QCD studies at the Tevatron

XXVII Rencontres de Physique de la Vallée d'Aoste, La Thuile

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(on behalf of the CDF and DØ Collaborations)

February 26th 2013

Recent QCD measurements

- Inclusive jets
  - Ratio of 3-jet to 2-jet cross-sections
  - Dijet azimuthal decorrelations
  - Angular correlations and extraction of α_s
- Vector boson plus jets
  - Inclusive W+jets
  - Inclusive Z+jets
  - W+ charm
  - W+ b-jet
  - Z + b-jet
- Photon + jet
  - Prompt di-photon
  - Photon + b-jet
  - Photon + c-jet
- Elastic/diffractive physics
  - Energy dependence of UE
  - Elastic scattering
  - Diffractive dijet production
  - Central Exclusive Production

Ratio of 3-jet to 2-jet cross-sections

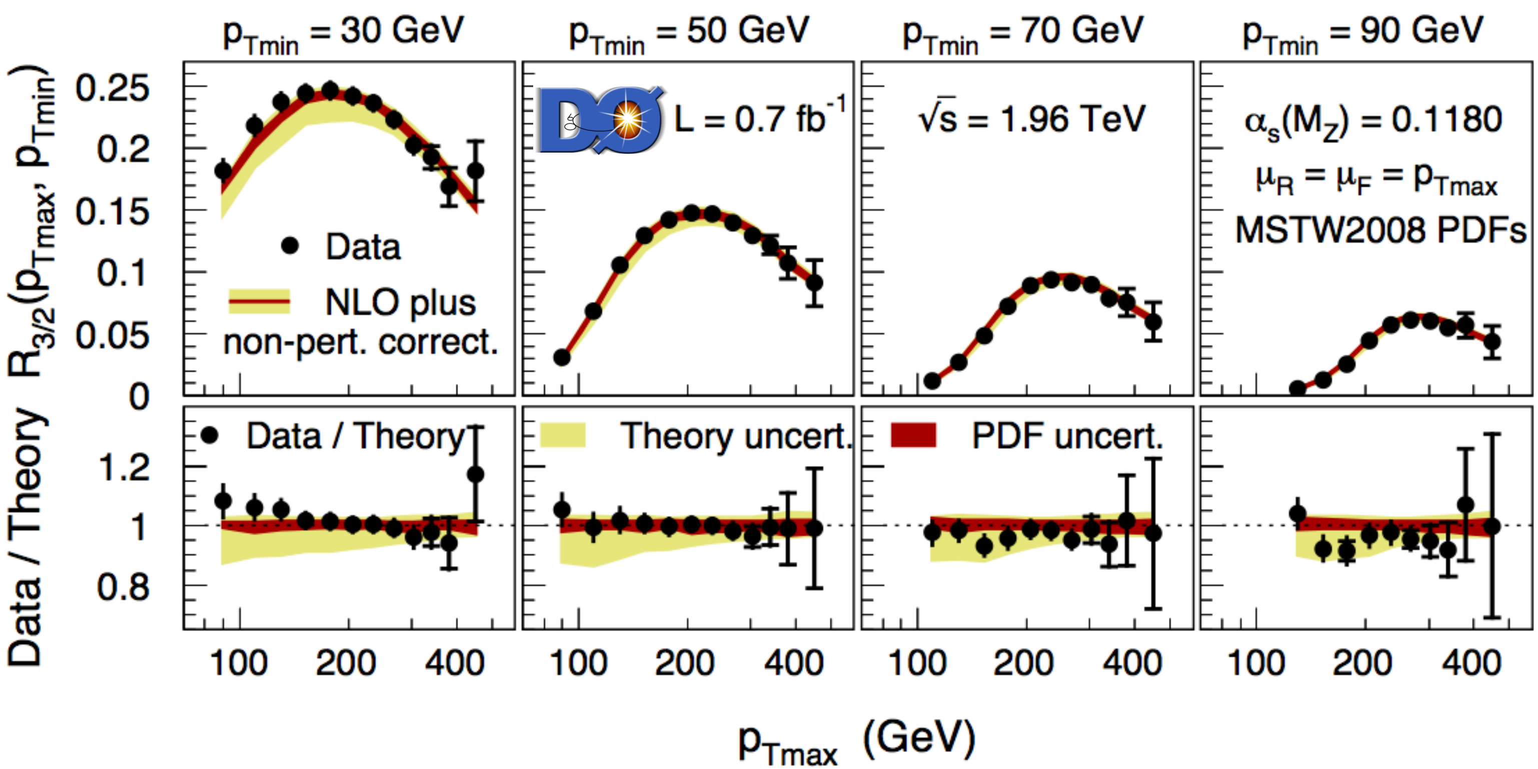
First measurement of ratios of multijet cross-sections at Tevatron

Test of QCD independent of PDFs (small residual dependence because of 2/3-jet sub-process compositions); many uncertainties cancel in ratio

Measure as a function of two momenta $R_{3/2}(p_{Tmax}, p_{Tmin})$= P(3rd jet | 2 jets):

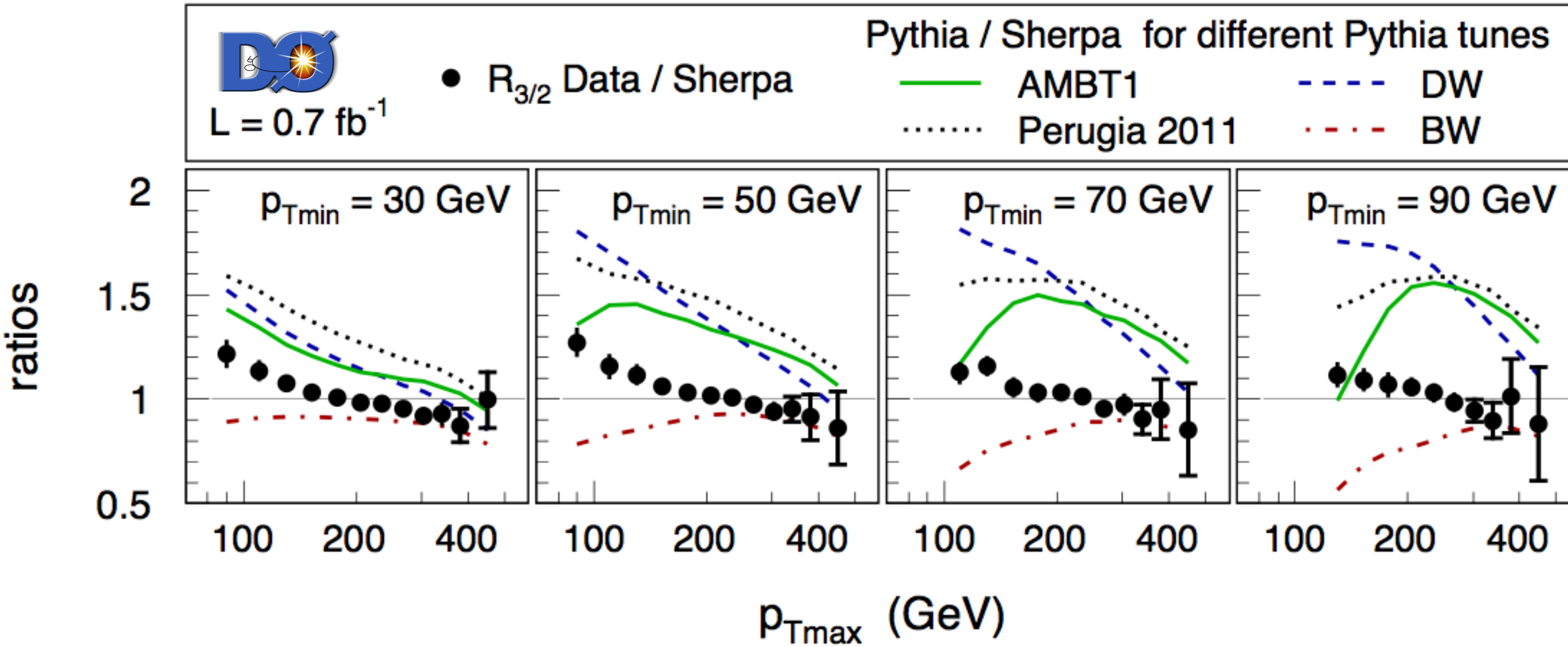
p_{Tmax} – leading jet p_T (common between 2- and 3-jet)
p_{Tmin} – scale at which other jets resolved

Probes running of α_s in Tevatron energy regime up to p_T of 500 GeV



arXiv:1209.1140 [hep-ex]
Submitted to Phys. Lett. B

Ratio of 3-jet to 2-jet cross-sections



Sherpa predictions show different p_T dependence to data

Pythia contains ME's for up to 2-jet: third jet directly dependent on shower

- Tune DW tuned to DØ dijet azimuthal decorrelation data
- Many tunes studied (more in paper), none found to be able to describe data

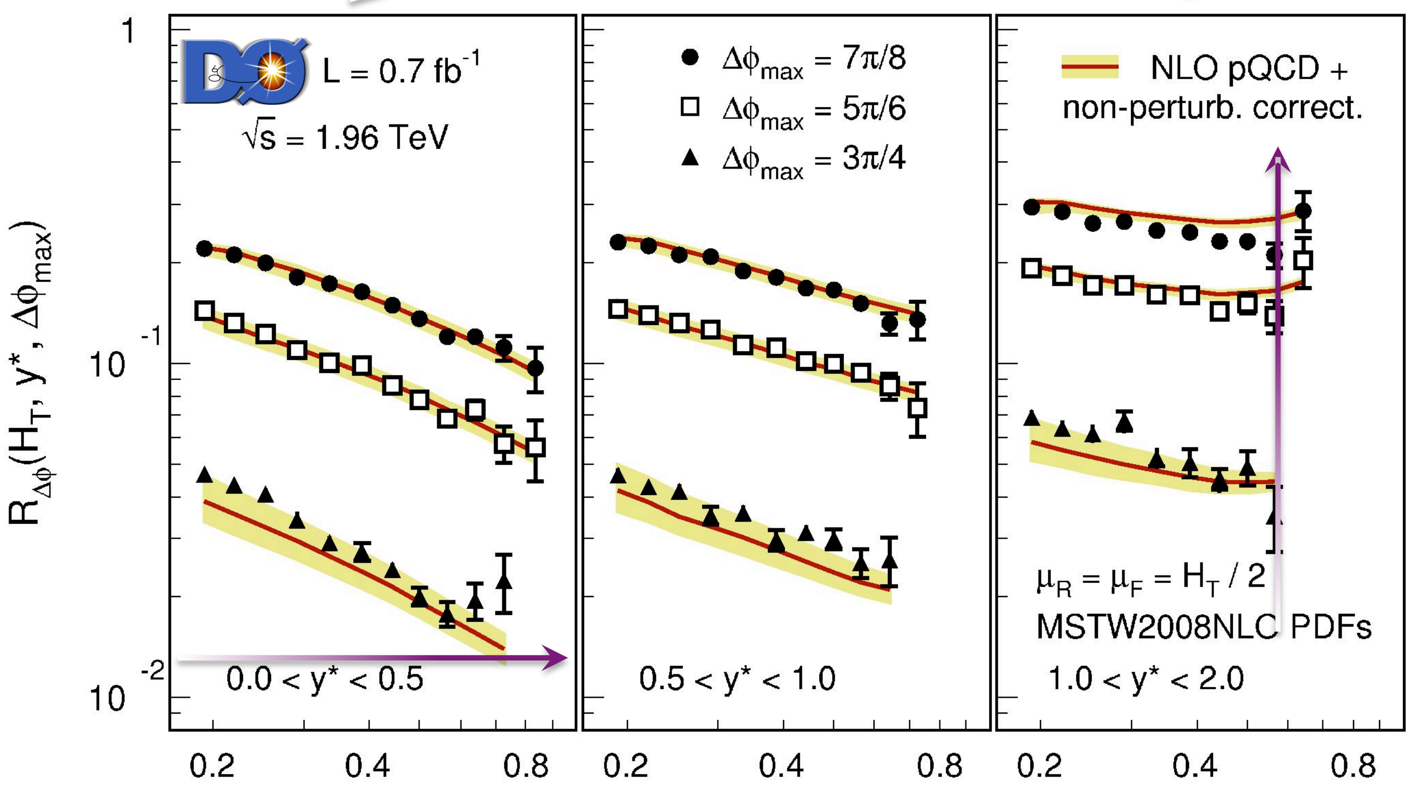
Dijet azimuthal decorrelations

First measurement of both p_T & rapidity dependence of azimuthal decorrelations

$R_{\Delta\varphi}$: fraction of inclusive dijet events where the $\Delta\varphi$ separation between the two highest p_T jets is less than a specified $\Delta\varphi_{max}$

$$R_{\Delta\phi}(H_T, y^*, \Delta\phi_{\max}) = \frac{\frac{d^2\sigma_{\rm dijet}(\Delta\phi_{\rm dijet}<\Delta\phi_{\max})}{dH_T\, dy^*}}{\frac{d^2\sigma_{\rm dijet}(\rm inclusive)}{dH_T\, dy^*}}$$

Increasing $y^*=|y_1-y_2|/2$ (jet rapidity separation)



Increasing $\Delta\varphi_{max}$

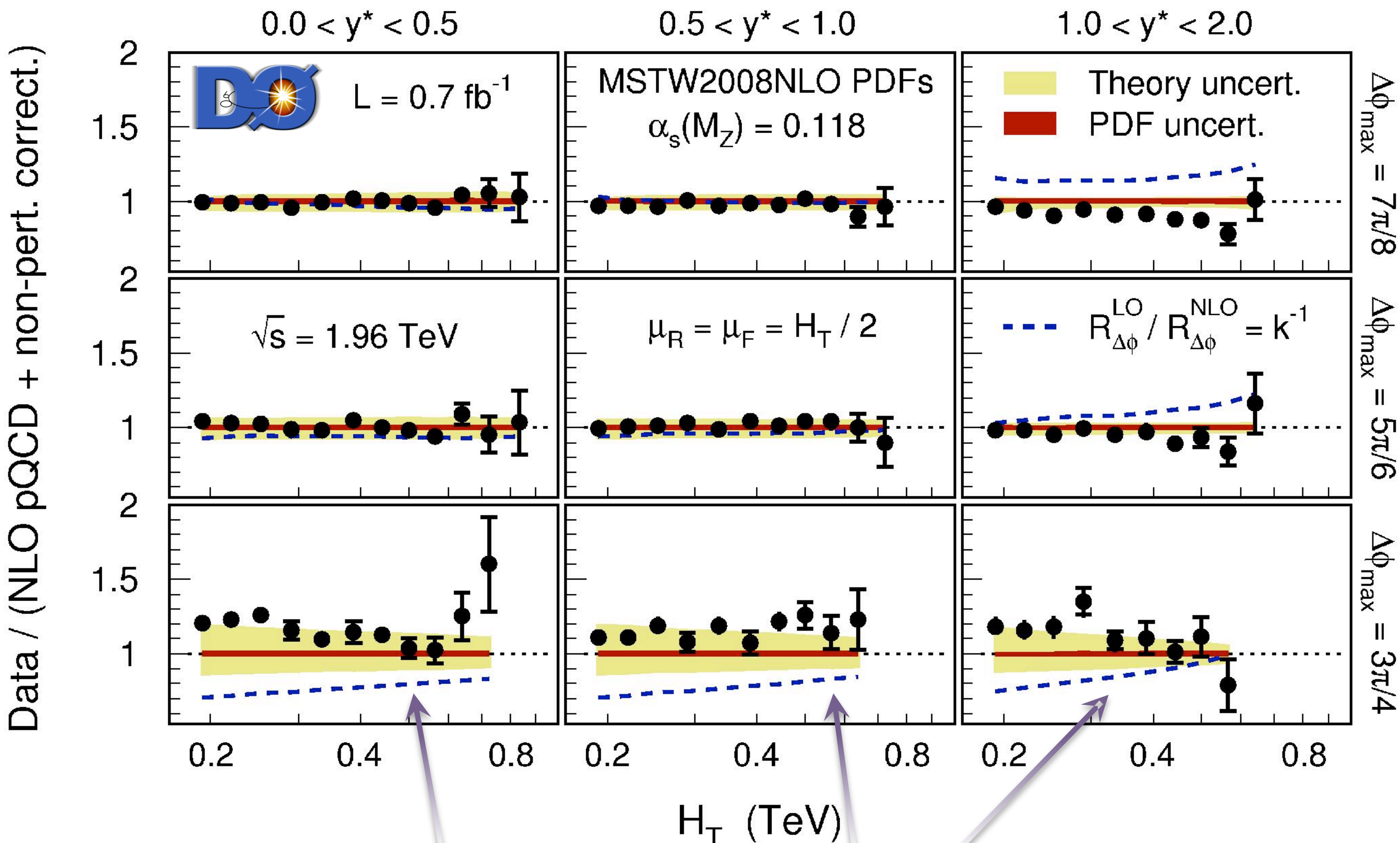
Increasing H_T

arXiv:1212.1842 [hep-ex]
Submitted to Phys. Lett. B

Dijet azimuthal decorrelations

Dependencies on PDFs largely cancel. Data sensitive to pQCD ME's and α_s

Ratio with NLO calculations: problems at wide rapidity separation + large $\Delta\varphi_{max}$



$\Delta\varphi_{max} \approx \pi$ sensitive to soft QCD radiation

Small $\Delta\varphi_{max}$ sensitive to hard higher order corrections

Challenging region to model for theoretical calculations due to large contributions from four-jet final states

W+jets production: jet rapidities

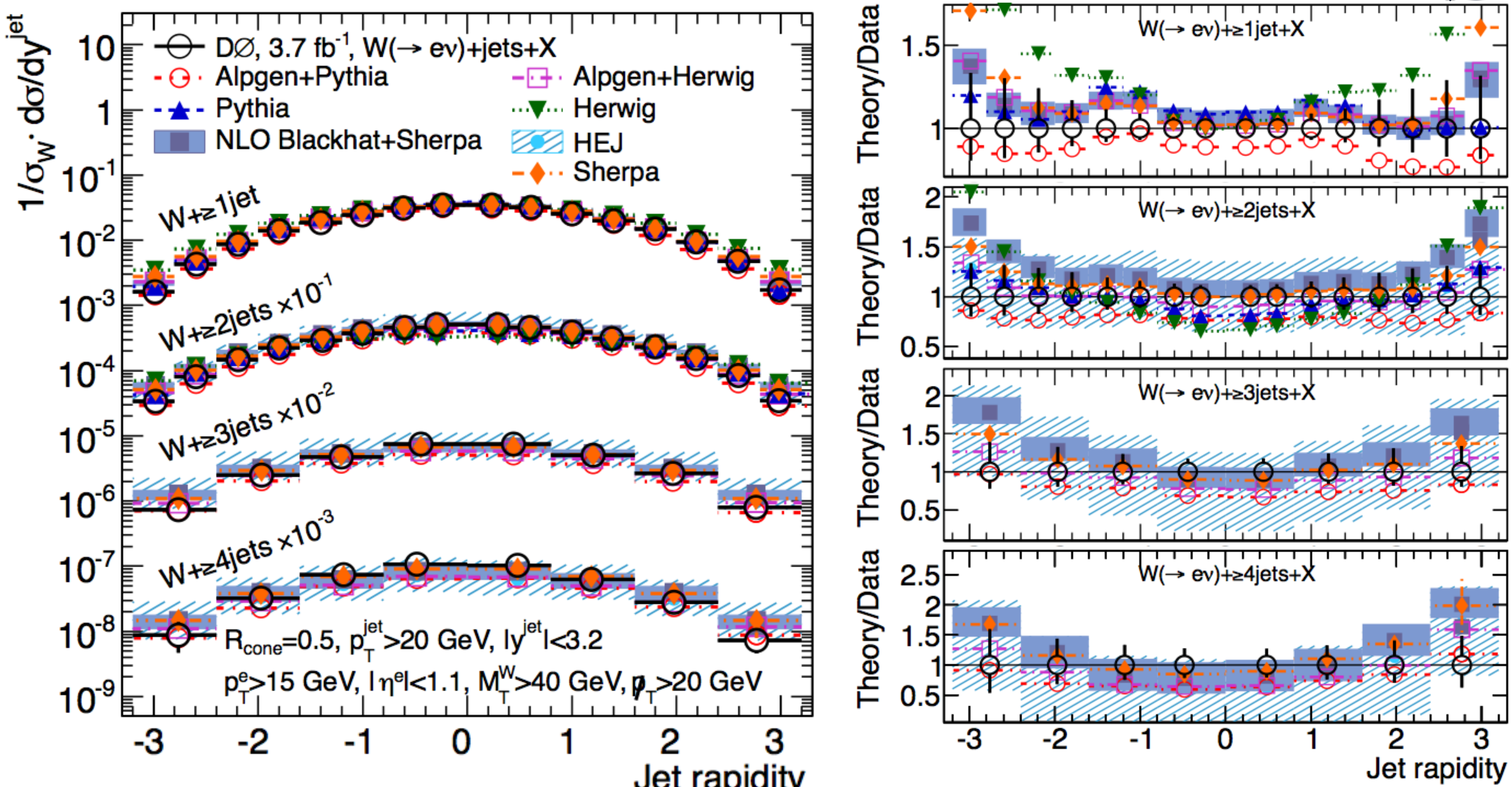
arXiv:1302.6508 [hep-ex]
Submitted to Phys. Rev. D
New results for this conference!

New, comprehensive study of inclusive W+jets production at the Tevatron

- Total of 40 measured observables (see backup for more details)

n^{th} jet rapidity in inclusive n-jet events (for n=1—4)

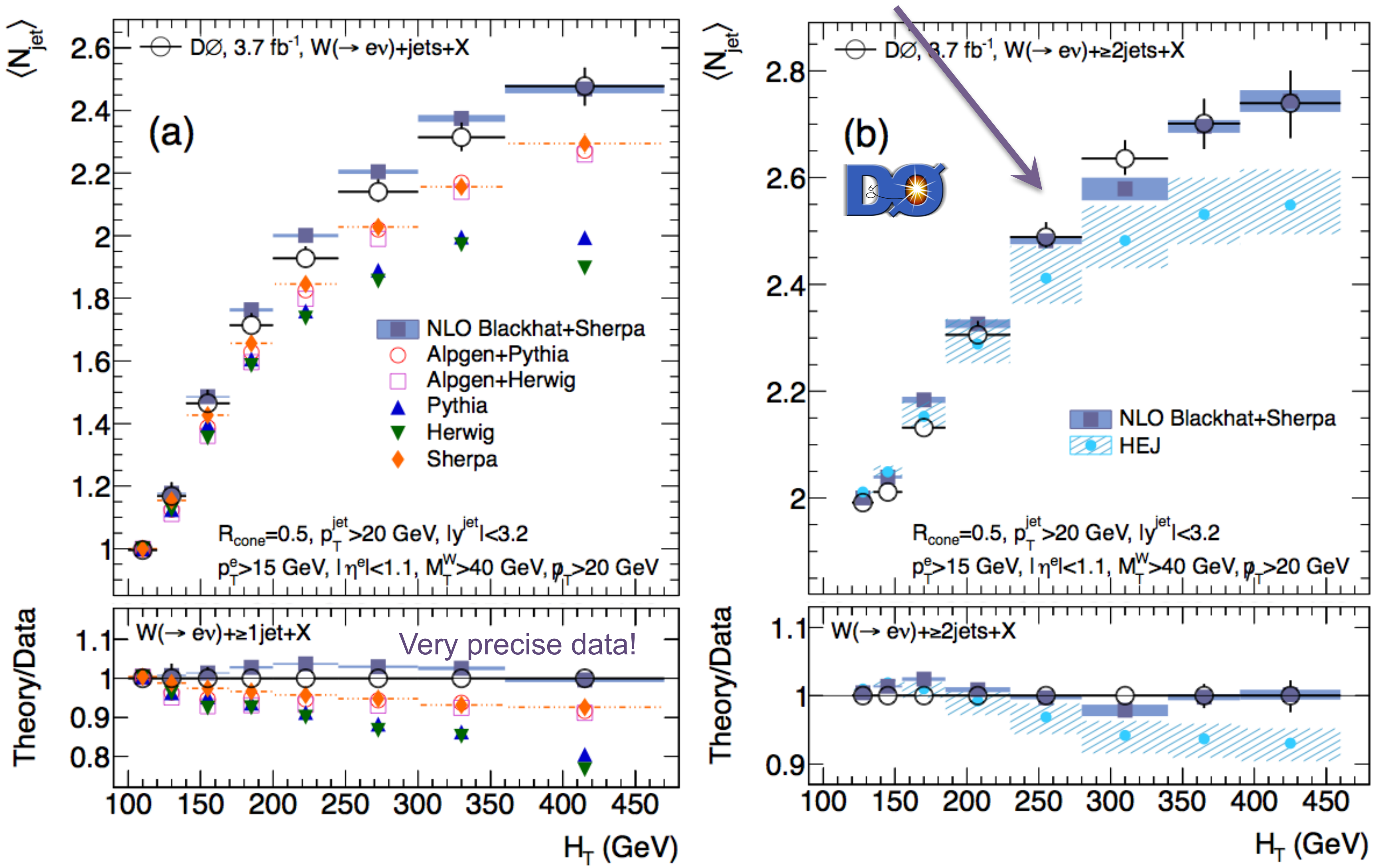
- Reasonable agreement between data and all theories at central rapidities
- Wide variety of forward jet predictions!



