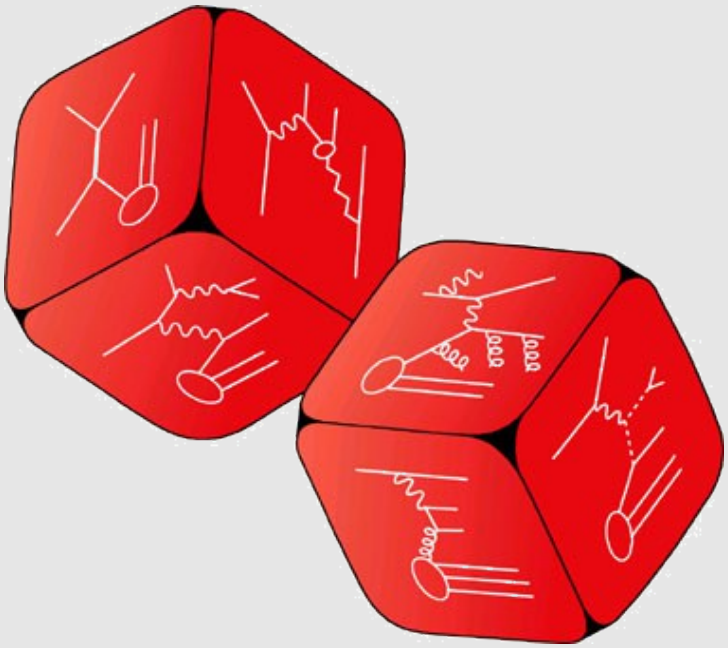
# QCD Studies

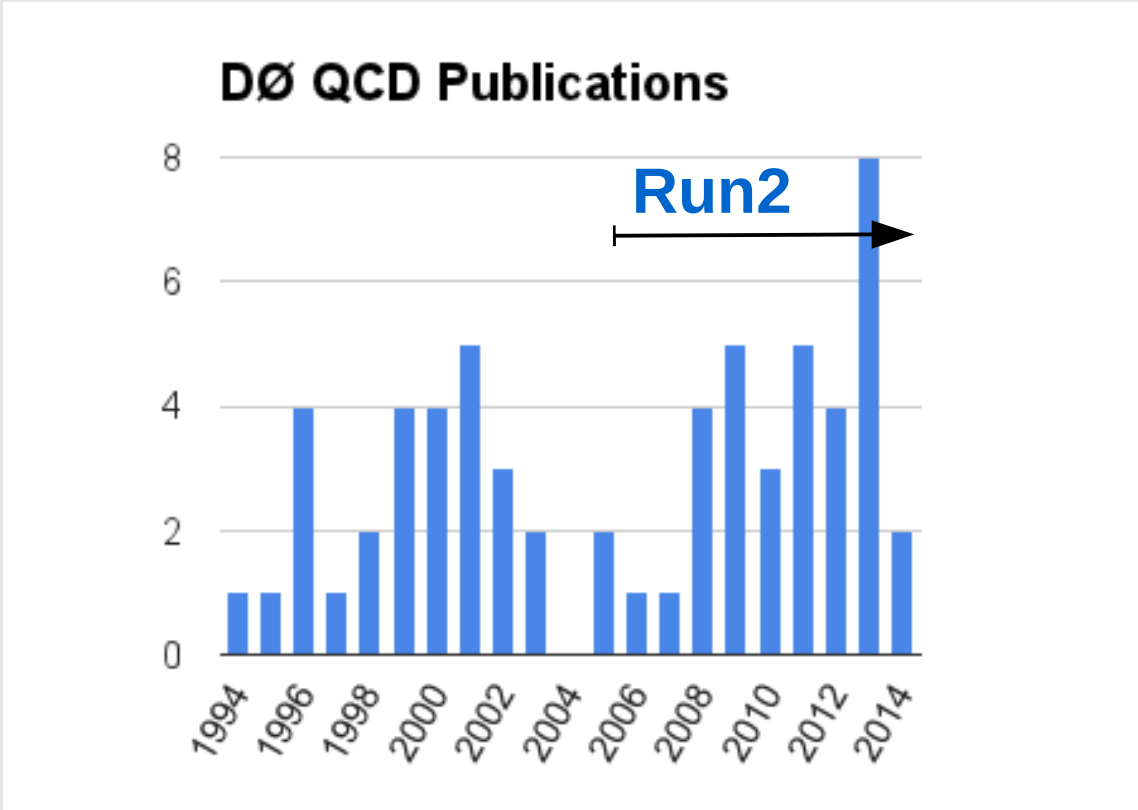
Bob Hirosky
for the many Run2
QCD group members

What have we done and learned

# QCD results by submission year

**35 QCD Run2 papers so far + JES!**

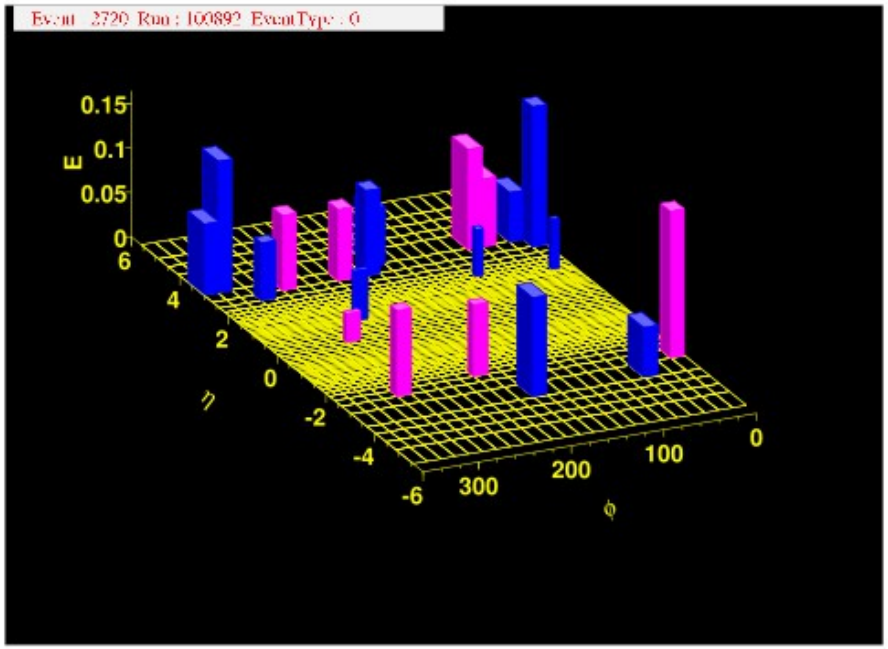




# Dawn of Run 2 QCD

Fermilab-Pub-00/297
November 2000

**QCD and Weak Boson Physics in Run II**




**Fermilab, March – November 1999**

**Editors: U. Baur, R.K. Ellis and D. Zeppenfeld**

Definition of Run 2 jet algorithms

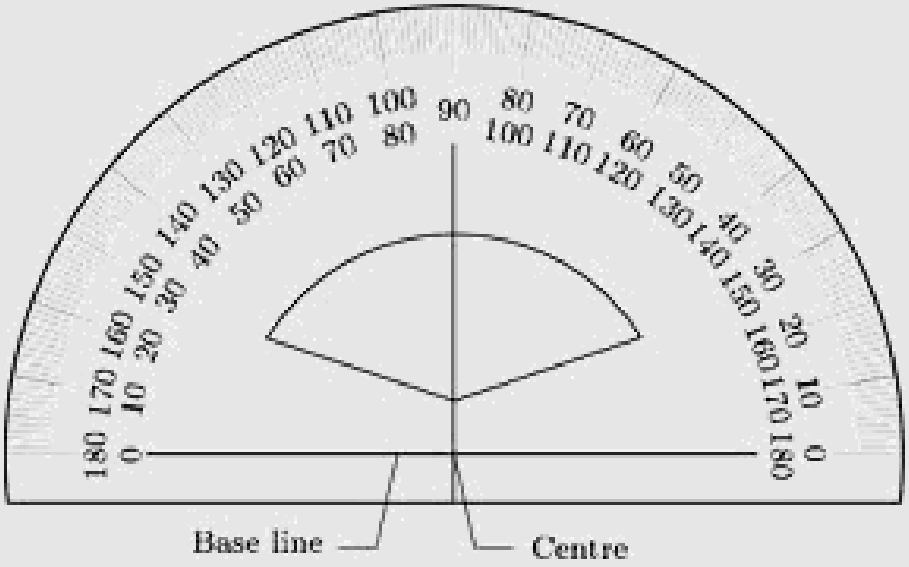
A manifesto on what defines an ideal jet algorithm from experimental and theory perspectives

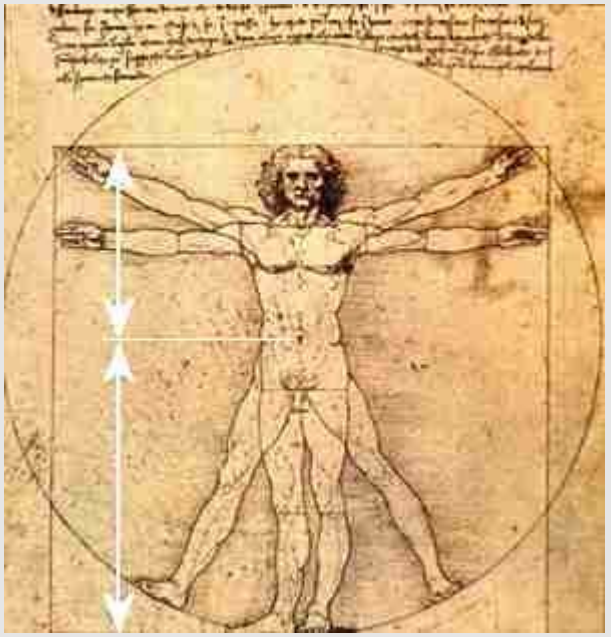
Full specification of “Run2” algorithms

Goal: to update Snowmass “accord” of 1990

Large participation from D0

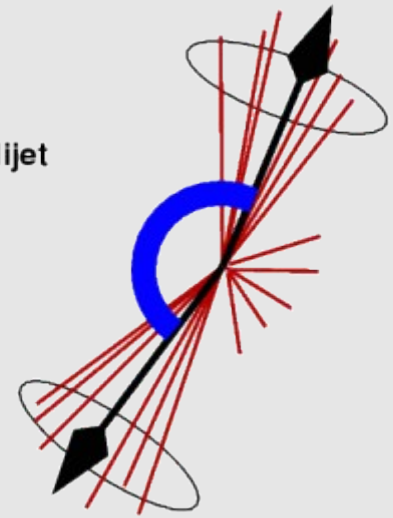
# Angles, Ratios, Multijets



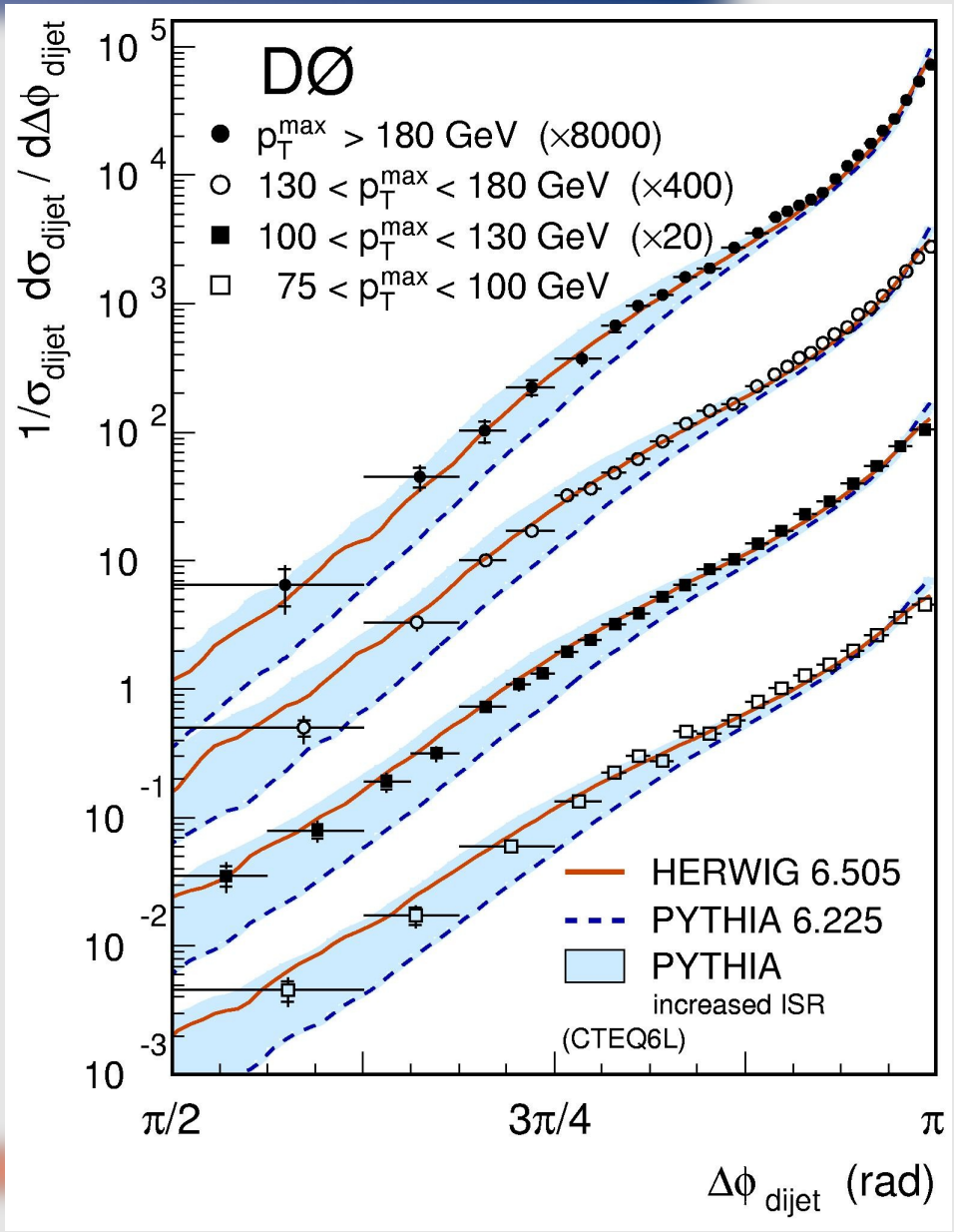
# (2005) Q1: Measurement of Dijet Azimuthal Decorrelations at Central Rapidities TOPCITE = 100+

1st QCD paper of Run2




Measure phi decorrelation versus PT jet

- NLO shows good agreement*
- Nominal PYTHIA tune underestimates effect of hard radiation

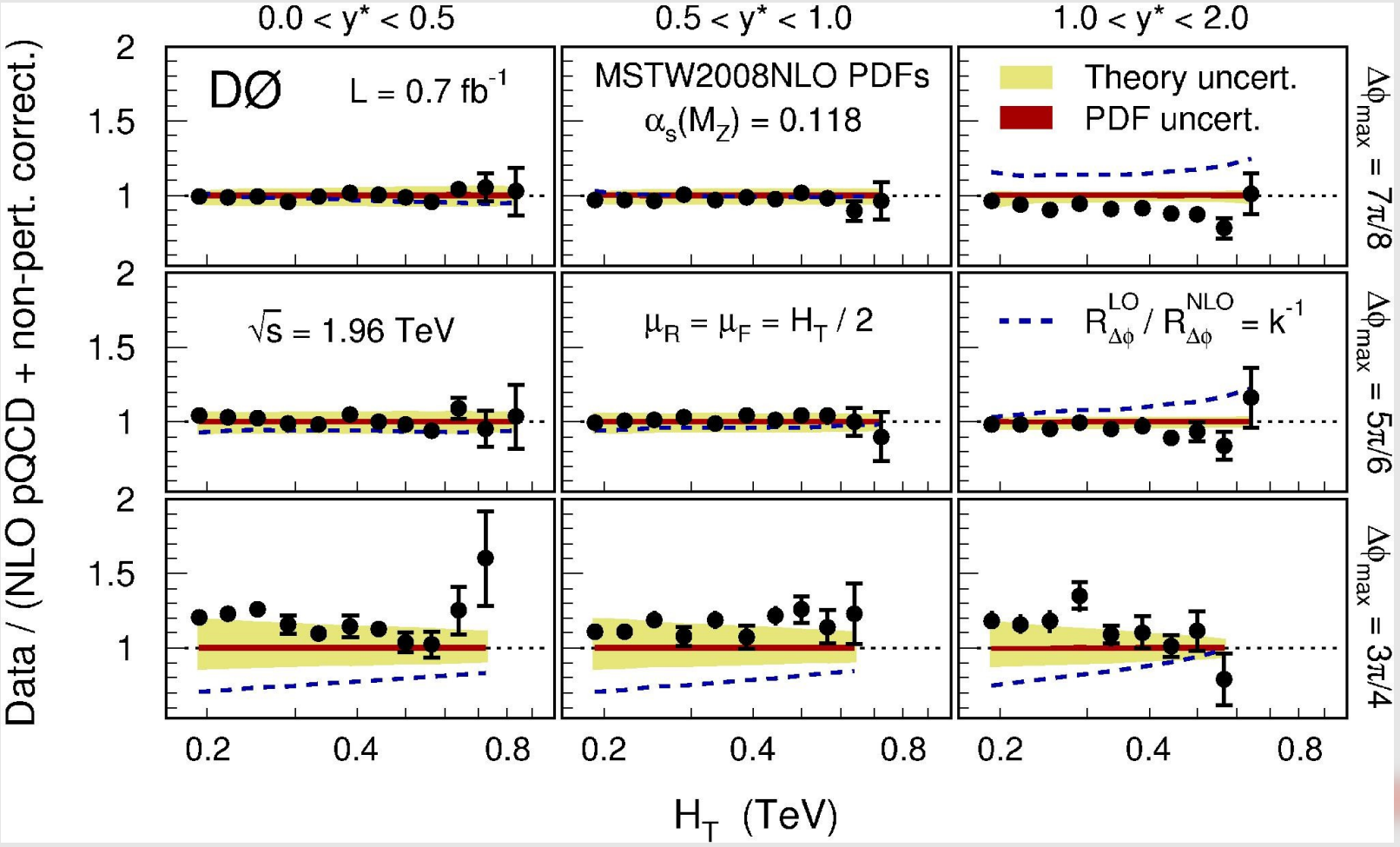



* until calculation breaks down

# (2013) Q27: Measurement of the combined rapidity and pT dependence of dijet azimuthal decorrelations in pp collisions at √s=1.96 TeV

## Measure decorrelation vs PT

Differentiate kinematic regions where NLO precisely models data

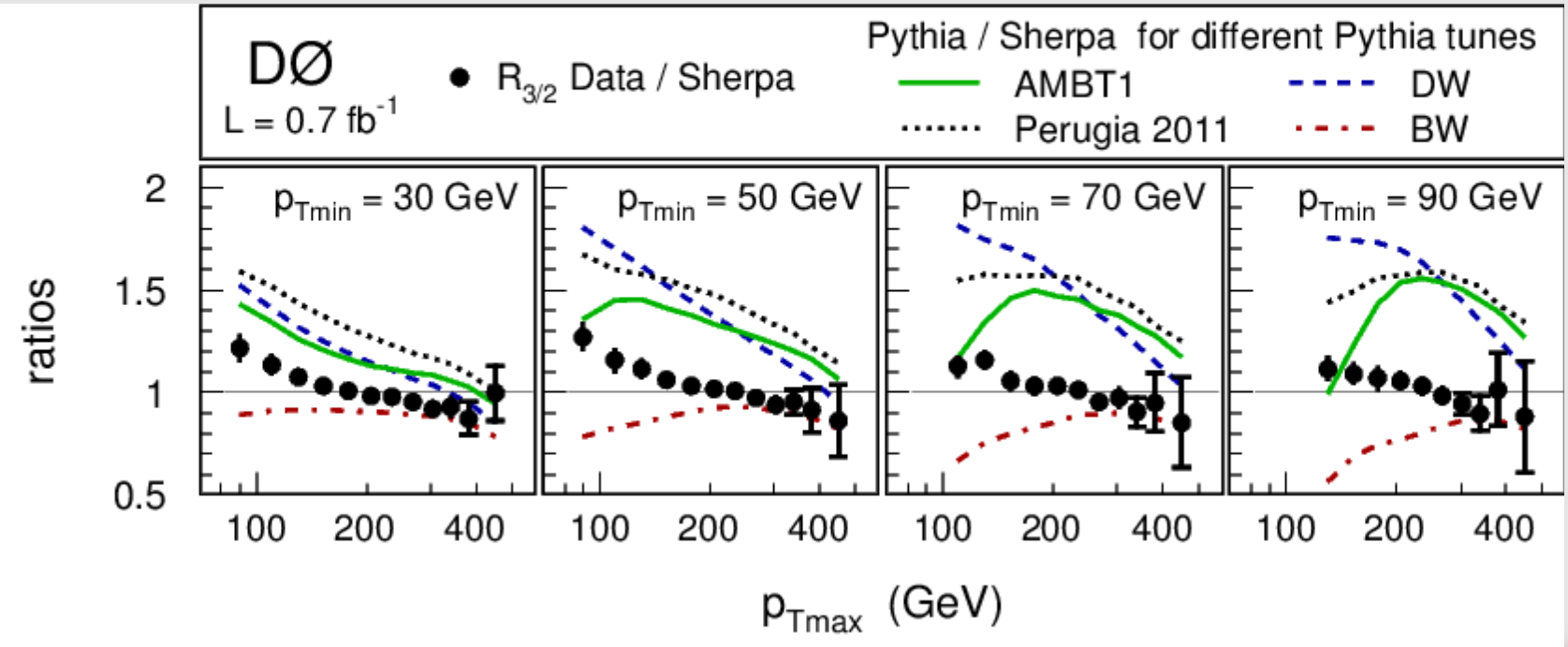



versus those where perburbative approximation is not converging well (systematic disagreement, large scale dependence)

# (2013) Q26: Measurement of the ratio of three-jet to two-jet cross sections in pp Collisions at √s = 1.96 TeV

$$R_{3/2}(p_{T\max}, p_{T\min}) = \frac{d\sigma_{3\text{-jet}}(p_{T\min})/dp_{T\max}}{d\sigma_{2\text{-jet}}(p_{T\min})/dp_{T\max}},$$

