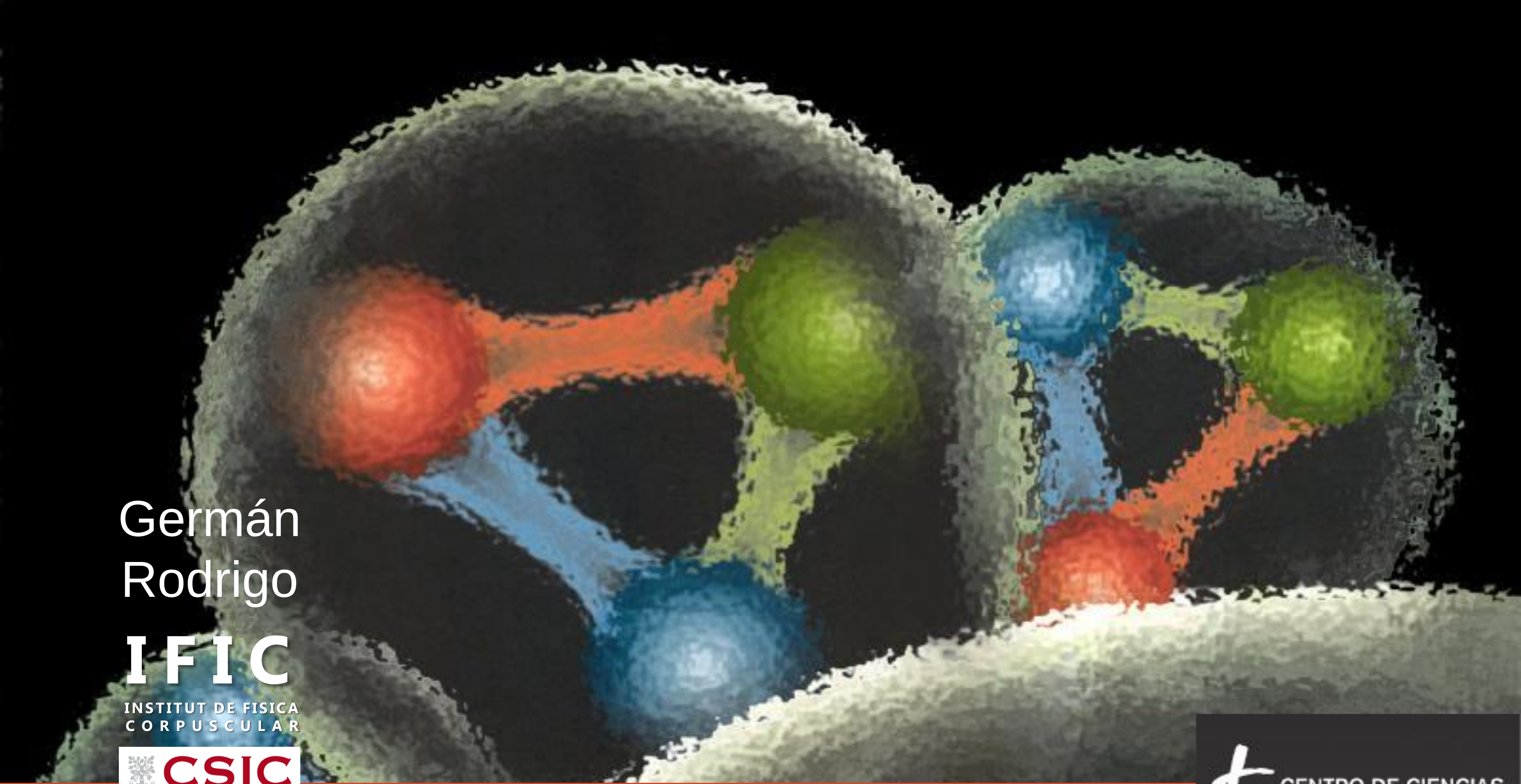

Germán Rodrigo

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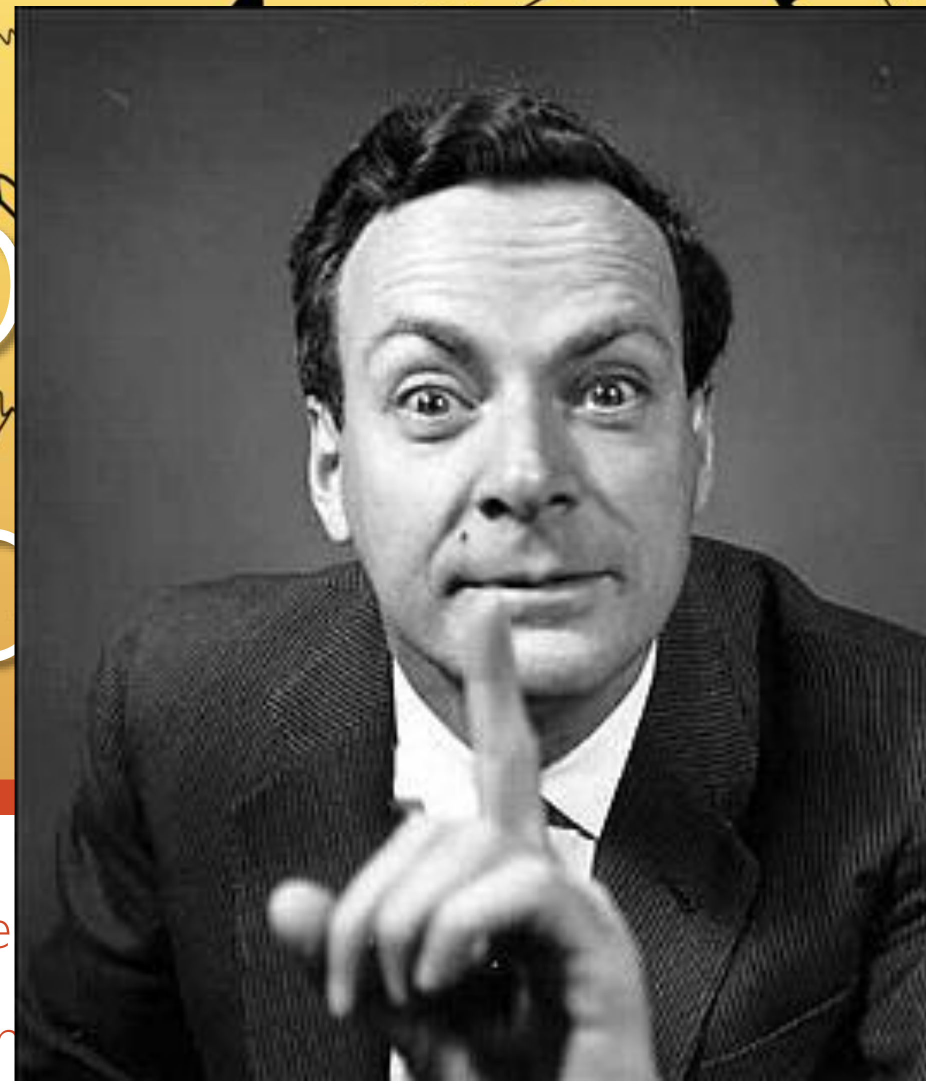
CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

QCD: 2nd lecture

Taller de Altas Energías TAE2015, September 2015

New perturb metho



- To reach a new frontier in highe
- But also to better understand th

One-loop amplitudes

The classical paradigm for the calculation of one-loop diagrams was established in **1979**

Calculation of one-loop scalar integrals

Reduction of tensor one-loop integrals to scalar integrals

Nuclear Physics B
Volume 153, 1979, Pages 365-401

Scalar one-loop integrals

G. 't Hooft, M. Veltman

Received 16 January 1979

Nuclear Physics B
Volume 160, 26 Nov 1979, Pages 151-207

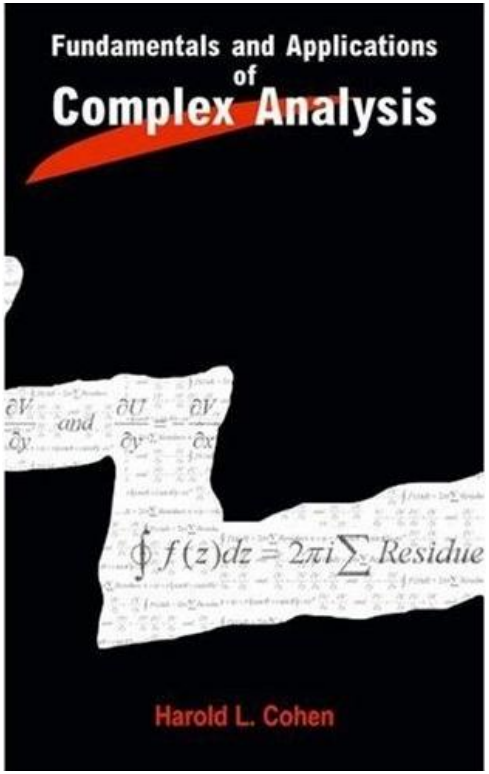
One-loop corrections for e+e− annihilation into μ+μ− in the Weinberg model

G. Passarino, M. Veltman

Received 22 March 1979

Not adequate for processes beyond 2→2
(Gramm determinants+large number of Feynman diagrams)

Recursion relations and unitarity methods



Properties of the S-Matrix

- **Analyticity:** scattering amplitudes are determined by their singularities
- **Unitarity:** the residues at singular points are products of scattering amplitudes with lower number of legs and/or less loops

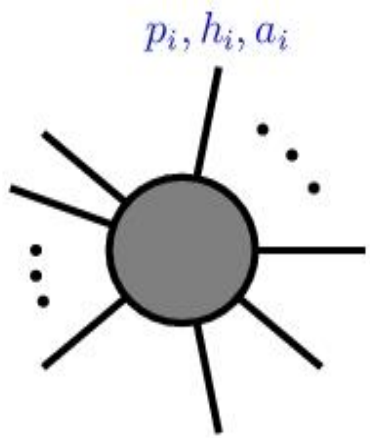
Here are the words of some enthusiast: "One of the most remarkable discoveries in elementary particle physics has been that of the existence of the complex plane", "... the theory of functions of complex variables plays the role not of a mathematical tool, but of a fundamental description of nature inseparable from physics … ."

