Quark and Gluon Jet Fragmentation Functions as measured by OPAL

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Parton Fragmentation Processes: in the vacuum and in the medium

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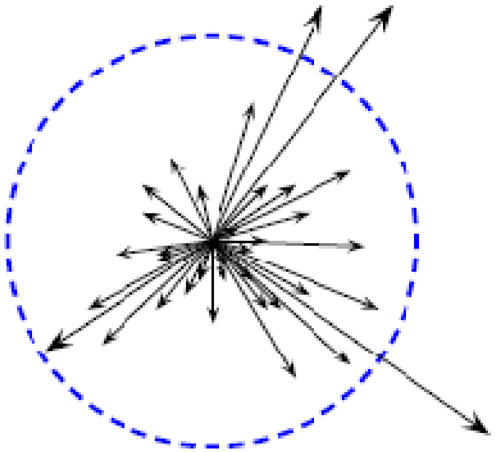
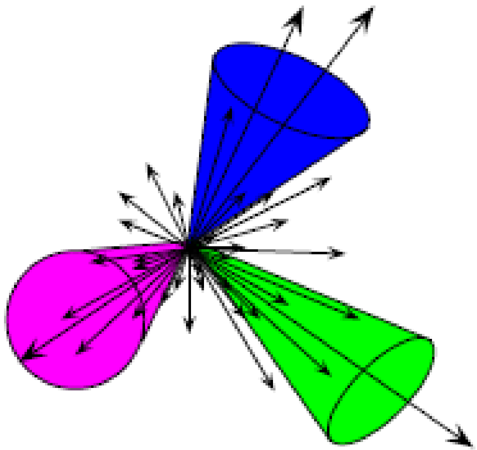
For OPAL collaboration, CERN

$e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}(g)$ at LEP





2 hemispheres

Jet properties defined by an inclusive sum over hemisphere

No jet finder

UNBIASED JETS

SCALE = $\sqrt{s}/2$

3 jets found by a jet alg.

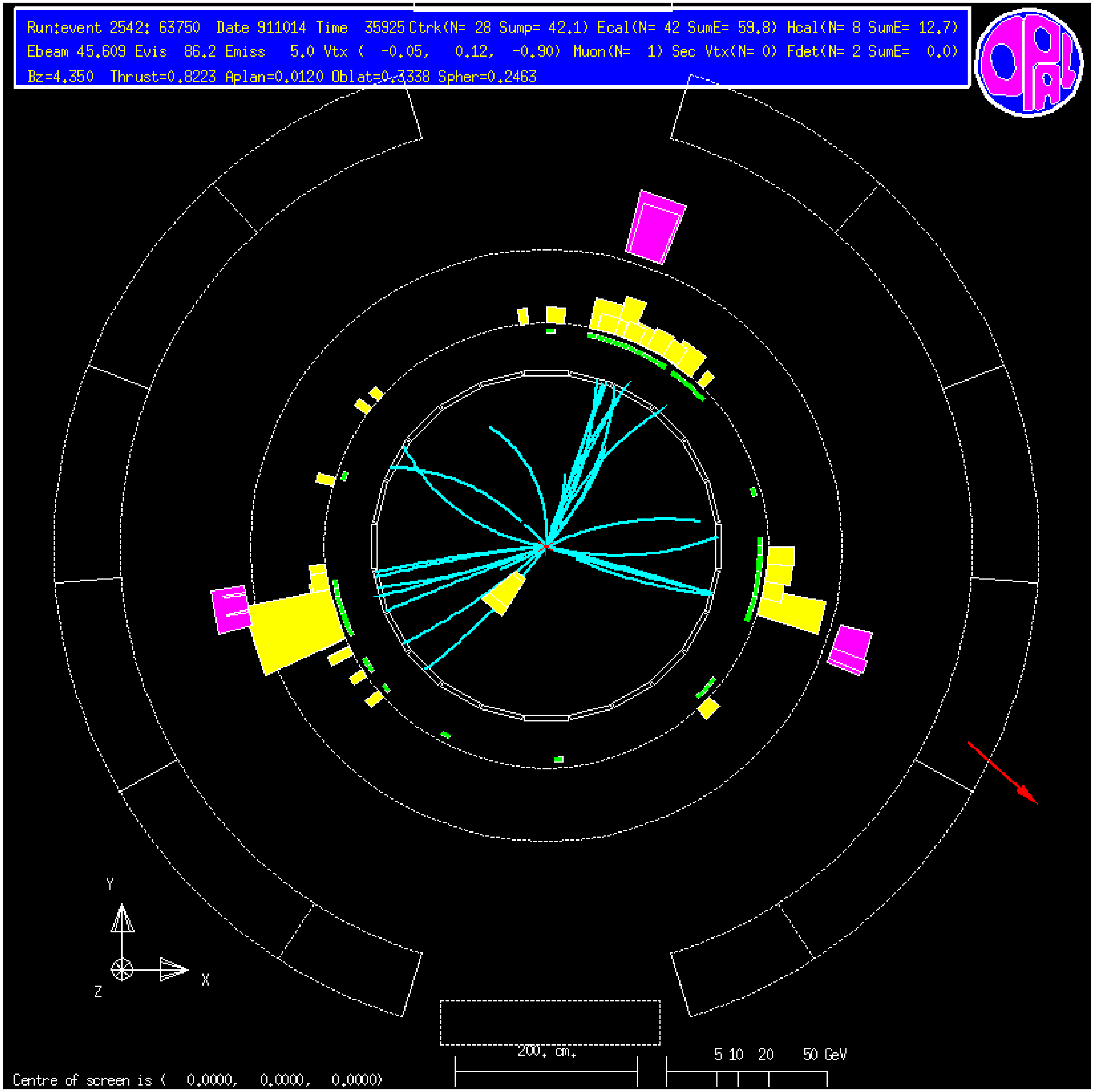
Jet properties defined by particles assigned to a jet

Jet finder dependence

BIASED JETS

SCALE = $\sqrt{s}/2$? E_{jet}? Q_{jet}!

Unbiased jets are used in theory calculations


Run:event 2542: 63750 Date 911014 Time 35925 Ctrk(N= 28 Sump= 42.1) Ecal(N= 42 SumE= 59.8) Hcal(N= 8 SumE= 12.7)
Ebeam 45.609 Evis 86.2 Emiss 5.0 Vtx (-0.05, 0.12, -0.90) Muon(N= 1) Sec Vtx(N= 0) Fdet(N= 2 SumE= 0.0)
Bz=4.350 Thrust=0.8223 Aplan=0.0120 Oblat=0.3338 Spher=0.2463
Y
Z
X
200. cm.
5 10 20 50 GeV
Centre of screen is (0.0000, 0.0000, 0.0000)

The measured fragmentation function is defined here as

$$\frac{1}{\mathbf{N_{jet}(scale)}} \frac{\mathbf{dN_p(x_E, scale)}}{\mathbf{dx_E}}$$

number of charged non-identified particles in bins of $x_E = \frac{E_{part}}{E_{jet}}$ and scale normalized to number of jets in bins of scale. E_{jet} = energy of the jet to which the particle with energy E_{part} is assigned.

In total, 7 types of frag.functions were measured:

UNBIASED JETS		BIASED JETS
udscb	← ARE →	udscb
udsc	← THEY →	udsc
b	← MUTUALLY →	b
	CONSISTENT ?	gluon

If there is a consistency, then:

- **Q_{jet} scale is an appropriate scale for hadron production in 3-jet events.**
- **Comparison of measured biased jets with theory makes sense.**

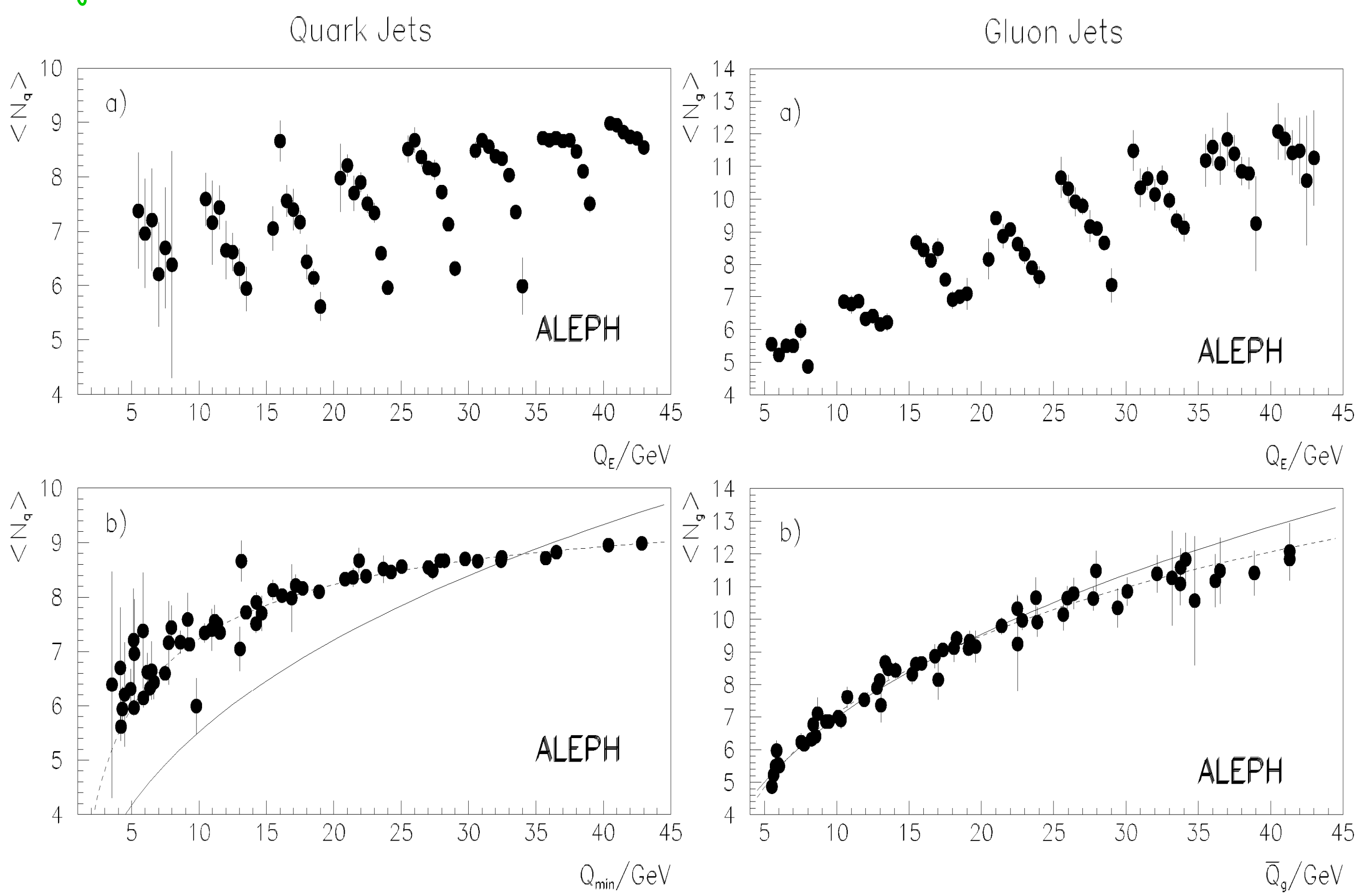
Which scale for biased jets?