arXiv:1302.6508 [hep-ex]
Submitted to Phys. Rev. D

W+jets: average number of jets vs. H_T

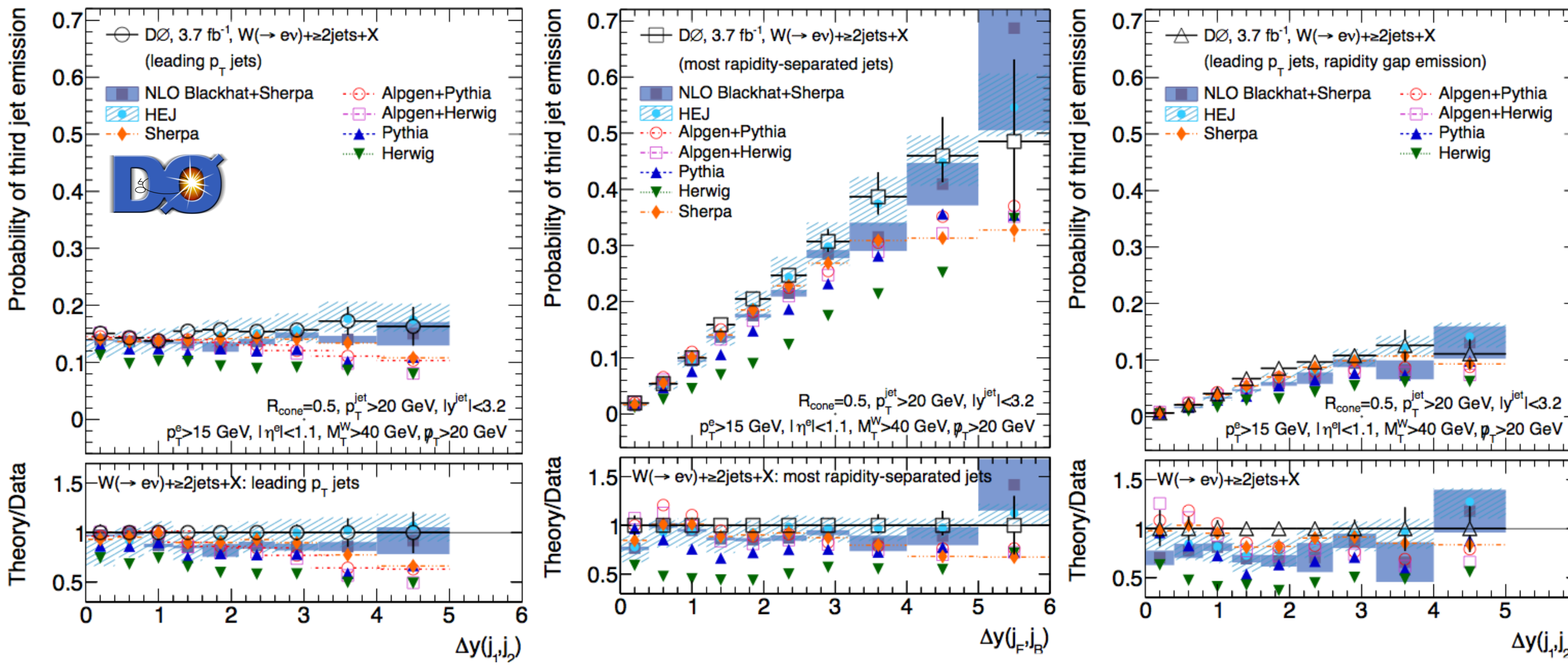
Both PS MC and MEPS fail to produce enough hard jets at high H_T
NLO does excellent job of describing jet-multiplicity evolution



W+jets: third jet emission probability vs. Δy

Very similar to previous, but now only interested in third jet emission.
Three configurations:

Two highest p_T jets	Two most rapidity-separated jets	Highest p_T jets with requirement that third jet be emitted in *between* the first two in rapidity



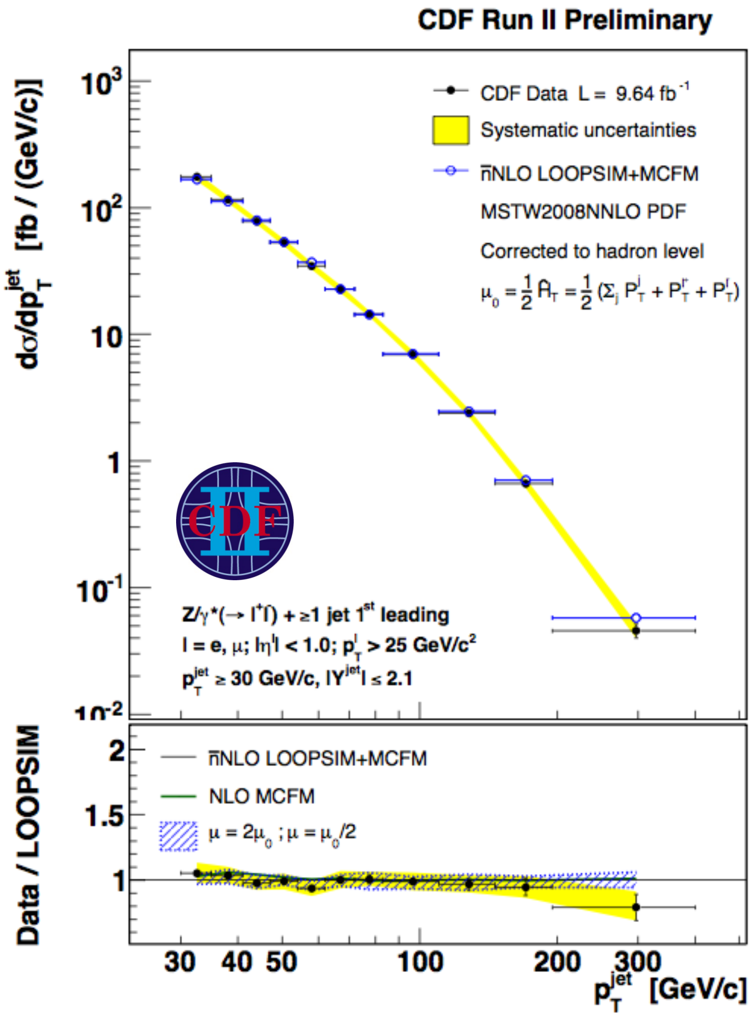
For rapidity-ordered jets:

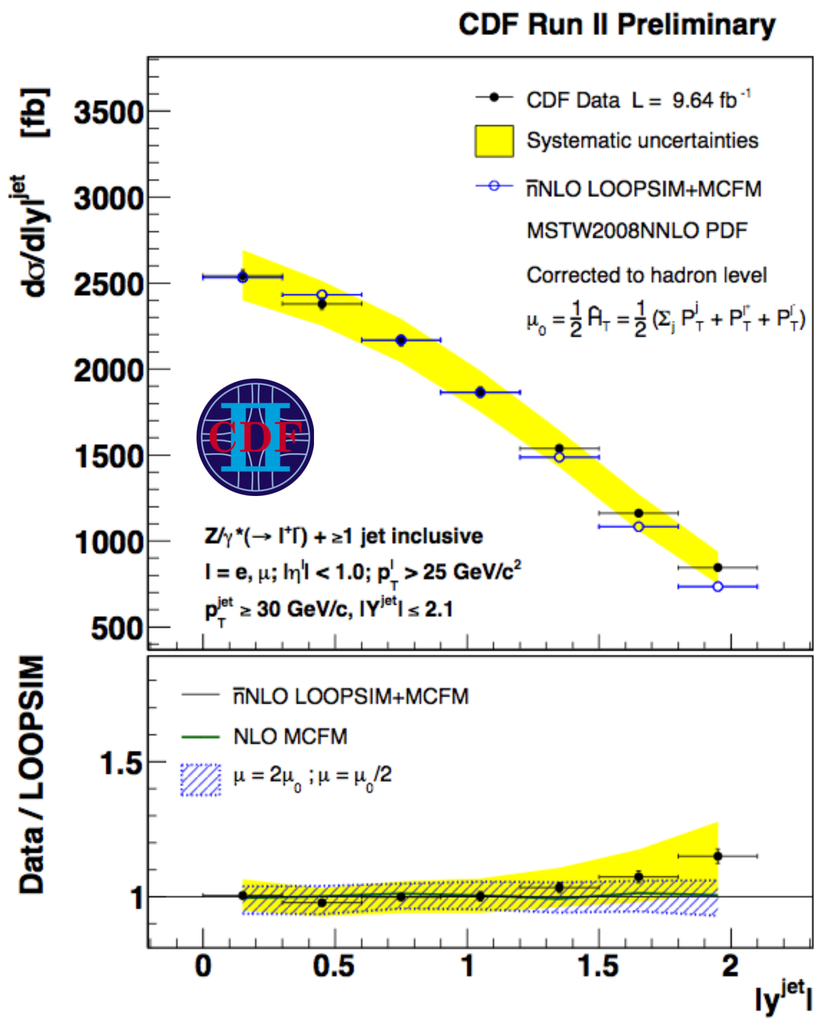
- HEJ in particular performs well, with small uncertainties at wide angle
- NLO agrees well, but with large uncertainties at large rapidity intervals
- Sherpa behaves like most MEPS (or PS) MC's with insufficient radiation at wide angle

Highlights a way to veto on SM W+jets production for searches

Z+jets production

Detailed analysis studying jet p_T and rapidities, Z p_T, dijet mass, ΔR, $\Delta\phi$, Δy, Z_{jj} mass, H_T, dihedral angle between $Z \rightarrow l^+l^-$ decay plane and dijet plane

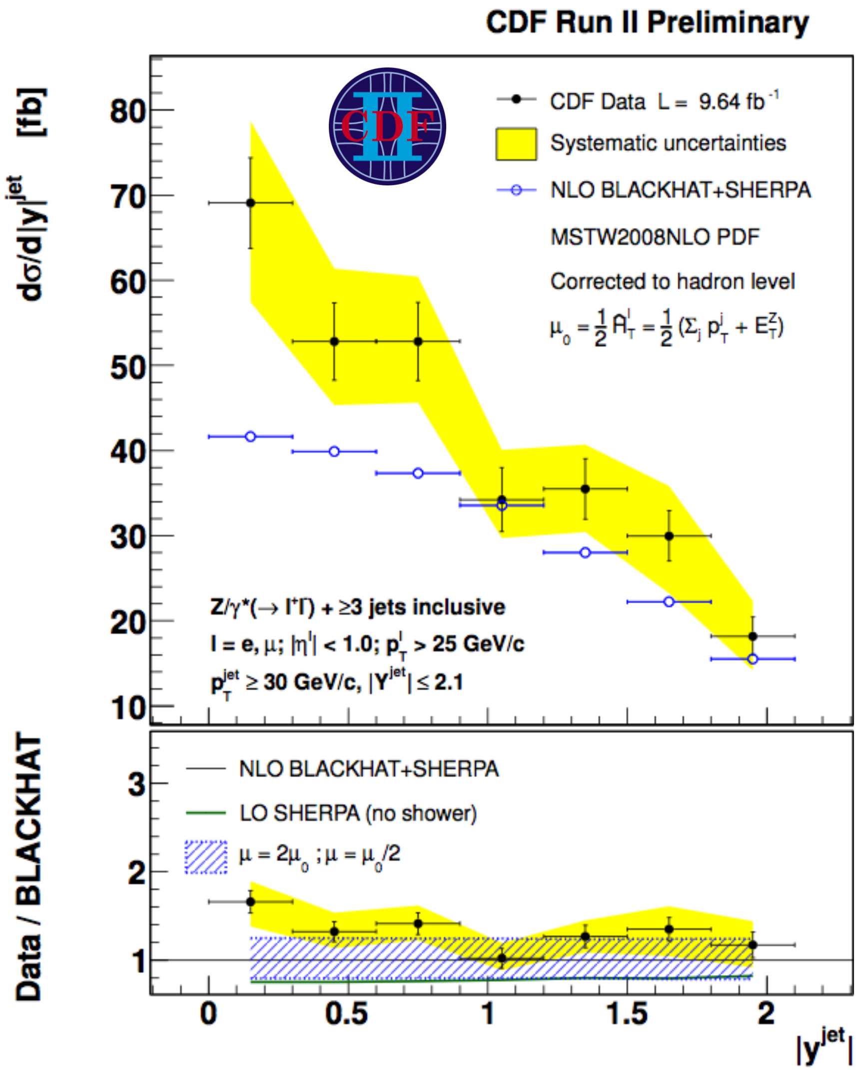


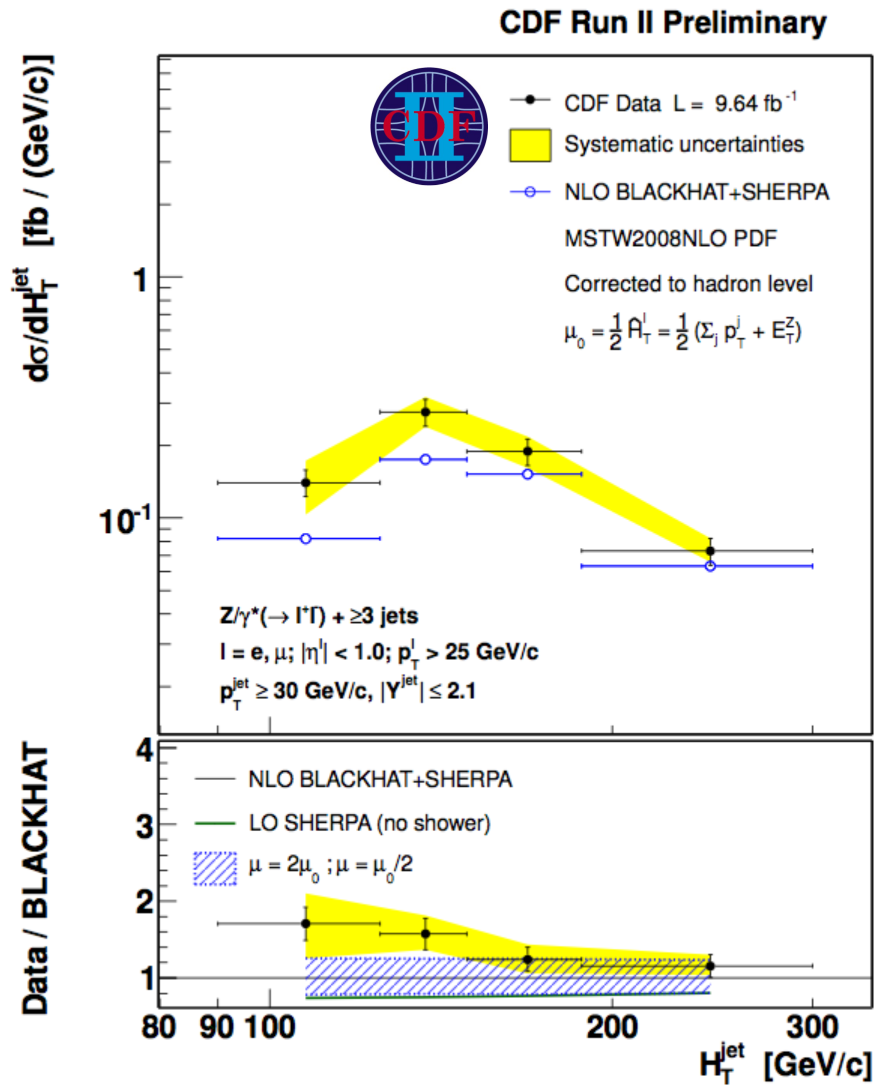


Good agreement with NLO and nNLO in jet p_T; possible trend at high rapidity

Z+jets: inclusive 3-jet

Z+3jet inclusive spectra show clear discrepancies between data and NLO





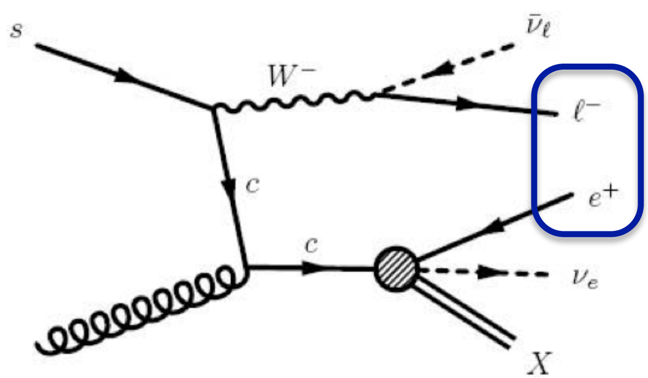
arXiv:1209.1921 [hep-ex]
Phys. Rev. Lett. 110, 071801 (2013)

W+charm production

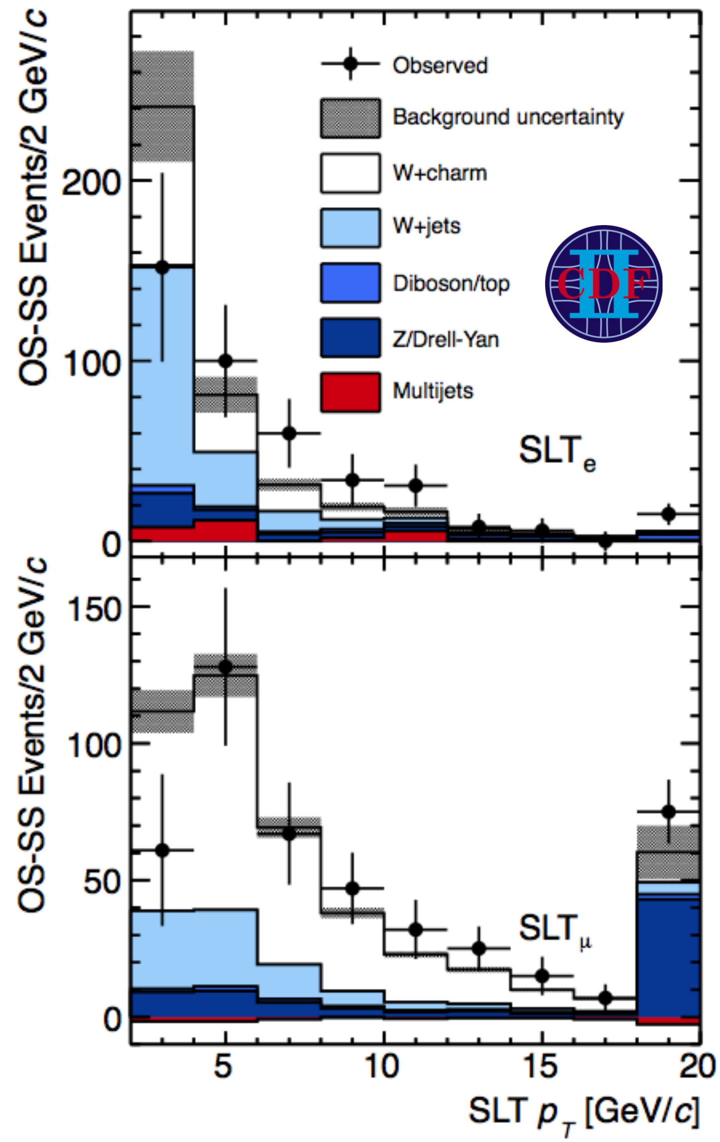
Measurement of W+c production: sensitive to s-quark PDF

Background to single-top and associated WH production

Charm identified through semi-leptonic decay:
use soft lepton tagging (SLT) to ID charm jet from soft lepton characteristics



Reduce backgrounds exploiting charge correlation in signal between leptons from W and charm



Measure W+c cross-section (μ+e combination)

$$= 13.6 \pm 2.2\ (\text{stat.})^{+2.3}_{-1.9}\ (\text{syst.}) \pm 1.1\ (\text{lumi.})\ \text{pb}$$

(NLO prediction $= 11.4 \pm 1.3$ pb)

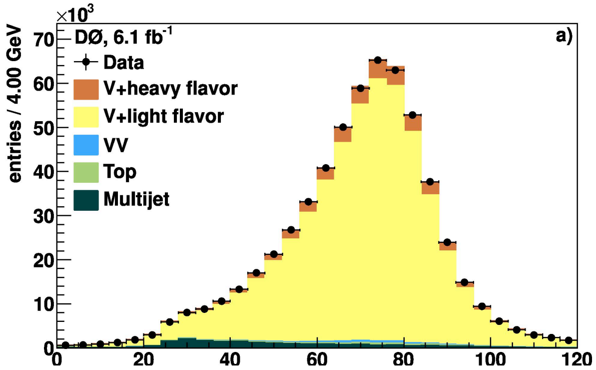
Derive 95% confidence limit on quark mixing matrix element: $|V_{cs}|>0.71$

W+b production

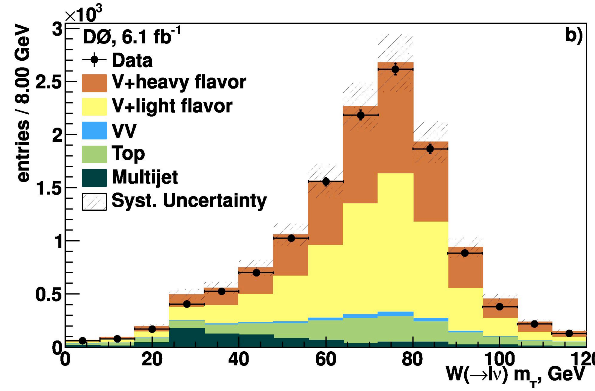
arXiv:1210.0627 [hep-ex]
Phys.Lett. B718 (2013) 1314

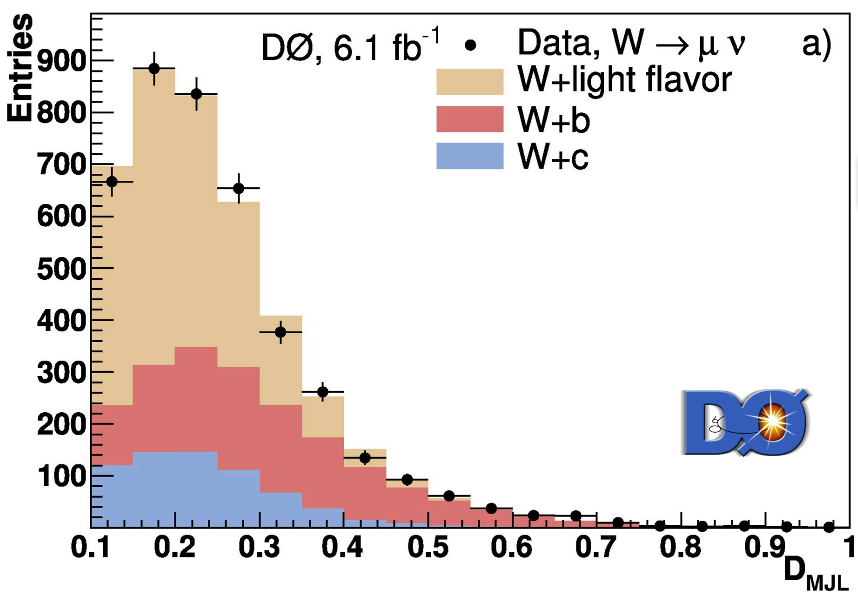
Excess of W+b production over NLO observed previously by CDF (1.9 fb^{-1})

Use b-jet identification to reject dominant W+light flavour backgrounds



Before and after b-jet identification





Use discriminant based MVA b-tagging output and vertex mass to extract b-component of data

$$\sigma(W+b+X) = 1.05 \pm 0.03\ (\text{stat.}) \pm 0.12\ (\text{syst.})\text{pb}$$

Theory

$$\text{MCFM NLO} = 1.28^{+0.40}_{-0.33}\ (\text{scale}) \pm 0.06\ (\text{PDF})^{+0.09}_{-0.05}\ (\text{m}_\text{b})\ \text{pb}$$

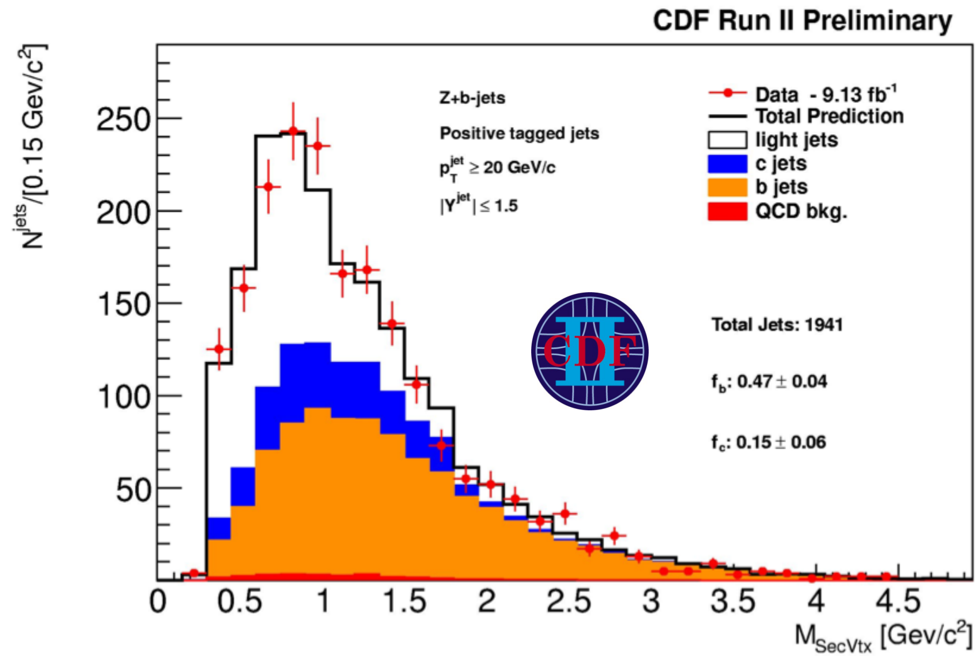
$$\text{Sherpa} = 1.08\ \pm 0.03(\text{stat.})\text{pb}$$

$$\text{MADGRAPH5} = 1.44\ \pm 0.02(\text{stat.})\text{pb}$$

Z+b production

Total Z+b-jet cross-section measured relative to inclusive Z, and inclusive Z+jet events

