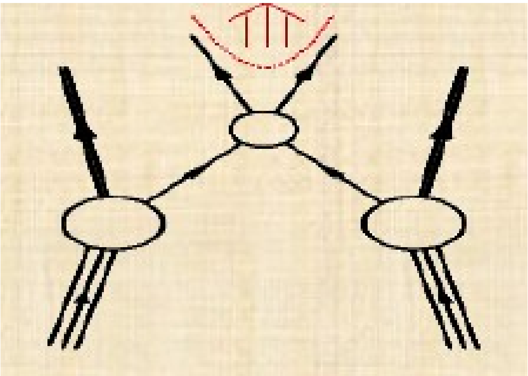
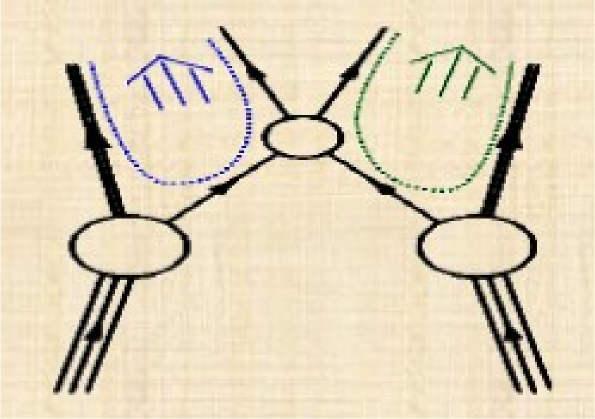
Measurement of color flow in ttbar events at D0



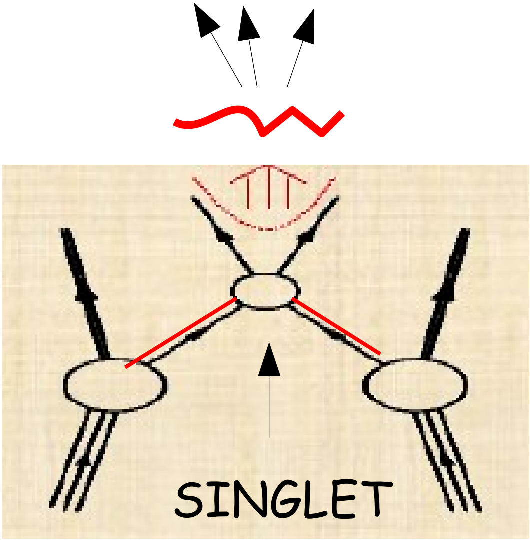


Andy Haas, SLAC
(working with Yvonne Peters at D0)

West Coast ATLAS Forum
December 15, 2010

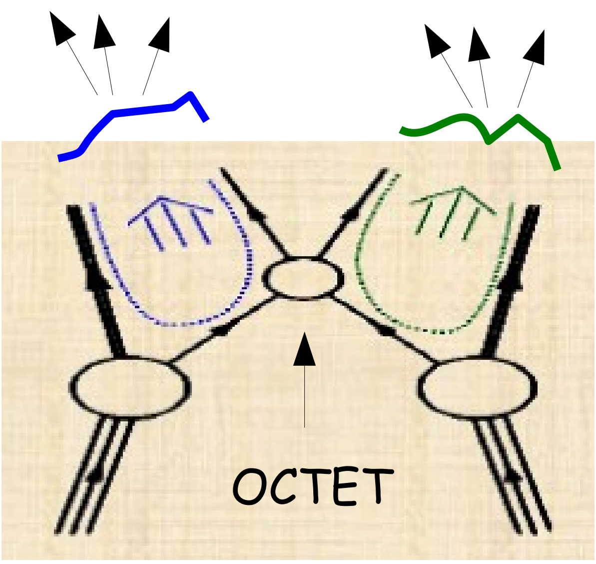
What is "color flow" ??

- QCD color charge is conserved locally
  - It "flows", just like electric charge



- Quarks carry one color (triplet)
- Gluons carry a **color** and an **anti-color** (octet)
- Others (W,Z,H,etc.) carry no color (singlet)

- Pulling apart a color from its anti-color takes a lot of energy (~1 GeV/fm)
  - "color string" or "color connection" formed



- Eventually color strings "break" by pulling quarks out of the vacuum → *hadronization*

How to see color flow → "Jet Pull"

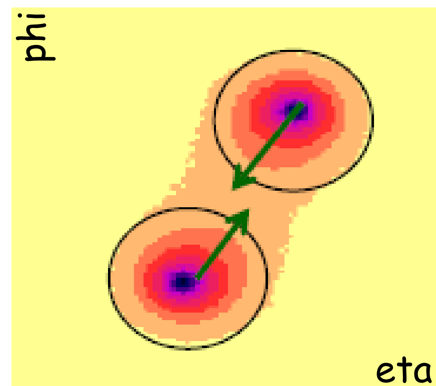
Jets are not "round" → shape is influenced by color flow !!!

Pull vectors point more *towards* each other for color singlet than octet

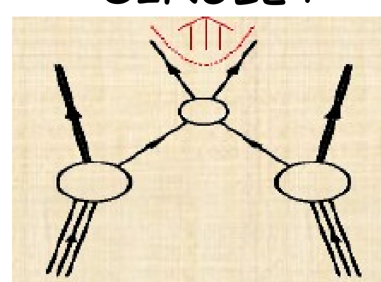
Loop over all cells in dR<0.7:

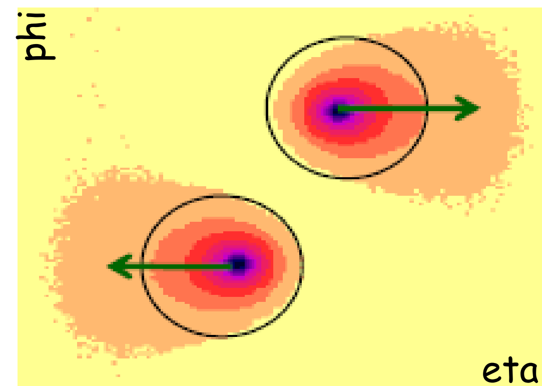
$$\vec{p} = \sum_i \frac{E_T^i \, |r_i|}{E_T^{jet}} \vec{r}_i$$

where r points from
jet center to each cell

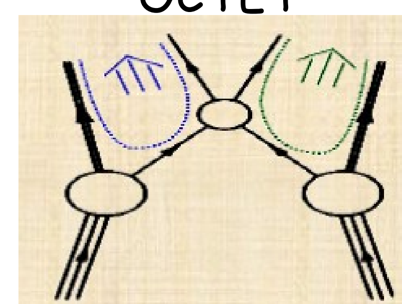


SINGLET





OCTET



Matt Schwartz and Jason Gallicchio
Phys.Rev.Lett.105:022001,2010
http://arxiv.org/abs/1001.5027

How to see color flow → "Jet Pull"

Jets are not "round" → shape is influenced by color flow !!!

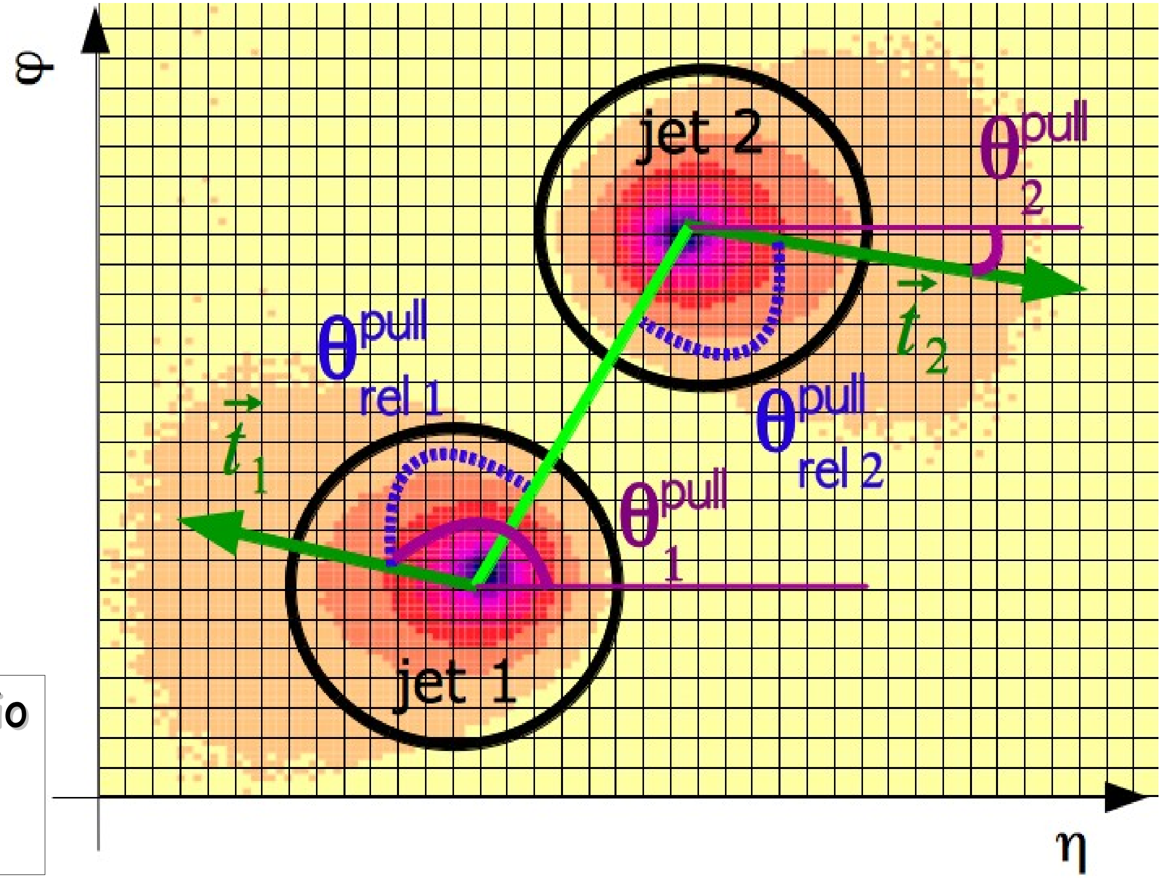
Pull vectors point more *towards* each other for color singlet than octet

Loop over all cells in dR<0.7:

$$\vec{p} = \sum_i \frac{E_T^i \, |r_i|}{E_T^{jet}} \vec{r}_i$$

where r points from jet center to each cell

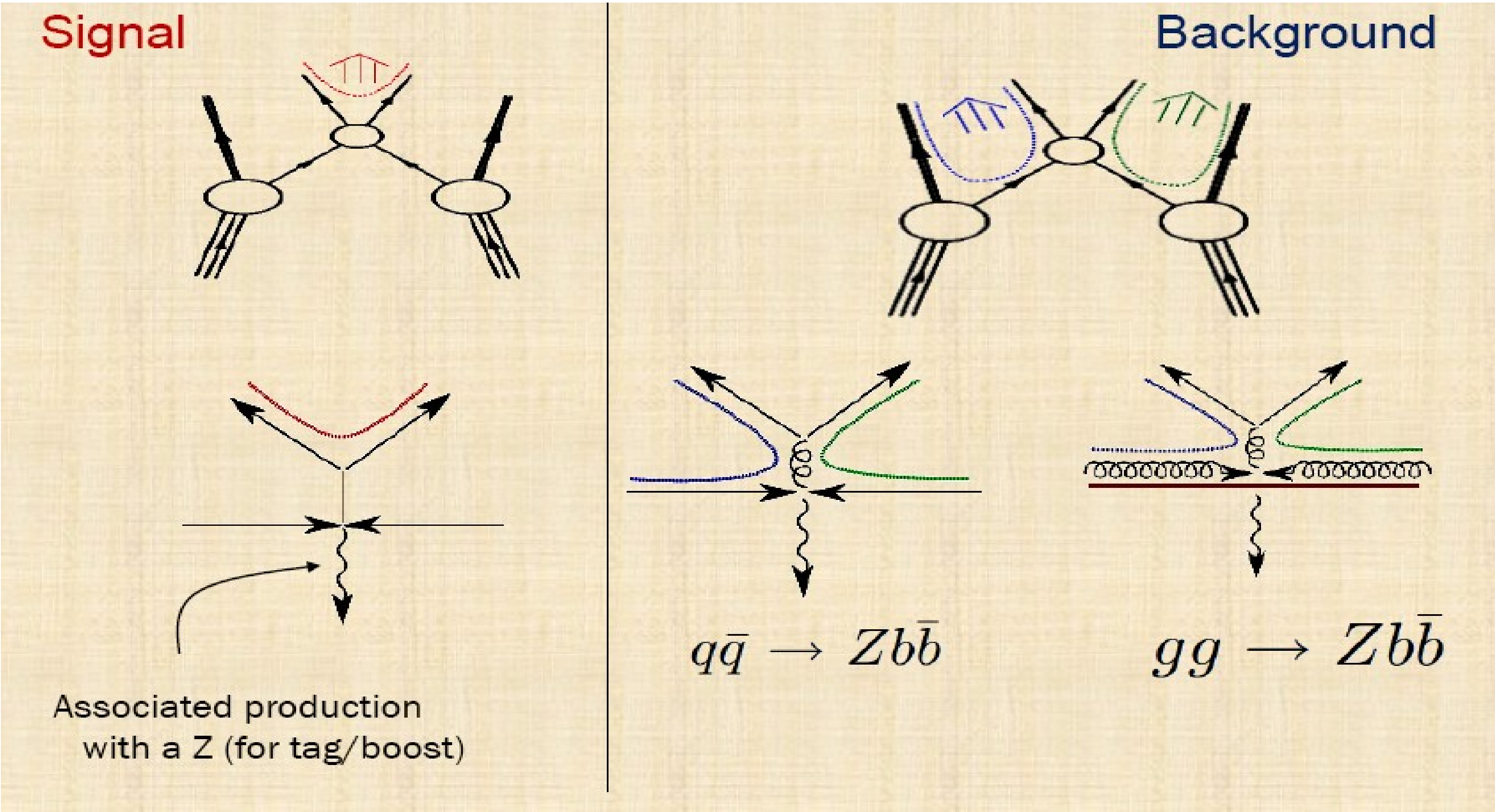
Matt Schwartz and Jason Gallicchio
Phys.Rev.Lett.105:022001,2010
http://arxiv.org/abs/1001.5027



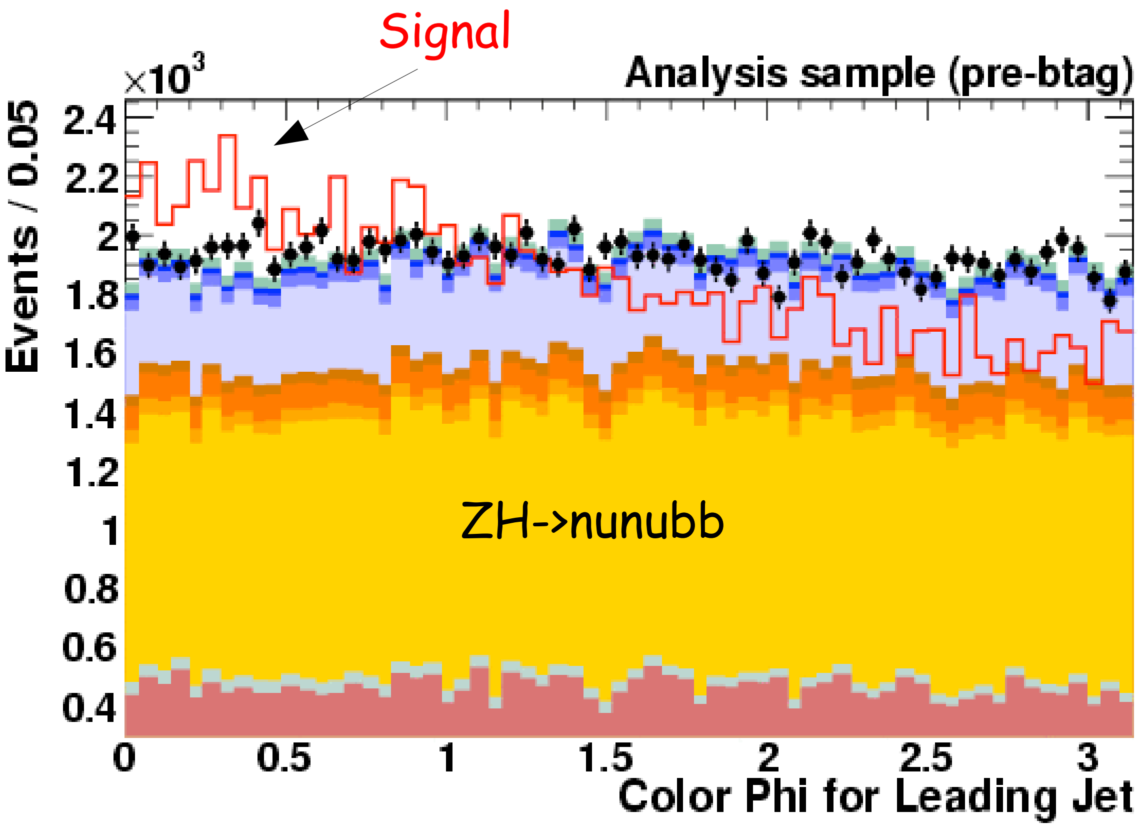
Low mass SM Higgs

Additional difference between H->bb and g->bb:

- H is color singlet – b's must have same color and are "connected together"
- g is color octet – b's have different color and are "connected to beam"



Example from D0 Higgs analysis



Used for D0's ICHEP'10
ZH -> nunu bb search

Extra ~5% sensitivity !

(Could be improved to >10%?)

