Were there any anomalies in the gluon jets in ALEPH?

Aug. 27, 2024

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& Yi Chen, Yen-Jie LEE (MIT)

John William - Ariadne

About this talk

- **Title**
  - **Were there any anomalies in the gluon jets in ALEPH?**
- **Abstract**
  - According to the **Abelian decomposition of QCD**, there is a theoretical prediction that **gluons can be classified into two types**, each **exhibiting distinct experimental signatures**. The optimal setting for experimental verification of this theory is a clean environment such as the LEP, rather than the LHC. We have investigated whether there were any anomalies observed already in the gluon jets recorded in the ALEPH experiment and **revisited the analyses with the archived ALEPH data**. In this presentation, we will show our latest updates on our study on the gluon jet properties in ALEPH.
- **Authors**

  - **Youngkwon Jo, Inkyu Park (University of Seoul)**
  - **Yi Chen, Yen-Jie Lee (MIT)**

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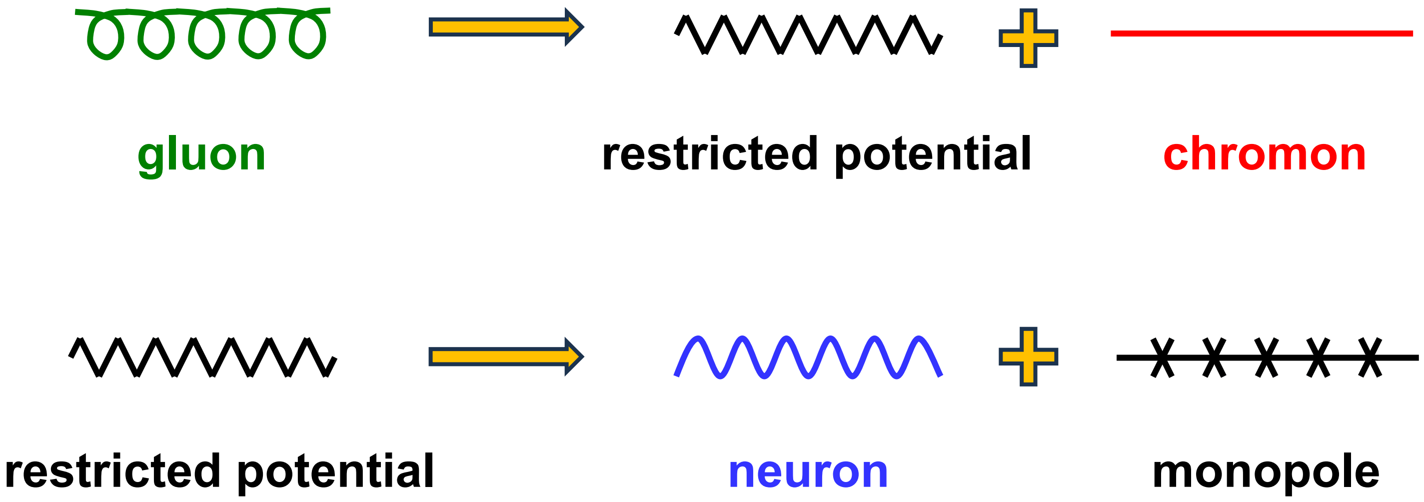
Theoretical motivation

- "Experimental verification of Two types of Gluon Jets in QCD"
  - Y. M. Cho, Pengming Zhang, and Li-Ping Zou
    - ✓ Phys. Rev. D 107, 054024 – Published 17 March 2023



PHYSICAL REVIEW D **107,** 054024 (2023)

Experimental verification of two types of gluon jets in QCD

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The Abelian decomposition of QCD tells that there are two types of gluons, the color neutral neurons and colored chromons. We propose to confirm the Abelian decomposition testing the existence of two types of gluon jets experimentally. We predict that one quarter of the gluon jet is made of the neurons which has the color factor 3/4 and the sharpest jet radius and smallest charged particle multiplicity, while the three quarters of the gluon jet are made of the chromons with the color factor 9/4, which have the broadest jet radius (broader than the quark jet). Moreover, we argue that the neuron jet has a distinct color flow which forms an ideal color dipole, while the quark and chromon jets have distorted dipole pattern. To test the plausibility of this proposal, we suggest to analyze the gluon distribution against the jet shape (the sphericity) and/or particle multiplicity from the existing gluon jet events and look for two distinct peaks in the distribution.

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I. INTRODUCTION

A common misunderstanding on QCD is that the non-Abelian color gauge symmetry is so tight that it defines the theory almost uniquely and thus, does not allow any simplification. This is not true. The Abelian decomposition of QCD tells that we can construct the restricted QCD (RCD), which inherits the full non-Abelian color gauge symmetry with the restricted potential obtained by the Abelian projection. This tells that QCD has a nontrivial core, RCD, which describes the Abelian subdynamics of QCD but has the full color gauge symmetry. Moreover, it tells that QCD can be viewed as RCD which has the gauge covariant valence gluons as the colored source [1,2]. This is because the Abelian decomposition decomposes the color gauge potential to the restricted potential made of the color neutral gluon potential, the topological monopole potential, and the gauge covariant valence potential, which describes the colored gluon gauge independently.

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There are ample motivations for the Abelian decomposition. Consider the proton made of three quarks. Obviously, we need the gluons to bind the quarks in the proton. However, the quark model tells that the proton has no valence gluon. If so, what is the binding gluon that bind the quarks in proton, and how do we distinguish it from the valence gluon?

Moreover, the simple group theory tells that the color gauge group has the Abelian subgroup generated by the diagonal generators and that the gauge potential, which corresponds to these generators, must be color neutral, while the potential which corresponds to the off diagonal generators must carry the color. This strongly implies that there are two types of gluon, the color neutral ones and colored ones. And they should behave differently, because they have different color charges. If so, how can we distinguish them?

Another motivation is the color confinement in QCD. Two popular proposals for the confinement are the monopole condensation [2,3] and the Abelian dominance [4,5]. To prove the monopole condensation, we first have to separate the monopole potential gauge independently. Similarly, to prove the Abelian dominance, we have to know what is the Abelian part and how to separate it.

The Abelian decomposition tells how to do this. It decomposes the non-Abelian gauge potential to two parts, the restricted Abelian part, which has the full non-Abelian gauge symmetry and the gauge covariant valence part,

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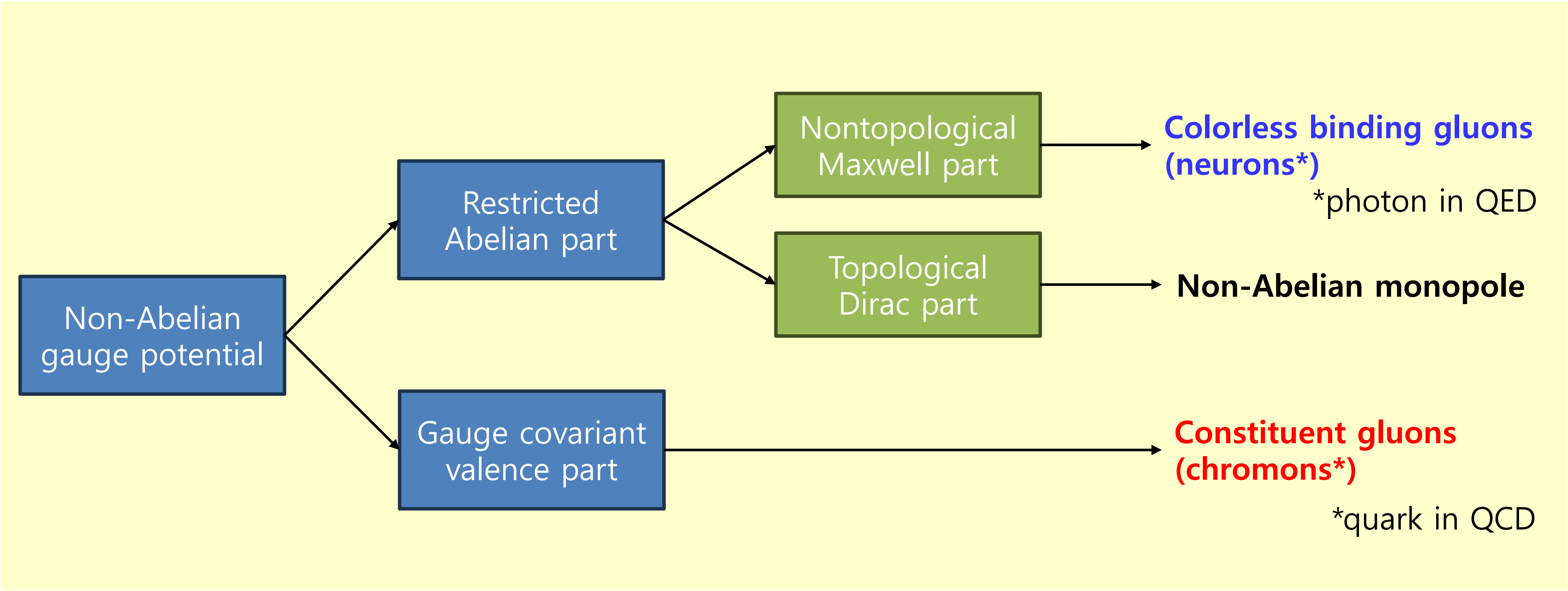
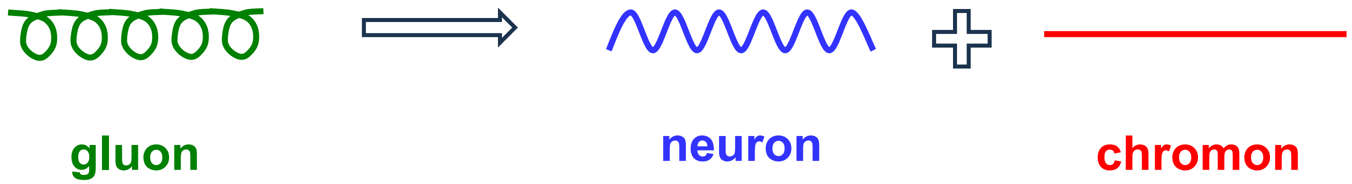
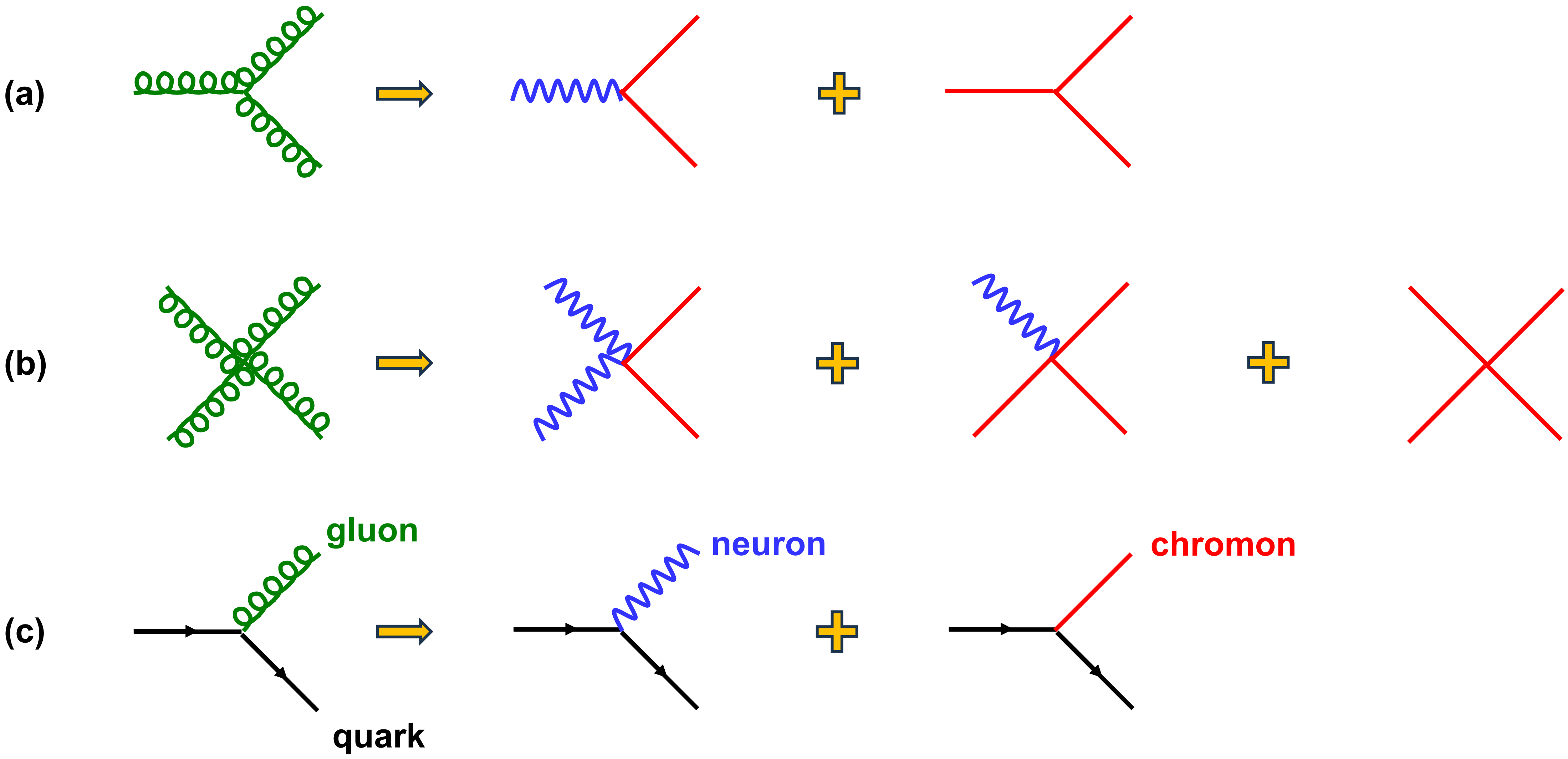
Abelian decomposition of QCD

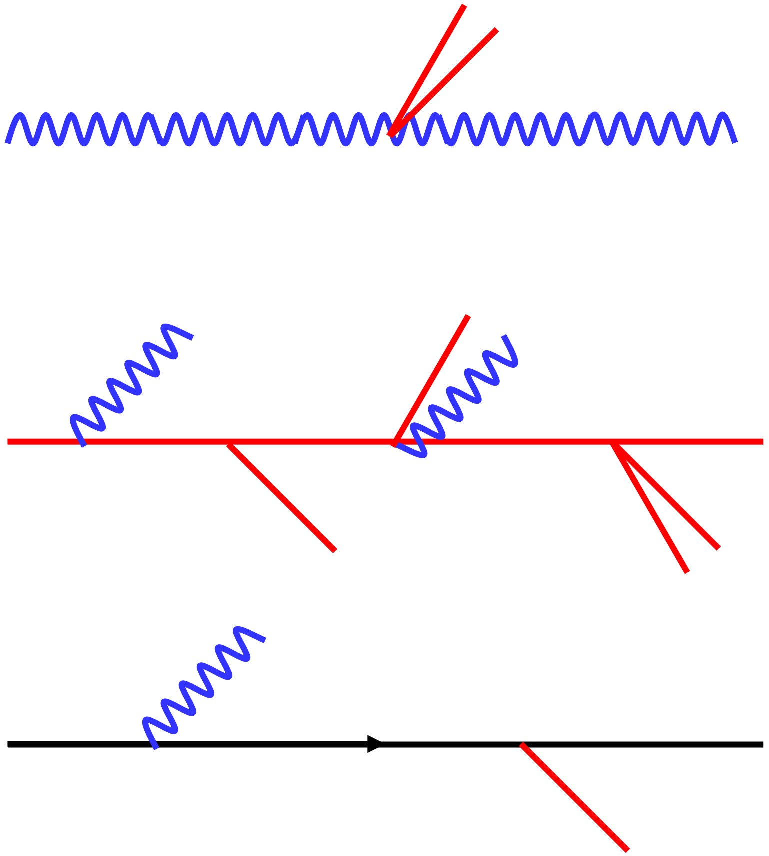




Decomposition of Feynman diagrams



Neuron jet and Chromon jet



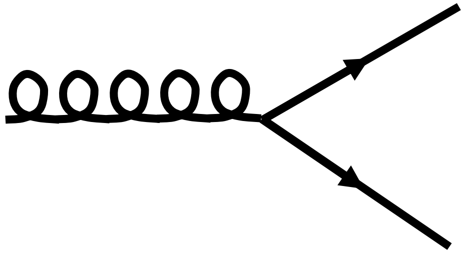
neurons — LO $O(g^2)$

chromons — LO $O(g)$

quarks — LO $O(g)$

Experimental signatures of gluon jets

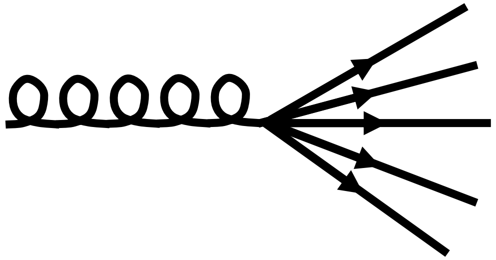
- if there exist two distinct types of gluons, then
  - Color neutral gluons (neurons) → EM jet like shape



→ Narrow jet

→ Low multiplicity

  - Colored gluons (chromons) → Typical hadronic jet shape

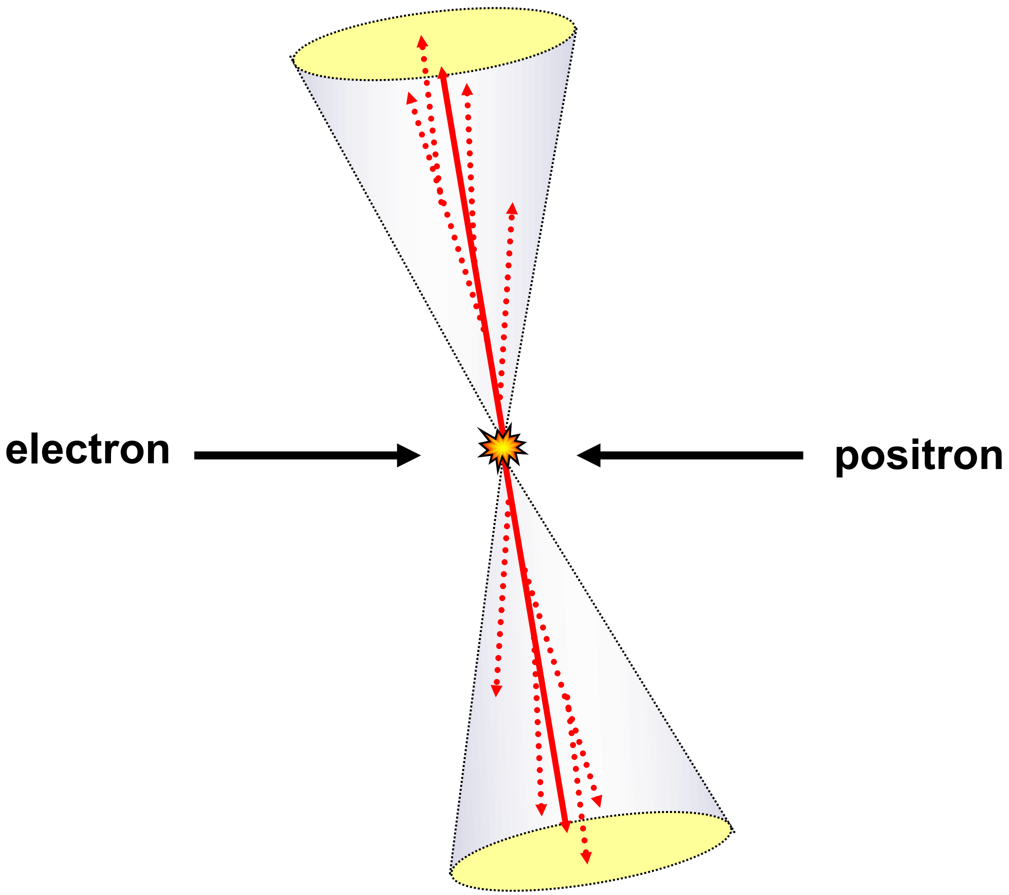


then, we might observed…

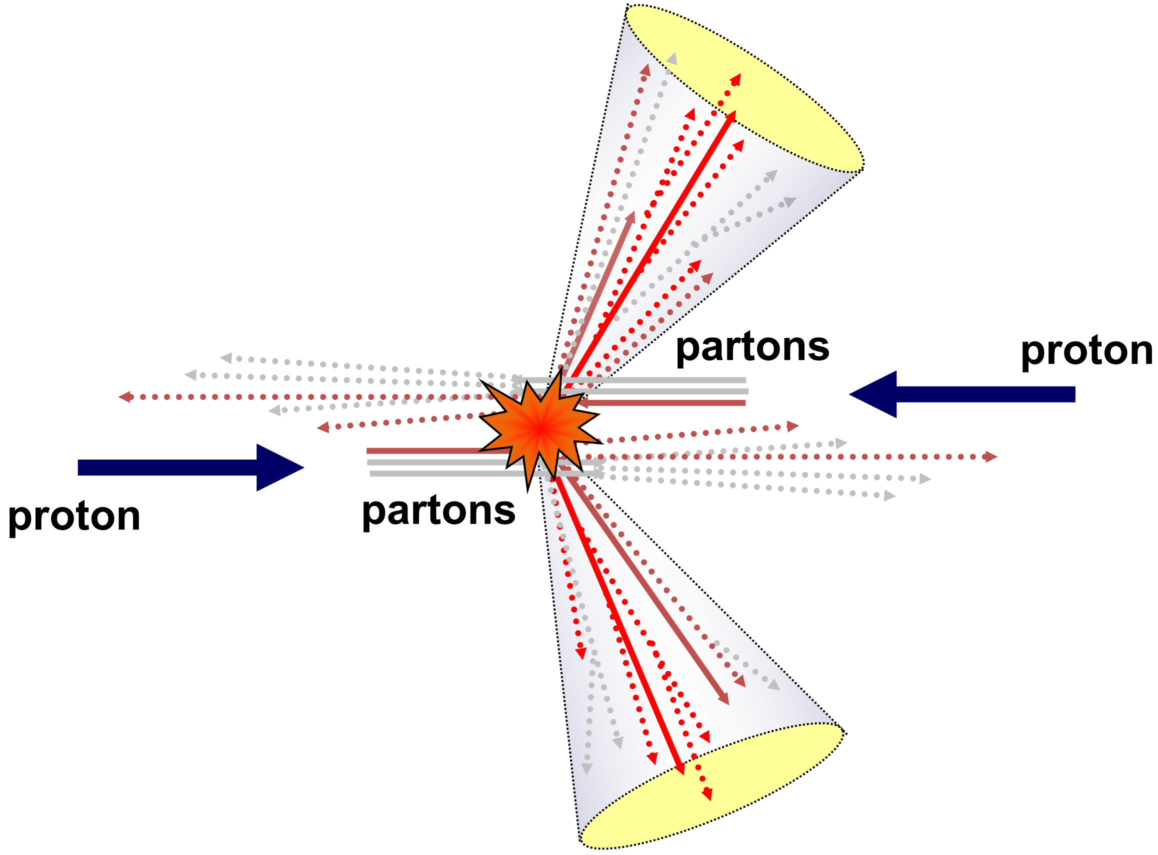
- due to the typical jet reconstruction techniques,
  - deficit of color neutral gluons
    - ✓ might not be reconstructed as jets
  - excess of jets with small number of tracks
    - ✓ check this easily by seeing # of tracks in jets
  - two distinct jet shapes
    - ✓ narrow jet (neurons) .vs. broad jet (chromons)
  - anomalies in energy shares of tracks in a jet
    - ✓ high share (neurons) .vs. low share (chromons)