Q_{jet} scale proposed in Sov.J.Nucl.Phys.47 (1988) 881, and first used by ALEPH (Z.Phys. C76 (1997) 191)

$$Q_{jet} = E_{jet}\sin(\theta/2)$$

θ = angle between jet with E_{jet} and the closest other jet

Q_{jet} ~ maximum allowed p_T or virtuality of showering gluons wrt



Each of 8 bands correspond to jets with the same energy but with a different angle to the nearest jet. Particle multiplicity in a jet depends on the event topology, not just the jet energy

Q_{jet} scale reduces the jet energy and topology dependences compared to the scale E_{jet}

Event selection

OPAL data: LEP1 (1993-1995): $\sqrt{s}$ = 91.2 GeV, L=130 pb^{-1}

LEP2 (1997-2000): $\sqrt{s}$ = 183-209 GeV, L=690 pb^{-1}

Standard hadronic event selection plus

- reduction of ISR bg in LEP2 data: $\sqrt{s} - \sqrt{s'} < 10$ (20*) GeV
- reduction of 4-fermion bg (WW, ZZ→4f) in LEP2 data: Event weight $W_{QCD}<0.5$

3-jet event selection:

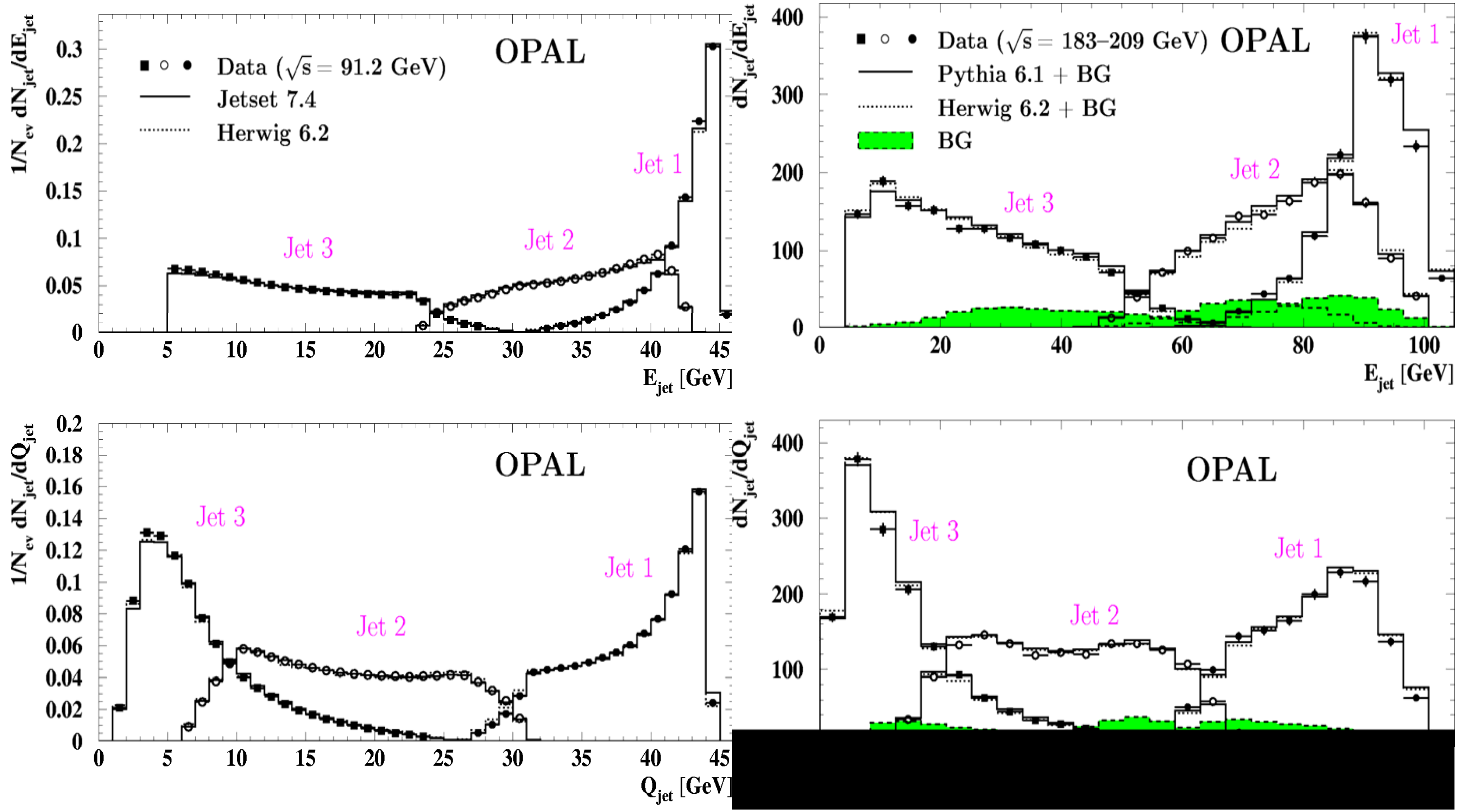
Durham (Cone and Cambridge) jet alg. forced to find 3 jets (smallest y_{cut} or largest cone)

- particle multiplicity per jet ≥ 2
- sum of inter-jet angles ≥ 358°
- polar jet angle $|\cos\theta_{jet}| \leq 0.90$ (0.95*)
- Inter-jet angle ≥ 30°
- Corrected jet energy ≥ 5 GeV; $E_i^{corr} = \sqrt{s}\,\sin\theta_{jk}/(\sin\theta_{ij} + \sin\theta_{jk} + \sin\theta_{ik})$ ← energy-momentum conservation + planar massless kinematics

Jets ordered in energy: Jet 1 = the most energetic jet

* = used in LEP2 3-jet analysis

E_{jet} and Q_{jet} scale in LEP1 + LEP2 data



Very good description of data by Pythia and Herwig plus GRC4F (for LEP2 BG)

Correction procedure

1.step: bin-by-bin subtraction of 4-fermion BG from LEP2 data using GRC4F MC

2.step: unfolding of detector level jets in data and MC to level of pure quark and gluon jets using purity matrices obtained from MC.

- Purity estimated via matching: a parton jet or a detector jet is assigned to the hadron jet to which they are nearest in angle.
- Pure quark (gluon) jet is a hadron jet matched to a parton jet which originates from a quark (gluon)

a) B-TAG method for biased and unbiased jets

- based on neural network
- output value of neural net, VNN, serves to separate udsc, b and gluon jets from each other

b) Energy-ordering method for biased gluon jets

- separates between udscb and gluon jets
- alternative to B-TAG

3.step: bin-by-bin correction for detector and ISR effects

(Typical bin purities for the Q_{jet} binning chosen are 75%, the lowest one is 65%)

B-TAG method for biased jets

Any of three jets is used to extract FFs! Jet 1 comes very likely from quark but 5% of Jets 1 come from a gluon.

Define: b-tag jet as jet containing sec.vtx with VNN>a

anti-tag jet as jet without sec. vtx or with sec. vtx but with VNN<b

→ Form b-tag and gluon jet samples from events with one or two b-tag jets and at least one anti-tag jet.

→ If one b-tag and two anti-tag jets found, the lower energy anti-tag jet enters the gluon jet sample.

→ Form udsc jet sample from all three jets in events with no b-tag jet found

To obtain pure udsc, b or gluon jets, one has to solve

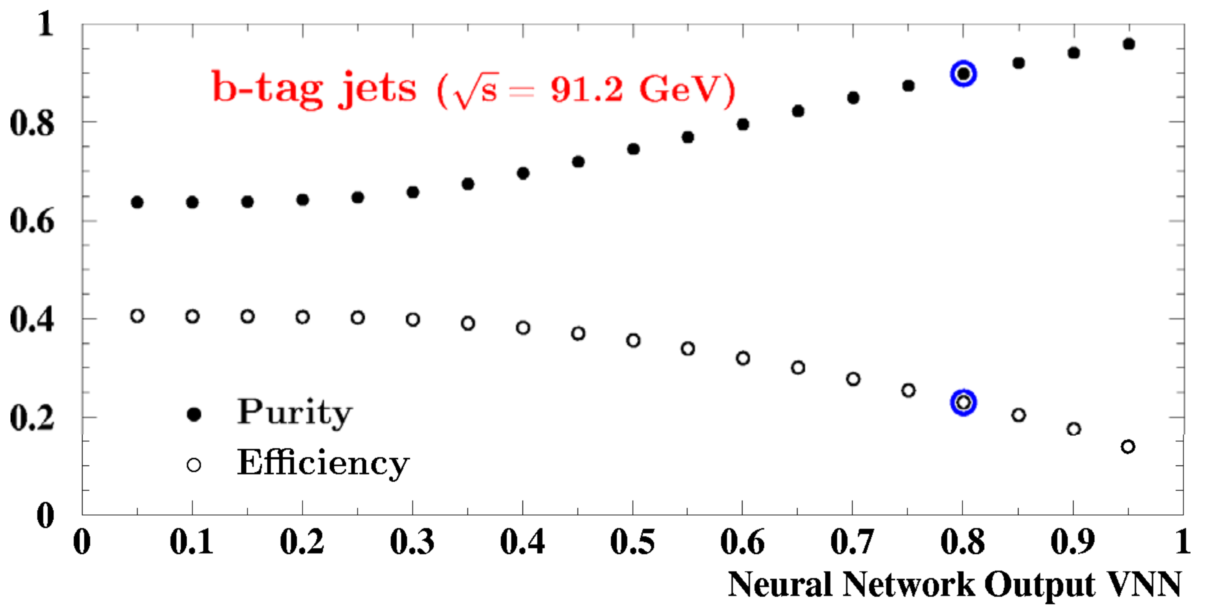
$$\begin{pmatrix} D_l \\ D_b \\ D_g \end{pmatrix}^{\text{uncor}} (x_E, Q) = \begin{pmatrix} P_{ll} & P_{lb} & P_{lg} \\ P_{bl} & P_{bb} & P_{bg} \\ P_{gl} & P_{gb} & P_{gg} \end{pmatrix} (Q) \begin{pmatrix} D_l \\ D_b \\ D_g \end{pmatrix}^{\text{pure}} (x_E, Q)$$

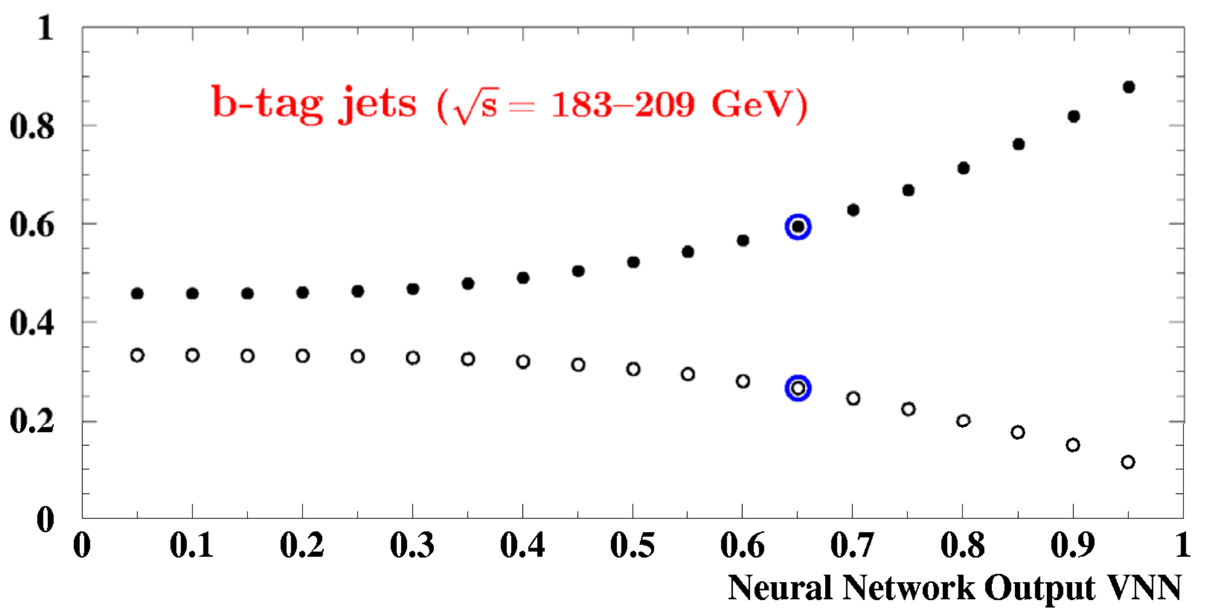
[redacted]

E.g. P_{lb} = prob. that a jet from the udsc jet sample comes from a b-quark.