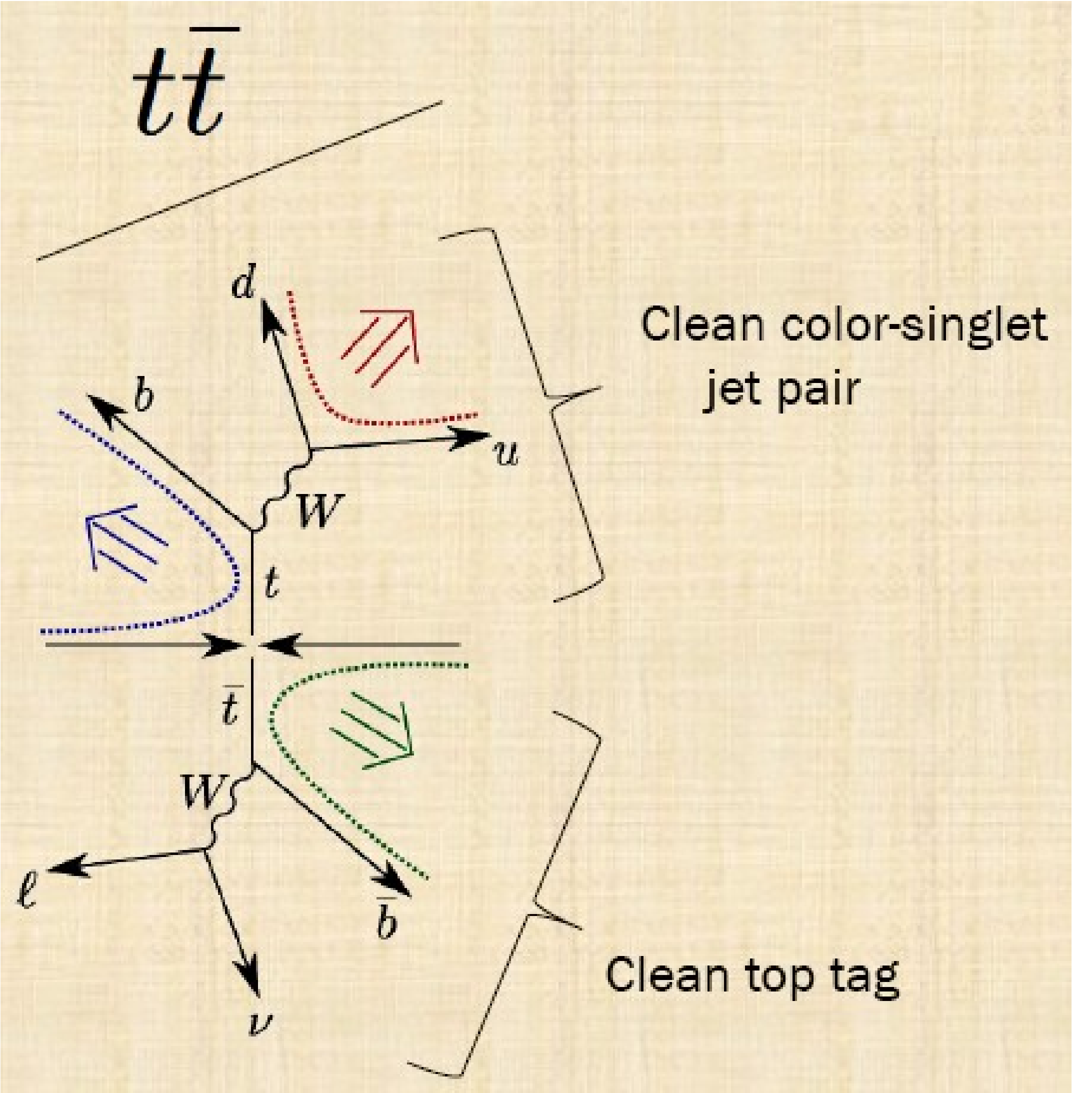
Background (mostly octet) shape well-modeled by MC

But is the signal (singlet) shape well-modeled by MC?

("Color flow" studied at LEP, but not jet pull, and these are hadron collisions...)

Testing color singlet jet pull in data

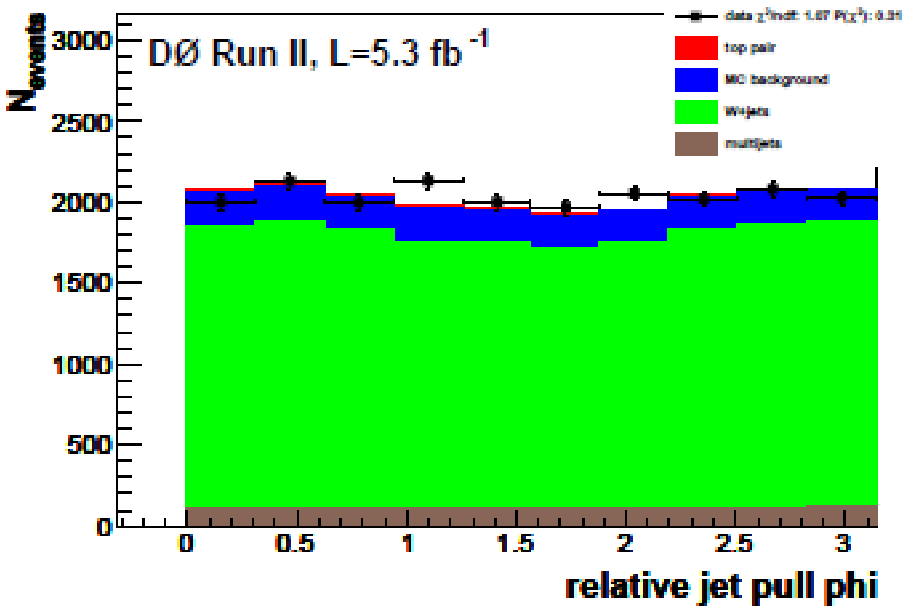
- Need clean sample of W/Z/H decays to jets!
- ttbar is the most promising
  - Have ~500 double b-tagged lepton+jet ttbar events at D0
  - ~90% pure sample
- W->jj decay is pure color singlet
- **Verifying singlet color flow / jet pull for the first time ever at a hadron collider !**



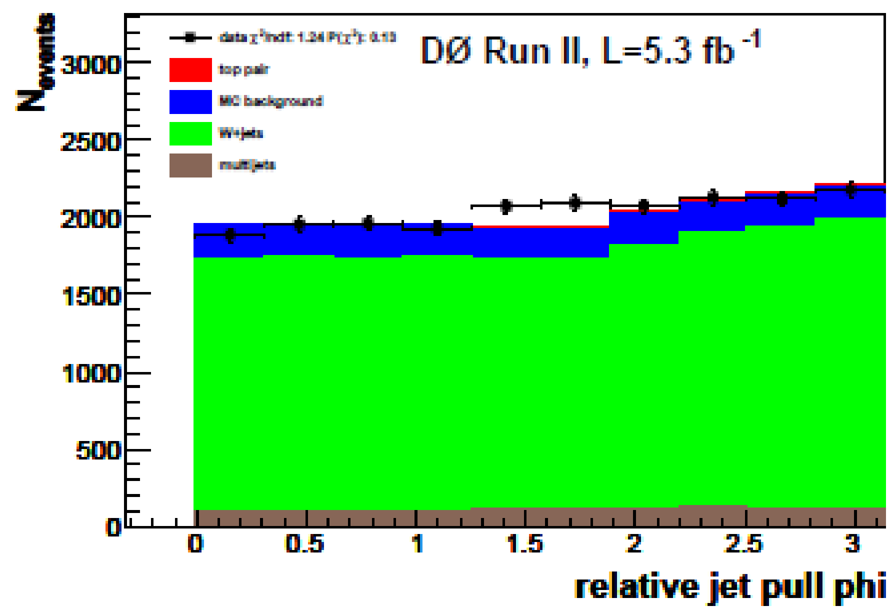
Jet pull in control samples, data/MC

- Look at light jets in *anti-b-tagged* W+jets samples
- Good data/MC agreement, for both jets

<u>Leading-pT light jet</u>

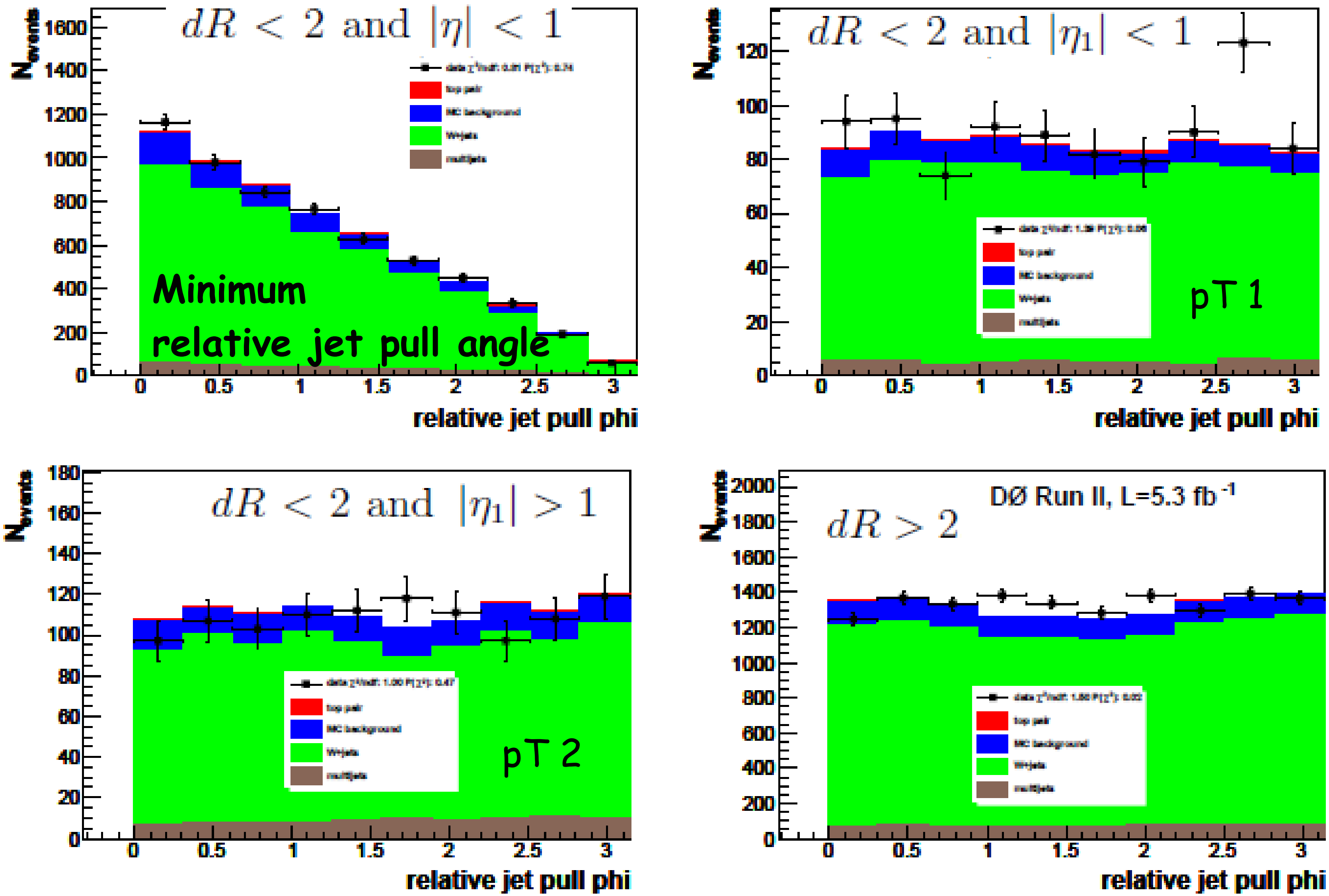


<u>Second-leading-pT light jet</u>



W + 2 light jets sample

Separated by eta's of jets

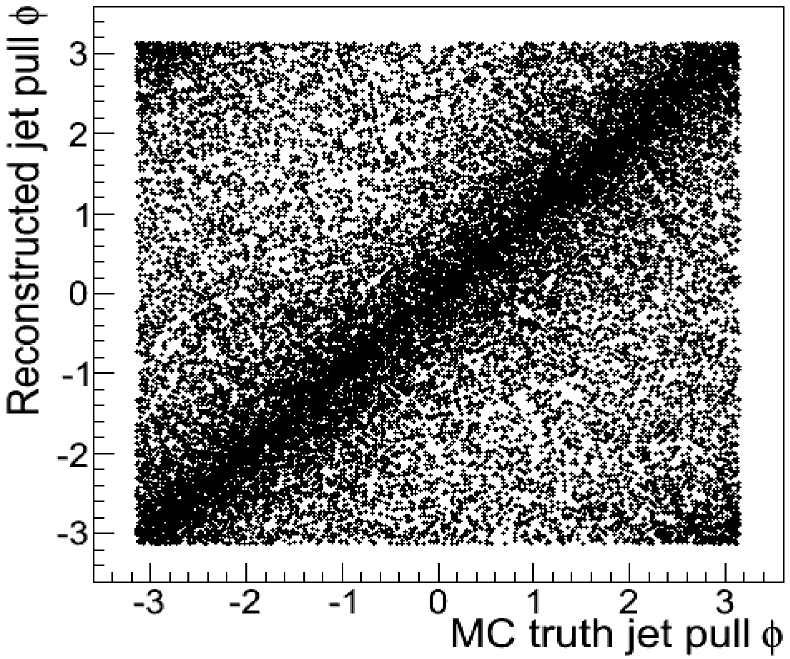


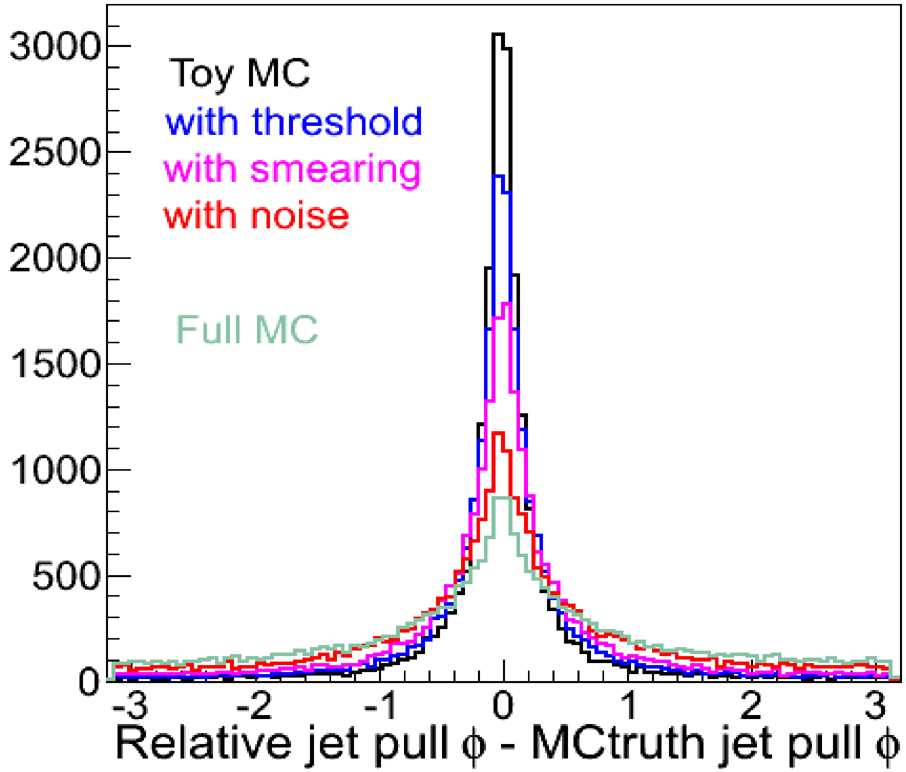
W + 2 light jets sample

Jet pull reconstruction

Compute "MC truth jet pull"

- Use truth particles within dR<0.7 of jet and |dz|<1 cm of primary vertex (except muons and neutrinos)



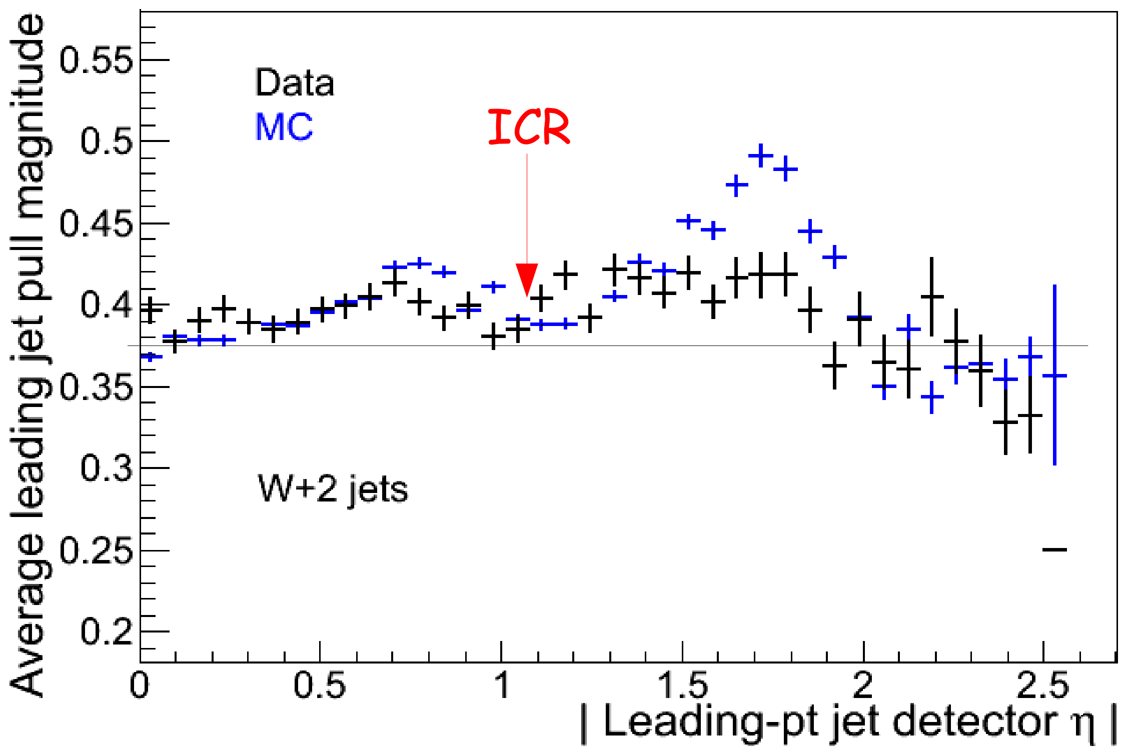


Do a "Toy MC" of calorimeter to see effects individually of:

- detector granularity
- energy thresholds / resolution
- detector noise / pileup

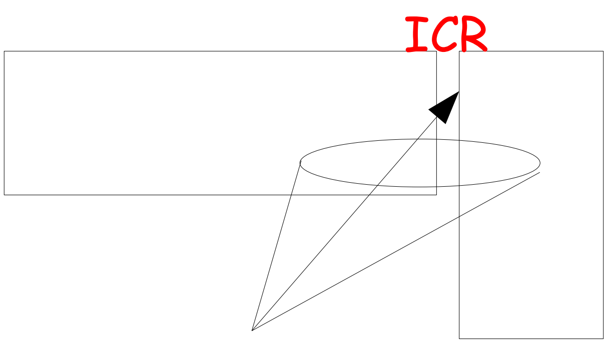
Checks of jet pull reconstruction

- Jet pull *magnitude* (amount of eccentricity) is also well-modeled
- But excess eccentricity is induced by the ICR
  - Corrected for by adding a vector to the jet pull opposite to ICR direction
- Correction is also ~20% different for data/MC, used as systematic