Recall: QCD Jet study @ LEP

LEP vs LHC for QCD study



No initial state colors, back-to-back jets



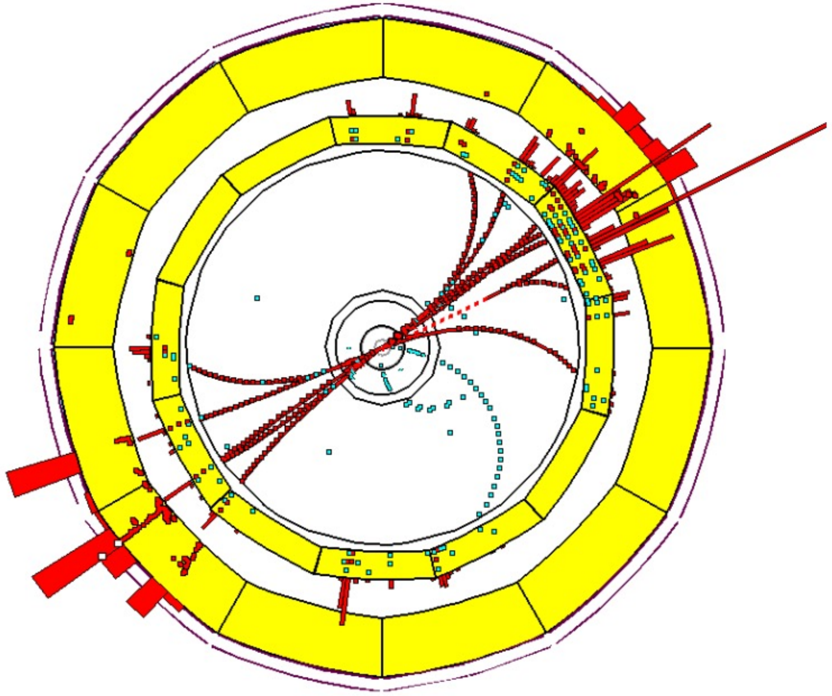
Initial state colors, boosted jets

QCD jet study @ LEP1

- **LEP1 : Z0 peak energy**
  - $e^{+} + e^{-} \rightarrow (\gamma, Z^{0}) \rightarrow q\bar{q}$
    - ✓ $\sqrt{s} = 91\ GeV$
      - – Z mass
  - Pros and Cons for QCD study
    - ✓ Pros: No initial state color → clean jets
      - – up to 90% gluon jet purity!!
    - ✓ Cons: difficult to access LEP data (already 30 years have passed)
      - – there were ALEPH, DELPHI, L3, OPAL, however, can we access to the data??

"But! You've got a friend"

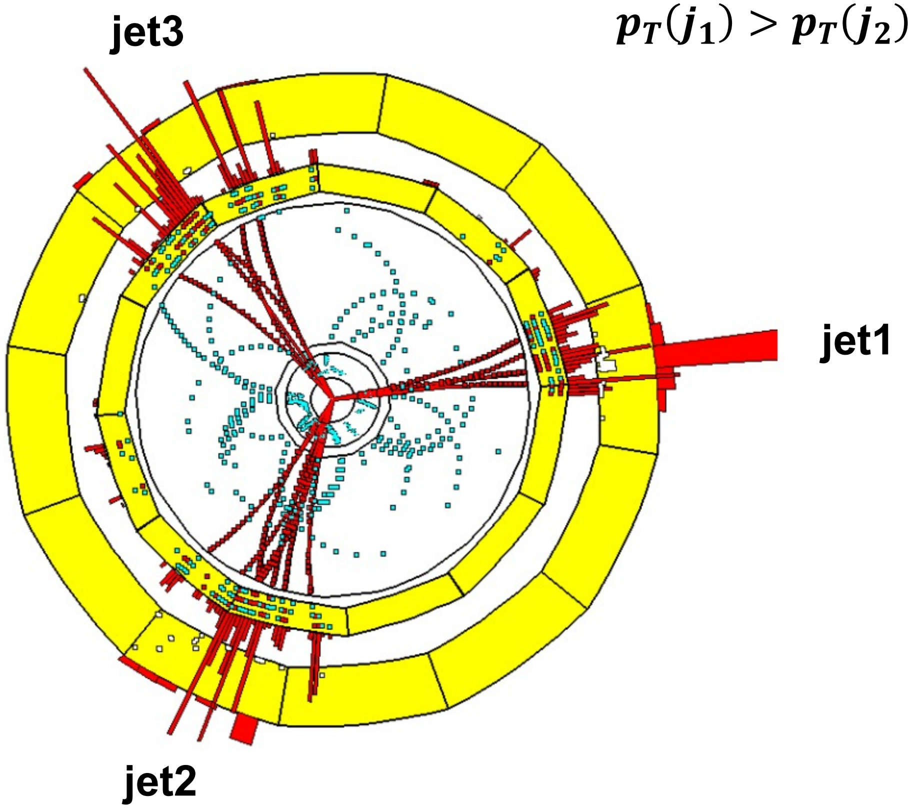
ALEPH 2-jet vs 3-jet events



$e^+ + e^- \rightarrow q\bar{q}$

$E(j_1) > E(j_2) > E(j_3)$

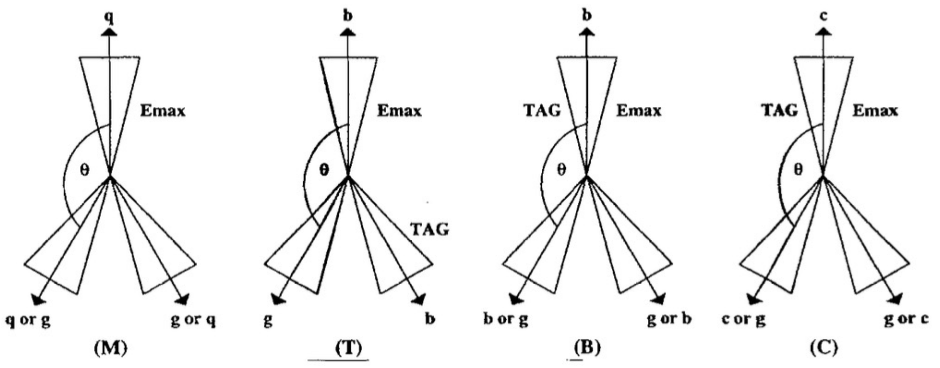
$p_T(j_1) > p_T(j_2) > p_T(j_3)$



$e^+ + e^- \rightarrow q\bar{q}g$

ALEPH study on gluon jets

- "Quark and Gluon jet properties in symmetric three-jet events"
  - **Phys. Lett. B 384, 353-364 (1996)**
    - ✓ after the ALEPH LEP1 runs



Sample	Number of jets	*uds*	*c*	*b*	*g*
M (J2 and J3)	45280	31.4	8.8	11.3	48.5
T (J2 or J3)	2071	6.1	1.7	2.2	90.0
B (J2 and J3)	872	2.5	3.0	44.5	50.0
C (J2 and J3)	40	0	35	15	50

N-H ELSEVIER
19 September 1996
PHYSICS LETTERS B
Physics Letters B 384 (1996) 353–364

Quark and gluon jet properties in symmetric three-jet events

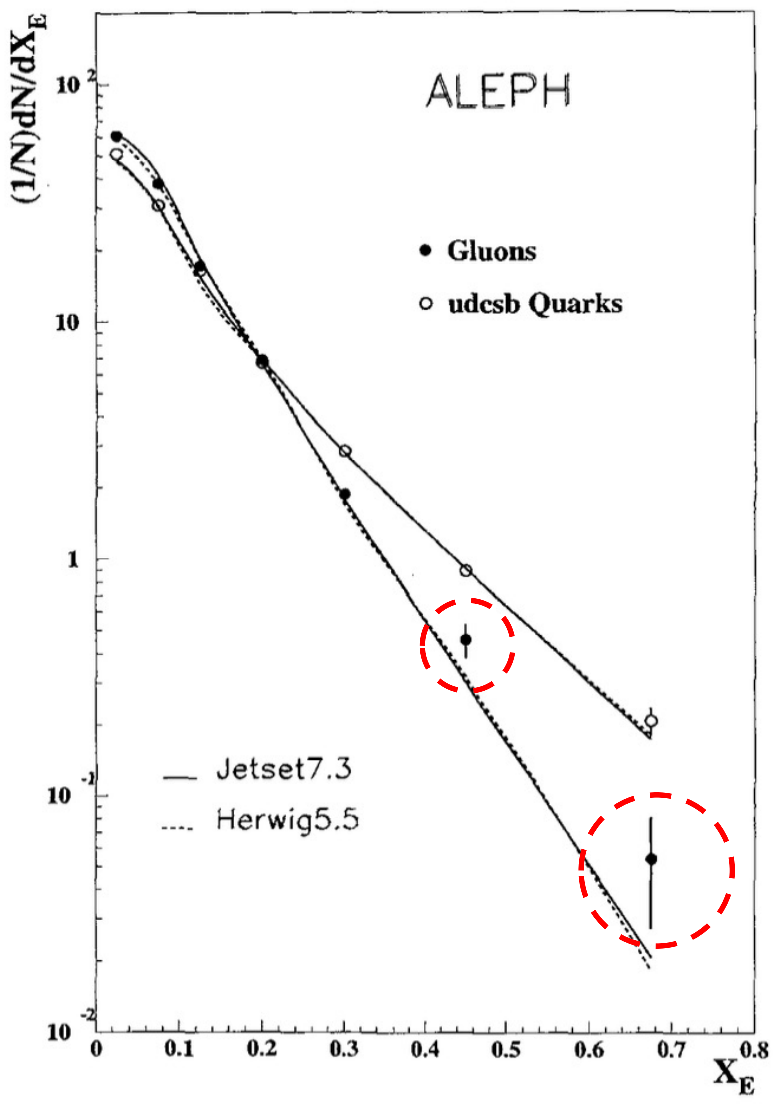
ALEPH Collaboration

D. Buskulic [a], D. Casper [a], I. De Bonis [a], D. Decamp [a], P. Ghez [a], C. Goy [a], J.-P. Lees [a], A. Lucotte [a], M.-N. Minard [a], P. Odier [a], B. Pietrzyk [a], M. Chmeissani [b], J.M. Crespo [b], I. Efthymiopoulos [b], E. Fernandez [b], M. Fernandez-Bosman [b], Ll. Garrido [b,15], A. Juste [b], M. Martinez [b], S. Orteu [b], A. Pacheco [b], C. Padilla [b], F. Palla [b], A. Pascual [b], J.A. Perlas [b], I. Riu [b], F. Sanchez [b], F. Teubert [b], A. Colaleo [c], D. Creanza [c], M. de Palma [c], A. Farilla [c], G. Gelao [c], M. Girone [c], G. Iaselli [c], G. Maggi [c,3], M. Maggi [c], N. Marinelli [c], S. Natali [c], S. Nuzzo [c], A. Ranieri [c], G. Raso [c], F. Romano [c], F. Ruggieri [c], G. Selvaggi [c], L. Silvestris [c], P. Tempesta [c], G. Zito [c], X. Huang [d], J. Lin [d], Q. Ouyang [d], T. Wang [d], Y. Xie [d], R. Xu [d], S. Xue [d], J. Zhang [d], L. Zhang [d], W. Zhao [d], R. Alemany [e], A.O. Bazarko [e], G. Bonvicini [e,23], M. Cattaneo [e], P. Comas [e], P. Coyle [e], H. Drevermann [e], R.W. Forty [e], M. Frank [e], R. Hagelberg [e], J. Harvey [e], R. Jacobsen [e,24], P. Janot [e], B. Jost [e], E. Kneringer [e], J. Knobloch [e], I. Lehraus [e], E.B. Martin [e], P. Mato [e], A. Minten [e], R. Miquel [e], Ll.M. Mir [e,2], L. Moneta [e], T. Oest [e], P. Palazzi [e], J.R. Pater [e,27], J.-F. Pusztaszeri [e], F. Ranjard [e], P. Rensing [e], L. Rolandi [e], D. Schlatter [e], M. Schmelling [e], O. Schneider [e], W. Tejessy [e], I.R. Tomalin [e], A. Venturi [e], H. Wachsmuth [e], T. Wildish [e], W. Witzeling [e], J. Wotschack [e], Z. Ajaltouni [f], A. Barrès [f], C. Boyer [f], A. Falvard [f], P. Gay [f], C. Guicheney [f], P. Henrard [f], J. Jousset [f], B. Michel [f], S. Monteil [f], J-C. Montret [f], D. Pallin [f], P. Perret [f], F. Podlyski [f], J. Proriol [f], J.-M. Rossignol [f], T. Fearnley [g], J.B. Hansen [g], J.D. Hansen [g], J.R. Hansen [g], P.H. Hansen [g], B.S. Nilsson [g], A. Wäänänen [g], A. Kyriakis [h], C. Markou [h], E. Simopoulou [h], I. Siotis [h], A. Vayaki [h], K. Zachariadou [h], A. Blondel [i,21], G. Bonneaud [i], J.C. Brient [i], P. Bourdon [i], A. Rougé [i], M. Rumpf [i], R. Tanaka [i], A. Valassi [i,6], M. Verderi [i], H. Videau [i,21], D.J. Candlin [j], M.I. Parsons [j], E. Focardi [k], G. Parrini [k], M. Corden [ℓ], M. Delfino [ℓ,12], C. Georgiopoulos [ℓ], D.E. Jaffe [ℓ], A. Antonelli [m], G. Bencivenni [m], G. Bologna [m,4], F. Bossi [m], P. Campana [m], G. Capon [m], V. Chiarella [m], G. Felici [m], P. Laurelli [m], G. Mannocchi [m,5], F. Murtas [m], G.P. Murtas [m], L. Passalacqua [m], M. Pepe-Altarelli [m], L. Curtis [n], S.J. Dorris [n], A.W. Halley [n], I.G. Knowles [n], J.G. Lynch [n], V. O'Shea [n], C. Raine [n], P. Reeves [n], J.M. Scarr [n], K. Smith [n], A.S. Thompson [n], F. Thomson [n], S. Thorn [n], R.M. Turnbull [n], U. Becker [o], O. Braun [o], C. Geweniger [o], G. Graefe [o], P. Hanke [o], V. Hepp [o], E.E. Kluge [o], A. Putzer [o], B. Rensch [o], M. Schmidt [o], J. Sommer [o], H. Stenzel [o], K. Tittel [o], S. Werner [o], M. Wunsch [o], D. Abbaneo [p], R. Beuselinck [p], D.M. Binnie [p], W. Cameron [p], D.J. Colling [p],

PII S0370-2693(96)00849-0

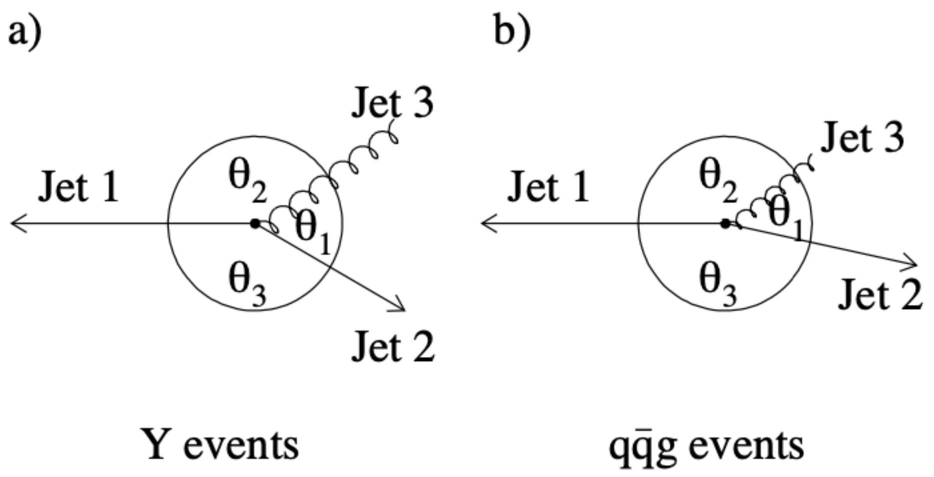
Fragmentation function X_E (ALEPH)

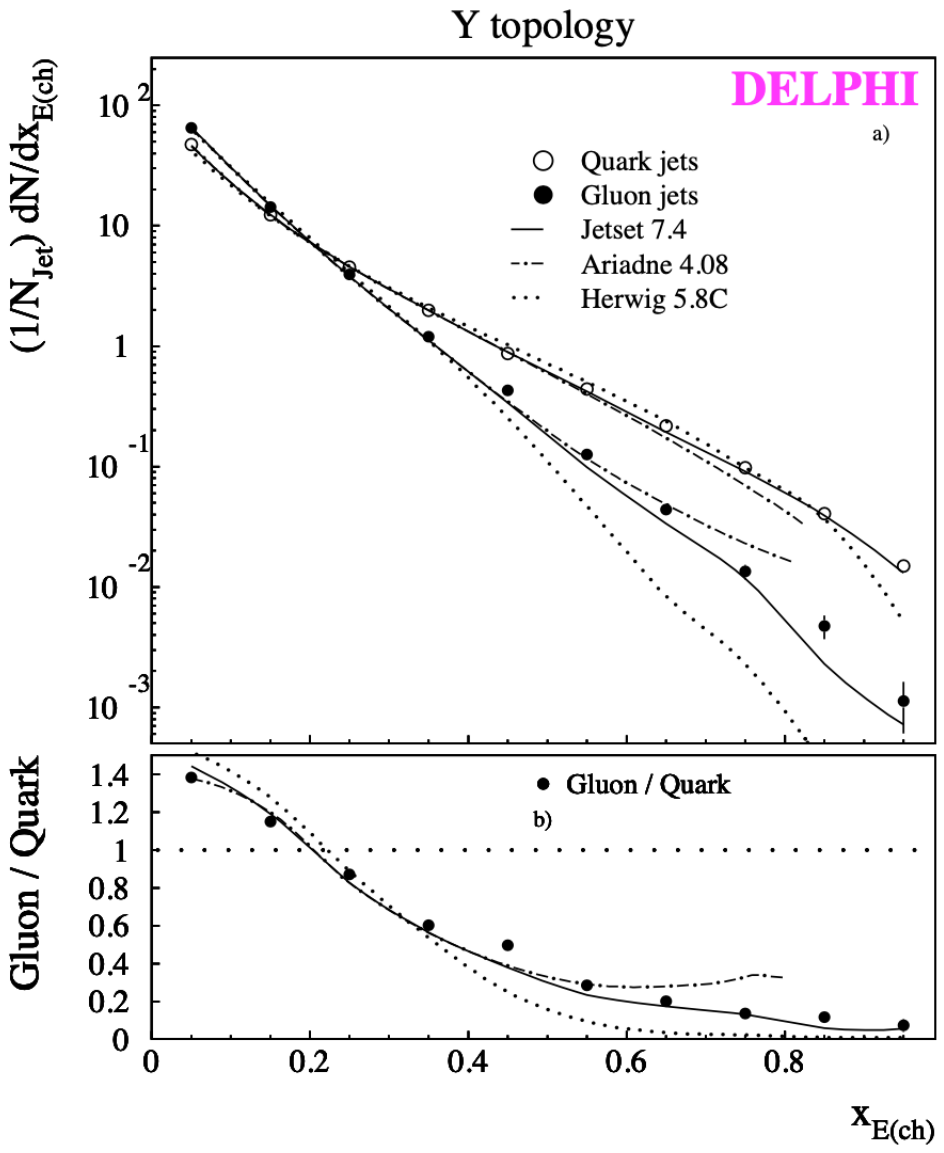
- **Fragmentation function (X_E)**
  - like Björken x (track's energy share)
    - ✓ $X_E = \frac{E_p}{E_j}$ → $\frac{1}{N}\frac{dN}{dX_E}$ as a function of X_E
- **ALEPH observations (PLB-384, 353-364)**
  - Gluons are softer
    - ✓ broader
  - Quarks are harder
    - ✓ collimated
- **Were there any ALEPH gluon anomalies?**
  - Quarks
    - ✓ good agreement between Data and MC
  - Gluons
    - ✓ Neurons → excess in high X_E
    - ✓ Chromons → excess in low X_E



