Outline:
- Introduction
- Quantum ChromoDynamics (QCD)
- Jet algorithms
- Tests of QCD
  - jet substructure
  - physics beyond the SM
- QCD analyses at HERA
Jet substructure
The investigation of the internal structure of jets gives insight into the transition between a parton produced in a hard process and the experimentally observable jet of hadrons.

**QCD predictions:**

- Jet substructure driven by gluon emission off primary partons (at sufficiently high $E_T^{jet}$, fragmentation effects negligible)
- Gluon jets are broader than quark jets (larger colour charge of the gluon)
- Jet substructure depends mainly on flavour of primary parton from which the jet originated and to a lesser extent on the hard scattering process.
Jet substructure: integrated jet shape

- $\psi(r)$: fraction of the jet transverse energy that lies inside a cone in the $\eta - \phi$ plane of radius $r$, concentric with the jet axis

$$
\psi(r) = \frac{E_T(r)}{E_T^{\text{jet}}}
$$

$$
\langle \psi(r) \rangle = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{E_T(r)}{E_T^{\text{jet}}}
$$

(mean integrated jet shape)

Jet substructure: subjjet multiplicity

- subjets: are resolved within a jet by reapplying the $k_T$ cluster algorithm until for every pair of particles $i, j$

$$
d_{ij} = \min(E_{Ti}, E_{Tj})^2[(\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2]
$$

is above $y_{\text{cut}} \cdot (E_T^{\text{jet}})^2$

$$
\langle n_{\text{sbj}}(y_{\text{cut}}) \rangle = \frac{1}{N_{\text{jets}}} \sum_{i=1}^{N_{\text{jets}}} n_{\text{sbj}}^i(y_{\text{cut}})
$$

(mean subjjet multiplicity)
QCD calculations of jet substructure

- **QCD-based Monte Carlo models:**
  - Pythia, Herwig, Ariadne, Lepto approximate the substructure of jets with parton showers

- **Fixed-order QCD calculations:**
  - at lowest order, a jet consists of one parton (no structure)
  - higher-order terms give the non-trivial contributions
  - NLO calculations in NC DIS are possible in LAB frame from $\mathcal{O}(\alpha_s^2)$ predictions since three partons can be inside one jet

- **Measurements of jet substructure provide a stringent test of pQCD calculations directly beyond LO**

- **pQCD calculations of jet shapes:**
  
  $$
  \langle 1 - \psi(r) \rangle = \frac{\int_{-1}^{1} dE_T \left( E_T / E_{\text{jet}}^0 \right) [d\sigma(ep \rightarrow 2 \text{partons})/dE_T]}{\sigma_{\text{jet}}(E_{\text{jet}}^0)}
  $$

- **pQCD calculations of subjet multiplicities:**
  
  $$
  \langle n_{\text{sbj}}(y_{\text{cut}}) \rangle = 1 + \frac{1}{\sigma_{\text{jet}}} \sum_{j=2}^{\infty} (j - 1) \cdot \sigma_{\text{sbj,j}}(y_{\text{cut}}) = 1 + C_1 \alpha_s + C_2 \alpha_s^2
  $$
Tests of pQCD using jet substructure at HERA

- Jet production in photoproduction up to $O(\alpha_s)$:

  \[ x^{obs}_\gamma = \frac{1}{E_\gamma} \left( \sum \text{jets} \ E_{T}^{\text{jet}} e^{-\eta^{\text{jet}}} \right) \]

  - Resolved processes give rise to quark and gluon jets through $q\gamma g_p \rightarrow qg, g\gamma g_p \rightarrow gg, \ldots$
  - Direct processes give rise mostly to quark jets through $\gamma g \rightarrow q\bar{q}$
  - $\eta^{\text{jet}}$ dependence of jet substructure expected to show quark-like jets for $\eta^{\text{jet}} < 0$ and gluon-like jets in forward direction due to HERA dynamics
Tests of pQCD using jet substructure at HERA

- Jet production in neutral and charged current deep inelastic $ep$ scattering up to $\mathcal{O}(\alpha_s)$:

  - Inclusive-jet sample expected to be dominated by quark jets
    - no dependence of jet substructure on $\eta_{\text{jet}}$ expected
  - Dijet sample expected to contain a larger fraction of gluon jets
    - jets expected to become broader as $\eta_{\text{jet}}$ increases
**Mean integrated jet shape in photoproduction**

- $\eta^{\text{jet}}$ dependence of $\langle \psi(r) \rangle$ in photoproduction
  - Jets searched using the cone algorithm
  - Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 4 \text{ GeV}^2$
  - At least one jet with $E_T^{\text{jet}} > 14 \text{ GeV}$ and $-1 < \eta^{\text{jet}} < 2$

- $\langle \psi(r) \rangle$ vs $r$ in different $\eta^{\text{jet}}$ regions:
  - Jets become broader as $\eta^{\text{jet}}$ increases

- Comparison to QCD predictions:
  - Models with only fragmentation predict jets too narrow
  - Models including initial- and final-state QCD radiation give a good description of the data for $-1 < \eta^{\text{jet}} < 1$
  - Parton radiation dominant mechanism responsible for jet shape
Mean integrated jet shape in photoproduction

- $\eta^{\text{jet}}$ dependence of $\langle \psi(r) \rangle$ in photoproduction
  - Jets searched using the cone algorithm
  - Kinematic region: $0.2 < y < 0.85$ and $Q^2 < 4 \text{ GeV}^2$
  - At least one jet with $E_T^{\text{jet}} > 14 \text{ GeV}$ and $-1 < \eta^{\text{jet}} < 2$

