Physics with jets at LHC and Tevatron

some selected topics

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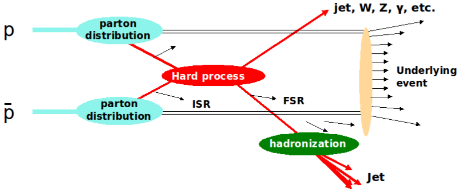
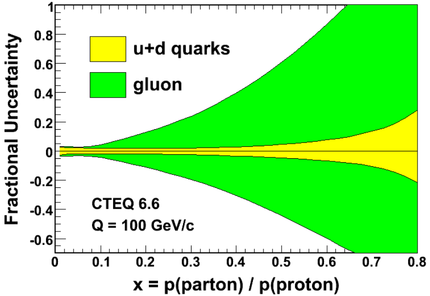
High E_T jet production at hadron colliders

- test perturbative QCD
- constrain structure of the proton

→ parton distribution functions (PDFs) in particular: inclusive jet production sensitive to gluon PDF

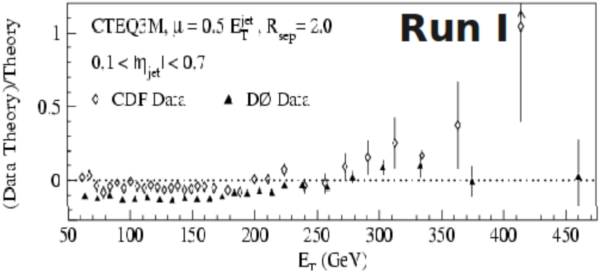
- measure important backgrounds to searches for Higgs, Supersymmetry, and other new physics
  - processes with large jet multiplicities only calc. to LO → large uncert.
  - data to constrain models, to tune generators for Tevatron and LHC
  - also important: jets in association with W/Z (tomorrow's topic)
- search for new phenomena in signatures with jets (e.g. resonances)





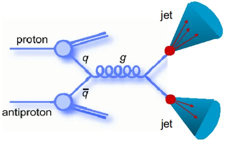
New Physics vs. Standard Model: e.g. quark substructure?

- quark substructure would result in an increased cross section at large E_T (cf. elastic → inelastic *ep* scattering)



- before one can claim discovery, need to fix:
  - jet energy calibration
  - gluon PDF at large x

Jet reconstruction



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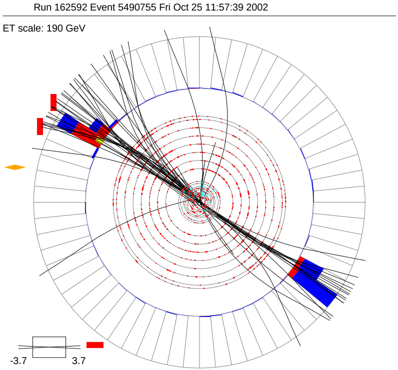
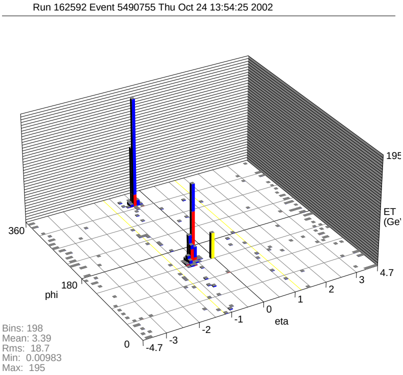
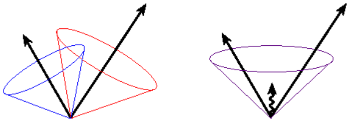


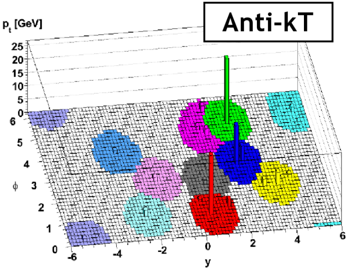


Jet reconstruction (see also Philipp's lecture)

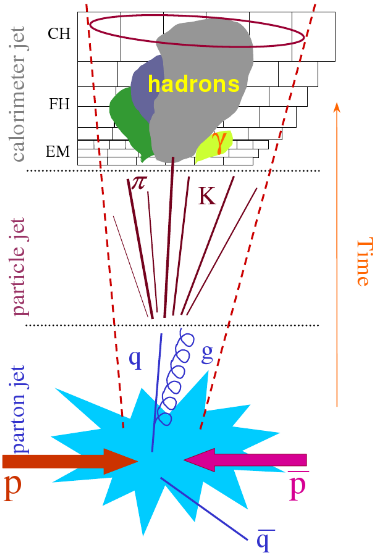
- Tevatron: standard in Run II: seeded, iterative, midpoint cone algorithm
  - use particles (calorimeter tower) as seeds
  - add particles within cone using 4-vectors (E-scheme)
  - iterate until stable
  - use mid-points between jets as additional seeds
    $\rightarrow$ improved infrared stability
  - split/merge jets with overlapping cones



- LHC: standard at ATLAS and CMS: anti-k_T algorithm
  - sequential clustering: successive recombination of particles using distance measure
    $d_{ij} = \min(k_{T_i}^{-2}, k_{T_j}^{-2}) \Delta R_{ij}/R$
    $\rightarrow$ clustering: high $\rightarrow$ low p_T
  - $\sim$ cone-shaped jets of radius R
  - infrared and collinear safe



Jet production and measurements



- unfold measurements to the hadron (particle) level
  - need jet energy scale calibration and energy resolution

$\Downarrow$

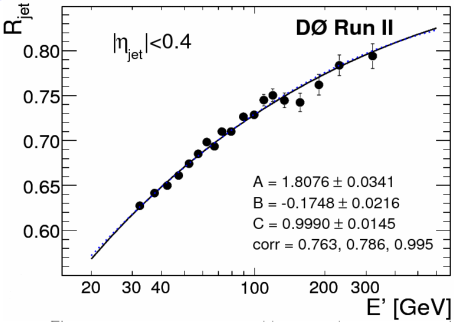
data-theory comparison at hadron (particle) level

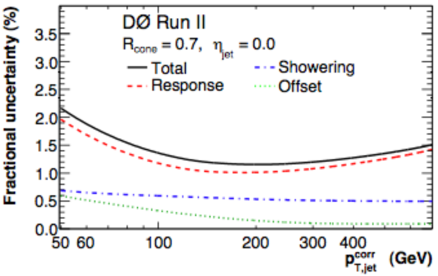
$\Uparrow$

- correct parton-level theory for non-perturbative effects
  - fragmentation/hadronization, underlying event

Jet energy scale (JES) calibration (see also Konstantinos' lecture)

