

# Jets for LHC

---

Davison E. Soper  
University of Oregon

Lawrence Berkeley Laboratory, May 2009

# Jet cross sections

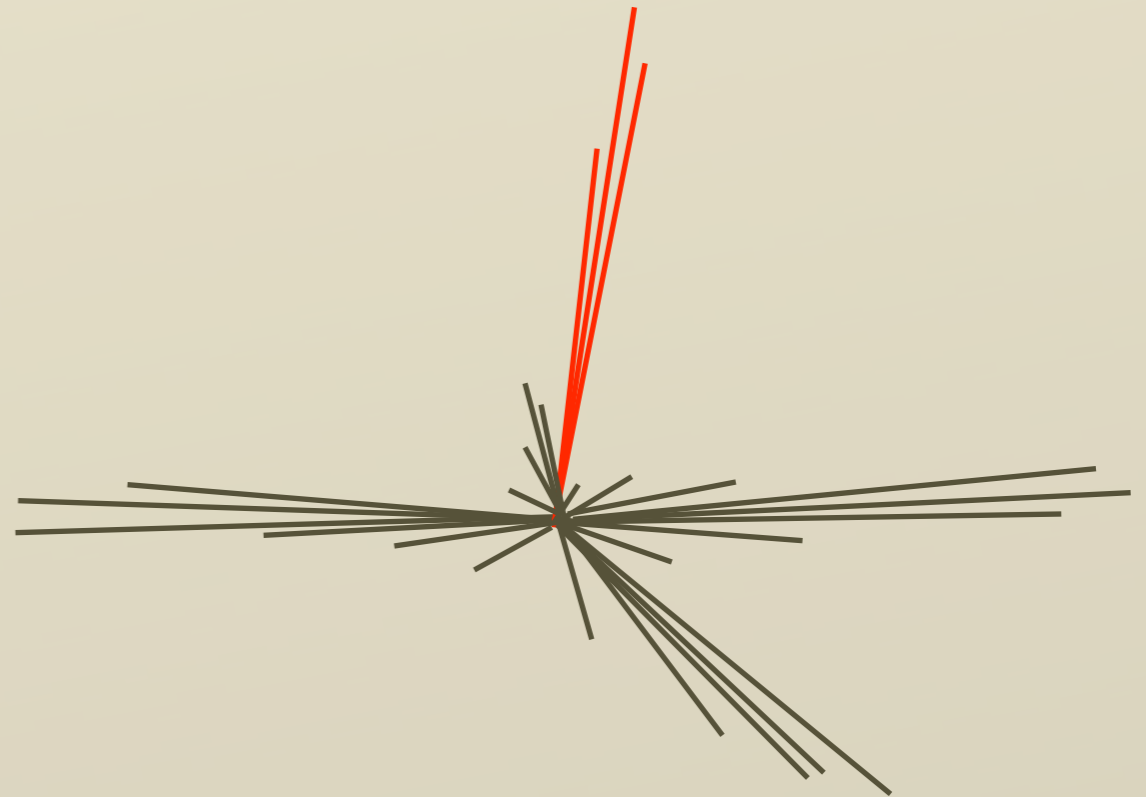
- Jets appear as part of lots of new-physics signals.
- One can also look for purely standard model jet cross sections.
- The simplest is the one-jet inclusive cross section.

$$\frac{d\sigma}{dP_T dy}$$

- I will start by talking about that.

# Jet definitions

- The intuitive definition of a jet is clear.
- But to be precise, you need an exact definition.
- The definition should be “infrared safe.”
- A partonic version of the definition goes into the subroutine that defines the observable.



# Programs for jet calculations

- Leading order, with full final state:
  - \* Pythia
  - \* Herwig
  - \* Sherpa
- NLO, but with partonic final state:
  - \* Jet (usually “EKS” ; Ellis, Kunszt, Soper)
  - \* JETRAD (Giele, Glover, Kosower)
  - \* NLOjet++ (Nagy)

# Comparison of NLOjet++ & “Jet” programs

- Do these give the same results?
- Let's see with the one jet inclusive cross section for the Tevatron. (Done with Z. Nagy.)
- Use cone algorithm with  $R = 0.7$ ,  $R_{\text{sep}} = 1.3 R$ , rapidity range 0.1 to 0.7, renormalization and factorization scale =  $1/2 * P_T$ .

# “Jet” result

PJ	Smearred XSECT	Integration error	Unsmearing Correction	Corrected XSECT	Unsmearred Fit XSECT
300.00	0.1618E-03	0.31E-06	0.26E-06	0.1620E-03	0.1615E-03
320.00	0.8679E-04	0.17E-06	0.10E-06	0.8689E-04	0.8714E-04
340.00	0.4682E-04	0.10E-06	0.34E-07	0.4685E-04	0.4706E-04
360.00	0.2536E-04	0.48E-07	0.75E-08	0.2537E-04	0.2541E-04
380.00	0.1371E-04	0.27E-07	-0.15E-08	0.1371E-04	0.1370E-04
400.00	0.7387E-05	0.15E-07	-0.38E-08	0.7384E-05	0.7359E-05
420.00	0.3949E-05	0.80E-08	-0.35E-08	0.3945E-05	0.3933E-05
440.00	0.2093E-05	0.43E-08	-0.27E-08	0.2090E-05	0.2086E-05
460.00	0.1098E-05	0.24E-08	-0.18E-08	0.1096E-05	0.1096E-05
480.00	0.5679E-06	0.16E-08	-0.11E-08	0.5668E-06	0.5684E-06
500.00	0.2880E-06	0.18E-08	-0.67E-09	0.2873E-06	0.2902E-06
520.00	0.1432E-06	0.14E-08	-0.38E-09	0.1428E-06	0.1453E-06
540.00	0.7002E-07	0.57E-09	-0.21E-09	0.6981E-07	0.7112E-07
560.00	0.3353E-07	0.14E-09	-0.11E-09	0.3342E-07	0.3385E-07
580.00	0.1559E-07	0.47E-10	-0.53E-10	0.1554E-07	0.1559E-07
600.00	0.7003E-08	0.22E-10	-0.25E-10	0.6978E-08	0.6899E-08