- Artificial neural network used to select Z candidates
- Secondary vertex mass template fits used to fit light, charm, and b-jet composition



$$\frac{\sigma_{Z+bjet}}{\sigma_Z} = 0.261 \pm 0.023^{stat} \pm 0.029^{syst}\%$$

$$\frac{\sigma_{Z+bjet}}{\sigma_{Zjet}} = 2.08 \pm 0.18^{stat} \pm 0.27^{syst}\%$$

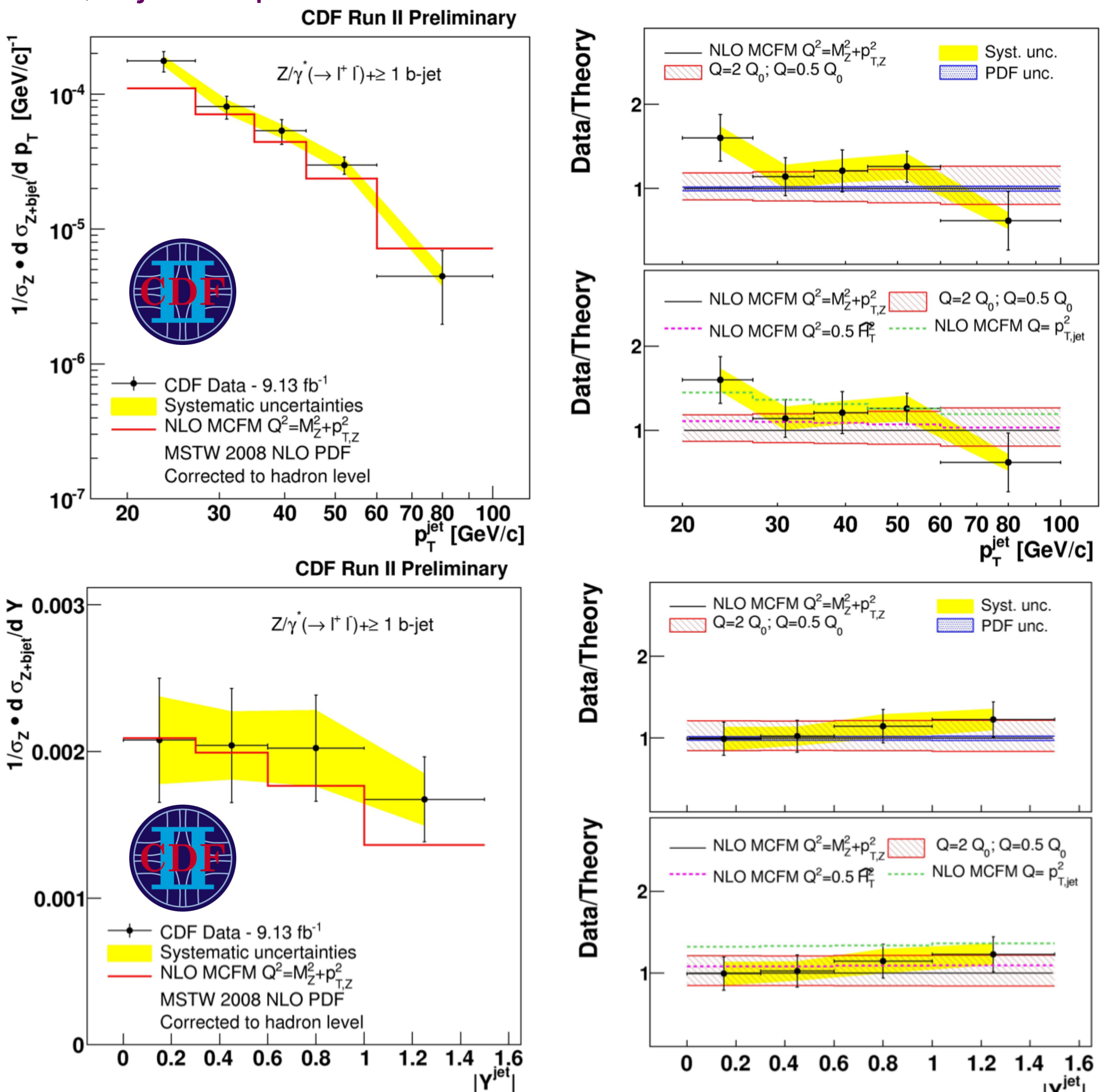
Results in agreement with MCFM NLO predictions:

	NLO $Q^2 = m_Z^2 + p_{T,Z}^2$	NLO $Q^2 = < p_{T,jet}^2 >$
$\frac{\sigma(Z+b)}{\sigma(Z)}$	2.3×10^{-3}	2.9×10^{-3}
$\frac{\sigma(Z+b)}{\sigma(Z+jet)}$	1.8×10^{-2}	2.2×10^{-2}

CDF public note 10594

Z+b/Z differential measurements

Fit light, charm, b-jet templates in kinematic intervals to derive differential spectra:

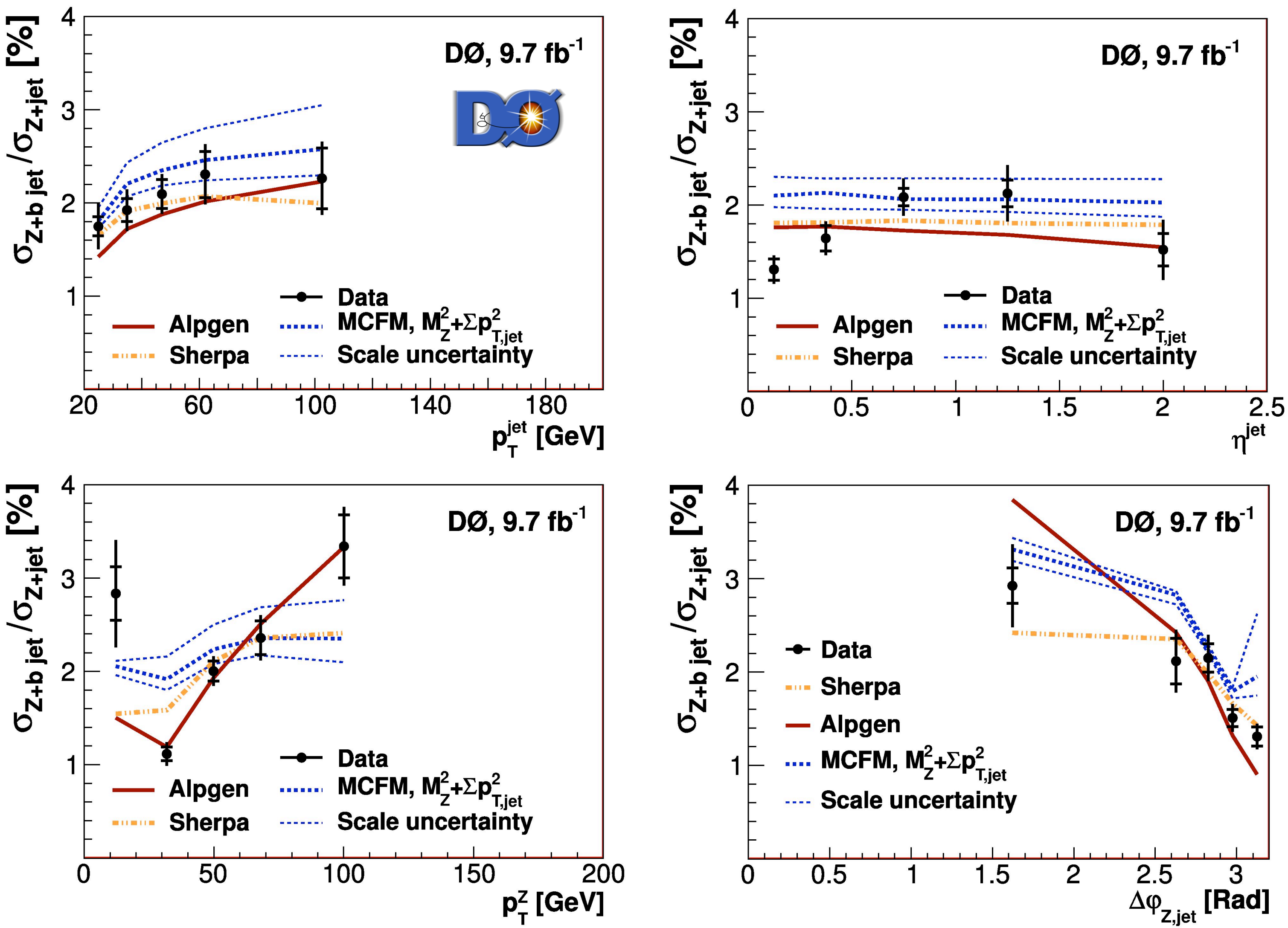


Z+b/Z+jets differential measurements

arXiv:1301.2233 [hep-ex]
Submitted to Phys. Rev. D

New DØ measurement extends differential studies to study of Z p_T, and azimuthal angle between Z and b-jet

Beware DØ/CDF comparison: these data normalised to Z+jet, CDF to inclusive Z!

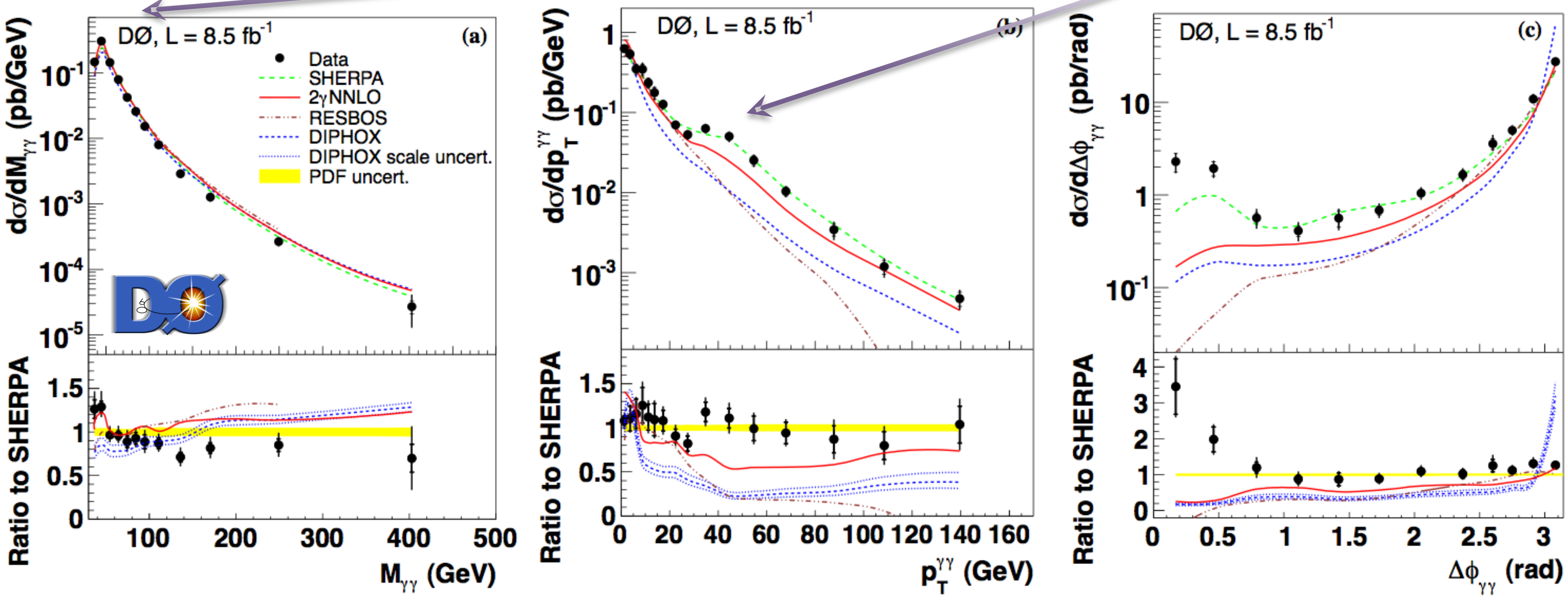


arXiv:1301.4536 [hep-ex]
Submitted to Phys. Lett. B

Prompt isolated di-photon production

Prompt di-photon production a background to H→γγ, new phenomena searches

At Tevatron, produced predominantly through quark-anti-quark annihilation and gluon-gluon fusion, with gg→γγ important at low di-photon invariant mass and intermediate p_T



Probe for NP searches, PDF sensitivity

ISR and fragmentation

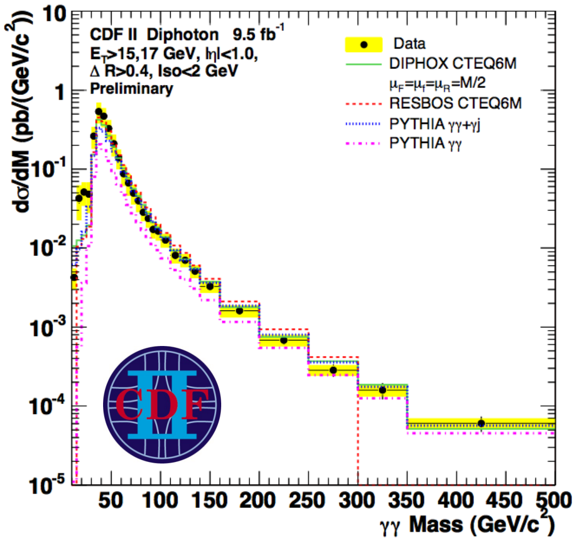
Angular measurement: very precise.
Supports conclusions of other variables

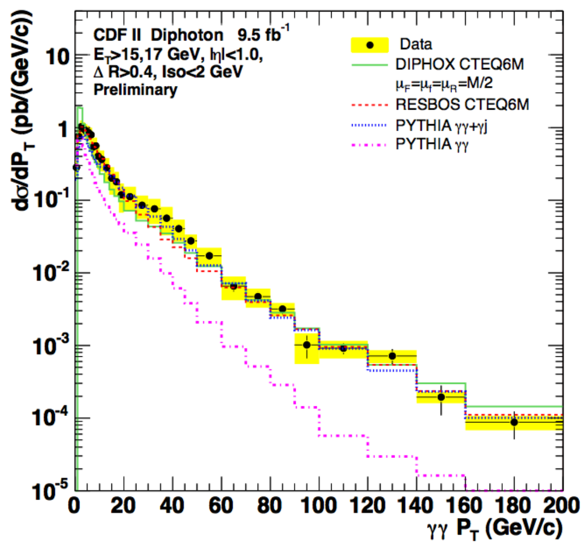
Polar scattering angle also studied as test of spin-correlations (see backup)

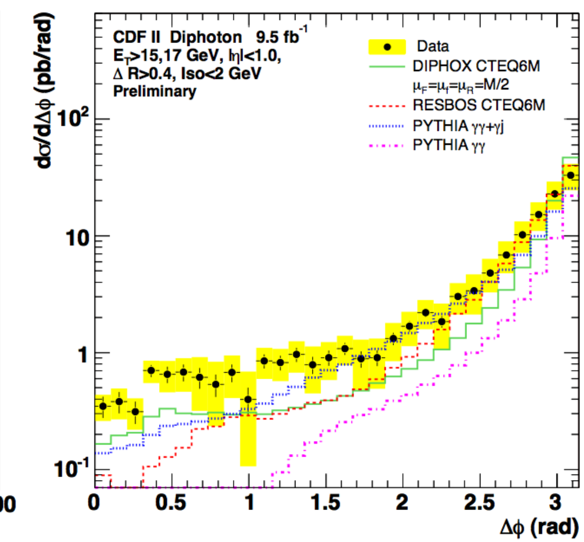
Prompt isolated di-photon production

arXiv:1212.4204 [hep-ex]
Submitted to Phys. Rev. Lett.

Detailed studies from CDF: many more differential distributions at:
http://www-cdf.fnal.gov/physics/new/qcd/diphoton_2012/diphoton_xsec_10fb/







Good agreement between data and theories at high (>30 GeV) invariant mass

ISR+FSR in Pythia improves modelling to level of NLO/NNLO

Resummation important at low p_T

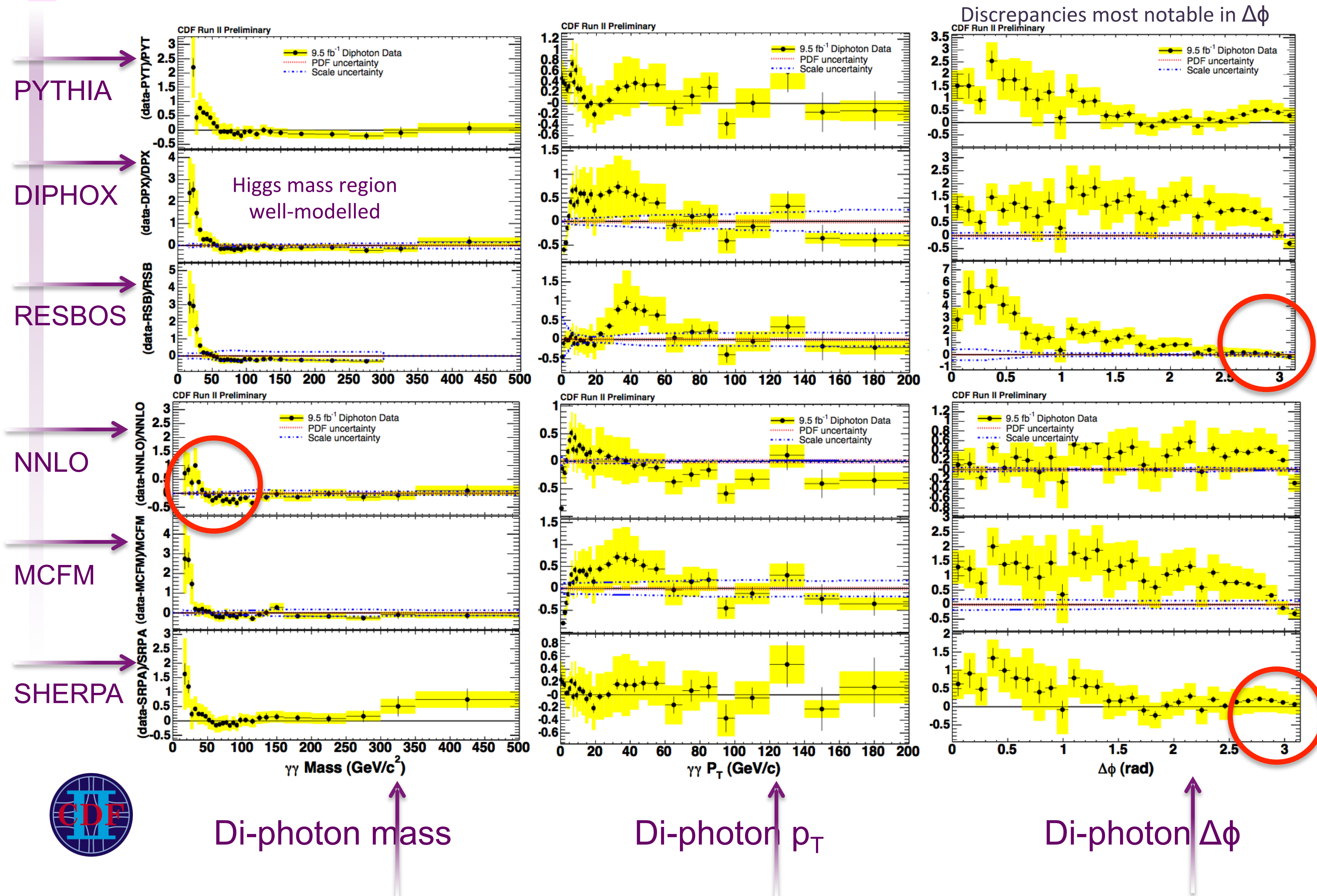
Fragmentation processes cause excess of data over theory for p_T=20—50 GeV

Soft gluon effects important at high Δϕ

In low Δϕ region fragmentation and higher order contributions important

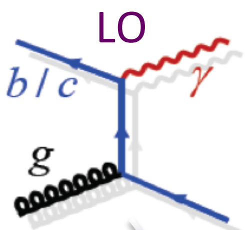
Prompt isolated di-photon production

arXiv:1212.4204 [hep-ex]
Submitted to Phys. Rev. Lett.



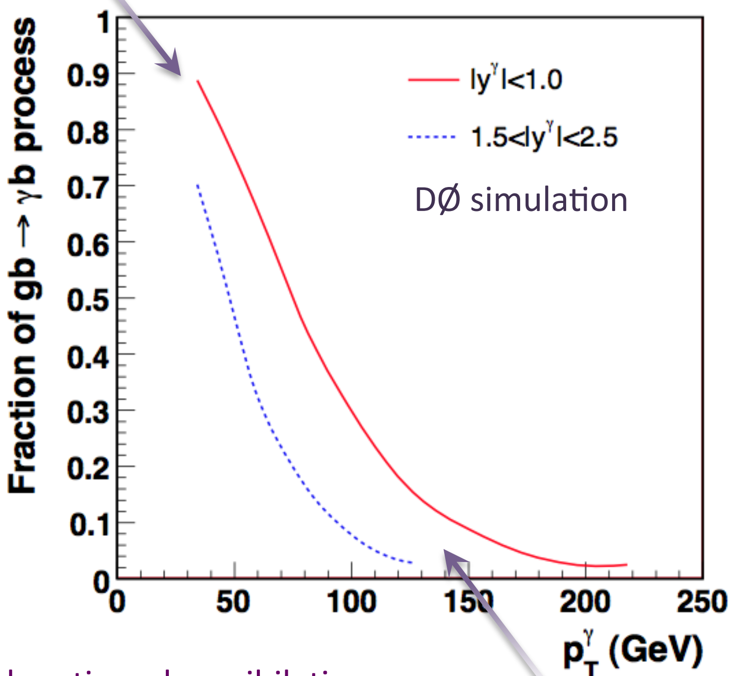
Photon+ b-jet production

arXiv:1203.5865 [hep-ex]
Phys. Lett. B 714 (2012) 32
+CDF public note 10818



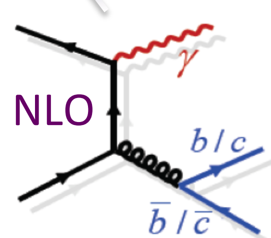
Compton scattering processes dominate at low p_T

b-quark comes from colliding hadrons, acts as a probe of b-quark PDF



Quark-antiquark annihilation becomes dominant at high p_T

b-quark comes from gluon splitting and thus acts as a probe of gluon PDF



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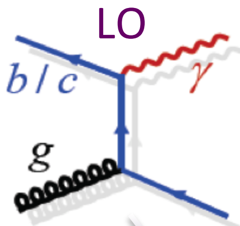

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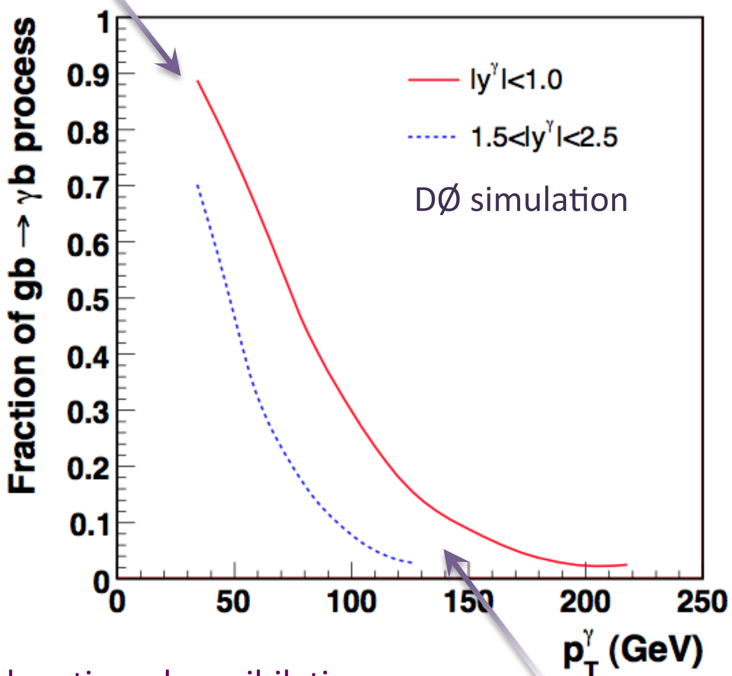

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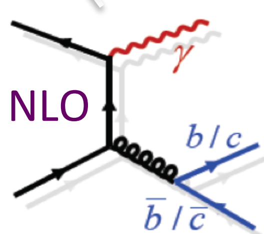
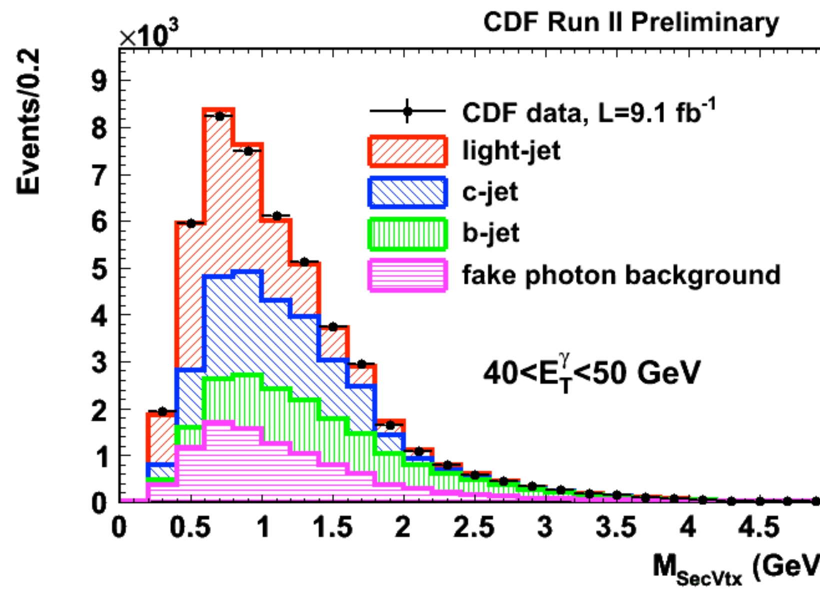


Significant backgrounds from multi-jet events where jet fakes a photon.