Fragmentation function X_E (DELPHI)

- "Measurement of the gluon fragmentation function and a comparison of the scaling violation in gluon and quark jets"
  - Eur. Phys. J. C. 13, 573-589 (2000)
    - ✓ LEP1 runs 1992-1995



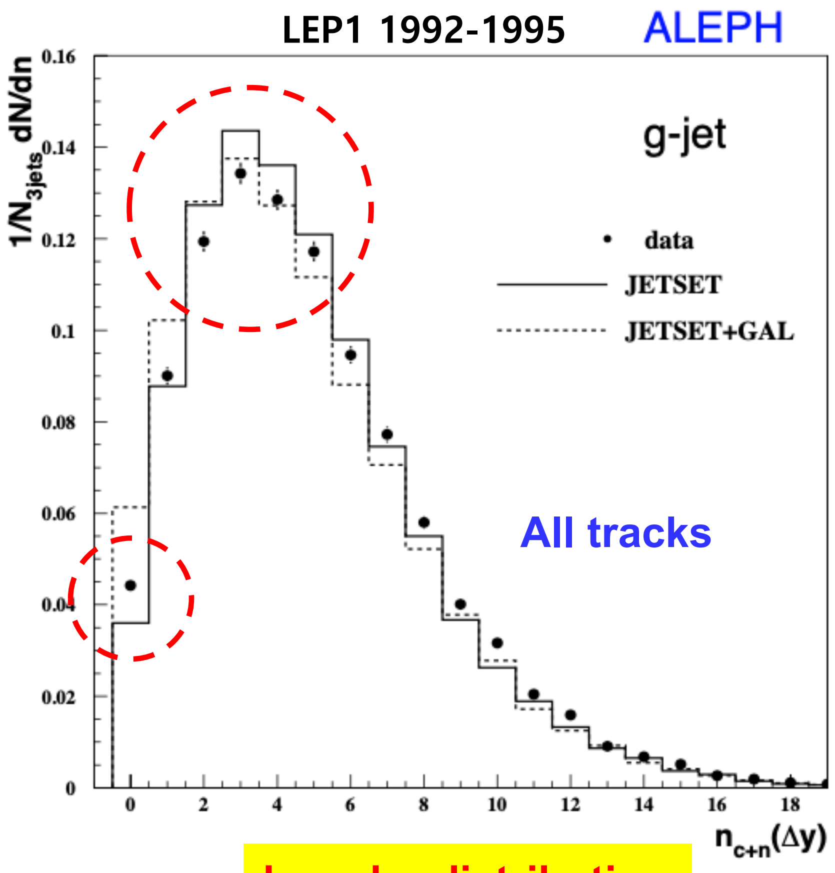


Anomaly in charged multiplicity

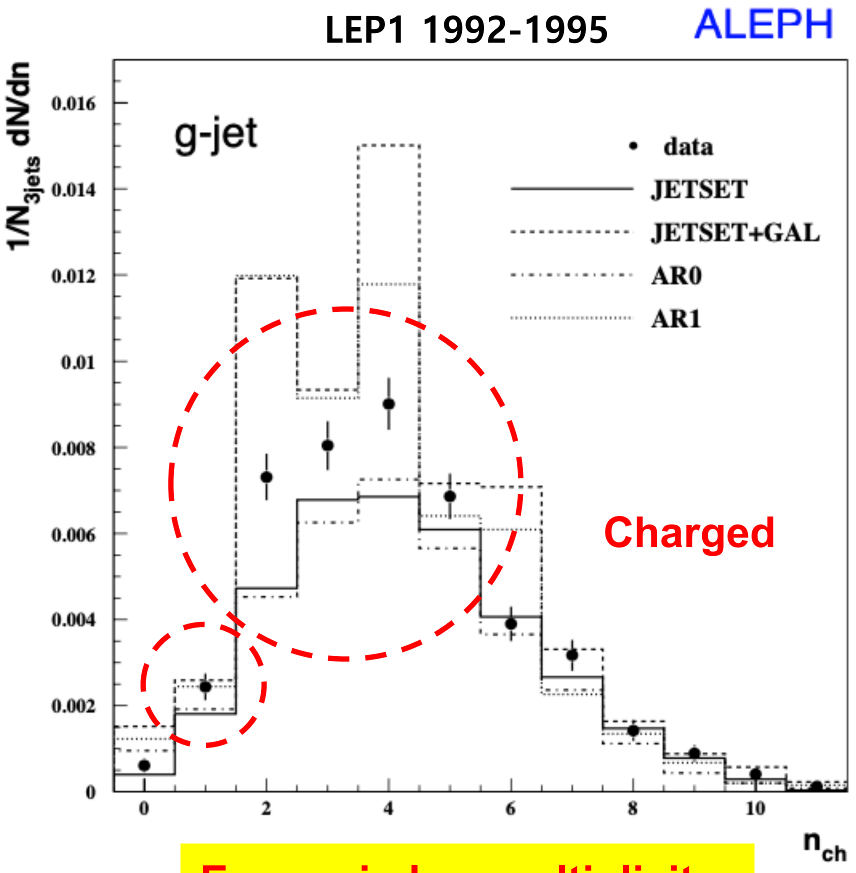
- "Test of colour reconnection models using three-jet events in hadronic Z decays"
  - Eur. Phys. J. C. 48, 685-698 (2006)

QCD model	million events
JETSET	7.6
JETSET+GAL, $R_0 = 0.04$	0.5
JETSET+GAL, $R_0 = 0.10$	3.4
JETSET+BE$_{32}$	0.5
ARIADNE AR0	3.4
ARIADNE AR1	3.4
HERWIG	0.5
HERWIG CR	0.5

jet number	$\langle E_{\rm jet}\rangle$, GeV	spread, GeV	$\langle n_{\rm ch}\rangle$	$P_{\rm g}$
1	40.8	2.7	8.81	0.059
2	32.7	4.5	8.28	0.248
3	17.7	5.1	7.02	0.693



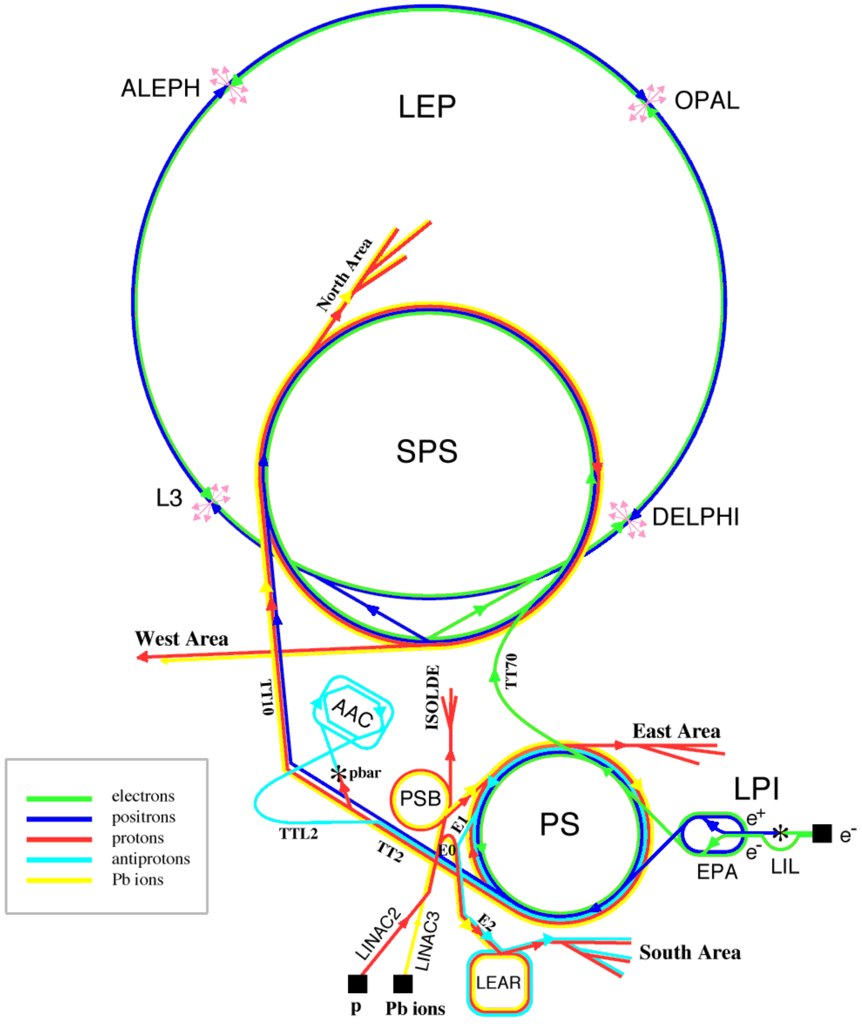
broader distribution

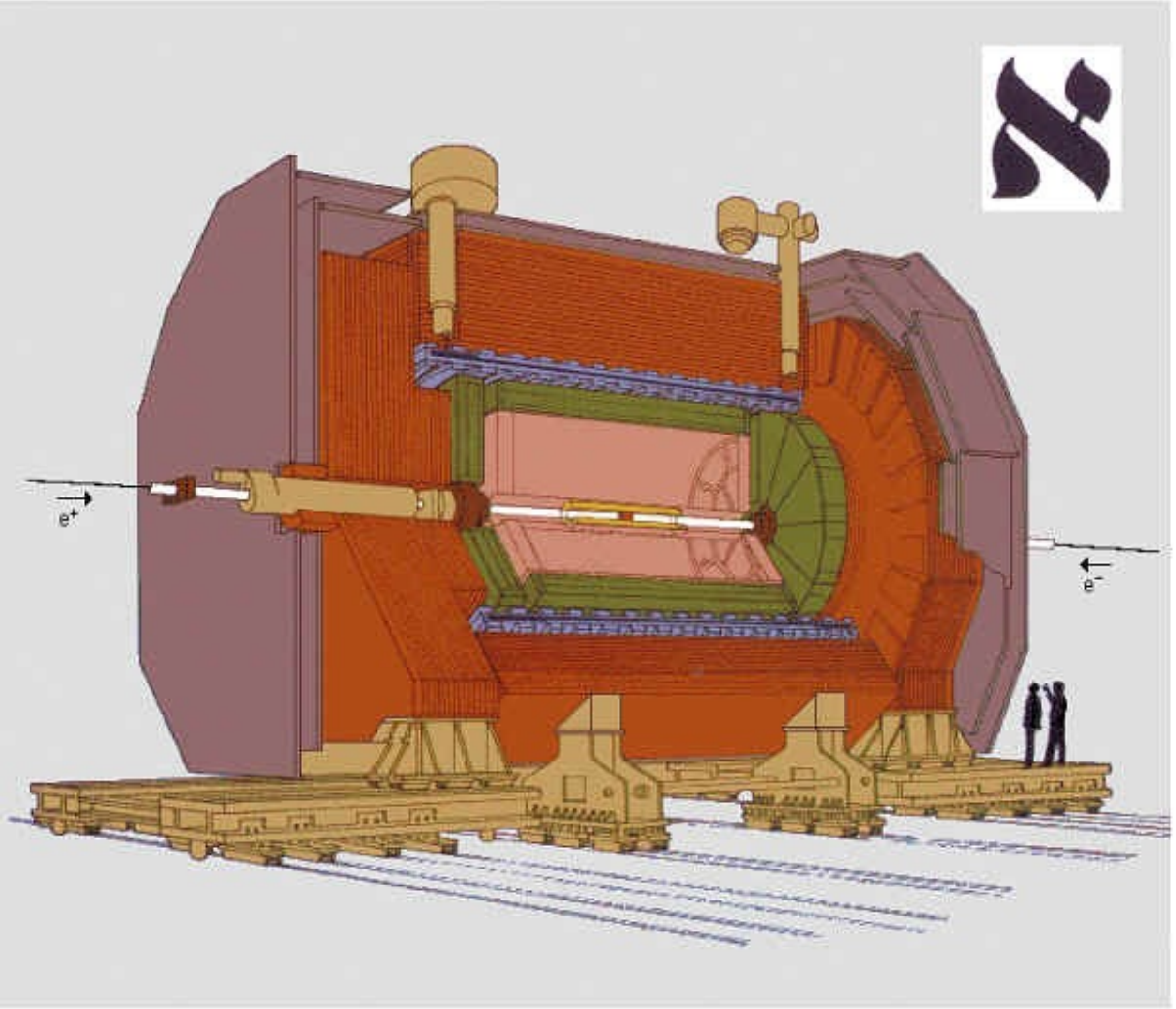


Excess in low multiplicity

Resurrection of the ALEPH data

ALEPH @ LEP1





- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors

TPC : $\sigma\left(\frac{1}{p_T}\right) \sim 0.06\%$

ECAL : $\frac{\sigma(E)}{E} \sim \frac{0.18}{\sqrt{E}} + 1\%$

HCAL : $\frac{\sigma(E)}{E} \sim \frac{0.85}{\sqrt{E}}$

MIT archived data

- Data Samples
  - Archived e^+e^- data
    - ✓ e^+e^- collisions in LEP1 @ $\sqrt{s} = 91$ GeV
      - – a total of 3.3M hadronic events

	Data	MC
1991	230,513	
1992	551,474	
1993	538,601	
1994	1,365,440	
1995	595,095	
Total	3,281,123	973,769

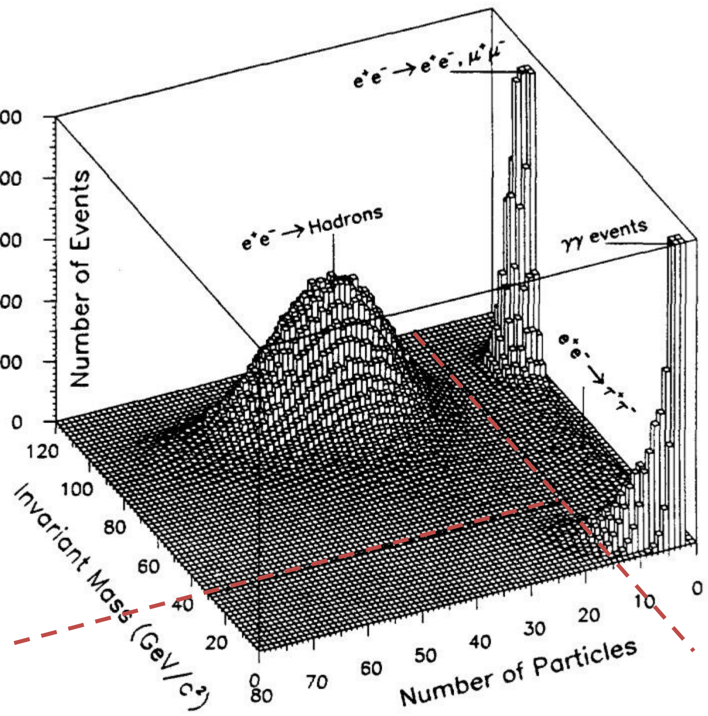
- MC Samples
  - Archived e^+e^- simulation data
    - ✓ e^+e^- collisions in PYTHIA 6.1 @ $\sqrt{s} = 91$ GeV
      - – a total of ~ 1M hadronic events

        stable GEN particles from PYTHIA

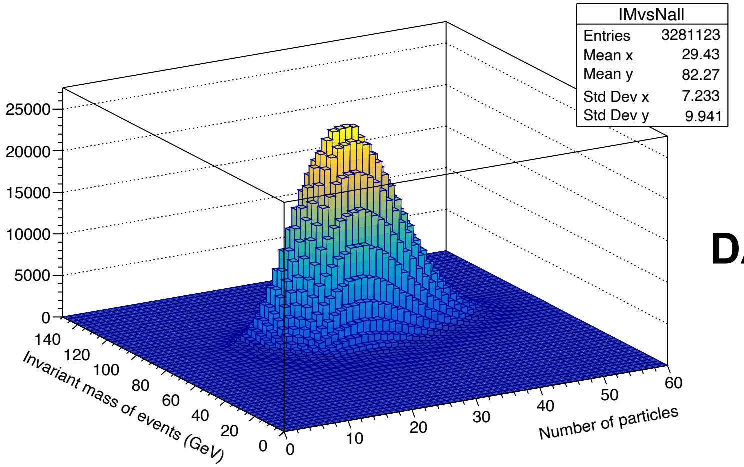
        reconstructed particles after GALEPH (GEANT3+ALEPH) detector simulation

Y.J. Lee & Y. Chen et al.