Use these numbers

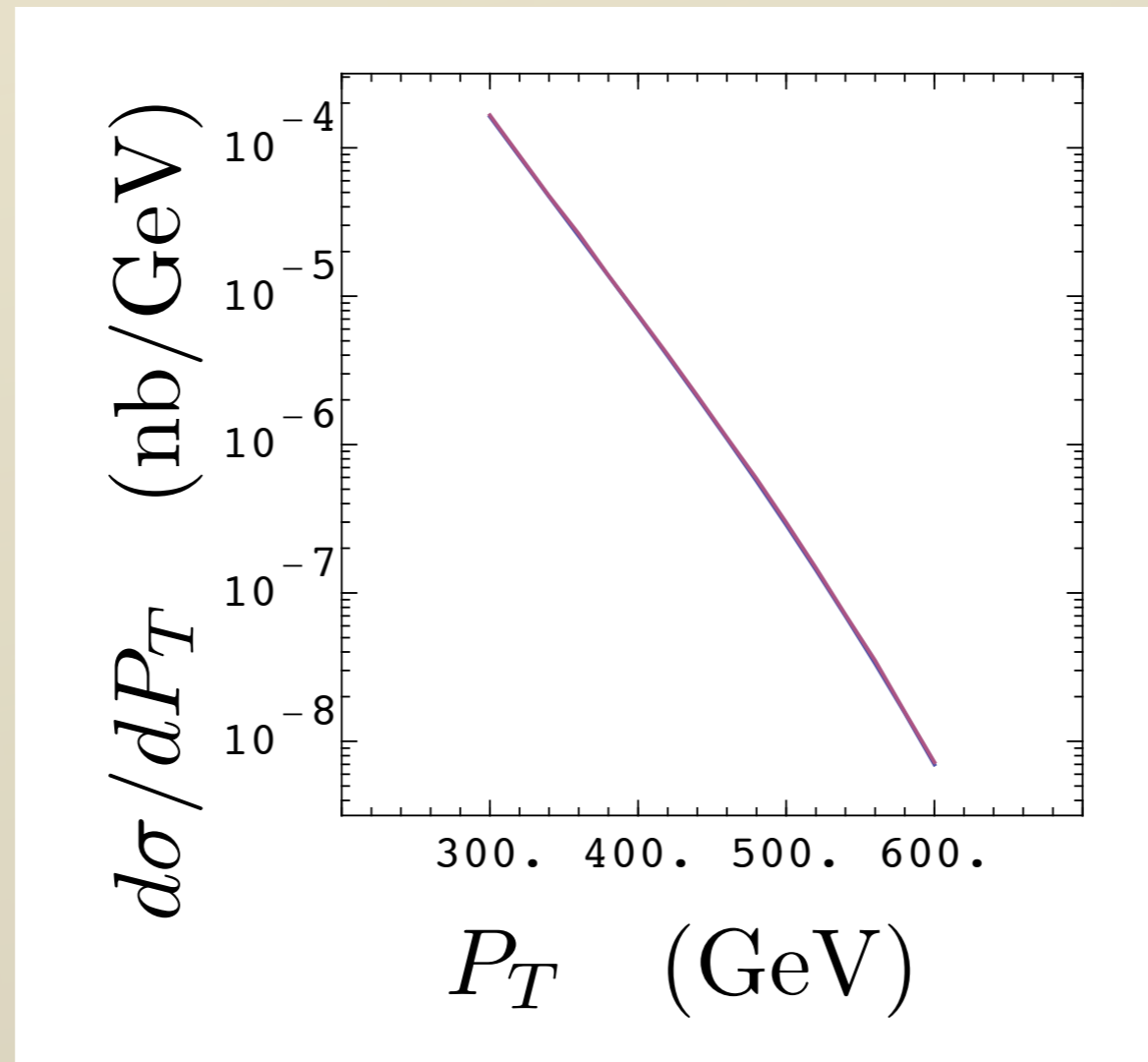


# NLOjet++ result

Left bin edge	Bin center	Right bin edge	Average cross section in bin	Integration error
2.900000e+02	3.000000e+02	3.100000e+02	1.656614e-04	1.215310e-06
3.100000e+02	3.200000e+02	3.300000e+02	8.844286e-05	7.198966e-07
3.300000e+02	3.400000e+02	3.500000e+02	4.741659e-05	4.776538e-07
3.500000e+02	3.600000e+02	3.700000e+02	2.630811e-05	2.122814e-07
3.700000e+02	3.800000e+02	3.900000e+02	1.383090e-05	1.442595e-07
3.900000e+02	4.000000e+02	4.100000e+02	7.493720e-06	6.156523e-08
4.100000e+02	4.200000e+02	4.300000e+02	4.033519e-06	3.364019e-08
4.300000e+02	4.400000e+02	4.500000e+02	2.135288e-06	2.300308e-08
4.500000e+02	4.600000e+02	4.700000e+02	1.118295e-06	1.446359e-08
4.700000e+02	4.800000e+02	4.900000e+02	5.881319e-07	8.272902e-09
4.900000e+02	5.000000e+02	5.100000e+02	2.983773e-07	3.333759e-09
5.100000e+02	5.200000e+02	5.300000e+02	1.475190e-07	1.634408e-09
5.300000e+02	5.400000e+02	5.500000e+02	7.149335e-08	1.013526e-09
5.500000e+02	5.600000e+02	5.700000e+02	3.504026e-08	4.864979e-10
5.700000e+02	5.800000e+02	5.900000e+02	1.580191e-08	2.779432e-10
5.900000e+02	6.000000e+02	6.100000e+02	7.232151e-09	1.454653e-10

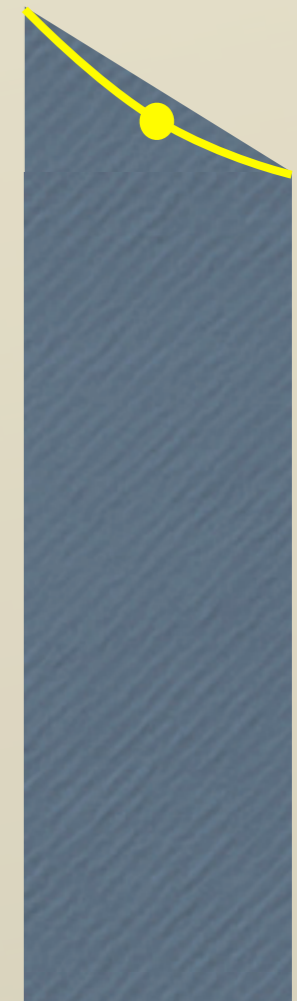
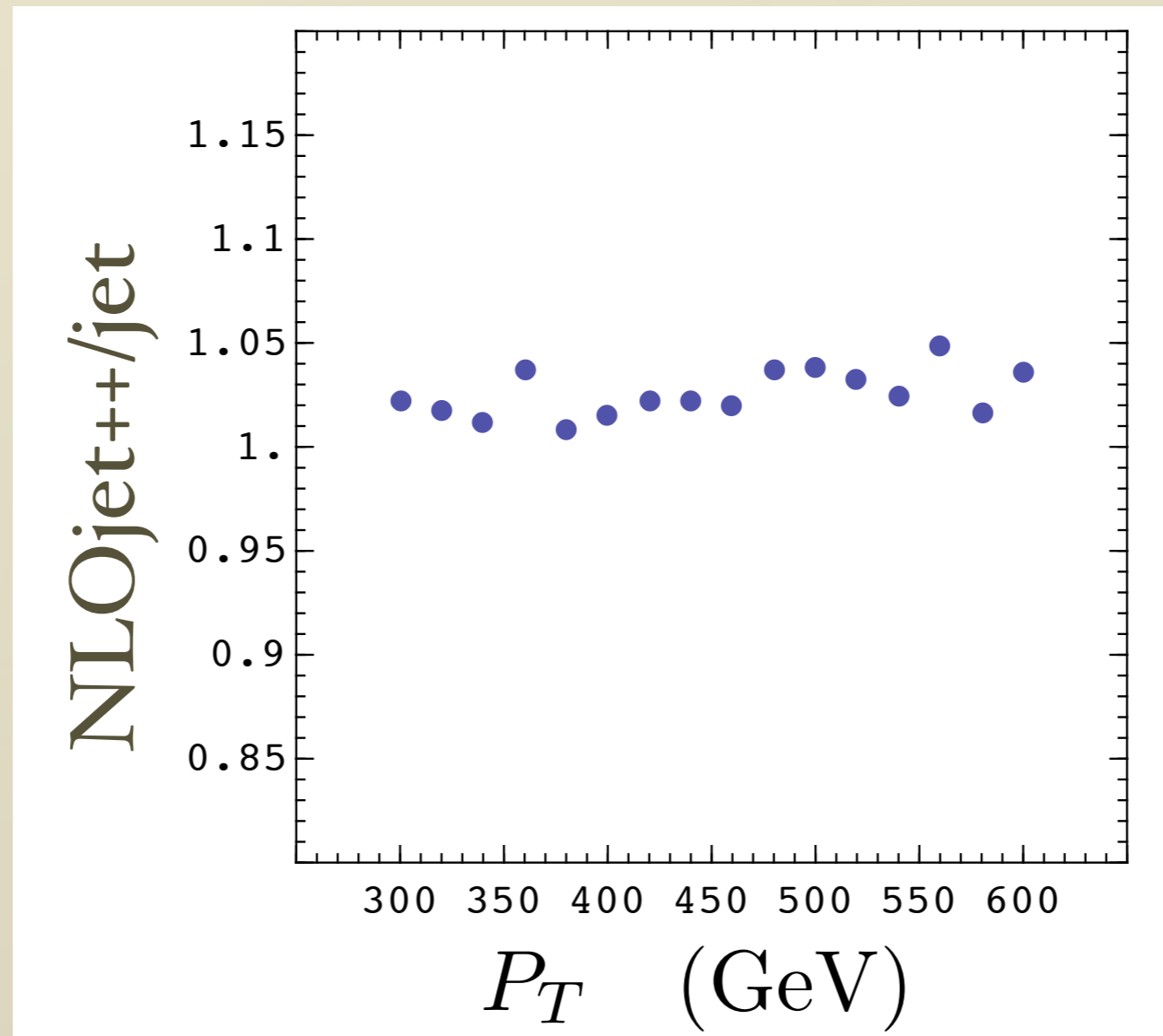
Use these numbers 

