Phenomenology at collider experiments [Part 1: QCD]

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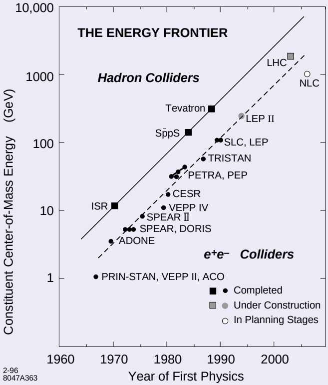
Outline

Chasing the energy frontier

View of the 1990's . . .



Phenomenology at colliders

The past up to LEP and Tevatron

- 1950's: The particle zoo
  Discovery of hadrons, but no order criterion
- 1960's: Strong interactions before QCD
  Symmetry: Chaos to order
- 1970's: The making of the Standard Model:
  Gauge symmetries, renormalisability, asymptotic freedom
  Also: November revolution and third generation
- 1980's: Finding the gauge bosons
  Non-Abelian gauge theories are real!
- 1990's: The triumph of the Standard Model at LEP and Tevatron
  Precision tests for precision physics

The present: LHC

- Historical trend: Hadron colliders for discovery physics
  Lepton colliders for precision physics.
- Historical trend: Shape your searches - know what you're looking for.
  This has never been truer.
- In last decades: Theory triggers, experiment executes.
  Also true for the LHC?!

Setting the scene

Reminder: The Standard Model

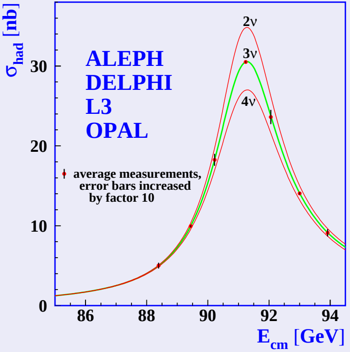
- 3 generations of matter fields:
  left-handed doublets, right-handed singlets

Quarks			Leptons		
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$
u_R d_R	c_R s_R	t_R b_R	e_R	μ_R	τ_R

- (Broken) gauge group: $SU(3) \times SU(2) \times U(1) \to SU(3) \times U(1)$:
  8 gluons, 3 (massive) weak gauge bosons, 1 photon
- Electroweak symmetry breaking (EWSB) by introducing a complex scalar doublet (Higgs doublet) with a vacuum expectation value (vev) $\Longrightarrow$ 1 physical Higgs scalar

How we know what we know (examples)

Generations



EW precision data

(from LEP EWWG public page, winter 2009 plot)

Open questions (private preference)

- True mechanism of EWSB: Higgs mechanism in its minimal or an extended version or something different?
- Generations: Three or more?
- More symmetry: Is there low-scale Supersymmetry?
- Space-time: How many dimensions? Four or more?
- Cosmology: Any candidates for dark matter?

LHC - The energy frontier

Design defines difficulty

- Design paradigm for LHC:
  1. Build a hadron collider
  2. Build it in the existing LEP tunnel
  3. Build it as competitor to the 40 TeV SSC
- Consequence:
  1. LHC is a *pp* collider
  2. LHC operates at 10-14 TeV c.m.-energy
  3. LHC is a high-luminosity collider: 100 $\mathrm{fb}^{-1}/\mathrm{y}$

  Trade energy vs. lumi, thus *pp*
- Physics:
  1. Check the EWSB scenario & search for more
  2. Fight with overwhelming backgrounds, QCD always a stake-holder
  3. Consider niceties such as pile-up, underlying event etc..

Some example cross sections

Or: Yesterdays signals = todays backgrounds

Process	Evts/sec.
Jet, $E_\perp > 100$ GeV	10^3
Jet, $E_\perp > 1$ TeV	$1.5 \cdot 10^{-2}$
$b\bar{b}$	$5 \cdot 10^5$
$t\bar{t}$	1
$Z \to \ell\ell$	2
$W \to \ell\nu$	20
$WW \to \ell\nu\ell\nu$	$6 \cdot 10^{-3}$

Rates at "low" luminosity, $\mathcal{L} = 10^{33}/\mathrm{cm}^2\mathrm{s} = 10^{-1}\mathrm{fb}^{-1}/\mathrm{y}$, and $s = 14$ TeV.

Cross sections at hadron colliders

Master formula

Production cross section for final state Φ in AB collisions:

$$\sigma_{AB\to\Phi+X} = \sum_{ab}\int\limits_0^1 \mathrm{d}x_1\mathrm{d}x_2\, f_{a/A}(x_1,\mu_F^2) f_{b/B}(x_2,\mu_F^2)\, \hat{\sigma}_{ab\to\Phi}(\hat{s},\mu_F^2,\mu_R^2)$$

where

- $x_{1,2}$ are momentum fractions w.r.t. the hadron, $\hat{s} = x_1 x_2 s$;
- $\hat{\sigma}_{ab\to\Phi}(\hat{s},\mu_F^2,\mu_R^2)$ is the parton-level cross section,
- and where $f_{a/A}(x,Q^2)$ is the parton distribution function (PDF).

Tree-level matrix elements

Simple scattering cross sections

- Detailed look into master formula above:
  Convolution of **parton-level cross section $\hat{\sigma}$ with PDFs**.
- Must evaluate $\hat{\sigma}$ as phase-space integral, respecting four-momentum conservation of amplitude squared:

$$\mathrm{d}\hat{\sigma}_{ab\to\Phi} = \frac{1}{4\sqrt{(p_a p_b)^2 - p_a^2 p_b^2}} |\mathcal{M}_{ab\to\Phi}(p_a,\, p_b,\, p_1,\, \dots,\, p_N)|^2$$
$$\prod_{i=1}^{N_\Phi}\left[\frac{\mathrm{d}^4 p_i}{(2\pi)^4}(2\pi)\delta(p_i^2 - m_i^2)\theta(E_i)\right](2\pi)^4\delta^4\left(p_a + p_b - \sum p_i\right).$$

- Note: Have to normalise on Lorentz-invariant flux.
- Smart choices for phase space integration helpful.

Generic Lorentz-invariant quantities

- Use Mandelstam variables (especially for $2 \to 2$ scatterings):

$$\begin{aligned}\hat{s} &= (p_a+p_b)^2 = (p_1+p_2)^2\\ \hat{t} &= (p_a-p_1)^2 = (p_b-p_2)^2\\ \hat{u} &= (p_a-p_2)^2 = (p_b-p_1)^2\,.\end{aligned}$$

- Relation to masses

$$\hat{s}+\hat{t}+\hat{u} = m_a^2+m_b^2+m_1^2+m_2^2 \stackrel{\text{massless}}{\longrightarrow} 0\,.$$

- In the massless case

$$\frac{\mathrm{d}\hat{\sigma}_{ab\to 12}}{\mathrm{d}\hat{t}} = \frac{1}{2\hat{s}}\,\frac{|\mathcal{M}_{ab\to 12}|^2}{8\pi\hat{s}}\,.$$

Kinematics at hadron colliders

- Typically, at hadron colliders: transverse momentum $p_\perp$ and rapidity y characterise kinematics.
- Note rapidity y vs. pseudorapidity η (identical for $m = 0$ only):

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \quad \longleftrightarrow \eta = -\ln\tan\frac{\vartheta}{2}\,.$$

- Rewrite four-momentum $(m_\perp^2 = p_\perp^2 + m^2)$

$$p^\mu = (E,\,p_x,\,p_y,\,p_z) = (m_\perp\cosh y, p_\perp\sin\phi, p_\perp\cos\phi, m_\perp\sinh y)\,.$$

- One-particle phase space element:

$$\frac{\mathrm{d}^4p}{(2\pi)^4}(2\pi)\delta(p^2-m^2)\theta(E) = \frac{\mathrm{d}^3p}{(2\pi^3)2E} = \frac{\mathrm{d}y}{4\pi}\,\frac{\mathrm{d}^2p_\perp}{(2\pi)^2}\,.$$

Resonance production ($2 \to 1$ processes)

- Assume **massless incoming partons**: $p_{a,b} = x_{1,2}(E,\, 0,\, 0,\, \pm E)$.

(Here, E is beam energy in c.m. system of collider, $s = 4E^2$.)

- Special form of cross section: $\hat{\sigma}_{ab\to\Phi} = g_\sigma(\hat{s},\, m_\Phi^2)\,\delta(\hat{s} - m_\Phi^2)$.
- Example: $q\bar{q} \to V$ with vector and axial vector coupling V and A.

