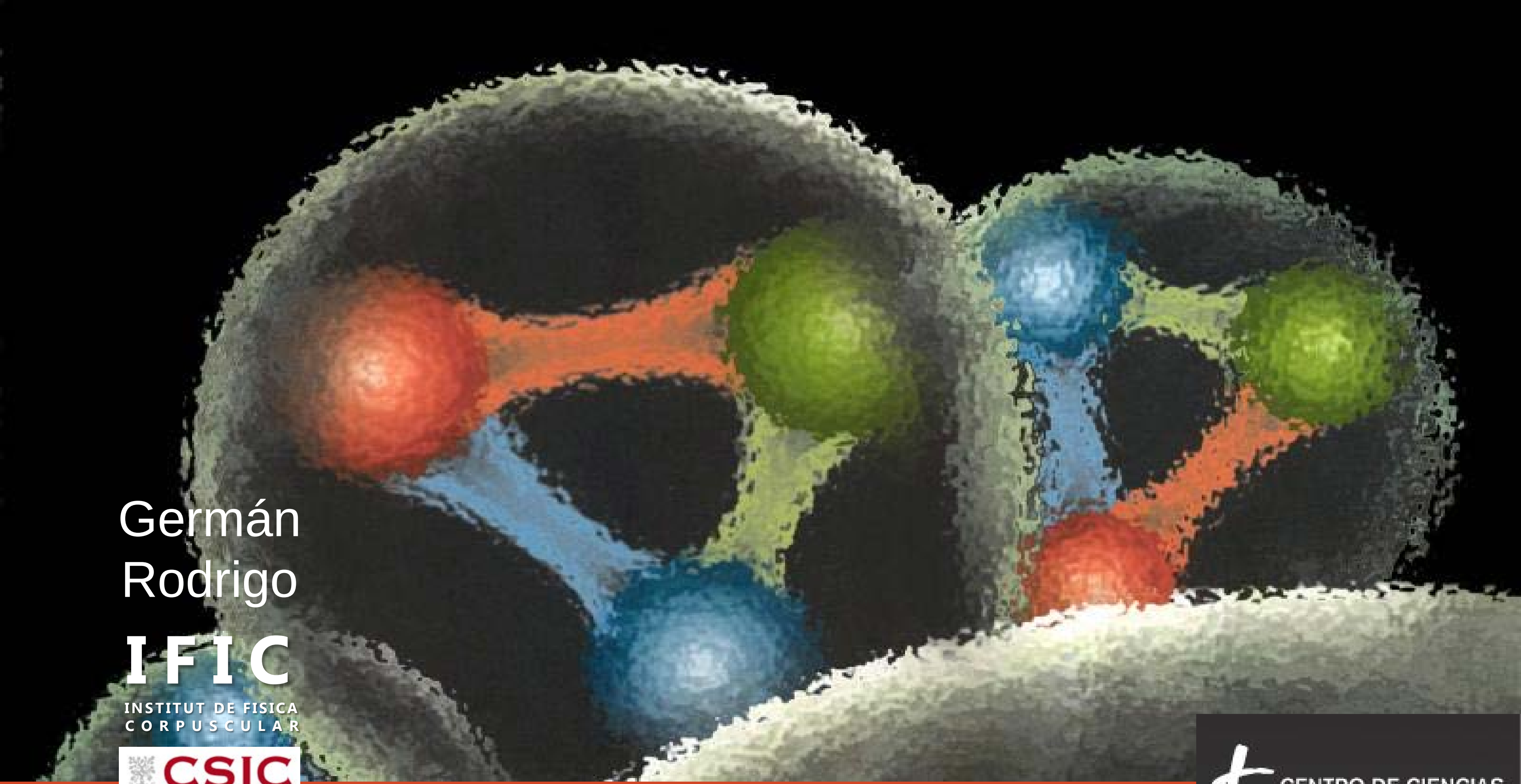

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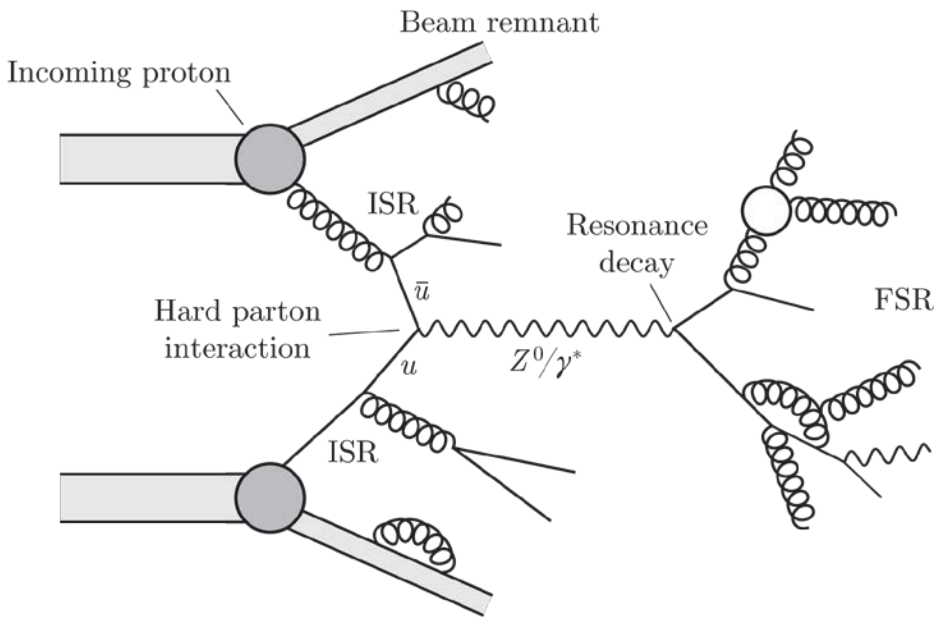
CENTRO DE CIENCIAS
DE BENASQUE
PEDRO PASCUAL

QCD, jets and Monte Carlo: 3rd lecture

Taller de Altas Energías TAE2014, September 2014

PDF

Factorization in hadronic collisions



- Factorize physics into long distance (hadronic ~ M_{had}), and short distance (partonic $Q \gg M_{\mathrm{had}}$),
- factorization violation is power supressed ~ $\mathcal{O}\left(M_{\mathrm{had}}/Q\right)^q$

Parton densities PDF

Hard scattering cross-section

$$\sigma = \sum_{a,b} \int dx_1\, dx_2\, f_a(x_1, \mu_F)\, f_b(x_2, \mu_F)\, \hat{\sigma}_{ab}(x_1 p_A, x_2 p_B; \mu_F, \mu_R) + O\left(\frac{1}{Q}\right)$$

Factorization and renormalization scales

Higher twist

Partonic cms energy $\hat{s} = x_1\, x_2\, s$

Parton distribution functions

- Non-perturbative input determined from global fits to collider data, scale evolution from pQCD (NNLO)
- Vast choice: e.g. http://hepdata.cedar.ac.uk/pdfs

The Durham HepData Project

Durham University

REACTION DATABASE • DATA REVIEWS • PDF PLOTTER   ABOUT HEPDATA • SUBMITTING DATA

HepData Compilation of Parton Distribution Functions

On-line Unpolarized Parton Distribution Calculator with Graphical Display.

Unpolarized Parton Distributions

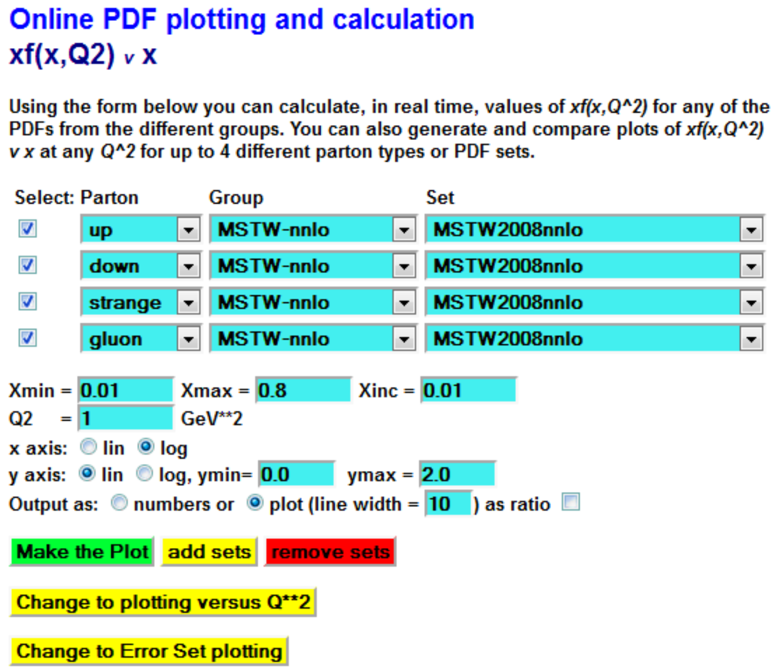
Access the parton distribution code, on-line calculation and graphical display of the distributions, from CTEQ, GRV, MRST/MSTW, Alekhin, ZEUS, H1, HERAPDF, BBG and NNPDF.

