Expectations for QCD with first LHC Data

On behalf of the ATLAS and CMS Collaborations
Klaus Rabbertz
University of Karlsruhe

Outline

- **Construction**
  - LHC Racing Rules
- **Practice**
  - Tracks
- **Qualifying**
  - Jets
- **Warming-up**
  - Photons
- **Pit stop**
  - PDFs
- **The Race**
  - New physics
- **Final Score**

The Race will be on soon ...

Formula 1 TM Formula One Licensing BV

BUL-PHO-2008-034

The Audience arrives ...

QCD

CERN OpenDays 5./6. April 2008: 76000 Visitors

BUL-PHO-2008-034

Blue flag for CDF and D0

The Circuit: LHC

Training: **End of June**
Qualifying: **August?**

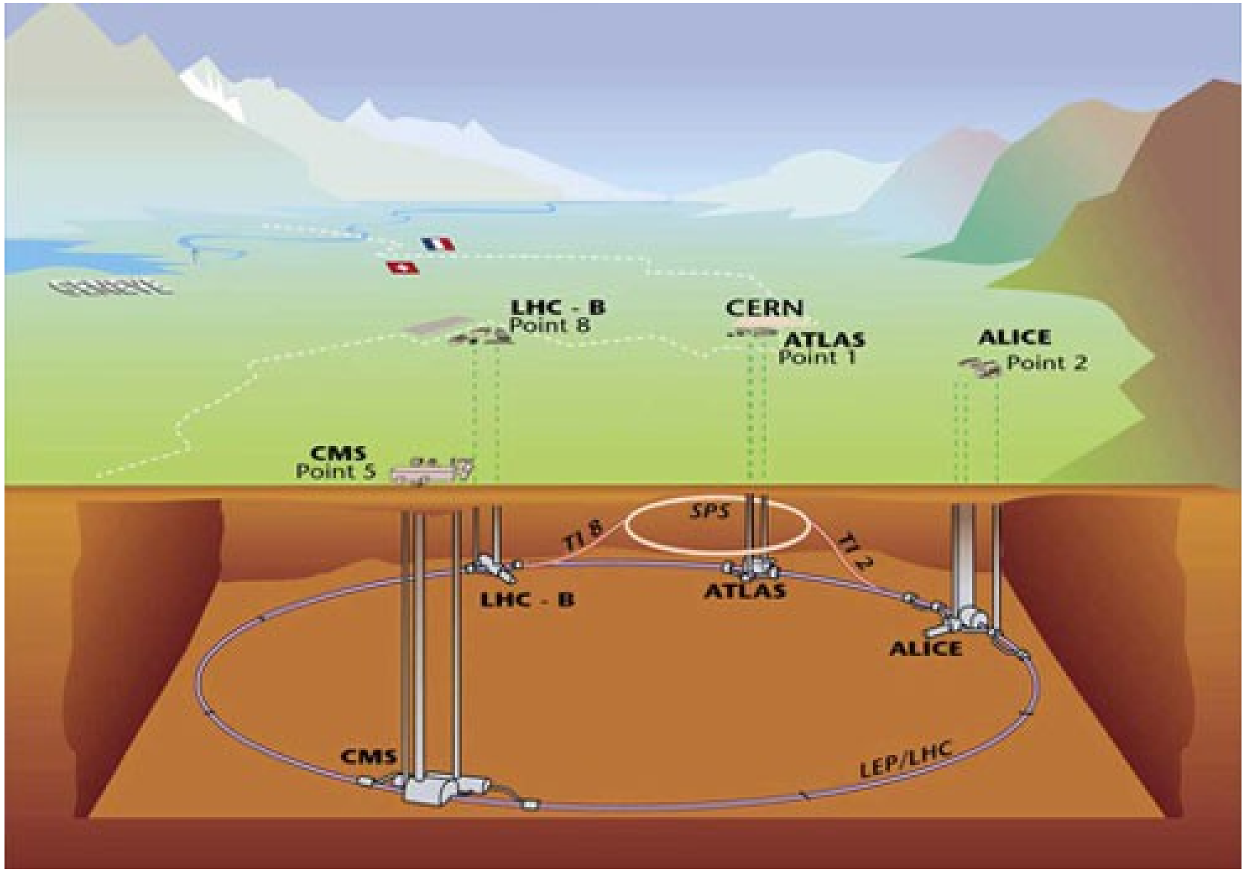
Fuel regulations:

- Engineering: Low grade 85 fuel:
  E_{cms} = 900 GeV, some days
- Start-up: 2008 with 90 octane only:
  E_{cms} = 10 TeV, L_{int} ~ 40/pb
- Race: From 2009 with high grade 95 octane:
  E_{cms} = 14 TeV

Bunch patterns:
43x43, 156x156

Specific luminosity:
$3 \cdot 10^{30} - 6 \cdot 10^{31}$ cm^{-2} s^{-1}

Most results presented in the following are for 14 TeV! Only exception next slide ...

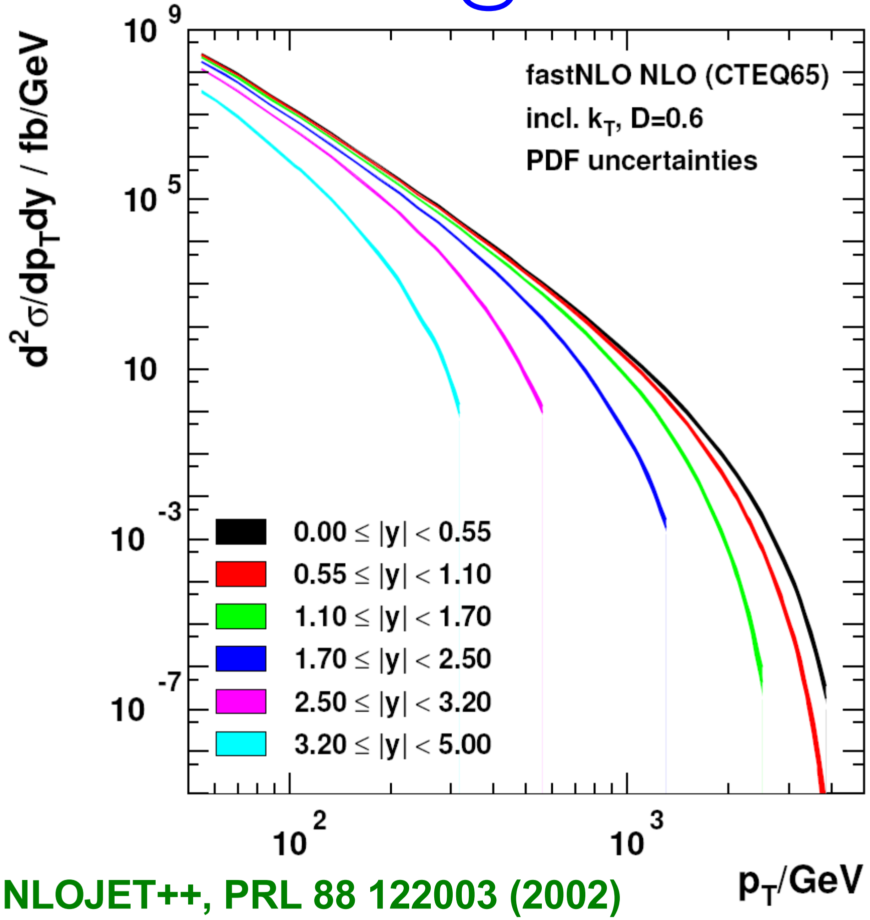


For the current machine status see talk by M. Lamont

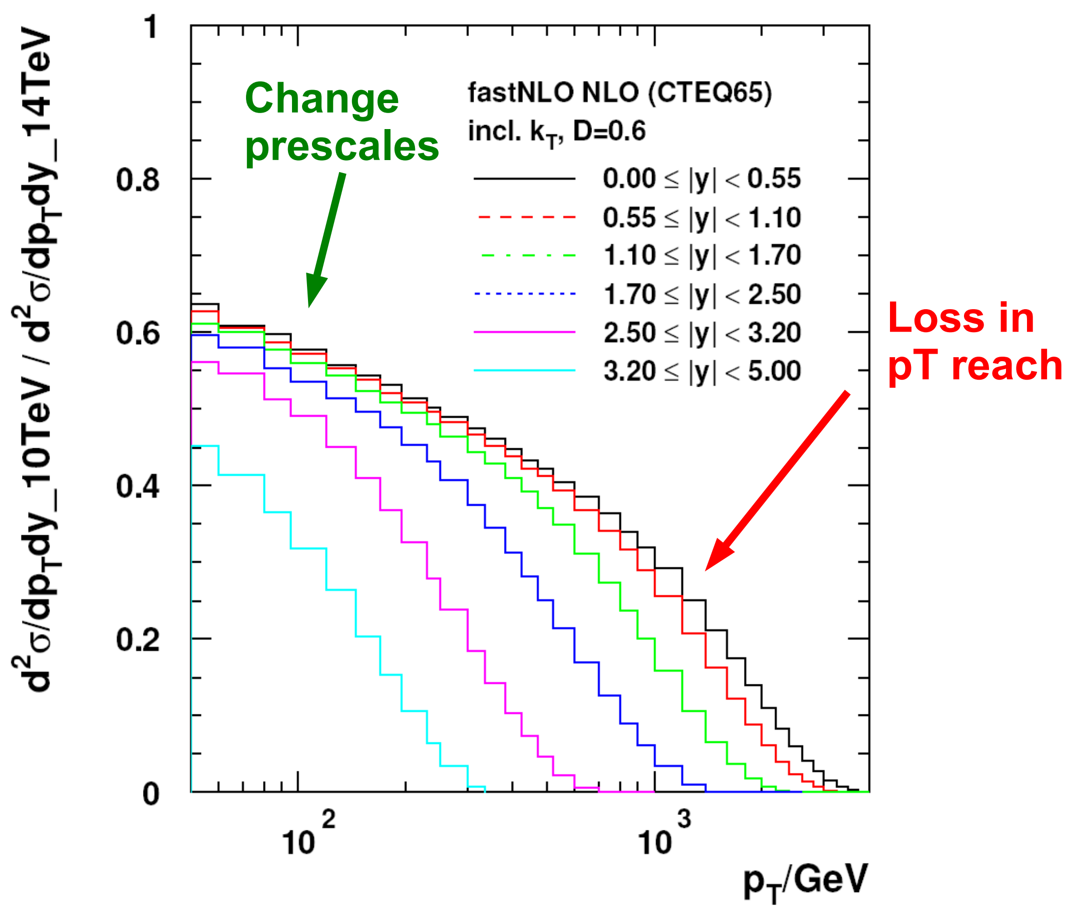
Ratio 10 TeV / 14 TeV

Inclusive kT cross section in 6 bins in rapidity y, D = 0.6

LHC @ 10 TeV



10 TeV / 14 TeV



NLOJET++, PRL 88 122003 (2002)
PR D68 094002 (2003)
fastNLO, hep-ph/0609285

NLO code by NLOJET++, Z. Nagy

Tracks: The Drivers

QCD

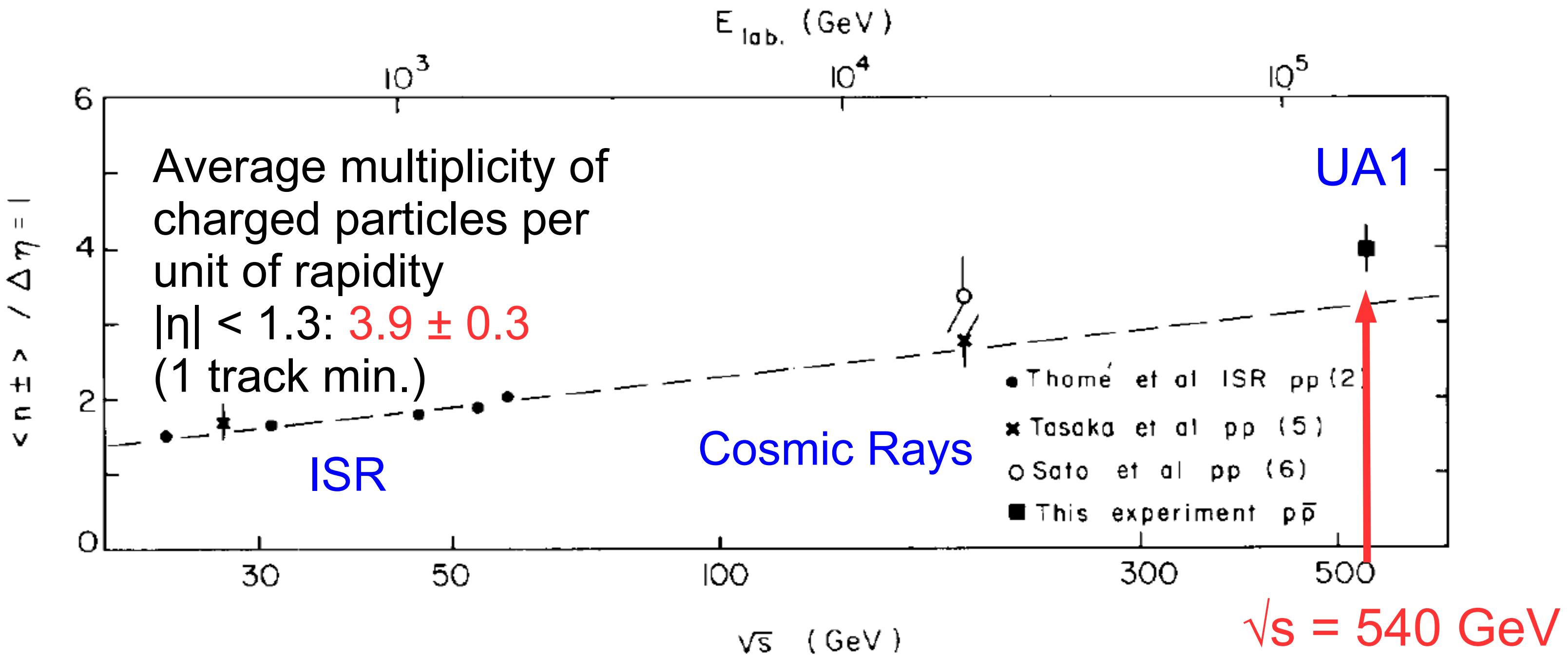
- **Track based analyses:**
  - Charged hadron spectra
  - Underlying event from transverse region of charged particle jets

Good candidates for measurements at 900 GeV

Phys.Lett.Vol.107B, no. 4 — First UA1 Publication — QCD — 17. Dezember 1981

Recall:

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



Charged Hadron Spectra

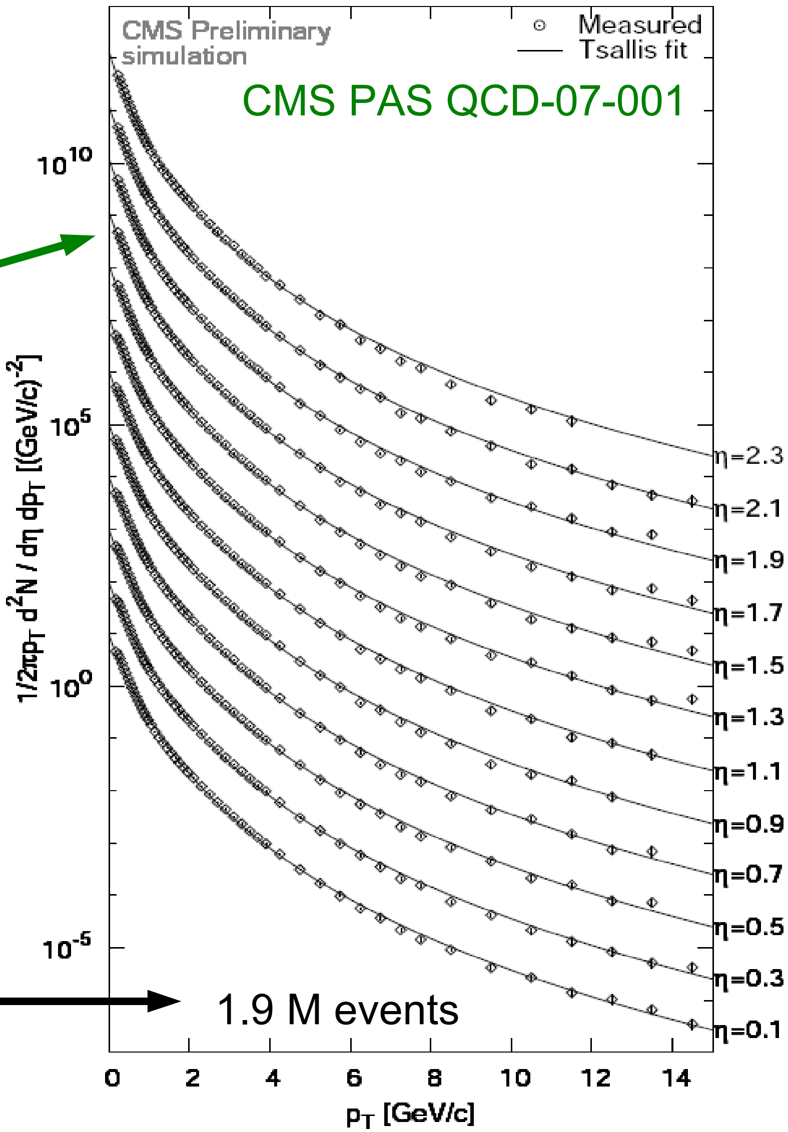
One of the first analyses possible ...