Photon neural net output template fits used to determine photon purity.

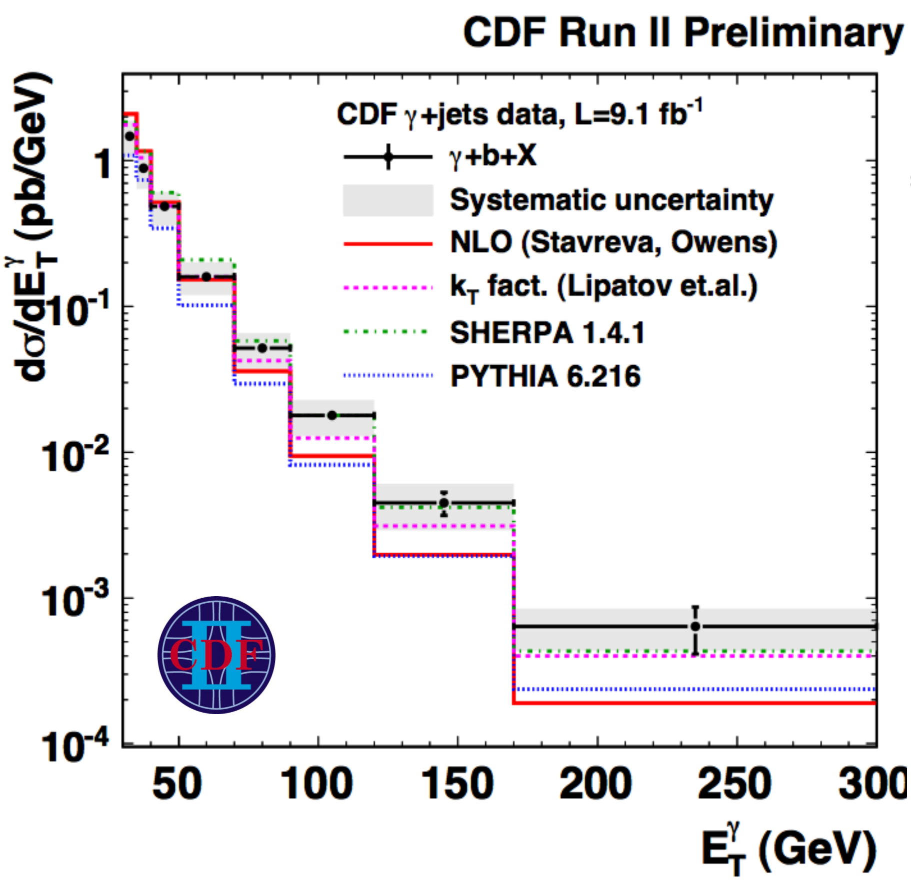


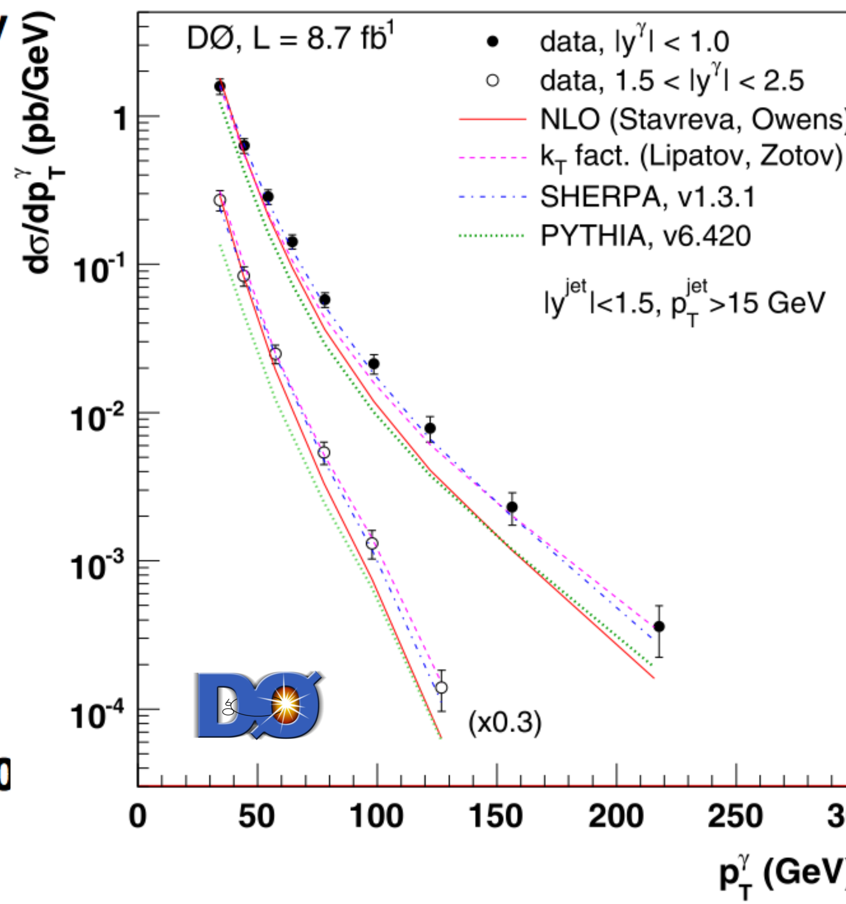
Secondary vertex mass template fits used to extract b-jet component

Photon+ b-jet production

arXiv:1203.5865 [hep-ex]
Phys. Lett. B 714 (2012) 32
+CDF public note 10818

- NLO describes data at low p_T but fails at high >70 GeV.
- Need for higher order corrections dominated by annihilation apparent

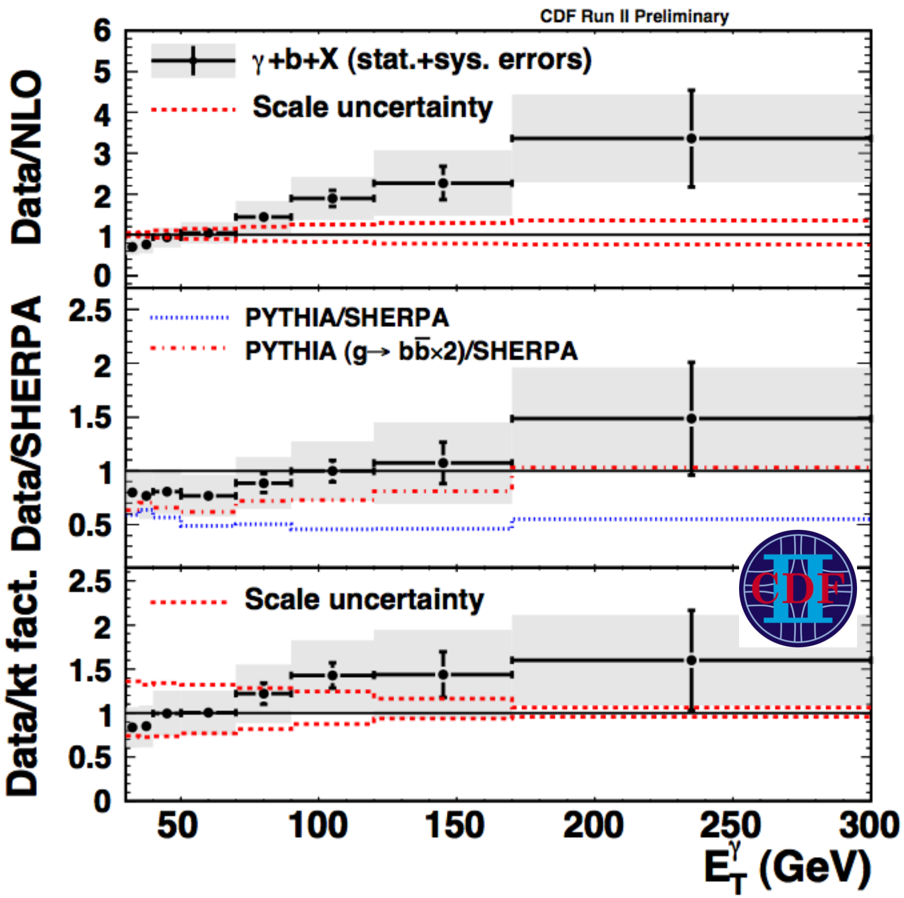


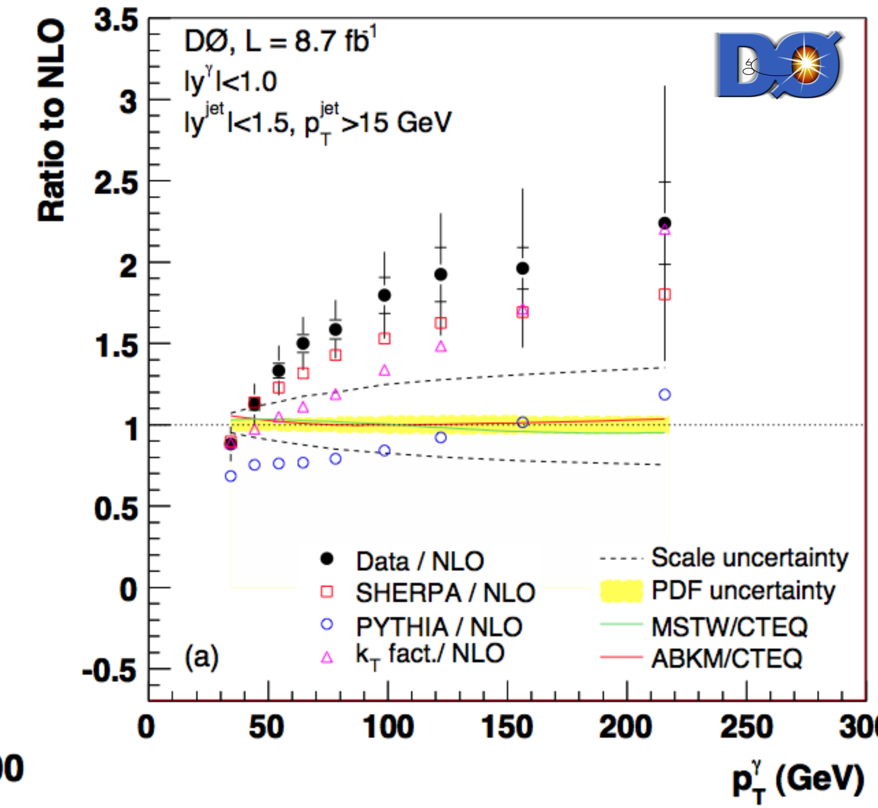


Photon+ b-jet production

arXiv:1203.5865 [hep-ex]
Phys. Lett. B 714 (2012) 32
+CDF public note 10818

- NLO and Pythia differ by up to a factor of two at high p_T
- Sherpa and k_T factorisation show good agreement with the data
- Little sensitivity in predictions with PDF choice: MSTW/CTEQ/ABKM





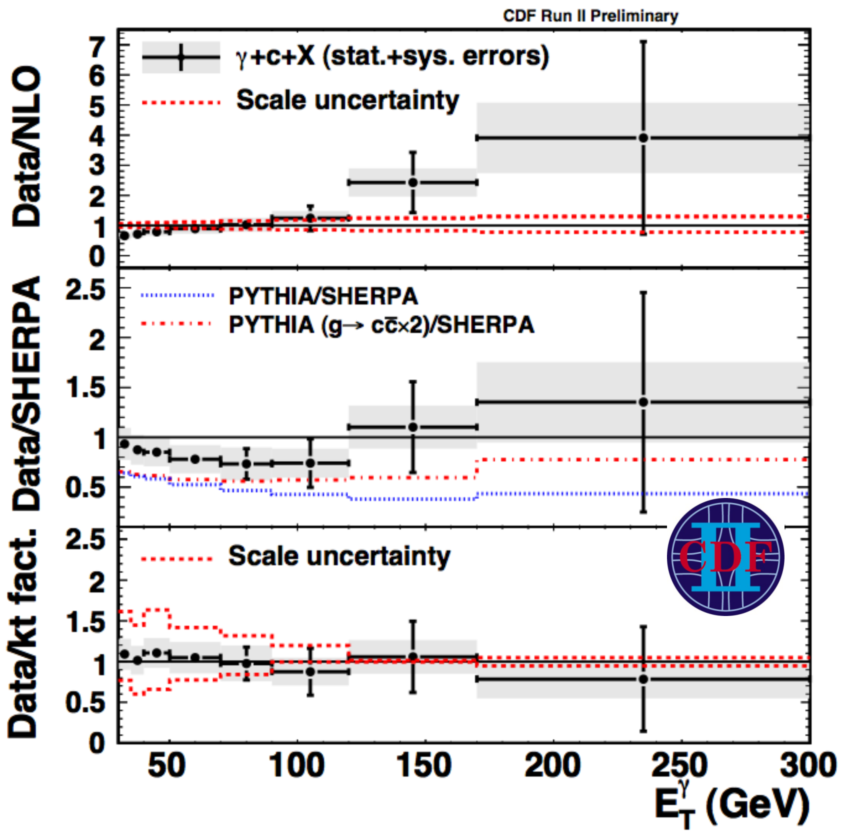
Photon + c-jet production

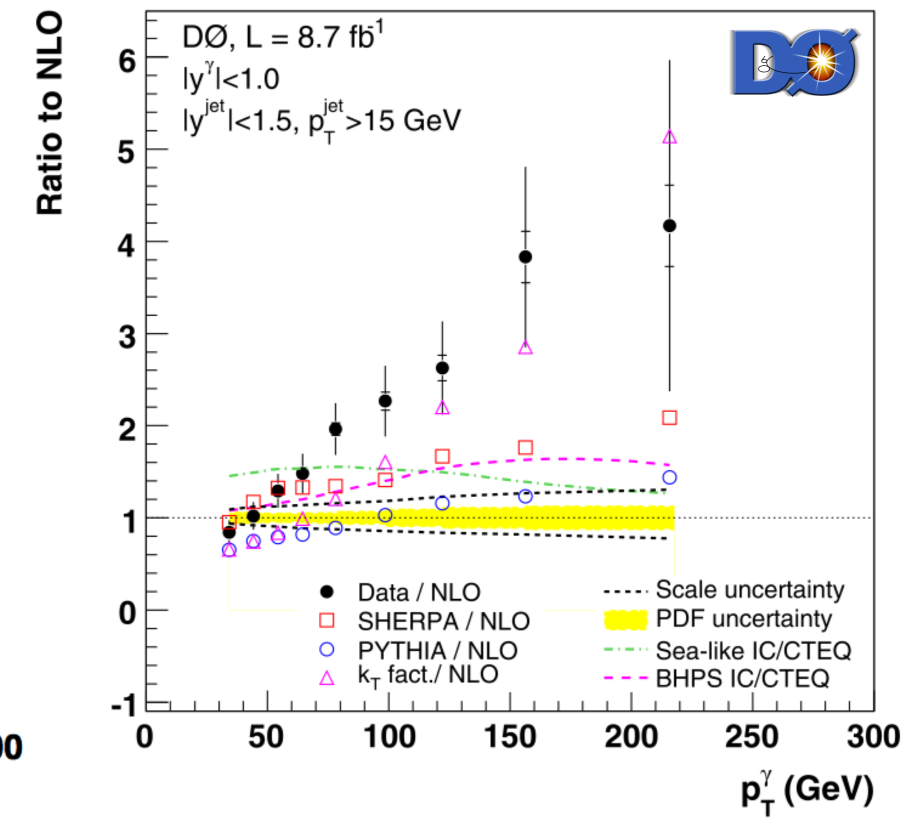
arXiv:1210.5033 [hep-ex]
Phys. Lett. B 179, 354 (2012)
+CDF public note 10818

Analysis proceeds as for b-jet measurements

DØ uses more stringent requirements on heavy-flavour selection to reduce light-jet rate to <5% of HF-enriched sample

- Trend for similar NLO/data disagreement as for b-jets observed (larger uncertainties)
- Data suggests improvements in Pythia modelling of gluon splitting rate in heavy flavour production needed





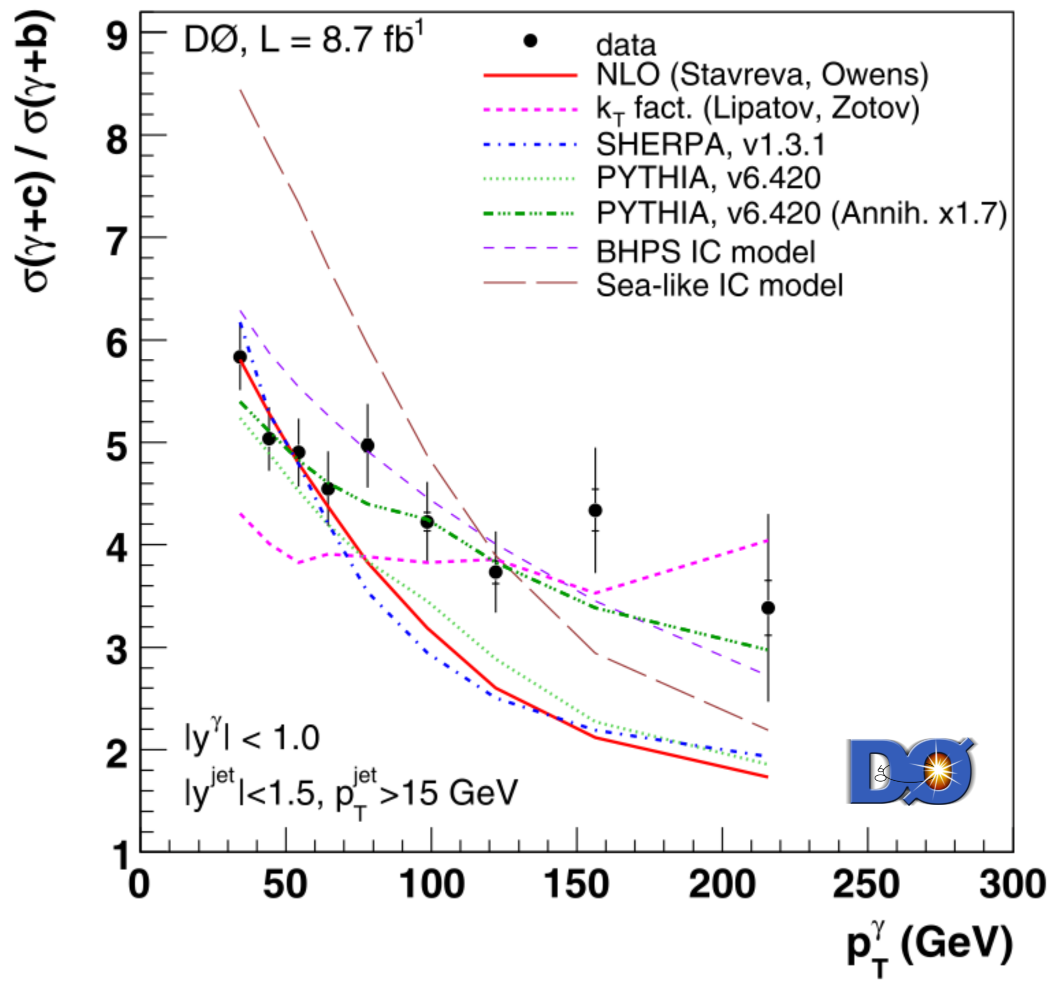
arXiv:1210.5033 [hep-ex]
Phys. Lett. B 179, 354 (2012)

Photon + c-jet/b-jet production

Photon+c-jet to photon+b-jet ratio leads to reduced measurement uncertainties

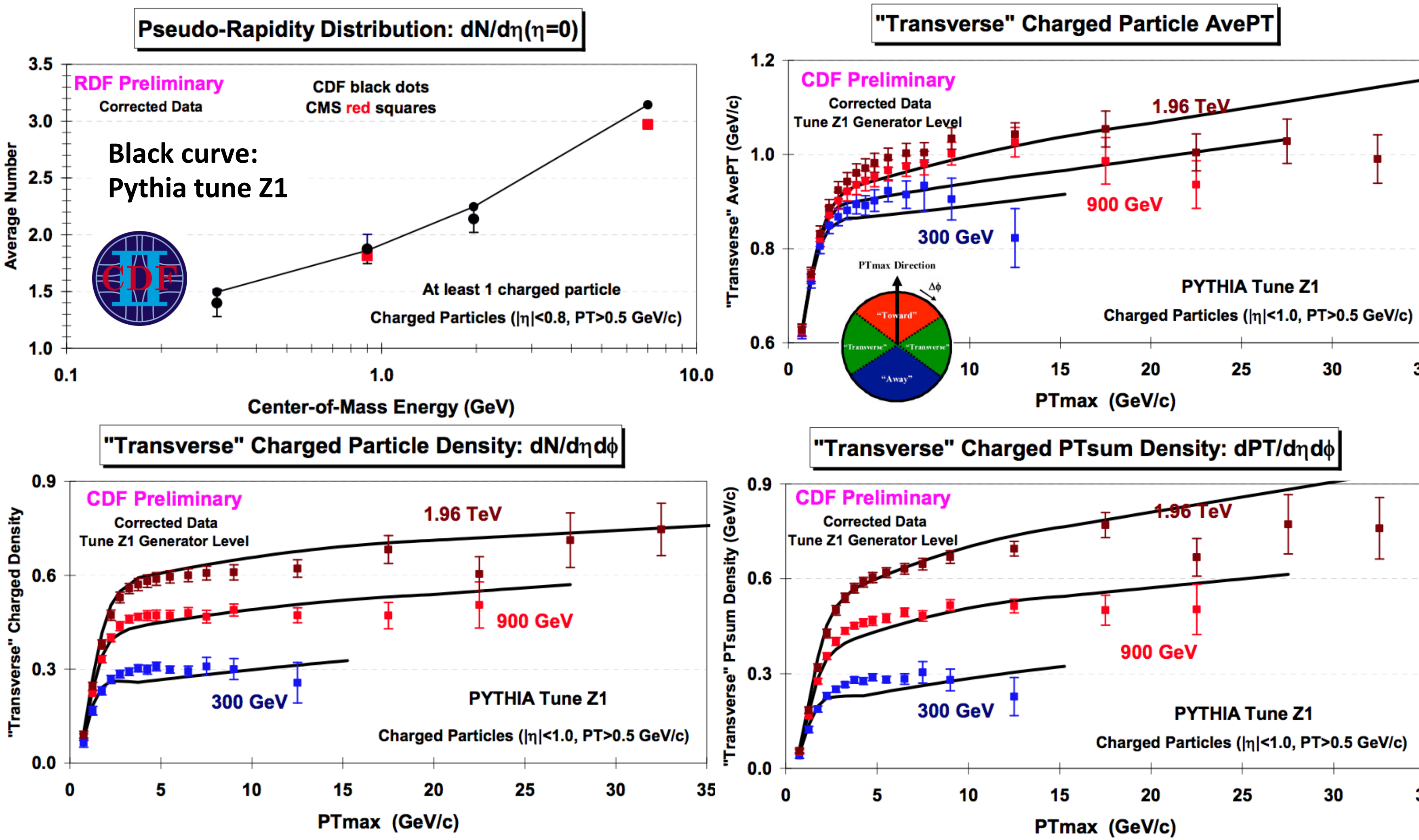
- Data again suggests improvements in Pythia modelling of gluon splitting rate in heavy flavour production needed

- Enhanced contribution from gluon splitting or intrinsic charm contribution can help explain the data/ theory disagreements



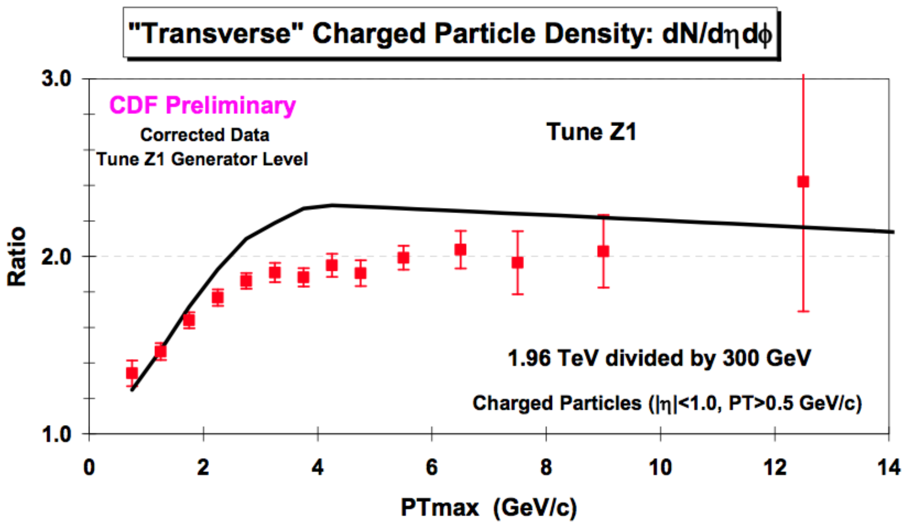
Energy dependence of Underlying Event

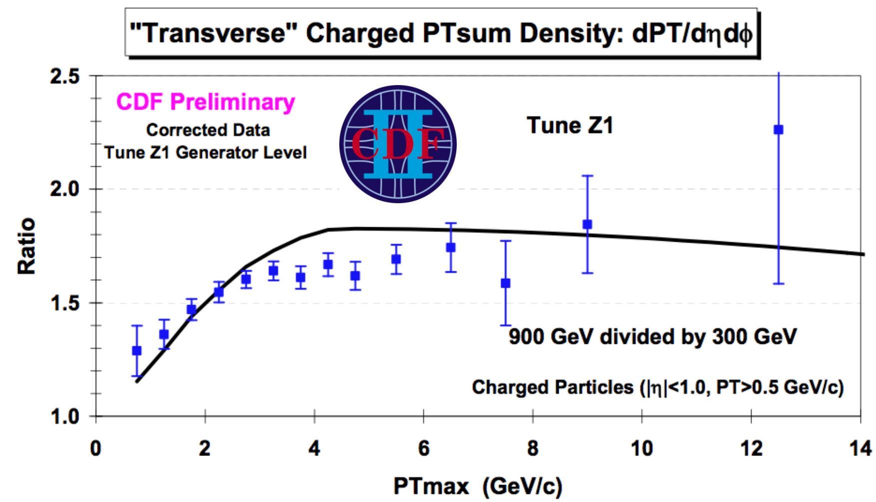
Data from short (<1 week) Tevatron energy-scan run @ 300 GeV & 900 GeV combined with 1.96 TeV data to study underlying event characteristics:

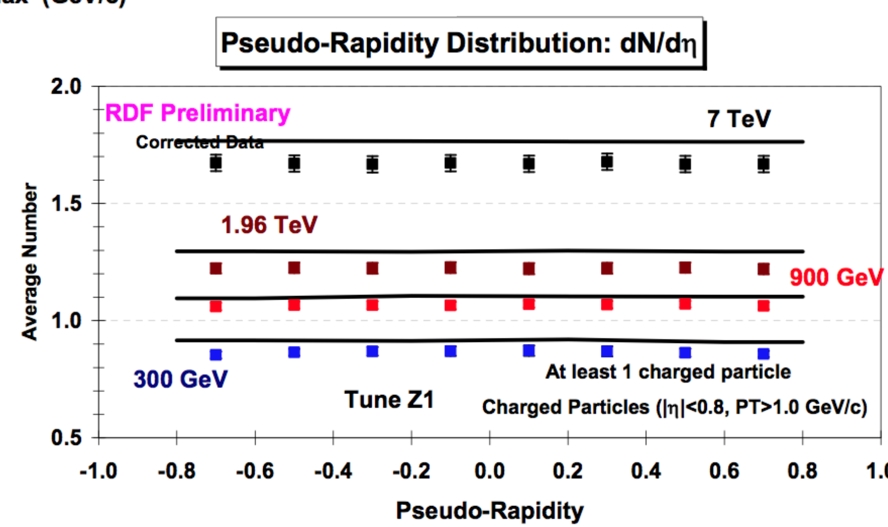


Energy dependence of Underlying Event

A wealth of information for understanding beam remnants / multiple interactions!







