+Pythia8, Powheg+Herwig++

- $Q$ unaffected by NLO effects, ISR or MPI
- FSR narrows the distribution
- data slightly broader than predictions

$$Q^j = \frac{1}{p_T^\kappa(jet)} \sum_i Q^i (p_T^i)^\kappa$$

Strong coupling constant $\alpha_s$

$p_T(\text{jet}) > 20\text{GeV}, |\eta| < 4.7, \text{anti-}k_T - R = 0.4$

from double-diff x-section at 8 TeV

theoretical comparison: CT10 NLO x NP x EW PDF (NP: non perturbative)

QCD fit → parton density functions and $\alpha_s$

$$\alpha_s(M_Z) = 0.1164^{+0.0014}_{-0.0015}\exp +0.0025(NP)^{+0.0053}_{-0.0028}(\text{scale}) = 0.1164^{+0.0060}_{-0.0043}$$
\( \alpha_s \) from cross-sections: affected by knowledge of PDFs and their Q dependence

\[ \rightarrow \text{dependence on normalization group equations, used in PDF extraction} \]

cross-section ratios: PDF uncertainty cancels to a large extend

\[ \rightarrow \text{theoretical cleaner extraction of } \alpha_s \text{ and its running} \]

jet algorithm: anti-\( k_T \) R=0.6

large enough to include soft and hard radiation, but avoiding underlying event

measure \( R(\Delta \Phi) \): fraction of di-jet events in which \( \Delta \Phi < \Delta \Phi_{\text{max}} \)

\[
R_{\Delta \Phi}(H_T, y^*, \Delta \Phi_{\text{max}}) = \frac{\frac{d^2\sigma_{\text{dijet}}(\Delta \Phi_{\text{dijet}}<\Delta \Phi_{\text{max}})}{dH_T dy^*}}{\frac{d^2\sigma_{\text{dijet inclusive}}}{dH_T dy^*}}
\]

\( H_T \): transverse momentum sum, \( y^* = |y_1 - y_2|/2 \)
Di-jet azimuthal decorrelation @ 8 TeV

\(\alpha_s\) extracted from measurement of \(R(\Delta\phi)\) with \(\Delta\phi_{\text{max}} = 7\pi/8\), \(0 < y^* < 0.5\) and \(0.5 < y^* < 1.0\).

<table>
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<tr>
<th>(\alpha_s(m_Z))</th>
<th>Total uncert.</th>
<th>Statistical</th>
<th>Experimental correlated</th>
<th>Non-perturb. corrections</th>
<th>MMHT2014 uncertainty</th>
<th>PDF set</th>
<th>(\mu_{R,F}) variation</th>
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<tr>
<td>0.1127 ±0.0027</td>
<td>+0.067</td>
<td>±0.5</td>
<td>+1.8</td>
<td>+0.3</td>
<td>+0.6</td>
<td>+2.9</td>
<td>+5.2</td>
</tr>
</tbody>
</table>

\[\alpha_s(M_Z) = 0.1127^{+0.0063}_{-0.0027}\]
Isolated Photons

unique colorless probe to test pQCD predictions
isolated photons (plus jets) @ 13 TeV

dominant production process: $qg \rightarrow q\gamma \rightarrow$ constrain on gluon at medium $x$, $x\sim 0.1$

isolated photons: background for many searches $\rightarrow$ important to understand production and MC modeling

CMS: $E_T(\gamma) > 190$ GeV, $|y(\gamma)| < 2.5$, BDT for separation of signal and backgrounds

agreement with NLO JETPHOX predictions within uncertainties but large uncertainties due to missing higher order terms in pQCD

CMS Preliminary

Inclusive measurement

$E_T(\gamma)$ distribution for isolated photons

Photon plus jet ($E_T > 30$ GeV)
NNLO predictions

NNLO calculations now available


→ theory uncertainties reduced by a factor 2
→ new opportunities for precision QCD and inclusion of photon data into PDF fits
two contributions to cross-section: direct and fragmentation

cross-section as function of $\theta^*$ → insight into relative contributions of direct vs fragmentation components, and testing of dominance of t-channel quark exchange

\[ \frac{d\sigma}{d|\cos \theta^*|} \, [\text{pb}] \]