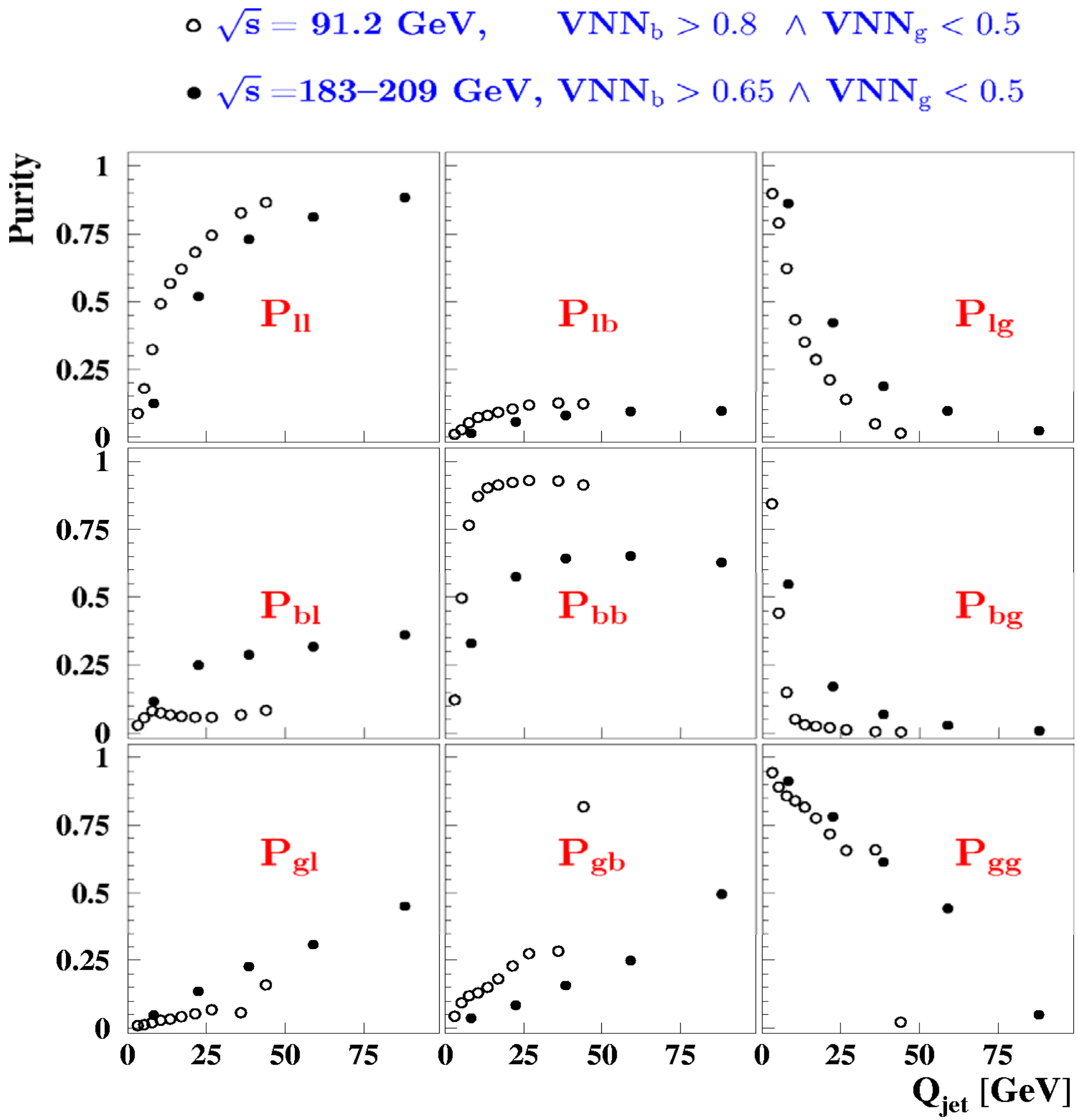
Overall P_{bb} =90%, P_{gg}=84% for LEP1, P_{bb} = 60%, P_{gg} = 80% for LEP2 data

Purity and Efficiency for B-TAG biased jets





Purity matrix for biased jets



Energy-ordering method for biased jets

Based on QCD prediction that in 3-jet events, the Jet 3 most likely comes from gluon

→ quark jet sample formed by jets 2;   gluon jet sample formed by jets 3

Unfolding to the level of pure quark and gluon jets:

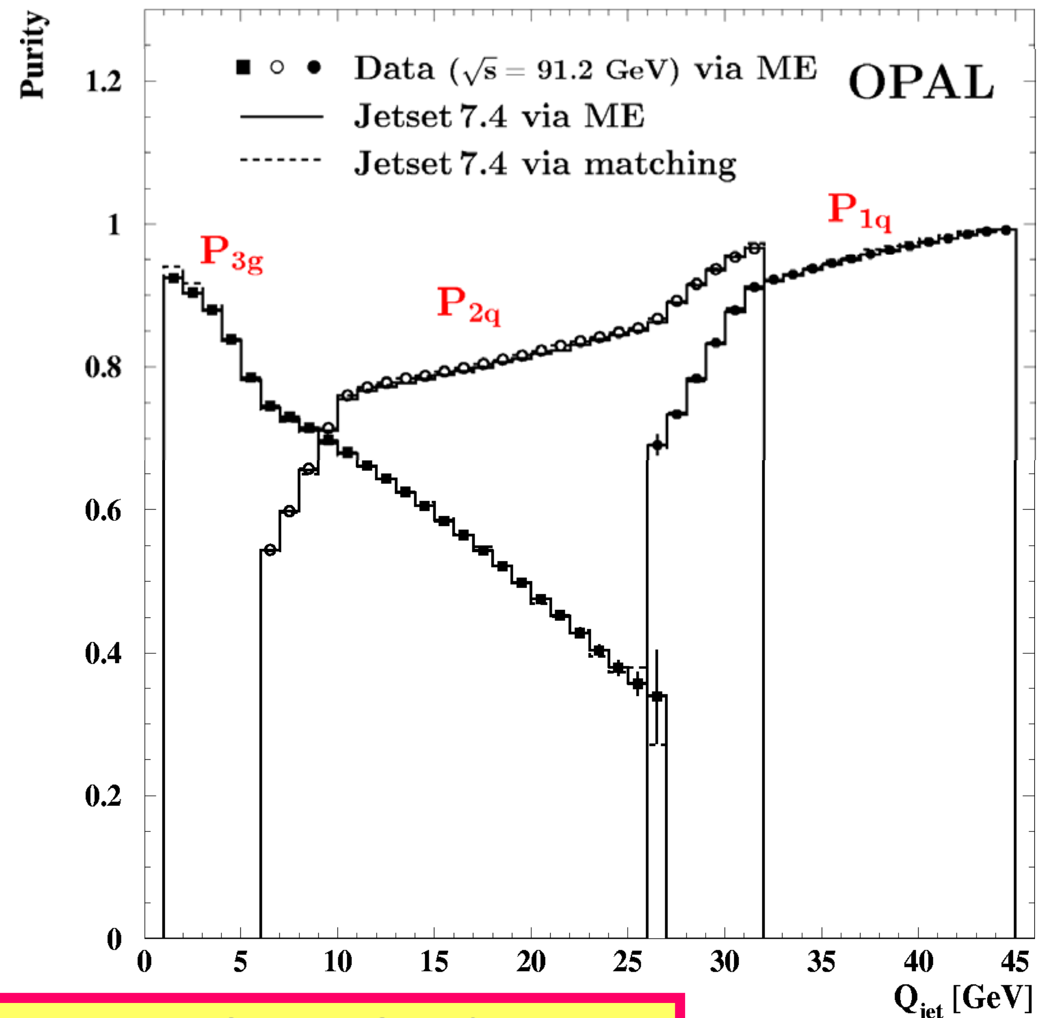
$$\begin{pmatrix} D_2 \\ D_3 \end{pmatrix}^{\text{uncor}} (x_E, Q) = \begin{pmatrix} P_{2q} & P_{2g} \\ P_{3q} & P_{3g} \end{pmatrix} (Q) \begin{pmatrix} D_q \\ D_g \end{pmatrix}^{\text{pure}} (x_E, Q)$$

where e.g. P_{3q} = prob. that a jet 3 comes from a quark and can be calculated via matrix elements or estimated using matching. From LO QCD ME:

$P_{3g} = (x_1^2 + x_2^2)/(1-x_1)/(1-x_2)$,

where $x_i = 2E_{jet,i}/\sqrt{s}$ and $P_{3q} = 1 - P_3$

ENERGY-ORDERING



Applicable only in the overlap region of jets 2 and 3: $6<Q_{jet}<27$ GeV for LEP1

B-TAG method for unbiased jets

Unbiased jets = hemispheres

LEP1: if two sec.vertices with VNN > 0.8 are found in an event, both hemispheres enter the b-tag sample

LEP2: if at least one sec. vtx with VNN > 0.8 is found in an event, both hemispheres enter the b-tag sample

In remaining events, both hemispheres enter the udsc sample

Unfolding to the level of pure udsc and b-quark hemispheres:

$$\begin{pmatrix} D_l \\ D_b \end{pmatrix}^{\rm uncor} (x_E, Q) = \begin{pmatrix} P_{ll} & P_{lb} \\ P_{bl} & P_{bb} \end{pmatrix} (Q) \begin{pmatrix} D_l \\ D_b \end{pmatrix}^{\rm pure} (x_E, Q)$$

E.g. P_{bb} = prob. that a b-tag hemisphere comes from a b-quark

Overall P_{bb} =99.7% (!!), P_{ll} = 79% for LEP1, P_{bb} =75%, P_{ll} = 89% for LEP2

Event statistics for data

UNBIASED JET ANALYSIS (INCLUSIVE HADRONIC EVENTS)

Selection	LEP1	LEP2	BG(LEP2)
Hadronic events	2 387 227	10 866	11%
udsc hemisph.	4 740 774	20 146	11%
b-tag hemisph.	33 680	1 586	5%

BIASED JET ANALYSIS (3-JET EVENTS)

Selection	LEP1	LEP2	BG(LEP2)
Hadronic events	2 387 227	12 653	14%
three-jet events	965 513	6 177	16%
udsc jets	2 675 679	16 344	16%
b-tag jets	83 549	820	9%
Gluon jets	73 620	729	9%

MC study of bias

*Generate inclusive hadronic events at $\sqrt{s}$=91.2 GeV, select 3-jet events and calculate FFs in Q_{jet} intervals
scale = Q_{jet}