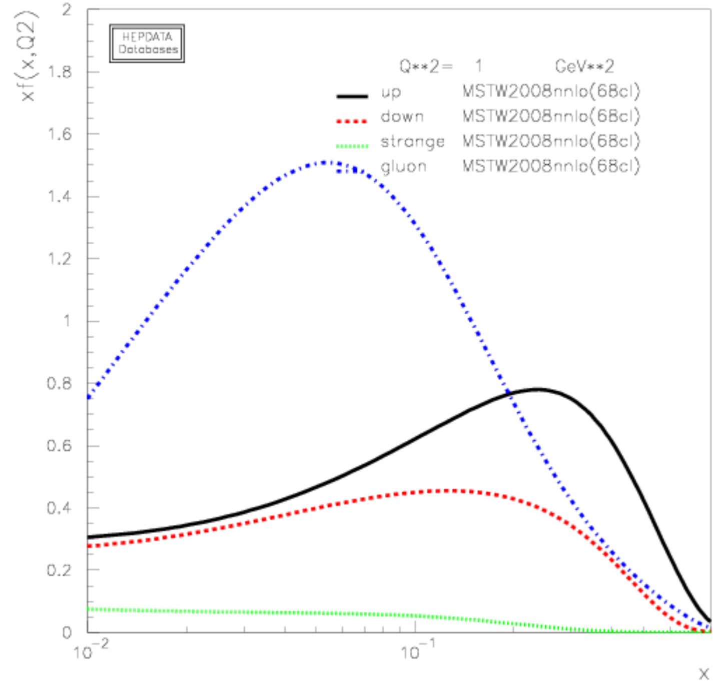
CTEQ	fortran code and grids
CTEQ-Jefferson Lab (CJ)	the CJ12 PDF sets
GRV/GJR	fortran code and grids
MRST	fortran code and grids, C++ code
MSTW	fortran, C++ and Mathematica codes + grids etc.
ALEKHIN	fortran,C++,Mathematica code, and grids
ZEUS	ZEUS 2002 PDFs, ZEUS 2005 jet fit PDFs
HERAPDF	Combined H1/ZEUS page, HERAPDF1.0 paper
H1	H1 2000
BBG	BBG06_NS
NNPDF	Non Singlet PDF code - hep-ph/0701127

Polarized Parton Distributions

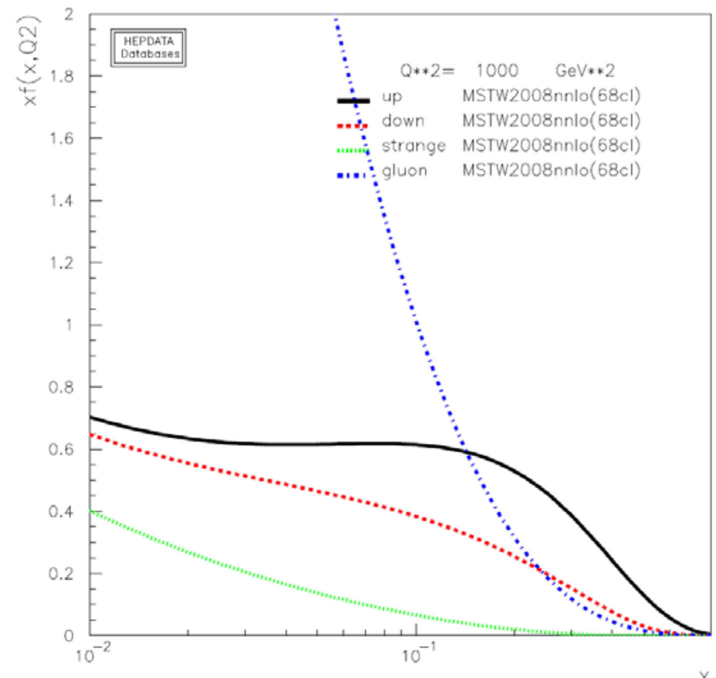
Currently available parametrizations

LSS2001	E.Leader, A.V.Sidorov and D.B.Stamenov, Eur.Phys.J.C23 (2002) 479

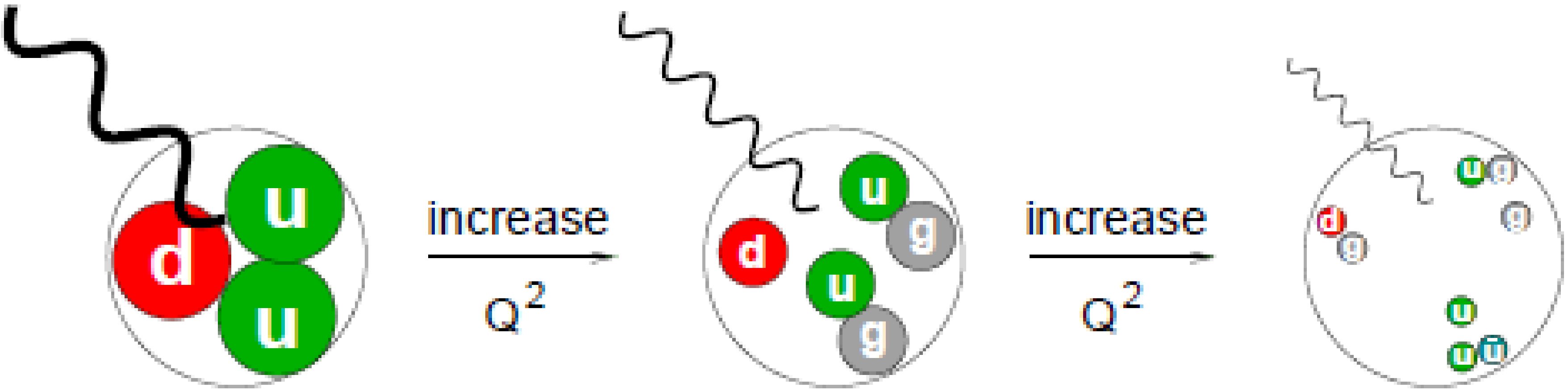




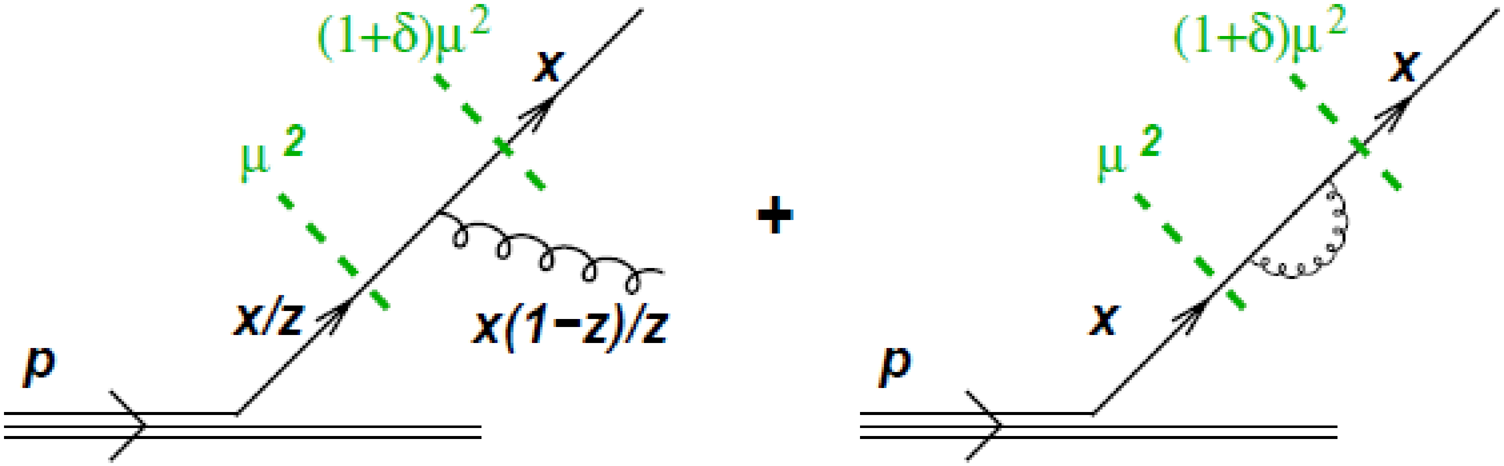
- Maximum of up and down at x = 1/3: three quarks sharing the proton momentum
- up = 2 x down
- Gluon evolves faster: color charge $C_A = 3$ versus quark color charge $C_F = 4/3$



looking inside de proton



DGLAP evolution



$$\frac{\partial q(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dz}{z} P_{q\to qg}(z)\, q(x/z,\mu^2)$$

DGLAP flavour structure

The proton contains both quarks and gluons: DGLAP is a matrix in flavour space

$$\frac{\partial}{\partial \log \mu^2} \begin{pmatrix} q \\ g \end{pmatrix} = \begin{pmatrix} P_{q\to qg} & P_{g\to q\bar{q}} \\ P_{q\to gq} & P_{g\to gg} \end{pmatrix} \otimes \begin{pmatrix} q \\ g \end{pmatrix}$$

spanning over all flavours and anti-flavours

$$P_{q\to qg} = C_F \left(\frac{1+z^2}{1-z} \right)_+$$

$$P_{q\to gq} = C_F \frac{1+(1-z)^2}{z}$$

$$P_{g\to q\bar{q}} = T_R[z^2 + (1-z)^2]$$

$$P_{g\to gg} = 2C_A \left[\frac{z}{(1-z)_+} + \frac{1-z}{z} + z(1-z) \right] + \delta(1-z) b_0$$

with the plus-prescription

$$\int_0^1 dz\, [g(z)]_+ \, f(z) = \int_0^1 dz\, g(z)\, [f(z) - f(1)]$$

PDFs: strategy in a nutshell

- Make an ansatz for the functional form of the PDFs at some fixed value low scale $Q_0^2 \sim 1\ \mathrm{GeV}^2$
  e.g. in MRST/MSTW

$$x\, u_V = A_u\, x^{\eta_1}\, (1-x)^{\eta_2}\, (1+\epsilon_u \sqrt{x} + \gamma_u\, x) \qquad u_V = u - \bar{u}$$

$$x\, d_V = A_d\, x^{\eta_3}\, (1-x)^{\eta_4}\, (1+\epsilon_d \sqrt{x} + \gamma_d\, x) \qquad d_V = d - \bar{d}$$

$$x\, g = A_g\, x^{-\lambda_g}\, (1-x)^{\eta_g}\, (1+\epsilon_g \sqrt{x} + \gamma_g\, x)$$

