Measurements of V + (heavy) jet, γ + (heavy) jet and $\gamma\gamma$ production cross sections at the DØ experiment

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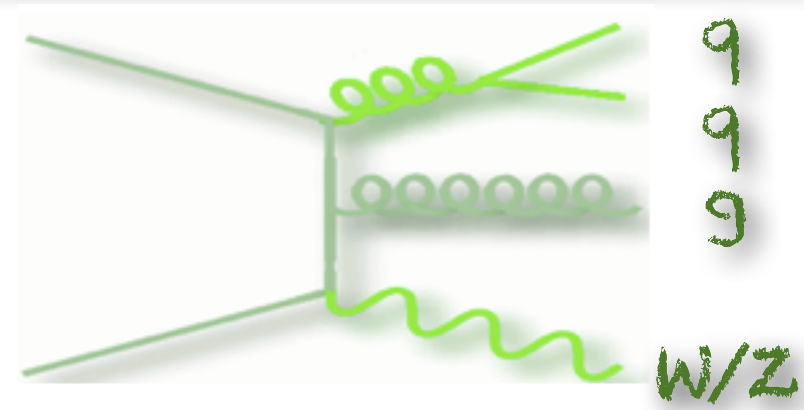
On behalf of the D0 collaboration

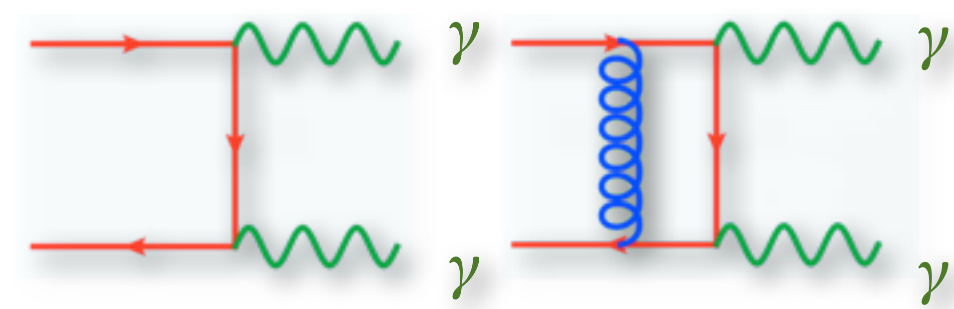
Why pursue these studies in times of the Higgs?

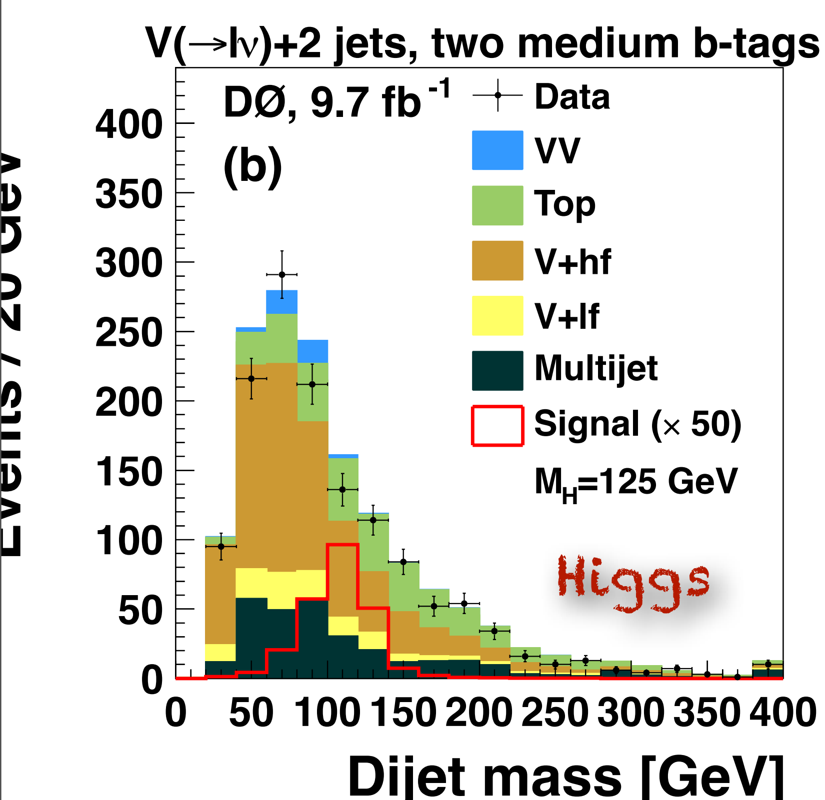
- **Test of perturbative QCD calculations:**
  recent high jet multiplicity calculations available, appropriate scale choice not always clear

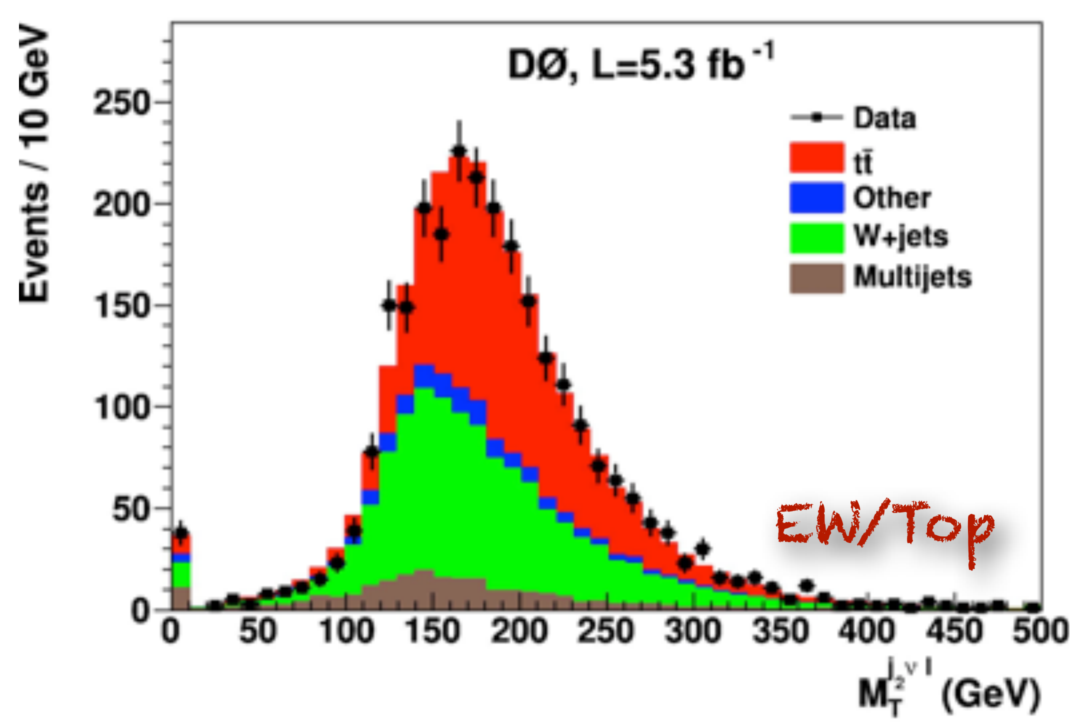
- **Monte Carlo modeling:**
  Parton Shower (PS) and Matrix Element (ME) approaches need tests/tuning

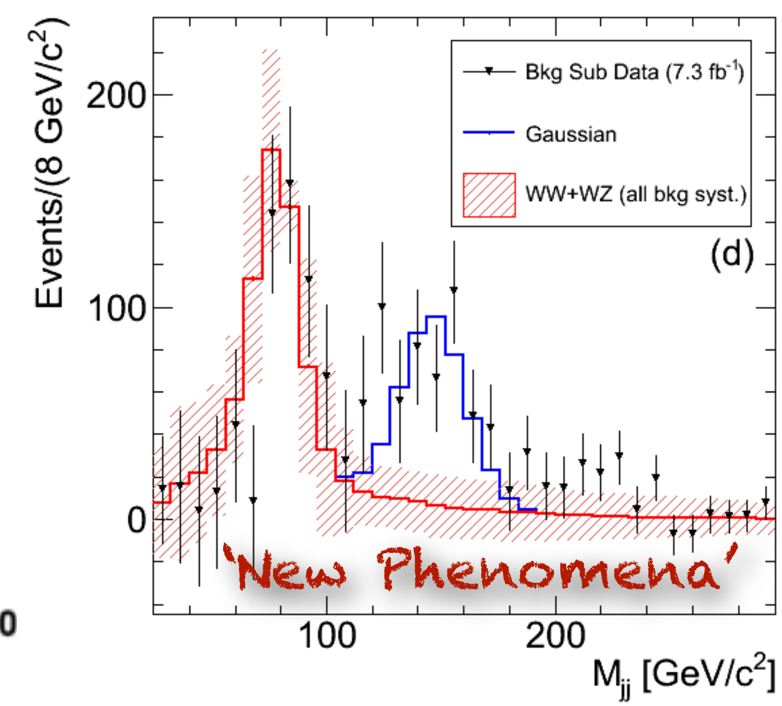
- **Measurements:**
  Bkgd to precision SM measurements and searches for NP



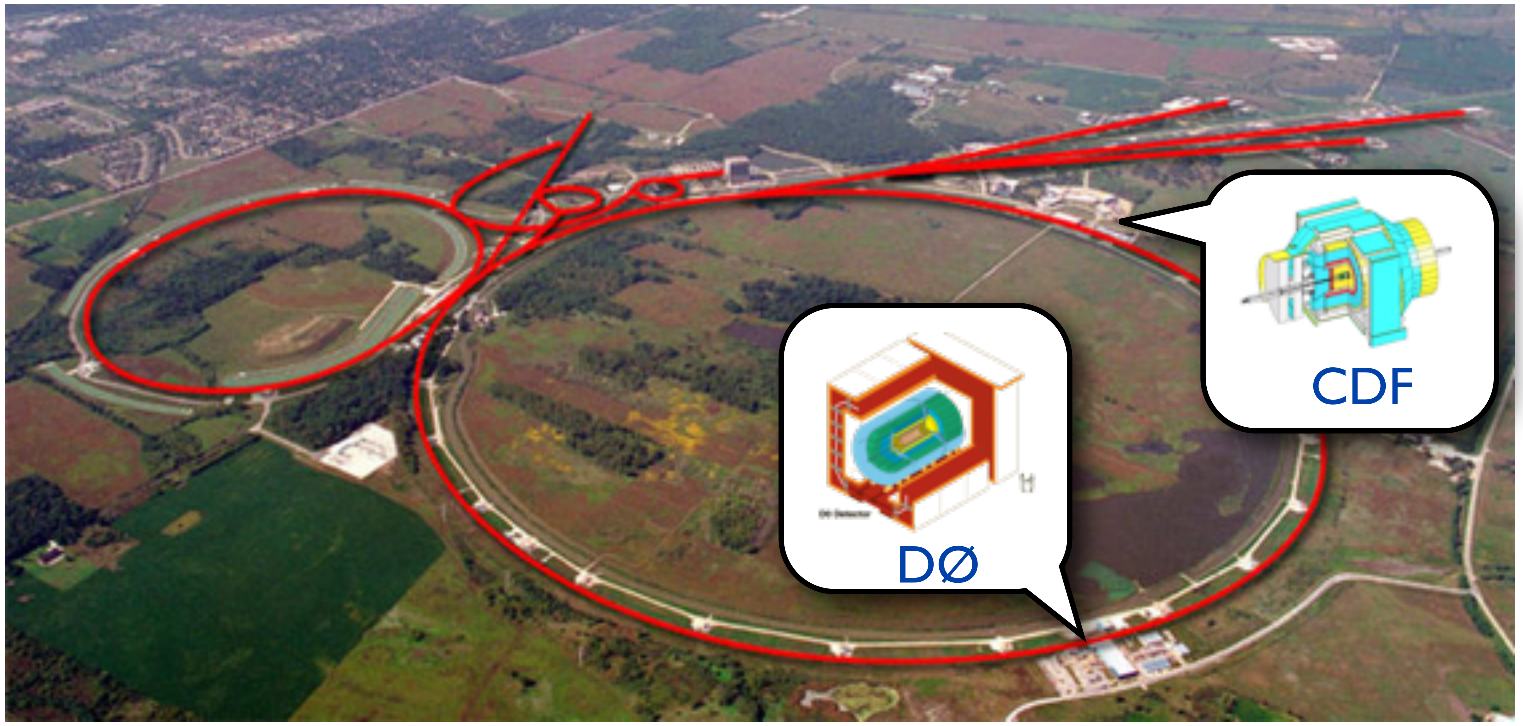








The Tevatron & DØ



Tevatron

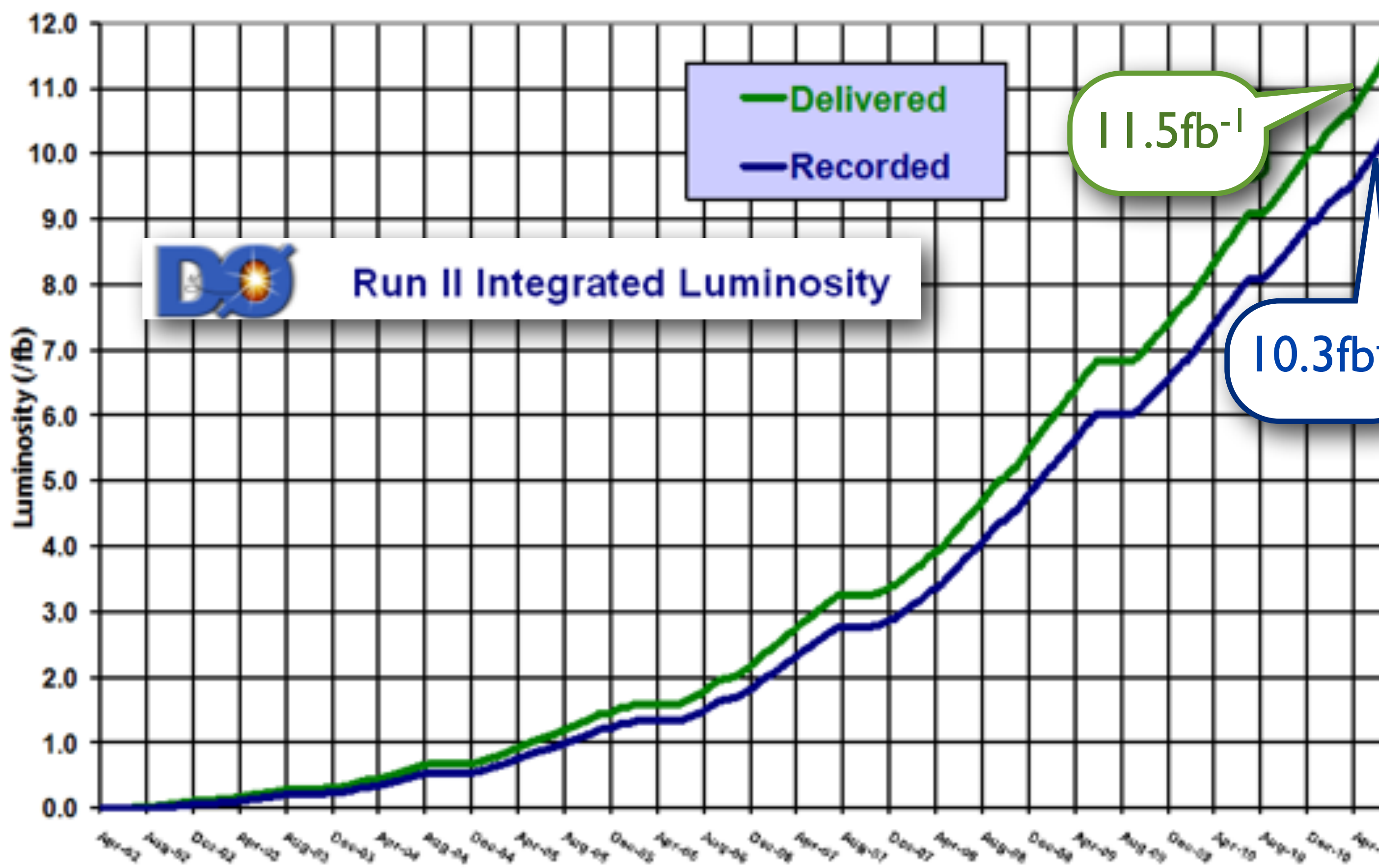
- $\sqrt{s} = 1.96$ TeV
- $\Delta t = 396$ ns
- RunII: 2001-2011: Typical average luminosity:

  $>400 \times 10^{30}$ cm^{-2} sec^{-1}

  ~70pb^{-1} per week

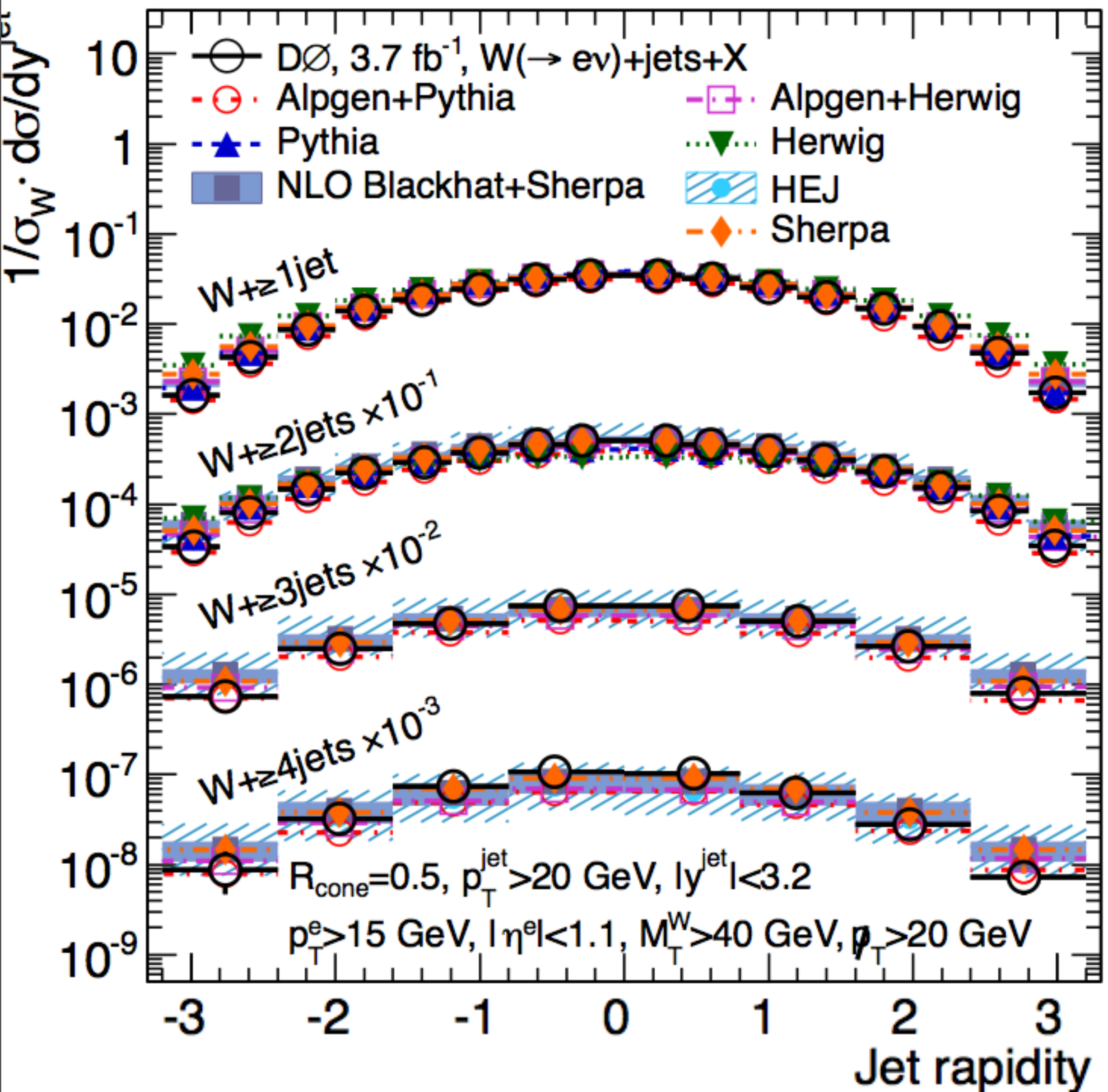
DØ Detector

- Central Tracking:
  Silicon vertex detector and fibre tracker in 2T field tracker and
- Calorimeter:
  Hermetic coverage $|\eta|<3.6$, LAr calorimeter
- Muon System:
  Excellent purity and coverage: $|\eta|<2$
- Excellent detector understanding after a decade of operation