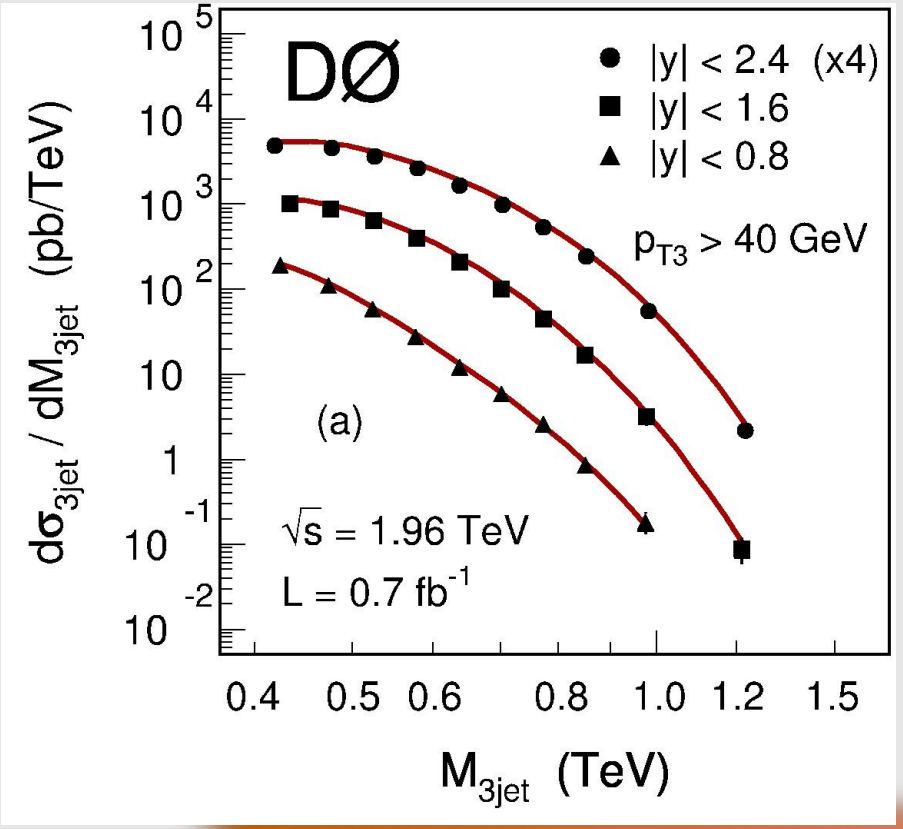
Demonstrated limitations of current PYTHIA tunes in multijet final states



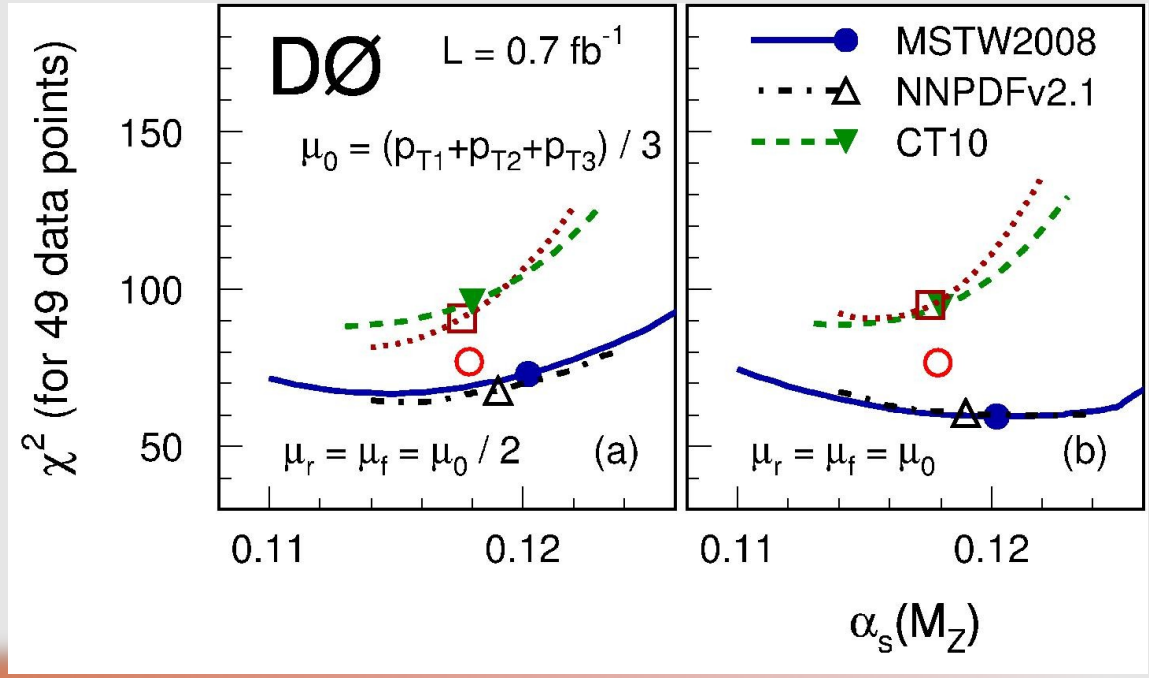
# (2011) Q17: Measurement of Three-Jet Differential Cross Sections dσ3jet/dM3jet

Measure in kinematic regions of |y_jet| and pT_min

Test the three-jet matrix elements in perturbative QCD calculations at NLO in $\alpha_s$

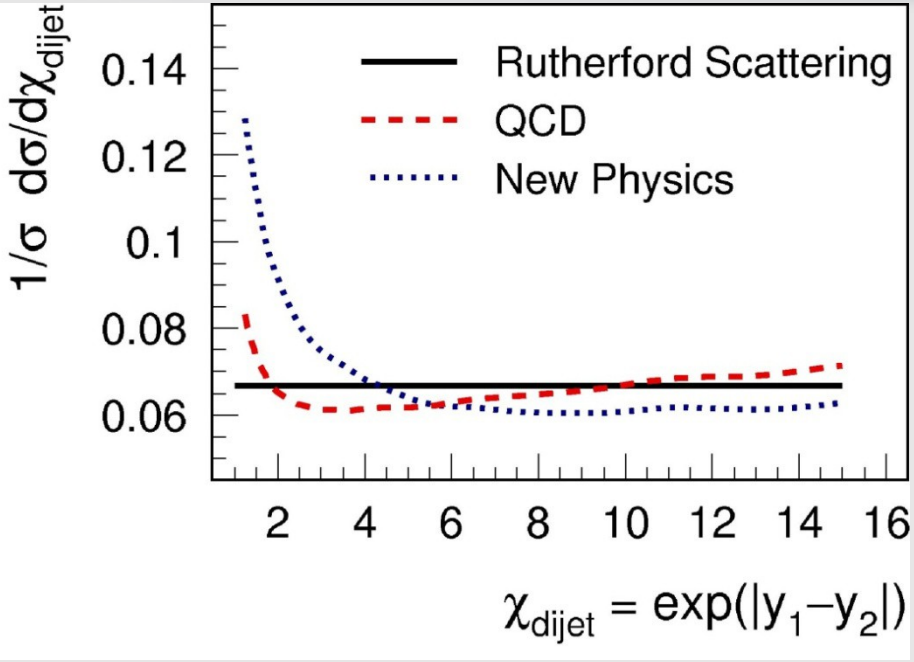



discriminate between PDF parametrization (+input $\alpha_s$)

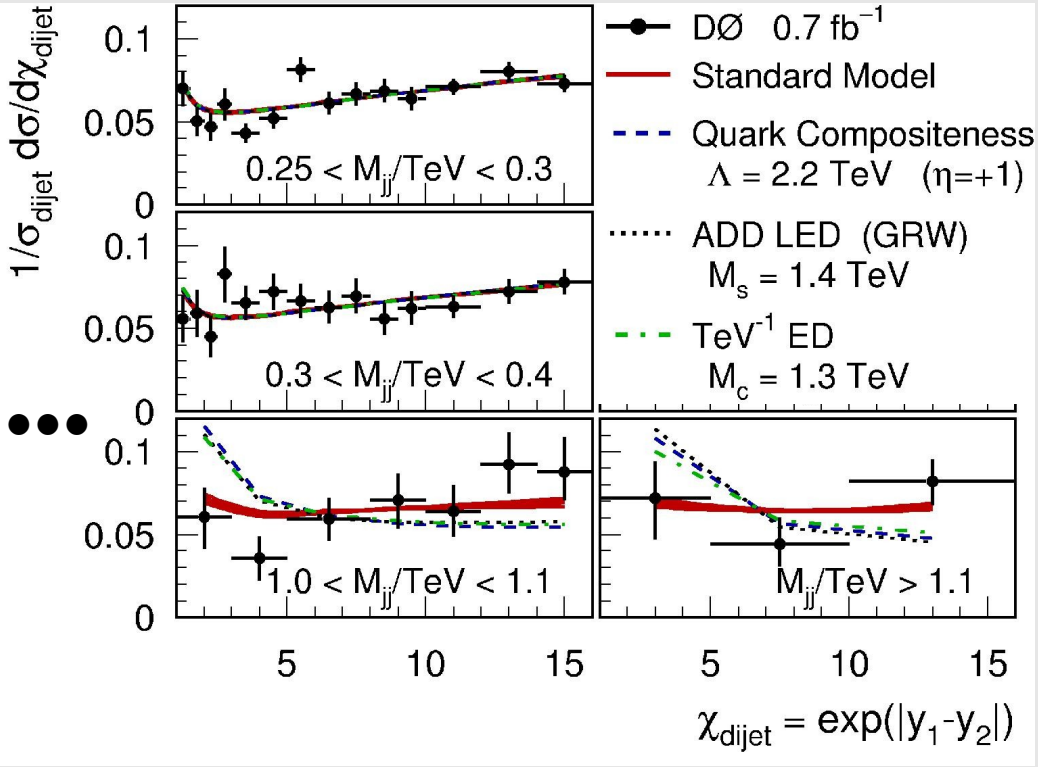


# (2009) Q9: Measurement of Dijet Angular Distributions at √s = 1.96 TeV and Searches for Quark Compositeness and Extra Spatial Dimensions

TOPCITE = 50+




| | composite quarks | $TeV^{-1}$ extra dims. | A.D.D. large extra dims. |
|---|---|---|---|
| | units of TeV | | |
| CDF Exclusions | | | |
| DØ Limits | $\Lambda$ $2.58^{(1)}$ | $M_S$ $1.42^{(2)}$ | $M_c$ $1.56^{(3)}$ |




At the time

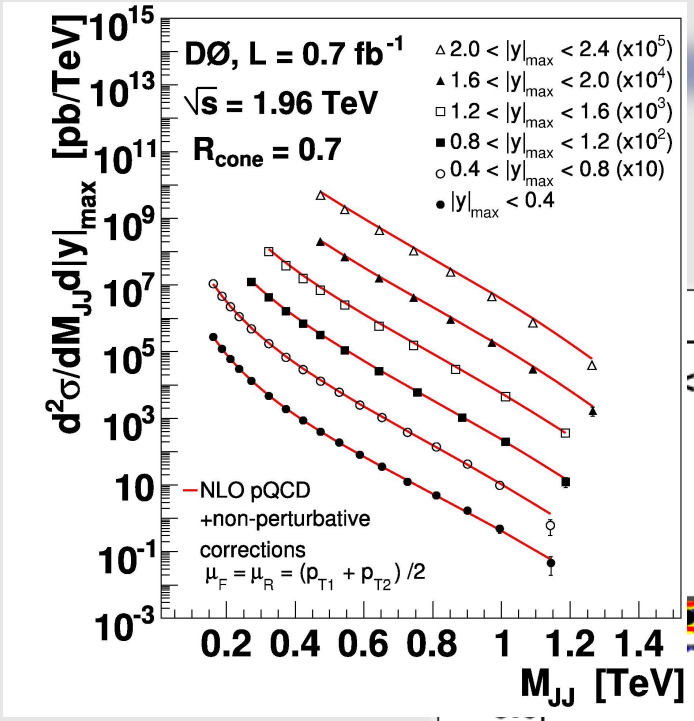
(1) Most stringent limit

(2) Best at hadron collider

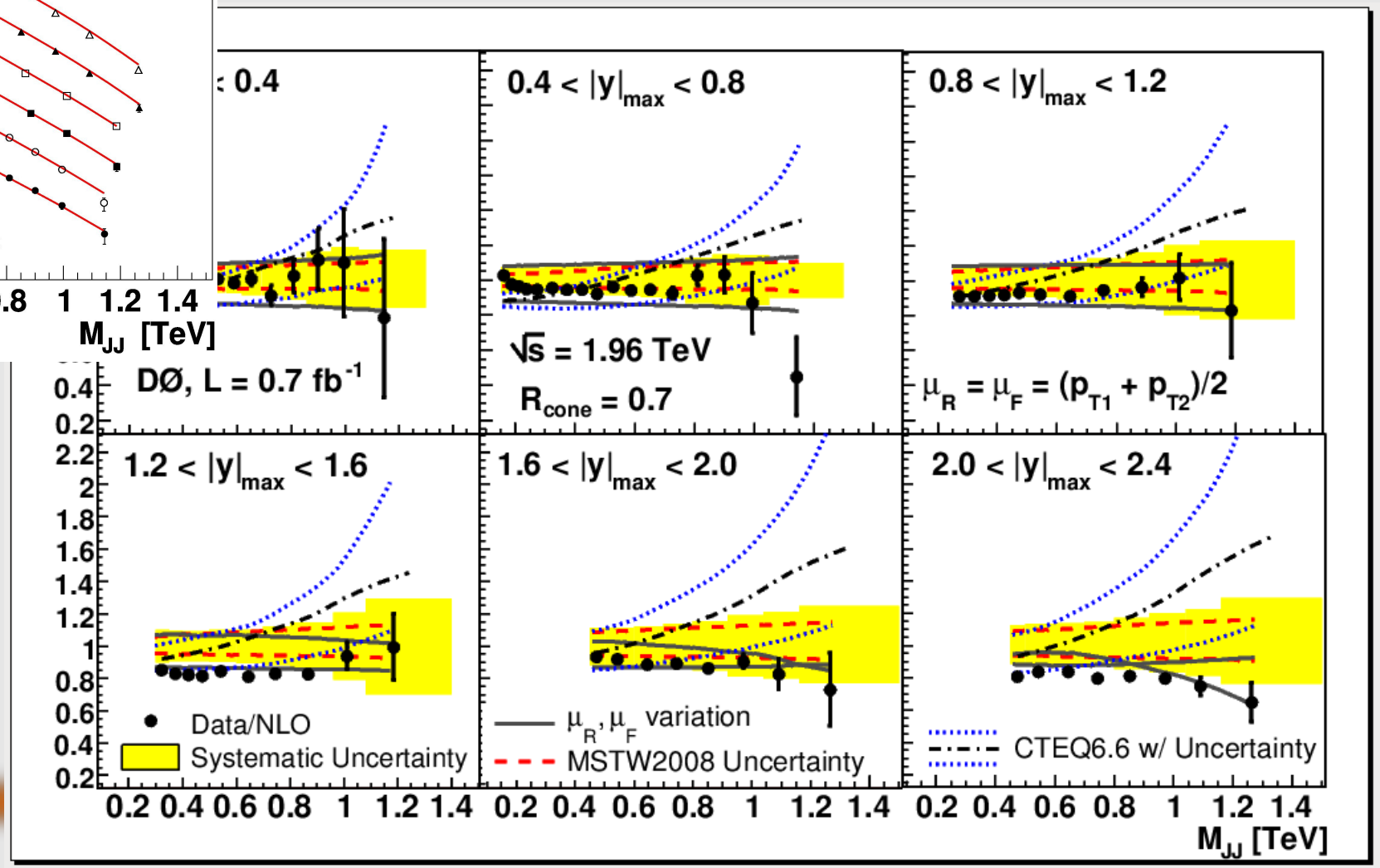
(3) Best limit from single process

First measurement of angular distributions of a scattering process above 1 TeV

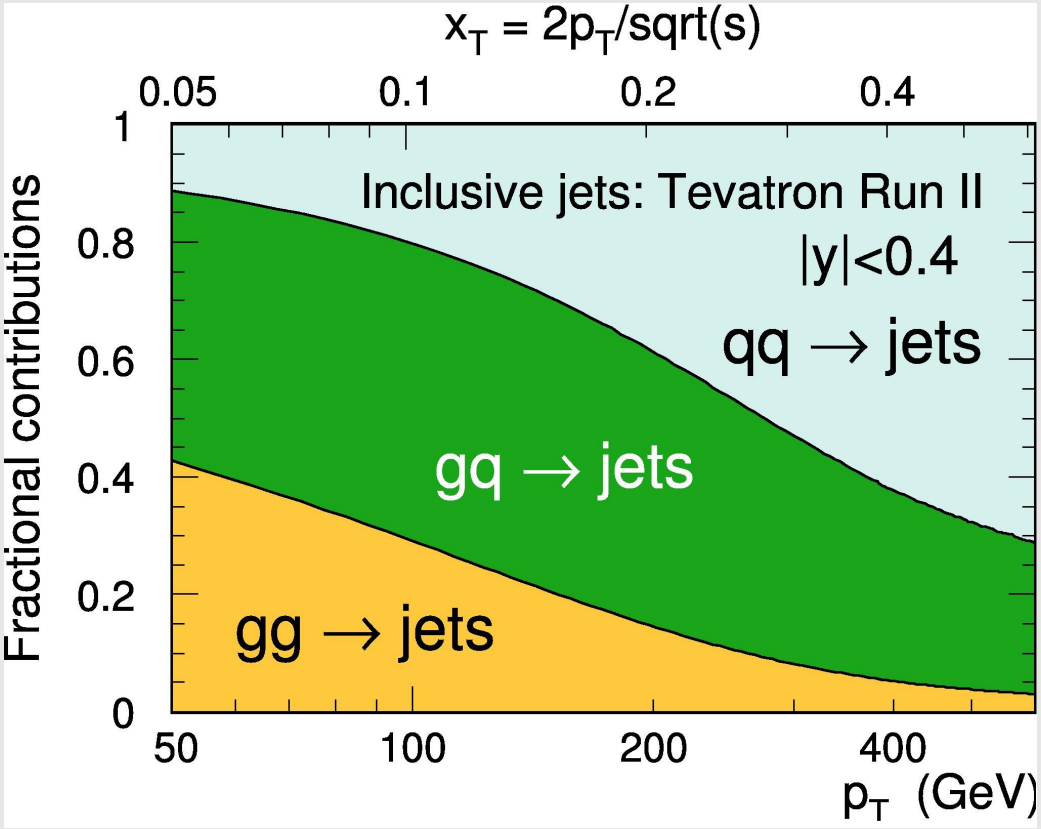
# (2010) Q14: Measurement of the Dijet Invariant Mass Cross Section in pp Collisions at √s = 1.96 TeV

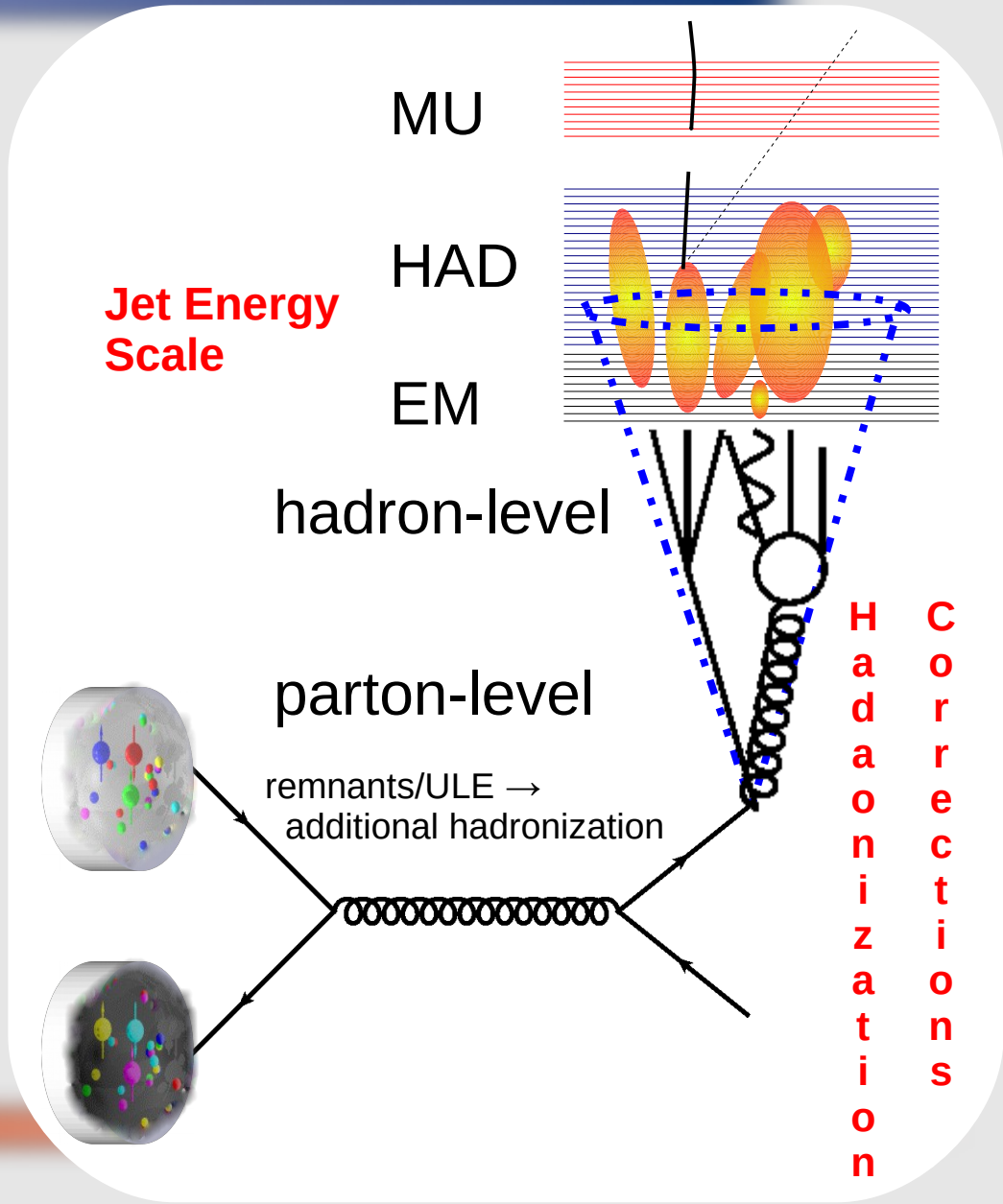



Small experimental uncertainties on par or better than those from PDF/scale => constraints



