Hadronisation: Models vs. Data

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- Introduction
- Remarks on Tuning
- Models compared to Data
  (shapes, incl. & ident. hadrons., rates, E-dependence, heavy q´s, resonances, baryons, soft γ´s, gluons<->quarks, Bose Einstein FSI)
- Summary

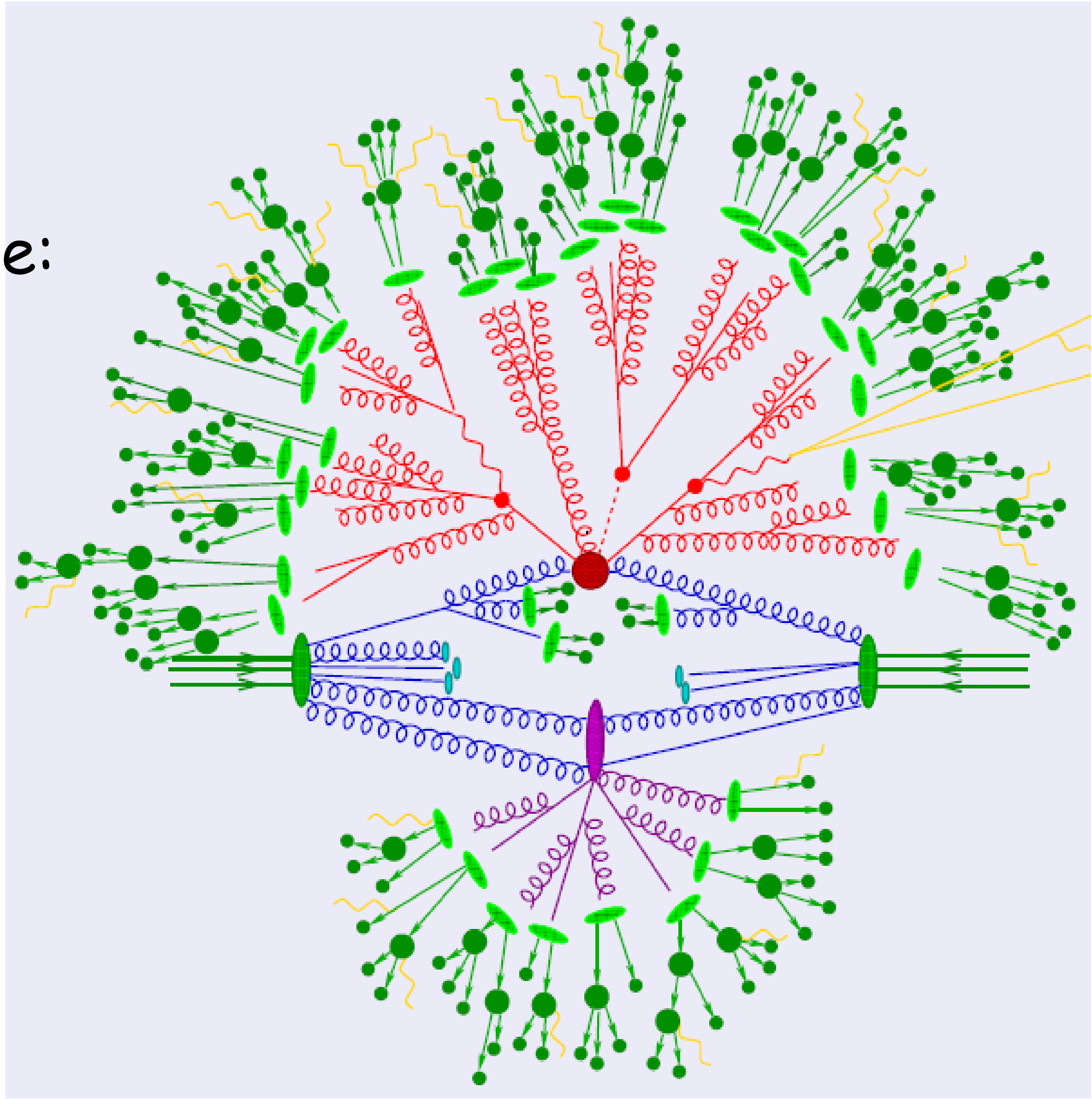
Introduction

At LHC/pp interactions:

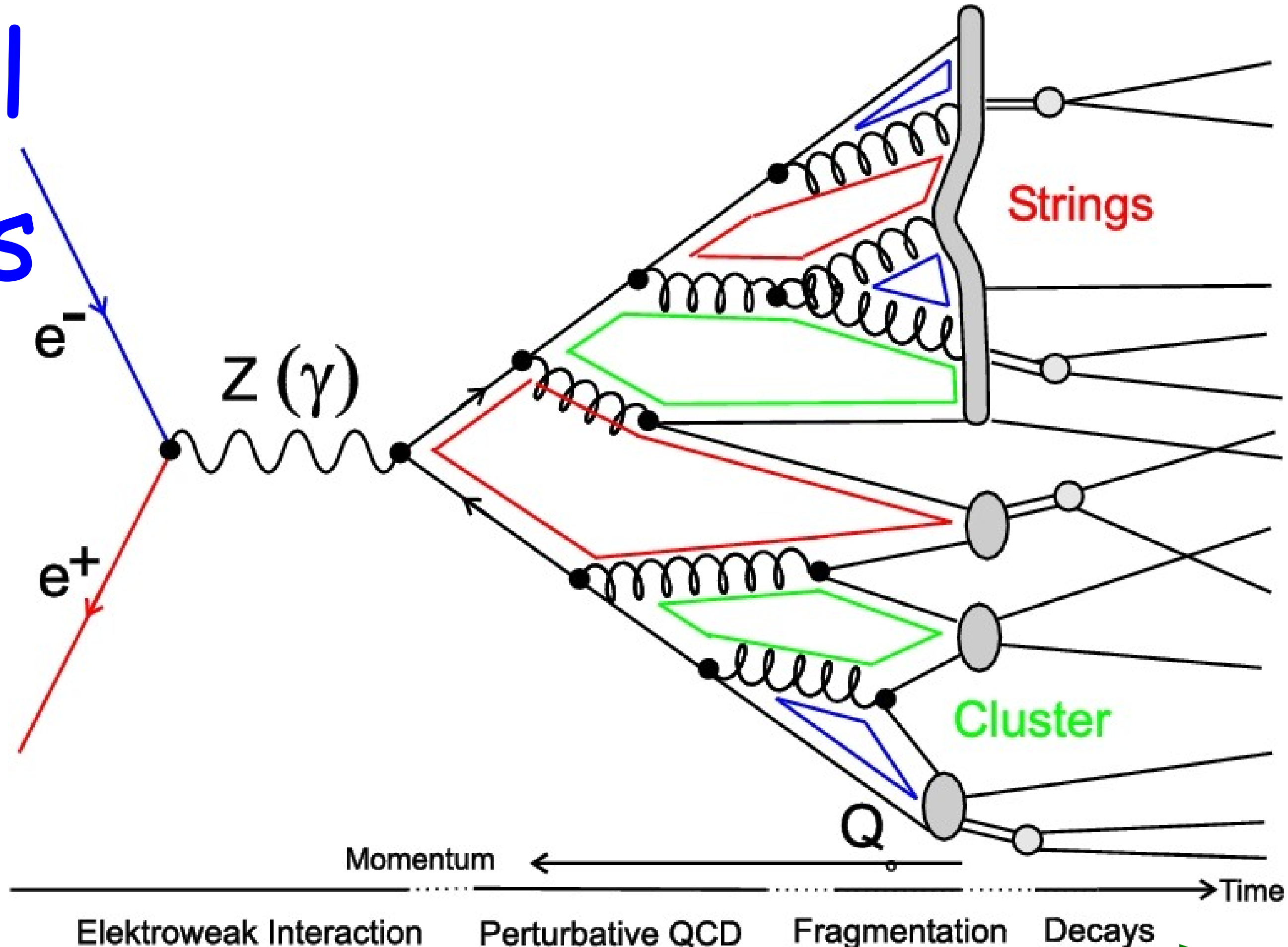
intricate event structure:

PDF´s,
ISR,
multiple interactions,
FSR,
hadronisation, ...

-> fix fragmentation mainly using e^+e^- data



Model Pieces (e^+e^-)



Z-qq couplings

ME .... PS

Theoretically "understood"

Fragmentation

Conservation laws, theory guided models

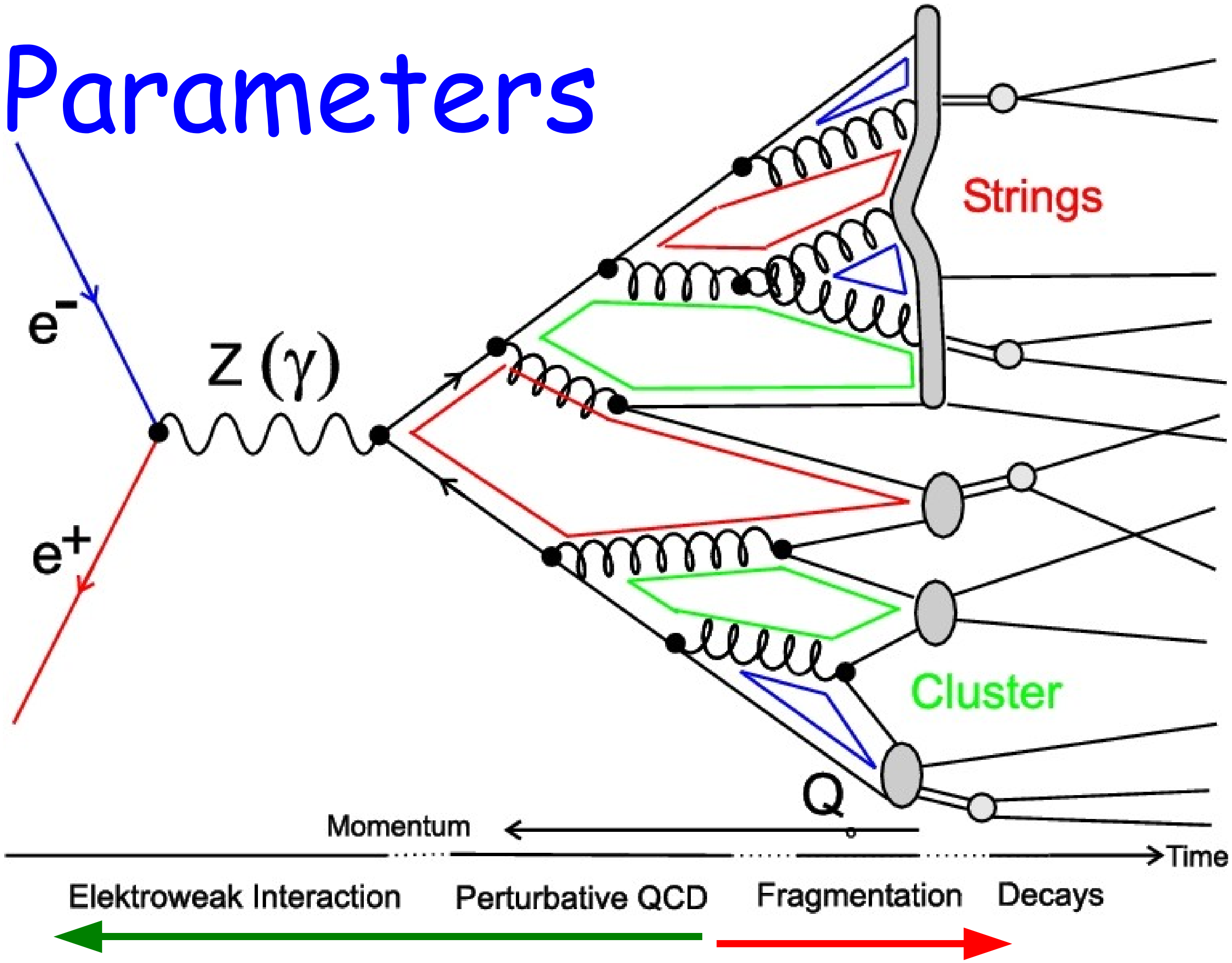
FSI, CR

Models

Decays

Data (BR´s)

Main Parameters



many parameters

less parameters

$\alpha_s(M_Z)$, $\alpha_s(p_t)$, p_t^{cut}

fragment. functions
flavour composition,
baryons, # resonances

Model pieces strongly correlated due to splitting processes:
partonic splittings - fragmentation splittings - decays

HERWIG Parameters (a la ALEPH)

parameter	MC name	HW0	HW-CR
P_{reco}	PRECO	0	1/9
min. virtuality (GeV^2)	VMIN2	-	0.1
Λ (GeV)	QCDLAM	0.190 ± 0.005	0.187 ± 0.005
gluon mass (GeV)	RMASS(13)	0.77 ± 0.01	0.79 ± 0.01
max. cluster mass (GeV)	CLMAX	3.39 ± 0.08	3.40 ± 0.08
angular smearing, dusc	CLSMR(1)	0.59 ± 0.03	0.66 ± 0.04
angular smearing, b	CLSMR(2)	0	0
power in cluster splitting, dusc	PSPLT(1)	0.945 ± 0.018	0.886 ± 0.017
power in cluster splitting, b	PSPLT(2)	0.33	0.32
decuplet baryon weight	DECWT	0.71 ± 0.06	0.70 ± 0.06
$\langle n_{\mathrm{ch}} \rangle$		20.96	20.98
f(reco)		-	0.08

PS (QCDLAM, RMASS(13))

params for heavy clusters decay (CLMAX, CLSMR(1), CLSMR(2), PSPLT(1), PSPLT(2))

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Few parameters for general fragmentation in HERWIG !

How to Fix Model Parameters

Require description of data : measured hadrons

- need complete model
  (from PDF ... to observed hadrons)
- need corrected data

Else no proper comparison possible !

How to Tune

- generate many event samples using random MC model param. sets (use physical parameters e.g. α_s instead of Λ);
- interpolate between samples -> parameterisation(MC param.) (2nd order multidimensional polynomial with correlations);
- fit analytic parameterisation to data -> best MC param.; regard standard fitting rules;
- if optimum MC params. outside initial param. hypervolume, or volume too big iterate (we used 2nd order interpolation!)
- for syst. errors exchange data distributions in the fit

Strategy tested for many (15) parameters simultaneously

Which Data Distributions ?

Start from

obvious

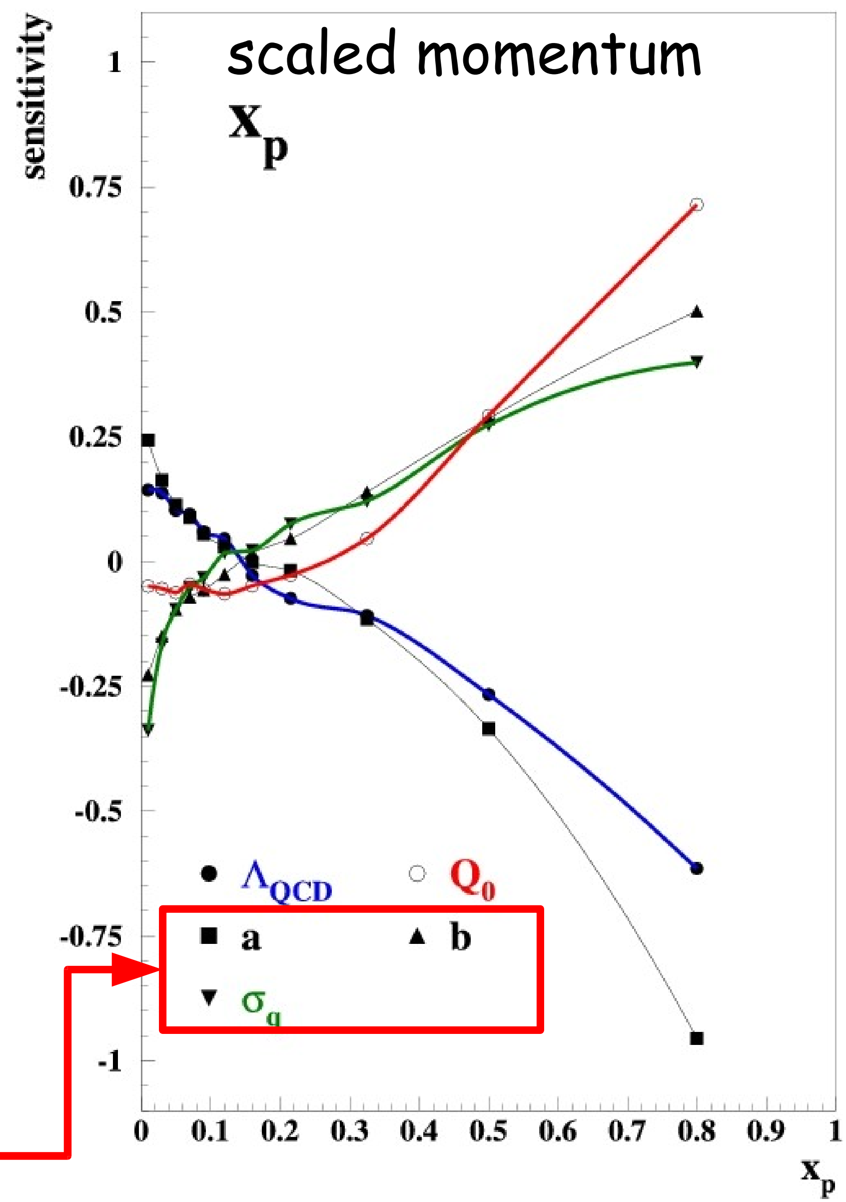
physics motivation

but check

sensitivity

of the data

distribution !