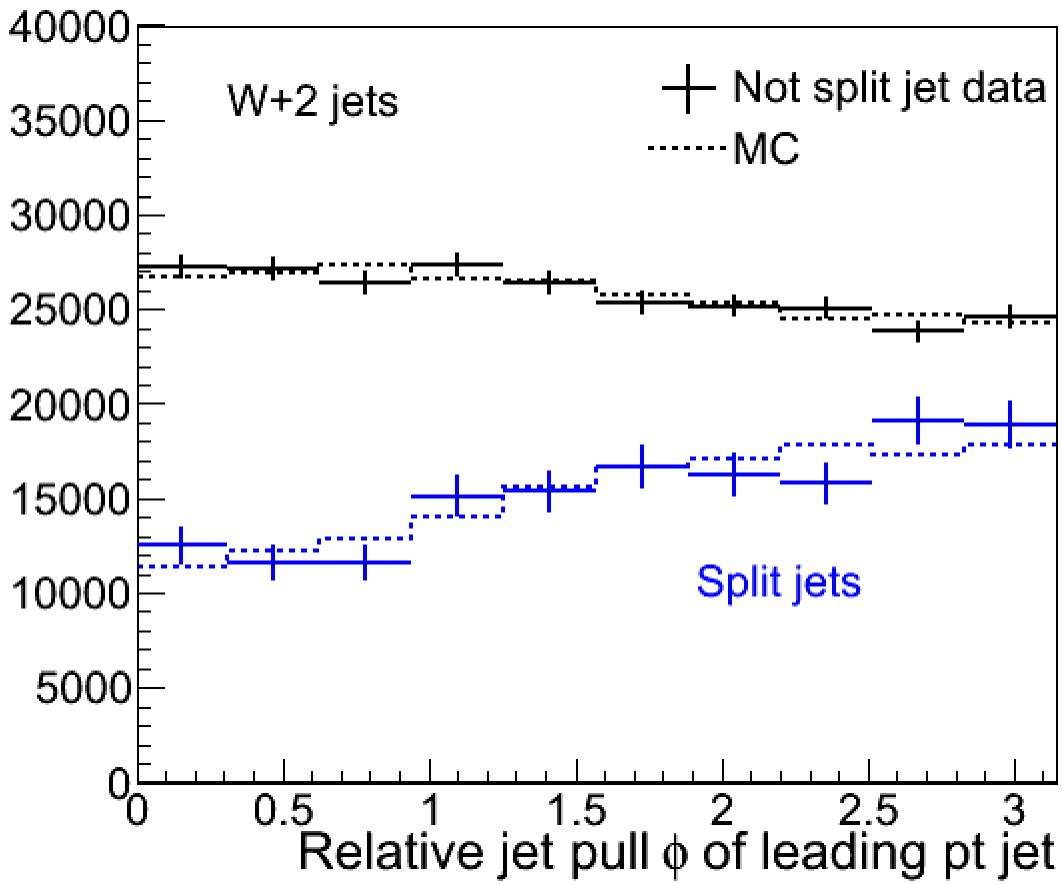
Different response/noise in ICR region

Pull biased towards +-eta direction

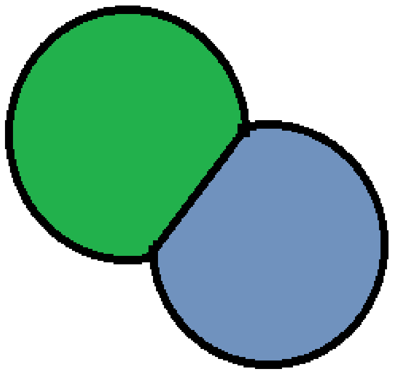


Checks of jet pull reconstruction

- Look at jets which were **split** and **not split**



Noise/pileup area smaller towards other jet!



Cells are assigned to the *nearest jet*

OK - back to ttbar !

Added "jet pull" variables to standard D0 l+jets analysis

5.3/fb **L+jets selection**

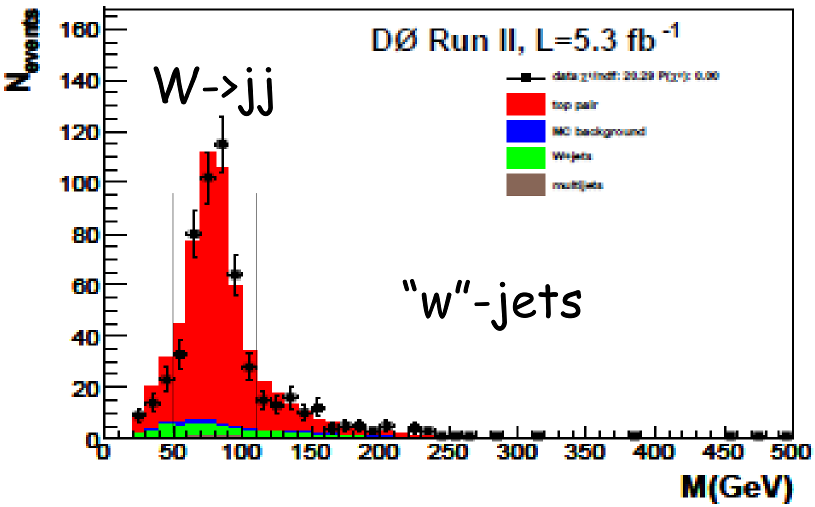
- Dataset: Run IIa & full RunIIb2 (Summer09 extended)
- SuperOr trigger for e+jets, SingleMuonTrigger for mu+jets Run IIb, MuJets for Run Iia
  - SingleMuonTrigger: Now the fully debugged version!
- Require one isolated electron or muon with p_T >20GeV
- $\not{E}$>20GeV (e) or $\not{E}$>25GeV (mu)
- 3 or at least 4 (in Run IIb: vertex confirmed) jets
  - p_T>20GeV
  - leading jet >40GeV
- Triangle cut:
  - ejets: $d\phi(\not{E},lep)>2.2-0.045\not{E}$
  - mujets: $d\phi(\not{E},lep)>2.1-0.035\not{E}$
- Additional cuts in mu+jets: M^W_T<250GeV & $\not{E}$<250GeV

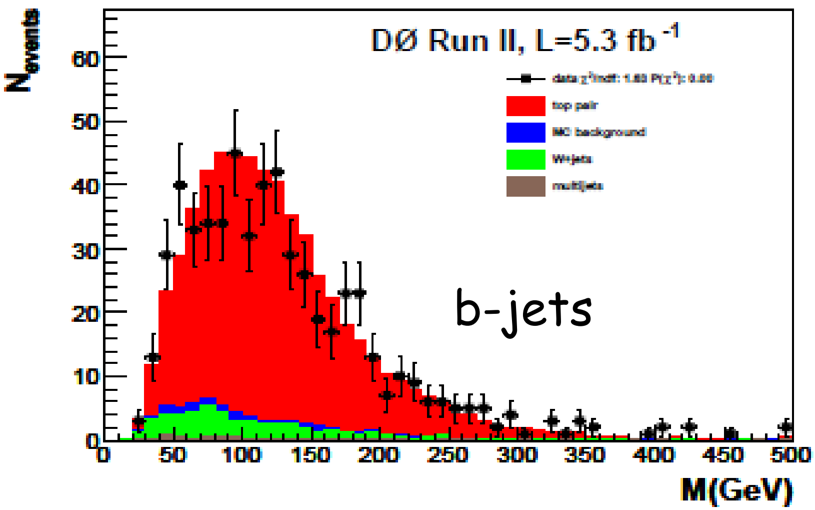
Extra Cuts:
>=2 L4 b-tags
4 or >=5 jets
|mW-(jj)|<30

Standard CSG MC samples
$t\bar{t}$ MC:
Alpgen+Pythia, top mass 172.5GeV

Studies of ttbar lepton+jets

- 66% (46%) pure W->jj decays in |M-mW|<30 GeV for 4 (>=5) jets

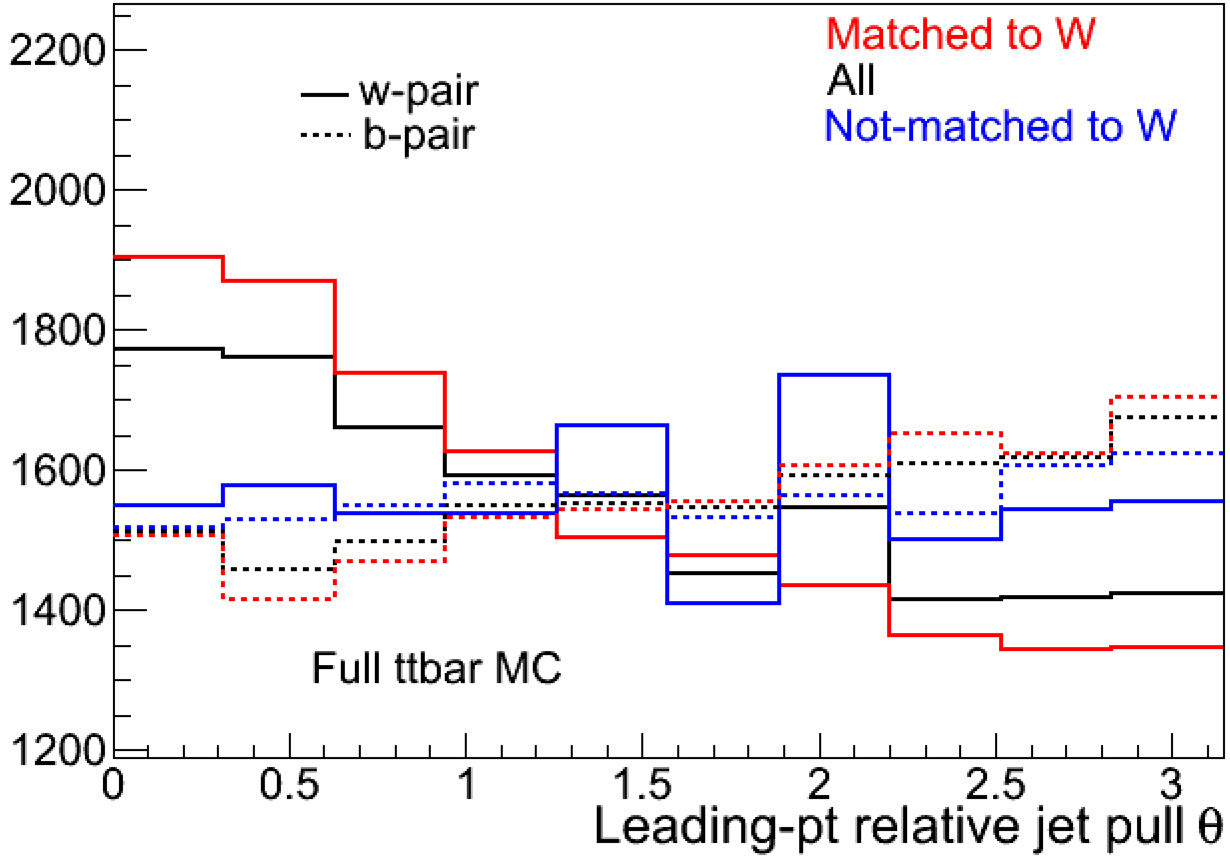




channel	sample	0 b-tags	1 b-tag	$\geq$ 2 b-tags
ℓ+4 jets	W+jets	576 ± 75	229 ± 32	49 ± 8
	Multijet	115 ± 16	46 ± 7	7 ± 2
	Z+jets	42 ± 6	16 ± 3	4 ± 1
	Other	31 ± 4	19 ± 2	9 ± 1
	$t\bar{t}$	160 ± 22	417 ± 38	519 ± 51
	Total	923 ± 62	727 ± 24	589 ± 48
	Observed	923	743	572
ℓ+$\geq$5 jets	W+jets	60 ± 22	26 ± 11	7 ± 3
	Multijet	17 ± 3	12 ± 2	3 ± 1
	Z+jets	4 ± 1	2 ± 1	1 ± 1
	Other	3 ± 1	3 ± 1	2 ± 1
	$t\bar{t}$	34 ± 6	90 ± 13	132 ± 17
	Total	118 ± 19	132 ± 7	145 ± 15
	Observed	112	127	156

Studies of ttbar lepton+jets

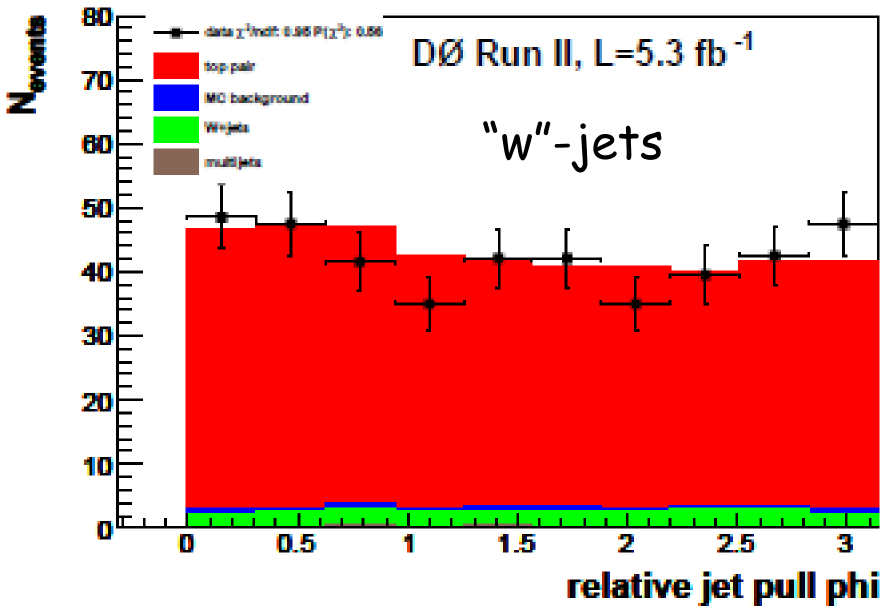
What do we expect from (full) MC ?

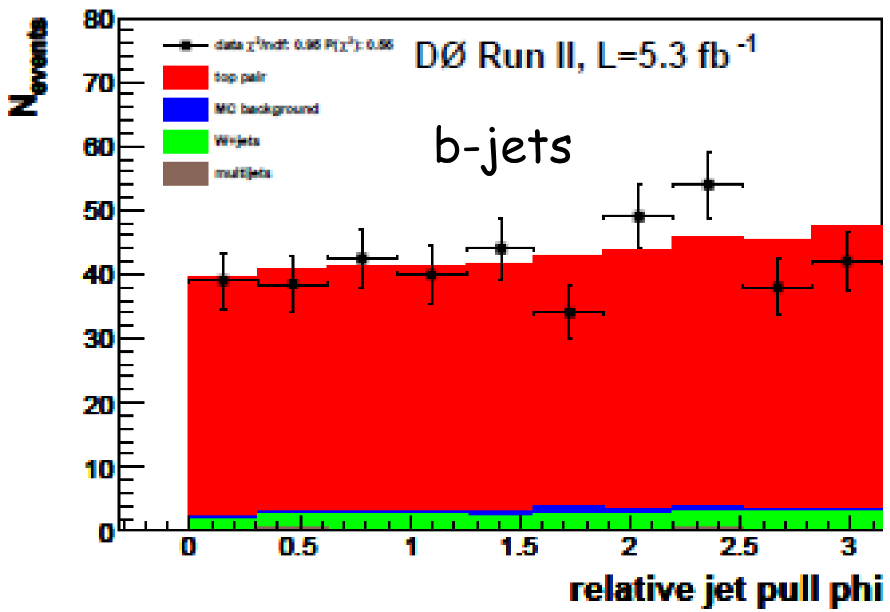


Separation is degraded by
misidentified W->jj decays

Jet pull in ttbar, data/MC

- Good data/MC agreement, for both “w” and b jets !
- w-jets peak more towards zero (pointing towards each other) !
- But this is not an apples-to-apples comparison → different kinematics and flavor for the light and b jets
- Later we do a *direct* comparison, in events with identical kinematics

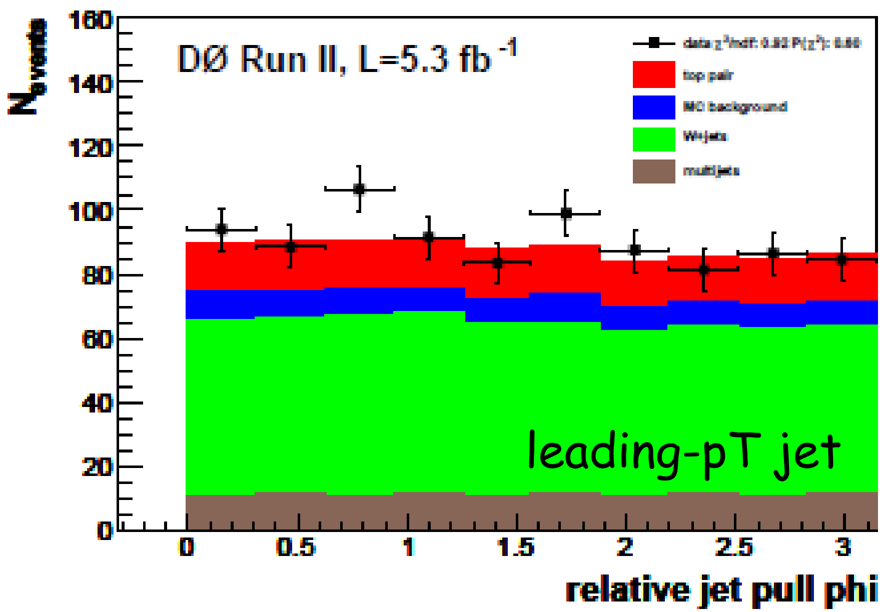




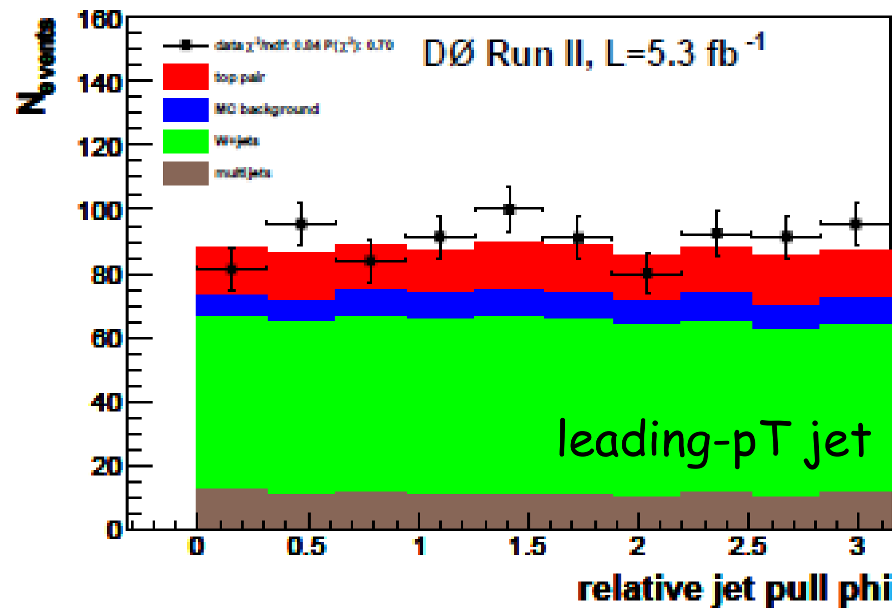
Jet pull in control samples, data/MC

- Look at *anti-b-tagged* W+4 jets samples
- Good data/MC agreement, for both sets of jets
- Flatter than in real ttbar (since there's not real color connections?)

