QCD Physics
Potential of CMS

On behalf of the CMS Collaboration
Klaus Rabbertz
University of Karlsruhe
Outline

- What is QCD?
- Tracks and Hadrons
- Jets
- Photons
- Summary
What is QCD?
What is QCD?

First of all … it is 98% of us (our mass) as we have heard yesterday from Raphael! So we should better know it.

**In Formulae:**

\[
\mathcal{L} = -\frac{1}{4} F^A_{\alpha\beta} F^{\alpha\beta}_A + \sum_{\text{flavours}} \bar{q}_a (i\not{D} - m)_{ab} q_b + \mathcal{L}_{\text{gauge-fixing}}
\]

**In Words:**

- QCD is the theory of the strong interaction, one of the four fundamental forces of nature, describing especially
  - the hard interactions between the coloured quarks and gluons
  - but also how they bind together to form hadrons.
What is QCD?

From a distance:
- Initial State Radiation
- Hadronization
- Final State Radiation
- PDF, Proton structure
- Decay
- Hard Process (ME)
- Not shown for simplicity:
  - Beam Remnants
  - Multiple Interactions
  - FSR off the hard partons
What is QCD?

Zoomed in:

High $P_T$ Jet Production

- Initial-State Radiation
- Underlying Event
- Multiple Parton Interaction
- Final-State Radiation
- Outgoing Parton

Initial- & Final-State Radiation

Outgoing Parton (or photon)

$PT(hard)$

$à$ la R. Field

Proton

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Isfahan, Iran, 24.04.2009
1st IPM Meeting on LHC Physics
CMS QCD Group:

- **Everything** … not excluded:
  - New particles, exotics, SUSY (Higgs, Exotica, SUSY)
  - Weak bosons (EWK)
  - Heaviest quarks (Top, B Physics)
  - Very forward topology (Forward Physics)
  - Colliding hadrons other than protons (Heavy Ions)

- **Three subdivisions:**
  - Low $p_T$ measurements (tracker, hadrons)
  - High $p_T$ measurements (calorimeter, jets)
  - Measurements with photons (ECAL, photons)

- **Plus common efforts** (PDFs, ...)
QCD at Startup

Still enough events/sec left 😊

- **Startup with QCD:**
  - Not statistically limited
  - First measurements at multi TeV energy scale
  - Re-establishment of Standard Model, i.e. test extrapolations from Tevatron energies
  - Background to be understood for almost everything
  - Physics commissioning of CMS
  - But be prepared for surprises ...

![Graph showing the cross-section for different processes: σ_{jet}(E_T^{jet} > 100 \text{ GeV}), σ_b, σ_w, σ_z.](image)

- Events/s for $L = 10^{33}$ cm$^{-2}$ s$^{-1}$:
  - MinBias
  - Around 10 TeV
  - 14 TeV
First Observations

... just a bunch of hadrons!

- Charged particle rapidity density
- Charged hadron spectra
- Underlying event from transverse region

Track based analyses:

- $L_{\text{max}} \approx 2.10^{25} \text{cm}^{-2} \text{s}^{-1}$

Phys. Lett. Vol. 107B, no. 4

First UA1 Publication

$\sqrt{s} = 540 \text{ GeV}$

Recall:

SOME OBSERVATIONS ON THE FIRST EVENTS
SEEN AT THE CERN PROTON–ANTIPROTON COLLIDER

Average multiplicity of charged particles per unit of rapidity $|\eta| < 1.3$: $3.9 \pm 0.3$

(1 track min.)
Hadron Trigger at Startup

At low luminosity want to collect “ideal” data meaning exactly one collision per bunch crossing.