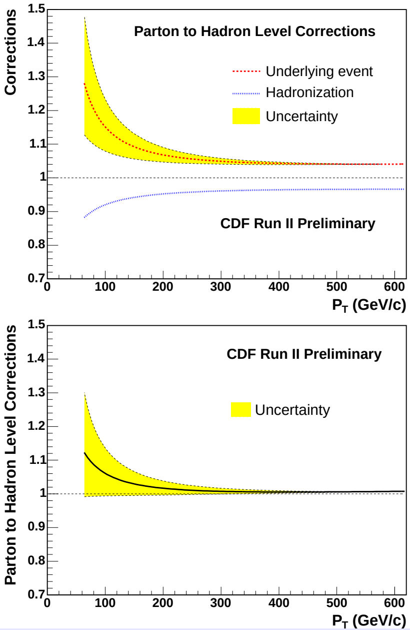
- $E_{\text{particle}} = \frac{E_{\text{cal}} - O}{R \cdot S}$
  - E_{cal}: measured energy (calorimeter, at EM scale)
  - O: offset energy: noise from electronics, uranium, pileup, multiple collisions
  - R: calorimeter response: determined from E_T-balance in γ+jet events
  - S: showering correction: net flow of energy in and out of cone
- DO: JES uncertainties as low as 1.2% for central jets with $p_T \sim 100\,\mathrm{GeV}$ $\leftarrow$ 7 years of work!





Parton to hadron correction

- parton-level prediction (e.g. NLO pQCD) needs to be corrected for non-perturbative effects
  - hadronization: particles originating from parton go outside jet cone (note: first hard gluon emission is already accounted for by NLO pQCD)
  - underlying event contributes energy to jet cone not associated with hard scatter
- correction factor and uncertainty estimated using event generators (e.g. (PYTHIA, HERWIG)
- e.g. midpoint cone, $R = 0.7$



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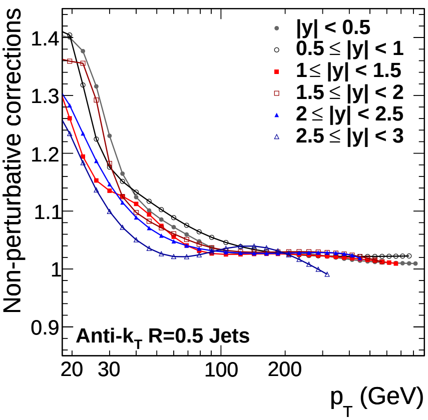
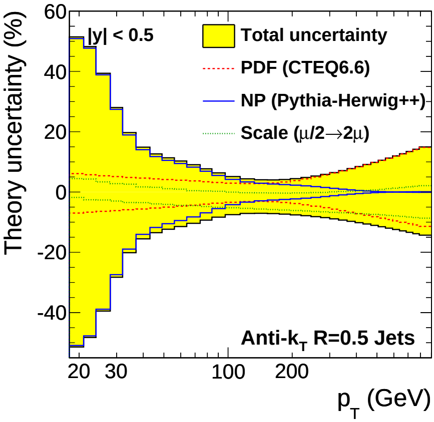
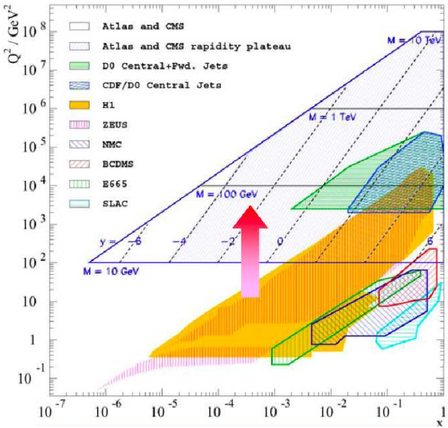




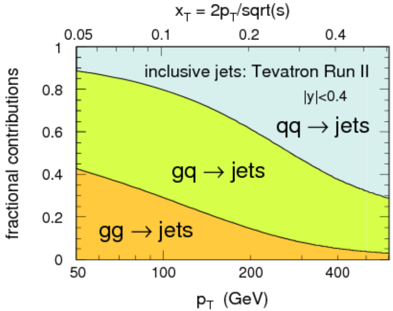
- e.g. anti-k_T, R=0.5 (CMS)
- near cancellation of hadronization and underlying event correction at large jet p_T
- large uncertainties at low p_T

Inclusive jet production

- kinematic reach in (x, Q^2) compared to HERA and fixed target experiments



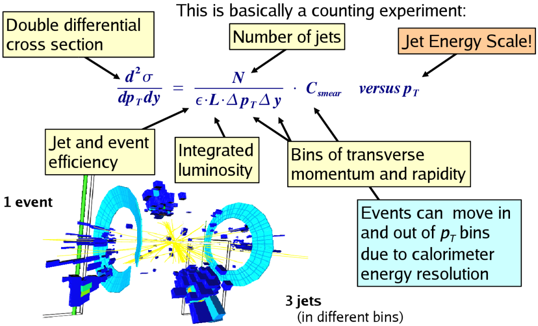
- Tevatron: sensitive to PDFs at large momentum fractions x and scales Q^2
- LHC: reaching even higher Q^2 and low x
- sensitive to gluon content of the proton



Towards a measurement of $\frac{d^2\sigma}{dp_T dy}$ for inclusive jet production

- reminder: rapidity of particle with E, p_z: $y \equiv \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

  note: if $p \gg m$:
  $y \approx \frac{1}{2}\ln\left(\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z}\right) = -\ln\left(\tan\frac{\theta}{2}\right) \equiv \eta$
  η: pseudo-rapidity



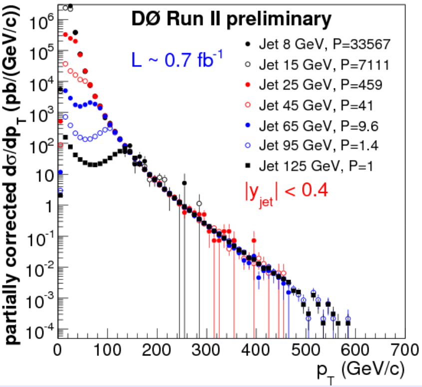
- ingredients:
  - trigger
  - event selection
  - background subtraction
  - jet energy calibration (already discussed)
  - jet energy resolution
  - jet reconstruction efficiencies
  - unsmearing/unfolding