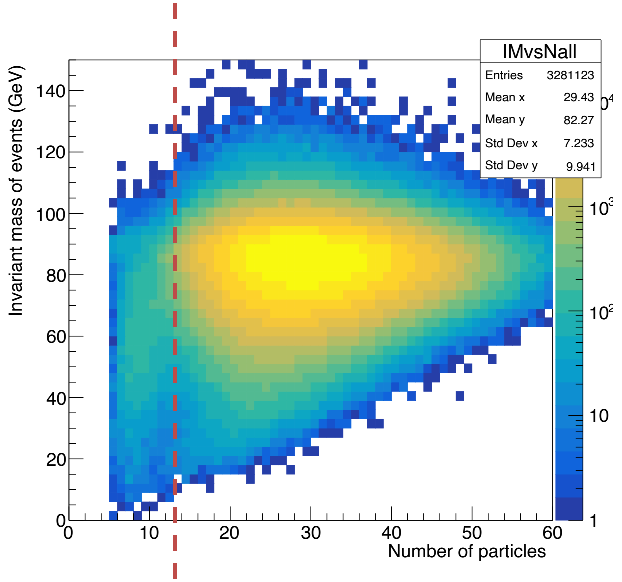
Hadronic event selection

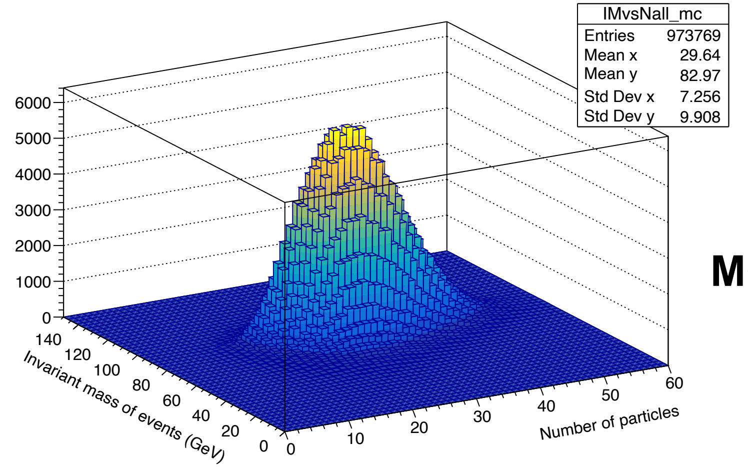


$N_{trk} \geq 13$ & $M_{inv} \geq 35$

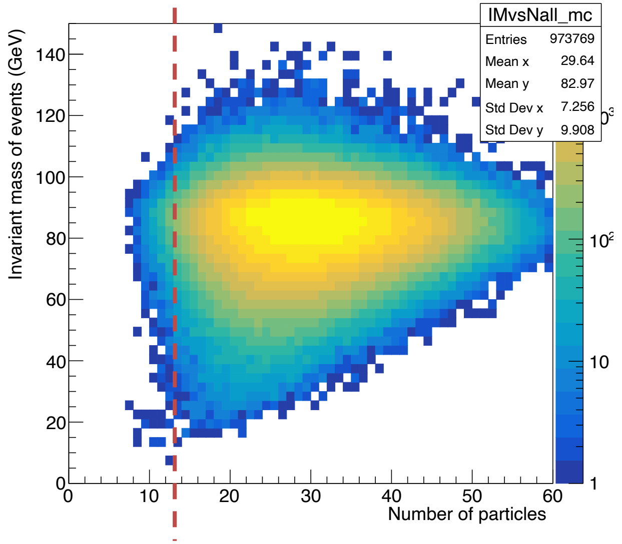


DATA





MC



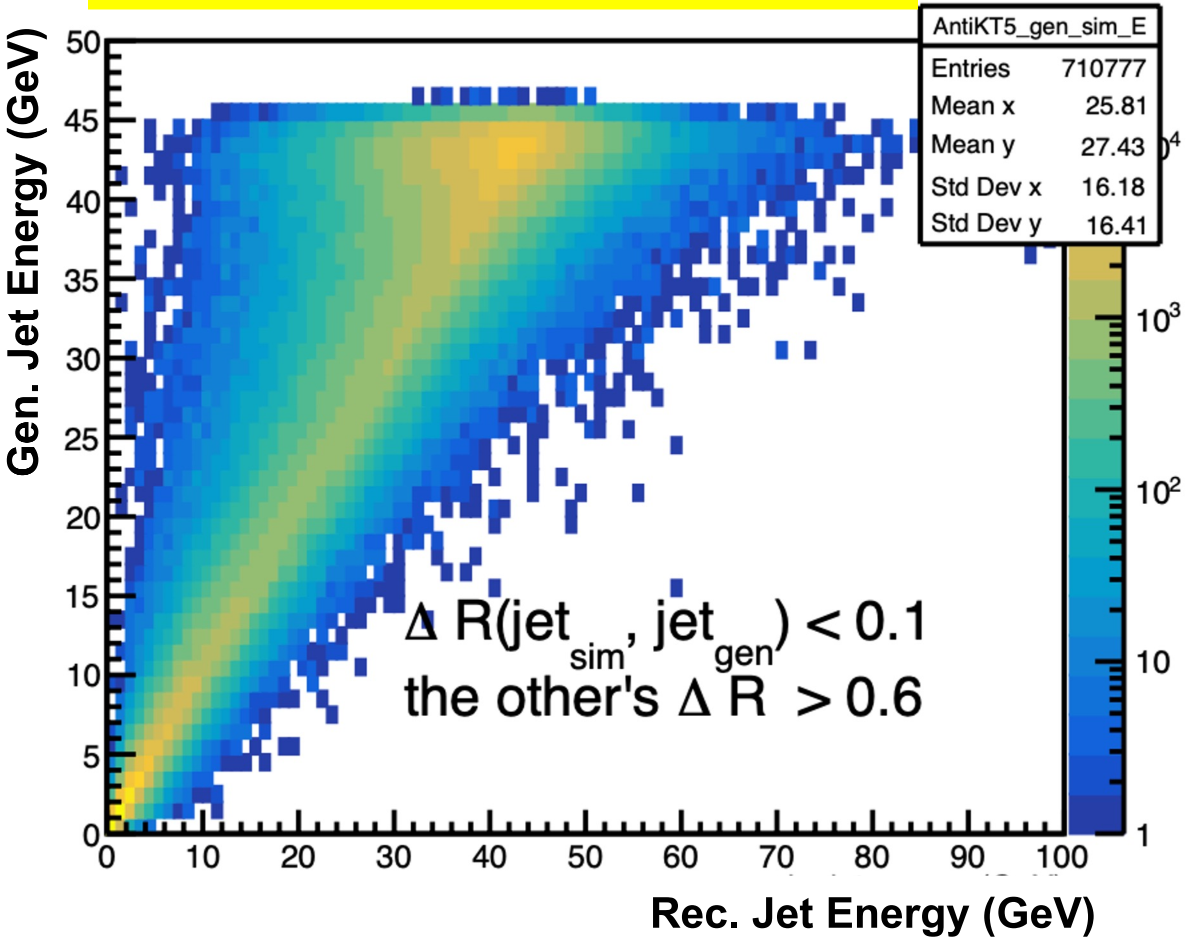
Jet reconstruction

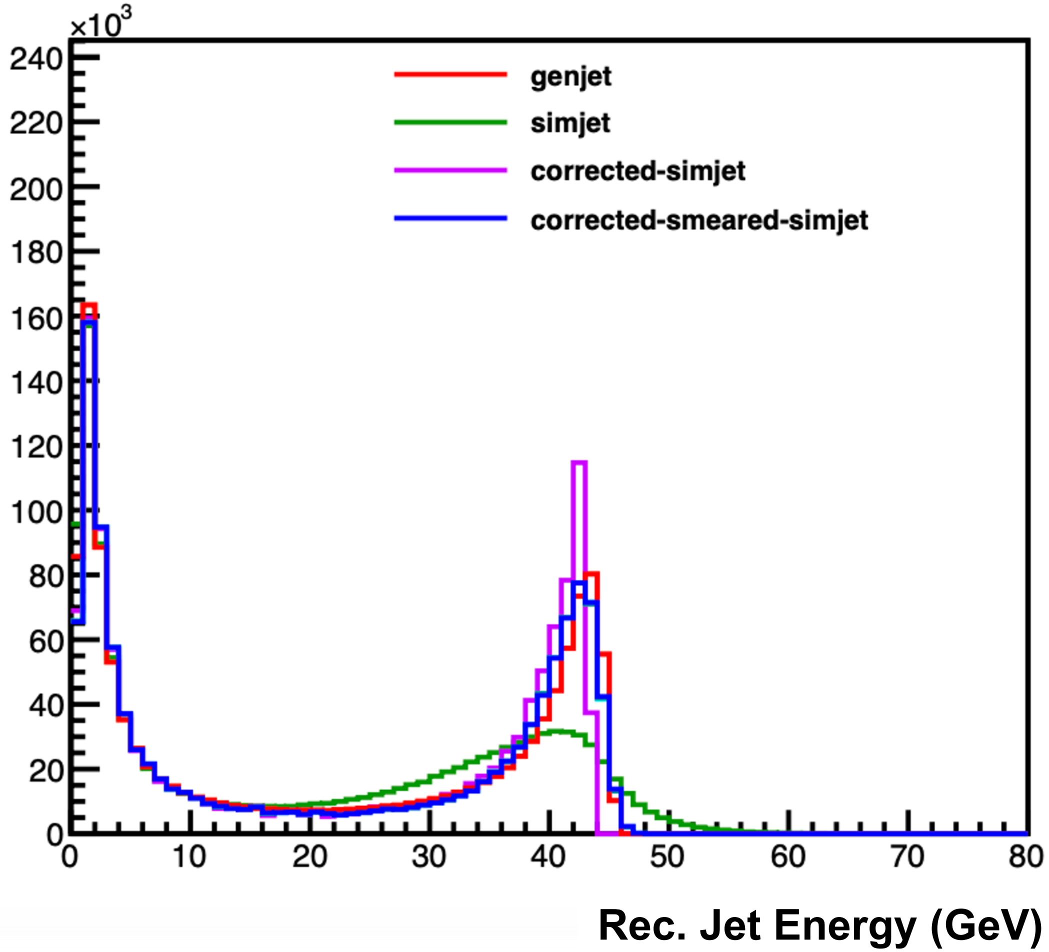
- **Jet reconstruction**
  - **ALEPH used Durham ($k_{\perp}$) algorithm**
  - **We use Fastjet (version 3.4.1.3)**
    - ✓ **Jet algorithm : "Anti-Kt algorithm"**
      - – **using 4-vector (pt, eta, phi, mass) of particles with an opening angle R = 0.5**

- **Jet energy resolution**
  - **ALEPH achieved a JER of $\frac{\sigma_E}{E} \sim 0.6/\sqrt{E/\mathrm{GeV}}$ with Particle Flow**
    - ✓ **TPC+VTX:** $\sigma\left(\frac{1}{p_T}\right) \sim 0.006\ (\mathrm{GeV}/c)^{-1}$
    - ✓ **ECAL:** $\frac{\sigma_E}{E} \sim 0.18/\sqrt{E/\mathrm{GeV}}$, **HCAL:** $\frac{\sigma_E}{E} \sim 0.85/\sqrt{E/\mathrm{GeV}}$
      - – **e.g. 36 GeV jet ⇒ 10% error**

Jet energy correction

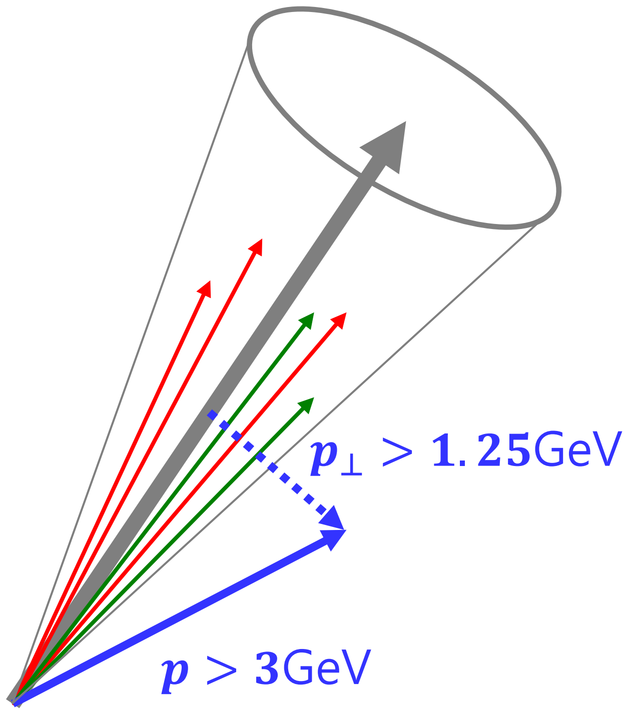
Correction factors = Egen/Erec





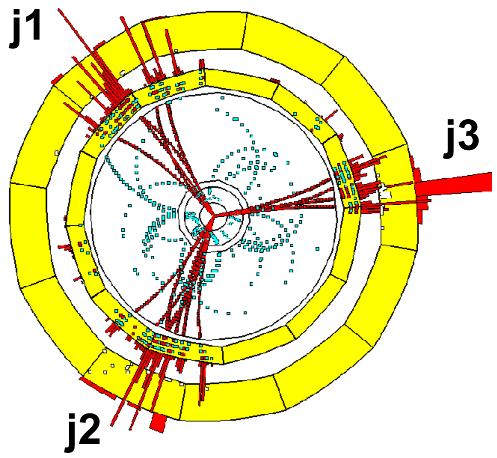
B tagging

- **B tagging**
  - **Lepton tagging method**
    - ✓ lepton with $p > 3\text{GeV}$ & $p_\perp > 1.25\text{GeV}$
      - – $p_\perp$ calculated from the jet reconstructed without lepton
  - **Tagging efficiency**
    - ✓ According to Jetset study
      - – b : 88.9 ± 1.2 %
      - – c : 6.1 ± 1.1 %
      - – uds: ~ 5 %

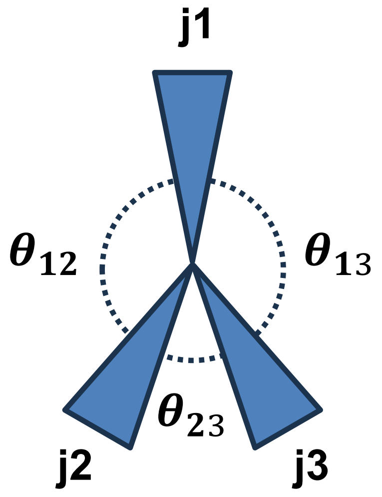


Event selections & observables

3-jet event selection



- S1 : Hadronic event selection
  - $N_{trk} \geq 13, \quad N_{chg} \geq 5, \quad \Sigma E_{chg} \geq 15$ GeV
- S2 : 3-jet event selection
  - $N_{jets} = 3 \quad (E_j > 10$ GeV$)$
- S3 : 3-jet geometry selection
  - $\theta_{12}, \theta_{13}, \theta_{23}$
    - ✓ $\theta_{12}, \theta_{13} = 150° \pm 7.5°$ (Tight: ALEPH revisited)
      - $E_{quark} \sim E_{gluon} \sim 24$ GeV
    - ✓ $0.5 < \theta_{23} < min(\theta_{12}, \theta_{13})$ (Loose: This analysis)
- S4 : b-jet tagging
  - Only one of J2 and J3 tagged as b-jet



Event selections

3-jet event selection	Data	MC
S0: 1991-1995 S1: $N_{trk} \geq 13, \quad N_{chg} \geq 5, \quad \Sigma E_{chg} \geq 15\ GeV$ S2: $N_{jets} = 3 \quad (E_j > 10\ GeV)$	2900317 2876547 432565	973769 767769 119655
Tight selection (ALEPH revisited)		
S3: $\theta_{12}, \theta_{13} = 150° \pm 7.5°$ S4: one b-jet among J2 & J3	26649 3064	8137 907
Loose selection (This analysis)		
S3: $0.5 < \theta_{23} < min(\theta_{12}, \theta_{13})$ S4: one b-jet among J2 & J3	341152 40984	96406 11243

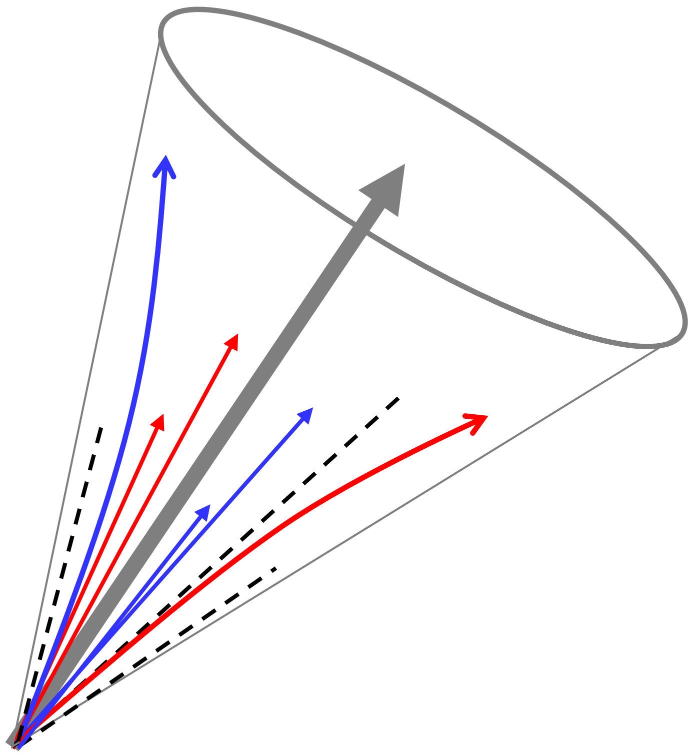
Analysis and results

What observables should we measure?

- **Particle multiplicities**
  - **number of particles in a jet**
    - ✓ n_{all}, n_{chg}, n_{neu}
      - – particles: charged + neutrals

        charged: Track objects ($e^{\pm}, \mu^{\pm}, \pi^{\pm}$)

        neutrals : ECAL/HCAL objects (γ, n)



- **Fragmentation functions**
  - **particle's energy fraction:** $X_E = \frac{E_p}{E_{jet}}$
    - ✓ X_E^{all}, X_E^{chg}, X_E^{neu}
      - – particles: charged + neutrals

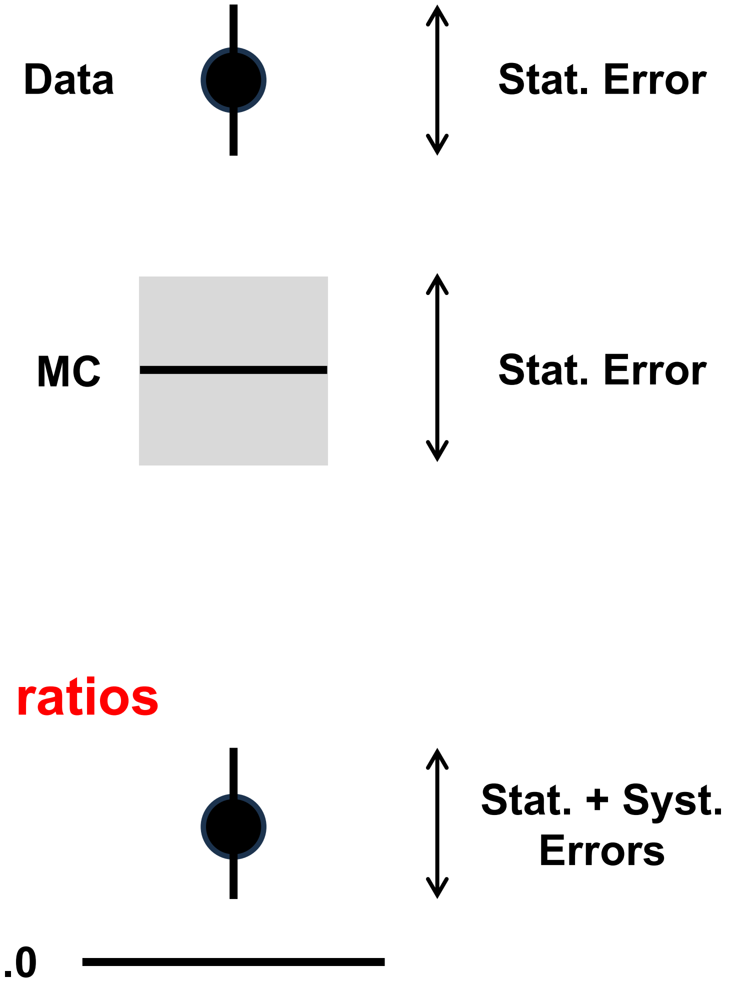
Systematic error estimation

- Basics: Model comparison study
  - To see the data anomaly
  - To test the MC model
- Most of detector related systematic effects cancel out in the ratio plot

$$R = \frac{A}{B} \quad \Longrightarrow \quad \frac{\sigma_R}{R} = \sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2}, \qquad \sigma_R^{Stat} = R\sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2}$$

$$\sigma_R = \sqrt{(\sigma_R^{Stat})^2 + \left(\sigma_R^{Syst}\right)^2}$$

In values

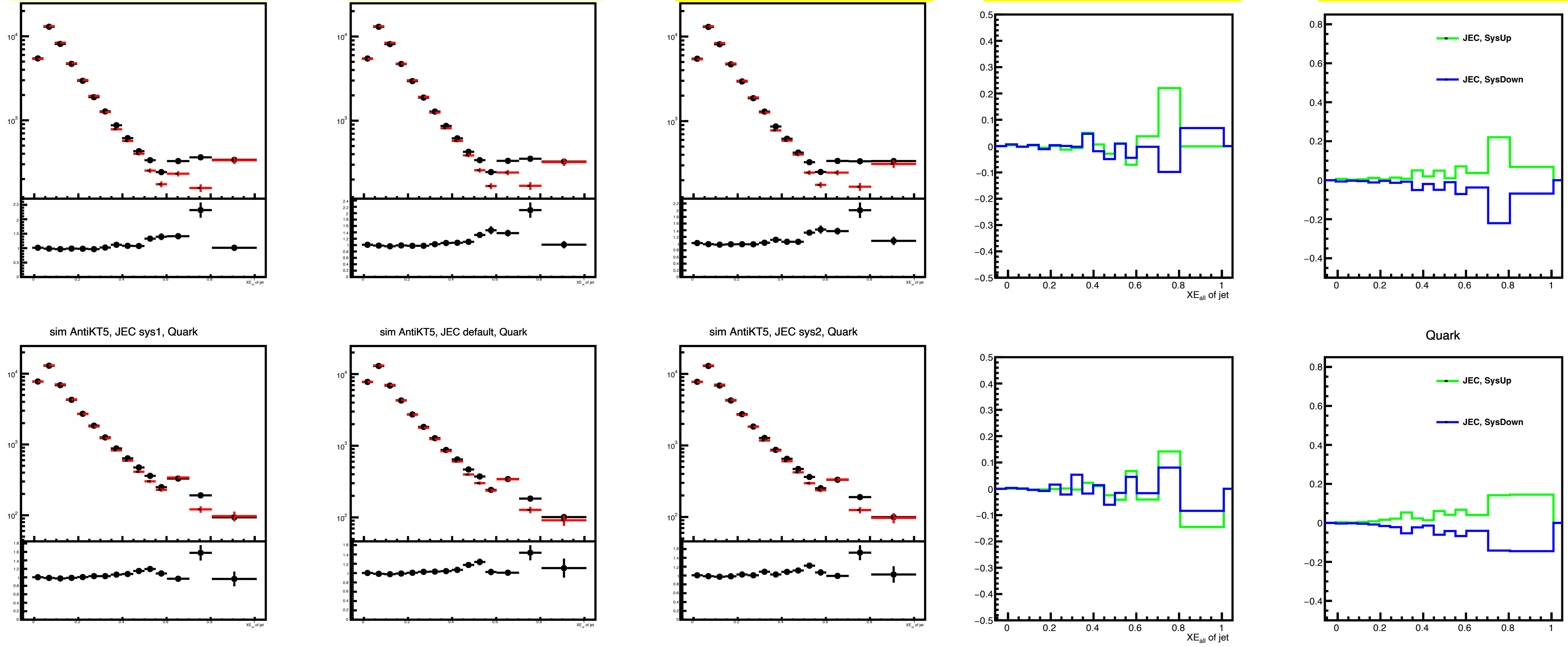


Systematic error: Jet Energy Correction

Under corrected | **Default** | **Over corrected** | **O-D & U-D** | **Syst. Error**