**ATLAS**

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

- Data
- LO QCD (JETPHOX)
  - direct (x2)
  - fragmentation (x23)

$$m_{\gamma\text{-jet}} > 450 \text{ GeV}$$

$$|\eta^{\gamma\text{-jet}}| < 2.37$$

shape agrees better with direct contribution

→ in agreement with expectation of process with quark exchange
Photon plus b/c @ 8 TeV

sensitive to heavy quark content of proton, test of HF modeling in MC generators
tagger discriminant distribution

HF yield extracted from a template fit to the distribution of the discriminant

- LO and NLO give a good description
- 5F scheme better agreement than 4F at high $E_T$
- predictions with intrinsic charm (BHPS1/2) higher at high $E_T$
Top quarks
focussing on tt-bar production
Top production @ LHC

dominated by gluon fusion:
qq/gg = 10% / 90% at LHC

rich phenomenology → test of SM predictions, sensitivity to PDF, $\alpha_s$, $m_t$

but: calculations are challenging: NNLO/NNLL corrections important

final states: di-lepton, fully hadronic (6 jets), lepton+jets

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG
Forward top pair production @ 13 TeV

forward: enhanced qq-bar contribution
→ larger charge asymmetry
→ better sensitivity to New Physics

sensitive to PDF at large and low x
previously measured at 7+ 8 TeV
13 TeV 10 times higher x-section

μeb channel:
isolated prompt μ,e, one b-jet
  b-tagging: secondary vertex in jet
p_T(l) > 20 GeV and p_T(jet) > 20 GeV
ΔR(l,J) > 0.5, ΔR(μ,e) > 0.1

→ 44 candidates, 86% purity
main background QCD multijets
First observation of forward top @ 13 TeV

\[ \sigma(t\bar{t}) = 126 \pm 19 \text{(stat)} \pm 15 \text{(syst)} \pm 5 \text{(lumi)} \text{ fb} \]

20% precision, compatible with the SM within 20σ

dominating systematic uncertainty: jet tagging: 10%

LHCb upgrade: measurement not statistically dominated
→ very promising channel for tt-bar studies
top reconstructed in lepton plus jets channel
sensitive to gluon radiation
study 4, 5 and 6 jets samples separately
\( p_T(t,\text{had}) \) with 4 jets
\( p_T(t\bar{t}) \) with 6 jets

measurements have potential to further constrain the models:
\( p_T(t,\text{had}) \) with 4 jets underestimated at high \( p_T(t,\text{had}) \)
\( p_T(t\bar{t}) \) disfavours some models
Underlying event in \( \text{tt-bar} \) @ 13 TeV

underlying event (UE): partons not participating in hard scattering process, multiple parton interactions, gluon radiation

electron, muon + 2b-jets → first measurement of UE properties at \( Q \) up to \( 2m_t \)

various variables investigated (\( N_{\text{ch}}, p_T, \) sphericity, …), various event categories

- UE event: typically 20 charged particles, average \( p_T \) and \( p_Z \) about 2 GeV
- Powheg+Pythia gives a good description
- models with MPI switched off and default Sherpa (○), Herwig (▲,▼) configuration disfavoured
- no dependence on ME (Powheg or Madgraph5aMC@NLO)

[Graphs and plots showing data and theory predictions for different models, such as CMS, Powheg, Madgraph, and EWK, with comparisons of data to theory at various \( N_{\text{ch}} \) values.]
Vector bosons
standard candles of the Standard Model
Forward $Z \rightarrow b \bar{b}$-bar @ 8 TeV