J. Schwinger, *Particles, Sources, and Fields*, Vol.1, p.36

- **recycling:** using scattering amplitudes to calculate other scattering amplitudes

Spinors

[Xu,Zhang,Chang, Berends, Kleiss, De Causmaeker, Gastmans, Wu,Gunion, Kunzst]



Four-dimensional spinors of definite helicity

$$|i^\pm\rangle = \frac{1}{2}(1 \pm \gamma_5)u(p_i) = v_\mp(p_i)\ , \qquad \langle i^\pm| = \bar{u}_\pm(p_i) = \bar{v}_\mp(p_i)$$

$$p_i^2 = 0\ , \qquad p_i^{a\dot{a}} = k_i^\mu \sigma_\mu^{a\dot{a}} = \lambda_i^a \tilde{\lambda}_i^{\dot{a}}$$

- spinor inner products and other useful identities

$$\langle ij\rangle = \langle i^-|j^+\rangle = \varepsilon_{ab}\lambda_i^a\lambda_j^b = \sqrt{|s_{ij}|}e^{i\phi_{ij}} = -\langle ji\rangle \qquad \text{holomorphic}$$

$$[ij] = [i^+|j^-] = \varepsilon_{\dot{a}\dot{b}}\tilde{\lambda}_i^{\dot{a}}\tilde{\lambda}_j^{\dot{b}} = -\langle ij\rangle^* = -[ji] \qquad \text{antiholomorphic}$$

$$[i|\gamma^\mu|j\rangle = \langle j|\gamma^\mu|i]$$

$$s_{ij} = (p_i + p_j)^2 = \langle ij\rangle[ji]$$

$$\not{p}_i = |i\rangle[i| + |i]\langle i| \qquad \text{sum over polarizations}$$

$$\not{p}_i|i^\pm\rangle = 0 \qquad \text{equation of motion} \qquad \langle ij] = 0 = \langle ii\rangle$$

- polarization vector $\qquad \epsilon^2 = 0\ , \quad \epsilon^+ \cdot \epsilon^- = 0\ , \quad k \cdot \epsilon^\pm(k) = 0$

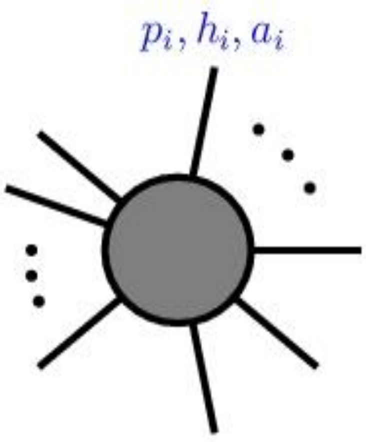
$$\epsilon_\mu^+(k,\xi) = \frac{\langle\xi|\gamma_\mu|k]}{\sqrt{2}\langle\xi k\rangle}$$

$$\epsilon_\mu^-(k,\xi) = \frac{[\xi|\gamma_\mu|k\rangle}{\sqrt{2}[k\xi]}$$

- equivalent to **axial gauge** $\boldsymbol{\xi = n}$
- a clever choice of the gauge momentum can simplify calculations

Spinors

[Xu,Zhang,Chang, Berends, Kleiss, De Causmaeker, Gastmans, Wu,Gunion, Kunzst]



- spinor identities

$$\langle 1|\gamma^\mu|2]\,[3|\gamma_\mu|4\rangle = 2\langle 14\rangle[32] \qquad \text{Fierz}$$

$$\langle 12\rangle\langle 34\rangle = \langle 14\rangle\langle 32\rangle + \langle 13\rangle\langle 24\rangle \qquad \text{Shouten}$$

Exercise: proof the Fierz and Shouten identities

Hint: divide and multiply by **⟨23⟩** and apply the Dirac identity $\gamma^\mu\gamma^\nu\gamma^\sigma\gamma_\mu = 4g^{\nu\sigma}$

Exercises:

Calculate the scattering amplitudes and square amplitude for $e^+e^- \to q\bar{q}$ by using the helicity method, and compare with the traditional calculation

How many independent helicity amplitudes there are ?

$$M_{e^+e^-\to q\bar{q}} \sim [\bar{u}(p_1)\gamma^\mu v(p_2)]\,[\bar{v}(p_3)\gamma^\nu u(p_4)]\,d_{\mu\nu}(p_{12},n)$$

$$|M|^2 \sim \mathrm{Tr}(\not{p}_1\gamma^\mu\not{p}_2\gamma^\sigma)\mathrm{Tr}(\not{p}_3\gamma^\nu\not{p}_4\gamma^\rho)d_{\mu\sigma}(p_{12},n)d_{\nu\rho}(p_{12},n)$$

On-shell recursion relations at tree-level: BCFW

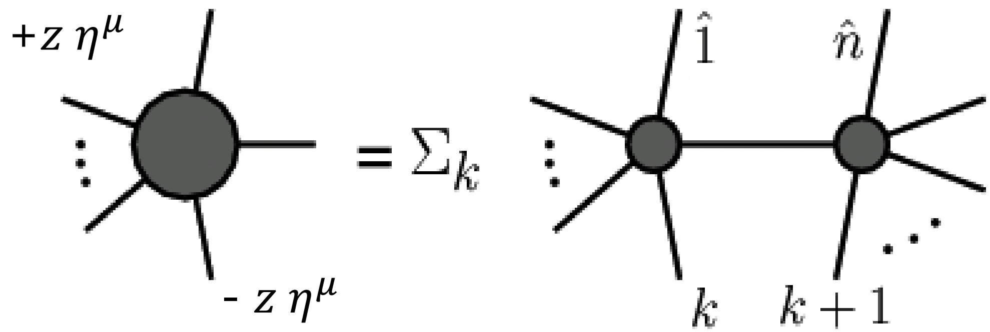
[Britto, Cachazo, Feng, Witten]

How to reconstruct scattering amplitude from its singularities

Add $z\,\eta^\mu$ (z complex) to the four-momentum of one external particle and subtract it on another such that the shift leaves them on-shell

$$0 = \frac{1}{2\pi i}\oint_{C\,\mathrm{at}\,\infty} \frac{A_n(z)}{z} = A_n(0) - \sum_{z_i} \frac{\mathrm{Res}_{z_i}(A_n(z))}{z_i}$$

has the correct residue at any multi-particle pole



$$A_n(1,2,\ldots,n) = \sum A_L(\hat{1},2,\ldots,-\hat{p}_{1,k})\,\frac{i}{s_{1,k}}\,A_R(\hat{p}_{1,k},k+1,\ldots,\hat{n})$$

- Diagrammatic proof [Draggiotis, Kleiss, Lazopoulos, Papadopoulos]
- Compact analytical results, although colour dressed Berends-Giele (off-shell recursion) might be more efficient numerically [Duhr, Höche, Maltoni]

in practice

holomorphic shift ((-,+) is not a safe shift)

$$\hat{p}_i^\mu = p_i^\mu + \frac{z}{2}[i|\gamma^\mu|j\rangle \qquad |\hat{i}\rangle = |i\rangle + z|j\rangle \qquad |\hat{i}] = |i]$$

$$\hat{p}_j^\mu = p_j^\mu - \frac{z}{2}[i|\gamma^\mu|j\rangle \qquad |\hat{j}\rangle = |j\rangle \qquad |\hat{j}] = |j] - z|i]$$

anti-holomorphic shift (i ↔ j)

z determined setting on-shell the intermediate momenta

$$\hat{p}_{1,k}^\mu = p_{1,k}^\mu + \frac{z}{2}[i|\gamma^\mu|j\rangle \;, \qquad \hat{p}_{1,k}^2 = 0 \;, \qquad z = -\frac{s_{1,k}}{[i|p_{1,k}|j\rangle}$$

- ☑ use only on-shell amplitudes
- ☑ rather compact expressions
- ☒ generates spurious poles at $[i|p_{1,k}|j\rangle$

  while physical IR divergences at $s_{i,j} = (p_i + p_{i+1} + \ldots + p_j)^2$

Exercises:

Proof by induction that the Maximal Helicity Violating (MHV) amplitude for gluons is given by the expression

$$A_n(1^+,\ldots,i^\pm,\ldots,n) = 0$$

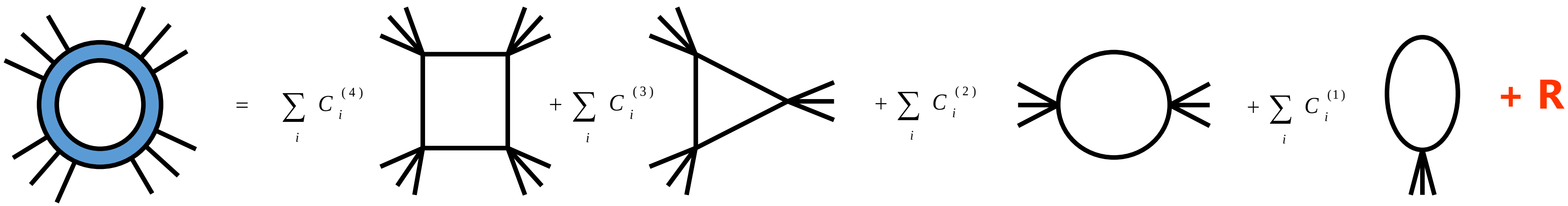
$$A_n^{\mathrm{MHV}}(1^+,\ldots,i^-,\ldots,j^-,\ldots,n^+) = i\,\frac{\langle ij\rangle^4}{\langle 12\rangle\langle 23\rangle\cdots\langle (n-1)n\rangle\langle n1\rangle}$$

Calculate by using BCFW the six-gluon amplitude

$$A_6(1^+,2^+,3^+,4^-,5^-,6^-) = \frac{i}{\langle 2|1+6|5]}\left(\frac{\langle 6|1+2|3]^3}{\langle 61\rangle\langle 12\rangle[34][45]s_{126}} + \frac{\langle 4|5+6|1]^3}{\langle 23\rangle\langle 34\rangle[56][61]s_{561}}\right)$$

Generalized Unitarity: the one-loop basis

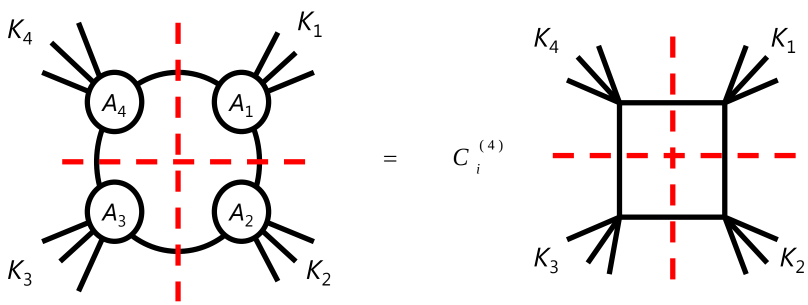
A dimensionally regulated n-point one-loop integral (scattering amplitude) is a linear combination of boxes, triangles, bubbles and tadpoles with rational coefficients



- Pentagons and higher n-point functions can be reduced to lower point integrals and higher dimensional polygons that only contribute at O(ε) [Bern, Dixon, Kosower]
- The task is reduced to determining the coefficients: by applying multiple cuts at both sides of the equation [Brito, Cachazo, Feng]
- R is a finite piece that is entirely rational: can not be detected by four-dimensional cuts

Generalized Unitarity

Quadruple cut



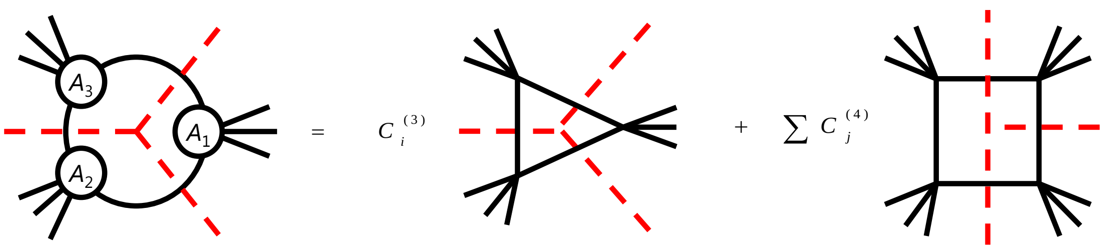
The discontinuity across the leading singularity is unique

$$C_i^{(4)} = A_1 \times A_2 \times A_3 \times A_4$$

Four on-shell constrains

→ freeze the loop momenta

Triple cut



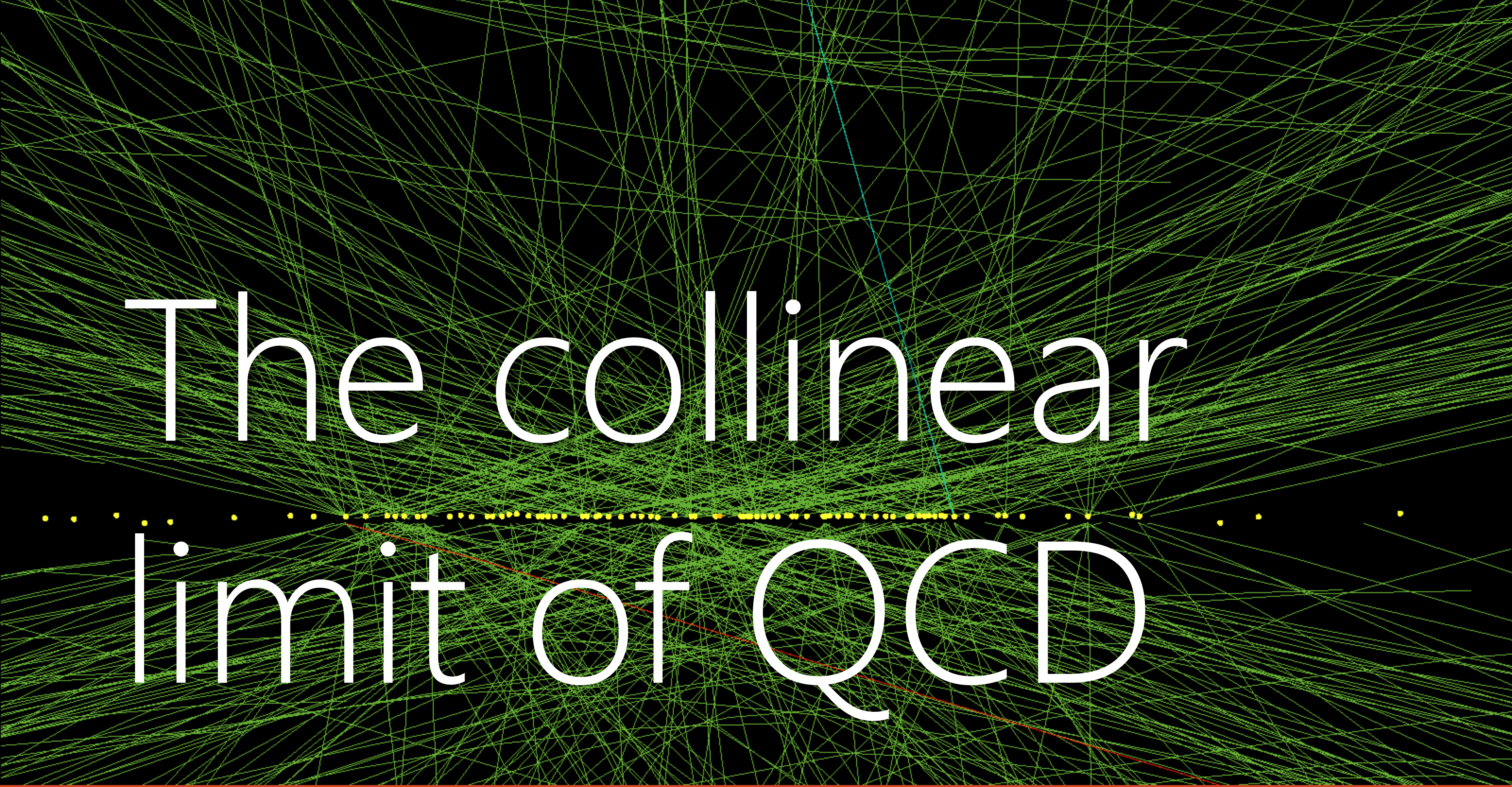
Only three on-shell constrains → one free component of the loop momentum

And so on for double and single cuts

- OPP [Ossola, Pittau, Papadopoulos]: a systematic way to extract the coefficients