<u>Two jets with Mjj closest to mW</u>

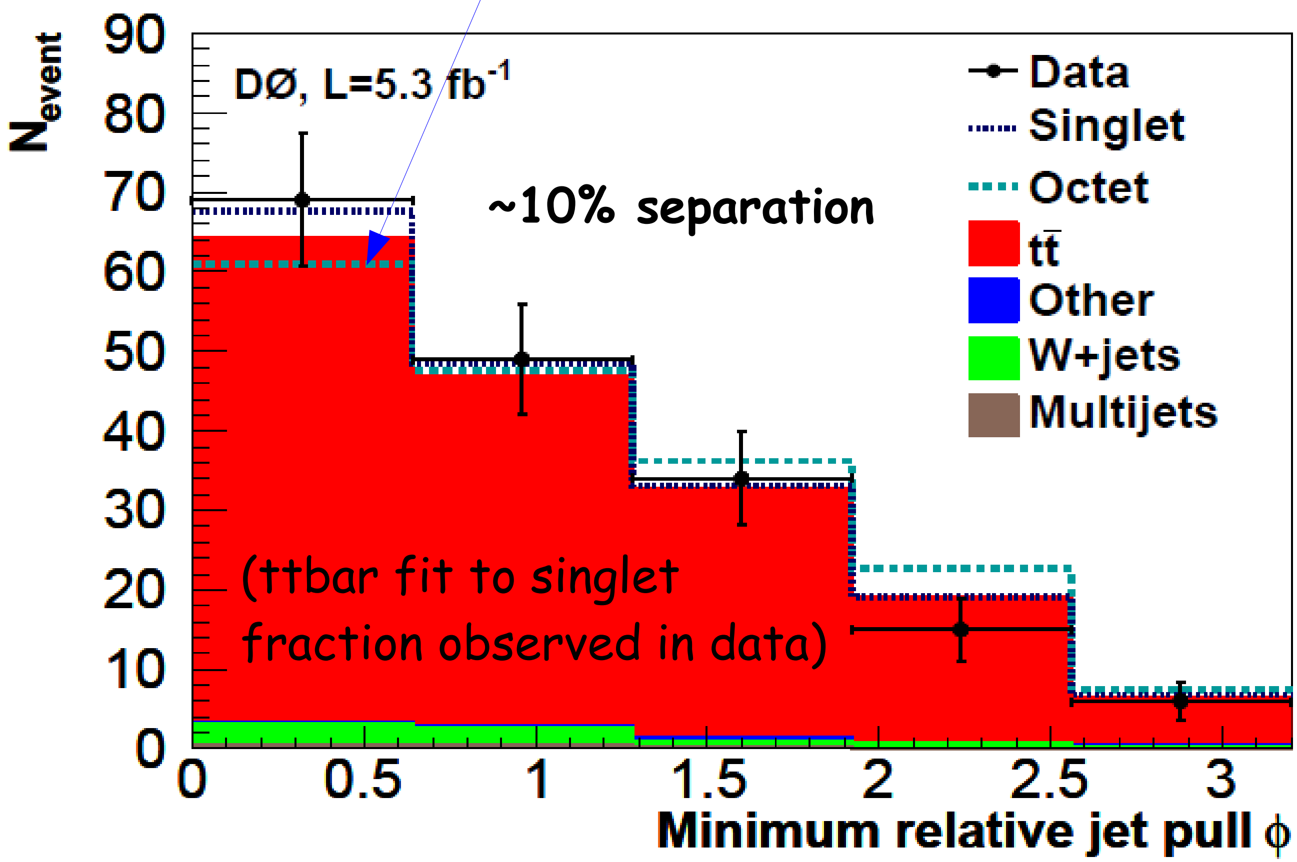


<u>Other two jets in the event</u>



What "color" is the X in ttbar->bbW(->lnu)X(->qq') ?

- Of course we know that X is a W, which is a color singlet…
- Test our sensitivity to separate singlet/octet and simulation modeling
- ttbar MC with OCTET hadronic"X" decay using MadGraph+Pythia



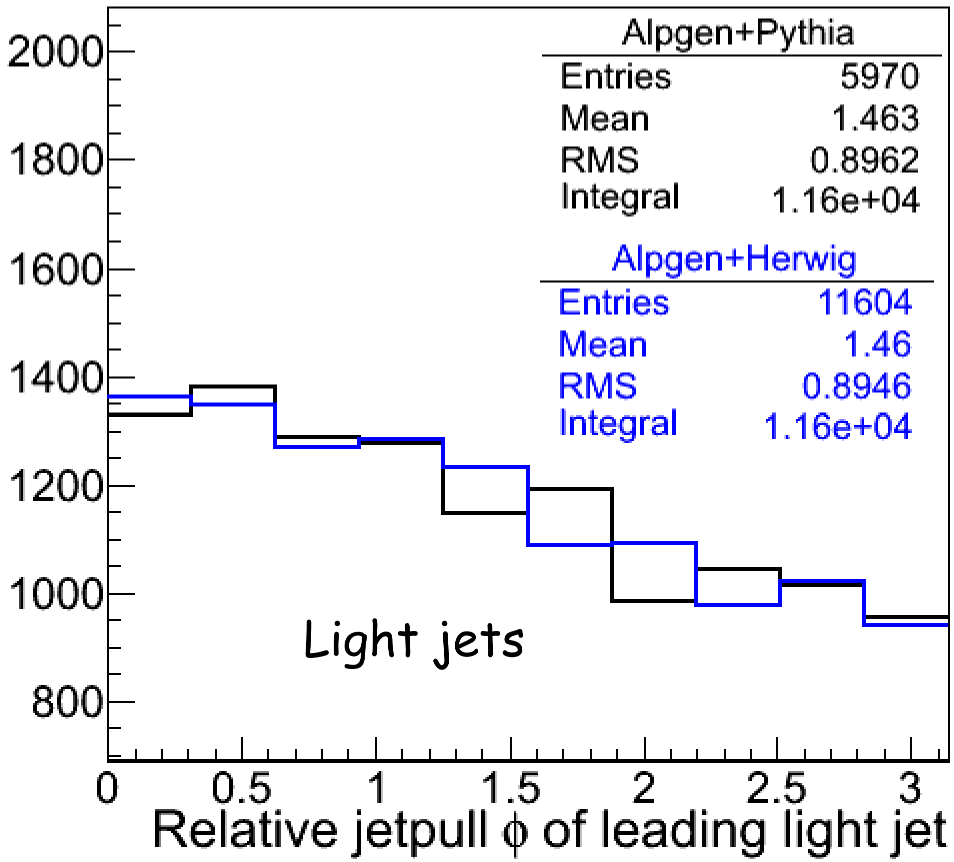
Split into 5 "regions" based on dR, eta, and mW

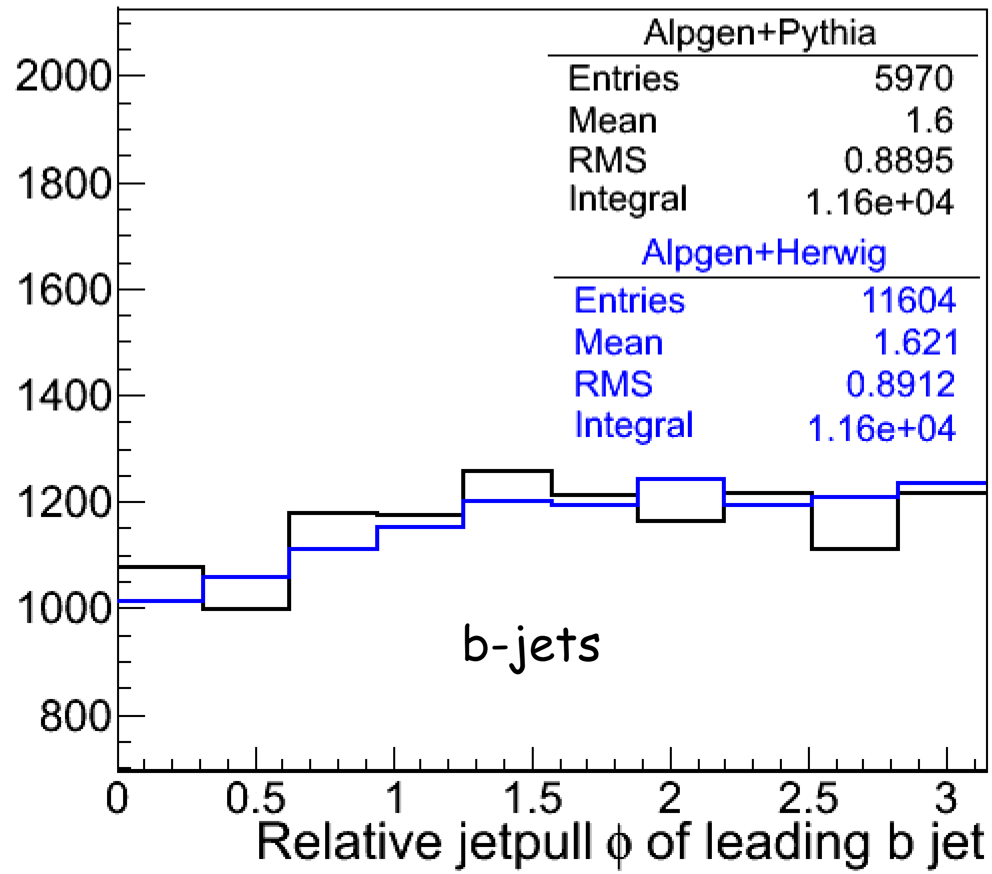
Central region, |M-mW| <30, with dR<2 is most sensitive

Data prefer a color singlet "X"

Systematics on jet pull shape

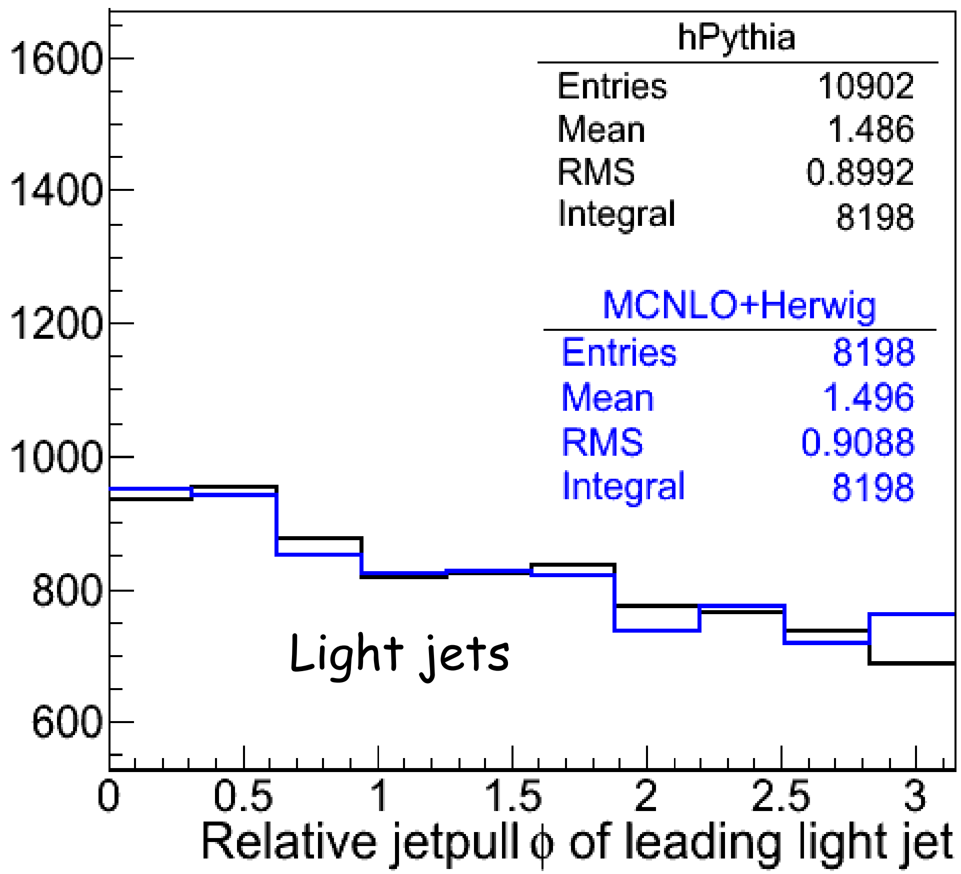
ALPGEN+Pythia agrees with ALPGEN+Herwig showering