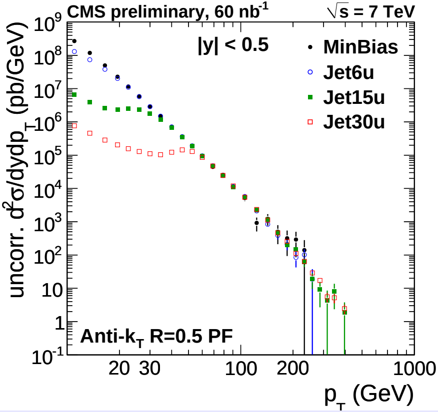
Trigger: raw spectra

- inclusive jet triggers are prescaled except for highest E_T threshold

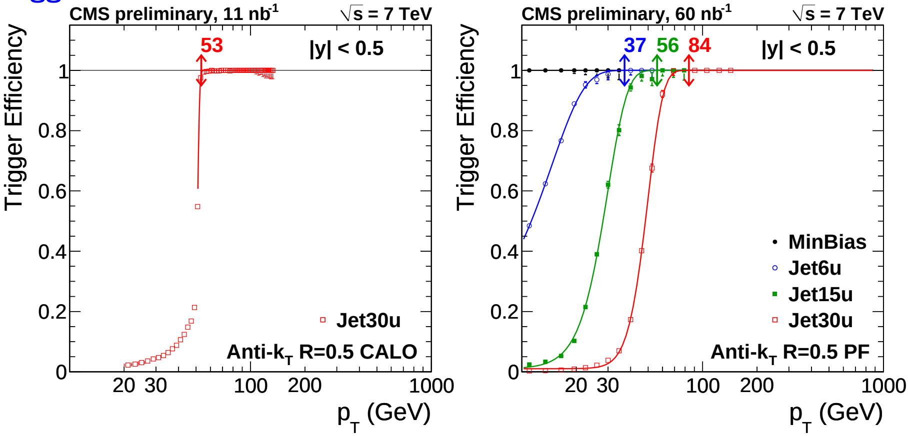
→ for each p_T bin: use fully efficient trigger with lowest possible prescale

- determine trigger efficiency using trigger with lower threshold (or minimum bias trigger for lowest threshold)





Trigger efficiencies



- use efficiency plateau to avoid trigger systematics

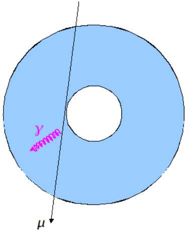
$\longrightarrow$ sharp turn-on required for efficient data taking

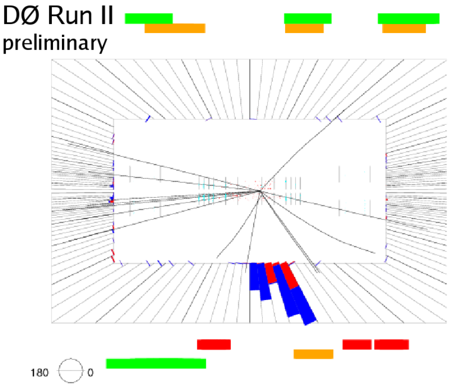
- using a different jet definition for offline reconstruction than for online triggering widens turn-on (e.g. particle-flow vs. calorimeter tower)

Background sources

- physics background: other sources of genuine jets essentially negligible
- instrumental backgrounds, fake jets
  - spurious jets from noisy cells, EM objects: remove with jet quality & shape cuts
  - remaining source (DØ): bremsstrahlung from cosmic rays

    $\rightarrow$ cut on $p_T/\not{E}_T$ ratio
  - another common variable to remove cosmic ray and beam related bgd.: $\not{E}_T$ significance $\not{E}_T/\sqrt{\sum E_T}$





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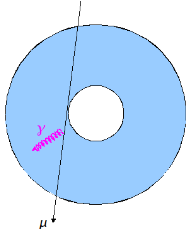
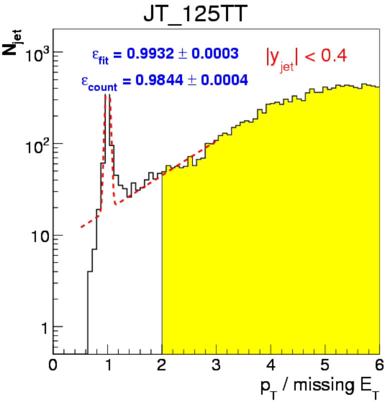
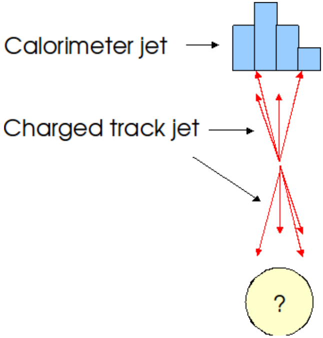
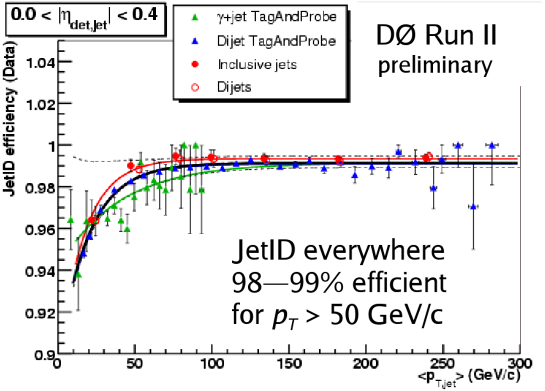




Jet ID efficiencies

- JetID efficiency can be determined with the tag-and-probe method
  - tag is a good jet (or a photon) and an opposite track jet
  - probe is a reconstructed jet close to the track jet





Jet energy resolution

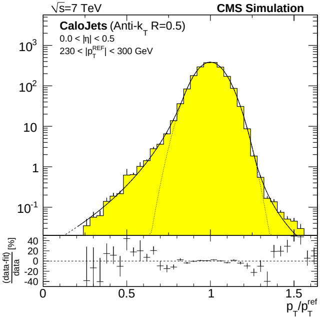
- defines migration true $p_T \leftrightarrow$ reco p_T
- from simulation: reco p_T vs. particle p_T

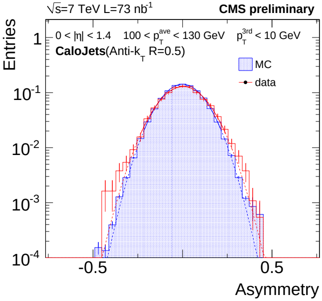
  $$\frac{\sigma_{p_T}}{p_T} = \sigma\left(\frac{p_T^{\mathrm{reco}} - p_T^{\mathrm{ptcl}}}{p_T^{\mathrm{ptcl}}}\right)$$

  tail at underestimated p_T^{reco} due to punch-through
- from measured dijet asymmetry A

  $$A = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \Rightarrow \frac{\sigma_{p_T}}{p_T} = \sqrt{2}\sigma_A$$

  requires corrections for soft radiation (unreconstructed soft jets) and particle level imbalance (e.g. fragmentation fluctuations, primordial k_T of partons inside proton)
- CMS: improved resolution using particle flow (especially at low p_T)