Note: NNPDF use neural networks and does not need such explicit functional form

- Collect data at various (x, Q^2) from different experiments (e.g. DIS), use DGLAP equation to evolve down to Q_0^2 and fit parameters, including α_S

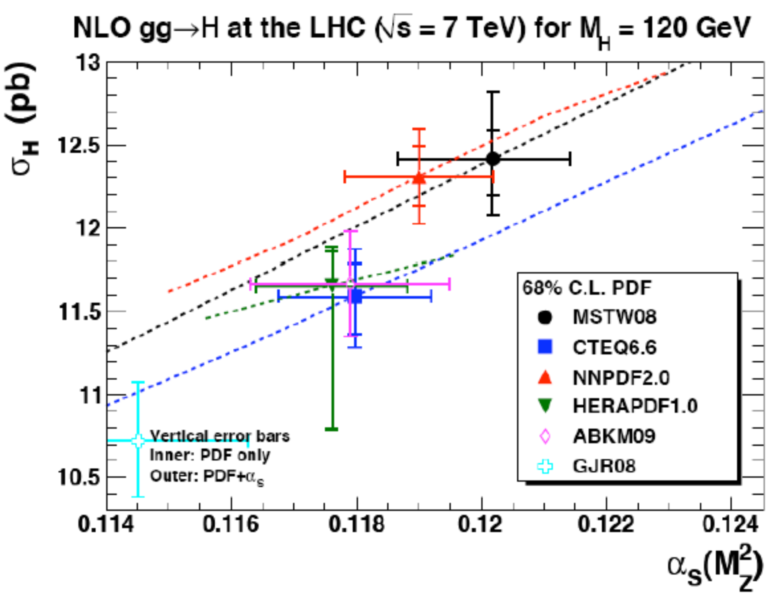
- Ensure sum rules (Gottfried, momentum, ...): $$\int dx\, x \sum_i f_i(x, Q^2) = 1$$

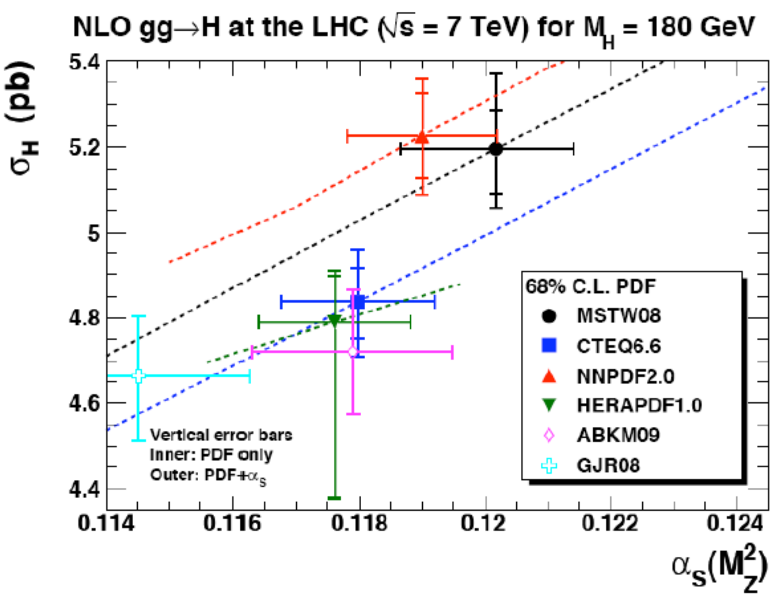
Parton distribution functions

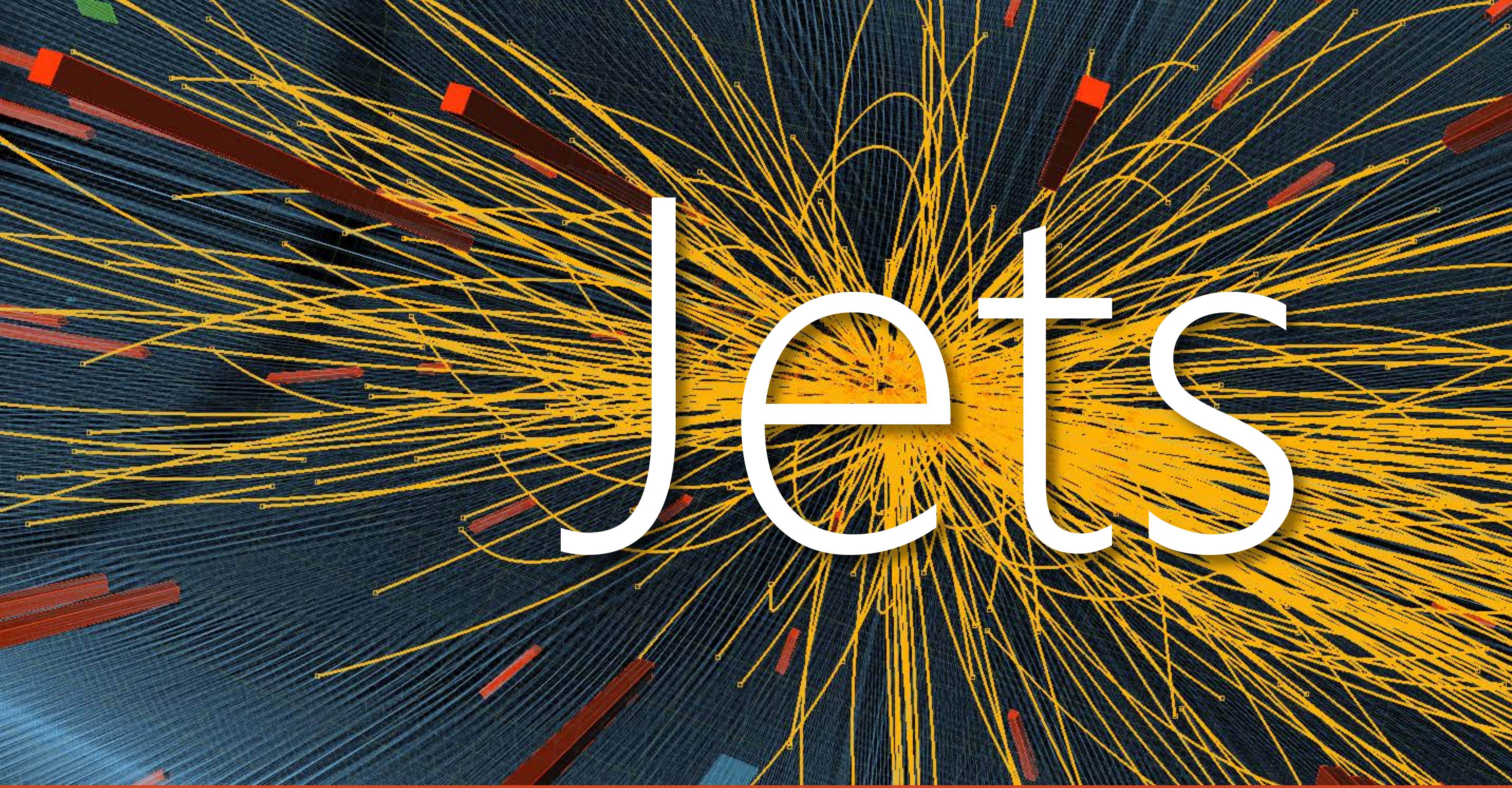
- Differences are due to different:

Data sets in fits, parameterization of starting distributions, order of pQCD evolution, power law contributions, nuclear target corrections, resummation corrections (ln 1/x, ...), treatment of heavy quarks, strong coupling, choice of factorization and renormalization scales.

