Overview of QCD measurements at LEP

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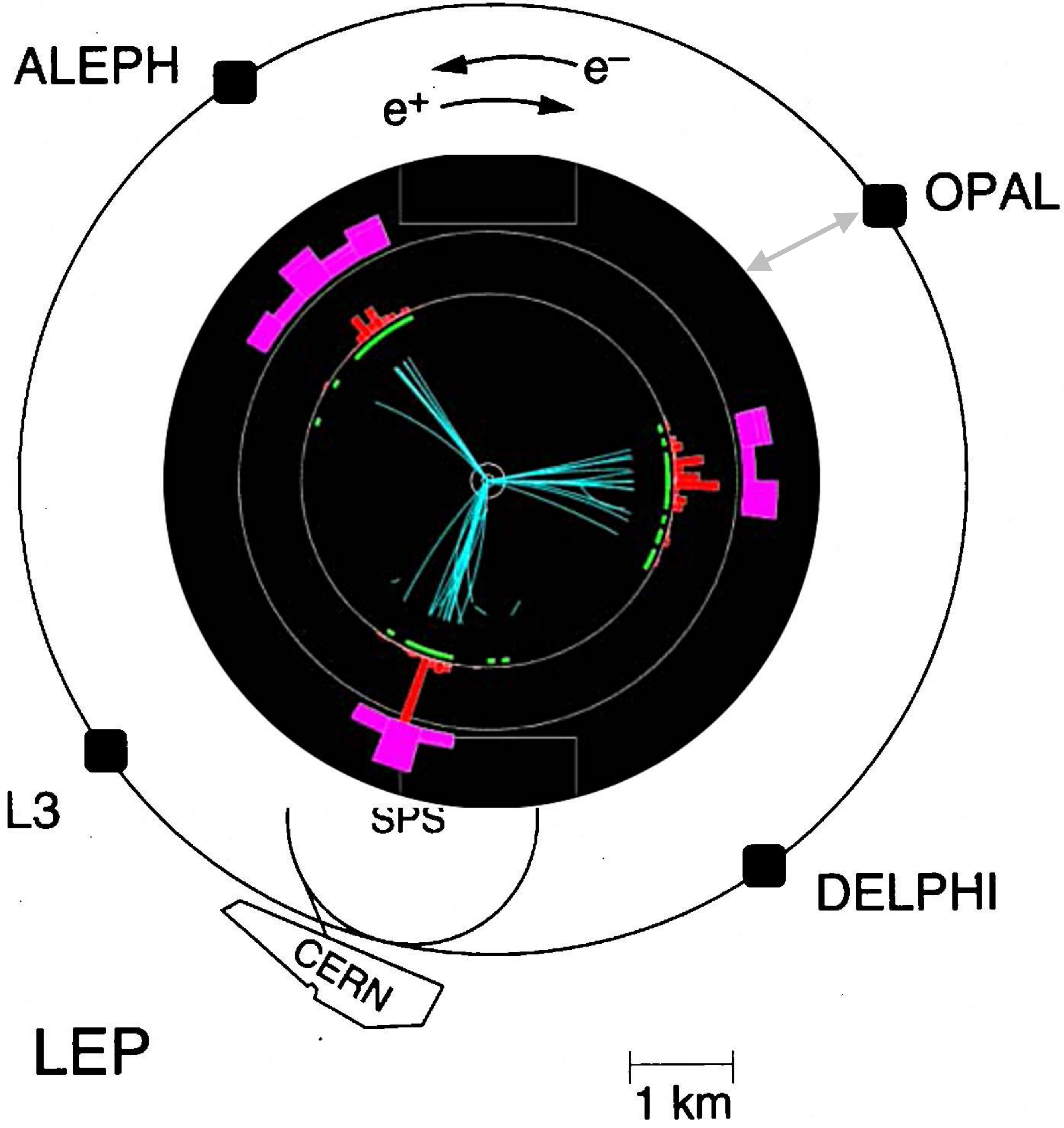
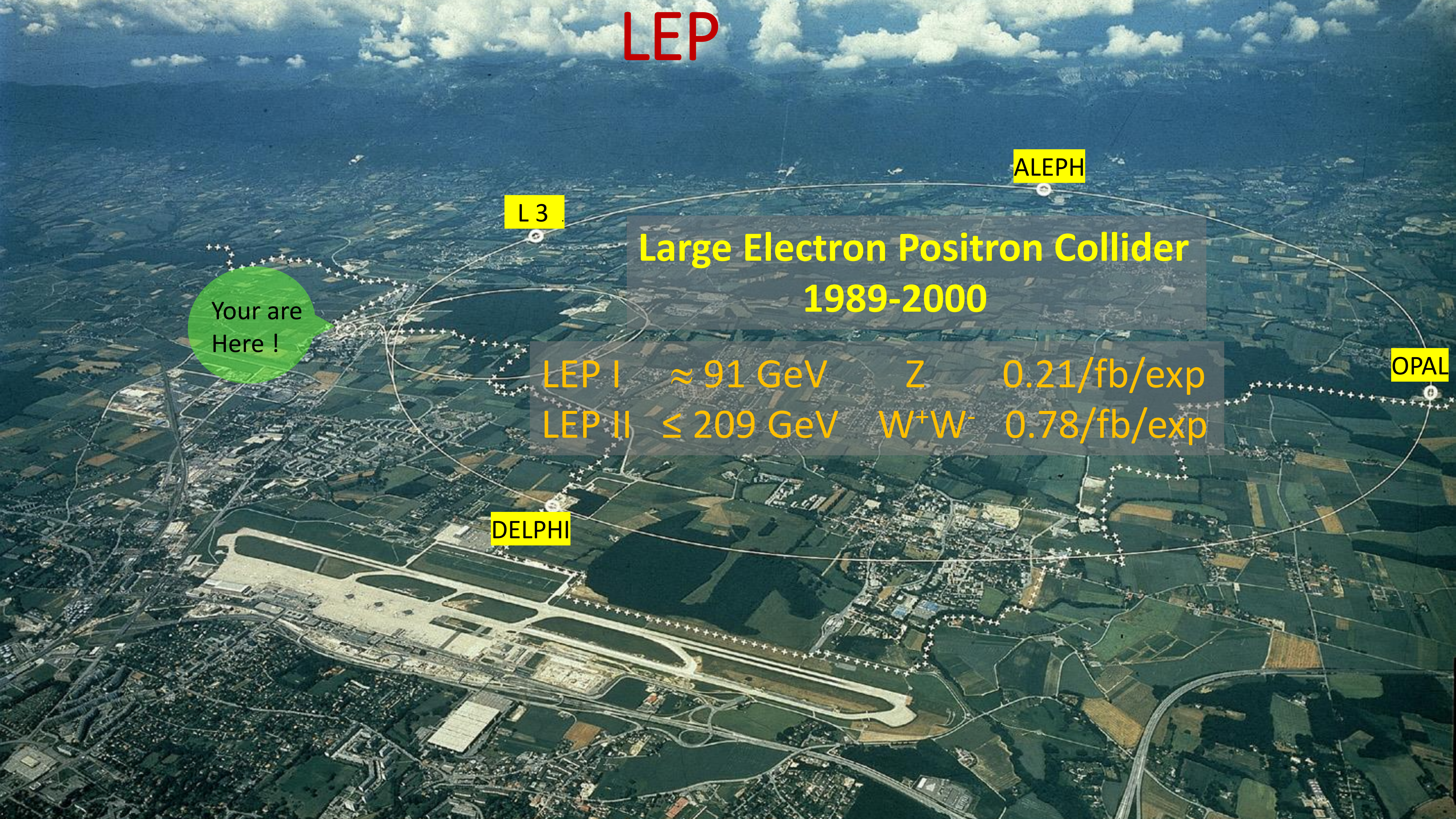
Parton Showers for future e^+e^- colliders

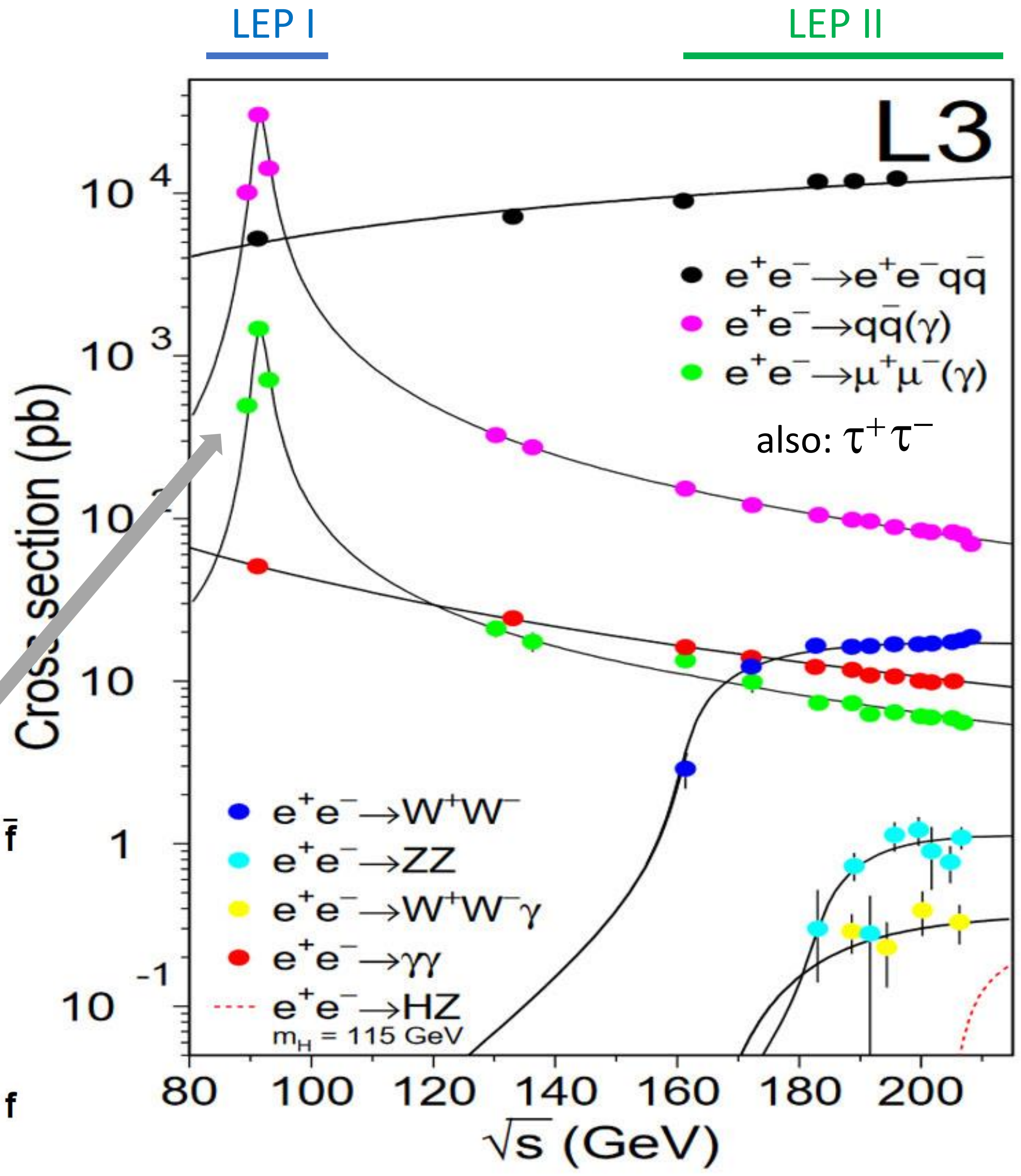
CERN

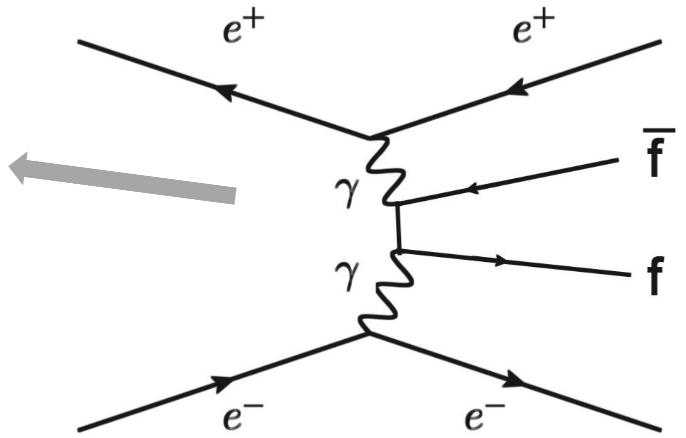
April 24-28, 2023

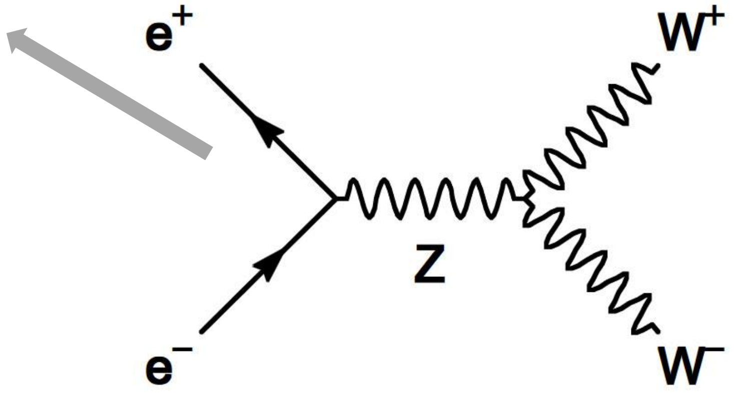


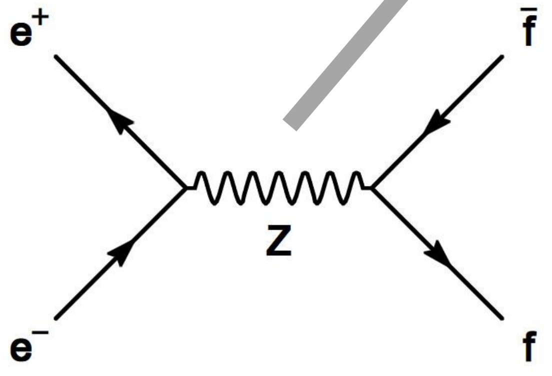

LEP
ALEPH
L 3
Large Electron Positron Collider
1989-2000
Your are Here !
OPAL
LEP I ≈ 91 GeV Z 0.21/fb/exp
LEP II ≤ 209 GeV W+W- 0.78/fb/exp
DELPHI