Regions of ideal data for different bunch patterns:
- **p+p - √s = 14TeV (σ = 79mb)**
- **Too many collisions per event**
- **Too many empty events with ZeroBias trigger**
- **Region not useful for ideal data**
- **Region for ZeroBias and triggered minimum bias ideal data**
- **ZeroBias MinBias**
- **Region for triggered minimum bias ideal data**

**Need trigger (Pythia):**
- 69% non-diffractive
- 18% single-diffractive
- 13% double-diffractive

**Possibilities:**
- single or double-sided HF Trigger Tower #
- others like PixelTracks under examination

**Efficiencies single:**
- 81% non-diffractive
- 15% single-diffractive
- 15% double-diffractive

**Double kills differ. events!**
Charged Particle Rapidity Density from Hits

**Strategy (used by Phobos at RHIC):**

- **No tracking**, just count clusters in the pixel barrel layers (4, 7 and 10 cm radii)
- Use cluster size to estimate z vertex and to remove hits at high $\eta$ from non-primary sources
- Correction for loopers, secondaries; systematic uncertainty expected below 10%

---

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**Isfahan, Iran, 24.04.2009**  
**1st IPM Meeting on LHC Physics**
**CMS Pixel Triplets**

**Expect:**
- ~ 2 million events assuming one month with 1 Hz allocated bandwidth

**Strategy:**
- Still “no” tracking, Pixel Triplets

**CMS pixel detector:**
- 3 barrel layers (4, 7 and 10 cm radii) and 2 end caps on each side
- 100 × 150 μm² pixels

**Hit triplets:**
- Use pixel hit triplets instead of pairs, loss of acceptance but lower fake rate
- Reconstructing down to $p_T = 0.075$ GeV
Simulation result from CMS:
- Charged particle pseudo-rapidity distribution
- Pythia tune DWT

CMS PAS QCD-07-001

Model expectations for charged particles at $|\eta| = 0$ vs. $\sqrt{s}$:
- Pythia: $\sim \ln^2(s)$
- Phojet: $\sim \ln(s)$

Will be able to differentiate

Assumes trigger efficiencies:
- SD $60\%$
- DD $70\%$
- ND $99\%$

Simulated tracks

8% syst.
Charged Hadron Spectra

Technique:
- Tracks from pixel triplet seeding
- Tracking down to $p_T$ of 75 MeV

Systematic:
- Trigger, feed-down, geom. acceptance, alg. efficiency

Events: ~ 2M
- One month with 1 Hz allocated bandwidth

CMS Preliminary simulation

14 TeV

CMS Preliminary simulation

14 TeV

CMS Preliminary simulation

14 TeV

CMS PAS QCD-07-001

Charged hadrons

Empirical fits

Pions

Protons

Limit in $p_T$ at $|y|<0.1$ for dE/dx differentiation

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**The Underlying Event**

The Underlying Event is everything but the hard scatter.

**High P_T Jet Production**

- **Initial-State Radiation**
- **PT(hard)**
- **Outgoing Parton**

**Measurement possibility:**
- Charged particle and $p_T$ sum densities in transverse region of leading jet of charged particles

**The Underlying Event** is everything but the hard scatter.

**Leading jet**
- ChgJet #1 Direction
- $\Delta \phi$
- "Toward"
- "Transverse"
- "Away"

**Balancing jet**
- "Toward" Region
- "Transverse" Region
- "Away" Region
The Underlying Event

Mix of contributing MinBias and calorimetric jet triggers

Decomposition of trigger contributions to charged particle density in $\Delta\Phi$ plane

14 TeV

14 TeV

CMS PAS QCD-07-003
The Underlying Event

Charged particle density in transverse plane vs. leading charged jet $p_T$

Extrapolation to LHC from CDF data

Comparison of different Pythia tunes

Tracks:
- $p_T > 900$ MeV
- $|\eta| < 2$

Statistics as for 100/pb

ATLAS

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14 TeV
The Underlying Event

Increase sensitivity with tracks from $p_T > 0.5$ GeV instead of $> 0.9$ GeV

Decrease systematic effects with ratio, but with similar systematic $\rightarrow 0.9 / 1.5$
Jets
Measured (or simulated) Event