- at least 5-10% uncertainty in theoretical predictions







Jets

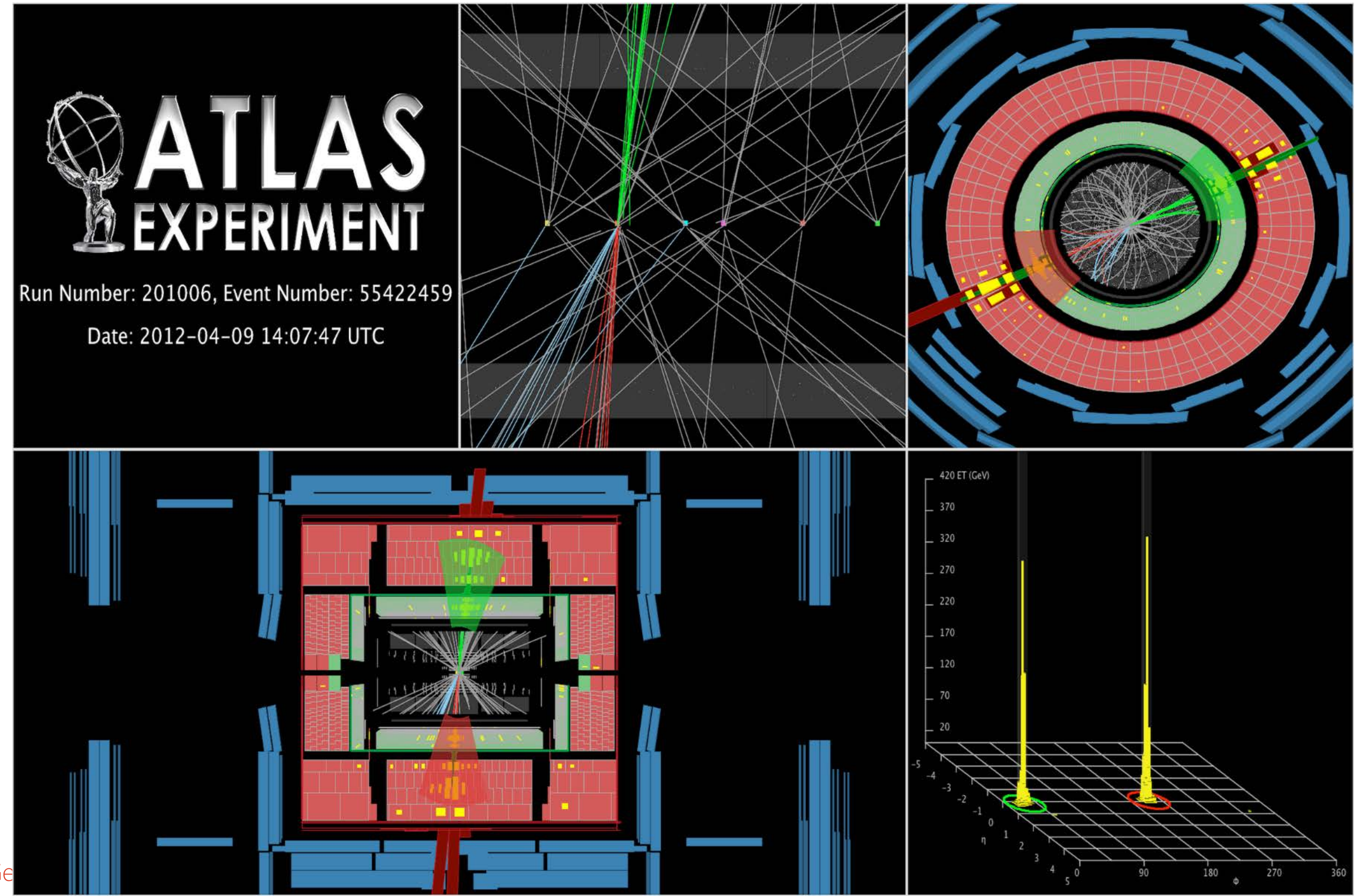
What´s a jet

- a bunch of energetic and collimated particles
- 60% of LHC papers use jets [Salam, Soyez]

High mass central di-jet event

A track p_T cut of 0.5 GeV has been applied for the display.

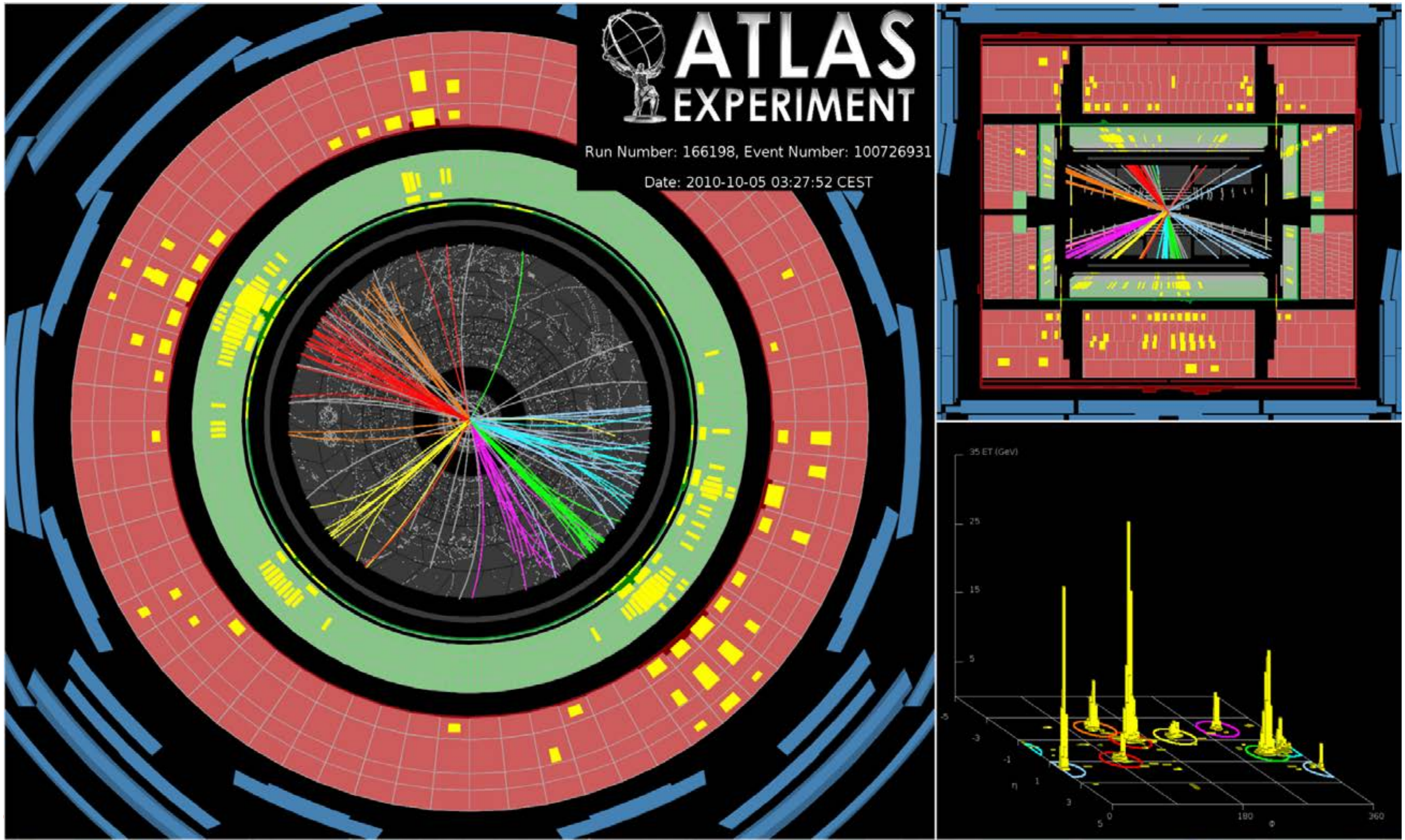
- 1st jet (ordered by p_T): p_T = 1.96 TeV, η = -0.07, φ = -2.68
- 2nd jet: p_T = 1.65 TeV, η = 0.17, φ = 0.48
- Missing E_T = 318 GeV, φ = 0.43
- Sum E_T = 3.81 TeV



A high jet multiplicity event

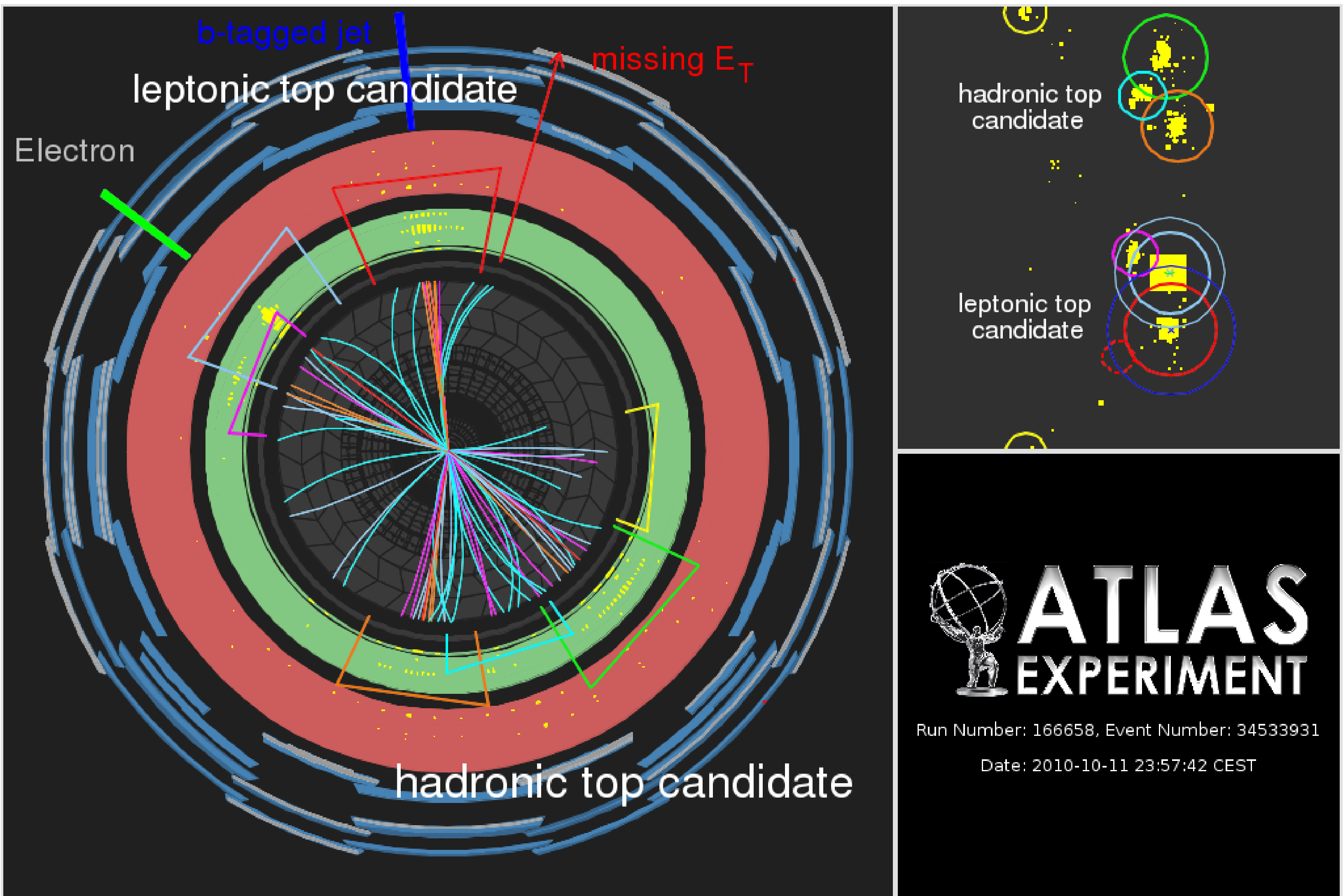
counting jets with p_T greater than 60 GeV: this event has eight