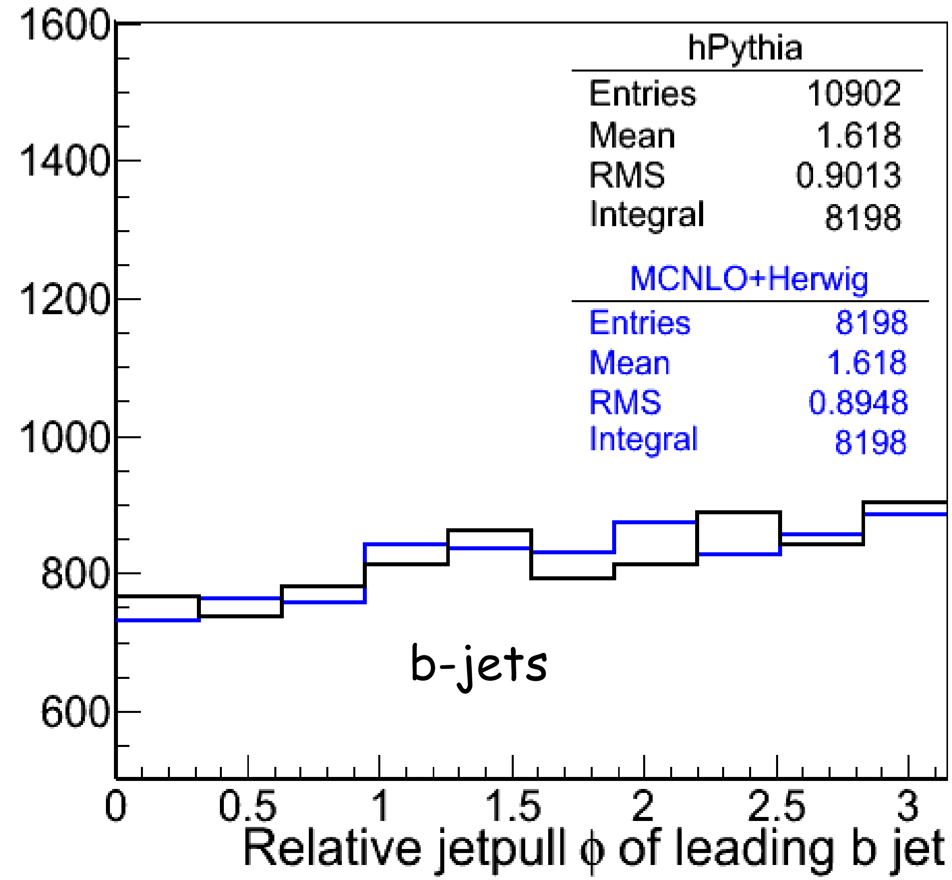




Systematics on jet pull shape

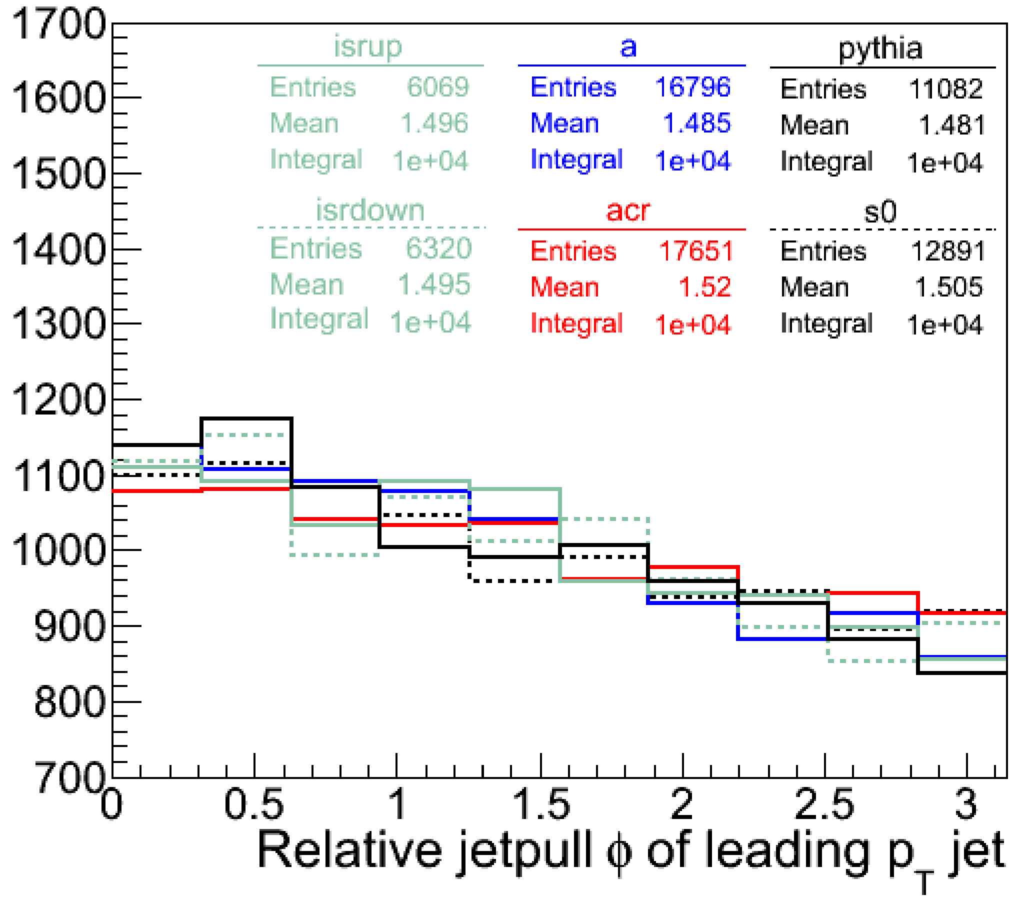
MCNLO+Herwig agrees with plain Pythia





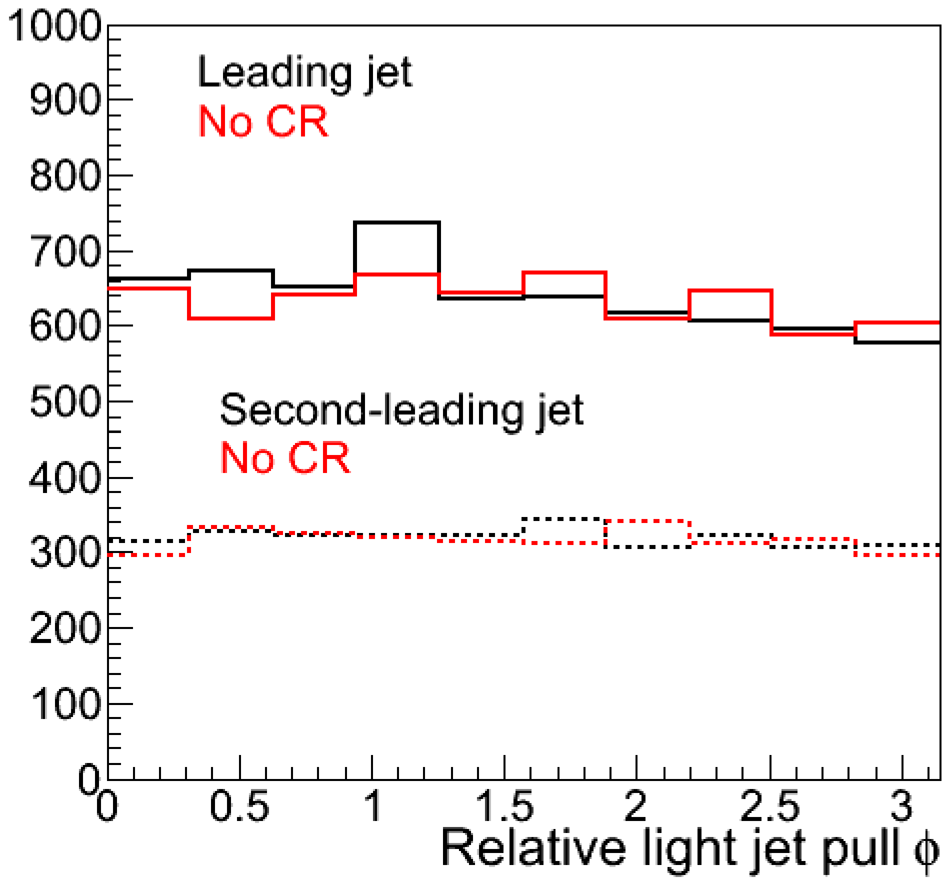
Systematics on jet pull shape

- Various Pythia "tunes", underlying event, other parameters, etc.
  - All give similar jet pull shapes
- Tune ACR is flatter, UNPHYSICAL color reconnection model for W



Systematics on jet pull shape

- Recent Pythia tunes have a more physical way of turning on/off color reconnection, while still maintaining (most) agreement with UE
- No large effects from color reconnection (theoretically also <10%)



Systematics

- Limited MC stats for singlet/octet templates
  - Private production
  - Managed to make ~1M events
  - Still less than statistical uncertainty from data
- Next largest is data/MC correction for ICR region

Source	$+\sigma$	$-\sigma$
Singlet/octet MC shapes	0.188	−0.188
Jet pull reconstruction	0.100	−0.093
Jet energy resolution	0.033	−0.013
Vertex confirmation	0.028	−0.029
PYTHIA tunes	0.023	−0.025
Jet energy scale	0.024	−0.009
Jet reconstruction and identification	0.017	−0.017
$t\bar{t}$ modeling	0.014	−0.033
Event statistics for matrix method	0.009	−0.010
Other Monte Carlo statistics	0.009	−0.007
Multijet background	0.006	−0.007
Total systematic	0.222	−0.218

Systematics

Other systematics (standard in ttbar analyses) are found to be very small...

Summary of systematics on $f_{Singlet}$ with standard method		
Source	sigma+	sigma-
Event pre-selection	0.000	-0.000
Muon identification	0.001	-0.000
Muon resolution and scale	0.000	-0.000
Electron identification and smearing	0.001	-0.000
Electron scale	0.000	-0.000
Luminosity reweighting	0.000	-0.000
Z p_T reweighting	0.001	-0.000
EM triggers	0.000	-0.000
Muon triggers	0.001	-0.001
Monte Carlo background x-section	0.001	-0.001
Monte Carlo signal & bkgd branching ratio	0.000	-0.000
b-Jet energy scale	0.001	-0.000
Taggability in data	0.001	-0.000
b-tag TRF	0.000 (0.001)	-0.000 (0.000)
light tag TRF	0.000 (0.000)	-0.000 (0.000)
b fragmentation	0.000	-0.000
W fractions matching + higher order effects	0.003	-0.004
Luminosity	0.001	-0.000

What "color" is the X in ttbar->bbW(->lnu)X(->qq') ?

Results!

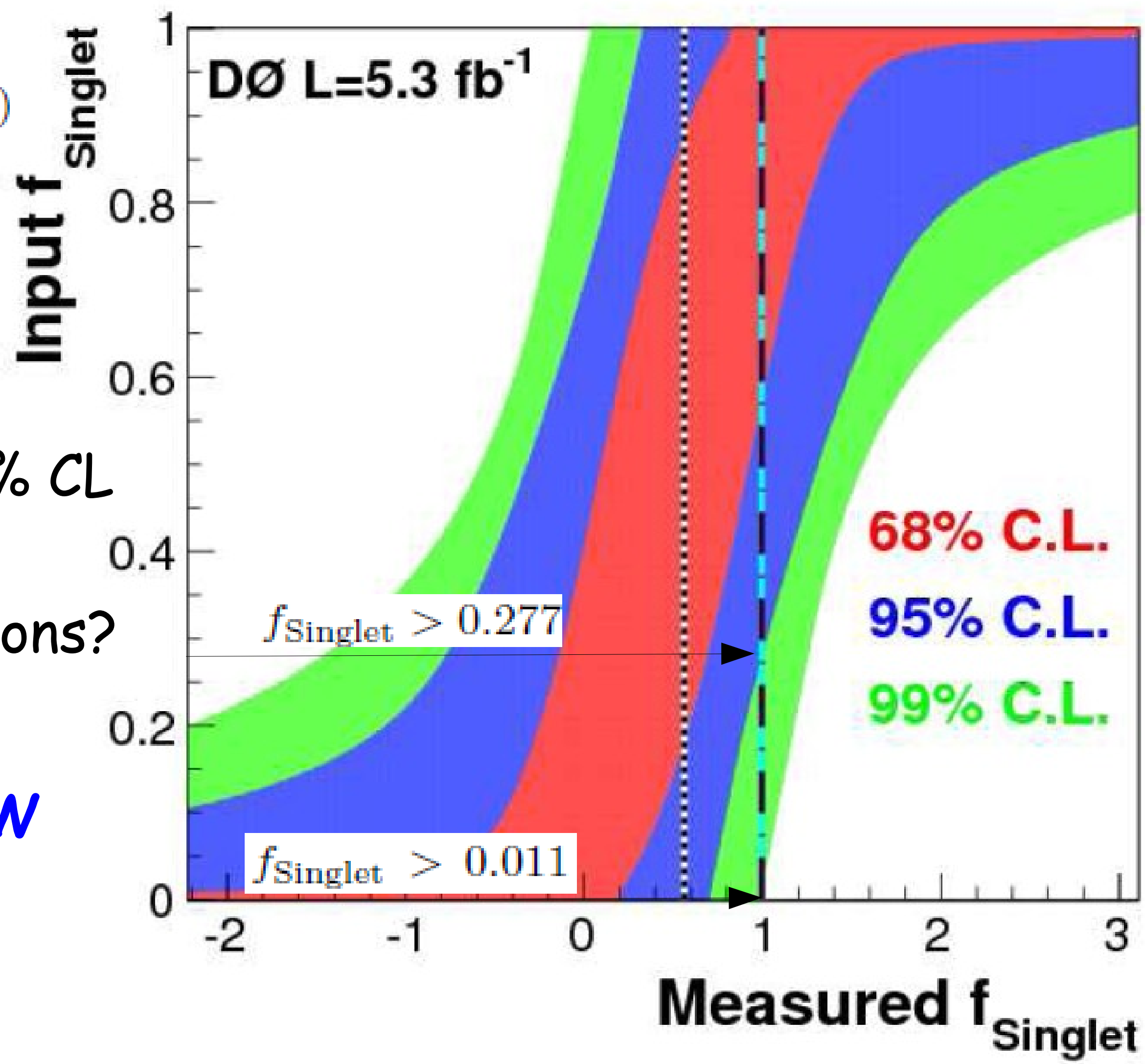
$$f_{\rm Singlet} = 0.56 \pm 0.38({\rm stat{+}syst}) \pm 0.19({\rm mcstat})$$

$$f_{\rm Singlet} = 0.65^{+0.37}_{-0.38}({\rm stat})^{+0.22}_{-0.22}({\rm syst})$$

$$\sigma_{t\bar{t}} = 8.54^{+0.32}_{-0.31}({\rm stat})^{+0.87}_{-0.81}({\rm syst{+}lumi})\ {\rm pb}$$

- Can't exclude octet W at 95% CL
- Data fluctuated by ~1 sigma?
  Or hint of imperfect simulations?

- **Expected to exclude octet W at 3 sigma (99% CL)**

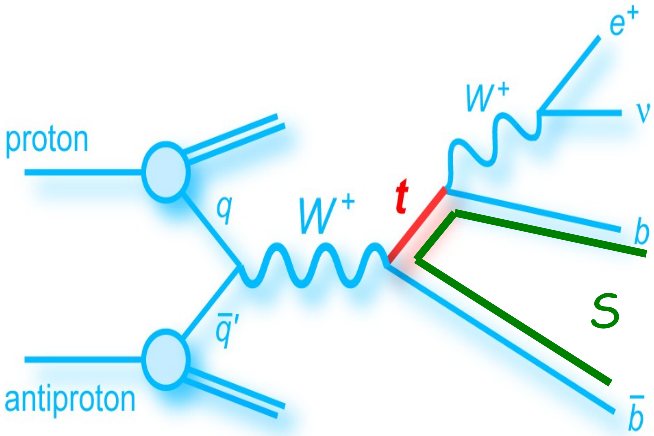


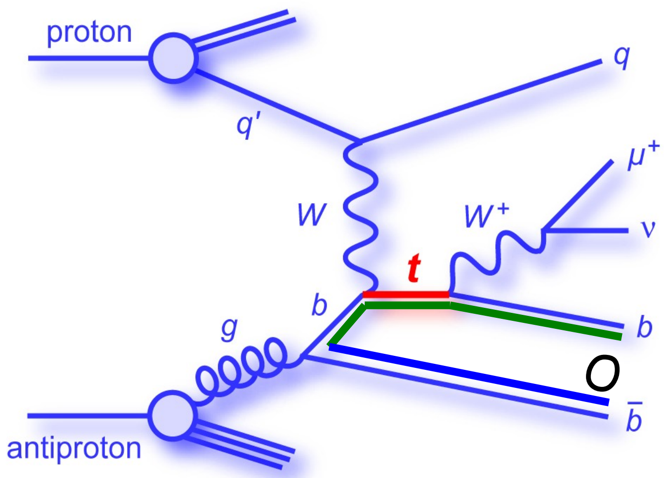
Color flow is extremely useful !

Jet pull is a new, general tool that makes it possible to reliably use color information !

Examples of what you can do with color flow:

- Learn new details of QCD
  (color reconnection, test "string theory"...)
- Understand SUSY decay chains
  - Can tell gluino decay from squark decay
  - Help pair jets coming from the same decay
- Separate s-channel from t-channel single-top
- Technicolor (predicts some heavy octets)
- Many other BSM models
- MSSM Higgs (b(h->bb), h is singlet!)
- SM Higgs (W/Z(H->bb), tt(H->bb), ...)





Summary

Color flow is an interesting and useful tool, but only if you can simulate and reconstruct it reliably

Jet pull is a new method which makes this possible

Performed the first measurement of color flow in ttbar events

Data contains a color singlet W->jj decay, within uncertainties

- *You can sleep well tonight knowing that !*

Measures accuracy of simulations / jet pull for color-singlet decays

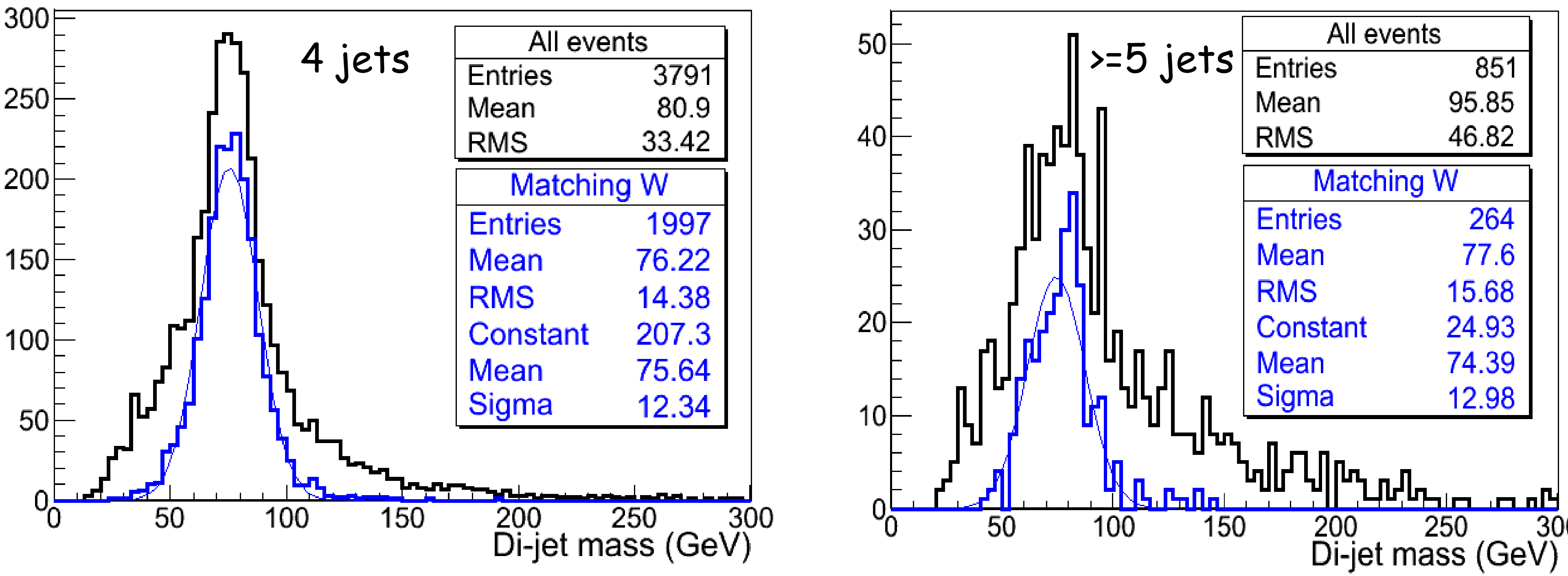
- Determines systematic uncertainty for jet pull in e.g. H->bb search

With more data and studies, jet pull will become a precise tool.

Should try out at ATLAS right away!