Technique:

Tracks from pixel hit triplet seeding
(Mis-alignment under investigation)
➔ **Tracking down to pT of 75 MeV/c**

Systematic:

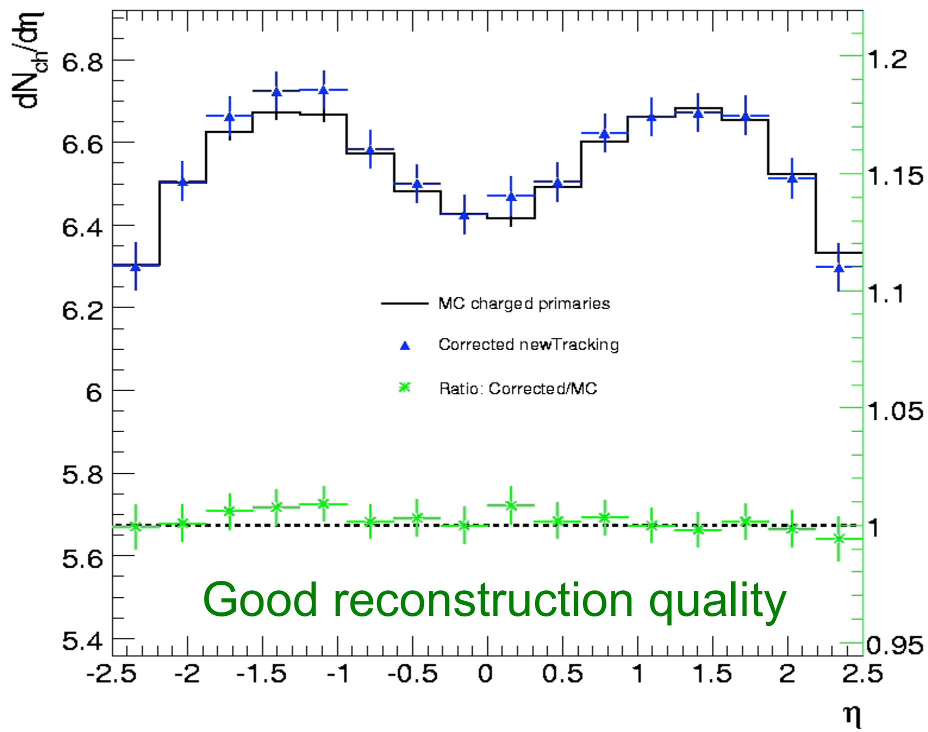
Trigger, feed-down, geom. acceptance, alg. efficiency



Assuming one month running with 1 Hz allocated bandwidth → 1.9 M events

ATLAS Track reconstruction

Largest systematic: Mis-alignment



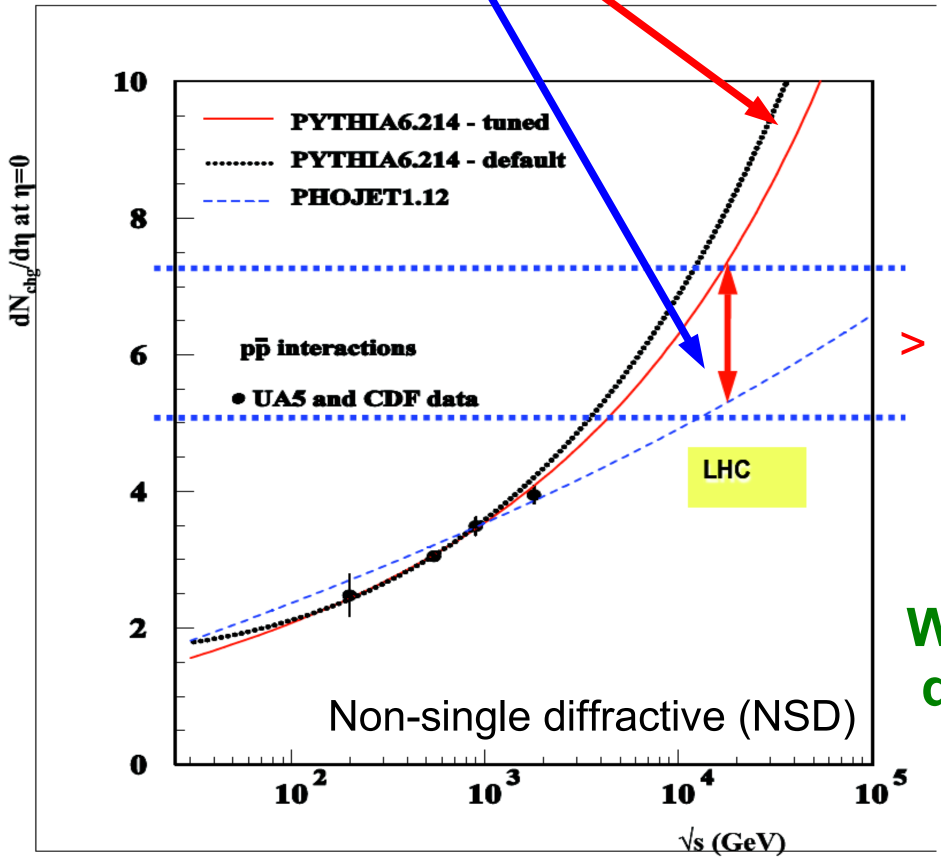
ATLAS

Charged Hadron Spectra

QCD

Model expectations for charged particles at |η| = 0 vs. √s:

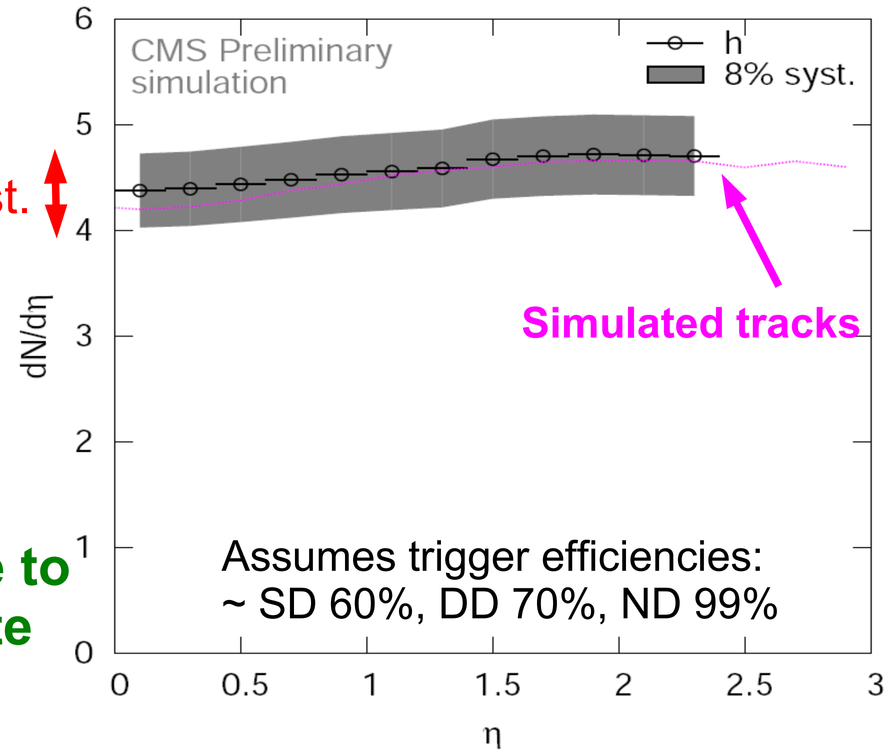
- Pythia: ~ $\ln^2(s)$
- Phojet: ~ $\ln(s)$



ATLAS

Simulation result from CMS:

- Charged particle pseudo-rapidity distribution
- Pythia tune DWT

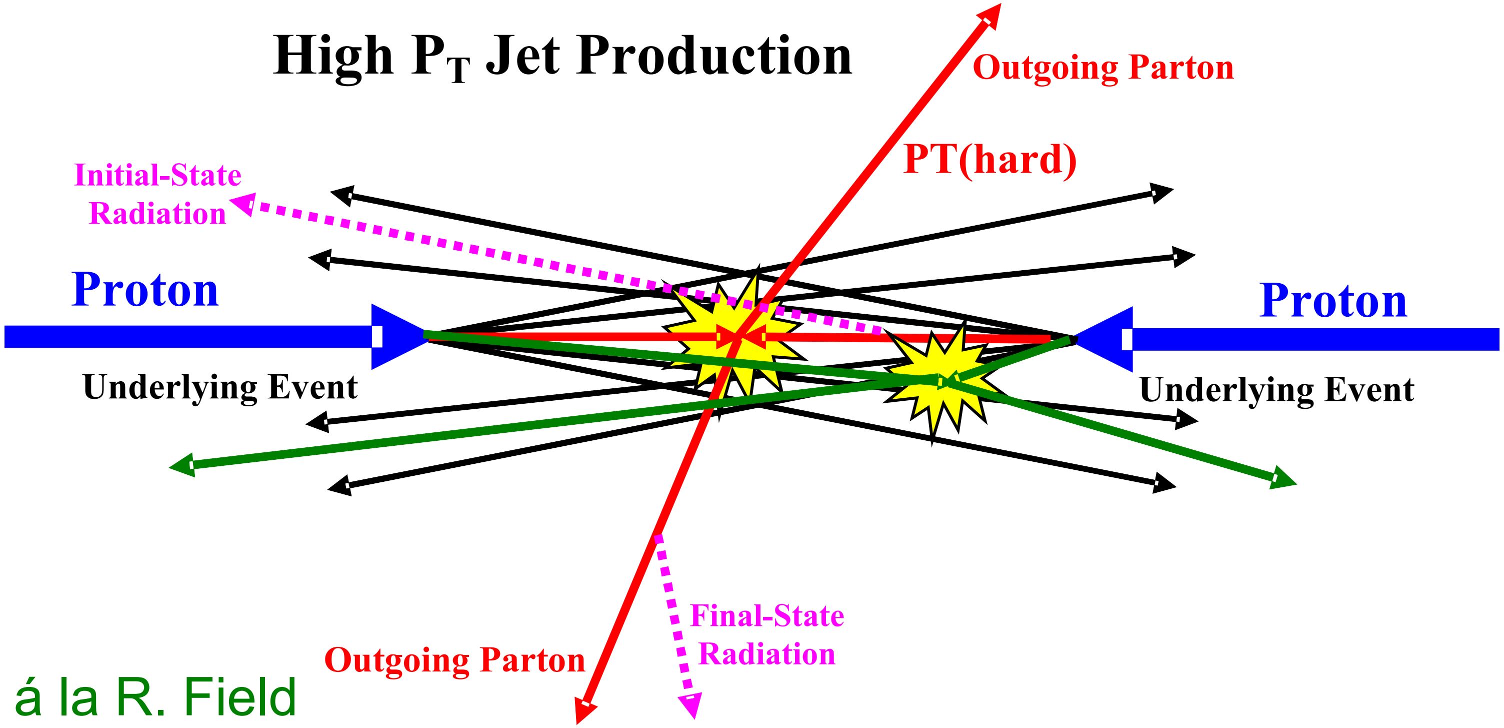


Will be able to differentiate

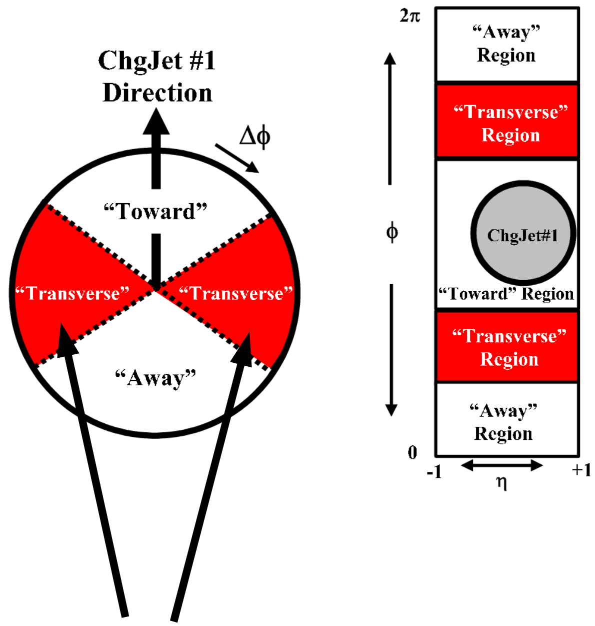
CMS PAS QCD-07-001

The Underlying Event

The Underlying Event is everything but the hard scatter.



á la R. Field



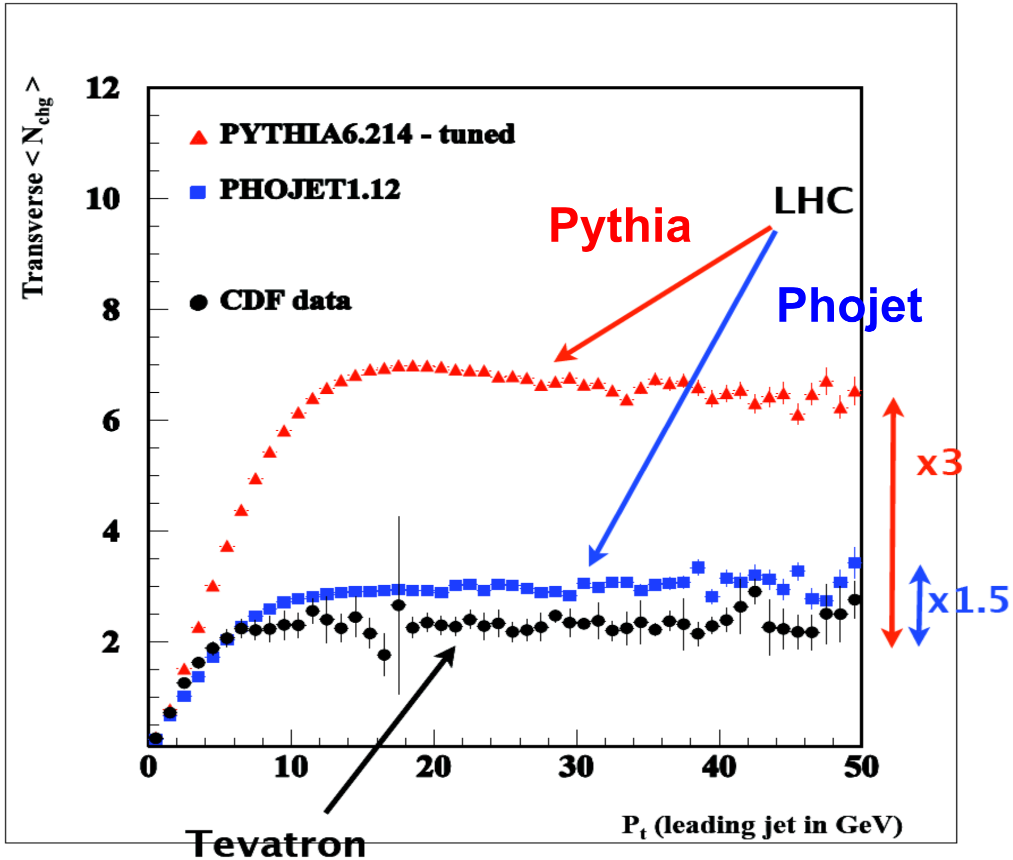
See also talks by R. Field and in multi-jets Tuesday morning session!

A measurement possibility:

- Charged particle and Ptsum densities in transverse region of leading charged jet

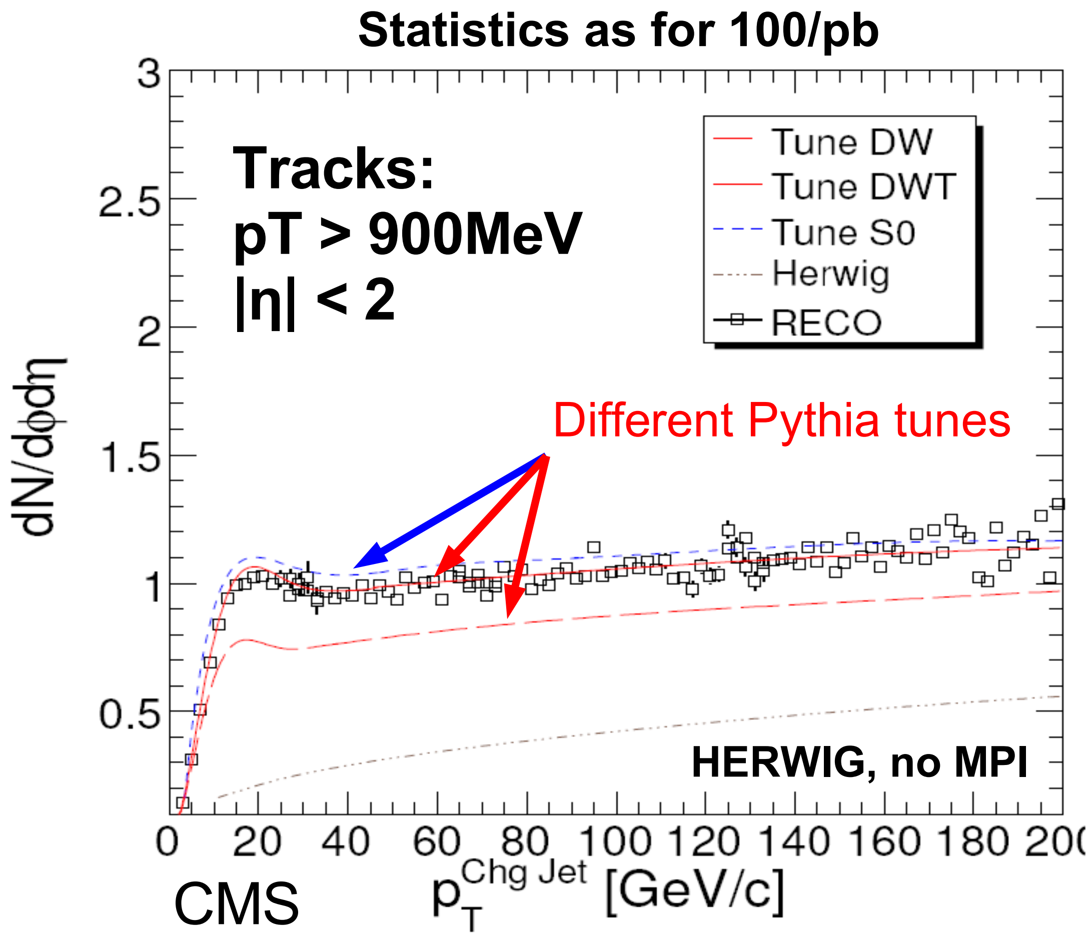
Charged particle density in transverse plane vs. leading charged jet pT

Extrapolation to LHC from CDF data



ATLAS

Comparison of different Pythia tunes



CMS PAS QCD-07-003

Jets: The Drivers

- **Jet algorithms** ➜ Talks by P.-A. Delsart, Chr. Sander
- **Jet energy calibration**
- **Jet analyses (calorimeter):**
  - **Dijet azimuthal decorrelation** ➜ Talk by M. Dasgupta
  - **Jet shapes**
  - **Inclusive jet cross sections**

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

Unsmearing correction (due to the finite detector Pt resolution)

The JES dominates the total uncertainty of the measurement

Borrowed from K. Kousouris

Jet Algorithms

Avoid pit stops for changing to a safe jet algorithm later ...