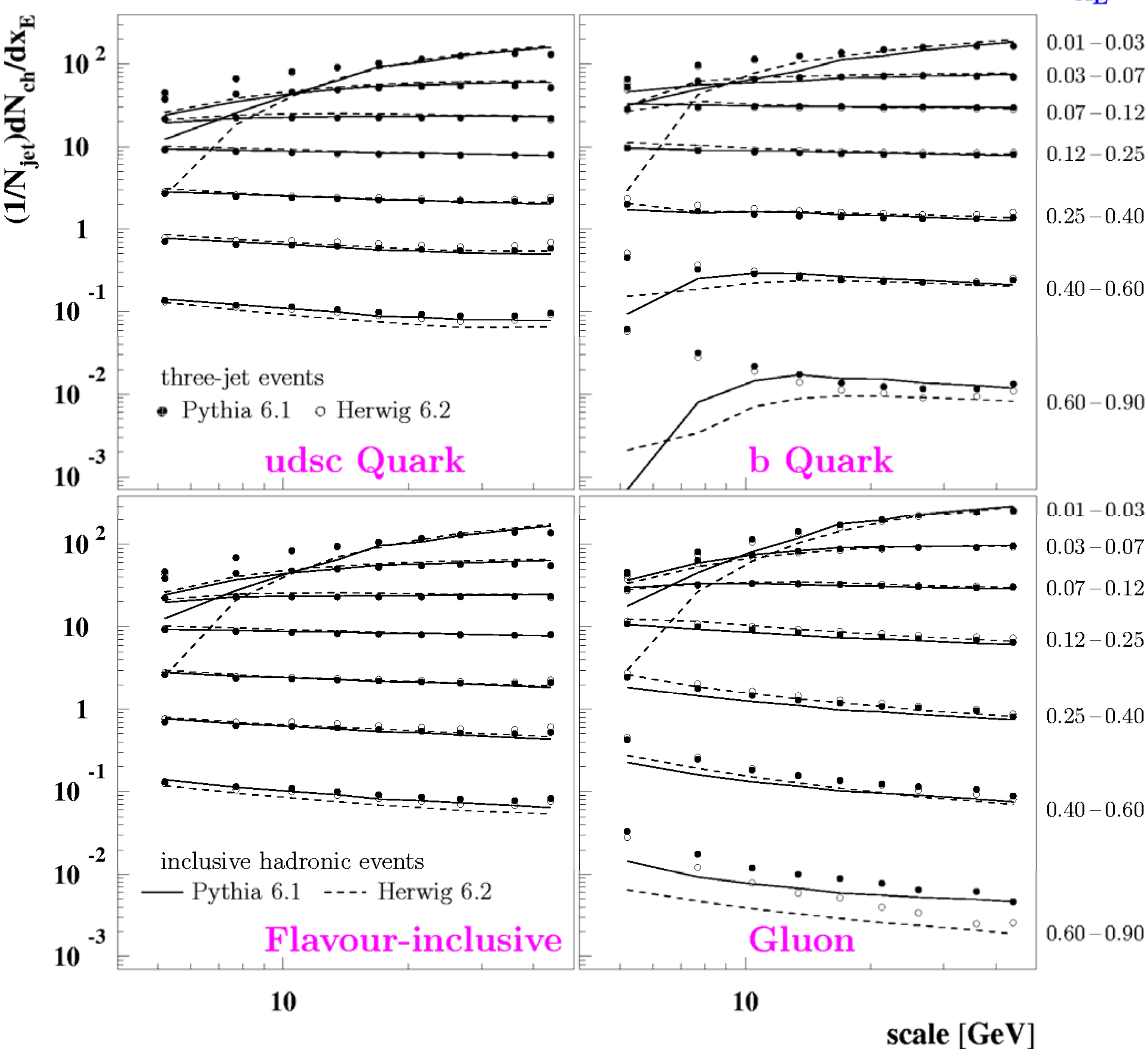
*Generate inclusive hadronic events separately for $\sqrt{s}=2<Q_{jet}>$ (mean Q_{jet} in Q_{jet} bins for 3-jet events) and calculate FFs using hemispheres
scale = $\sqrt{s}/2$

4 regions where differences > 15%:

1) **All FFs at low x_E with low scales**
   HADRON MASS EFFECT
2) **b-FF at high x_E with low scales:**
   b-QUARK MASS EFFECT
3) **ALL FFs at last scale bin:**
   BIAS
4) **Gluon-FF at x_E > 0.4:**
   BIAS

Results independent of MC model and of jet algorithm

OPAL Pythia 6.125 and Herwig 6.2



Biased-unbiased jet diff's not caused by bias

1) All FFs at low x_E with low scales

Difference decreases with incr. scale and x_E → in part explained by hadron mass effect: at small √s, the hadron masses not negligible wrt E_{jet} → FF suppressed at very low x_E. This effect not present in theory and less strong in 3-jet events ($\langle Q_{jet} \rangle$=5.2 GeV, $\langle E_{jet} \rangle$~13 GeV in 1. Q_{jet} interval).

Processes affecting the region of very low x_E but not studied here:

- Resonance decays giving soft partricles mainly present in hemispheres produced at low energies
- QCD coherent radiation of soft gluons disables to assign unambiguously soft particles to 3 jets

2) b-FF at high x_E with low scales

Difference increases with incr. x_E and decr. scale → may be explained by b-quark mass effect, i.e. by ratio m_b/E_{jet}: at small √s (just above the bb production threshold, ~2m_b), m_b/E_{jet}≈100% and almost all particles in hemispheres come from B-hadron decays. As the scale increases, the decay particles are boosted and the most massive takes most of the energy. The same holds for 3-jet events but the boost already big in the 1.Q_{jet} bin ($\langle E_{jet} \rangle$~13 GeV) and m_b/E_{jet}≈40% there.

- In both types of events, rise of soft gluon mult. with incr. E_{jet} reduced by dead cone effect
- In current NLO calc., mass terms of type quark-mass/hard scale not considered;
- Similar behaviour of NLO calc. and 3-jet data at small scales suggests that the mass terms may behave like m_b/E_{jet}

NLO calculations

1. **Kniehl, Kramer, Pötter** (KKP)
   [Nucl.Phys.B582 (2000) 514]
2. **Kretzer** (Kr)
   [Phys. Rev. D62 (2000) 054001]
3. **Bourhis, Fontannaz, Guillet, Werlen** (BFGW)
   [hep-ph 0009101]

→ They provide NLO predictions of

$$\frac{1}{\sigma_{\text{tot}}} \frac{d\sigma^{(e^+e^- \to \gamma/Z \to hX)}}{dx_E}$$

based on unbiased jet definition

→ α_s accuracy of hard subprocess $\sigma^{(e^+e^- \to q\bar{q})}$
→ α_s^2 accuracy of splitting functions
NLO corrections to $\sigma^{(e^+e^- \to q\bar{q}g)}$ not known yet but they will depend on a jet finder used

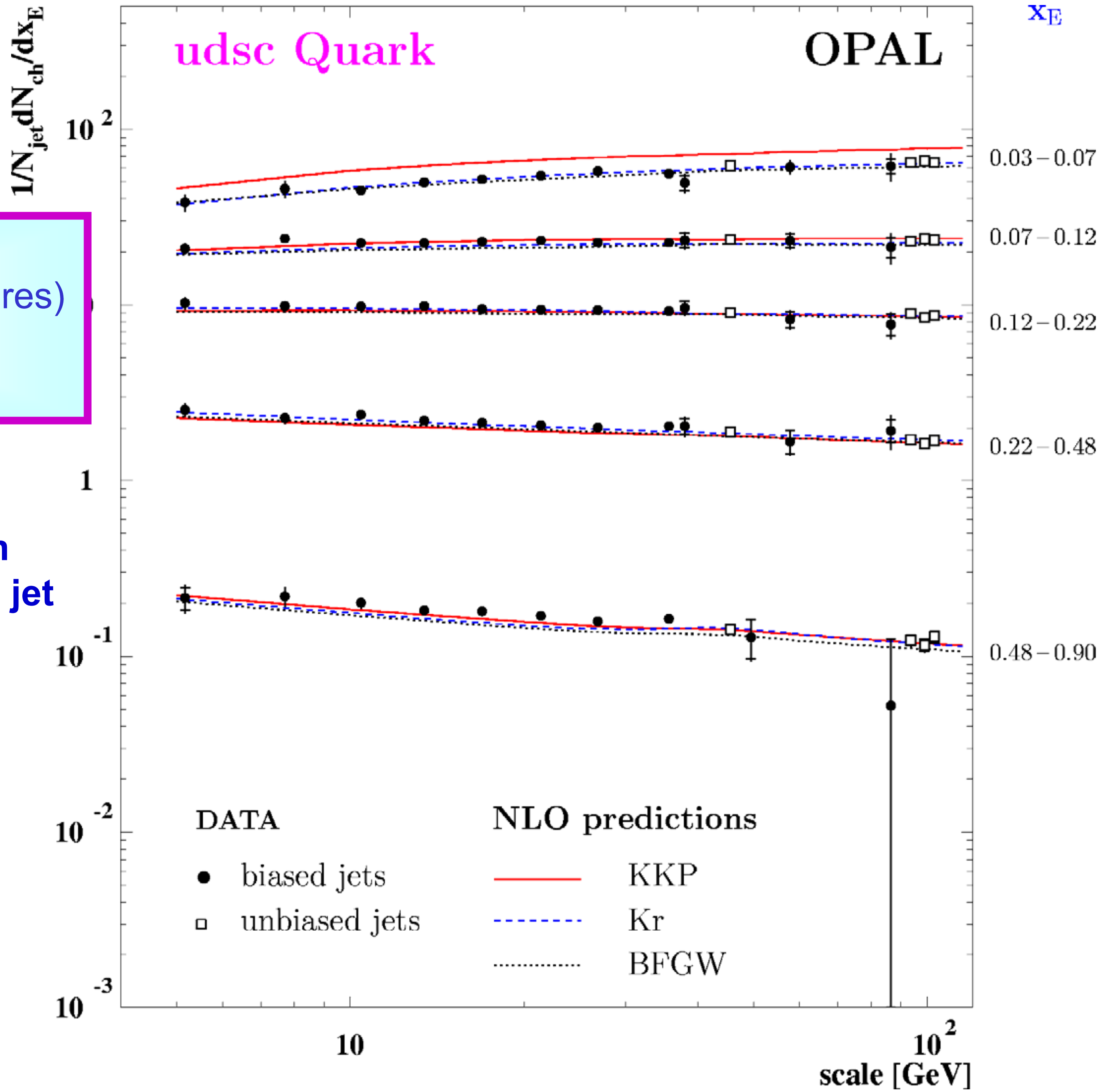
Assumption

Biased jet results consistent with unbiased jet results
⇓
NLO corrections to 3-jet processes small
⇓
Comparison of biased jet results to theory meaningful

The three groups use $\mu_r = \mu_f =$ hard scale Q but differ in

! choice of data sets used in fits - definition of the scale Q - fit ranges - prescription for number of active flavours - treatment of heavy quarks and gluons. !

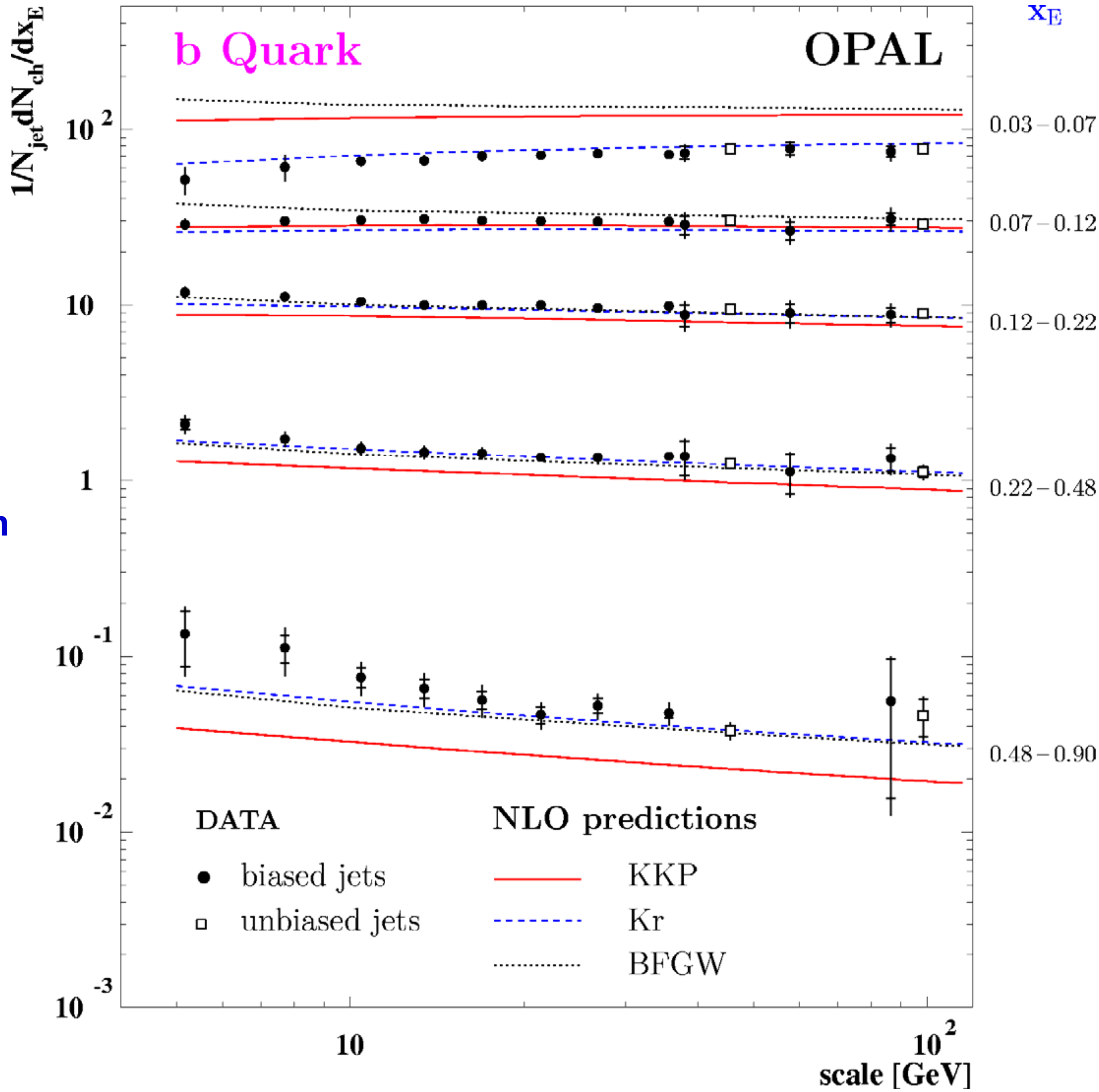
Scale = $\sqrt{s}/2$ for
Unbiased jets (hemispheres)
= Q_{jet} for
Biased jets (3-jet events)