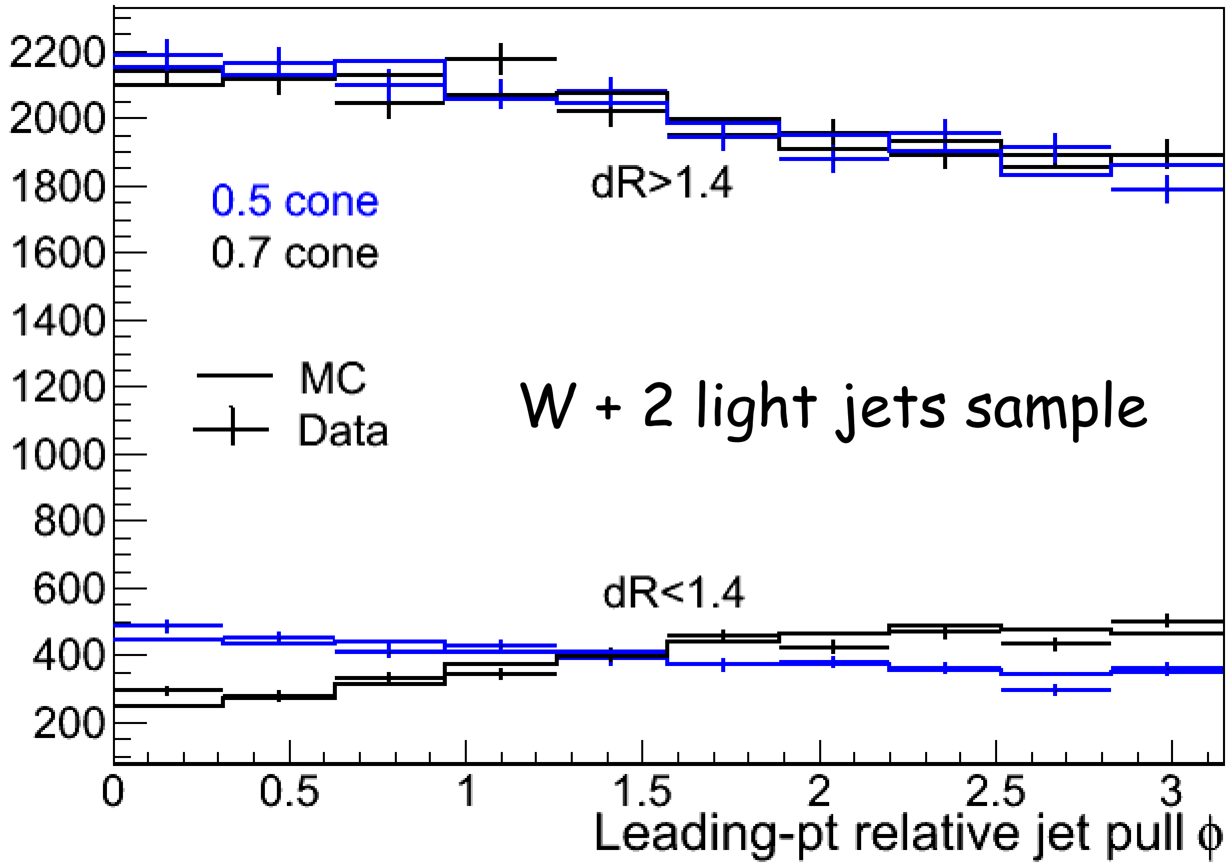
Backup Slides

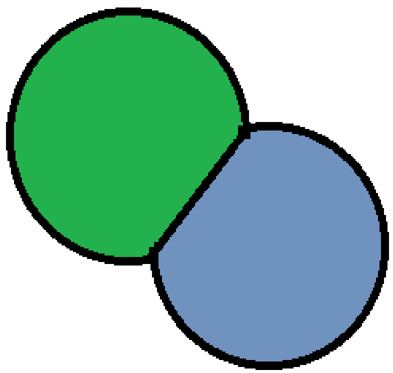
W matching fraction



Checks of jet pull reconstruction

- Look at jets which overlap and don't overlap for .5 and .7 cones

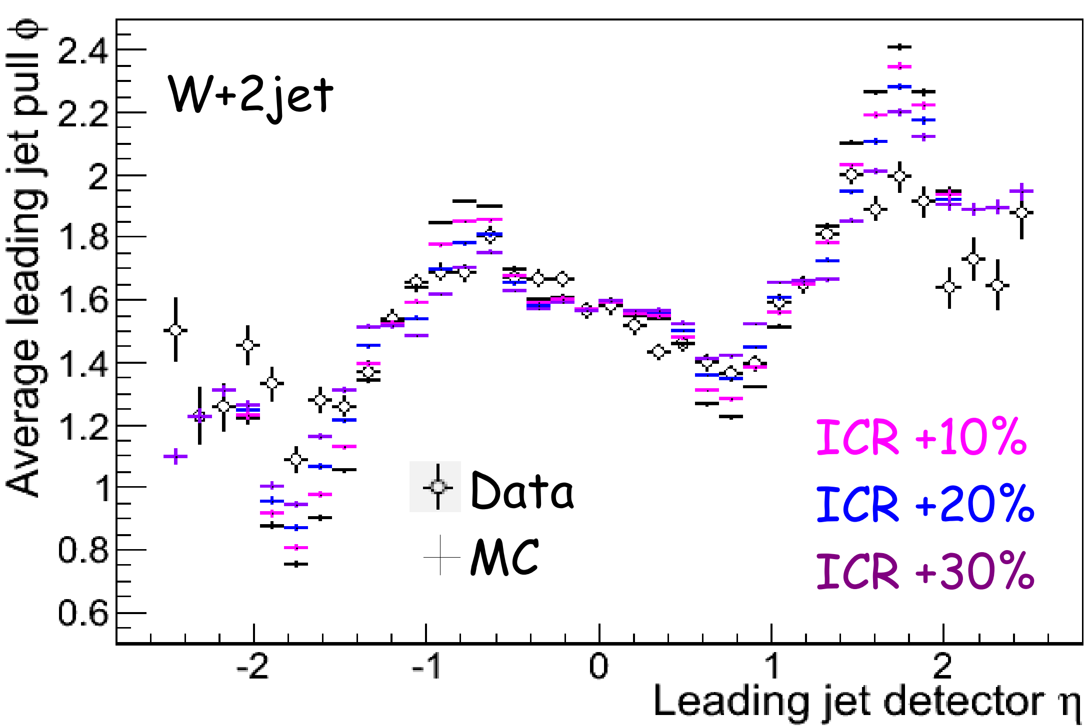


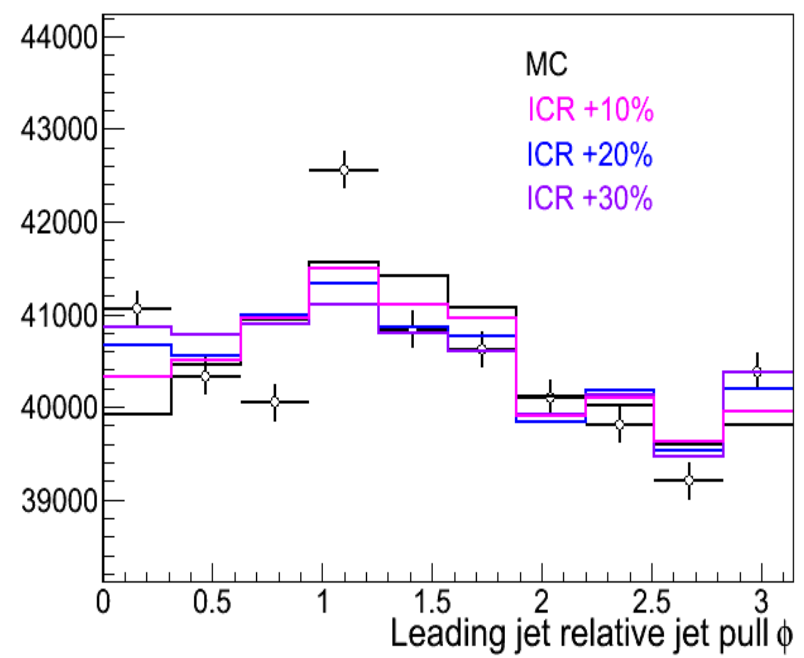


Cells are assigned to the *nearest jet*

Checks of jet pull reconstruction

- Bias of jet pull direction from *non-uniformity of calorimeter vs. eta*
  - Particularly the ICR has lower response and more noise
- Fairly well-modeled by the MC, within ~20%
- Relative jet pull angle is not significantly affected

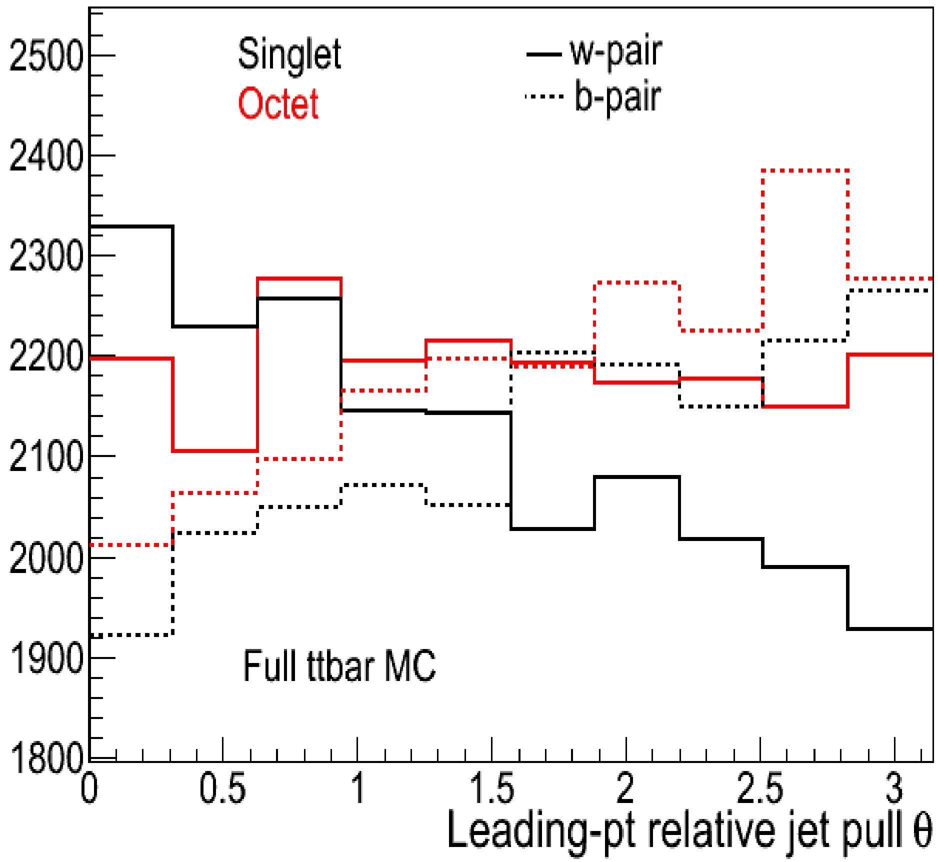


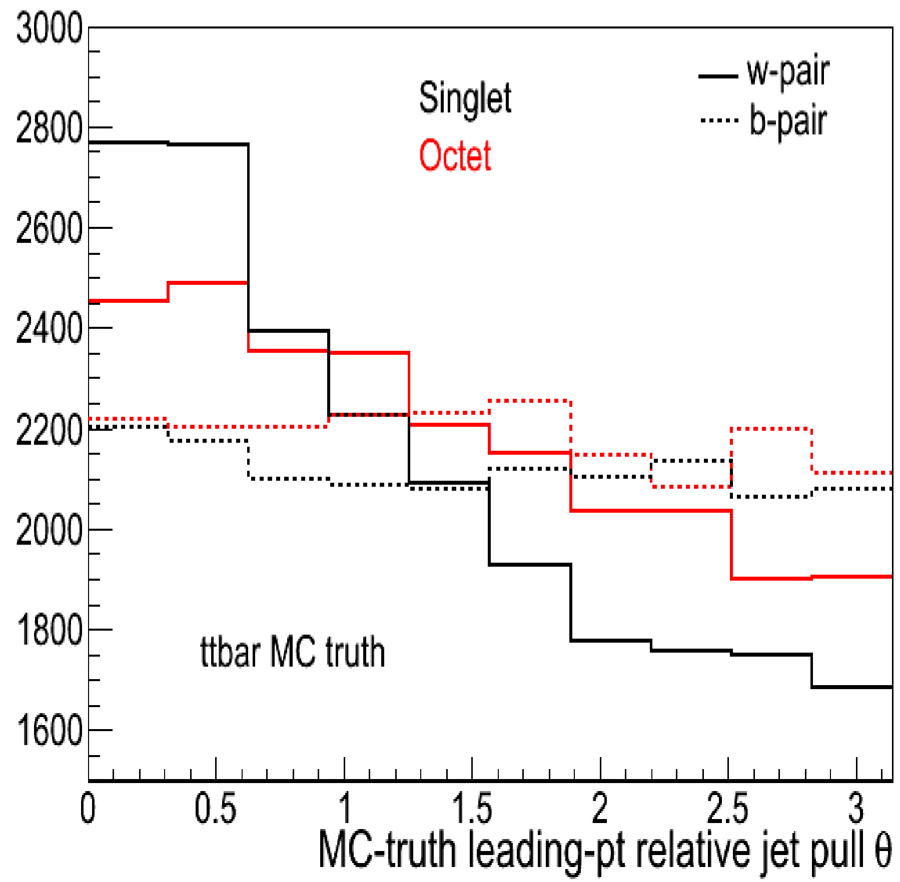


Jets touching ICR region

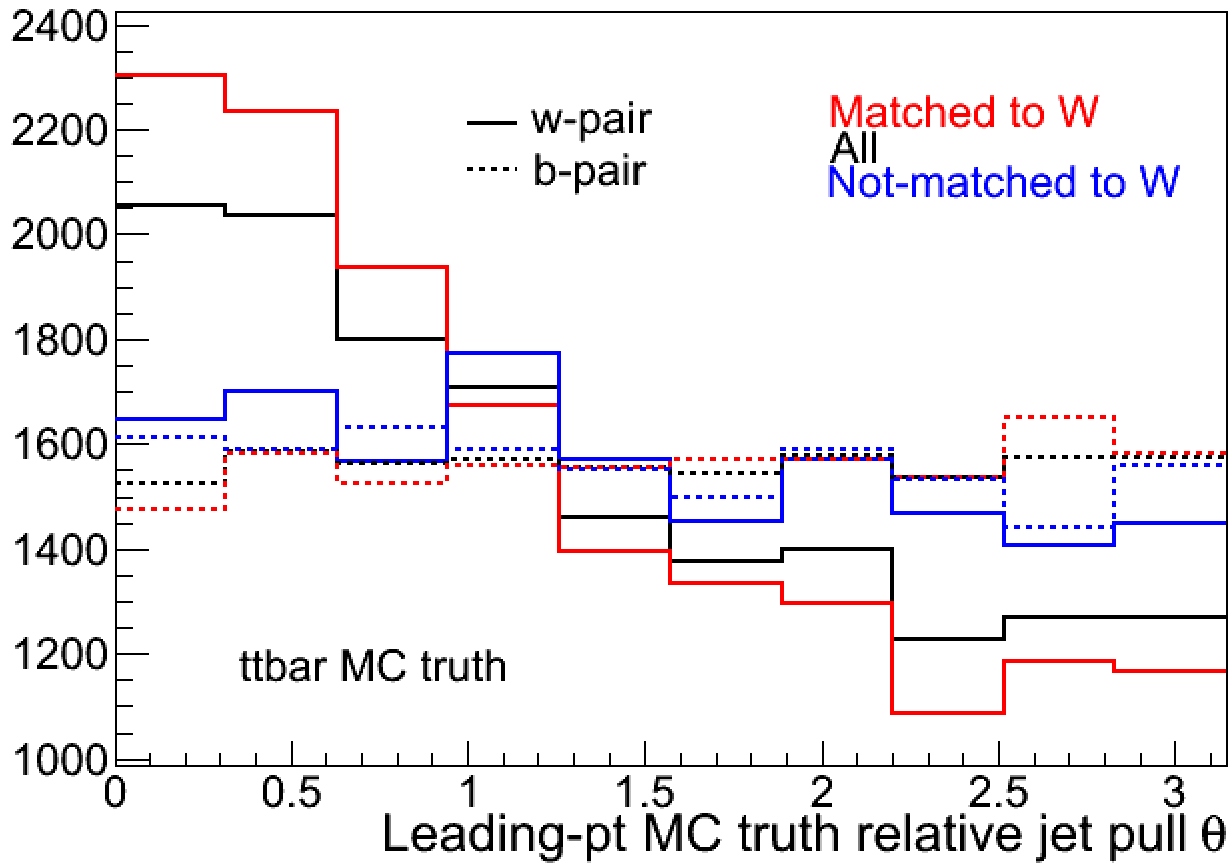
Full MC vs. MC truth

~75% more separation of "w" vs. b pairs in MC truth





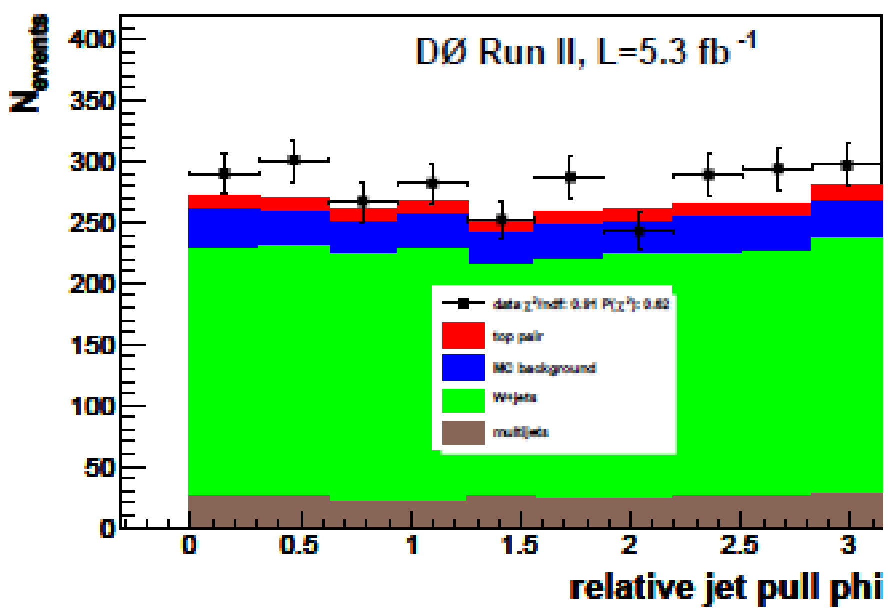
Matching W in ttbar MC truth



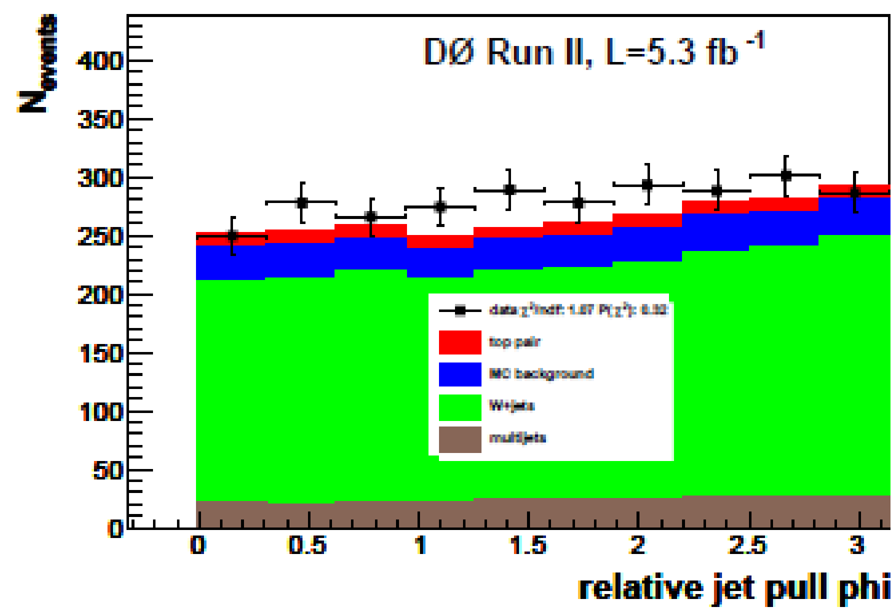
Jet pull in control samples, data/MC

- Look at light jets in *anti-b-tagged* W+3 jets sample
- Good data/MC agreement, for both jets