- standard candle of the SM: background for many new physics processes, $H_{bb}$
- first measurement in forward region ever made!
- challenging measurement, huge QCD background $\rightarrow$ MVA for separation
- 2 b-tagged jets, $p_T > 20$ GeV and $45 < m_{JJ} < 165$ GeV ; $\Delta \phi(b\bar{b}) < 2.5$
- simultaneous fit to dijet mass in signal and control regions

![Graphs showing signal and control regions](image)

**Signal Region**

**Control Region**

\[
\sigma(pp \rightarrow Z) B(Z \rightarrow b \bar{b}) = 332 \pm 46 \text{(stat)} \pm 50 \text{(syst)} \text{ pb}
\]

\[
\sigma(pp \rightarrow Z) B(Z \rightarrow b \bar{b}) = 272^{+9}_{-12} \text{(scale)} \pm 5 \text{(PDF)} \text{ pb (aMC@NLO)}
\]
Forward $Z \rightarrow \tau^+\tau^-$ @ 8 TeV

- probe of high energy tau reconstruction at LHCb
- reconstruction in leptonic (electron, muon) or hadronic (one or three) final state
  7 streams: ee, $\mu\mu$, $e\mu$, $\mu\mu_1$, $\mu\mu_3$, $e\mu_1$, $e\mu_3$
- main backgrounds: data driven techniques
- signal yield: data – expected background

**$\mu\mu_1$ channel**

![Graph showing $\mu\mu_1$ channel](image)

**$\mu\mu$ channel**

![Graph showing $\mu\mu$ channel](image)

LHCb: arXiv:1806.05008
Z → τ⁺τ⁻ @ 8 TeV

fiducial region: 2.0<η(τ)<4.5, pT(τ)>20 GeV, 60<M(ττ)<120 GeV

measurements agree with each other, compatible with NNLO predictions
Z+jets @ 13 TeV

High cm energy allows production of a large number of jets, background for tt-bar, Higgs, ... main background at large jet multiplicities: tt-bar and diboson.

Reasonable description by NNLO and NLO predictions.

MC generators: LO (MG5_aMC+PY8 CKKWL) predicts too hard $p_T$ distribution.
measurement of the transverse momentum balance between Z and the jets, sensitive to soft gluon radiation

multiparton predictions:
- NLO: good
- LO: softer distribution
→ NLO corrections important
- Geneva: NNLO Z prod. +NNLL resummation fails to describe distribution for $N_{jet}>1$
Z+di-jets @ 13 TeV

production mechanism:
QCD: abundant
electroweak: rare

EW:
jets: large E, large $\eta$-separation
large di-jet mass
no colour connection between protons
→ less hadronic activity (veto on jets)

EW Zjj x-section extracted in EW enriched sample
high di-jet mass (M>1 TeV): Sherpa+PH, MG+PH overestimate x-section
Z+di-jets @ 13 TeV

EW contribution from fit to BDT with 6 discriminating variables (event and jet properties)

- Signal established → study event activity in EW enhanced region (BDT>0.92)
- Data disfavours background only prediction

$$\sigma(\text{EW}) = 552 \pm 19 (\text{stat}) \pm 55 (\text{syst}) \text{ fb}$$

SM prediction ( LO) $$\sigma(\text{EW}) = 543 \pm 24 \text{ fb}$$

ATLAS-CMS results cannot be directly compared because of different phase space
first measurement of $Z$ plus c-jets in central region (plus ratios to $Z+b$ jets)

- sensitivity to intrinsic charm
- $p_T(l)>20$ GeV, $|\eta(l)|<2.71$, $111< m_{ll}< 111$ GeV, $p_T(jet)>25$ GeV, $|\eta(jet)| < 2.5$
- HF selection in three modes:
  - **semileptonic**

**Data driven techniques to control modelling and tagging efficiency**

c-jets: W+c events, b-jets: tt-bar events
Z+c-jets @ 8 TeV

extraction of Z+c and Z+b yields from template fits to

- corrected secondary vertex mass (semileptonic)
  \[ M_{\text{vertex}}^{\text{corr}} = \sqrt{M_{\text{vertex}}^2 + p_{\text{vertex}}^2 \sin^2 \theta + p_{\text{vertex}} \sin \theta}, \]
- probability that tracks come from primary vertex (D\(^\pm\), D* modes)

\[ \frac{d\sigma(Z+c)}{dp_T} \quad \frac{d\sigma(Z+c)}{dp_T} / \frac{d\sigma(Z+b)}{dp_T} \]