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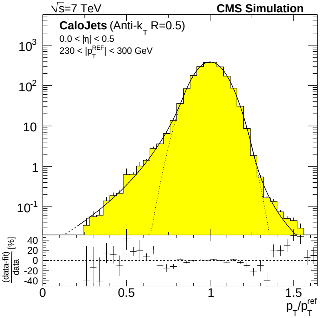
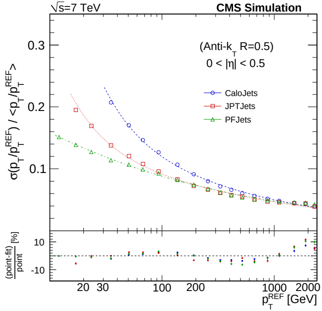
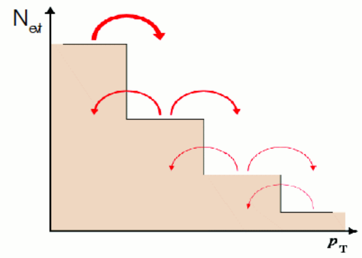


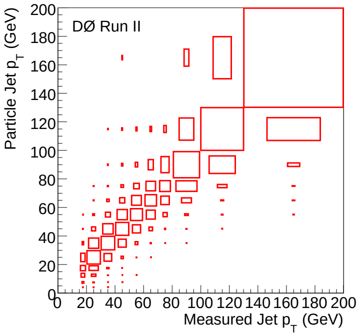


Unsmearing/unfolding

- need to unfold/unsmear for resolution and efficiency
- steeply falling spectrum → mostly migration to higher p_T
- several unfolding techniques
  - (iterative) bin-by-bin unsmearing
  - Bayesian unfolding
  - regularized matrix inversion
- most popular (for incl. jet meas.): bin-correction using ansatz function
  - true distribution: $f(p_T)$
  - reco distr.: $F(p_T) = \int_0^\infty f(p'_T) R(p'_T - p_T; \sigma) \mathrm{d}p'_T$ with smearing function $R(p'_T - p_T; \sigma)$

  → unfolding correction $C_{\mathrm{res}}(p_T) = f(p_T)/F(p_T)$





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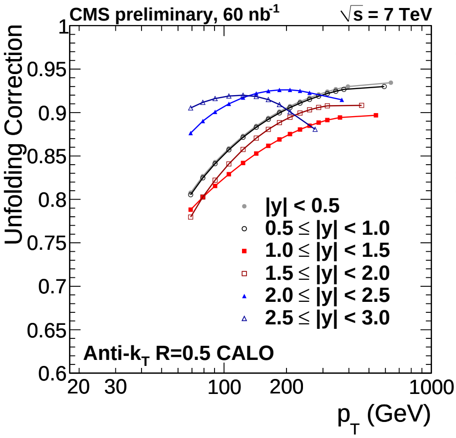
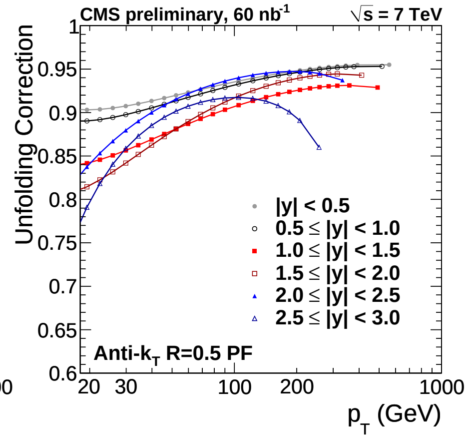
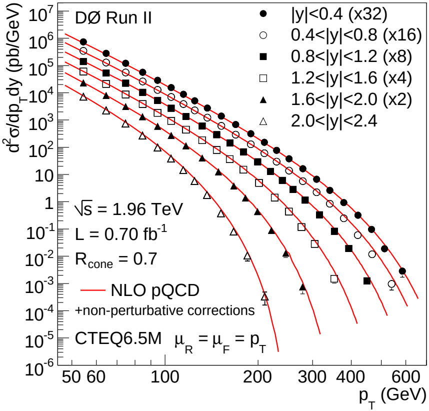




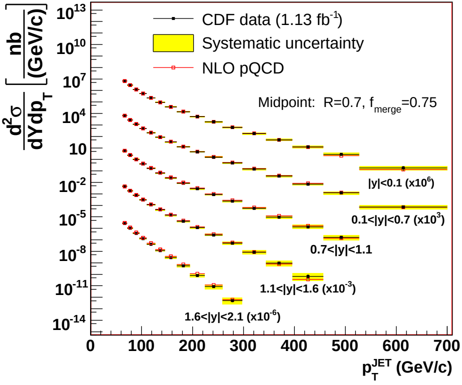
- CMS: smaller unfolding correction for particle flow compared to calorimeter jets thanks to improved resolution

Inclusive jet p_T cross sections

- measurements of $\frac{d^2\sigma}{dp_T dy}$: tests of pQCD over 8 decades
- sensitive to new physics at high $p_T(\mathrm{jet})$
  - benefits from increased Run II energy ($\sqrt{s} = 1.8 \rightarrow 1.96$ *TeV*), e.g. cross section $\times 5$ at $p_T(\mathrm{jet}) = 600\,\mathrm{GeV}$



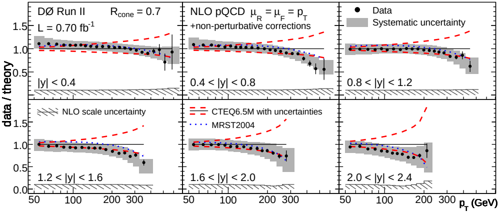
Phys. Rev. Lett. 101, 062001 (2008)

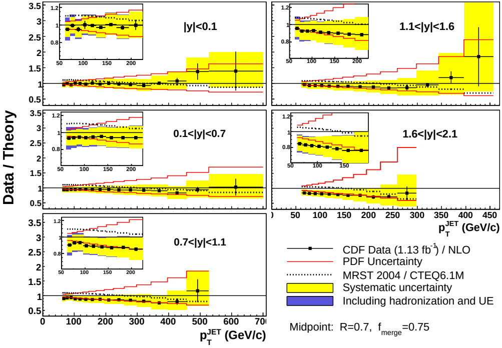


Phys. Rev. D 78, 052006 (2008)