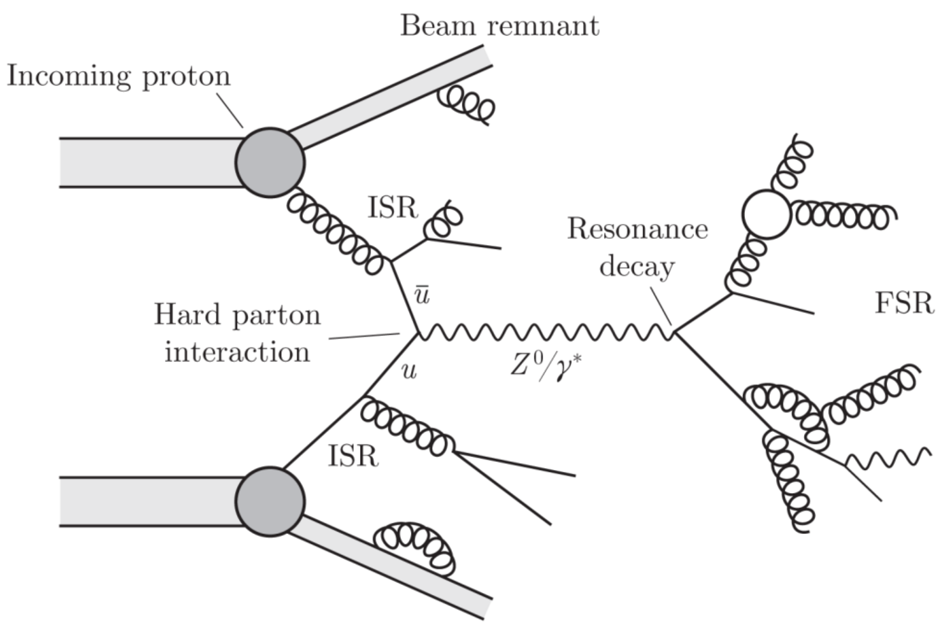
Rational terms

d-dimensional cuts, recursion relations (BCFW), Feynman rules …



The collinear limit of QCD

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

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

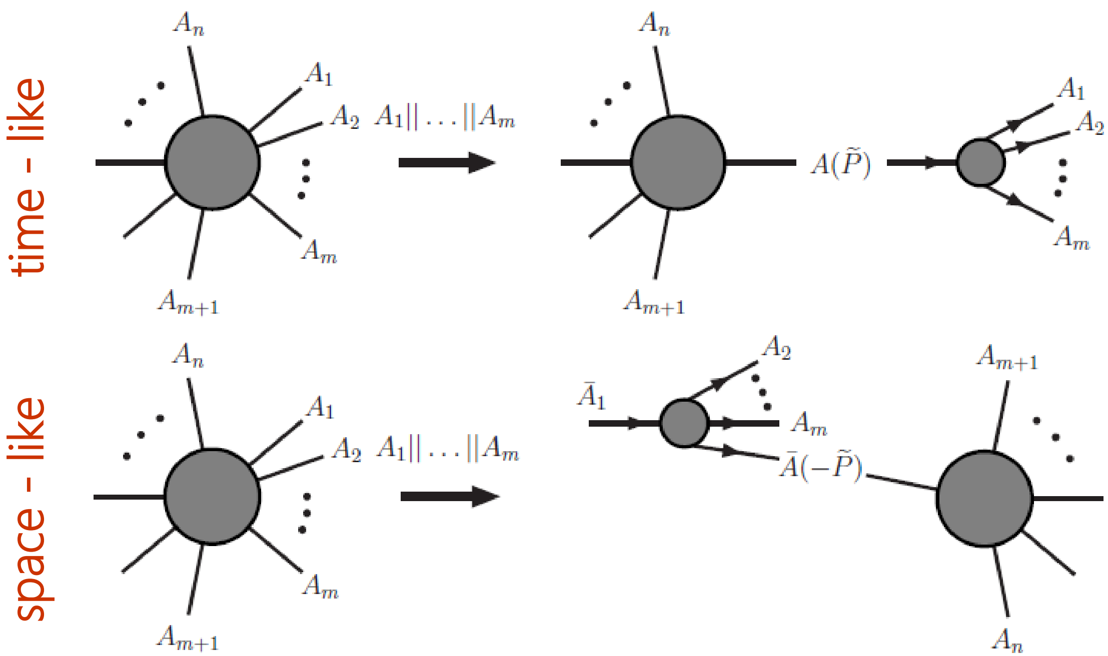
Factorization and renormalization scales

Higher
twist

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

Collinear factorization at tree-level

- Momenta $p_1, \ldots, p_m$ of m partons become parallel
- Sub-energies $s_{ij} = (p_i + p_j)^2$ of the same order and vanish simultaneously
- Leading behaviour $\left(\frac{1}{\sqrt{s_{1,m}}}\right)^{m-1}$



Collinear limit

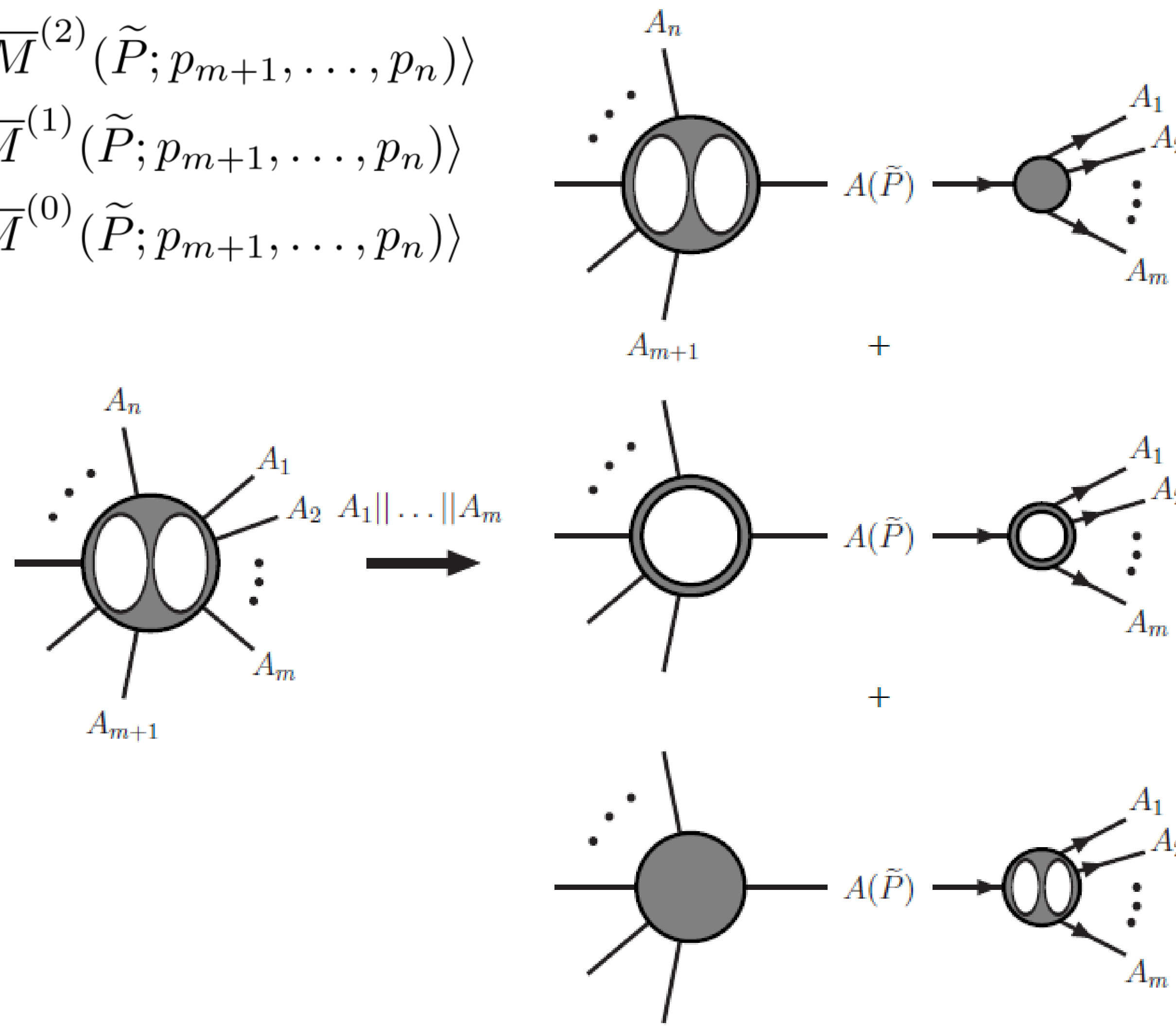
- Most singular behaviour captured by **universal** (process independent) factorisation properties
- **Splitting matrix** depends on the collinear partons only.
- Space-like and time-like related by crossing

$$|M^{(0)}(p_1, \ldots, p_n)\rangle$$

$$= \mathbf{Sp}^{(0)}(p_1, \ldots, p_m; \widetilde{P})\, |\overline{M}^{(0)}(\widetilde{P}; p_{m+1}, \ldots, p_n)\rangle + \mathcal{O}\left((\sqrt{s})^{3-m}\right)$$

At two loops

$$|M^{(2)}(p_1,\ldots,p_n)\rangle$$
$$\simeq \mathbf{Sp}^{(0)}(p_1,\ldots,p_m;\widetilde{P})\,|\overline{M}^{(2)}(\widetilde{P};p_{m+1},\ldots,p_n)\rangle$$
$$+\mathbf{Sp}^{(1)}(p_1,\ldots,p_m;\widetilde{P})\,|\overline{M}^{(1)}(\widetilde{P};p_{m+1},\ldots,p_n)\rangle$$
$$+\mathbf{Sp}^{(2)}(p_1,\ldots,p_m;\widetilde{P})\,|\overline{M}^{(0)}(\widetilde{P};p_{m+1},\ldots,p_n)\rangle$$