Algorithms in use by ATLAS and CMS

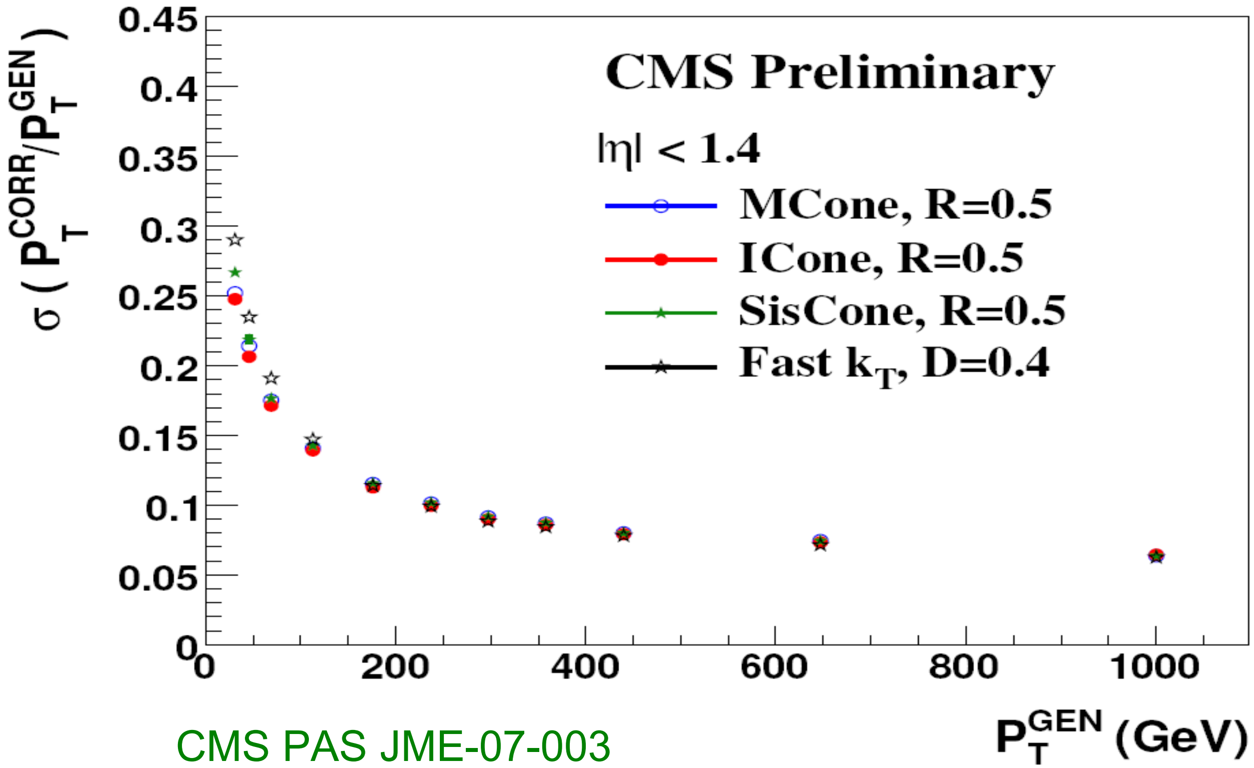
ATLAS:
- Iterative Cone R = 0.4, 0.7
- SISCone in future??
- kT D = 0.4, 0.6

CMS:
- Iterative Cone R = 0.5
- SISCone R = 0.5, 0.7
- kT D = 0.4, 0.6

For many more details, see talk by G. Salam and in multi-jets Tuesday afternoon sessions!

Jet energy resolution from CMS performance study

SISCone performs equally well as MidPoint Cone

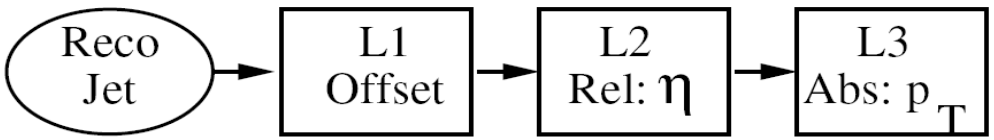


CMS PAS JME-07-003

Jet Energy Calibration

Description simplified, jet energy corrections are a very complex matter!

Factorized multi-level Calibration: CMS
- offset correction for pile-up, noise, thresholds
- relative correction for response variations in η (di-jets)
- absolute correction to particle level (pT balance in γ/Z + jet, M_W,M_{top} in ttbar → WbWb



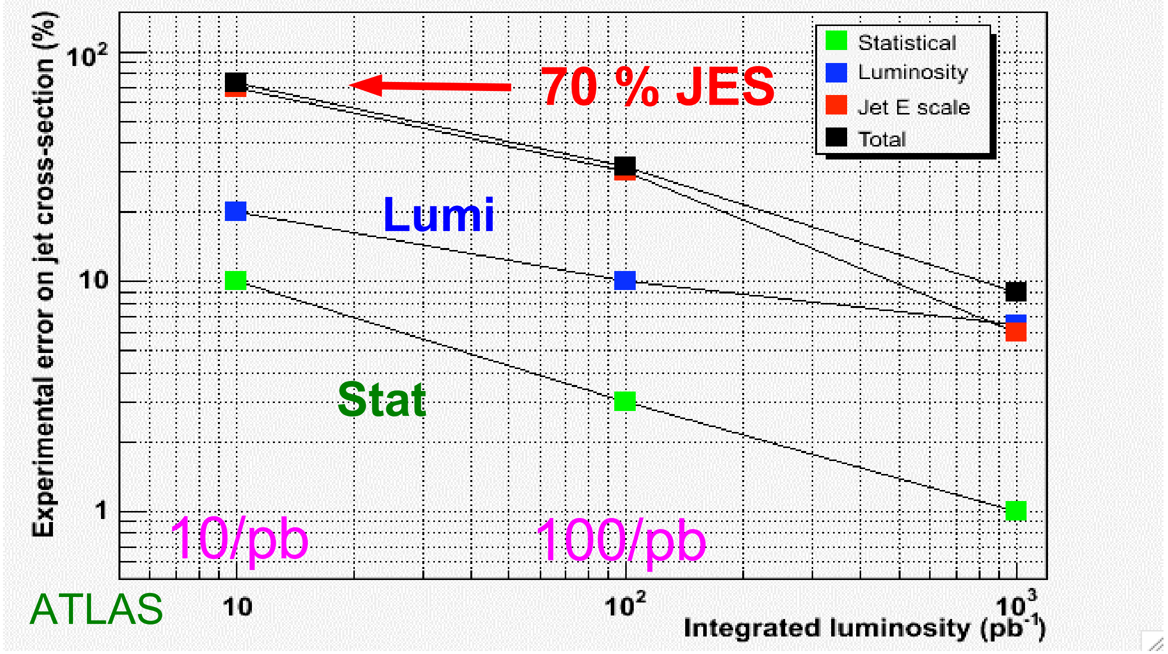
Habitual jet input:
- **calorimeter towers (ATLAS & CMS)**

Additionally:
- **topological clusters of lAr cells (ATLAS)**

Local Hadron Calibration: ATLAS
- calibrate clusters independent of any jet algorithm to individual particle scale
- make jets out of calibrated clusters

Projection of uncertainties on TeV jets

(Jets with pT = 1 TeV, |η| < 2)



Dijet Azimuthal Decorrelation

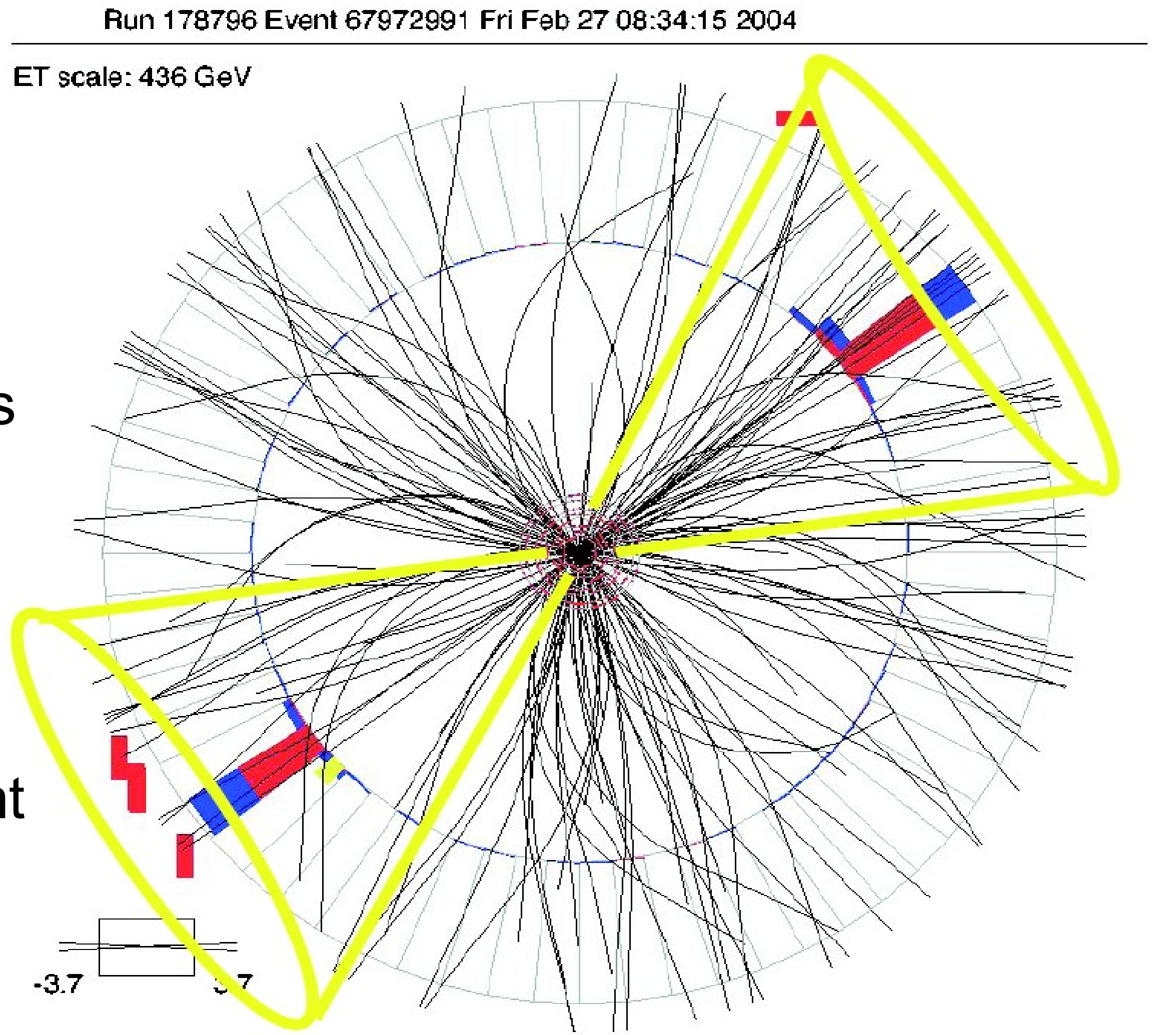
Dijets in pp collisions:

Δφ dijet = π →
Exactly two jets, no further radiation

Δφ dijet small deviations from π →
Additional soft radiation outside the jets

Δφ dijet as small as 2π/3 →
One additional high-pT jet

Δφ dijet small – no limit →
Multiple additional hard jets in the event



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

Dijet Azimuthal Decorrelation

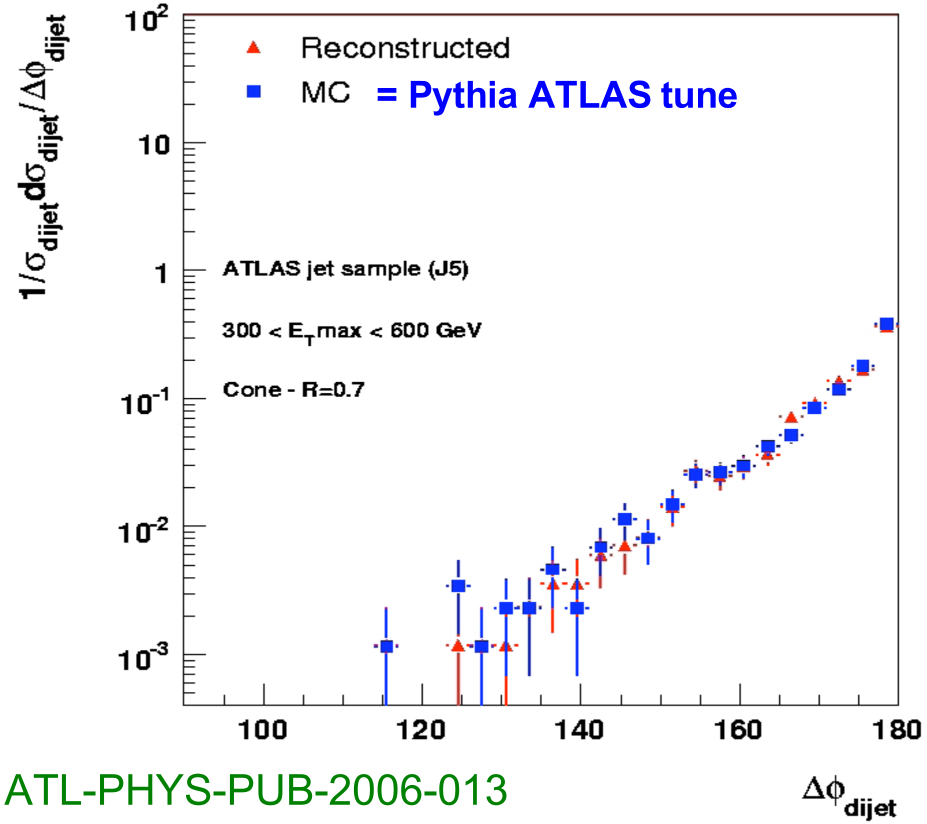
QCD

ATLAS comparison between generated and reconstructed Δφ in two bins of ET

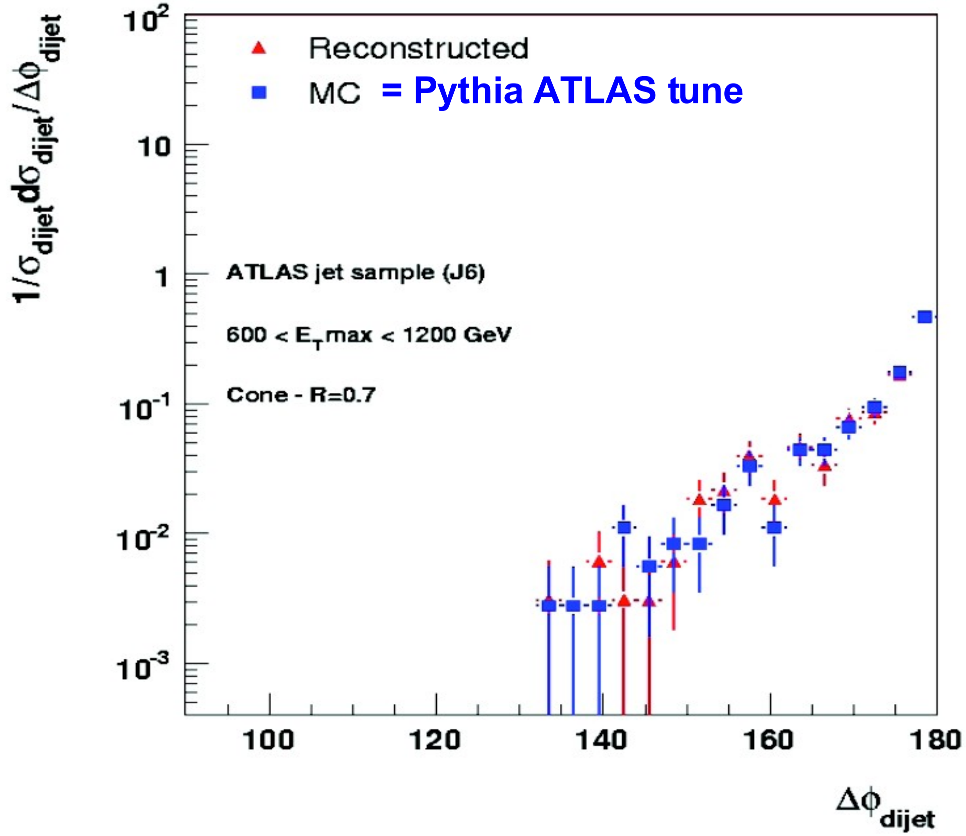
Cone jet algorithm:

- R=0.7
- $N_{jets} = 2$
- $|\eta_{jet}| < 0.5$
- $ET_{jet\ \#2} > 80$ GeV

300 < ET MAX < 600 GeV



600 < ET MAX < 1200 GeV



ATL-PHYS-PUB-2006-013

Jet Shapes

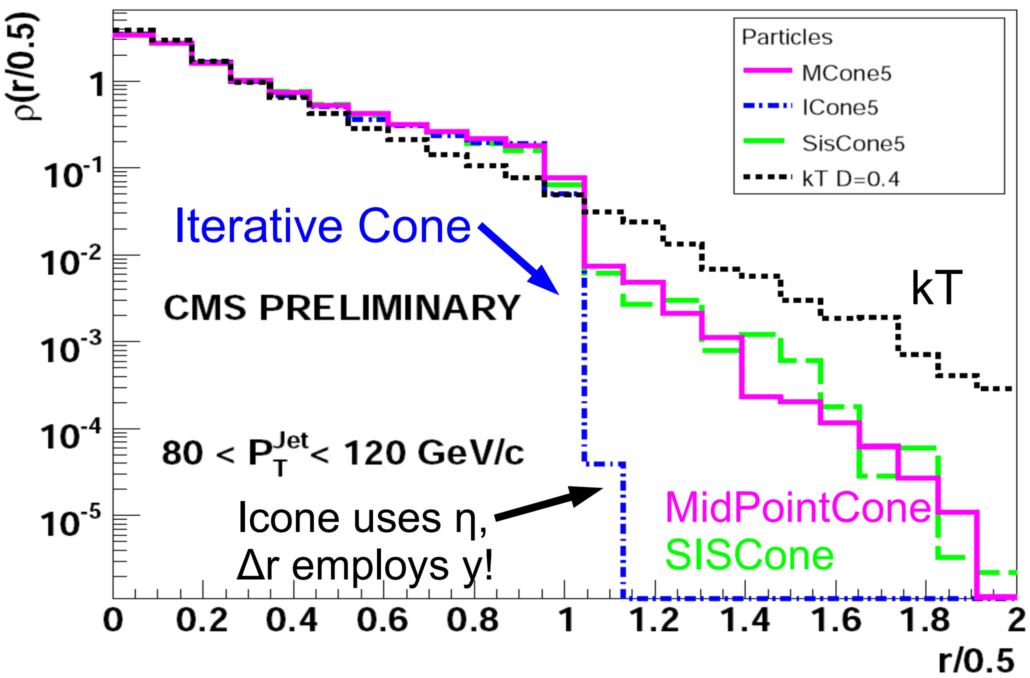
A possibility to look into details of QCD and jet structure!