Comparison with predictions:
LO (□) and NLO (○) Madgraph: good
MCFM (incl. corrections for hadronisation) is too low: missing PS and non pert. effects

sensitivity to intrinsic charm ▼ at high \( p_T(Z, \text{jet}) \) mostly through ratio to Z+b
→ experimental uncertainties too large
Conclusions

the LHC experiments allow for extensive tests of QCD

- many standard candle measurements - important for Higgs physics and searches beyond the SM
- Measurements sensitive to structure of the protons and $\alpha_s$
- measurements of multiple final states → explore regions of phase space where current theory still struggles to match data
- systematic exploration of final states with several beam energies → may improve our understanding of QCD
Backup
Kinematic range

\[
\sigma(x, Q^2) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1 Q^2) f_b(x_2 Q^2) \times \hat{\sigma}(x_1, x_2, Q^2)
\]

- x-section measurements and ratios sensitive to parton density functions (PDFs)
- measurements used to constrain PDFs → important for e.g. searches
- LHC, HERA, Tevatron and fixed target data: wide range in x-Q^2 plane
- precision tests of pQCD
- background for new physics and Higgs → important validation of ME+PS MC Generators
two categories: Z plus >0 and >1 b tagged jets
b jets \( p_T > 30 \text{ GeV}, |\eta| < 2.5 \), Z+b unfolded to particle level
several differential cross sections:
angles, \( p_T \), \( H_T \), bbZ and bZ system explored
compared to NLO predictions by MadGraph and Powheg, 4F and 5F schemes tested
fraction of Z+b-jet vs \( p_T \)

- 4F scheme fails to describe fraction of b-jet events vs \( p_T \), 20% low in normalisation
- Z plus 2 b-jets in general well described
**Z → bb-bar: Jet tagging**

b, c tagging with secondary vertex in jet cone

- two BDTs to separate
  1) heavy from light jets (bc|udgs)
  2) bottom from charm jets (b|c)

**D+jet sample:** enriched in b- and c-jets

**Powerful heavy jet tagging**

- jets with 20 GeV < $p_T$ < 100 GeV:
  - efficiency of b-jet tagging $\sim 65\%$
  - efficiency of c-jet tagging $\sim 20\%$
  - misidentification of a light-jet $\sim 0.3\%$

- performance validated in data

**ATLAS & CMS:**

- several taggers based on tracks, muon, SV using MVA and NN

lepton + jets channel: absolute and normalised cross sections
particle level (fiducial phase space), parton level (full phase space)
compared to several SM predictions
• reasonable description of kinematic variables of the top quarks and the tt-bar system
• no prediction describes all the measured distributions
• largest deviation $p_T(t)$: softer than predicted
Underlying event in tt-bar @ 13 TeV

- UE is anisotropic ($S < 1$)
- no extra jet: UE more isotropic
- MPI contribution is crucial
- sensitivity to colour reconnection
Strong coupling constant $\alpha_s$

$\mathbf{p}_T(\text{jet}) > 100\text{GeV}$, $|\eta| < 2.5$, anti $k_T$ – $R=0.4$

energy-energy correlations and their associated asymmetries in multi-jet even bins of the scalar sum of the transverse momenta of the two leading jets

unfolded distributions fitted to NLO calculations

$\alpha_s = 0.1162 \pm 0.0011(\text{exp.}) + 0.0084 -0.0070(\text{th.})$
### Detectors

<table>
<thead>
<tr>
<th>Experiment</th>
<th>cm energy [TeV]</th>
<th>integrated luminosity [fb⁻¹]</th>
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<td>ATLAS, CMS</td>
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