Leading pT light jet



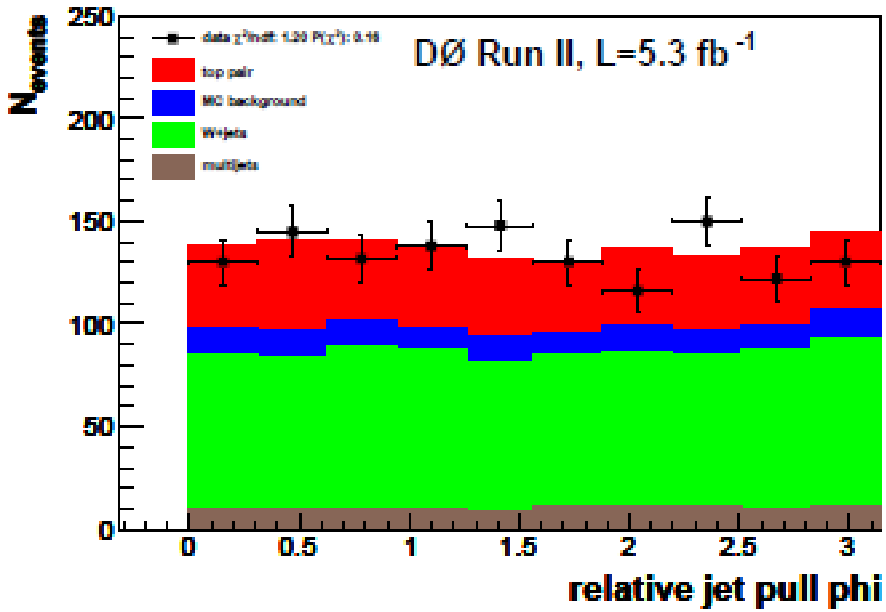
Second-leading pT light jet



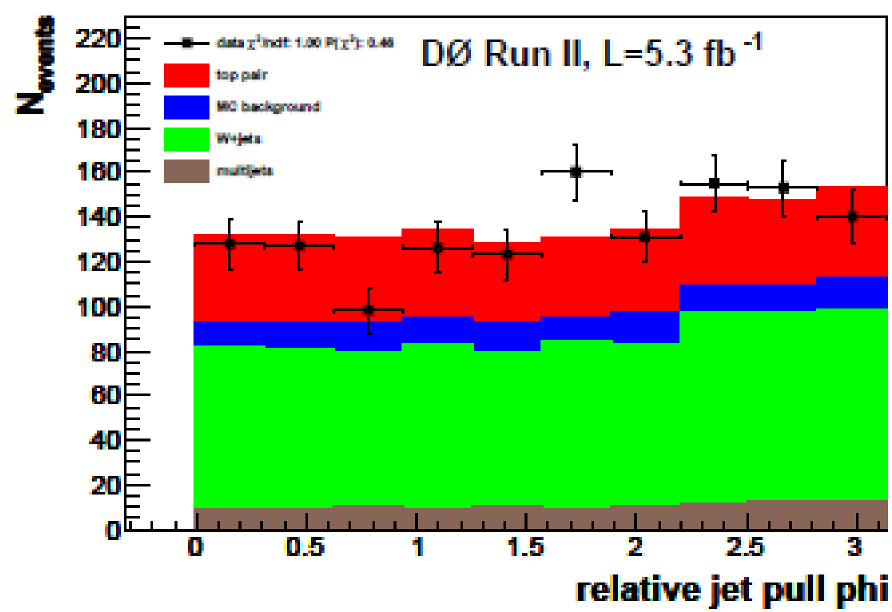
Jet pull in control samples, data/MC

- Look at light jets in *b-tagged* W+3 jets sample
- Good data/MC agreement, for both jets