Norm. transverse energy distribution:

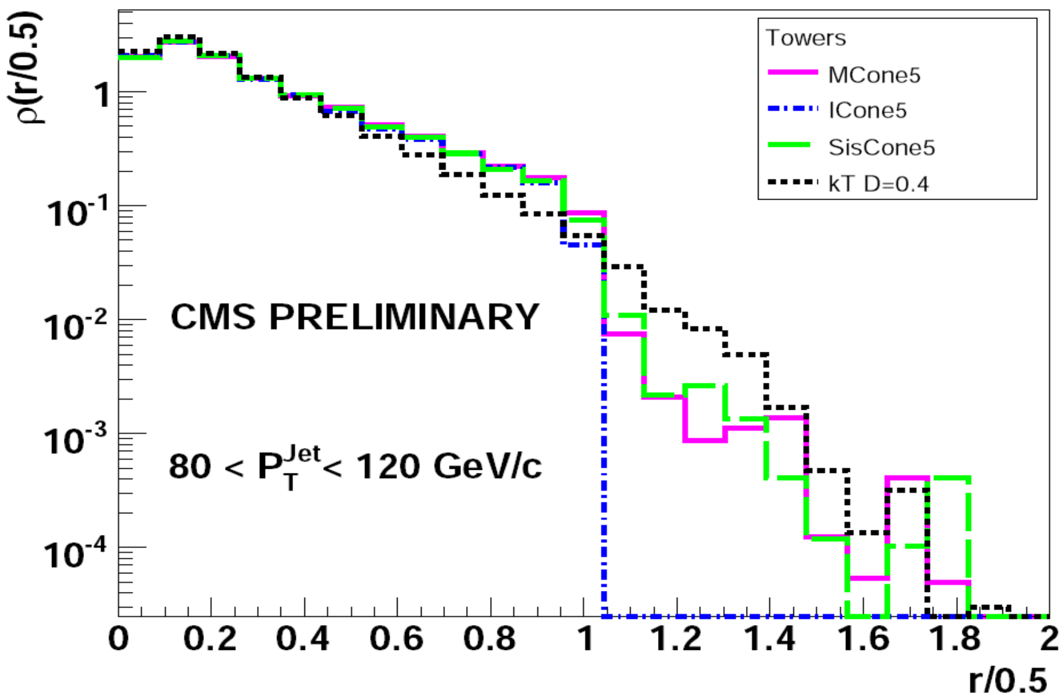
$$\rho(r) = \frac{\sum p_{\mathrm{T}}(r - \Delta r/2, r + \Delta r/2)}{\Delta r \sum p_{\mathrm{T}}^{Jet}}$$

Good reproduction of general properties (central region |η| < 1, matched jets)

Jets from generator particles



Jets from calorimeter towers



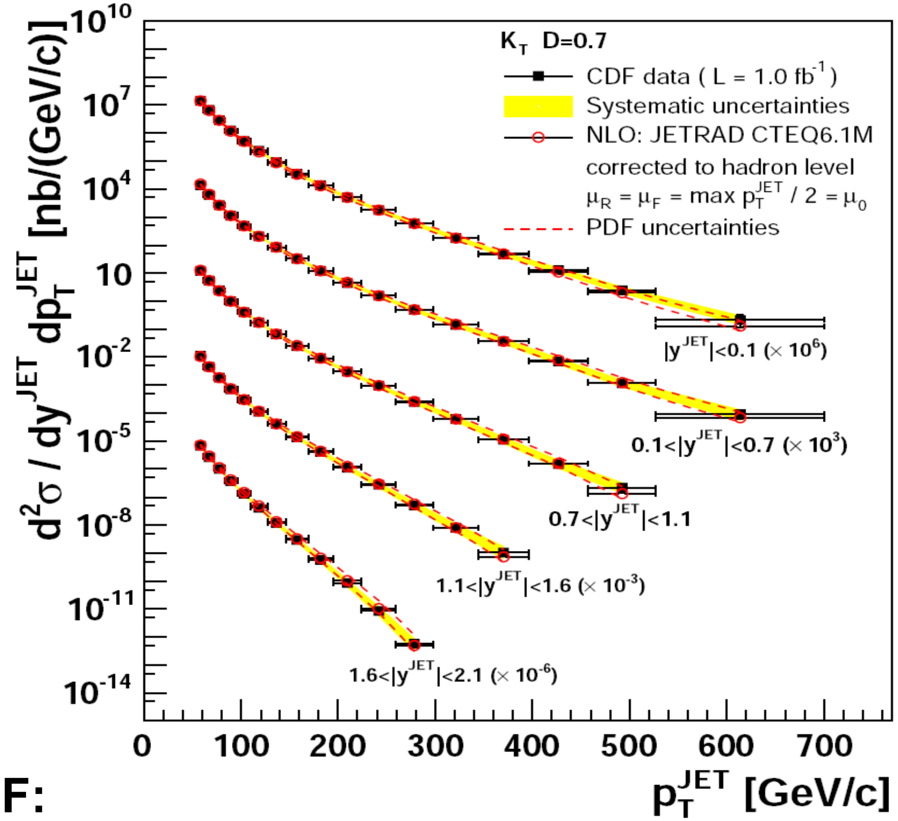
CMS PAS JME-07-003

Inclusive Jets at the Tevatron

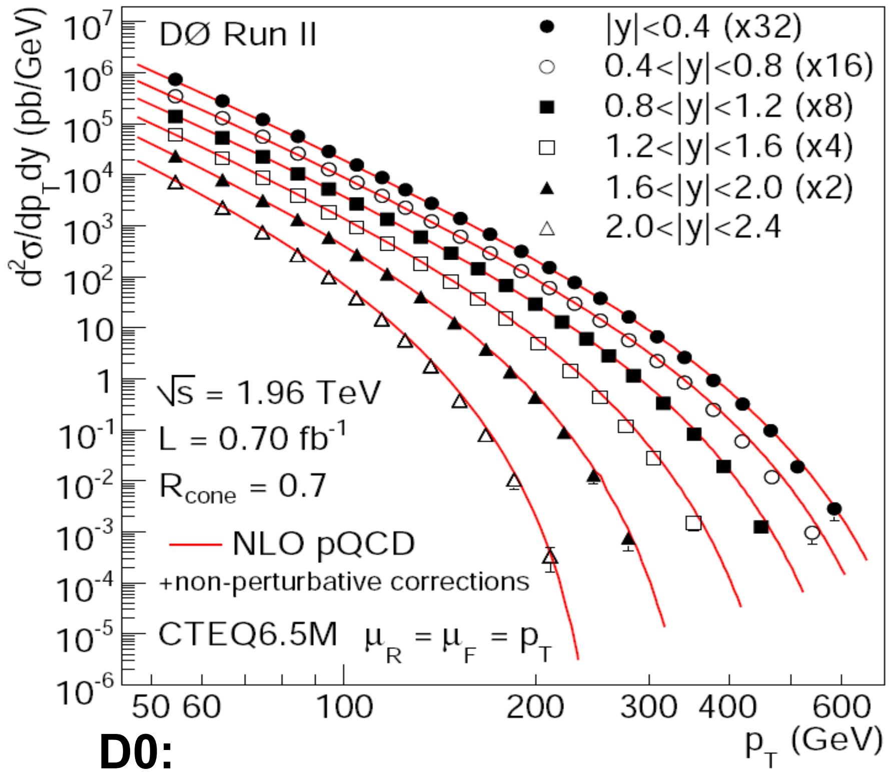
QCD

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

Phys.Rev.D75:092006,2007



D0 Incl. Midpoint cone jets, R=0.7
Theory: NLO with CTEQ6.5M



arXiv:0802.2400 [hep-ex]

CDF:
Z+jets (Phys.Rev.Lett.100:102001,2008)
W+jets (Phys.Rev.D77:011108,2008)
Incl. midpoint cone jets (Phys.Rev.D74:071103,2006)

D0:
Gamma + jet + X (arXiv:0804.1107 [hep-ex])

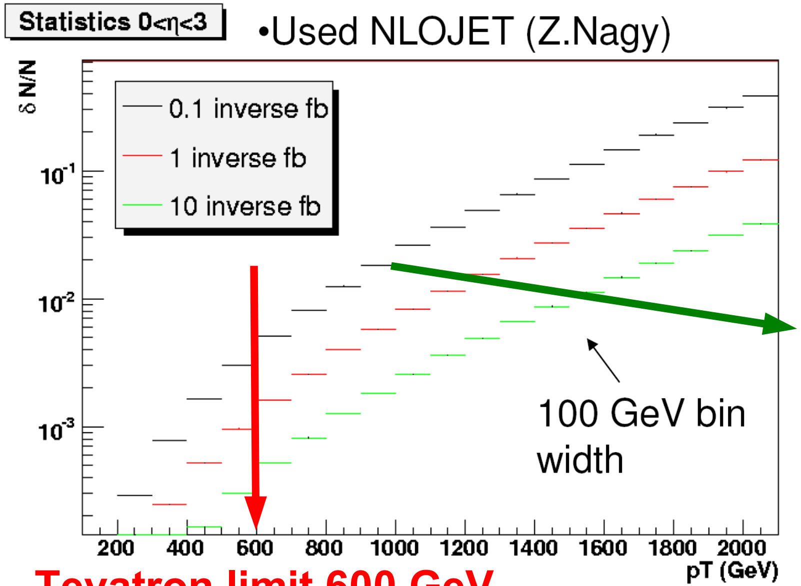
<u>Color code:</u>
Blue: Good description by NLO
Red: Not described by NLO (photons ...)

Inclusive Jets at the LHC

Q C D

Evaluation of jet cross section uncertainties by ATLAS

•Used NLOJET (Z.Nagy)



Tevatron limit 600 GeV

Statistics:

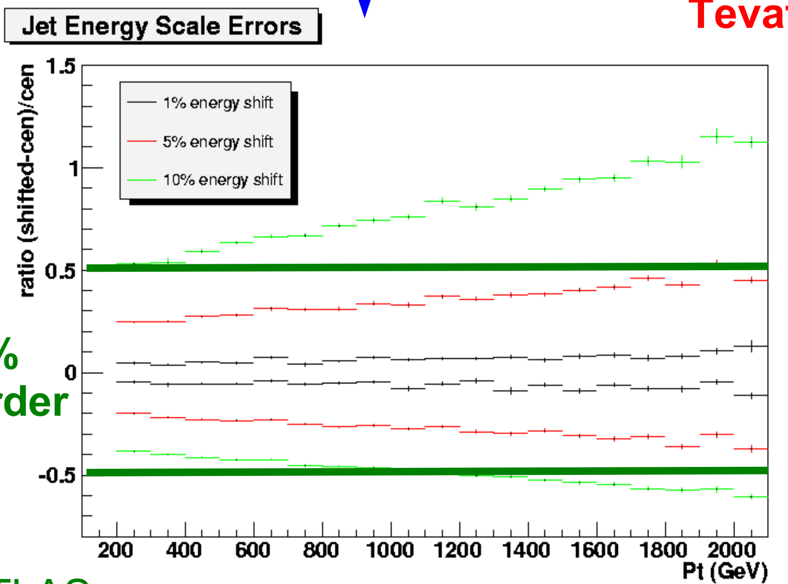
Estimated as √N/N from NLO cross section

- 10 / fb
- 1 / fb
- 0.1 / fb

100/pb LHC: 2% at 1 TeV
30% at 2 TeV

Jet Energy Scale

- 10% shift
- 5% shift
- 1% shift

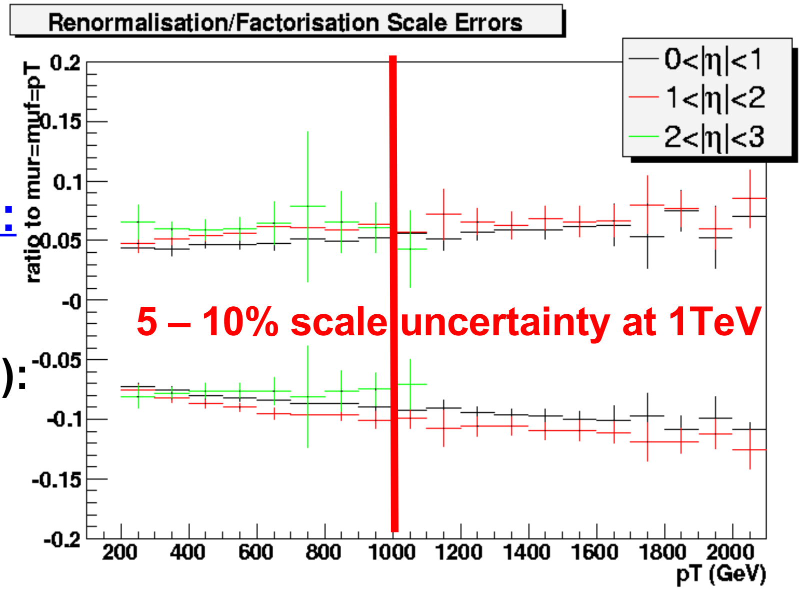


50% border

Scale Uncertainty:

By varying $\mu_r = \mu_f$ from pT/2 to 2 pT (in pseudorapidities):

- 2 < |η| < 3
- 1 < |η| < 2
- 0 < |η| < 1

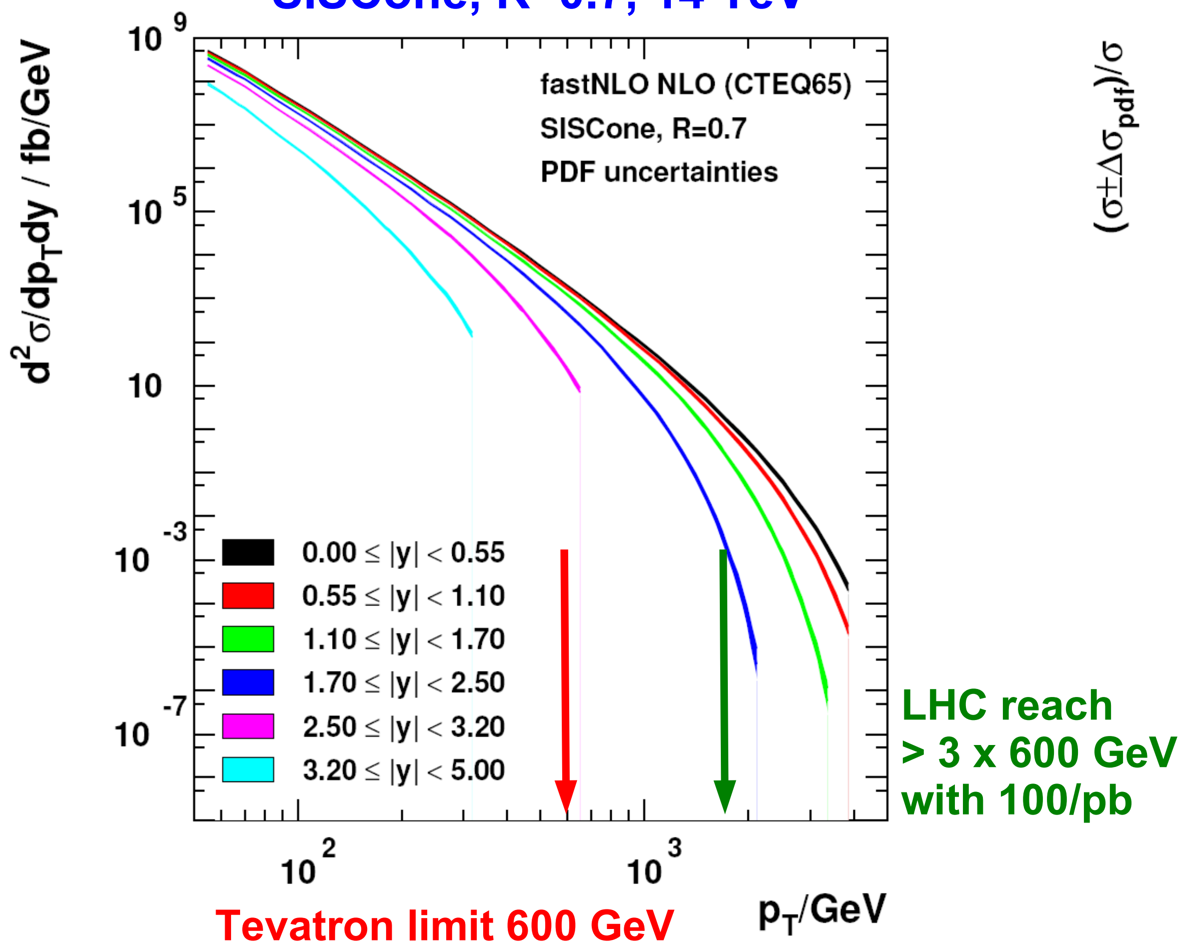


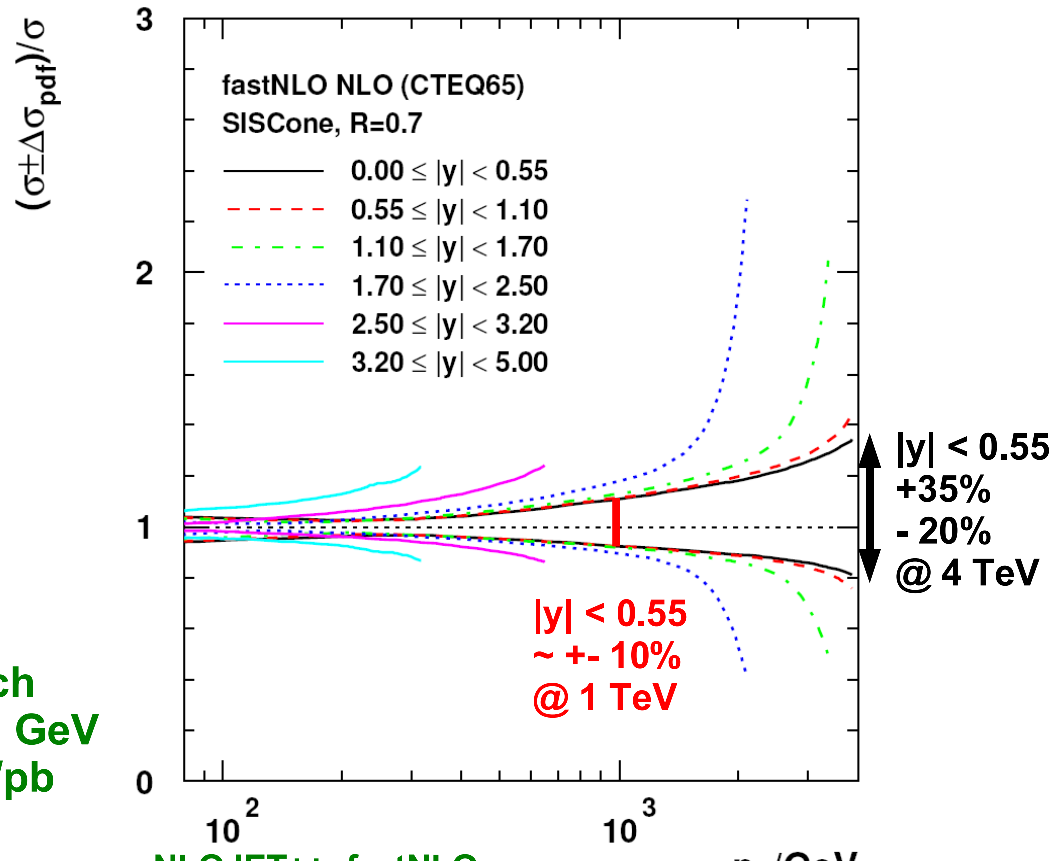
ATLAS

Inclusive Jets at the LHC

QCD

Expected PDF uncertainties according to standard procedure with error sets from CTEQ 6.5