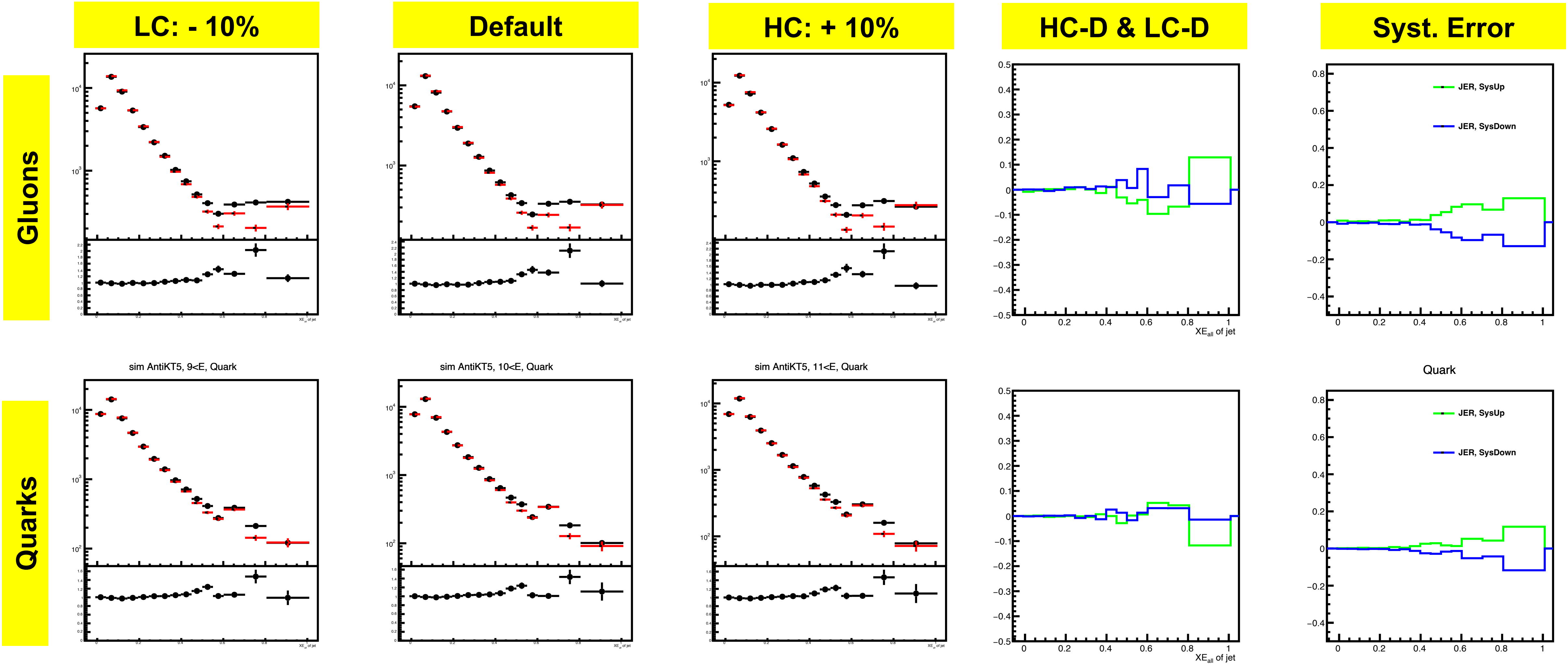
Gluons

Quarks



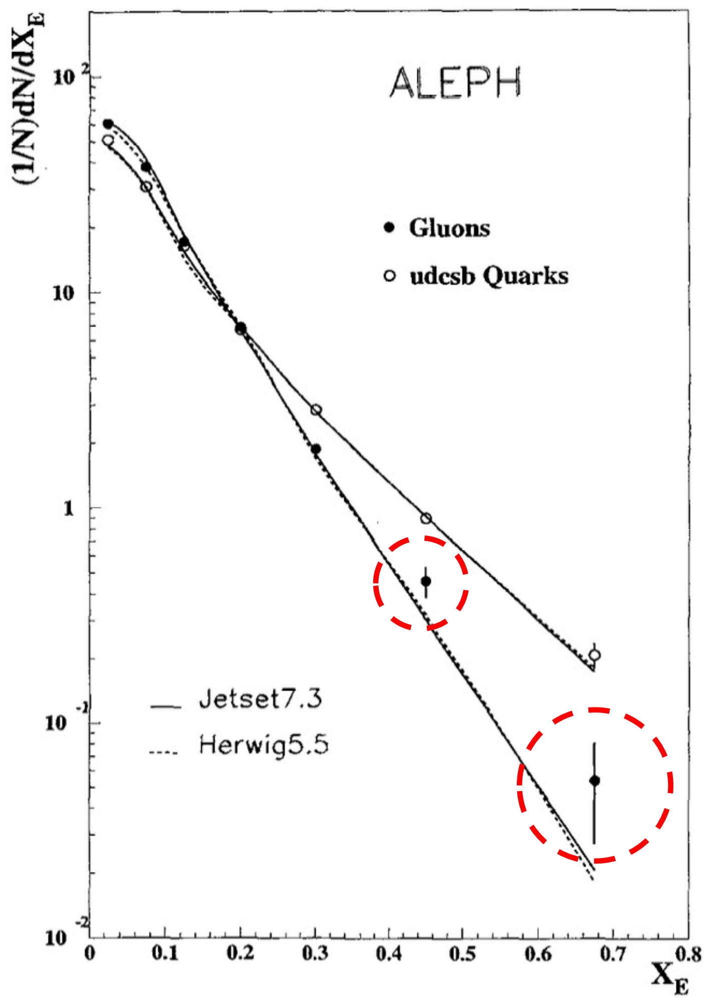
Based on statistical errors from JEC factor estimation (Profile histogram)

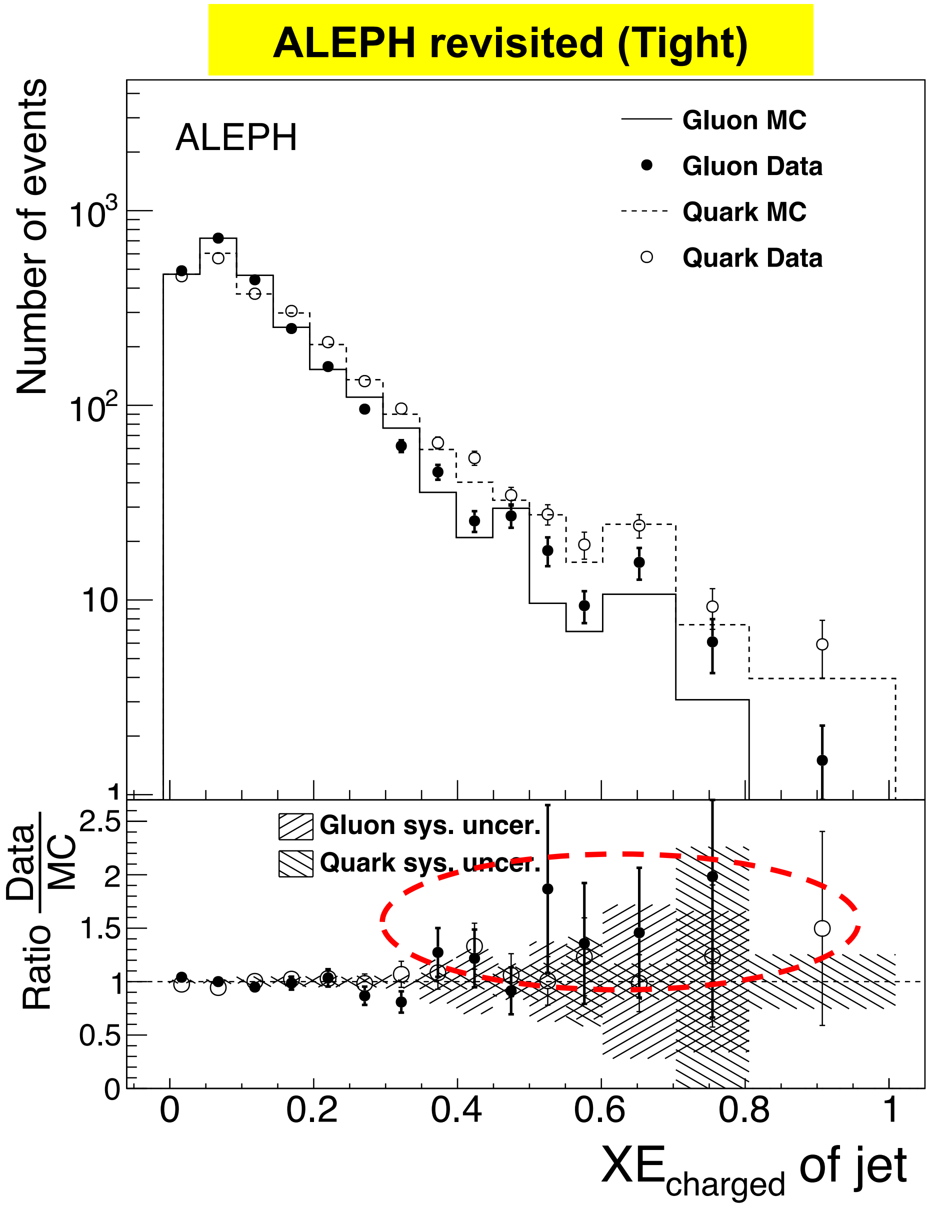
Systematic error: Jet Energy Resolution



Based on 10% variations on Jet Energy Cut : Default ± 1 GeV

Fragmentation function X_E : charged only (Tight cut)





No meaningful excesses were found from our ALEPH reanalysis, within statistical and systematical errors.

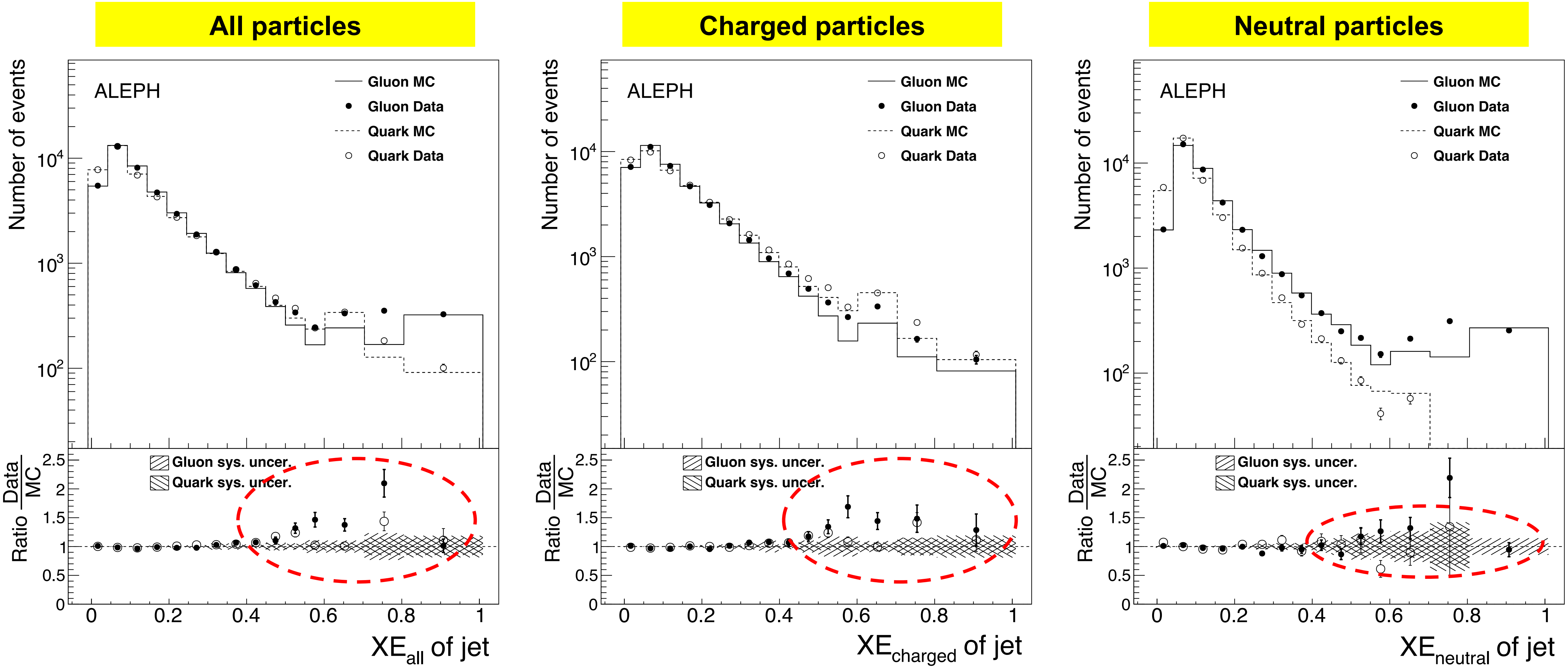
3064 events only

→ more statistics needed
→ control systematic errors

⇒ Use the loose cut

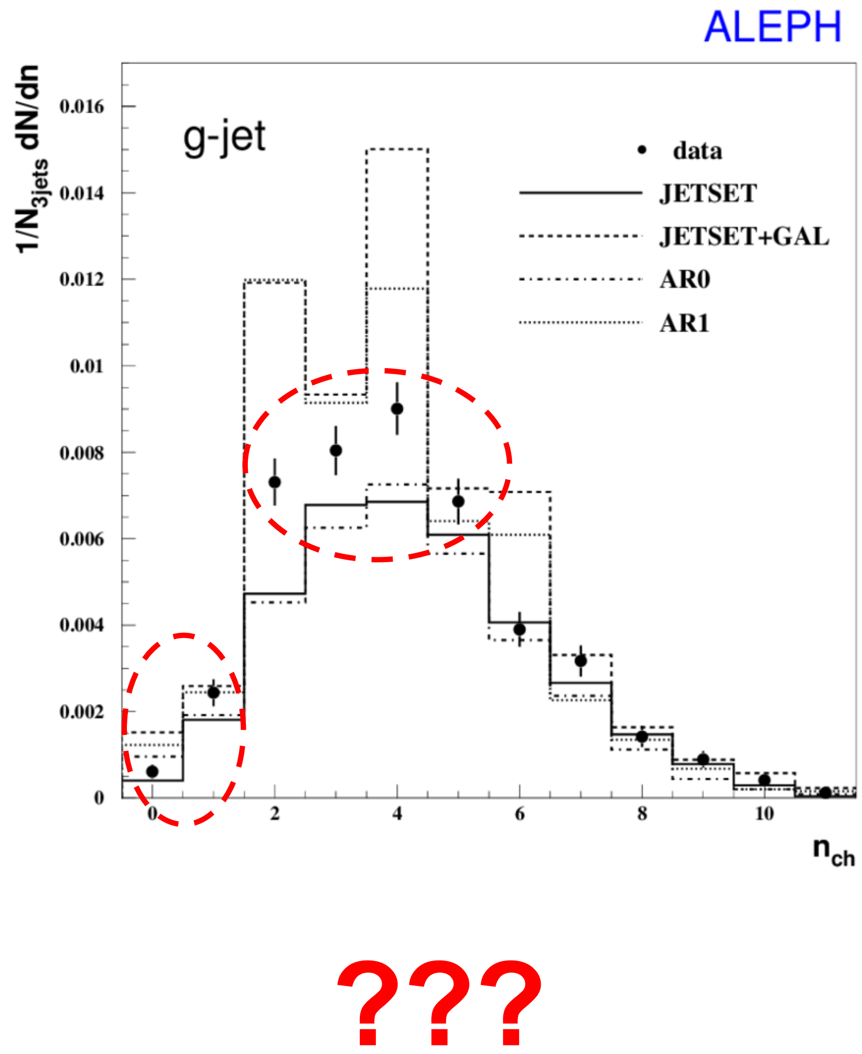
40984 events are available

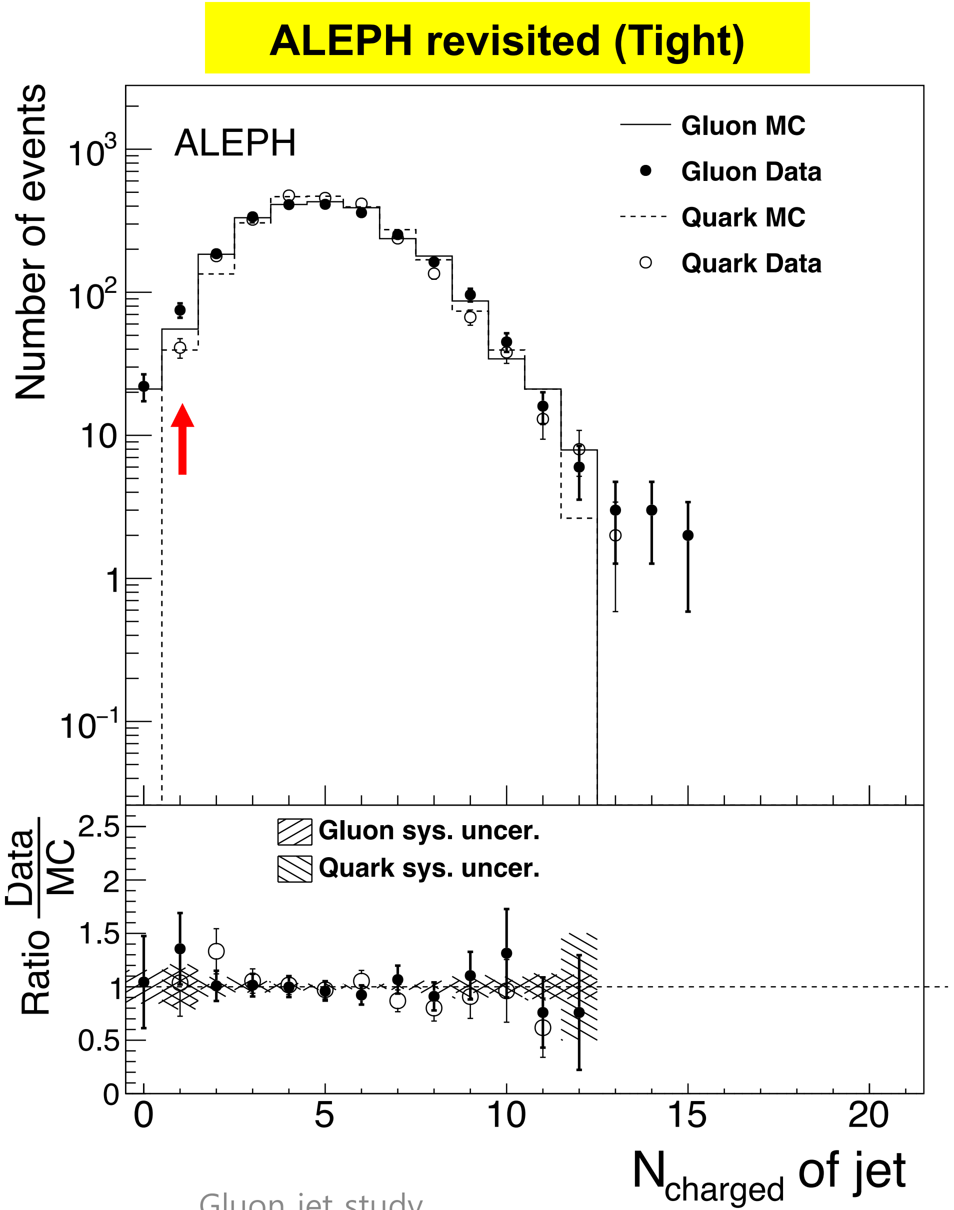
X_E : charged vs neutral (Loose cut)



Particles with high energy share are more often in gluons in data than those of in MC.

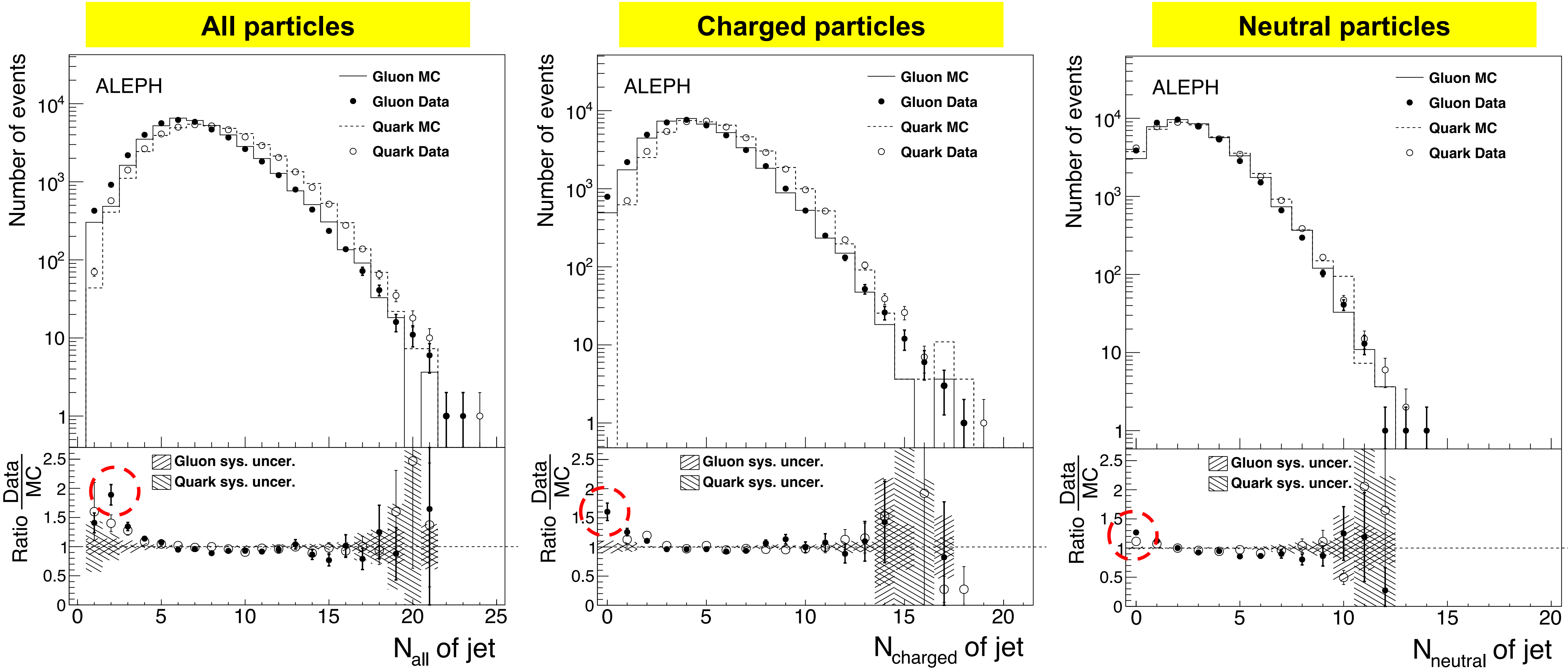
Charged particle multiplicity (Tight cut)