- Add. Collisions
  - Minimum Bias (MB)
  - → Pile-up (PU)

- Multiple Parton Interactions
  - (MPI Models)

- Hard Interaction
  - ME (LO, NLO)

Parton Shower
- (perturbative QCD)
- + Hadronization
  - (non-pert. Model)

For Jets:
- “splash in”

Parton Shower
- (perturbative QCD)
- + Hadronization
  - (non-pert. Model)

For Jets:
- “splash out”

Hadronic Final State, colourless Particles
Experimental Picture

All jets in the event satisfying the selection criteria

$$\frac{d^2\sigma}{dp_T dy} = \frac{N_{jets}}{\epsilon \cdot L \cdot \Delta p_T \cdot \Delta y} \times C_{unsm}$$

Jet Efficiency
Event Efficiency

Bins of corrected Jet Pt and Jet rapidity

The JES dominates the total uncertainty of the measurement

Unsmearing correction (due to the finite detector Pt resolution)
**Generic Jet Analysis**

- **Requires:**
  - PDFs
  - LO & NLO MC
  - Det. simulation
  - Jet energy scale and resolution
  - Calorimeter calibration
  - Jet triggers
  - Luminosity
  - and ...
  - Data, of course!

```
LO MC Generators
  └─ Hard Partons
      ├─ PARTON SHOWER
      │   └─ Partonic Final State
      │       └─ HADRONIZATION, DECAYS
      │           └─ Hadronic Final State
      │               └─ JET CALIBRATION
      │                   └─ Uncalibrated Jets
      │                           └─ RECONSTRUCTION
      │                                └─ Calorimeter Jets
      │                                           └─ MC CORRECTIONS
      └─ NLO Calculation
          └─ Corrected Jets
```

Jet Analysis Uncertainties

Theoretical Uncertainties (~ in order of importance):
- PDF Uncertainty
- pQCD (Scale) Uncertainty
- Non-perturbative Corrections
- PDF Parameterization
- Electroweak Corrections
- Knowledge of $\alpha_s(M_Z)$
- ...

Experimental Uncertainties (~ in order of importance):
- Jet Energy Scale (JES)
- Noise Treatment
- Pile-Up Treatment
- Luminosity
- Jet Energy Resolution (JER)
- Trigger Efficiencies
- Resolution in Rapidity
- Resolution in Azimuth
- Non-Collision Background
- ...

Recall: Jet Algorithms used by CMS:
- Iterative Cone $R = 0.5$
- SISCone $R = 0.5, 0.7$
- $k_T$ $D = 0.4, 0.6$
Jet analyses at high transverse momenta:
- Dijet azimuthal decorrelation
  - Less sensitive to JES, not dependent on luminosity
- Event shapes
  - Reduced sensitivity to JES & JER, not dependent on luminosity
- Dijet production ratios & angles
  - Reduced sensitivity to JES, not dependent on luminosity
- Jet cross section ratios (3-jet / all, R=0.7 / R=0.5, SISCon / kT)
  - Reduced sensitivity to JES, not dependent on luminosity
- Jet shapes
- Multi-jet studies
- Inclusive jet cross section
  - Most complicated, requires all uncertainties to be under control!
Inclusive Jets at the Tevatron

CDF Incl. $k_T$ jets, $D=0.7$
Theory: NLO with CTEQ6.1M

D0 Incl. MidPoint cone jets, $R=0.7$
Theory: NLO with CTEQ6.5M
Inclusive Jets at the LHC

\[ k_T, D=0.6, 10 \text{ TeV} \]

\[ \text{SISCones, } R=0.7, 10 \text{ TeV} \]

Log Scale

LHC reach > 2 x 600 GeV with 10/pb

Tevatron limit 600 GeV

Bands are PDF uncertainties from CTEQ6.5

fastNLO, hep-ph/0609285
Cross Section Ratios

Cross section ratios in 6 bins in rapidity $y$

**SISCones 0.7 / $k_T$ 0.6 @ 10 TeV**

- About 14 – 8% higher cross section than $k_T$

**$k_T$ 0.6 10 TeV / 14 TeV**

- Change pre-scales
- Loss in $p_T$ reach
"The data are compared with QCD predictions for various sets of parton distribution functions. The cross section for jets with $E_T > 200$ GeV is significantly higher than current predictions based on $O(\alpha_S^3)$ perturbative QCD calculations. ..."