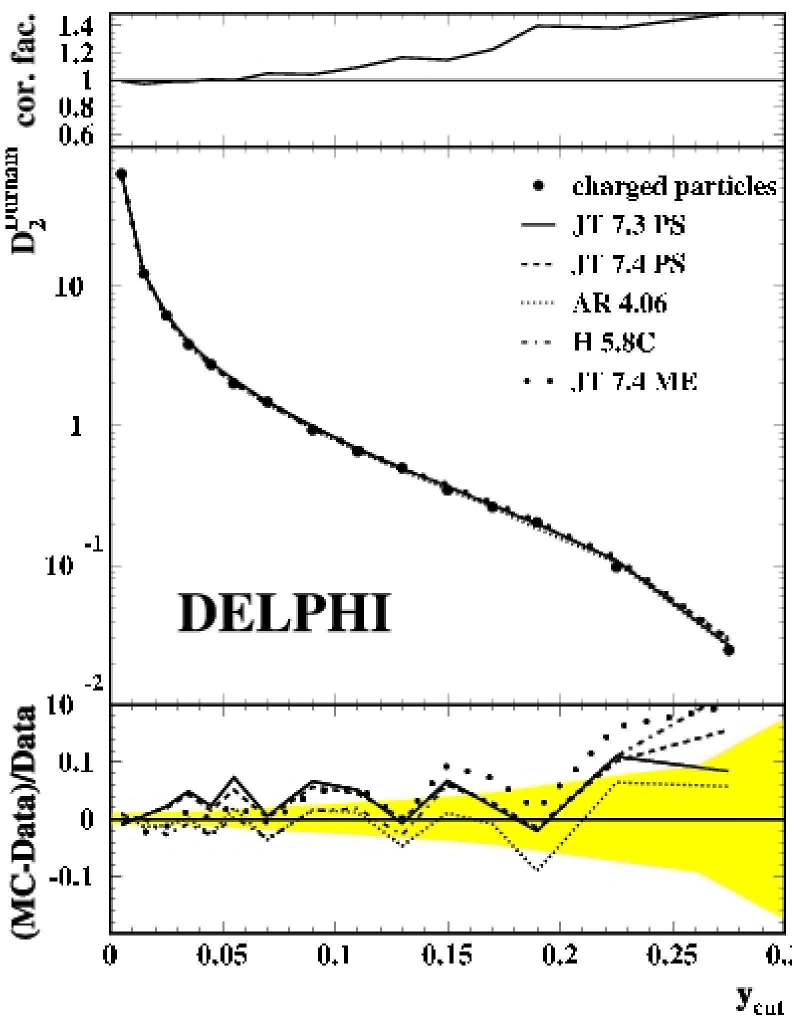
Lund string frag. fct. parameters

Which Data to Chose !

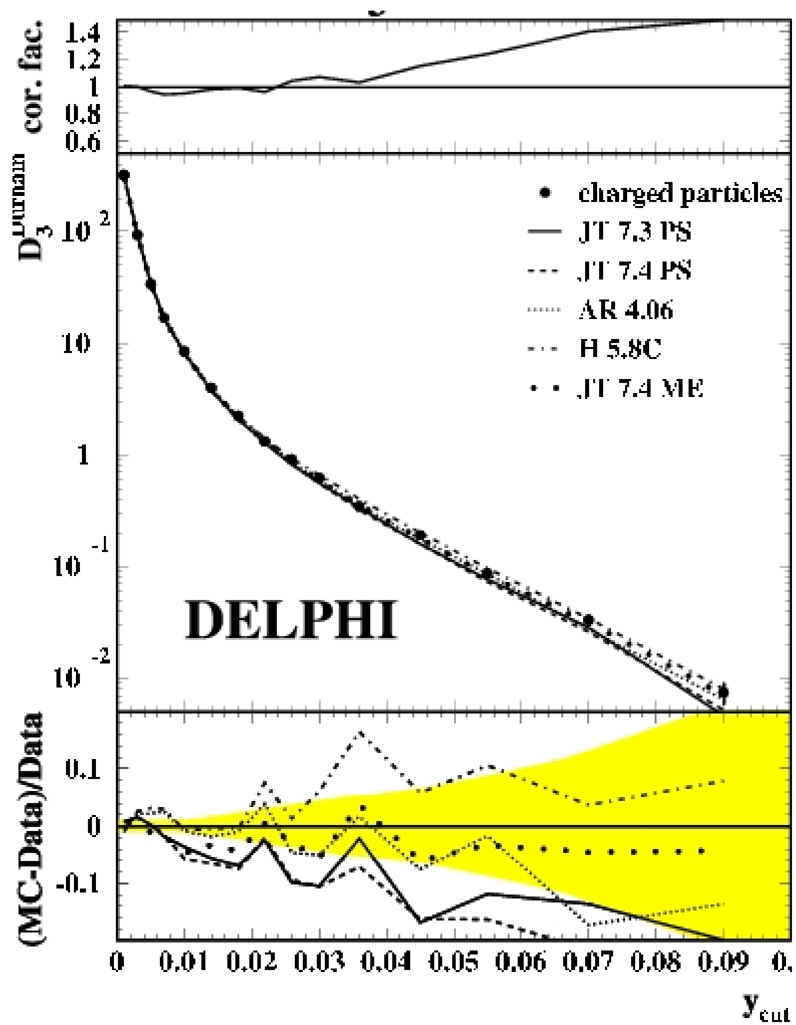
- use only sensitive data
- try to avoid large correlation btw. parameters like in previous plot
  $\alpha_s <> p_t^{cut}$; $\alpha_s <>$ frag. fct. ; $p_t^{cut} <> \#$ resonances
- a tune is a fit =>
  exclude badly described distributions
  e.g. only use baryon rate not baryon momentum spectrum.
  Problem if model describes data badly =>
  model parameters ill-defined!

Models vs Event Shapes

3 Jet Rate



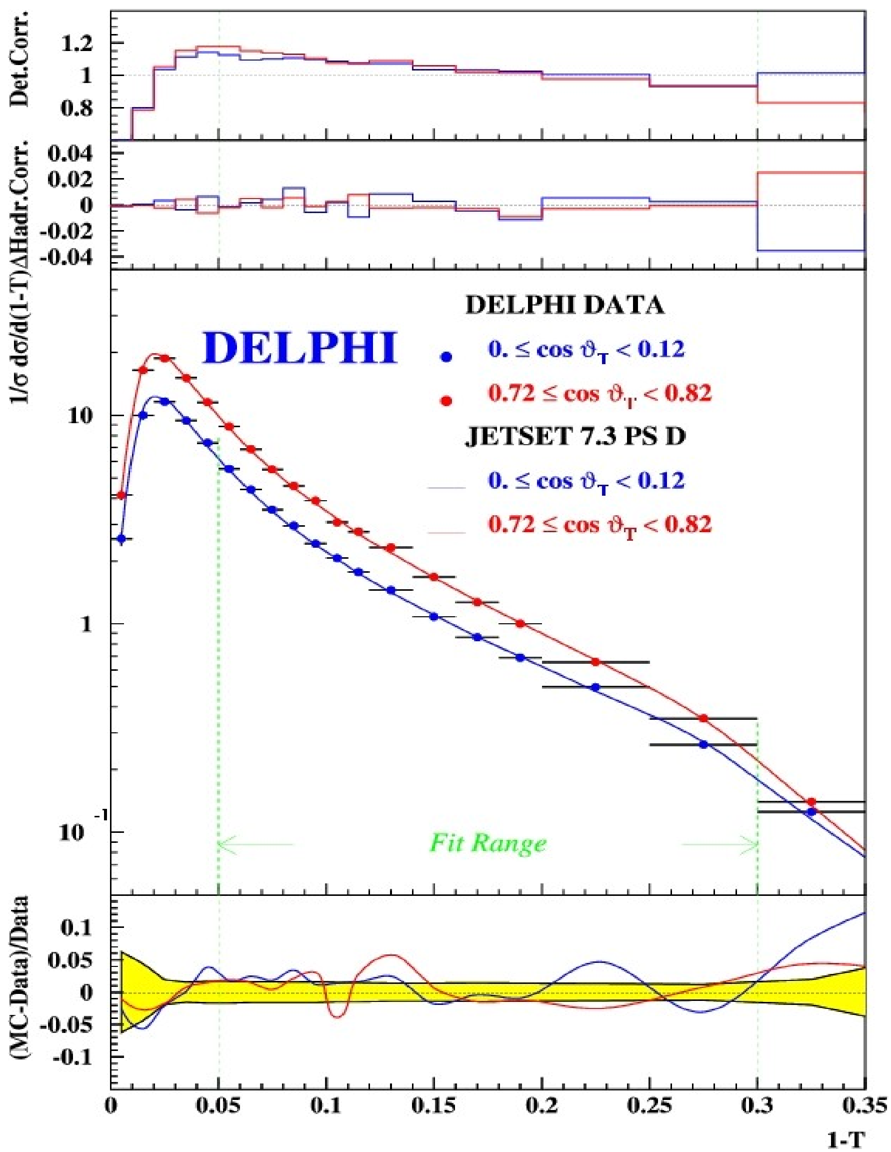
4 Jet Rate

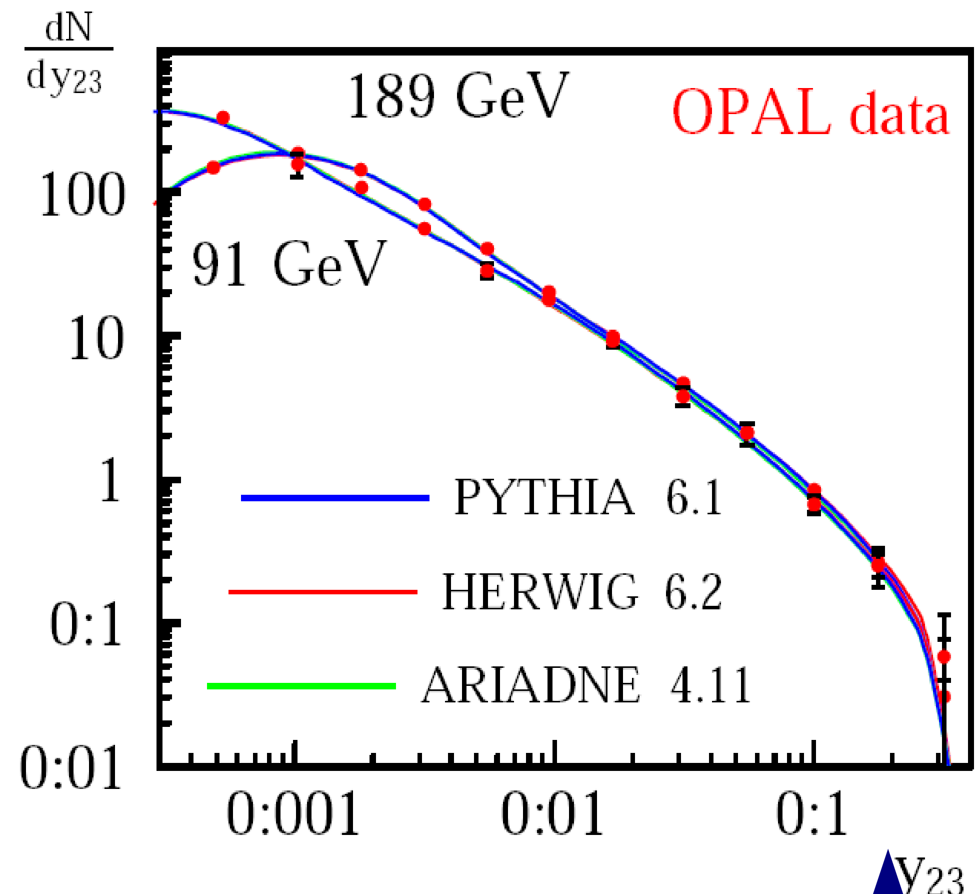


For 3 Jet rate observables description ok (typical deviations O(3%))

-> 4 Jet rate obs. too low for Pythia, too high for Herwig, Ariadne ~ok

Check ME/PS Matching





Polar angle or energy dependence of 3-Jet observables ~ ok

Check ME/PS matching

E- and/or cosΘ-dependence

of 3- and 4-jet observables have

to be described simultaneously!

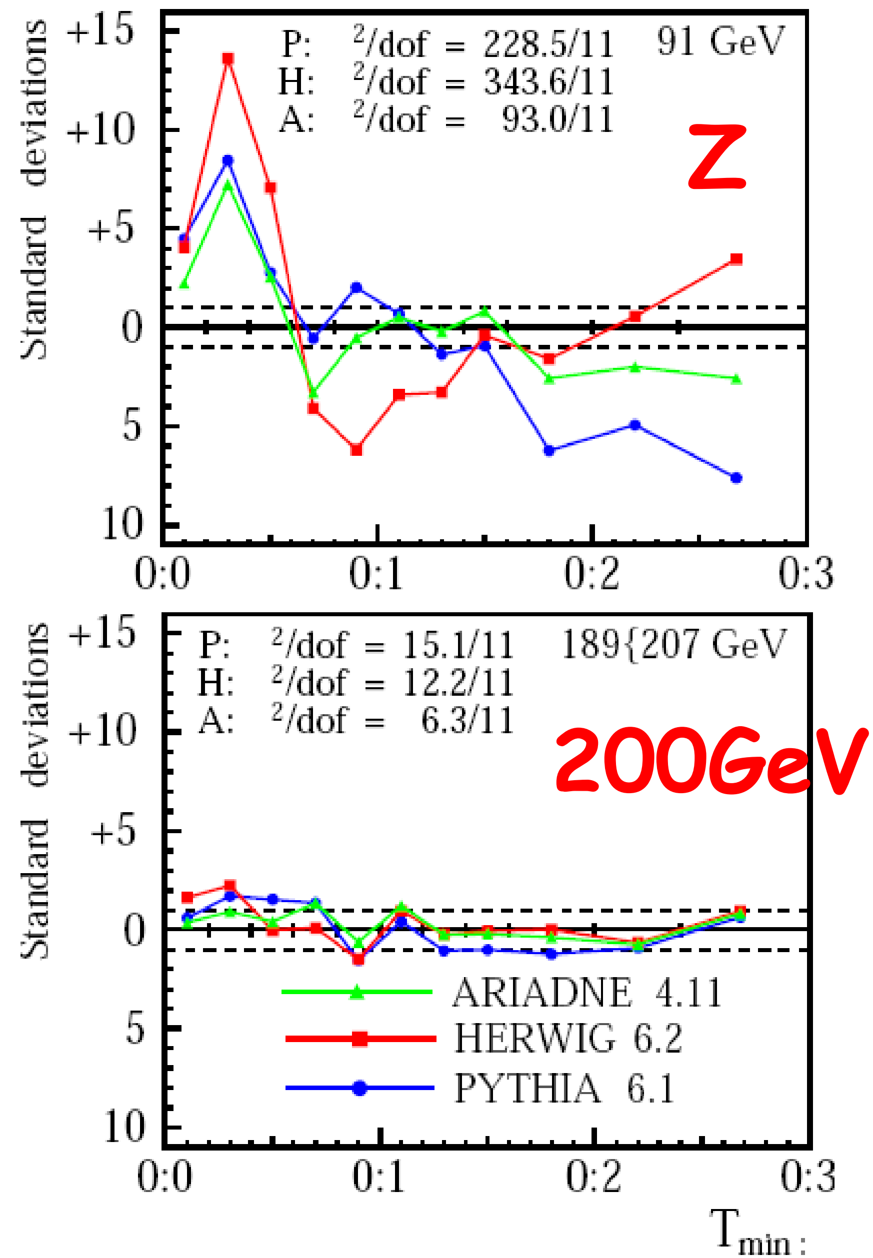
but:

little 4-jet data published

OPAL (M. Ford) =>

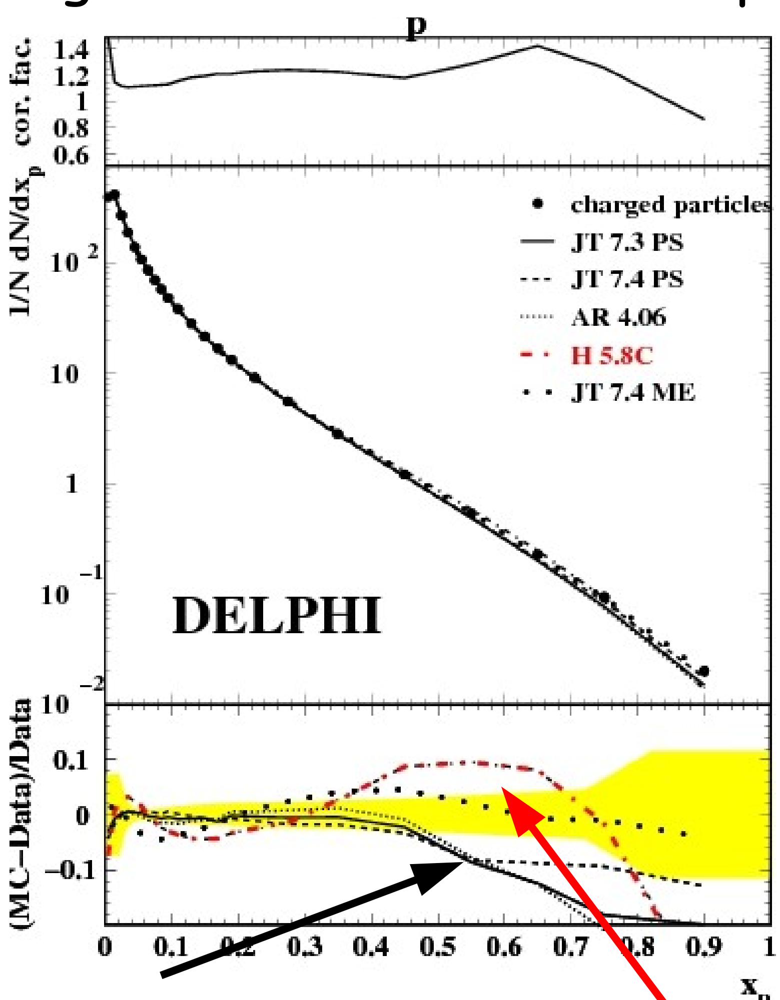
also ALEPH data

Minor

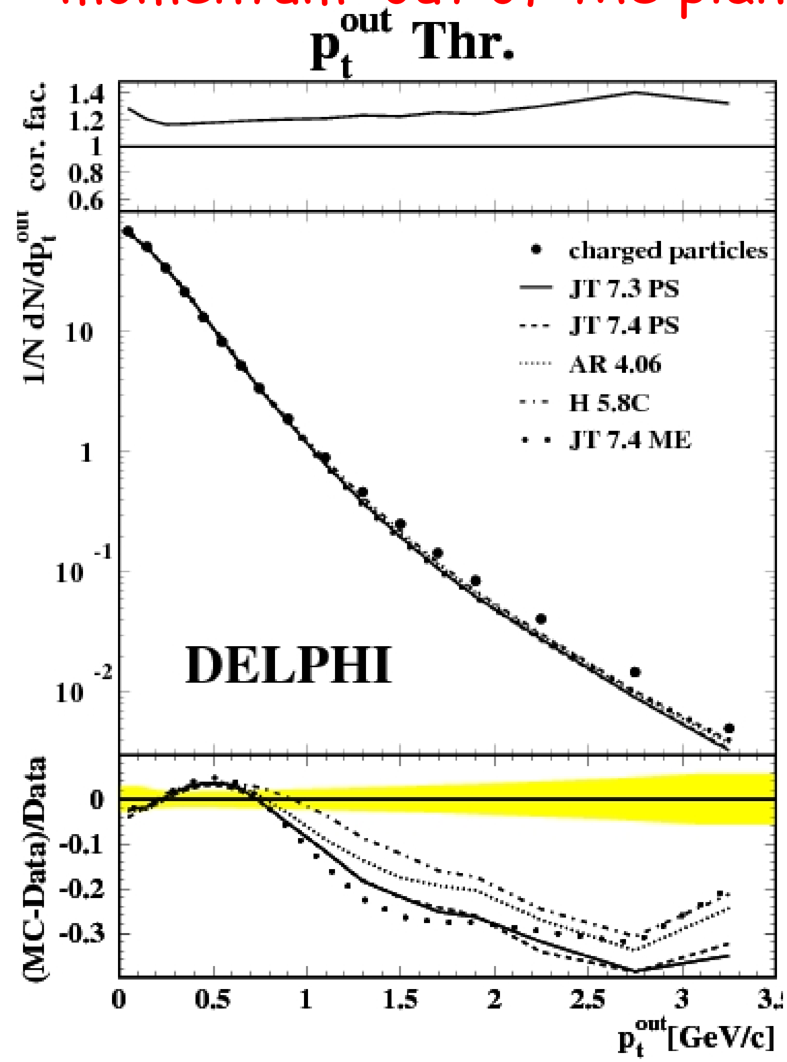


Inclusive Charged Hadrons

scaled momentum -
high correlation with multiplicity



All models **underestimate momentum out of the plane**

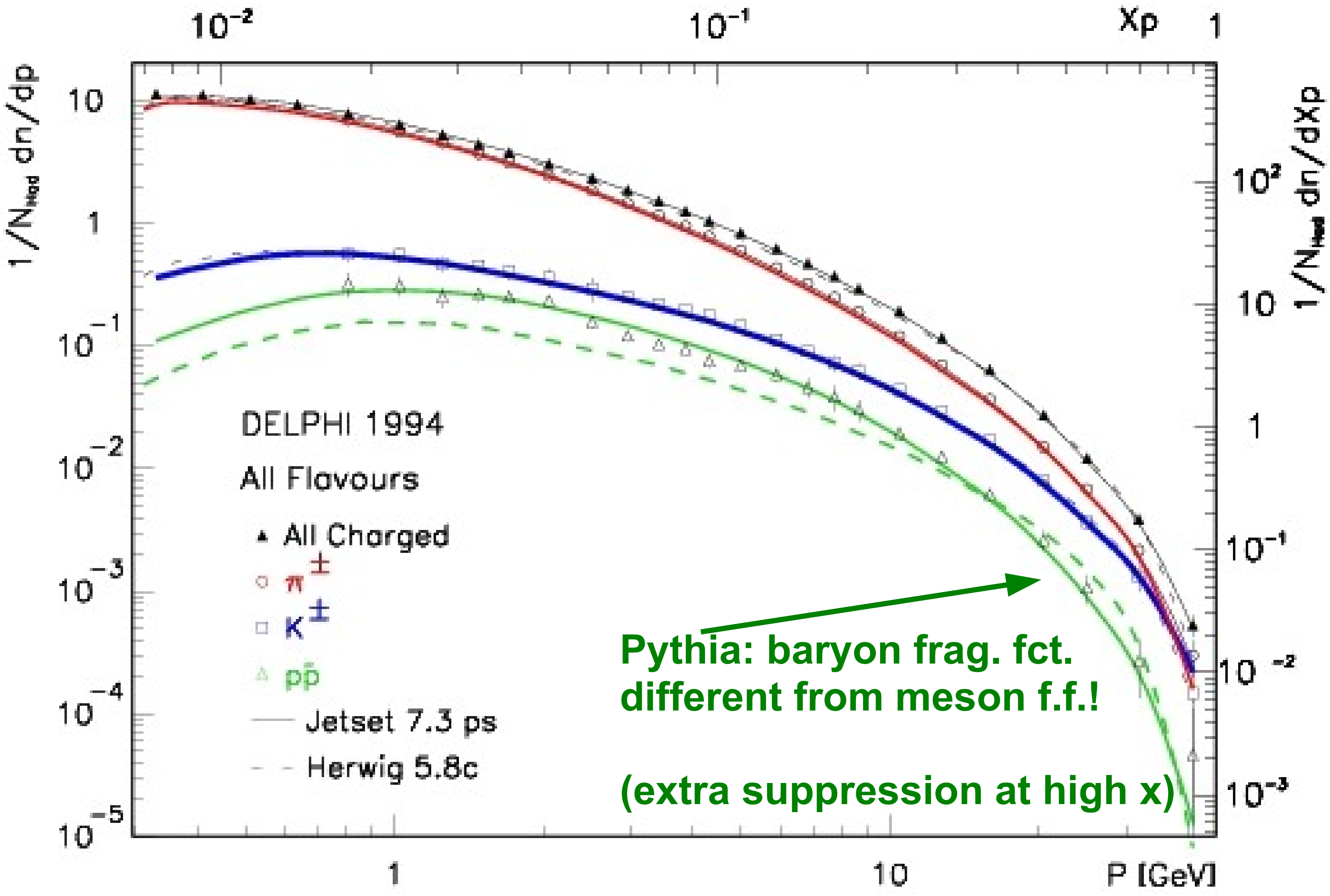


likely exptl. resolution

feature of cluster fragmentation

(p_t^{in} ~ ok)