The collinear projection

- The projection over the collinear limit is obtained by setting the parent parton at on-shell momenta

$$\widetilde{P}^{\mu} = p_{1,m}^{\mu} - \frac{s_{1,m}\, n^{\mu}}{2n\cdot\widetilde{P}}$$

$\tilde{P}^{\mu}$: collinear direction

n^{μ}: describes how the collinear limit is approached $\qquad \tilde{P}^2 = 0, n^2 = 0$

$z_i = \frac{n\cdot p_i}{n\cdot\tilde{P}}$: longitudinal momentum fraction, $\sum z_i = 1$

- Work in the axial gauge (physical polarizations): only diagrams where the parent parton emitted and absorbed collinear radiation

$$\frac{1}{\not{p}_{12}} = \frac{1}{s_{12}}\not{p}_{12} = \frac{1}{s_{12}}\left(\widetilde{\not{P}} + \frac{s_{12}}{2n\cdot\widetilde{P}}\not{n}\right) \simeq \frac{1}{s_{12}}\, u(\widetilde{P})\bar{u}(\widetilde{P}) + \ldots$$

$$d_{\mu\nu}(p_{12}, n) = d_{\mu\nu}(\widetilde{P}, n) + \cdots = \epsilon_{\mu}(\widetilde{P})\epsilon_{\nu}^{*}(\widetilde{P}) + \cdots$$

Splitting functions

The square of the splitting amplitude, summed over final-state colours and spins, and averaged over colours and spins of the parent parton, defines the m-parton splitting function

$$\langle P^{(0)}_{a_1\cdots a_m} \rangle = \left(\frac{s_{1,m}}{2\mu^{2\epsilon}} \right)^{m-1} \overline{|\mathbf{Sp}^{(0)}_{a_1\ldots a_m}|}$$

Which is a generalization of the customary (i.e. with $m = 2$) Altarelli-Parisi splitting function

- Probability to emit further radiation with given longitudinal momenta, from the leading singular behavior
- Universal (process independent): e+e-, DIS or hadron collisions

Exercise:

Calculate the splitting functions for the collinear processes $q \to qg$, $g \to q\bar{q}$ and $g \to gg$ by using the helicity method

Hint:

$$\mathbf{Sp}^{(0)}_{q\to q_1 g_2} = \mathbf{T}^a \frac{1}{s_{12}} \bar{u}(p_1) \not\epsilon(p_2)\, v(\widetilde{P})$$

$$P^{(0)}_{q\to q_1 g_2} = C_F \frac{1+z^2}{1-z} \qquad z = z_1 = \frac{n\cdot p_1}{n\cdot \widetilde{P}} \qquad z_2 = 1 - z$$

Relevance of the collinear limit in QCD

- evaluate IR finite cross-sections ▶ subtraction terms
- IR properties of amplitudes exploited to compute logarithmic enhanced perturbative terms ▶ resummations
- improve physics content of Monte Carlo event generators ▶ parton showers
- Evolution of PDF´s and fragmentation functions
- beyond QCD: hints on the structure of highly symmetric gauge theories (e.g. N=4 super-Yang-Mills)
- Factorization theorems: pQCD for hard processes

Altarelli, Parisi, Berends, Giele, Mangano, Parke …

PDF

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

Online PDF plotting and calculation

xf(x,Q2) *v* x

Using the form below you can calculate, in real time, values of *xf(x,Q^2)* for any of the PDFs from the different groups. You can also generate and compare plots of *xf(x,Q^2) v x* at any *Q^2* for up to 4 different parton types or PDF sets.

Select:	Parton	Group	Set
☑	up	MSTW-nnlo	MSTW2008nnlo
☑	down	MSTW-nnlo	MSTW2008nnlo
☑	strange	MSTW-nnlo	MSTW2008nnlo
☑	gluon	MSTW-nnlo	MSTW2008nnlo

Xmin = 0.01 Xmax = 0.8 Xinc = 0.01

Q2 = 1 GeV**2

x axis: ○ lin ◉ log

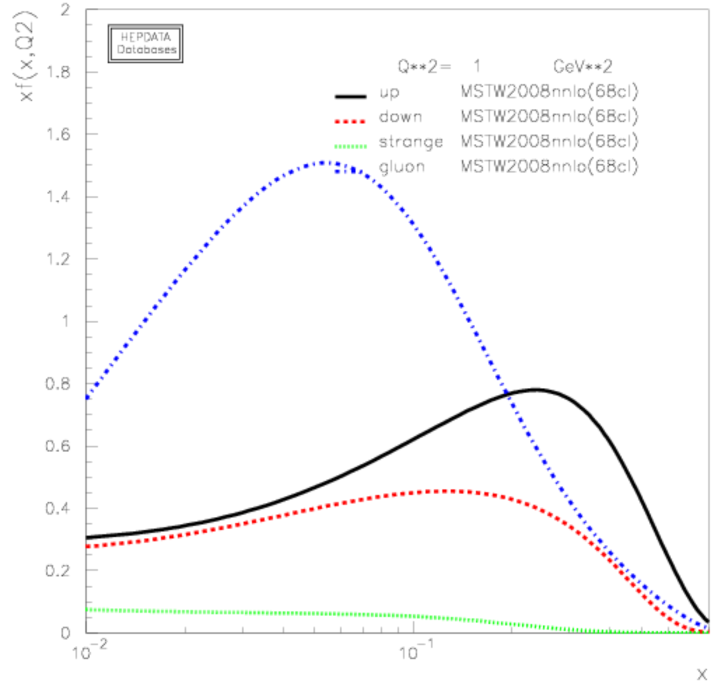
y axis: ◉ lin ○ log, ymin= 0.0 ymax = 2.0

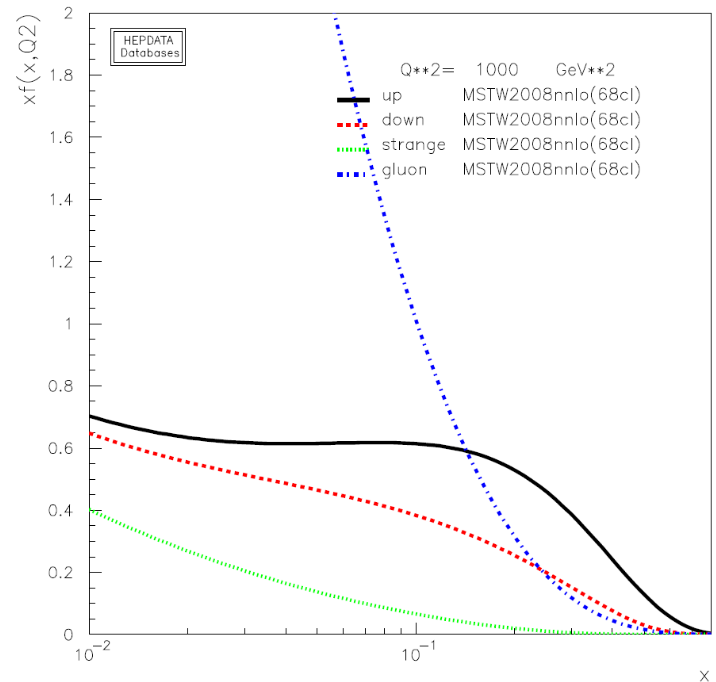
Output as: ○ numbers or ◉ plot (line width = 10) as ratio ☐