# The result



Well, they agree, but maybe we should look at the ratio...

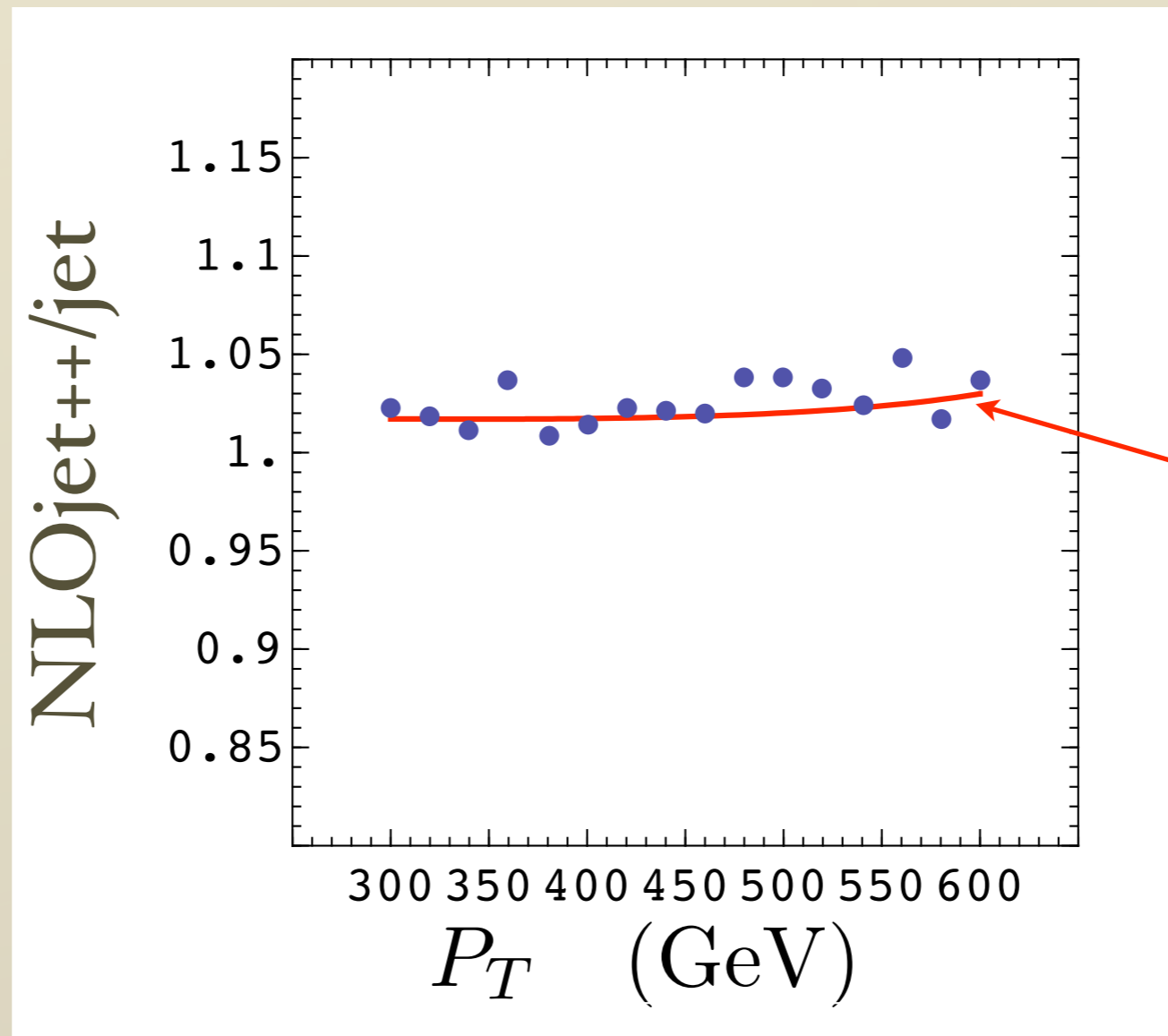
# The result for the ratio



This looks like a 2% discrepancy, but we should plot also the expected ratio, given that the average over a bin and the value at the bin center are not the same.

# The result for the ratio

We have agreement within the 2% statistical error of NLOjet++.



Expected ratio

- There is also agreement between JETRAD and “Jet” (at about the 5% level).

# Observable specification

- NLO programs may come predefined to calculate, say

$$\frac{1}{y_{\max} - y_{\min}} \int_{y_{\min}}^{y_{\max}} dy \frac{d\sigma}{dP_T dy}$$

- But they can calculate whatever infrared-safe two-jet observable you want. (Or, for NLOjet++, also three-jet observables.)

- In Pythia, you get events.
- Then you specify whether it has jets, what transverse momentum, etc.
- In the NLO programs, the specification is in a subroutine within the program.
- You can modify the definitions.

# The observable definition in program “Jet”

**SUBROUTINE**

**> JETDEF (CASE, Y1, P2, Y2, PHI2, P3, Y3, PHI3, OK, PJ, YJ, UNUSED, SVALUE)**

...