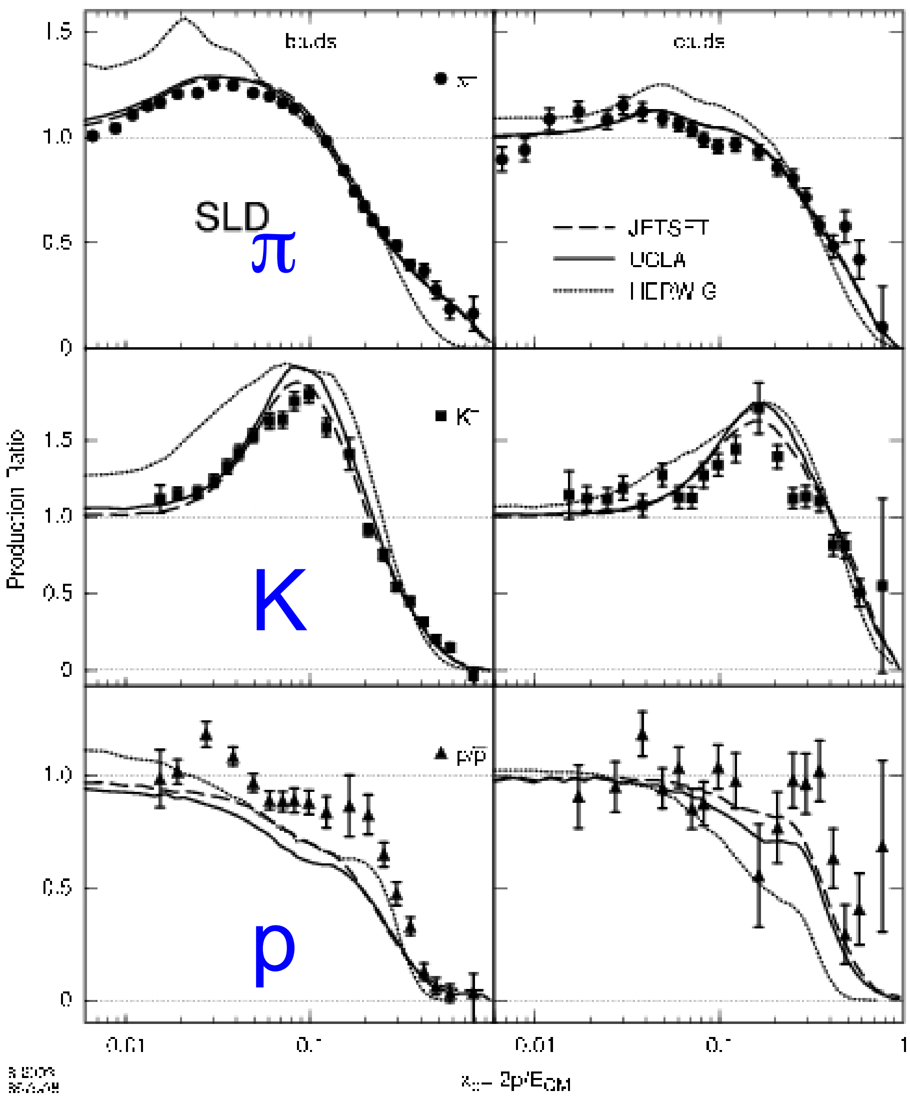
Identified Charged Hadrons



Identified Charged Hadrons

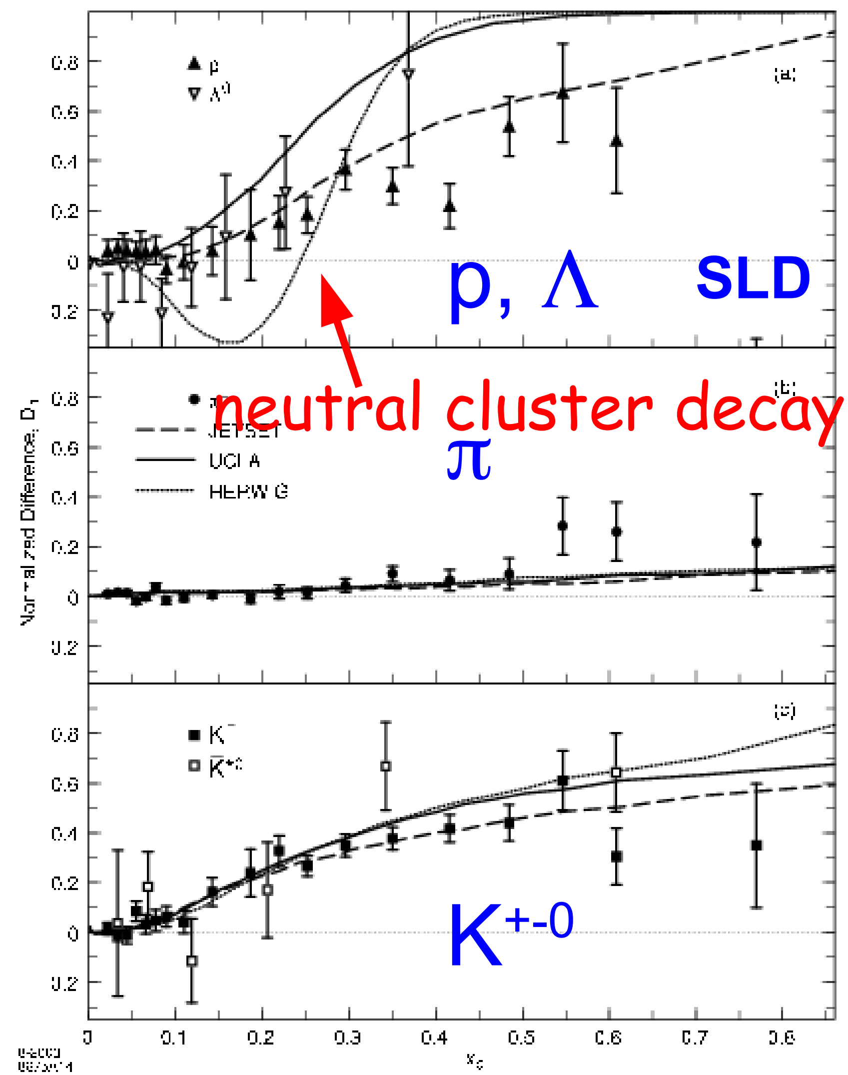
flavour dependence

Ratio b/uds ▼ **c/uds** ▼

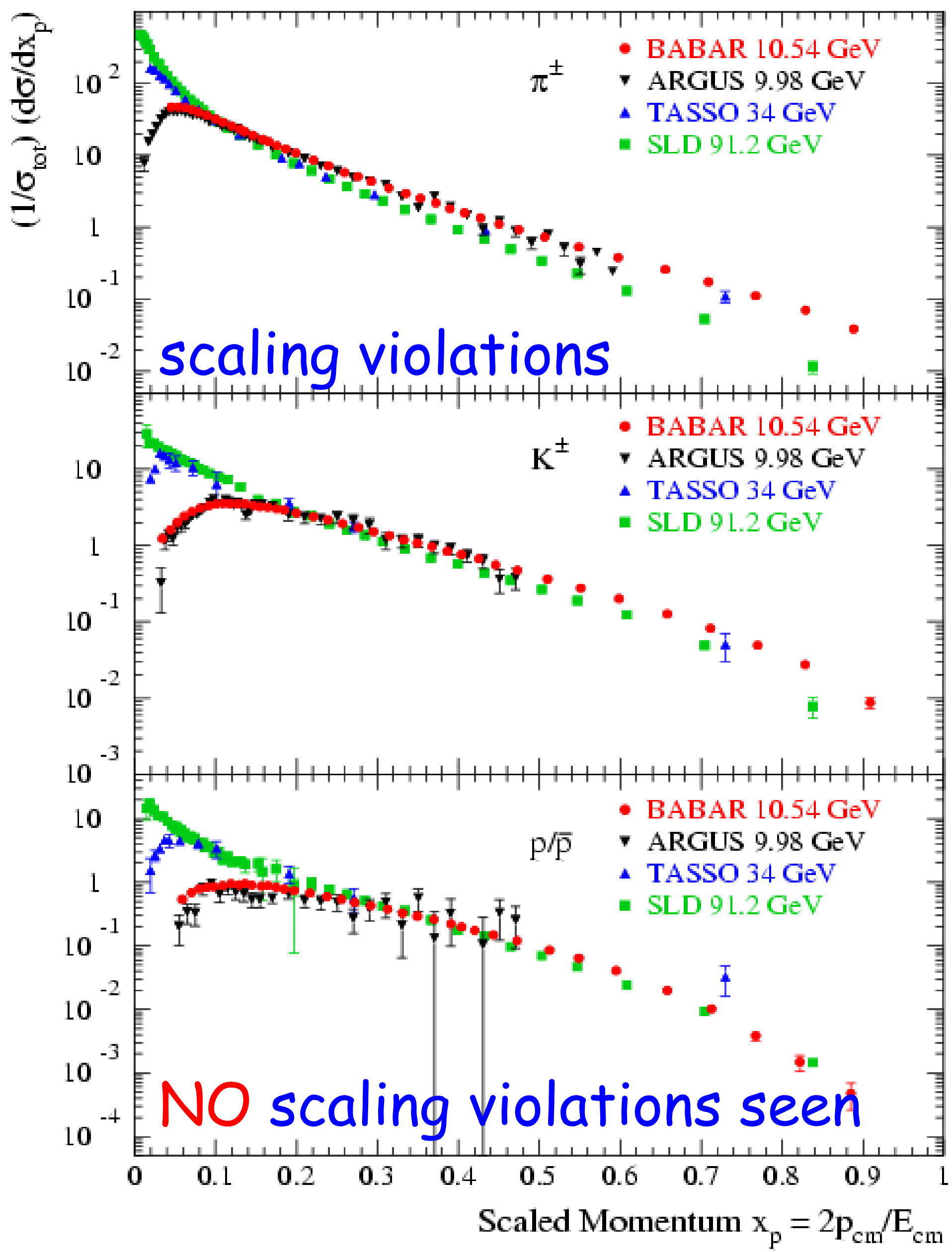


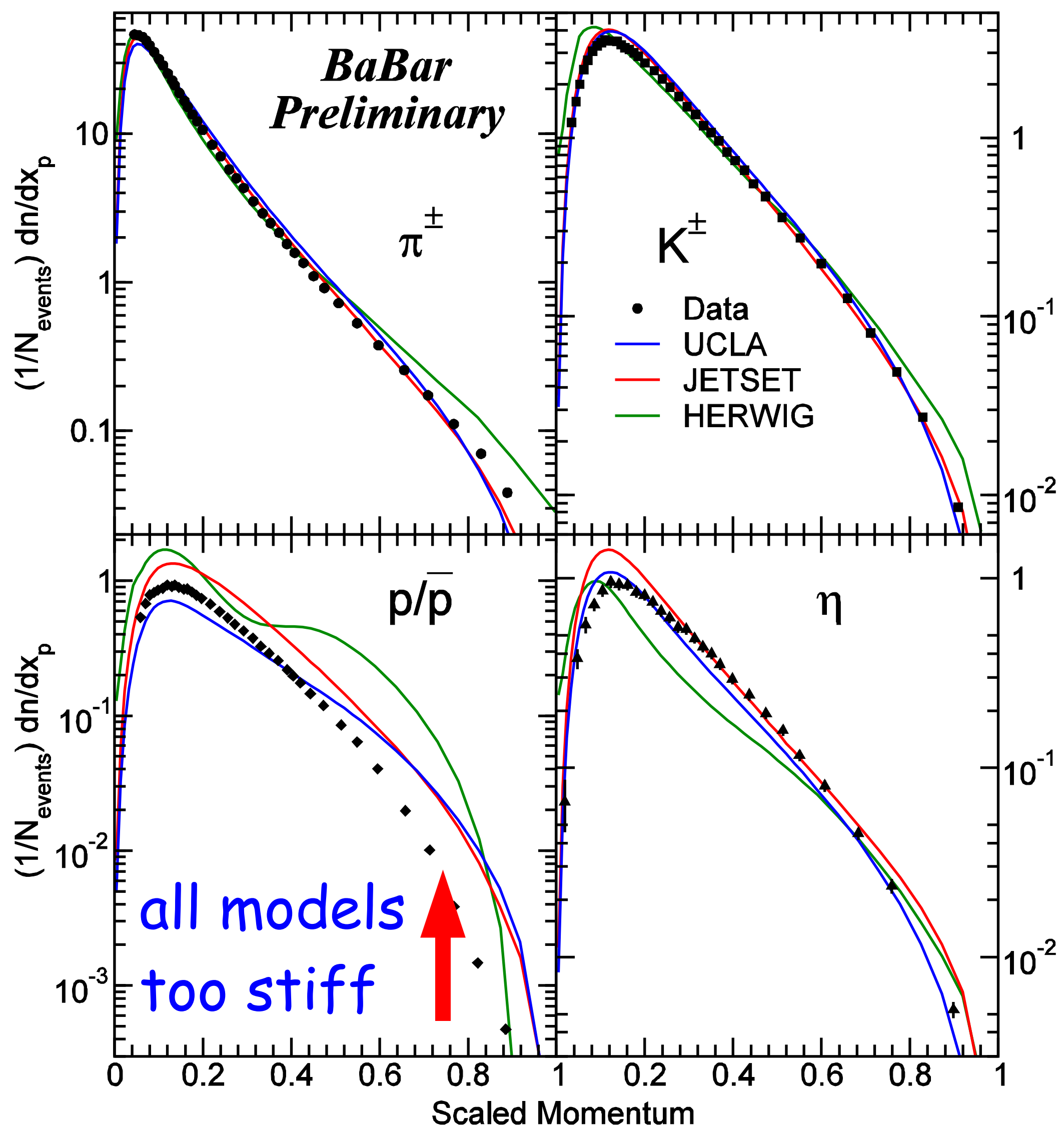
leading particles

$$\Delta = (D_q^h - D_{\bar{q}}^h) / (D_q^h + D_{\bar{q}}^h)$$



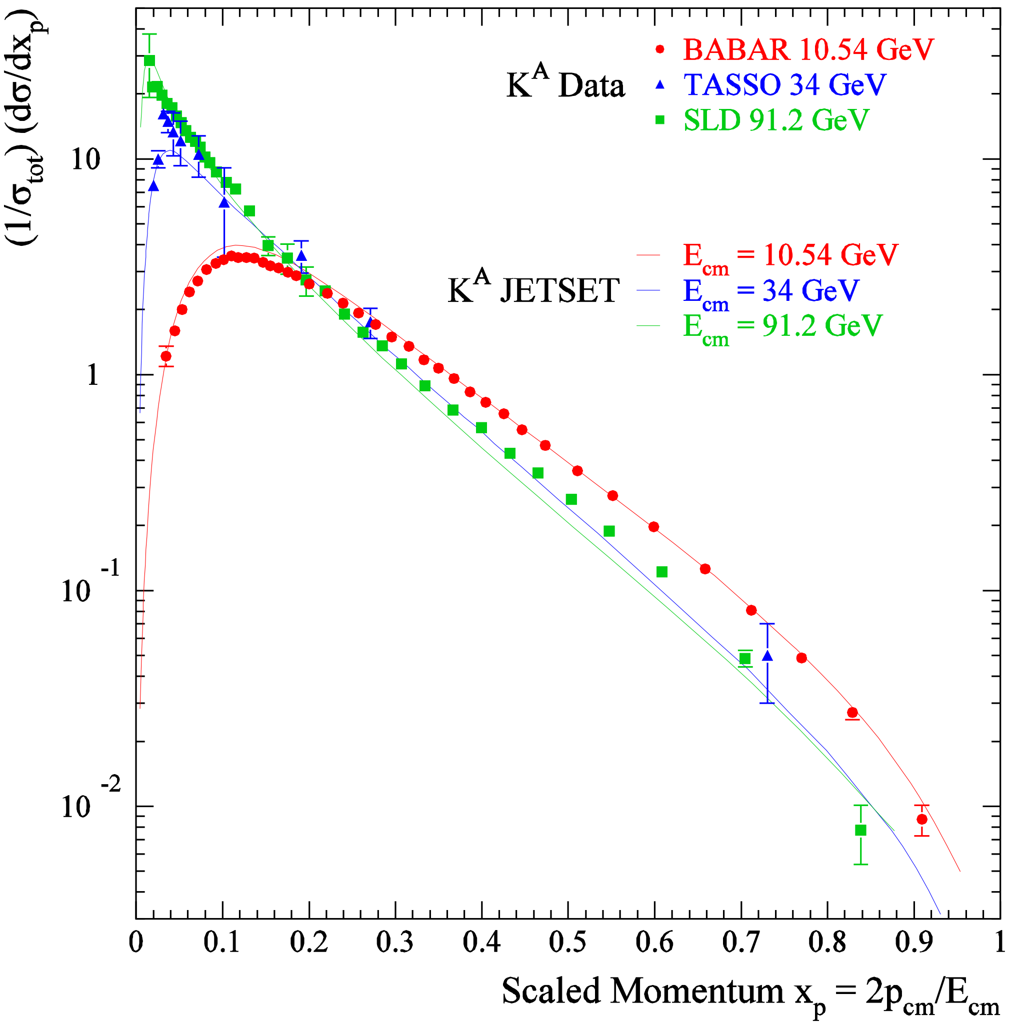
Identified Hadrons from BaBar ($E<Y_{4s}$)

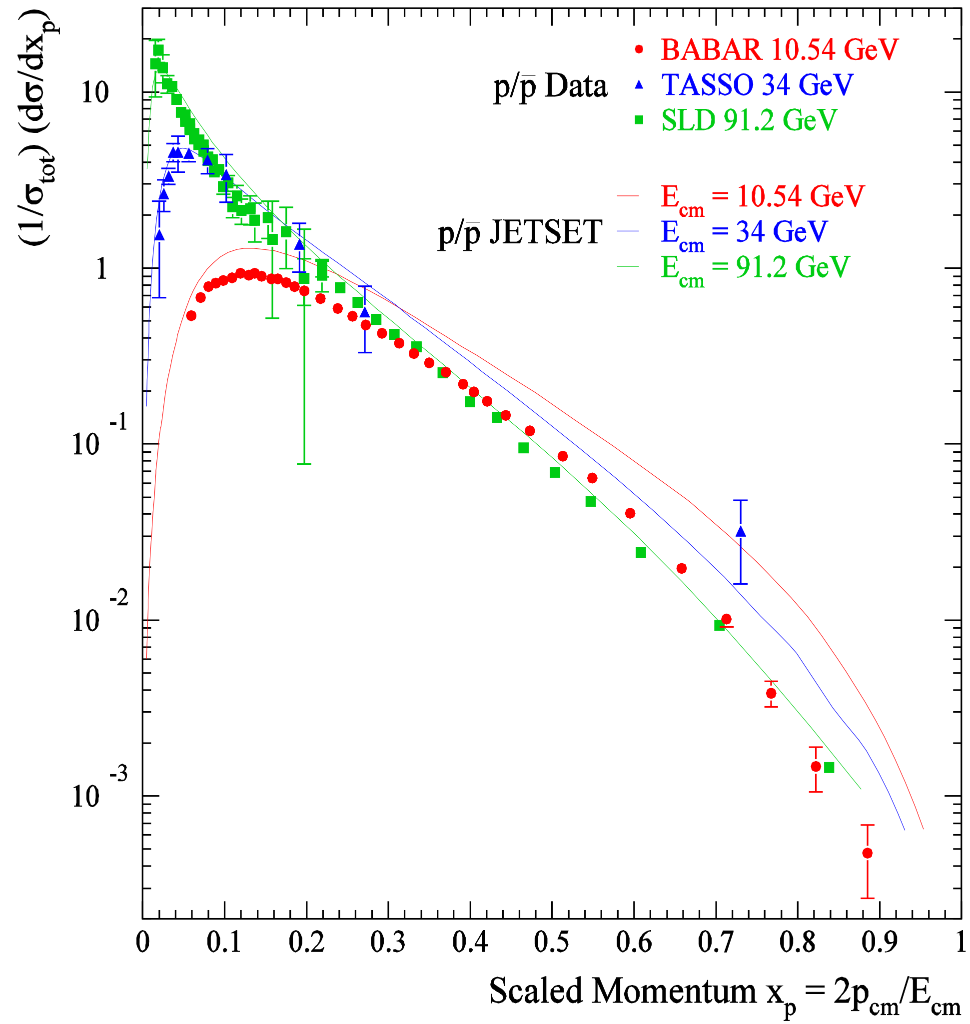




protons badly described (why) !

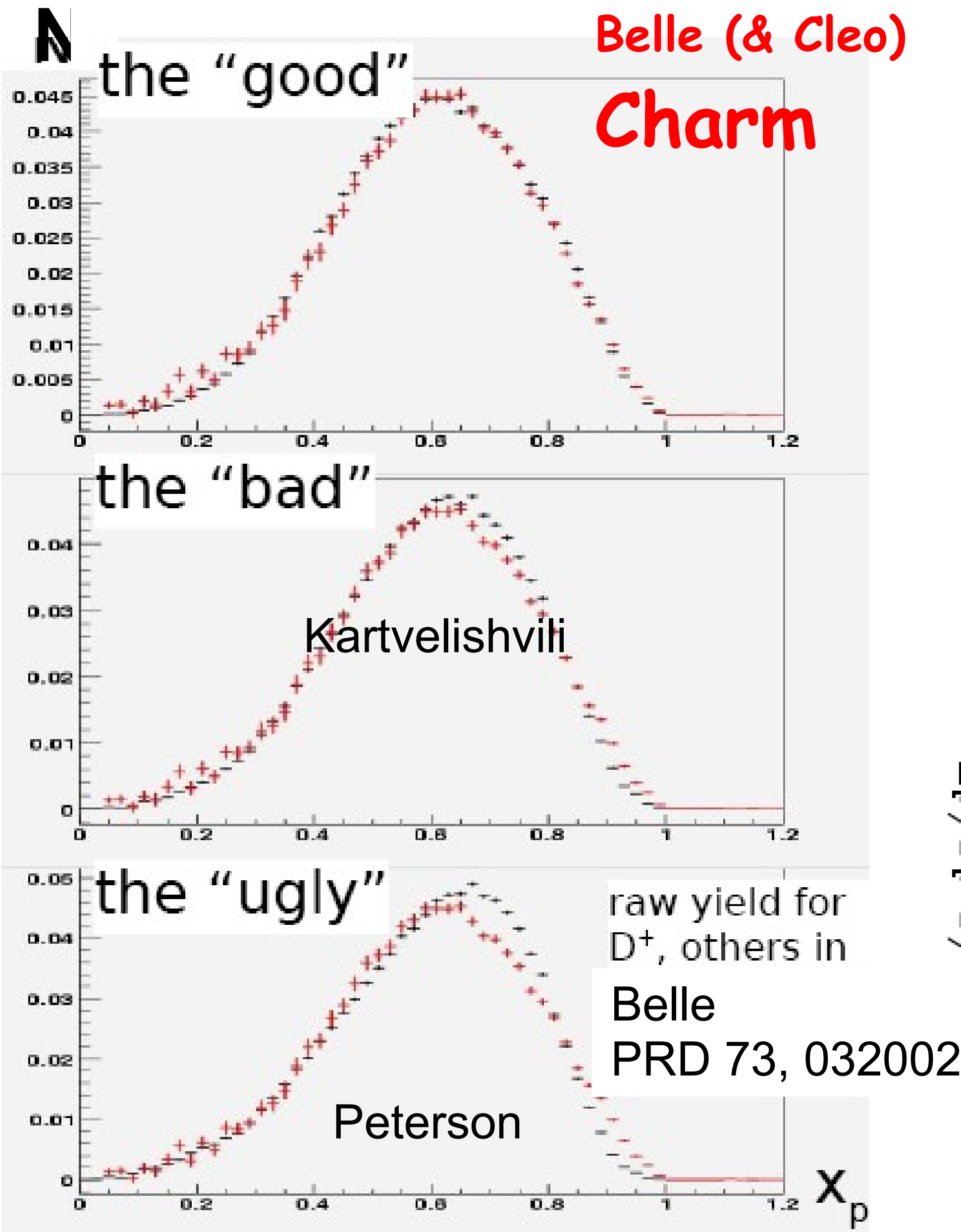
Inclusive Charged Hadrons E-Dep.





Models describe energy evolution (*10) for mesons but fail for protons

Heavy Quark Fragmentation



Belle (& Cleo)

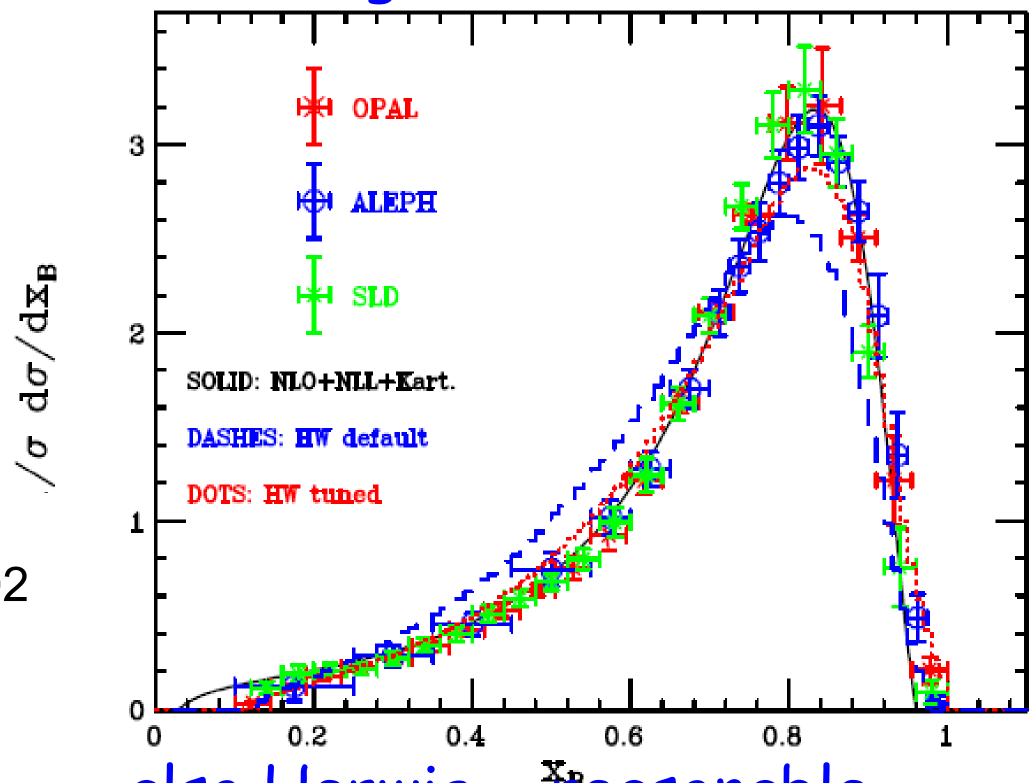
Charm

Pythia --- Bowler FF best:

$$f(z) = \frac{N_B}{z^{1+bm^2}}(1-z)^a \exp\left(\frac{-b\, m_t^2}{z}\right)$$

(a|b)=(0.12|0.58) χ^2/nf.=188/60

Similar findings from SLD/LEP for b fragmentation



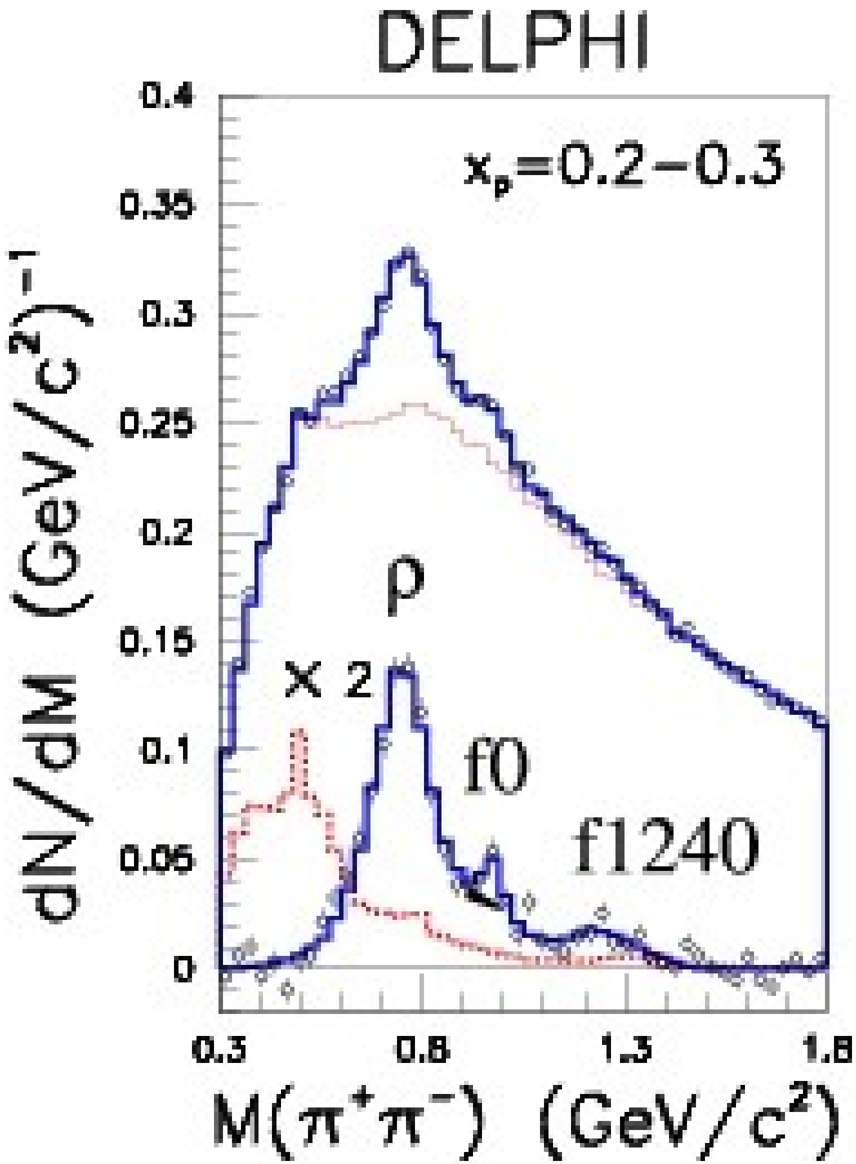
also Herwig ~ reasonable

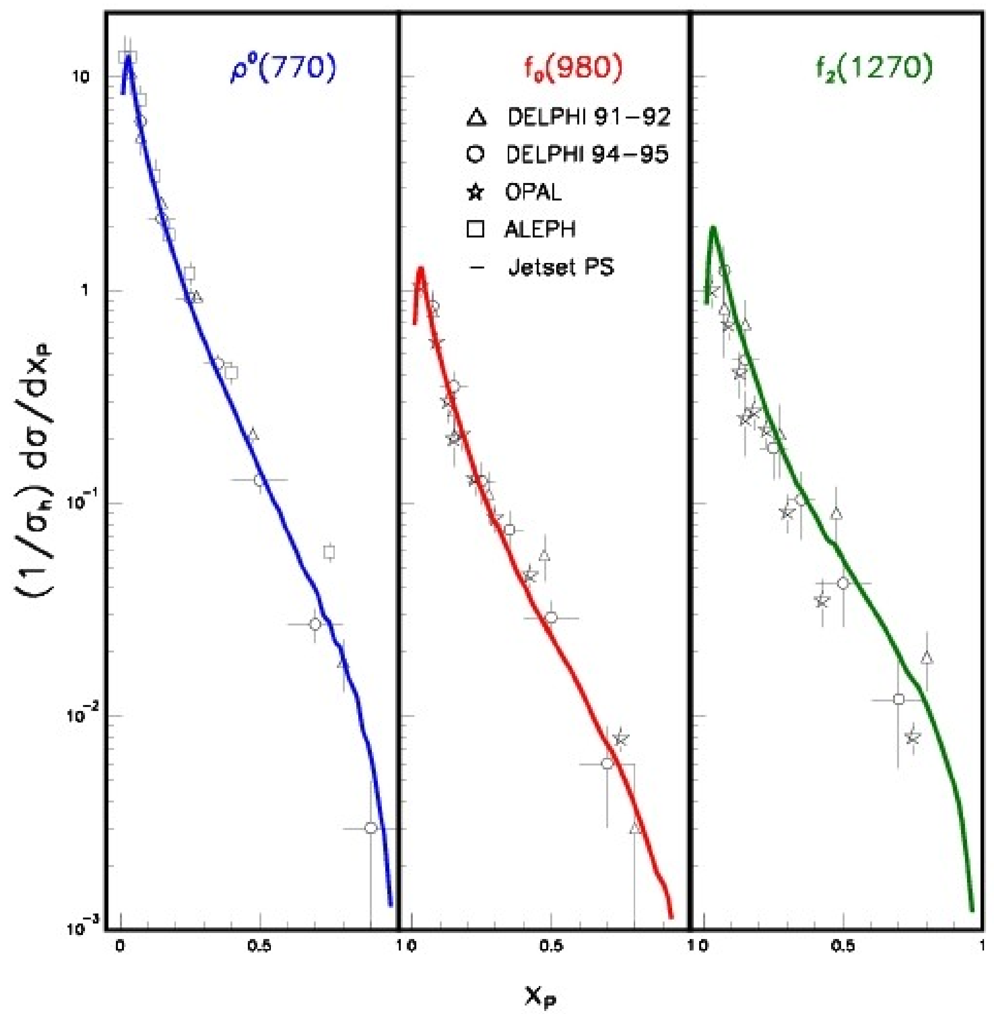
Heavy Quark Resonances

pseudoscalar/vector/higher resonance (**) ratios

- b
  V/(V+P)~3/4 (spin counting expectation)
  N(B**)/N(B)~30%
- c
  V/(V+P)~0.6
  many clear D** states seen at B-factories
- Compare model fits for light quarks
  P:V:(**) ~ 1:1:1 (V: tiny pref. long. polar.)

Resonances – Light Flavours





Abundant production of hadron resonances, also L=1 not expected in string fragmentation

Rates: Data vs. Models

Particle	LEP measured	Pythia	Herwig
charged	20,9±0,24	20,800	20,900
π^0	9,2±0,32	9,800	9,800
$\pi^{\pm}$	8,5 ± 0,1	8,550	8,800
K^0	1,025±0,013	1,090	1,040
K^+	1,115±0,03	1,120	1,060
$\eta+\eta'$	1,2±0,09	1,190	1,160
p	0,49±0,05	0,485	0,390
Λ	0,186±0,008	0,175	0,184
Δ^{++}	0,064±0,033	0,0800	0,0770
$\Xi(1530)^0$	0,0055±0,0006	0,0035	0,0125

General rates are well described (HERWIG !)

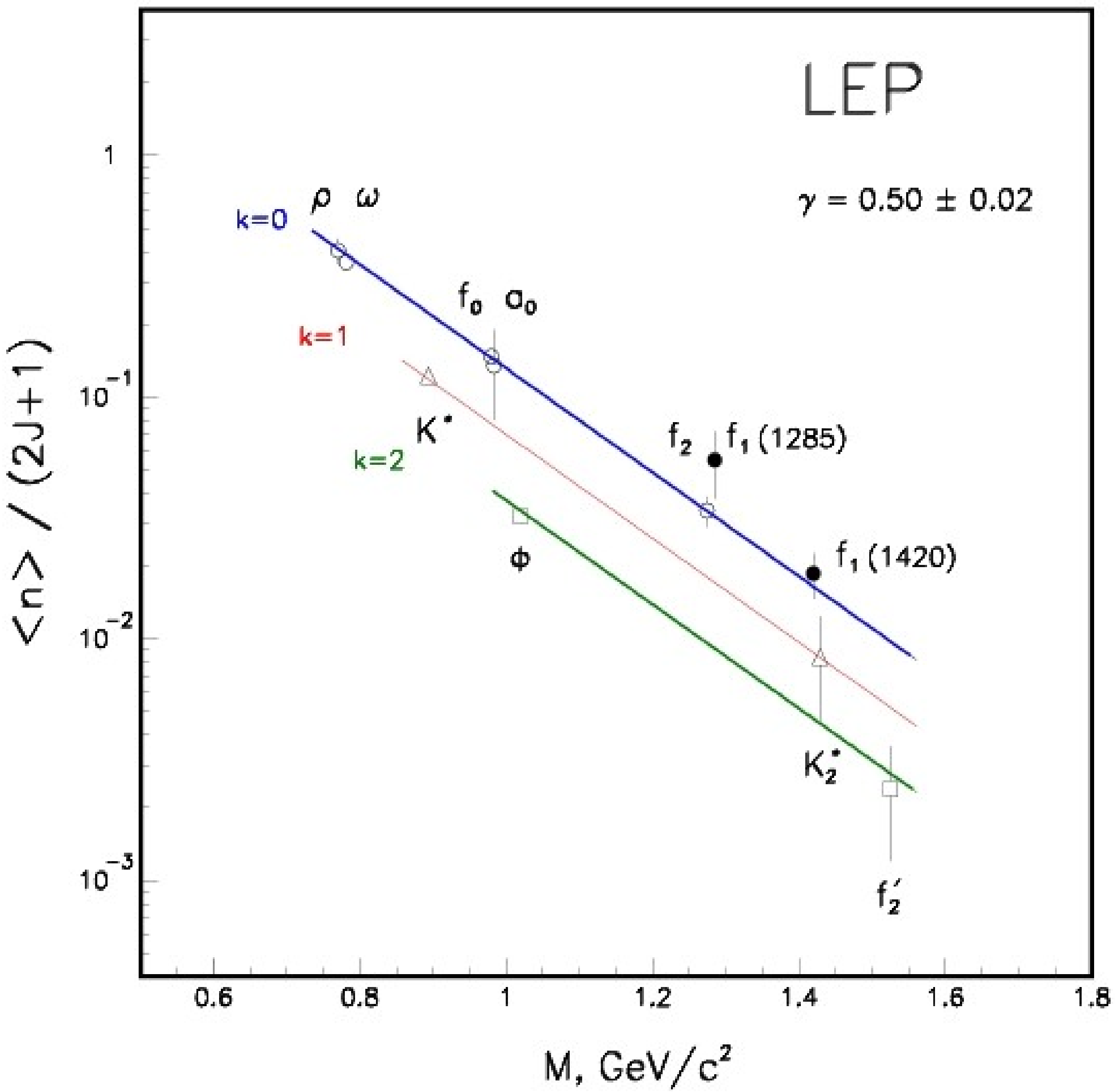
Rates: Data vs. Models

Particle	LEP measured	Pythia	Herwig
f^0	0,146±0,012	0,160	-
ρ^0	1,23±0,1	1,270	1,430
K^{*0}	0,369±0,012	0,390	0,370
K^{*+}	0,357±0,039	0,390	0,370
ω	1,016±0,065	1,320	0,910
φ	0,0963±0,0032	0,107	0,100
$f_2(1270)$	0,25±0,08	0,290	0,260
$K^*_2(1430)0$	0,095±0,035	0,075	0,079
$f'_2(1525)$	0,0224±0,0062	0,026	0,030
$\Lambda(1520)$	0,0225±0,0028	0	"0"

O(30%) of light quark primary mesons have L=1

Mass splitting for baryon smaller --> similar baryonic states?

Rates - Light Flavour Resonances



Phenomomenological parametrisation of meson rates:

$$\frac{\langle n \rangle}{(2J+1)} \propto \gamma^{k} \cdot e^{-b\,M}$$

- γ ~ 0,5 b~5/GeV

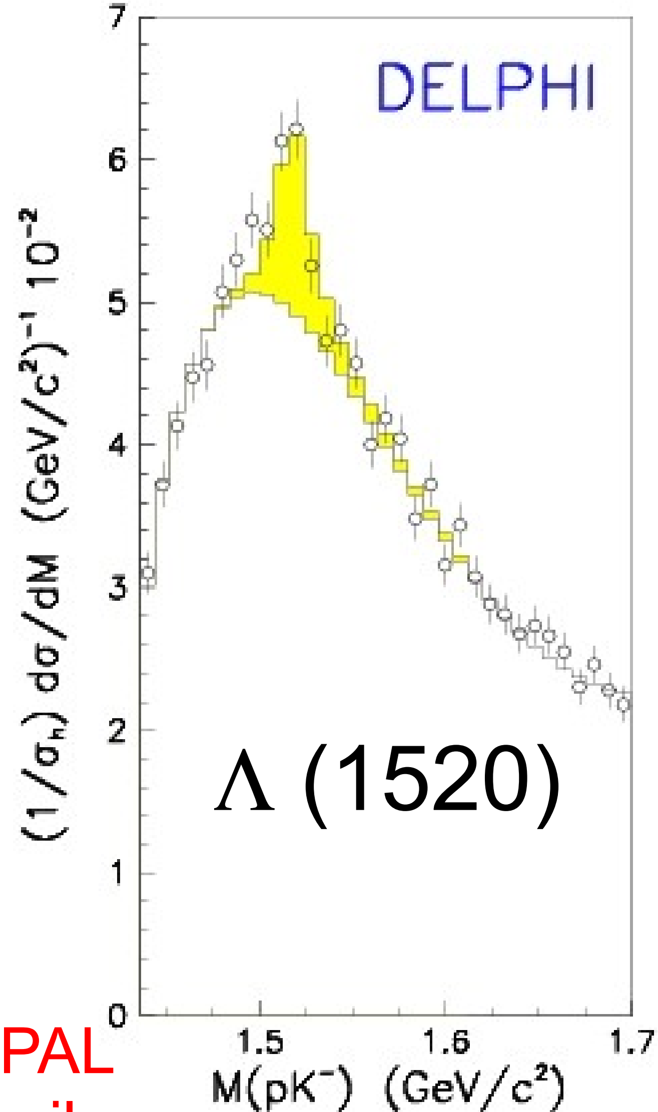
k # s-q´s J spin

suggests:

- democratic production of spin states
- production of higher mass resonances

Baryon Resonances ?

Baryon resonances (L>0) difficult to observe, exception, $\Lambda(1520)$

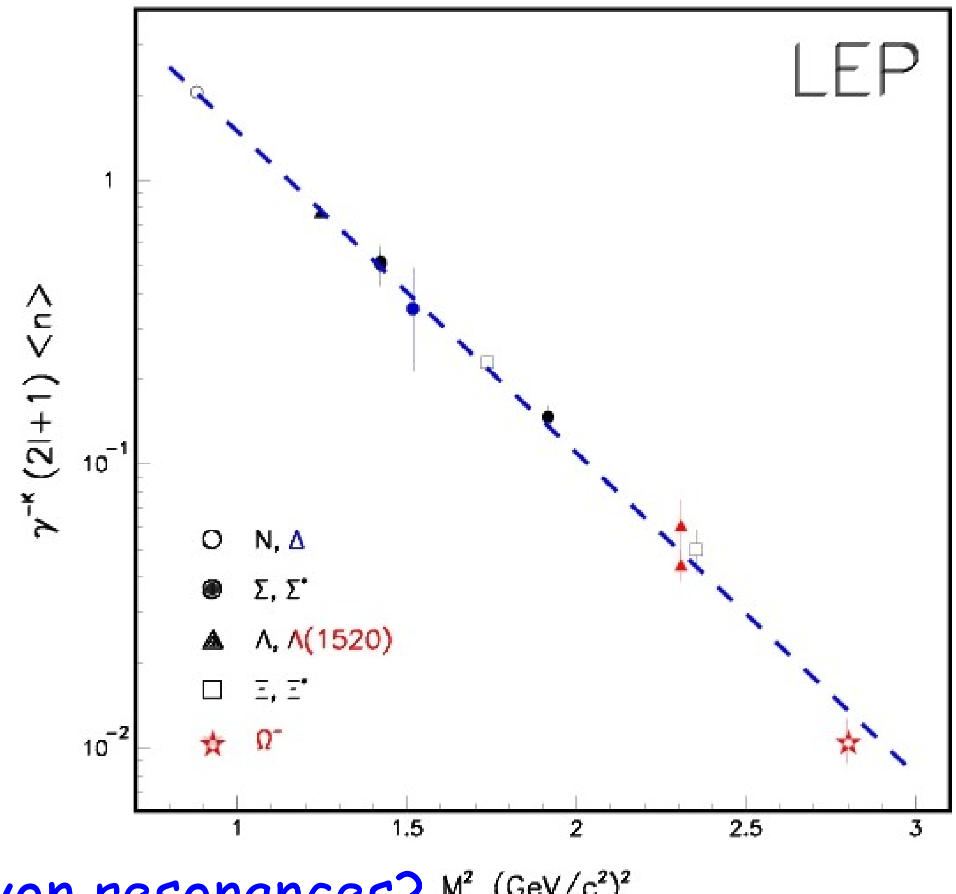


OPAL similar

Similarly simple parametrisation for baryons

$$(2I+1)\langle n\rangle \propto \gamma^{k}\cdot\exp - bM^{2}$$

**2!



Baryon resonances?

Influence on proton rate at low E ?

Direct Soft Photons

expect ~0.02 γ per jet from Bremsstrahlung from hadrons (soft, small angle)

observe 4-6 times more

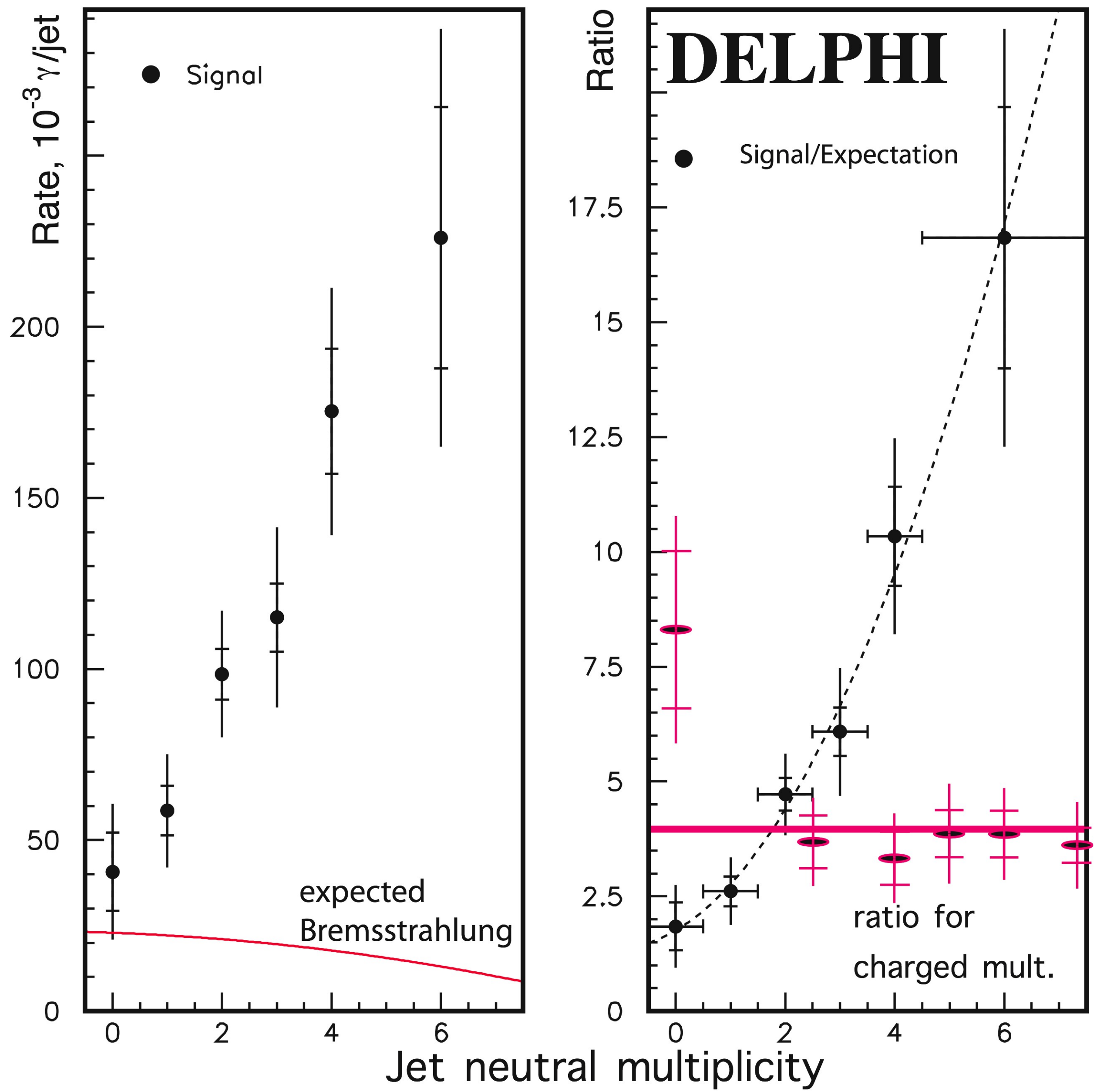
new result:
γ multiplicity proportional to # of neutral hadrons

meson dipole moment

$$\vec{d} = \sum_{i=1}^{2} q_i \vec{r}_i$$ q quark charge

$$\vec{d}^{\,2}_{neutral} \approx 10 \cdot \vec{d}^{\,2}_{charged}$$

γ´s may stem from quarks!
-> see through hadronisation.