Make the Plot | add sets | remove sets

Change to plotting versus Q**2

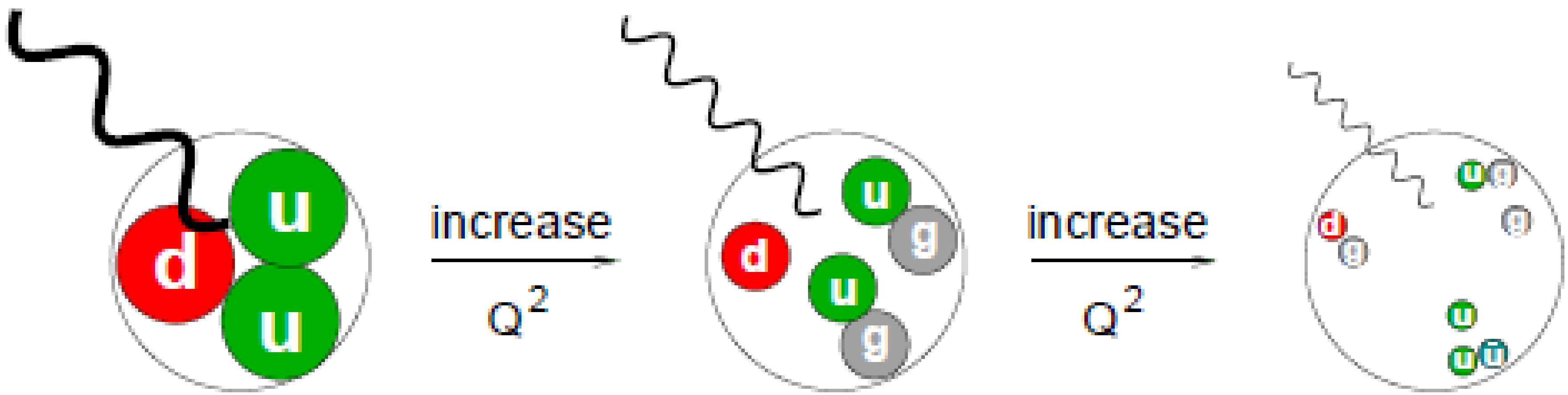
Change to Error Set plotting



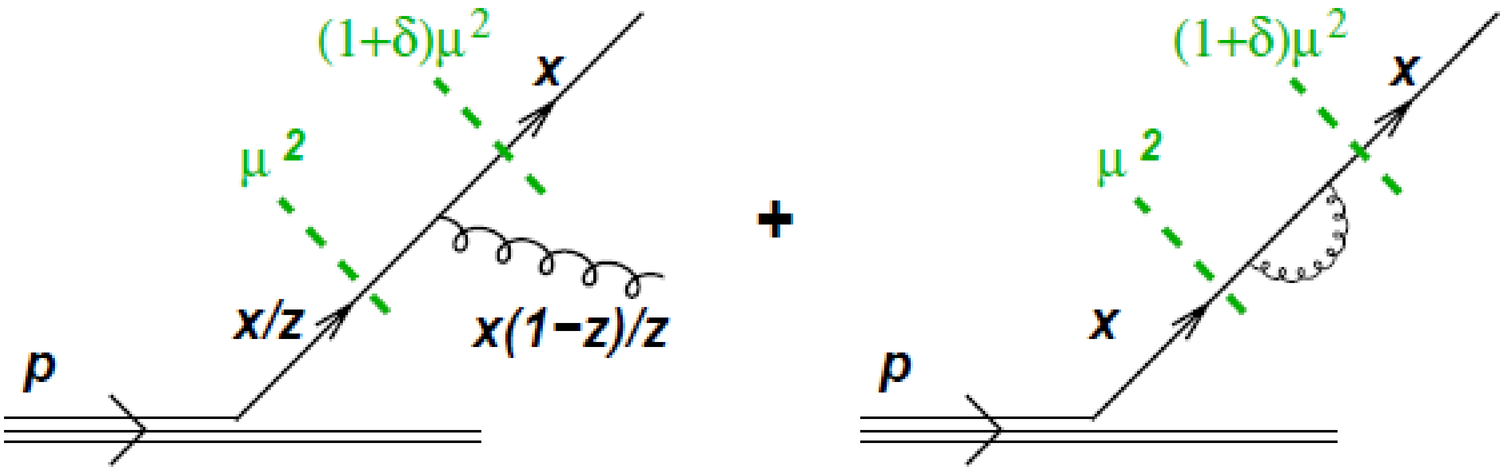


- Maximum of up and down at x = 1/3: three quarks sharing the proton momentum
- up = 2 x down
- Gluon evolves faster: color charge $C_A = 3$ versus quark color charge $C_F = 4/3$

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, ...):

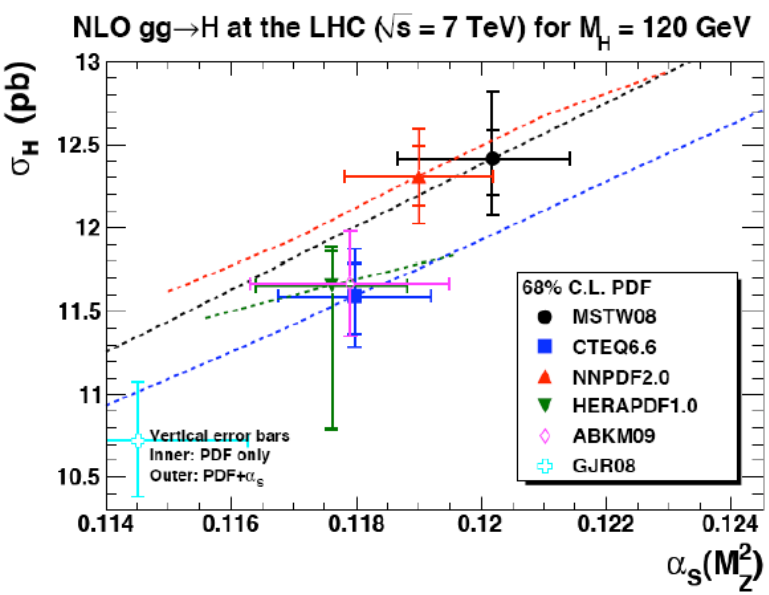
$$\int dx\, x \sum_i f_i(x, Q^2) = 1$$

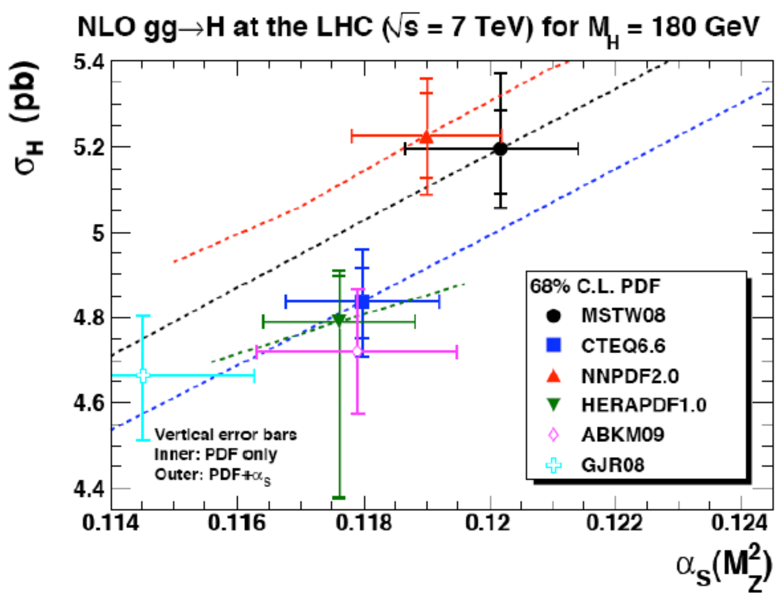
Parton distribution functions

- 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]

Why and how do we see jets?

Gluon emission

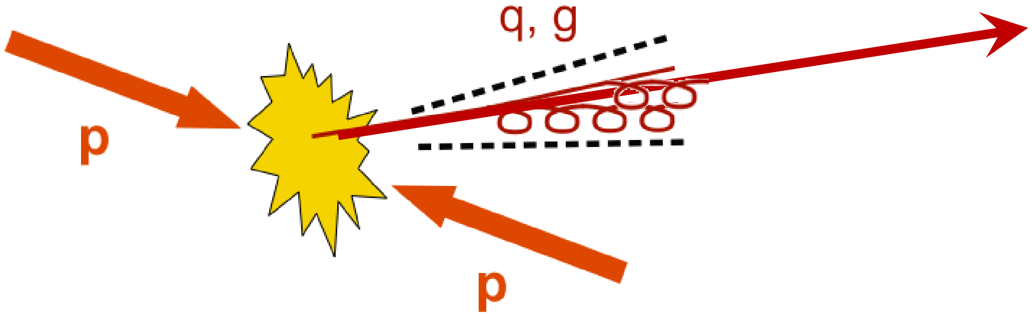
$$\int \alpha_S \frac{dE}{E} \frac{d\theta}{\theta} \gg 1$$

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

Non-perturbative transition to hadrons

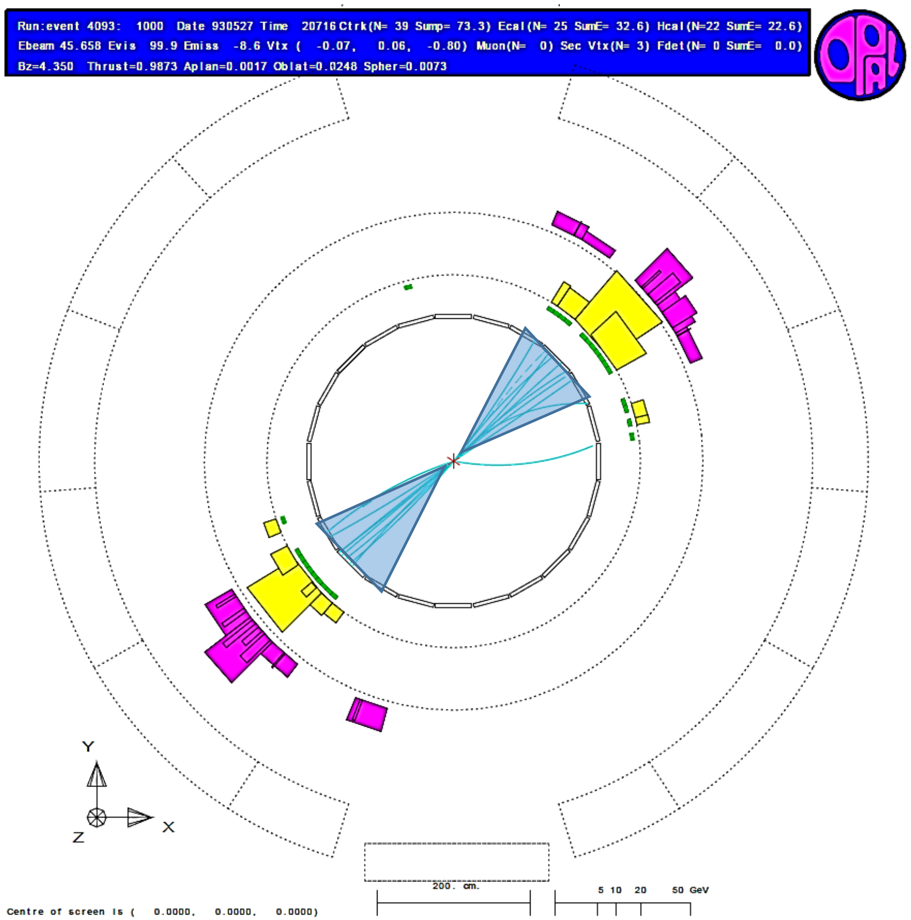
$$\alpha_S \sim 1 \quad \Lambda_{QCD} \sim 200\text{MeV}$$