Inclusive jet p_T: data/theory, uncertainties

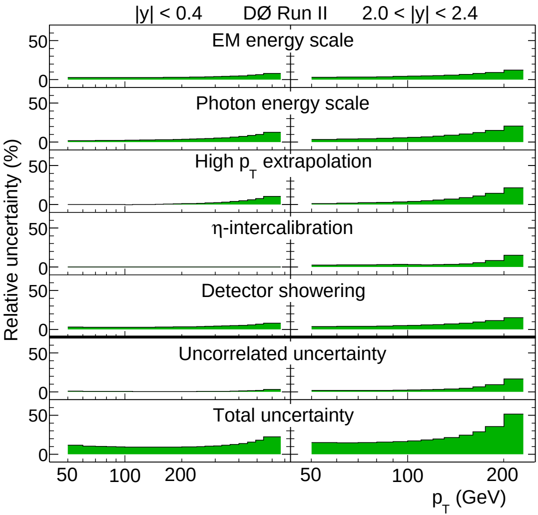
- both measurements are in agreement with NLO pQCD
  - both data sets favor smaller gluon densities
- exp. systematics (dominated by JES uncertainty) < theory uncert. (mostly PDF)
  - thanks to precise JES
- PDF sensitivity: $x \propto 2p_T/\sqrt{s}$





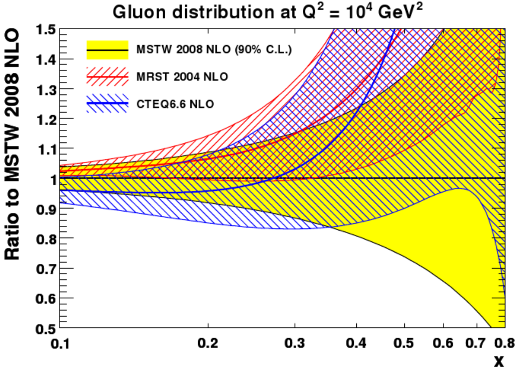
Correlation of uncertainties

- using correlation information in global PDF fit should reduce the effective uncertainty of the measurement
- main uncertainties are from JES
- 23 correlated systematic uncertainties considered

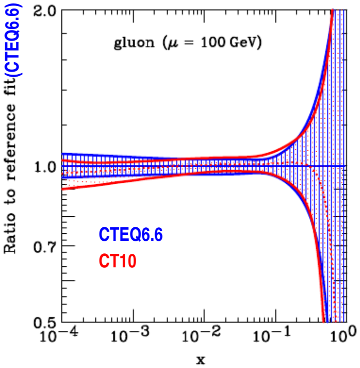


PDF influence of Tevatron data

- MSTW2008 and CT10 (also CT09) PDF fits include Tevatron Run II inclusive jets
  - Run II data lead to softer high-x gluons and provide more precise constraints
    - no visible reduction in PDF uncertainty due to new fit procedures
  - Run II data more consistent with DIS measurements than Run I



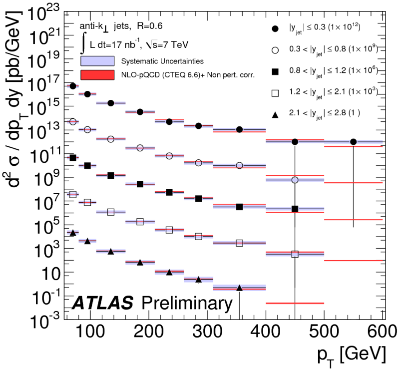
MSTW2008: Eur.Phys.J.C63:189-285,2009



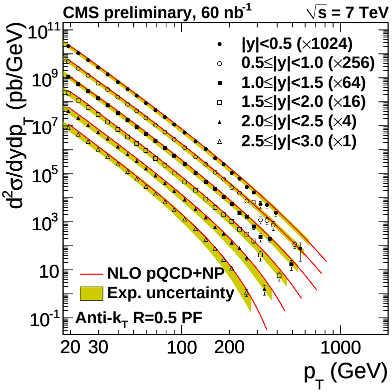
CT10: arXiv:1007.2241

First LHC results

- inclusive jet cross sections based on first ATLAS and CMS data
- both ATLAS and CMS use anti-k_T jets (default algorithm)
- CMS: 3 methods to reconstruct jets using different detector information: calorimeter, calorimeter corrected w. tracks, particle flow



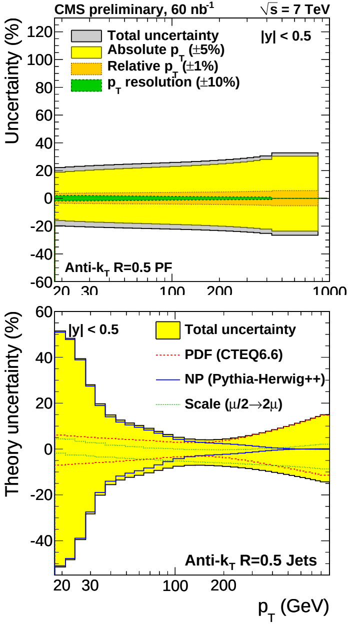
ATLAS-CONF-2010-050



CMS-PAS-QCD-10-011

LHC: PDF sensitivity

- jet energy scale uncertainty largely dominates exp. systematics
  - conservative estimates: ATLAS: 7%, CMS (particle flow): 5%
  - expect significant improvements soon, but remember long process at Tevatron
- theory: NLO pQCD, uncert. dominated by
  - low p_T: non-perturbative corrections
  - high p_T: PDF uncertainty
- for central rapidities, cross section for fixed $x_T = 2p_T/\sqrt{s} \propto x$: $\sigma(\mathrm{LHC}) \ll \sigma(\mathrm{Tevatron})$
  - Tevatron will still be more sensitive to high-x gluon for several years.