Processes and cross sections



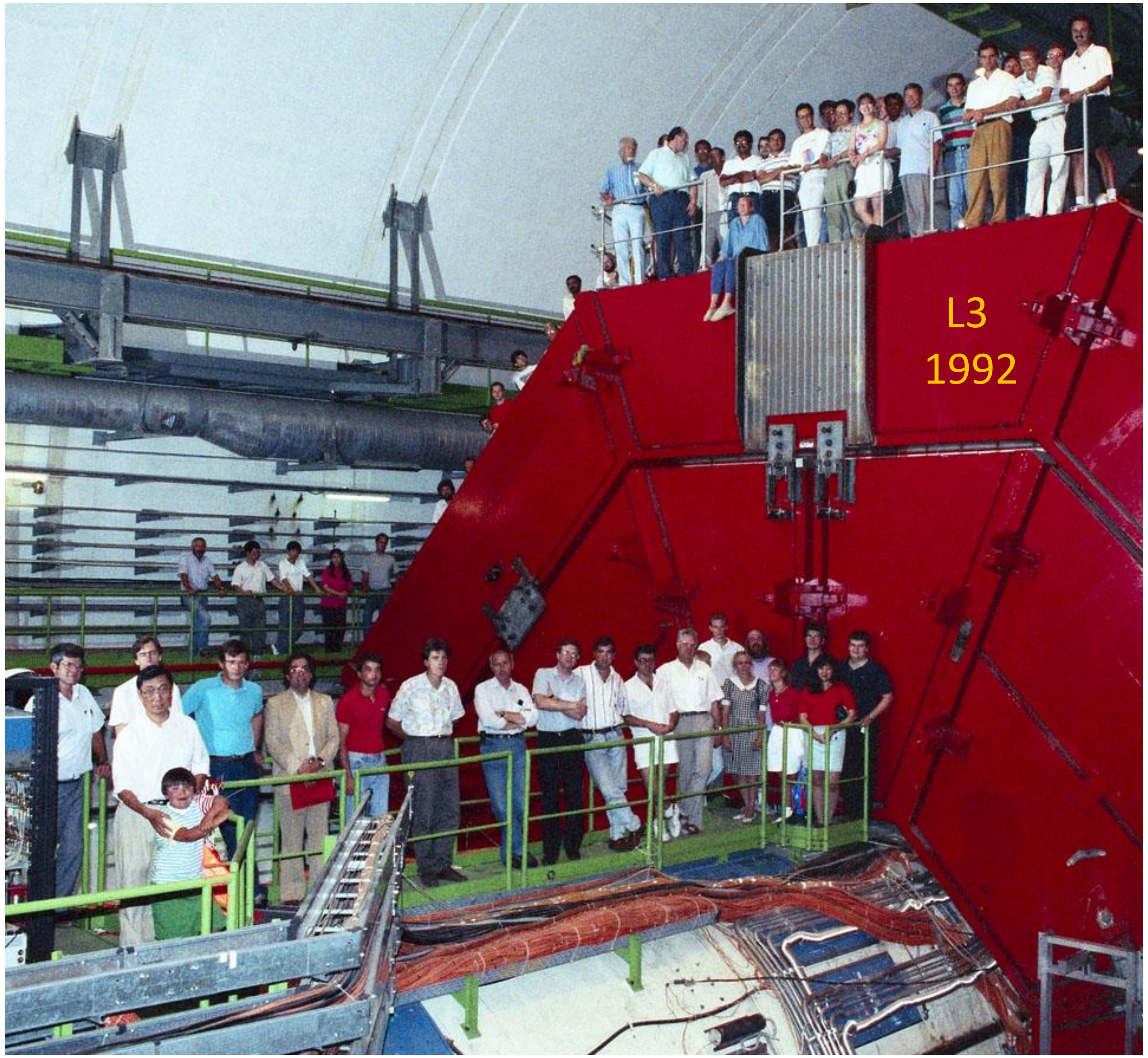






LEP detectors

- **ALEPH** = **A**pparatus for **LEP PH**ysics at CERN
- **DELPHI** = **DE**tector with **L**epton, **P**hoton and **H**adron **I**dentification
- **L3** = **L**EP experiment **3** ➔ ALICE
- **OPAL** = **O**mni-**P**urpose **A**pparatus for **LEP**



Common features:

- Tracker / calorimeters / muon detector
- Magnetic field
- Angular coverage θ_{min} = 10°-15°
- Hadron identification (except L3): dE/dx, RICH (DELPHI)

Statistics:

few million Z events per experiment
$\approx$ 10 000 WW events per experiment

Personal look back

QCD studies at LEP

Thomas Hebbeker
Phys. Inst. III A, RWTH Aachen

International Lepton-Photon Symposium
and
Europhysics Conference on High Energy Physics

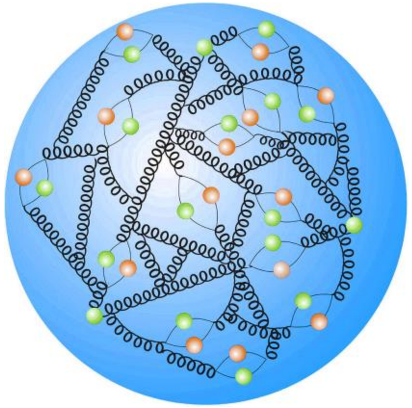
Geneva, July-August 1991

Summary and Conclusions

- Strong coupling constant
  - $\boxed{\alpha_s = 0.120 \pm 0.007}$
  - **'running'** √
- Precise tests of $O(\alpha_s^2)$ QCD matrix element
  - **gluon self interaction** √
- soft hadron physics
  - **all distributions reproduced by QCD Monte Carlo programs or analytical calculations**

LEP has increased our confidence in QCD significantly

Outline



- Introduction: LEP ✓
- Measurements of α_s
- Fundamental tests of QCD
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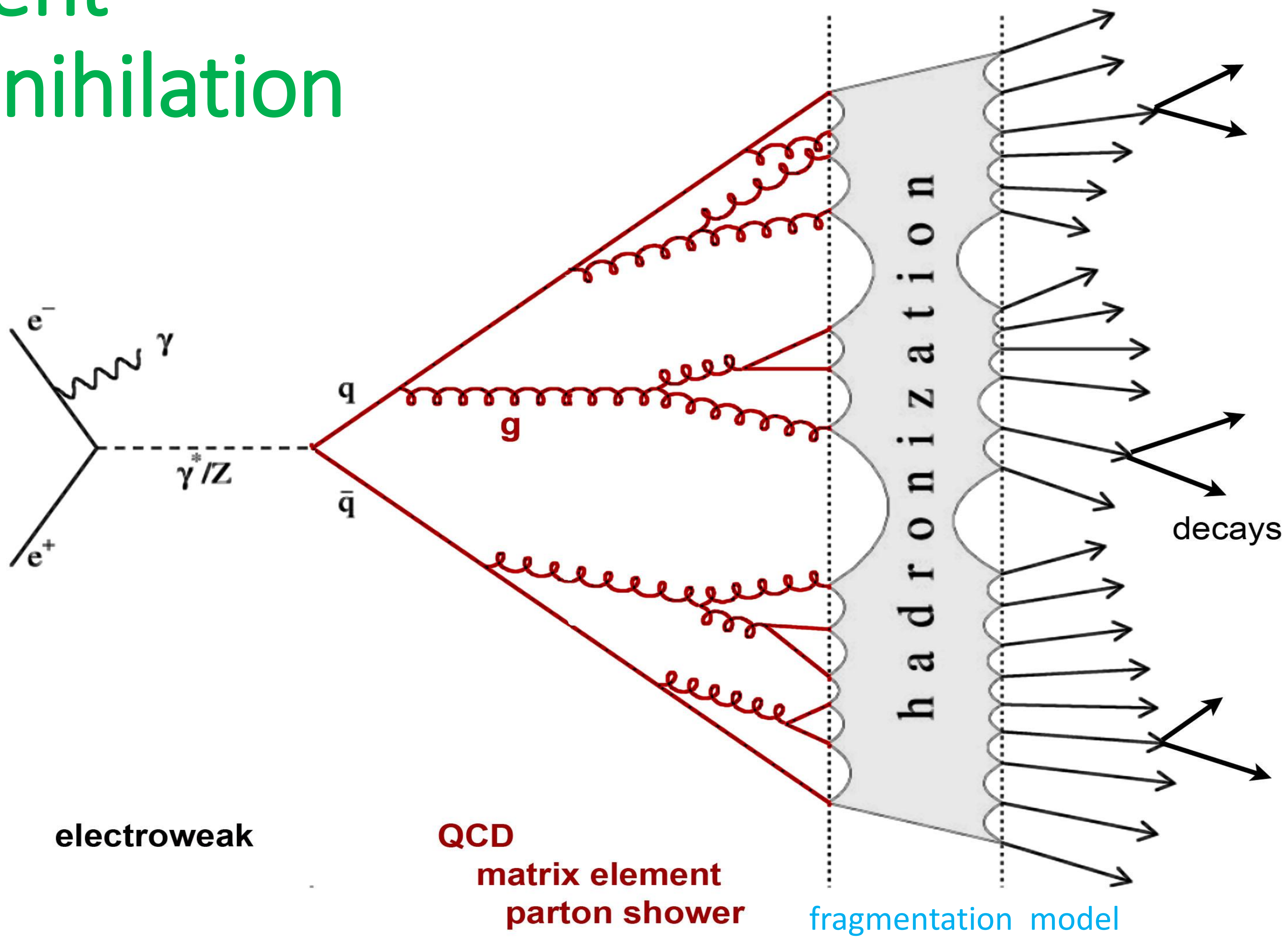
- Two photon physics

chicken – egg problem:
need to assume QCD to measure α_s

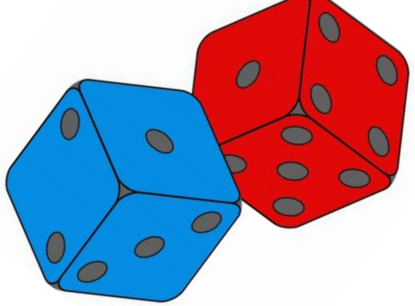
`QCD event‘
in e e annihilation

Jetset, Herwig, Ariadne….



adapted from O. Biebel / Physics Reports 340 (2001) 165}289

e^+e^- Monte Carlo event generators



- **JETSET** 7.4 T. Sjöstrand, Comput. Phys. Comm. 82 (1994) 74.

  Matrix element (up to α_s^2), Parton shower (leading log, angular ordering)
  String fragmentation

- PYTHIA 6.2 T. Sjöstrand, L. L önnblad, S. Mrenna, PYTHIA 6.2: Physics and manual, http://arxiv.org/abs/hep-ph/0108264

  Physics similar (originally for hadron colliders)

- ARIADNE 4.12 L. Lönnblad, Comput. Phys. Comm. 71 (1992) 15.

  Parton shower via color dipole model
  String fragmentation

- **HERWIG** 6.2 G. Marchesini, B.R. Webber, et al, Comput. Phys. Comm. 67 (1992) 465.

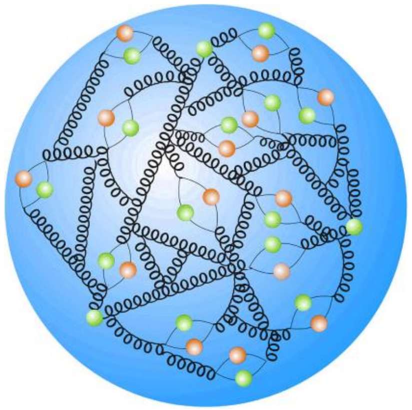
  (Leading order) Matrix element, Parton shower (including coherence)
  Cluster fragmentation

- COJETS, NLLJET, …

around year 2000
written in Fortran

many free parameters, needed tuning

Outline



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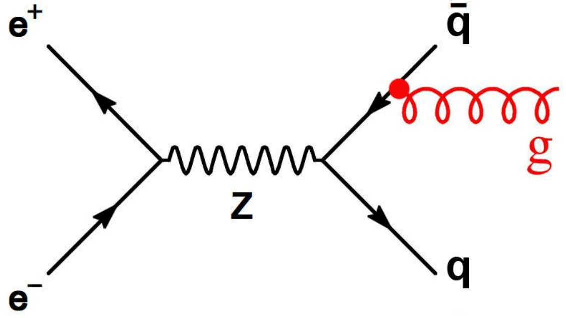
- Hadronic widths Z τ
- Event shapes