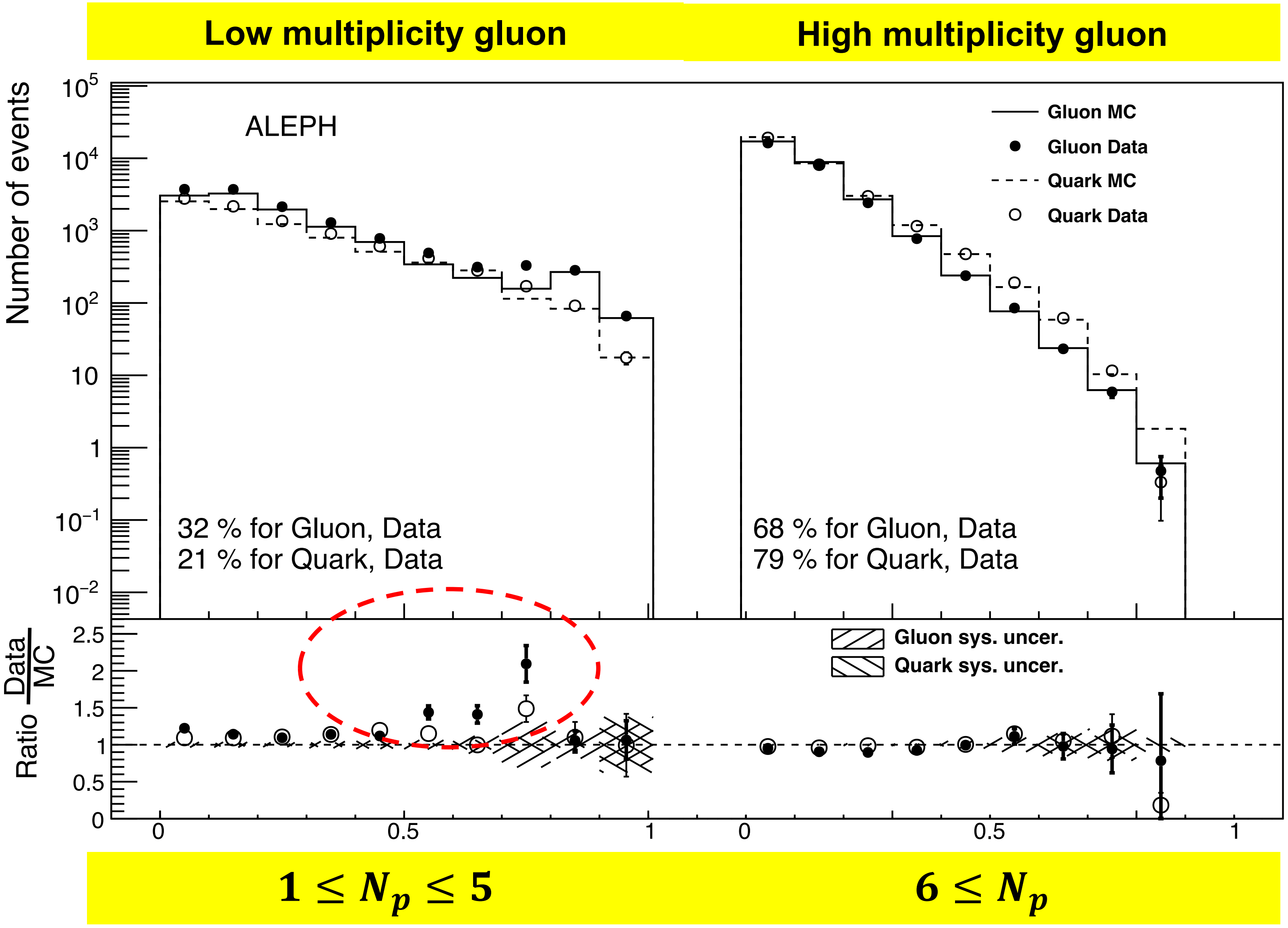
No meaningful discrepancies were found from our ALEPH reanalysis, within statistical and systematical errors.

Gluon jet particle multiplicity anomaly? (Loose cut)



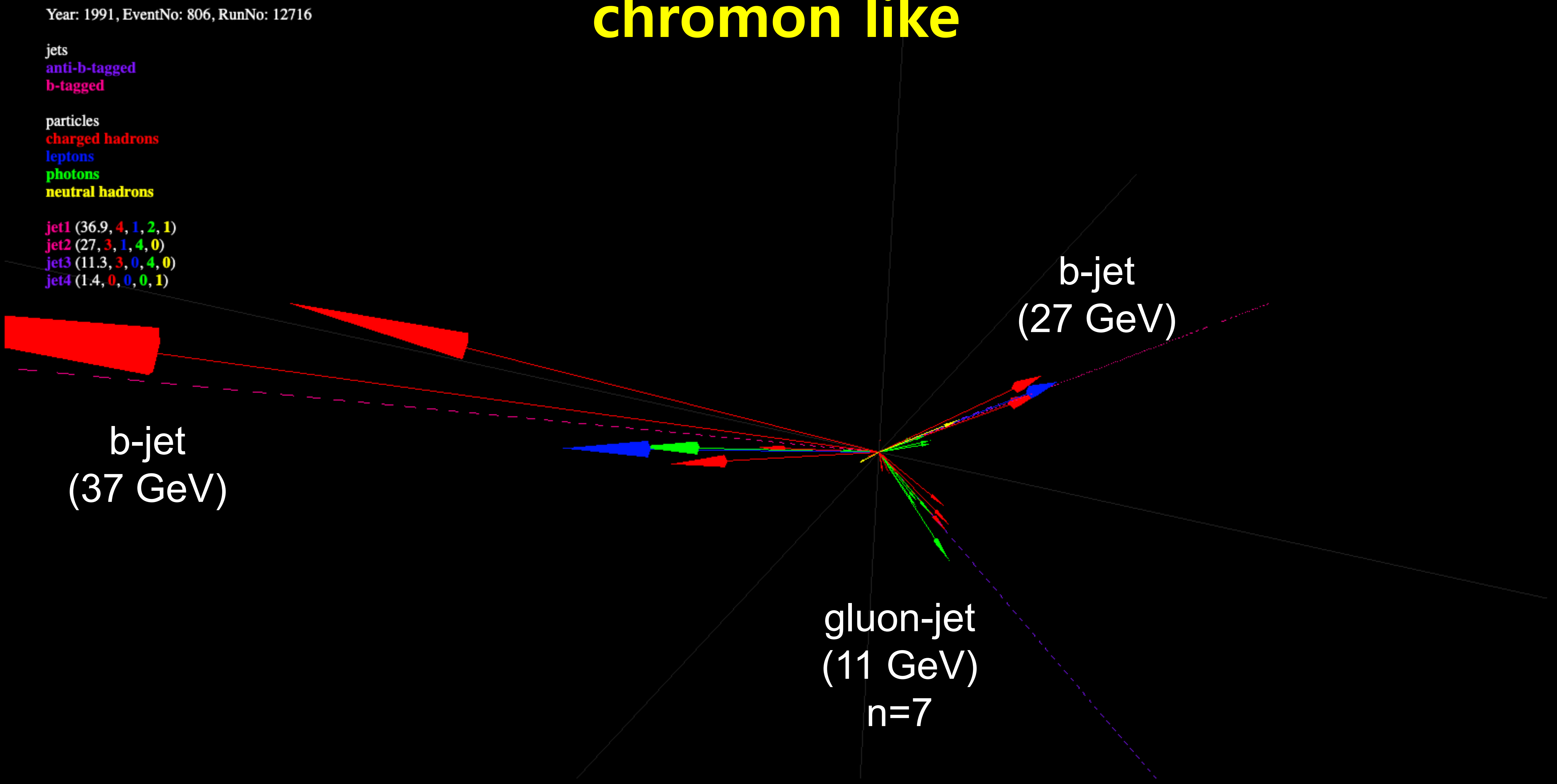
Gluons with two tracks! Gluons without charged tracks.

Correlation between X_E and (all)