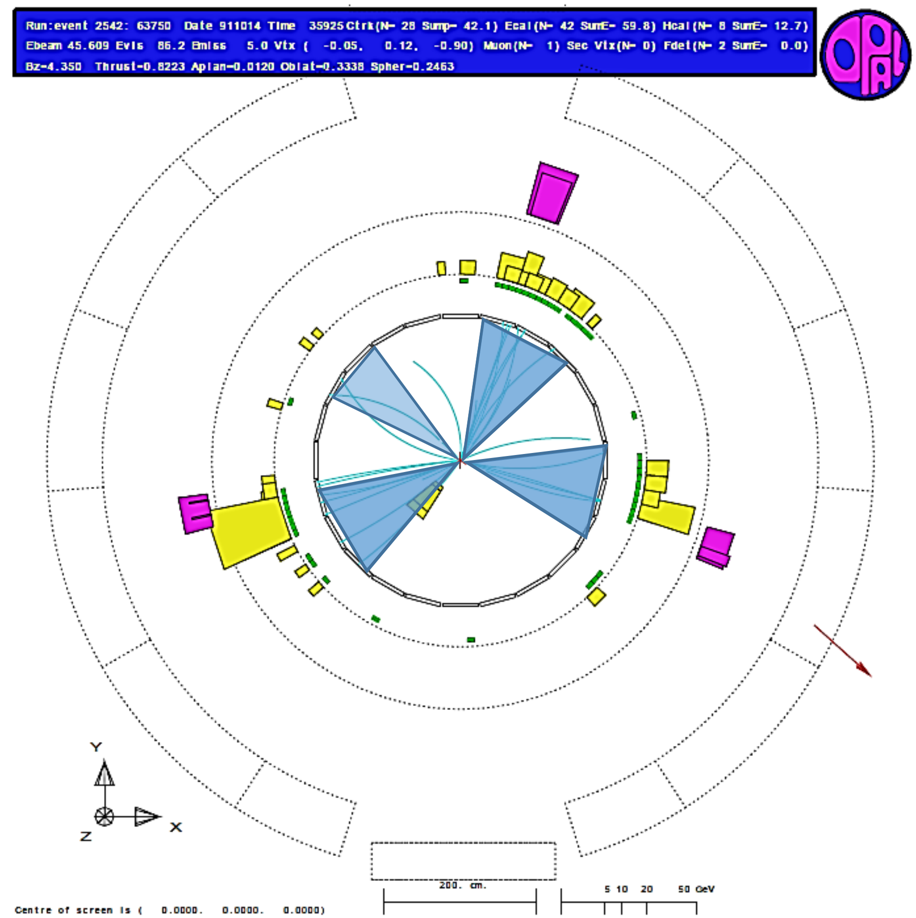
Parton level

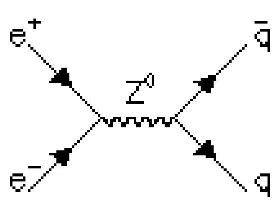


$$\{j_k\} \xleftarrow{\text{jet definition}} \{p_i\}$$

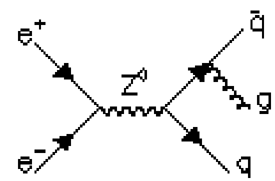
jets — final-state 4-momenta

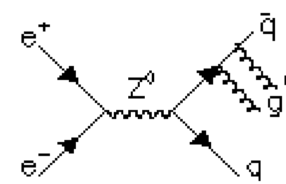






- Clearly a two-jet event





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

The k_T jet algorithm at hadron colliders

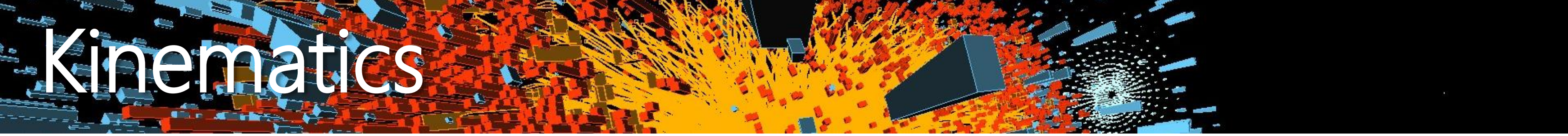
[Catani, Dokshitzer, Seymour, Webber, 93]
[Ellis, Soper, 93]

- Define distance among particles: e.g. $d_{ij} = (p_i+p_j)^2$
- Is this distance smaller than a resolution parameter ? Combine into the same jet recursively
- At hadron colliders there are beams, introduce also “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)

Kinematics



Longitudinal variables

- Rapidity: $$y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$
- Pseudo-rapidity: $$\eta = -\log\left(\tan(\theta/2)\right)$$

Transverse plane

- Azimuthal angle ϕ
- Transverse momentum $$p_T = \sqrt{p_x^2 + p_y^2}$$
- Transverse mass $$m_T = \sqrt{p_T^2 + m^2}$$

$$p^\mu = (m_T \cosh(y), p_T \cos(\phi), p_T \sin(\phi), m_T \sinh(y))$$

Exercises:
1. Show that $\eta = y$ for massless particles
2. Show that $\Delta y = y_i - y_j$ is invariant under boost

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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

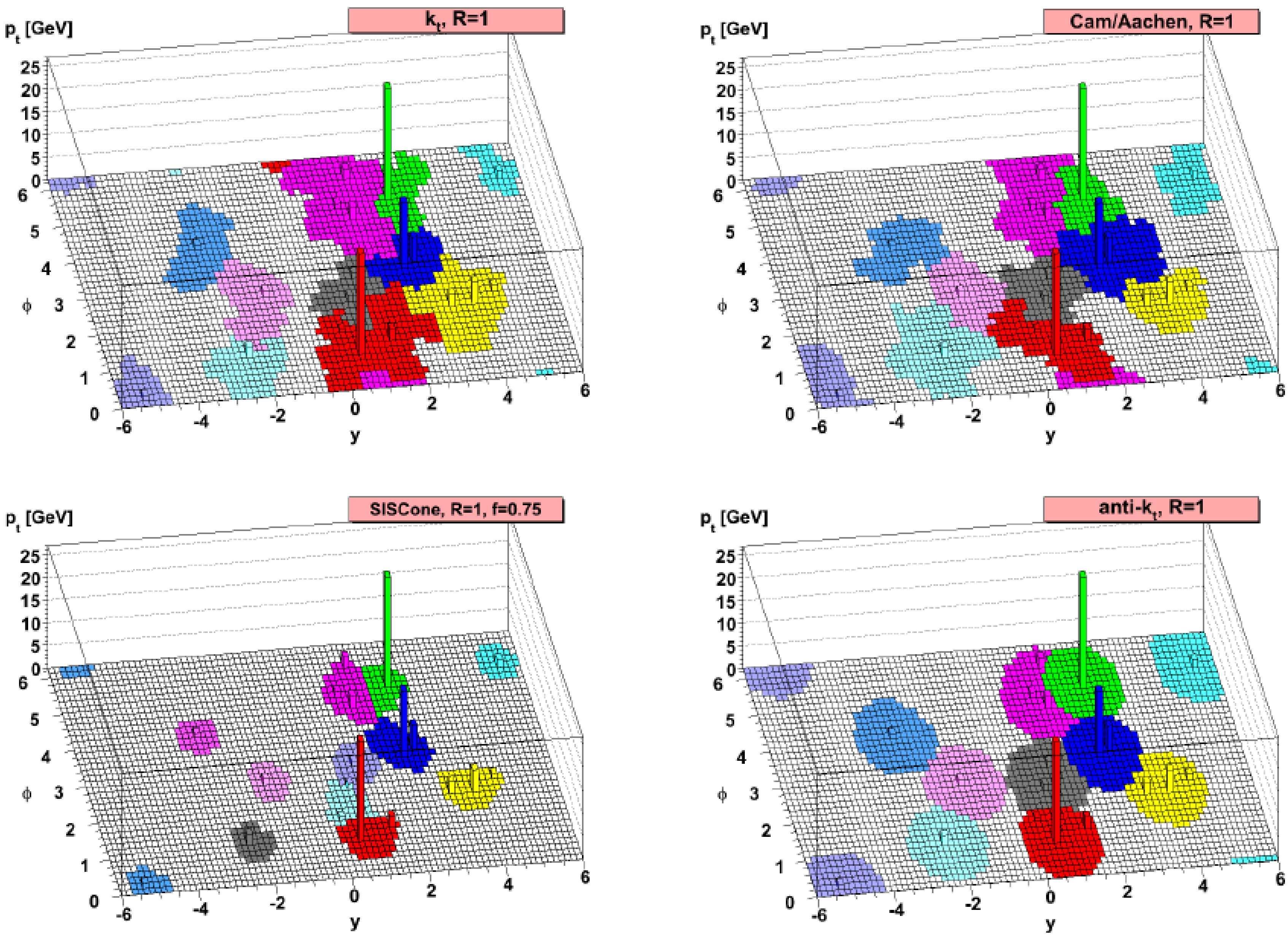
anti-k_T

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

- 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 carries out measurements that can be consistently compared with theoretical (perturbartive QCD) calculations
- Cones extensively used at Tevatron are not IRC safe