Measurements of α_s

event counting

Z **total cross section / total width Γ_Z**



QCD correction
to hadronic cros section

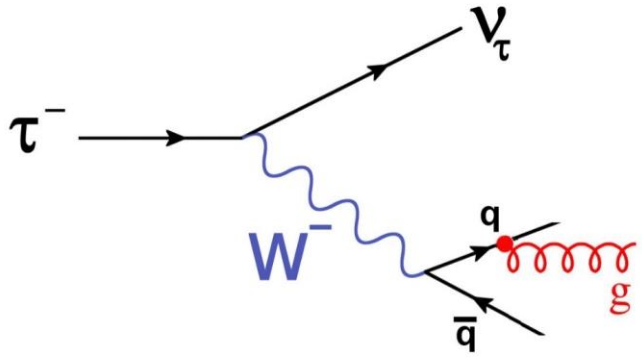
$$1 + \frac{\alpha_s}{\pi} + \ \ldots \alpha_s^4 \ \sim 1.04$$

independent of hadronization
assume factorization

$$\alpha_s (m_Z) = 0.1208 \pm 0.0028$$

experimental uncertainty dominant

τ **total width Γ_τ**



$\alpha_s (m_\tau)$ = 0.312 ± 0.015

$$\alpha_s (m_Z) = 0.1178 \pm 0.0019$$

theoretical uncertainty dominant

Review of particle properties 2022

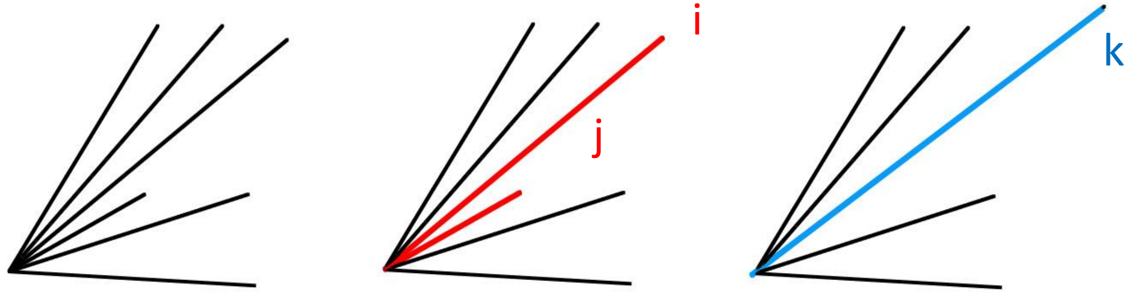
Jet algorithms (sequential recombination)

- for all pairs of particles i, j calculate distance parameter :

$$y_{ij} = 2\,\frac{E_i\,E_j\,(1-\cos\theta_{ij})}{s}$$ „JADE“

$$y_{ij} = 2\,\frac{\min(E_i{}^2, E_j{}^2)(1-\cos\theta_{ij})}{s}$$ „Durham“ „kt“

- find pair i, j with smallest $y_{ij}{}^{\min}$
- add 4-momenta: $p_i + p_j = p_k$ replace p_i, p_j by p_k
- iterate till $y_{ij}{}^{\min} > y_{cut}$



Hadron colliders:

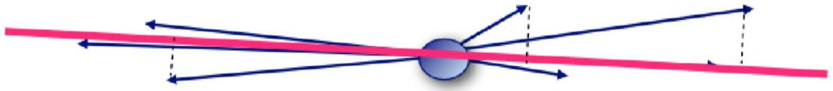
Cone algorithms

Nowadays:

Anti-kt algorithm

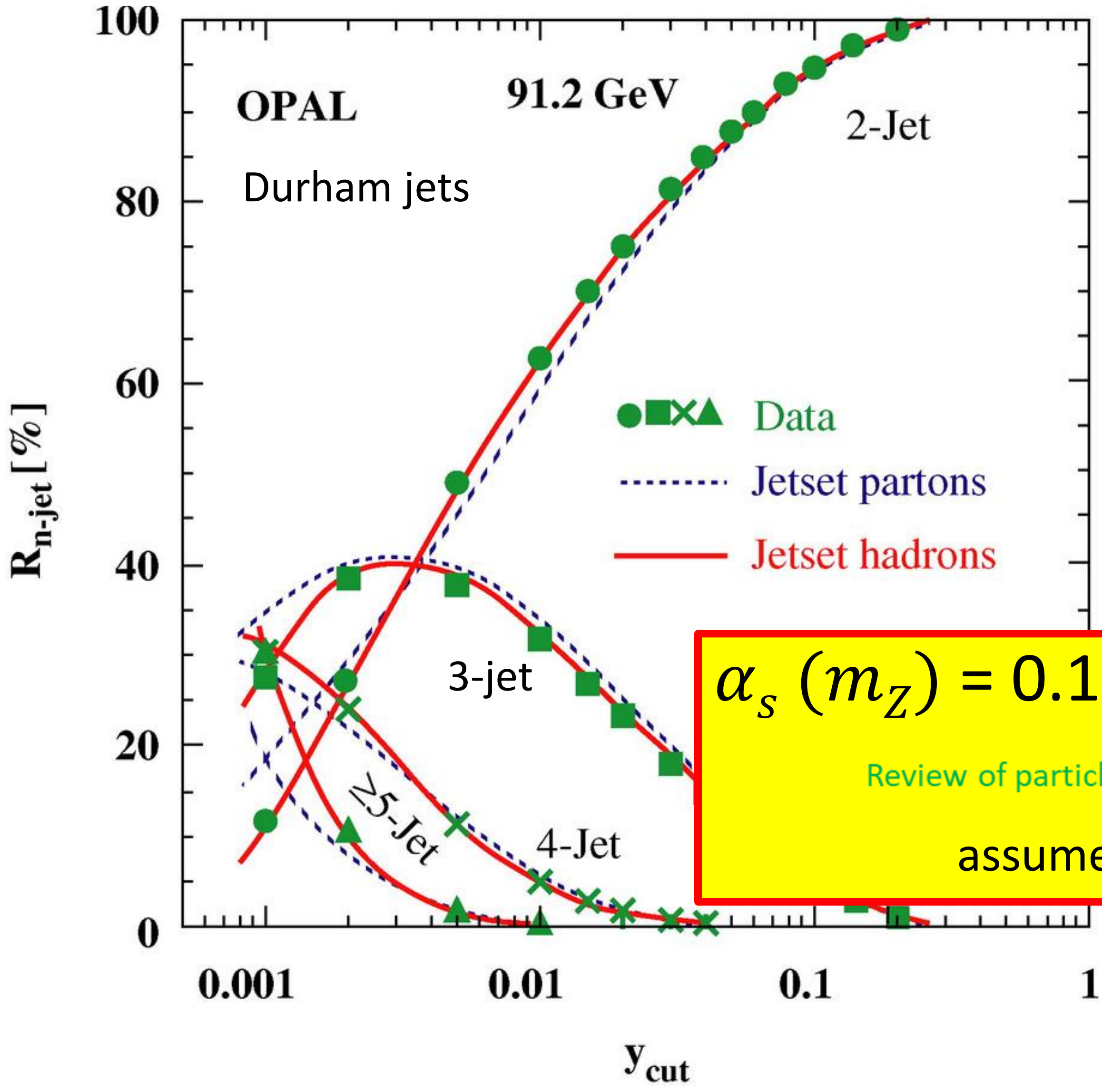
$E_{i,j}{}^2 \longrightarrow E_{i,j}{}^{-2}$

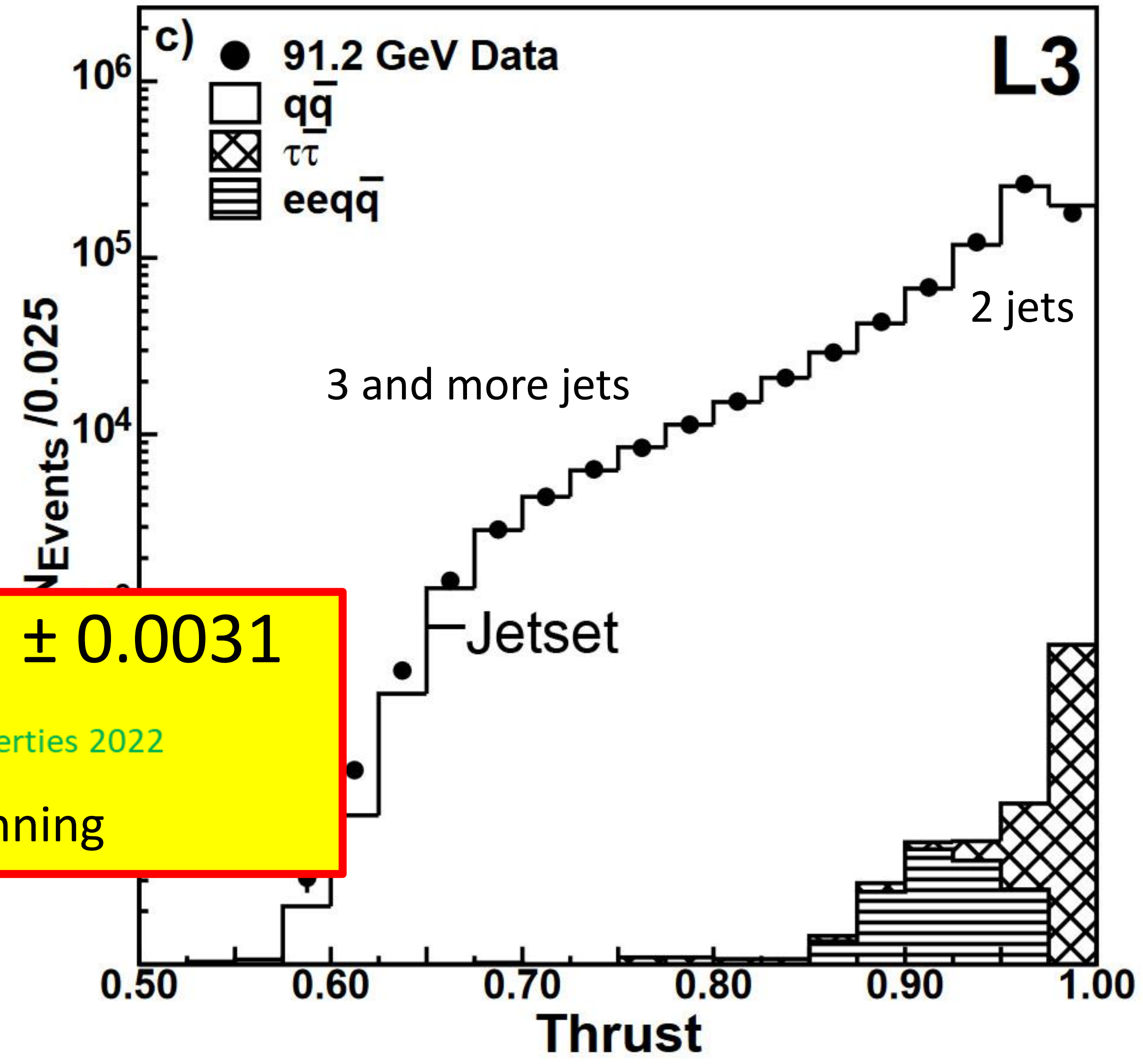
Measurements of α_s



event topology

$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$$



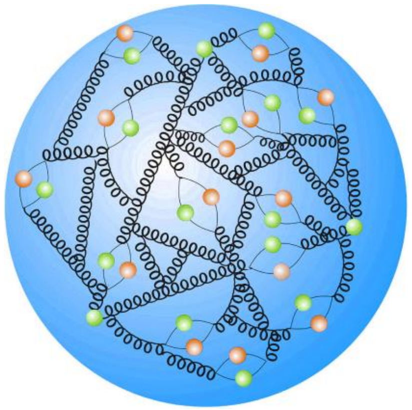


$\alpha_s(m_Z)$ = 0.1171 ± 0.0031

Review of particle properties 2022

assumes running

Outline



- Introduction: LEP
- Measurements of α_s
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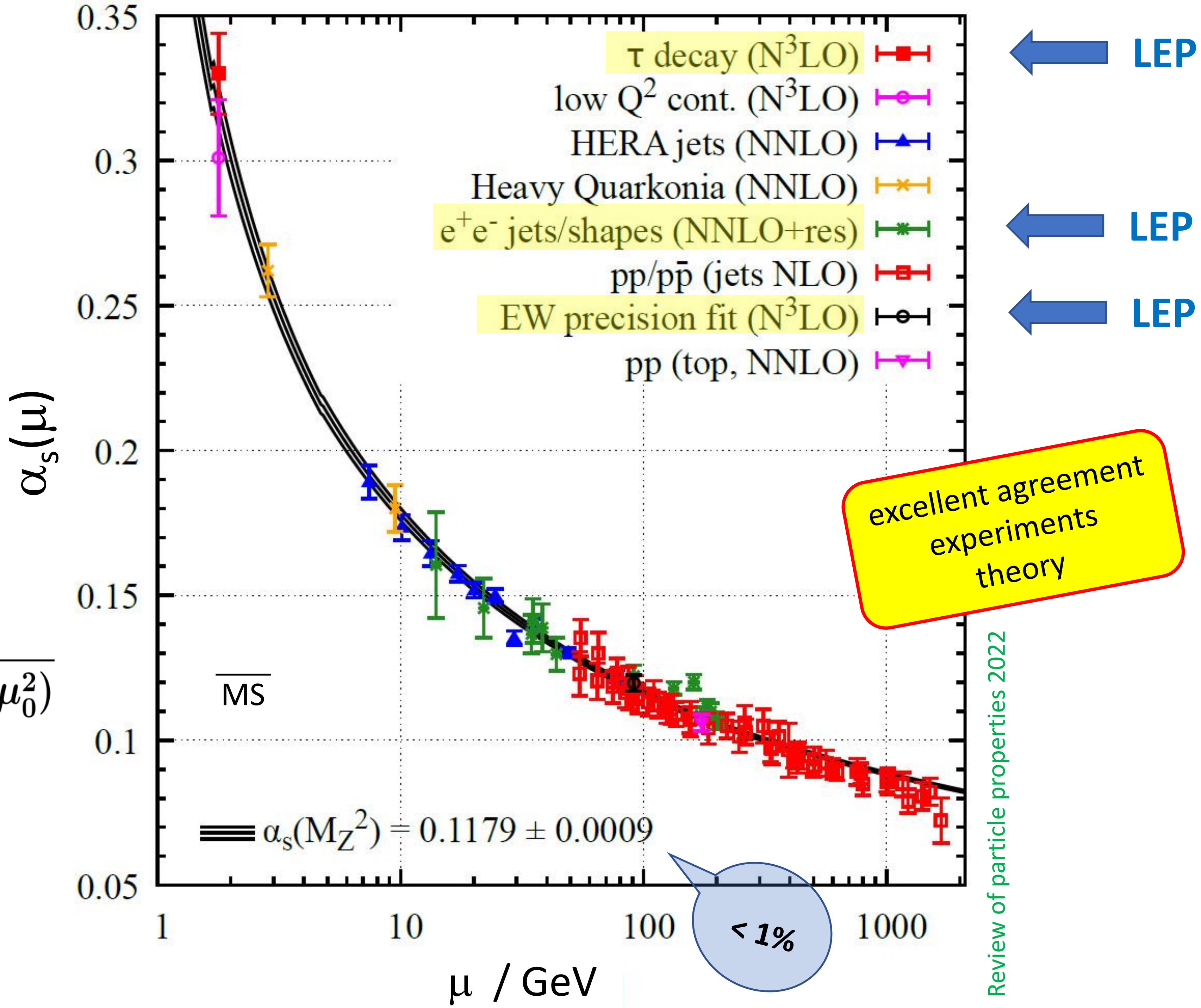
- Two photon physics