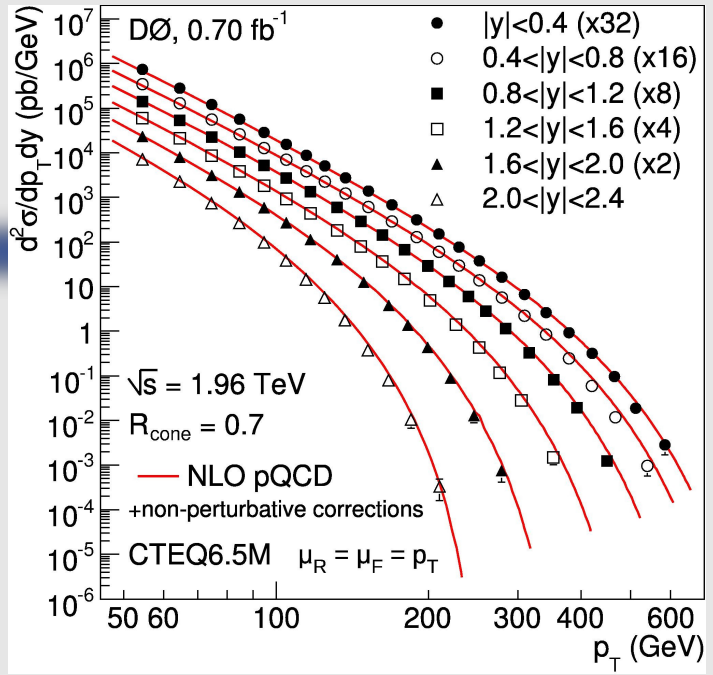
# Inclusive Jets & JES



# Q5, Q20: Measurement of the Inclusive Jet Cross Section

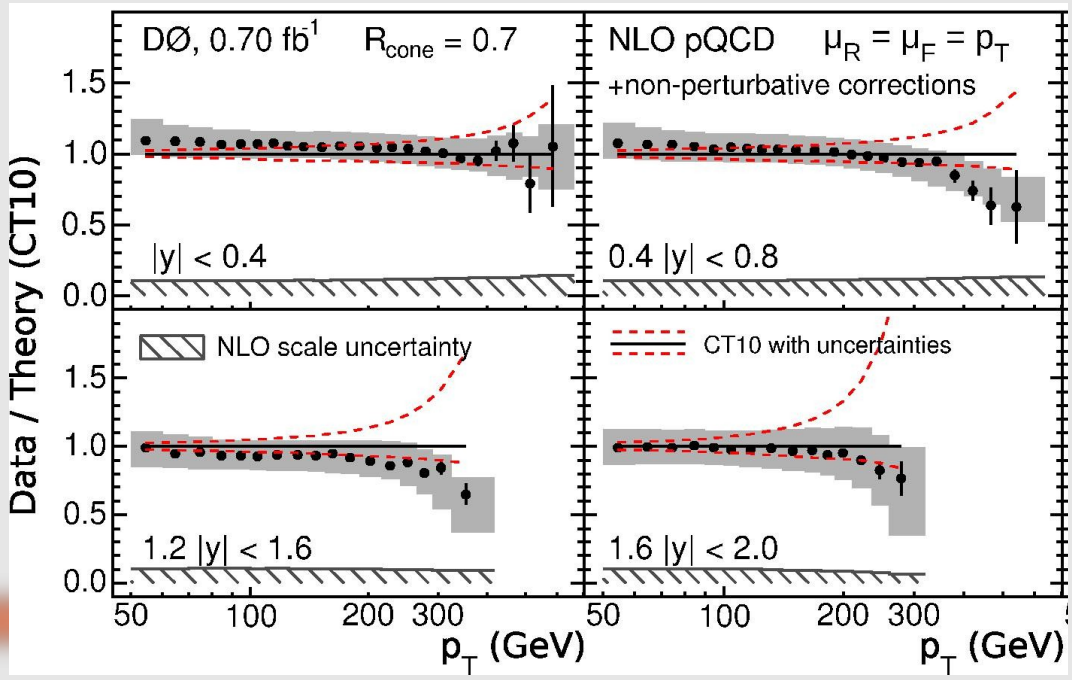
## The jet counting experiment



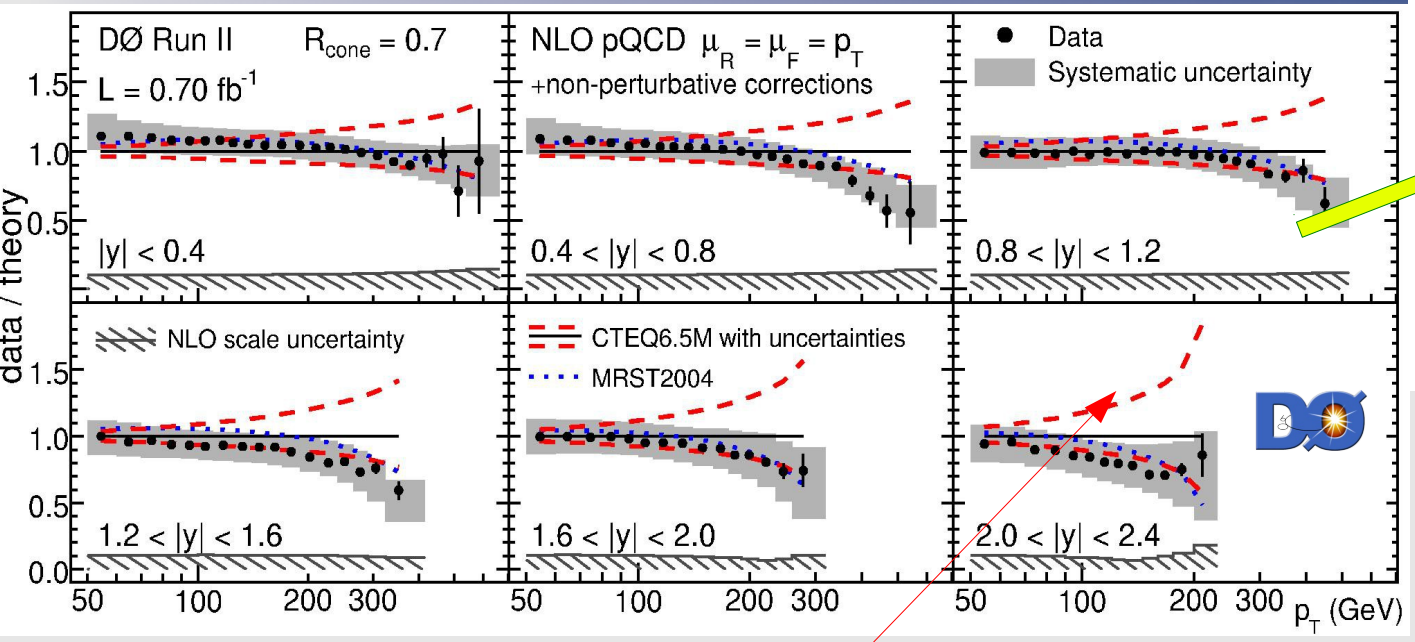

Seemingly basic measurement, but
Herculean effort to control JES systematics

Results:
"measurement precision unprecedented for a hadron collider"
=>
Differentiate & tune PDF models

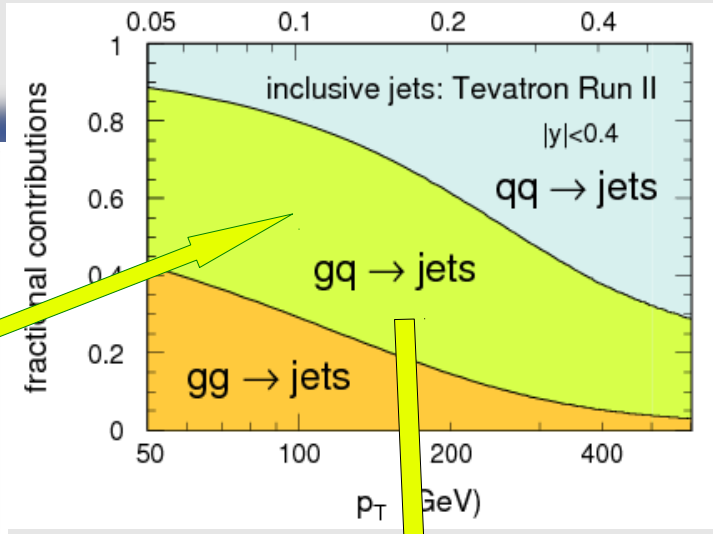
Full correlation analysis for systematics
-> method to reduce complexities of numerous sources
-> increase potential impact data in global PDF fits

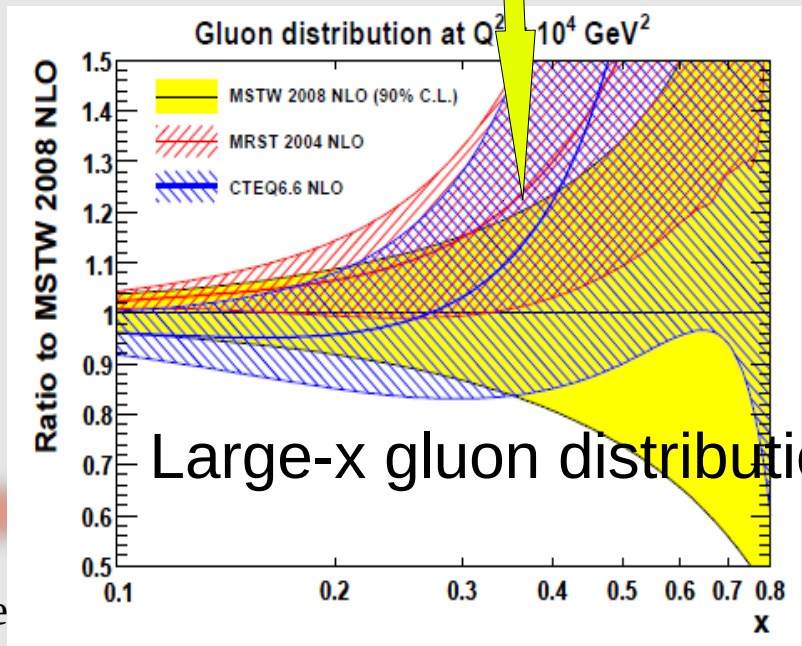


# Constraints on PDFs




PRD75, 092006 (2007), PRL 101, 062001 (2008), PRD85, 052006 (2012)




Experimental uncertainties at high pT are lower than theoretical (largely PDF ones):
=> constrain PDF models

Large-x gluon distributi

# Jet energy calibration

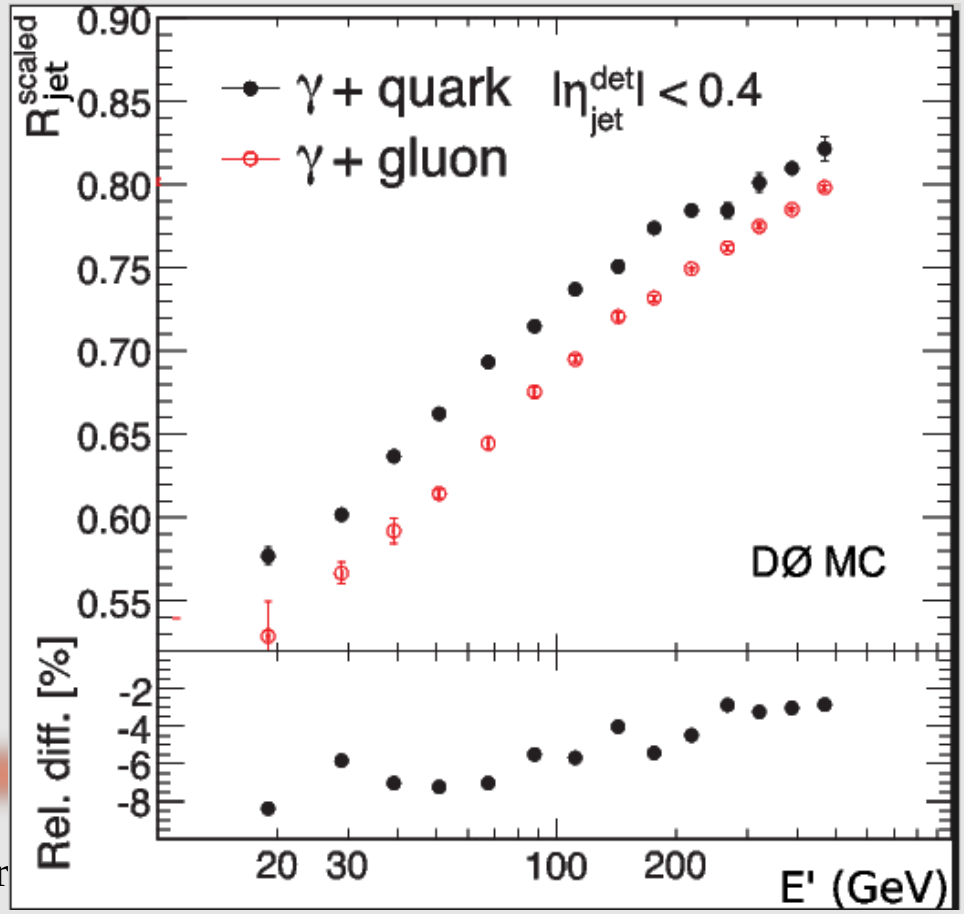
$$E_{\rm jet}^{\rm ptcl} = \frac{E_{\rm jet}^{\rm meas} - O}{F_\eta \cdot R \cdot S} \cdot k_{bias}$$

Multistage correction
- large data sets to map out detector features
- finely tuned MC to extrapolate measurements
- careful determination of physics and instrumental biases

Example: flavor dependence in jet response.

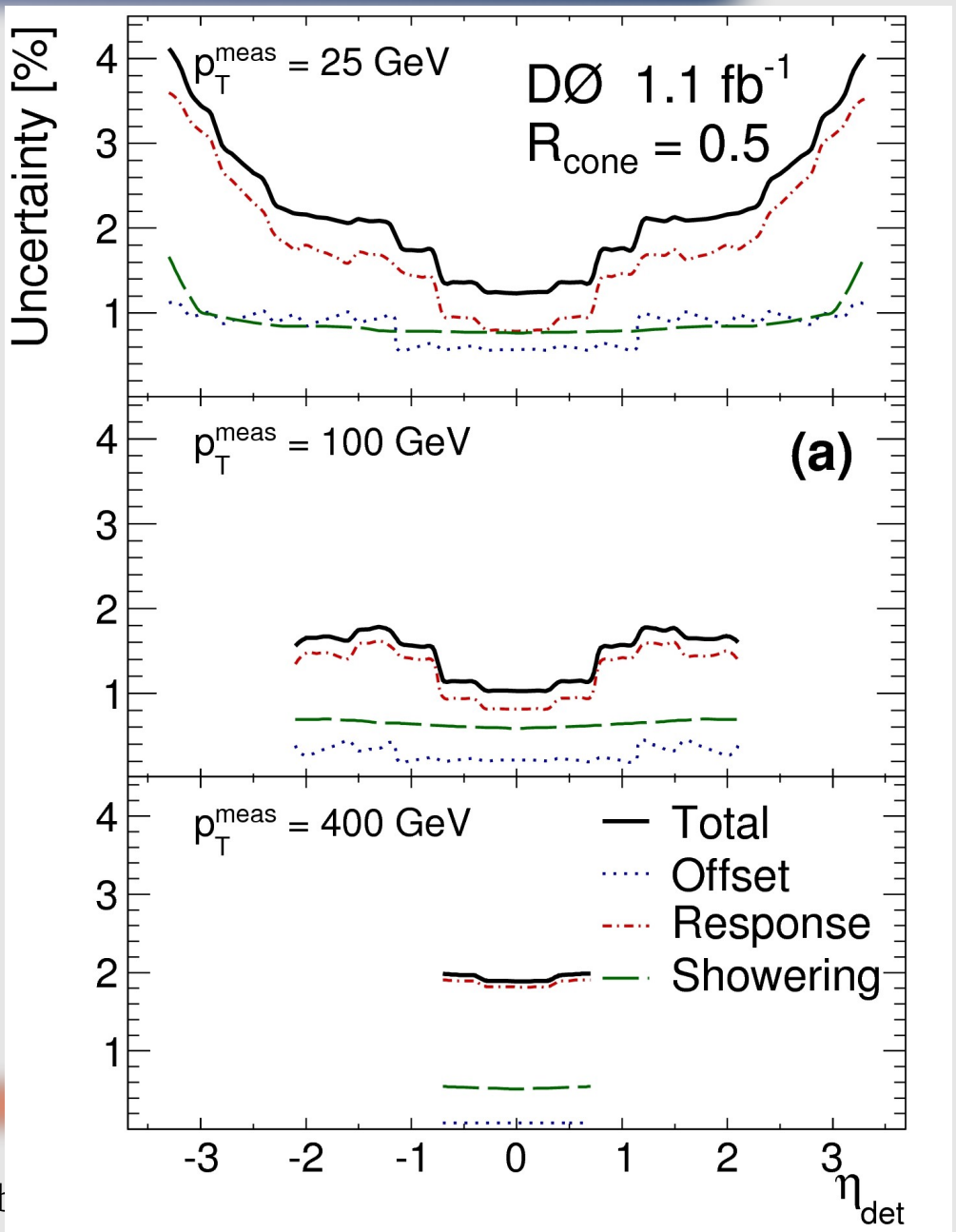
Large effect may have unexpected consequences if not carefully considered (at least on average)

We've learned a lot over the past decade -> precision, avoiding biases/bumps (Run 1 and Run 2...)



# Jet energy calibration

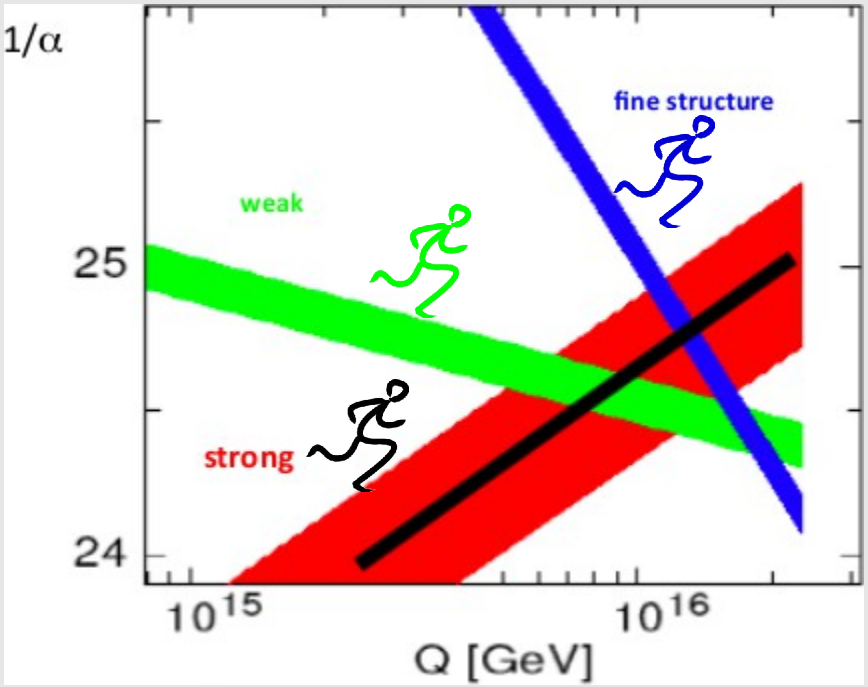
"Precision QCD" may have been an oxymoron at start of Run1, but it is the STANDARD today

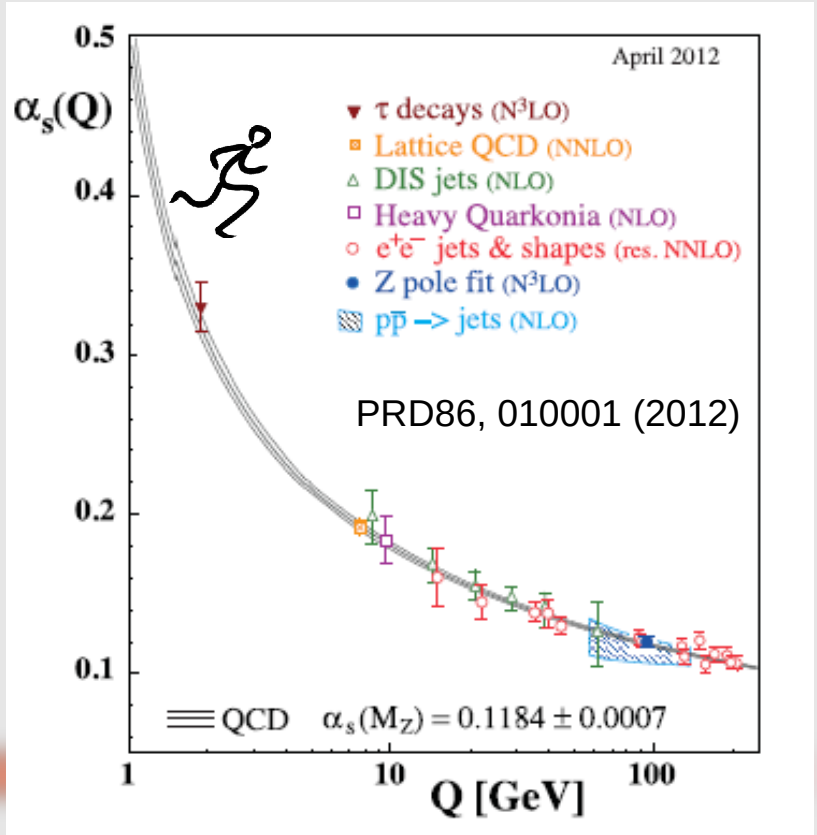


# Alpha Strong

- least known of the couplings ($\triangle\alpha_s$ (WA) = 0.6%)
- translates into uncertainty on PDFs and hadronic cross sections
- has influence on GUT

Renormalization Group Equation relates $\alpha_s$ values at different scales (Q)