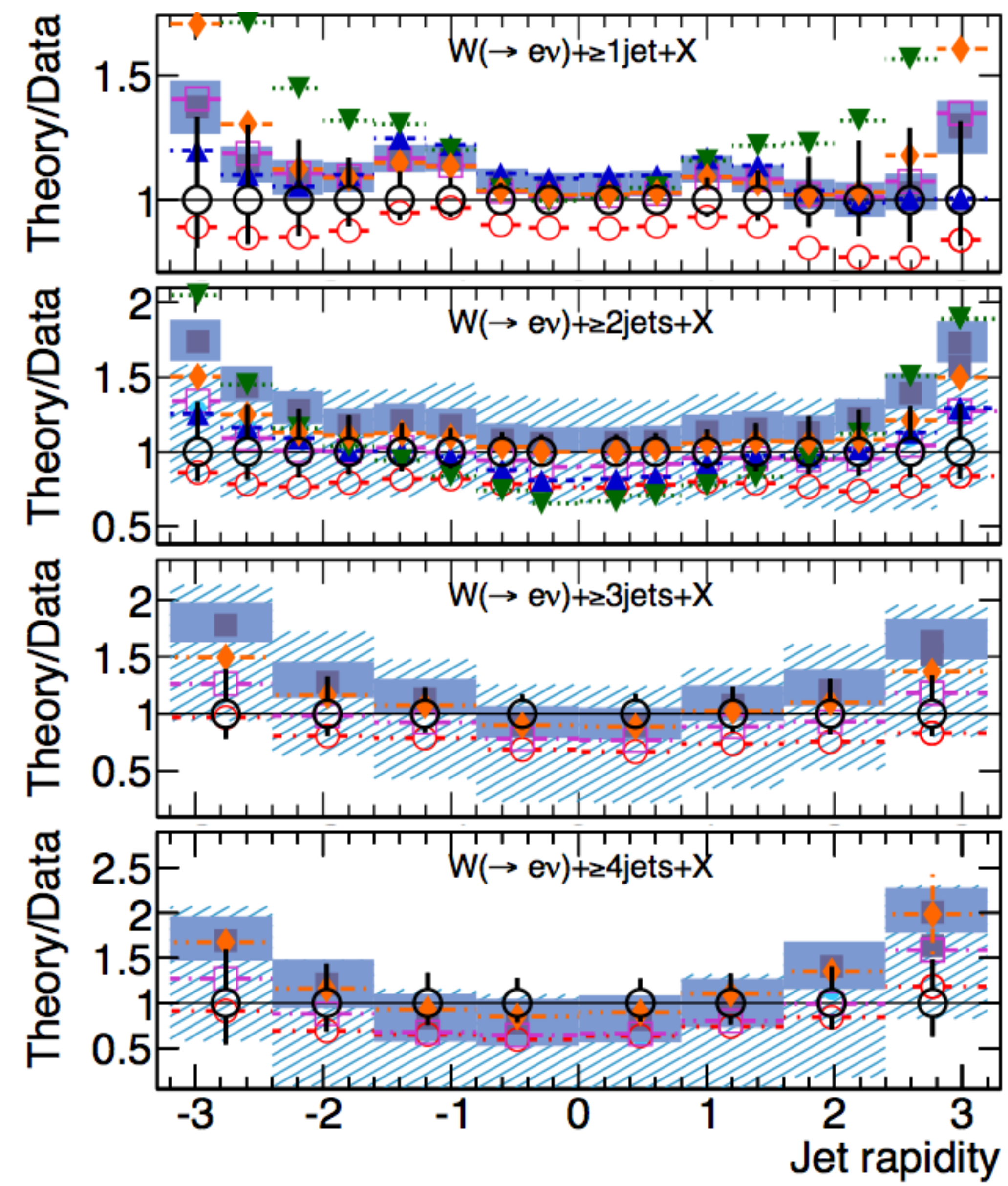


W+jets production

Sub. Phys. Rev. D, arXiv:1302.6508

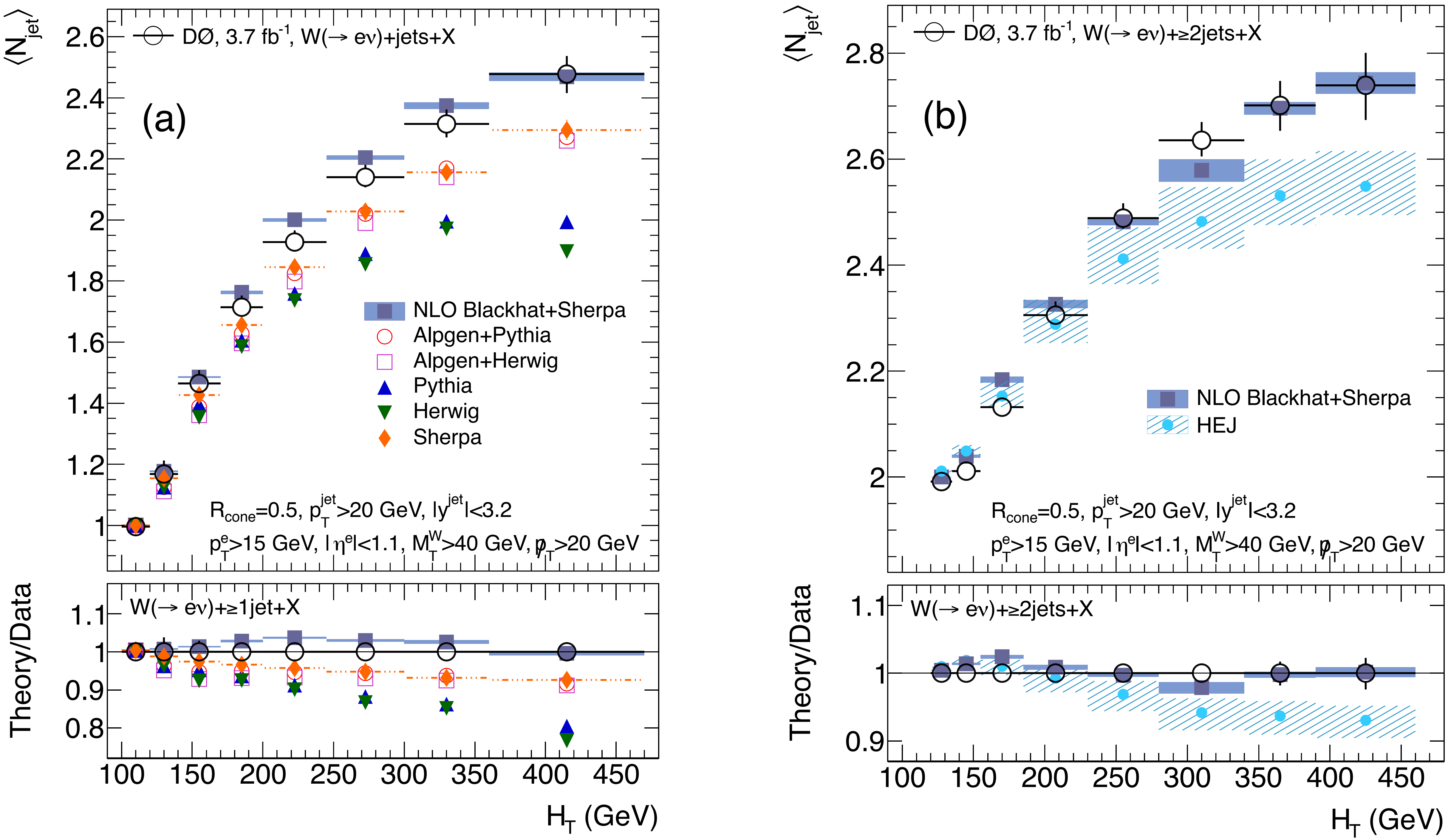


- Fundamental test of pQCD & bkgd for many measurements
- Test of W+≤4j production, measurement of diff. cross-section in nth jet mult. bin for many kinematic distributions.



- Compared to Blackhat+Sherpa
- Reasonable agreement between data and all theories in central region, variation of predictions for high rapidity jets

W+jets production

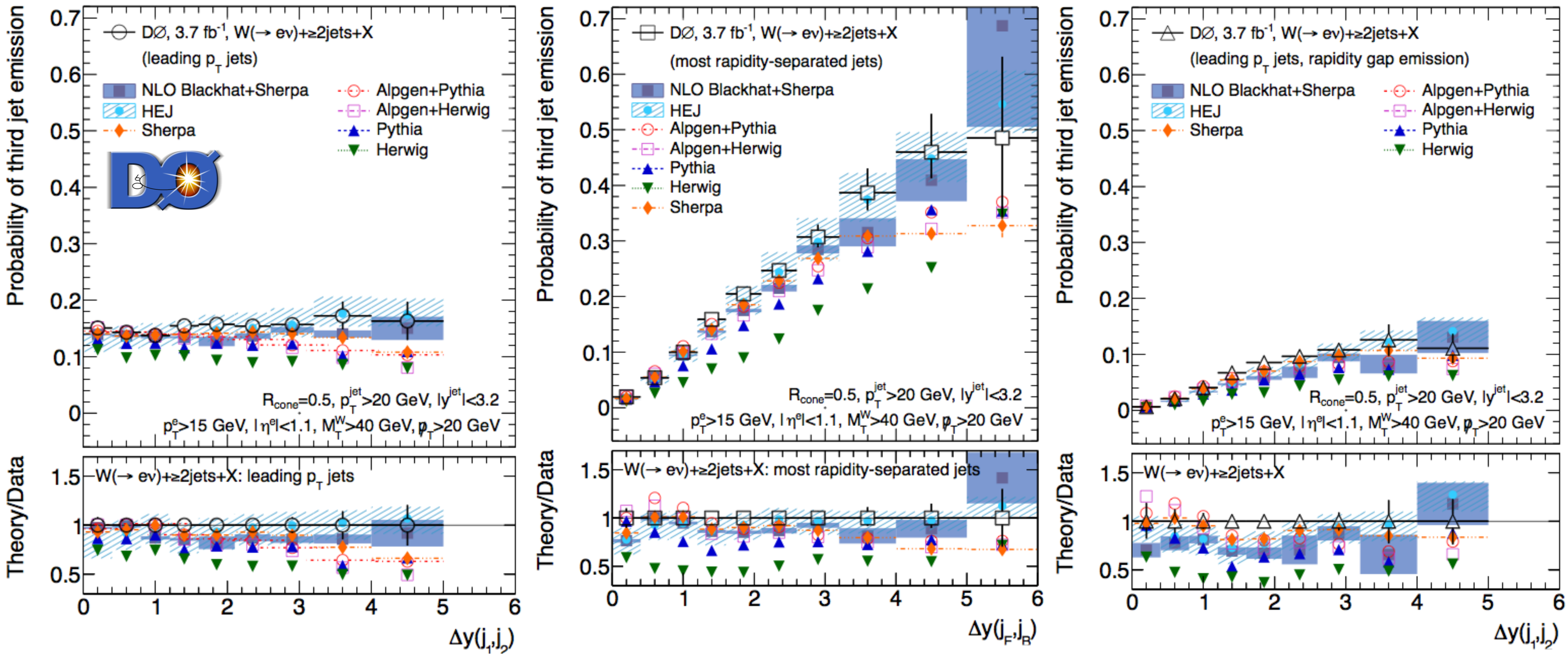


- Dependence of average jet multiplicity in W+jet events on transverse energy of hard interaction tested for first time
- Both PS MC and MEPS underestimate high p_T jets, NLO fit well over entire range

two highest p_T jets

two most rapidity separated jets

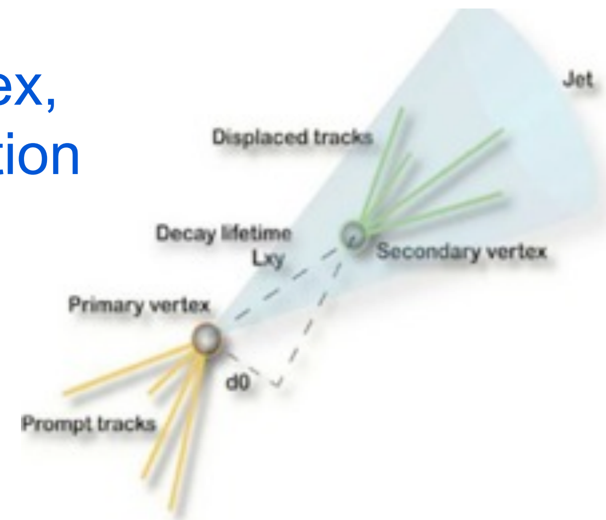
highest p_T jets emitted between first two in rapidity

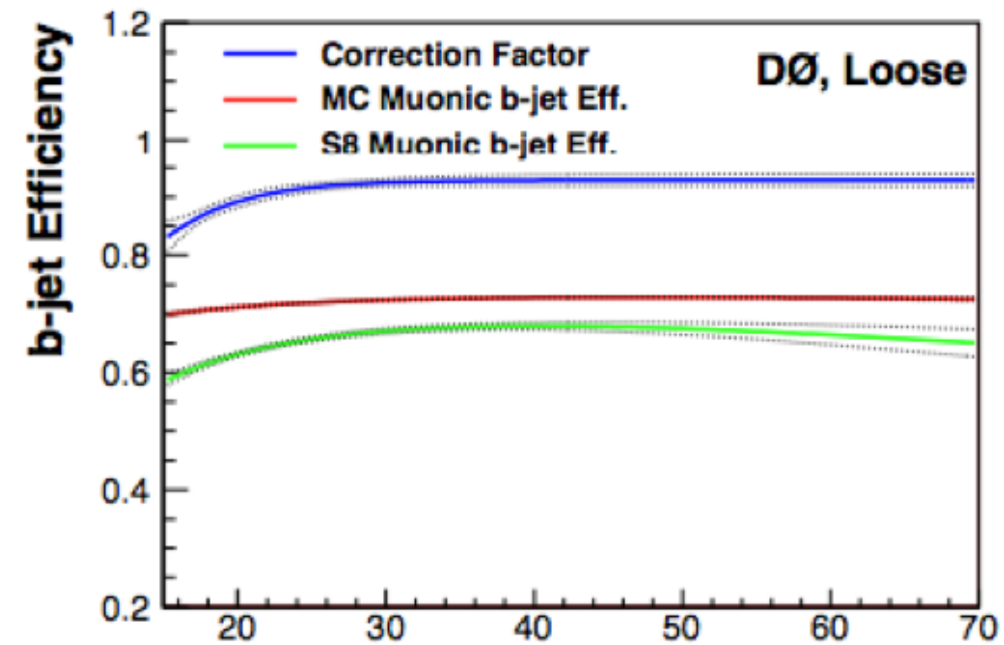


- Study radiation emissions into rapidity interval between two energetic jets in events with a W boson (important for jet vetoes)
- HEJ and NLO perform well with some with NLO exhibiting large uncertainties at large rapidity rapidity
- Sherpa and other (ME)PS MCs exhibit insufficient radiation at wide angels

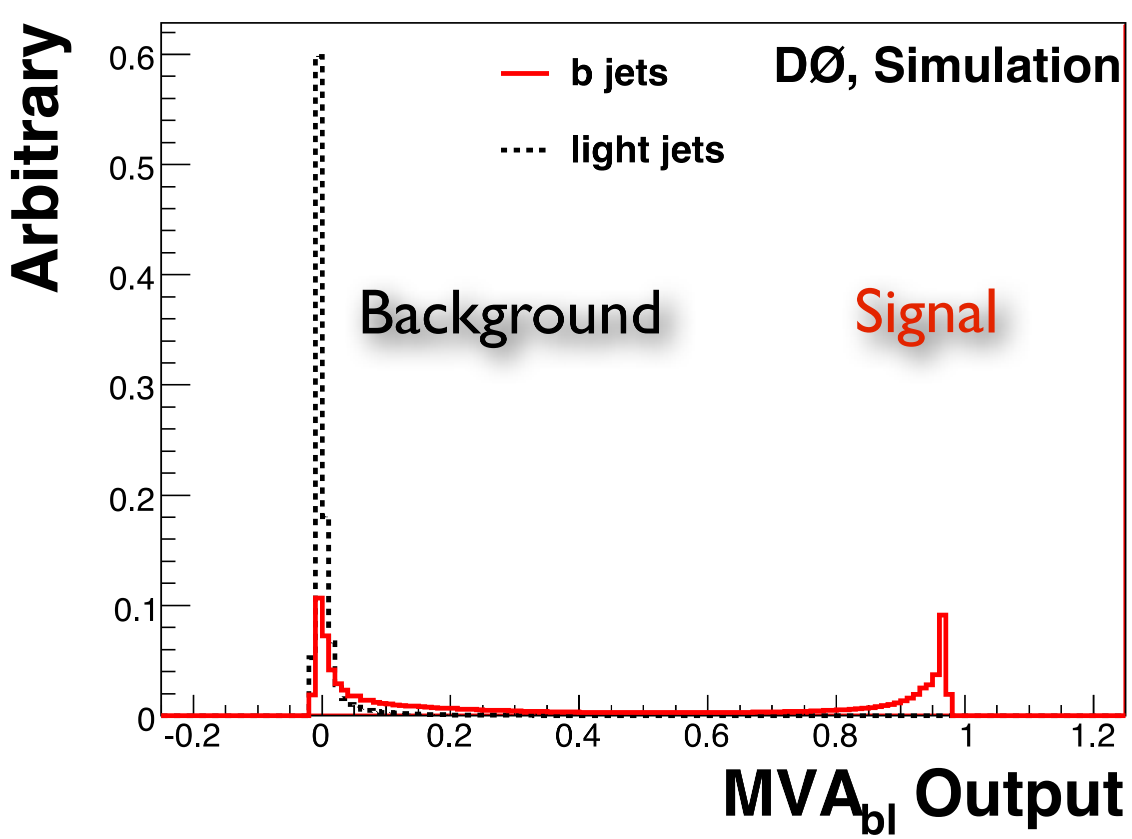
b/c-tagging

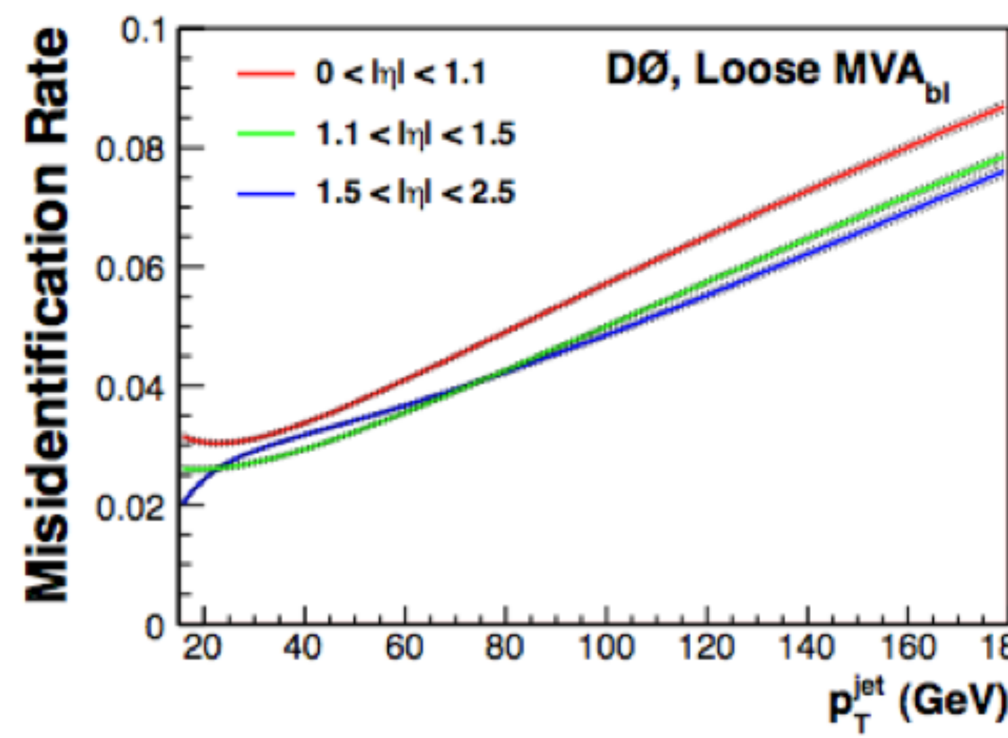
- Long life-time of b/c-hadrons → displaced vertex
- DØ uses MVA, exploiting
  - information of displaced vertex, track impact and PV association probability
  - Typically 50-60% efficient for 0.5-1.5% fake rate