- Running of α_s
- Quark flavor and α_s
- Gluon self coupling
- QCD color factors

Running of α_s

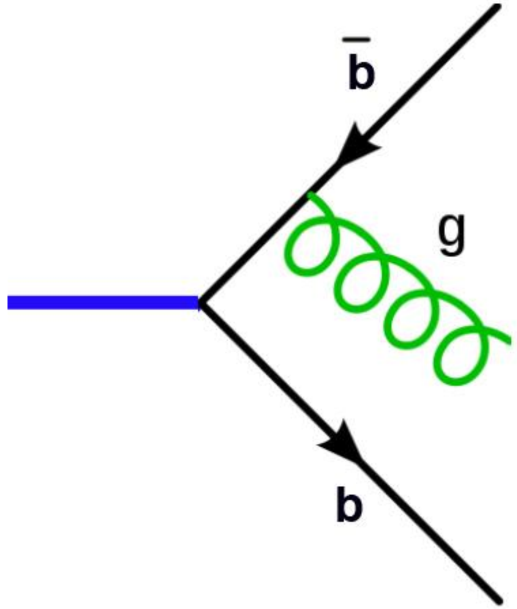
$$\alpha_s(\mu) = \frac{\alpha_s(\mu_0)}{1 - \beta_0^s\,\alpha_s(\mu_0)\,\ln(\mu^2/\mu_0^2)}$$

$$\beta_0^s = \frac{1}{6\pi}\cdot[N_F - 16.5] < 0$$



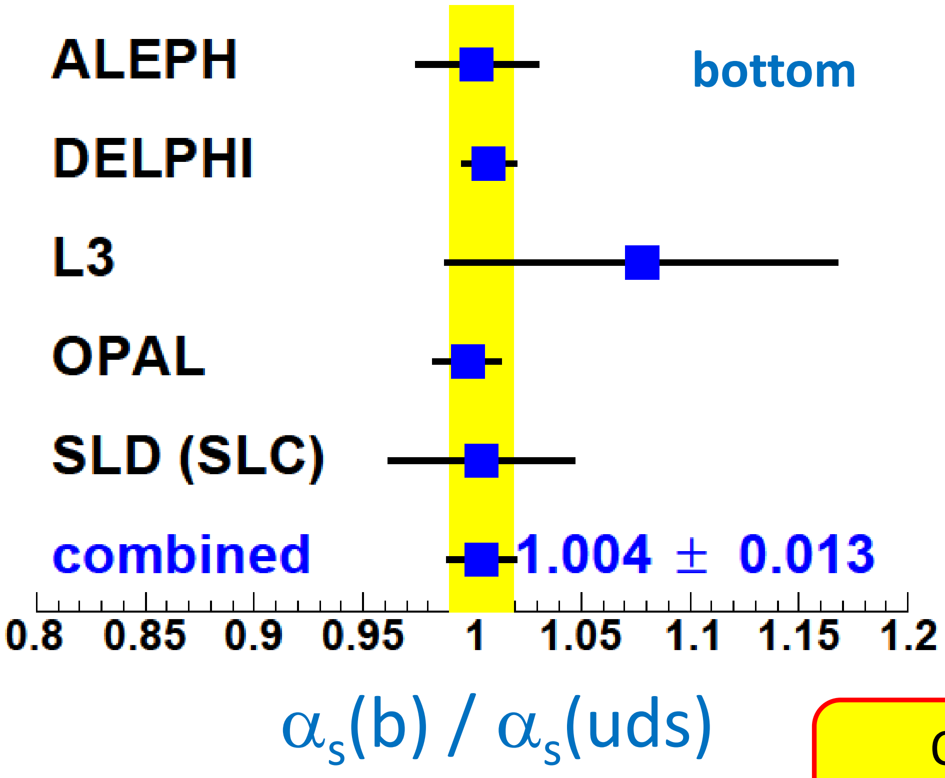
Review of particle properties 2022

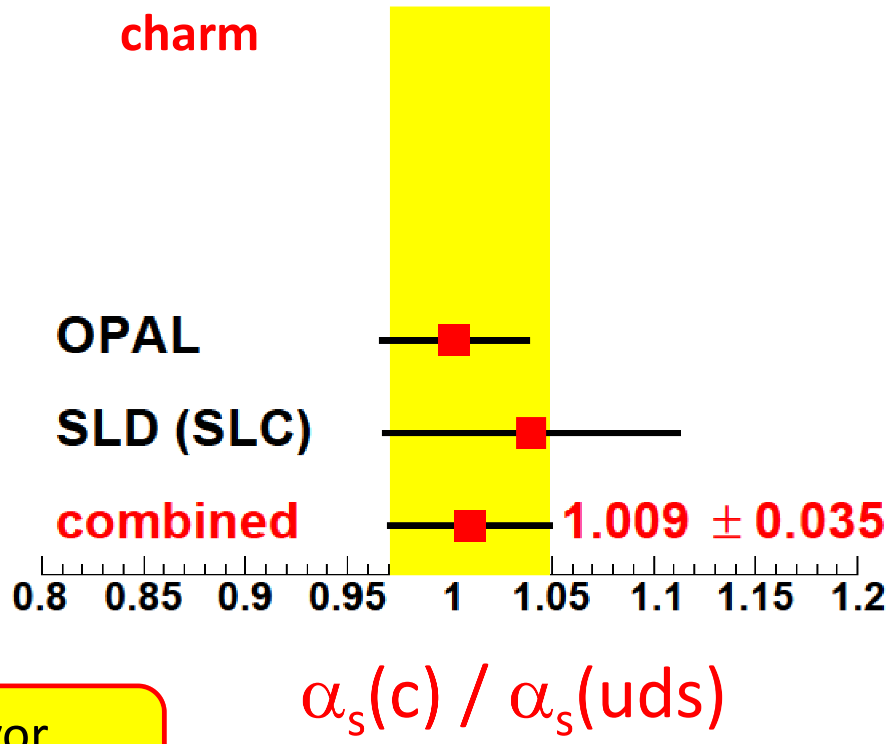
Flavor (in)dependence of α_s



Determine α_s from 3-jet rates and event shape distributions

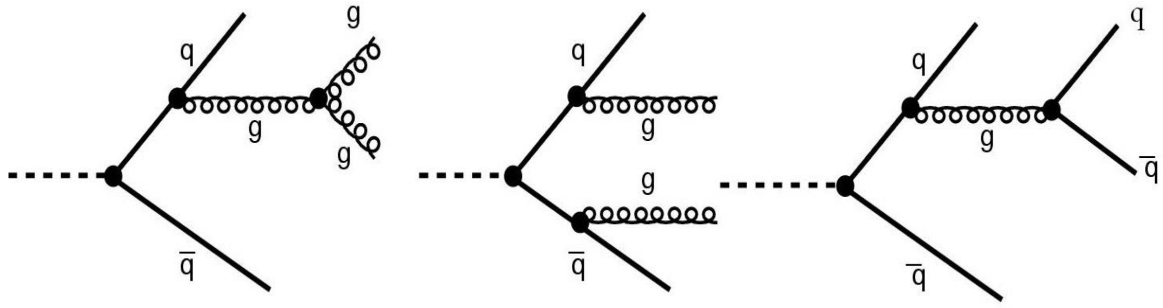
separately for **light quark events** and
for **heavy flavor events** (tagging via secondary vertices)





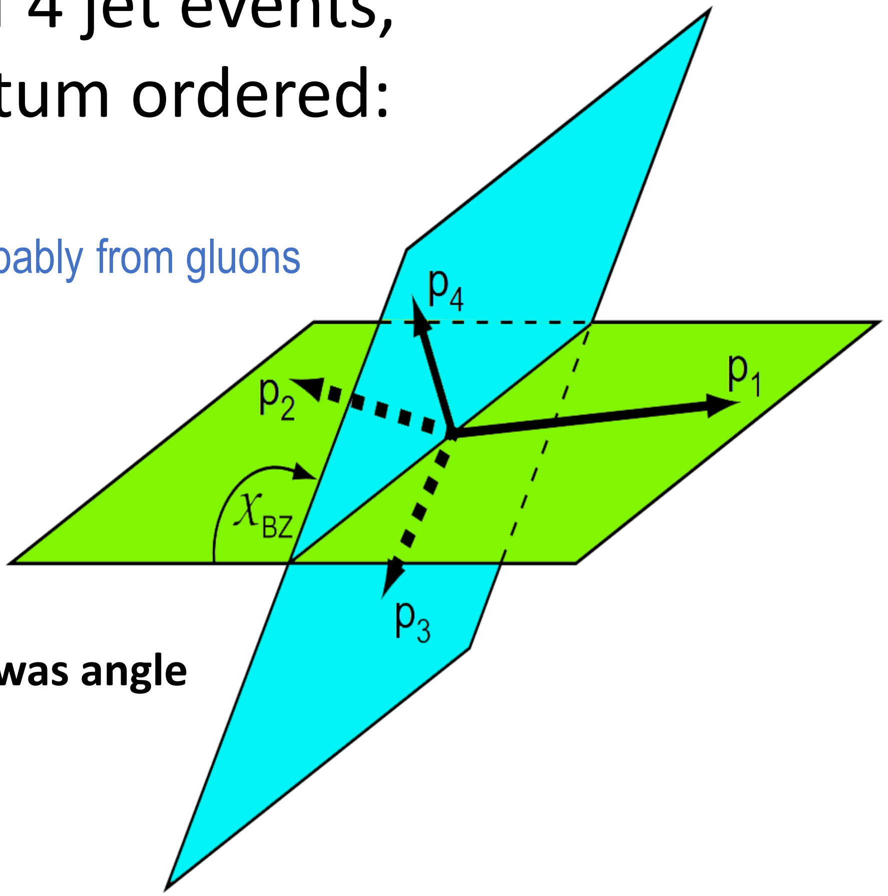
QCD is flavor independent!

Gluon self interaction

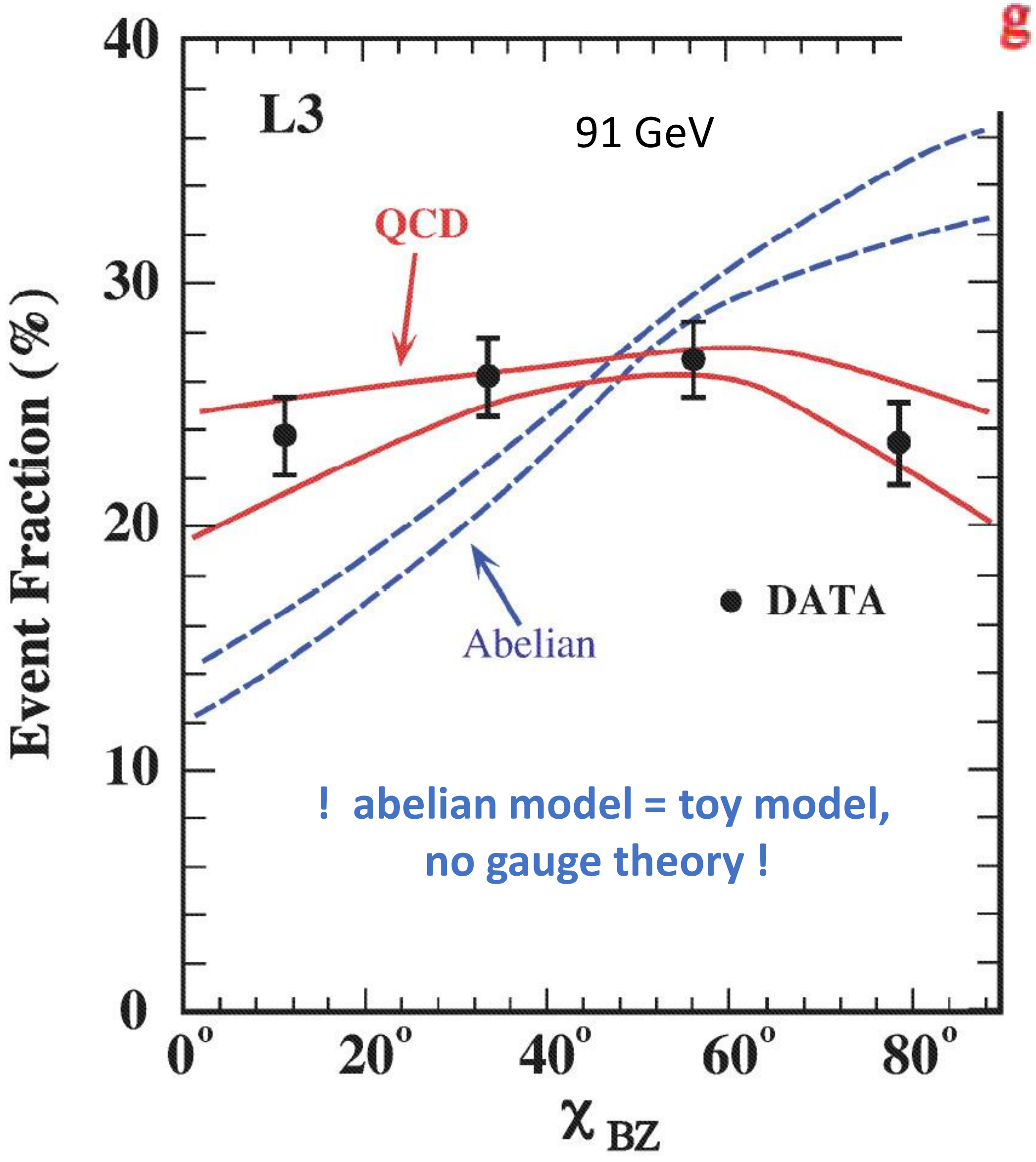


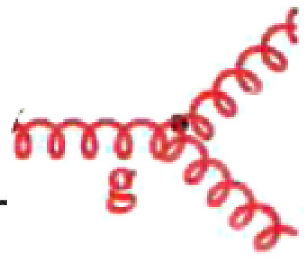
Analysis of 4 jet events, momentum ordered:

Jets 3 and 4 probably from gluons



Bengtsson-Zerwas angle



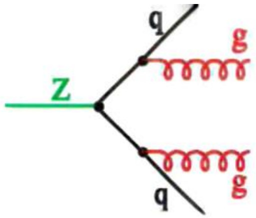


L3 Collaboration, B. Adeva et al., Phys. Lett. B248 (1990) 227

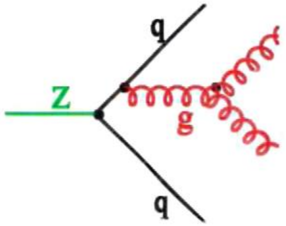
QCD color factors

Differential 4 jet cross section:

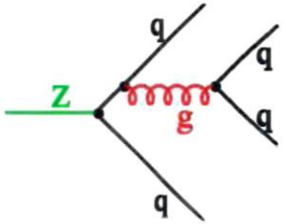
$$\sigma \sim C_{\mathrm{F}} \cdot \sigma_{\mathrm{A}} + (C_{\mathrm{F}} - C_{\mathrm{A}}/2) \cdot \sigma_{\mathrm{B}}$$



$$+ C_{\mathrm{A}} \cdot \sigma_{\mathrm{C}}$$

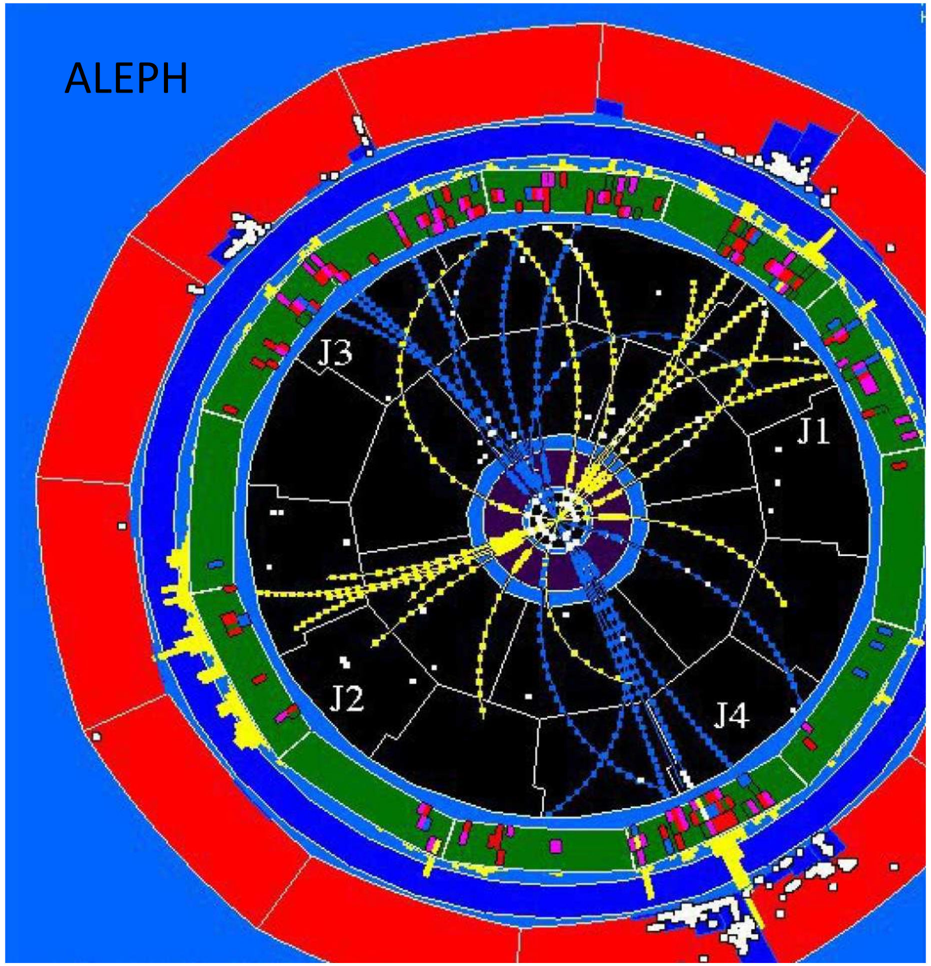


$$+ T_{\mathrm{R}} \cdot \sigma_{\mathrm{D}} + (C_{\mathrm{F}} - C_{\mathrm{A}}/2) \cdot \sigma_{\mathrm{E}}$$

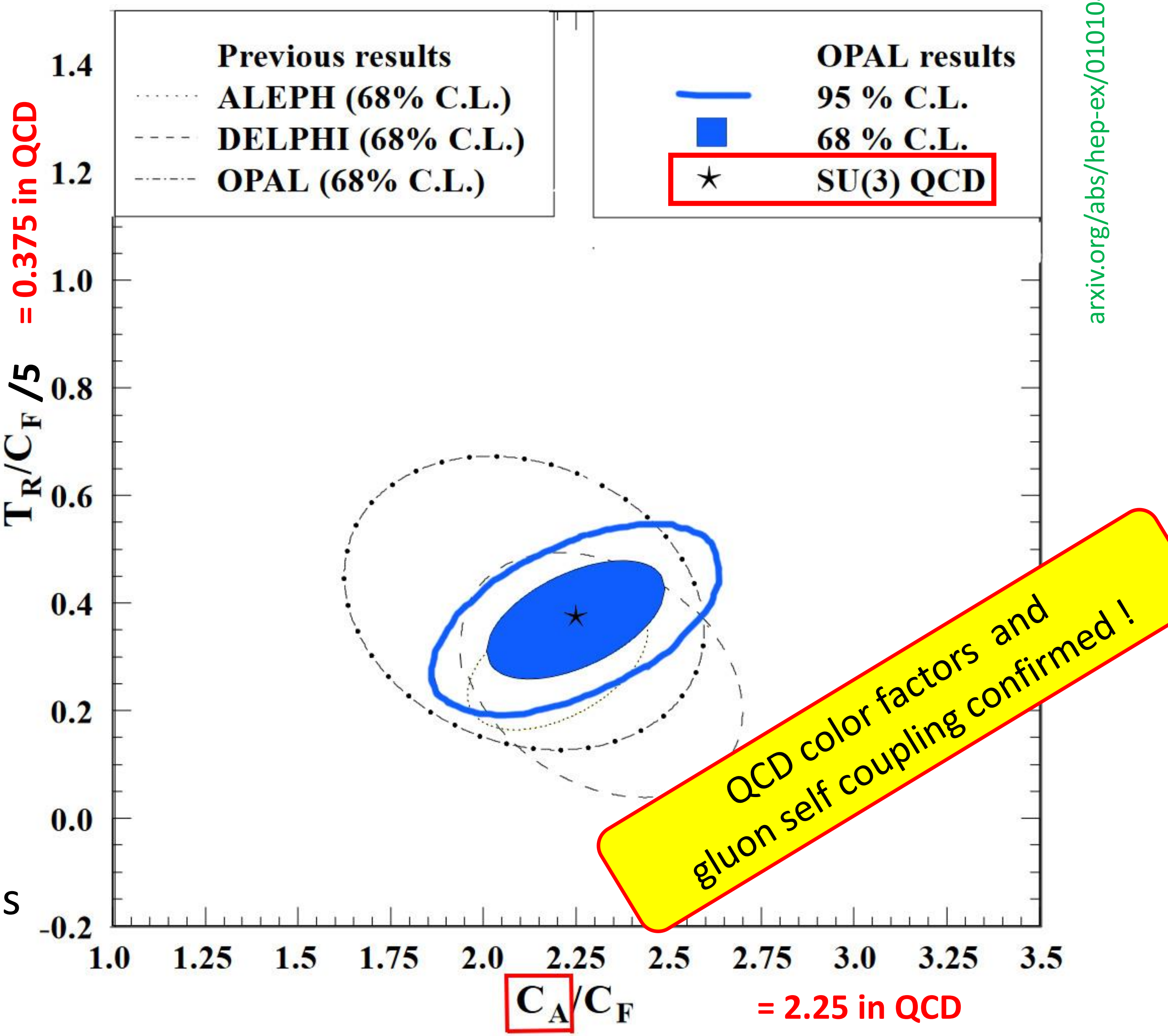


	C_{F}	C_{A}	T_{R}
QCD	4/3	3	5/2
abelian	1	0	15

QCD color factors

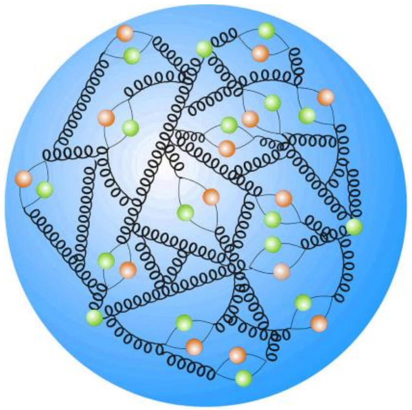


Fit to various **4-jet** angular correlations and other variables



arxiv.org/abs/hep-ex/0101044

Outline



- Introduction: LEP ✓
- Measurements of α_s
- Fundamental tests of QCD

Matrix elements

- `Soft' hadronic physics

Parton showering
Hadronization
Decays

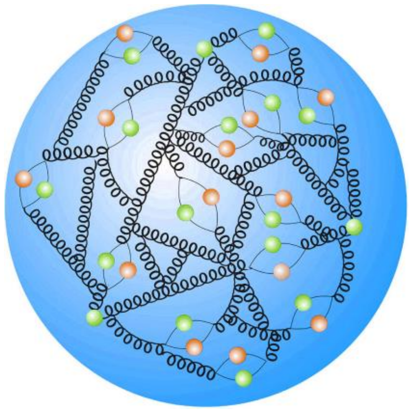
- Two photon physics

← **Inclusive measurements (Γ_Z):**
no dependence on soft effects

← **Jets:**
little dependence on soft effects

← **Multiplicities, Inter-jet regions:**
strong dependence on soft effects

Outline



- Introduction: LEP ✓
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- Particle multiplicity
- Gluon versus quark jets
- Inter-jet regions

Charged particle multiplicity

gluons: $\langle n_G(Q) \rangle \sim$

$$\alpha_s^b(Q^2) \cdot \exp\left[\frac{c}{4\pi b_0\sqrt{\alpha_s(Q^2)}} \cdot \left(1 + 6a_2\frac{\alpha_s(Q^2)}{\pi}\right)\right]$$

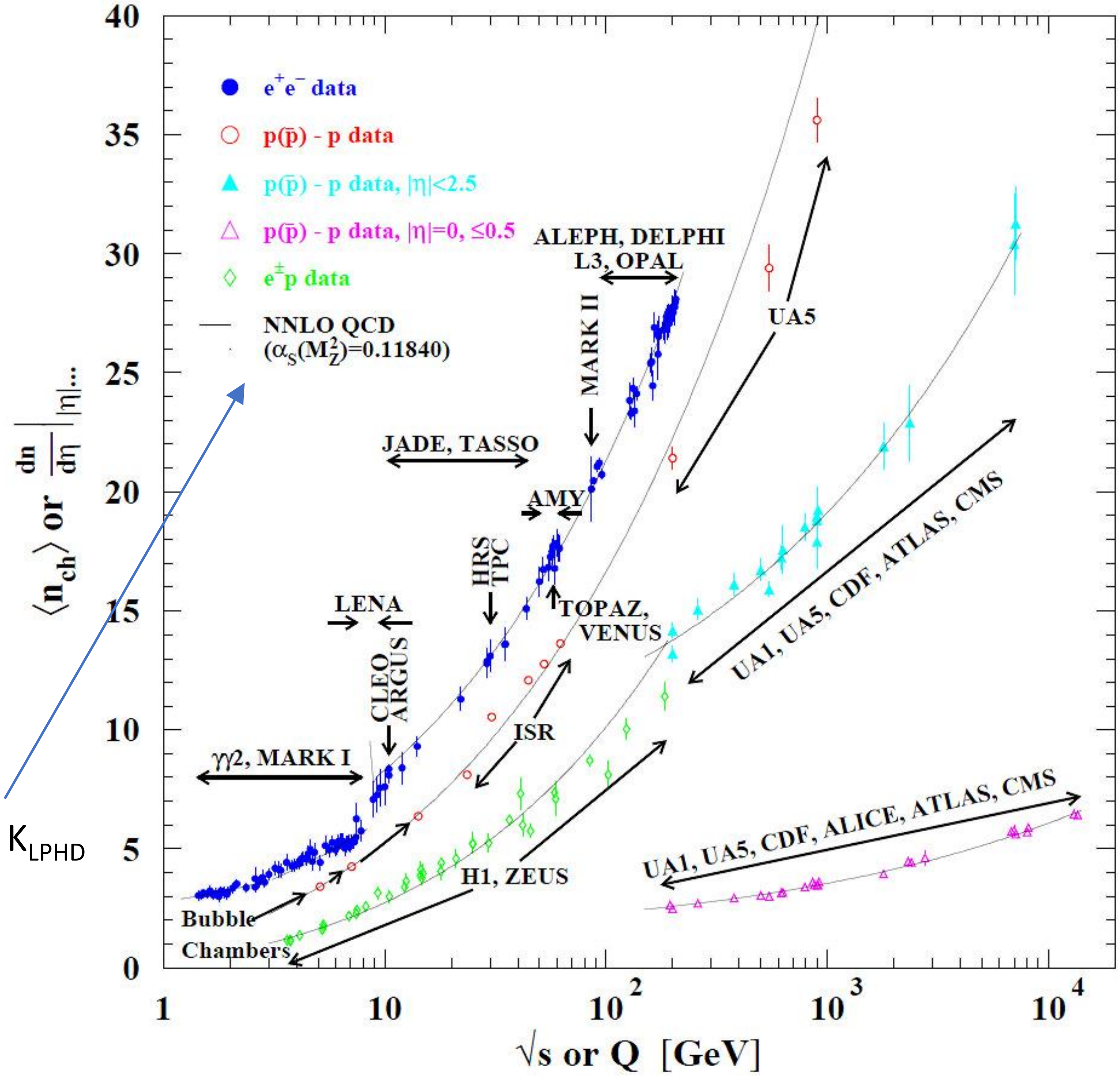
particles: $\langle n_{ch}(Q) \rangle =$