- 1st jet (ordered by p_T): p_T = 290 GeV, η = -0.9, φ = 2.7
- 2nd jet: p_T = 220 GeV, η = 0.3, φ = -0.7
- missing E_T = 21 GeV, φ = -1.9
- sum E_T = 890 GeV



Display of a semi-leptonic top quark pair event

at high invariant mass (714 GeV)
The top quark boosts lead the decay products to be collimated, albeit still distinguishable using standard reconstruction algorithms.



Why and how do we see jets?

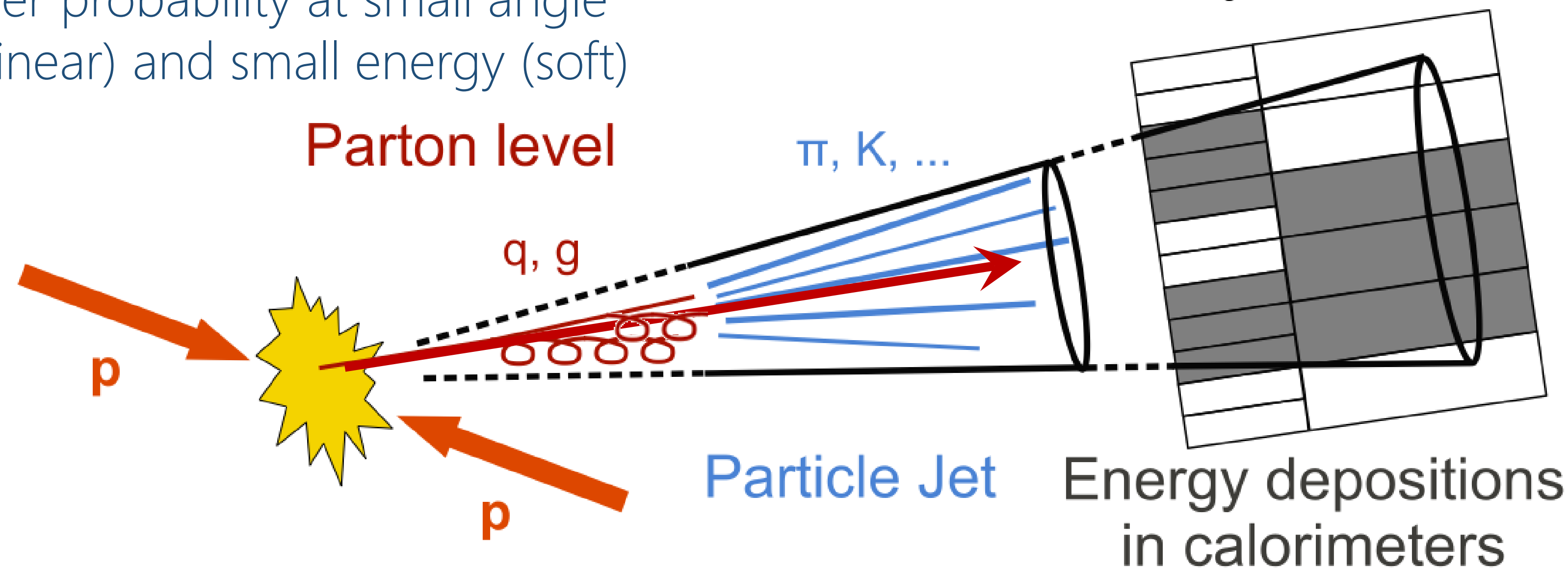
Gluon emission

$$\int \alpha_S \frac{dE}{E}\frac{d\theta}{\theta} \gg 1$$

higher probability at small angle (collinear) and small energy (soft)

Non-perturbative transition to hadrons

$$\alpha_S \sim 1 \quad \Lambda_{QCD} \sim 200\text{MeV}$$



hard partons $\xleftarrow{\text{interpretation}}$ $\{j_k\}$ jets $\xleftarrow{\text{jet definition}}$ $\{p_i\}$ final-state 4-momenta

Jet clustering algorithms at e^+e^- colliders

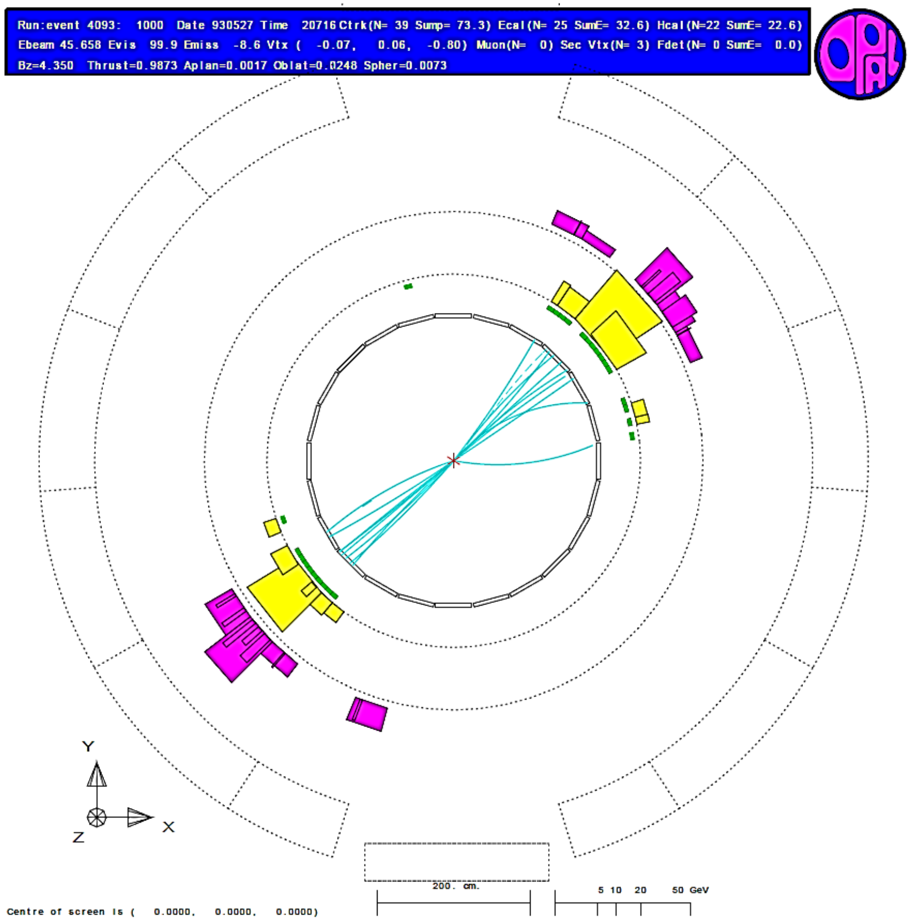
- Iterative and univocal procedure that tries to reverse the pattern of QCD multi-parton emissions

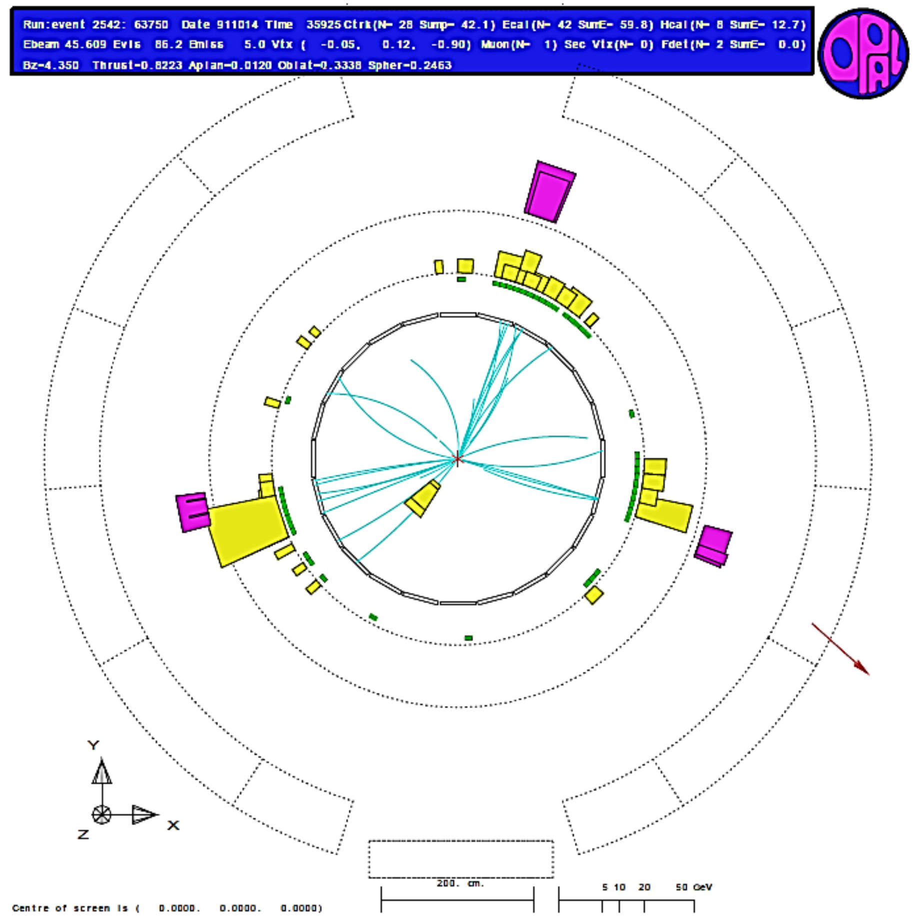
Define a distance d_{ij} between all pairs of particles