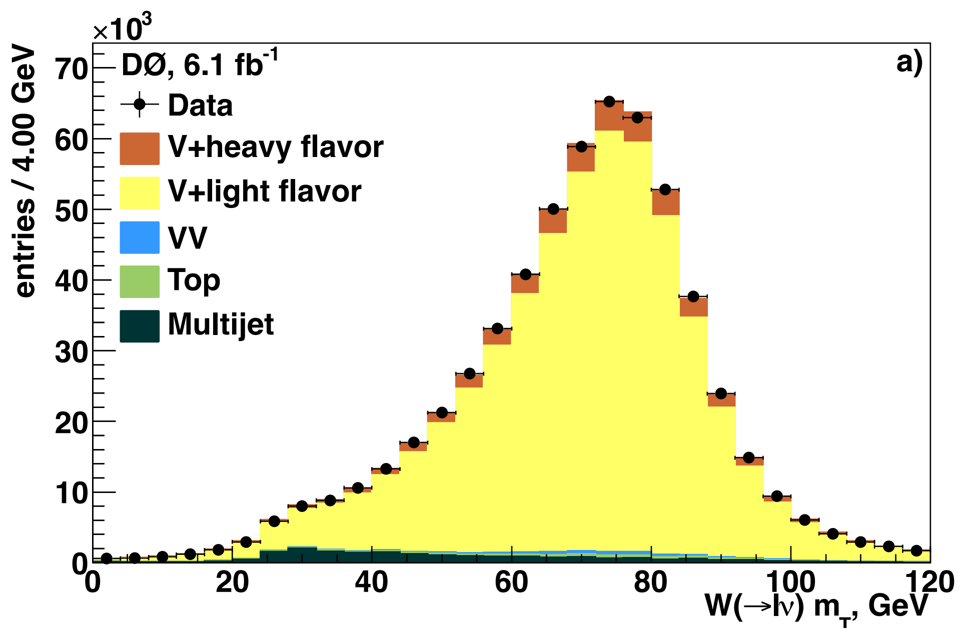
b-tag efficiencies

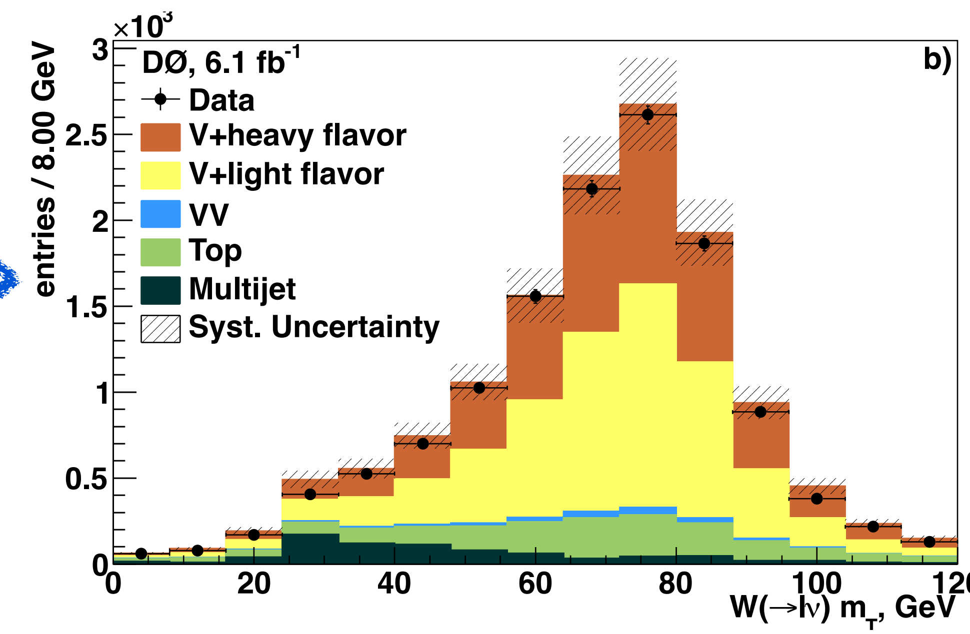


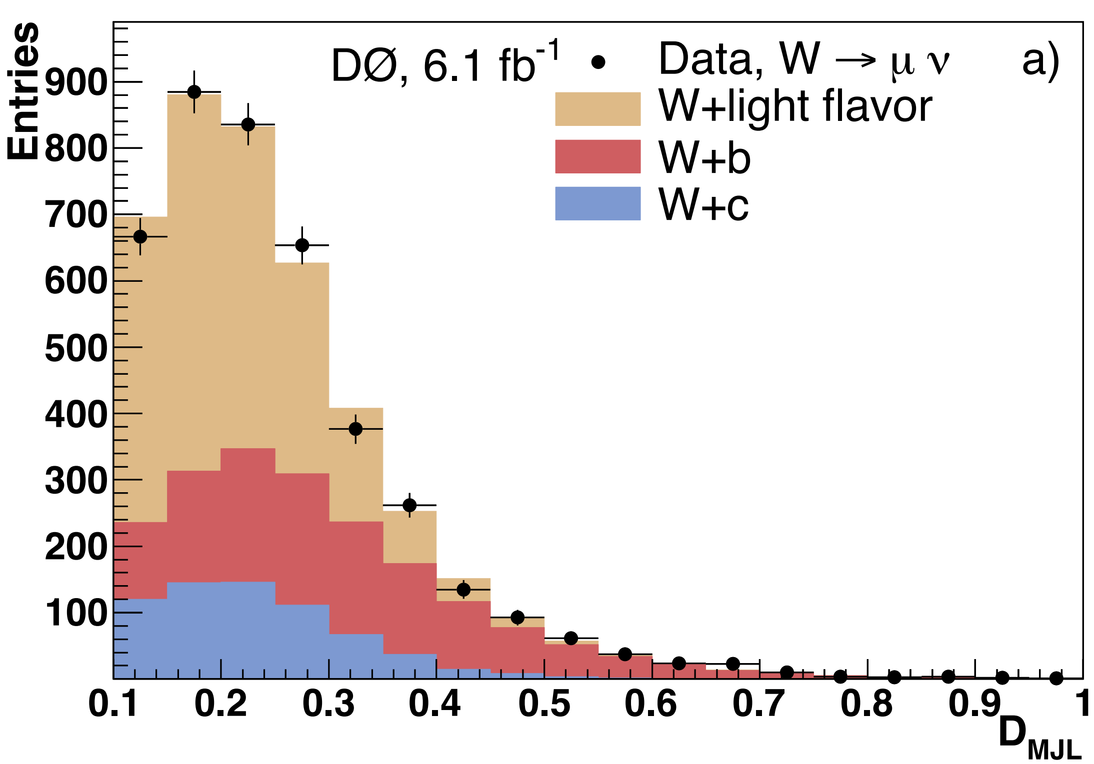


Phys. Lett. B **718**, 1314 (2013), arXiv:1210.0627

- Main background for many searches and Higgs boson measurements
- Significant excess over NLO observed by CDF







- Reduce background with b-tagging and use MVA b-ID and vertex mass do extract b-fraction
- Good agreement observed

Prediction

MCFM NLO $= 1.28^{+0.40}_{-0.33}$ (scale) ± 0.06 (PDF)$^{+0.09}_{-0.05}$ (m_b) pb

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

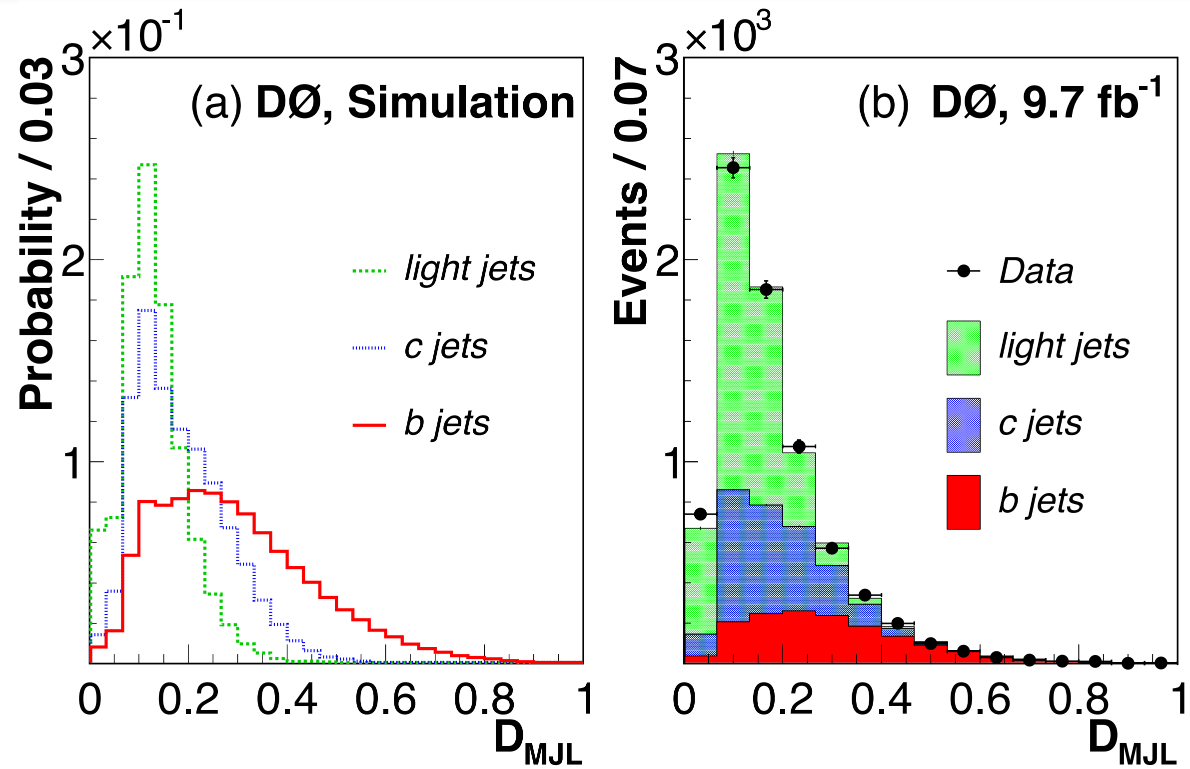
MADGRAPH5 $= 1.44 \pm 0.02$(stat.)pb

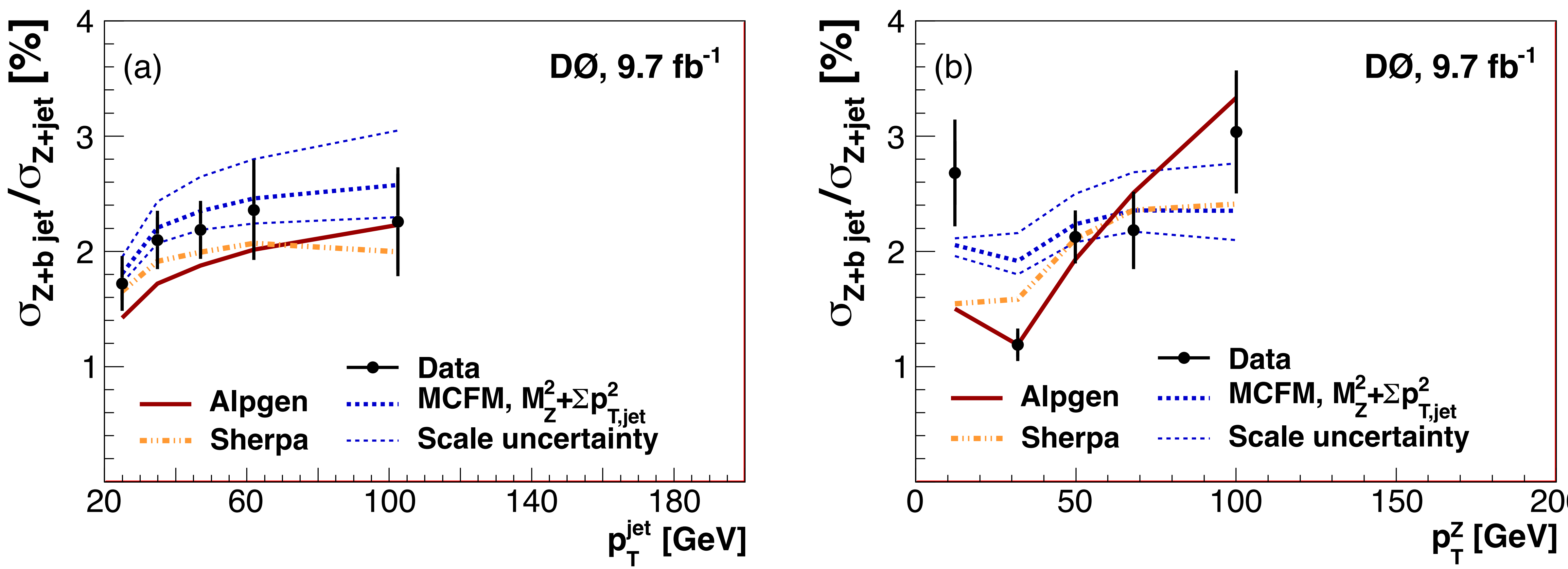
$$\sigma(W+b)\cdot\mathcal{B}(W\to\ell\nu) =$$
$$1.05 \pm 0.03\,(\text{stat.}) \pm 0.12\,(\text{syst.})\ \text{pb}.$$

$\sigma(Z+b)/\sigma(Z+\text{jet incl})$

Phys. Rev. D **87**, 092010 (2013) arXiv:1301.2233

- Probe of pQCD and b-quark fragmentation
- Z+b important background to Single-Top, ZH, NP
- New measurement extends to differential distributions