$$K_{LPHD} \cdot \langle n_G(Q) \rangle / r + n_0$$

$$r = C_A/C_F = 9/4$$

with fitted normalization K_{LPHD} and offset n_0

QCD reproduces Q dependence



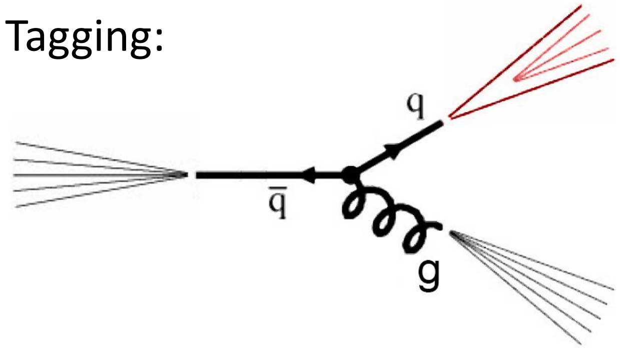
Review of particle properties 2022

Quark jets

versus

Gluon jets

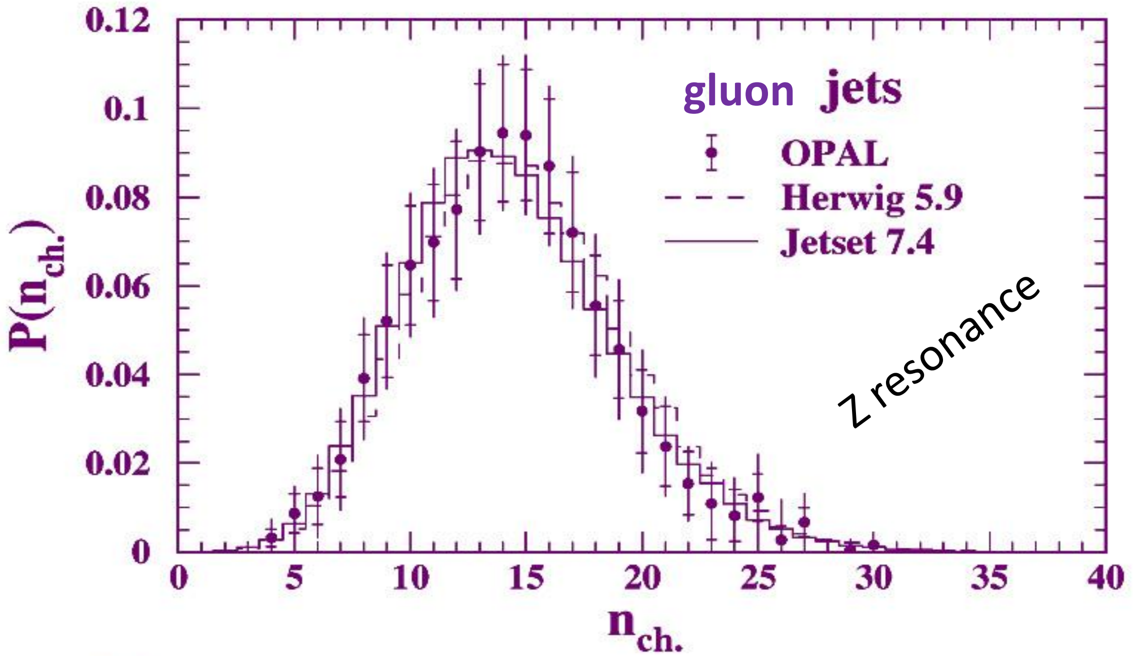
Tagging:

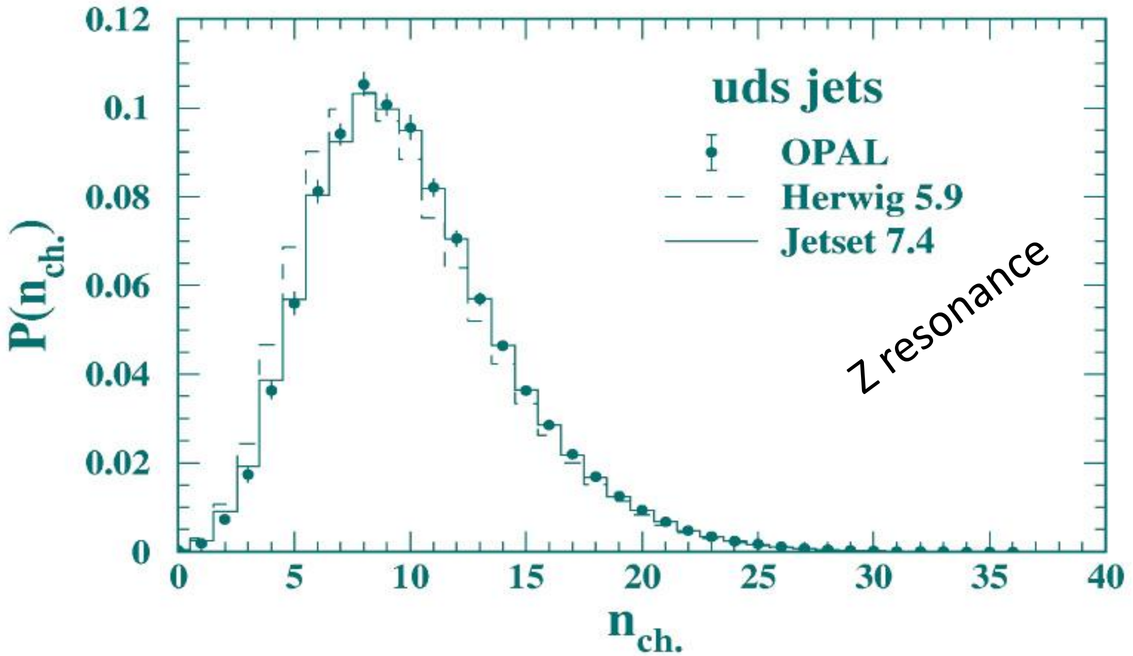


secondary vertex
c, b quark

r = n_{ch} (gluon) / n_{ch} (light quarks)

Gluon jets do have higher multiplicity!





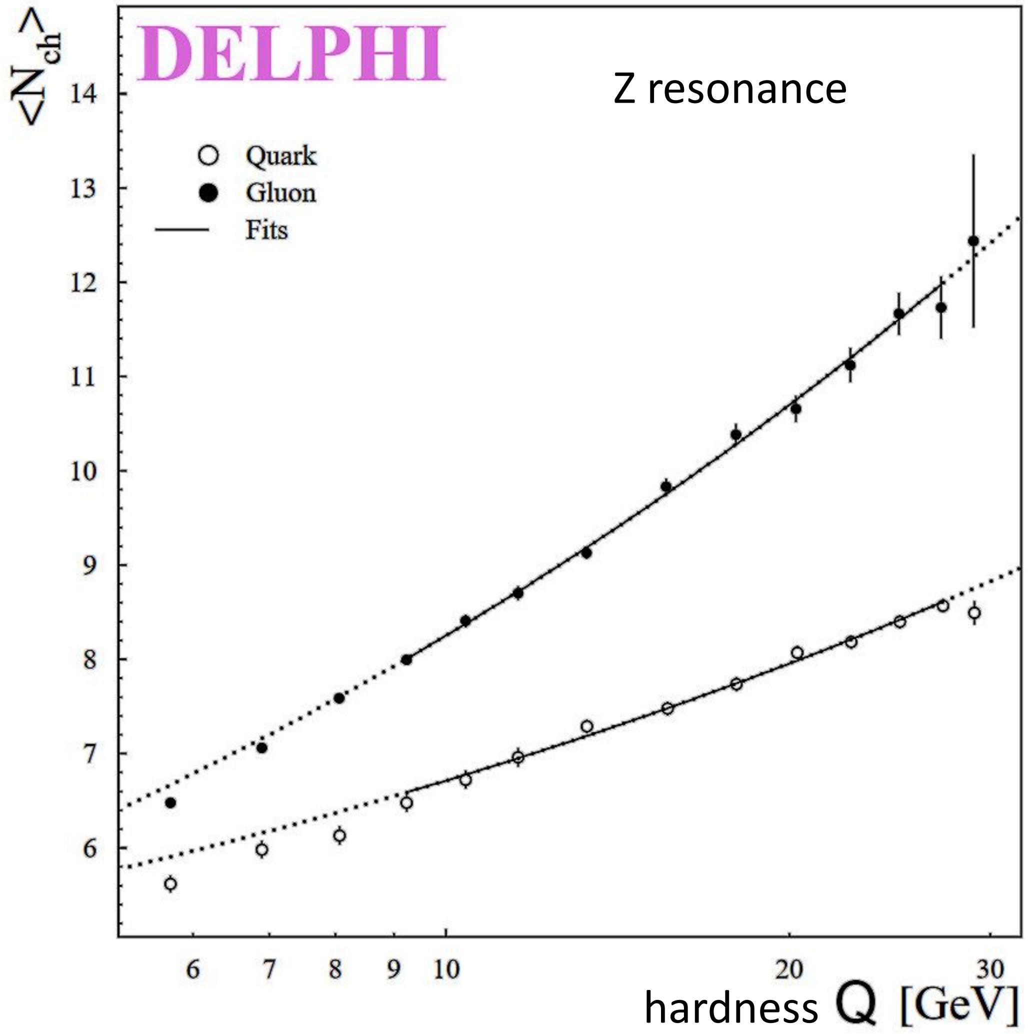
arxiv.org/abs/hep-ex/9903027

$$r(m_Z^2/4) = 1.471 \pm 0.024\ (\text{stat.}) \pm 0.043\ (\text{syst.})$$

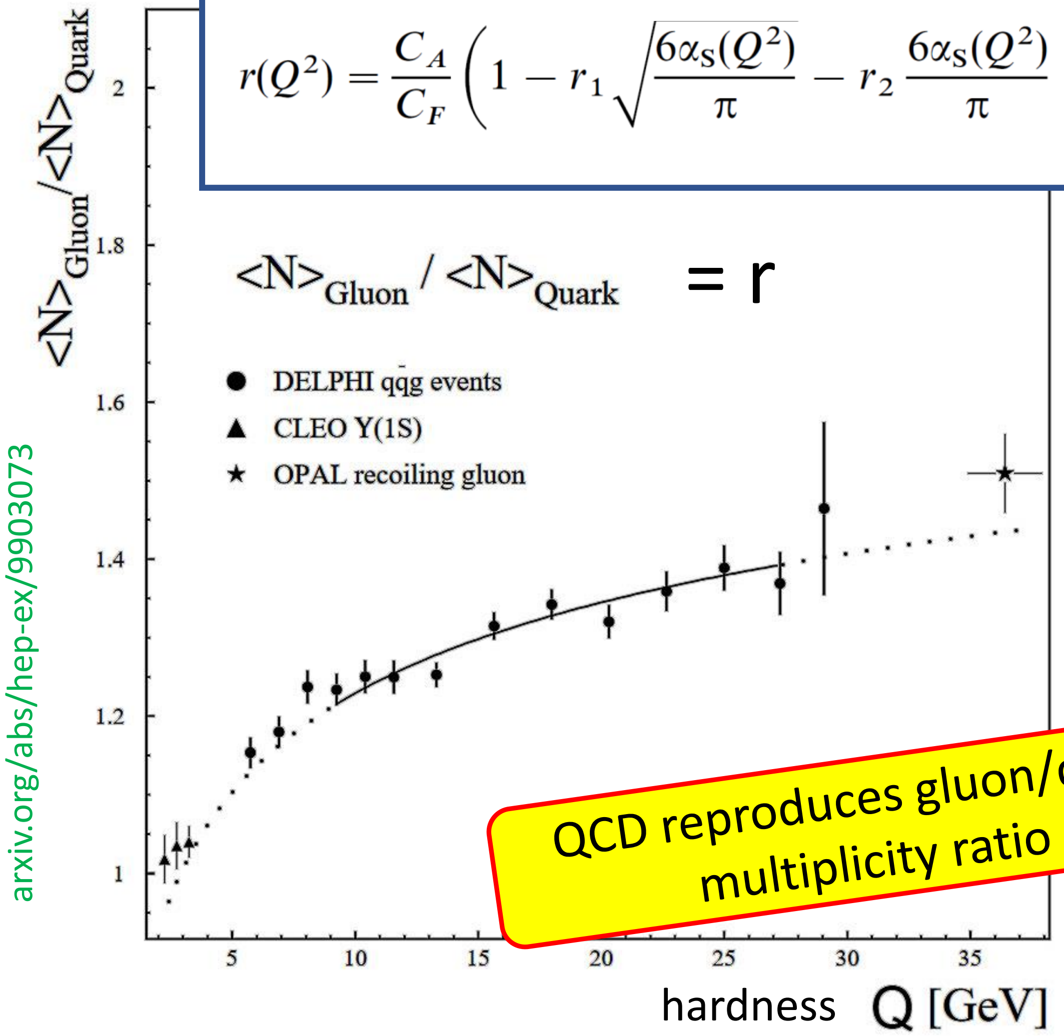
Quark jets versus Gluon jets

Naive: $r = C_A/C_F = 9/4$ = 2.25

$$r(Q^2) = \frac{C_A}{C_F}\left(1 - r_1\sqrt{\frac{6\alpha_S(Q^2)}{\pi}} - r_2\,\frac{6\alpha_S(Q^2)}{\pi} + \mathcal{O}(\alpha_S^{3/2})\right)$$