- $\langle \psi(r) \rangle$ vs $r$ in different $\eta^{\text{jet}}$ regions:
  - Jets become broader as $\eta^{\text{jet}}$ increases

- Comparison to QCD predictions:
  - Predictions for gluon and quark jets show that the measured jets are
    - quark-like for $-1 < \eta^{\text{jet}} < 0$
    - gluon-like for $1 < \eta^{\text{jet}} < 2$
Mean integrated jet shape in photoproduction

- $\eta^{\text{jet}}$ and $E_T^{\text{jet}}$ dependence of $\langle \psi (r = 0.5) \rangle$ in photoproduction
  - Jets searched using the $k_T$ cluster algorithm
  - Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 1$ GeV$^2$
  - At least one jet with $E_T^{\text{jet}} > 17$ GeV and $-1 < \eta^{\text{jet}} < 2.5$

- The measured $\langle \psi (r = 0.5) \rangle$ decreases with $\eta^{\text{jet}}$
  → the jets become broader as $\eta^{\text{jet}}$ increases

- The measured $\langle \psi (r = 0.5) \rangle$ increases with $E_T^{\text{jet}}$
  → the jets become narrower as $E_T^{\text{jet}}$ increases

- Comparison with the predictions for gluon and quark jets:
  → the broadening of the jets is consistent with an increasing fraction of gluon jets as $\eta^{\text{jet}}$ increases
Mean integrated jet shape in photoproduction

- $x_\gamma^{\text{obs}}$ and $\eta^{\text{jet}}$ dependence of $\langle \psi(r) \rangle$ in photoproduction
  - Jets searched using the $k_T$ cluster algorithm
  - Kinematic region: $0.2 < y < 0.8$ and $Q^2 \leq 1 \text{ GeV}^2$
  - At least two jets with $E_T^{\text{jet}} > 7, 6 \text{ GeV}$ and $-0.75 < \eta^{\text{jet}} < 1.5$

- $\langle \psi(r) \rangle$ vs $r$ in different $x_\gamma^{\text{obs}}$ regions:
  - Jets for $x_\gamma^{\text{obs}} \leq 0.75$ are broader than for $x_\gamma^{\text{obs}} > 0.75$

- $\langle \psi(r = 0.5) \rangle$ decreases with $\eta^{\text{jet}}$
  - Jets become broader as $\eta^{\text{jet}}$ increases

- $\langle \psi(r = 0.5) \rangle$ increases with $x_\gamma^{\text{obs}}$
  - Jets become narrower as $x_\gamma^{\text{obs}}$ increases

- Comparison to QCD predictions for resolved and direct:
  - Good description of data by predictions
  - Data consistent with being dominated by resolved for $x_\gamma^{\text{obs}} \leq 0.75$ and by direct for $x_\gamma^{\text{obs}} > 0.75$
Mean integrated jet shape in NC DIS

- $r$, $\eta_B^{\text{jet}}$ and $E_{T,B}^{\text{jet}}$ dependence of $\langle \psi(r) \rangle$ in NC DIS;
  - Jets searched using the $k_T$ cluster algorithm in Breit frame;
  - Kinematic region: $10 < Q^2 < 120 \text{ GeV}^2$;
  - At least two jets with $E_{T,B}^{\text{jet}} > 5 \text{ GeV}$ and $-1 < \eta_{LAB}^\text{jet} < 2$.

- The measured $\langle \psi(r=0.5) \rangle$ decreases with $\eta_B^{\text{jet}}$;
  - The jets become broader towards proton direction;
  - Effect more pronounced at low $E_{T,B}^{\text{jet}}$.

- The measured $\langle \psi(r=0.5) \rangle$ increases with $E_{T,B}^{\text{jet}}$;
  - The jets become narrower as $E_{T,B}^{\text{jet}}$ increases.

- Comparison to QCD predictions:
  - The data are well described by the QCD-based MC models;
  - MC models predict jet sample dominated by quark-initiated jets;
  - Observed jet substructure compatible with that of quark-initiated jets.

\[ r, \eta_B^{\text{jet}} \text{ and } E_{T,B}^{\text{jet}} \text{ dependence of } \langle \psi(r) \rangle \text{ in NC DIS} \]
Mean integrated jet shape in NC DIS

- \( \eta^{\text{jet}} \) dependence of \( \langle \psi(r) \rangle \) in NC DIS
  - Jets searched using the \( k_T \) cluster algorithm in LAB frame
  - Kinematic region: \( Q^2 > 125 \text{ GeV}^2 \)
  - At least one jet with \( E_T^{\text{jet}} > 17 \text{ GeV} \) and\(-1 < \eta^{\text{jet}} < 2.5\)

- \( \langle \psi(r) \rangle \) vs \( r \) in different \( \eta^{\text{jet}} \) regions:
  - no significant variation with \( \eta^{\text{jet}} \) is observed

- Comparison to QCD predictions:
  - NLO predictions in NC DIS are possible in LAB frame from \( O(\alpha_S^2) \) calculations since three partons can be inside one jet

- the data are well described by the NLO QCD calculations for \( r > 0.1 \)
Mean integrated jet shape in NC DIS

- $E_T^{\text{jet}}$ dependence of $\langle \psi(r) \rangle$ in NC DIS
  - Jets searched using the $k_T$ cluster algorithm in LAB frame
  - Kinematic region: $Q^2 > 125 \text{ GeV}^2$
  - At least one jet with $E_T^{\text{jet}} > 17 \text{ GeV}$ and $-1 < \eta^{\text{jet}} < 2.5$