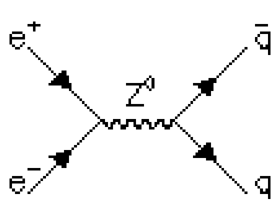
JADE	$2(E_i E_j)(1-\cos\theta_{ij})/s$
DURHAM(k_T)	$2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})/s$
CAMBRIDGE	DURHAM + angular ordering

- Compute the smallest distance d_{ij}
- then cluster i and j together ($p_i \to p_i + p_j$) if $d_{ij} < y_{cut}$ (jet resolution parameter)
- Repeat until all $d_{ij} > y_{cut}$
- Number of jets equals number of final-state (pseudo)particles ≈ underlying partonic hard process
- Jet clustering algorithms are IR safe

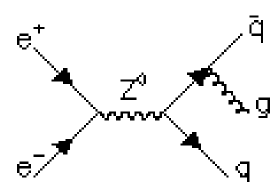
- Jet clustering algorithms were extensively used at LEP: but Tevatron used cones: good experimental behavior but not infrared safe

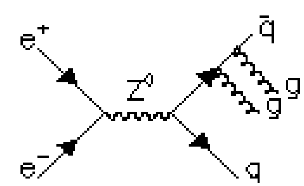




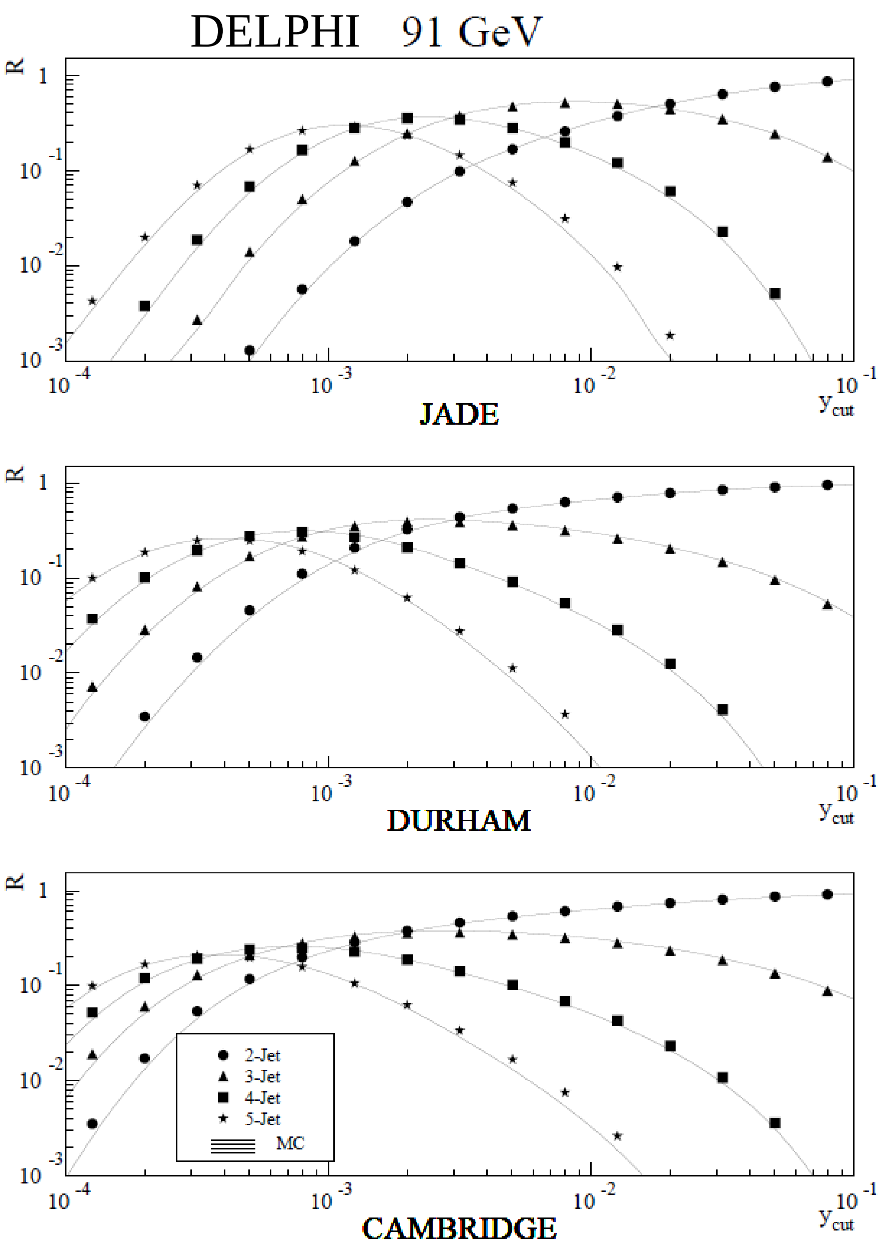


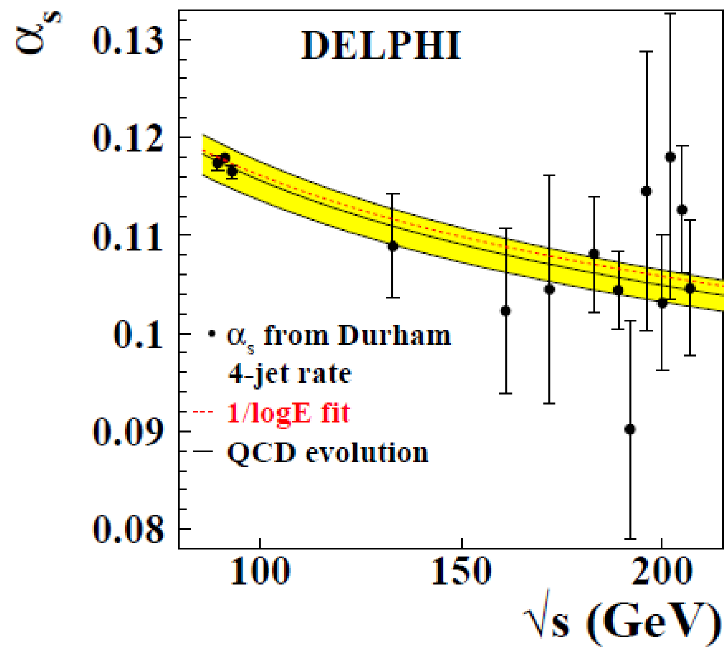
- Clearly a two-jet event

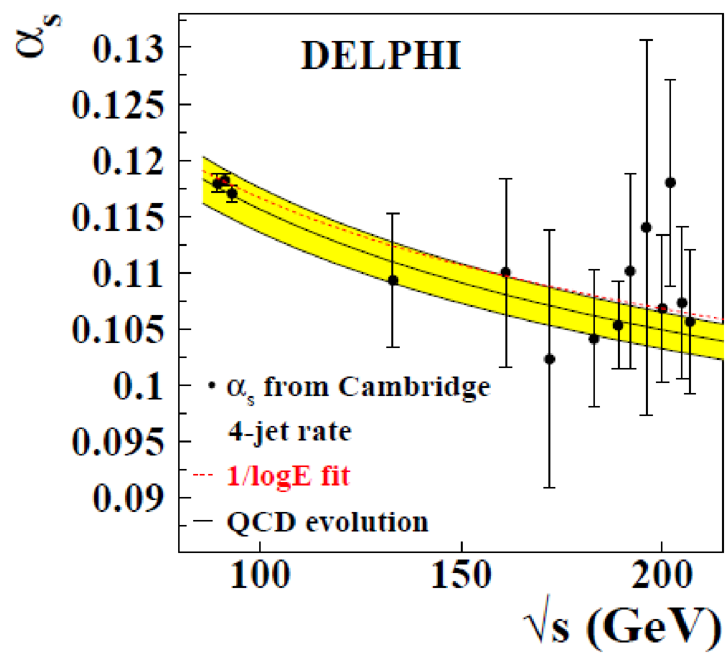




- Three- or four-jet event ?
- Depends on the jet resolution parameter


DELPHI 91 GeV
R
JADE
DURHAM
CAMBRIDGE
y_{cut}
2-Jet
3-Jet
4-Jet
5-Jet
MC


α_s
DELPHI
α_s from Durham 4-jet rate
1/logE fit
QCD evolution
$\sqrt{s}$ (GeV)


α_s
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α_s from Cambridge 4-jet rate
1/logE fit
QCD evolution
$\sqrt{s}$ (GeV)

The k_T jet algorithm at hadron colliders

[Catani, Dokshitzer, Seymour, Webber, 93]
[Ellis, Soper, 93]

What changes at hadron colliders ?