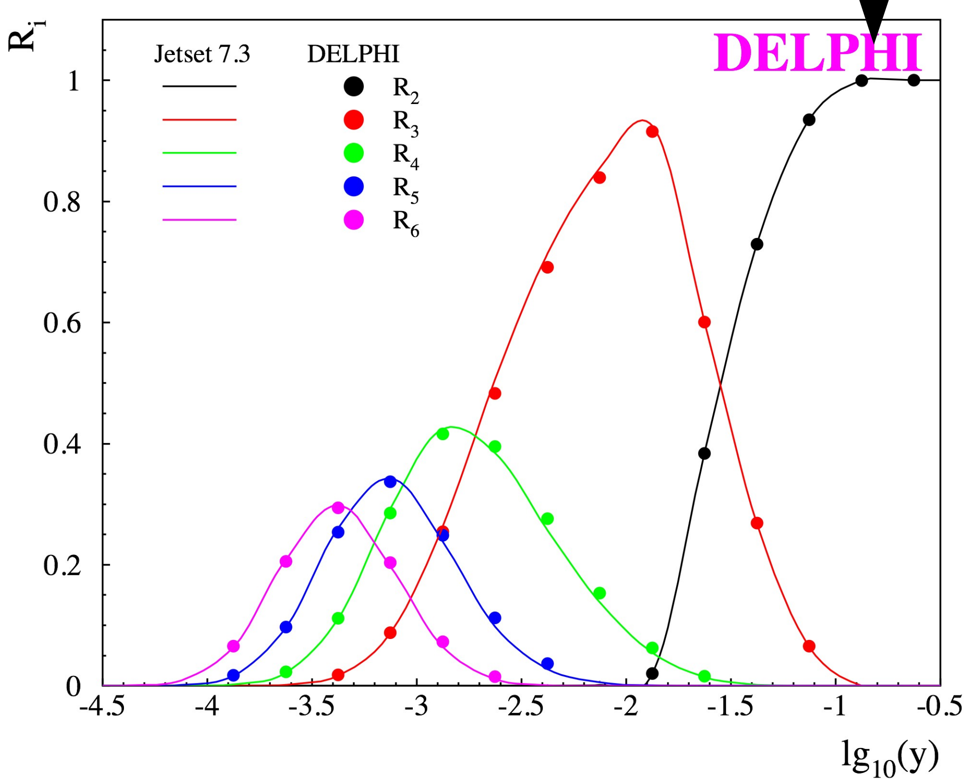


Compare Gluon vs. Quark Splitting Kernels

relate e+e- jet rates / Sudakovs

$$R_2 = \Delta_q^2(y)$$

$$\Delta_q(y) = \exp - \int_{y_0}^{y} dy' \, \Gamma_q(y, y')$$

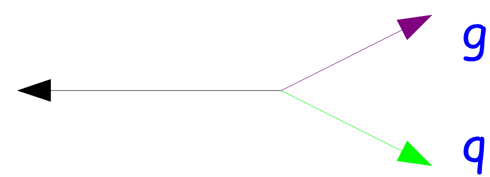


Kernels

$$\Gamma_{q\to qg}(Q,q) = \frac{2C_A}{\pi} \frac{\alpha_s(q)}{q} \ln\left(\frac{Q}{q} - \frac{3}{4}\right)$$

$$\Gamma_{g\to gg}(Q,q) = \frac{2C_A}{\pi} \frac{\alpha_s(q)}{q} \ln\left(\frac{Q}{q} - \frac{11}{12}\right)$$

$$\Gamma_{q\to qg}(Q,q) = \frac{2n_f T_F}{3\pi} \frac{\alpha_s(q)}{q}$$



Similarly apply strategy to single gluon and quark jets in 3-jet events

$$R_1^g = \Delta_g(y) \qquad R_1^q = \Delta_q(y)$$

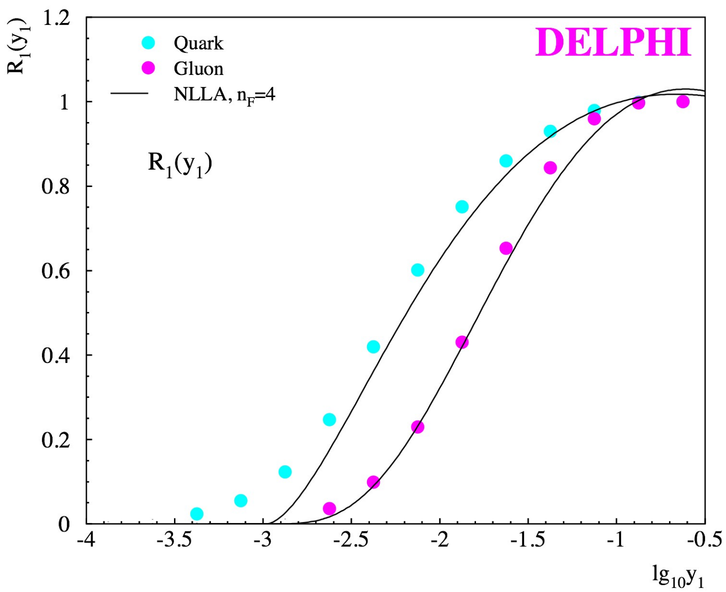
Compare g vs. q Jet Rates/Splitting Prob.

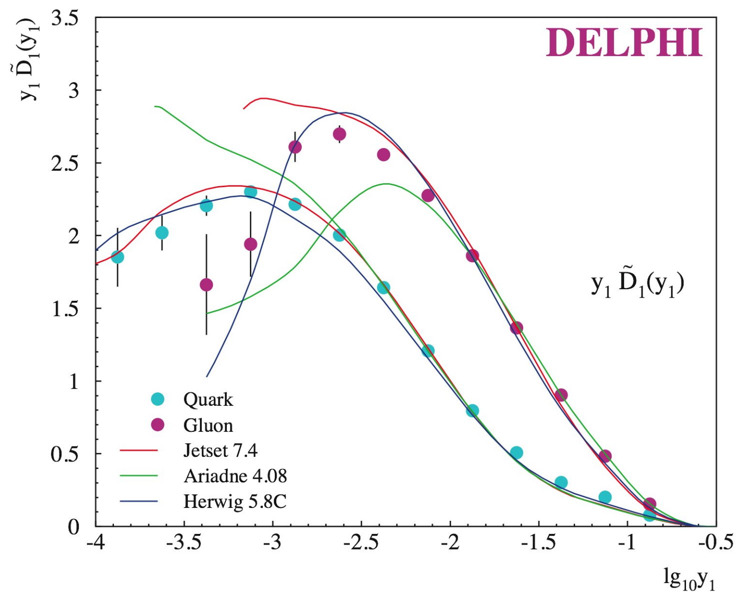
$$R_1(y) = \frac{N_1(y)}{N_{tot}}$$

%tage of non-split jets

$$\tilde{D}_1(y) = \frac{1}{N_1(y)} \cdot \frac{\Delta N_1(y)}{\Delta y}$$

~ differential splitting probability





gluons split “earlier” (high y)

$$R_1^{q/g}(y) = \Delta^{q/g}_{experim.}(y)$$

quarks take over at small y

described ok by models

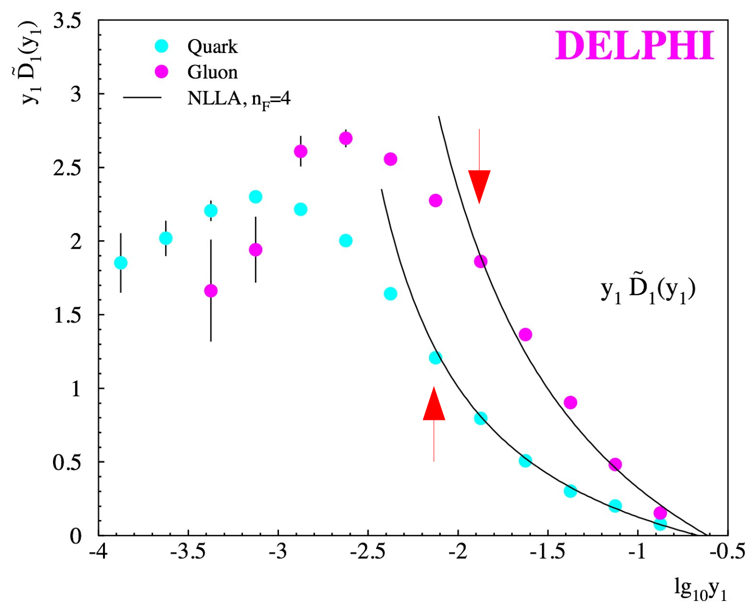
Compare g vs. q To NLL Splitting Kernels

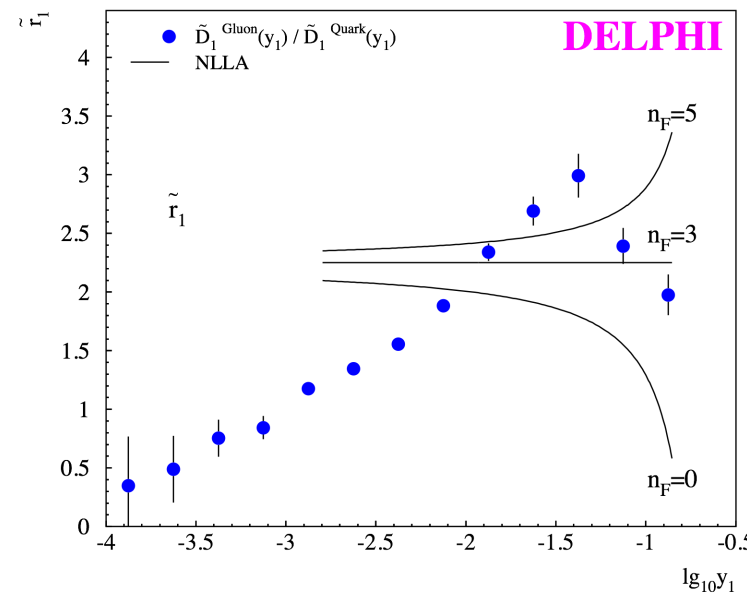
$$\tilde{D}_1^g(y) \simeq \Gamma_{g\to gg} + \Gamma_{g\to q\bar{q}}$$

$$\tilde{D}_1^q(y) \simeq \Gamma_{q\to qg}$$

splitting probability = kernel

$$\frac{\tilde{D}_1^g(y)}{\tilde{D}_1^q(y)} \simeq \frac{\Gamma_{g\to gg} + \Gamma_{g\to q\bar{q}}}{\Gamma_{q\to qg}}$$





C_A/C_F

Gluons deviate "earlier" (bigger y) from NLL expectation than quarks

Hadronisation sets in "earlier" for g than q

Reason:

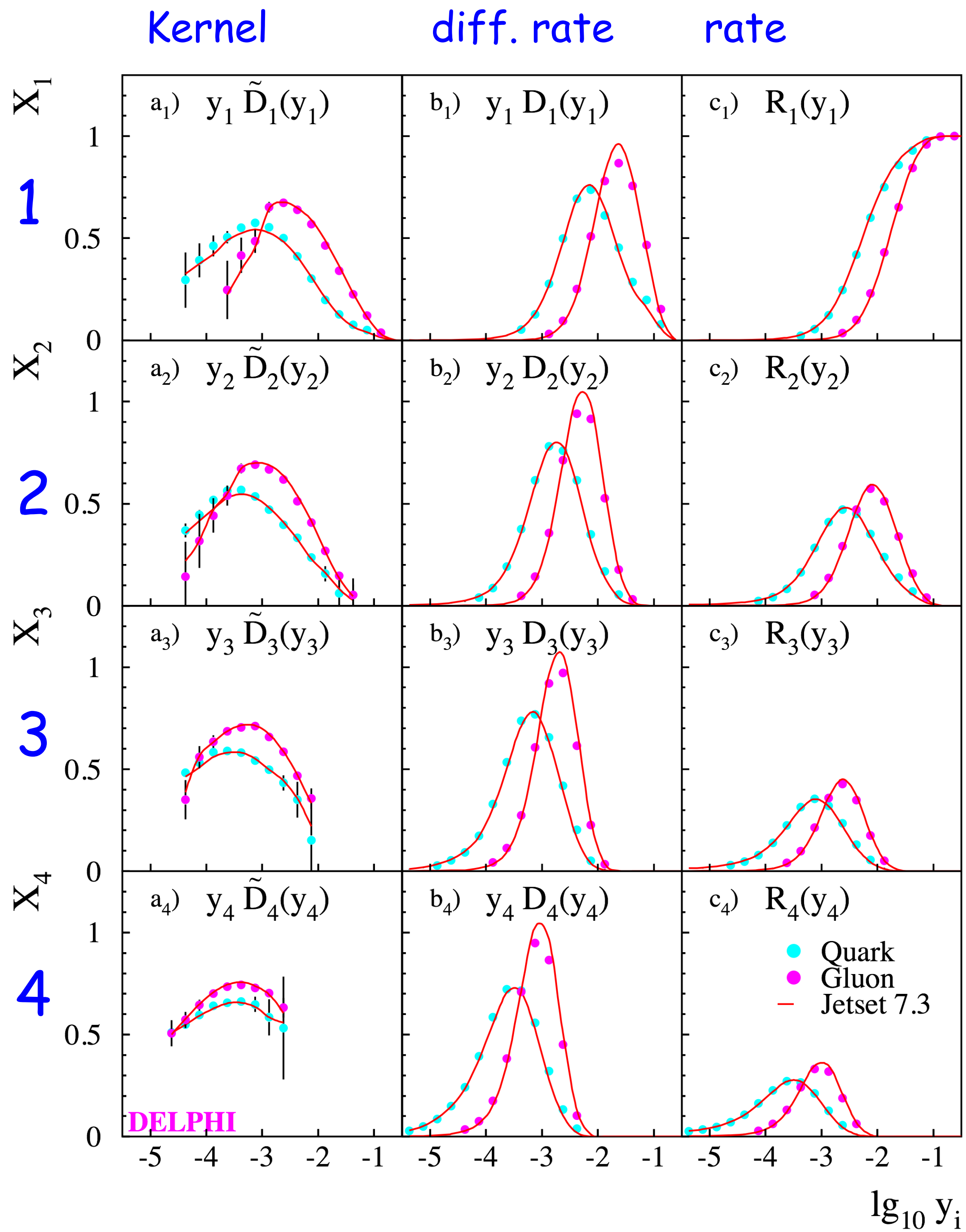
=> quarks are valence particles

=> E-conservation

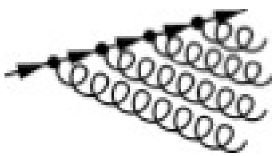
Compare g vs. q higher splittings

Gluons split "earlier" but quarks keep up later

g & q jet splitting probability about equal for high splittings



g to q Ratio



Exp. confirm PS picture

All jets dominated by gluon radiation

Expect differences (beyond colour factor) only for leading particles

RATIO

Kernel

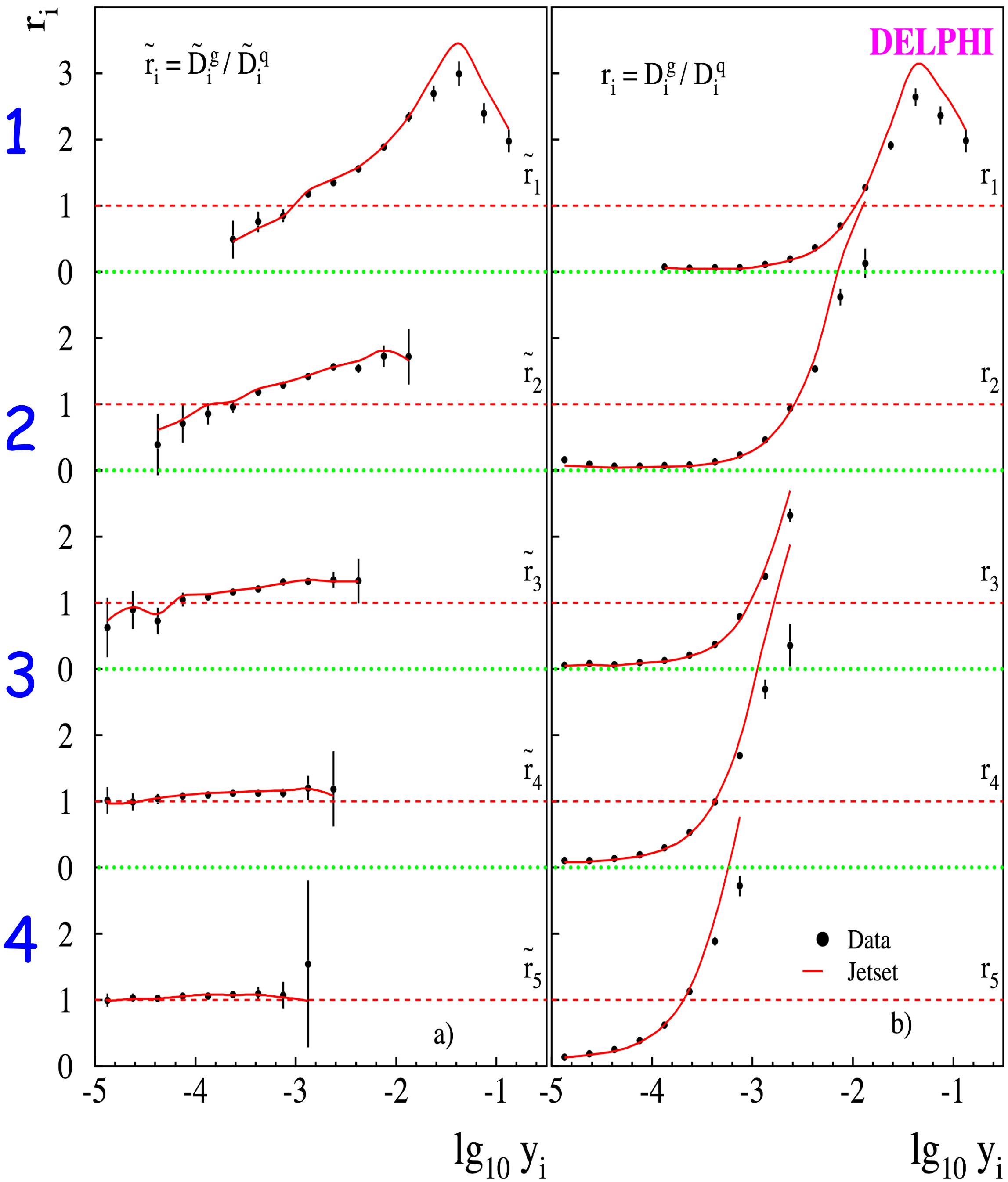
diff. rate

1

2

3

4

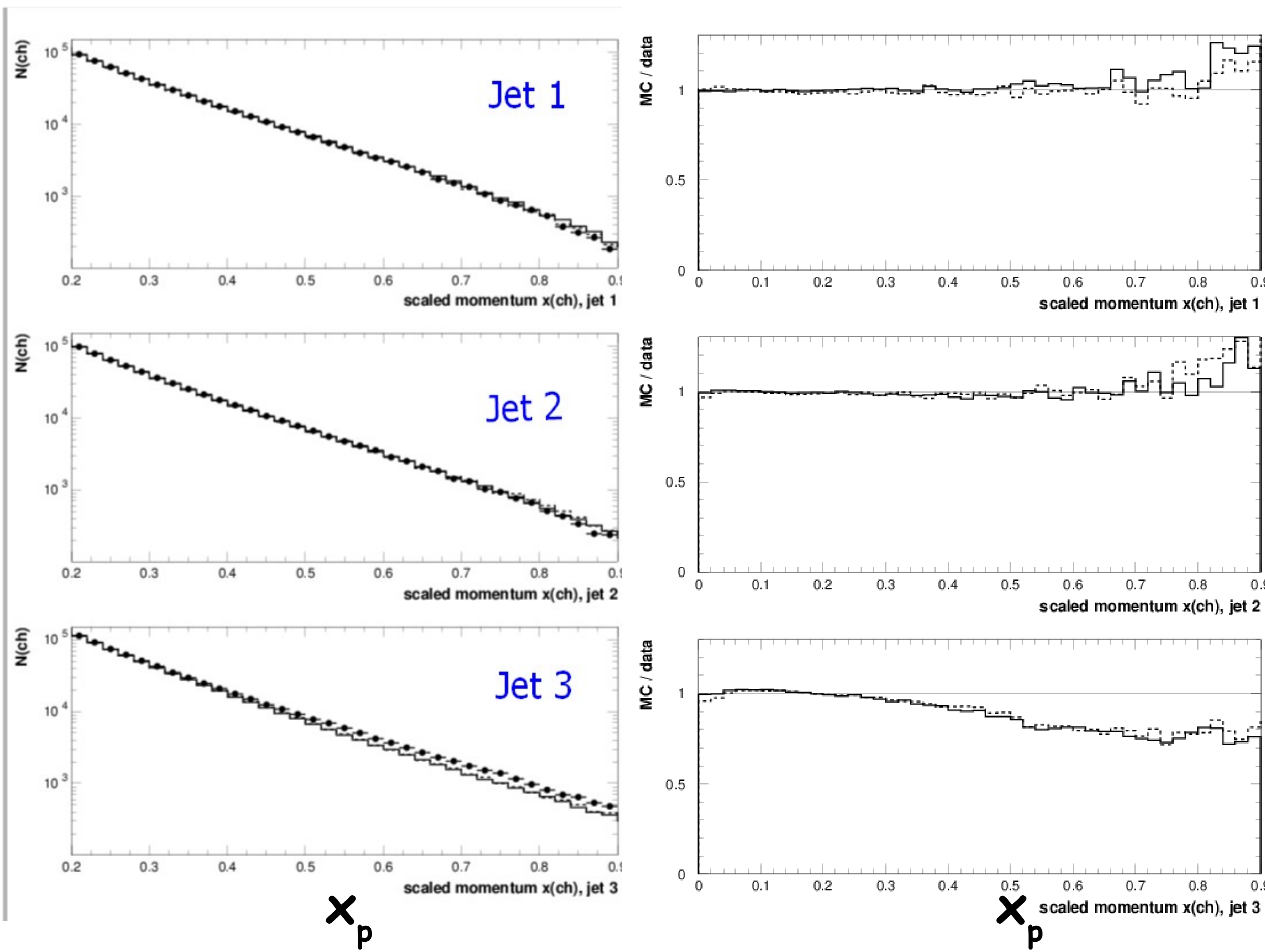


3 Jet Evts. -Gluon Fragmentation

ALEPH, preliminary :

3-jet evts (D,0.01) at $E_{cm}=M_Z$ of all topologies, photonic jets removed, =>890 000 evts.

energy-ordering $E_{jet1} > E_{jet2} > E_{jet3}$, Jet 3 is 71% gluon



Ratio MC/data

— JETSET

--- ARIADNE

MC low

at x > 0.4

why ?

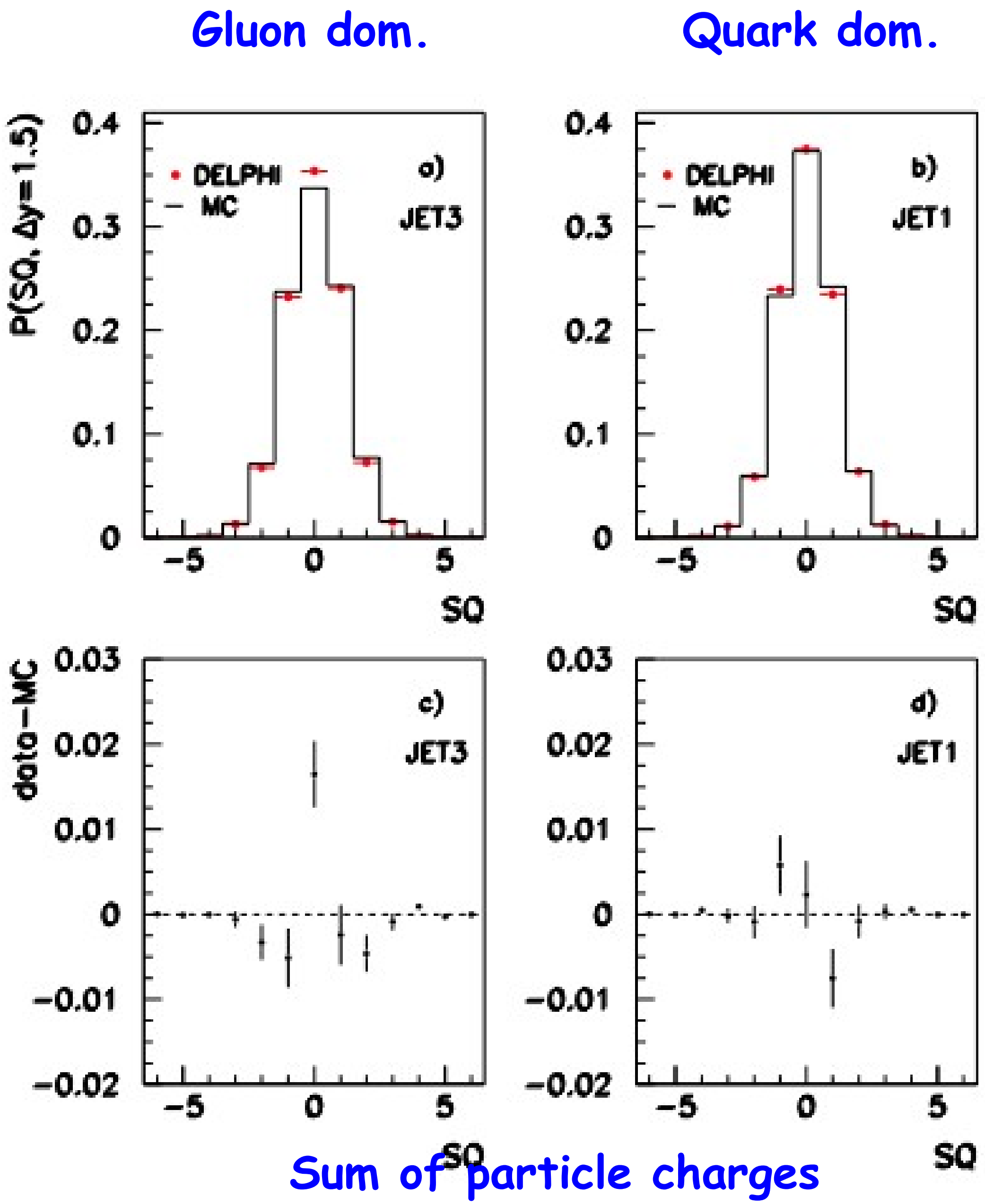
(overall small effect)

Delphi, Opal similar trend

Gluons

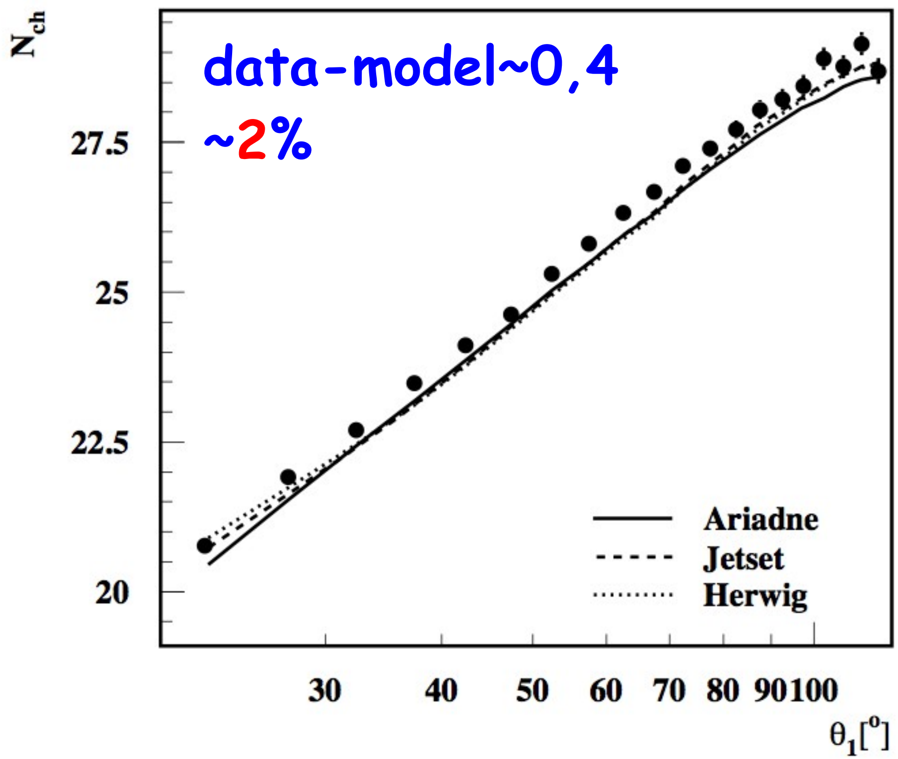
tiny excess (2%) of fast neutal systems cmp. to model

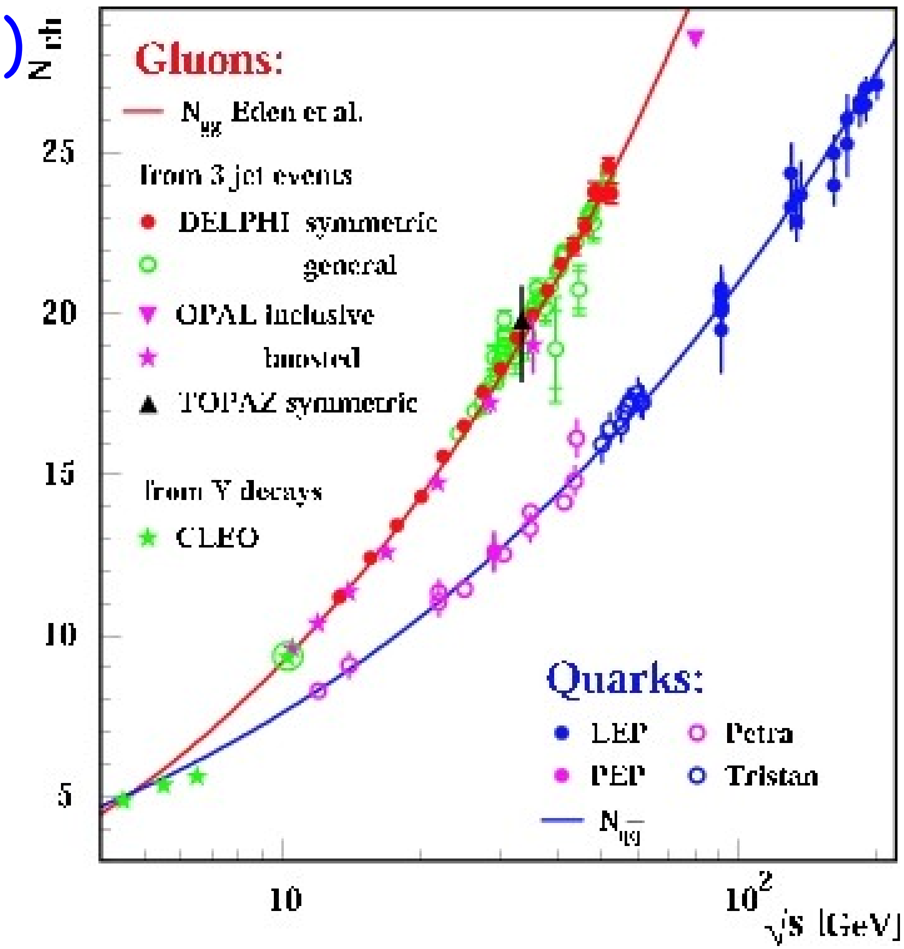
octett fragmentation ???



3 Jet Evts. -Gluon Fragmentation

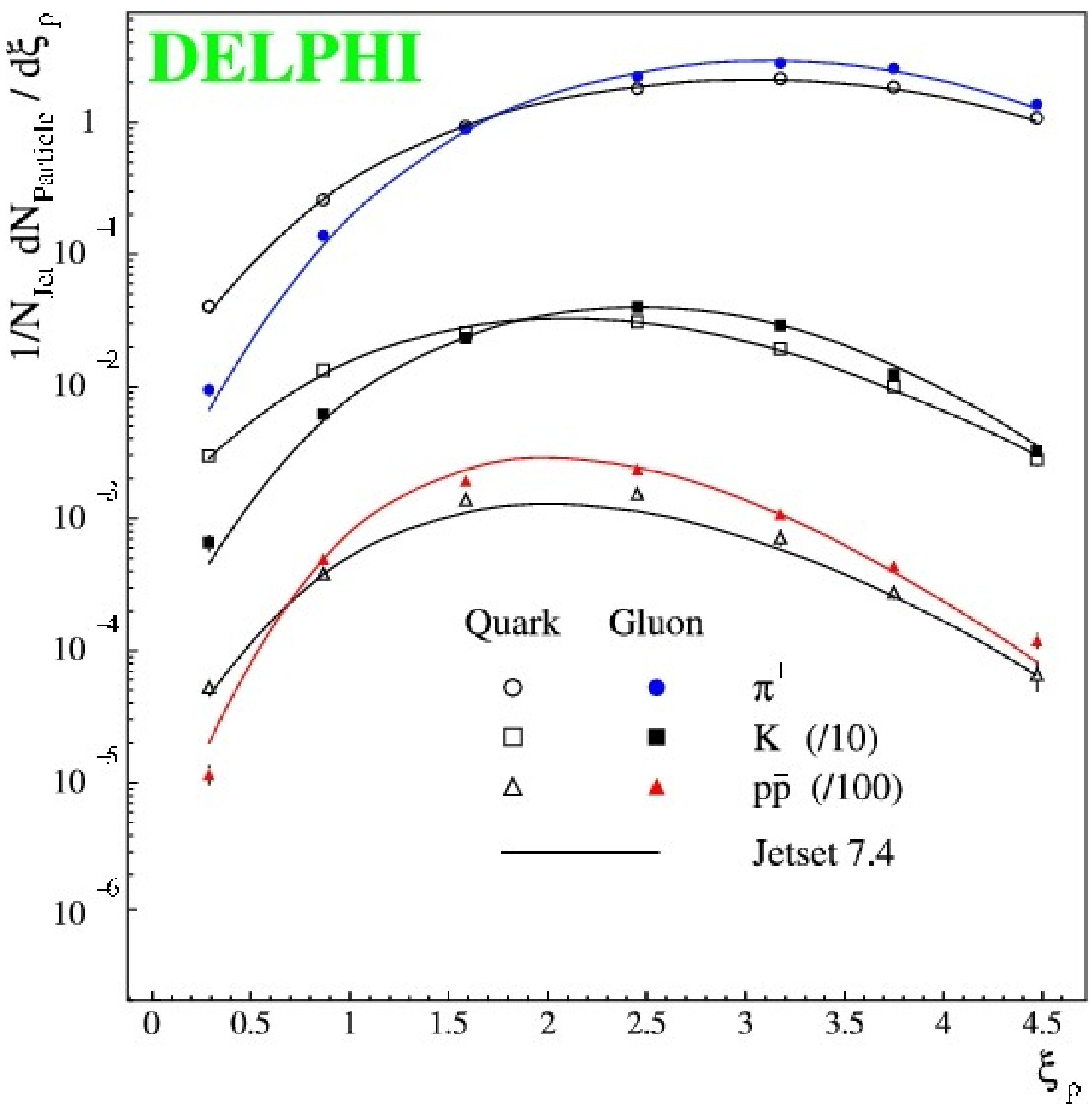
Topology dependence of (symm.)
3-jet event multiplicity