arxiv.org/abs/hep-ex/9903073

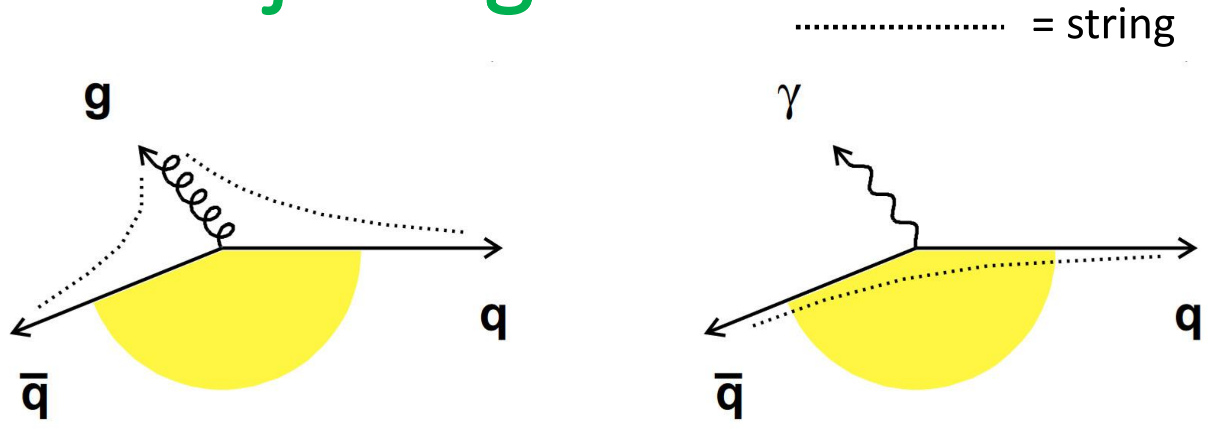


QCD reproduces gluon/quark multiplicity ratio

Fit (offset free parameter): $$\frac{C_A}{C_F} = 2.246 \pm 0.062\ (stat.) \pm 0.080\ (syst.) \pm 0.095\ (theo.)$$