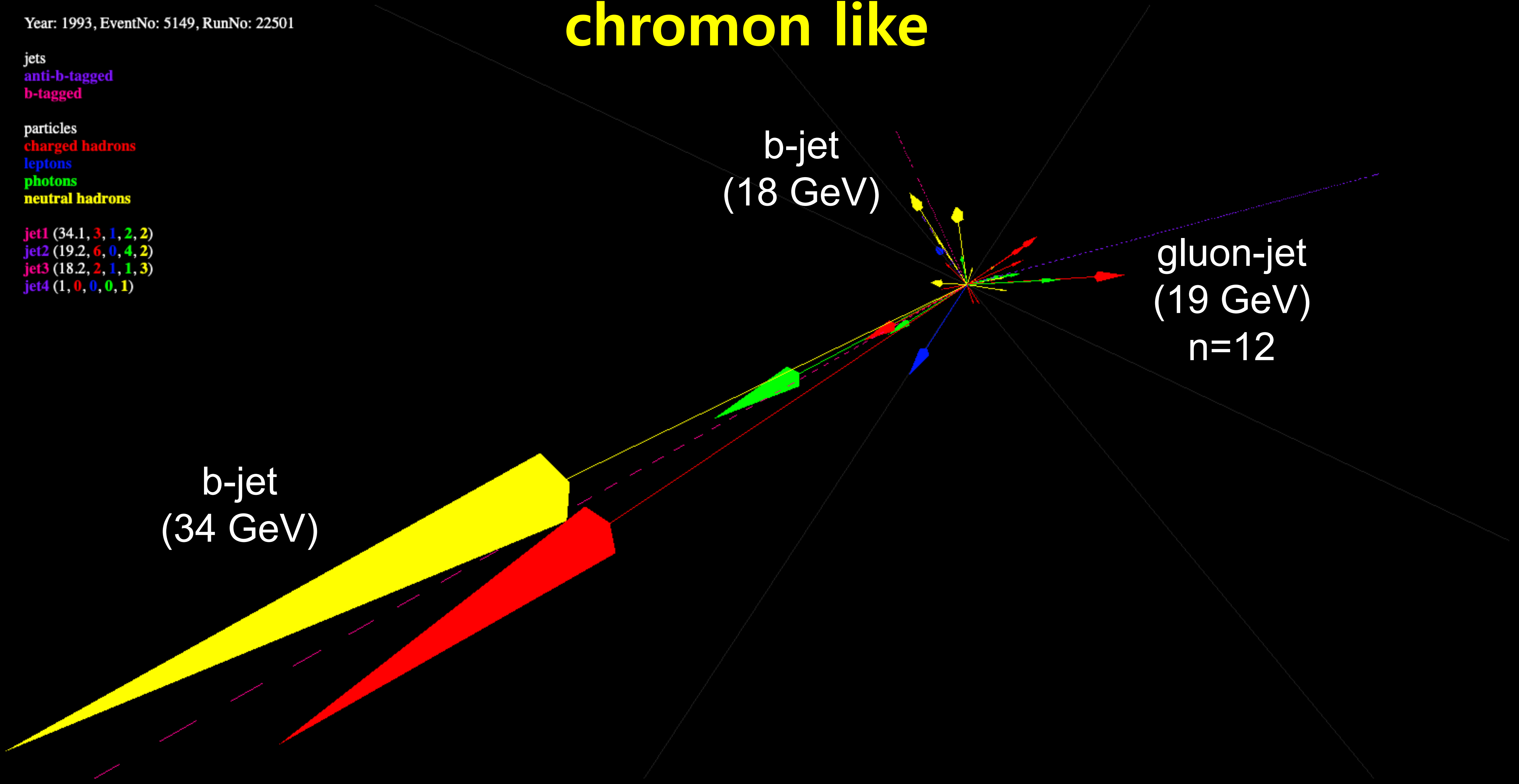


Event display

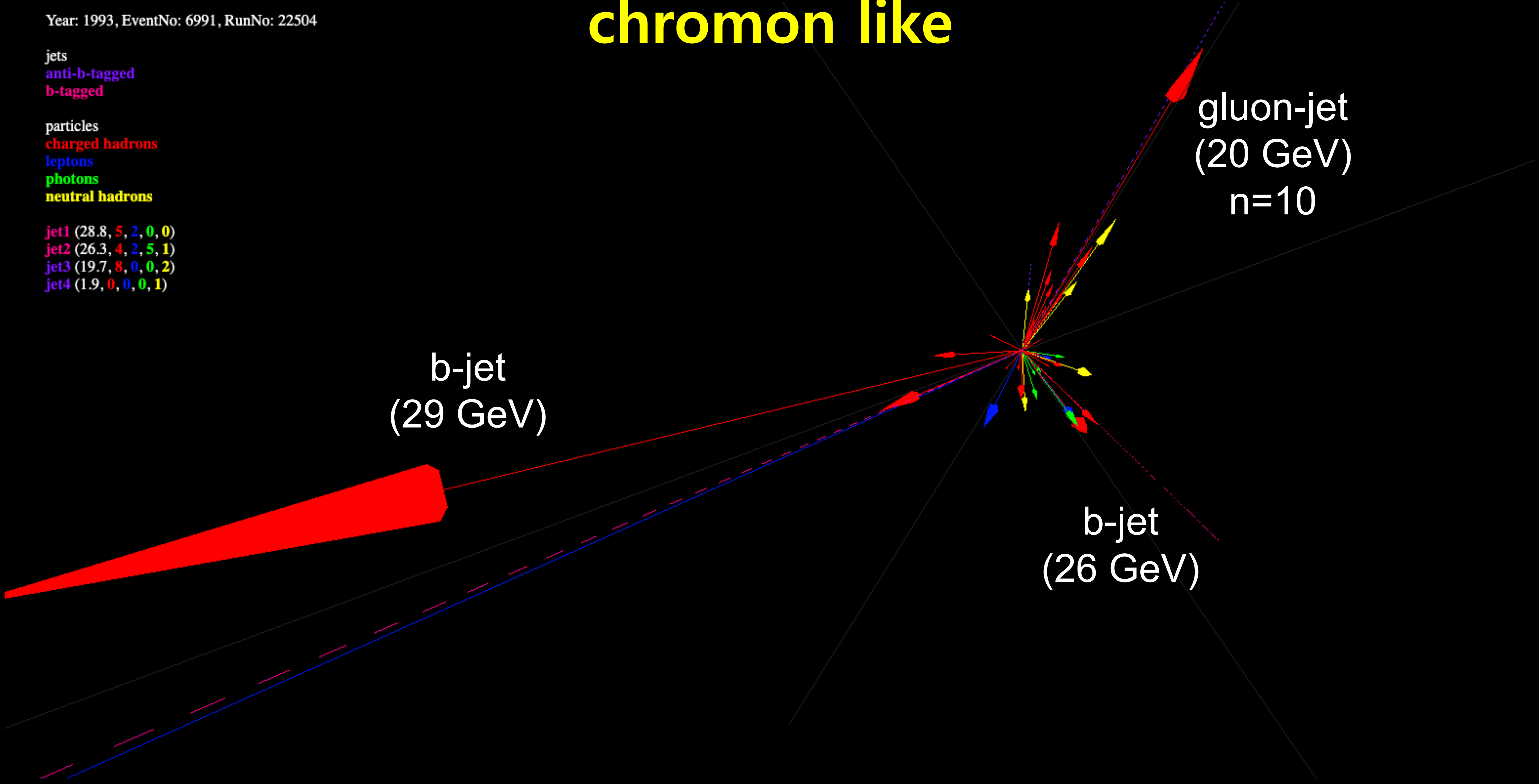
chromon like



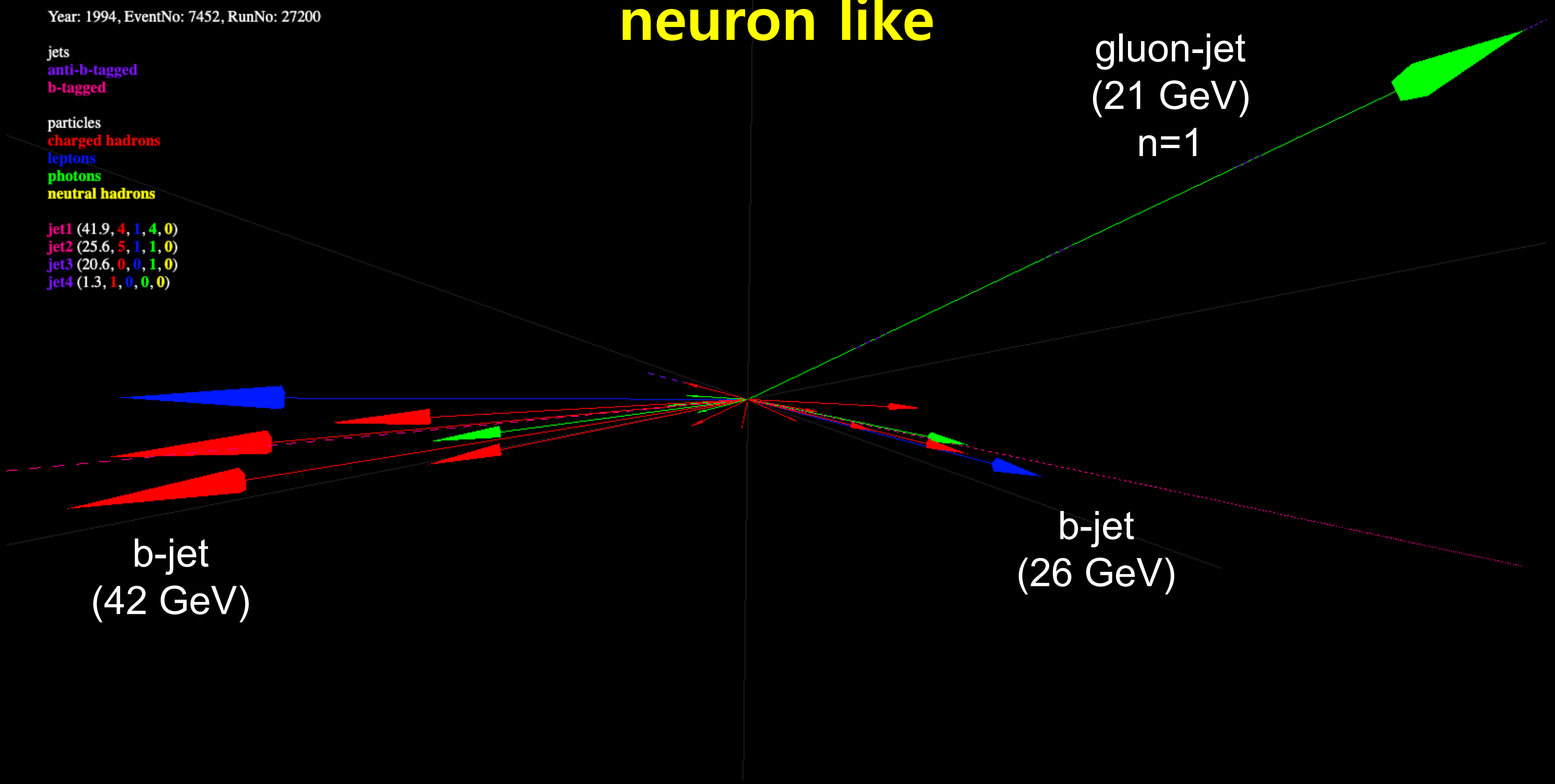
chromon like



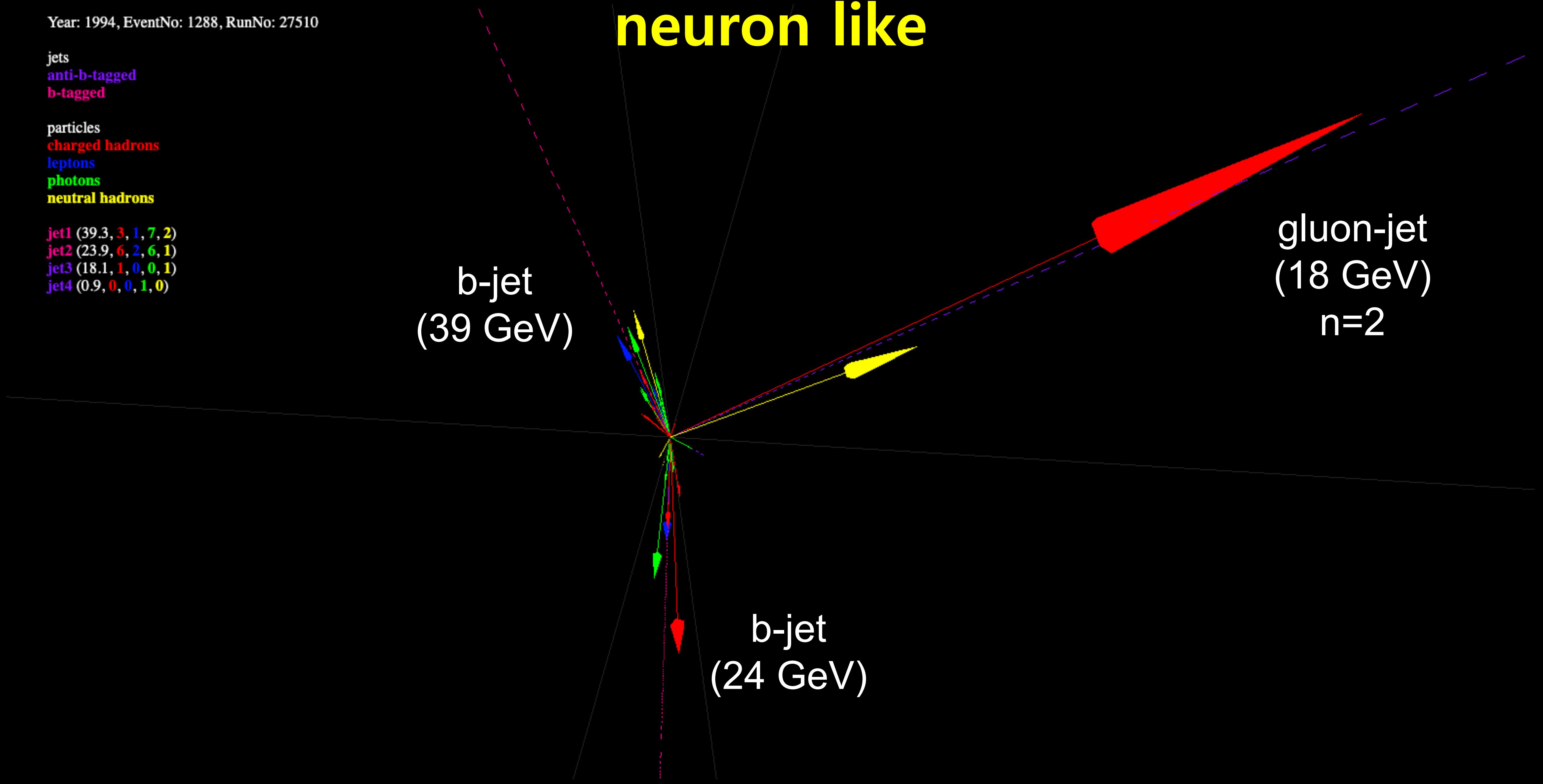
chromon like



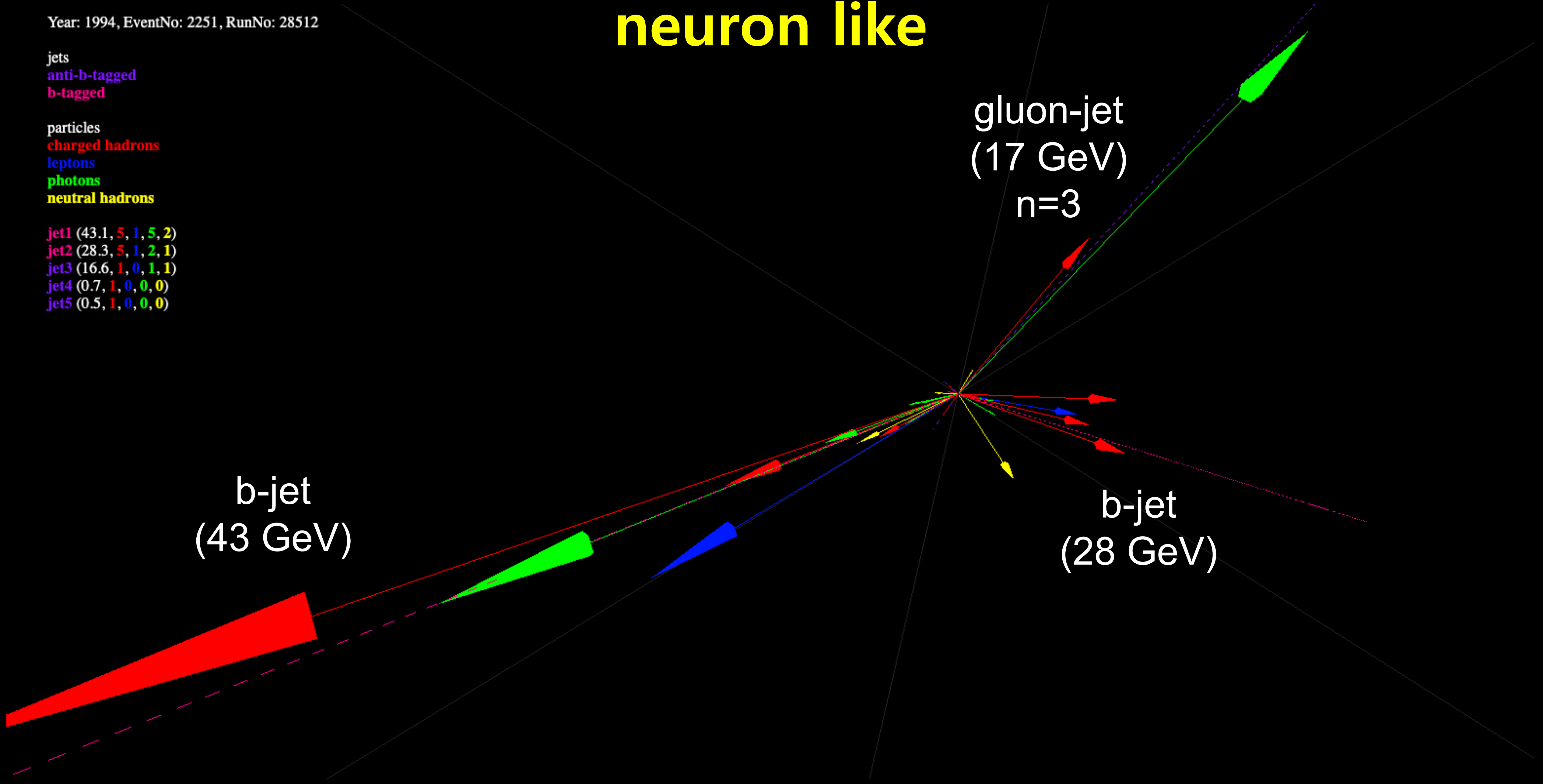
neuron like


Year: 1994, EventNo: 7452, RunNo: 27200
jets
anti-b-tagged
b-tagged
particles
charged hadrons
leptons
photons
neutral hadrons
jet1 (41.9, 4, 1, 4, 0)
jet2 (25.6, 5, 1, 1, 0)
jet3 (20.6, 0, 0, 1, 0)
jet4 (1.3, 1, 0, 0, 0)
gluon-jet
(21 GeV)
n=1
b-jet
(42 GeV)
b-jet
(26 GeV)

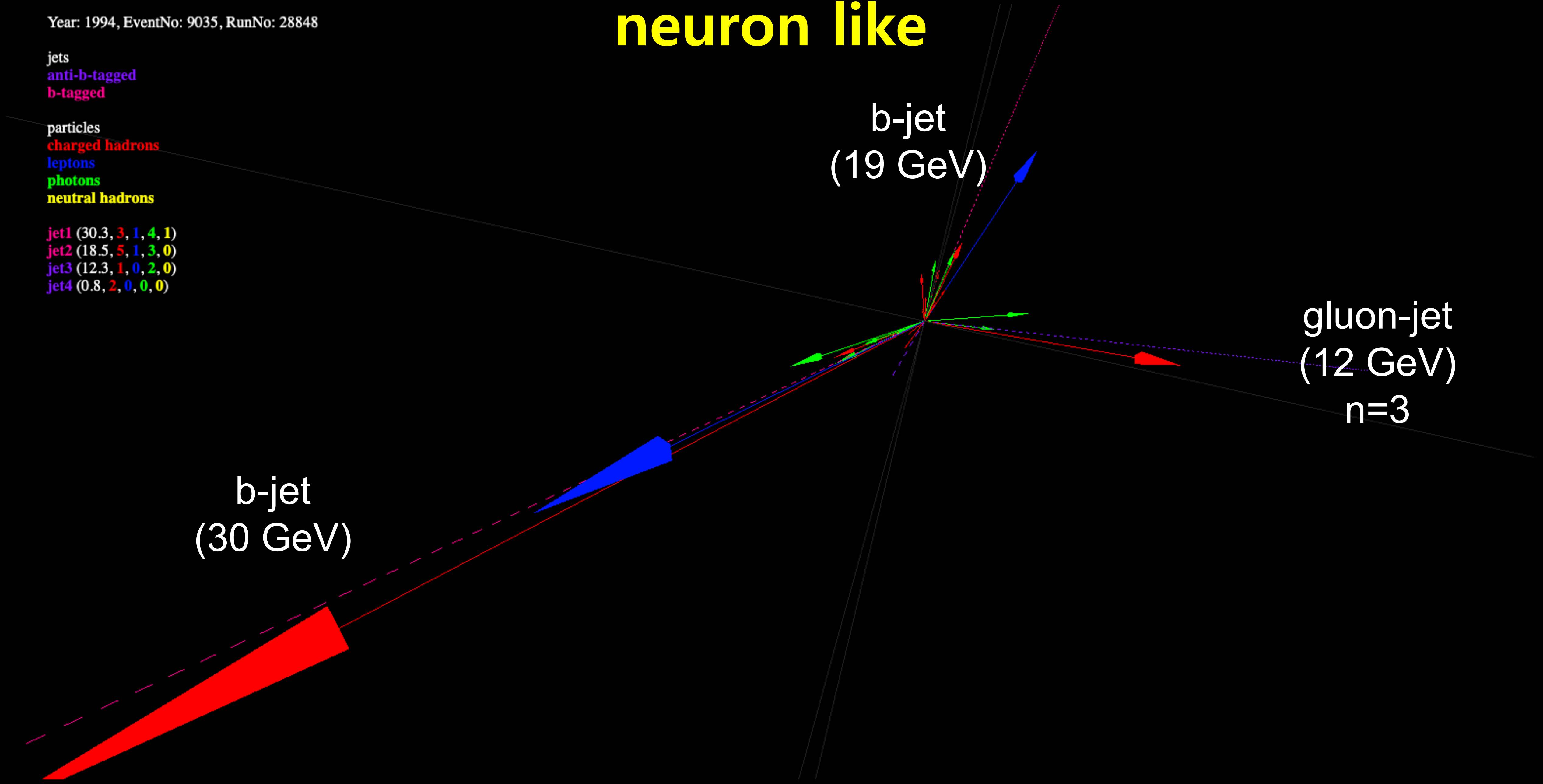
neuron like


Year: 1994, EventNo: 1288, RunNo: 27510
jets
anti-b-tagged
b-tagged
particles
charged hadrons
leptons
photons
neutral hadrons
jet1 (39.3, 3, 1, 7, 2)
jet2 (23.9, 6, 2, 6, 1)
jet3 (18.1, 1, 0, 0, 1)
jet4 (0.9, 0, 0, 1, 0)
b-jet
(39 GeV)
gluon-jet
(18 GeV)
n=2
b-jet
(24 GeV)

neuron like

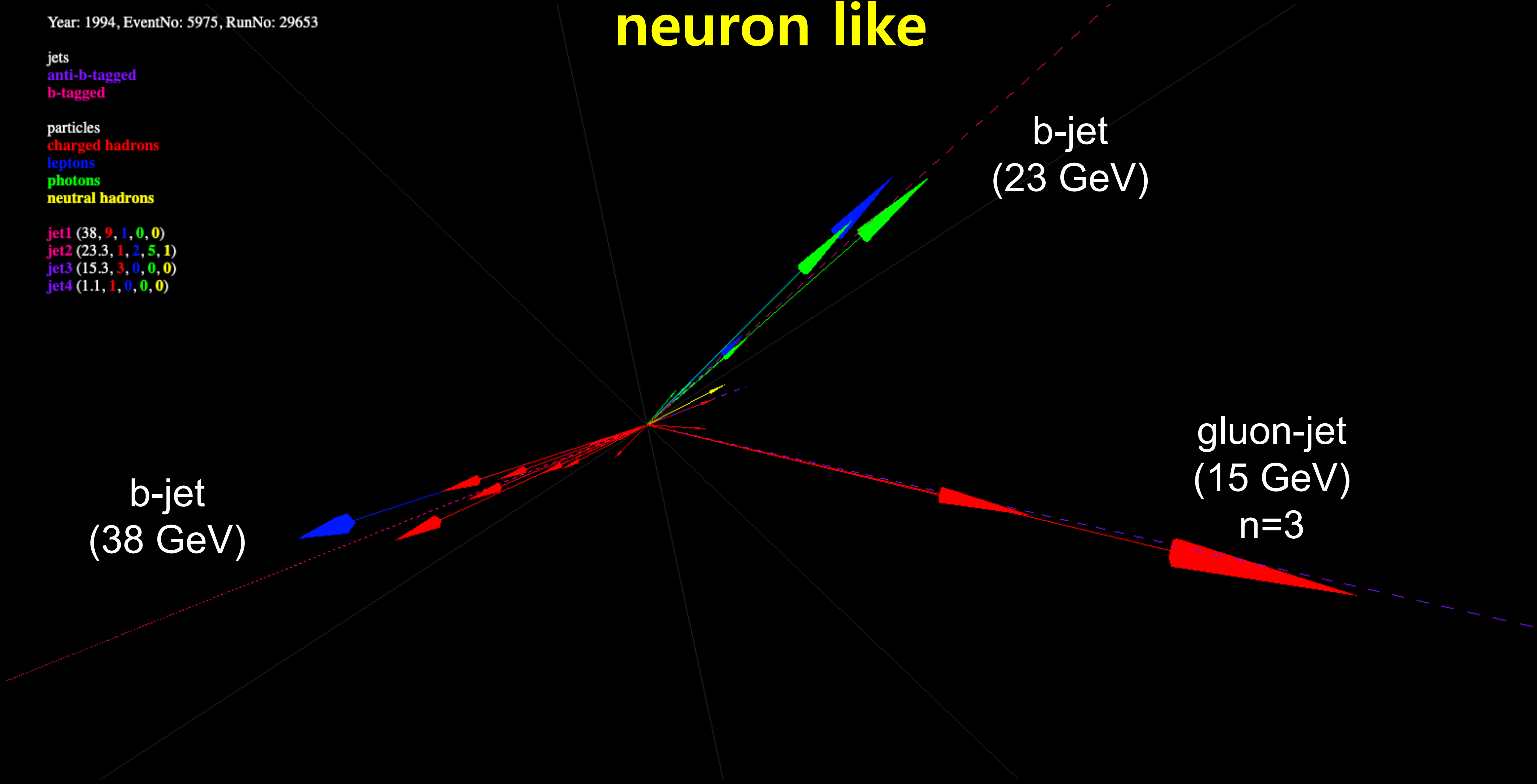

Year: 1994, EventNo: 2251, RunNo: 28512
jets
anti-b-tagged
b-tagged
particles
charged hadrons
leptons
photons
neutral hadrons
jet1 (43.1, 5, 1, 5, 2)
jet2 (28.3, 5, 1, 2, 1)
jet3 (16.6, 1, 0, 1, 1)
jet4 (0.7, 1, 0, 0, 0)
jet5 (0.5, 1, 0, 0, 0)
gluon-jet
(17 GeV)
n=3
b-jet
(43 GeV)
b-jet
(28 GeV)

neuron like



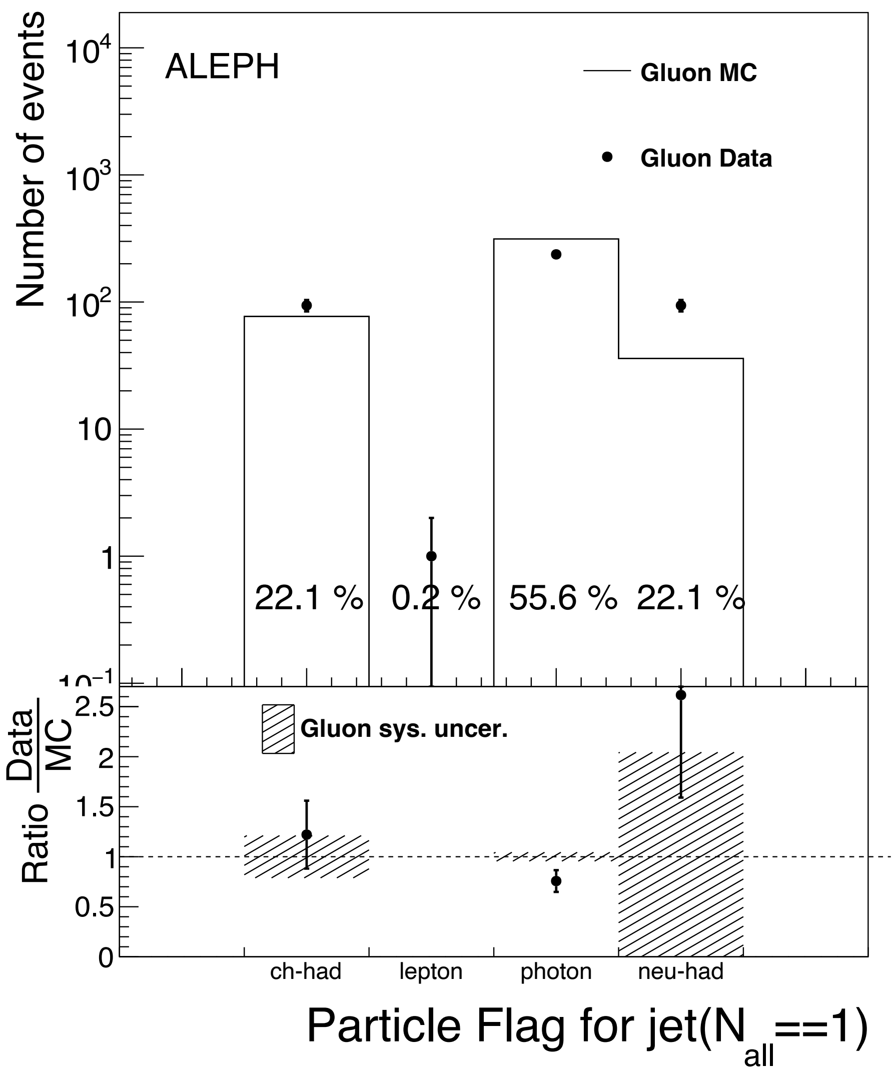
Year: 1994, EventNo: 9035, RunNo: 28848
jets
anti-b-tagged
b-tagged
particles
charged hadrons
leptons
photons
neutral hadrons
jet1 (30.3, 3, 1, 4, 1)
jet2 (18.5, 5, 1, 3, 0)
jet3 (12.3, 1, 0, 2, 0)
jet4 (0.8, 2, 0, 0, 0)
b-jet
(19 GeV)
gluon-jet
(12 GeV)
n=3
b-jet
(30 GeV)

neuron like


Year: 1994, EventNo: 5975, RunNo: 29653
jets
anti-b-tagged
b-tagged
particles
charged hadrons
leptons
photons
neutral hadrons
jet1 (38, 9, 1, 0, 0)
jet2 (23.3, 1, 2, 5, 1)
jet3 (15.3, 3, 0, 0, 0)
jet4 (1.1, 1, 0, 0, 0)
b-jet
(23 GeV)
gluon-jet
(15 GeV)
n=3
b-jet
(38 GeV)

Single track gluons? Who are they?

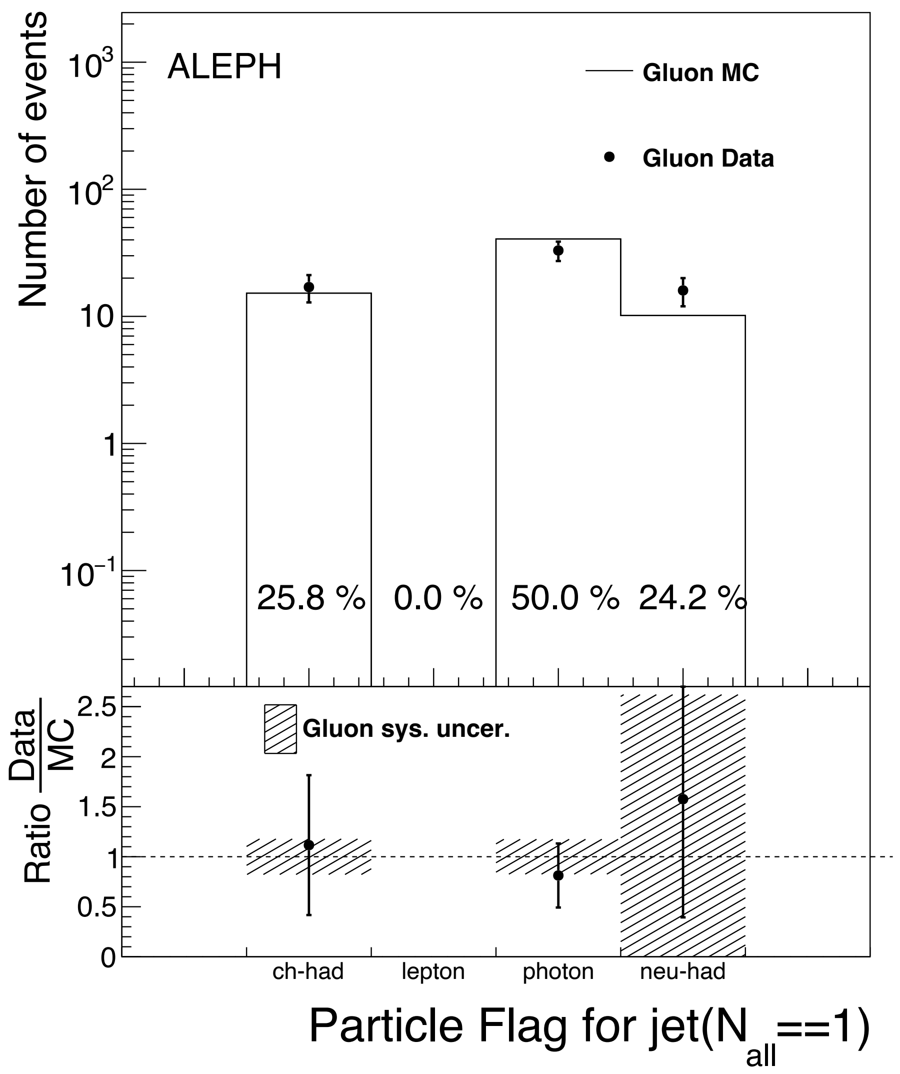
j2/j3 : b-jet & gluon (426 evts)