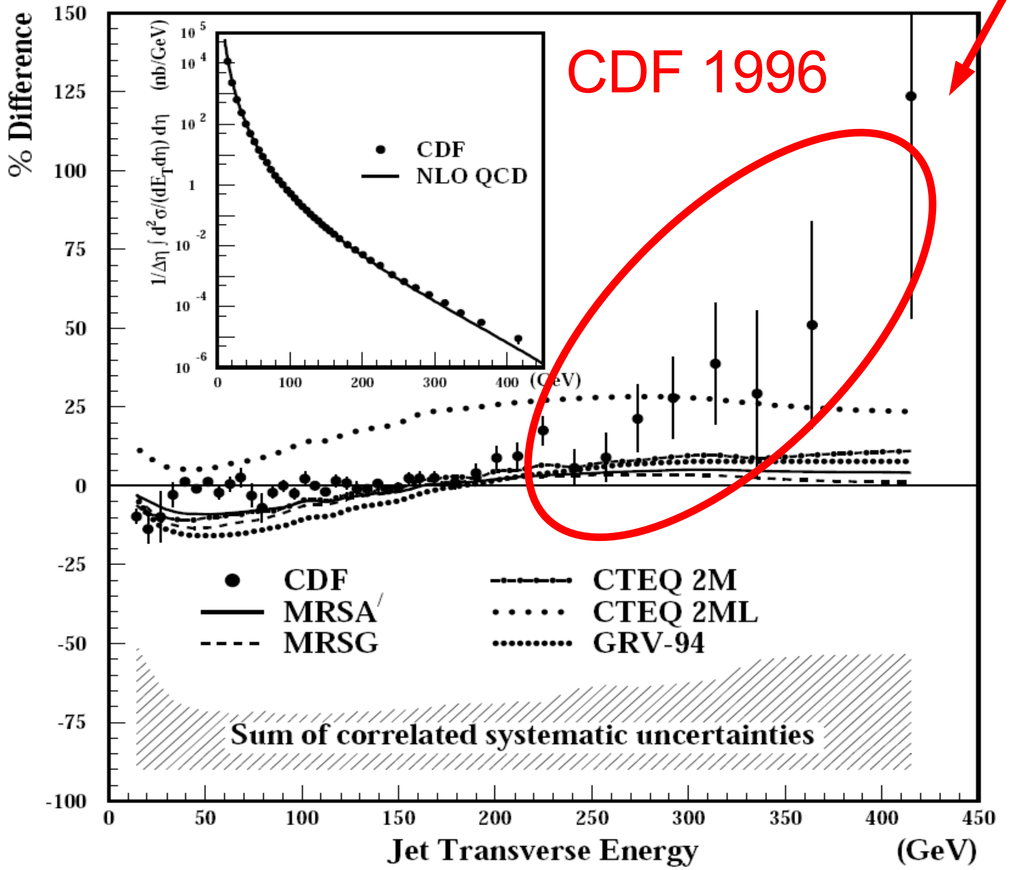
NLOJET++; fastNLO;
fastjet: PLB641 (2006) [hep-ph/0512210],
SISCone: JHEP 05 (2007) 086 [arXiv:0704.0292 (hep-ph)]

Pit Stop: PDF uncertainties

QCD

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(α_s^3) perturbative QCD calculations. ...

Phys.Rev.Lett. 77 (1996)

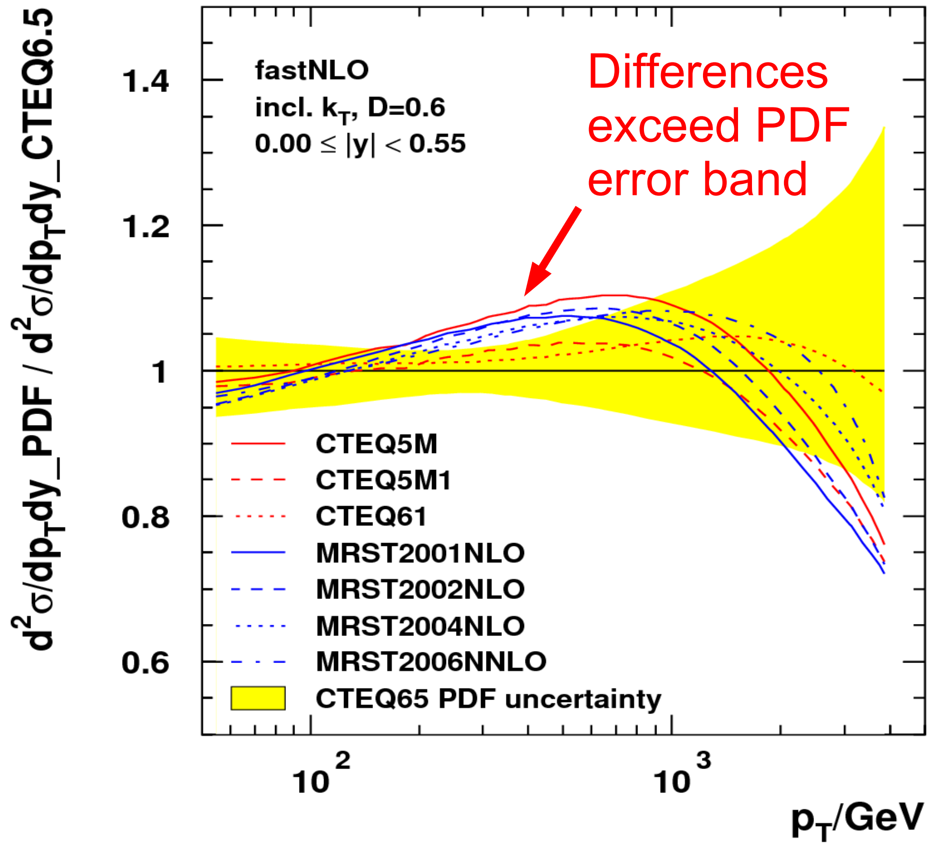


Explained by change in gluon density which then can be constrained by jets!

Today:

Much better estimates of PDF uncertainties

But still ...

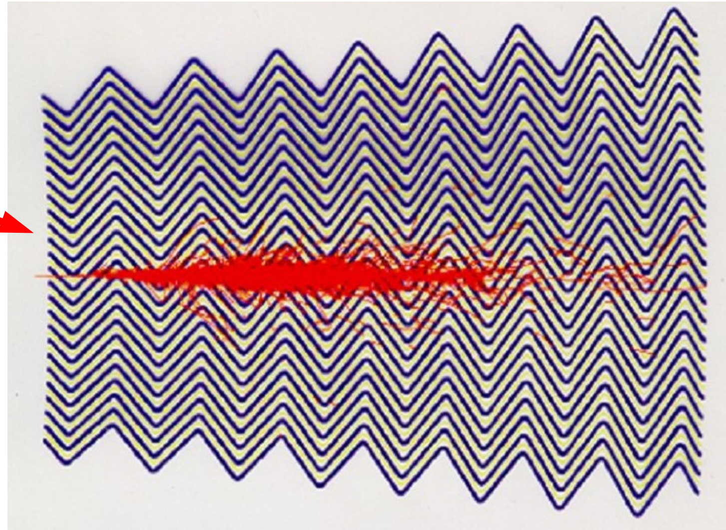


KR

Photons: The Drivers

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

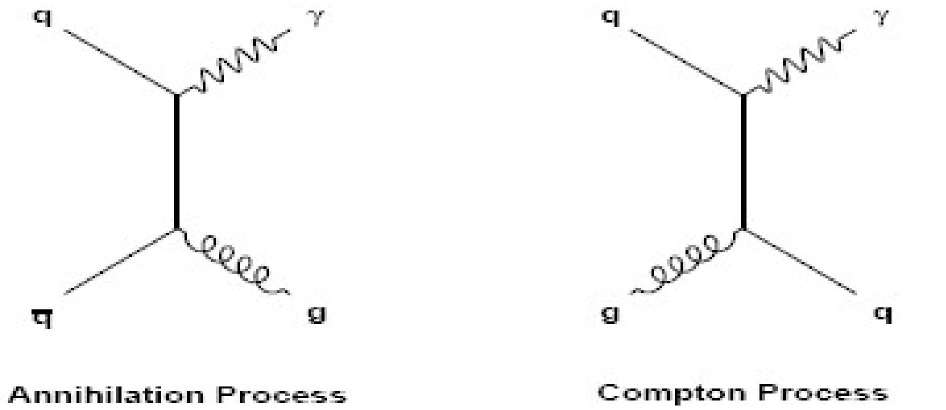
Photons:
- Experimental
- Theory



Gauge boson production gives important additional information:

- Luminosity measurement
- Detector calibration
- PDFs
- Background for new physics :-(

< 20% LO Dominant: > 80%



Photon Rates

QCD

# bunches	β^* (m)	I_b	L ($cm^{-2}s^{-1}$)	Pileup	Photons/hour ($p_T > 20\,GeV$)
1x1	18	10^{10}	10^{27}	low	$3.2 \cdot 10^{-1}$
43x43	18	$3 \cdot 10^{10}$	$3.8 \cdot 10^{29}$	0.05	$1.2 \cdot 10^{2}$
43x43	4	$3 \cdot 10^{10}$	$1.7 \cdot 10^{30}$	0.21	$5.4 \cdot 10^{2}$
43x43	2	$4 \cdot 10^{10}$	$6.1 \cdot 10^{30}$	0.76	$2.0 \cdot 10^{3}$
156x156	4	$4 \cdot 10^{10}$	$1.1 \cdot 10^{31}$	0.38	$3.6 \cdot 10^{3}$
156x156	4	$9 \cdot 10^{10}$	$5.1 \cdot 10^{31}$	1.9	$1.6 \cdot 10^{4}$
156x156	2	$9 \cdot 10^{10}$	$1.1 \cdot 10^{32}$	3.9	$3.6 \cdot 10^{5}$

CMS

Not taken into account (Pileup)

Photon rate estimations:

- **Photon pT > 20GeV**
- **Photon |η| < 2.5**

ATLAS trigger simulation results for L = $10^{31} cm^{-2}s^{-1}$:

- **Trigger on photon pT > 20 GeV in |eta| < 2.4**
- **Signal sample: γ+jet (γ generated with pT >10 GeV)**
- **Background from jet-jet sample generated with pT > 15 GeV is 7 Hz**

	Jet energy range (GeV)	Trigger Efficiency%) γ20
1	17-35	75.1 ±0.3
2	35-70	83.5 ±0.3
3	70-140	89.3 ±0.2
4	140-280	91.7 ±0.2
5	280-560	94.4 ±0.2
6	560-1120	92.4 ±1.1

ATLAS

Photon Conversion & Isolation

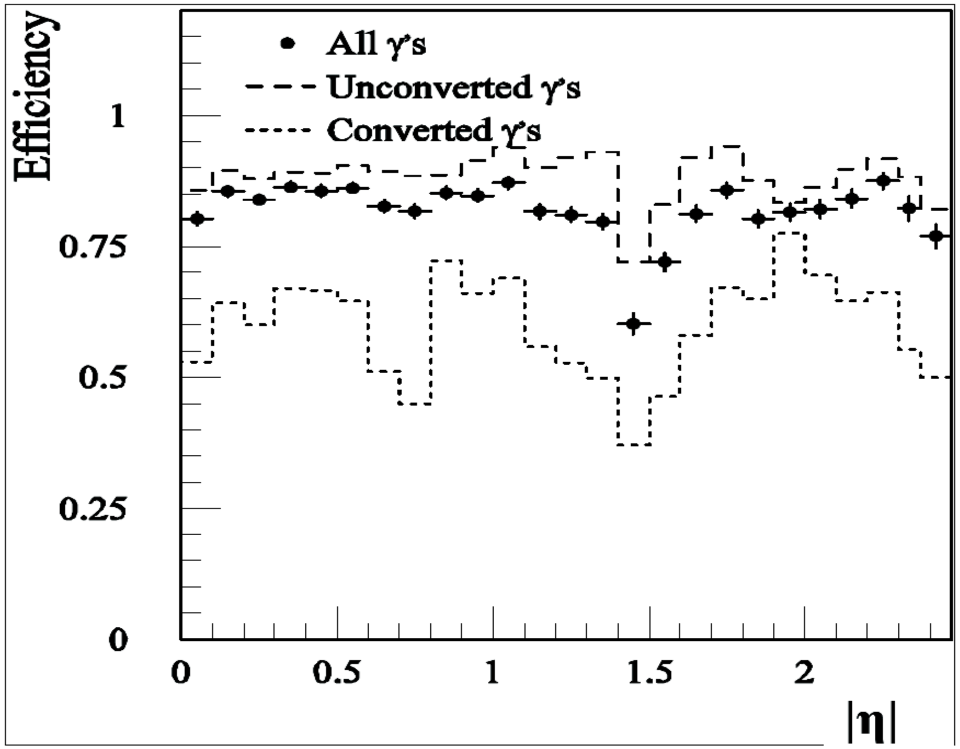
QCD

Important steps:

- Good efficiency including photon conversions
- Proper photon isolation to suppress background

ATLAS photon efficiency:

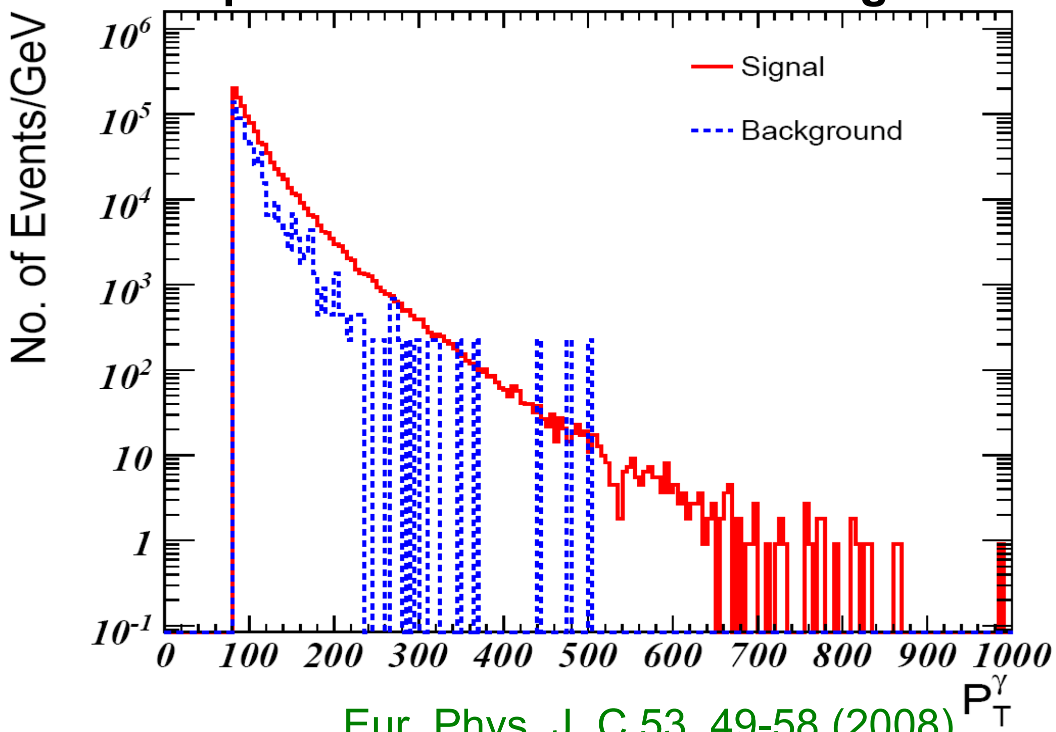
- > 80% at low luminosity
- including converted & unconverted photons



ATLAS

CMS photon study:

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



Eur. Phys. J. C 53, 49-58 (2008).

New Physics: The Drivers

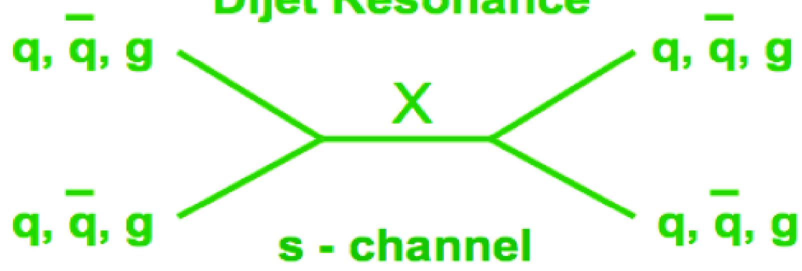
New Physics with Jets:

- **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)

Need $E_{CMS} > M$

- **Di-jet mass distribution**

Dijet Resonance

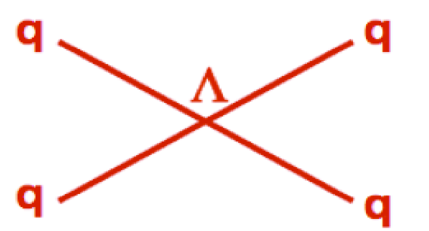


Model	J	Color	Cross Section (pb)					
			M=0.7 TeV		M=2.0 TeV		M=5.0 TeV	
			$\|\eta\| < 1$	$\|\eta\| < 1.3$	$\|\eta\| < 1$	$\|\eta\| < 1.3$	$\|\eta\| < 1$	$\|\eta\| < 1.3$
q*	1/2	Triplet	7.95×10^{2}	1.27×10^{3}	9.01	1.36×10^{1}	1.82×10^{-2}	2.30×10^{-2}
A,C	1	Octet	3.22×10^{2}	5.21×10^{2}	5.79	8.82	1.55×10^{-2}	2.04×10^{-2}
D	0	Triplet	8.11×10^{1}	1.26×10^{2}	4.20	5.97	4.65×10^{-2}	5.75×10^{-2}
G	2	Singlet	3.57×10^{1}	5.47×10^{1}	1.83×10^{-1}	2.60×10^{-1}	2.64×10^{-4}	3.19×10^{-4}
W'	1	Singlet	1.46×10^{1}	2.37×10^{1}	3.49×10^{-1}	5.31×10^{-1}	8.72×10^{-4}	1.17×10^{-3}
Z'	1	Singlet	8.86	1.44×10^{1}	1.81×10^{-1}	2.77×10^{-1}	5.50×10^{-4}	7.26×10^{-4}

  - **Contact Interactions**
    - ★ Sensitive to Scale $\Lambda >> \sqrt{s}$!

$$L_{qq} = \frac{Ag^2}{2\Lambda^2}(\bar{q}_L\gamma^{\mu}q_L)(\bar{q}_L\gamma_{\mu}q_L)$$