**C**

**PHI32 = CONVERT(PHI3 - PHI2)**

**RLIMITSQ = MIN( RSEP\*\*2, ( (P2+P3)/P2 \* R )\*\*2 )**

**DELTASQ = (Y3-Y2)\*\*2 + PHI32\*\*2**

...

**C**

**C**

**CASE 1: 2 and 3 are the jet**

**C**

**IF (CASE.EQ.1) THEN**

**IF( DELTASQ.LT.RLIMITSQ ) THEN**

**PJ = P2 + P3**

**YJ = ( P2\*Y2 + P3\*Y3 )/PJ**

**IF ( INBOUNDS(PJ, YJ) ) THEN**

**OK = .TRUE.**

**ENDIF**

**ENDIF**

**RETURN**

...

# The NLO jet programs

- JETRAD (Giele, Glover, Kosower): widely used; cannot set scales to jet  $P_T$ .
- Jet (Ellis, Kunszt, Soper): perhaps the fastest, but there are some subtleties to make it faster.
- NLOjet++ (Nagy): the newest, and the only one that can do three-jet observables.

<http://vircol.fnal.gov/MCdownload/jetrad.html>

<http://physics.uoregon.edu/~soper/EKSjets/jet.html/>

<http://nagyz.web.cern.ch/nagyz/Site/NLOjet++/html>

# The theory errors

- Given the definition of the observable (and given a specification of conventions) there is a precise definition of the NLO cross section.
- But this does not mean that we know the standard model prediction exactly.
- Most importantly, there are NNLO and higher order terms that are unknown.
- Thus there is a theory error.

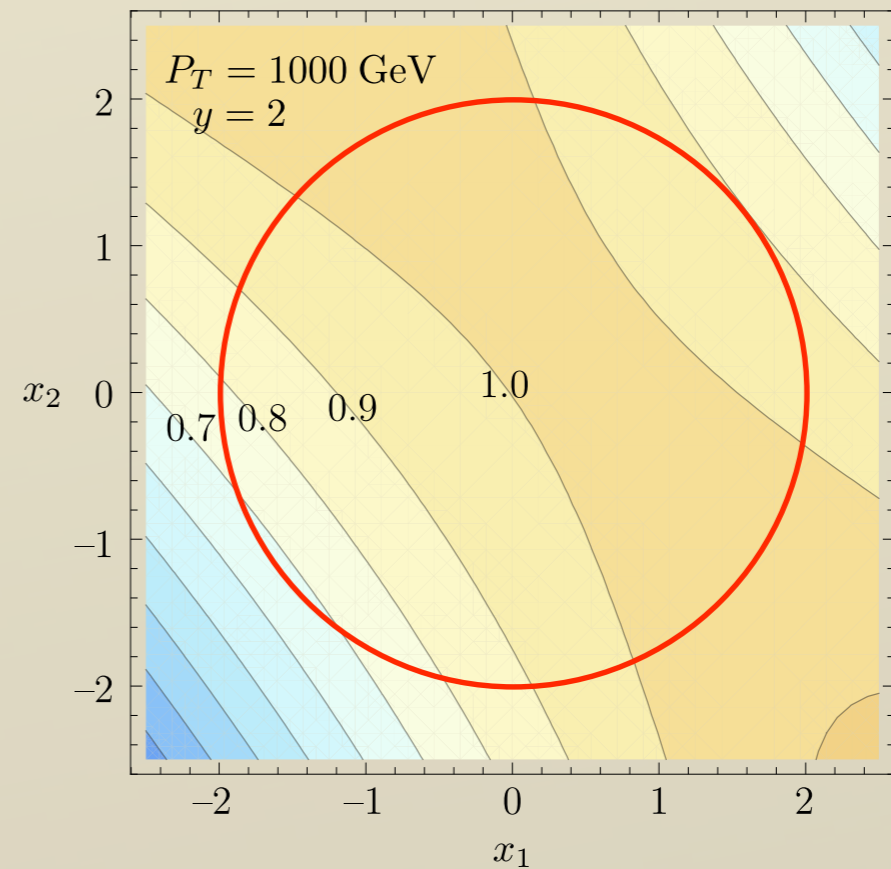
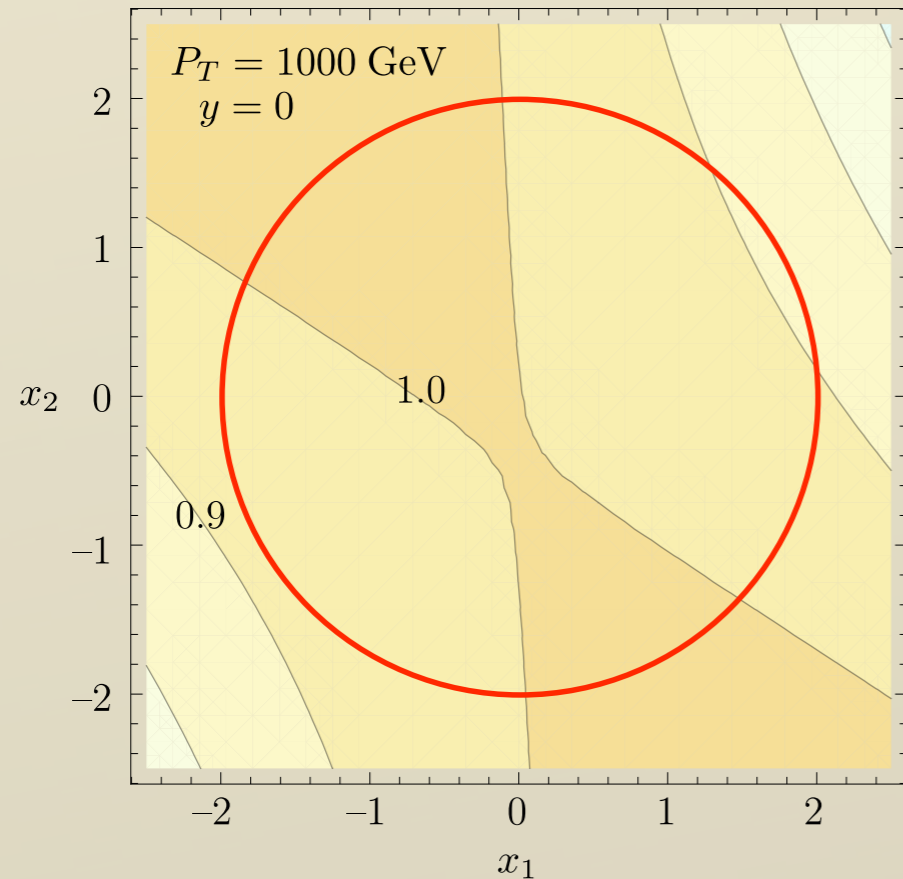
- One way to estimate the perturbative theory error (or, perhaps one should say “guess”) is to look at how the NLO cross section depends on the renormalization and factorization scales.
- This is a plausible guess because cross section calculated at higher order has correspondingly less dependence on the cross section.
- So look at fractional change in the cross section as a function of

$$x_1 = \log_2(2\mu_{uv}/P_T)$$

$$x_2 = \log_2(2\mu_{co}/P_T)$$

- F. Olness and I are studying this.