- There a beams, then introduce "beam distance": $d_{iB} = p_{Ti}^2 = 2E_i^2(1 - \cos\theta_{iB})$
- Preference to use longitudinal invariant variables: transverse momenta (p_T), rapidity (Δy) and azimuthal angle (ϕ)

Inclusive k_T

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\frac{\Delta R_{ij}^2}{R^2} \quad d_{iB} = p_{Ti}^2 \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- Compute the smallest distance d_{ij} or d_{iB}
- If d_{ij}, cluster i and j together
- If d_{iB}, call i a jet and remove from the list of particles
- Repeat until no particle is left
- Two parameters: R and minimal transverse momentum $p_{Ti} > p_{T,min}$

The anti-k_T jet algorithm

[Cacciari, Salam, Soyez 08]

- **k_T has a physical meaning:** the stronger the divergence between a pair of particles, the more likely it is they should be associated with each other
- However, **ATLAS and CMS** have adopted **anti-k_T** as default

anti-k_T

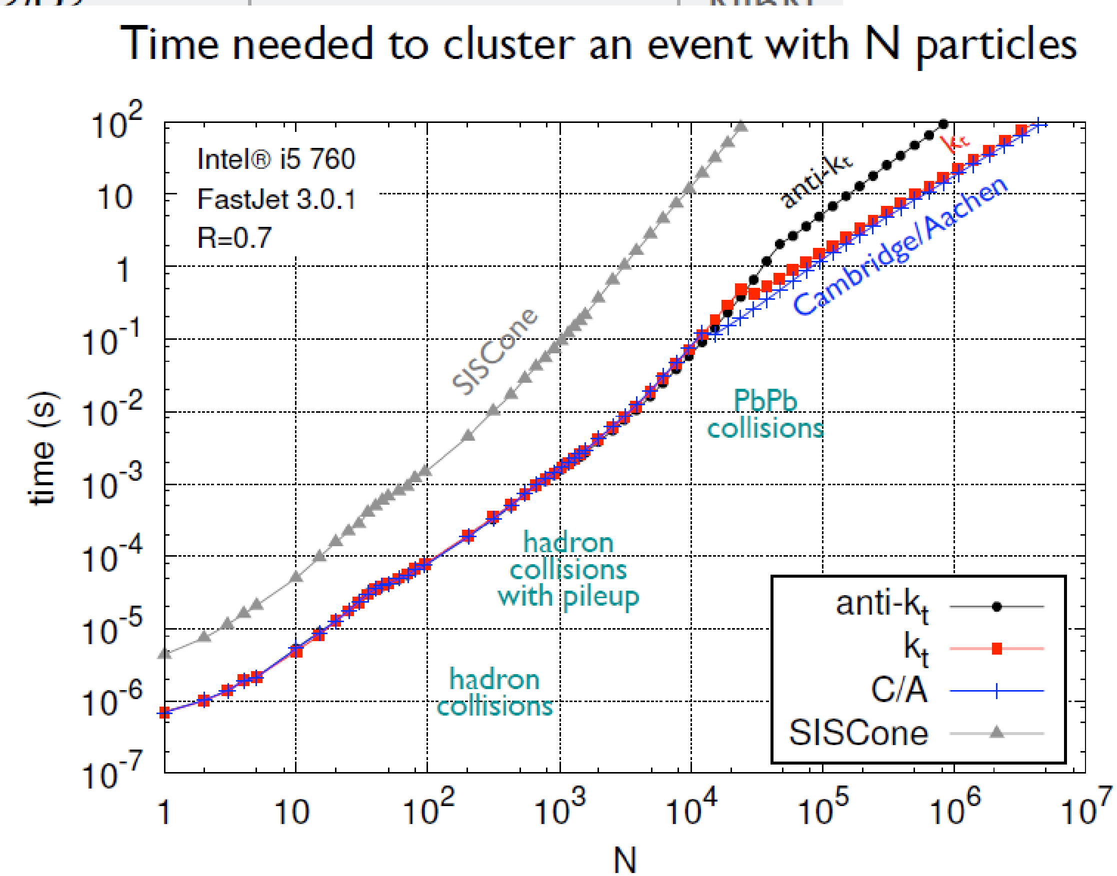
$$d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2} \quad d_{iB} = p_{Ti}^{-2} \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- Clusters hardest particles first
- IRC safe, and cone-shaped jets
- Easier to get jet energy scale right
- CAMBRIDGE/AACHEN: $d_{ij} = \Delta R_{ij}/R^2$

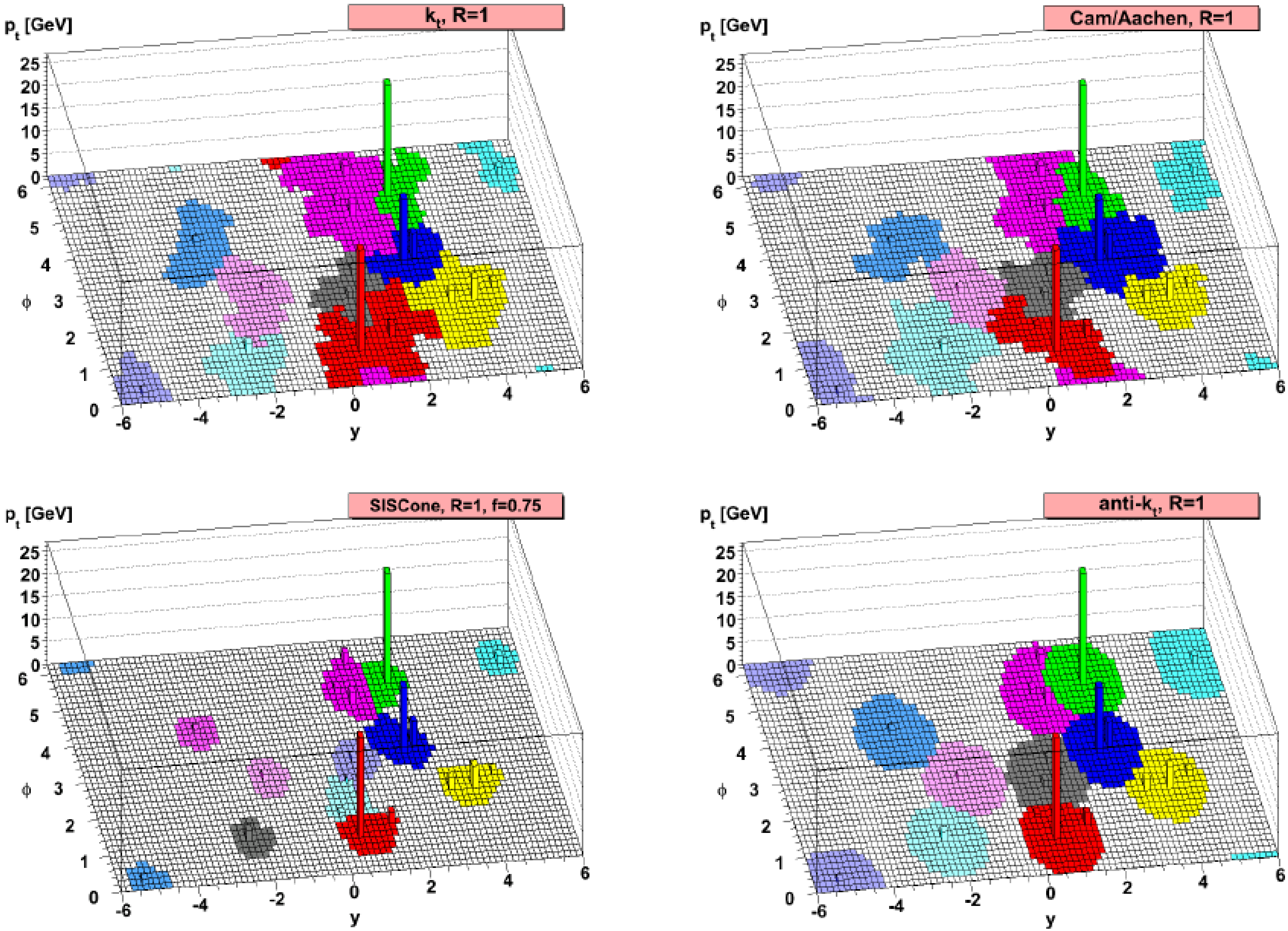
For the first time ever, a hadron collider will carry out measurements that can be consistently compared with theoretical (perturbartive QCD) calculations

k_t	sequential recombination $d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$ hierarchical in relative p_t	Catani et al '91 Ellis, Soper '93	NlnN
Cambridge/ Aachen	sequential recombination $d_{ij} = \Delta R_{ij}$ hierarchical i	Dokshitzer et al '97	[illegible]
anti-k_t	sequential rec $d_{ij} = \min(k_{ti}^{-2}, k_{tj}$ gives perfectly con		
SISCone	Seedless itera with split- gives 'econom		

http://fastjet.fr



[Cacciari, Salam, Soyez 08]



Jet substructure

[Almeida, Butterworth, Cacciari, Chen, Davison, Ellis, Falkowsky, Han, Katz, Kim, Kribs, Krohn, Lee, Martin, Nojiri, Perez, Plehn, Racklev, Rehermann, Roy, Rojo, Rubin, Salam, Shelton, Sreethawong, Son, Soyez, Sung, Thaler, Tweedie, Schwartz, Seymour, Soper, Spannowski, Sterman, Virzi, Vos, Wang, Zhu, ...]