Contact Interaction



CMS

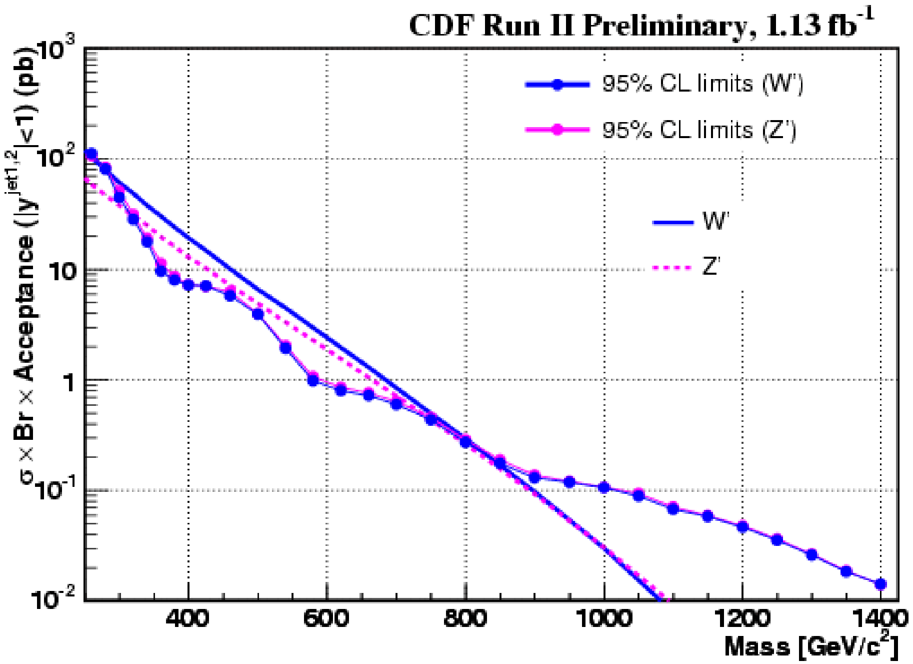
Recent Limits

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

Dijet resonance search

Resonance	Excluded (GeV)	Resonance	Excluded (GeV)
A or C	260 - 1250	D	290 - 630
ρ_{T8}	260 - 1110	W'	280 - 840
q*	260 - 870	Z'	320 - 740

CDF Preliminary 03/2008



Exclusion limits for W' and Z'

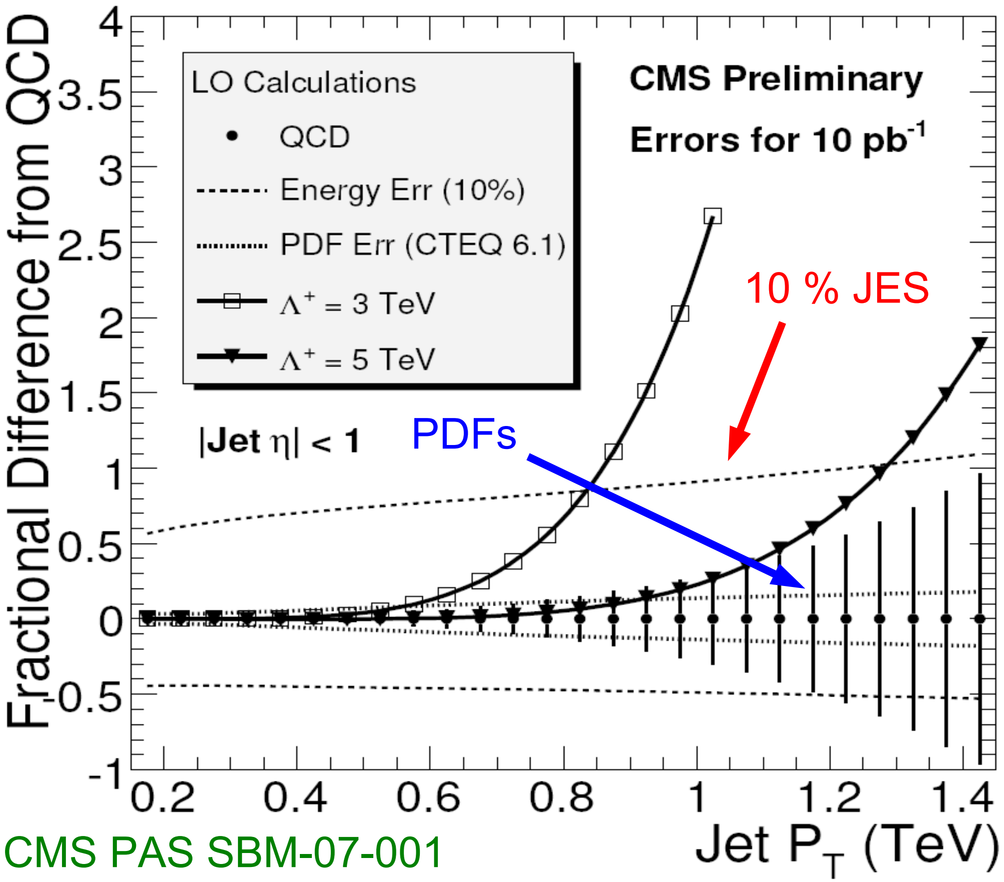
New Physics from Di-jets

QCD

Search for deviation from expected event rate:

- QCD from PYTHIA (here) or NLO
- Contact interaction: PYTHIA or LO

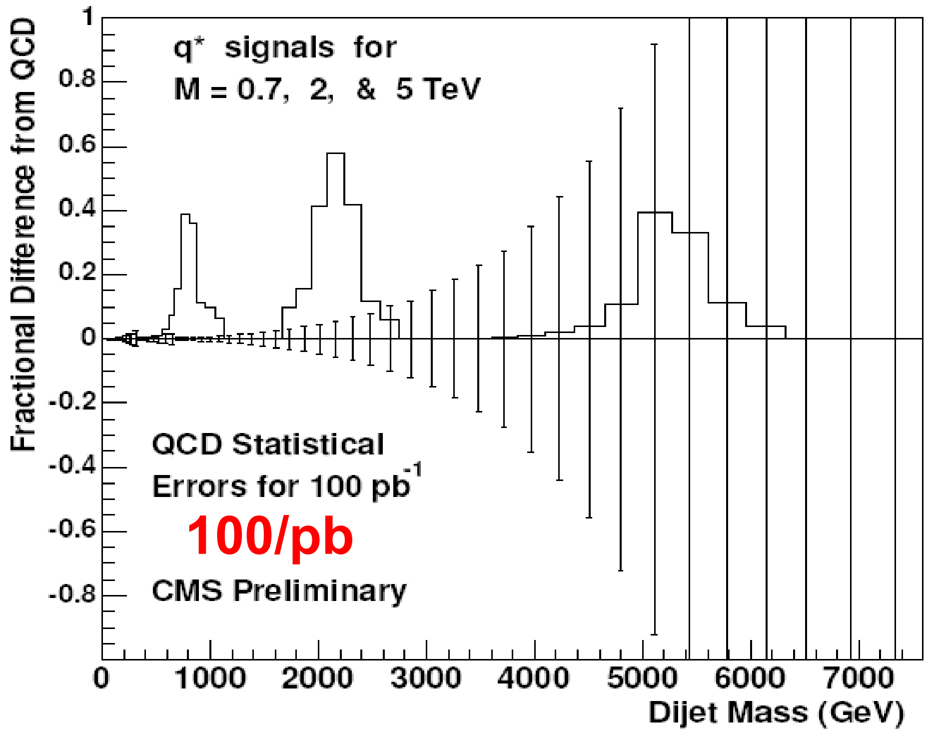
Cross section ratios



CMS PAS SBM-07-001

Search for resonances

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



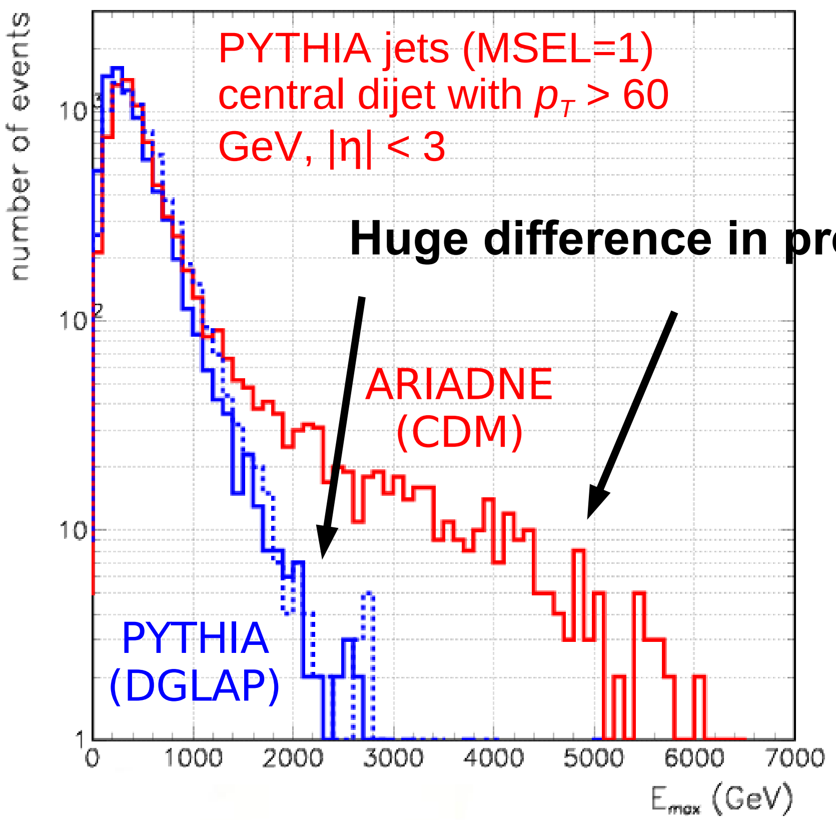
One means to avoid systematics is by looking into cross section ratios in η

Spare Cars

- **Very important to have ...**
- **Only test drive today:**
  - **Forward jets:**
    - **Fwd jets in HF, 3 < |η| < 5 probe x ~ 10^{-4}**
    - **Fwd jets in CASTOR, 5.1 < |η| < 6.5 probe x down to 10^{-6}**
    - **Sensitivity to possible PDF saturation effects**

Many talks during this workshop!

“Jet energy” in forward detector (CASTOR)



CMS

Spare Cars

- **Very important to have ...**
- **But did not race at all this time:**
  - **Drell-Yan**
  - **Event shapes** ➔ Talk by G. Luisoni
  - **3-jets, 3-jet rates**
  - **4-jets:**
    - **From QCD**
    - **From double parton interactions** ➔ Talk by D. Treleani
    - **From ttbar → bbar qq'bar $l\nu_l$**
  - **Double parton interactions in γ + 3 jets** ➔ Talk by F. Bechtel
  - **...**

Outlook

- Team ATLAS and Team CMS are preparing for first LHC data soon!
- Some tough experimental systematics to deal with
  - Trigger, alignment, jet energy scale, photon isolation, ...
- LHC will explore unknown territory in QCD
- First measurements, even with low grade 900 GeV fuel, will be QCD:
  - Minimum Bias tracks, Underlying Event
  - Important for detector alignment and MC tuning
- Measurements of jets and photons are important tests of QCD:
  - Angular distributions, inclusive jets, di-jets, photon+jets, di-photons, forward jets
  - Calibration of the calorimeters
  - Better understanding of dominant background to many new physics channels
  - Constraints on PDFs
- New physics might be just ahead!

Final Score

It's a race! It's a race!

And QCD is in the Pole Position!

What about you?

Thanks to all colleagues helping in preparing this presentation!

Backups

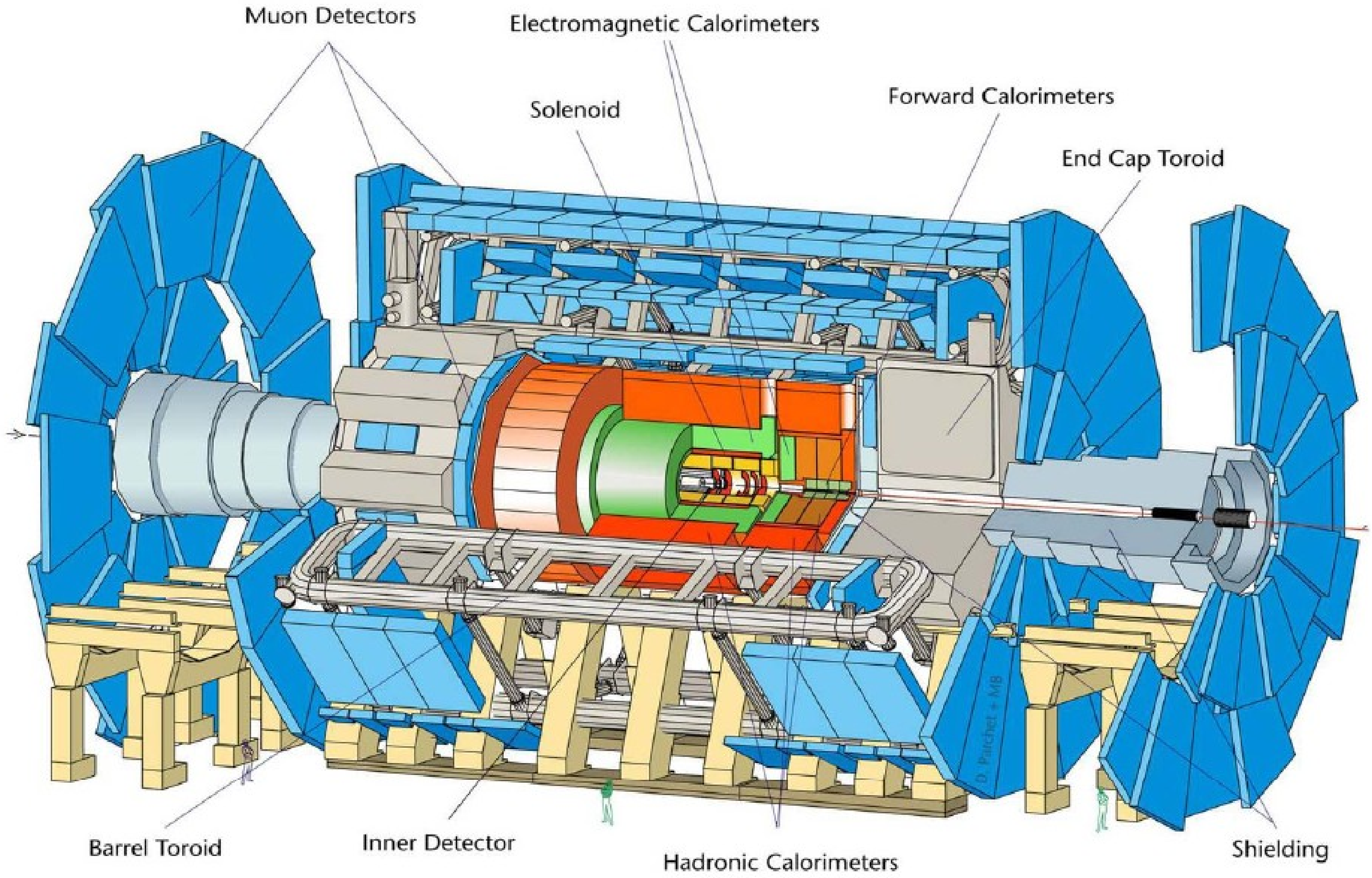
ATLAS Detector

Inner Detector (ID) tracker:
- Si pixel and strip + transition rad. tracker
- $\sigma(d_0)$ = 15µm@20GeV
- $\sigma/p_T \approx 0.05\% p_T \oplus 1\%$

Calorimeter
- Liquid Ar EM Cal, Tile Had.Cal
- EM: $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
- Had: $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$

Muon spectrometer
- Drift tubes, cathode strips: precision tracking +
- RPC, TGC: triggering
- $\sigma/p_T \approx$ 2-7%

Magnets
- Solenoid (ID) → 2T
- Air toroids (muon) → up to 4T



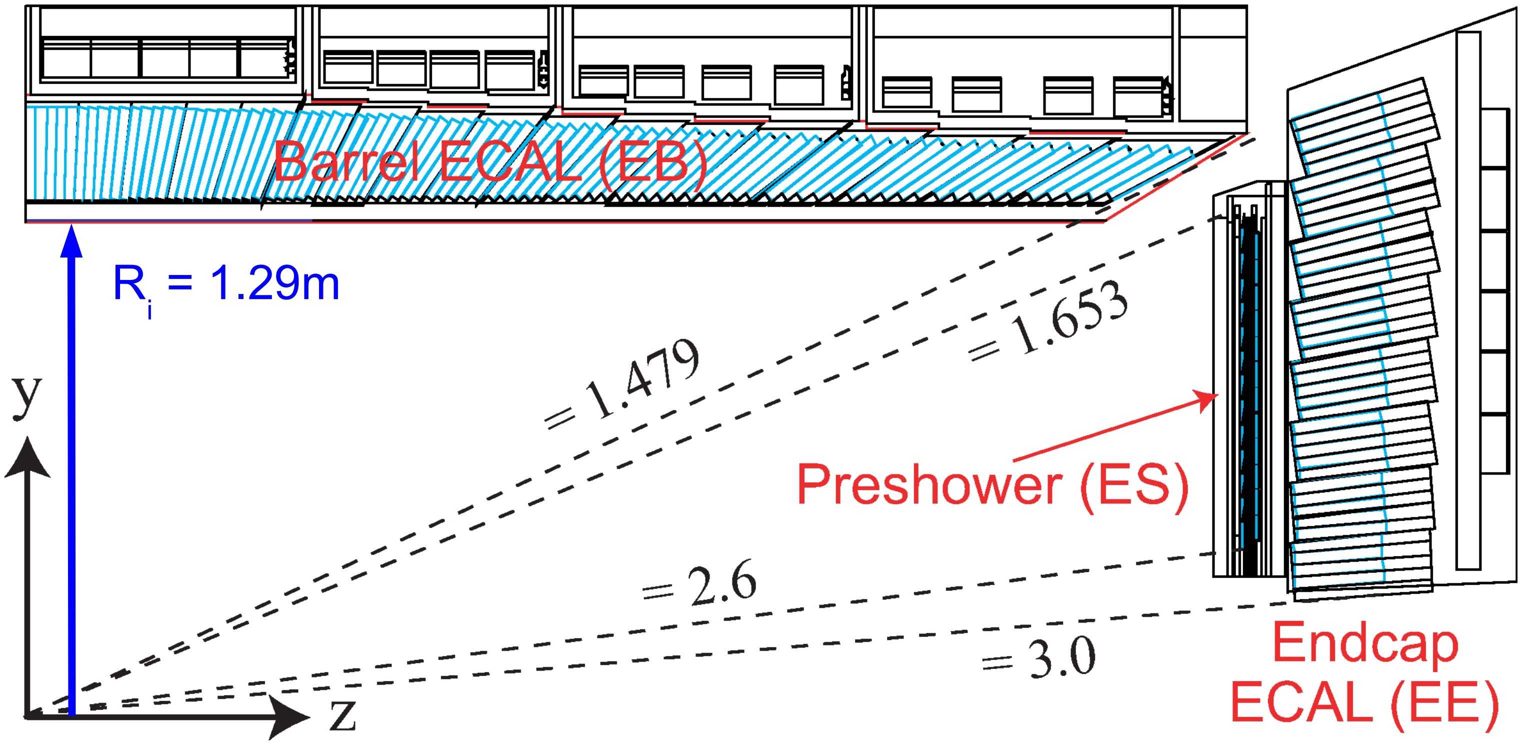
Full coverage for |η|<2.5, calorimeter up to |η|<5