Multiple ongoing analyses making use of these unique datasets!
(including study of Central Exclusive Production: see backup)

Summary

There is a rich and active QCD physics program at the Tevatron!
Wide range of measurements, with many more still to come

I was only able to cover a *fraction* of *recent* results today

Observables (many studied for the first time) in:

- inclusive dijet production,
- vector boson plus jets,
- photon + jets,

all show areas where data fails to be described across full range of study

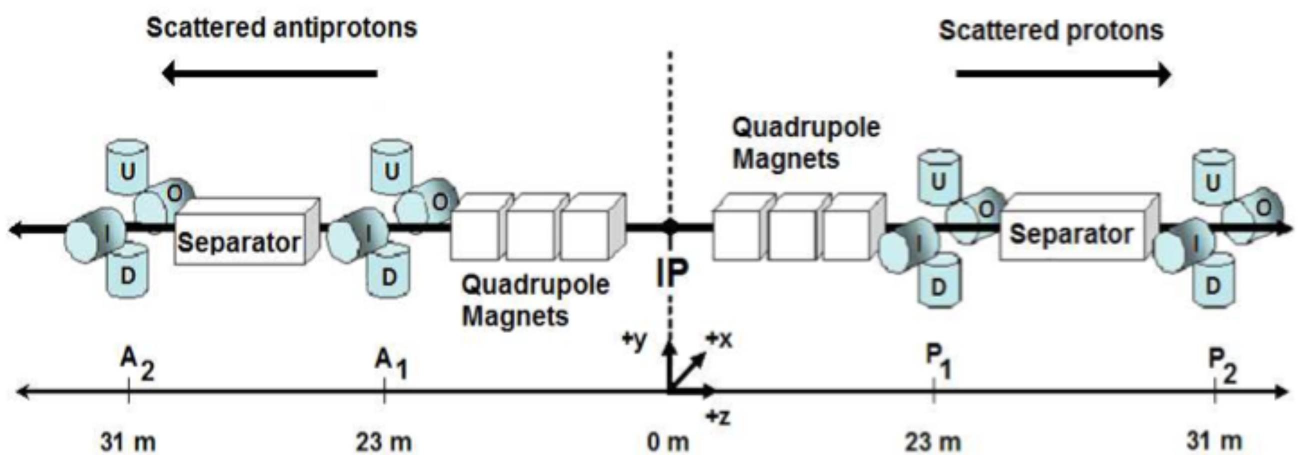
Tevatron energy scan (300 GeV & 900 GeV centre-of-mass energies) offer unique opportunities for study and tuning of theoretical predictions.

Additional Material

Elastic scattering

Elastic scattering cross-section $p\bar{p} \rightarrow p\bar{p}$ measured differentially as function of four-momentum transfer squared, t.
Sensitive to proton structure / npQCD aspects of hadron-hadron interactions

Measured in |t| range $0.26<|t|<1.2$ GeV^2 using forward proton detectors (FPD)
Two(x2) quadrapole spectrometers on proton/anti-proton sides of interaction point:



Pseudorapidity range covered by detectors: $7.3<|\eta|<8.6$
(placement within a few mm of the beam)

Elastic scattering

Use of forward proton detectors requires special run conditions:

- Tevatron β*=1.6m (0.35 m nominal)
- Only 1 proton/anti-proton bunch colliding
  (0.8 mean interactions per bunch crossing)
- Heavy beam halo scraping
  (primary source of background in analysis)

Luminosity of combined runs ~31 nb^{-1}

Integrated luminosity for this special data-taking period calculated by comparing number of inclusive jet events to that obtained in standard run with identical selection criteria.

Results in overall normalisation uncertainty of 14.4%
(6.1% from standard luminosity uncertainty, 13% from jet analysis).

Elastic scattering

arXiv:1206.0687 [hep-ex]
Phys. Rev. D 86 (2012) 012009

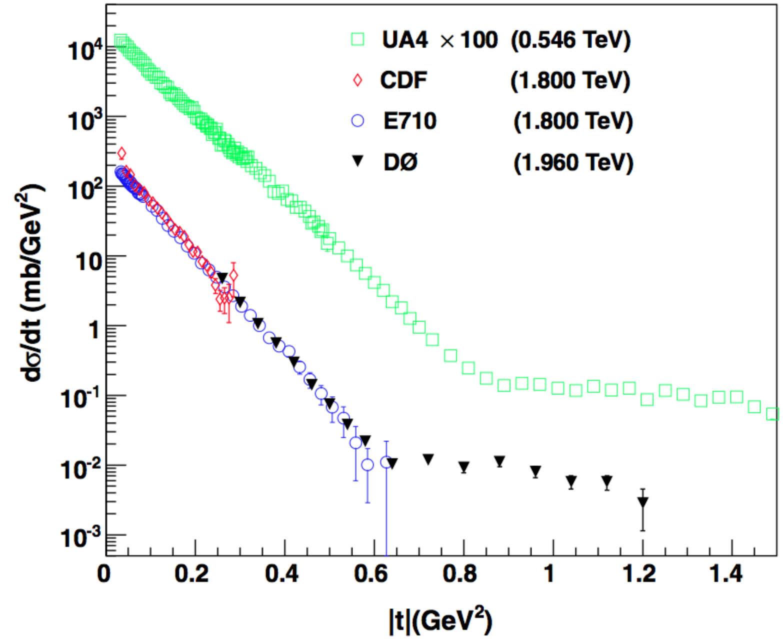
Measure cross-section over $0.26<|t|<1.2$ GeV^2

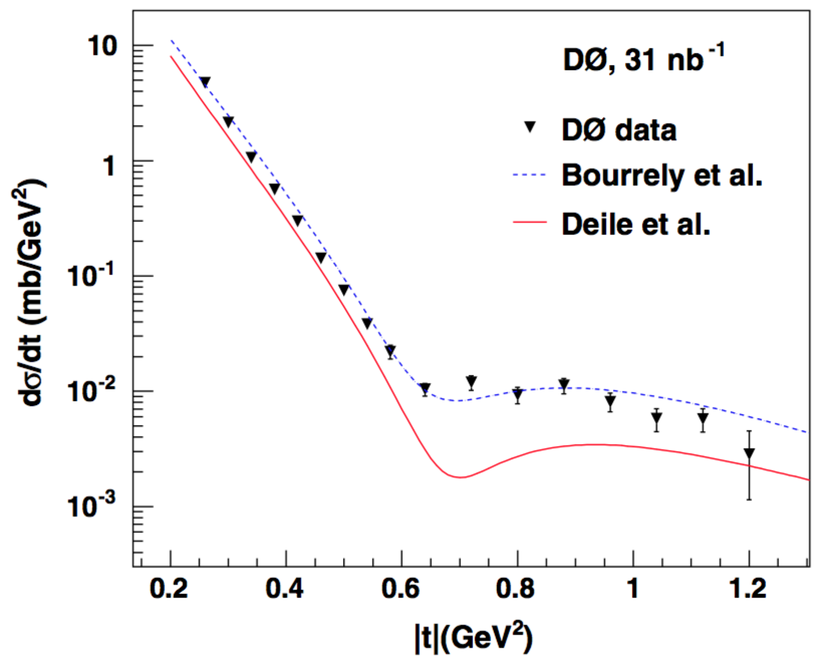
Exponential dependence observed at low |t|, slope: $16.86\pm0.10^{stat}\pm0.20^{syst}$
consistent with prior measurements at CDF/E710 (1.8 TeV)

Complementary to TOTEM results from LHC

- Change in slope occurs at 0.6 GeV^2, moving to lower |t| at increasing centre of mass energy
- Local diffraction minimum seen in pp results much more distinct than in proton-antiproton

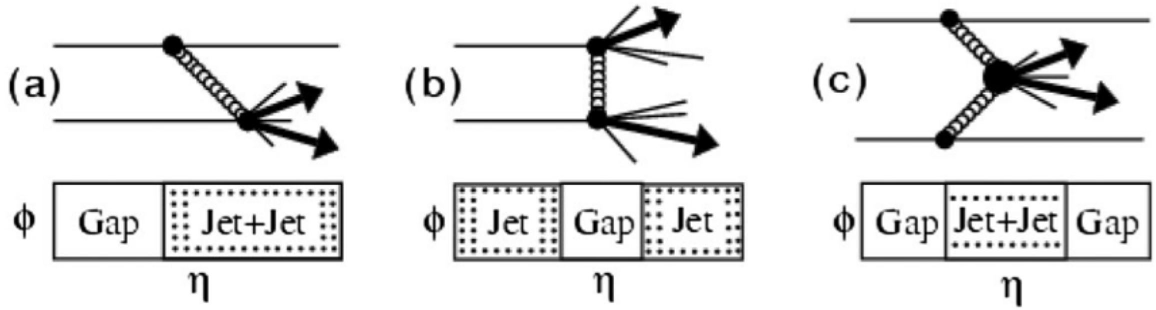
Data able to differentiate between and provide input to phenomenological models





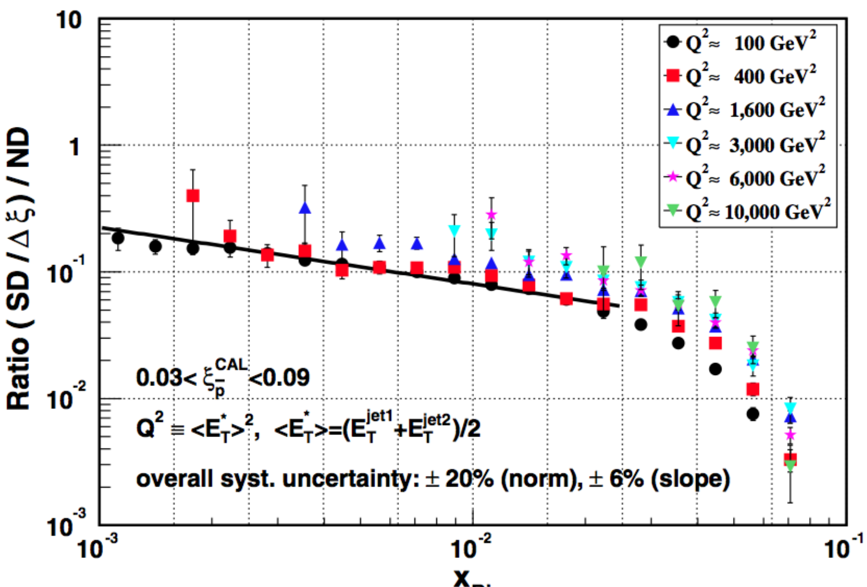
Diffractive dijet production

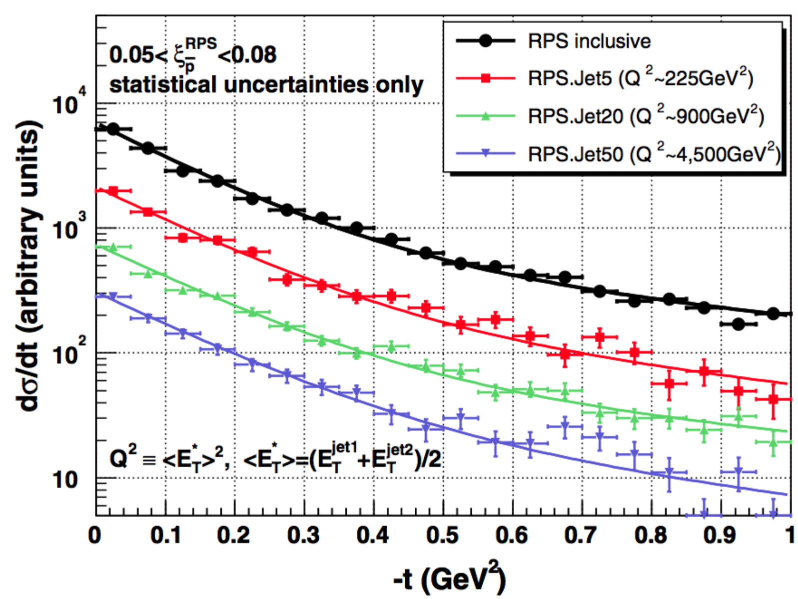
RunI diffractive measurements showed breakdown of QCD factorisation (factor of 10 suppression of diffractive structure function over HERA)



Single Diffraction Double Diffraction Pomeron Exchange

Characterise Pomeron exchange by study of Q^2 and t dependence





small Q^2 dependence for $100 < Q^2 < 10{,}000$ GeV^2 suggests Pomeron evolves as proton

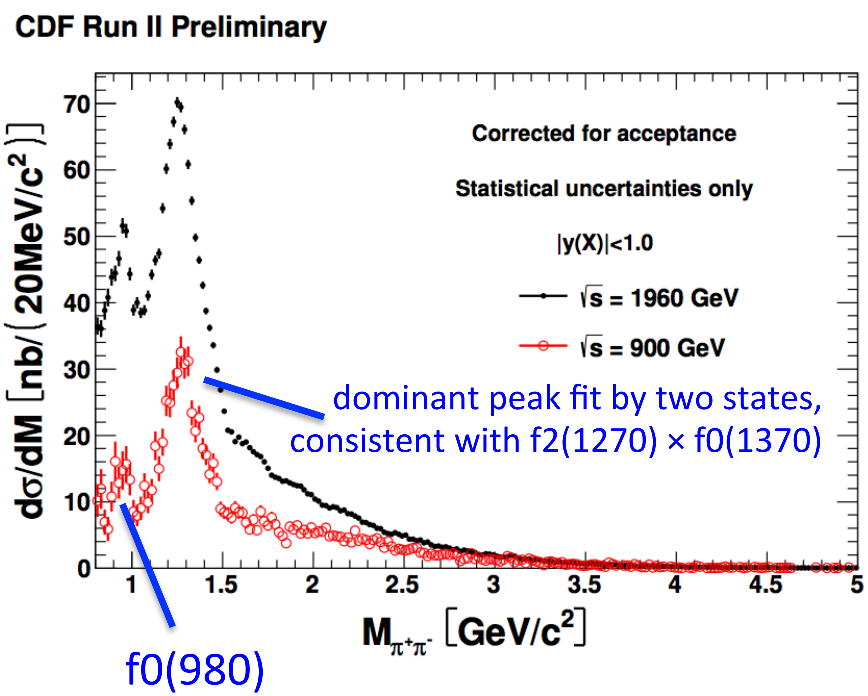
no diffraction minimum observed for $|t|<1$

Central Exclusive Production

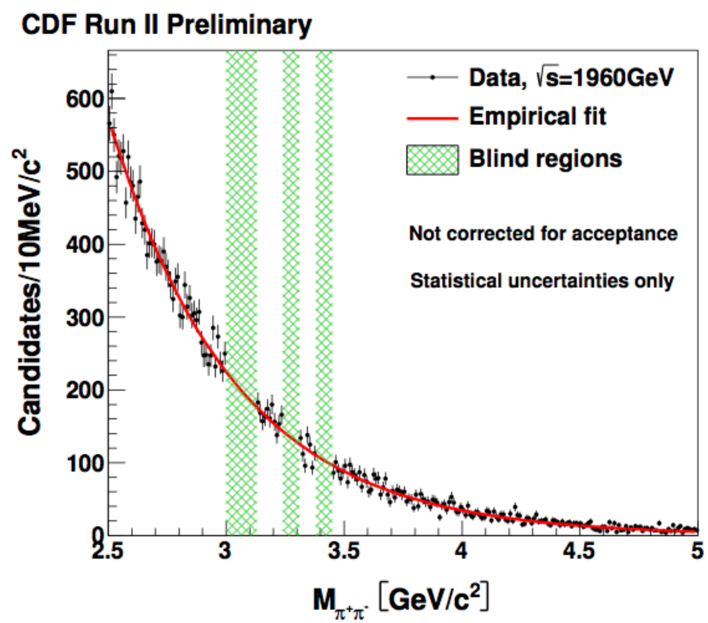
p + p¯ → p + X + p¯ reaction studied at centre-of-mass energies 900 GeV and 1960 GeV

Exclusive hadronic systems, produced through double pomeron exchange have potential of opening a rich new window on hadron spectroscopy and the diffraction mechanism.
Restrictions on the quantum numbers of X: Q = S = 0, C = +1, J = 0 or 2.

Determine cross-sections of production with di-particle invariant mass:



Search for χ_{c0} @ 1.96 TeV: set 90% limit
for → π+π− at 21.4 ± 4.3 nb
for → K^+K^- at 19.0 ± 3.8 nb

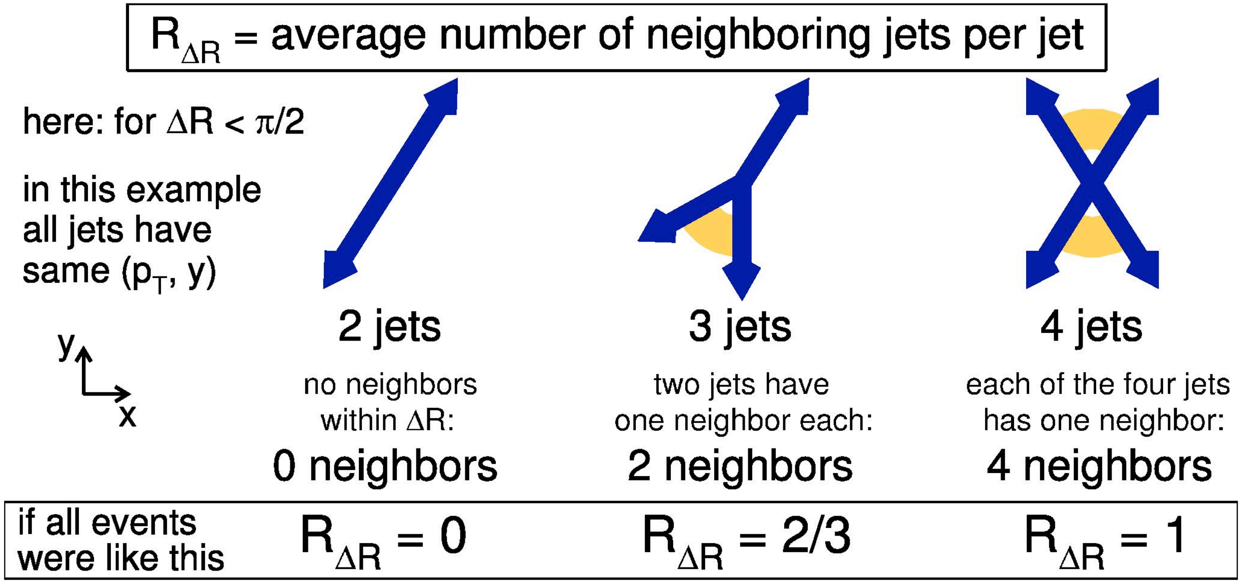


Studies are a work in progress – other channels being studied + improvements!