# (2009) Q11: Determination of the Strong Coupling Constant from the Inclusive Jet Cross Section

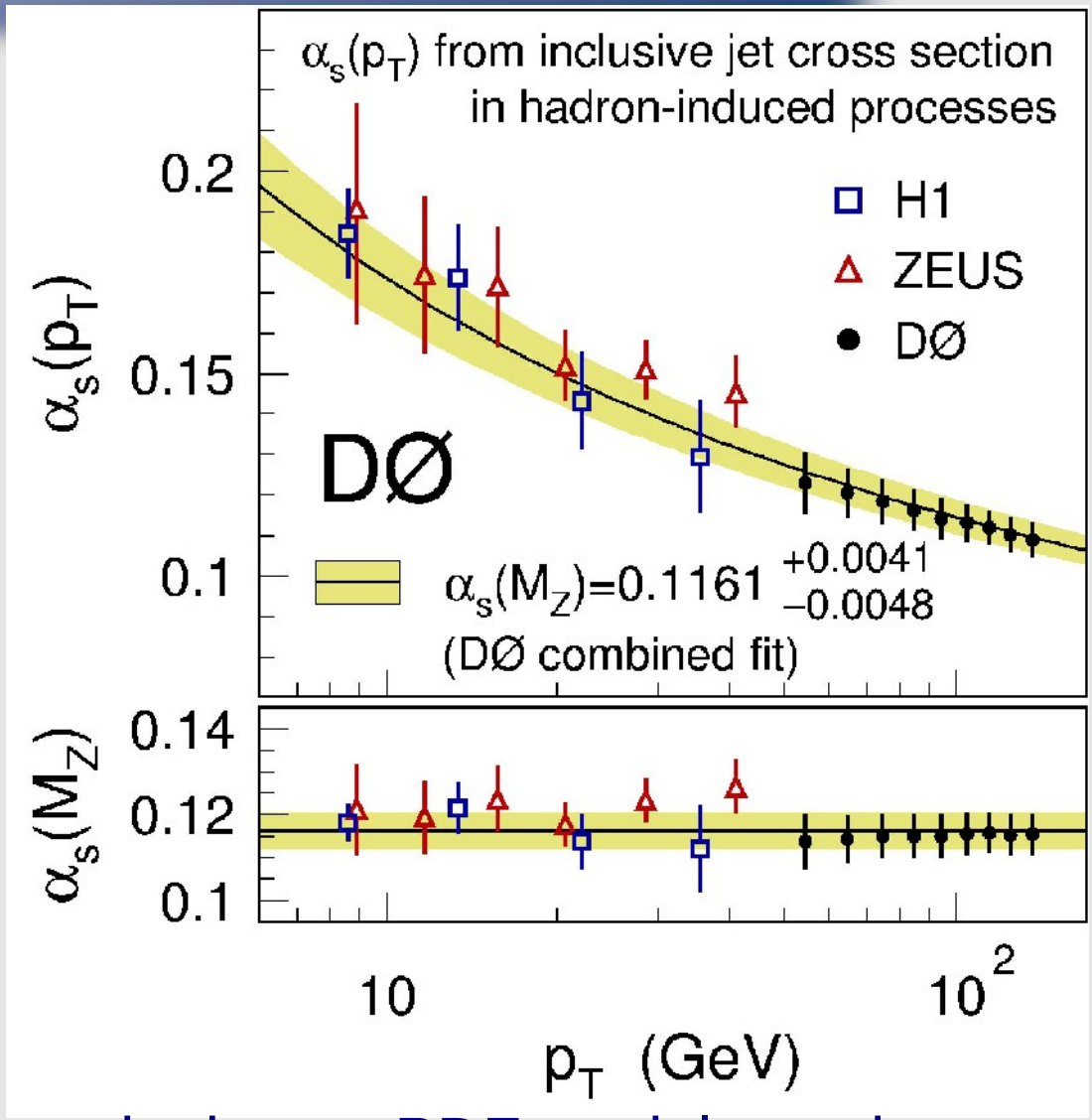
TOPCITE = 50+

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

- NLO MEs for 5 flavors, + 2-loop threshold corrections (reducing renormalization/ factorization scale dependence)
- MSTW2008 NNLO PDFs

At its release:

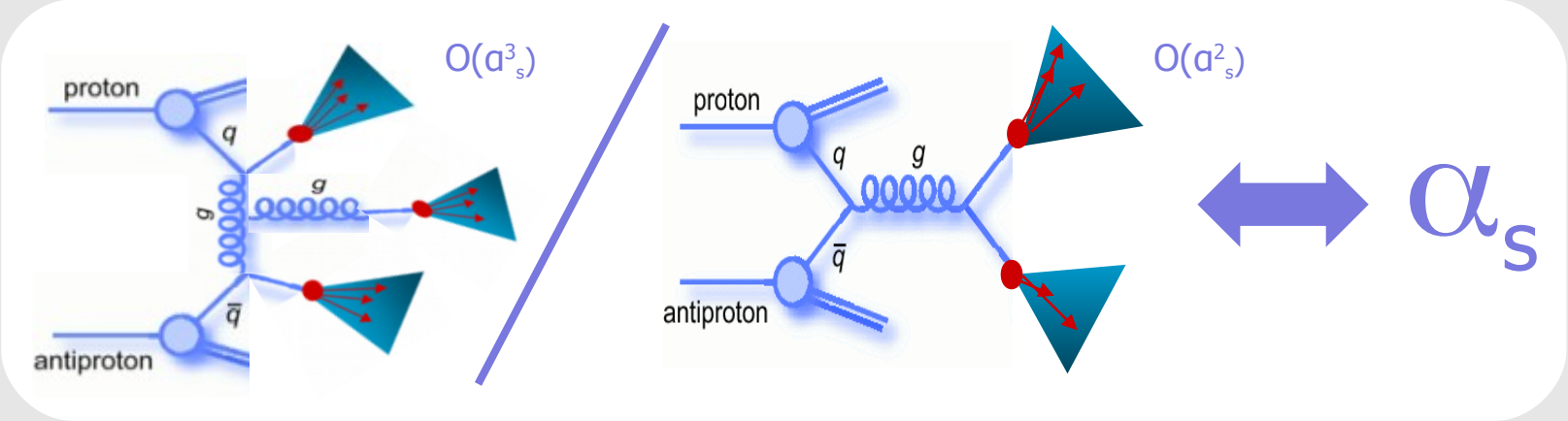
- **Highest $P_T$ measurements of running $\alpha_s$ to date**
- **most precise determination of the $\alpha_s$ from a hadron collider, comparable to ep→jets**




Possible due to improvements in theory, PDF models, and unprecedented quality of measurements

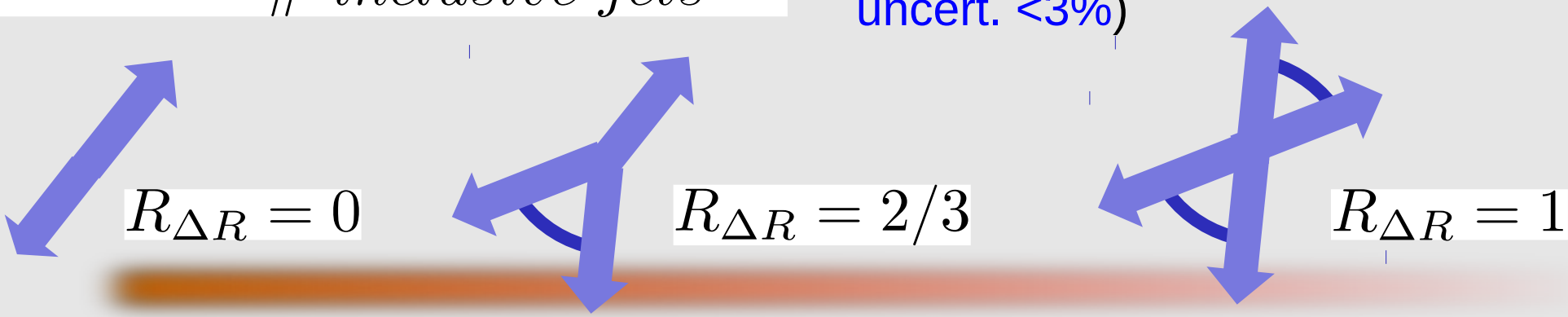
# (2012) Q23: Measurement of angular correlations of jets at √s=1.96 TeV and determination of $\alpha_s$ at high momentum transfers

Average number of neighboring jets above some $p_T$ threshold within a given ΔR interval




$$R_{\Delta R} = \frac{\#\ of\ neighboring\ jets}{\#\ inclusive\ jets}$$

Benefits: systematic uncertainties mostly cancel out in the ratio (PDF uncert. <3%)



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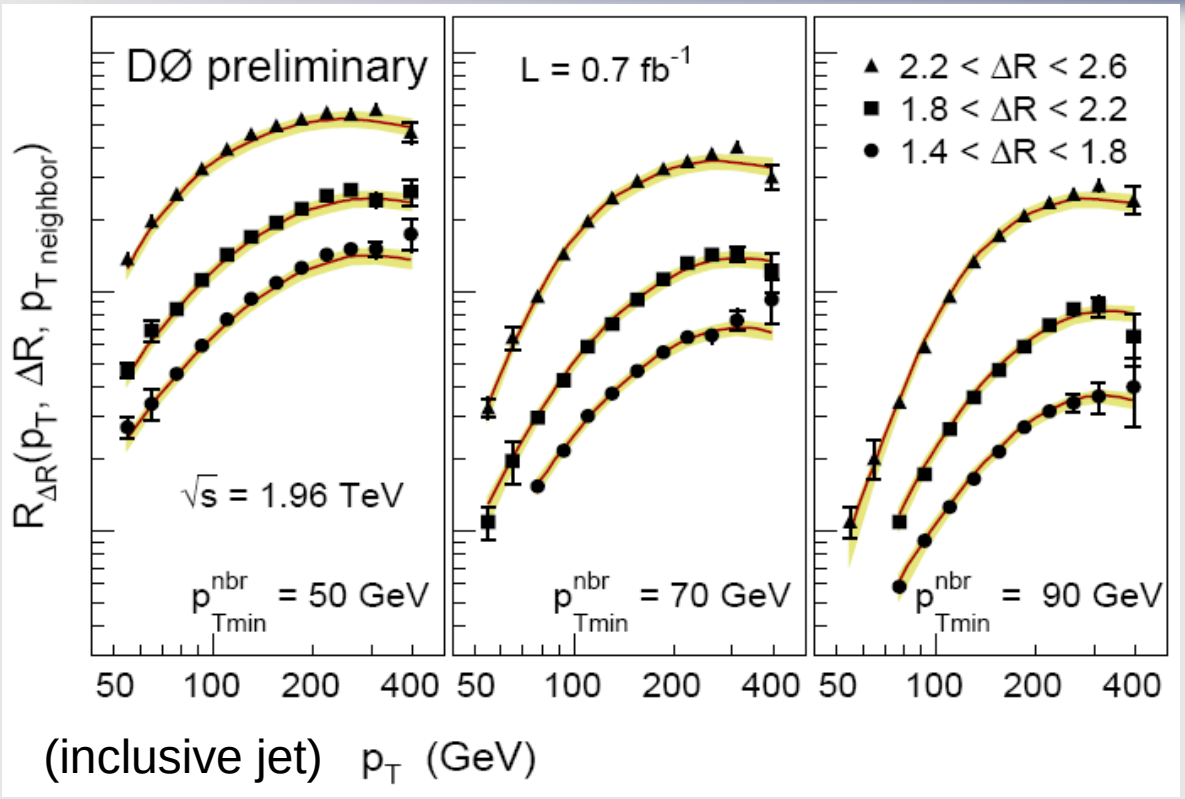
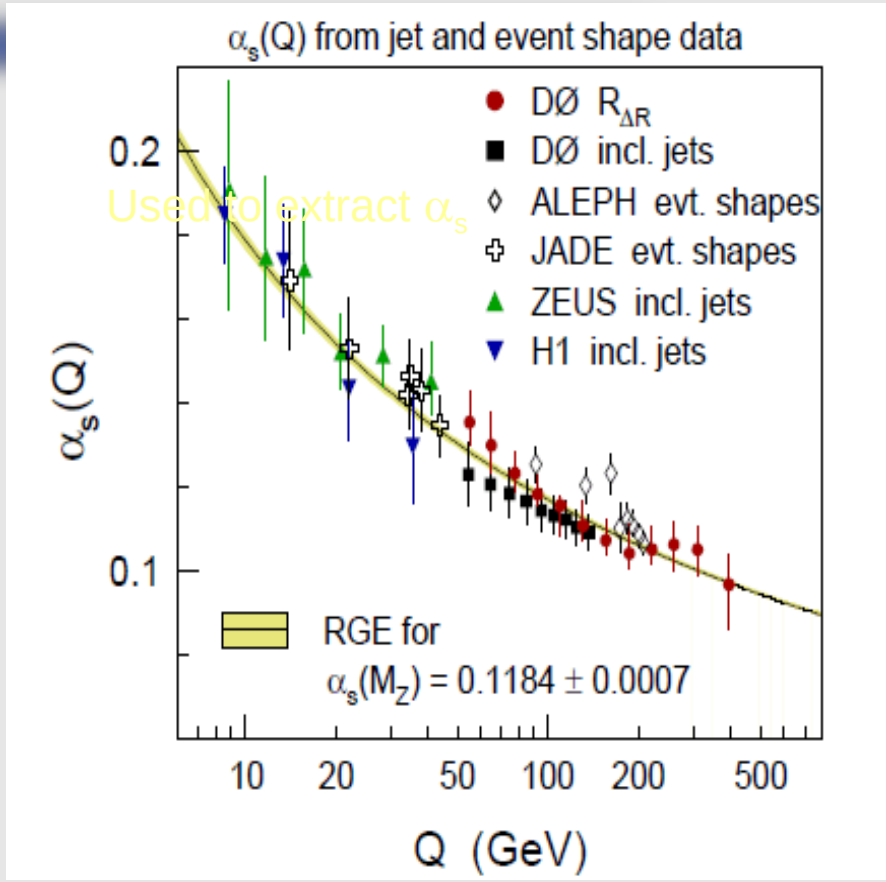


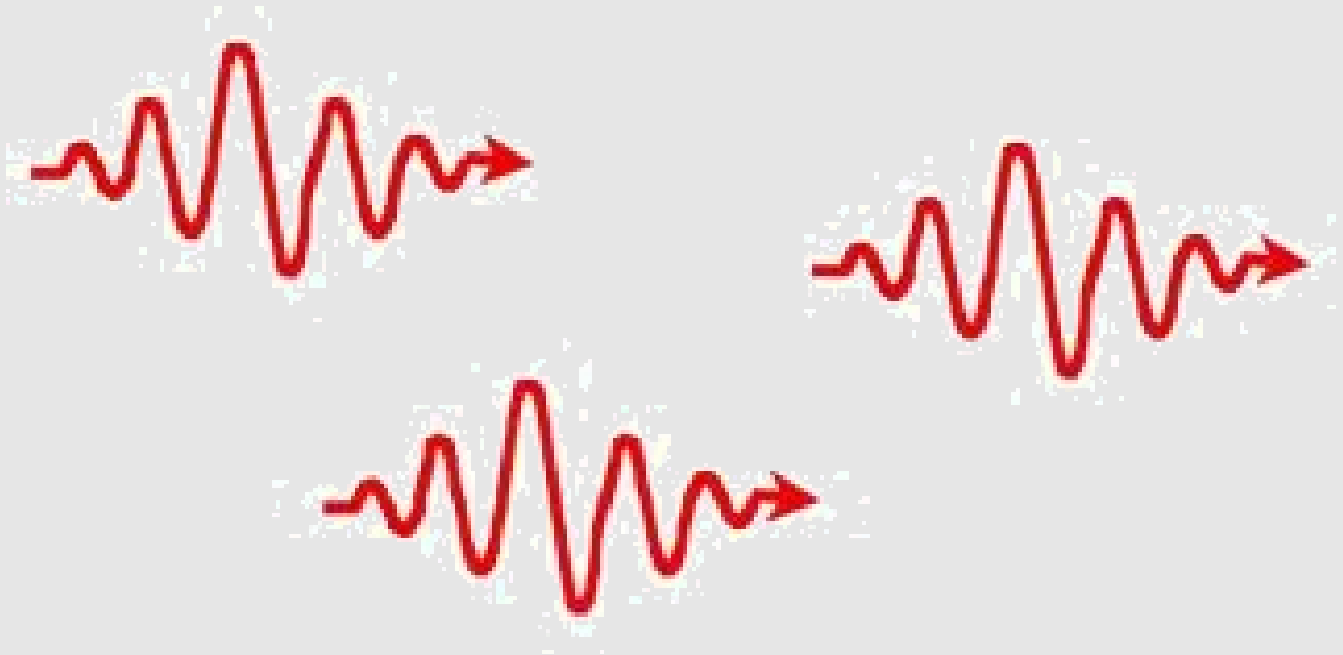

Using $R_{\Delta R}$ and NLO+MSTW2008NNLO PDFs

$$\alpha_s(M_z) = 0.1191^{+0.0048}_{-0.0071}$$

→ **$\alpha_s(p_T)$ results up to 400 GeV!**

→ $\alpha_s(p_T)$ decreases with $p_T$ as predicted by the RGE

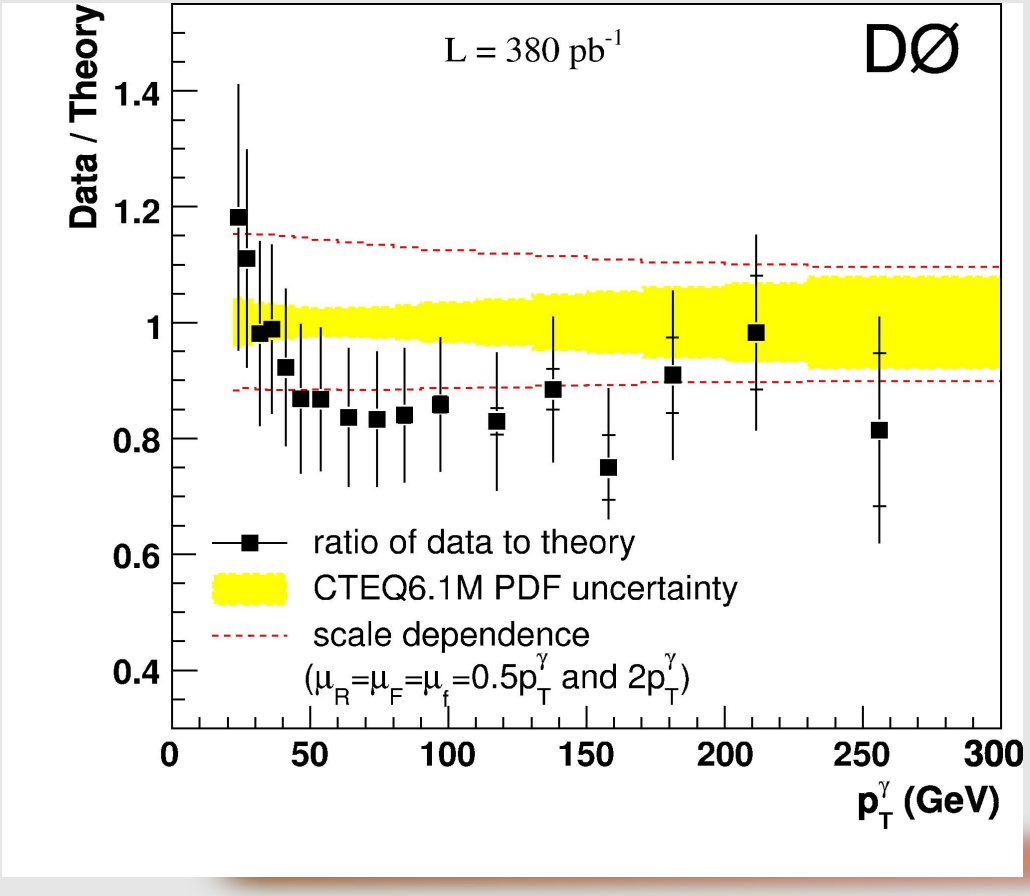
# Photons

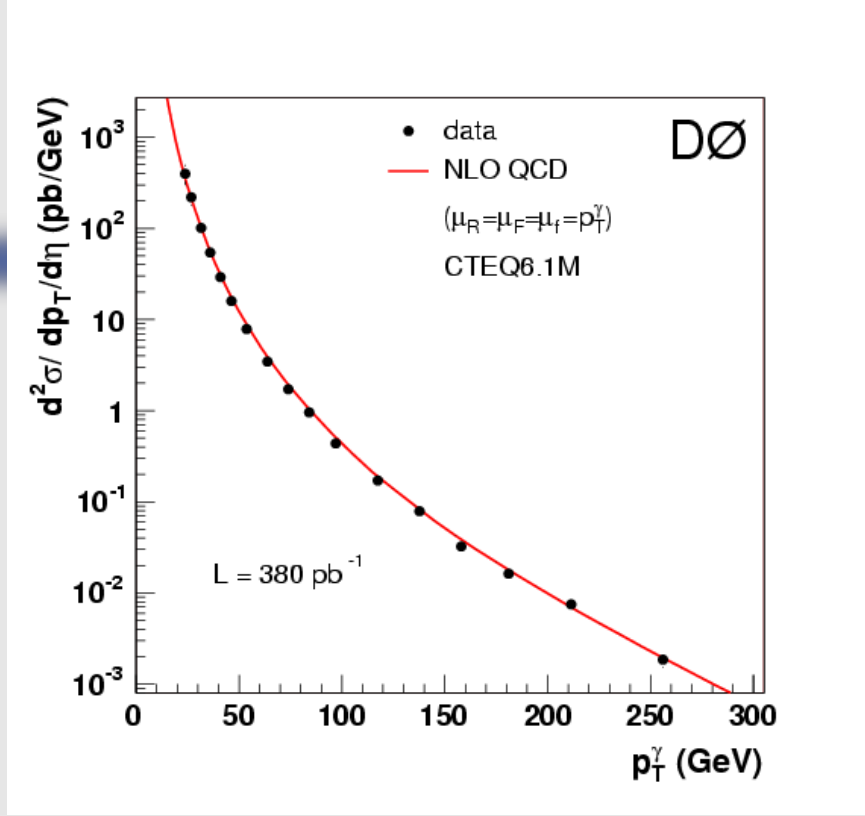


# Q2: Measurement of the Isolated Photon Cross Section

Early paper:

- extended Run 1 measures
- reasonable agreement w/ NLO



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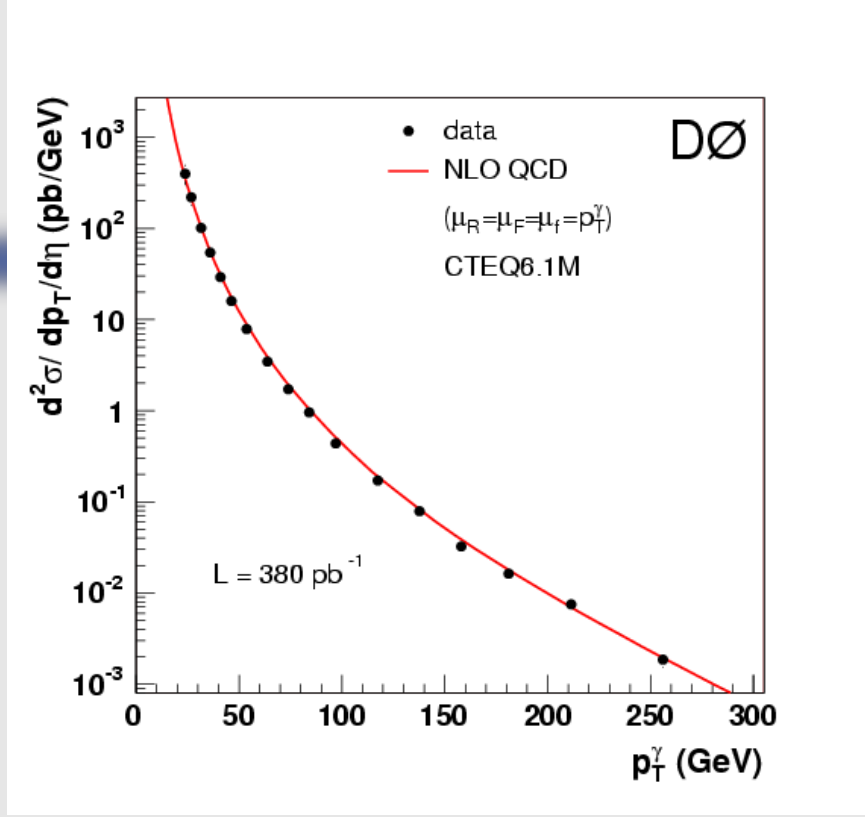
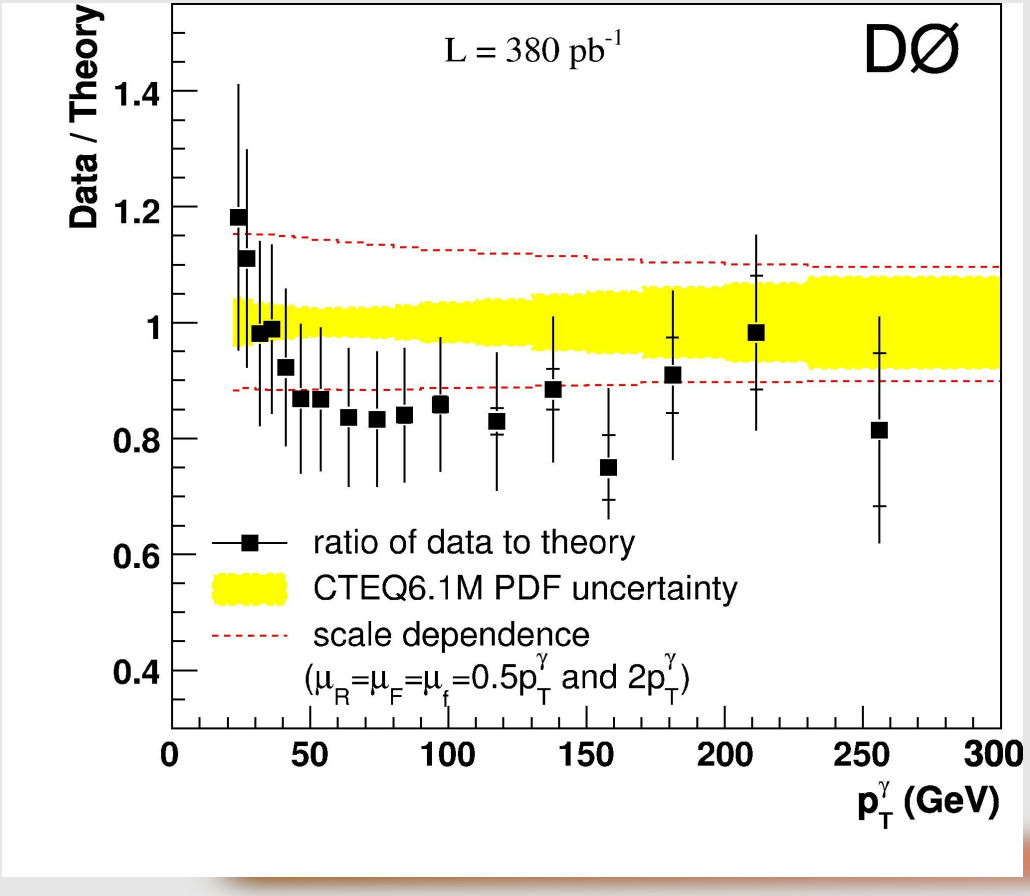


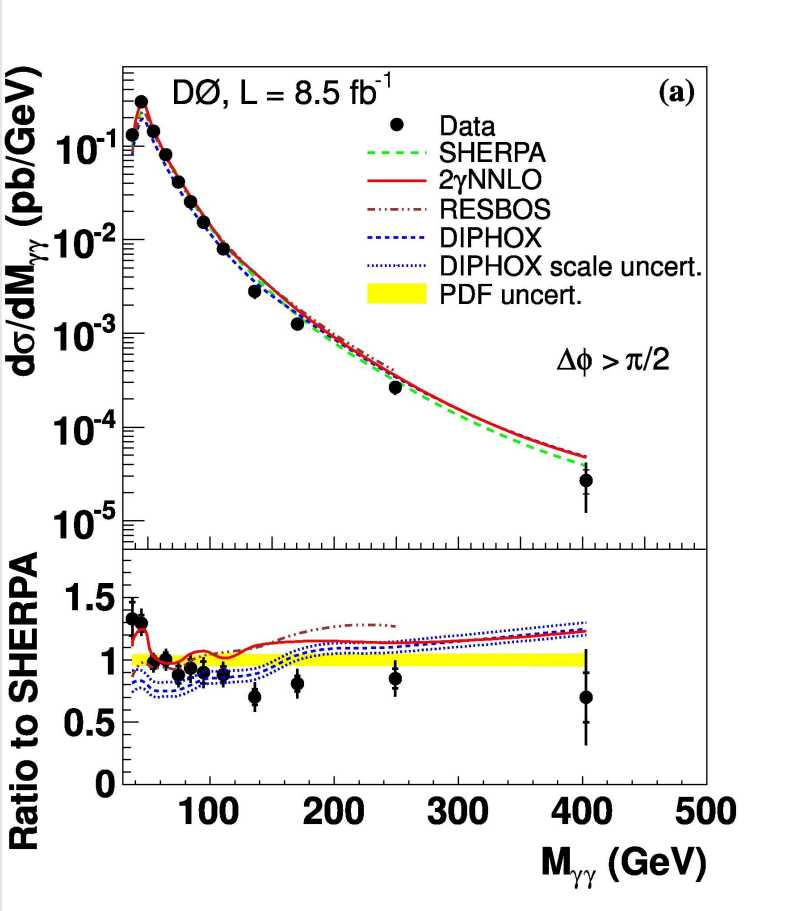


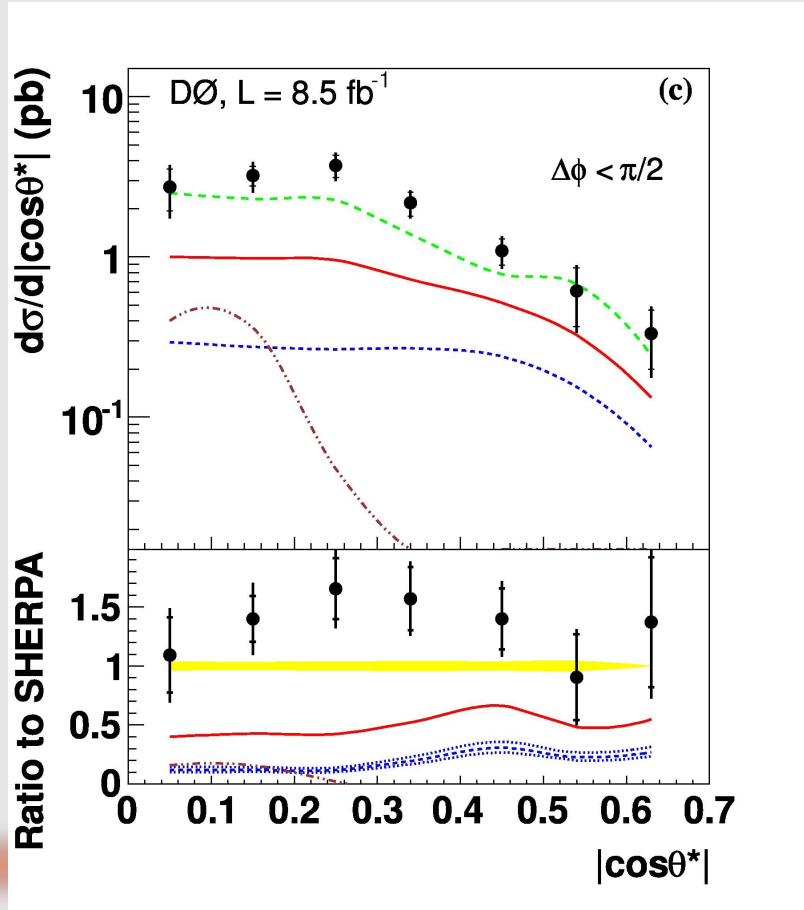
380 pb$^{-1}$ ?

# Q13,29: Measurement of direct photon pair production

## Detailed comparisons of distros. w/ numerous NLO, MC, resummed models

=> no model found to describe results in all kinematic regions
=> points to requirement for future tuning, corrections



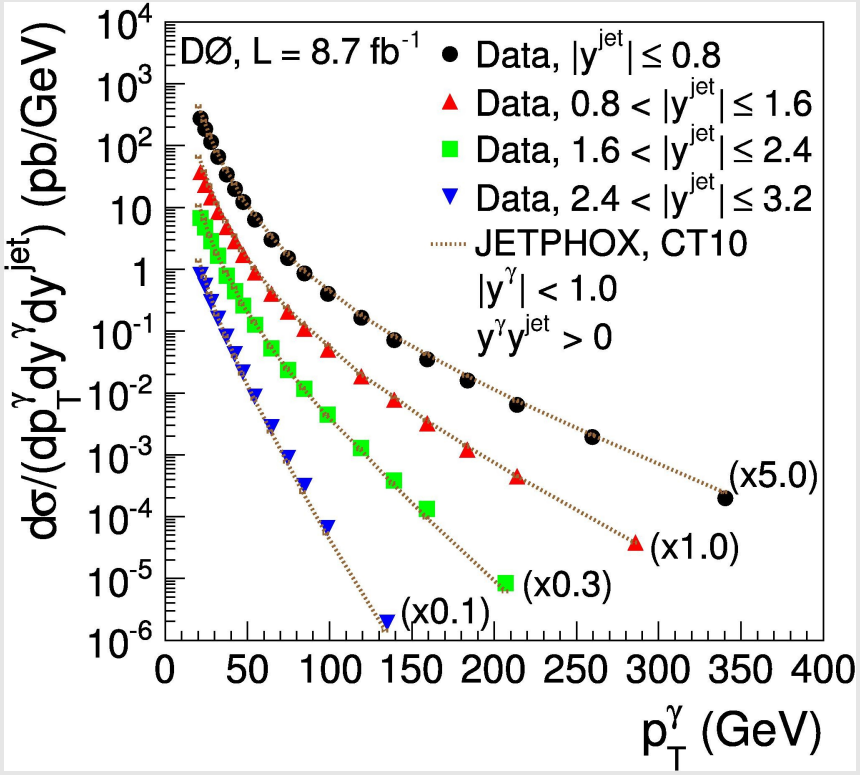
# γ/Z/W+jets (heavy flavor)

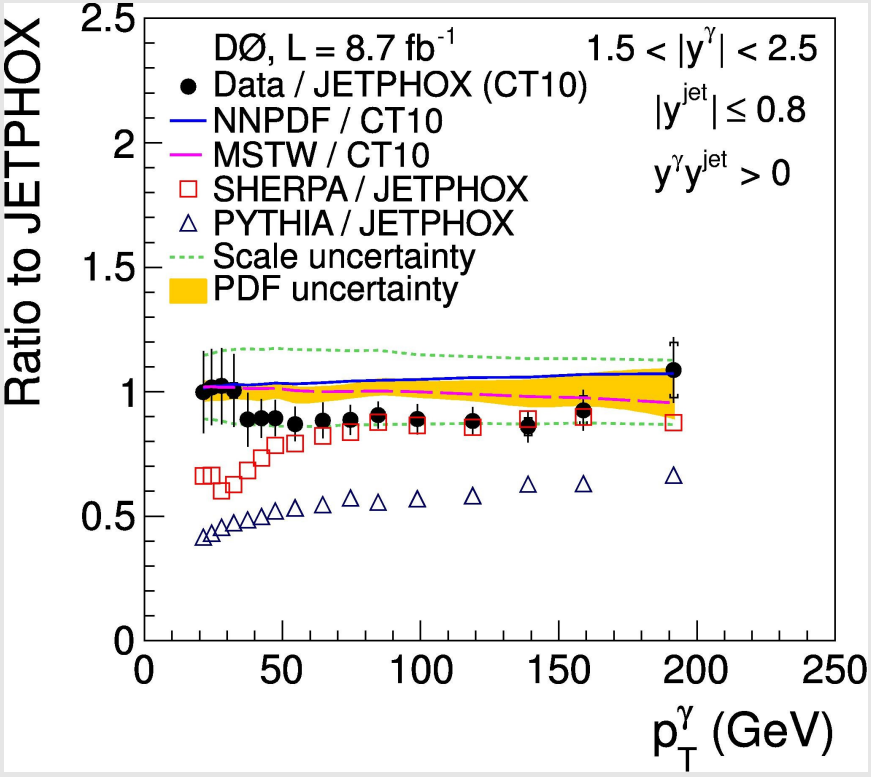
Many first measurements!

# Q4,30: Photon + jet Differential Cross Section TOPCITE = 50+

## Detailed comparison to NLO/MC in many kinematic regions

Find generally good description by NLO, but isolate kinematic regions w/ modeling inaccuracies

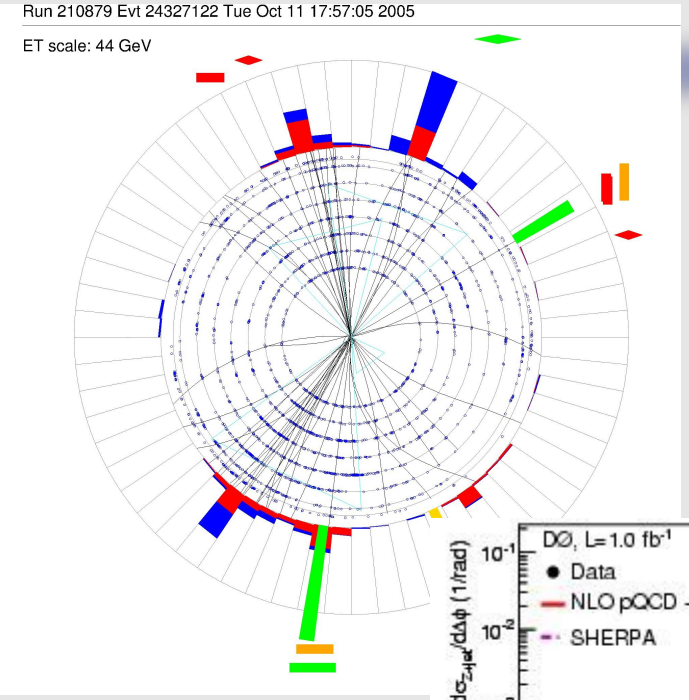


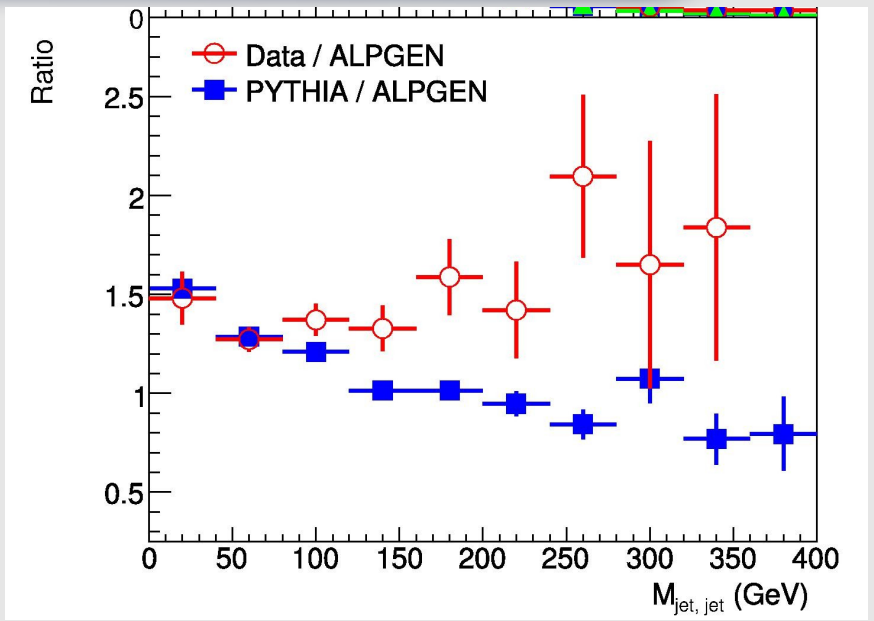

The same can be said for the next few analyses....

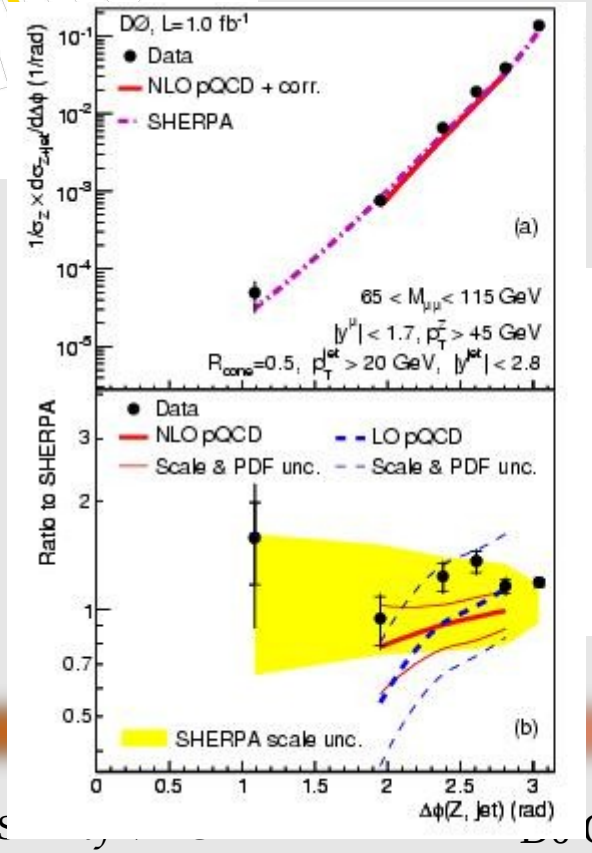
# ('08/9)Q6,8,10: Measurement of Differential Z/γ* + jet + X Cross Sections TOPCITE = 50+

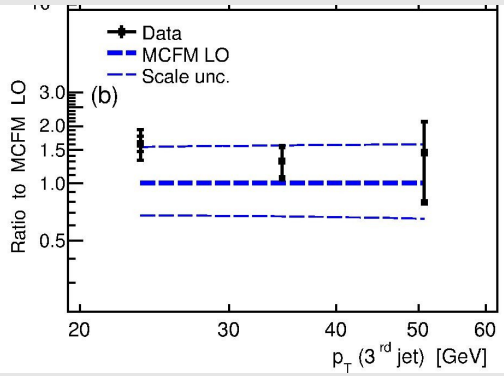
(1st unfolded measures of Z+jets!)

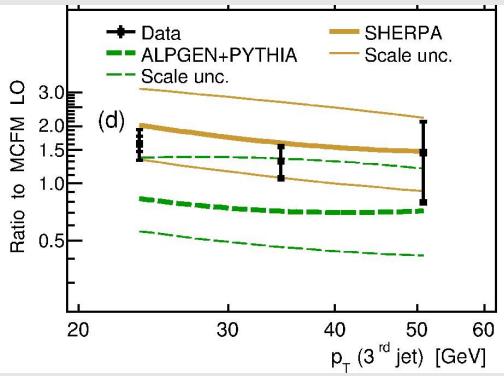



Z+4jet event

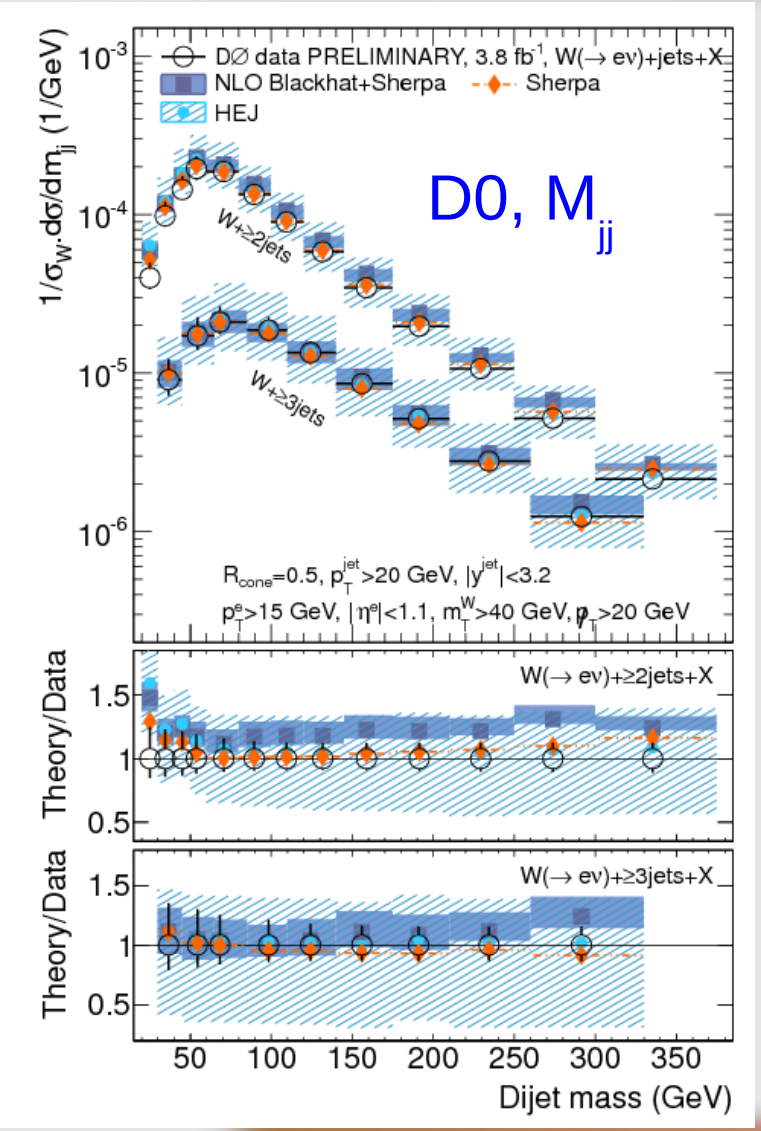


# ('11/13)Q18,31: Studies of W boson plus jets production



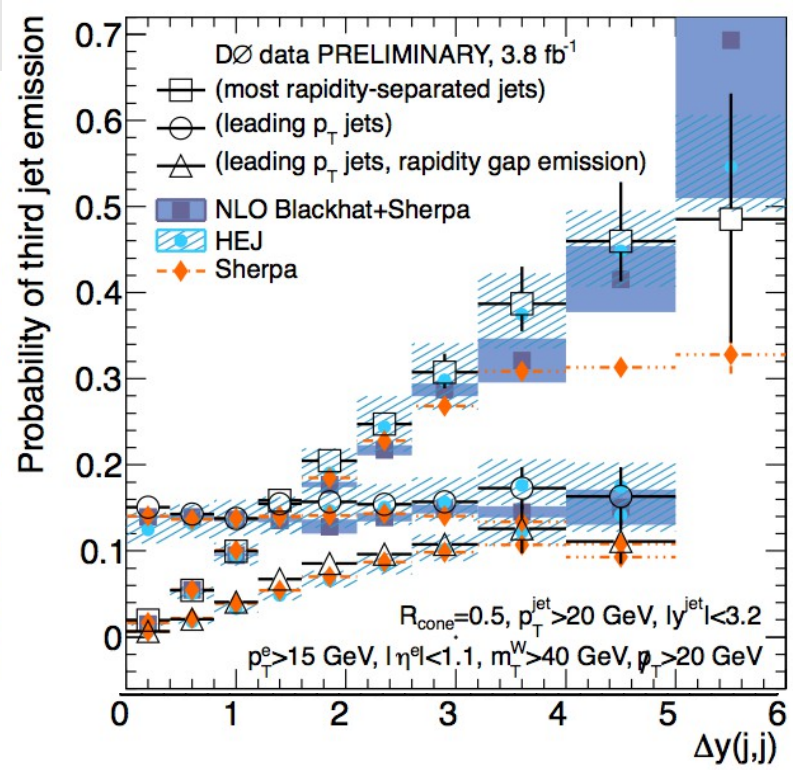

**Dominant background to ttbar production, Higgs boson, many non-SM processes**

jet $p_T$, $H_T$, #jets, jet angular, masses, 3rd jet emission prob, etc.