CMS Electromagnetic Calorimeter

Barrel (EB):
- η segments: 2x85
- φ segments: 360

→ 61200 crystals ($PbWO_4$, 26 X_0)

→ Δη x Δφ ≈ 0.0174 x 0.0174



Energy resolution from test beam:

S = 3.63%, N = 124 MeV, C = 0.26%

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

Endcaps (EE):
- (x,y) grid on two halfs
- front face 28 x 28 mm^2

→ 2 x 2 x 3662 crystals = 14648 ($PbWO_4$, 25 X_0)

CMS Hadronic Calorimeter

QCD

HCAL (tower structure):
- Barrel (HB): |η| < 1.4, 2304 towers
- Endcaps (HE): 1.3 < |η| < 3.0, „ towers
- Outside coil (HO): |η| < 1.26 (tail catcher)

→ 4608 towers (Plastic scintillator tiles, ≈ 10 λ_N)

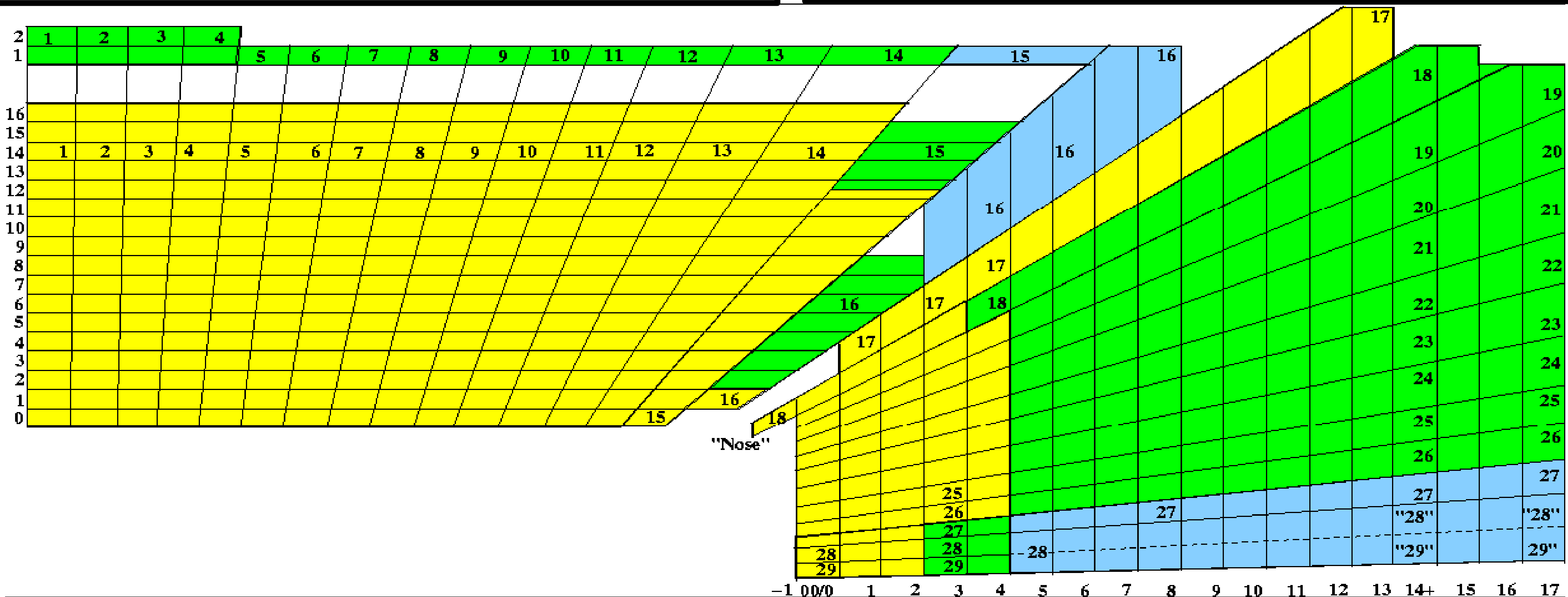
→ Δη x Δφ ≈ 0.087 x 0.087 → 0.350 x 0.175

- Forward (HF): 2.9 < |η| < 5.0 (not shown)

→ 2 x 900 towers (Quartz fibers, ≈ 10 λ_N)

→ Δη x Δφ ≈ 0.111 x 0.175 → 0.302 x 0.350

CASTOR calorimeter (not shown):
- 5.1 < |η| < 6.5, ≈ 22 X_0, ≈ 10 λ_N

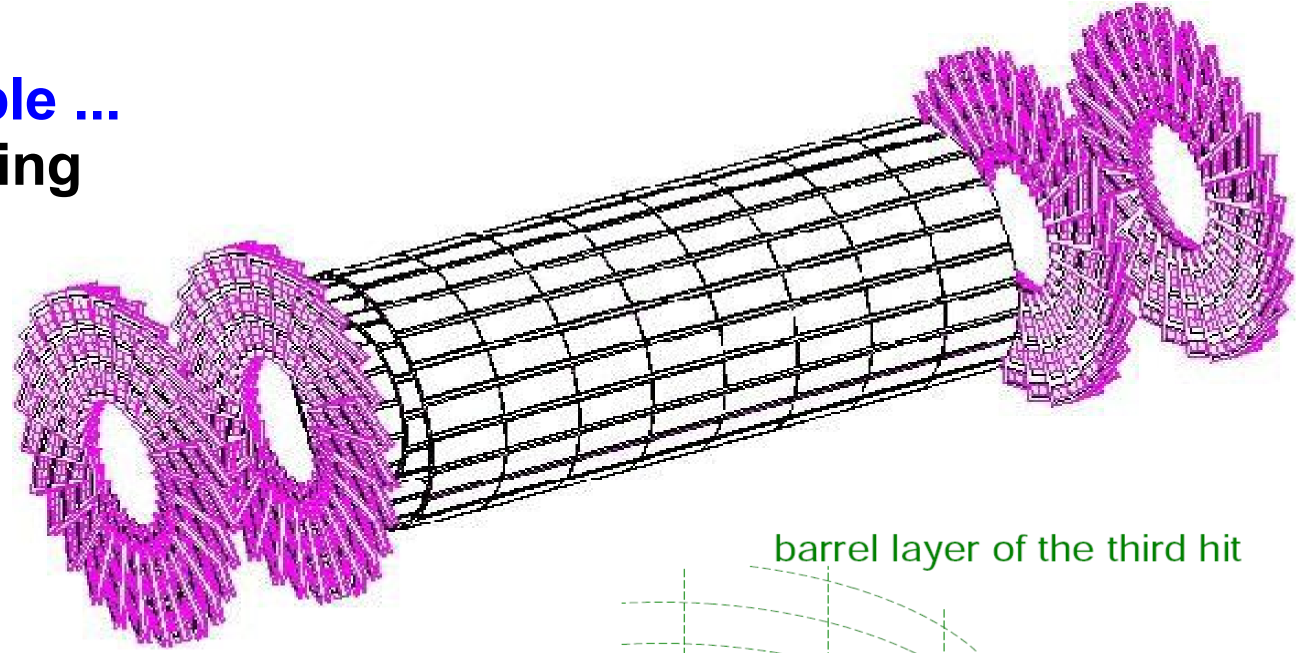


CMS Pixel Triplets

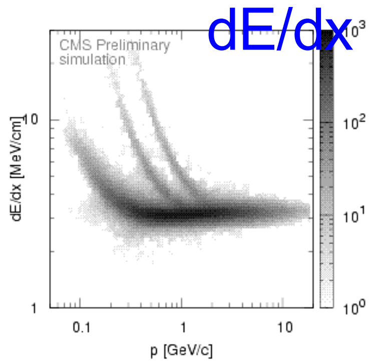
QCD

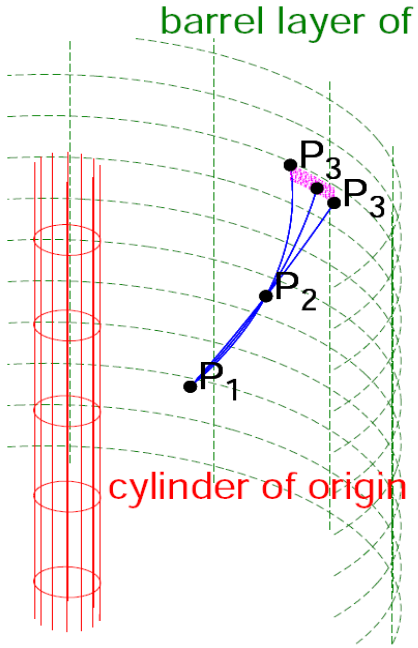
One of the first analyses possible ...

Here: 1.9 million events, assuming one month of running with 1 Hz allocated bandwidth



- **CMS pixel detector:**
  - 3 barrel layers (4, 7 and 10 cm radii) and 2 endcap on each side
  - 100 × 150 μm^2 pixels, 2% occupancy even at dN/dch = 5000
- **Hit triplets:**
  - Use pixel hit triplets instead of pairs, loss of acceptance but lower fake rate
  - Reconstructing down to pT = 0.075 GeV/c





Hadron Spectra Systematics

QCD

CMS Pixel triplets

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

Correction	Dependence on kine	part	mult	Corr. [%]	Syst. [%]
Trigger	no	no	yes	15	5
Geometrical acceptance	yes	yes	no	10-20	2
Algorithmic efficiency	yes	yes	no	10-20	2
Multiple track counting	yes	no	no	small	small
Fake track rate	yes	no	yes	small	small
Feed-down	yes	yes	no	2-15	1-2
η, p_T resolution	no	no	no	1-5	1-5
Total	yes	yes	yes		7-9

CMS PAS QCD-07-001

ATLAS track reconstruction

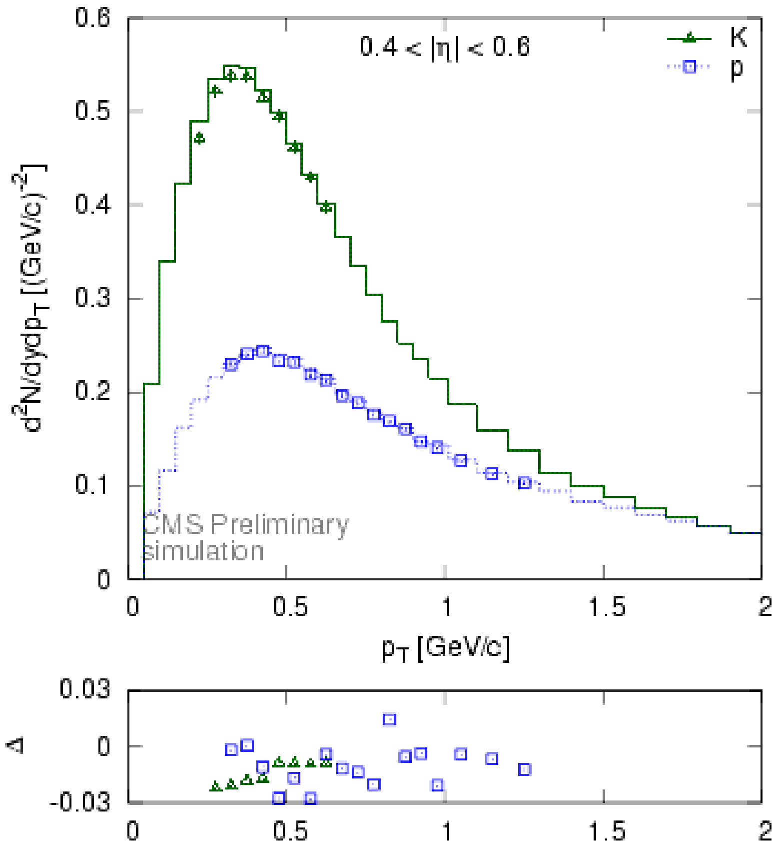
Summary of systematic uncertainties

Track selection cuts	2%
Mis-estimate of secondaries	1.5%
Vertex reconstruction	0.1%
Mis-alignment	6%
Beam-gas & pile-up	1%
Particle composition	2%
Diffractive cross-sections	0.1%
Total:	**6.9%**

ATLAS

Hadron Spectra: dE/dx

Kaon and proton spectra with dE/dx analysis



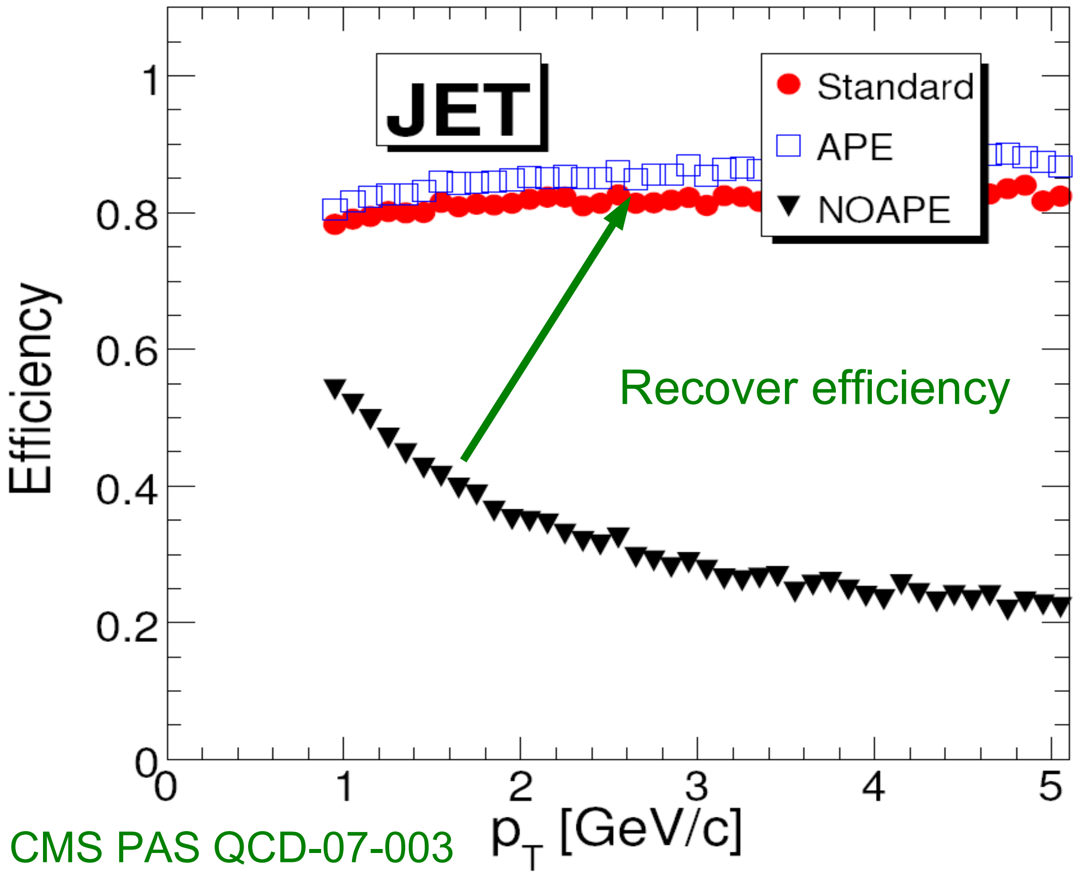
CMS PAS QCD-07-001

Tracking Performance

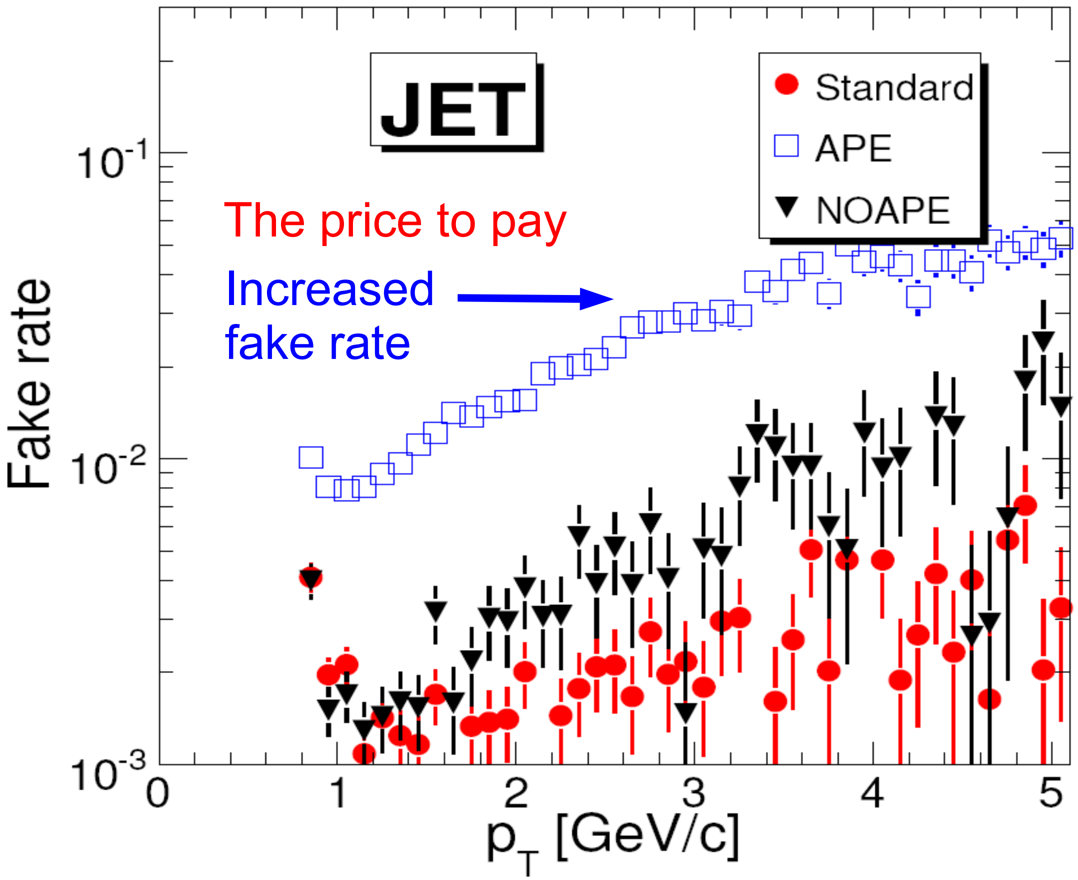
<u>Comparison of tracking performance for:</u>