Explained by change in gluon density which then can be constrained by jets!

Today:

Much better estimates of PDF uncertainties
But beware ...


CDF 1996

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PDF and Scale Uncertainties

$|y| < 0.55$
$\sim \pm 10\%$
@ 1 TeV

PDF uncertainties from CTEQ 6.5
At 4 TeV in $p_T$ about -20% to +35%

SISCone: Similar result

Scale variation of $p_{T,\text{jet}}$ to
$0.5 \times p_{T,\text{jet}}$ and $2 \times p_{T,\text{jet}}$

SISCone: Up to twice as large!
**Forward Jets and PDFs**

Possible constraint on PDFs, but need to know JES!

**CMS PAS FWD-08-001**

**Forward jets relative yields: 14 TeV**

- $\Delta JES = 5\%$

**CMS Preliminary**

$p_{T,\text{jet}} > 35$ GeV

**pp → jet +X , 3 < |\eta| < 5, \int L \, dt=1$ pb$^{-1}$**

SiS Cone, $R = 0.5$

- Unsmereed CorrCaloJets (CTEQ5L)
- fastNLO (CTEQ6M)
- fastNLO (MRST03)
Non-perturbative Corrections

To compare with data correct NLO for:

- Multiple Parton Interactions (MPI)
- Hadronization & Decays (Lund, Cluster)

Less compensation of these effects for $k_T$ than for SISCone, not negligible in both cases. Need MC tunes for UE with first LHC data!

Compared 3 different tuned MC:

- Pythia Tune D6T
- Herwig++
- Herwig/Jimmy with settings from ATLAS

Take e.g. correction as average of Pythia and half of each, Herwig++ and Herwig/Jimmy, as uncertainty
JES and New Physics

- Dominating experimental uncertainty: JES (assumed ±10% at startup)
- More data and improved JES knowledge needed to start constraining PDFs
- Sensitive to Contact Interactions beyond Tevatron reach (2.7 TeV) with 10 pb⁻¹

CMS PAS SBM-07-001

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Jet Energy Resolution

Jet energy resolution from CMS performance study

JER usually parameterized by:

\[ \sigma(p_T) = p_T \cdot \sqrt{C^2 + \frac{S^2}{p_T} + \frac{N^2}{p_T^2}} \]

Derived from MC comparison
Fairly independent of jet algo

Finite detector resolution on a steeply falling jet \( p_T \) spectrum leads to strongly asymmetric bin migrations!

Can be derived from dataMC with dijet asymmetry method

CMS PAS JME-07-003

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Artificially smear jets by Gaussian with an arbitrary but reasonable $p_T$ dependent width.

- Apply ansatz method
- Method corrects $p_T$ smearing effects on steeply falling spectrum
**Unsmearing Steps**

**Motivation**

The observed cross section is higher than the true one due to the falling shape of the spectrum and the finite $p_T$ resolution. More events migrate into a bin of measured $p_T$ than out of it.

**Unsmearing steps:**

Analytical expression of the $p_T$ resolution

Ansatz function with free parameters to be determined by the data

Fitting the data with the Ansatz function smeared with $p_T$ resolution.