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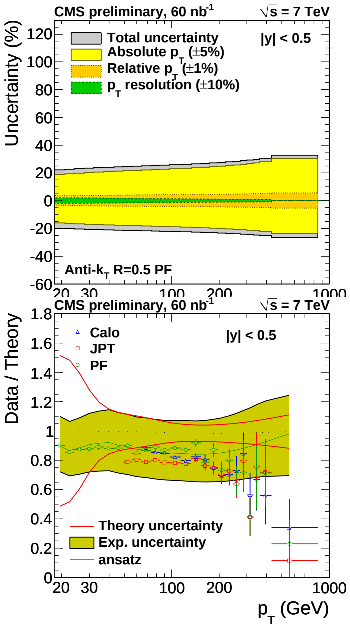

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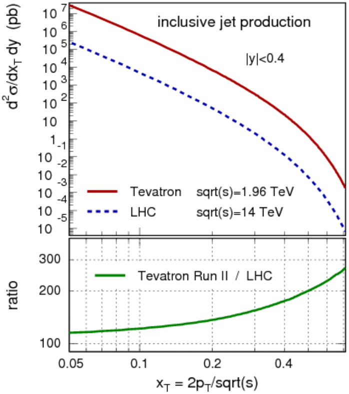
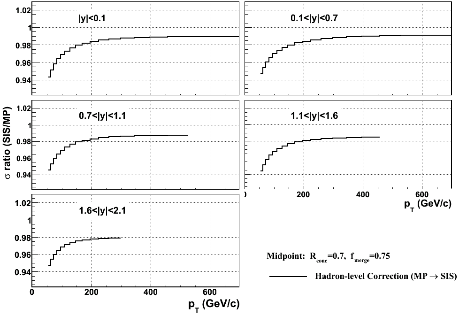
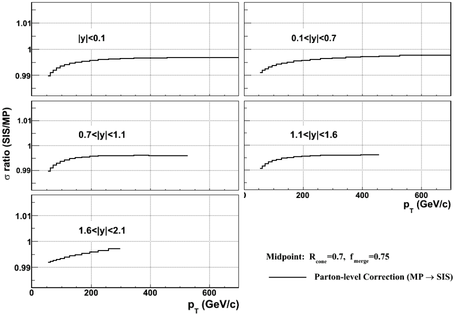


Inclusive jets: SIS cone vs. midpoint cone

hadron level

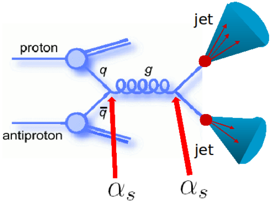


parton level

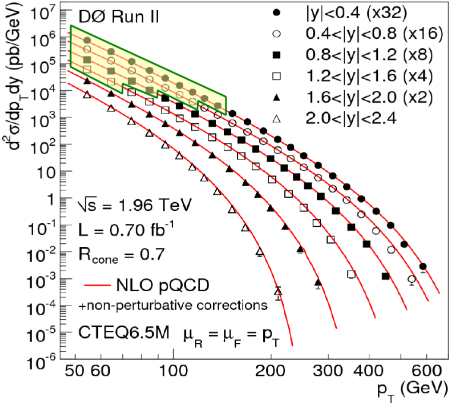


$\Rightarrow$ effect on data/pQCD comparison $< 1\%$

α_s from inclusive jets



- inclusive jet cross section directly related to α_s measurement:
  $\sigma_{\text{theory}}(\alpha_s) = \sigma_{\text{pert}}(\alpha_s) \cdot c_{\text{nonpert}}$
  $\sigma_{\text{pert}}(\alpha_s) =$
  $(\sum_n \alpha_s^n c_n) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$
- c_n: NLO pQCD + 2-loop corr.
- $f_{1,2}(\alpha_s)$: MSTW2008NNLO α_s dependent fits:
  $\alpha_s(M_Z) = 0.110 - 0.130$
- keep only 22 (of 110) data points in kinematic region where PDF fit is not dominated by Tevatron:
  $x_{\max} \lesssim 0.25$



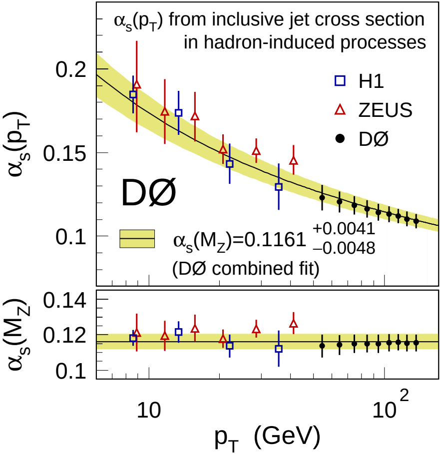
α_s from inclusive jets

- measurement of running α_s at highest p_T (together with CDF Run I)
- most precise determination of α_s from hadron collider

$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$

- uncertainties:
  - experimental: ${}^{+0.0034}_{-0.0033}$
  - theory: ${}^{+0.0023}_{-0.0035}$

    ($\mu_{r/f}$ variation, non-perturbative corrections , PDF)

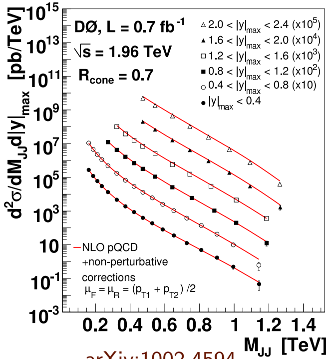


Phys. Rev. D 80, 111107 (2009)

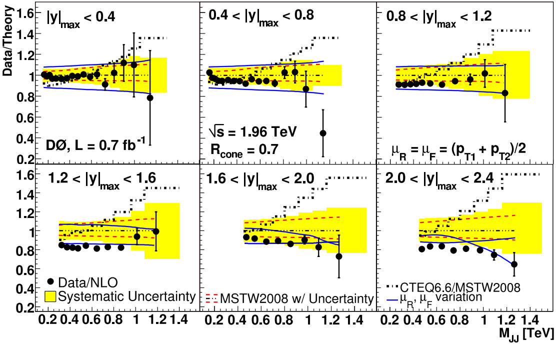
Dijet mass cross section

- measurement of $\frac{d^2\sigma}{dM_{JJ}d|y|_{max}}$ in 6 rapidity bins up to $M_{JJ} \sim 1.3\,\text{TeV}$

  M_{JJ}: dijet mass, $|y|_{max} = \max(|y_1|, |y_2|)$, $p_{T1,2} > 40\,\text{GeV}$
- central rapidities: data well described by pQCD
- forward region: data below prediction
  - reminder: MSTW2008 includes Run II incl. jets
  - discrepancy w.r.t. CTEQ6.6 even larger



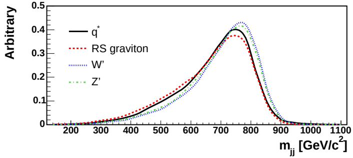
arXiv:1002.4594

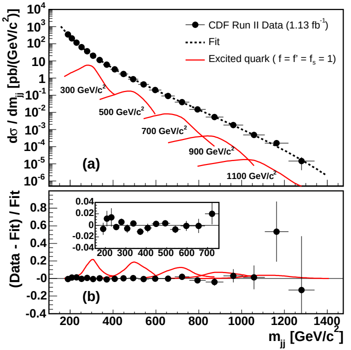


Dijet mass: searches for resonances

- dijet mass distribution for jet rapidities $|y| < 1$
- sensitive to new particles decaying into dijets: q^*, W', Z', ρ_T, axigluon, Randall-Sundrum-graviton, etc.
  - produced more centrally
    s-channel production vs. *t*-channel scattering (QCD)
- search for narrow mass resonance as signal of physics beyond the Standard Model (BSM), lower mass bounds, e.g.:
  - $M(q^*) > 870\,\mathrm{GeV}$
  - $M(\mathrm{axigluon}) > 1.25\,\mathrm{TeV}$

This is history by now...