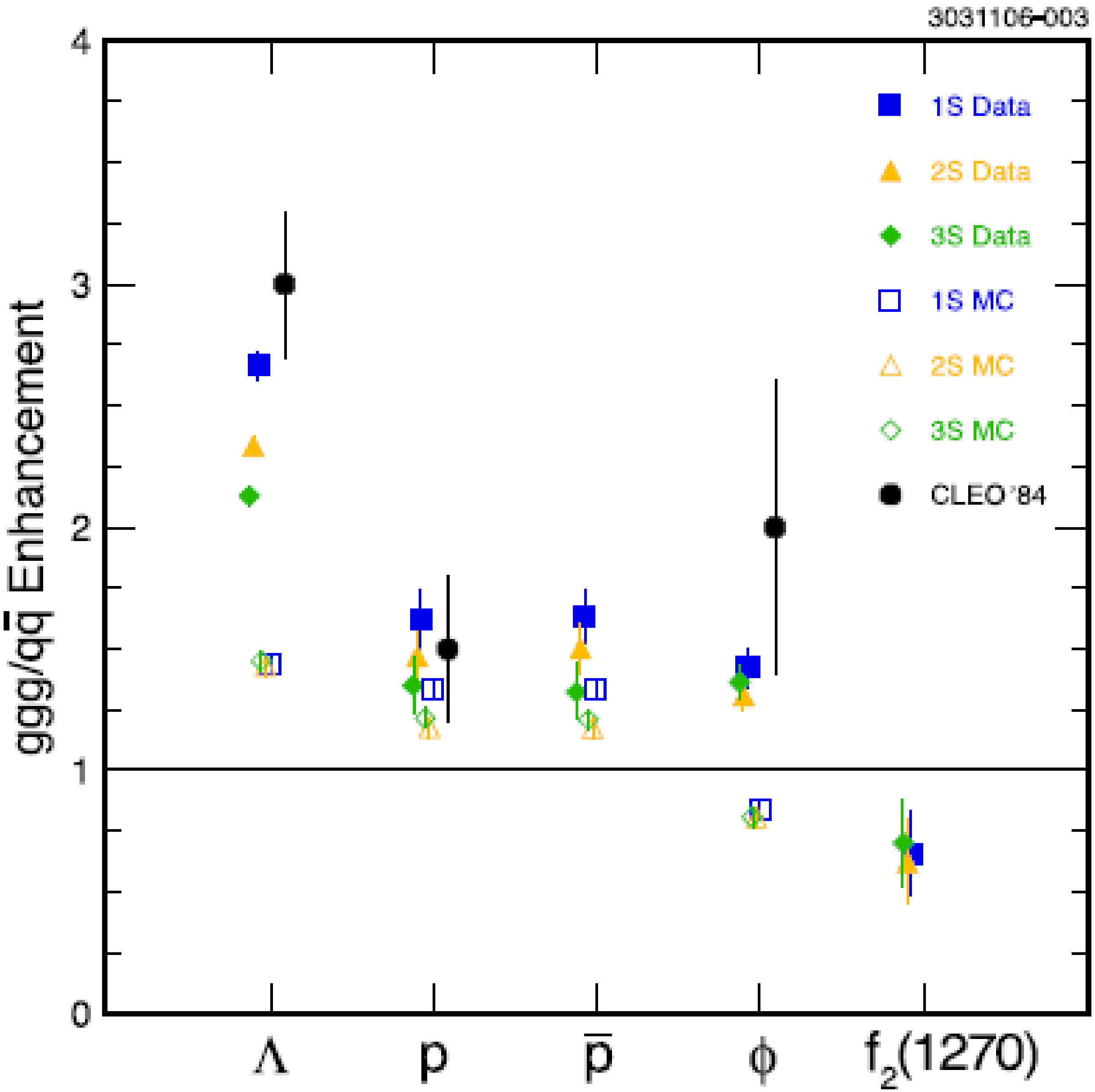
Gluon multiplicity very well described by analytic prediction
=> little room for qg differences (except leading particles)

Gluon Fragmentation Identified H´s



Models reasonably describe identified spectra

Gluon Fragmentation ggg vs. $q\bar{q}$



CLEO compares quarkonium -> ggg (or gg) vs. continuum qqbar

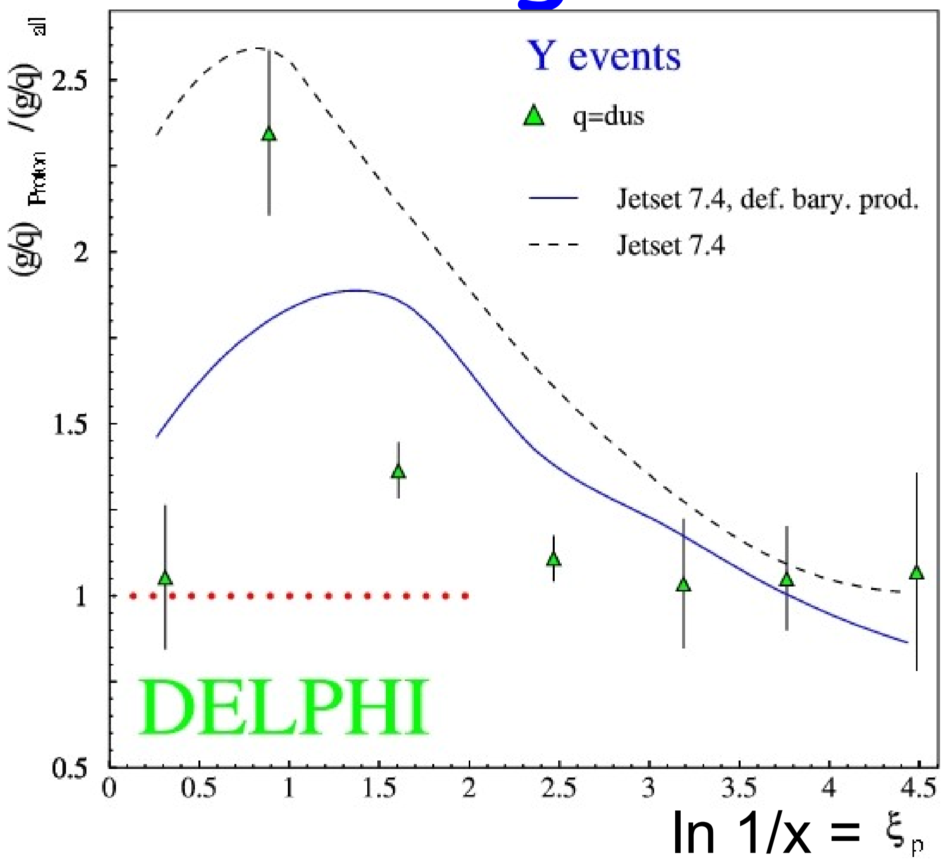
strong baryon (Λ ! why) enhancement

excess in gg decays is about $\frac{3}{4}$ of ggg case

baryon excess not concentrated at high x

φ enhancement not seen at LEP (why)

Gluon Fragmentation - Baryons

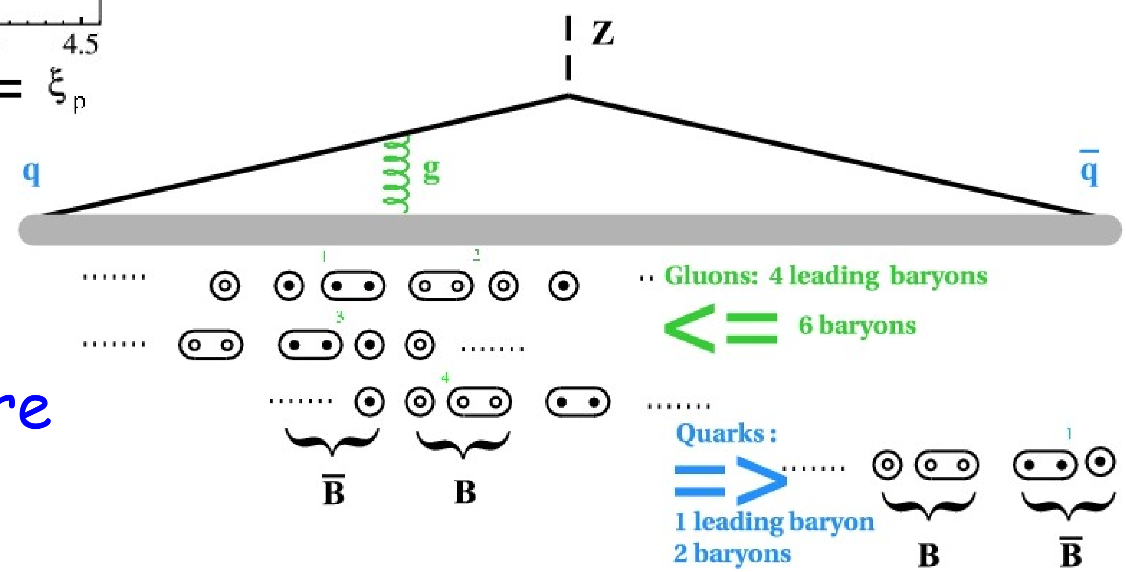


← double ratio

$(g/q)_{proton} / (g/q)_{all\ hadrons}$

baryon excess at CLEO
at small momentum
(but no double ratio shown)

Baryon excess understood
in string picture →



Cluster models would require
g-> $(qq)(\overline{qq})$ splitting !

Final State Interactions

Colour Reconnection

not discussed; cures ptout problem

Bose Einstein Correlation

- describe equal boson correlations.
- required for small (tiny) p_t description

Implemented as a classical "field"

in PYTHIA

- destroys energy-momentum-conservation
- rescaling (may) disturb shape distributions
  => "unphysical" PS parameters

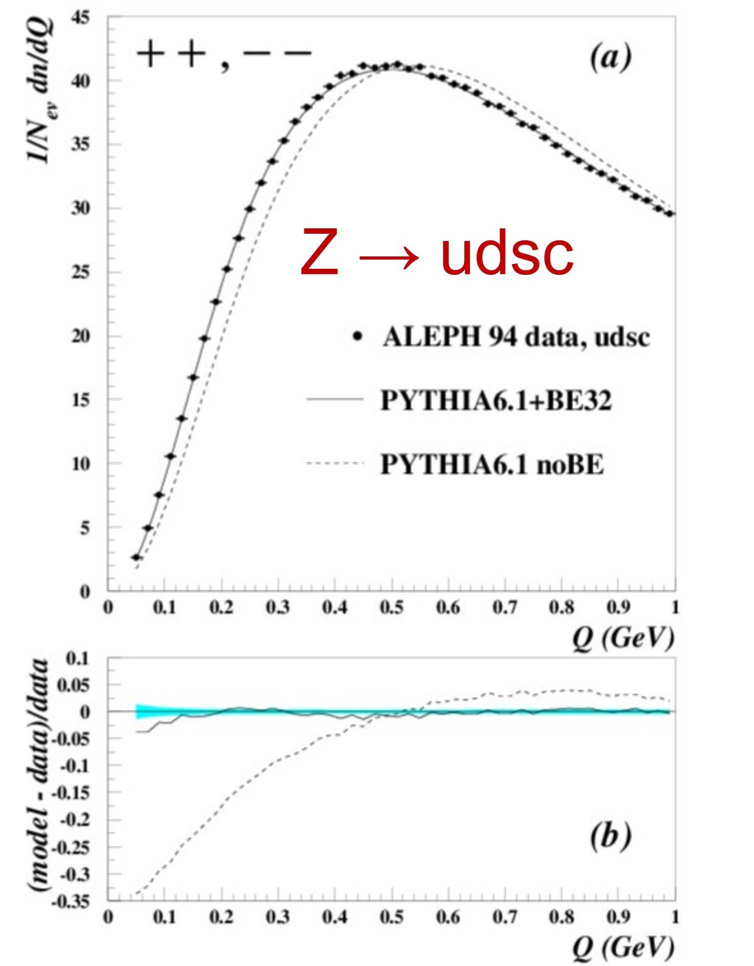
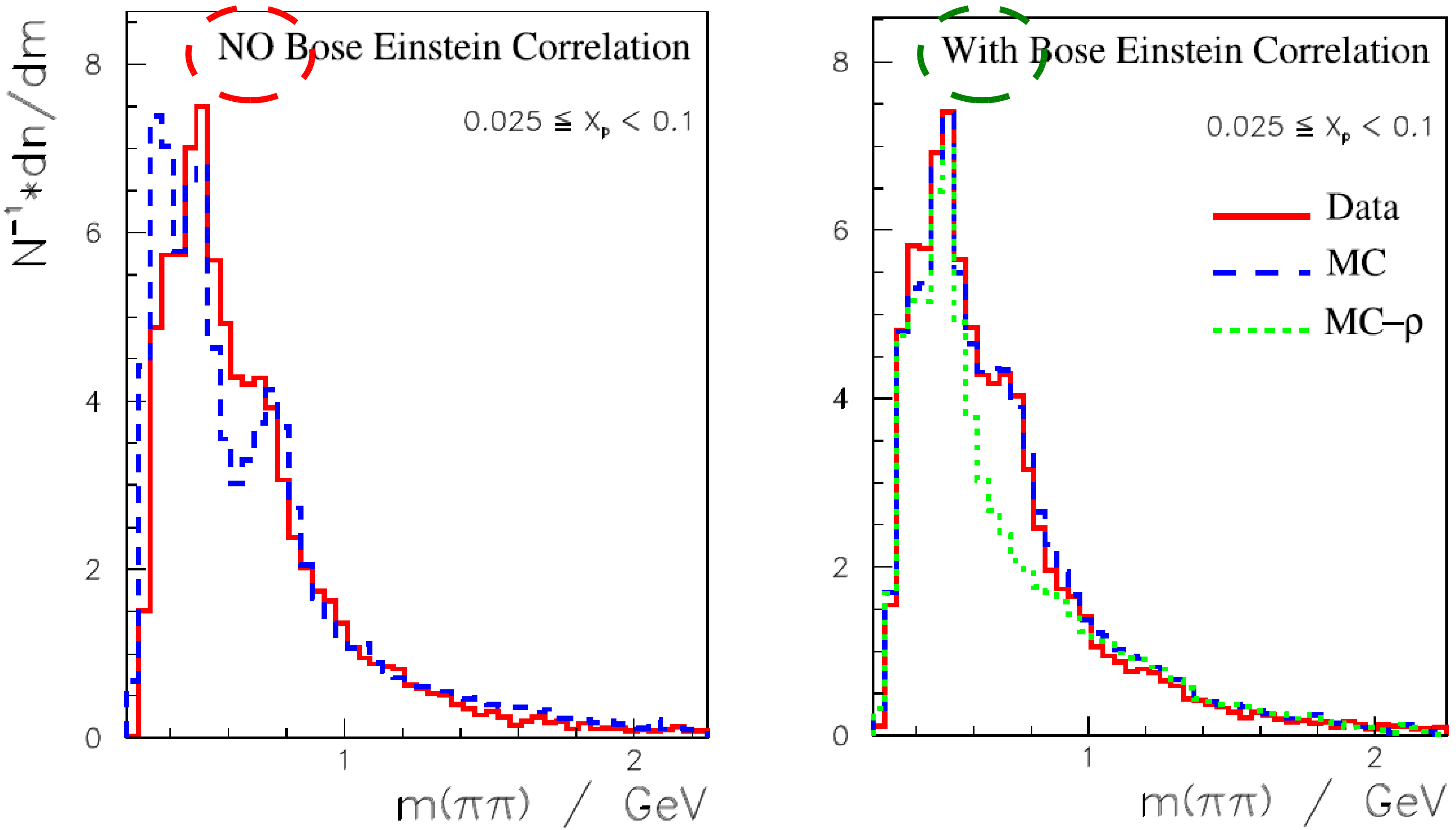


Figure 1: The normalized and corrected Q distribution of same-sign charged particle pairs in b-deplete
Z decays, compared to model predictions (a). The relative deviation of the model predictions from th
data is shown in (b). The grey band indicates the statistical errors.

BE Field also Acts on Unlike Sign Pairs !



h^+h^- mass spectrum,
like sign subtracted

resonance line shape description
strongly improved

Summary

- Quality of data description by MC models:

  - very good for event shapes, global inclusive distributions
  - rates reasonably described even with few param. cluster model
  - heavy quarks well described by Lund/Bowler FF
  - "large" amount of high mass resonances

    (understanding of mass dependence of hadron production?)
  - baryons show some discrepancies (but baryons are pair produced)

- Models very good were we have real understanding

  (PS-ME matching to be checked)
- More trouble in the qualitative corners of the models

PYTHIA Parameters (ALEPH)

parameter	name in program	default value	range generated	fit result value	error	syst.
Λ_{QCD} (GeV)	PARJ(81)	0.29	0.21 - 0.37	0.292	$\pm$ 0.003	$\pm$ 0.006
M_{min} (GeV)	PARJ(82)	1.0	1.0 - 2.0	1.57	$\pm$ 0.04	$\pm$ 0.13
σ_q (GeV)	PARJ(21)	0.36	0.28 - 0.44	0.370	$\pm$ 0.002	$\pm$ 0.008
a	PARJ(41)	0.30	0.20 - 0.60	0.40	(fixed)	
b (GeV^{-2})	PARJ(42)	0.58	0.60 - 1.00	0.796	$\pm$ 0.012	$\pm$ 0.033
ϵ_c	–PARJ(54)	0.050	0.015 - 0.065	0.040	adjusted	
ϵ_b	–PARJ(55)	0.005	0.0005 - 0.0075	0.0035	adjusted	
$p(S=1)_{d,u}$	PARJ(11)	0.50	0.40 - 0.70	0.55	$\pm$ 0.02	$\pm$ 0.06
$p(S=1)_s$	PARJ(12)	0.60	0.35 - 0.65	0.47	$\pm$ 0.02	$\pm$ 0.06
$p(S=1)_{c,b}$	PARJ(13)	0.75	0.50 - 0.80	0.65	adjusted	
$p(J^P=2^+; L=1, S=1)$	PARJ(17)	0.0	0.10 - 0.30	0.20	adjusted	
extra η' suppression	PARJ(26)	0.40	0.05 - 0.55	0.27	$\pm$ 0.03	$\pm$ 0.09
s/u	PARJ(2)	0.30	0.19 - 0.39	0.285	$\pm$ 0.004	$\pm$ 0.014
qq/q	PARJ(1)	0.10	0.05 - 0.15	0.106	$\pm$ 0.002	$\pm$ 0.003
$(su/du)/(s/u)$	PARJ(3)	0.40	0.4 - 1.0	0.71	$\pm$ 0.04	$\pm$ 0.07
leading baryon suppr.	PARJ(19)	1.0	0.2 - 1.0	0.57	$\pm$ 0.03	$\pm$ 0.10
switch				setting		
fragmentation function	MSTJ(11)	4		3		
baryon model	MSTJ(12)	2		3		
azimuthal distrib. in PS	MSTJ(46)	3		3		

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