Unsmearing correction calculated bin by bin.

\[
R(p_T', p_T) = \frac{1}{\sqrt{2\pi}\sigma(p_T')} \exp\left[-\frac{(p_T' - p_T)^2}{2\sigma^2(p_T')}\right]
\]

\[
f(p_T) = N \cdot p_T^{-\alpha} \cdot \left(1 - \frac{2\cosh(y_{\text{min}})p_T}{\sqrt{s}}\right)^\beta \exp(-\gamma p_T)
\]

\[
F(p_T) = \int_0^\infty f(p_T')R(p_T', p_T)dp_T'
\]

\[
C_{\text{bin}} = \frac{\int_{\text{bin}} f(p_T)dp_T}{\int_{\text{bin}} F(p_T)dp_T}
\]
JER Uncertainty

Good knowledge of the resolution required!
A wrong assumption can shift the final spectrum easily by some percent ...

Two scenarios studied:

- Very pessimistic:
  - Resolution in unsmearing is “real” resolution (in %) - 1 %: 1% better (-)
  - Resolution in unsmearing is “real” resolution (in %) + 4%: 4% worse (+)

- Optimistic:
  - Resolution in unsmearing is 0.95 times “real” resolution (in %): 5 % better (*)
  - Resolution in unsmearing is 1.05 times “real” resolution (in %): 5 % worse (*)
Jet Shapes

Jet shape measurements can be used to discriminate between different underlying event models.

Can be used to distinguish gluon originated jets from quark jets.

Jet shape measurements can be used to test the showering models in the MC generators.

Measurement of the average integrated (differential) energy flow inside jets.
**Event Shapes**

**Definition:**
Transverse global Thrust
(k_\perp jets, E_{T,1} > 80 GeV, E_{T,all} > 60 GeV)

\[ T_{\perp,g} \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}} \]

- In praxis, need to restrict rapidity range: |\eta| < 1.3 → Transverse central Thrust
- Less sensitive to JES & JER uncertainty
- No luminosity uncertainty
- Useful for MC tuning

**Similar as Event Shapes in e^+e^- and ep**

- Includes stat. & syst.
- Linear

**CMS preliminary**

QCD-Multijets
kt6-algo, E_{T,1} > 80 GeV
- corrected CatoJets (PYTHIA)
- GenJets (PYTHIA)
- GenJets (ALPGEN)

10 pb^{-1}

Includes stat. & syst.

Linear \[ \tau_{\perp,g} \equiv 1 - T_{\perp,g} \]

Spherical

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Event Shapes

- Distributions get more peaked at higher $E_T$
- Corrected pseudo-data follow behaviour of original Pythia MC
- Alpgen makes different predictions

![Graph showing distributions and predictions](image)

CMS PAS QCD-08-003
Some Photons (and Jets)
**Photons**

**Photon processes:**
- Direct photon production
- Di-photons
- Photon + n jets

---

<table>
<thead>
<tr>
<th># bunches</th>
<th>( \beta^* ) (m)</th>
<th>( I_b )</th>
<th>( L ) (cm(^{-2})s(^{-1}))</th>
<th>Pileup</th>
<th>Photons/hour (( p_T &gt; 20 ) GeV)</th>
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<td>1x1</td>
<td>18</td>
<td>( 10^{10} )</td>
<td>( 10^{27} )</td>
<td>low</td>
<td>( 3.2 \cdot 10^{-1} )</td>
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<tr>
<td>43x43</td>
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<td>( 3 \cdot 10^{10} )</td>
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<td>0.05</td>
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<td>( 3 \cdot 10^{10} )</td>
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<td>( 5.4 \cdot 10^2 )</td>
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<td>1.9</td>
<td>( 1.6 \cdot 10^4 )</td>
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<tr>
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<td>( 9 \cdot 10^{10} )</td>
<td>( 1.1 \cdot 10^{32} )</td>
<td>3.9</td>
<td>( 3.6 \cdot 10^5 )</td>
</tr>
</tbody>
</table>