(Add normalisation: average over incoming degrees of freedom, include incoming flux.)

$$
\begin{aligned}
|\overline{\mathcal{M}}_{q\bar{q}\to V}|^2 &= \frac{1}{3} M_V^2 (V^2 + A^2) \\
\hat{\sigma}_{q\bar{q}\to V} &= \frac{\pi}{3}(V^2 + A^2)\delta(\hat{s} - M_V^2)\,.
\end{aligned}
$$

- Trivial relation to partial decay widths of the produced particles:

($|\overline{\mathcal{M}}_{V\to q\bar{q}}|^2 = 36/3|\overline{\mathcal{M}}_{q\bar{q}\to V}|^2$.)

$$
\mathrm{d}\Gamma = \frac{1}{8\pi M}|\overline{\mathcal{M}}_{V\to q\bar{q}}|^2\,.
$$

Resonance production (cont'd)

- Then

$$\hat{s} = x_1 x_2 s \quad \text{and} \quad \hat{y} = \frac{1}{2}\ln\frac{x_1+x_2+x_1-x_2}{x_1+x_2-x_1+x_2} = \frac{1}{2}\ln\frac{x_1}{x_2}\,.$$

- Relation of Bjorken-x and rapidity:

$$x_{1,2} = \sqrt{\frac{\hat{s}}{s}}\,e^{\pm\hat{y}} \quad \text{and} \quad \hat{y} = \frac{1}{2}\ln\frac{x_1^2 s}{m_\phi^2} \le \ln\frac{2E}{m_\phi} = \hat{y}_{\max}\,.$$

- Together ($s\mathrm{d}x_1\mathrm{d}x_2 = \mathrm{d}\hat{s}\mathrm{d}\hat{y}$):

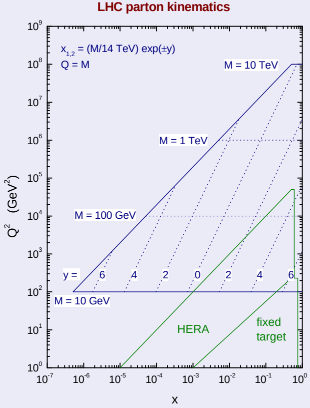
$$\sigma_{AB\to\Phi} = \sum_{ab}\int\limits_{-\hat{y}_{\max}}^{\hat{y}_{\max}} \mathrm{d}\hat{y}\, x_1 f_{a/A}(x_1,\,\mu_F^2)\, x_2 f_{b/B}(x_2,\,\mu_F^2)\,\frac{g_\sigma(m_\phi^2,\,m_\phi^2)}{m_\phi^2}\,.$$

Resonance production (cont'd)

- Note: Only dependence on rapidity through the PDFs $\Longrightarrow$ rapidity distribution of Φ contains information on the PDFs of partons a and b.

(Remember: $x_{1,2} = m_\phi / s e^{\pm\hat{y}}$.)

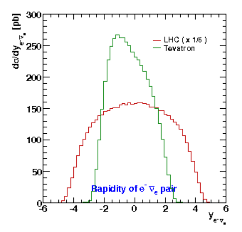
- Obvious consequence: The higher the mass of the produced system the more central it is.

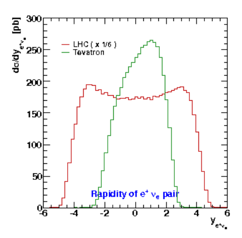


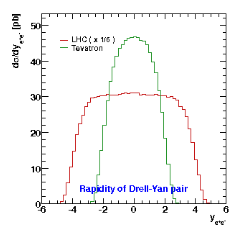
(Plot from MSTW homepage)

Aside: Rapidities of gauge bosons

From the Tevatron to the LHC







Kinematics of $2 \to 2$ processes

- Use transverse momenta and (pseudo-) rapidities: $p_\perp$, y_3, y_4.
- Introduce average (centre-of-mass) rapidity and rapidity distance,

$$\bar{y} = (y_3 + y_4)/2 \text{ and } y^* = (y_3 - y_4)/2.$$

- Relate rapidities to Bjorken-x:

$$x_{1,2} = \frac{p_\perp}{\sqrt{2}}\left(e^{\pm y_3} + e^{\pm y_4}\right) = \frac{p_\perp}{2\sqrt{s}}\, e^{\pm\bar{y}} \cosh y^*.$$

Therefore: $$\hat{s} = M_{12}^2 = 4p_\perp^2 \cosh y^*.$$

Similarly $$\hat{t},\ \hat{u} = -\frac{\hat{s}}{2}\left(1 \mp \tanh y^*\right).$$

Kinematics of $2 \to 2$ processes (cont'd)

- Partonic cross section (keep all massless) reads

$$\begin{aligned}\hat{\sigma}_{ab\to 12} &= \frac{1}{2\hat{s}} \int \frac{\mathrm{d}^3 p_1}{(2\pi)^3 2E_1} \frac{\mathrm{d}^3 p_2}{(2\pi)^3 2E_2} |\overline{\mathcal{M}}_{ab\to 12}|^2 \\ &\qquad (2\pi)^4 \delta^4(p_a + p_b - p_1 - p_2) \\ &= \frac{1}{2\hat{s}^2} \int \frac{\mathrm{d}^2 p_\perp}{(2\pi)^2} |\overline{\mathcal{M}}_{ab\to 12}|^2 .\end{aligned}$$

- Fold in the PDFs (sum over a, b, integrate over $x_{1,2}$):

$$\sigma_{AB\to 12} = \sum_{ab} \int \frac{\mathrm{d}y_1 \mathrm{d}y_2 \mathrm{d}^2 p_\perp}{16\pi^2 s^2} \frac{f_a(x_1,\, \mu_F) f_b(x_2,\, \mu_F)}{x_1 x_2} |\overline{\mathcal{M}}_{ab\to 12}|^2 .$$

- Note: Do not forget a factor $1/(1+\delta_{12})$ for identical final states.

QCD matrix elements

- Common feature: t-channel dominance

  (If existing, "elastic" scattering wins.)

- Note: Typically $t\longrightarrow 0 \Longleftrightarrow p_\perp^2 \longrightarrow 0$.
- Consequence: parton-parton cross section grows fast for $p_\perp \longrightarrow 0$.
- Effect further enhanced by running α_s.

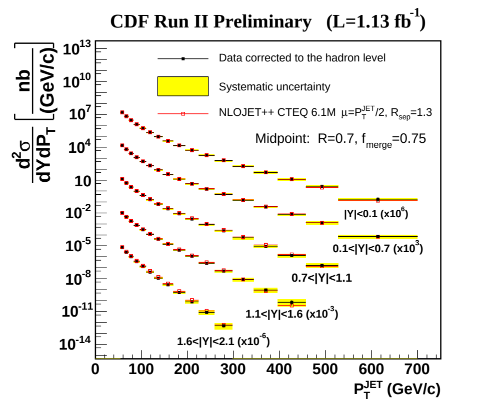
  (Would use $\mu_R = p_\perp$ as scale.))

Examples:

$qq' \longrightarrow qq'$	$\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
$q\bar{q} \longrightarrow q'\bar{q}'$	$\frac{4}{9}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$q\bar{q} \longrightarrow gg$	$\frac{32}{27}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} - \frac{8}{3}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$qg \longrightarrow qg$	$\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} - \frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}$
$gg \longrightarrow q\bar{q}$	$\frac{1}{6}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} - \frac{3}{8}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$gg \longrightarrow gg$	$\frac{9}{2}\left(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$
$q\bar{q} \longrightarrow g\gamma$	$\frac{8}{9}\,\frac{\hat{t}^2+\hat{u}^2+2\hat{s}(\hat{s}+\hat{t}+\hat{u})}{\hat{t}\hat{u}}$
$qg \longrightarrow q\gamma$	$-\frac{1}{3}\,\frac{\hat{s}^2+\hat{u}^2+2\hat{t}(\hat{s}+\hat{t}+\hat{u})}{\hat{s}\hat{u}}$
	Note: For real photons $\hat{t}+\hat{u}+\hat{s}=0$

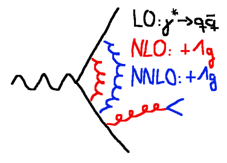
(multiply with couplings, e.g. $g^4 = (4\pi\alpha_s)^2$, $g^2e^2e_q^2$)

Jet production at Tevatron



Higher-order corrections

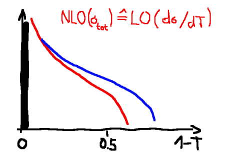
Specifying higher-order corrections: $\gamma^* \longrightarrow$ hadrons



- In general: N^{n}LO $\leftrightarrow \mathcal{O}(\alpha_s^n)$
- But: only for inclusive quantities

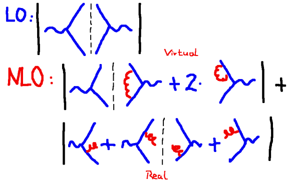
(e.g.: total xsecs like $\gamma^* \longrightarrow$hadrons).