The LHC is the first place where heavy particles (~ 100 GeV) are produced copiously well **above threshold**

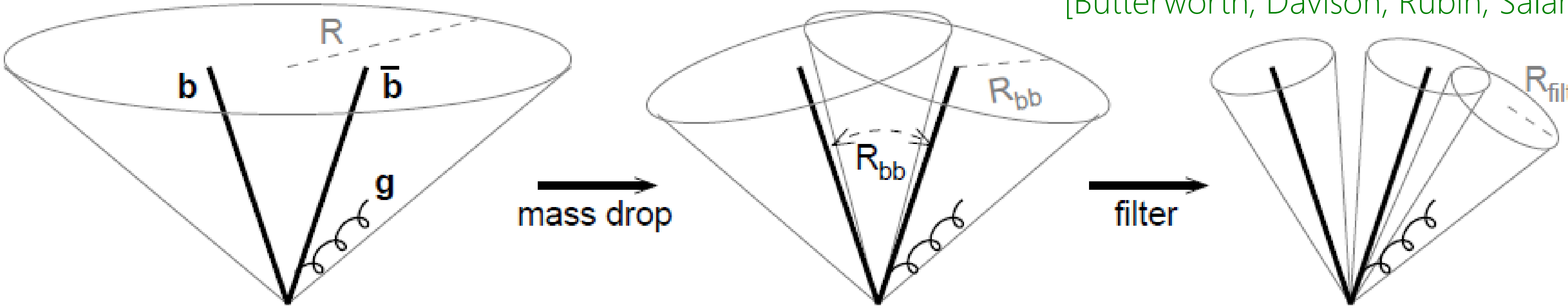
They are often very **boosted**, and decay hadronically

Decay products appear as a **single jet**

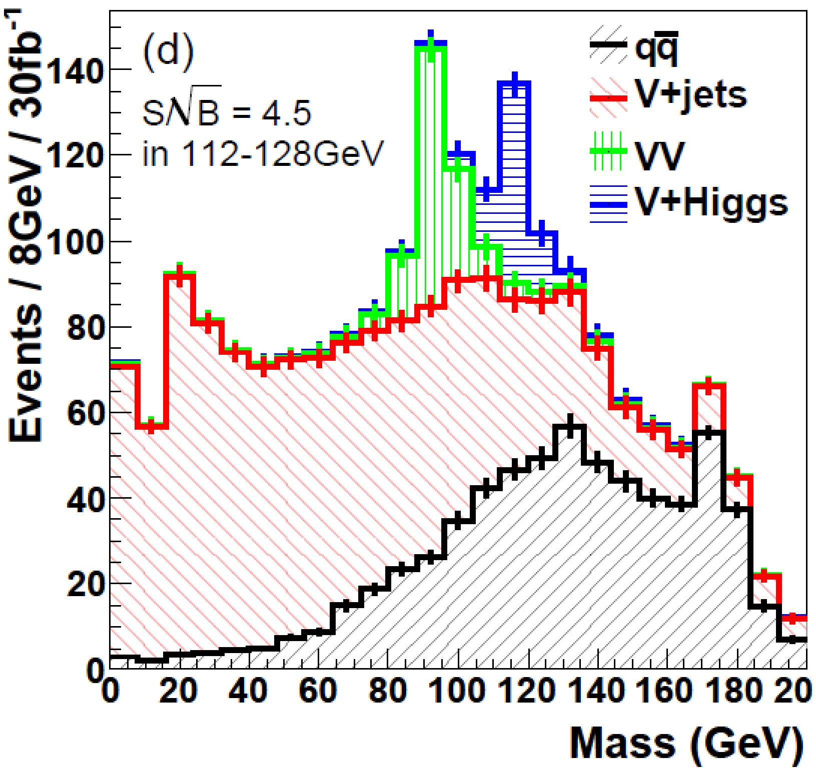
Need to examine the jet substructure to get the physics out

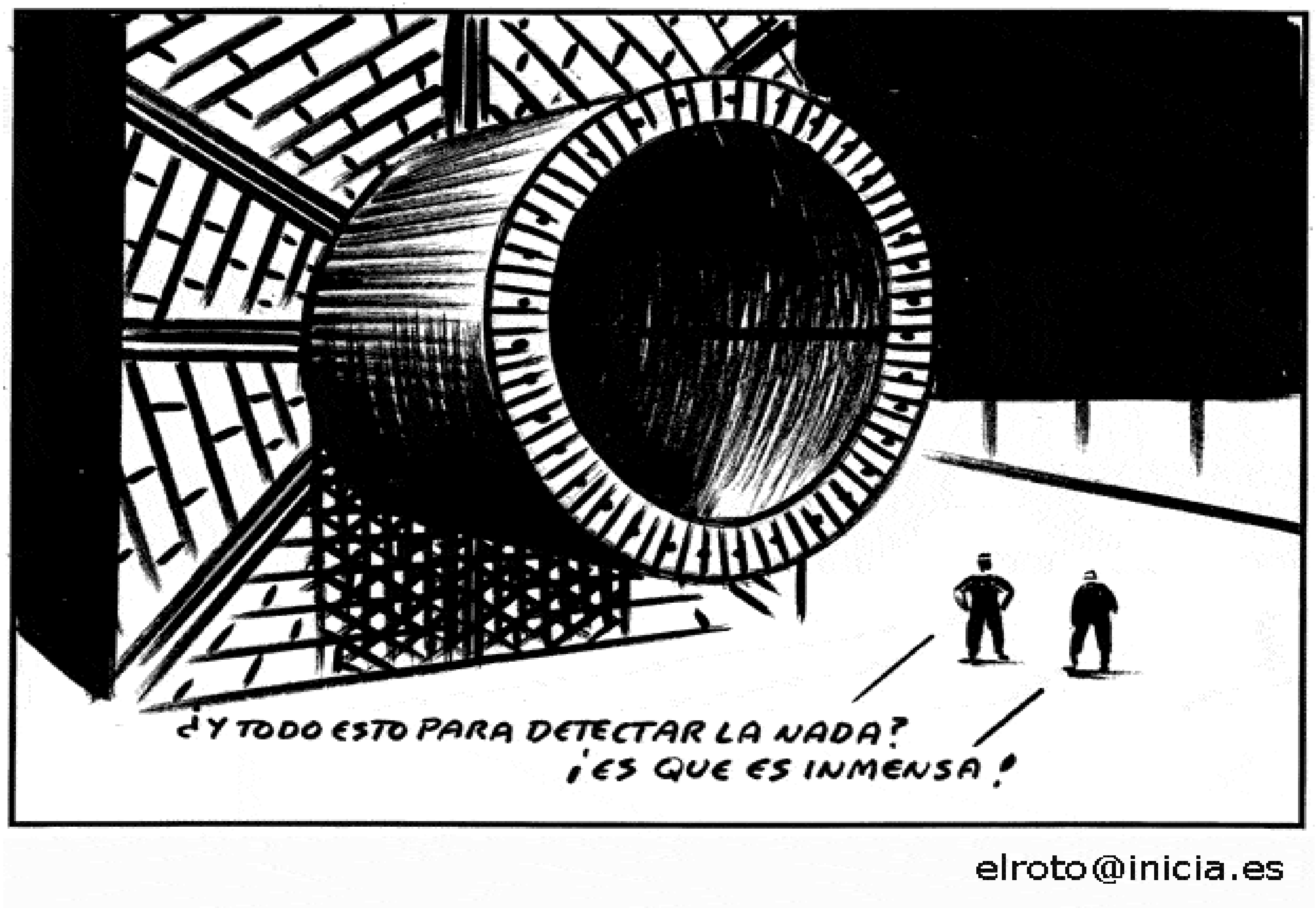
e.g. ZH, WH with H→ $b\bar{b}$

[Butterworth, Davison, Rubin, Salam 08]



- High p_T Higgs boson decaying to $b\bar{b}$: back-to-back to the Z/W
- Lower rates compensated by reduced backgrounds
- Recovers ZH and WH as significant channels for a light Higgs discovery (and couplings determination)




¿Y TODO ESTO PARA DETECTAR LA NADA?
¡ES QUE ES INMENSA!
elroto@inicia.es

Why and how do we see jets?

Gluon emission

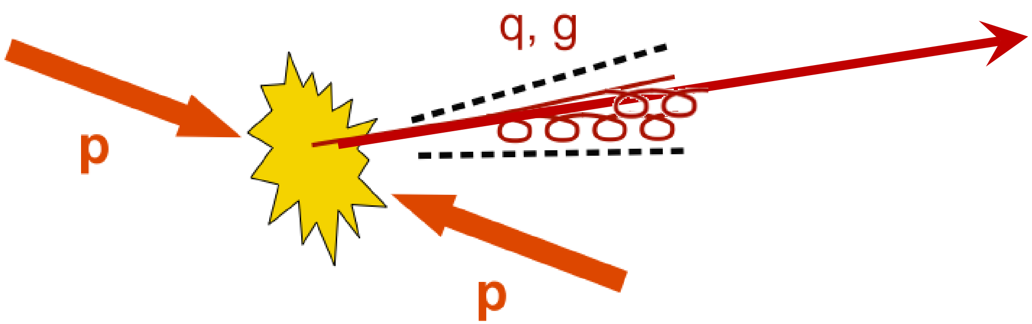
$$\int \alpha_S \frac{dE}{E} \frac{d\theta}{\theta} \gg 1$$

higher probability at small angle (collinear) and small energy (soft)

Non-perturbative transition to hadrons

$$\alpha_S \sim 1 \quad \Lambda_{QCD} \sim 200\text{MeV}$$

Parton level



$$\{j_k\} \xleftarrow{\text{jet definition}} \{p_i\}$$

jets — final-state 4-momenta