Not taken into account

---

**Photon rate estimations:**
- Photon \( p_T > 20 \) GeV
- Photon \( |\eta| < 2.5 \)

---

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S. Ganjour
Photon Isolation

Gauge boson production gives important additional information:
- Luminosity measurement
- Detector calibration
- PDFs
- Background for new physics :-(

Important steps:
- Good efficiency including photon conversions
- Proper photon isolation to suppress background

CMS photon study:
- Photon $p_T$ spectrum for 1/fb
- Background QCD jets in blue
- After photon isolation cuts
- Improves S/B > 2 orders of magnitude

![Graph showing photon spectrum](image)

Outlook

- CMS is preparing (again) for first LHC data in autumn
- At the LHC we will go beyond Tevatron limits and explore unknown territory in QCD and new physics immediately
- First measurements, even at 900 GeV, will be QCD
- Some tough experimental systematics to deal with, but combining detector parts may help in certain phase space regions (jets+tracks, particle flow)
- Measurements of jets and photons are important tests of QCD and help to
  - calibrate the calorimeters
  - better understand the dominant background to many new physics channels
  - constrain the PDFs
- New measurements are just ahead!

Thanks to all colleagues helping in preparing this presentation!
Be prepared for

at the LHC in autumn!

Thank you for your attention!
CMS Electromagnetic Calorimeter

Barrel (EB):
- $\eta$ segments: 2x85
- $\phi$ segments: 360
→ 61200 crystals
  ($\text{PbWO}_4$, 26 $X_0$)
→ $\Delta \eta \times \Delta \phi \approx 0.0174 \times 0.0174$

Energy resolution from test beam:
$S = 3.63\%$, $N = 124 \text{ MeV}$, $C = 0.26\%$

\[
\left( \frac{\sigma}{E} \right)^2 = \left( \frac{S}{\sqrt{E}} \right)^2 + \left( \frac{N}{E} \right)^2 + C^2
\]

End caps (EE):
- (x,y) grid on two halves
- front face 28 x 28 mm$^2$
→ 2 x 2 x 3662 crystals = 14648
  ($\text{PbWO}_4$, 25 $X_0$)

Preshower (ES)

Endcap ECAL (EE)
**CMS Hadronic Calorimeter**

**HCAL (tower structure):**
- **Barrel (HB):** $|\eta| < 1.4$, 2304 towers
- **End caps (HE):** $1.3 < |\eta| < 3.0$, " towers
- **Outside coil (HO):** $|\eta| < 1.26$ (tail catcher)
  $\rightarrow$ 4608 towers (Plastic scintillator tiles, $\approx 10 \lambda_N$)
  $\rightarrow$ $\Delta\eta \times \Delta\phi \approx 0.087 \times 0.087 \rightarrow 0.350 \times 0.175$

- **Forward (HF):** $2.9 < |\eta| < 5.0$ (not shown)
  $\rightarrow$ 2 x 900 towers (Quartz fibers, $\approx 10 \lambda_N$)
  $\rightarrow$ $\Delta\eta \times \Delta\phi \approx 0.111 \times 0.175 \rightarrow 0.302 \times 0.350$

**CASTOR calorimeter (not shown):**
- $5.1 < |\eta| < 6.5$, $\approx 22 X_0$, $\approx 10 \lambda_N$
## Hadron Spectra Systematics

### CMS Pixel triplets

\[
\Delta N_{\text{corrected}} = \frac{(1 - \text{fakeRate}) \cdot (1 - \text{feedDown})}{\text{geomAccep} \cdot \text{algoEffic} \cdot (1 - \text{multiCount})} \cdot \Delta N_{\text{measured}}
\]