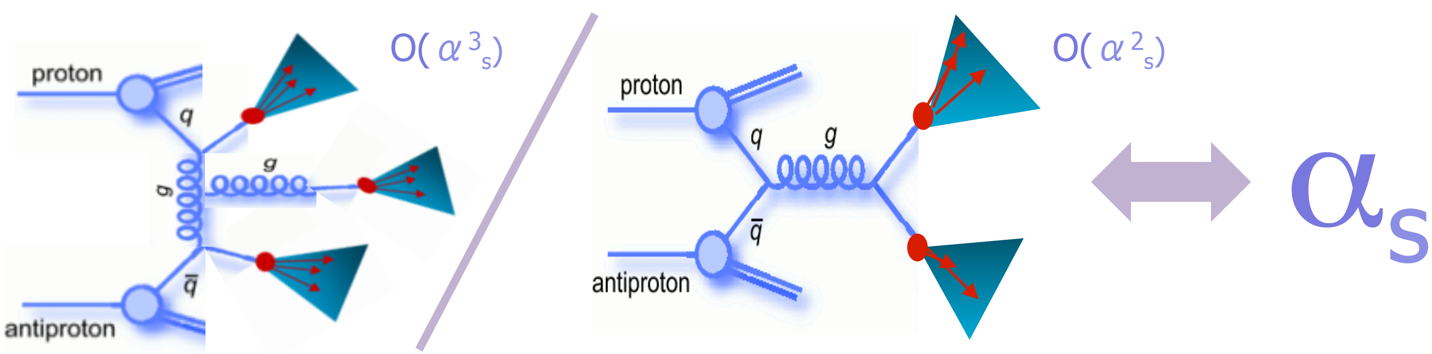
Angular jet correlations

arXiv:1207.4957 [hep-ex]
Phys. Lett. B 718, 56 (2012)

New observable $R_{\Delta R}$: average number of neighbouring jets within given ΔR interval above some p_T threshold

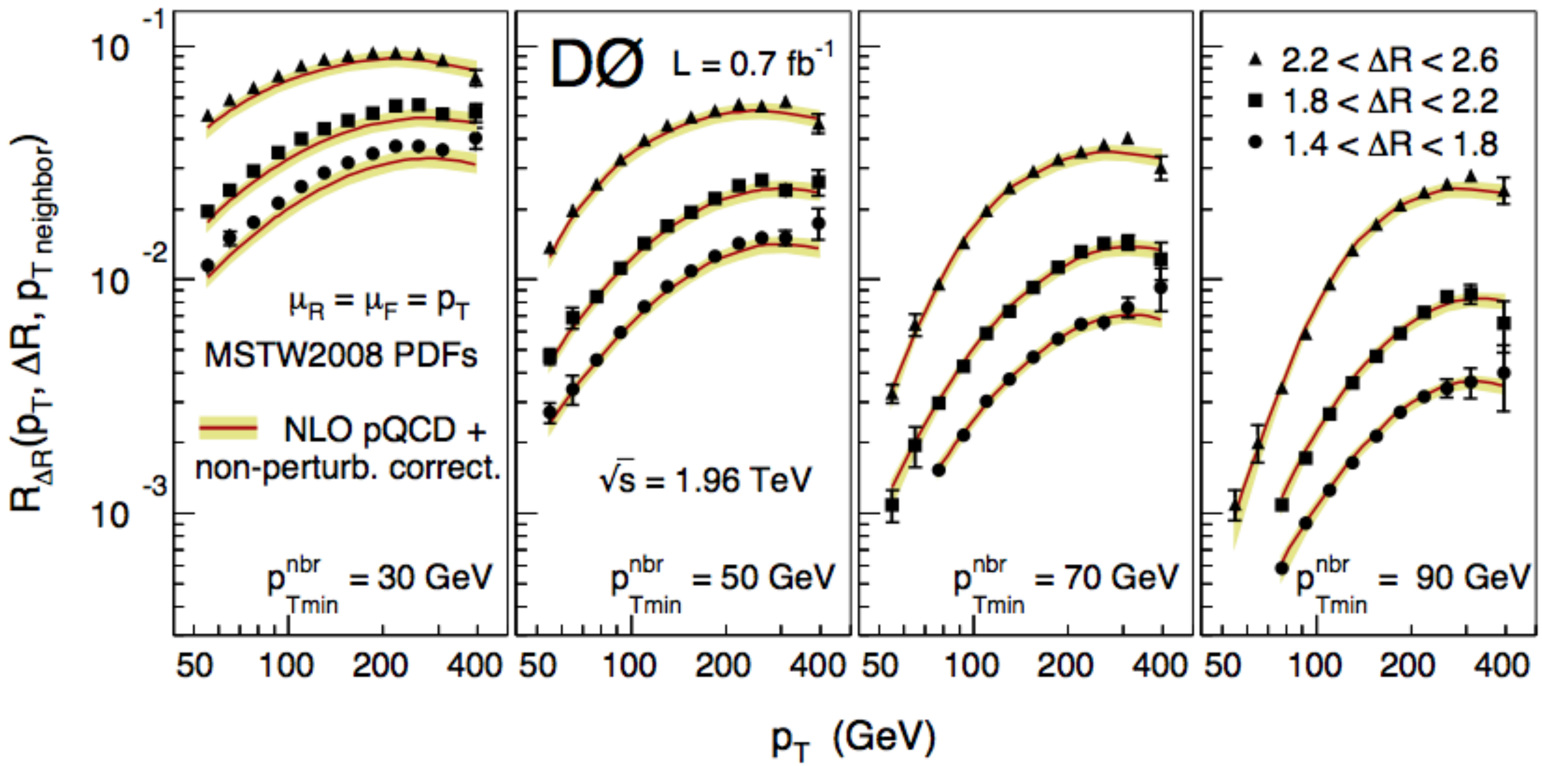


Benefits: sensitive to strong coupling constant, weakly sensitive to PDF



Angular jet correlations

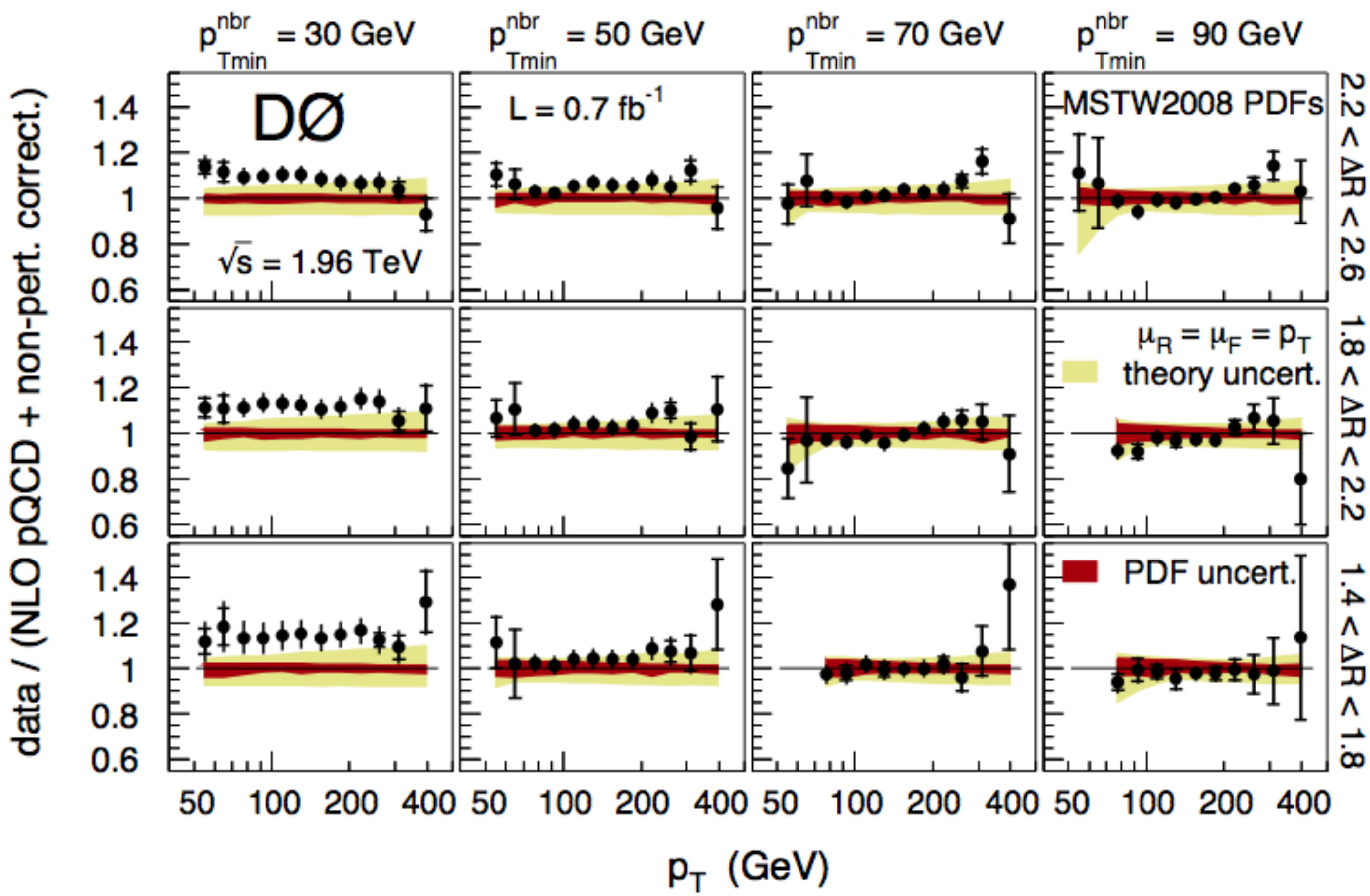
Jet selection:
|y|<1.0 (midpoint cone algorithm R=0.7), 50<pT<450 GeV
Three ΔR ranges, four neighbouring jet pT thresholds



Dominant measurement uncertainties from jet energy calibration (2-5%), model-dependence of data correction factors (2-3%)

Angular jet correlations

arXiv:1207.4957 [hep-ex]
Phys. Lett. B 718, 56 (2012)

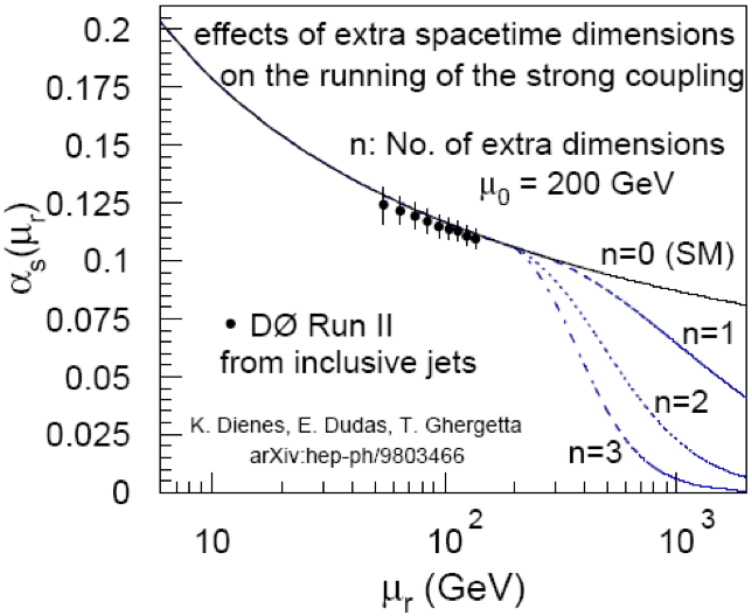


NLO predictions from FastNLO (based on NLOjet++), non-perturbative corrections from Pythia, and mstw2008nlo PDFs

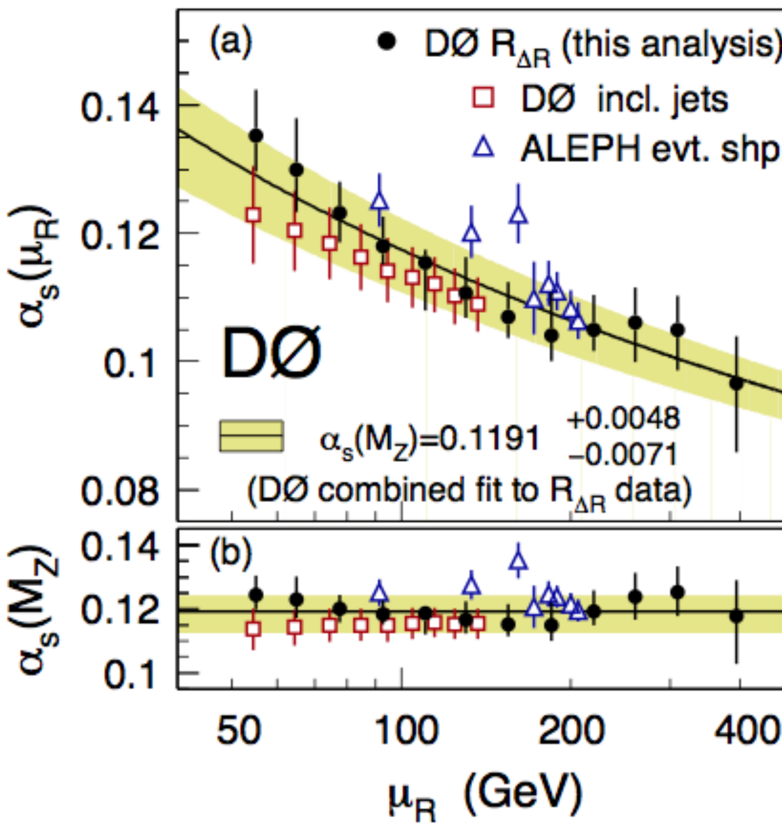
Good agreement for neighbour $p_T > 50$ GeV, some problems at 30 GeV

arXiv:1207.4957 [hep-ex]
Phys. Lett. B 718, 56 (2012)

Measurement of the strong coupling



Strong coupling tested up to scale of 208 GeV.
Modification of running at higher scales could occur due to New Physics e.g. extra dimensions



In each analysis region, determine combined $\alpha_s(M_Z)$ and fit quality

Use $R_{\Delta R}$ data for neighbour $p_T > 50, 70, 90$ GeV and at each jet p_T combine all neighbour p_T / ΔR

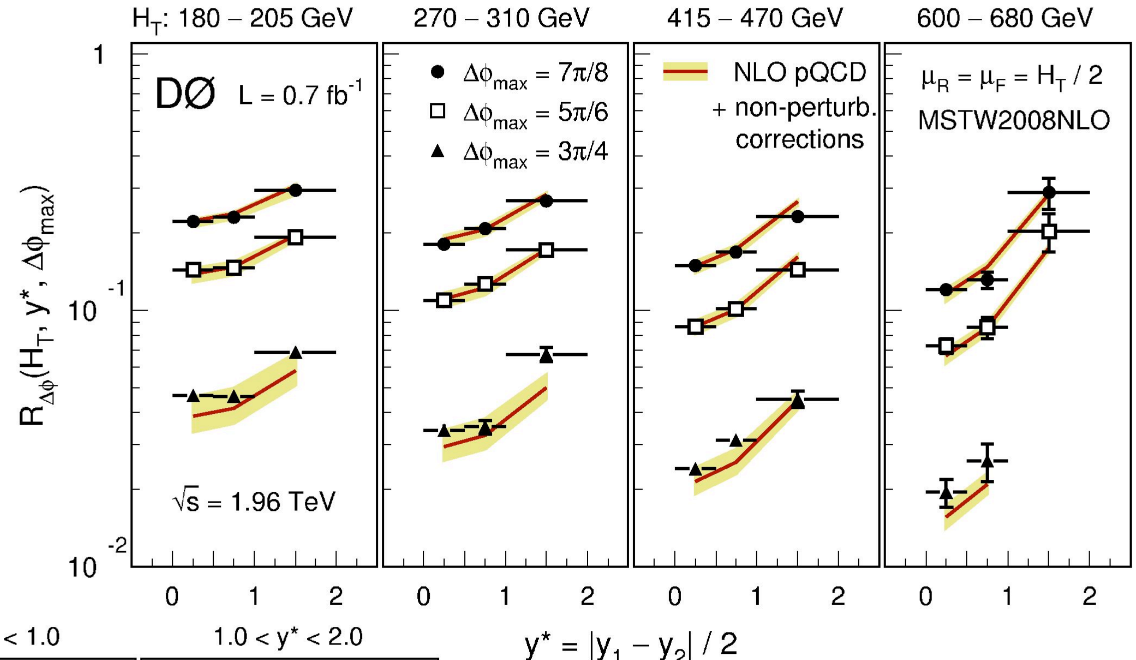
New $\alpha_s(p_T)$ results up to scale of 400 GeV
Decrease in $\alpha_s(p_T)$ with p_T as predicted by RGE

World average $\alpha_s(M_Z) = 0.1184 \pm 0.004$

Dijet azimuthal decorrelations

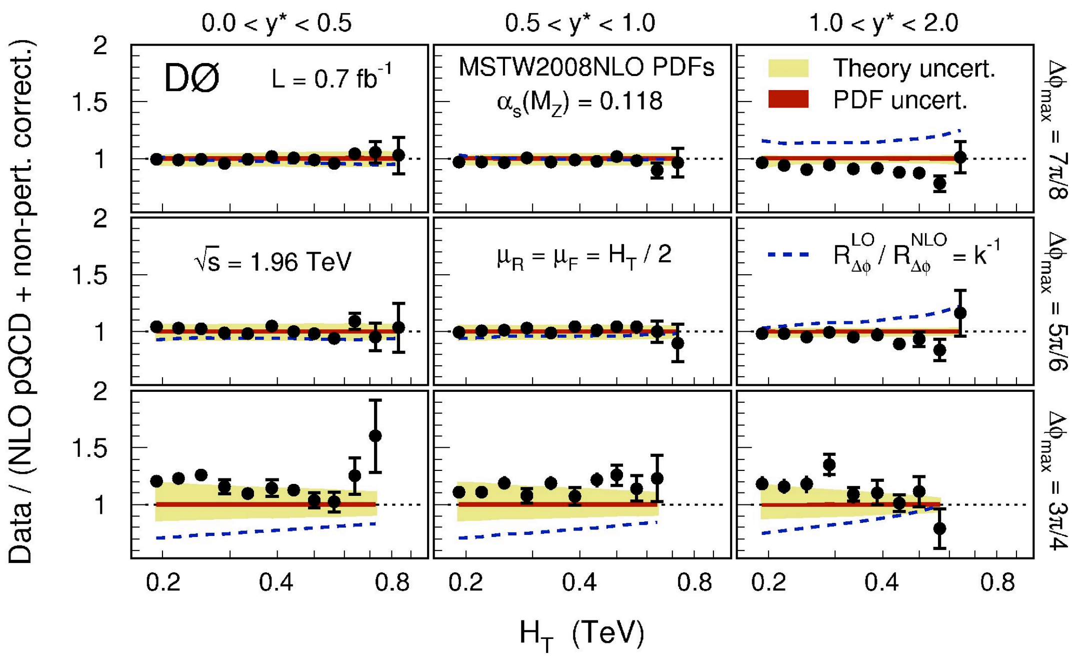
arXiv:1212.1842 [hep-ex]
Submitted to Phys. Lett. B

$R_{\Delta\varphi}$ as a function of rapidity separation in four H_T intervals:



H_T dependence increases towards lower $\Delta\varphi_{max}$

H_T dependence stronger for smaller y^*



Comparison with NLO as a function of H_T

Problems at wide rapidity separation and large $\Delta\varphi_{max}$

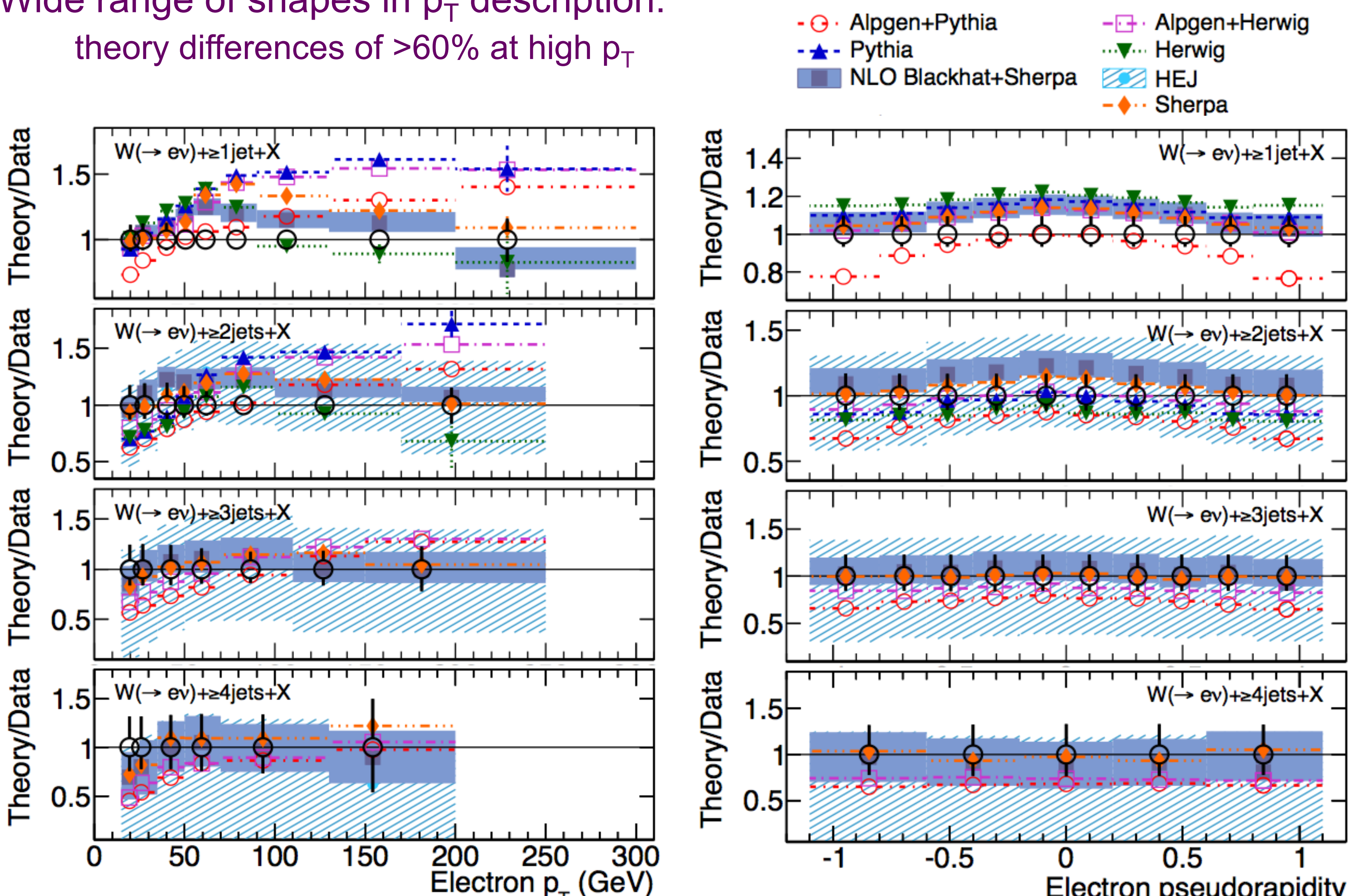
W+jets: lepton p_T and pseudorapidity

arXiv:1302.6508 [hep-ex]
Submitted to Phys. Rev. D

Modelling issues observed, most noticeable at low p_T

Wide range of shapes in p_T description:

theory differences of >60% at high p_T

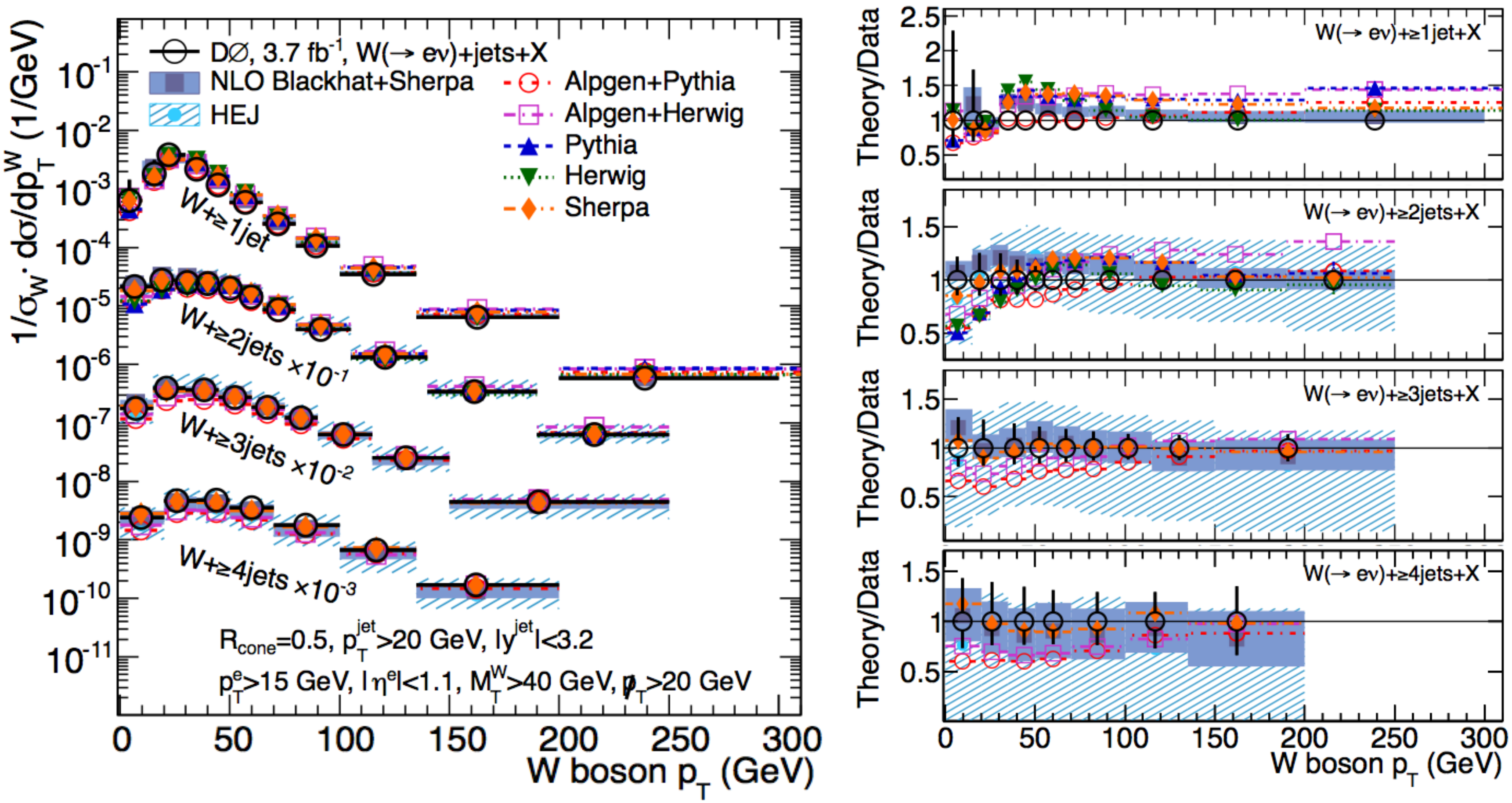


W+jets: W boson p_T

arXiv:1302.6508 [hep-ex]
Submitted to Phys. Rev. D

Lepton p_T analogue, but includes missing energy vector.