- $\langle \psi(r) \rangle$ vs $r$ in different $E_T^{\text{jet}}$ regions:
  - the jets become narrower as $E_T^{\text{jet}}$ increases

- Comparison to QCD predictions:
  - NLO predictions in NC DIS are possible in LAB frame from $\mathcal{O}(\alpha_s^2)$ calculations since three partons can be inside one jet

$\rightarrow$ the data are well described by the NLO QCD calculations for $r > 0.1$
Mean integrated jet shape in NC DIS

- $\eta^{\text{jet}}$ and $E_T^{\text{jet}}$ dependence of $\langle \psi(r = 0.5) \rangle$ in NC DIS
  - Jets searched using the $k_T$ cluster algorithm in LAB frame
  - Kinematic region: $Q^2 > 125 \text{ GeV}^2$
  - At least one jet with $E_T^{\text{jet}} > 17 \text{ GeV}$ and $-1 < \eta^{\text{jet}} < 2.5$

- The measured $\langle \psi(r = 0.5) \rangle$ shows no significant variation with $\eta^{\text{jet}}$

- The measured $\langle \psi(r = 0.5) \rangle$ increases with $E_T^{\text{jet}}$ → the jets become narrower as $E_T^{\text{jet}}$ increases

- Comparison with NLO QCD calculations → the calculations provide a good description of the data and show sensitivity to the value of $\alpha_s(M_Z)$

- Observable sensitive to $\alpha_s(M_Z)$!
Mean subjet multiplicity in photoproduction and NC DIS

- \( y_{\text{cut}}, \eta^{\text{jet}} \) and \( E_T^{\text{jet}} \) dependence of \( \langle \psi(r=0.5) \rangle \) in photoproduction and NC DIS:
  
  → same conclusions as for the integrated jet shape

- **Observables sensitive to \( \alpha_s(M_Z) \)**!
**Jet properties in different hard scattering processes**

- **$r$ dependence:** jets in NC DIS are
  - narrower than in $\gamma p$ with $x_{\gamma}^{\text{obs}} < 0.75$ → resolved dominated by gluon jets
  - similar to $\gamma p$ with $x_{\gamma}^{\text{obs}} > 0.75$ → direct dominated by quark jets

- **$\eta^{\text{jet}}$ dependence:**
  - inclusive jets in $\gamma p$: the fraction of gluons increases as $\eta^{\text{jet}}$ increases
  - $\gamma p$ with $x_{\gamma}^{\text{obs}} > 0.75$ → mainly quarks
  - inclusive jets in DIS → no $\eta^{\text{jet}}$ dependence
Jet properties in different hard scattering processes

- $\eta^{\text{jet}}$ dependence:
  - DIS: no significant dependence
  - $\gamma p$: jets become broader as $\eta^{\text{jet}}$ increases

- Comparison with QCD:
  - DIS: consistent with being dominated by quark-initiated jets
  - $\gamma p$: broadening of data consistent with increase of fraction of gluon-initiated jets

- $E_T^{\text{jet}}$ dependence:
  - DIS and $\gamma p$: jets become narrower as $E_T^{\text{jet}}$ increases
Jet properties in different hard scattering processes

- $E_T^{\text{jet}}$ and $Q^2$ dependence of $\langle n_{\text{sbj}}(y_{\text{cut}} = 10^{-2}) \rangle$ in CC DIS
  - Jets searched using the $k_T$ cluster algorithm in LAB frame
  - Kinematic region: $Q^2 > 200$ GeV$^2$ and $y < 0.9$
  - At least one jet with $E_T^{\text{jet}} > 14$ GeV and $-1 < \eta^{\text{jet}} < 2$

- The measured $\langle n_{\text{sbj}}(y_{\text{cut}} = 10^{-2}) \rangle$ decreases with $E_T^{\text{jet}}$ or $Q^2$
  → jets get narrower as $E_T^{\text{jet}}$ or $Q^2$ increase

- Comparison with NLO QCD calculations
  → the calculations provide a good description of the data

- Comparison with NC DIS data
  → $E_T^{\text{jet}}$ dependence: $\langle n_{\text{sbj}} \rangle$ slightly larger in NC than in CC
  → $Q^2$ dependence of $\langle n_{\text{sbj}} \rangle$ similar in NC and CC
  → differences in $E_T^{\text{jet}}$ dependence can be attributed to different $Q^2$ spectra in NC and CC
Jet properties in different hard scattering processes

Jets in $ep$ and $e^+e^-$ are:

→ similar: jets in $ep$ and $e^+e^-$ come predominantly from quarks
→ pattern of QCD radiation within a quark jet is to a large extent independent of hard scattering process
→ narrower than those in $p\bar{p}$: jets in $p\bar{p}$ come predominantly from gluons
Identification of quark and gluon jets

- Charm photoproduction provides a handle to identify quark and gluon jets by selecting dijet events with one jet tagged as the charmed jet and measuring the substructure of the other ("untagged") jet in the event: enriched and unbiased sample of charm jets

- In photoproduction:
  - in direct processes, the "untagged" jet is also a charm quark
  - in resolved processes, there are several contributing processes:
    - gluon-gluon fusion ("untagged" jet: also charm)
    - charm-excitation processes ("untagged" jet: gluon or quark)
Substructure of quark and gluon jets