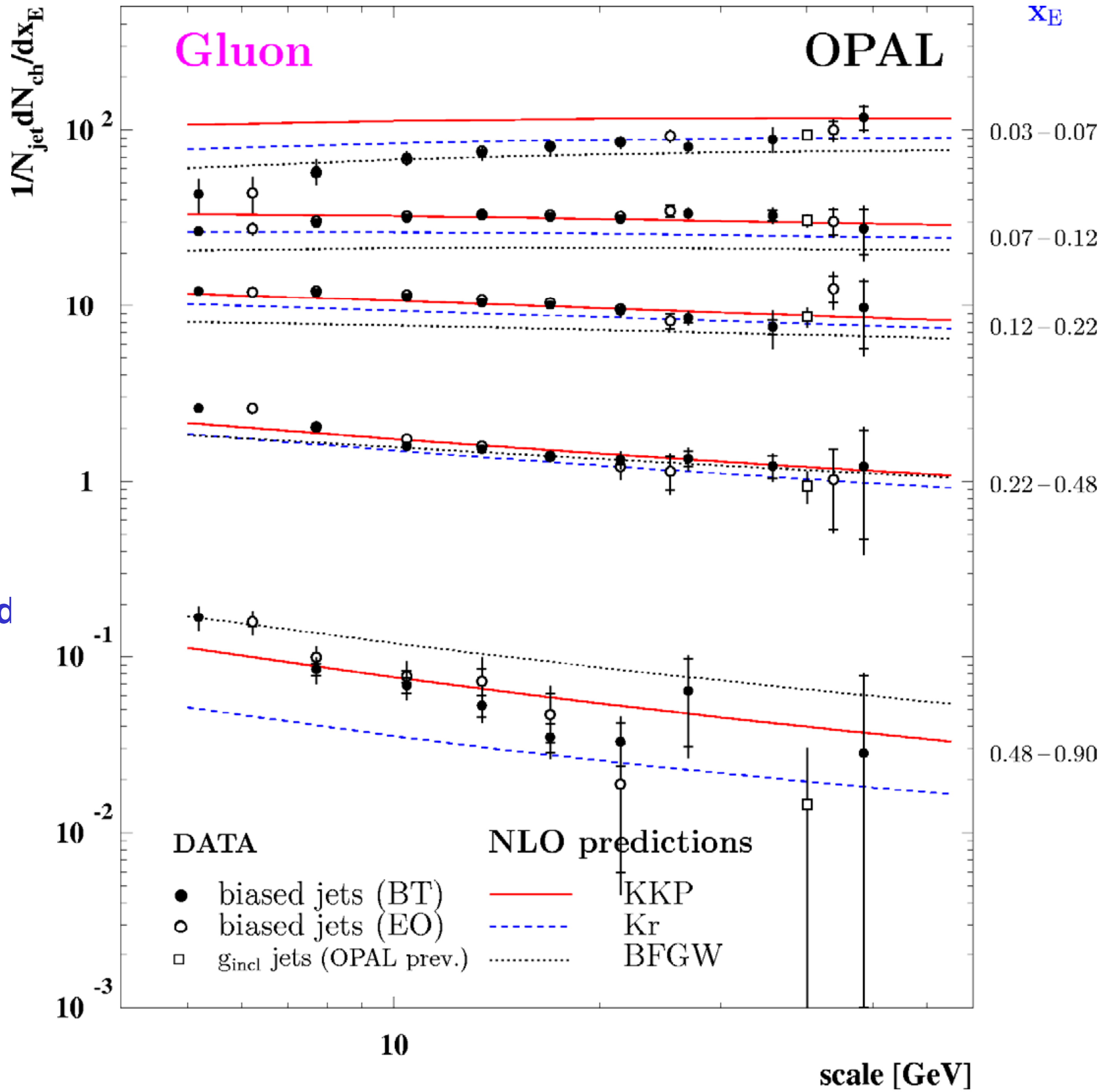


*** Consistency between biased and unbiased jet data**

* Consistency between biased and unbiased jet data

* Large spread of NLO predictions





* Consistency between two methods for biased jets (BTAG and Energy ordering)

* Consistency between biased and unbiased jet data

* Large spread of NLO predictions

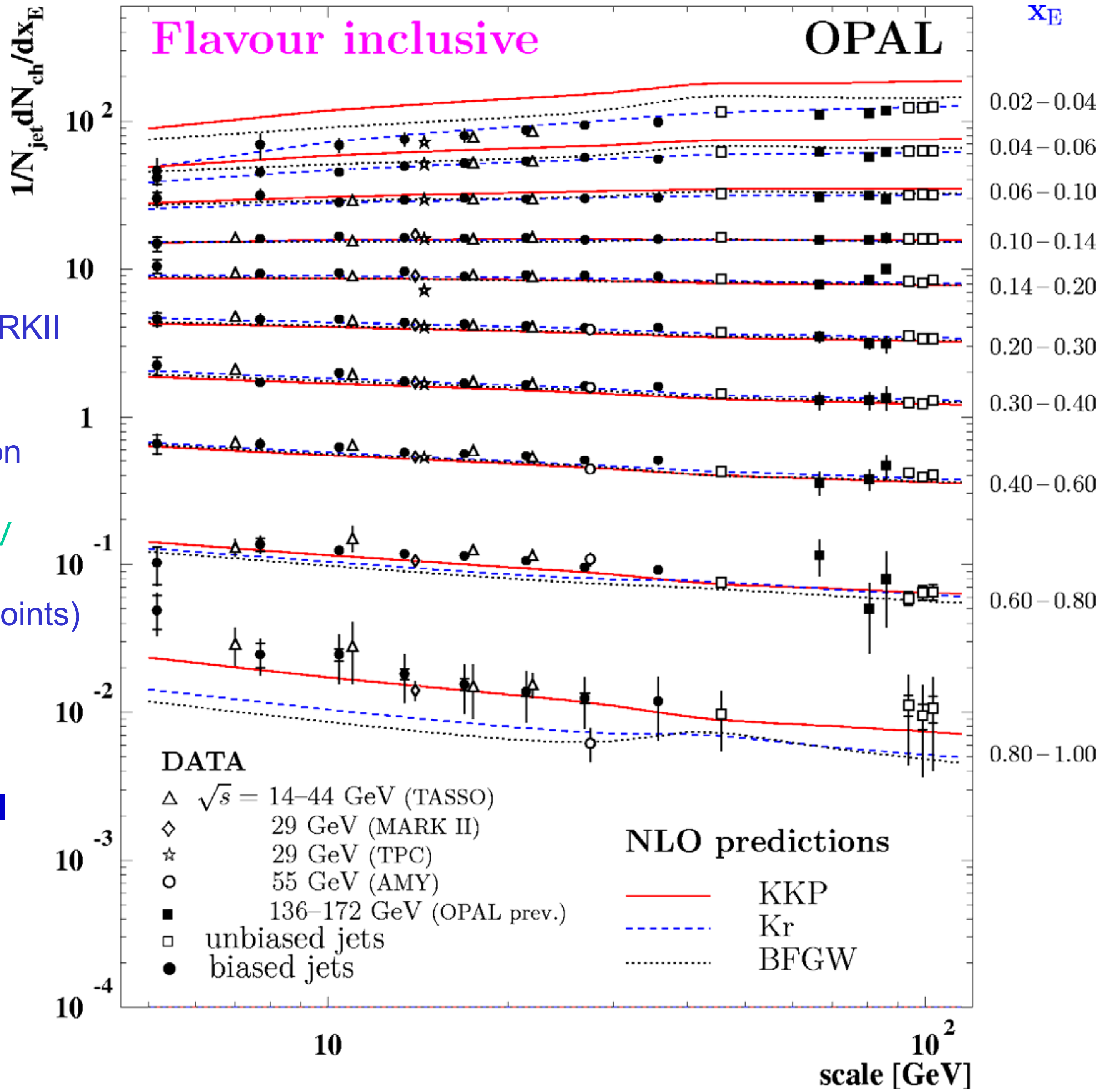
NB: FFs from TASSO, MARKII and AMY are defined via

$x_p = 2p/\sqrt{s}$

This difference in x-definition affects the region

$x_E < 0.1$ and $\sqrt{s} < 22$ GeV

This region not shown (5 points)



*** Measured biased and unbiased jet data consistent with published unbiased jet data**

NB: FFs from TASSO are defined via $x_p = 2p/\sqrt{s}$

This difference in x-definition affects the region $x_E < 0.1$ and $\sqrt{s} < 22$ GeV