Counter-example: thrust distribution



- In general, distributions are HO.
- Distinguish real & virtual emissions:
  Real emissions $\longrightarrow$ mainly distributions,
  virtual emissions $\longrightarrow$ mainly normalisation.

Anatomy of HO calculations: Virtual and real corrections



NLO corrections: $\mathcal{O}(\alpha_s)$

Virtual corrections	=	extra loops
Real corrections	=	extra legs

- UV-divergences in virtual graphs $\longrightarrow$ renormalisation
- But also: IR-divergences in real & virtual contributions
  Must cancel each other (Kinoshita-Lee-Nauenberg & Bloch-Nordsieck theorems),
  non-trivial to see: N vs. $N+1$ particle FS, divergence in PS vs. loop

Cancelling the IR divergences: Subtraction method

- Total NLO xsec: $\sigma_{\rm NLO} = \sigma_{\rm Born} + \int {\rm d}^D k |\mathcal{M}|^2_V + \int {\rm d}^4 k |\mathcal{M}|^2_R$
- IR div. in real piece $\longrightarrow$ regularise: $\int {\rm d}^4 k |\mathcal{M}|^2_R \longrightarrow \int {\rm d}^D k |\mathcal{M}|^2_R$
- Construct subtraction term with same IR structure:

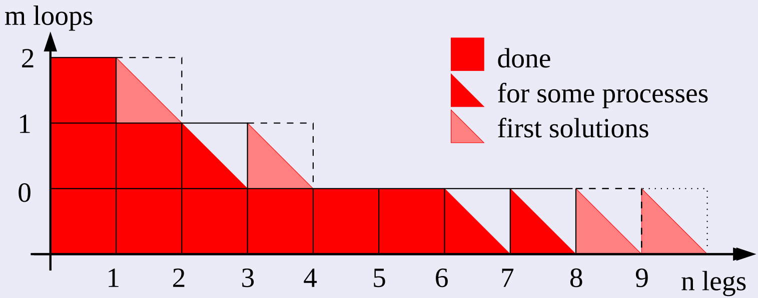
  $\int {\rm d}^D k \left(|\mathcal{M}|^2_R - |\mathcal{M}|^2_S\right) = \int {\rm d}^4 k |\mathcal{M}|^2_{RS} =$ finite.

  Possible: $\int {\rm d}^D k |\mathcal{M}|^2_S = \sigma_{\rm Born} \int {\rm d}^D k |\tilde{\mathcal{S}}|^2$, universal $|\tilde{\mathcal{S}}|^2$.
- $\int {\rm d}^D k |\mathcal{M}|^2_V + \sigma_{\rm Born} \int {\rm d}^D k |\tilde{\mathcal{S}}|^2 =$ finite (analytical)
- Has been automated in various programs.
- Remark: Part of the collinear divergences in initial state absorbed in PDFs.

(This introduces scheme dependence and spoils probabilistic interpretation of PDFs.)

Cross sections @ hadron colliders

Availability of exact calculations



Tree-level tools (publicly available)

	Models	$2 \longrightarrow n$	Ampl.	Integ.	lang.
Alpgen	SM	$n = 8$	rec.	Multi	Fortran
Amegic	SM,MSSM,ADD	$n = 6$	hel.	Multi	C++
CompHep	SM,MSSM	$n = 4$	trace	1Channel	C
COMIX	SM	$n = 8$	rec.	Multi	C++
HELAC	SM	$n = 8$	rec.	Multi	Fortran
MadEvent	SM,MSSM,UED	$n = 6$	hel.	Multi	Fortran
O'Mega	SM,MSSM,LH	$n = 8$	rec.	Multi	O'Caml

(One-)Loop-level tools (publicly available)

	Processes	lang.
MCFM	SM, 3-particle FS	Fortran
NLOJET++	up to 3 light jets	C++
Prospino	MSSM pair production	Fortran

PDFs and factorisation

Parton picture

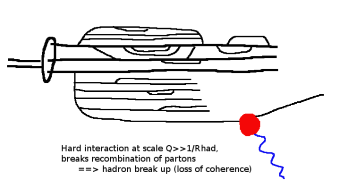
- Parton picture: Hadrons made from partons.
- Distribution(s) of partons in hadrons:
  not from first principles, only from measurements.
- First idea: probability to find parton a in hadron h only dependent on Bjorken-x ($x = E_a/E_h$ or similar) – "Bjorken-scaling"
  $\mathcal{P}(a|h) = f_a^h(x)$ (LO interpretation of PDF).
- But QCD: Partons in partons in partons
  $\Longrightarrow$ scaling behaviour of PDFs: $f = f(x,\, Q^2)$.
- Still: PDFs must be measured, but scaling in Q^2 from theory (DGLAP, resums large logs of Q^2)

Space-time picture of hard interactions

Partons "collinear" with hadron: $k_\perp \ll 1/R_{\rm had}$.

Lifetime of partons $\tau \sim 1/x$, $r \sim 1/Q$.

Hard interaction at scales $Q_{\rm hard} \gg 1/R_{\rm had}$.



- Too "fast" for colour field - only one parton takes part.
- Other partons feel absence only when trying to recombine.
- Universality (process-independence) of PDFs.
- Collinear factorisation.

Revealing the inner structure: *ep*-scattering

A detour: Elastic scattering & Form factors

- Extended objects have a matter density $\rho(\vec{r})$.

$$\text{Normalisation:} \int \mathrm{d}^3 r\, \rho(\vec{r}) = 1$$

- Its Fourier transform is called a form factor:

$$F(\vec{q}) = \int \mathrm{d}^3 r\, \exp[-i\vec{q}\vec{r}]\rho(\vec{r}) \Longrightarrow F(0) = 1$$

- Naive modification of cross sections for scattering on such objects:

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}^2\Omega}\right|_{\mathrm{ptlike}} \Longrightarrow \left.\frac{\mathrm{d}\sigma}{\mathrm{d}^2\Omega}\right|_{\mathrm{extended}} \approx \left.\frac{\mathrm{d}\sigma}{\mathrm{d}^2\Omega}\right|_{\mathrm{ptlike}} |F(q)|^2$$

Elastic *ep* scattering and the Rosenbluth formula

- Simple test of proton's charge distribution: elastic *ep* scattering (exchange of a photon). Elastic: **Nucleon remains intact.**
- Rosenbluth-formula (E and E' are energies of electron before and after scattering, M is the proton mass, q^2 is the space-like momentum transfer, and θ is the scattering angle):

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}^2\Omega} &= \frac{\alpha^2\cos^2\frac{\theta}{2}}{4E^2\sin^4\frac{\theta}{2}}\,\frac{E'}{E}\left[\left(F_1^2(q^2)-\frac{\kappa^2q^2}{4M^2}F_2^2(q^2)\right)\right.\\ &\left.\quad -\frac{q^2}{2M^2}\left(F_1(q^2)+\kappa F_2(q^2)\right)^2\tan^2\frac{\theta}{2}\right]\end{aligned}$$

Compare with Rutherford scattering (on very massive objects):

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2\Omega} = \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}$$

Elastic *ep* scattering and charge radius of the proton

- Differences due to relativistic kinematics plus recoil of the protons (in Rutherford scattering, the nuclei stay at rest).
- Also inner structure: there are two form factors $F_{1,2}$. They are related to the electric and magnetic form factors, and are parametrised as

$$F_{1,2} \approx \left[\frac{1}{1 - q^2/0.71\mathrm{GeV}^2}\right]^2$$

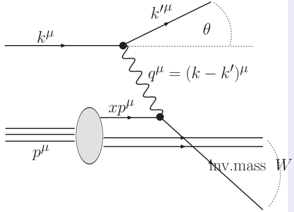
- Connection to charge radius: Assume $F_1 = F_2$ and

$$F(q^2) = \int \mathrm{d}^3 r\, \rho(\vec{r}) \exp[-i\vec{q}\vec{r}] \approx 1 - \frac{\vec{q}^2}{6}\langle r^2\rangle + \dots$$

- Therefore: $r_{\mathrm{proton}} \equiv \langle r^2\rangle^{1/2} \approx 0.75 \pm 0.25$ fm.