- $\langle \psi(r) \rangle$ in photoproduction with charm jets
  - Jets searched using the $k_T$ cluster algorithm
  - Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 1$ GeV$^2$
  - At least two jets with $E_{T}^{\text{jet}} > 7, 6$ GeV and $-1 < \eta^{\text{jet}} < 2$

- Subsample of dijet events with a $D^*\pm$ meson matched to one of the jets
- The other jet in the event (“untagged” charm jet) provides an enriched and unbiased sample of charm jets

→ Model predictions for charm jets and light-quark jets describe the data well
Characterization of the substructure of gluon jets:

- Extraction of $\mathcal{O}_{\text{gluon}}$ from $\mathcal{O}_{\text{dijet}} = f_q \cdot \mathcal{O}_{\text{quark}} + f_g \cdot \mathcal{O}_{\text{gluon}}$

  - $\mathcal{O}_{\text{dijet}}$ is the measured observable
  - $\mathcal{O}_{\text{quark}}$ is approximated by $\mathcal{O}_{\text{charm}}$
  - $f_q$ ($f_g = 1 - f_q$) is estimated using the MC models

Extraction of gluon properties for $E_T^{\text{jet}} > 15$ GeV

- Gluon jets are broader than quark jets

Model predictions for quark and gluon jets describe the measurements well
Substructure of quark and gluon jets

- $\langle \psi(r) \rangle$ in photoproduction with charm jets
  - Jets searched using the $k_T$ cluster algorithm
  - Kinematic region: $0.2 < y < 0.8$ and $Q^2 \leq 1$ GeV$^2$
  - At least two jets with $E_T^{\text{jet}} > 7, 6$ GeV and $-0.75 < \eta^{\text{jet}} < 1.5$

- Subsample of dijet events with a $\mu$ matched to one of the jets

- The other jet in the event ("untagged" charm jet) provides an enriched and unbiased sample of charm jets
  $\rightarrow$ purity of the tagged jet: 71 $-$ 73%

- The predictions of PYTHIA (including charm-excitation) describe the data well for $x_\gamma^{\text{obs}} > 0.75$

- Differences are observed for $x_\gamma^{\text{obs}} \leq 0.75$
  $\rightarrow$ the data suggest a smaller fraction of gluon jets at low $x_\gamma^{\text{obs}}$ than predicted by PYTHIA
Substructure of quark and gluon jets

- Differences between quark and gluon jets were investigated by exploiting the different type of parton content in the final state for one-jet and dijet events in NC DIS in LAB frame

- Jets searched using the $k_T$ cluster algorithm in LAB frame
- Kinematic region: $Q^2 > 125$ GeV$^2$
- At least one (two) jet(s) with $E_T^{\text{jet}} > 17$ GeV and $-1 < \eta^\text{jet} < 2.5$

→ In the dijet sample, the lowest-$E_T^{\text{jet}}$ jet is considered if distance jet-jet = $\sqrt{\Delta \eta^2 + \Delta \phi^2} \leq D = 2$

→ The lowest-$E_T^{\text{jet}}$ jet in the two-jet sample is broader than the one-jet sample consistent with a higher gluon content in dijet events, as predicted by pQCD
Identification of quark and gluon jets

- The Monte Carlo predictions of $\psi(r)$ for quark- and gluon-initiated jets show the expected differences.

- Statistical identification of quark and gluon jets assuming:

  - gluon jets ↔ “broad” jets
  - quark jets ↔ “narrow” jets

→ Samples enriched in gluon-like (“broad”) jets: $\psi(r = 0.3) < 0.6$

→ quark-like (“narrow”) jets: $\psi(r = 0.3) > 0.8$
Substructure dependence of jet cross sections

- $d\sigma/d\eta^\text{jet}$ for broad and narrow jets in photoproduction
  - Jets searched using the $k_T$ cluster algorithm
  - Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 1 \text{ GeV}^2$
  - At least one jet with $E_T^\text{jet} > 17 \text{ GeV}$ and $-1 < \eta^\text{jet} < 2.5$

- $d\sigma/d\eta^\text{jet}$ for "broad" and "narrow" jets show different shape

- Comparison with leading-logarithm parton shower MC calculations:
  * same jet-shape cuts as the data
  * MC area normalised to data
  → good description of the shape of the data

- Parton content of the final state from MC calculations of PYTHIA (HERWIG):
  → "broad" jets: $17(15)\% \, gg$, $58(54)\% \, gq$ and $25(31)\% \, qq$
  → "narrow" jets: $54(56)\% \, qq$, $41(41)\% \, qg$ and $5(3)\% \, gg
Substructure dependence of jet cross sections

- $\frac{d\sigma}{d|\cos \theta^*|}$ for samples of two “broad”-jet events and two “narrow”-jet events exhibit a different slope:
  - data and MC normalised to unity at $|\cos \theta^*| = 0.1$
  - $\frac{d\sigma}{d|\cos \theta^*|}$ at $|\cos \theta^*| = 0.7$ for “broad-broad” (“narrow-narrow”) events is more than seven (only two) times larger than at 0.1

- Comparison with MC:
  - same selection cuts as the data for “broad”/“narrow” sample
    - PYTHIA gives a reasonable description of the shape of the data

- Different slope understood in terms of the dominant two-body processes:
  - $qg \rightarrow qg$ (dominant in “broad-broad” sample) rises more steeply than $\gamma g \rightarrow q\bar{q}$ (dominant in “narrow-narrow” sample) due to different spin of exchanged particle
Substructure dependence of jet cross sections