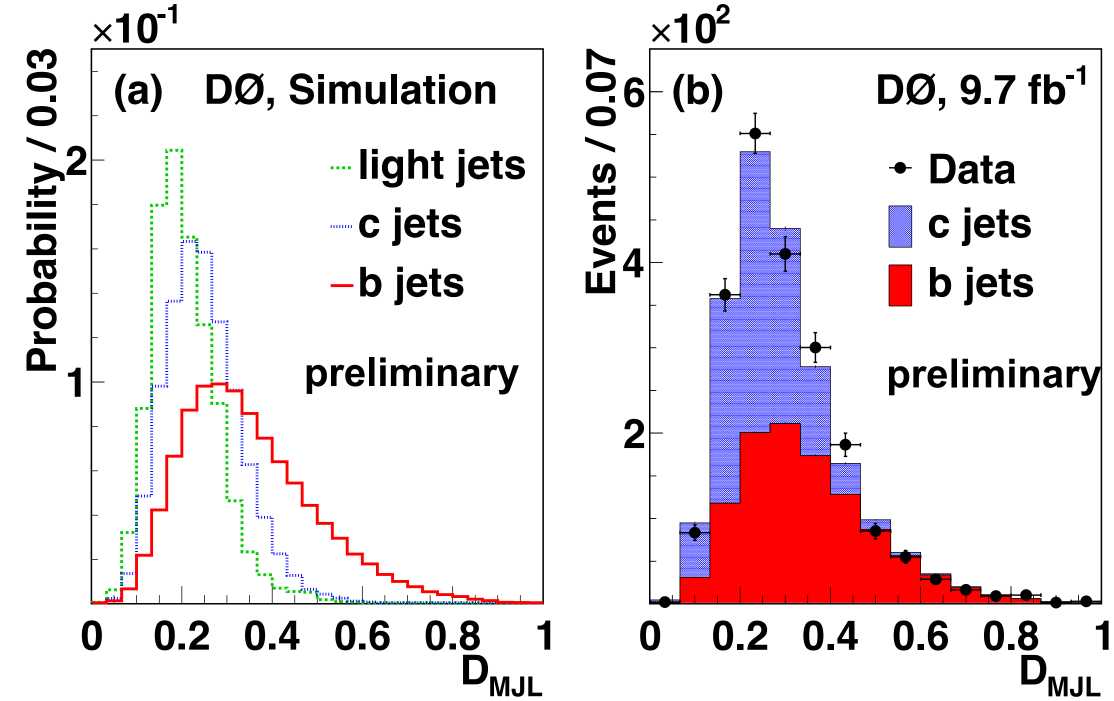


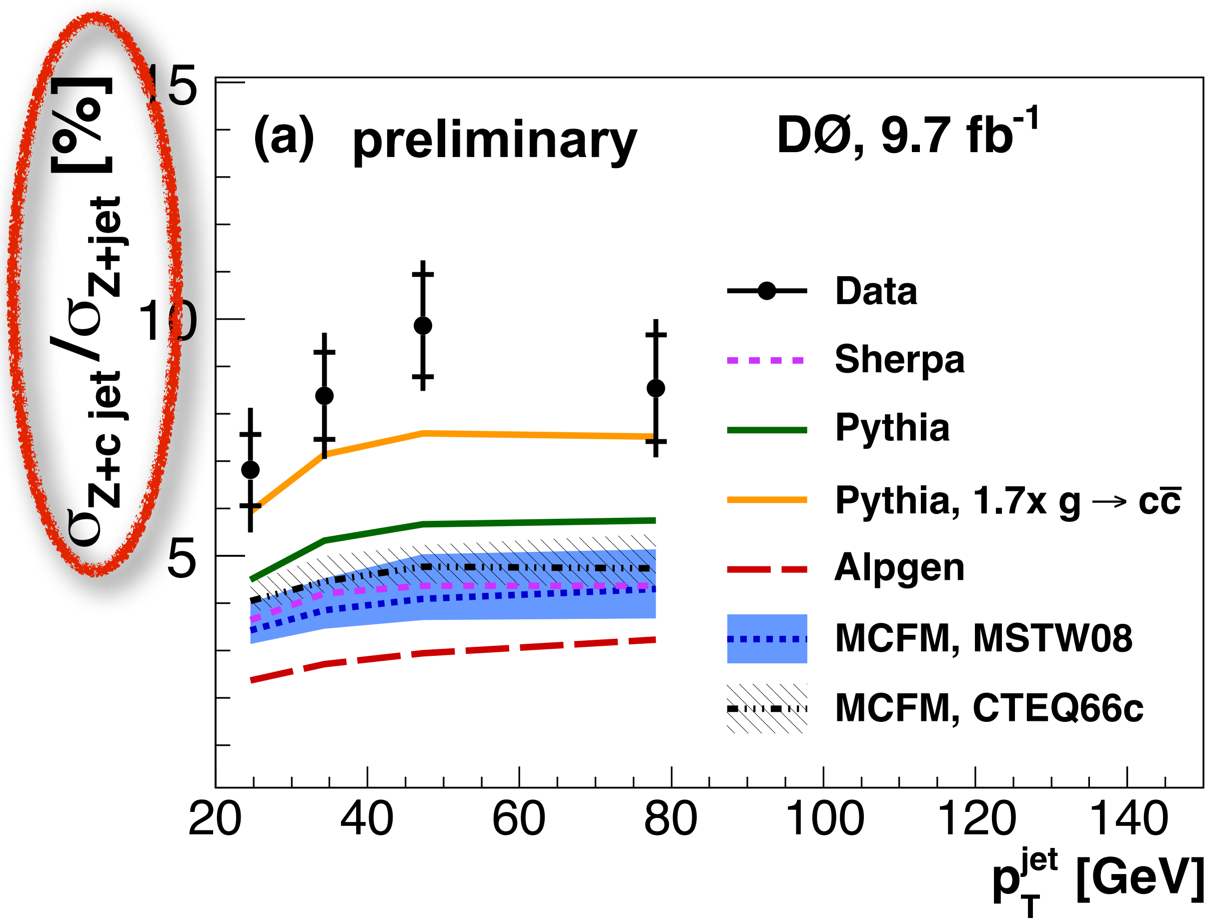


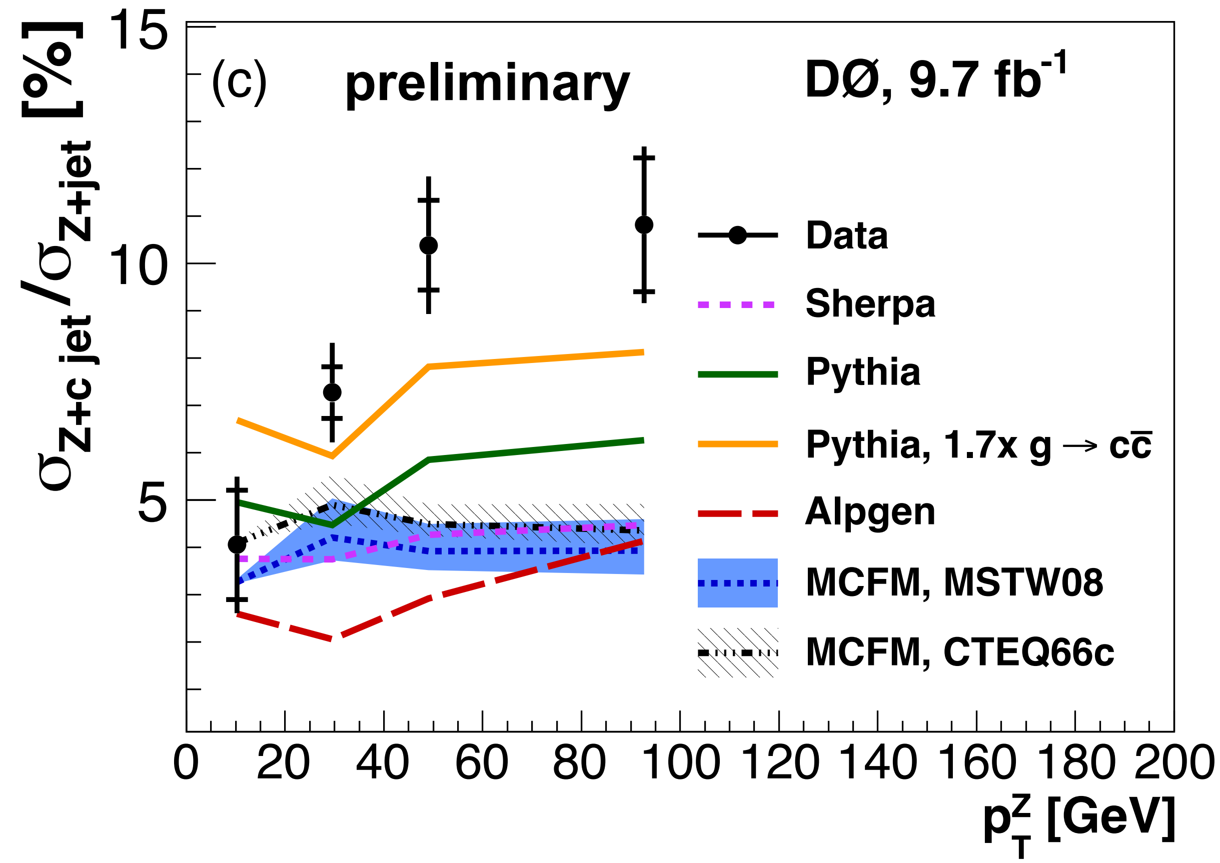
Measurement in agreement with NLO predictions

$\sigma(Z+c)/\sigma(Z+jet\ incl)$

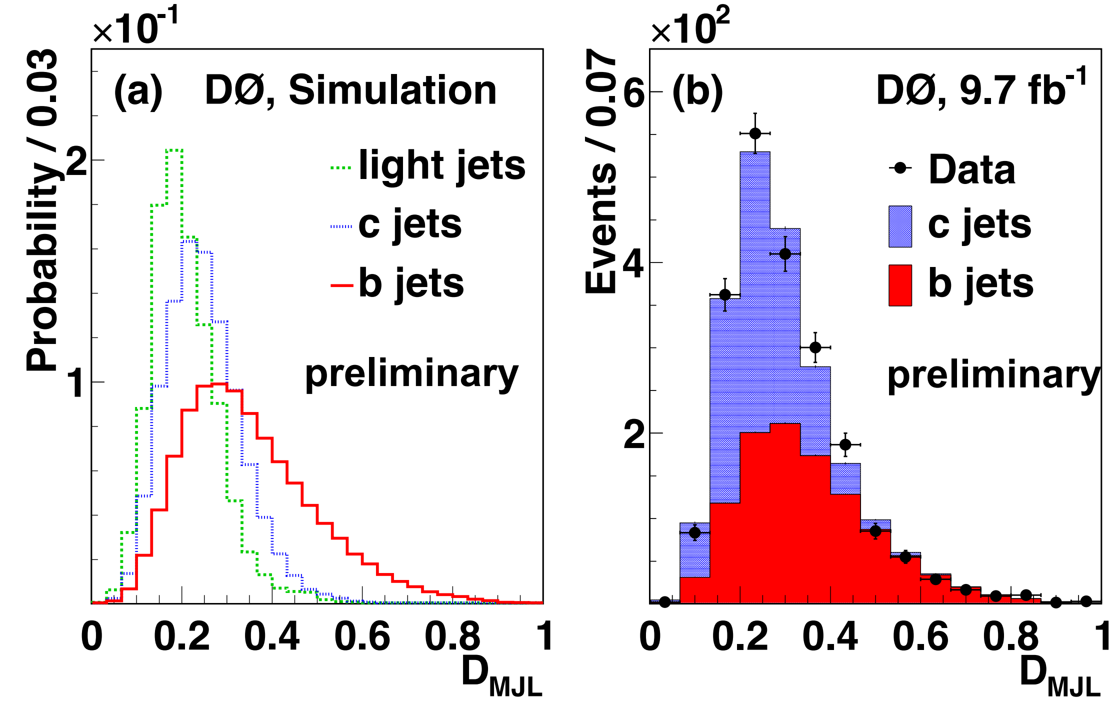
- Similar measurement of production with c-jets

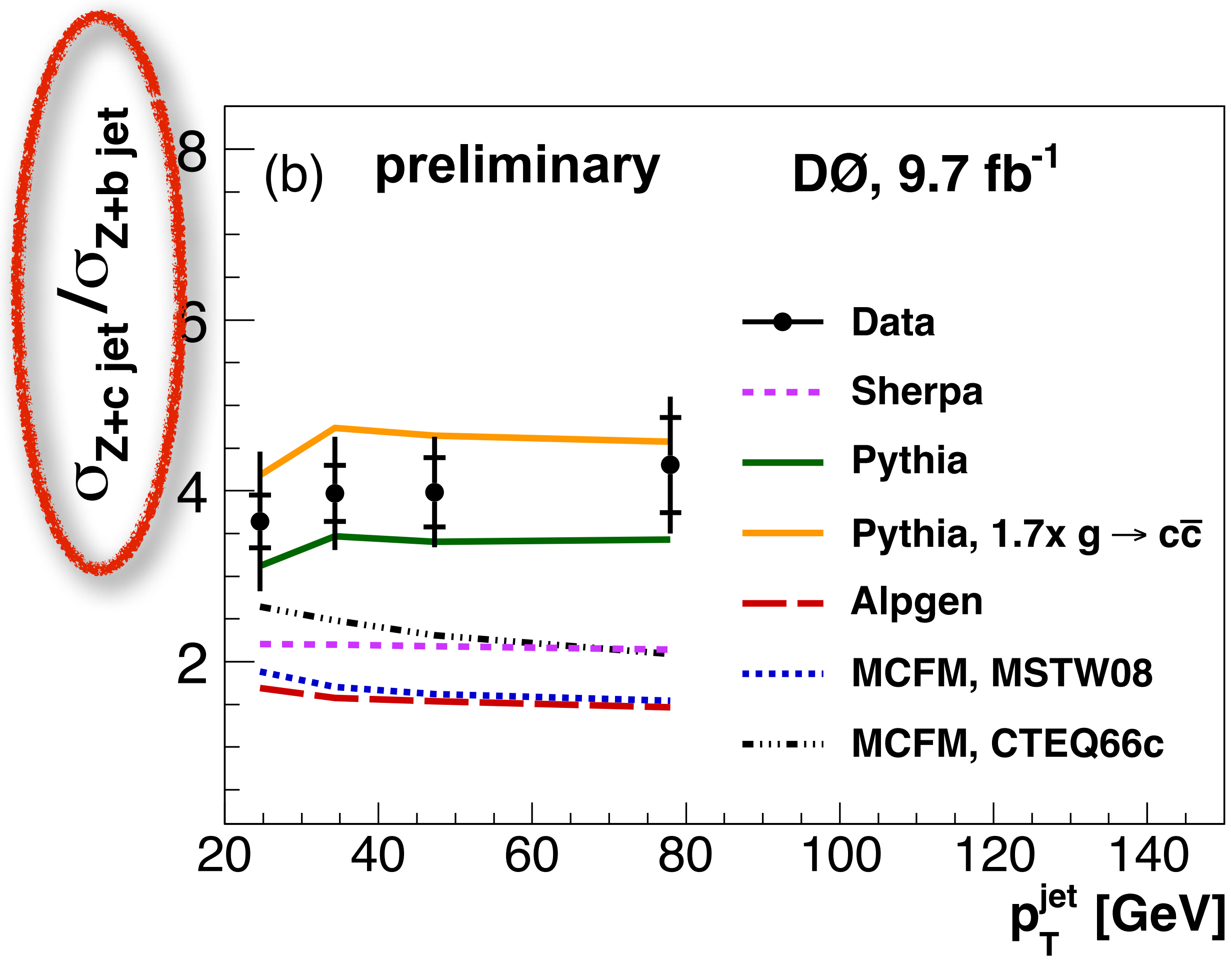






- Similar measurement of production with c-jets
- The NLO pQCD predictions disagree
- Pythia agrees better with the measured ratios, especially when the gluon splitting into heavy flavor pairs is adjusted





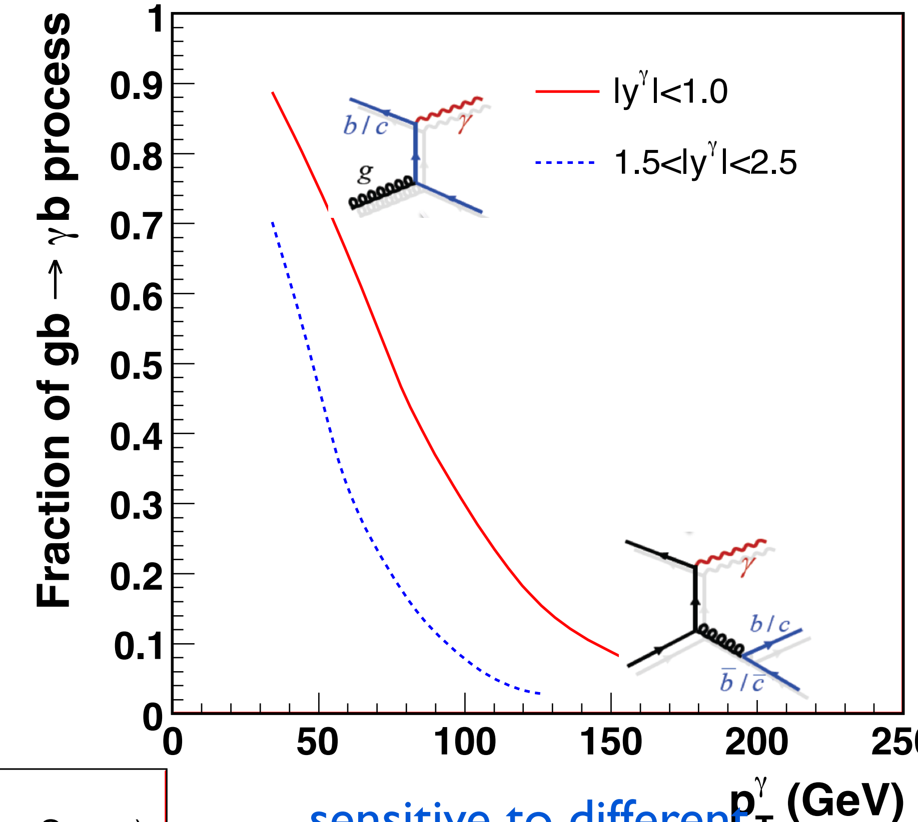
Photon+heavy jets

- Photon+b provides information about b/c-quark and gluon PDF

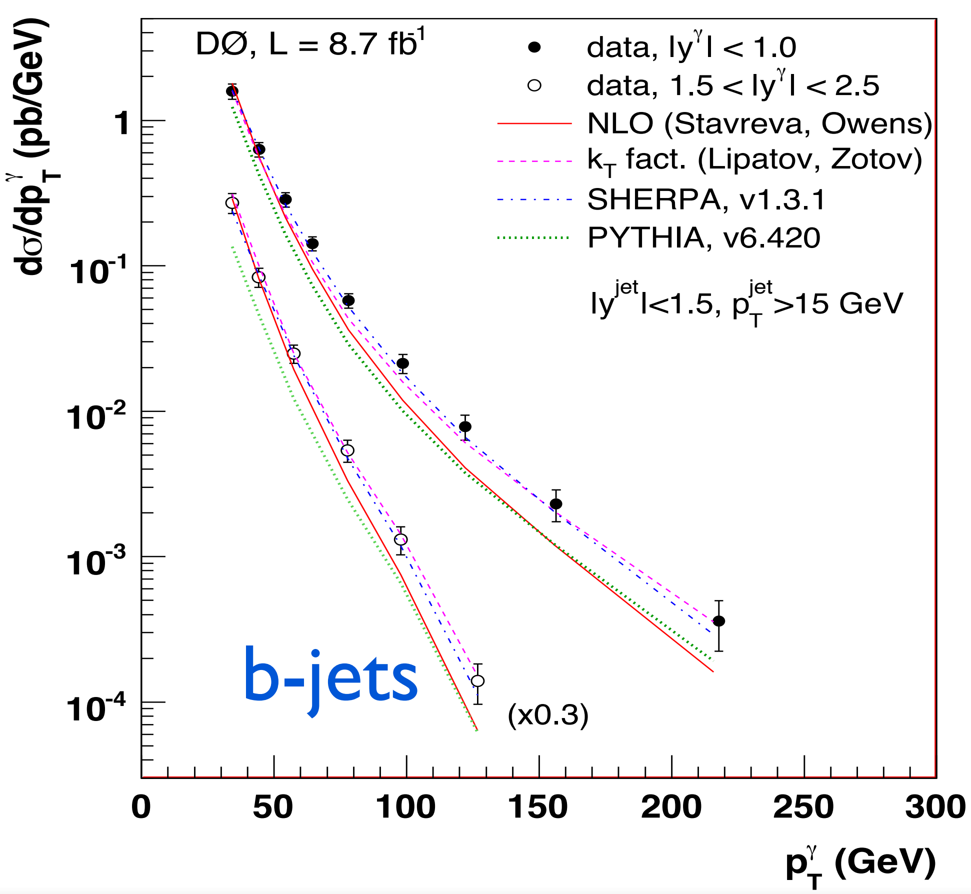
$$gb \rightarrow \gamma b$$
$$q\bar{q} \rightarrow \gamma g \rightarrow \gamma b\bar{b}$$