Deep-inelastic scattering: The process

- Terminology arises because in contrast to elastic scattering the **nucleon nearly always disintegrates**.
- Typically in DIS proton is probed with γ's.
  From $p \approx 1/\lambda$: If momentum transfer larger than 1 GeV, ($\approx 1/0.2\mathrm{fm}$) then inner structure revealed.
- Kinematics:



$$\nu = \frac{2pq}{m_p} \longrightarrow E - E'$$

(energy transfer)

$$x = \frac{Q^2}{2pq} \longrightarrow \frac{Q^2}{E-E'}$$

(momentum fraction of parton)

$$Q^2 = -q^2 = -2EE'(1-\cos\theta)$$

(momentum transfer squared)

Two basic ideas

- Typically, the behaviour of the cross section with varying x (or, alternatively ν) and Q^2 is being measured.
  In addition, νp-scattering with W exchange is considered.
- Two basic ideas:
  - The parton model (by R.Feynman):
    The nucleon is made of smaller bits (partons). Later knowledge: Can be identified with quarks and gluons. But: In addition to the three **valence** quarks, carrying the quantum numbers (e.g. $|p\rangle = |uud\rangle$), there are virtual quarks and gluons, the **sea**.
  - The scaling hypothesis (by J.D.Bjorken):
    At large energies and momentum transfers, the cross section depends on one variable only. Reason: The photon ceases to scatter coherently off the nucleon, but solely sees the individual, point-like partons.

Bjorken-scaling

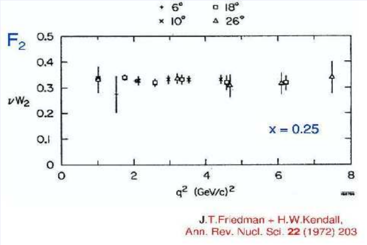
- Equation for cross section (cf. elastic scattering, replacing form factors $F_{1,2}(q^2)$ with **structure functions** $W_{1,2}(\nu, Q^2)$):

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2\Omega} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} \left[W_2(\nu, Q^2) + 2W_1(\nu, Q^2)\right]$$

- Bjorken scaling implies that with no special scale present in the dynamics of the scattering the $W_{1,2}(\nu, Q^2)$ can be replaced:

$$m_p W_1(\nu, Q^2) \longrightarrow F_1(x)$$
$$\frac{Q^2}{2m_p x} W_2(\nu, Q^2) \longrightarrow F_2(x)\,,$$

Independence of W_2 on q^2:



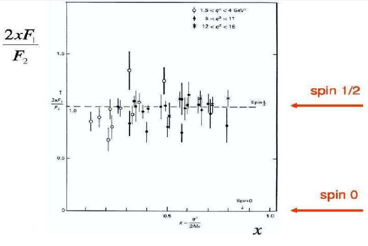
The spin of the quarks: The Callan-Gross relation

- Bjorken scaling established that DIS in fact must be described in terms of parton-photon processes.
  But what are the properties of these point-like constituents?
- In 1969 Callan and Gross suggested that Bjorken's scaling functions are related:

$$2xF_1(x) = F_2(x)\,.$$

- This reflects the assumption that the partons inside the proton are indeed quarks, i.e. spin-1/2 particles (spin-0 for example would lead to $2xF_1(x)/F_2(x) = 0$.)

Measuring the quark spin



Deriving the Callan-Gross relation

- Basic idea: Compare *eq*-scattering cross section (free quark) with the DIS *ep* cross section and assume identity:

$$
\begin{aligned}
\frac{\mathrm{d}^2\sigma_{eq}}{\mathrm{d}^2\Omega \mathrm{d}E'} &= \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2\sin^4\frac{\theta}{2}}\left[1+\frac{Q^2}{2m_p^2}\tan^2\frac{\theta}{2}\right]\delta\left(\nu-\frac{Q^2}{2m_p x}\right)\\
\frac{\mathrm{d}^2\sigma_{ep}}{\mathrm{d}^2\Omega \mathrm{d}E'} &= \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2\sin^4\frac{\theta}{2}}\left[\frac{1}{\nu}F_2(x)+\frac{2}{m_p}\tan^2\frac{\theta}{2}F_1(x)\right]
\end{aligned}
$$

Parton distributions and sum rules

- Define probabilities (possible at LO only) $f_a(x)$ to find a parton of type a with energy fraction between x and $x + dx$:

$$F_1(x) = \sum_a q_a^2 f_a(x)\,, \quad q_a = \text{parton's charge.}$$

- The parton momenta must add to the proton momentum:

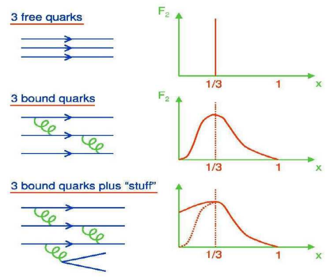
$$\int_0^1 \mathrm{d}x\, x\, [f_u(x) + f_{\bar{u}}(x) + f_d(x) + f_{\bar{d}}(x) + f_s(x) + f_{\bar{s}}(x) + \dots] = 1\,.$$

- The parton types must yield a "net proton", $p\rangle = |uud\rangle$:

$$\begin{array}{rclrcl}
\int\limits_0^1 \mathrm{d}x\, [f_u(x) - f_{\bar{u}}(x)] & = & 2 & \int\limits_0^1 \mathrm{d}x\, [f_d(x) - f_{\bar{d}}(x)] & = & 1 \\
\int\limits_0^1 \mathrm{d}x\, [f_s(x) - f_{\bar{s}}(x)] & = & 0 & \int\limits_0^1 \mathrm{d}x\, [f_c(x) - f_{\bar{c}}(x)] & = & 0\,.
\end{array}$$

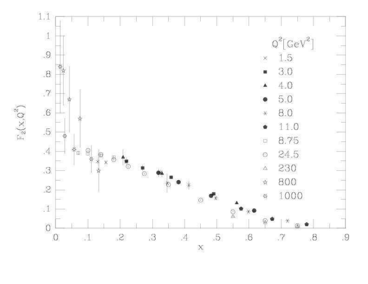
QCD effect on structure functions: Scaling violations

- Now it is possible to quantify the picture of "proton = quarks + stuff"



- Leads to evolution equations: "Russian dolls"

- This implies dependence of $F_{1,2}$ on the momentum transfer.
- Therefore: $F_{1,2}$ depend on both x and Q^2 - not constant in Q^2 any more.



Quantifying scaling violations: Evolution equations

- Explanation: As the proton is hit harder and harder (i.e. at larger Q^2), the virtual photon starts resolving gluons and quark-antiquark fluctuations (partons in partons!).
- The scale Q^2 plays the role of a "resolution parameter".
- Described by the DGLAP equations. Basic structure:

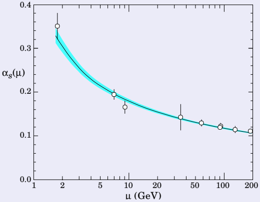
$$\frac{\mathrm{d}q(x,Q^2)}{\mathrm{d}\ln Q^2} = \alpha_s(Q^2)\int\limits_x^1 \mathrm{d}y \left[q(y,Q^2)\,P_{q\to qg}\left(\frac{x}{y}\right) + g(y,Q^2)\,P_{g\to q\bar{q}}\left(\frac{x}{y}\right)\right]$$

Here the quark at x can come from a quark (gluon) at y, the functions P encode the details of the decays $q \to qg$ ($g \to q\bar{q}$) responsible for it.

Aside: The "running" coupling in QCD & asymptotic freedom

- Reassuring: Can understand the proton structure at large Q^2 in terms of perturbative objects (quarks and gluons). This implies that the coupling g_s is sufficiently small there:
  Asymptotic freedom.
- But measurements (left) and calculation show that the coupling becomes stronger the lower the scale ($\simeq Q^2$), i.e. the larger the distance.
- In fact, the perturbative α_s diverges for $\mu = \Lambda_{\rm QCD} \approx 300$ MeV, signalling the breakdown of the expansion.

$\alpha_s = g_s^2/(4\pi)$



- Non-perturbative regime, where **only colour-less states** can exist:
  Confinement.
- Therefore, only hadrons (no quarks or gluons) as observable initial and final states in experiments.