<table>
<thead>
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<th>Correction</th>
<th>Dependence on</th>
<th>Corr.</th>
<th>Syst.</th>
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<td></td>
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<td>part</td>
<td>mult</td>
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<td>Trigger</td>
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<td>Multiple track counting</td>
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<td>no</td>
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<tr>
<td>Fake track rate</td>
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<td>yes</td>
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<tr>
<td>Feed-down</td>
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<td>yes</td>
<td>no</td>
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<tr>
<td>(\eta, p_T) resolution</td>
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<td>no</td>
<td>no</td>
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<tr>
<td><strong>Total</strong></td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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</table>
Comparison of tracking performance for:

- Ideal conditions
- Start-up (misaligned)
- Alignment Position Error application

**Track reconstruction efficiency**

Recover efficiency

**Fake rate**

The price to pay

Increased fake rate
Dijets in pp collisions:

$\Delta \phi$ dijet = $\pi \rightarrow$
Exactly two jets, no further radiation

$\Delta \phi$ dijet small deviations from $\pi \rightarrow$
Additional soft radiation outside the jets

$\Delta \phi$ dijet as small as $2\pi/3 \rightarrow$
One additional high-$p_T$ jet

$\Delta \phi$ dijet small – no limit $\rightarrow$
Multiple additional hard jets in the event

hep-ex/0409040
PRL 94, 221801 (2005)
**Partonic Subprocesses**

- For $hh \rightarrow$ jets there are **seven** relevant partonic subprocesses:

1) $gg \rightarrow$ jets $\propto H_1(x_1, x_2)$

2) $qg, \bar{q}g \rightarrow$ jets $\propto H_2(x_1, x_2)$

3) $gq, g\bar{q} \rightarrow$ jets $\propto H_3(x_1, x_2)$

4) $q_iq_j, \bar{q}_i\bar{q}_j \rightarrow$ jets $\propto H_4(x_1, x_2)$

5) $q_iq_i, \bar{q}_i\bar{q}_i \rightarrow$ jets $\propto H_5(x_1, x_2)$

6) $q_i\bar{q}_i, \bar{q}_i q_i \rightarrow$ jets $\propto H_6(x_1, x_2)$

7) $q_i\bar{q}_j, \bar{q}_i q_j \rightarrow$ jets $\propto H_7(x_1, x_2)$

- Seven linear combinations $H_i$ of PDFs
Subprocess Decomposition

Decomposition of the total ppbar, pp → jets cross section (NLO) into subprocesses at central rapidity against the scaling variable $x_T = 2p_T/\sqrt{s}$.
New Physics from Dijets

New Physics with Jets:

- **Contact interactions**
- **Resonances**
  - $W'$ & $Z'$ (Grand Unified Theory)
  - $E_6$ diquarks (D) (Superstrings & GUT)
  - Excited quarks ($q^*$) (Compositeness)
  - RS Gravitons (G) (Extra Dimensions)
  - Colorons (C) & Axigluons (A) (Extra Color)

**Di-jet mass distribution**

$E_{CMS} > M$

### Cross Section (pb)

| Model | J | Color | $|\eta| < 1$ | $|\eta| < 1.3$ | $|\eta| < 1$ | $|\eta| < 1.3$ |
|-------|---|-------|------------|------------|------------|------------|
| $q^*$ | 1/2 | Triplet | $7.95 \times 10^4$ | $1.27 \times 10^3$ | $9.01$ | $1.36 \times 10^1$ |
| A,C | 1 | Octet | $3.22 \times 10^2$ | $5.21 \times 10^2$ | $5.79$ | $8.82$ |
| D | 0 | Triplet | $8.11 \times 10^1$ | $1.26 \times 10^2$ | $4.20$ | $5.97$ |
| G | 2 | Singlet | $3.57 \times 10^1$ | $5.47 \times 10^1$ | $1.83 \times 10^{-1}$ | $2.60 \times 10^{-1}$ |
| W' | 1 | Singlet | $1.46 \times 10^1$ | $2.37 \times 10^1$ | $3.49 \times 10^{-1}$ | $5.31 \times 10^{-1}$ |
| Z' | 1 | Singlet | $8.86$ | $1.44 \times 10^1$ | $1.81 \times 10^{-1}$ | $2.77 \times 10^{-1}$ |

**Contact Interactions**

- Sensitive to Scale $\Lambda >> \sqrt{s}$!
Search for deviation from expected event rate:
- QCD from PYTHIA (here) or NLO
- Contact interaction: PYTHIA or LO

Cross section ratios

Search for resonances
Possible signals of q* relative to QCD prediction, visible for < 2 TeV
(statistical uncertainty only!)