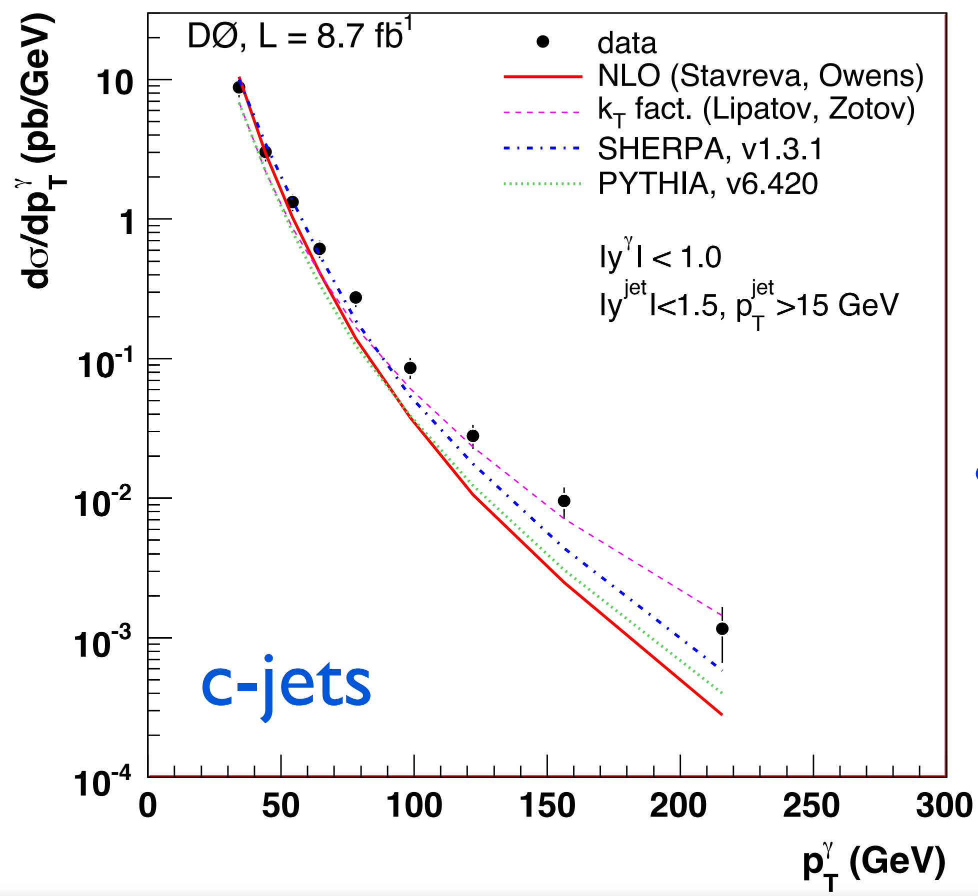
- Heavy quark fraction estimated from fitting secondary mass templates
- Measured cross sections agrees within uncertainties with theoretical and experimental uncertainties

Phys. Lett. B 714, 32 (2012), arXiv:1203.5865
Phys. Lett. B 719, 354 (2013), arXiv:1210.5033



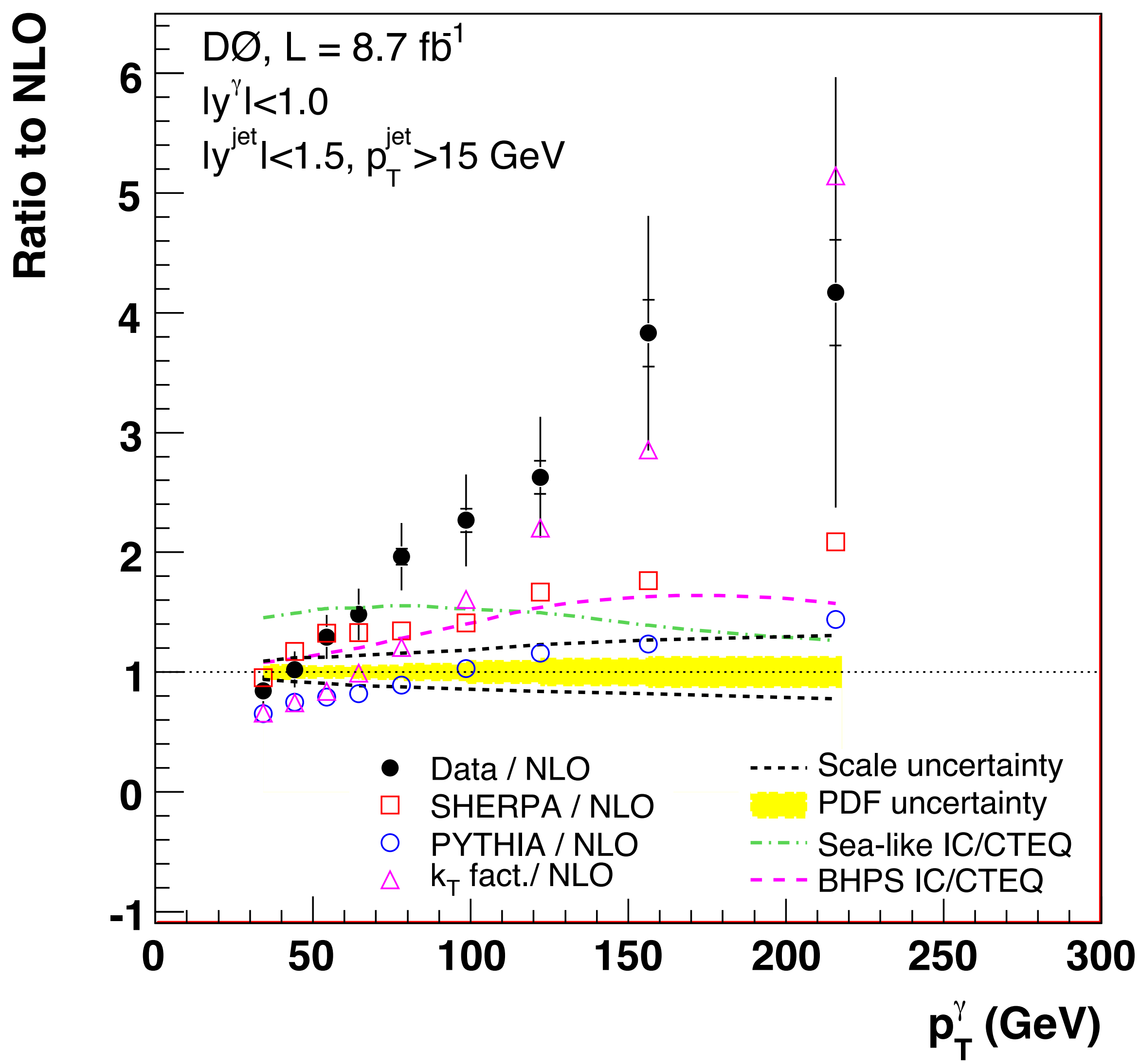
sensitive to different processes at different

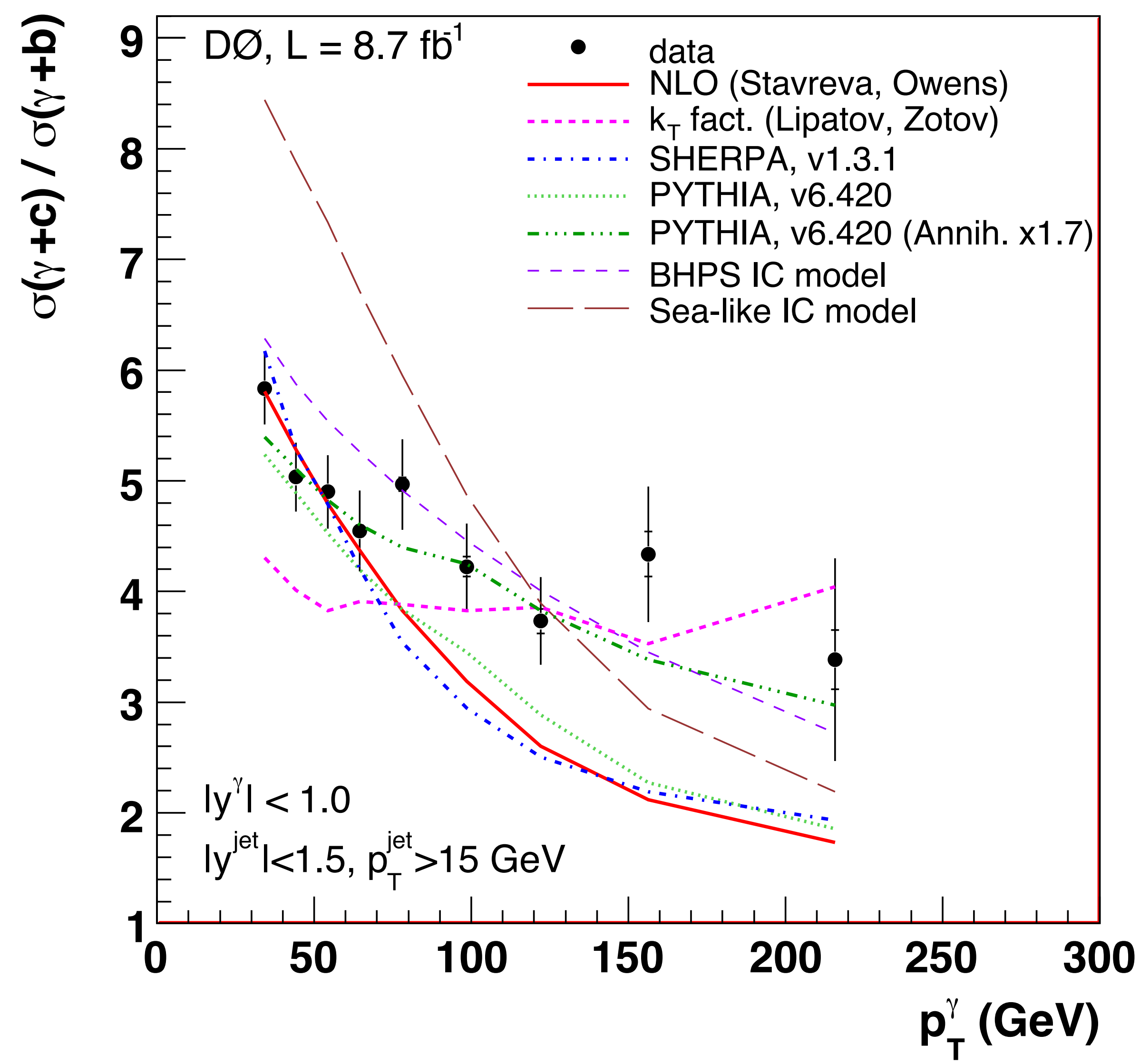




- Slope differs significantly

Photon+heavy jets



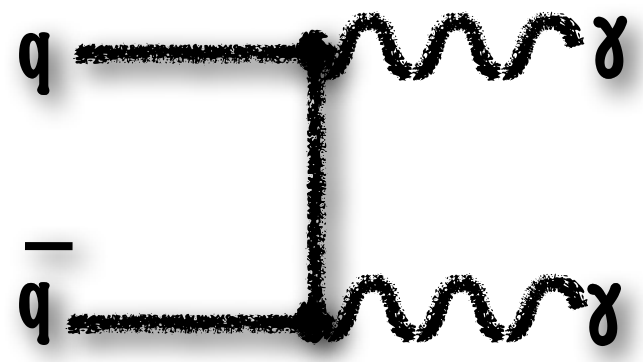


- Ratio agrees within (large) uncertainties with NLO calculations
- Ratio c/b significantly larger at large $p_T(\gamma)$
- Trend for similar NLO/data (dis)agreement as for b-jets observed (larger uncertainties)
- Data suggests improvements in Pythia modeling of gluon splitting rate in heavy flavor production needed

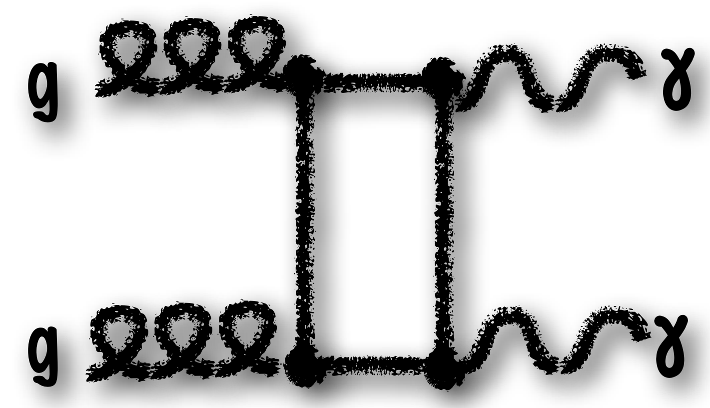
Di-Photon

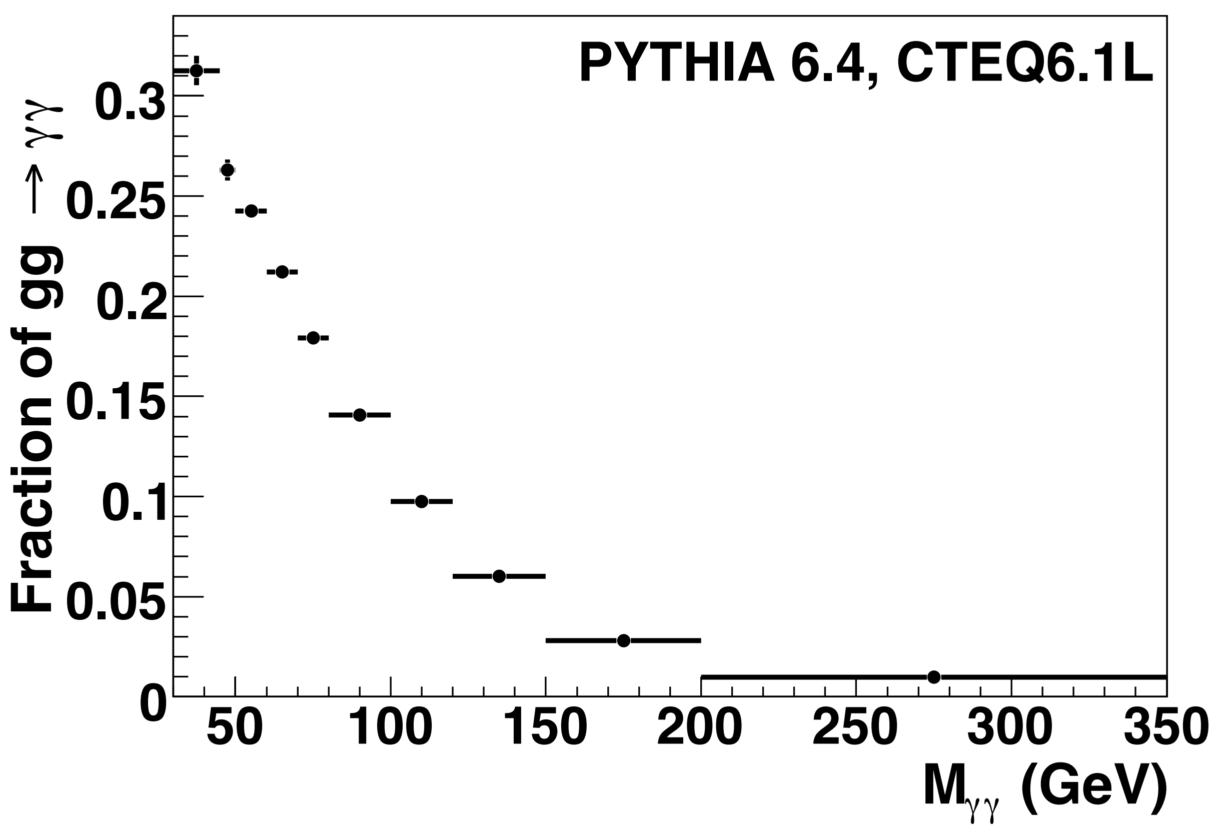
Phys. Lett. B (10.1016/j.physletb.2013.06.036), arXiv:1301.4536

- Direct Diphoton Production:
  Important tool to test validity of theoretical predictions (fragmentation effects, soft-gluon resummations etc)
- (Possible) sources:
  Higgs production, Extra dimensions, SUSY etc
- Measurement for $\Delta\Phi(\gamma\gamma) \leq \pi/2$ and full region (smaller, larger fragmentation contribution)



$$gg/q\bar{q} \rightarrow \gamma\gamma$$

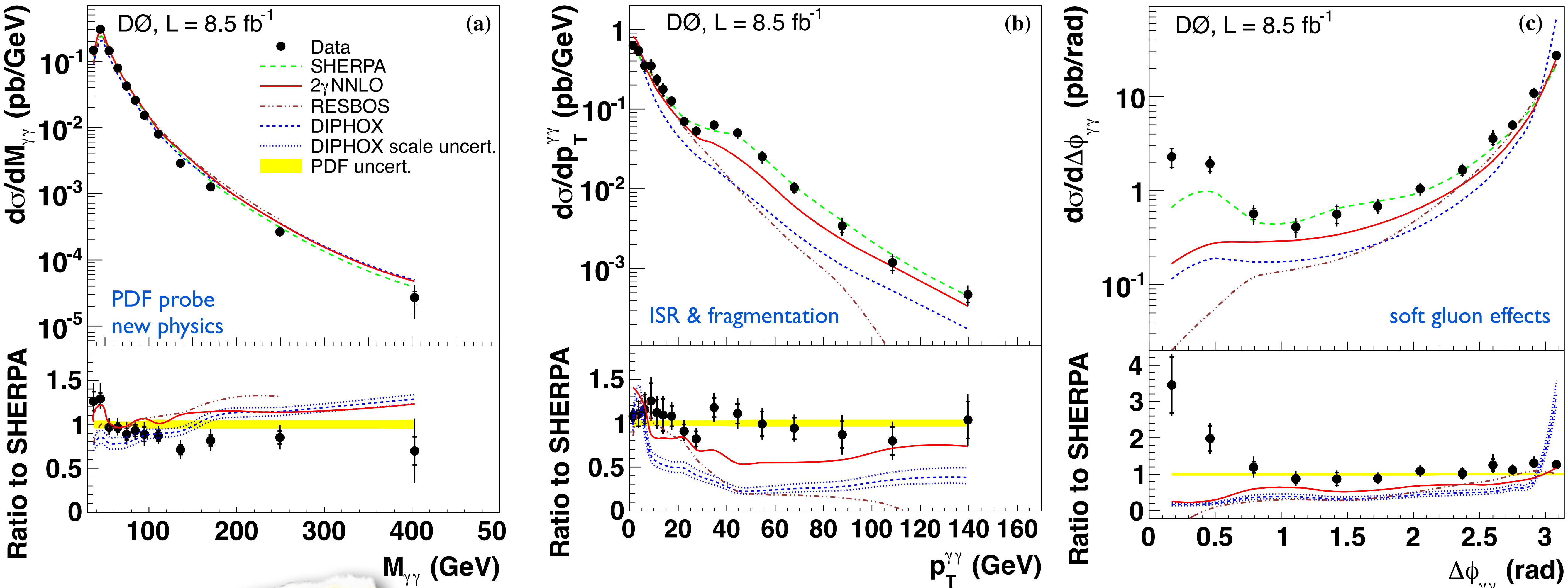




- Differential distributions:
  $$\Delta\phi(\gamma\gamma)\ \ M(\gamma\gamma)\ \ p_T(\gamma\gamma)\ \ |cos\theta^*|$$
- Sherpa: ME with two photon and two partons, no gg→γγ real parton emission
- Diphox: NLO generator, NLO fragmentation, no resummation
- Resbos: NLO generator, (N)LO fragmentation, soft-, collinear gluon resummation
- 2γNNLO: NNLO generator, no fragmentation, no soft gluon resummation

Di-Photon

differential cross section for full ΔΦ(γγ) region



Source of systematics:

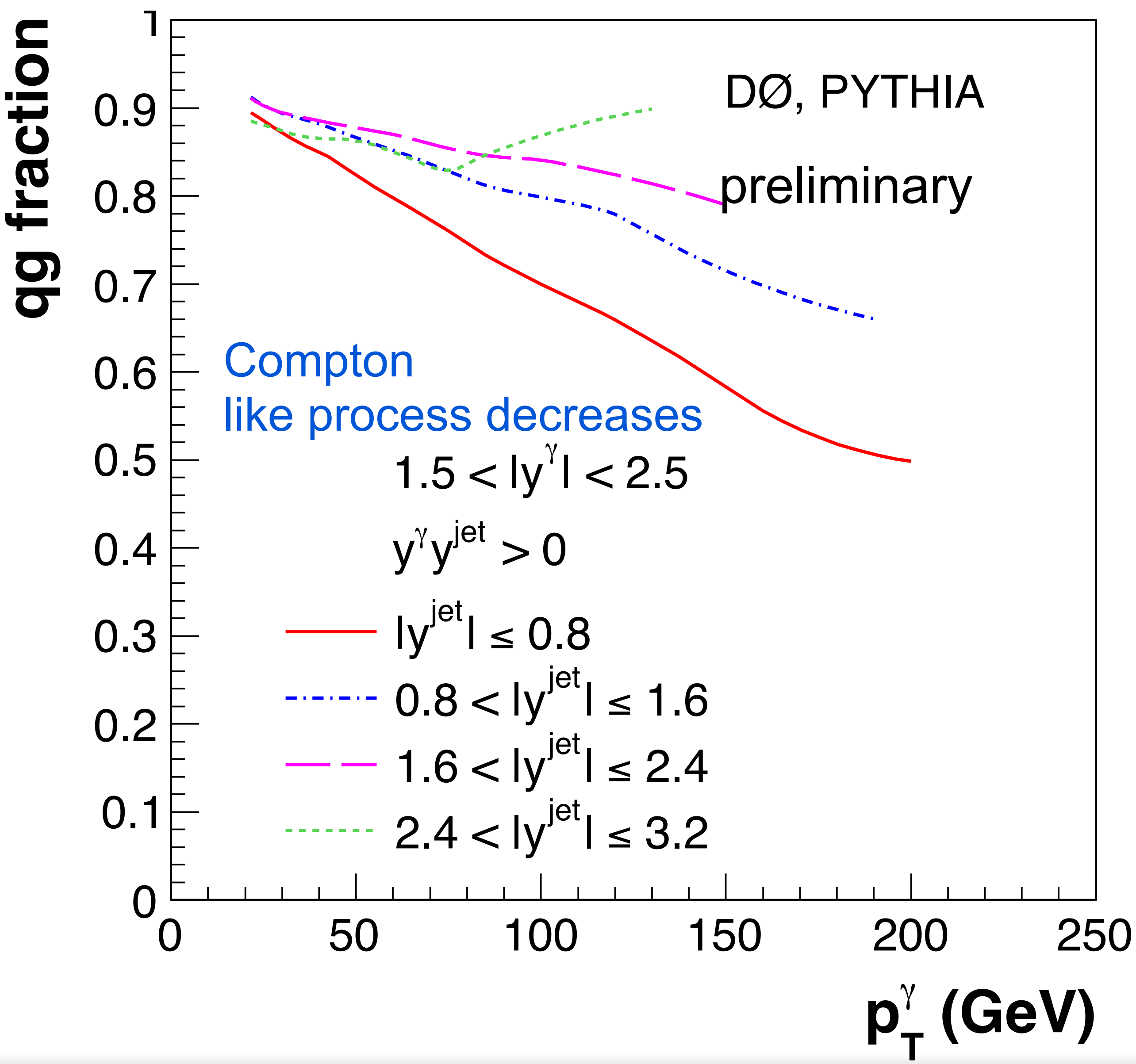
- Purity
- Acceptance
- Trigger-Efficiency
- Photon Selection Eff.
- Luminosity

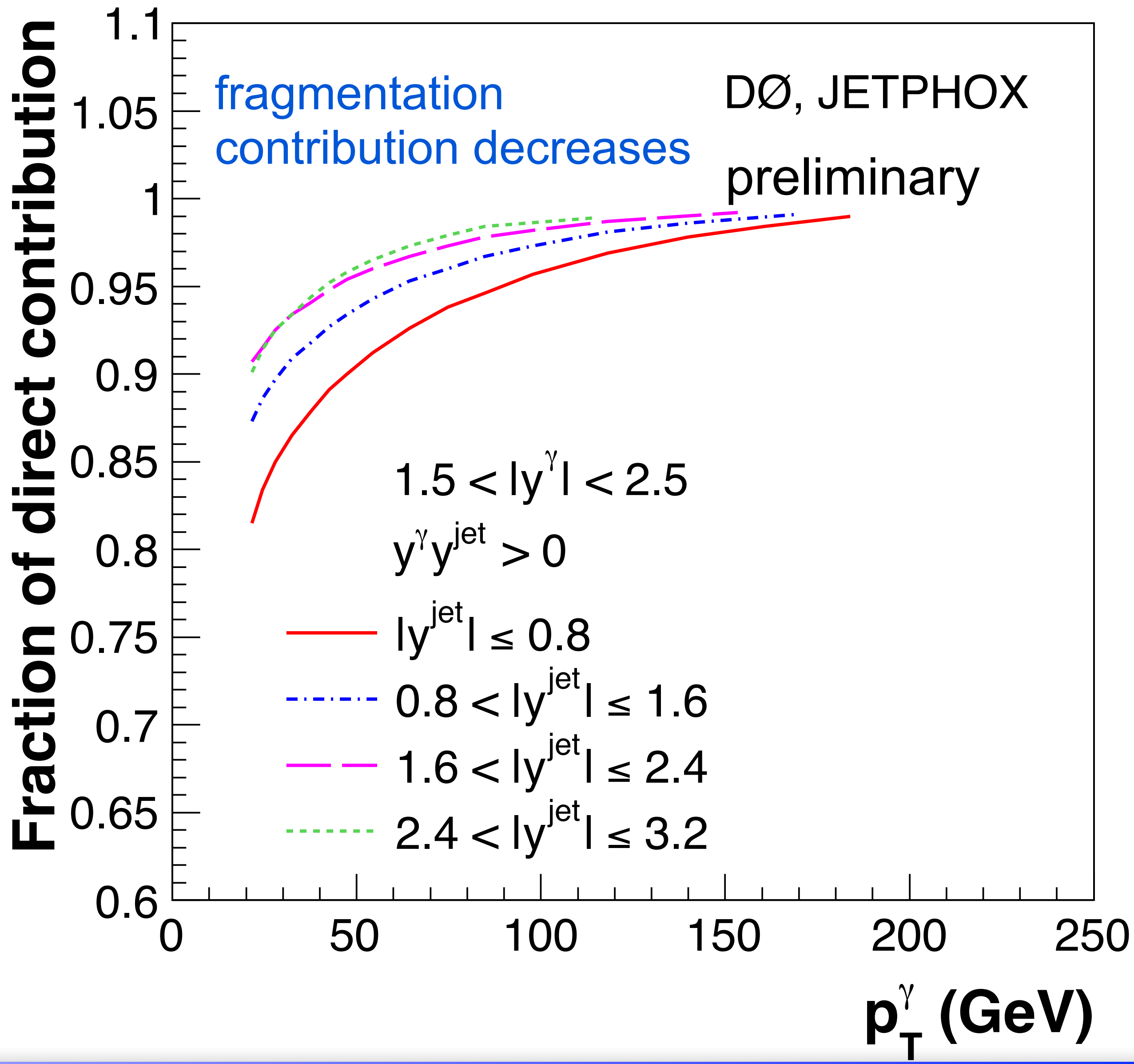
Typical Size: 15-20%

- No perfect generator
- Sherpa doing well except low ΔΦ, overall best
- Resbos/Diphox discrepancy due to absence of soft-gluon-resummation

Triple Differential Cross Section

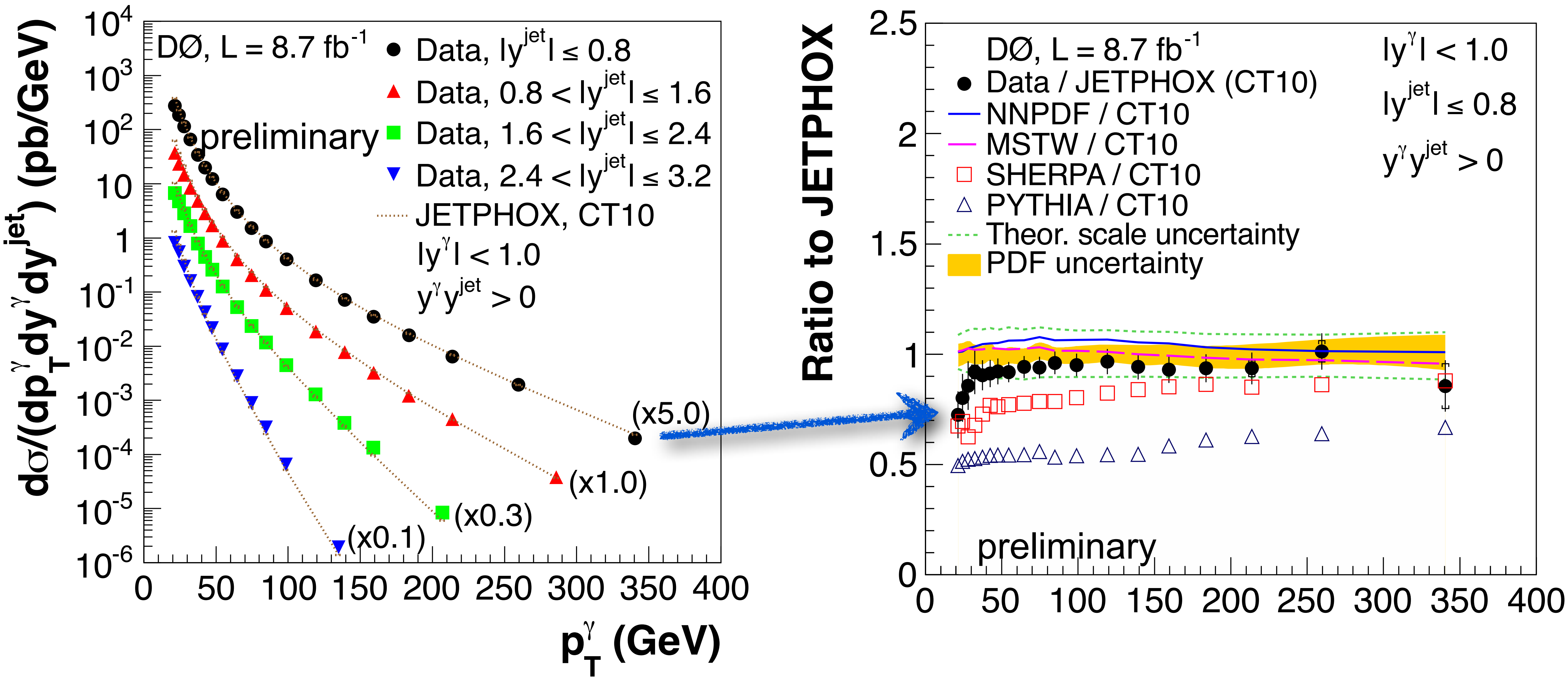
- Triple diff. cross section: $\mathrm{d}^3\sigma/\mathrm{d}p_T^\gamma \mathrm{d}y^\gamma \mathrm{d}y^{\mathrm{jet}}$,
- Direct production: $gq \to \gamma q, q\bar{q} \to \gamma q$
- Different angular configurations between photon and jets probe different ranges of parton momentum fraction x and hard-scattering scales Q^2





Triple Differential Cross Section

- Triple diff. cross section $d^3\sigma / dp_T^\gamma dy^\gamma dy^{jet}$,
- Study γ+jet production in two photon and four rapidity jet regions and os/ss jet/photon regions: $|y^{jet}|<0.8$, $0.8 <|y^{jet}|<1.6$, $1.6 <|y^{jet}|<2.4$, $2.4 <|y^{jet}|<3.2$ and $y^{jet}y^\gamma \gtrless 0$

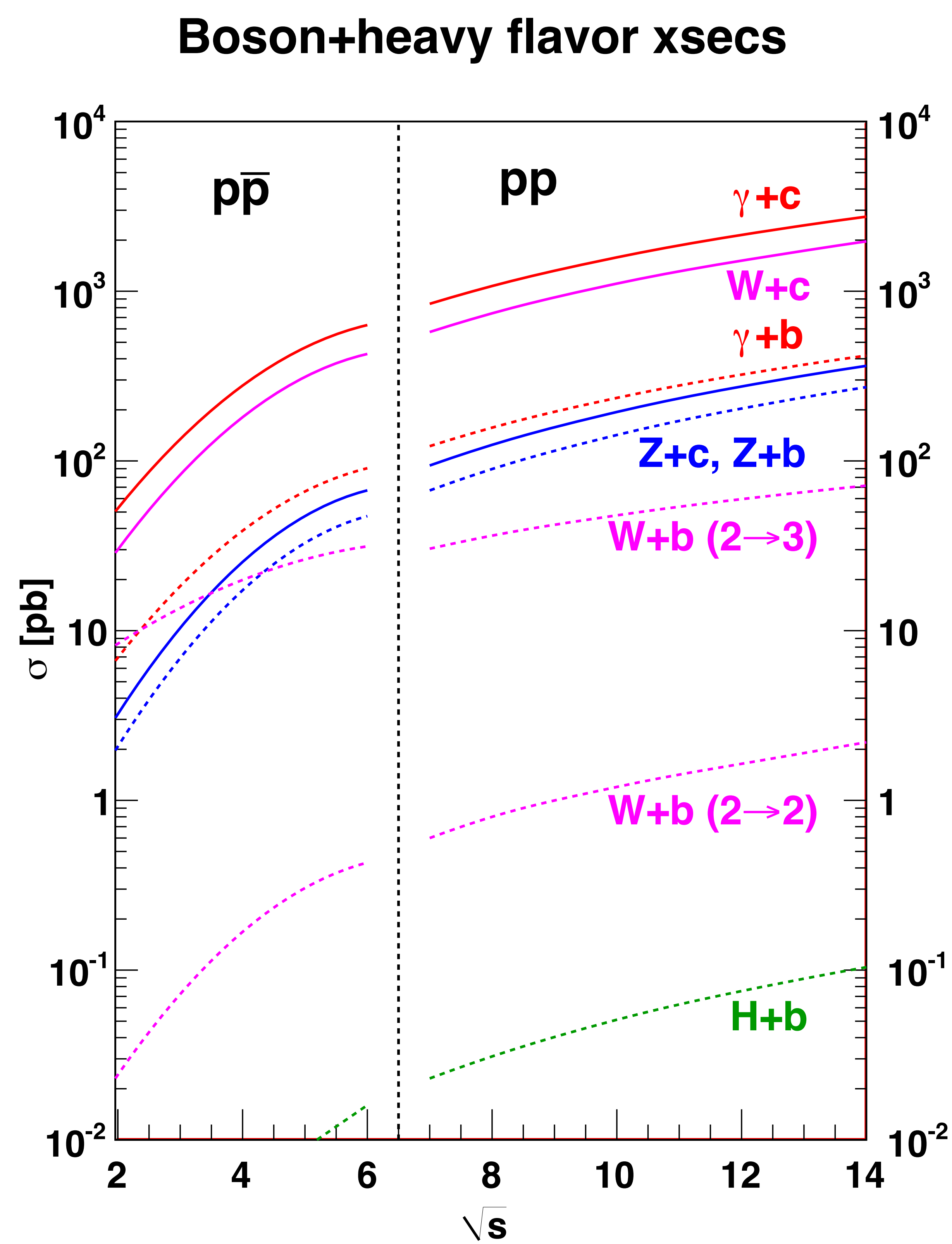


- Typical uncertainties similar or smaller than PDF+scale uncertainties
- pQCD NLO describe data well in all rapidity and $p_T(\gamma)$ regions

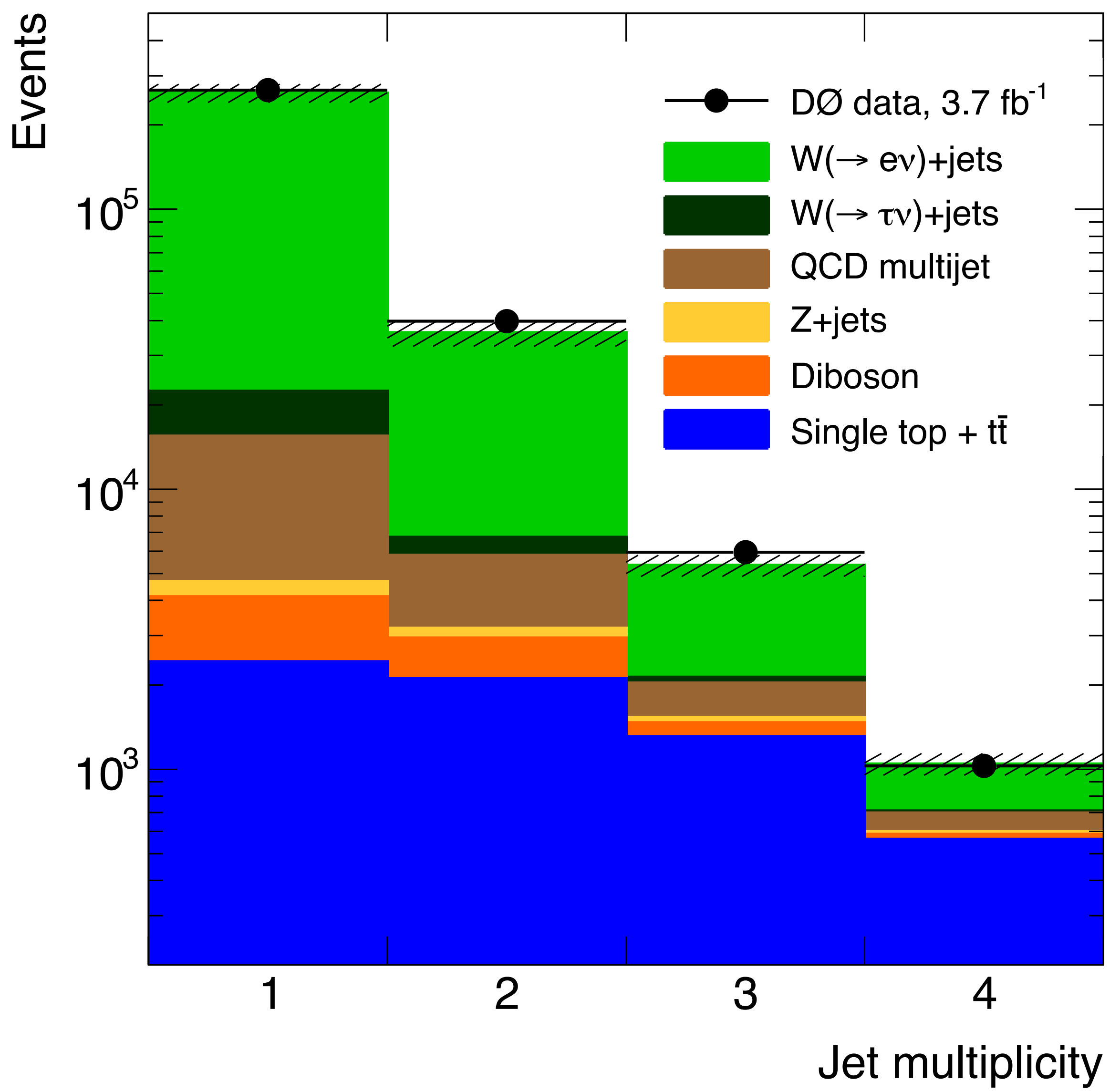
Summary

- There is a rich and active QCD physics program at the Tevatron! Wide range of measurements, with many more still to come
- Precise knowledge of DØ object IDs, energy scales and systematics lead to experimental uncertainties comparable or lower than theoretical uncertainties
- Observables (many studied for the first time):
  - W/Z+jets
  - photon+jets,
  - heavy flavor
- Many show areas where description of data over full range can be improved
- Tevatron offer unique opportunities for study and tuning of theoretical predictions
- Only covering fraction of results
- More available: http://www-d0.fnal.gov/Run2Physics/qcd/
  e.g: extraction of α_s, jet algorithm studies, underlying/double parton events, etc.