Fitting PDFs: Strategy in a nutshell

- Ansatz $g(x)$ for PDFs at some fixed value of $Q_0^2 = Q^2 \approx 1\mathrm{GeV}^2$.
  For example, MRST/MSTW: (personal Durham bias)

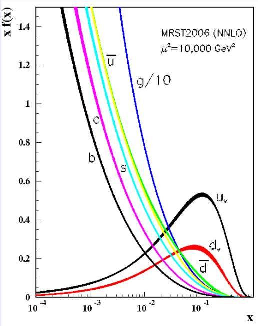
$$
\begin{aligned}
xu_V &= A_u x^{\eta_1}(1-x)^{\eta_2}(1+\varepsilon_u\sqrt{x}+\gamma_u x)\\
xd_V &= A_d x^{\eta_2}(1-x)^{\eta_4}(1+\varepsilon_d\sqrt{x}+\gamma_d x)\\
xS &= A_S x^{-\lambda_S}(1-x)^{\eta_S}(1+\varepsilon_S\sqrt{x}+\gamma_S x)\\
xg &= A_g x^{-\lambda_g}(1-x)^{\eta_g}(1+\varepsilon_g\sqrt{x}+\gamma_g x)
\end{aligned}
$$

- Collect data at various x, Q^2, use DGLAP equation to evolve down to Q_0^2, also fix α_s.
- Order of fit $\Longleftrightarrow$ order of kernels.
- Enforce sum rules (momentum, ...)

(Partially relaxed for LO* and LO**.)

Generic structure

- Large sea for $x \to 0$
- Valence at $x \approx 0.15$



Determination of PDFs: Data input

Example: MSTW parameterisation and their effect:

New data included.

NuTeV and Chorus data on $F_2^{\nu,\bar\nu}(x,Q^2)$ and $F_3^{\nu,\bar\nu}(x,Q^2)$ replacing CCFR.

NuTeV and CCFR dimuon data included directly. Leads to a direct constraint on $s(x,Q^2)+\bar{s}(x,Q^2)$ and on $s(x,Q^2)-\bar{s}(x,Q^2)$. Affects other partons.

CDFII lepton asymmetry data in two different E_T bins – $25\mathrm{GeV} < E_T < 35\mathrm{GeV}$ and $35\mathrm{GeV} < E_T < 45\mathrm{GeV}$.

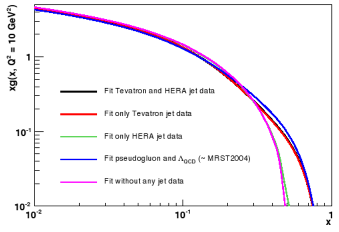
HERA inclusive jet data (in DIS).

New CDFII high-E_T jet data.

Direct high-x data on $F_L(x,Q^2)$.

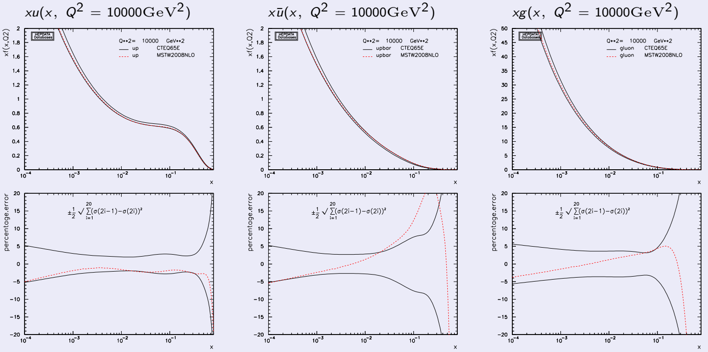
Update to include all recent charm structure function data.

Look at dependence of fit on m_c – defined as pole mass.



(From R.Thorne's talk at DIS 2007)

Uncertainties of global PDFs: CTEQ65E vs. MSTW2008 NLO



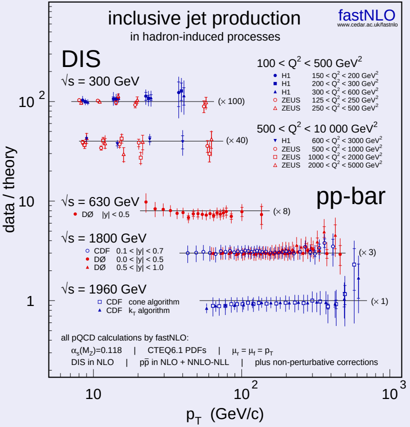
(From Hepdata base)

Remark on scales and PDF choices

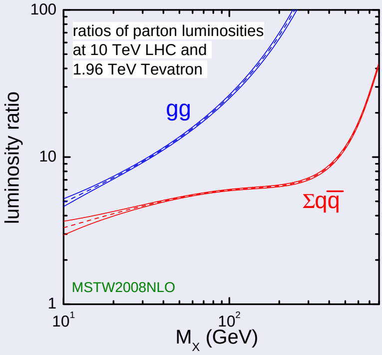
- In perturbative calculations at hadron colliders, two (unphysical) scales enter:
  - Renormalisation scale μ_R (scale for coupling constants)
  - Factorisation scale μ_F (scale for PDFs)
- In principle, all-orders results would be independent, in practise, results shows a dependence on scales.
- This dependence decreases by adding more orders.
- Smart process-dependent choices can mimic some HO effects.
- A common recipe to estimate higher-order effects and the related uncertainty is to vary both scales by a factor (typically 2). This is not always reliable $\Longleftrightarrow$ nothing replaces the true HO calculation

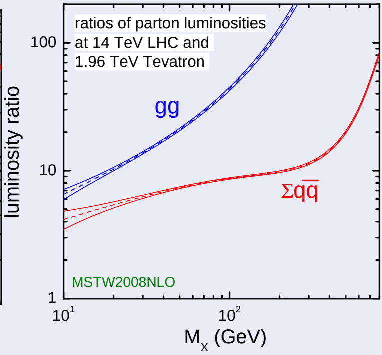
. . . especially if we want to know for sure . . . .

Understanding of perturbative QCD



PDFs: From Tevatron to LHC

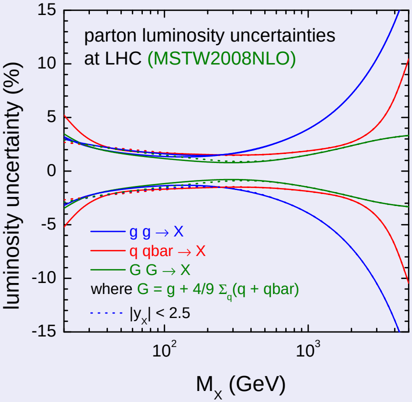




(From MSTW homepage.)

PDF uncertainties at LHC

(Propaganda plot by MSTW collaboration, CTEQ similar.)



From parton to hadron level

Limitations of parton level calculations

- Fixed order parton level (LO, NLO, ...) implies fixed multiplicity
  $\Longrightarrow$ no clean way toward exclusive final states.
- No control over potentially large logs
  (appear when two partons come close to each other).
- Parton level is parton level
  experimental definition of observables relies on hadrons.

Therefore: Need hadron level!
Must dress partons with radiation!
(will also enable universal hadronisation)

Origin of radiation

Accelerated charges radiate

- Well-known: Accelerated charges radiate
- QED: Electrons (charged) emit photons
  Photons split into electron-positron pairs
- QCD: Quarks (coloured) emit gluons
  Gluons split into quark pairs
- Difference: Gluons are coloured (photons are not charged)
  Hence: Gluons emit gluons!
- Cascade of emissions: Parton shower

Pattern of radiation

Leading logs: $e^+e^- \longrightarrow$ jets

- Differential cross section:

$$\frac{d\sigma_{ee\to 3j}}{dx_1\,dx_2} = \sigma_{ee\to 2j}\frac{C_F\alpha_s}{\pi}\,\frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)}$$

  Singular for $x_{1,2} \longrightarrow 1$.

- Rewrite with opening angle θ_{qg} and gluon energy fraction $x_3 = 2E_g/E_{\rm c.m.}$:

$$\frac{d\sigma_{ee\to 3j}}{d\cos\theta_{qg}\,dx_3} = \sigma_{ee\to 2j}\frac{C_F\alpha_s}{\pi}\left[\frac{2}{\sin^2\theta_{qg}}\,\frac{1+(1-x_3)^2}{x_3} - x_3\right]$$

  Singular for $x_3 \longrightarrow 0$ ("soft"), $\sin\theta_{qg} \longrightarrow 0$ ("collinear").