↓

Do a $x_p \rightarrow x_E$ transformation using pion mass and shift TASSO points

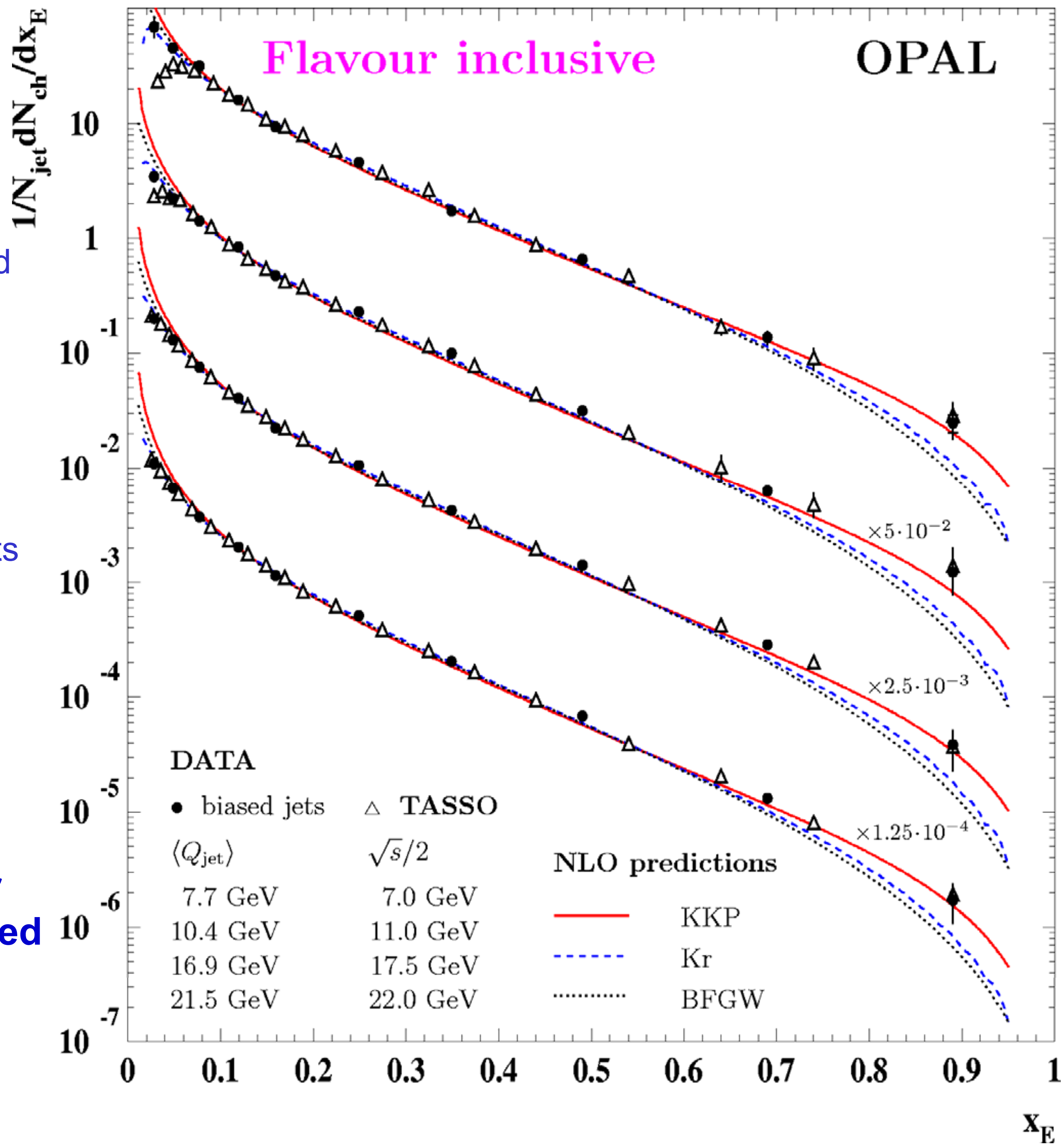
*** Low x_E with low scale:**

1) Hadron mass effect in unbiased jet data

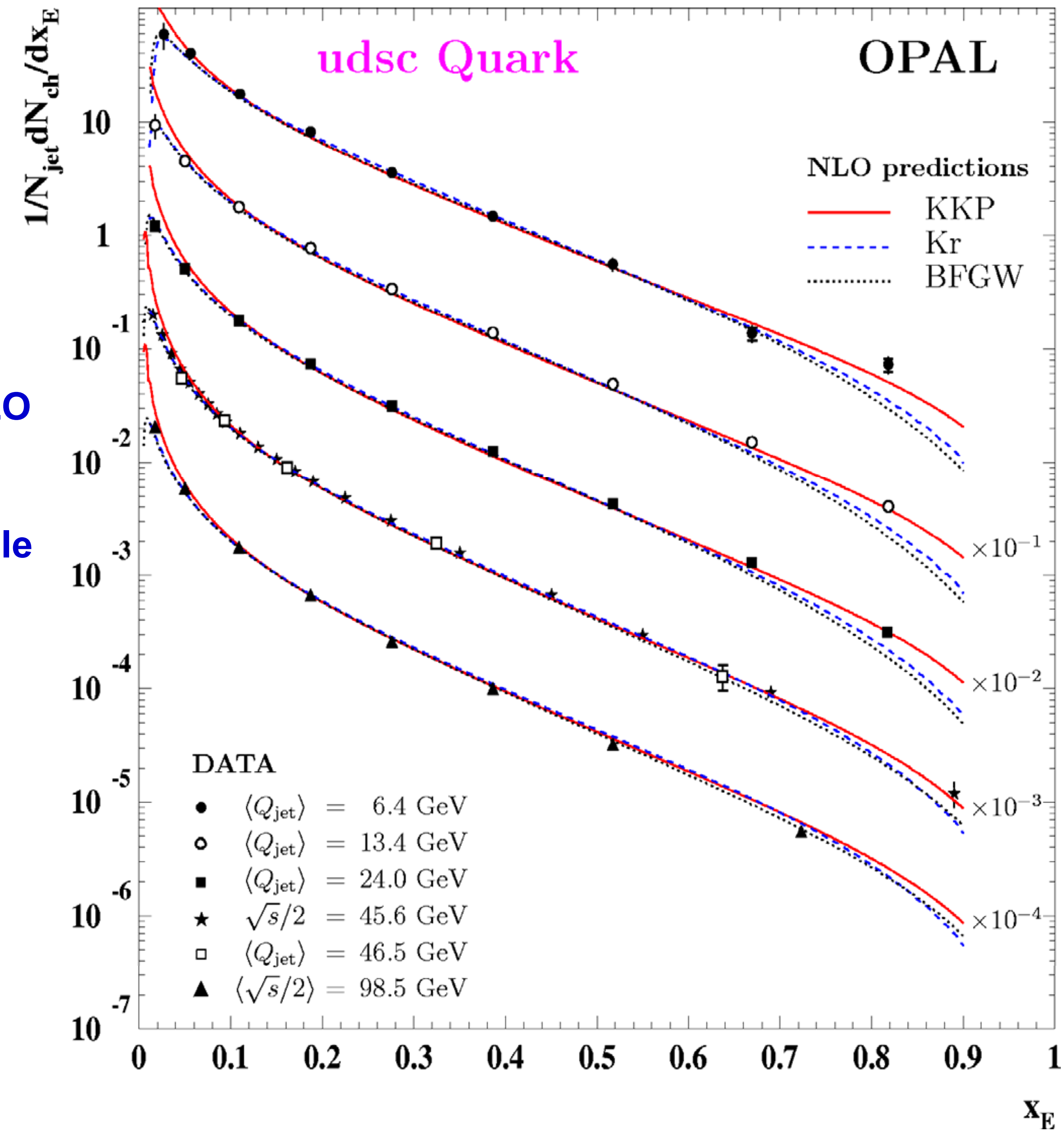
2) Biased jets agree better with theory than unbiased

↓

Data confirm observations made in the MC study

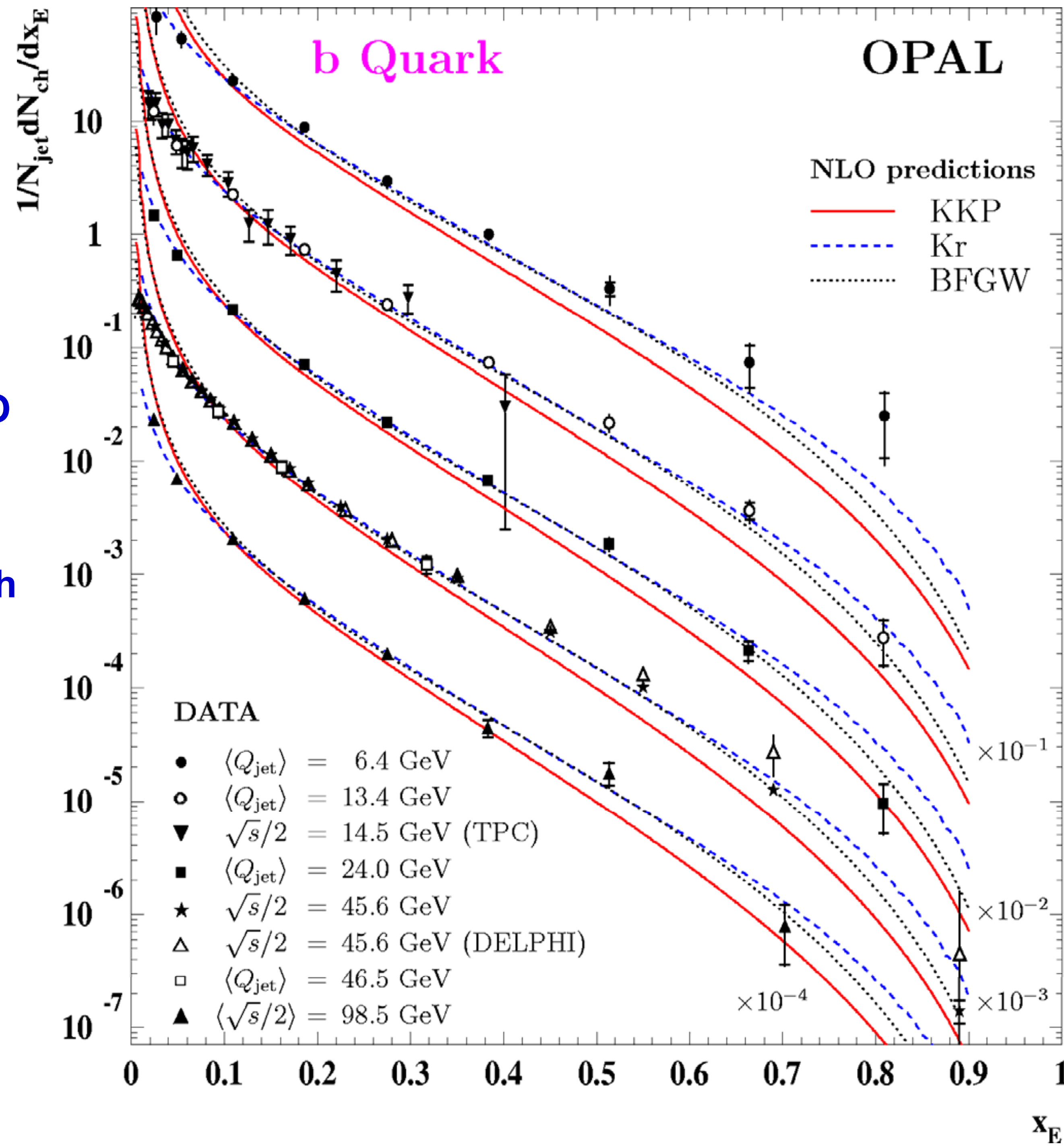


* Differences between NLO predictions at very low and very high $x_{E.}$
They decrease as the scale increases