Phys. Rev. D 79, 112002 (2009)

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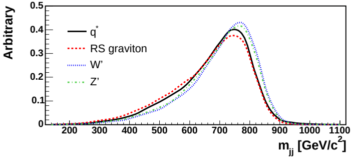
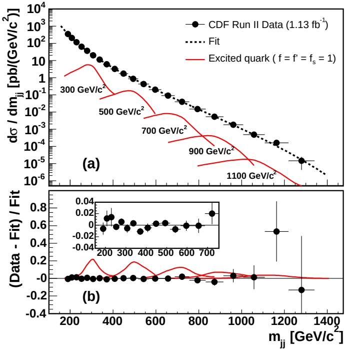
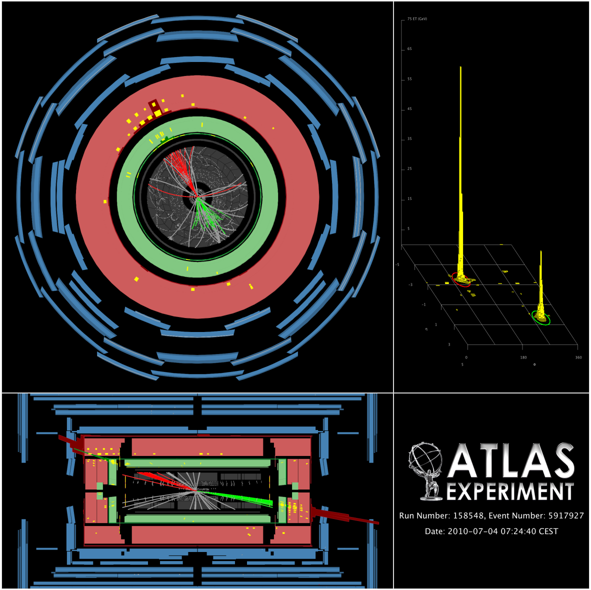




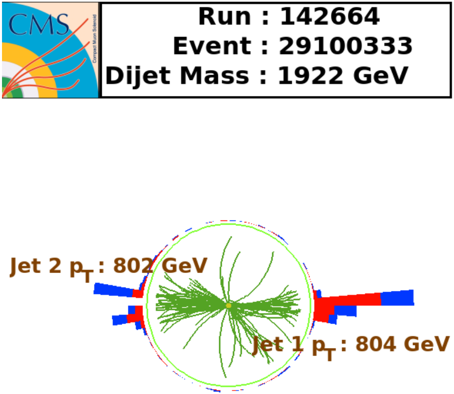
Phys. Rev. D 79, 112002 (2009)

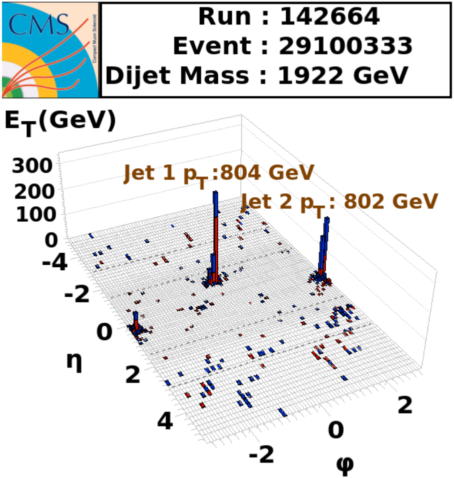
Dijet event with $M_{jj} = 2.55\,\mathrm{TeV}$

$$p_{T,1} = 420\,\mathrm{GeV}$$
$$\eta_1 = 1.51$$
$$p_{T,2} = 320\,\mathrm{GeV}$$
$$\eta_2 = 2.32$$



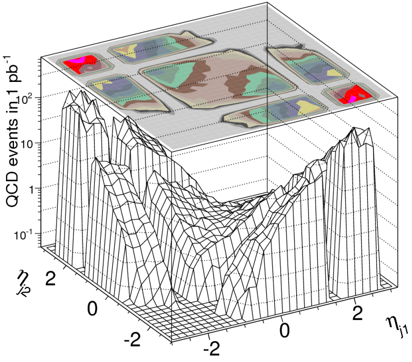
dijet event with $M_{jj} = 1.92\,\mathrm{TeV}$





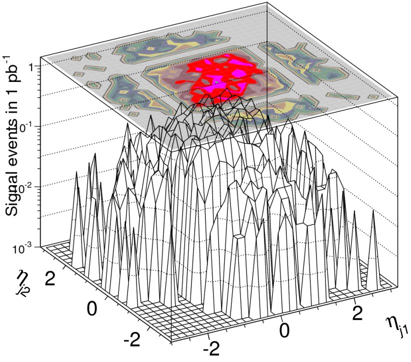
Dijets: QCD vs. q^* signal

QCD, $875 \leq M_{jj} < 1020\,\mathrm{GeV}$



ATLAS Preliminary

signal, $M(q^*) = 1\,\mathrm{TeV}$

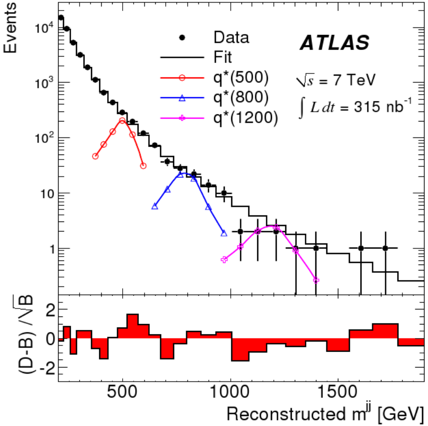


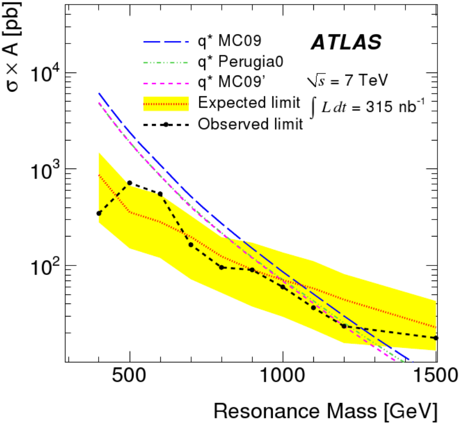
ATLAS Preliminary

- maximize $S/\sqrt{B}$ by requiring $|\eta_{1,2}| < 2.5$ and $|\eta_1 - \eta_2| < 1.3$

Dijet resonances: LHC takes over...