Leading logs: Collinear singularities

- Use

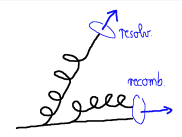
$$\frac{2\mathrm{d}\cos\theta_{qg}}{\sin^2\theta_{qg}} = \frac{\mathrm{d}\cos\theta_{qg}}{1-\cos\theta_{qg}} + \frac{\mathrm{d}\cos\theta_{qg}}{1+\cos\theta_{qg}} = \frac{\mathrm{d}\cos\theta_{qg}}{1-\cos\theta_{qg}} + \frac{\mathrm{d}\cos\theta_{\bar{q}g}}{1-\cos\theta_{\bar{q}g}} \approx \frac{\mathrm{d}\theta^2_{qg}}{\theta^2_{qg}} + \frac{\mathrm{d}\theta^2_{\bar{q}g}}{\theta^2_{\bar{q}g}}$$

- Independent evolution of two jets (q and $\bar{q}$):

$$\mathrm{d}\sigma_{ee\to 3j} \approx \sigma_{ee\to 2j} \sum_{j\in\{q,\bar{q}\}} \frac{C_F\alpha_s}{2\pi}\frac{\mathrm{d}\theta^2_{jg}}{\theta^2_{jg}} P(z)\,,$$

where $P(z) = \frac{1+(1-z)^2}{z}$ (DGLAP splitting function)

Leading logs: Parton resolution

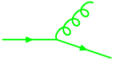


- What is a parton?
  Collinear pair/soft parton recombine!
- Introduce resolution criterion $k_\perp > Q_0$.

- Combine virtual contributions with unresolvable emissions:
  Cancels infrared divergences $\Longrightarrow$ Finite at $\mathcal{O}(\alpha_s)$

  (Kinoshita-Lee-Nauenberg, Bloch-Nordsieck theorems)

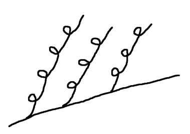
- Unitarity: Probabilities add up to one
  $\mathcal{P}(\text{resolved}) + \mathcal{P}(\text{unresolved}) = 1.$

 $+$  $+$  $=1.$

Occurrence of large logarithms

Many emissions: Parton parted partons

- Iterate emissions (jets)



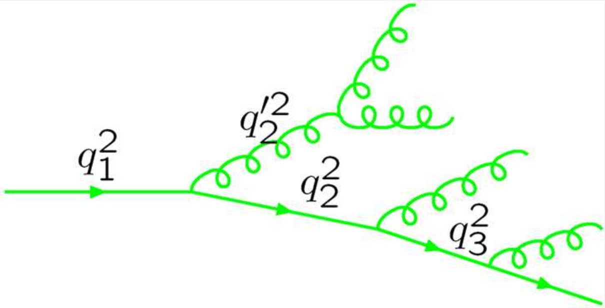
Maximal result for $t_1 > t_2 > \dots t_n$:

$$d\sigma \propto \sigma_0 \int_{Q_0^2}^{Q^2} \frac{dt_1}{t_1} \int_{Q_0^2}^{t_1} \frac{dt_2}{t_2} \dots \int_{Q_0^2}^{t_{n-1}} \frac{dt_n}{t_n} \propto \log^n \frac{Q^2}{Q_0^2}$$

- How about Q^2? Process-dependent!

Towards a parton cascade/shower

Ordering the emissions : Pattern of parton parted partons

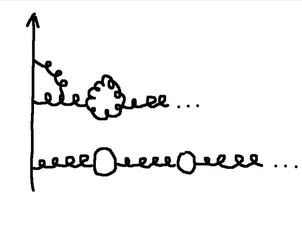


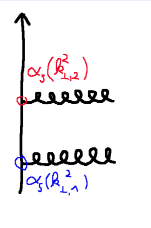
$$q_1^2 > q_2^2 > q_3^2,\ q_1^2 > q_2'^2$$

Aside: Inclusion of quantum effects

Running coupling

- Effect of summing up higher orders (loops): $\alpha_s \to \alpha_s(k_\perp^2)$

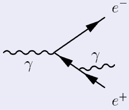




- Much faster parton proliferation, especially for small $k_\perp^2$.
- Must avoid Landau pole: $k_\perp^2 > Q_0^2 \gg \Lambda^2_{\rm QCD}$
  $\Longrightarrow Q_0^2 =$ physical parameter.

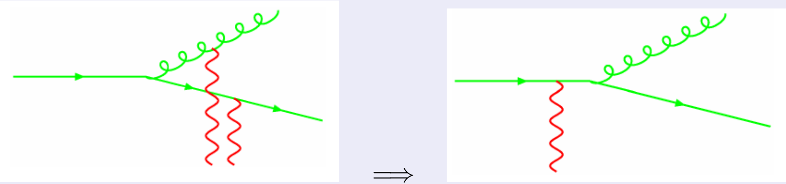
Soft logarithms : Angular ordering

- In principle, independence on collinear variable: t (inv.mass), $k_\perp^2$, θ all lead to same leading logs
- But: Soft limit for single emission also universal
- Problem: Soft gluons come from all over (not collinear!) Quantum interference? Still independent evolution?
- Answer: Not quite independent.
  - Assume photon into e^+e^- at θ_{ee} and photon off electron at θ
  - Transverse momentum and wavelength of photon: $k_\perp^\gamma \sim zp\theta$, $\lambda_\perp^\gamma \sim 1/k_\perp^\gamma = 1/(zp\theta)$.
  - Formation time of photon: $\Delta t \sim 1/\Delta E$, $\Delta E \sim \theta/\lambda_\perp^\gamma \sim zp\theta^2$.
  - ee-separation: $\Delta b \sim \theta_{ee}\Delta t \sim \theta_{ee}/(zp\theta^2)$.
  - Must be larger than transverse wavelength: $\Delta b > \lambda_\perp^\gamma \implies \theta_{ee} > \theta$



- Thus: Angular ordering takes care of soft limit.

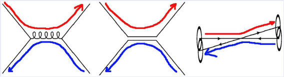
Soft logarithms : Angular ordering in pictures

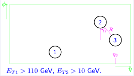


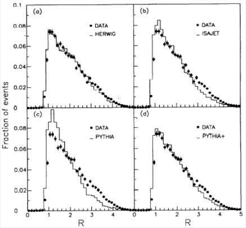
Gluons at large angle from combined colour charge!

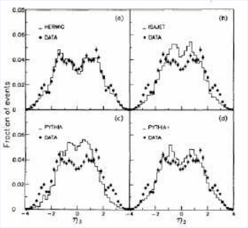
Experimental manifestation of angular ordering

ΔR of 2nd & 3rd jet in multi-jet events in pp-collisions @ Tevatron









(from CDF, Phys. Rev. **D50** (1994) 5562)

Parton showers

Simulating parton radiation

- Catch: Can exponentiate all emissions due to universal log pattern.
- For parton showers use Sudakov form factor:

$$\begin{aligned}\Delta_q(Q^2, Q_0^2) &= \exp\left[-\int\limits_{Q_0^2}^{Q^2}\frac{\mathrm{d}k^2}{k^2}\int \mathrm{d}z\,\frac{\alpha_s[k_\perp^2(z,k^2)]}{2\pi}\,P(z)\right]\\ &= \exp\left[-\int\limits_{Q_0^2}^{Q^2}\frac{\mathrm{d}k^2}{k^2}\,\bar{P}(k^2)\right] \approx \exp\left[-C_F\frac{\alpha_s}{2\pi}\log^2\frac{Q^2}{Q_0^2}\right]\end{aligned}$$

- Interpretation: No-emission probability between Q^2 and Q_0^2.

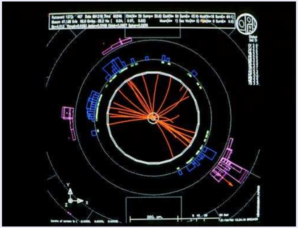
Parton showers

Tools

	Shower variable	A0?	lang.
Pythia	inv.mass: t	approx.	Fortran
Pythia8	transv.mom.: $k_\perp^2$	yes(?)	C++
Herwig	opening angle	yes	Fortran
Herwig++	mod.opening angle	yes	C++
Ariadne	dipole transv.mom.	yes	Fortran
Sherpa	2 showers: t and $k_\perp^2$	varying	C++

What are jets?

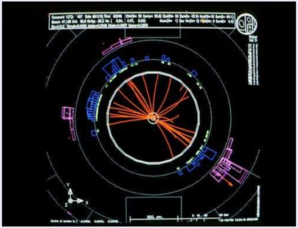
Jets = collimated hadronic energy



- Jets (unavoidably) happen in high-energy events: a collimated bunch of hadrons flying roughly in the same direction.
- Note: hundreds of hadrons contain a lot of information.
- More than we can hope to make use of.

What are jets?