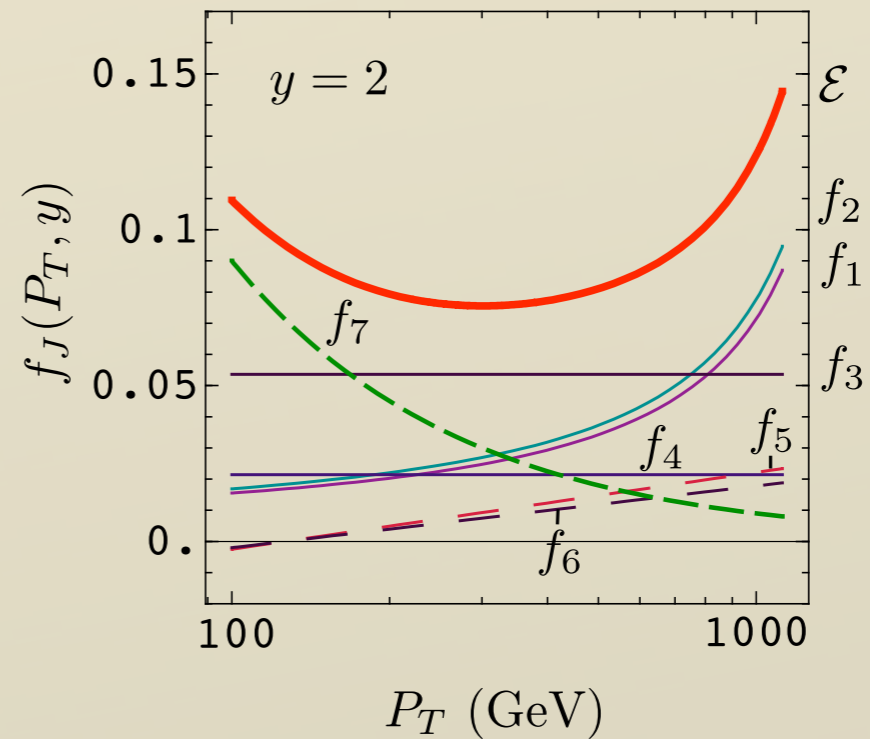
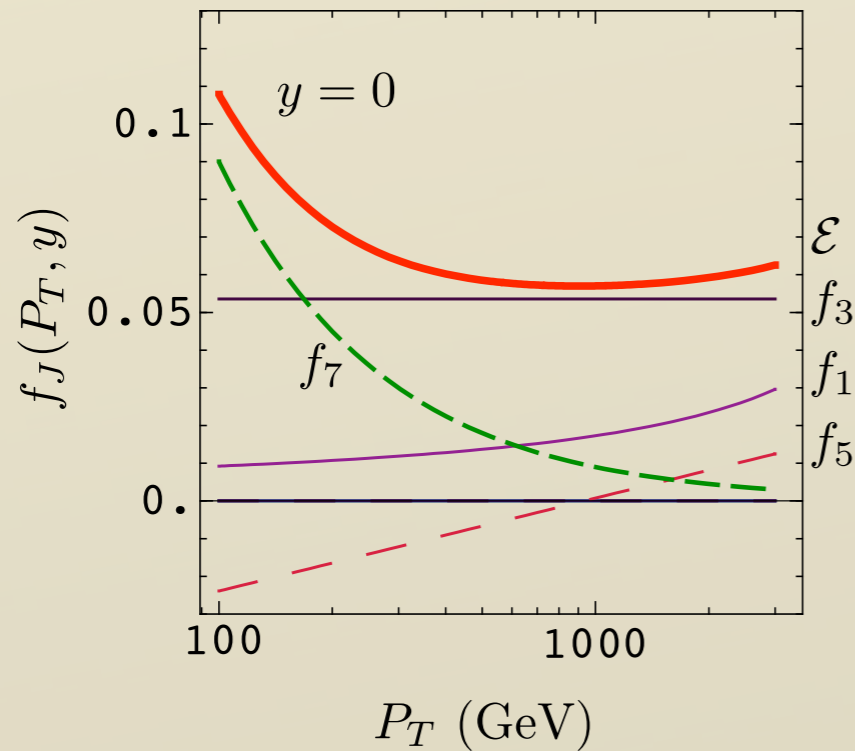
$$\left[ \frac{d\sigma(x_1, x_2)}{dP_T dy} \right]_{\text{NLO}} \approx \left[ \frac{d\sigma(0, 0)}{dP_T dy} \right]_{\text{NLO}} [1 + P(\vec{x})]$$



Our estimated error, with  $|\vec{x}| = 2$ ,

$$\mathcal{E}_{\text{scale}}^2 = \frac{1}{2\pi} \int_0^{2\pi} d\theta P(|\vec{x}| \cos \theta, |\vec{x}| \sin \theta)^2$$

# Our estimate for LHC



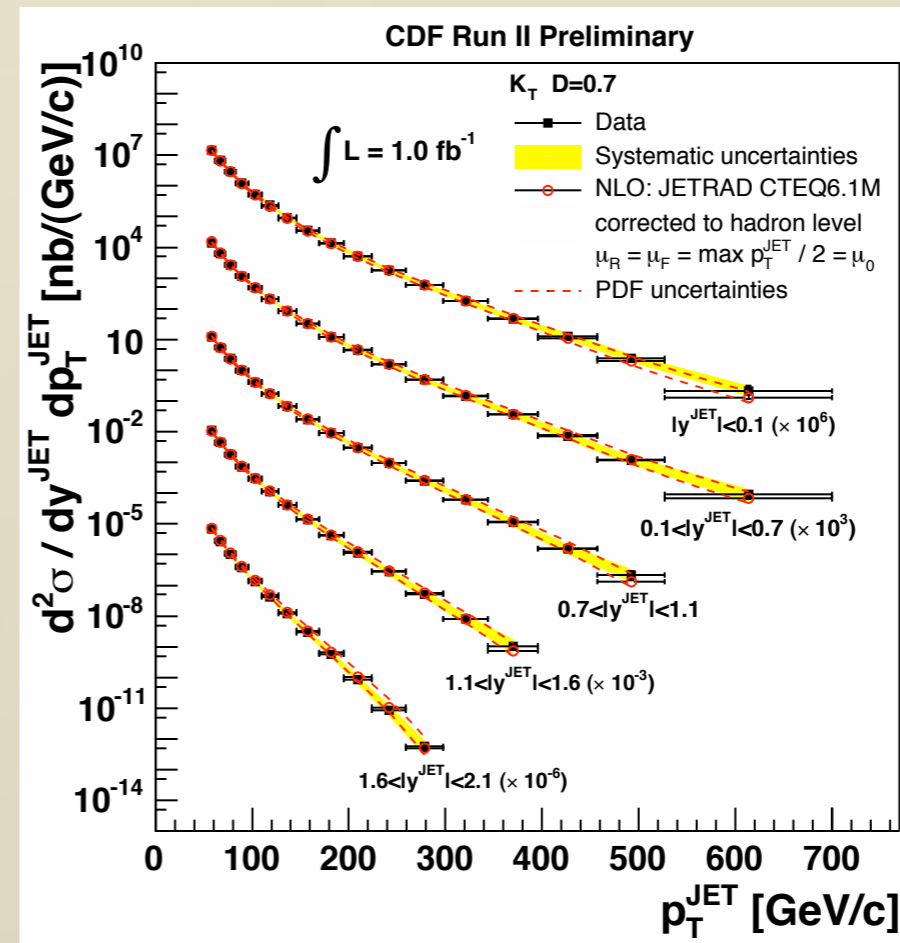
- The  $f_1 \dots f_6$  are correlated parts of the estimated error from higher orders.
- The  $f_7$  curve is an estimate of non-perturbative corrections.
- The red curve is the r.m.s. total.