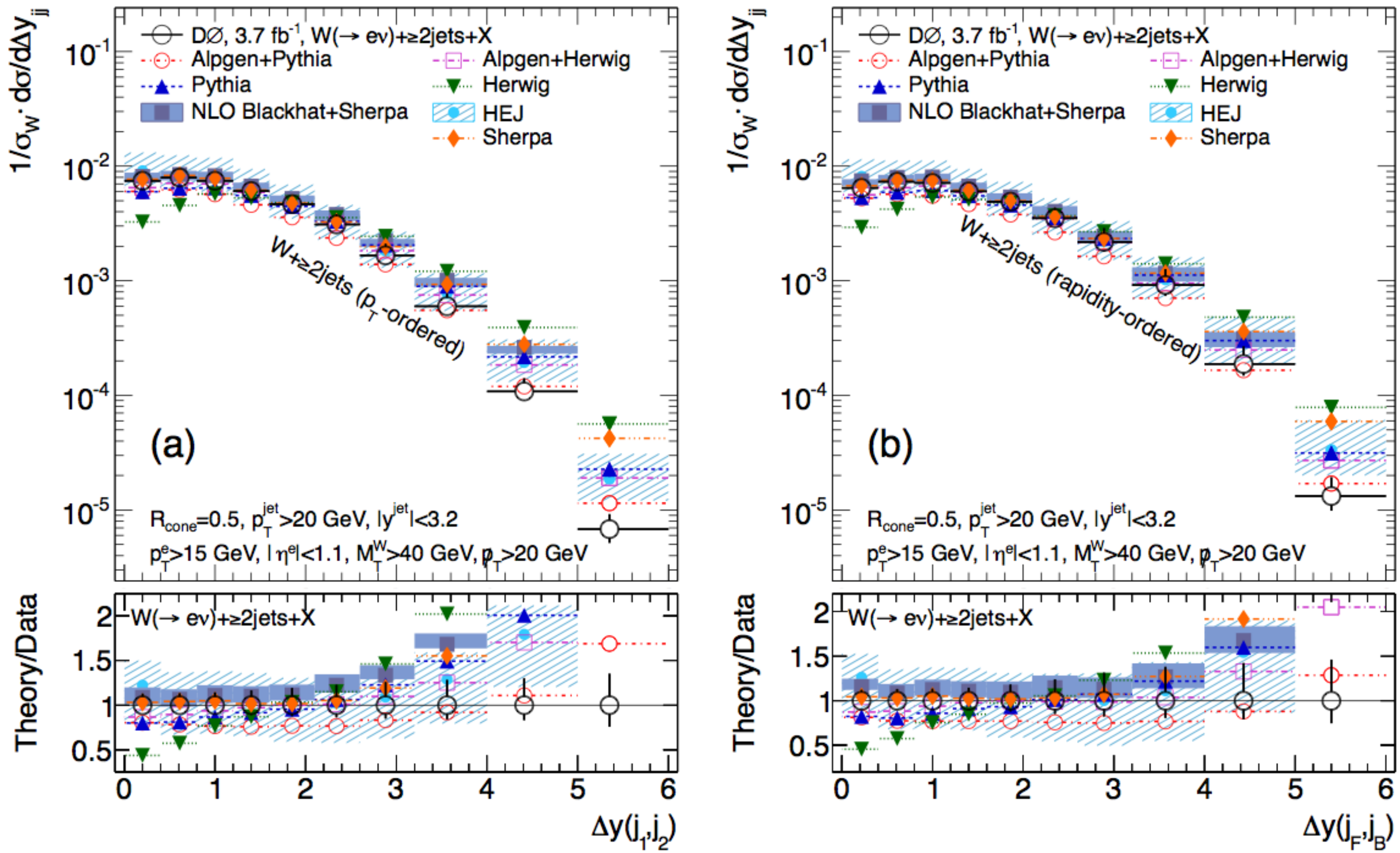
Agreement between data and NLO
Various theoretical predictions still have large variance



W+jets: Dijet rapidity separation [two-jet bin]:

Two configurations studied: separation between highest p_T jets (left) and between most rapidity-separated jets (right)

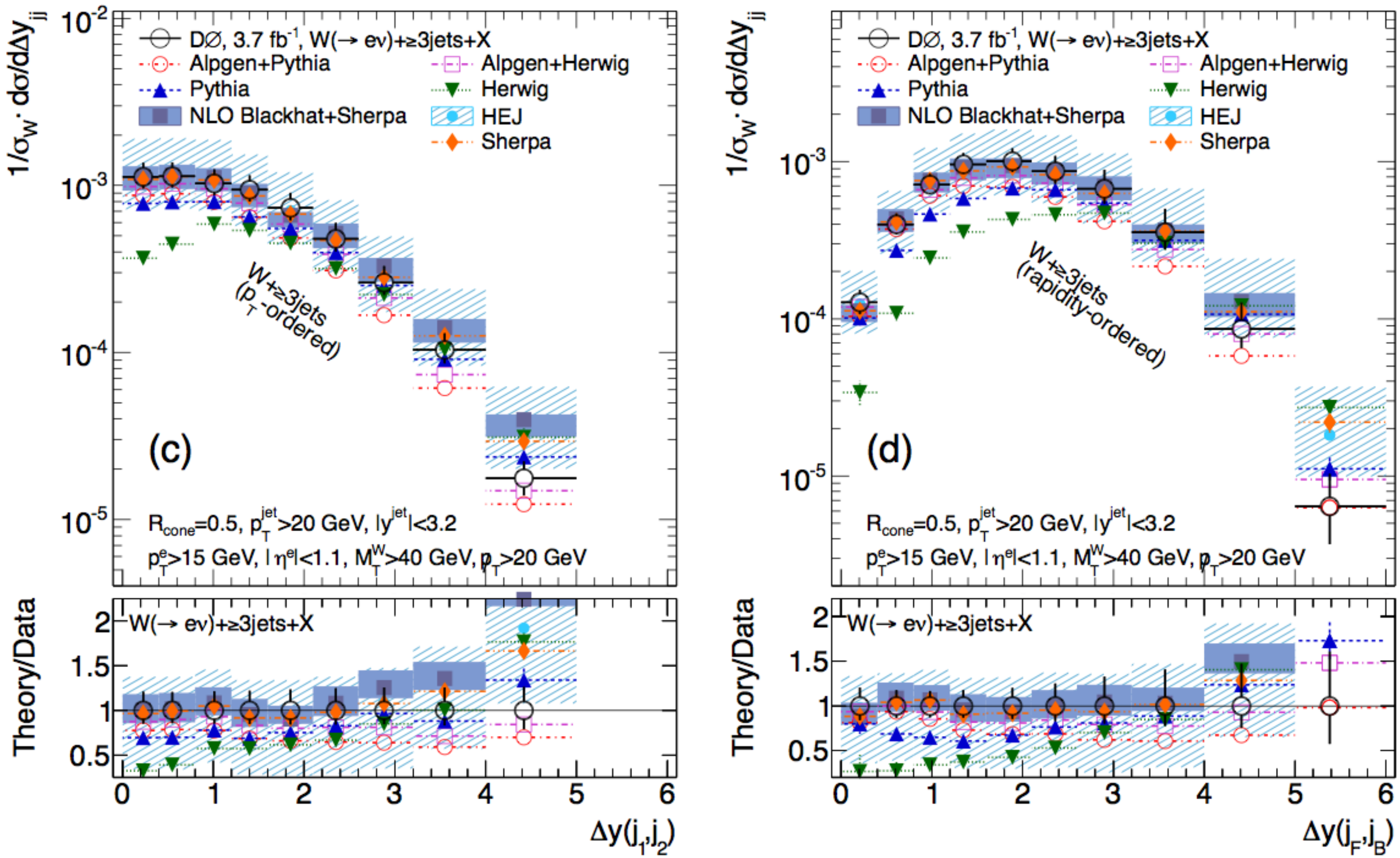
See a trend for overestimation of highly rapidity separated jet production rate



W+jets: Dijet rapidity separation [three-jet bin]:

Two configurations studied: separation between highest p_T jets (left) and between most rapidity-separated jets (right)

See a trend for overestimation of highly rapidity separated jet production rate

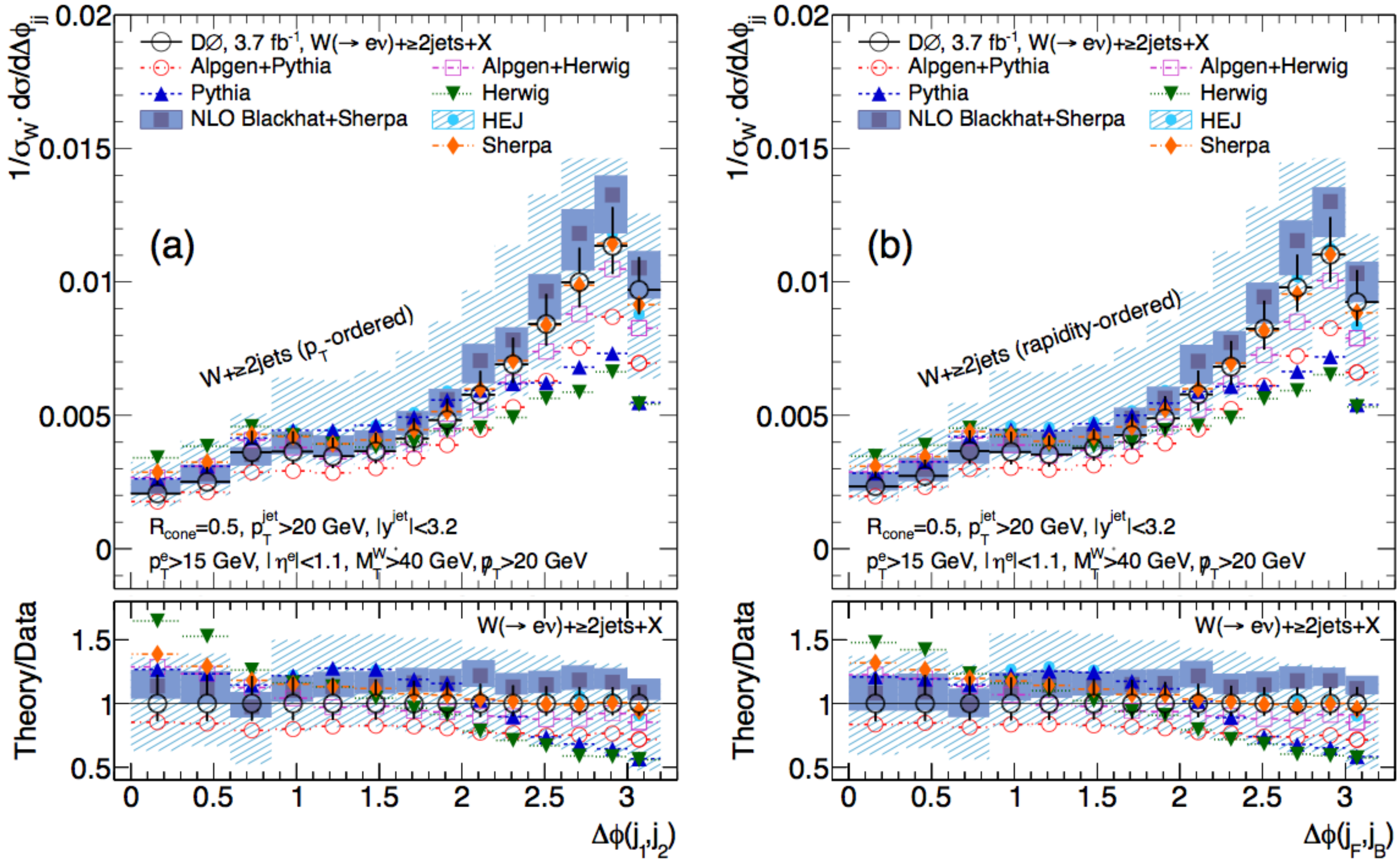


W+jets: Dijet azimuthal angle separation:

Sensitive to soft radiation emission, input to MC tuning

Wide variety of predictions, NLO and Sherpa do a good job

PS MC's in particular give more collinear emissions and significantly reduced high $\Delta\phi$ emissions than observed in data



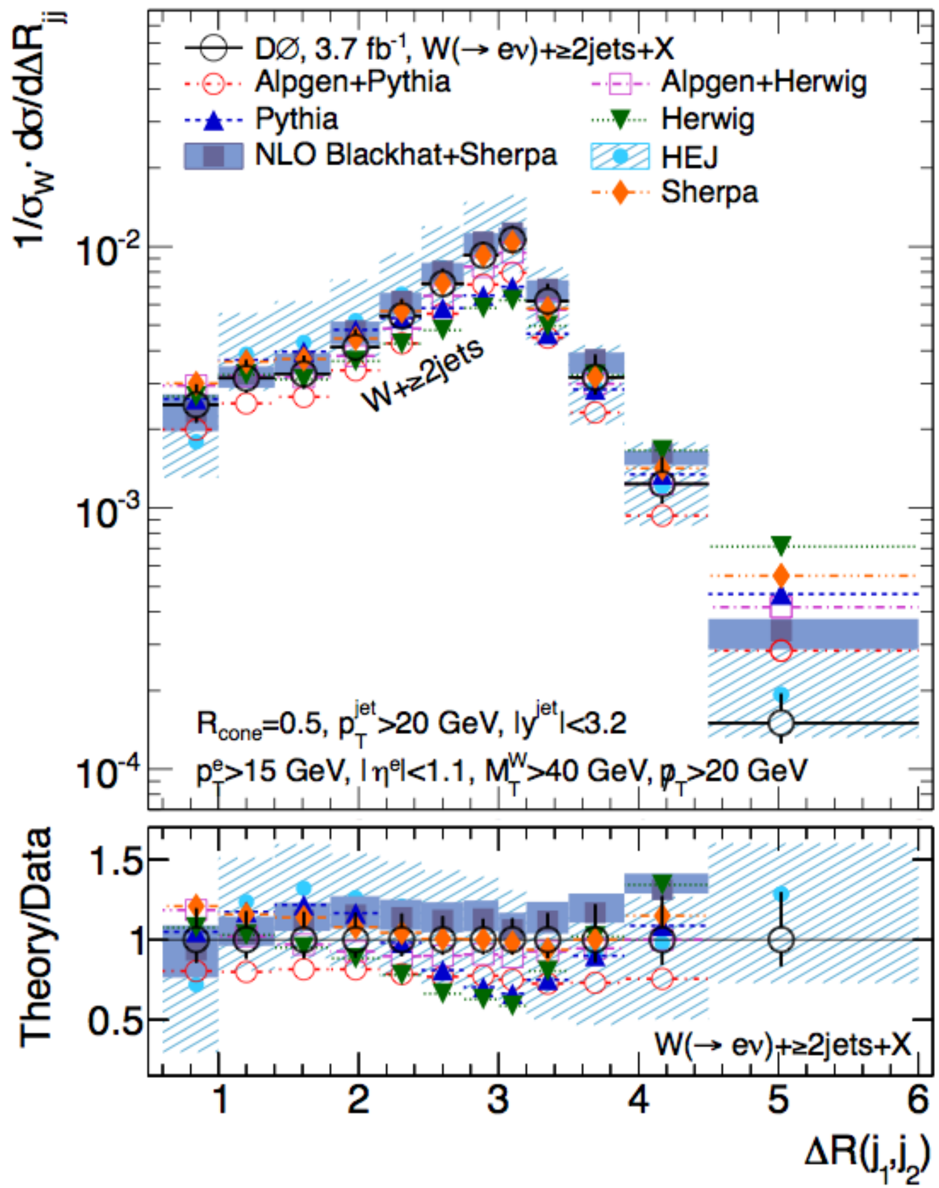
W+jets: Dijet opening angle:

Spatial opening angle ΔR defined in (true) rapidity and azimuthal angle space

Encodes discrepancies between theory and data seen in the two opening angle (y–ϕ) measurements, with correlations.

Large shape variations seen, and large (>50%) divergences between various theoretical descriptions

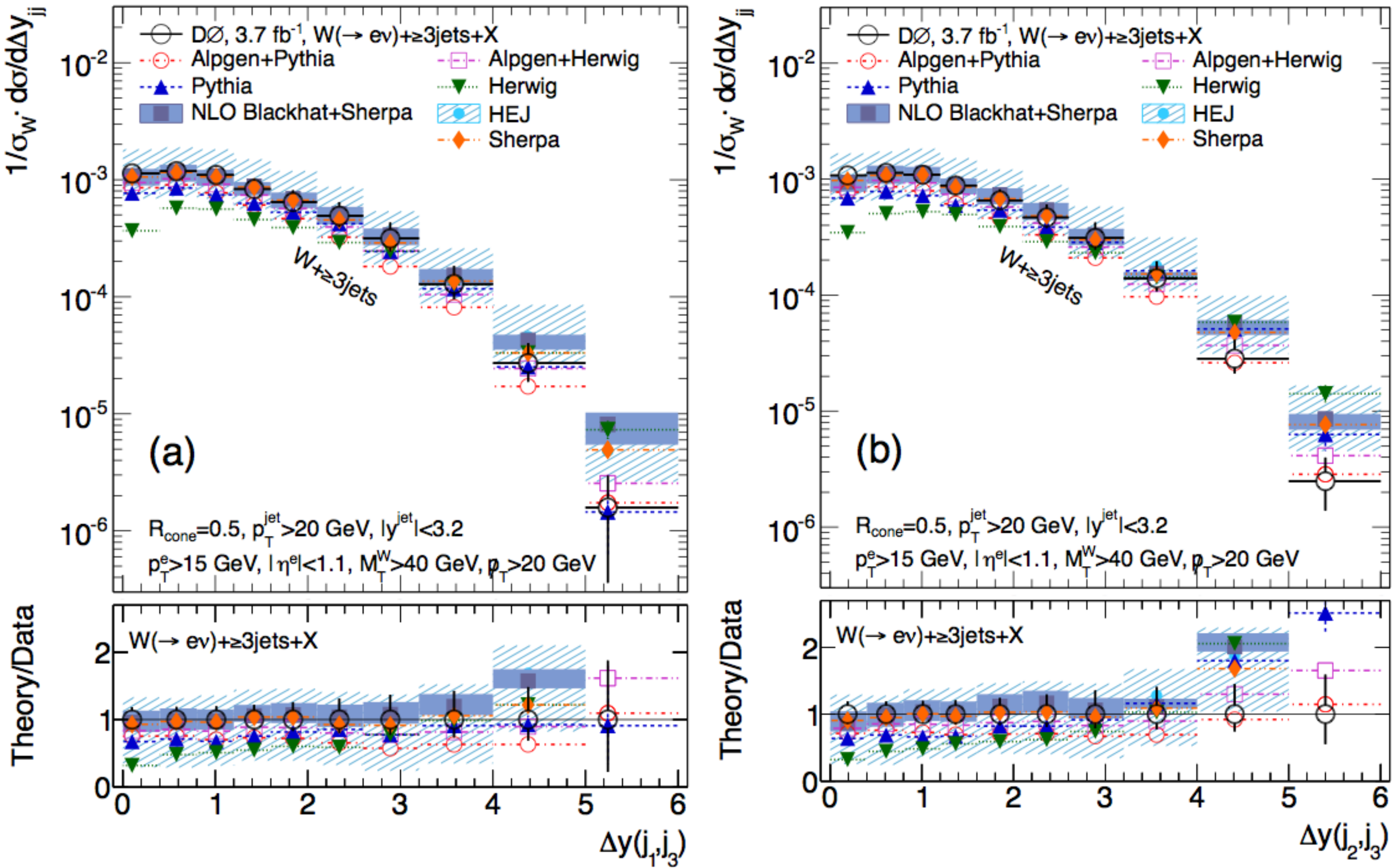
Important testing variable for MC modelling (e.g. FSR) and for experimental searches/measurements



W+jets: First/second-third jet rapidity separation:

Test rapidity separation between first-third and second-third jet pairings.

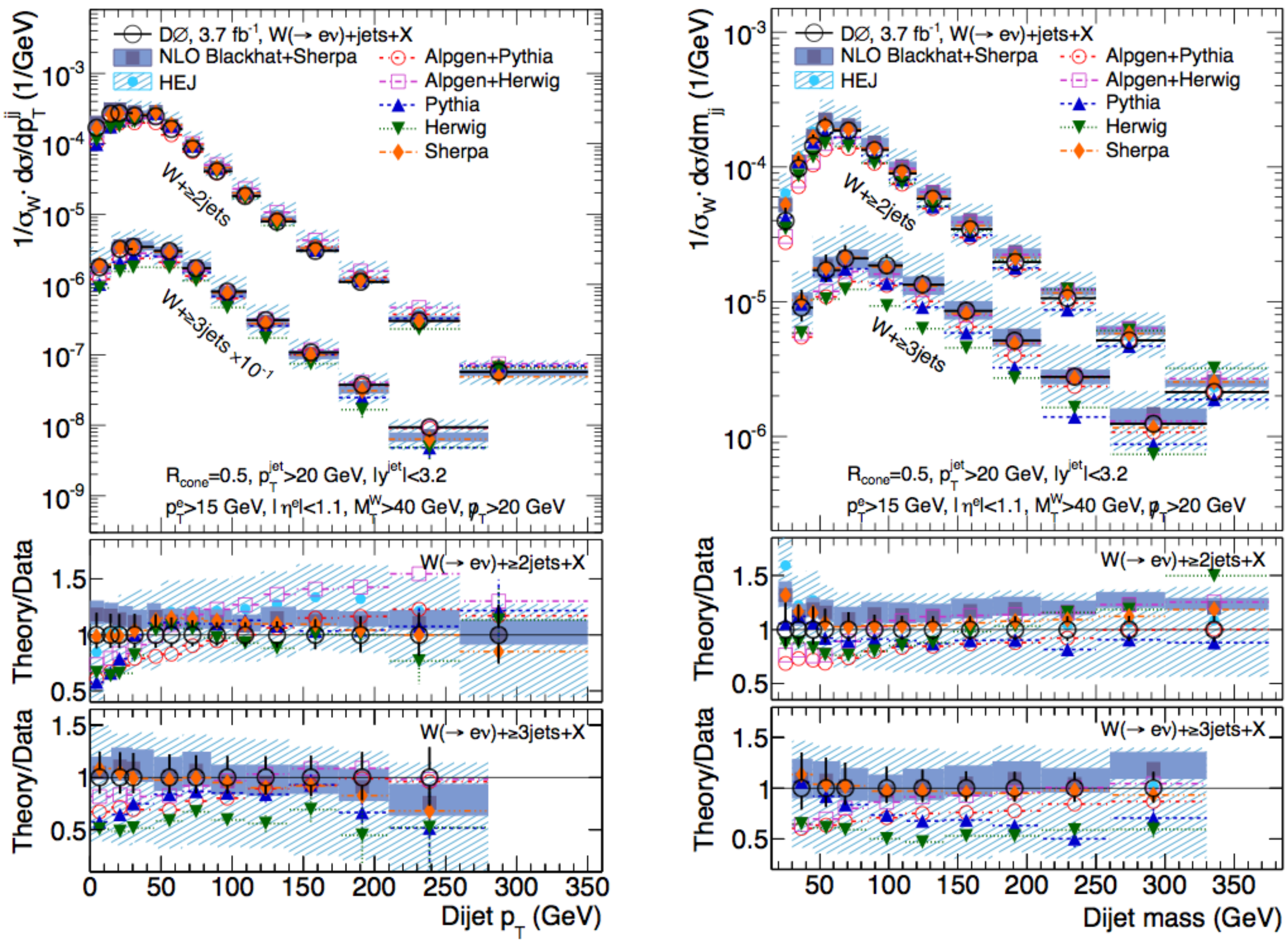
(Useful for QCD modelling purposes, in particular constraining ISR modelling in MC)



W+jets: Dijet p_T/mass

Probe dijet kinematic correlations further; also has interest for studying MC/NLO description of these variables for searches & systematics

NLO tends to overestimate rate at high dijet mass, MC predictions vary widely



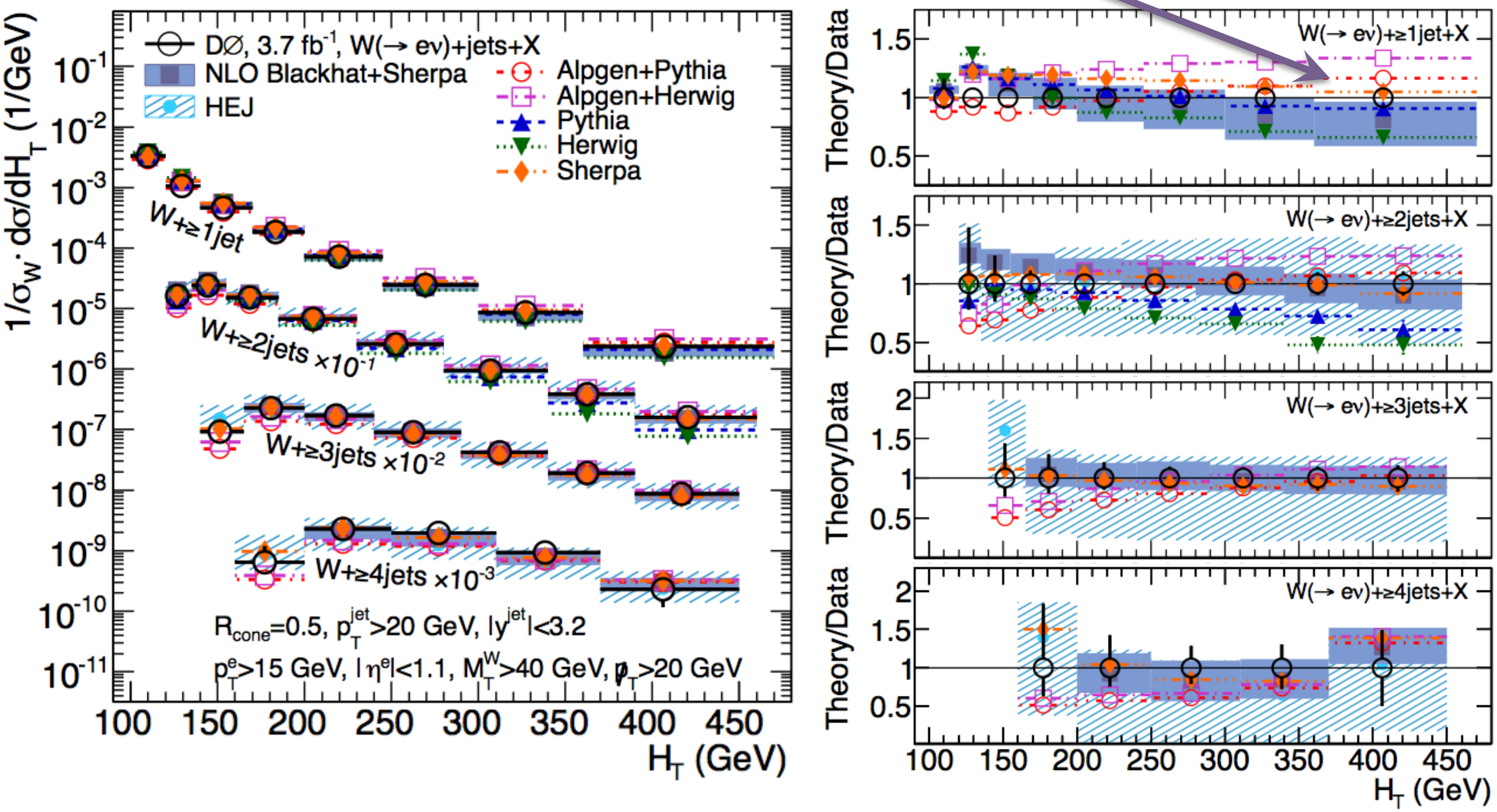
W+jets: event H_T

H_T defined as the scalar sum of the W boson and jet transverse momentum

H_T is often used as the basis for setting the scale in pQCD theoretical calculations