Good agreement with NLO (Blackhat+Sherpa, HEJ) for most of phase space

(Blackhat: some tension for W+2jet in $M_{jj,}$ and high $H_T$)

# jet emission




Examine probability of third jet emission in inclusive W+dijet events, as a function of dijet rapidity separation(s).

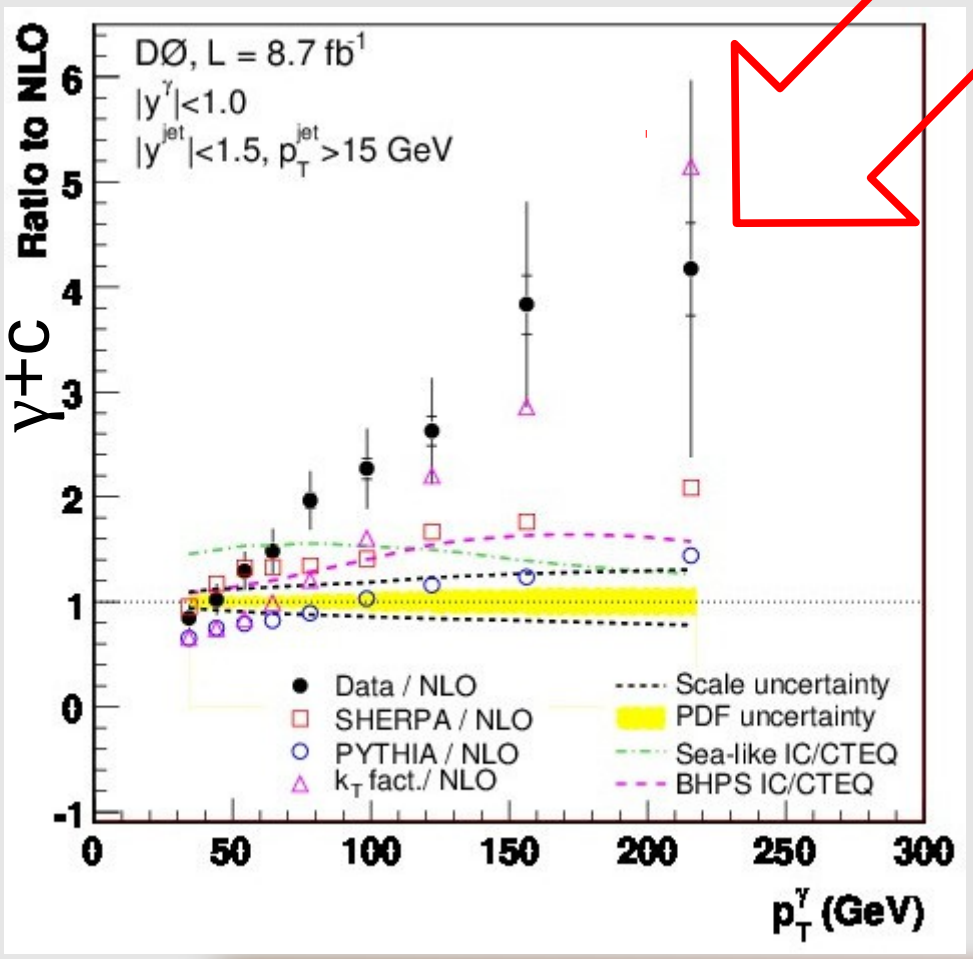
1) $\Delta y$ (leading jets)
2) $\Delta y$ (leading jets w/ emission in rapidity gap)
3) $\Delta y$, (most forward/backward jets)

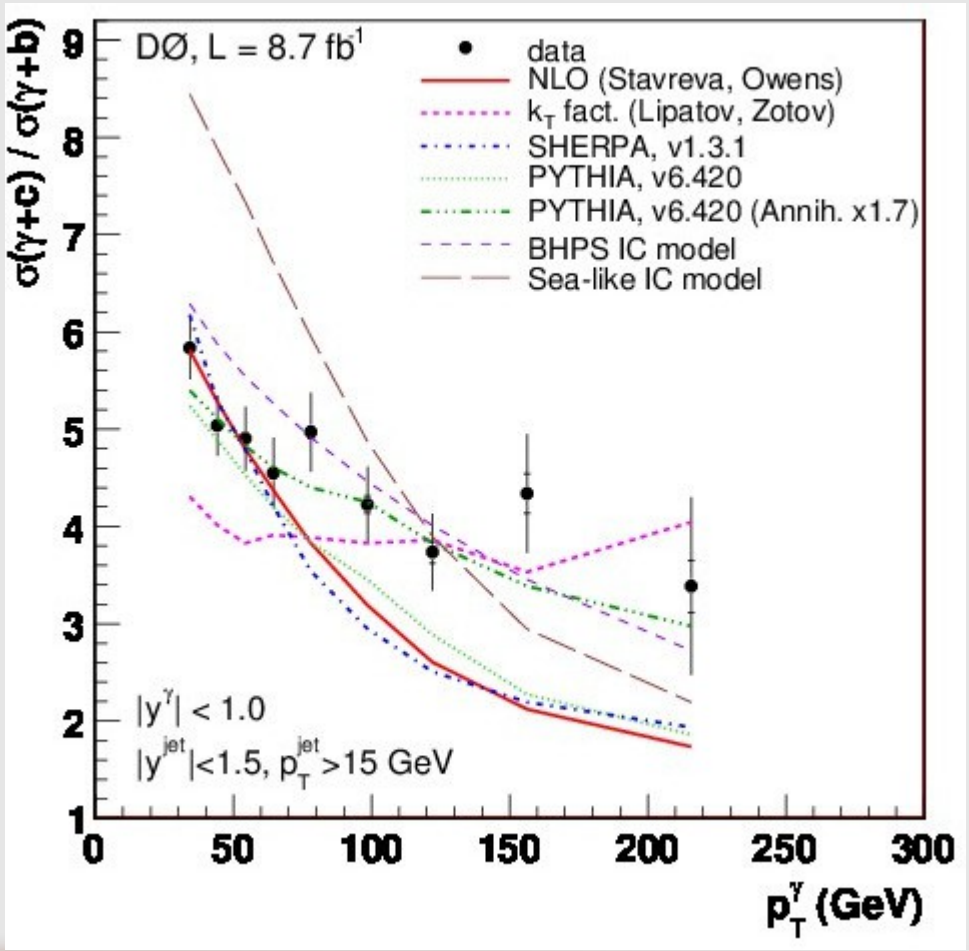
Notable differences in jet emission into the rapidity gap for $p_T$ and rapidity ordered jets

First results of their kind for V+jet precesses => unique inputs for event generator models (also >40 other distributions under study!)

Data can be reinterpreted as a measure of the gap fraction (with a jet veto scale of 20 GeV), relevant for processes like Vector Boson Fusion

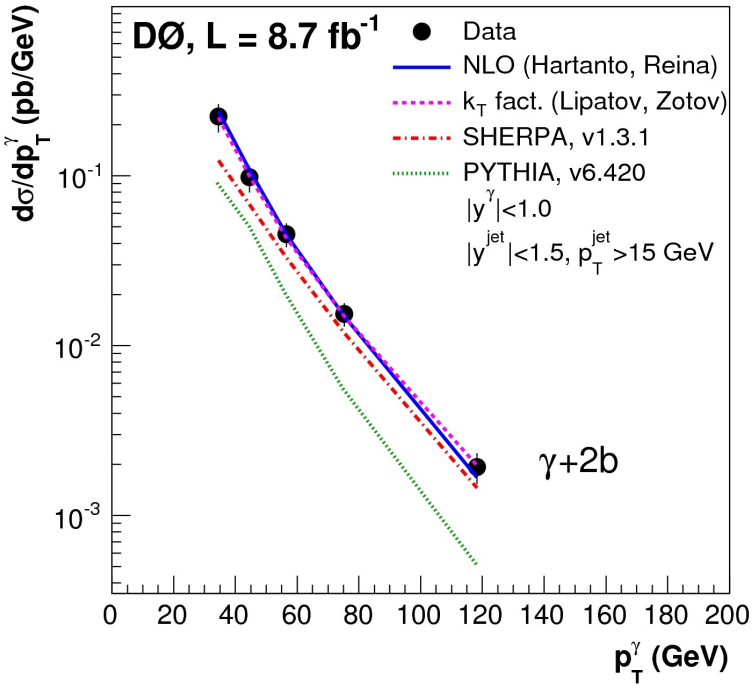
# (2009,12) Q7,21, 25: Measurements of γ+b and γ+c

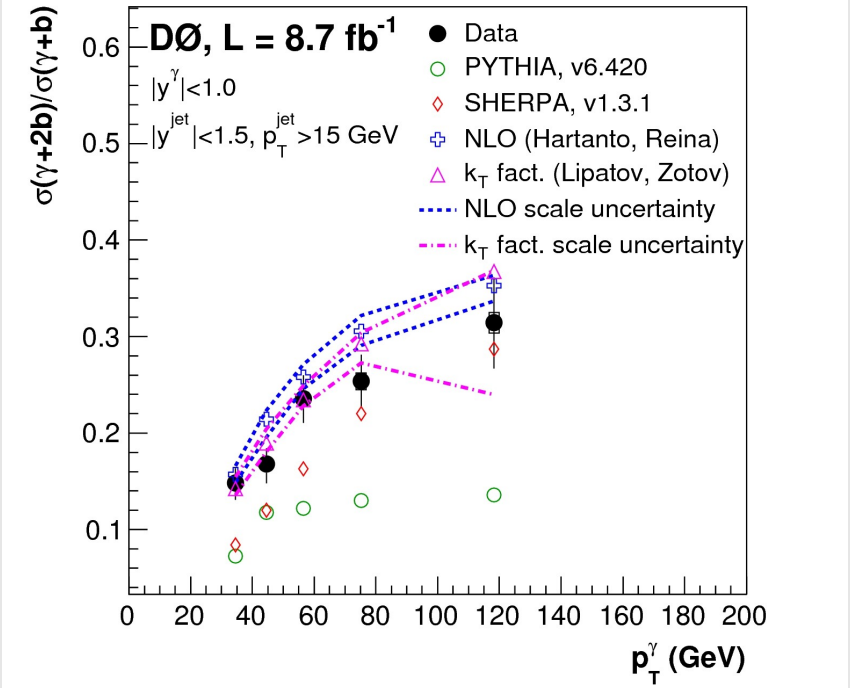


# (2014) Q34: Measurement of the differential inclusive γ + 2 b-jets cross section and the ratio σ(γ + 2 b)/σ(γ + b)

First of its kind
- agreement w/ NLO and “kt-factorization approach”
- again (there's a LOT of work left for model tuning....)

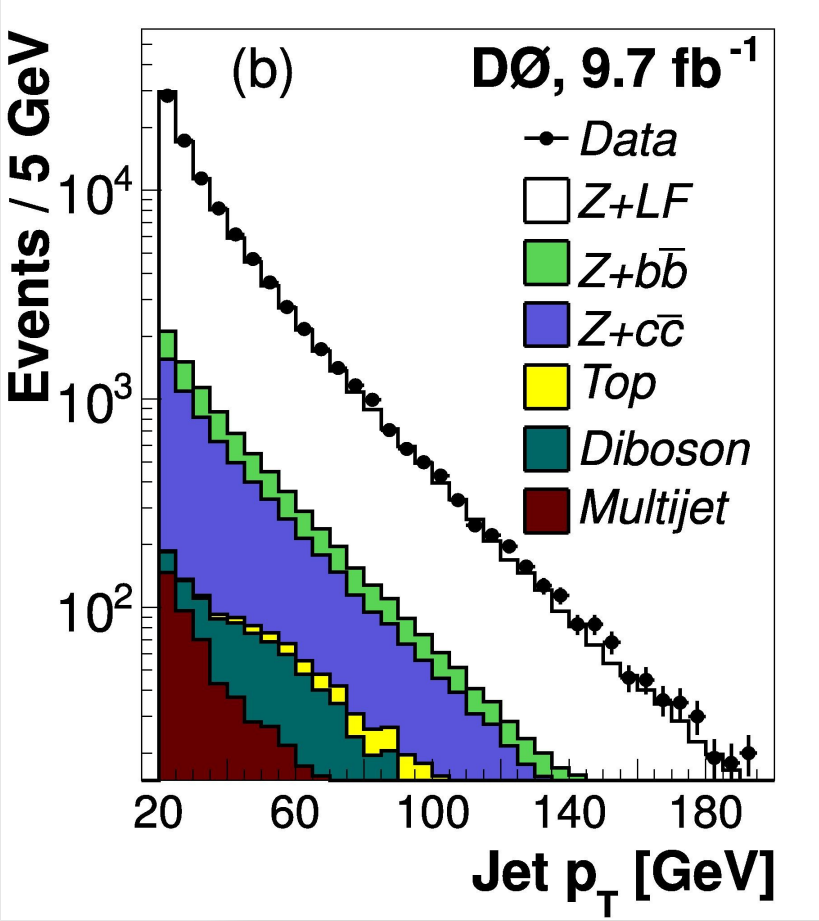


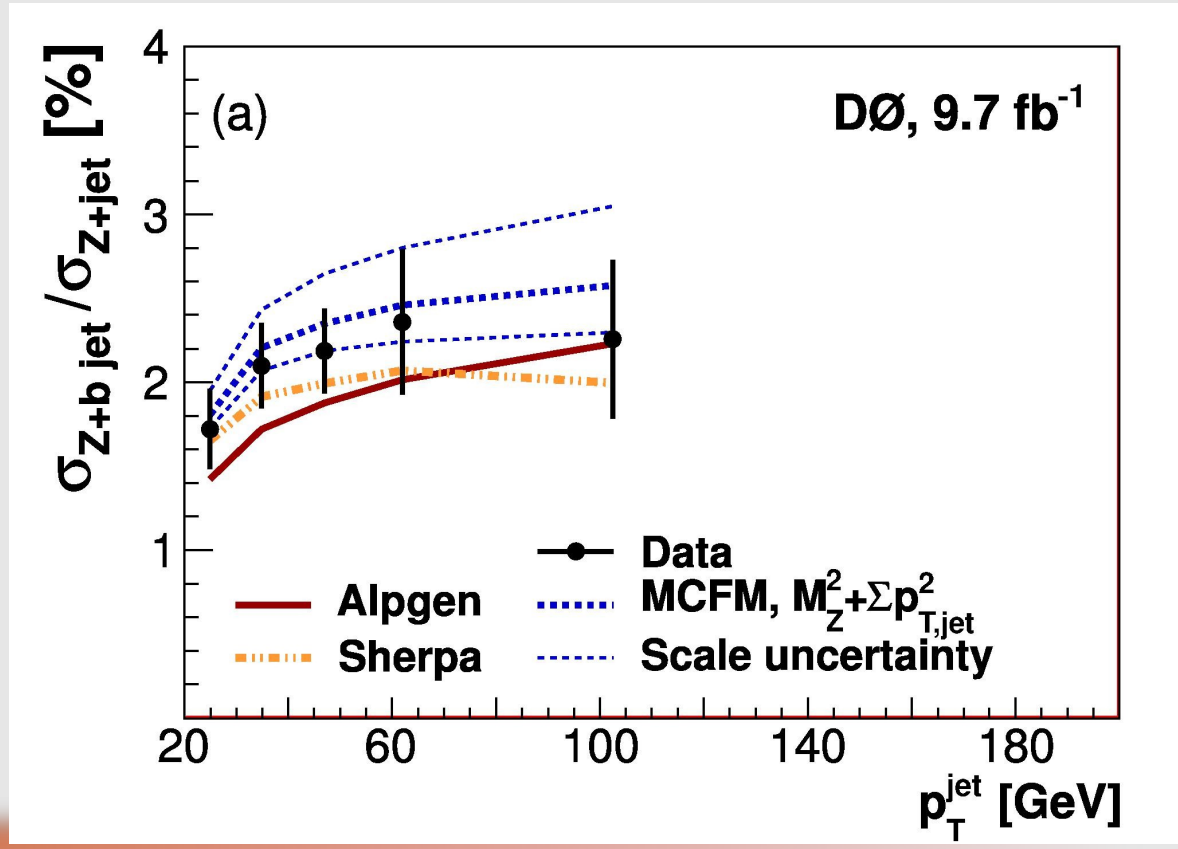



# ('10,13) Q15,28: Ratio of σ(pp → Z+b-Jet) / σ(pp → Z+Jet)

Moving to ever more rare processes...

None of the predictions provide a consistent description of all the examined variables.

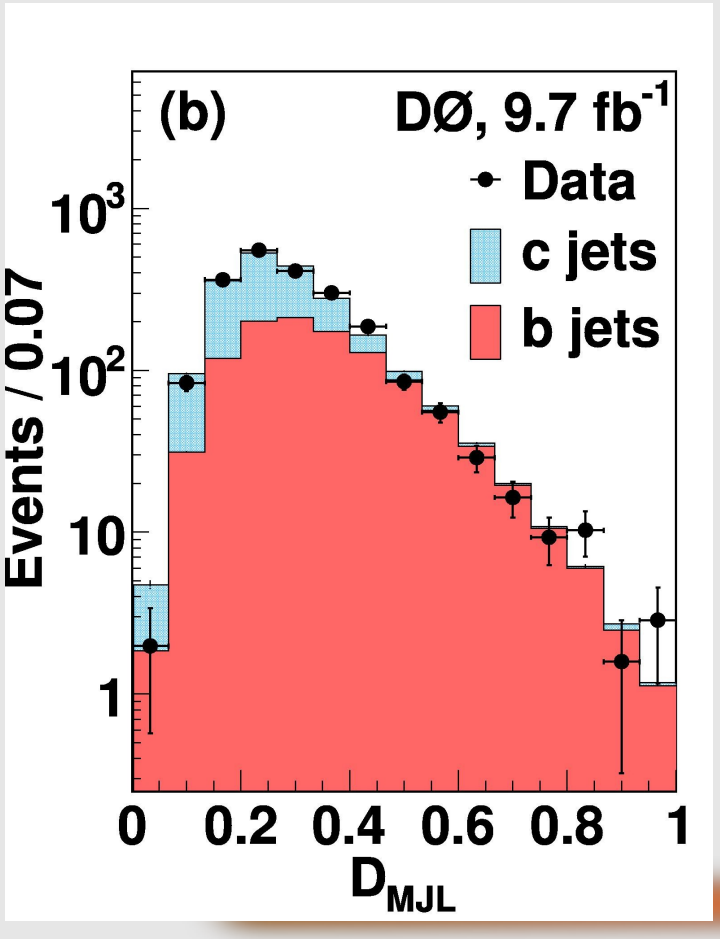


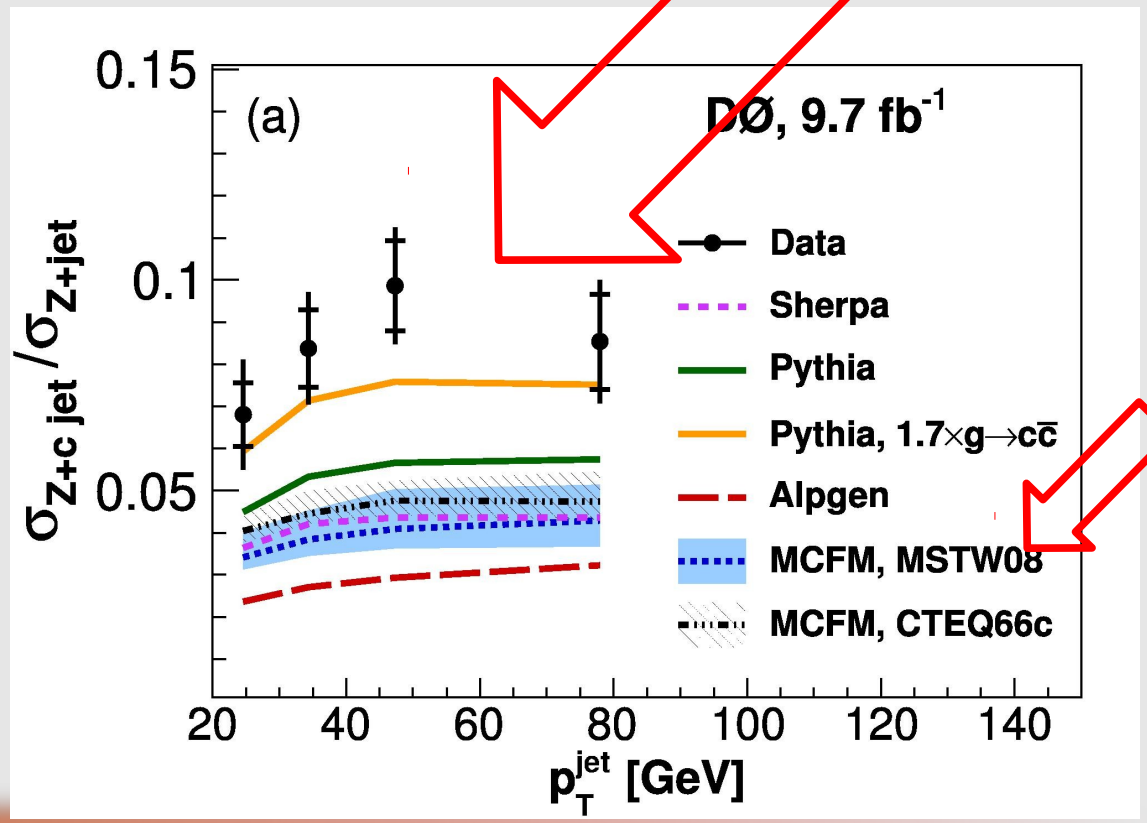



# (2013) Q32: Measurement of associated production of Z bosons with charm quark jets

Another first!