One means to avoid systematics is by looking into cross section ratios in η

New Physics from Dijets

CMS PAS SBM-07-001

Klaus Rabbertz

Isfahan, Iran, 24.04.2009

1st IPM Meeting on LHC Physics
Recent Limits

Tevatron limit on contact interaction scale (qqqq): > 2.4 - 2.7 TeV

Dijet resonance search

CDF Preliminary 03/2008

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Excluded (GeV)</th>
<th>Resonance</th>
<th>Excluded (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A or C</td>
<td>260 - 1250</td>
<td>D</td>
<td>290 - 630</td>
</tr>
<tr>
<td>$\rho_{T8}$</td>
<td>260 - 1110</td>
<td>$W'$</td>
<td>280 - 840</td>
</tr>
<tr>
<td>$q^*$</td>
<td>260 - 870</td>
<td>$Z'$</td>
<td>320 - 740</td>
</tr>
</tbody>
</table>

CDF Run II Preliminary, 1.13 fb$^{-1}$

Exclusion limits for $W'$ and $Z'$
Dijet Ratios

- Sensitivity to new physics from dijet x section ratios in pseudo-rapidity
- Reduced sensitivity to jet energy scale

CMS PAS SBM-07-001

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Isfahan, Iran, 24.04.2009

1st IPM Meeting on LHC Physics
Jet Shapes

A possibility to look into details of QCD and jet structure!

**Norm. transverse energy distribution:**

\[
\rho(r) = \frac{\sum p_T (r - \Delta r/2, r + \Delta r/2)}{\Delta r \sum p_T^{Jet}}
\]

Good reproduction of general properties (central region $|\eta| < 1$, matched jets)

Jets from generator particles

Jets from calorimeter towers

- Iterative Cone
- CMS PRELIMINARY
- 80 < $p_T^{Jet}$ < 120 GeV/c
- Icone uses $\eta$, $\Delta r$ employs $\gamma$

- MidPointCone
- SIS Cone

- CMS PAS JME-07-003
Multiple Parton Interactions

Phase space:

As low as possible in pT:
- photon pT > 10 GeV
- jet pT > 20 GeV for calojets
=> could consider jets from tracks

- Double-parton-scattering
  - four-jet production (→ AFS, UA2, CDF)
  - like-sign W production
  - γ + 3-jet production (→ CDF)

- Need double-parton component to describe the data

\[
\sigma_{\text{eff}}(\text{CDF}) = 11 \text{ mb}
\]
→ no x-dependence found!
Influence of $\alpha_s(M_Z)$

Cross section ratios at central rapidity $\alpha_s(M_Z)$ varies from 0.112 to 0.125

With CTEQ6.6 central PDF

PDG Value $\alpha_s(M_Z) = 0.1176 \pm 0.0020$
Would lead to 2 to 4% variation

With CTEQ6.6A $\alpha_s$ PDF series

Only $\alpha_s$ changed

$\alpha_s$ different already in PDF fit
Some UA1 Quotations

Quotations from Phys. Lett. Vol. 107B, no. 4:

- ... dipole magnet which produces a field of 0.7 T over a volume of 7m x 3.5m x 3.5m ...

- ... yields space points at centimetre intervals on the detected tracks

- ... two short accelerator development periods in October and November 1981 ...

- The events were scanned by physicists on a Megatek display.

- ... was examined independently by all physicists who participated in the scanning. The combined effect of the scanner variations ...