Test of fragmentation models

inter-jet regions

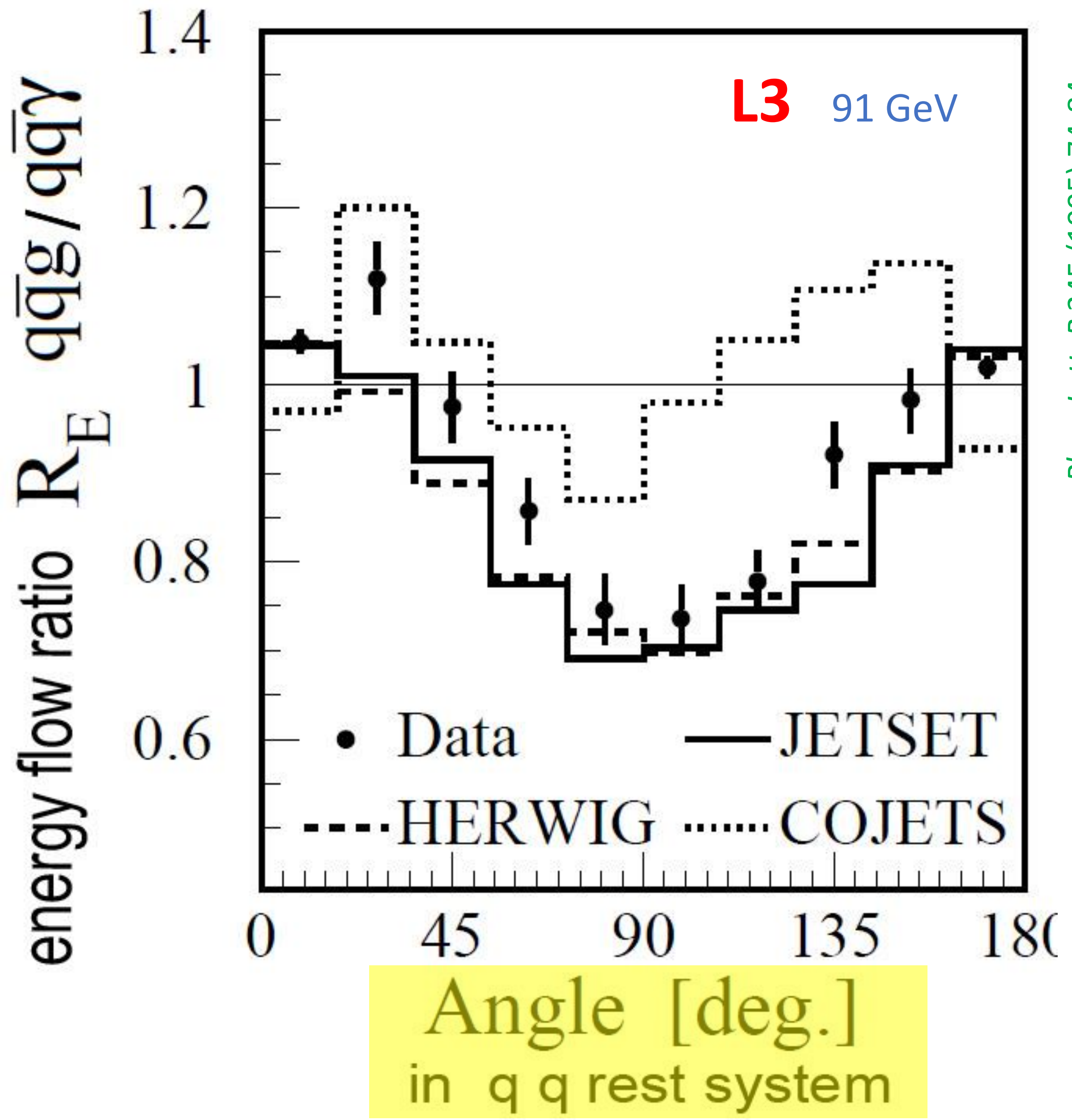


JETSET 7.3: **string** fragmentation

HERWIG 5.4: **cluster** fragmentation

COJETS 6.23: **independent** fragmentation model

Both JETSET and HERWIG good

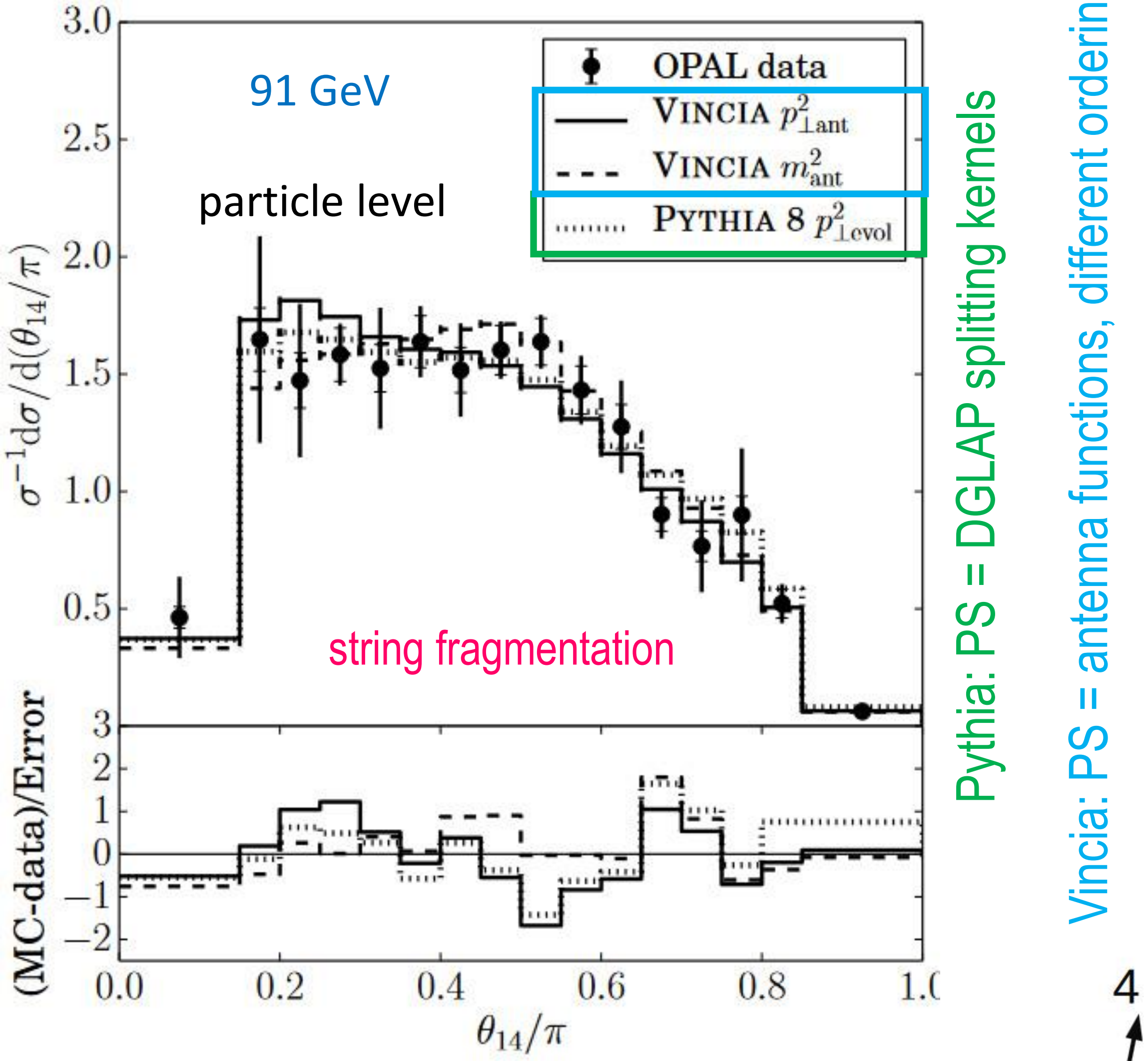


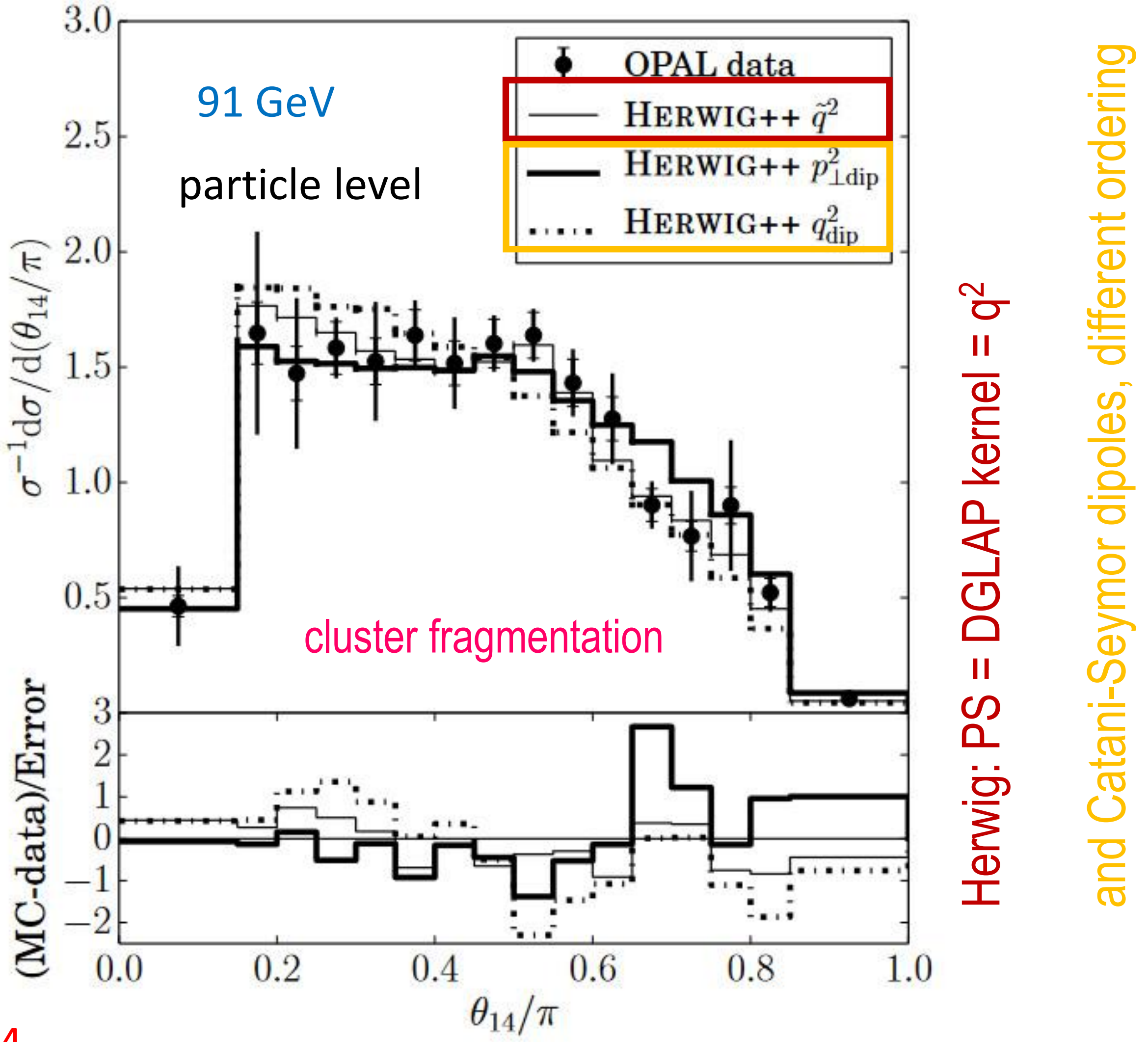
Phys. Lett. B 345 (1995) 74-84

Test of Parton Shower Models

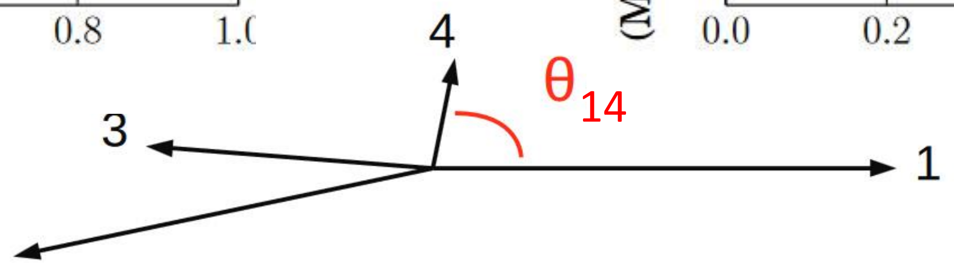
! PS **and** hadronization different !

N. Fischer et al, EPJ Web of Conferences 120, 05001 1500 (2016)



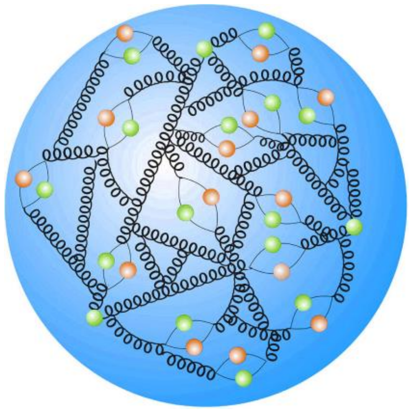


inter-jet regions



All models do a decent job

Outline



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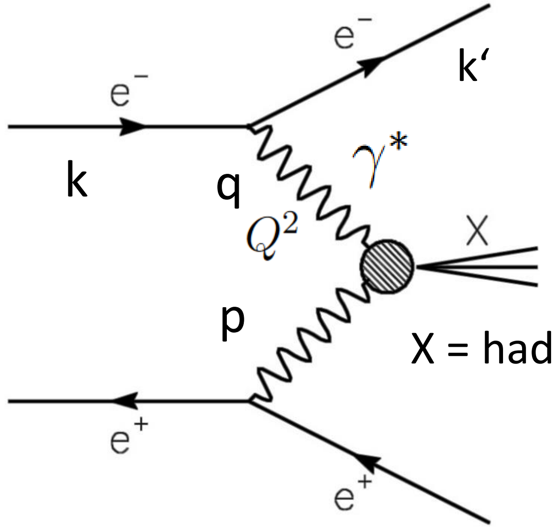
- Two photon physics

- Structure function F_2^{γ}
- Heavy flavor production

Two Photon Physics

Inclusive hadron production (light quarks)



at least one e^- / e^+ tagged

X = hadrons

$$x = Q^2/2(p\cdot q)$$

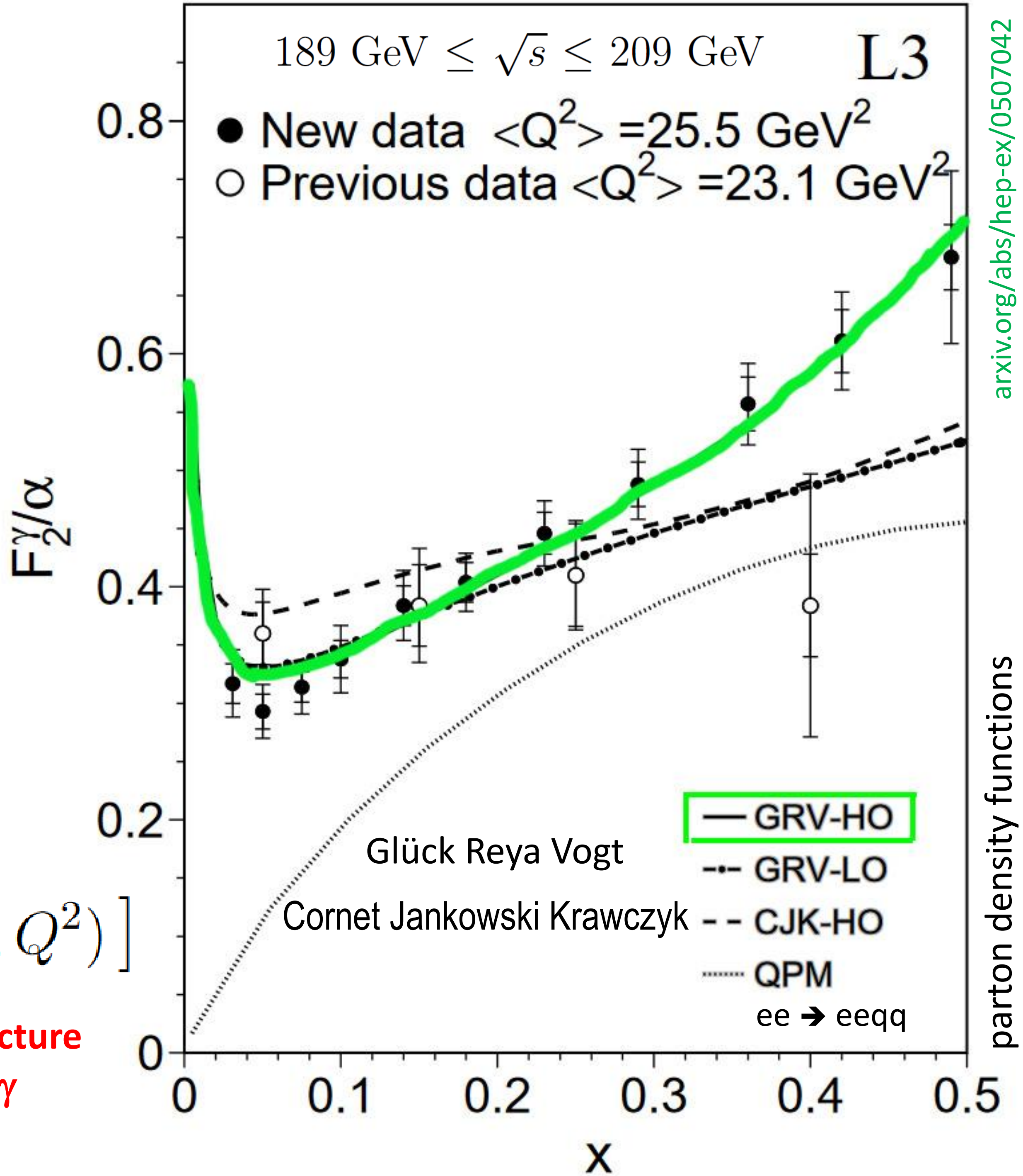
$$y = (q\cdot p)/(k\cdot p)$$

for small y:

$$\frac{d\sigma_{e\gamma\to eX}(x,Q^2)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2^\gamma(x,Q^2)\right]$$

photon structure function F_2^γ

QCD models can reproduce LEP data

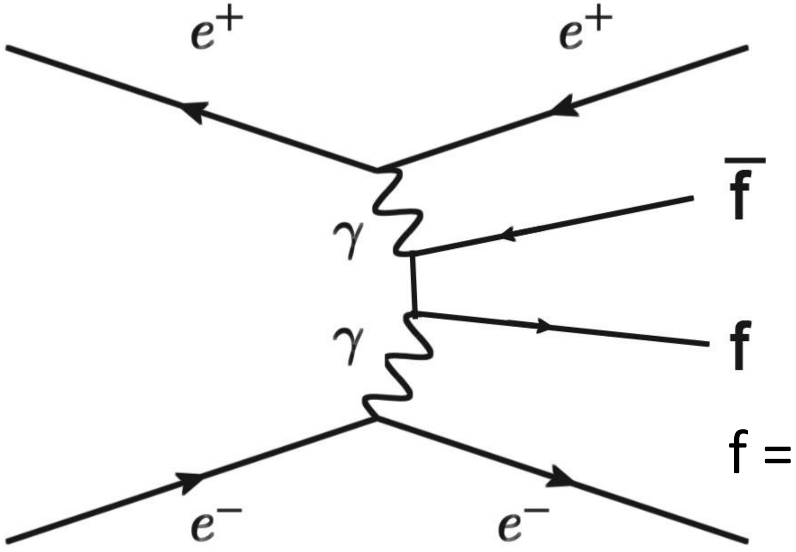


arxiv.org/abs/hep-ex/0507042

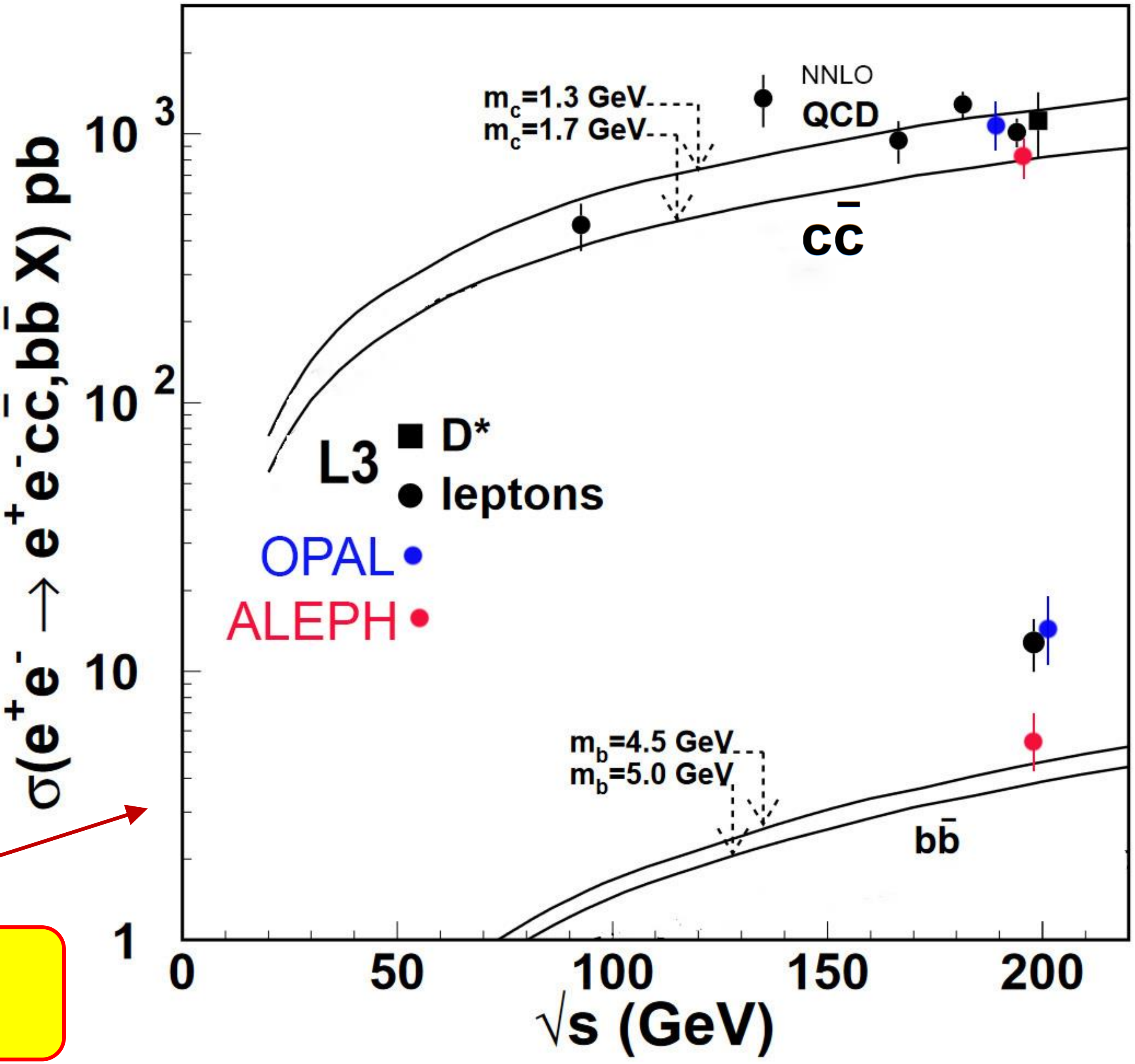
parton density functions

Two Photon Physics

heavy quark production (c,b)



f = c, b



log scale!

Charm: good matching experiments - QCD
Bottom: poor agreement

/arxiv.org/pdf/hep-ex/0507041.pdf modified

Larger context

- LEP: many QCD results,
  several still unbeaten
- LHC: remarkable precision
  also for QCD measurements
- Future e^+e^-: need hard work to
  improve further

Opportunities:
W^+W^- high statistics
H ➔ gg gluon source
top physics