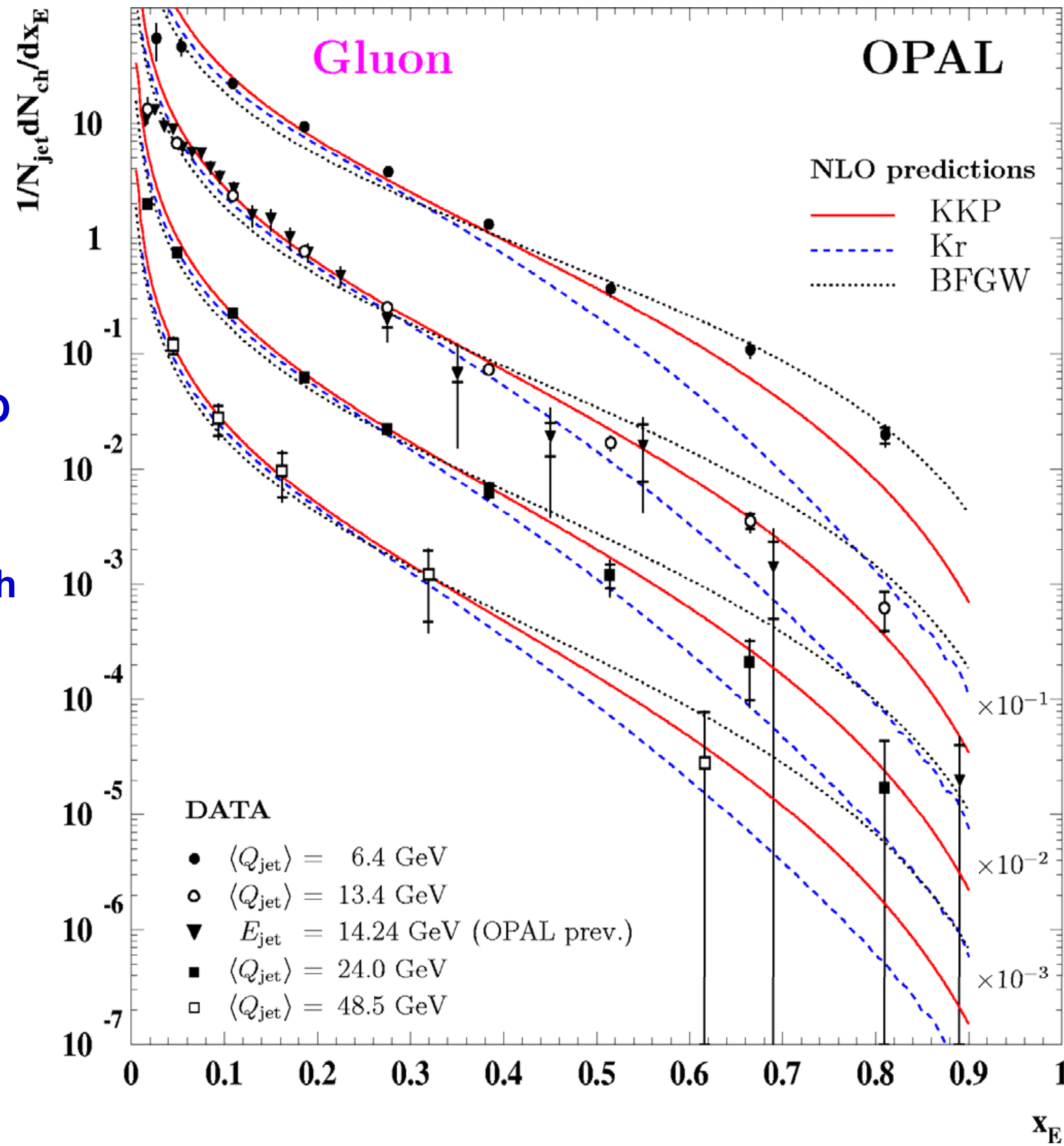
* Differences between NLO predictions at very low and very high x_E

* Biased jet data agree with published unbiased jet data by TPC and DELPHI



* Differences between NLO predictions at very low and very high x_E

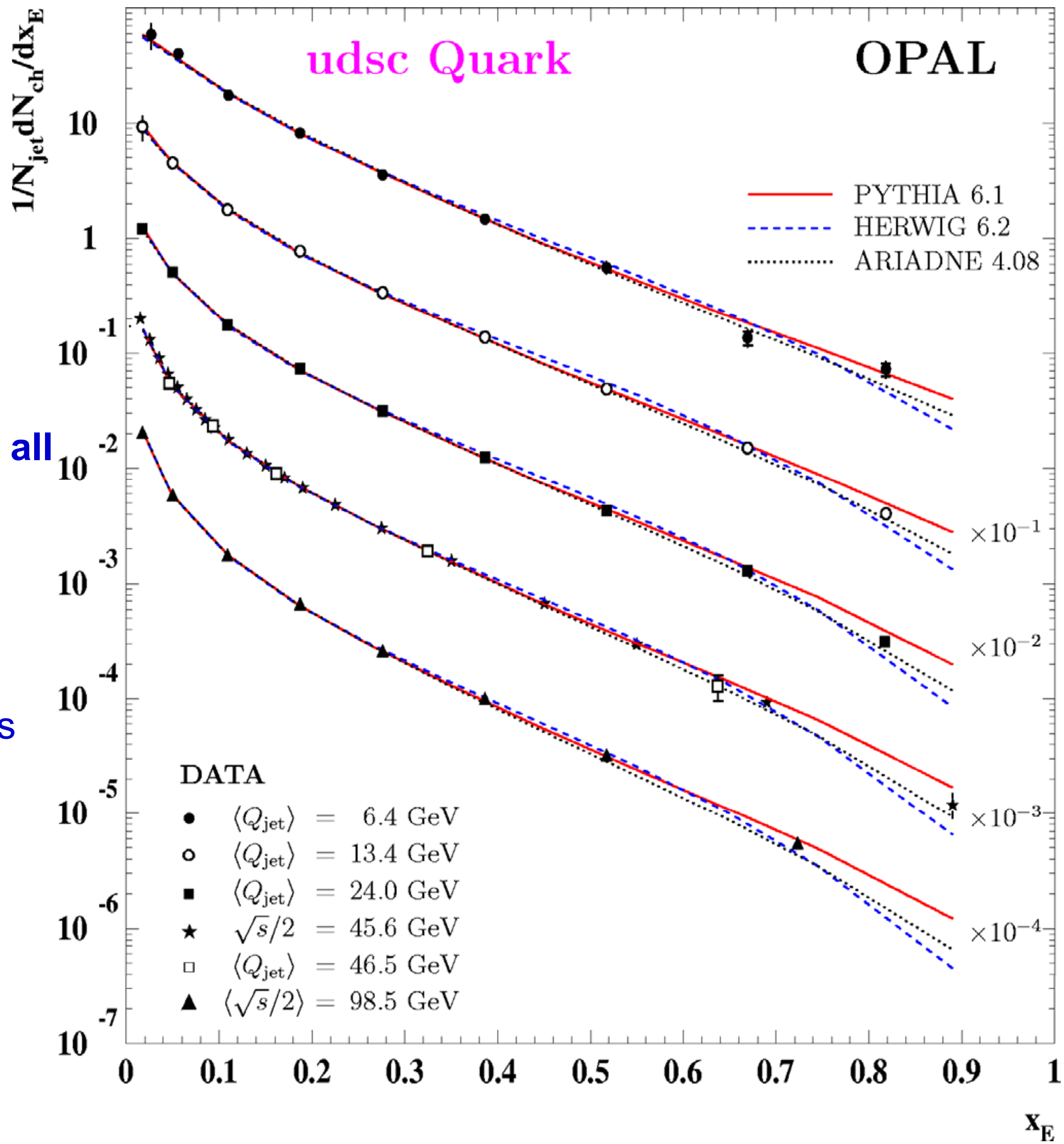
* Biased jet data agree with published OPAL boost algorithm results



* **Very good description by all three MC generators.**

BUT : - measured unbiased (biased) jet data compared to MC unbiased (biased) jets

* **OPAL tune for LEP1 data still good for LEP2 data**



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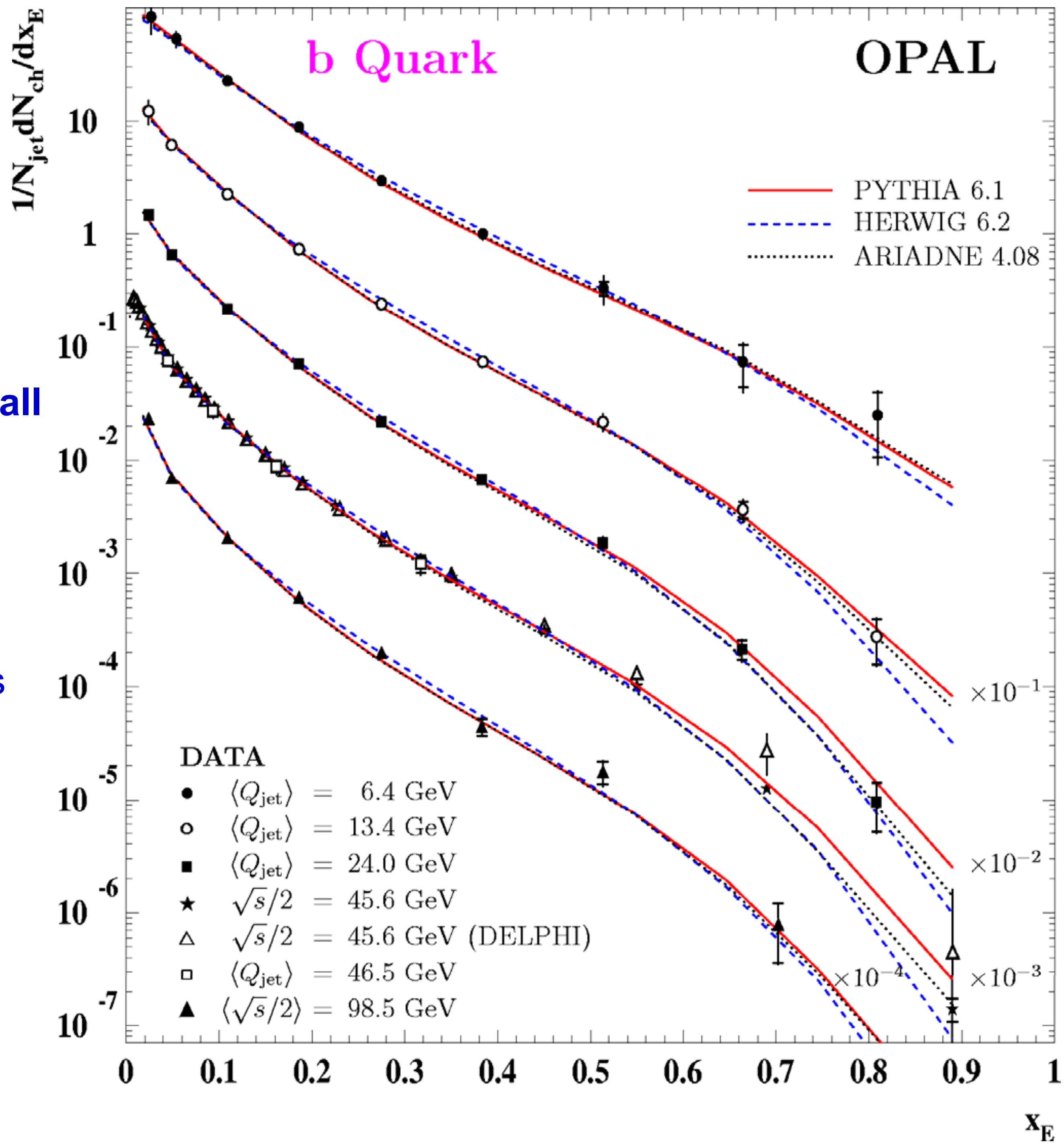
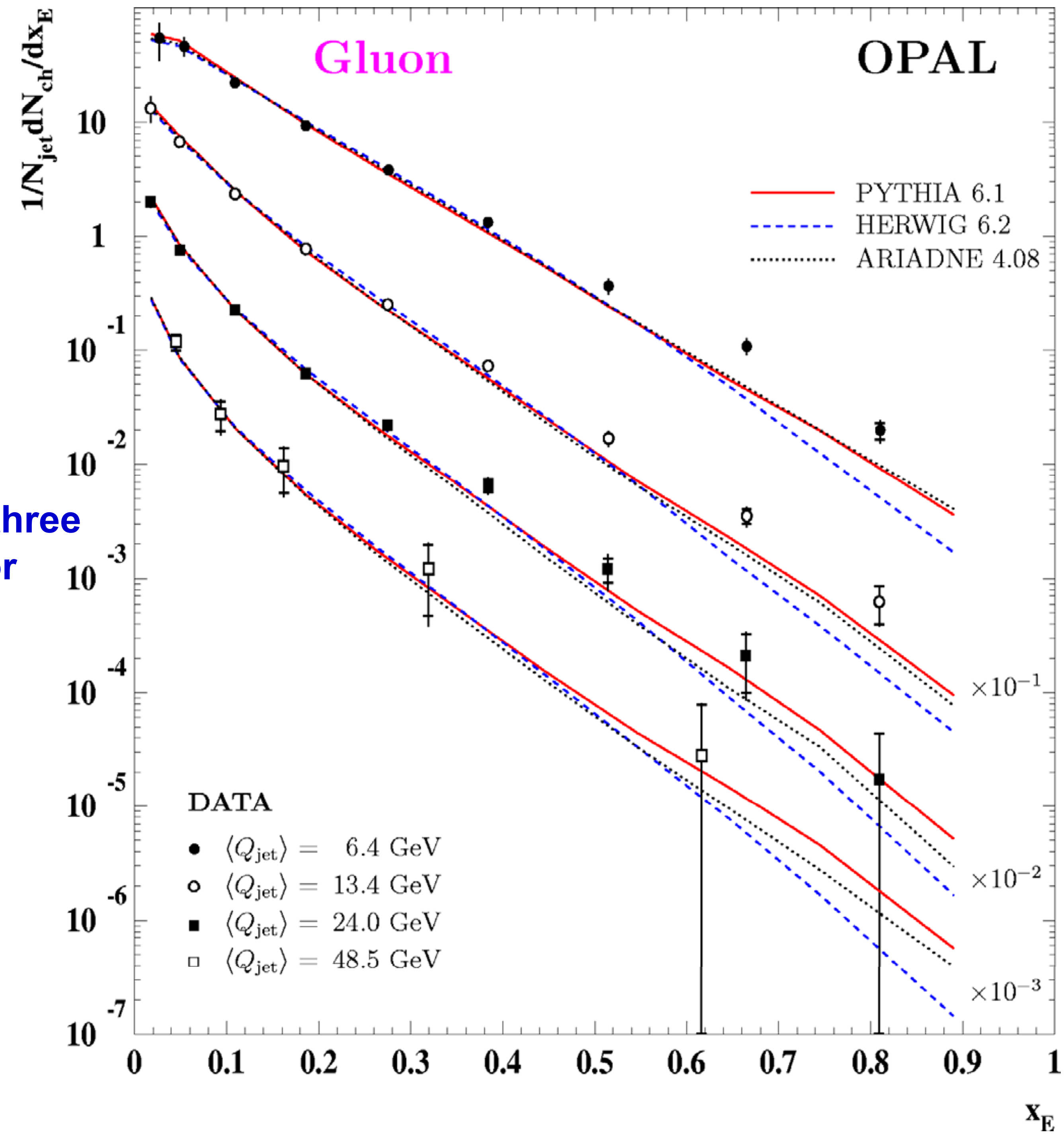