# What to measure?

- One jet inclusive cross section

$$\frac{d\sigma}{dP_T dy}$$

- This is simple.

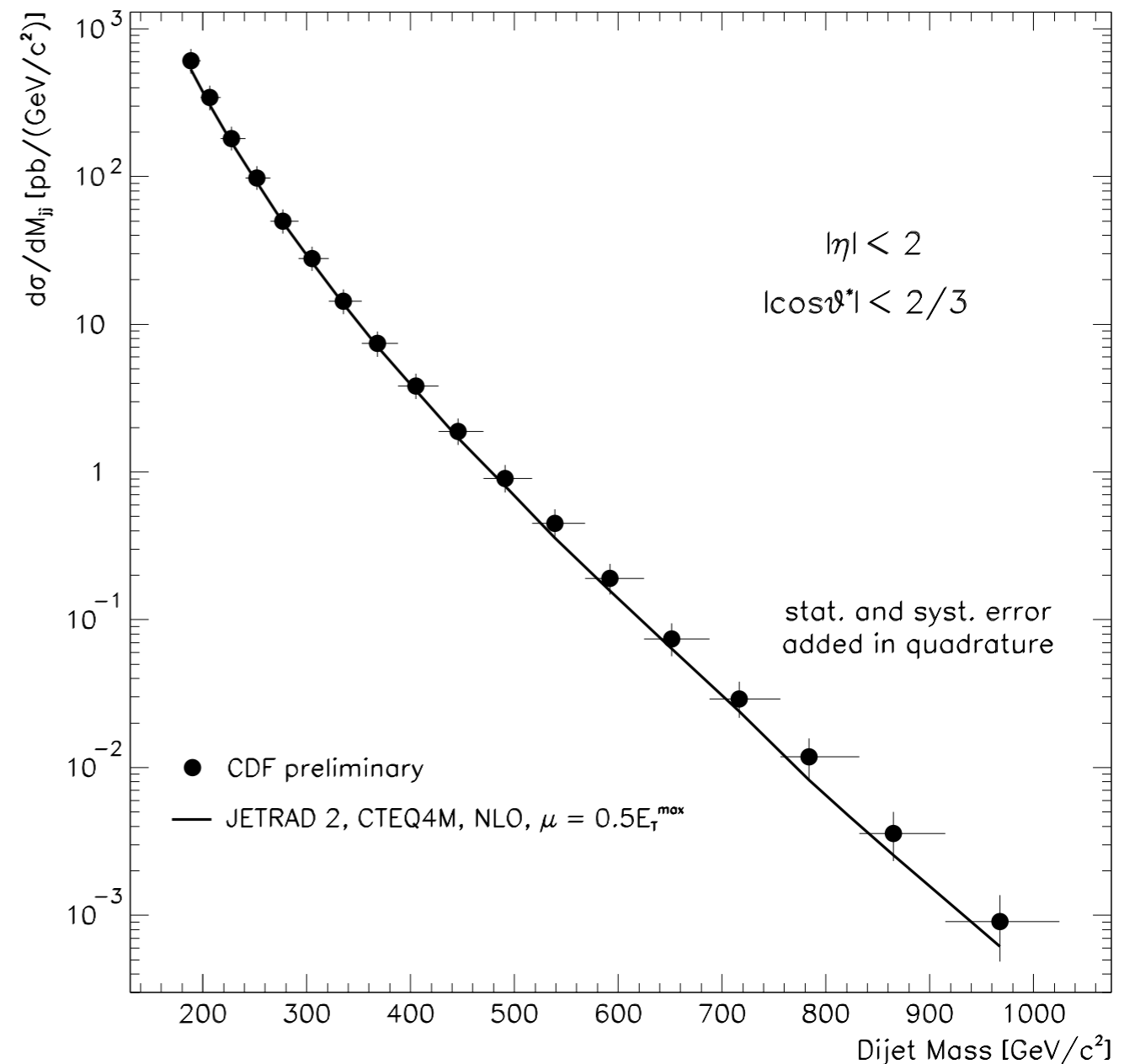
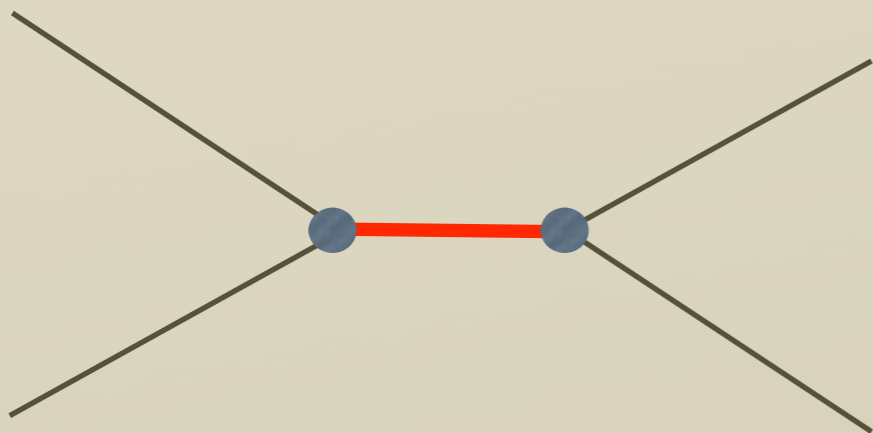


- The rapidity dependence can help sort out between new physics and experimental problems.

- **Two jet cross section**  
(inclusive, measure mass)

$$\frac{d\sigma}{dM_{JJ} dy}$$

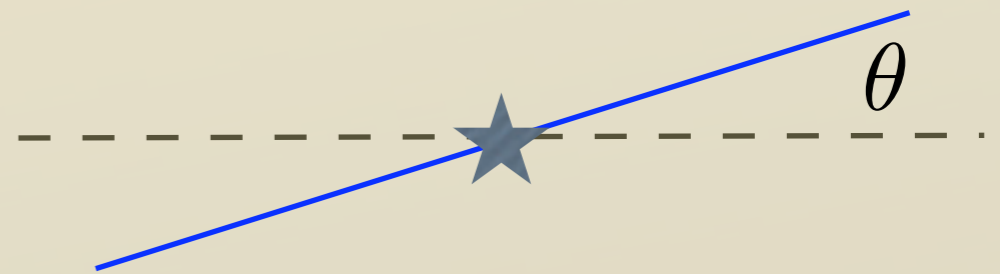
- If there is any kind of a resonance that decays to two jets, this will find it.