Backup

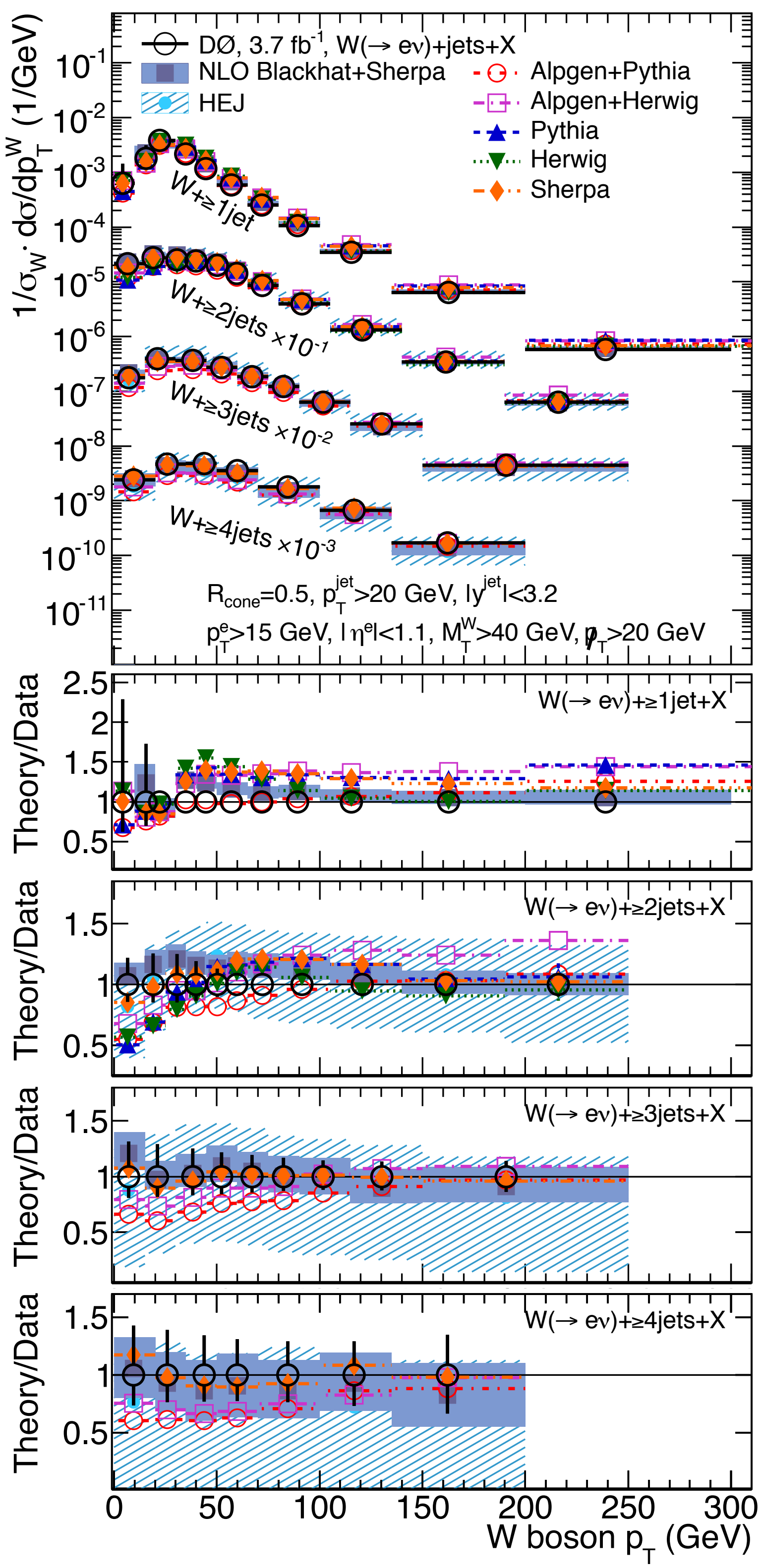

Boson+heavy flavor xsecs
pp̄
pp
γ+c
W+c
γ+b
Z+c, Z+b
W+b (2→3)
W+b (2→2)
H+b
σ [pb]
√s
10^4
10^3
10^2
10
1
10^-1
10^-2
2
4
6
8
10
12
14

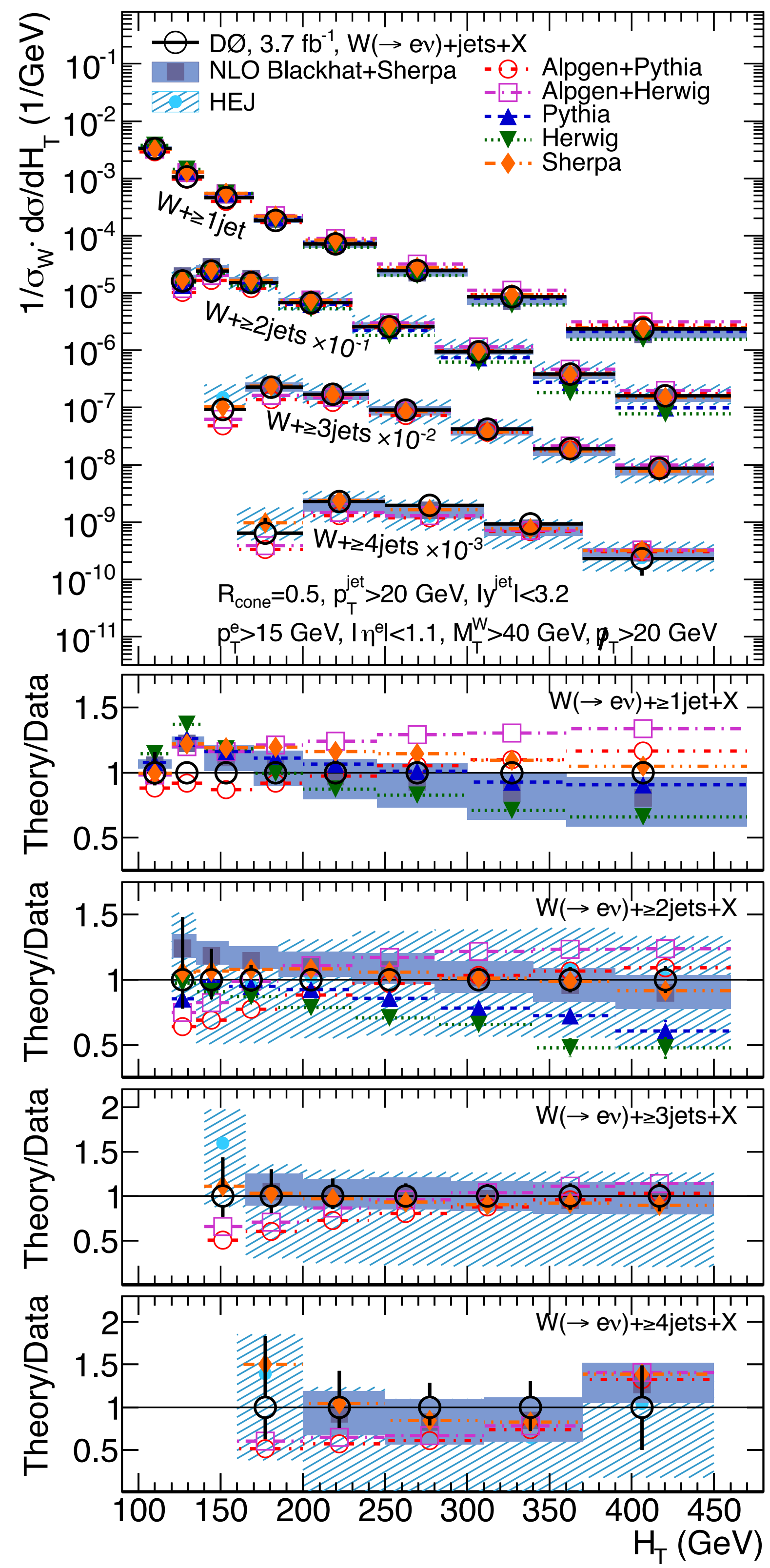
Phys. Lett. B **719**, 354 (2013), arXiv:1210.5033

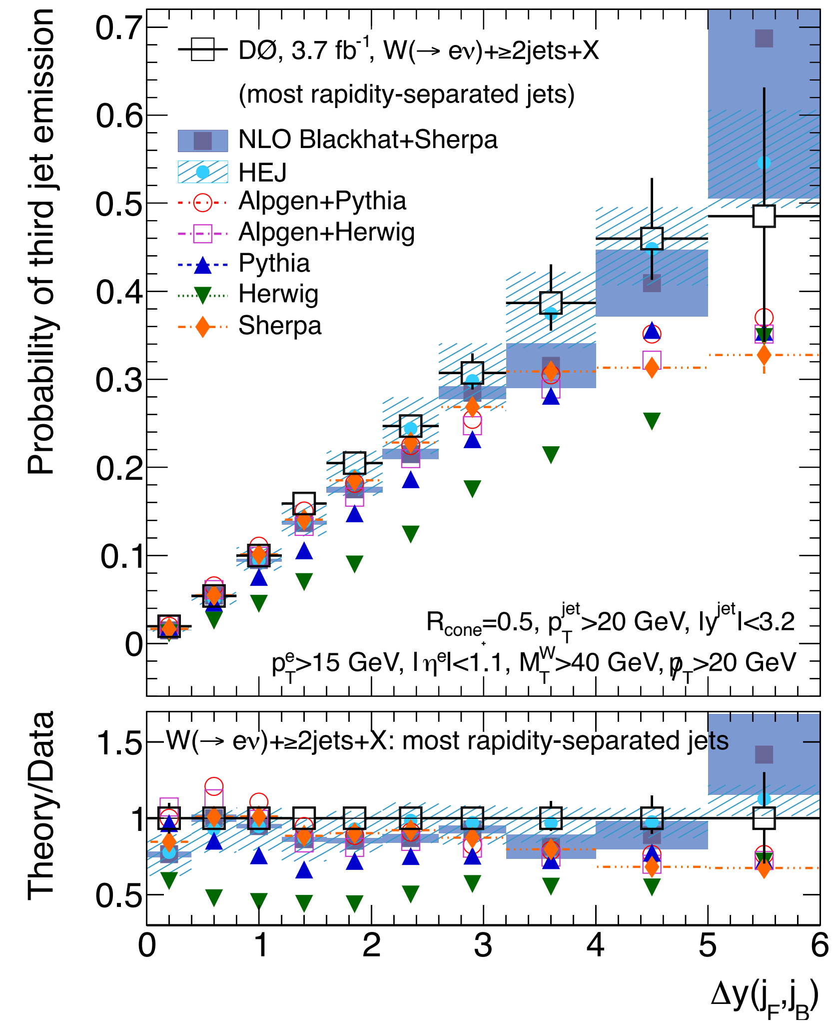


Jet transverse momentum	$p_T^{\text{jet}} > 20$ GeV
Jet rapidity	$\lvert y_{\text{jet}}\rvert < 3.2$
Electron transverse momentum	$p_T^e > 15$ GeV
Electron pseudorapidity	$\lvert\eta^e\rvert < 1.1$
Sum of all neutrino transverse energies	$\not{p}_T > 20$ GeV
Transverse W boson mass requirement	$M_T^W > 40$ GeV

- Fundamental test of pQCD & bkgd for many measurements
- Test of W+≤4j production
- Measurement of diff. cross-section in n^{th} jet mult. bin for many kinematic distributions
- Unfolding to particle level using GURU matrix rather than traditional bin-by-bin method
- Compared to Blackhat+Sherpa (prevous studies of Blackhat+Sherpa with show good agreement Rocket+MCFM)

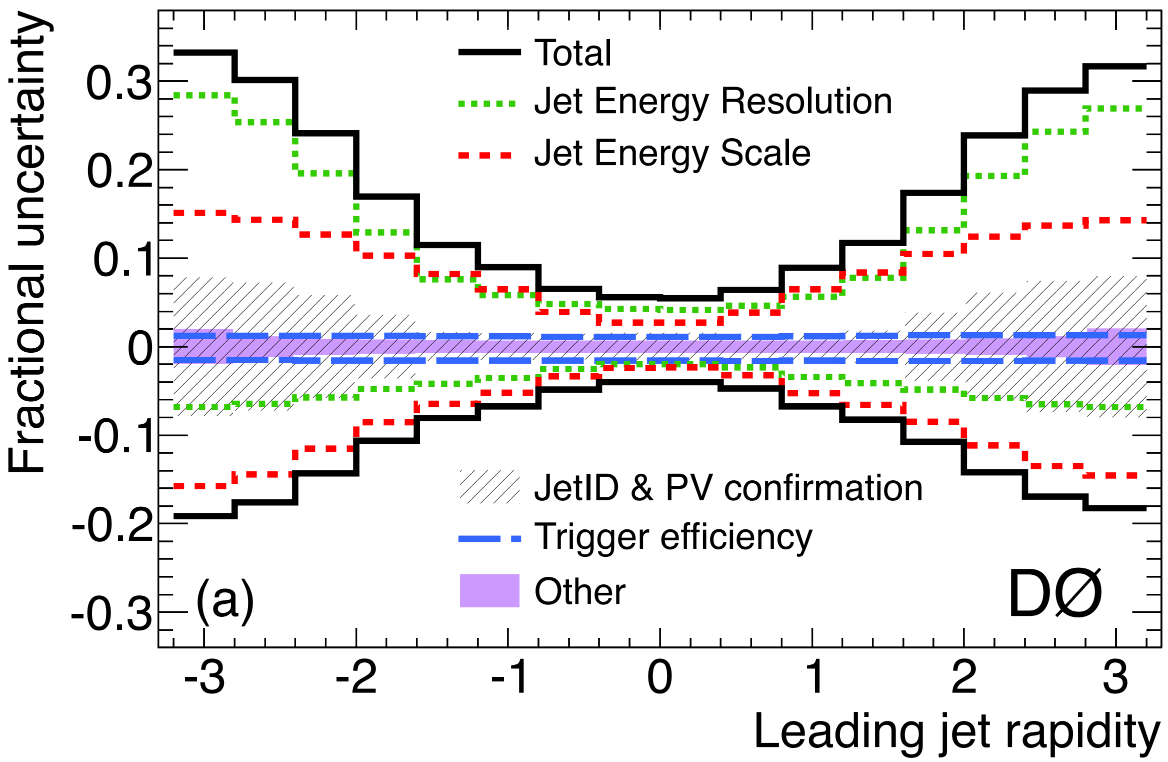


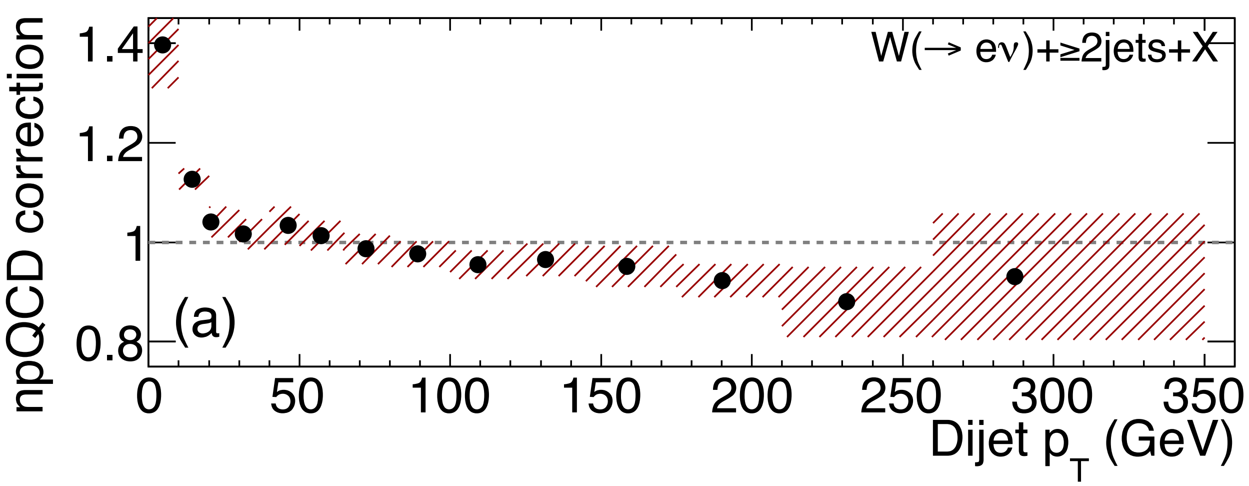


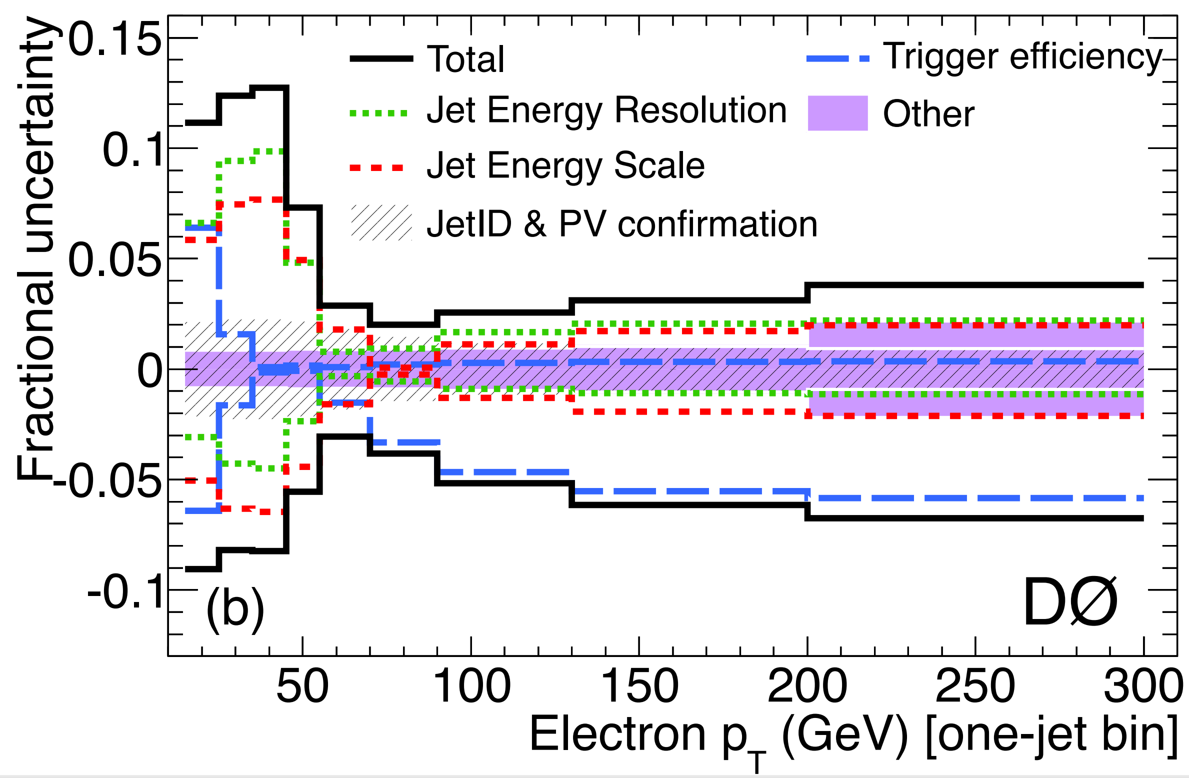


- Probability of third jet to be emitted in W +2jet production as function of rapidity gap
- Many more distributions in paper