- $d\sigma / d \cos \theta^*$ for a sample of events with one “broad” jet and one “narrow” jet measured wrt the “broad” jet shows different behaviour on the negative and positive sides:
  - * data and MC normalised to unity at $\cos \theta^* = 0.1$

  $\Rightarrow$ $d\sigma / d \cos \theta^*$ at 0.7 is $\approx$ two times larger than at $-0.7$

- **Comparison with MC:**
  - * same “broad-narrow” selection as for the data

  $\Rightarrow$ **PYTHIA** gives a reasonable description of the shape of the data

  $\Rightarrow$ Observed asymmetry understood in terms of the dominant resolved subprocess: $q\gamma g_p \rightarrow qg$

  $\Rightarrow$ The asymmetry is due to the different dominant diagrams for $\cos \theta^* \rightarrow \pm 1$:
  - * $t$—channel gluon exchange at $\cos \theta^* = +1$
  - * $u$—channel quark exchange at $\cos \theta^* = -1$
Pattern of parton radiation

- Subjet distributions can be used to study:
  - pattern of parton radiation from a primary parton
  - direct test of splitting functions $P_{ab}(z, \mu)$ and their scale dependence
  - colour coherence
  - soft gluon radiation tends to be emitted towards proton direction

- Measurements of normalised cross sections as functions of $E_{T}^{s\text{bj}} / E_{T}^{\text{jet}}, \eta^{s\text{bj}} - \eta^{\text{jet}}, |\phi^{s\text{bj}} - \phi^{\text{jet}}|$ and $\alpha^{s\text{bj}}$
  - and their dependence with $E_{T}^{\text{jet}}, Q^{2}$ and $x$
  - Jets searched using the $k_{T}$ cluster algorithm in LAB frame
  - Kinematic region: $Q^{2} > 125 \text{ GeV}^{2}$
  - At least one jet with $E_{T}^{\text{jet}} > 14 \text{ GeV}$ and $-1 < \eta^{\text{jet}} < 2.5$
  - Final sample: jets that have two subjets for $y_{\text{cut}} = 0.05$
Normalised subjet cross sections compared with NLO calculations:

- \( E_T^{\text{subj}} / E_T^{\text{jet}} \): the two subjets tend to have similar \( E_T^{\text{subj}} \)
- \( \eta^{\text{subj}} - \eta^{\text{jet}} \): asymmetric two-peak structure
- \( |\phi^{\text{subj}} - \phi^{\text{jet}}| \): suppression around 0 because the two subjets cannot be resolved when close
- \( \alpha^{\text{subj}} \): higher \( E_T^{\text{subj}} \) subjet tends to be in rear direction
  → consistent with asymmetric peaks of \( \eta^{\text{subj}} - \eta^{\text{jet}} \)
  → The NLO predictions, which contain these diagrams
describe the data adequately
Subjet distributions

- $\eta^{\text{subj}} - \eta^{\text{jet}}$ normalised cross section for $E_{T,\text{low}}^{\text{subj}}/E_T^{\text{jet}} < 0.4$

→ The higher (lower) $E_T^{\text{subj}}$ subjet tends to be in the rear (forward) direction
→ colour-coherence effects between the initial and final states
→ subjet with lower $E_T^{\text{subj}}$ emitted predominantly towards proton beam direction
Subjet distributions

- Comparison with predictions for quark- and gluon-induced processes

→ NLO prediction:
  81% of q-induced and 19% of g-induced

- Predictions for these two types of processes are different:
  - the two subjets in q-induced have more similar $E_{T}^{\text{subj}}$ and are closer to each other than in g-induced

→ The data are better described by the calculations for jets arising from the splitting of a quark into a quark-gluon pair
Physics beyond the Standard Model
Physics beyond the SM

- The SM presently provides an accurate description of all phenomena observed in particle physics.
- One of the fundamental features of SM is that neutral currents are flavour diagonal.
- Flavour-changing neutral current (FCNC) transitions are suppressed at lowest order by the GIM mechanism and they occur only at second or higher orders through loops → very small rates of FCNC in SM.
- Observables sensitive to FCNC probe directly physics beyond SM since many extensions give rise to enhanced rates of FCNC.
- The GIM mechanism explained in 1970 the suppression of $s \leftrightarrow d$ transitions by postulating the existence of the charm quark.
- The presence of the charm quark was inferred from its effect on the very low value of $Br(K_L^0 \rightarrow \mu^+\mu^-) \sim 10^{-9}$, which is mediated by neutral current exchange, whereas the charged current decay $K^+ \rightarrow \mu^+\nu_\mu$ is $\sim 60\%$.
- The same GIM mechanism applied to $b \leftrightarrow s$ transitions predicted the existence of the top quark.
Flavour-changing neutral currents

- A suitable reaction to search for new physics involves a top quark since FCNC transitions of the type $tqV$ ($q = u, c$, $V = \gamma, Z$) are very small in the SM.
- Besides, the top quark is the only known fermion with a mass close to the EWSB scale → unusual decays might provide insight into the mechanism of EWSB.
- Manifestations of new physics (SUSY, extended Higgs sector, new fermion families, dynamical mass generation mechanism) in the top sector would alter its couplings to gauge bosons.
- Such anomalous couplings would modify top production and decay rates and affect loop-induced processes → any observation of FCNC transitions involving the top quark would unambiguously signal the presence of new physics.