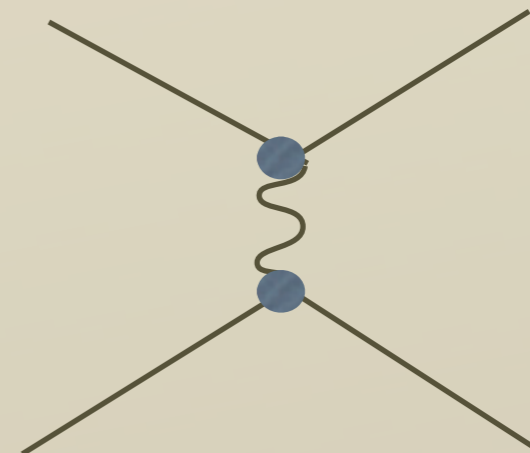
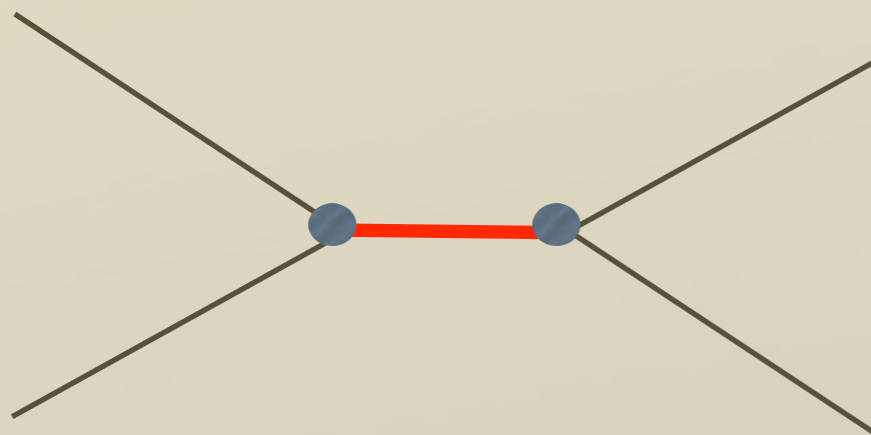
CDF data

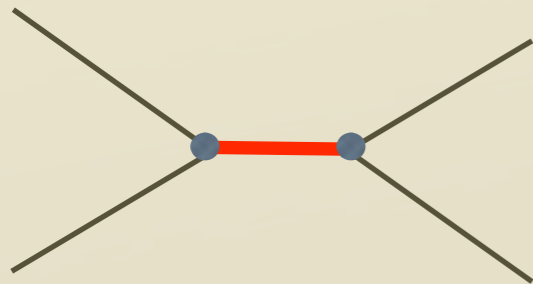
- Two jet angular distribution

$$\frac{d\sigma}{dM_{JJ} dy d\cos\theta} / \frac{d\sigma}{dM_{JJ} dy}$$

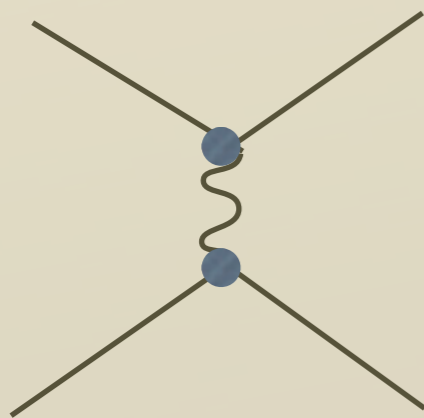


- New physics signals have a different dependence on angle than does QCD.