- Particle level corrections derived from Sherpa
  - non-perturbative QCD effects, due to hadronization
  - Jet alrogithm
- Dominant uncertainties: jet energy scale (JES), jet energy resolution (JER), jet vertex confirmation







JES Energy Scale Corrections

- What we call ‘GeV’ in the detector ar
actually ADC counts
→ translate to cell energies

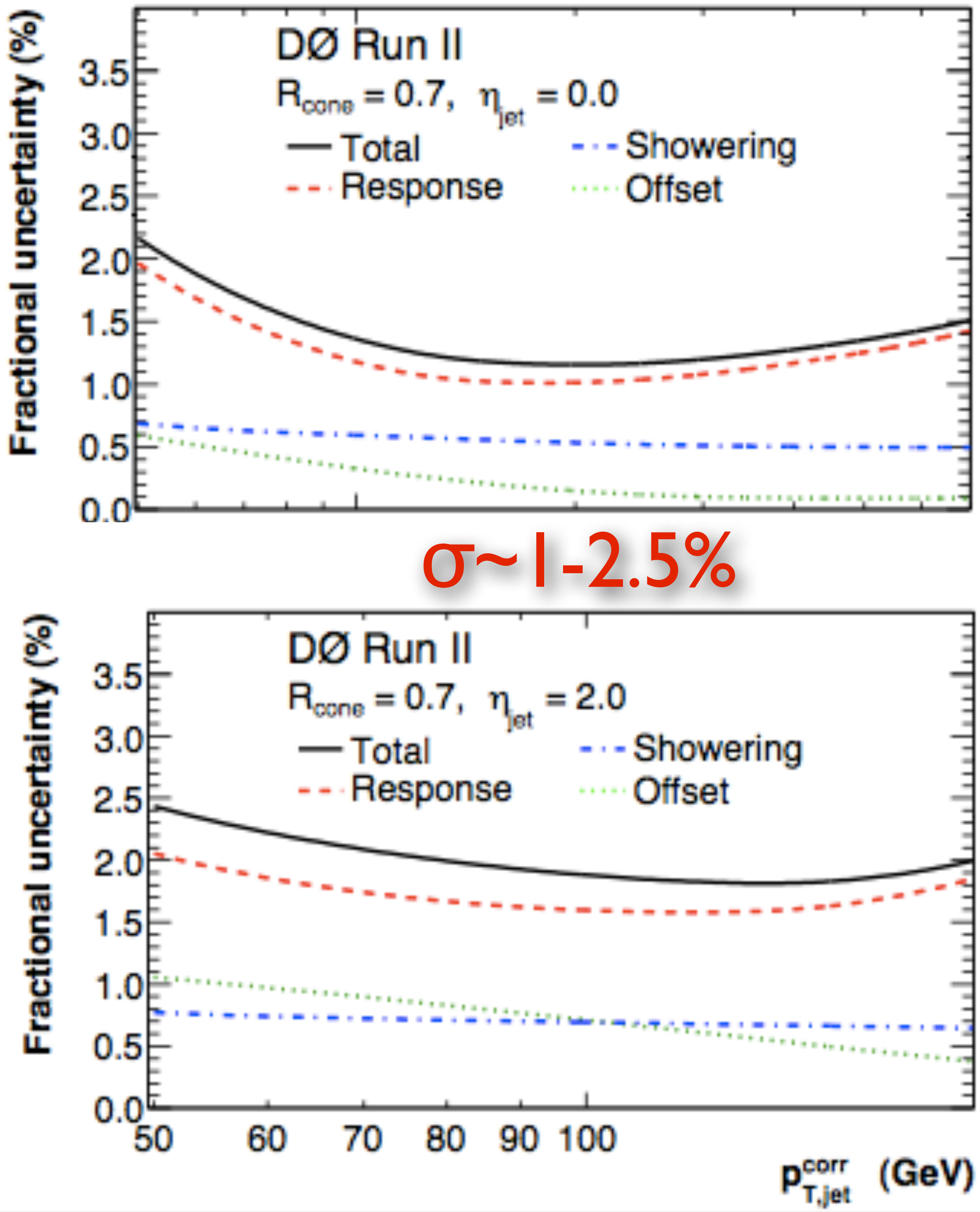
- RunII jet cone algorithm with
$\Delta R = \sqrt{(\Delta y^2 + \Delta\Phi^2)} < R_{cone}$

- Jet Energy Scales (JES) corrected t
the particle level:

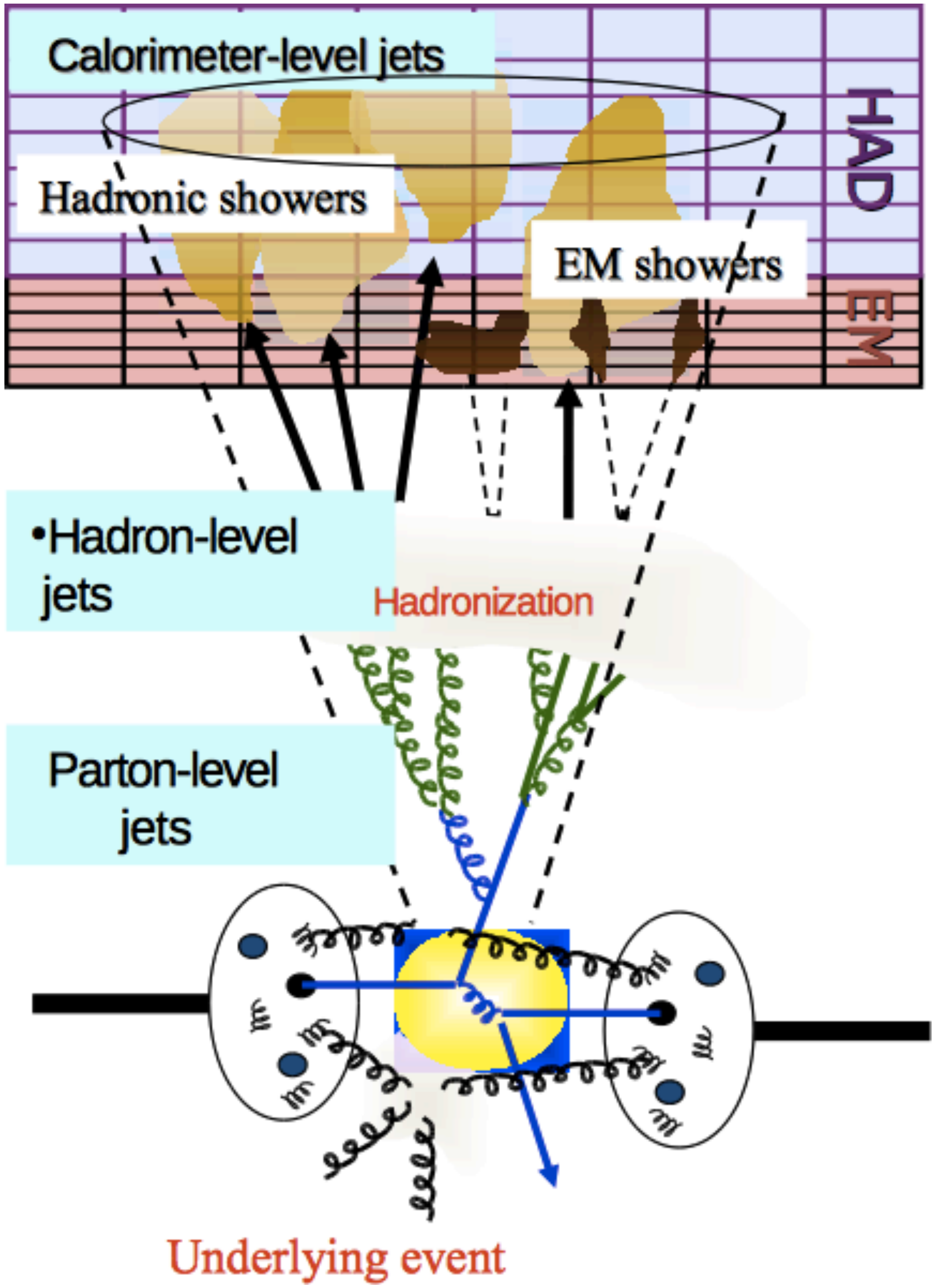
  - Calibrated using γ+jets
  (dijets and Z+jets)

  - JES includes: Energy Offset
  (energy not from the main hard
  scattering process); Detector
  Response, Out-of-Cone
  showering; Resolution

  - Different response for quark and
  gluon jets



Particle Level Corrections

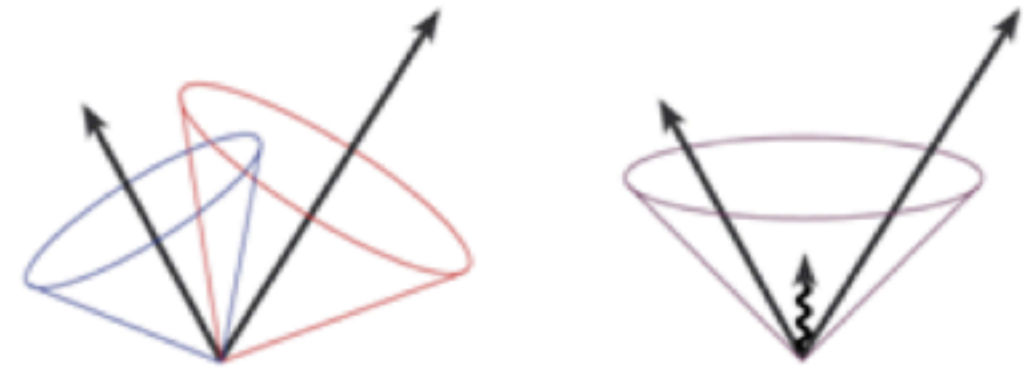


- In RunII jet results, in most cases:
  - Data are corrected to particle level
  - Particle level measurements are compared to NLO theory
  - NLO theory is corrected to particle level using parton shower MC
- Corrections for the underlying events (UR) and hadronization.

Midpoint cone-based algorithm

- Cluster objects based on their proximity in y-ϕ space
- Starting from seeds (calorimeter towers/particles above threshold), find stable cones (kinematic centroid = geometric center).
- Seeds necessary for speed, however source of infrared unsafety.
- In recent QCD studies, we use "Midpoint" algorithm, i.e. look for stable cones from middle points between two adjacent cones
- Stable cones sometime overlap
  → merge cones when p_T overlap > 75%

Infrared unsafety:
soft parton emission changes jet clustering

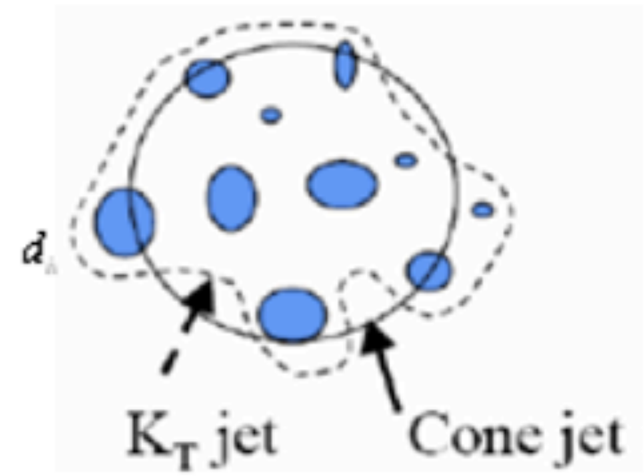


More advanced algorithm(s) available now, but negligible effects on this measurement.

k_T algorithm

- Cluster objects in order of increasing their relative transverse momentum (k_T)
  - $d_{ii} = p^2_{T,i}, \quad d_{ij} = \min\,(p^2_{T,i}, p^2_{T,j})\ \frac{\Delta R^2}{D^2}$

  until all objects become part of jets
- D parameter controls merging termination and characterizes size of resulting jets



- No issue of splitting/merging. Infrared and collinear safe to all orders of QCD.
- Every object assigned to a jet: concerns about vacuuming up too many particles.
- Successful at LEP & HERA, but relatively new at the hadron colliders
  - More difficult environment (underlying event, multiple *pp* interactions...)

Direct Diphoton Prodcution

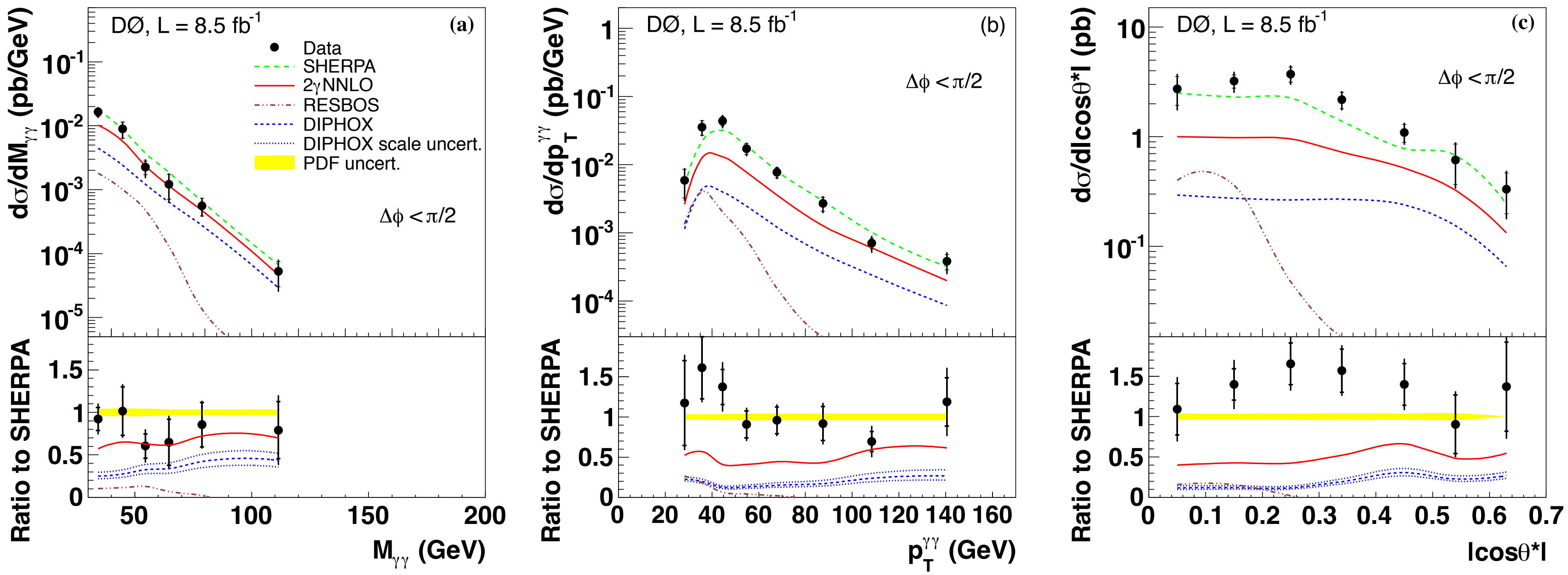


FIG. 2: (Color online) The differential cross section as a function of (a) $M_{\gamma\gamma}$, (b) $p_T^{\gamma\gamma}$, and (c) $|\cos\theta^*|$ for the $\Delta\phi_{\gamma\gamma} < \pi/2$ region. The notations for points, lines and shaded regions are the same as in Fig. 1.

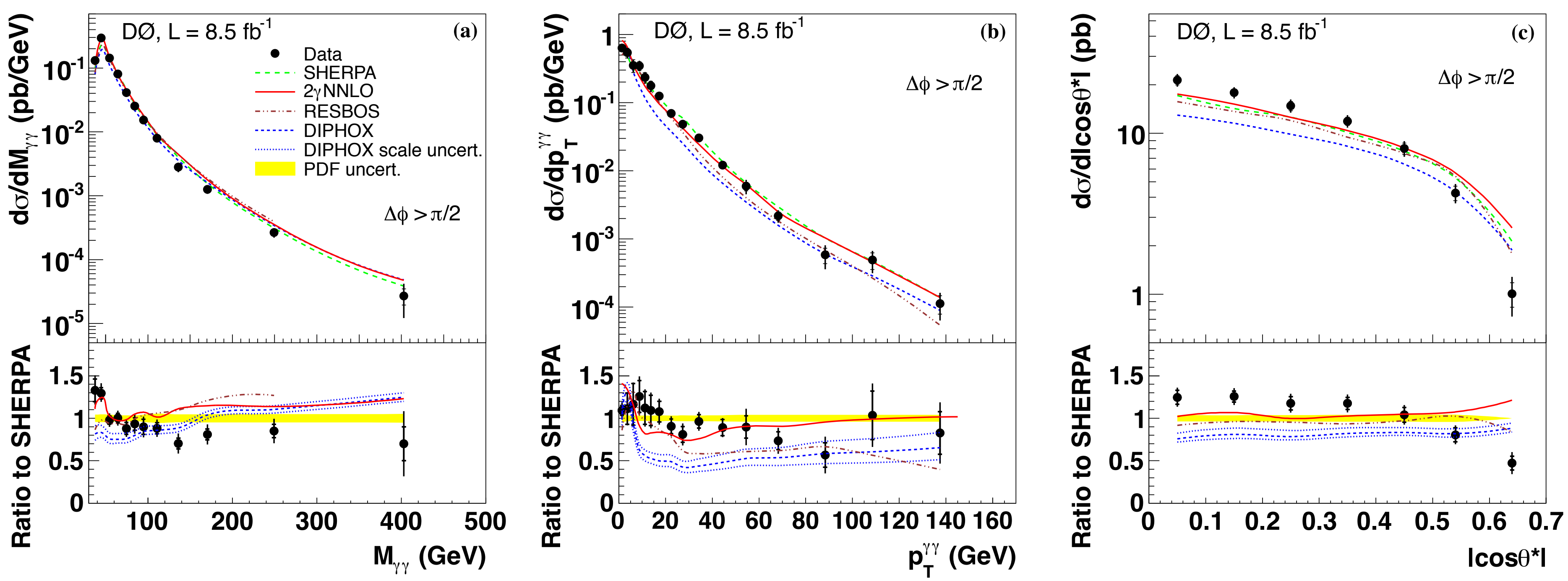


FIG. 3: (Color online) The differential cross section as a function of (a) $M_{\gamma\gamma}$, (b) $p_T^{\gamma\gamma}$, and (c) $|\cos\theta^*|$ for the $\Delta\phi_{\gamma\gamma} \geq \pi/2$ region. The notations for points, lines and shaded regions are the same as in Fig. 1.