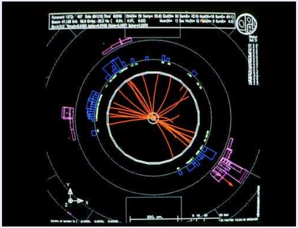
Jets = collimated hadronic energy



- Often you don't need a fancy algorithm to "see" the jets.
- But you do to give them a precise and quantitative meaning.

What are jets?

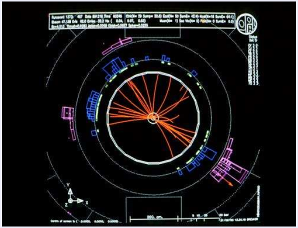
Jets = collimated hadronic energy



- Jets are usually related to some underlying perturbative dynamics (i.e. quarks and gluons).
- The purpose of a "jet algorithm" is then to reduce the complexity of the final state, simplifying many hadrons to simpler objects that one can hope to calculate.

What are jets?

Jets = collimated hadronic energy



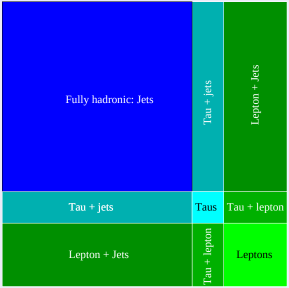
- A jet algorithm maps the momenta of the final state particles into the momenta of a certain number of jets:

$$\{p_i\} \stackrel{\text{jet algo}}{\longleftrightarrow} \{j_J\}$$

  It can act on momenta, calo towers, etc..
- Most algorithms contain a resolution parameter, R, which controls the extension of the jet.

Linking partons and detector signals

Jets occur in decays of heavy objects:
Z, $W^\pm$ bosons, tops, SUSY, ...
Example: top-decays



Event rates for 10 fb^{-1}:

Process	Number
$t\bar{t}$	10^7
QCD Multijets	
3	$9 \cdot 10^8$
4	$7 \cdot 10^7$
5	$6 \cdot 10^6$
6	$3 \cdot 10^5$
7	$2 \cdot 10^4$
8	$2 \cdot 10^3$

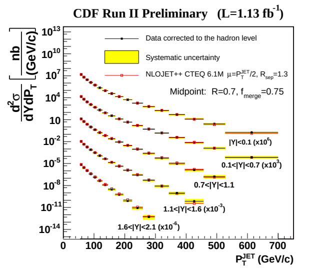
Tree-level (parton-level) numbers

$p_\perp^{\rm jet} > 60$ GeV, $\theta_{ij} > \pi/6$, $|y_i| < 3$

Draggiotis, Kleiss & Papdopoulos '02

But: Jets $\neq$ partons!

- Jets are unavoidable whenever partons scatter.
- Perturbative picture well understood.
  Example: Jet cross sections
- Partons fragment through multiple parton emissions:
  - Soft & collinear divergences dominate
  - Large logs overcome "small" coupling
- No quantitative understanding for transition to hadrons (fate of non-perturbative QCD)
- But: Fragmentation & hadronisation dominated by low $p_\perp$.
- Therefore: Partons result in collimated bunches of hadrons



Jet definitions

General considerations

A jet definition is a set of rules to project large numbers of objects (dozens of partons, hundred's of hadrons, thousand's of calorimeter towers) onto a small number of parton-like objects with one well-defined four-momentum each.
For this jet definition to be useful,

- the rules must be the same, independent of the level of application: QCD resilience/robustness;
- the rules must be complete, with no ambiguities;
- the rules must be experimental feasible and theoretically sensible.
  $\Longrightarrow$ Infrared safety crucial!

Robustness

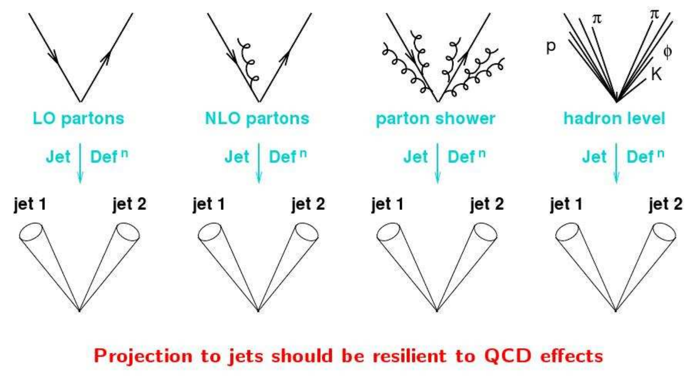


Figure from G.Salam

Collinear/infrared safety

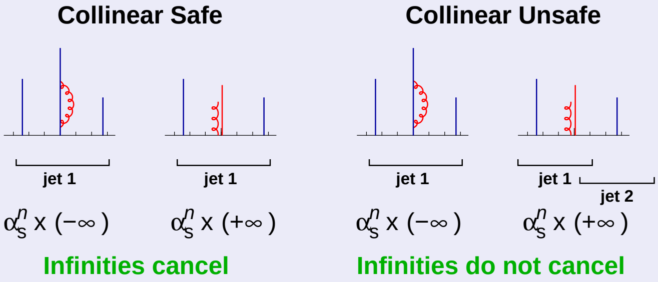
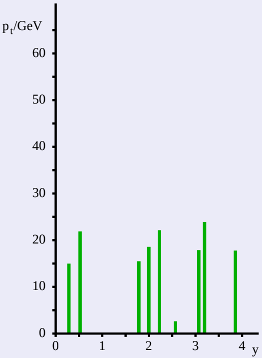


Figure from G.Salam

Cone jets: Fixed cone, progressive removal

- Main idea: Define jets geometrically, remove found jets.
- Take hardest particle = cone axis.
- Draw cone around it.
- Convert contents into a "jet" and remove them.
- Repeat until no particles left.
- Parameters: Cone-size, $p_\perp^{\rm min}$
- good feature: Simple.
- Bad feature: Infrared safe.



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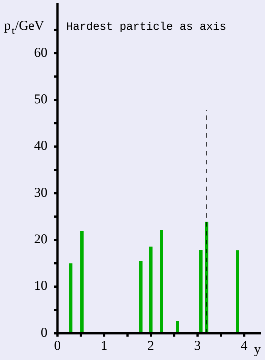

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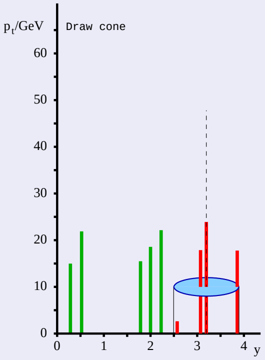

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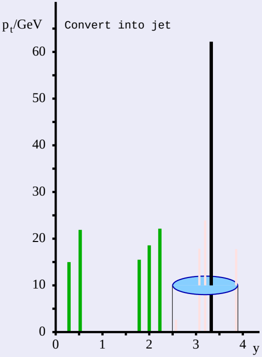

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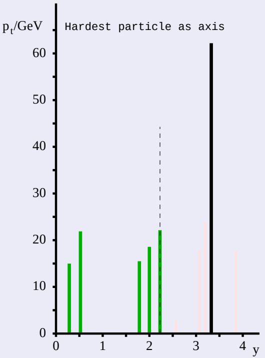

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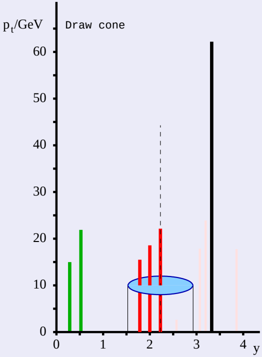

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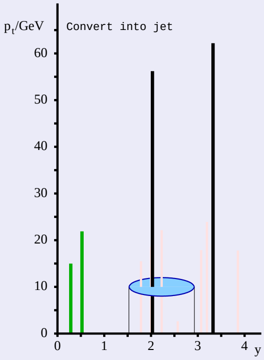

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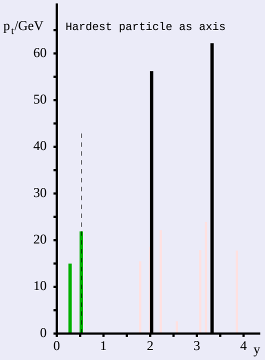

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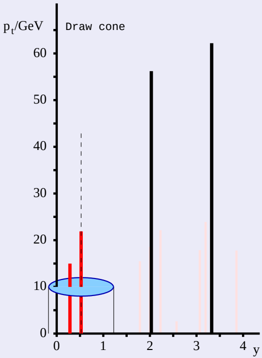

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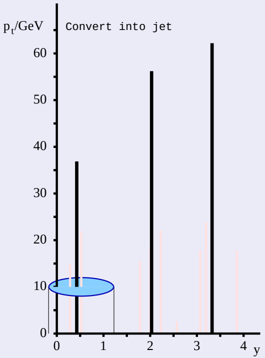

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Cone jets: IR safety does matter

(stolen from M.Cacciari)

- All cone jets apart from SIS-cone are not infrared safe.
- The best ones typically fail at (3+1) partons, others already at (2+1).