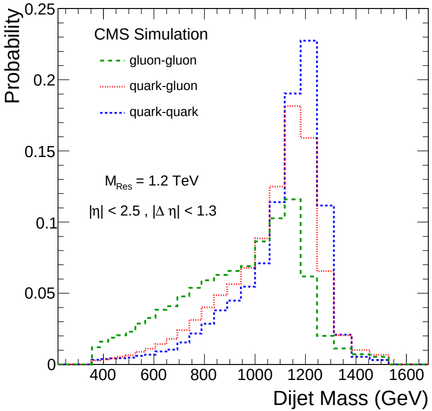
- with just $0.0003\,\text{fb}^{-1}$ LHC exceeds Tevatron sensitivity
  - $M(q^*) > 1.26\,\text{TeV}$

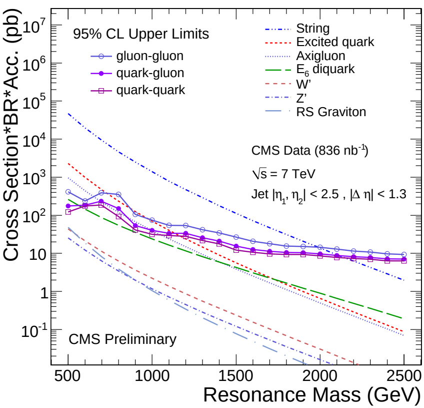




arXiv:1008.2461

Dijet mass resonances

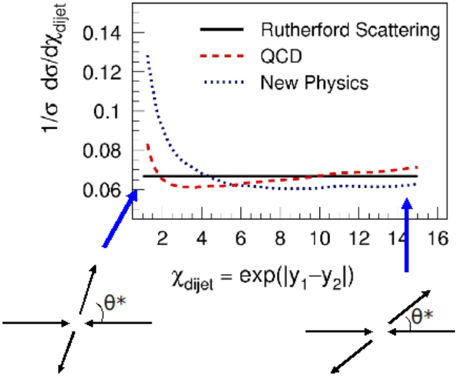




- preliminary search with similar sensitivity as ATLAS
- studied generic *qq*, *qg*, and *gg* parton resonances
  - wider mass spectrum for *gg* resonances due to steeply rising gluon PDF at low *x*
  - $\longrightarrow$ less stringent limits for *gg*

Dijet angular distribution

- provides sensitivity for NP without mass resonance or resonance mass above kinematic reach
- measurement of
  $1/\sigma_{\text{dijet}} \cdot \mathrm{d}\sigma/\mathrm{d}\chi_{\text{dijet}}$ in bins of M_{jj}
  - $\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$
  - massless $2 \to 2$ scattering:
    $\chi_{\text{dijet}} = \frac{(1+\cos\theta^\star)}{(1-\cos\theta^\star)}$
  - BSM: excess at large M_{jj} and small χ_{dijet}
- consistent with NLO QCD
- limits on BSM mass scales:
  - quark compositeness (contact interaction scale Λ): $\sim$2.9 TeV
  - large extra dimensions (ADD (GRW) and TeV^{-1}): $\sim$1.6 TeV



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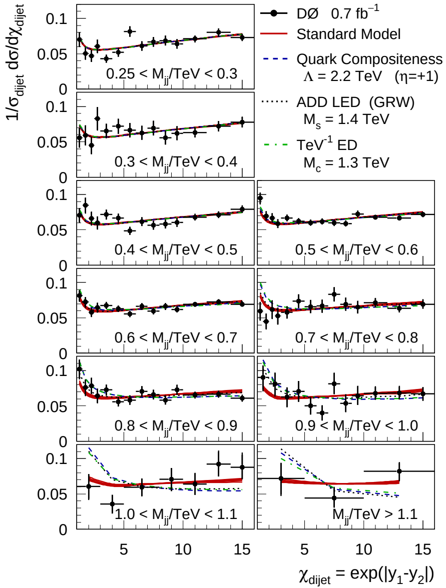
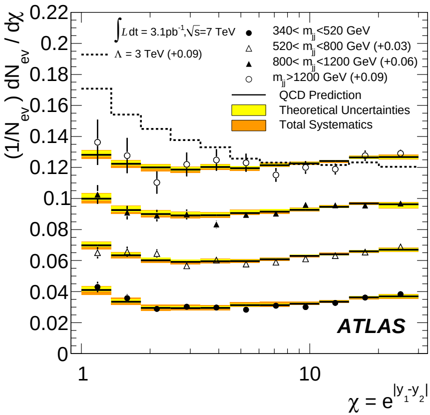


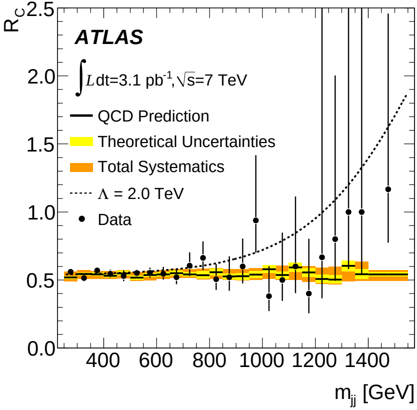
Phys. Rev. Lett. 103, 191803 (2009)

LHC has taken over again...

χ distribution



centrality ratio R_C



- χ distribution: limit on contact interaction scale $\Lambda > 3.4\,\mathrm{TeV}$ (expected $3.5\,\mathrm{TeV}$)
- centrality ratio $R_C = N(|j_{1,2}| < 0.7)/N(0.7 < |j_{1,2}| < 1.3)$: $\Lambda > 2.0\,\mathrm{TeV}$ (expected $2.6\,\mathrm{TeV}$) $\rightarrow$ less sensitive

Conclusions

- rich physics program with jets ranging from QCD to searches
- understanding of high E_T jet production significantly advanced over the last years at Tevatron and now also LHC
- inclusive jet cross section
  - precise jet energy scale calibration is crucial
  - → precision measurement of running α_s
  - → stringent constraints on gluons at high x
  - LHC: need improved calibration and higher luminosities
- multijets
  - agreement with NLO QCD, but Tevatron data prefer lower bound on theory
- dijet mass and angular distribution sensitive to various new phenomena
  - LHC sensitivity has already surpassed Tevatron
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  - LHC sensitivity has already surpassed Tevatron
- Stay tuned for rapidly improving precision, sensitivity to new phenomena and maybe discoveries!