- FCNC can be probed in:
  - top decays (Tevatron, $p\bar{p} \rightarrow t\bar{t} \rightarrow qV$);
    - SM rates → $Br(t \rightarrow qV) \sim 10^{-13}$
  - single-top with associated light quark production (LEP, $e^+e^- \rightarrow V \rightarrow tq$);
    - SM rates → $\sigma(e^+e^- \rightarrow tq) \sim 10^{-9}$ fb
  - single-top production (HERA, $ep \rightarrow et$ via $t$-channel $V$ exchange);
    - SM rates → $\sigma(ep \rightarrow \nu t\bar{b}) < 1$ fb
Flavour-changing neutral current transitions in the top sector

- Deviations from the SM due to FCNC transitions involving the top quark can be parametrised in terms of couplings of the type $tqV$, $\kappa_{tq\gamma}$ and $\nu_{tqZ}$, and described by a linear effective Lagrangian which contains operators in an expansion series in powers of $1/\Lambda$ ($\Lambda$: scale characteristic of new interactions)

- The FCNC Lagrangian has the form

$$\mathcal{L}_{\text{FCNC}} = e e_t t \frac{i\sigma_{\mu\nu}q^\nu}{\Lambda} \kappa_{tq\gamma} q A^\mu + \frac{g}{2 \cos \theta_W} \bar{t} \gamma_\mu \nu_{tqZ} q Z^\mu + \text{h.c.}$$

where $e$ ($e_t$) is the electron (top-quark) electric charge, $g$ is the weak coupling constant, $\theta_W$ is the weak mixing angle, $\sigma_{\mu\nu} = \frac{1}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$, $\Lambda$ is set to the top mass (by convention), $q^\nu$ is the momentum of the gauge boson and $A^\mu$ ($Z^\mu$) is the $\gamma$ ($Z$) field

- The magnetic $\kappa_{tq\gamma}$ and vector $\nu_{tqZ}$ couplings define the strength of the anomalous vertices

- $\kappa_{tq\gamma}$ and $\nu_{tqZ}$ are zero at tree level and extremely small at the one-loop level in the SM
Search for FCNC decays of the top quark at the Tevatron

- **CDF analysis:** $\sqrt{s} = 1.8$ TeV; $\mathcal{L} = 110$ pb$^{-1}$
- **Search for FCNC top decays:** $t \rightarrow qV$, $q = u, c$ and $V = \gamma, Z$
- **If the branching fraction of the top into a FCNC decay is $x$, the branching fraction into $Wb$ can be no larger than $(1 - x)$**
  - The ratio $r$ of the number of events detected in a FCNC decay normalised to the $Wb$ decay mode is at least $x/(1 - x)$
  - The measurement of $r$ allows the calculation of an upper limit on the branching fraction $x \leq r/(1 + r)$
- **The normalisation sample consisted of events identified as**
  \[ p\bar{p} \rightarrow t\bar{t} \rightarrow Wb \ Wb \rightarrow l\nu b \ q\bar{q}b \]
  - these events should have a high-$p_T$ $e$ or $\mu$, large missing transverse momentum from the $\nu$ and three or more jets, one of which should be "$b$-tagged"
  - 34 $t\bar{t}$ candidates were found with an estimated background of $9 \pm 1.5$ events
Search for FCNC decays of the top quark at the Tevatron

- The FCNC $t \rightarrow q\gamma$ sample consisted of events identified as
  \[ p\bar{p} \rightarrow t\bar{t} \rightarrow Wb \, q\gamma \rightarrow l\nu \, (q\bar{q'}) \, b \, q\gamma \]
  → these events should have a high-$E_T$ photon and either
  * a high-$p_T$ lepton, large missing transverse momentum and at least two jets (leptonic decay of $W$, $W \rightarrow l\nu$) or
  * at least four jets, one of them “$b$-tagged” (hadronic decay of $W$, $W \rightarrow q\bar{q'}$)
  in both cases, there must be a photon and jet combination with a mass consistent with $M_{top}$

- The background in the leptonic mode is dominated by $W + \gamma + 2$ or more jet events → estimated to be less than half an event
- The background in the hadronic mode is dominated by QCD multi-jet events → estimated to be less than half an event
- To set conservative limits, any event passing the selection requirements was assumed to be signal and no background subtraction was performed
- In 110 pb$^{-1}$ of data, one event is observed in the leptonic channel and no event is observed in the hadronic channel
- Observation of one event implies a 95% CL of fewer than 6.45 events
  \[ Br(t \rightarrow c\gamma) + Br(t \rightarrow u\gamma) < 3.2\% \text{ at 95\% CL} \]
Search for FCNC decays of the top quark at the Tevatron

- The FCNC $t \rightarrow qZ$ sample consisted of events identified as
  \[
  p\bar{p} \rightarrow t\bar{t} \rightarrow Wb qZ \rightarrow q\bar{q}' b q l^+l^-
  \]
  - these events should have at least four jets and two leptons with an invariant mass consistent with $M_Z$

- The background consists of
  - $Z +$ multijet production: 0.5 events are expected from $Z + 4$ jet production
  - $tt\rightarrow WbWb$ events with a topology similar to the signal (both $W$ decay leptonically, the two leptons have an invariant mass within the $Z$ candidate range, and there are two jets produced via gluon radiation): 0.6 events
  - diboson ($WZ$ or $ZZ$) +2 or more jets in which the $Z$ decays leptonically: 0.1 events are expected

- To set conservative limits, any event passing the selection requirements was assumed to be signal and no background subtraction was performed

- In 108 pb$^{-1}$ of data, one event is observed in the $Z \rightarrow \mu^+\mu^-$ channel