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

Track reconstruction efficiency



Fake rate

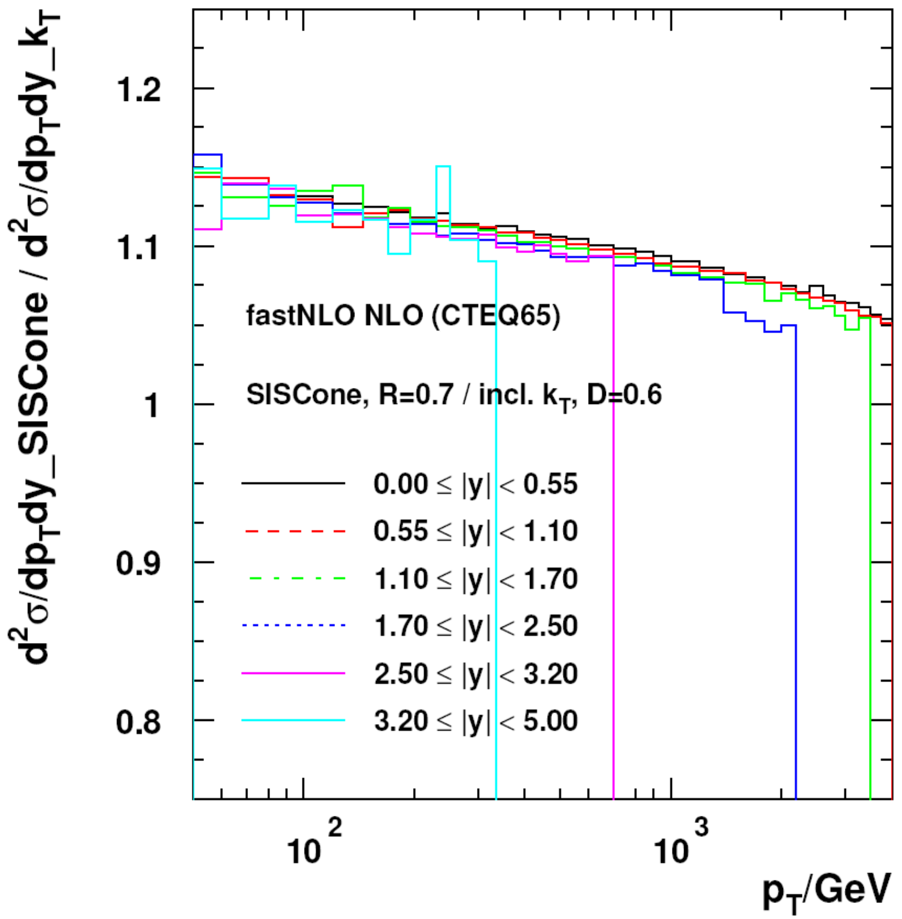


CMS PAS QCD-07-003

SISCone / kT

SISCone, R=0.7 / kT, D=0.6

About 12 – 8% higher x section compared to kT



NLOJET++; fastNLO;
fastjet: PLB641 (2006) [hep-ph/0512210],
SISCone: JHEP 05 (2007) 086 [arXiv:0704.0292 (hep-ph)]

Jet Input

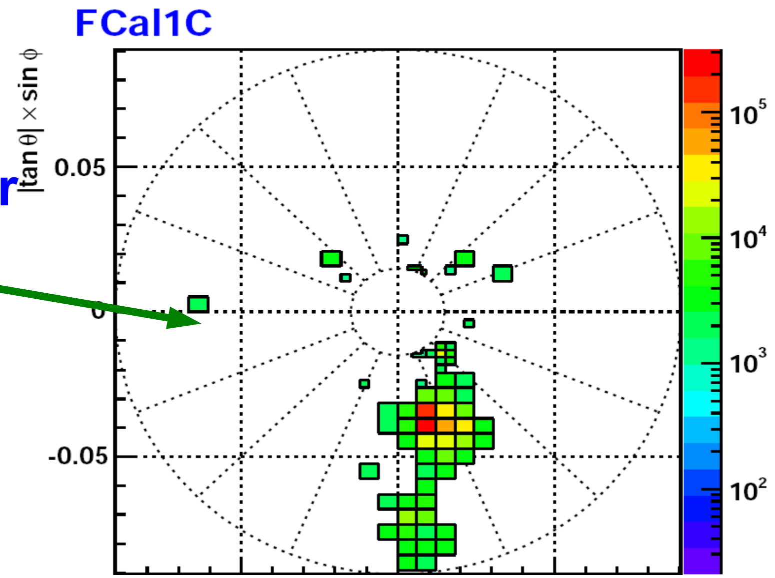
QCD

Habitual jet input:
- calorimeter towers (ATLAS & CMS)

Additionally:
- topological clusters of lAr cells (ATLAS)

4σ noise cut to seed cluster maker

Colors show $|E_{cell}|$ on log scale in MeV



Pro's & Con's

Towers

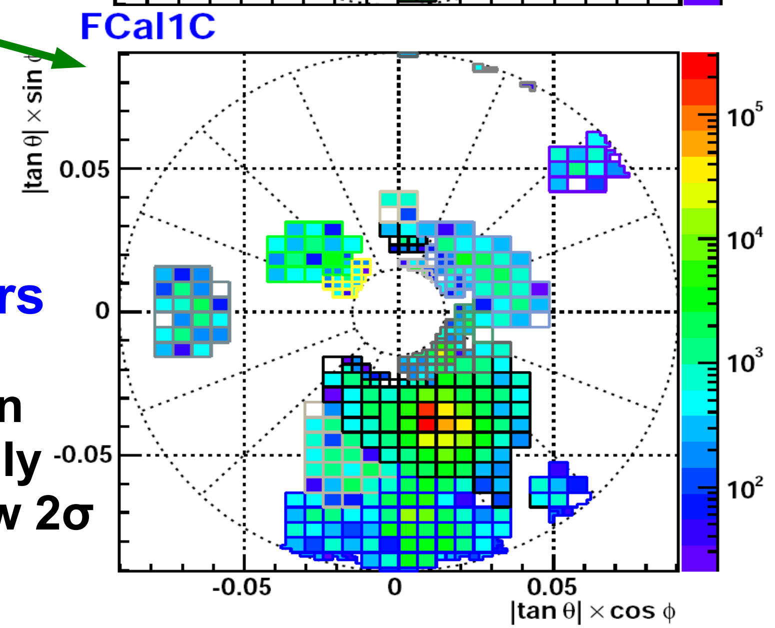
- + fixed size Δφ × Δη ≈ 0.1 × 0.1
- + no seeds – all cells end up in towers
- − no noise or pile-up suppression
- − do not contain showers

Clusters

- + provide efficient noise and pile-up suppression
- + optimized to contain showers of individual hadrons
- − typically have detector region dependent size

Determines topological clusters

Cells in signal region reintegrate previously cut noise cells below 2σ



ATLAS

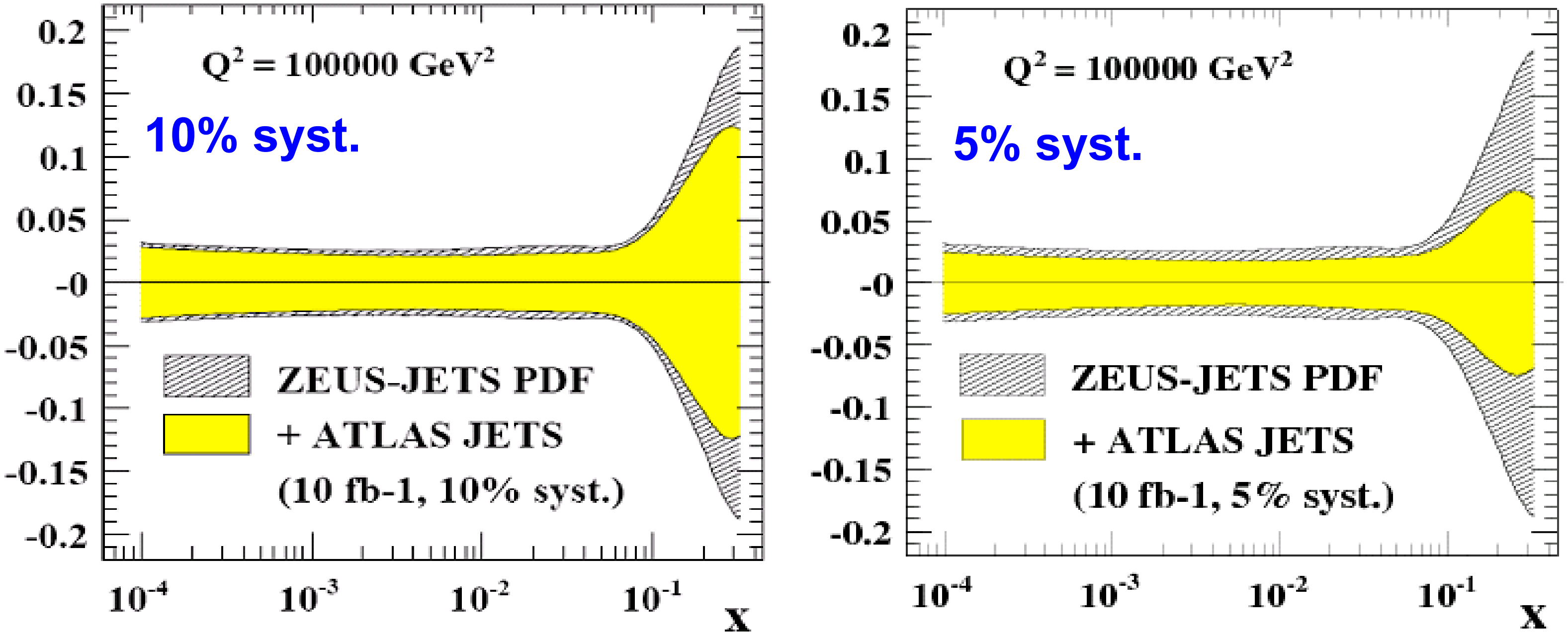
Constraining PDFs

QCD

One example:

Include in ZEUS fit:
ATLAS pseudo jet data,
0<η<1,1<η<2, 2<η<3,
pT up to 3 TeV, L_{int} = 10/fb

Gluon fractional uncertainty



Reduced systematics has larger effect than just statistics

Did not mention:
Drell-Yan
Forward jets
Photon + jets ...

➡ Previous talk and PDF sessions on Wednesday

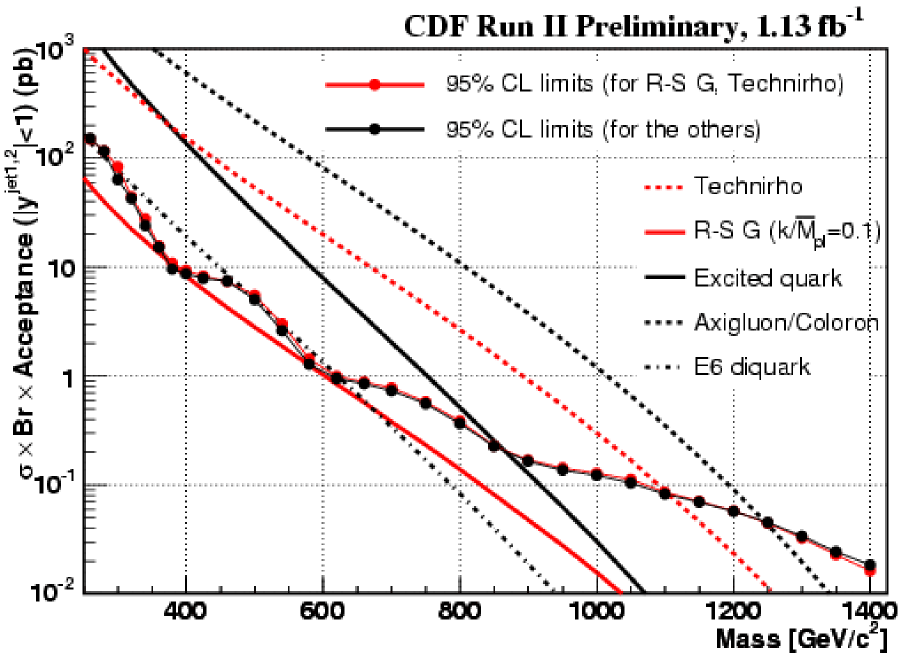
Recent Limits

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

Dijet resonance search

Resonance	Excluded (GeV)	Resonance	Excluded (GeV)
A or C	260 - 1250	D	290 - 630
ρ_{T8}	260 - 1110	W'	280 - 840
q*	260 - 870	Z'	320 - 740

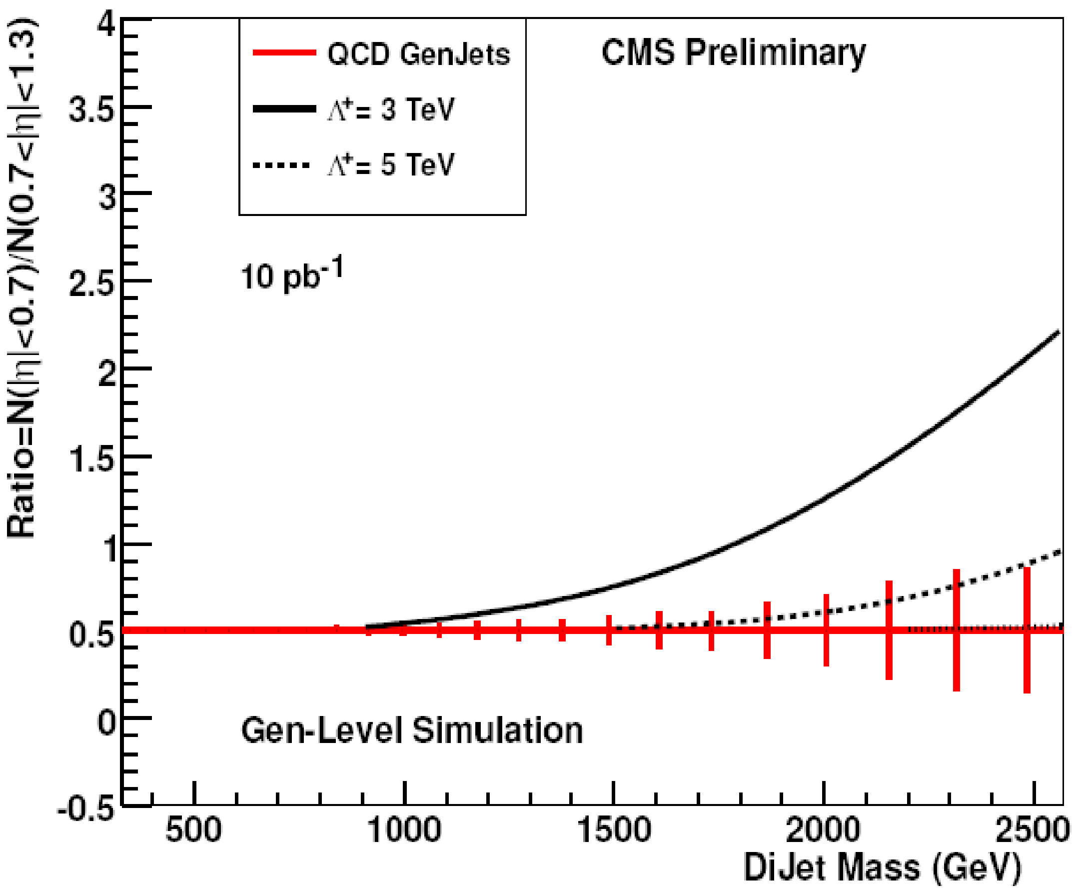
CDF Preliminary 03/2008

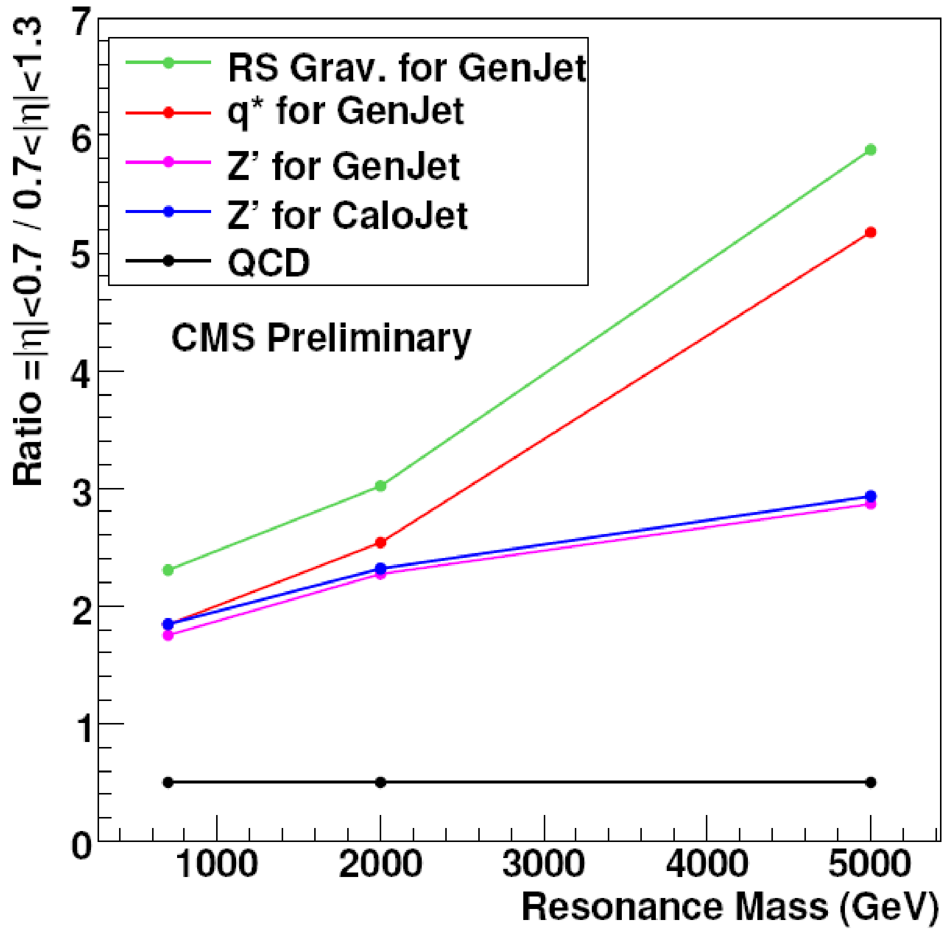


Dijet Ratios

Q C D

Sensitivity to new physics from dijet ratios in pseudo-rapidity





CMS PAS SBM-07-001

Some UA1 Quotations

QCD

- **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** ...