– good description of this quantity over wide kinematic range is vital

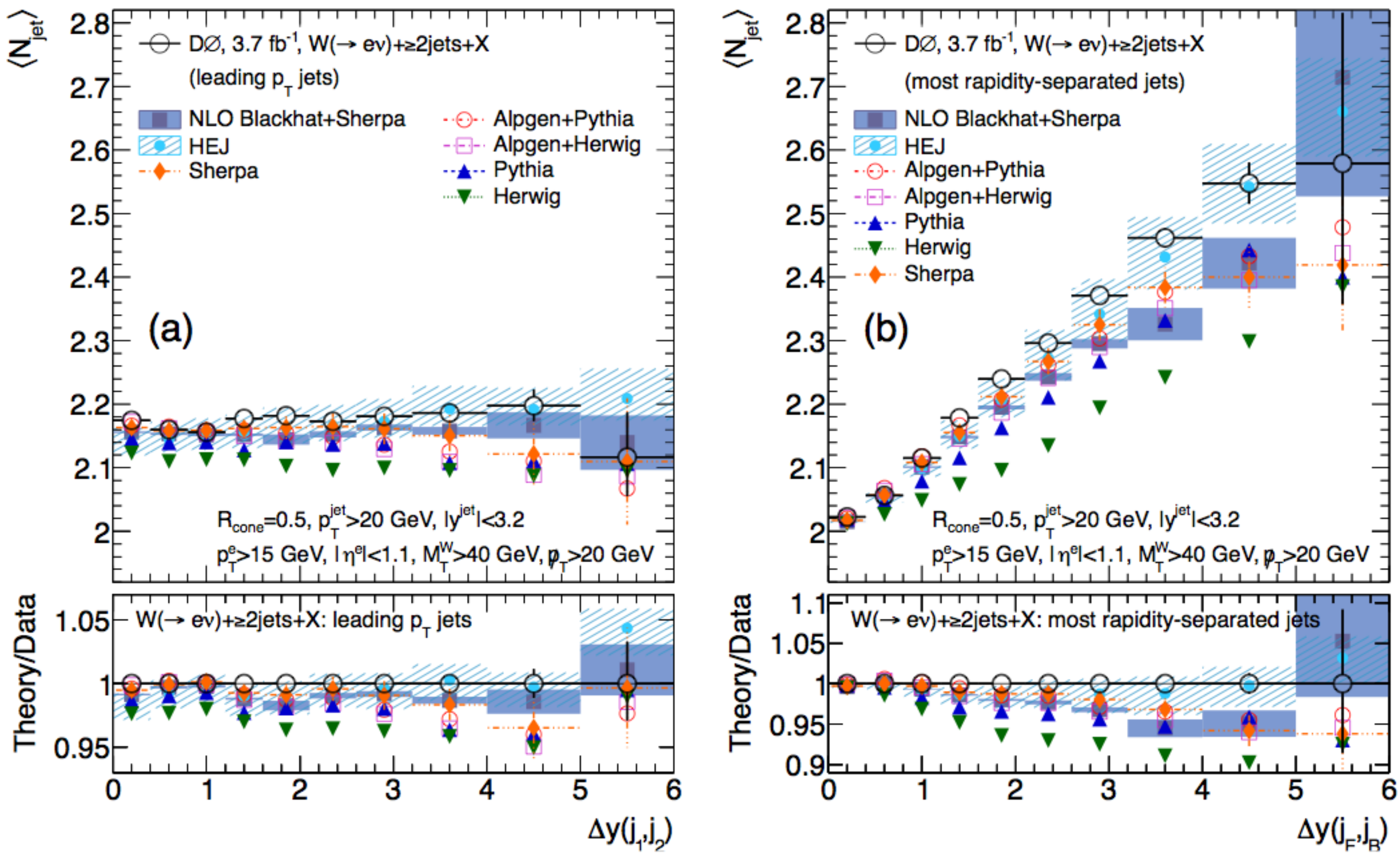
Higher order corrections important at high H_T (even at Tevatron).



W+jets: average numbers of jets vs. Δy

arXiv:1302.6508 [hep-ex]
Submitted to Phys. Rev. D

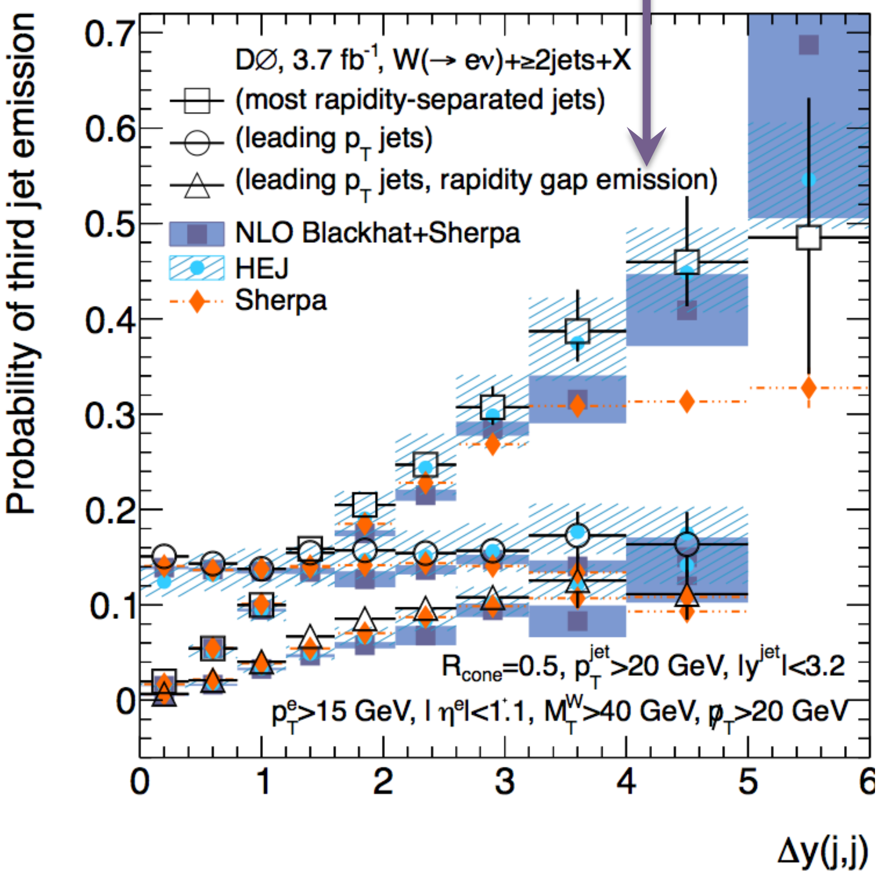
Studied as a function of dijet rapidity separation in two configurations:
- between the two highest p_T jets
- between the two most rapidity-separated (hard) jets

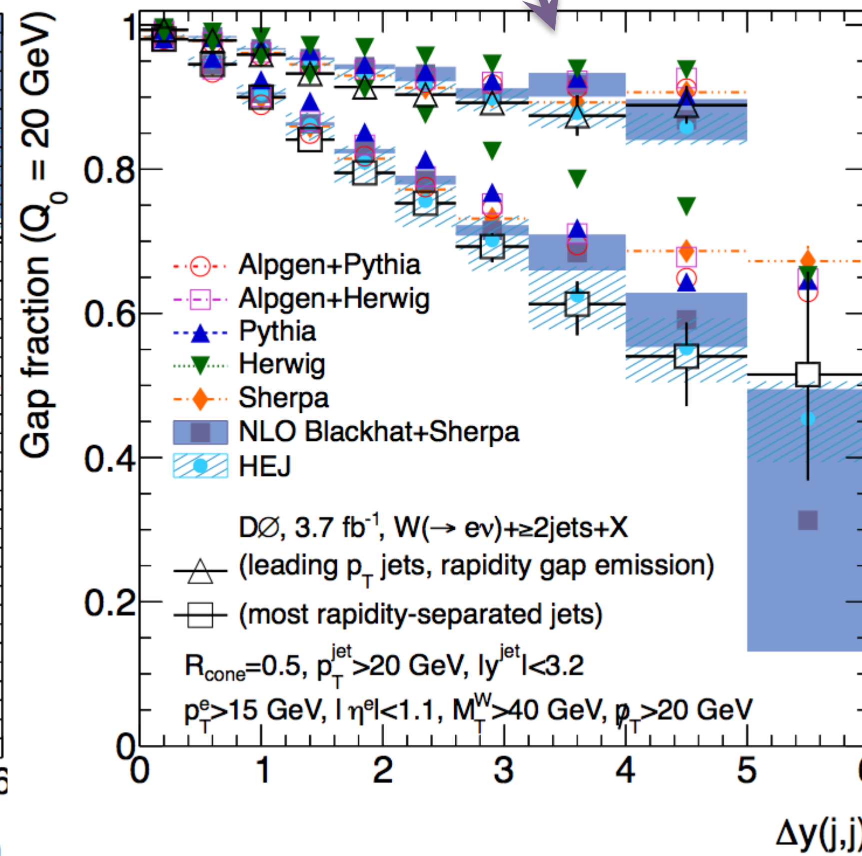


arXiv:1302.6508 [hep-ex]
Submitted to Phys. Rev. D

W+jets: rapidity gap fraction vs. gap size

Third jet emission probability P can be used to define a quantity f=1-P, known as the "gap fraction"



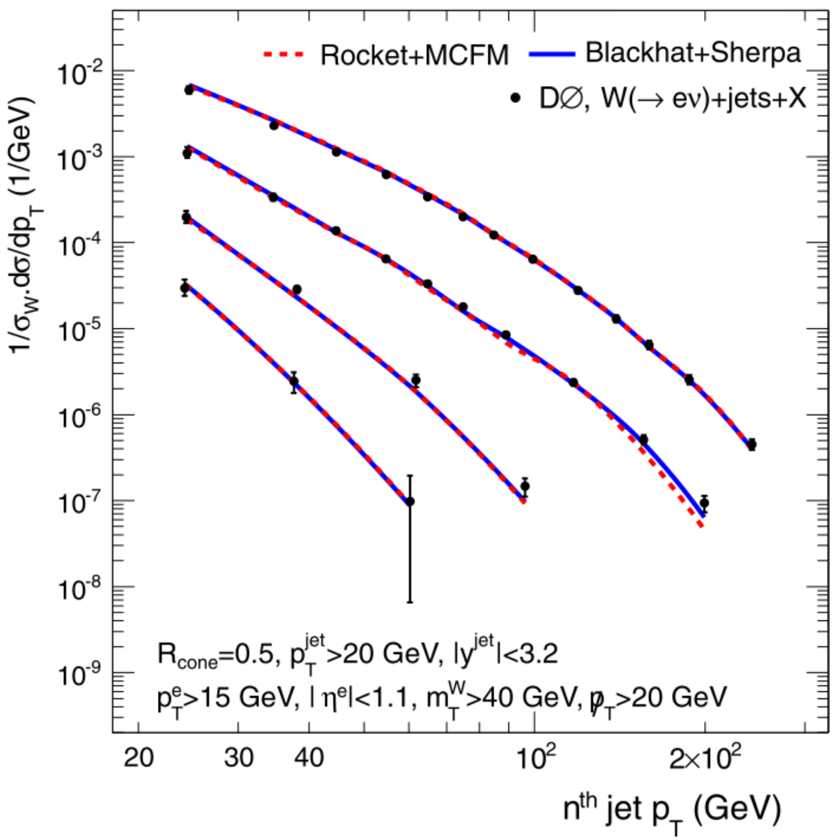


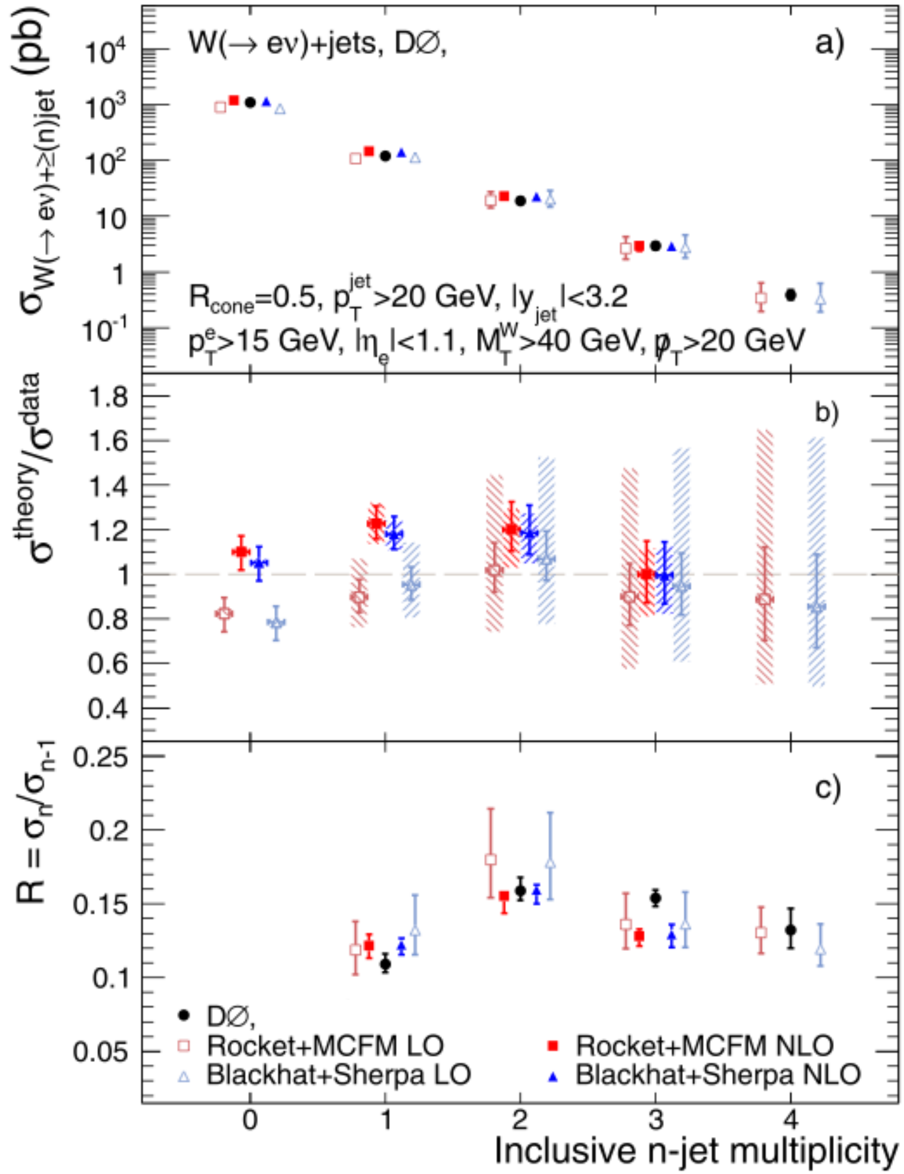
Answers the question: "What fraction of V+dijet events, with rapidity gap Δy, have no jets (p_T>20 GeV) emitted into this gap?"

Relevant for VBF studies (Higgs, SUSY etc.) and benefits from low p_T threshold (increased sensitivity) – first time studied in vector boson plus jet events

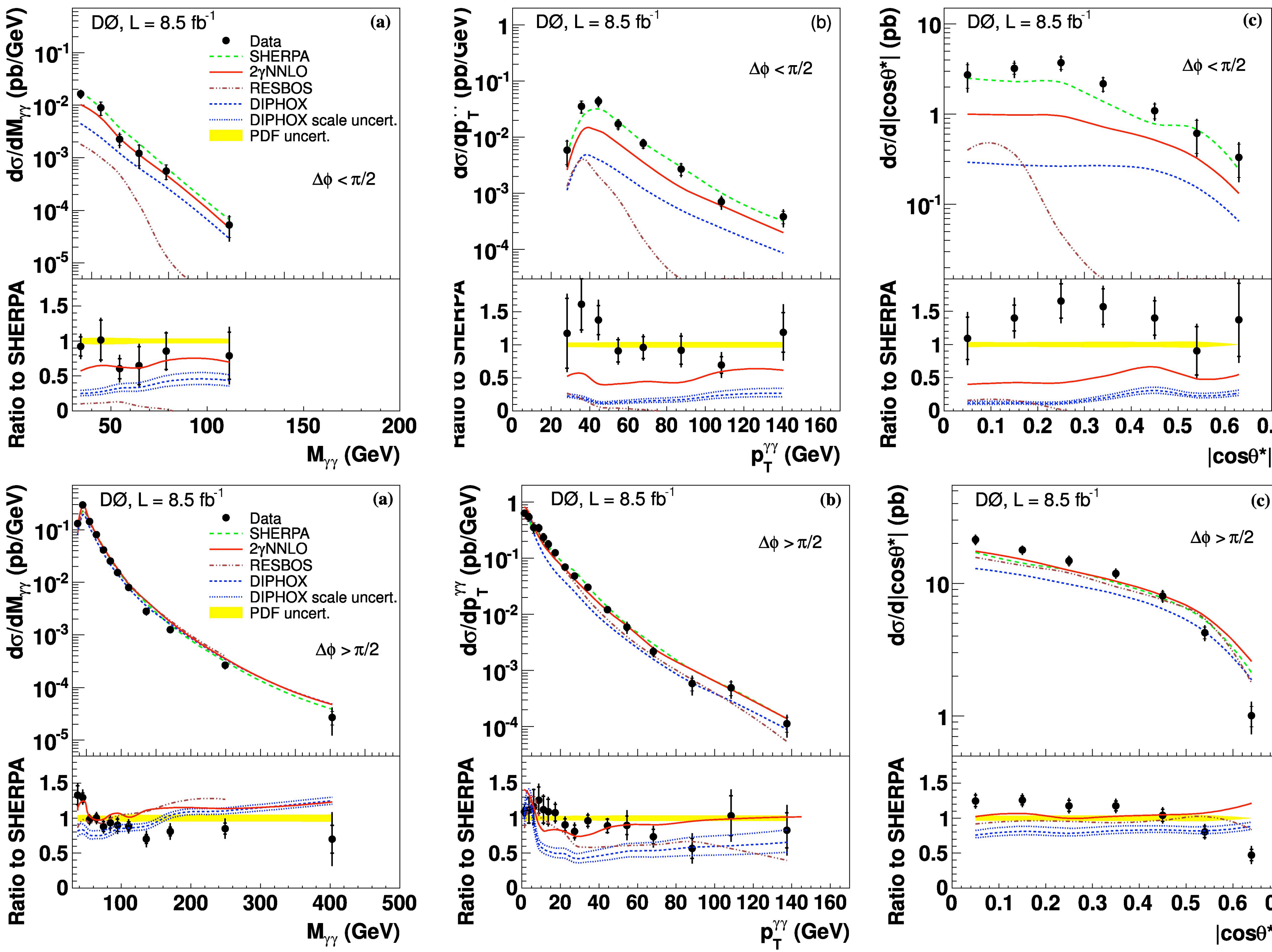
W+jets: previous DØ measurement

Previous paper arXiv:1106.1457, Phys. Lett. B 705 (2011) 200-207 studied differential jet p_T and inclusive n-jet cross-sections



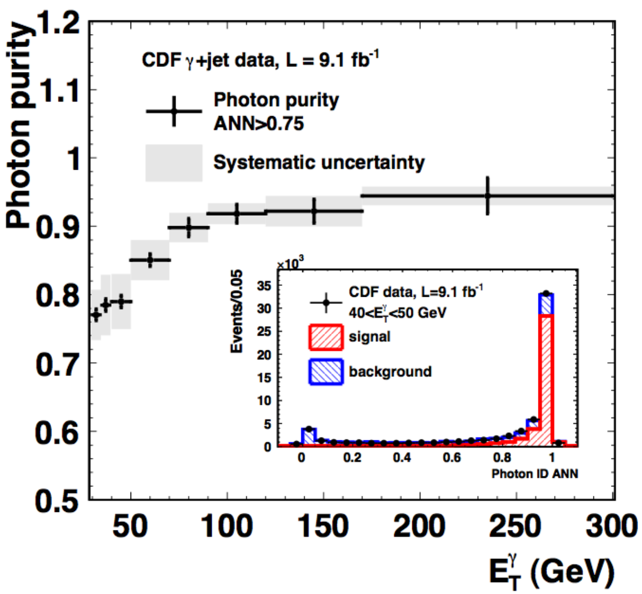


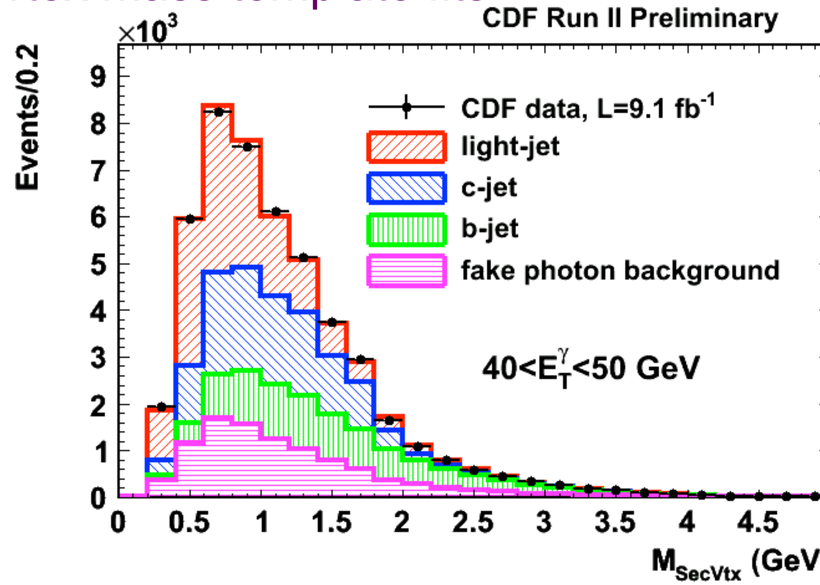
Prompt isolated di-photon production – further distributions

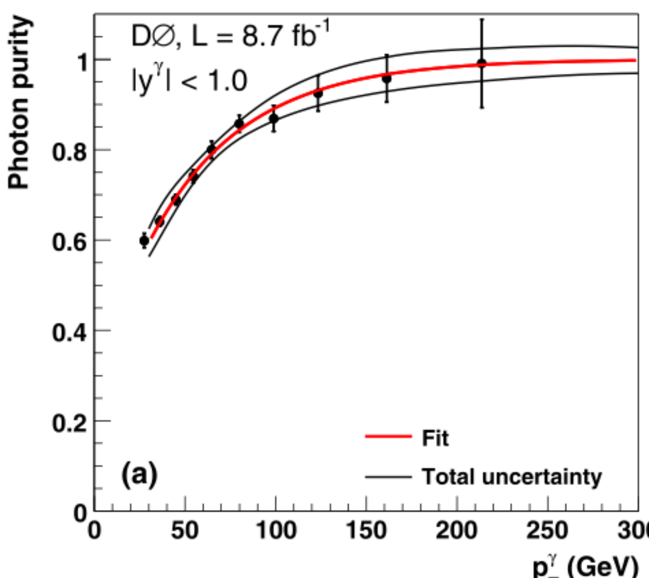


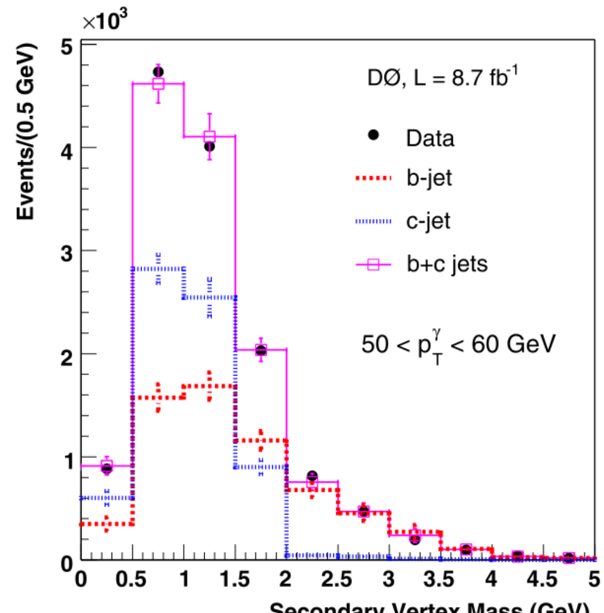
Photon + heavy-flavour jets

Photon purities and secondary vertex mass template fits









(Fake photon and light flavour backgrounds subtracted)