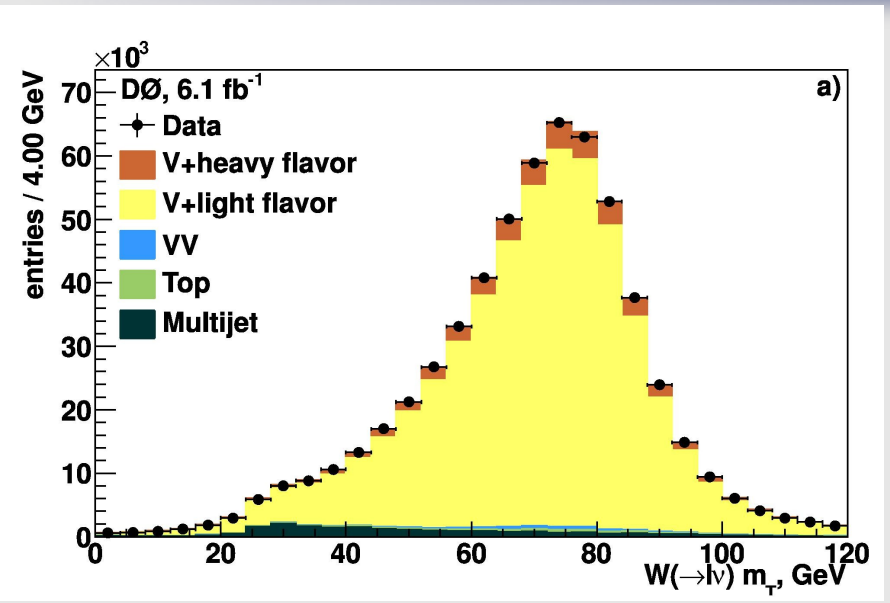
=> NLO pQCD predictions disagree significantly with the results.
=> PYTHIA agrees better with ratio to Z+jets, especially when the gluon splitting to $c\bar{c}$ pairs is enhanced.

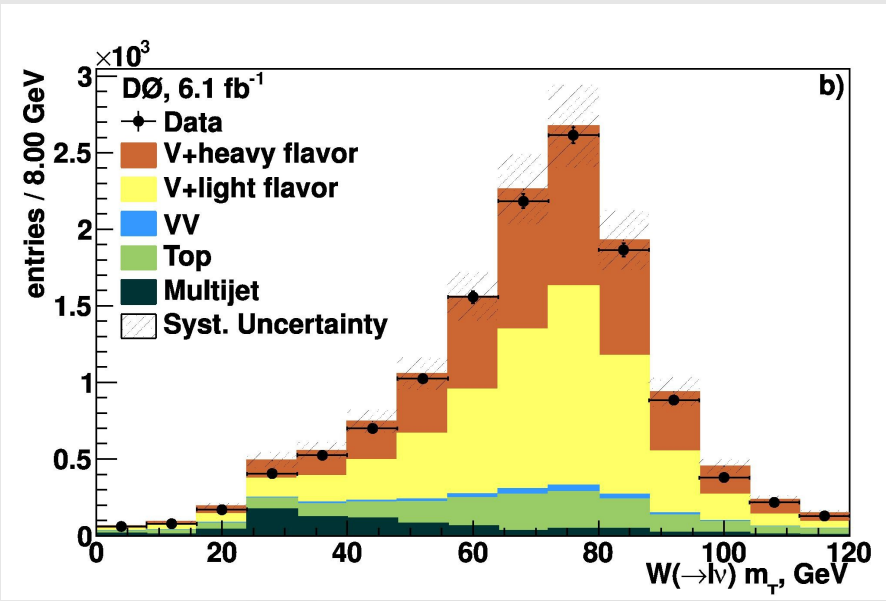


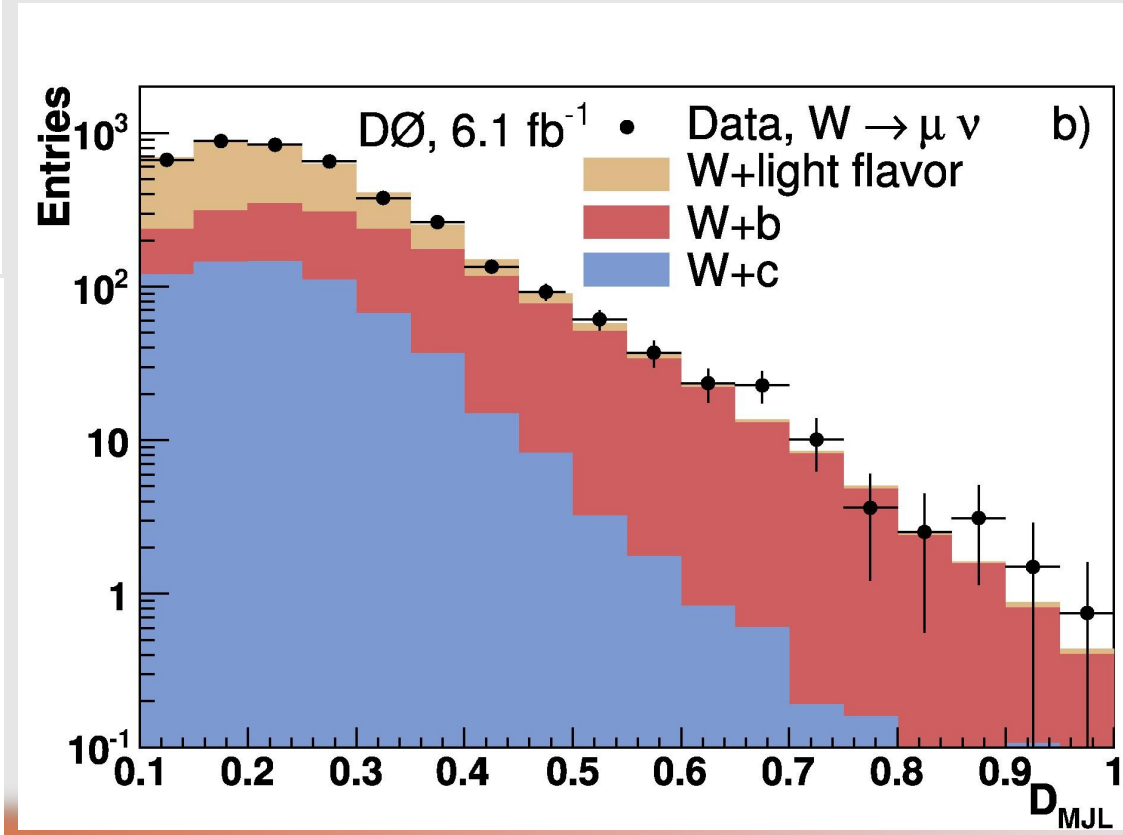
# ('08,12) Q3,24: W + c/b

First measurement (in agreement) with SM predictions




=> Important result for gaining confidence in modeling of Higgs backgrounds

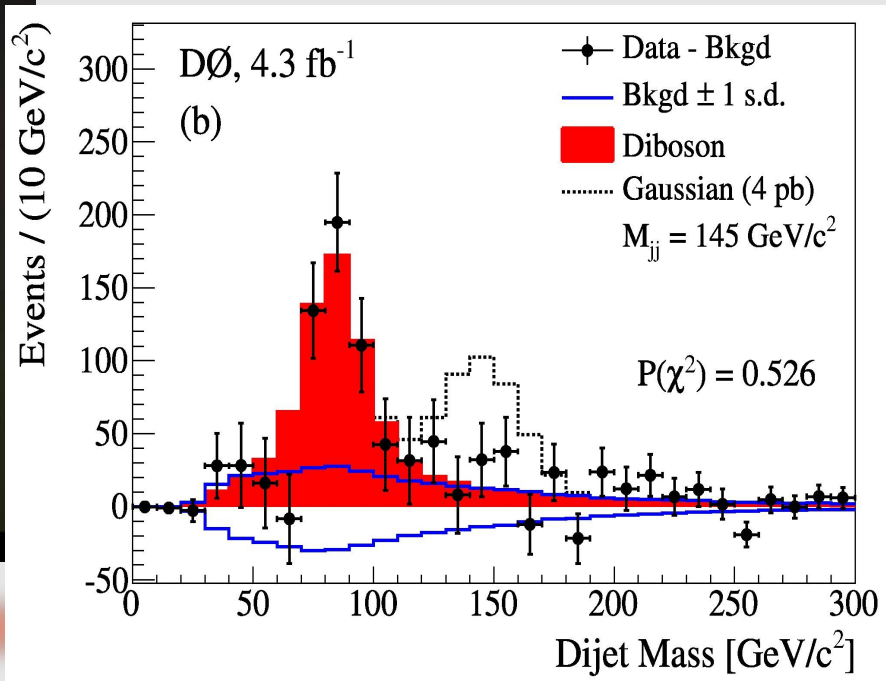


# Speaking of important verifications of SM

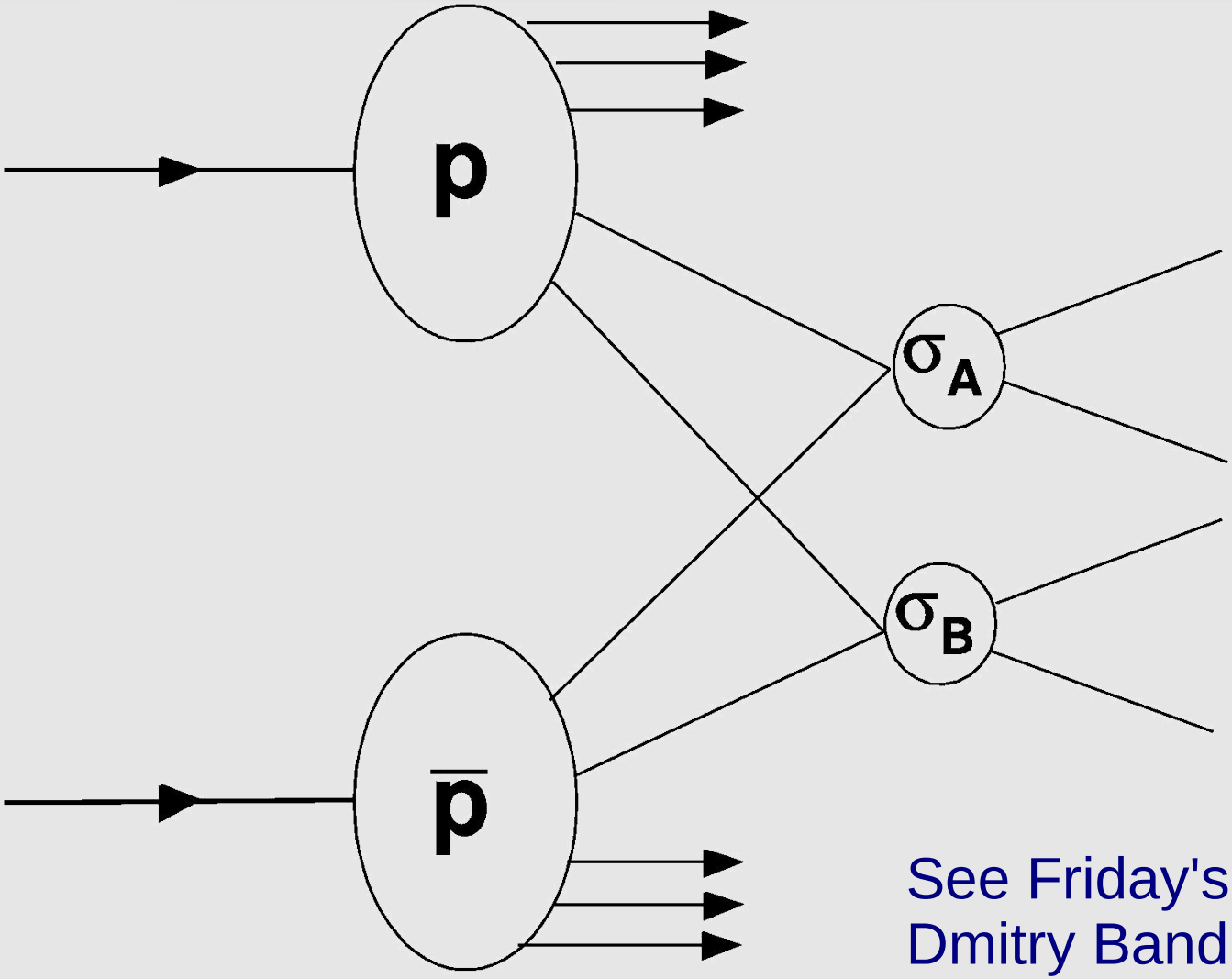
Bounds on an Anomalous Dijet Resonance in W+Jets Production in pp Collisions at √s = 1.96 TeV

TOPCITE = 50+ Physics Synopsis article Internet Meme

(honorable QCD mention)