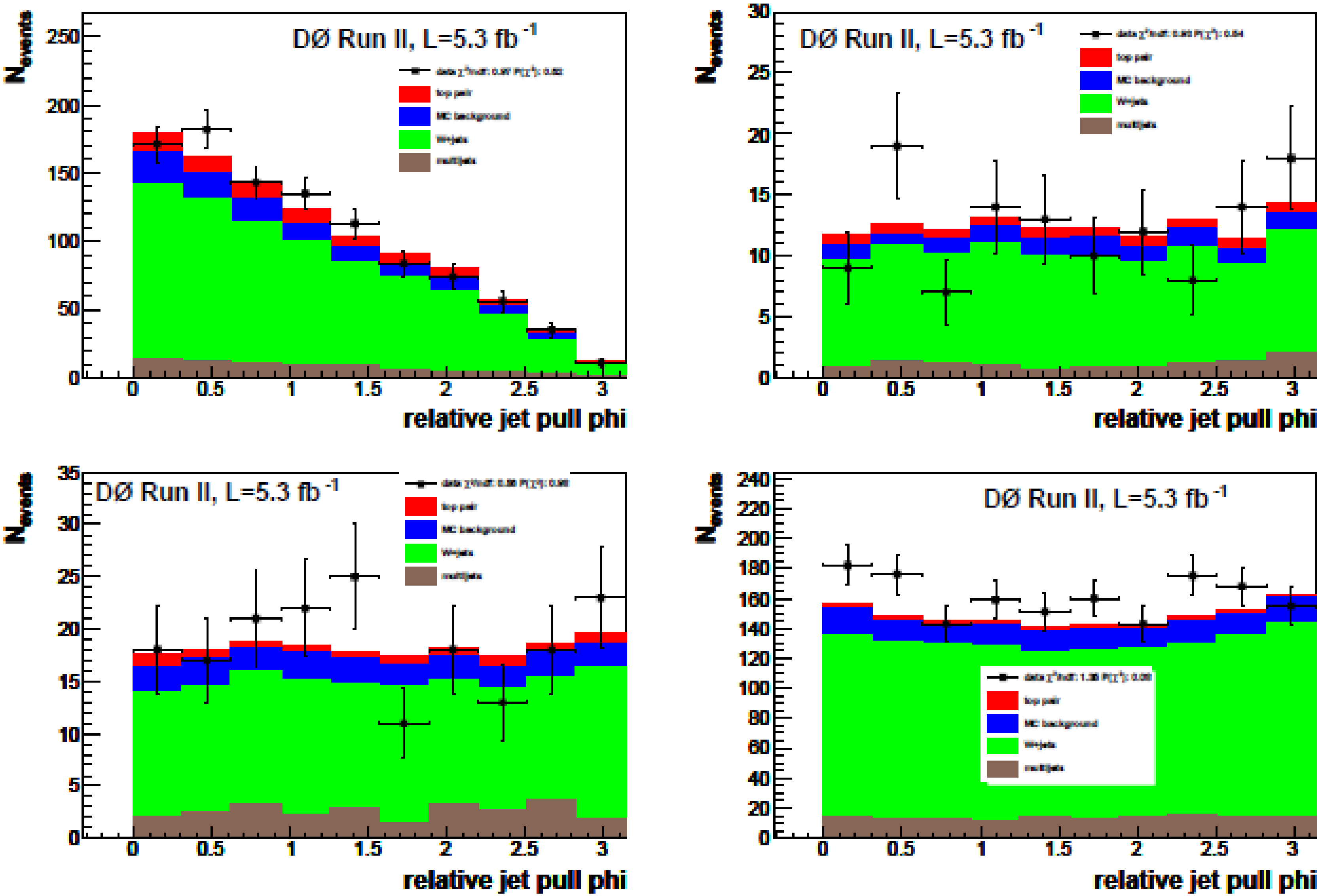
Leading pT light jet



Second-leading pT light jet

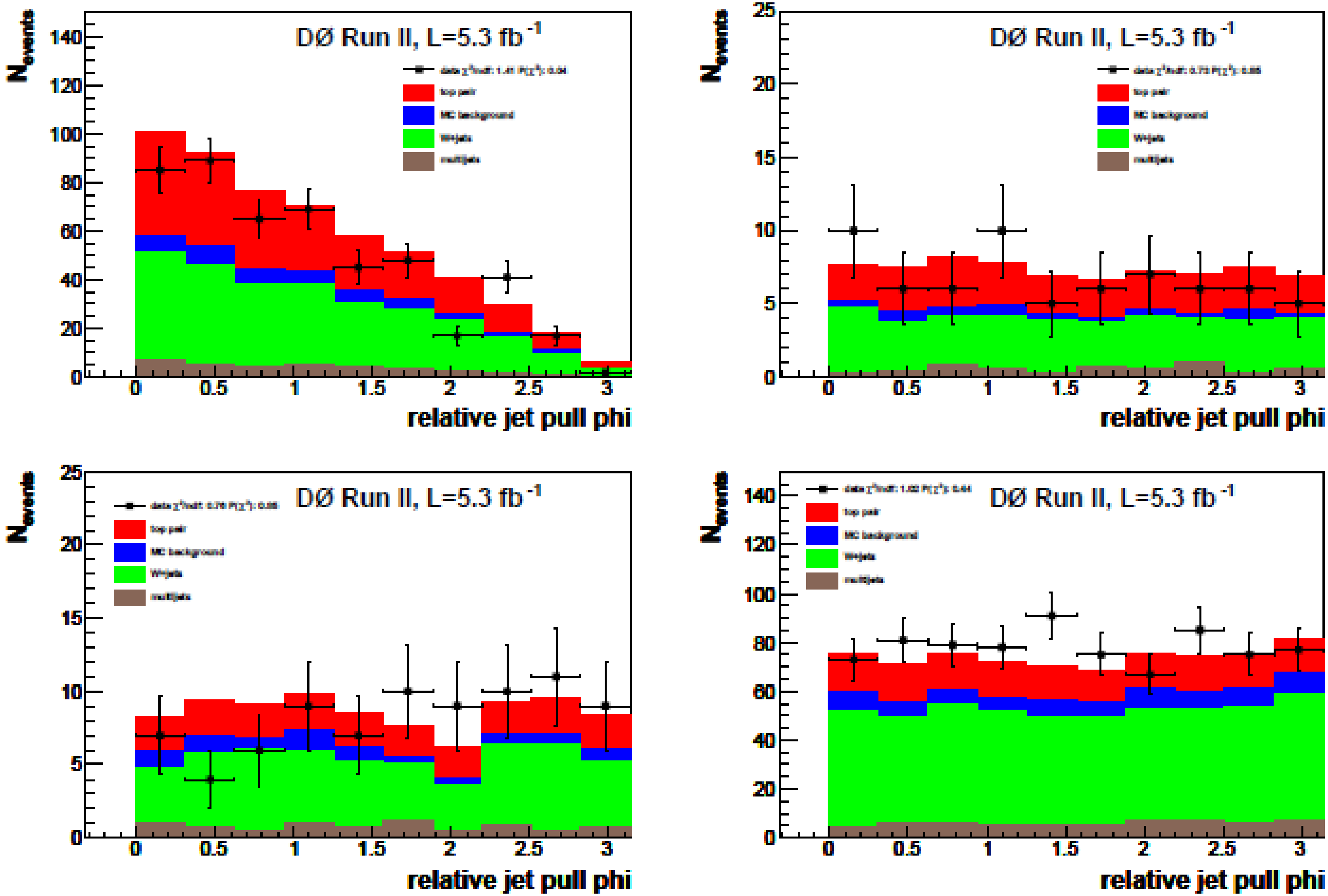


Separated by eta's of jets



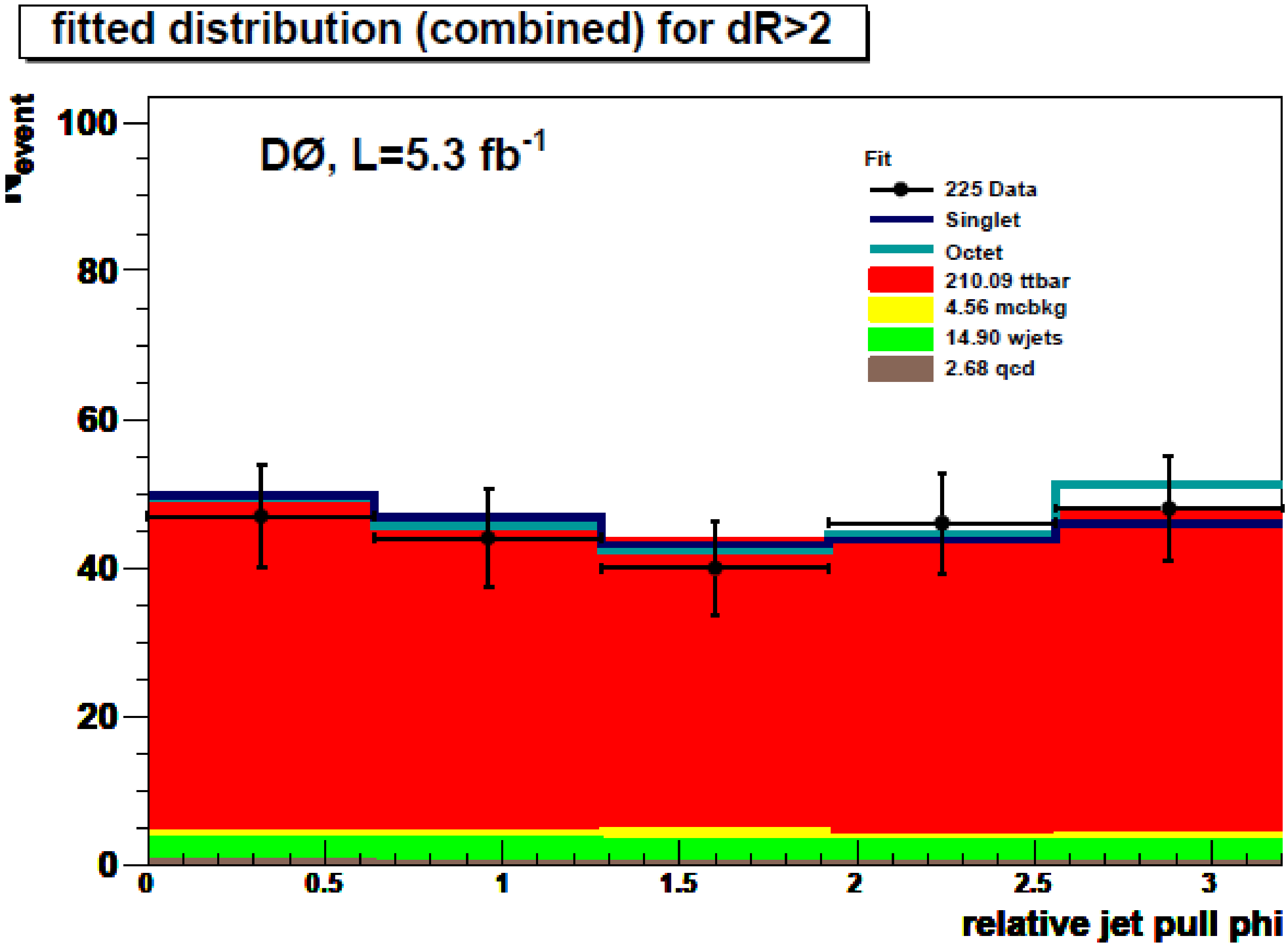
W + 3 light jets sample

Separated by eta's of jets

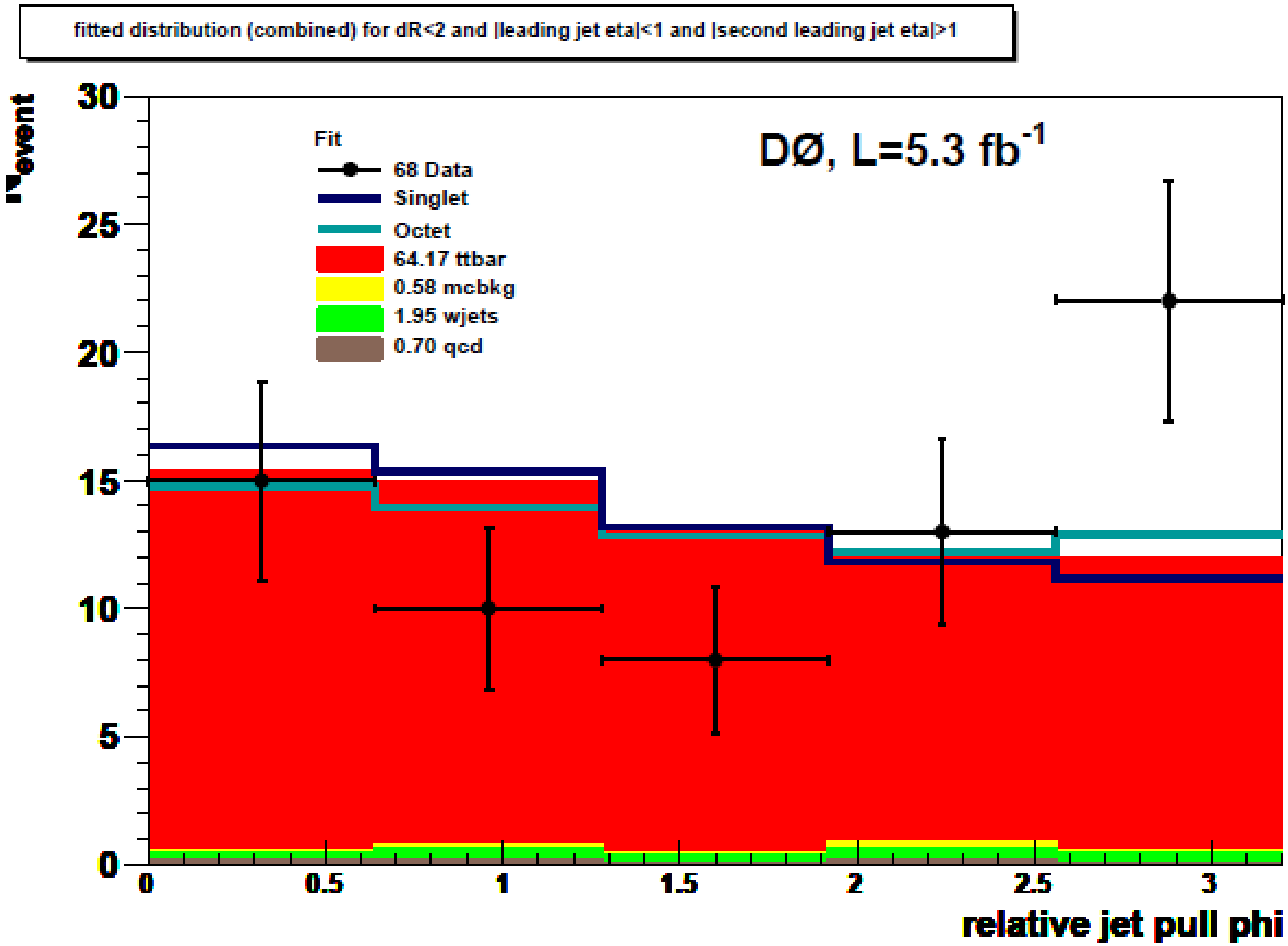


W + 3 jets *b-tagged* sample

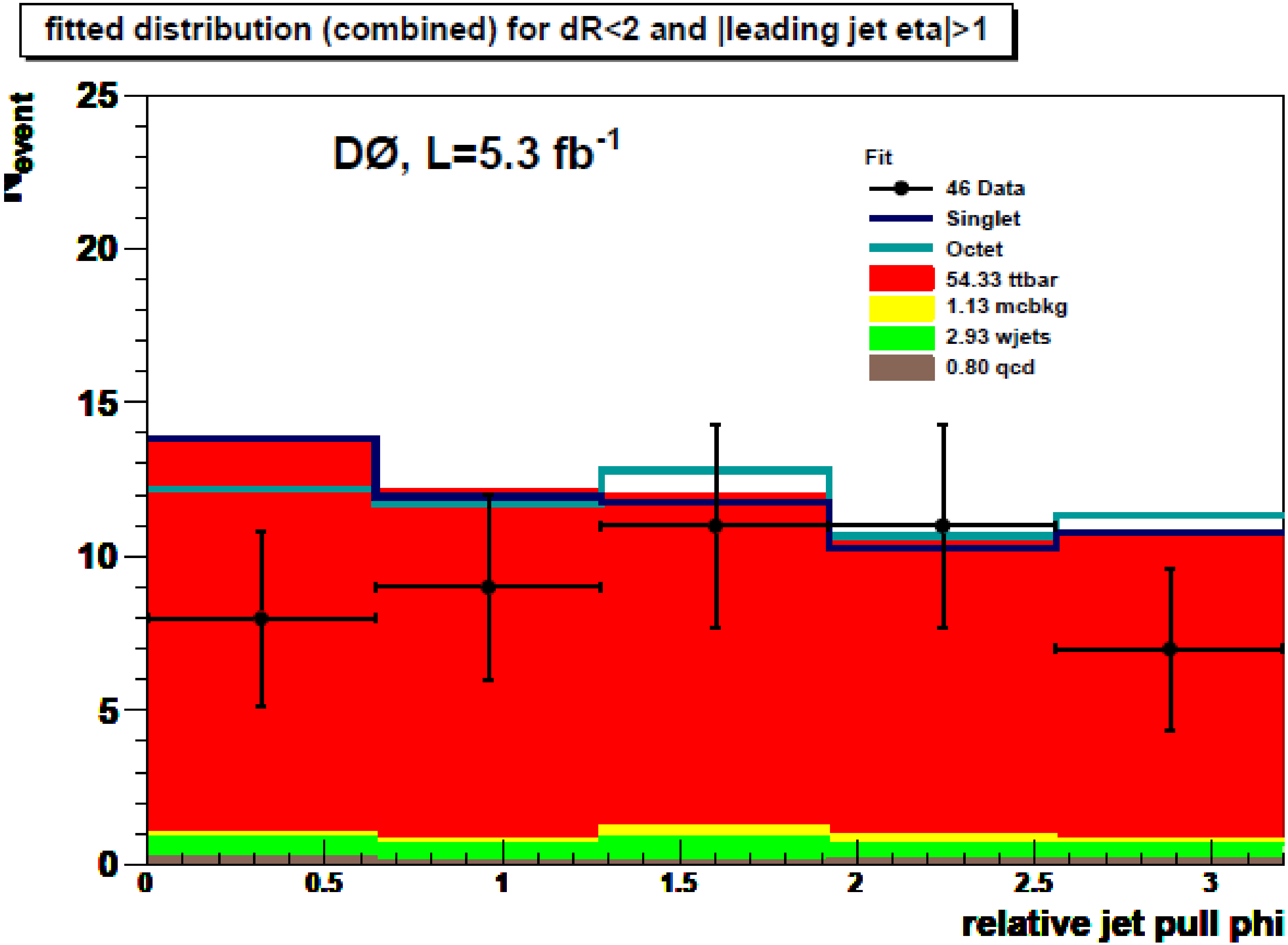
Other eta,dR regions



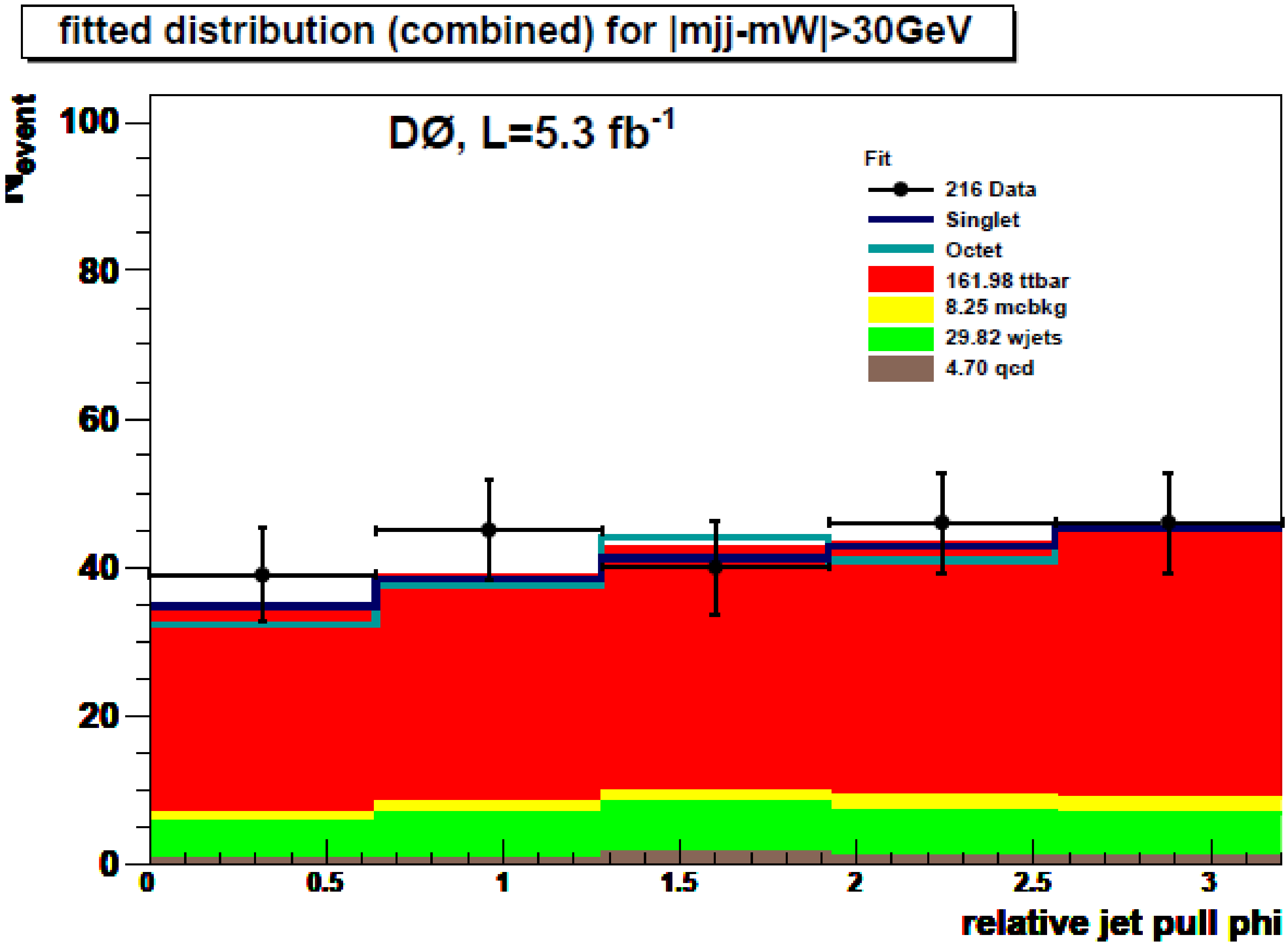
Other eta,dR regions



Other eta,dR regions



Other eta,dR regions

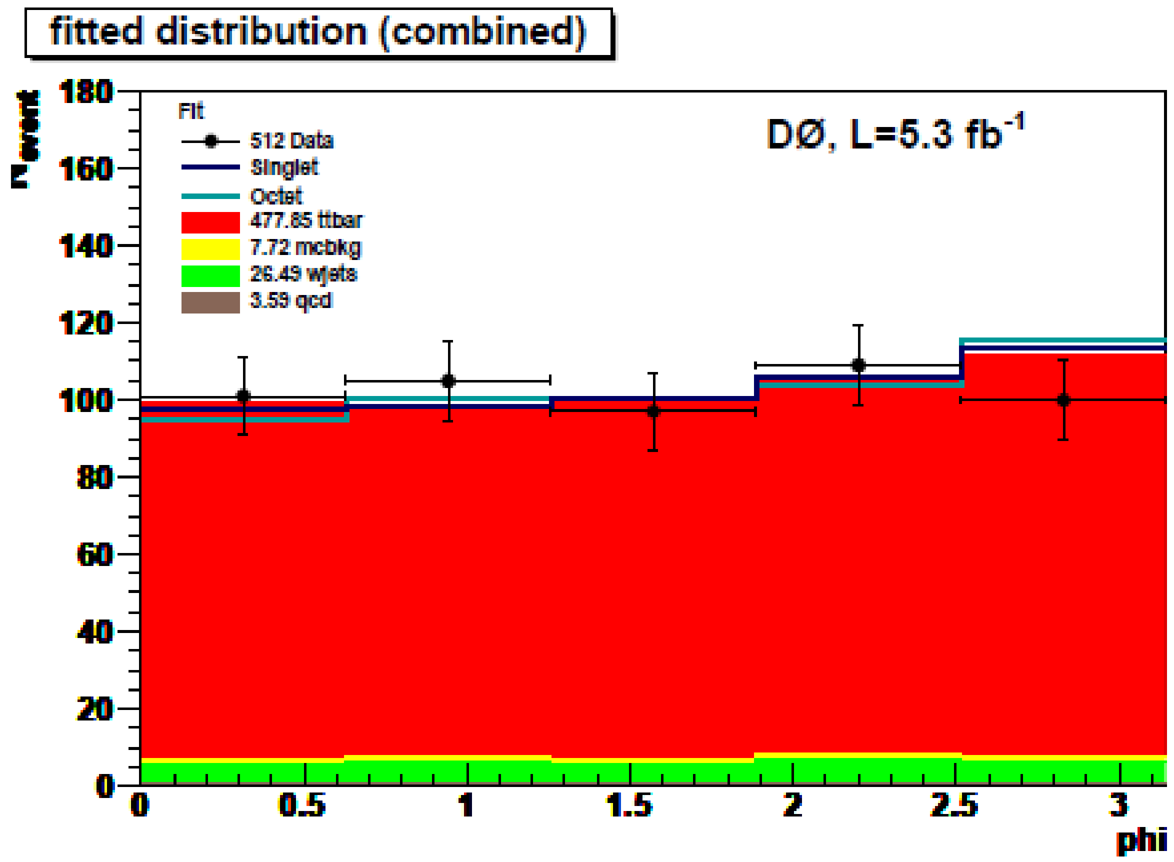


Results in various sub-samples

channel	$\sigma_{t\bar{t}}$[pb]	$f_{Singlet}$
e+jets	$7.78^{+0.40}_{-0.39}$ (stat)$^{+0.82}_{-0.76}$ (syst+lumi)	$0.394^{+0.483}_{-0.491}$ (stat) $^{+0.305}_{-0.297}$ (syst)
μ+jets	$9.67^{+0.53}_{-0.51}$ (stat)$^{+1.06}_{-0.97}$ (syst+lumi)	$1.012^{+0.557}_{-0.586}$ (stat) $^{+0.291}_{-0.294}$ (syst)
Run IIa	$8.40^{+0.65}_{-0.62}$ (stat)$^{+0.88}_{-0.81}$ (syst+lumi)	$0.081^{+0.595}_{-0.609}$ (stat) $^{+0.366}_{-0.367}$ (syst)
Run IIb	$8.59^{+0.37}_{-0.36}$ (stat)$^{+0.98}_{-0.90}$ (syst+lumi)	$1.041^{+0.483}_{-0.491}$ (stat) $^{+0.275}_{-0.268}$ (syst)

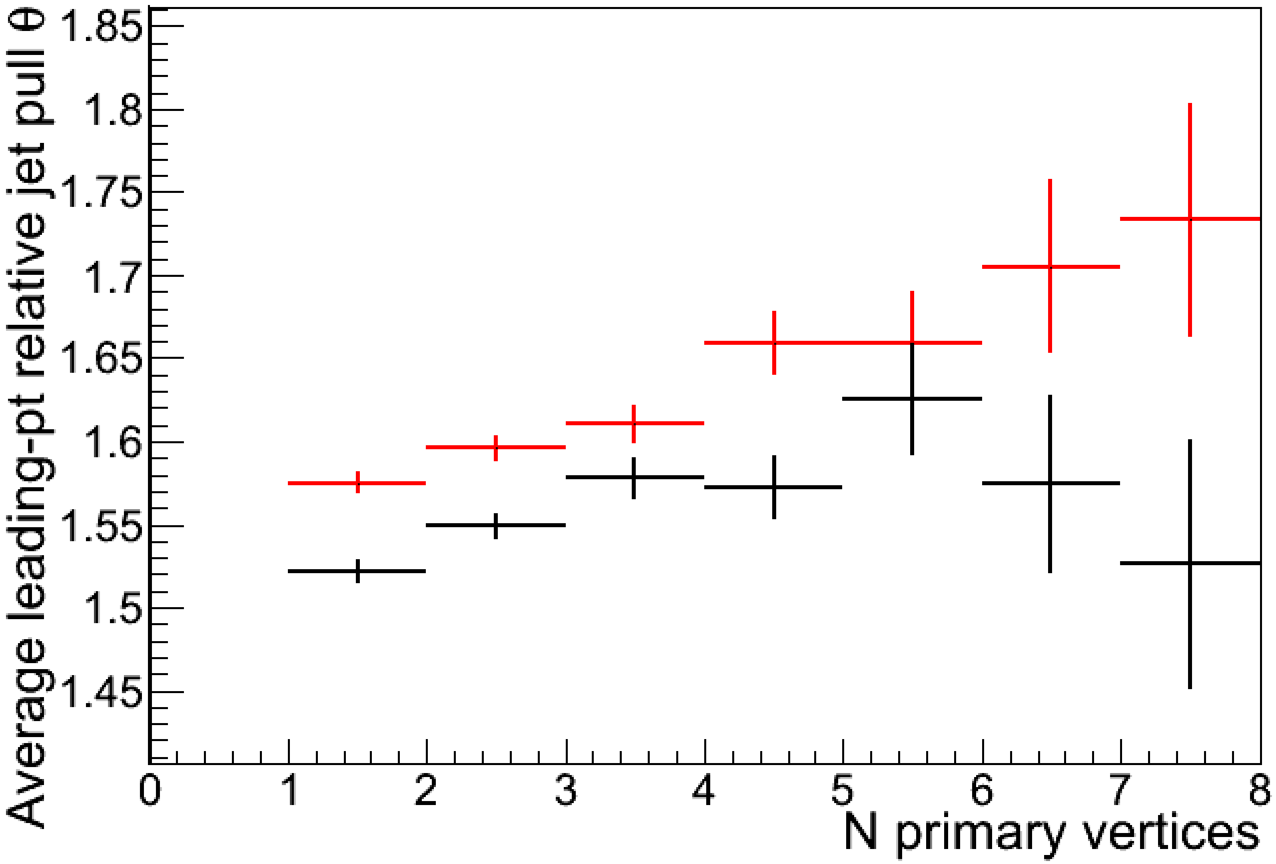
b-jets

- b-jets don't care much about the color representation of the "X"

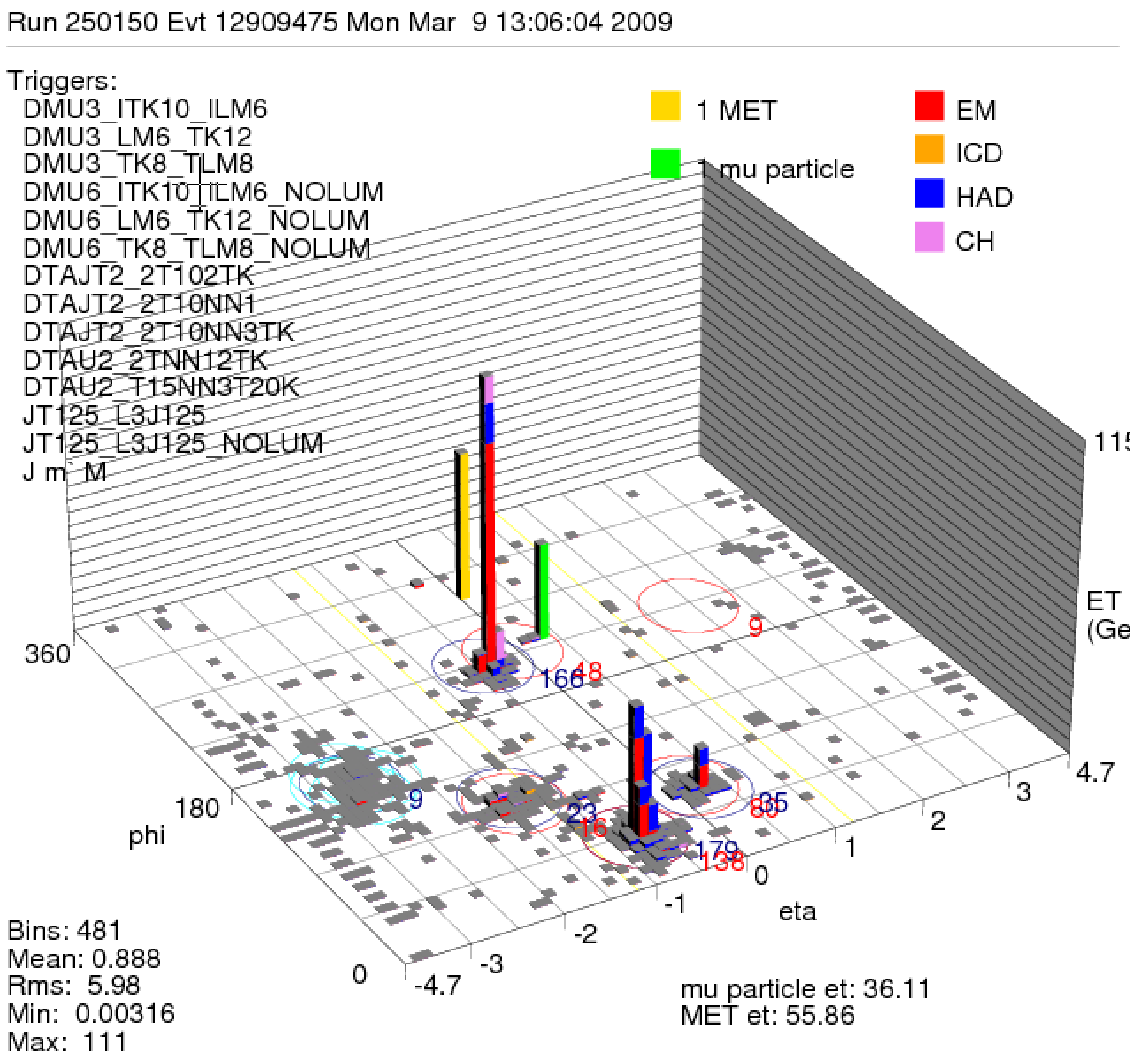


Pileup

- Amount of “noise” increases with #PV
- Changes average relative jet pull angles
- Separation between singlet and octet degrades only slightly



Event display



Event display