$N_l : N_\gamma : N_h : N_n$

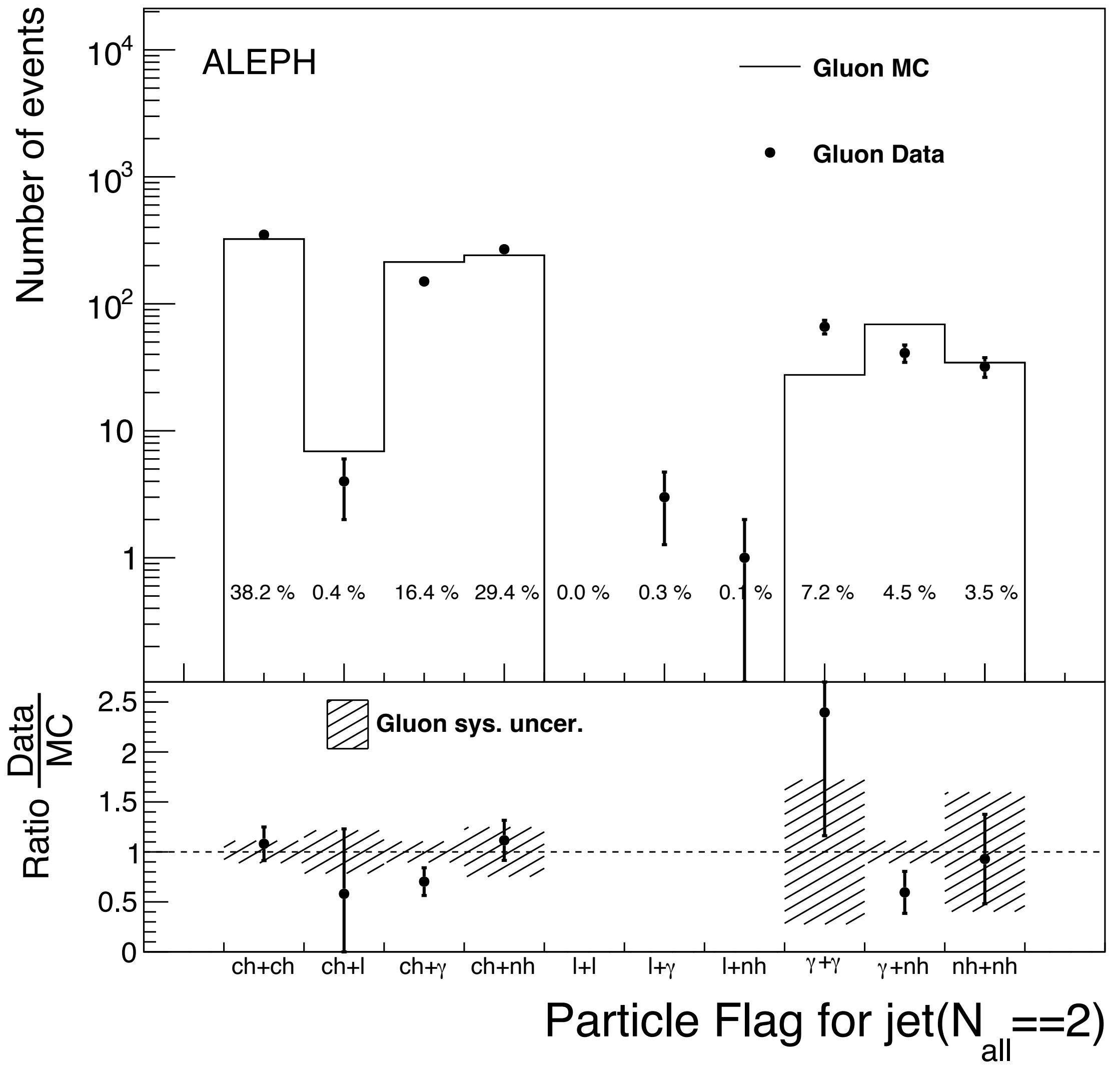
$0 : \frac{1}{2} : \frac{1}{4} : \frac{1}{4}$

j1/j2/j3 : 2 b-jet & gluon (66 evts)

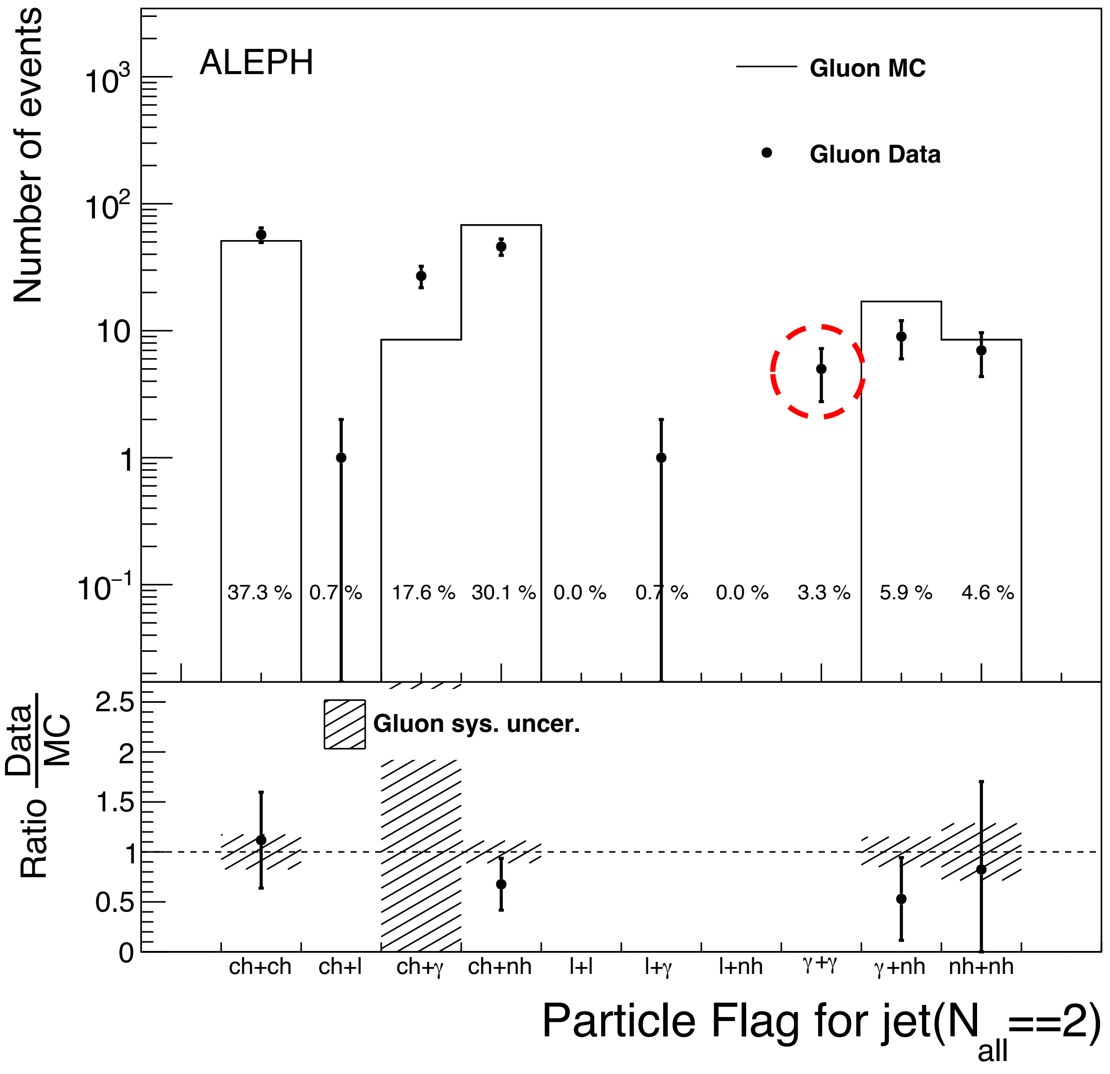


2-track gluons? Who are they?

j2/j3 : b-jet & gluon (916 evts)



j1/j2/j3 : 2 b-jet & gluon (153 evts)



Remarks & Discussions

Conclusions

- **We followed ALPEH's previous QCD jet analysis.**
  - **Reconfirm the ALEPH's uncertain anomalies in N and X_E**
    - ✓ **Excess of charged tracks with a large energy share**
    - ✓ **Correlation between two anomalies in N and X_E**
      - – **Excess of low multiplicity jet in ALEPH data**
- **We cannot claim the existence of two types of gluons; how ever, we see that Cho-gluons could explain such anomalies.**
  - **In-depth studies of the Gluon anomaly are needed**
    - ✓ **using other variables**
    - ✓ **using other elaborated jet algorithms that are sensitive to the jet shape.**
  - **MC generator level studies are also necessary**
    - ✓ **for unfolded analysis**
    - ✓ **with implementation of Neurons & Chromons**

Thank you

backup slides

charged multiplicity

- **ALEPH**
  - $\langle n_g \rangle = 9.90 \pm 0.10 \pm 0.27$
  - $\langle n_{uds} \rangle = 7.90 \pm 0.44 \pm 0.26$
  - $\langle n_b \rangle = 9.32 \pm 0.27 \pm 0.27$
  - $\langle n_c \rangle = 8.37 \pm 1.64 \pm 0.28$
- **Model**
  - $R_{g/b} = 1.077\ (JETSET)\ 1.003\ (HERWIG)$

* NFM=Natural Flavor Mix @ Z

$$R_{g/\mathrm{NFM}} = 1.194 \pm 0.027(\mathrm{stat}) \pm 0.019(\mathrm{syst})$$

$$R_{g/uds} = 1.249 \pm 0.084(\mathrm{stat}) \pm 0.022(\mathrm{syst})$$

$$R_{g/b} = 1.060 \pm 0.041(\mathrm{stat}) \pm 0.020(\mathrm{syst})$$

$$R_{g/c} = 1.183 \pm 0.221(\mathrm{stat}) \pm 0.021(\mathrm{syst})$$

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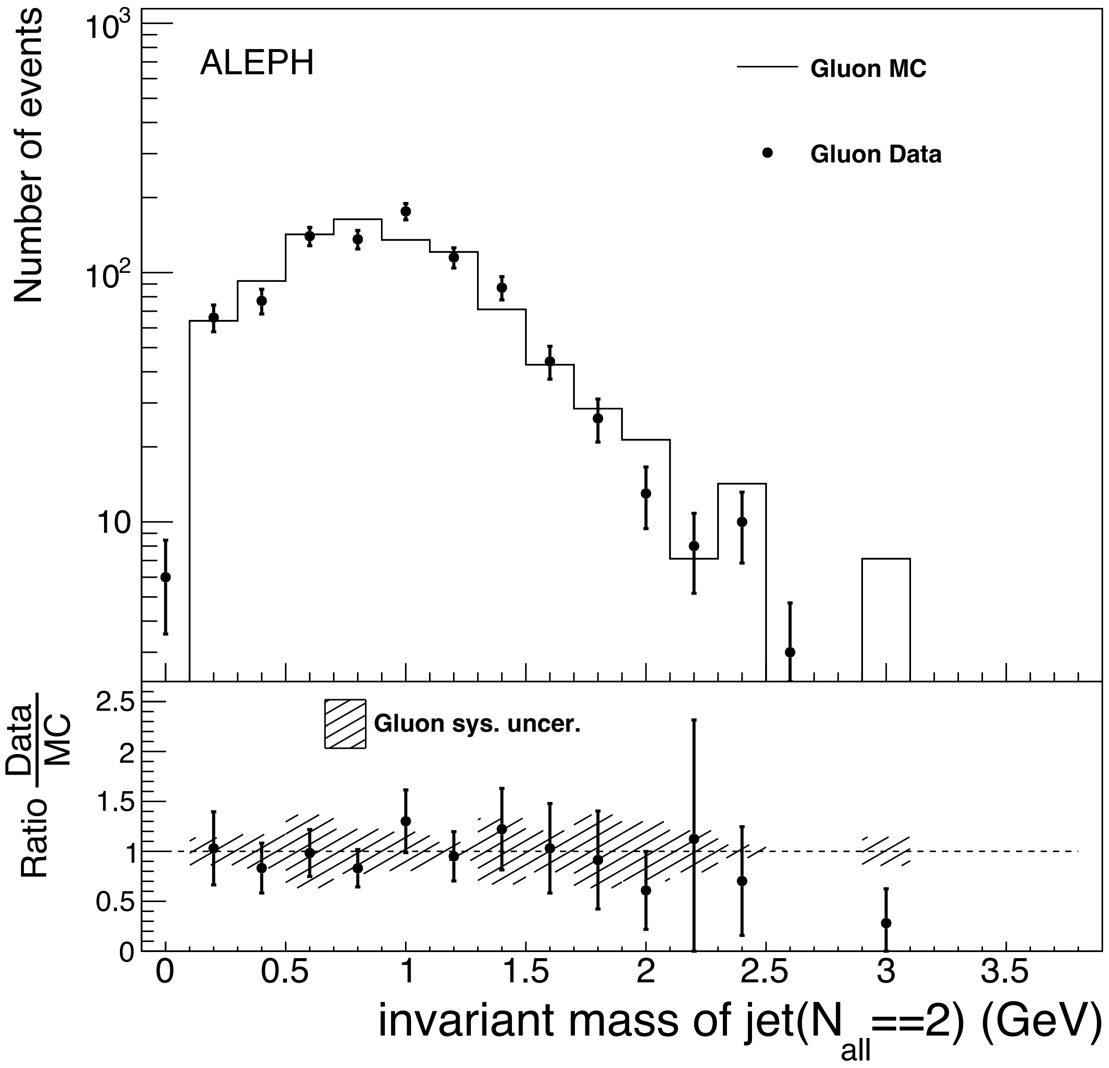
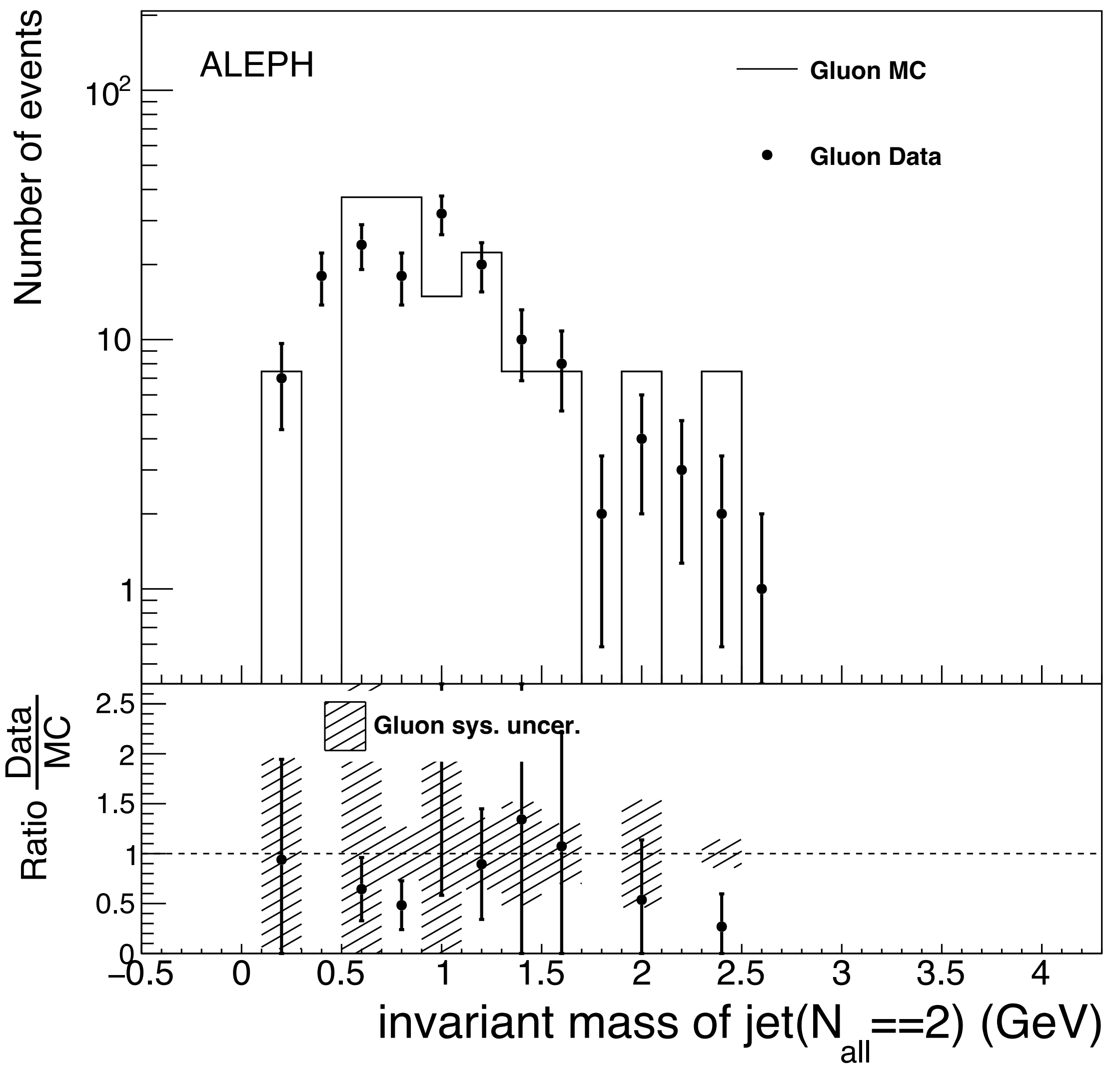
mass of 2-trk gluons (inclusive)

j2/j3 : b-jet & gluon (911 evts)

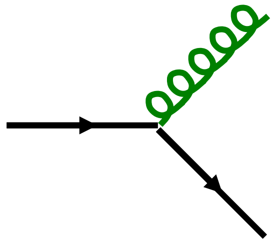


j1/j2/j3 : 2 b-jet & gluon (149 evts)

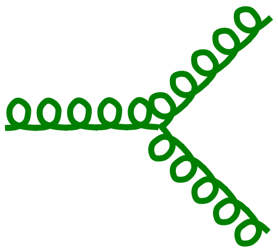


Casimir operators

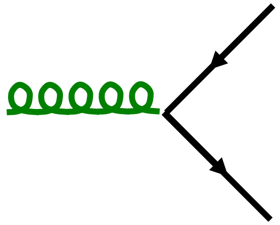
- In QCD, the strong force is described by the SU(3) gauge theory, where:
  - Quarks are in the fundamental representation (triplet) of SU(3).
  - Gluons are in the adjoint representation (octet) of SU(3).
- C_F : Casimir Operator for the Fundamental Representation
  - strength of the interaction between quarks
    - ✓ $C_F = \frac{N_c^2 - 1}{2N_c} = \frac{4}{3}$ (for QCD)
- C_A : Casimir Operator for the Adjoint Representation
  - characterizes the self-interaction of gluons
    - ✓ $C_A = N_c = 3$ (for QCD)



$C_F = \frac{4}{3}$



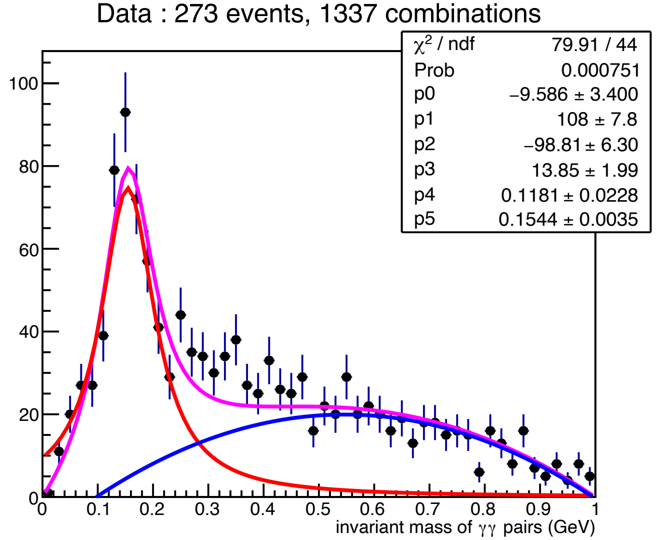
$C_A = 3$

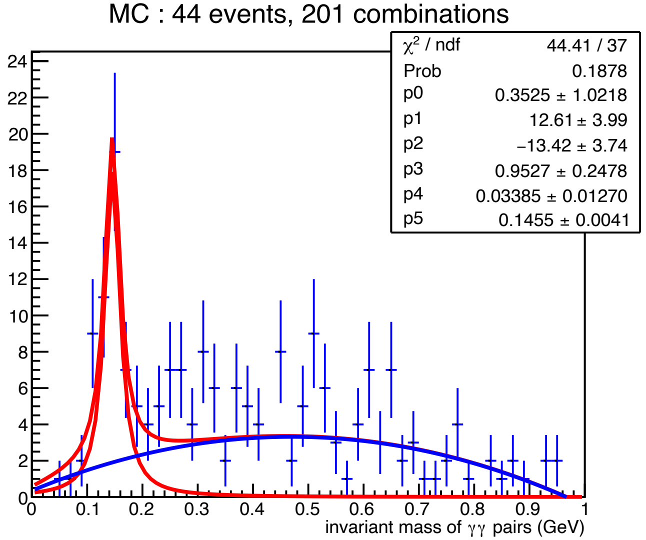


$T_F = \frac{1}{2}$

gluons without a charged track

- **two photon mass**





- **such gluons have pi0, however no noticeable difference is found**

Our obsevations & implications

- **Data excesses in gluon jets (compared to MC)**
  - X_E
    - ✓ Gluon jets have more charged tracks with high energy share (high X_E)
  - N_{trk}
    - ✓ Gluon jets with small number of tracks (2 tracks) are more
- **Implications**
  - It is unclear whether this is simply MC's fault or if there is any gluon anomaly in the data.
    - ✓ MC tuning for fragmentations is required.
    - ✓ Can this be natually explained by Cho-gluon theory?