- Observation of one event implies a 95% CL of fewer than 6.4 events
  \[
  Br(t \rightarrow cZ) + Br(t \rightarrow uZ) < 33\% \text{ at 95\% CL}
  \]
The expressions for the widths are

$$\Gamma(t \rightarrow q\gamma) = \kappa_{tq\gamma}^2 \frac{\alpha e_t^2}{2} \left( \frac{M_{top}^2}{\Lambda^2} \right) M_{top}$$

$$\Gamma(t \rightarrow qZ) = v_{tqZ}^2 \frac{\alpha}{4 \sin^2 2\theta_W M_Z^2} M_{top}^3 \left( 1 - \frac{M_Z^2}{M_{top}^2} \right)^2 \left( 1 + 2 \frac{M_Z^2}{M_{top}^2} \right)$$

Then,

- $M_{top} (\text{GeV}) = 175$
- $\kappa_{tq\gamma} < 0.42$
- $v_{tqZ} < 0.73$
- $Br(t \rightarrow \gamma q) < 3.2\%$
- $Br(t \rightarrow Z q) < 33.0\%$

CDF exclusion region

Excluded by CDF ($M_{top} = 175$ GeV)
Search for single-top production at LEP

- **L3 analysis:** $\sqrt{s} = 189 - 209$ GeV; $\mathcal{L} = 634$ pb$^{-1}$
- **Search for single-top with associated light-quark production:**
  
  \[ e^+ e^- \rightarrow V \rightarrow t\bar{q}, \bar{q} = \bar{c} \text{ and } V = \gamma, Z \]
- The top quark is produced almost at rest at LEP energies and quickly decays via $t \rightarrow Wb$ without forming top-flavoured hadrons
- The signal is searched for in both the leptonic ($l\nu$) and hadronic ($qq'$) channels of $W$ decay
- The $c$-quark energy, $E_c$, has a fixed value for a given $\sqrt{s}$:
  \[ \rightarrow E_c = \frac{\sqrt{s}}{2} \left( 1 - \frac{M_{\text{top}}^2}{s} \right) \]
- The $b$-quark energy, $E_b$, has an almost fixed value which does not depend on $\sqrt{s}$ in the limit of a $t$-quark at rest in the cms:
  \[ \rightarrow E_b \sim \frac{M_{\text{top}}}{2} \left( 1 - \frac{M_W^2}{M_{\text{top}}^2} \right) \]
Search for single-top production at LEP

- The sample of leptonic channel of $W$ decay consisted of events identified as
  \[ e^+e^- \rightarrow t\bar{c} \rightarrow Wb\bar{c} \rightarrow l\nu b\bar{c} \]
  these events should have one energetic lepton, large missing momentum from the neutrino and two jets with a large difference in energy; the most energetic jet was assumed to be the $b$-quark; a “$b$-tag” was required

- The main background processes are $e^+e^- \rightarrow W^+W^-$ and $e^+e^- \rightarrow q\bar{q}(\gamma)$

- In 634 pb$^{-1}$ of data, 346 events are observed whereas 357.0 $\pm$ 1.8 SM background events are expected

- The efficiency of the signal is $\epsilon = 10.6\%$

- Signal and SM events have very different shapes

- SM processes give a good description of the data → no excess observed

- Final selection proceeded using a neural network
The sample of hadronic channel of $W$ decay consisted of events identified as

$$e^+e^- \rightarrow t\bar{c} \rightarrow Wb\bar{c} \rightarrow q\bar{q}'b\bar{c}$$

these events should have four jets, two of which must have an almost fixed energy (the $b$- and $c$-quark jets), and the remaining two jets must have an invariant mass consistent with $M_W$; a “$b$-tag” was required.

The main background processes are $e^+e^- \rightarrow W^+W^-$ and $e^+e^- \rightarrow q\bar{q}(\gamma)$.

In $634\text{ pb}^{-1}$ of data, 321 events are observed whereas $287.9 \pm 1.6\text{ SM}$ background events are expected.

The efficiency of the signal is $\epsilon = 21.1\%$.

Signal and SM events have very different shapes.

SM processes give a good description of the data → no significant excess observed.

Final selection proceeded using a neural network.
Search for single-top production at LEP

- The final discrimination variable from the neural network gives a good discrimination between signal and background

[Graphs showing data and signal distributions for leptonic and hadronic channels]

- No deviation from the SM is observed $\rightarrow$ 95% CL upper limits on single-top total cross section for $e^+e^- \rightarrow t\bar{c}$ are derived assuming $Br(t \rightarrow Wb) = 100%$
  
  $\rightarrow \sigma(M_{top} = 170 \text{ GeV}) < 0.36 - 0.87 \text{ pb}$
  $\sigma(M_{top} = 175 \text{ GeV}) < 0.22 - 0.73 \text{ pb}$
  $\sigma(M_{top} = 180 \text{ GeV}) < 0.21 - 0.75 \text{ pb}$
The Born-level cross section for single-top production in the presence of anomalous couplings is given by

$$\sigma = \frac{\pi\alpha^2}{s} (1 - \frac{M_{\text{top}}^2}{s})^2 \left[ \frac{2\kappa_{tq\gamma}e_t^2s}{M_{\text{top}}^2}(1 + \frac{2M_{\text{top}}^2}{s}) + \frac{v_{tqZ}^2(1 + a^2_W)(2 + \frac{M_{\text{top}}^2}{s})}{2S^2_W(1 - \frac{M^2_{Z^0}}{s})^2} \right]$$

Limits on the anomalous couplings are computed taking into account QCD and ISR and the FCNC decays of the top:

- $M_{\text{top}}$ (GeV) < 170, 175, 180
- $\kappa_{tq\gamma}$ < 0.43, 0.43, 0.49
- $v_{tqZ}$ < 0.38, 0.37, 0.43
- $\text{Br}(t \rightarrow \gamma q)$ (%) < 4.4, 4.1, 4.9
- $\text{Br}(t \rightarrow Z q)$ (%) < 13.6, 13.7, 17.0

Improved limit for $v_{tqZ}$ from $e^+e^- \rightarrow tq$
Search for single-top production at HERA

- **ZEUS analysis:** $\sqrt{s} = 300 \text{ and } 318 \text{ GeV}; \mathcal{L} = 130 \text{ pb}^{-1}$
- **Search for single-top production:**
  $$ep \rightarrow etX \text{ via } t\text{-channel } \gamma \text{ or } Z \text{ exchange}$$
- The FCNC couplings, $tqV$, would induce the NC reaction
  $$ep \rightarrow etX,$$ in which the incoming $e$ exchanges a $\gamma$ or $Z$ with an up-type quark in the proton, yielding a top quark in the final state.
- Due to the large $Z$ mass, this process is most sensitive to a coupling of the type $tq\gamma$
- Since large values of $x$ are needed to produce a top and the $u$-quark proton PDF dominates at large $x$, the production of single top would proceed via a coupling of the type $tu\gamma$ at HERA.
- Single-top production is predicted to proceed predominantly through the exchange of a quasi-real photon (photoproduction) between the $e$ and a valence $u$ quark in the proton.
- The top quark was assumed to decay $100\%$ to $Wb$ and the signal was searched for in both the leptonic ($l\nu$) and hadronic $(q\bar{q}')$ channels of $W$ decay.
Search for single-top production at HERA

- The sample of leptonic channel of $W$ decay consisted of events identified as
  \[ ep \rightarrow etX \rightarrow eWbX \rightarrow el\nu bX \]
  
  these events should have an isolated high-energy lepton, significant missing transverse momentum arising from the emitted neutrino and a jet stemming from the $b$-quark decay; the scattered $e$ goes down the beam pipe in most of the events.

- The main background processes are DIS and single-$W$ production.

- Signal and SM events have different shapes.

- SM processes give a good description of the data \(\rightarrow\) no excess observed.

- In 130 pb\(^{-1}\) of data, no event is observed after final selection whereas \(1.89^{+0.14}_{-0.10}\) SM events are expected.

- The efficiency of the signal is \(\epsilon = 7\%\).
Search for single-top production at HERA

- The sample of hadronic channel of $W$ decay consisted of events identified as

$$ep \rightarrow etX \rightarrow eWbX \rightarrow eqq'bX$$

- these events should have three jets in the final state with a dijet invariant mass for the correct pair of jets consistent with $M_W$ and a three-jet invariant mass consistent with $M_{top}$

- The main background process is multi-jet QCD production

- Signal and SM events have different shapes

- SM processes give a good description of the data → no excess observed

- In 127 pb$^{-1}$ of data, 14 events are observed after final selection whereas $17.6^{+1.7}_{-1.1}$ SM events are expected

- The efficiency of the signal is $\epsilon = 16.5\%$
Search for single-top production at HERA

- **Final selection**

![Graphs showing event distributions for different mass ranges.](image)

(leptonic channel: no events)

- **No deviation from the SM is observed** → **95% CL upper limits on single-top total cross section** for $ep \rightarrow etX$ are derived

$\rightarrow \sigma(M_{top} = 170 \text{ GeV, } \sqrt{s} = 318 \text{ GeV}) < 0.230 \text{ pb}$

$\sigma(M_{top} = 175 \text{ GeV, } \sqrt{s} = 318 \text{ GeV}) < 0.225 \text{ pb}$

$\sigma(M_{top} = 180 \text{ GeV, } \sqrt{s} = 318 \text{ GeV}) < 0.265 \text{ pb}$
The Born-level cross section for single-top production in the presence of anomalous couplings is given for $\gamma$ exchange by

$$
\frac{d\sigma_{eu\rightarrow et}}{dt\, du} = \frac{\kappa_{tu\gamma}^2 e^4 e_t^2}{8\pi M_{\text{top}}^2 t^2(s - M_e^2)^2} \left\{ -t \left[ 2M_e^4 + M_{\text{top}}^4 - 2s^2 + (2s + t) \right. \times \left(2s - M_{\text{top}}^2 - 2M_e^2\right) \right. \\
\left. \left. - 2M_e^2 M_{\text{top}}^4 \right\} \delta(s_2) \right. 
$$

Limits on the anomalous couplings are computed taking into account QCD corrections and the FCNC decays of the top.

- $M_{\text{top}}$ (GeV): 170, 175, 180
- $\kappa_{tq\gamma} < 0.158, 0.174, 0.210$
- $Br(t \rightarrow \gamma q) (%) < 0.52, 0.59, 0.80$

- Much improved limit for $\kappa_{tu\gamma}$ from $ep \rightarrow etX$
An improved limit on $v_{tuZ}$ has been obtained by using

- a signal simulation which includes also $Z^0$ exchange
- a full simulation of the FCNC process, considering the anomalous $tuZ$ and $tu\gamma$ couplings ($v_{tuZ}$, $\kappa_{tu\gamma}$) both in the top production and decay

This allowed the exclusion limits in the $\kappa_{tu\gamma} - v_{tuZ}$ plane to be improved at large values of $v_{tuZ}$ (though still not as good as the limit from LEP)