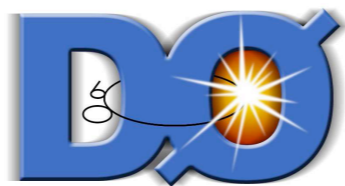




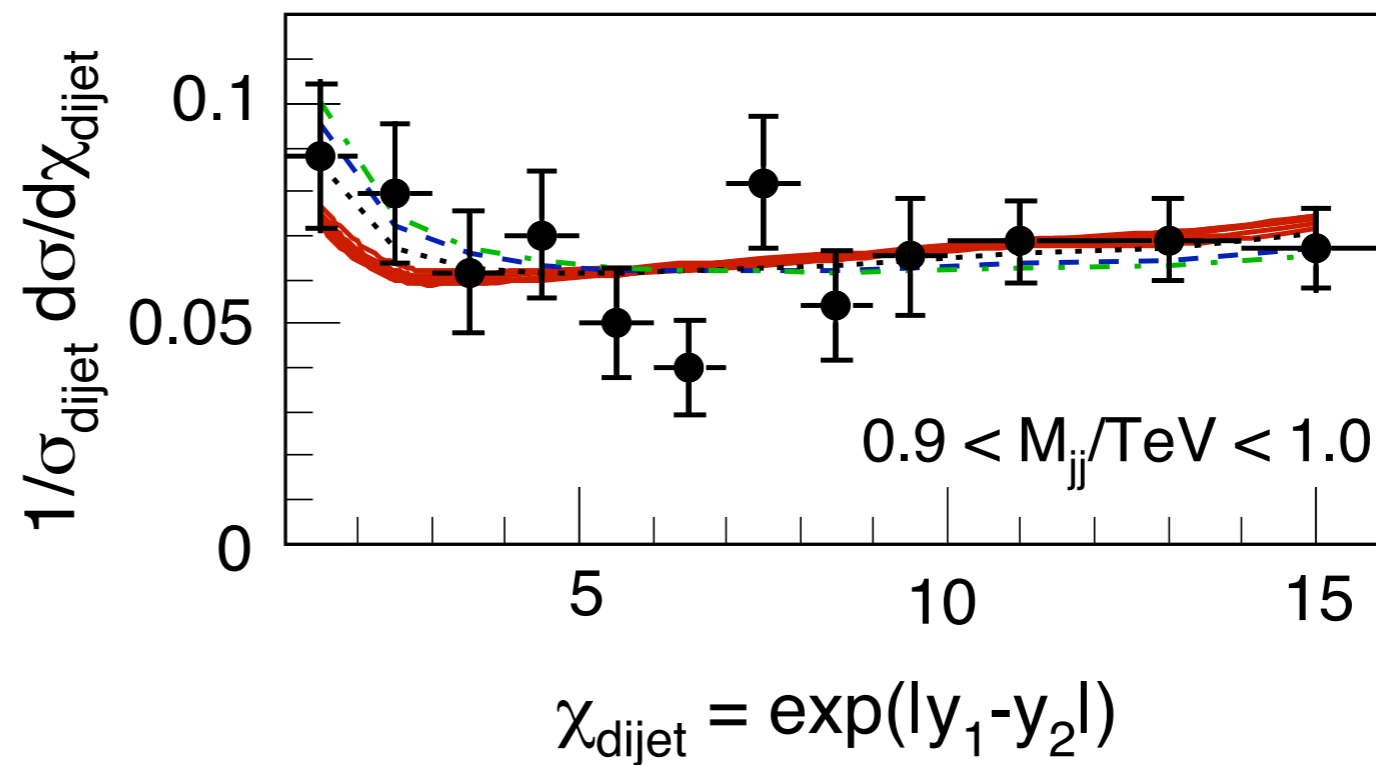
small angle



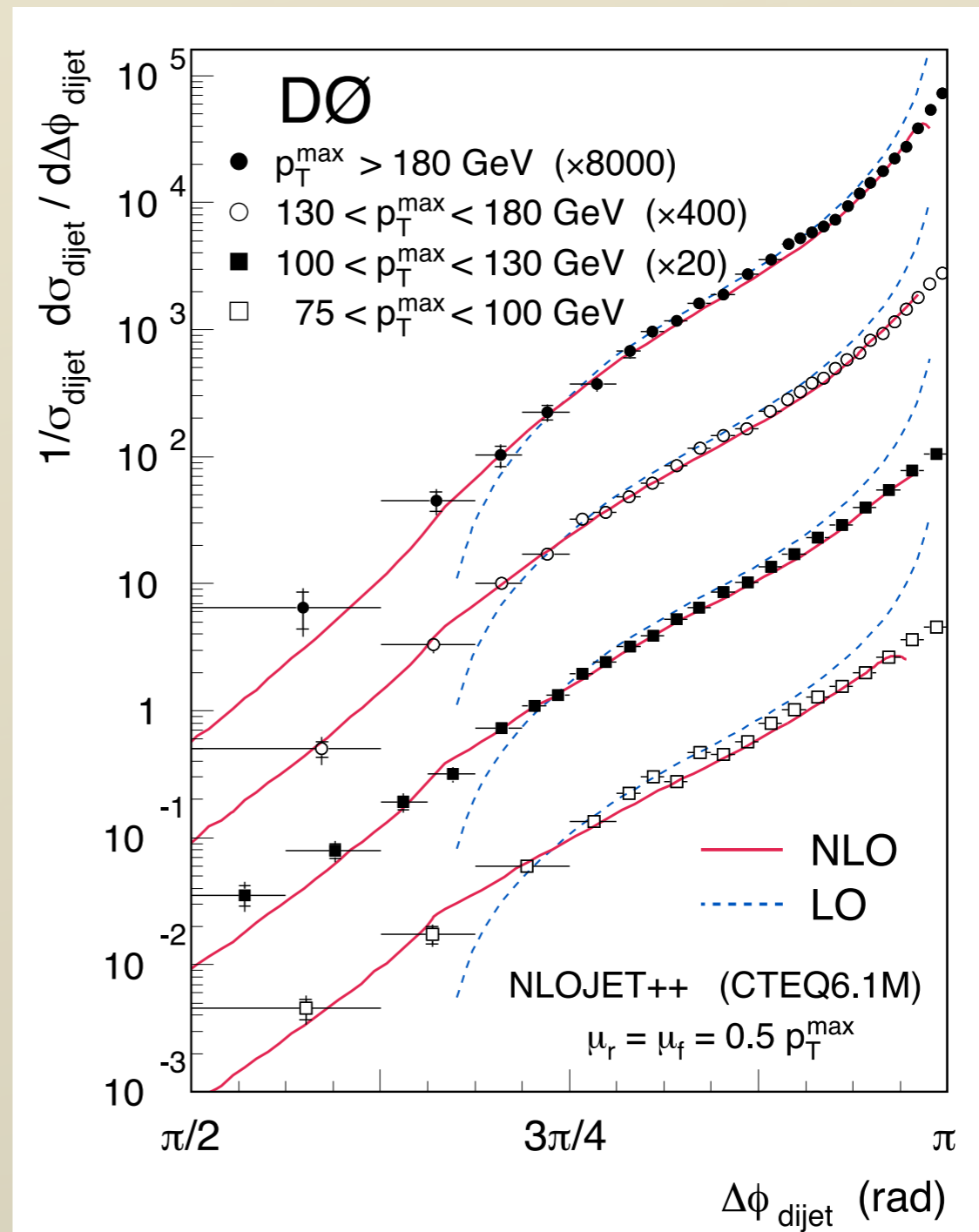
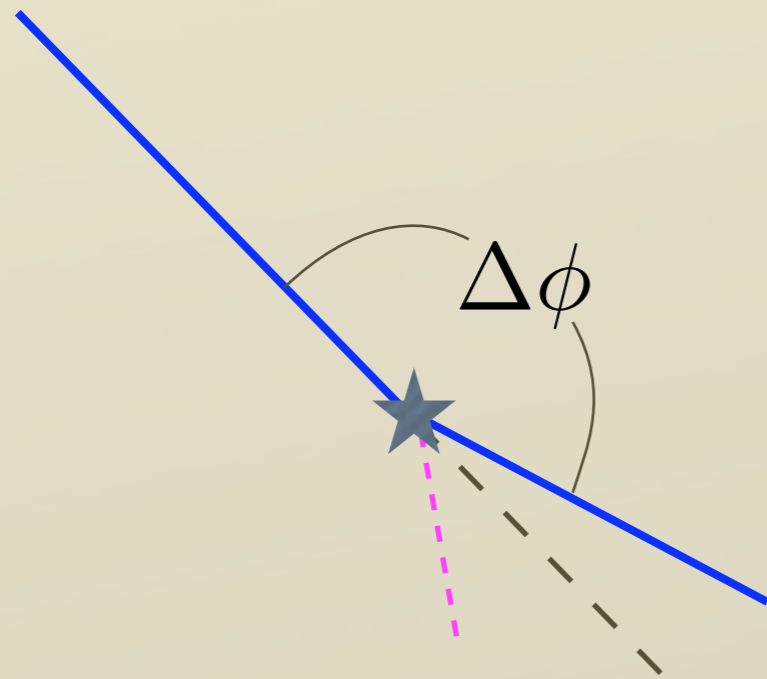
large angle



- DØ preliminary
- Standard Model
- - - Quark Compositeness  
 $\Lambda=2.56\text{TeV}$  ( $\lambda=+1$ )
- ..... ADD Lg. Extra Dim.  
 $M_s=1.55\text{TeV}$  (GRW)
- · - TeV<sup>-1</sup> Extra Dim.  
 $M_c=1.41\text{TeV}$



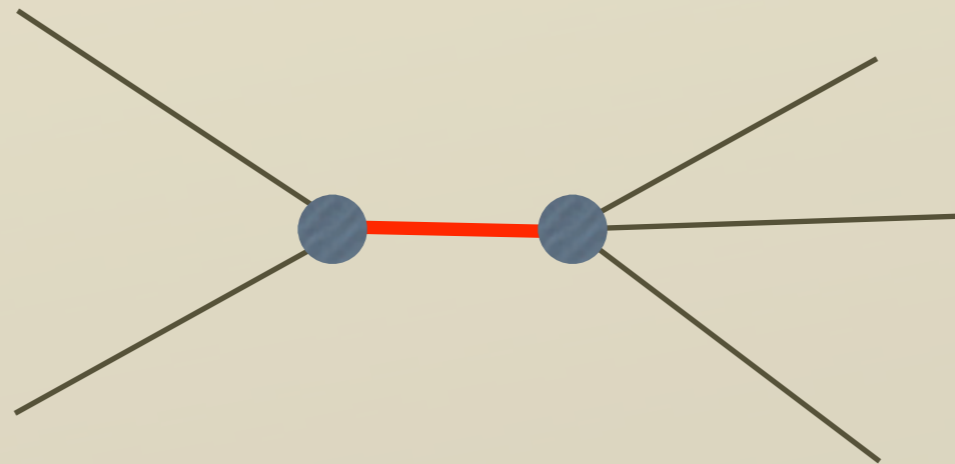
- Two jet azimuthal angular decorrelation.



- This is really a three jet observable.

- Three jet invariant mass distribution

$$\frac{d\sigma}{dM_{JJJ} dy_{JJJ}}$$



- This should be good for finding new physics objects that can decay to three jets.