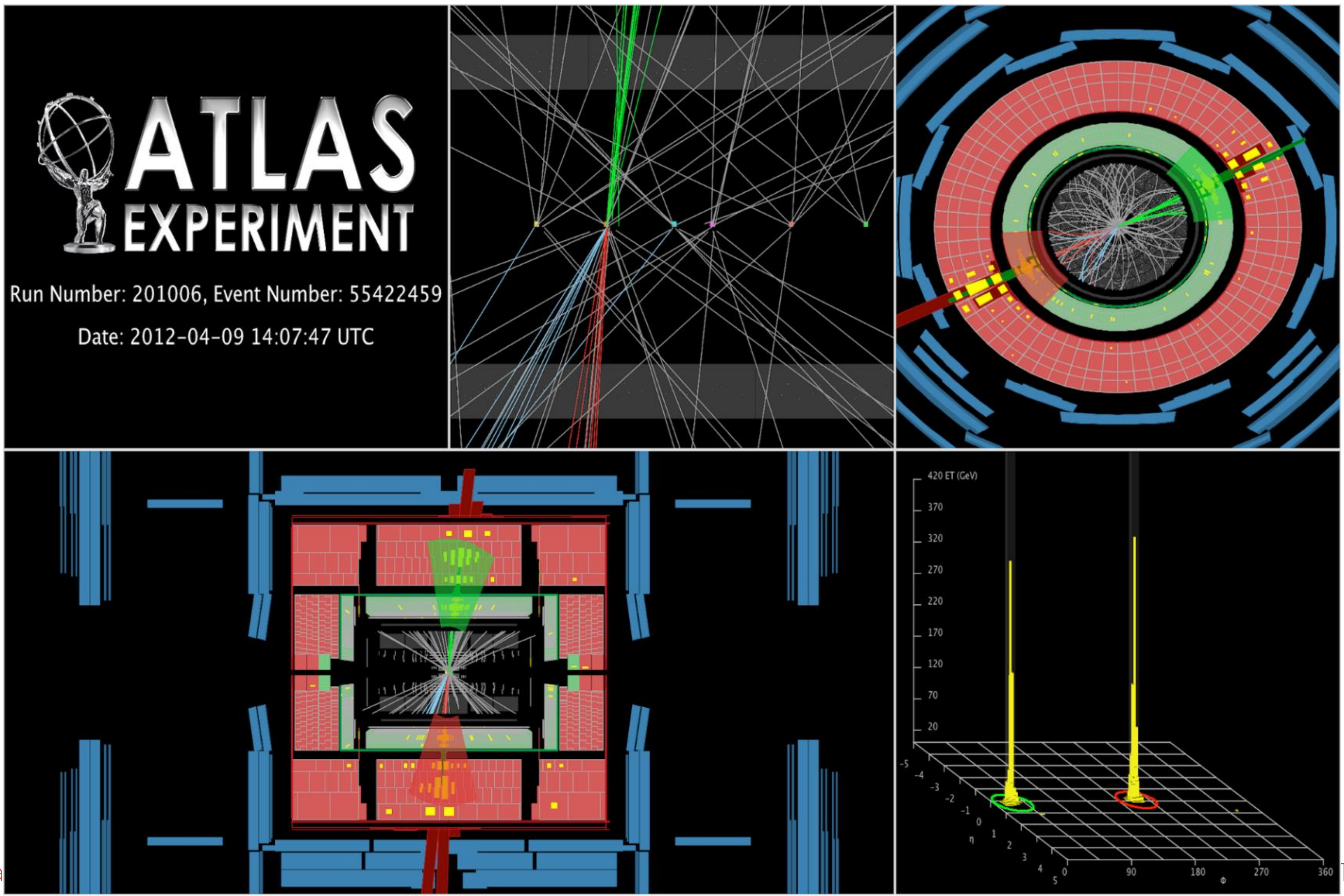
[Cacciari, Salam, Soyez 08]



High mass central di-jet event

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

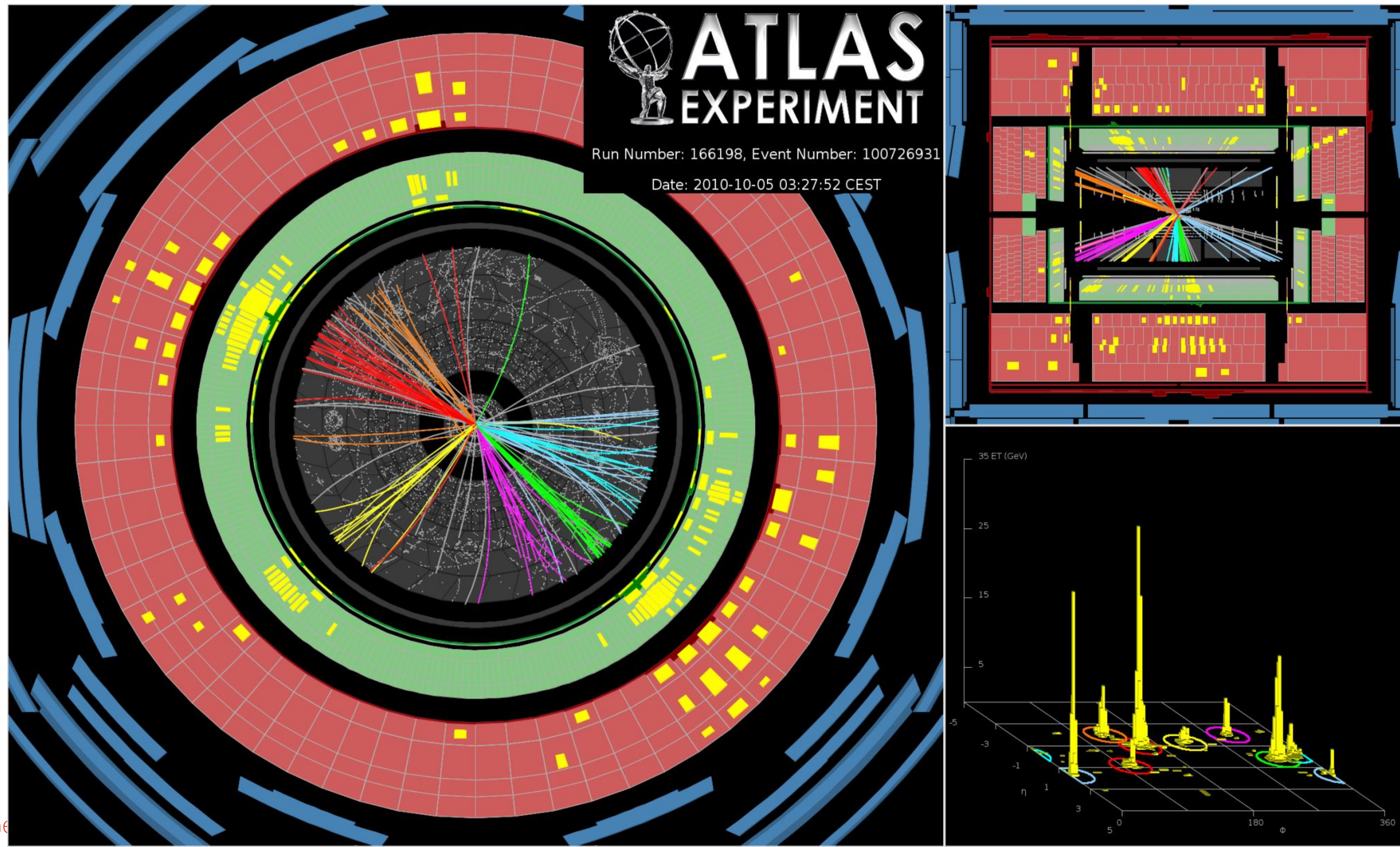
- 1st jet (ordered by p_T): p_T = 1.96 TeV, η = -0.07, φ = -2.68
- 2nd jet: p_T = 1.65 TeV, η = 0.17, φ = 0.48
- Missing E_T = 318 GeV, φ = 0.43
- Sum E_T = 3.81 TeV



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.