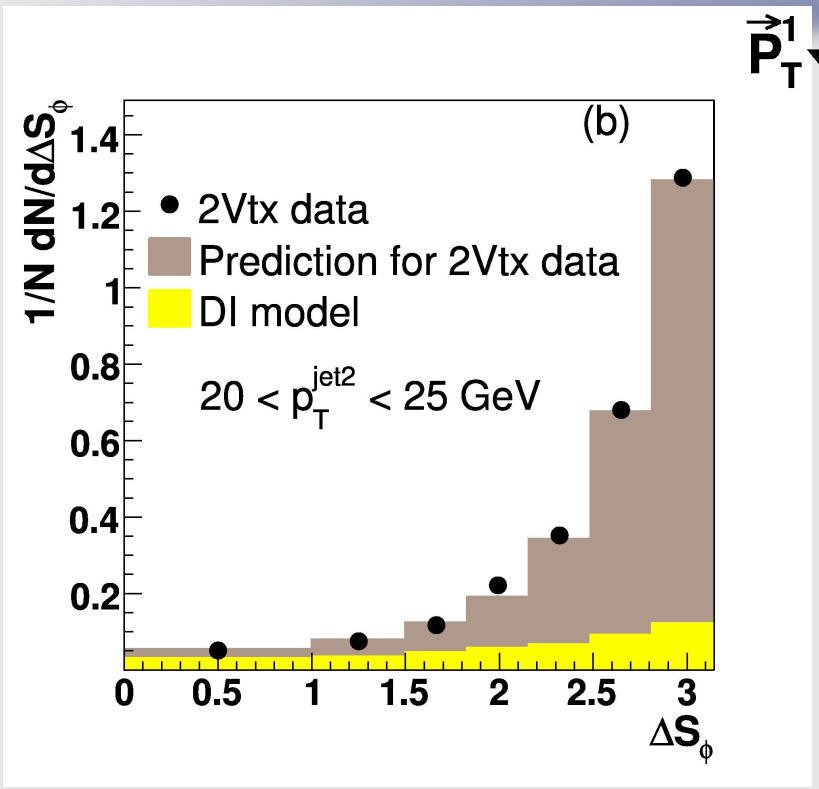
# Double Parton Interactions

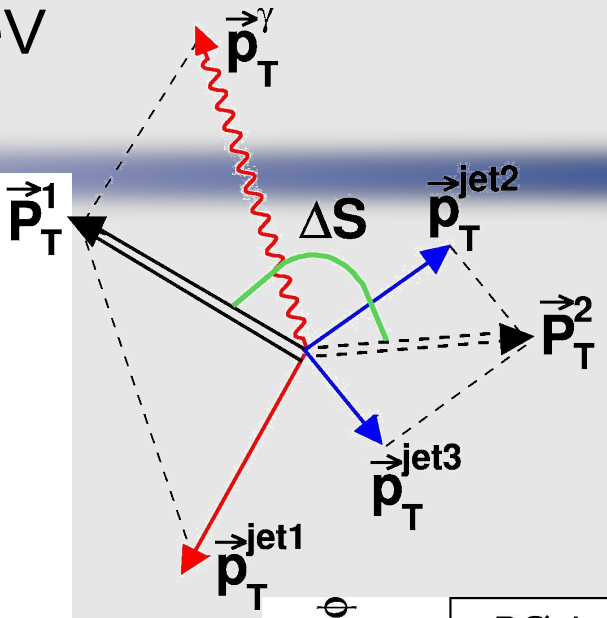


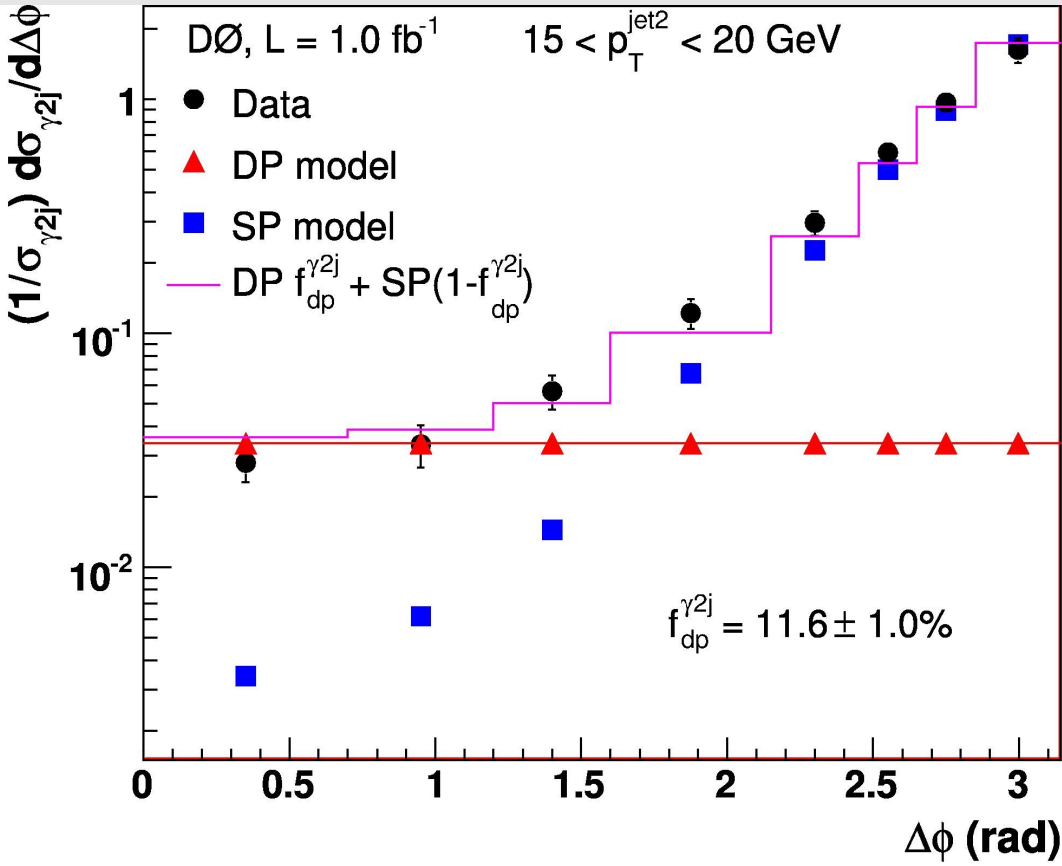

See Friday's W&C talk by Dmitry Bandurin

# (2010) Q12: Double Parton Interactions in γ+3 Jet Events in pp Collisions at √s = 1.96 TeV

TOPCITE = 50+

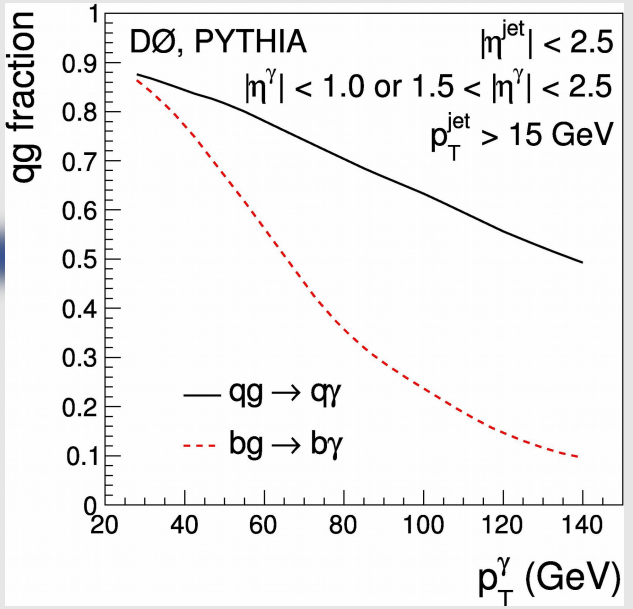


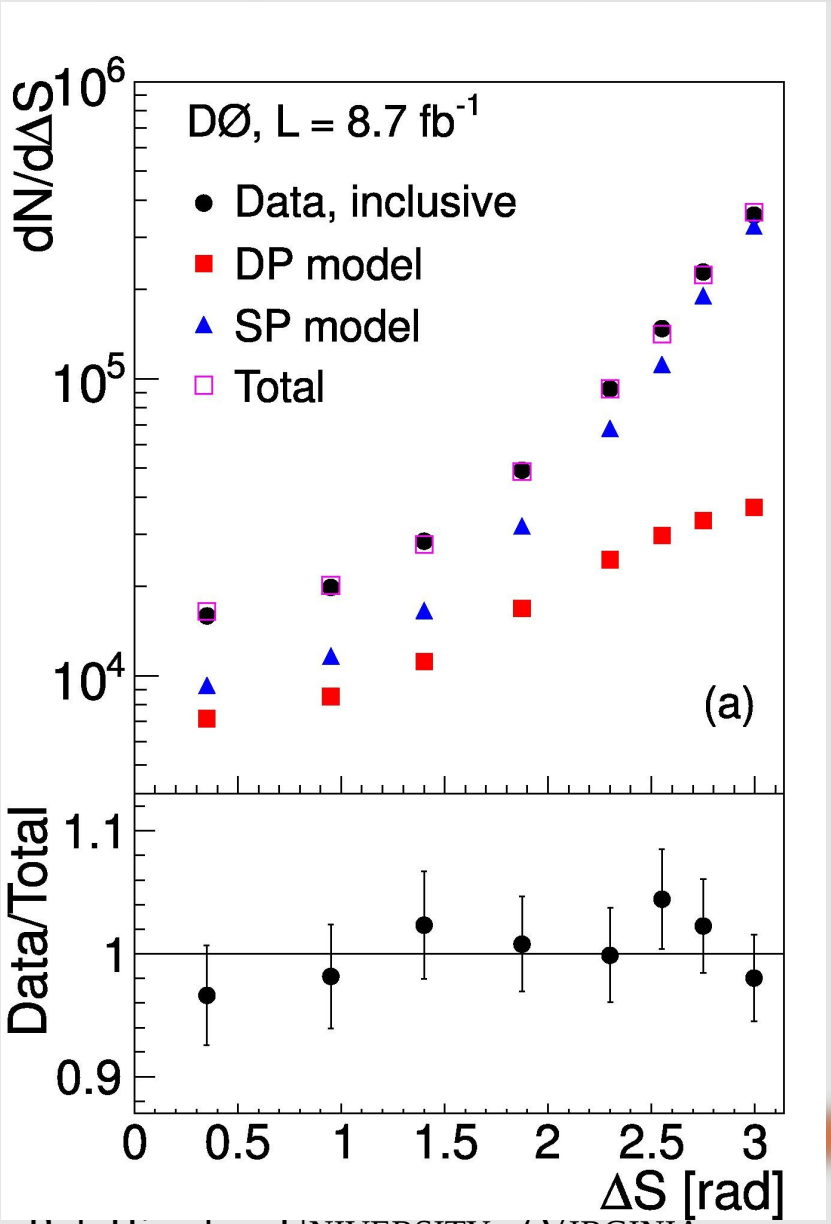



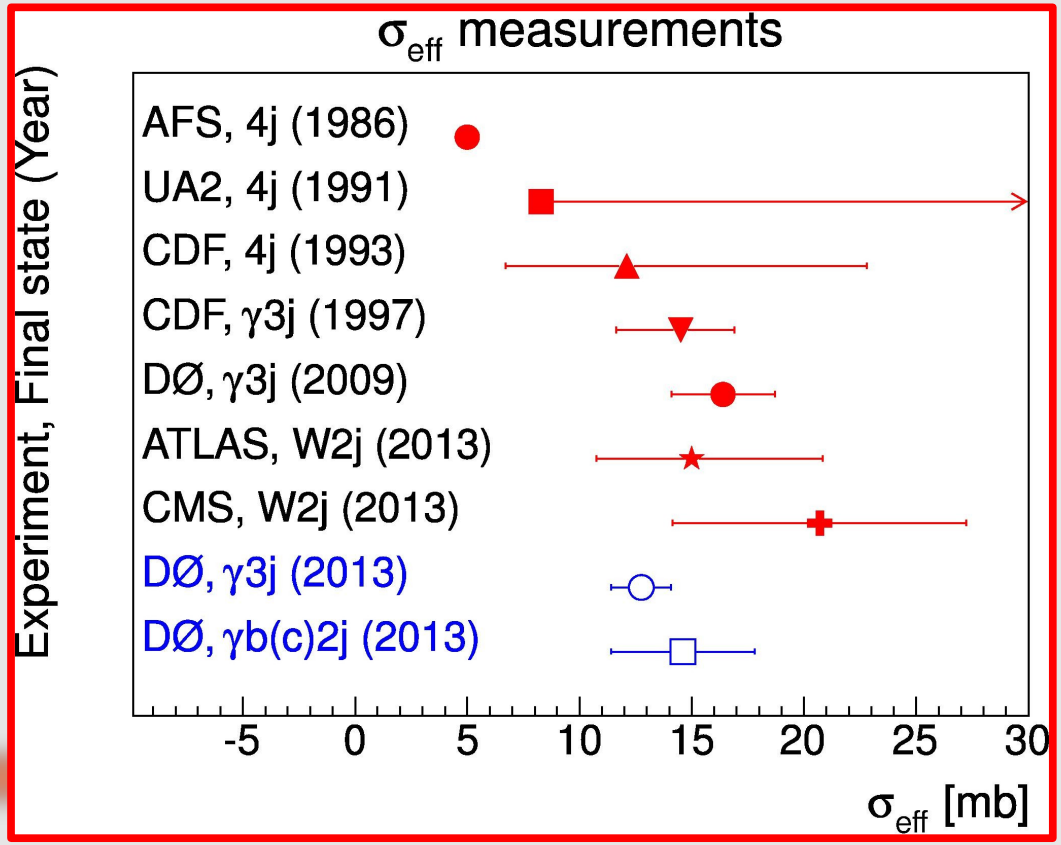

# (2011) Q16: Azimuthal Decorrelations and Multiple Parton Interactions in γ + 2 Jet and γ + 3 Jet Events

# (2014) Q33: Double Parton Interactions in γ + 3 jets and γ + b/c + 2 jets events in pp collisions at √s = 1.96 TeV in D0



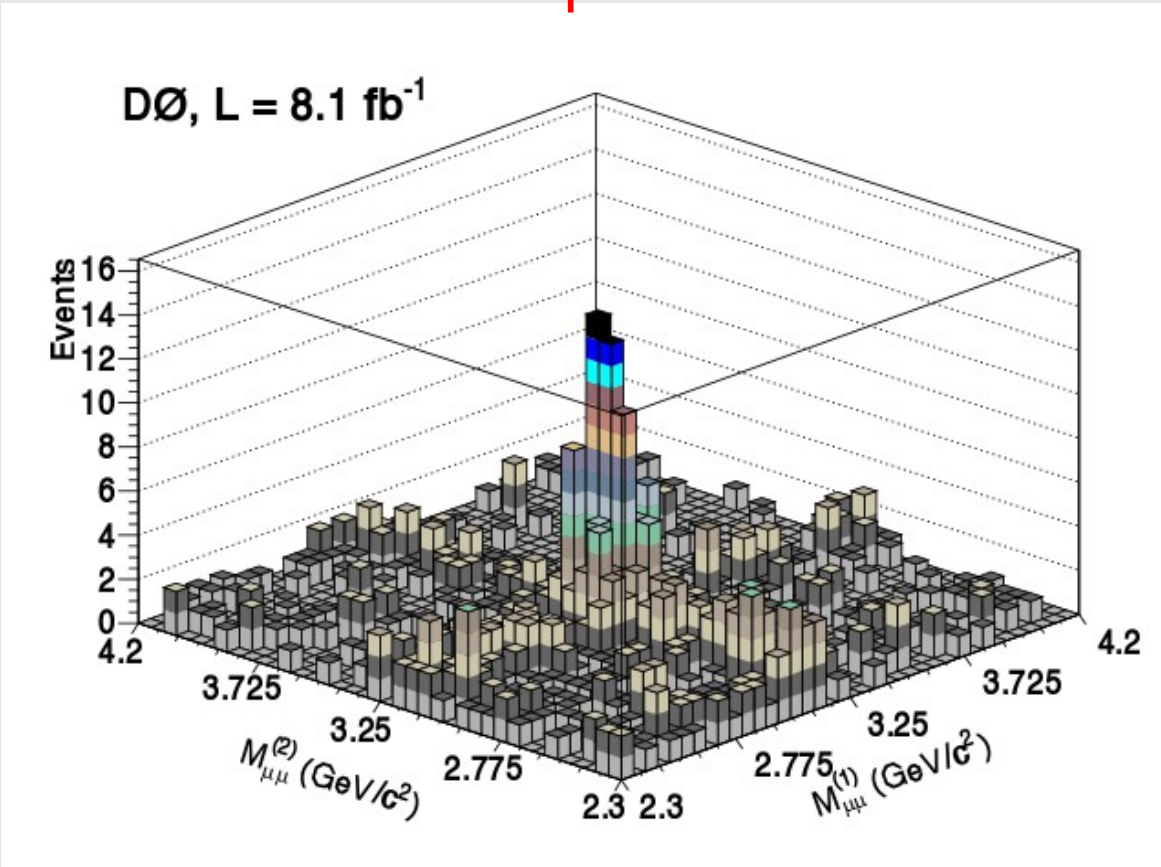



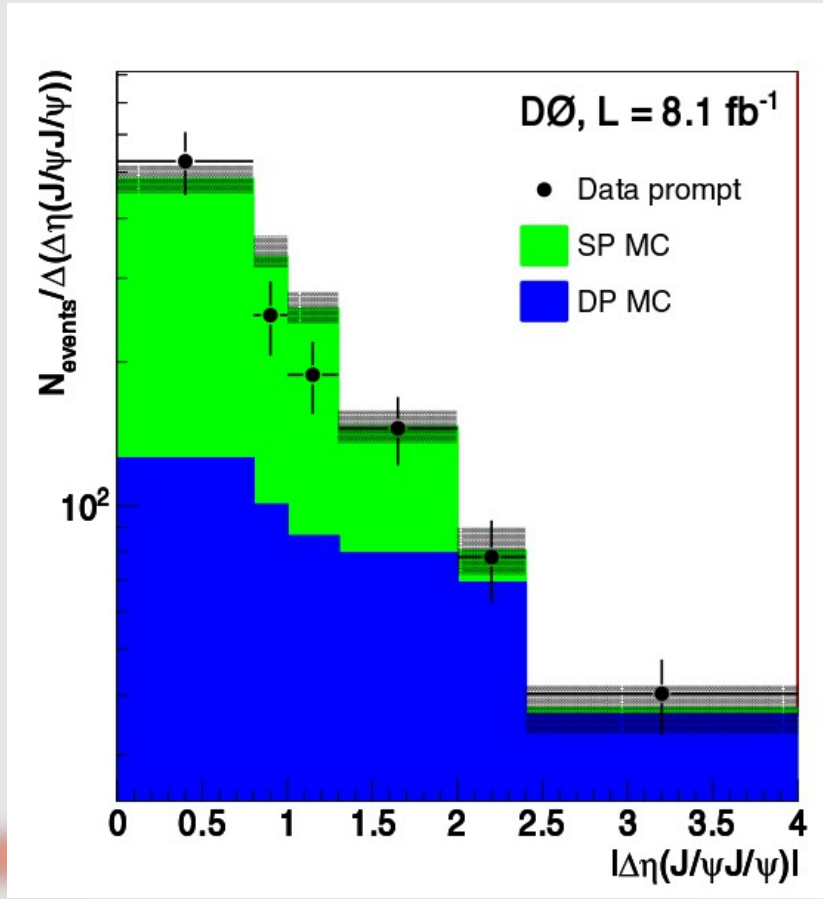

Another first!
=> indication $\sigma_{eff}$ is flavor independent



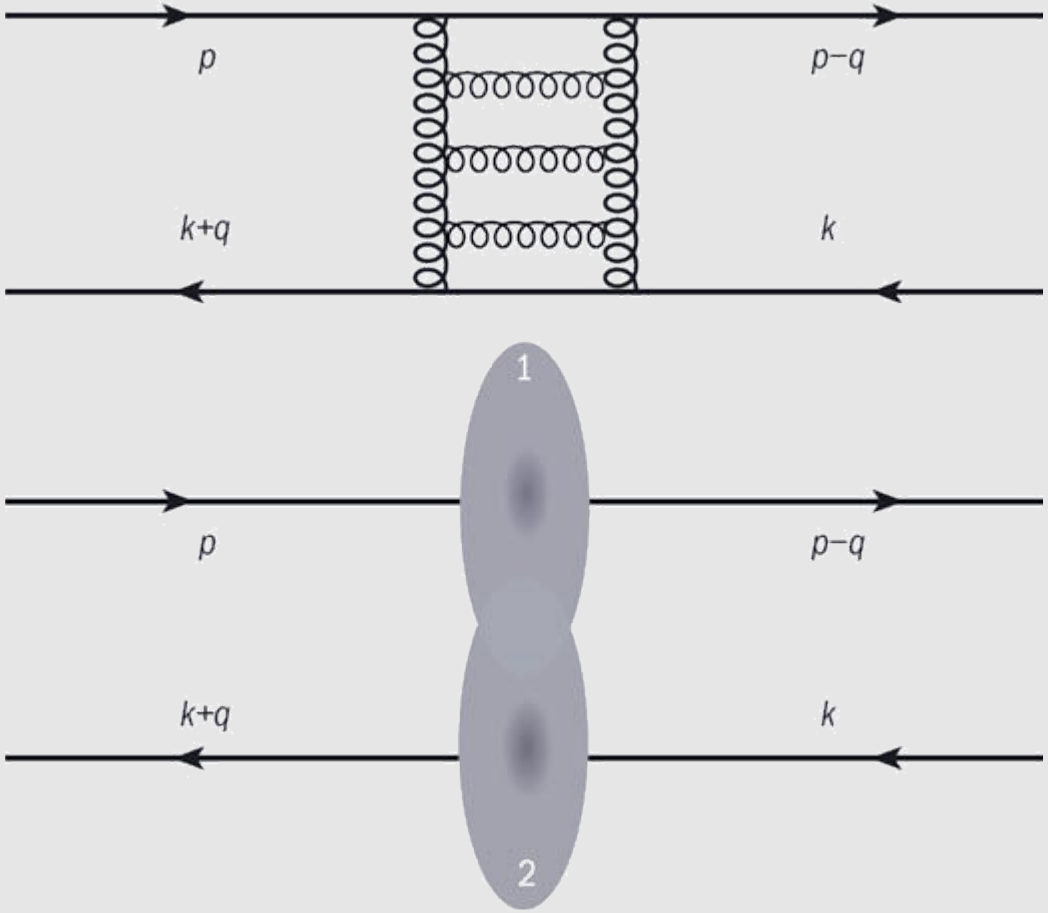
# (2014) Q35: Measurements of the prompt single J/psi and double J/psi cross sections at the Tevatron

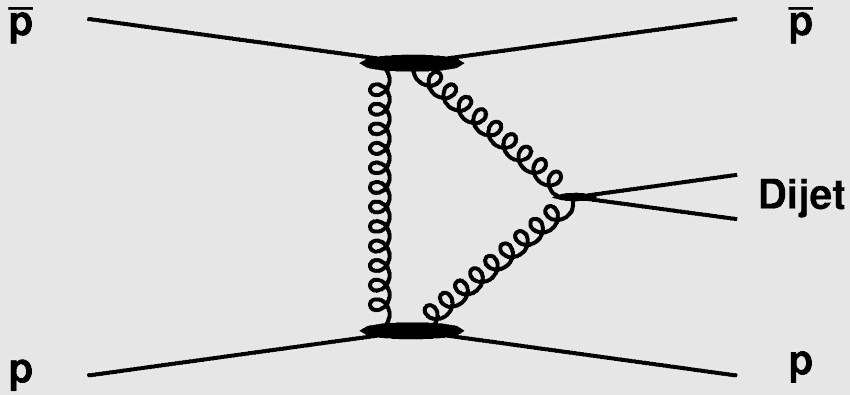
Hot off the presses (and another first)!
- gluon dominated initial state
- “measured σeff may indicate a smaller average distance between gluons than between quarks or between a quark and a gluon, in the transverse space”



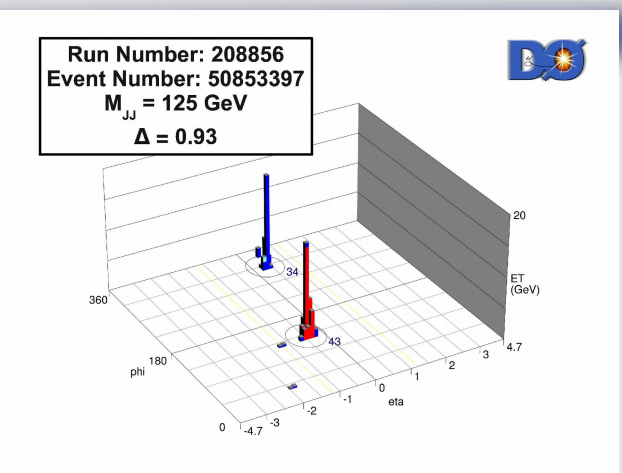



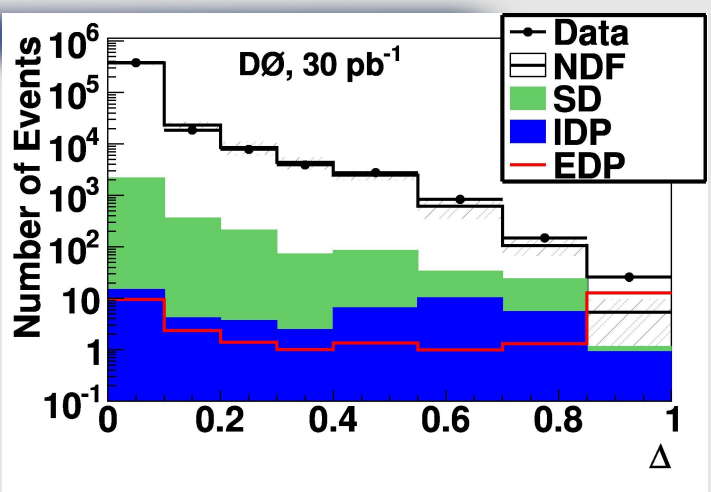
# Elastic/Diffractive



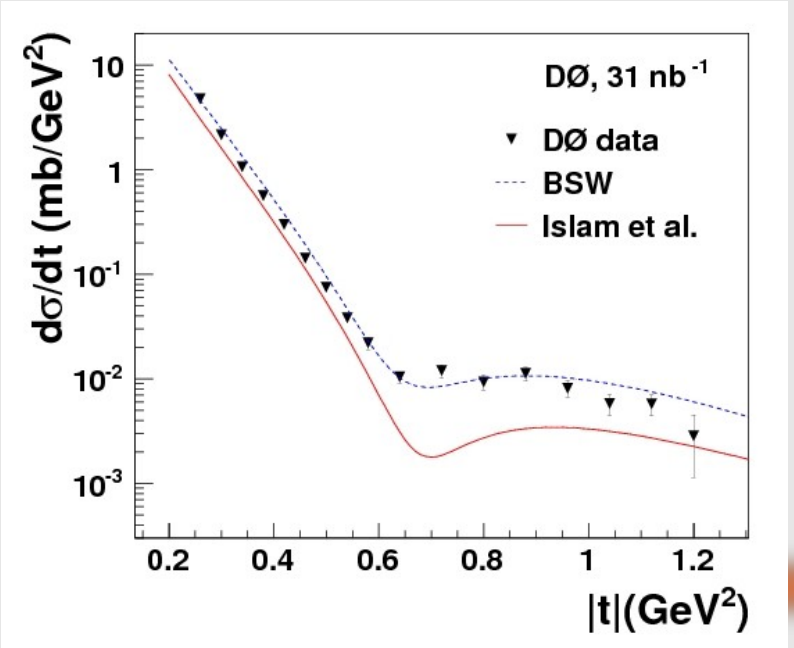



# Q19: High Mass Exclusive Diffractive Dijet Production
# Q22: Measurement of the Differential Cross Section dσ/dt in Elastic pp Scattering



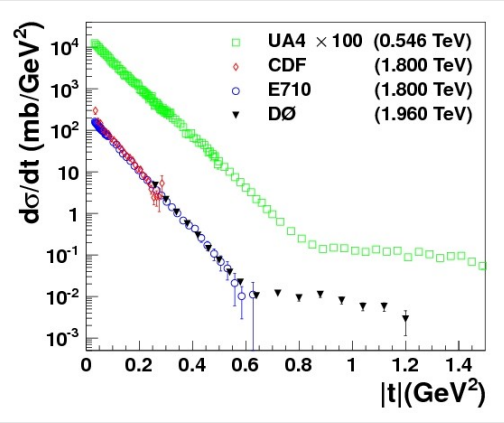




Highest mass states studied for exclusive production at hadron colliders




Extend previous => kinematic ranges (|t|,√s)

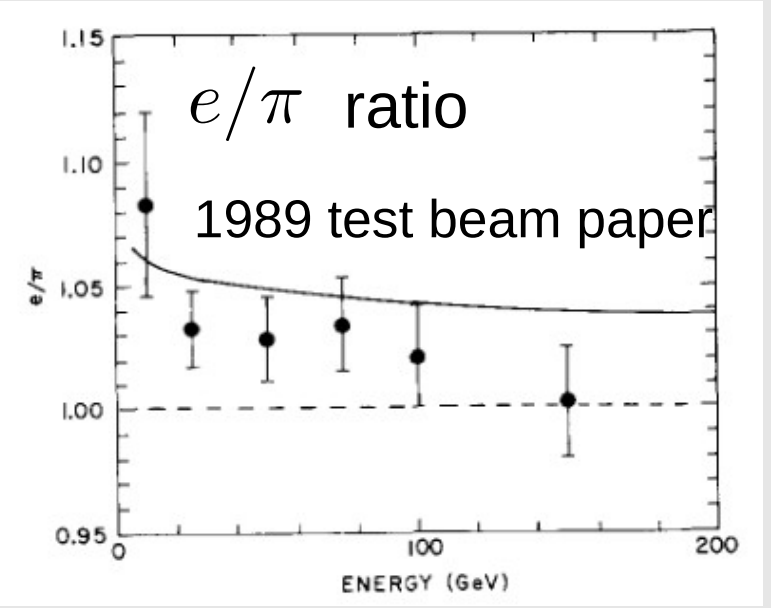
<= Test modern pheno models

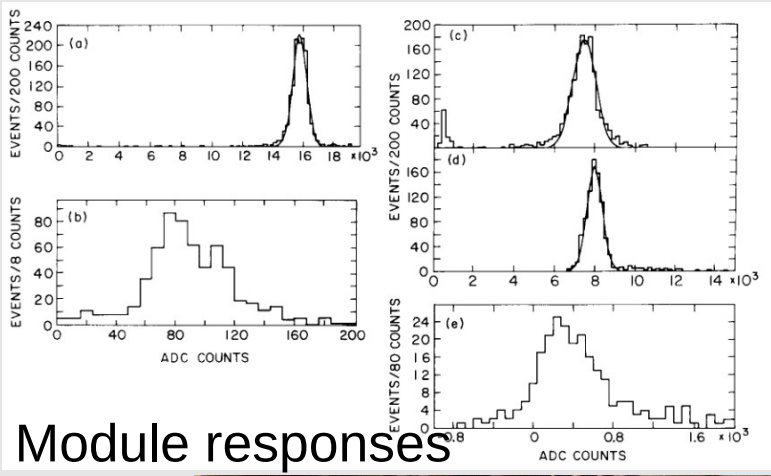


# We've come a LONG way

QCD analyses at D0 are central to the history of an amazing revolution in the precision and depth of QCD studies over the past 25 years

Congratulations (but not good bye) to all!




Module responses