* Good description by all three MC generators except for small scales and high x_E



Charged particle multiplicities

Obtained by integrating unbiased jet FFs over x_E

$\sqrt{s}$ [GeV]	$\langle n_{ch}^{incl} \rangle$
91.2	$20.93 \pm 0.01 \pm 0.23$
183–189	$26.80 \pm 0.24 \pm 0.46$
192–202	$27.68 \pm 0.26 \pm 0.50$
204–209	$27.75 \pm 0.29 \pm 0.67$

$\sqrt{s}$ [GeV]	$\langle n_{ch}^{udsc} \rangle$
91.2	$20.32 \pm 0.03 \pm 0.27$
183–189	$26.43 \pm 0.26 \pm 0.81$
192–202	$27.38 \pm 0.31 \pm 0.85$
204–209	$26.87 \pm 0.32 \pm 0.99$

$\sqrt{s}$ [GeV]	$\langle n_{ch}^{b} \rangle$
91.2	$23.28 \pm 0.09 \pm 0.70$
183–209	$30.01 \pm 0.53 \pm 0.82$

Found in agreement with previous measurements and with predictions of PYTHIA 6.1, HERWIG 6.2 and ARIADNE 4.08

Unbiased gluon jets using jet boost algorithm

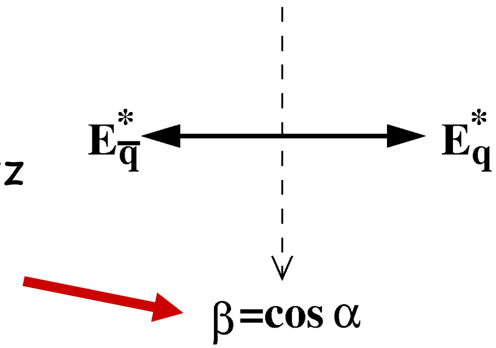
The jet boost alg. motivated by Color Dipole Model of QCD:

$q\bar{q}$ color dipole viewed in a frame where

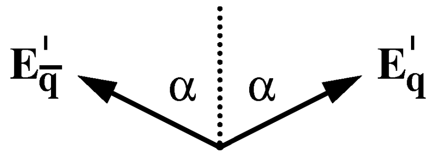
q and $\bar{q}$ are back-to-back

Lorentz boost along the hemi boundary

Lorentz boost factor



(a)

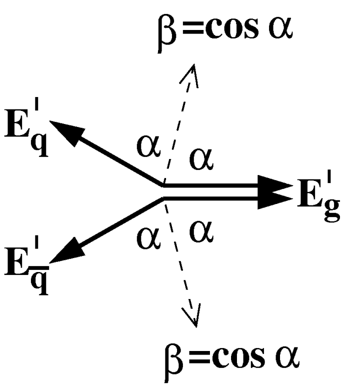


$E_i^* = E_i' \sin(\theta/2)$

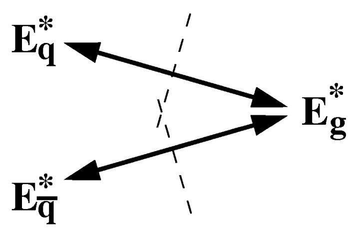
$= 2\alpha$

(b)

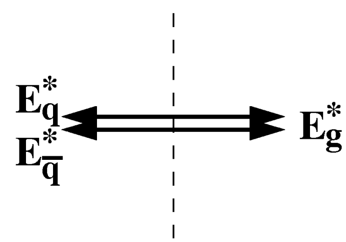
Symmetric 3-jet $q\bar{q}g$ event with $\theta(q,g) = \theta(\bar{q},g) = 2\alpha$:



(a)



(b)



(c)

2 indep. color dipoles

Each dipole boosted to back-to-back frame

2 dipoles in back-back frames combined to gluon-gluon event in a color singlet

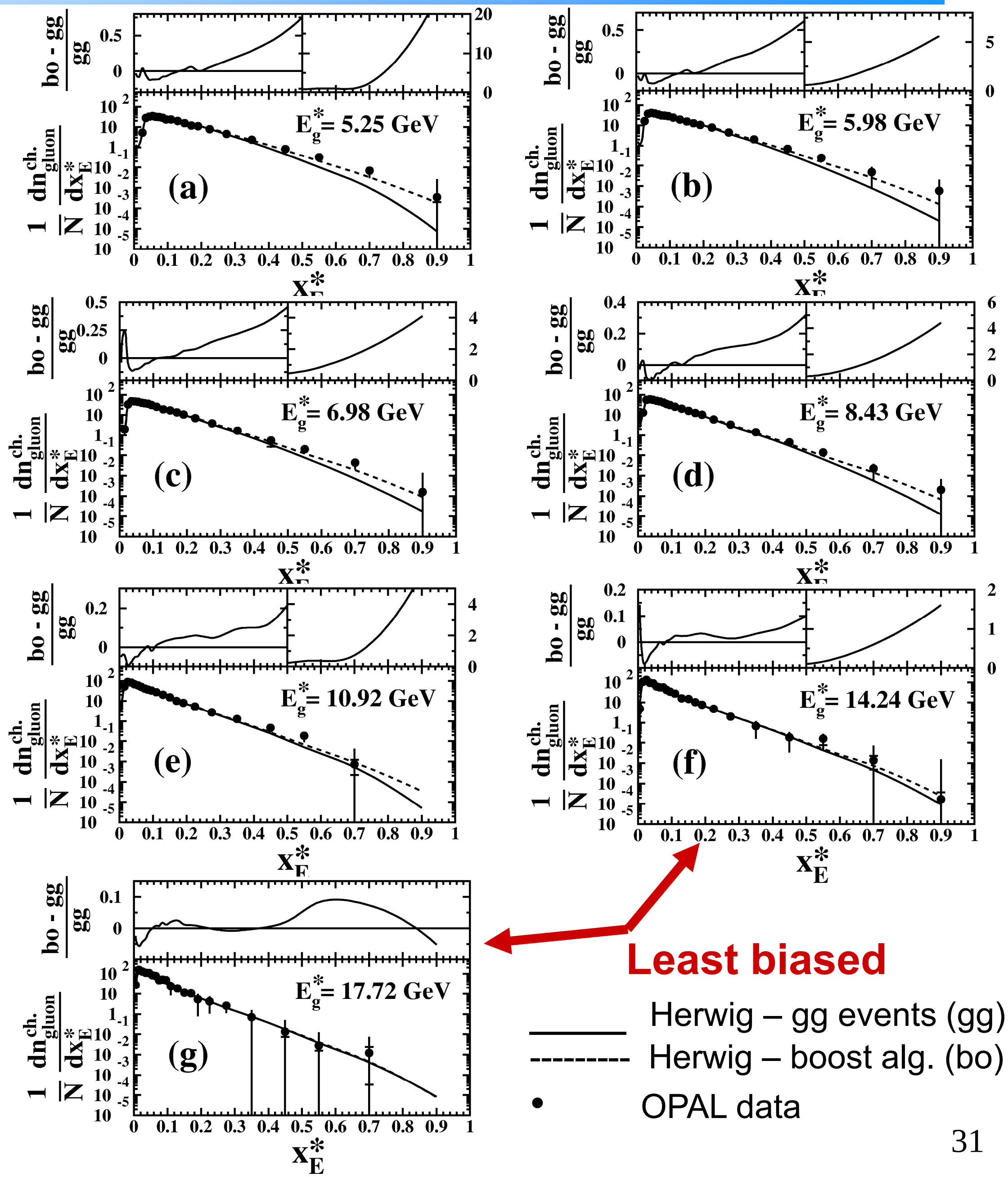
FFs using jet boost algorithm

Event selection:

1) Standard hadronic event selection
2) k_T alg. forced to resolve 3 jets (y_{cut} variable)
3) Assume Jet 1 = quark jet. Require just one of Jets 2 or 3 to be b-tagged. The other jet is gluon jet.
4) $E_g^* > 5$ GeV
5) For quark jets: $Q_{jet} > 8$ GeV
6) Boost the event to symmetric frame and put $E_g^* = p_{T,gluon} = 1/2\text{sqrt}(s(q,g)s(\bar{q}g)/s)$ (ensures the gluon jet is indep. of jet resolution scale, i.e. is unbiased)

Nr. of selected events: 25 396

(Results indep. of jet alg. and of quark flavour)



Conclusions

1) 7 types of FFs measured: biased jets, scale=Q_{jet}[GeV] | unbiased jets, scale=$\sqrt{s}/2$[GeV]

	biased jets, scale=Q_{jet}[GeV]	unbiased jets, scale=$\sqrt{s}/2$[GeV]
Udscb	4.0 – 42.0	45.6; 91.5 – 104.5
Udsc	4.0 – 104.5	45.6; 91.5 – 104.5
B	4.0 – 104.5	45.6; 91.5 - 104.5
Gluon	4.0 – 70.0	

2) Results found consistent with published results.

3) Consistency between biased and unbiased jet results:
Q_{jet} is an appropriate choice of scale in events with a general 3-jet topology justifies the comparison of unbiased jets with NLO calculations

4) Scaling violation of gluon FFs observed stronger than that of quark FFs

5) NLO calc. describe well udsc FFs, but much worse the b- and gluon jet FFs

6) Data compared to different fragmentation models. Pythia, Herwig and Ariadne describe the data well, except for high x_E with small scale for gluon jet FFs

7) Charged particle multiplicities in udscb, udsc and b events measured and found consistent with previous measurements and with predictions of all three MCs.

8) First results from jet boost algorithm: gluon jets for FF measurement found unbiased in the range of E_{jet} of 13-20 GeV.

BACKUP SLIDES

Systematic uncertainties

Sources and variations :

1. Jetset/Pythia $\rightarrow$ Herwig (mostly below 6%!)
2. $|\cos\theta_{\mathrm{part}}| \leq 0.95 \rightarrow |\cos\theta_{\mathrm{part}}| \leq 0.70$

[redacted]

(mostly below 10%!)

Udsc jet FFs less sensitive to these variations then b- and gluon jet FFs

* Gives the largest change in numbers of b-tag and gluon jets

* Gives the largest change in b-tag and gluon jet purities