Process	Last meaningful order JetClu, Atlas cone	MidPoint	CMS, it.cone	Known at
incl.jets	LO	NLO	NLO	NLO ($\longrightarrow$ NNLO)
$V+1$ jet	LO	NLO	NLO	NLO
3 jets	none	LO	LO	NLO
$V+2$ jets	none	LO	LO	NLO
$m_{\rm jet}$ in $2j+X$	none	none	none	LO

- But: HO calculations cost real money

(100 theorists $\times$ 15 years $\approx$ 100 MEuro.)

- Using unsafe tools makes them pretty much useless.

Cone jets: IR safety does matter

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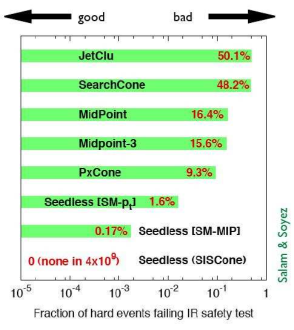
Question: How often are hard jets changes by soft stuff?

- Generate events with $2 < N < 10$ hard partons & find jets.
- Add $1 < N_{\rm soft} < 5$ soft particles & repeat.
- How often do we end up with different jets?



$k_\perp$ jets

- Main idea: Sequential recombination
- Distance between two objects i and j:
$$d_{ij} = \min\{p^2_{i,\perp},\, p^2_{j,\perp}\}\Delta R_{ij},$$
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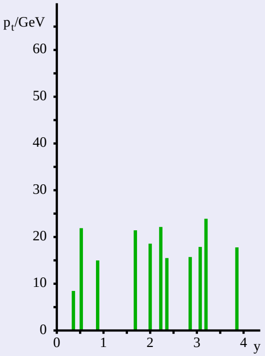

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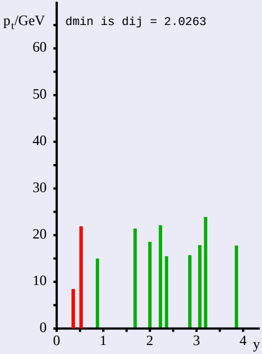

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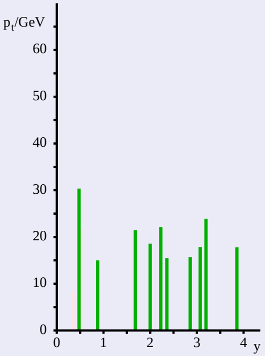

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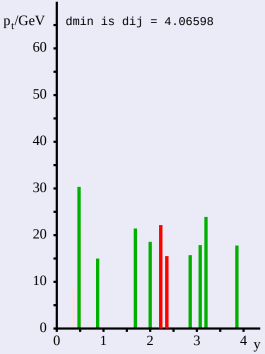

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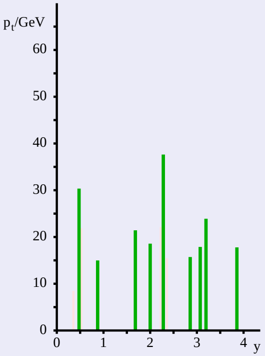

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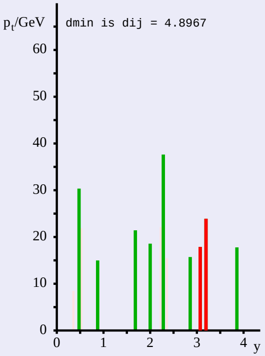

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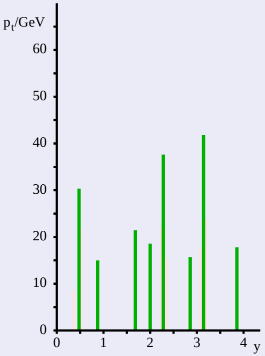

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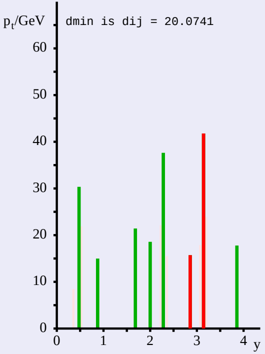

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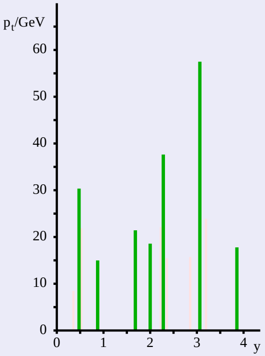

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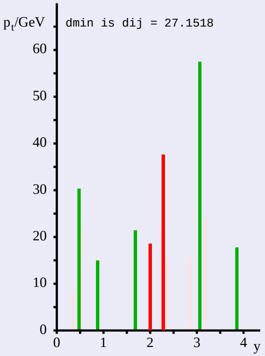

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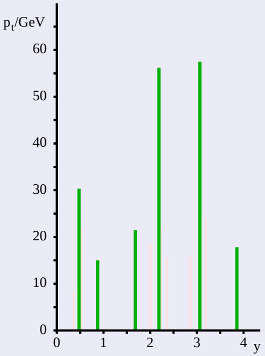

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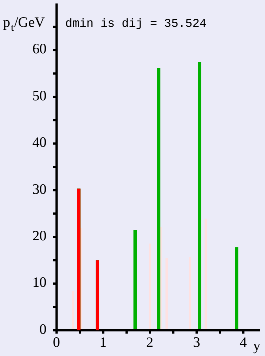

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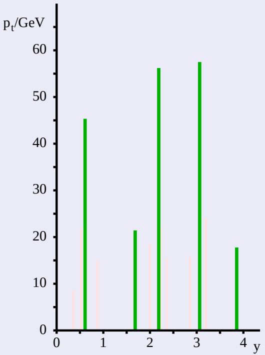

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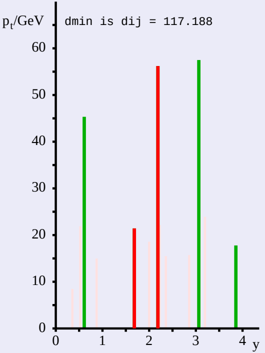

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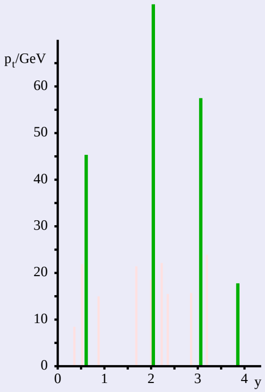

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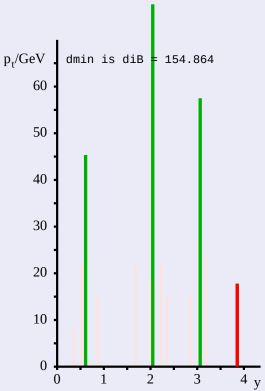

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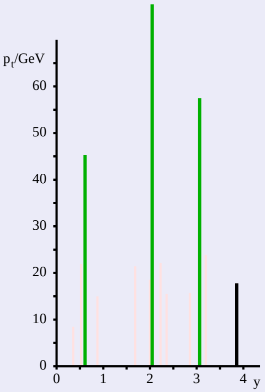

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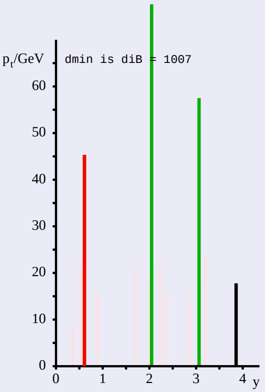

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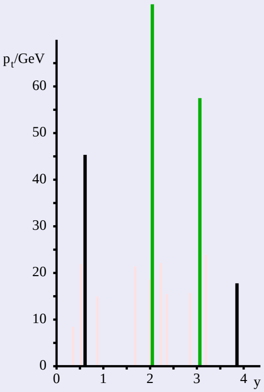
- Include beams, distance to beam:
$$d_{iB} = p^2_{i,\perp}.$$
- Combine two objects with smallest d_{ij}, until smallest $d_{ij} > d_{\rm cut}$.
- Good feature: Infrared safe.



(from G.Salam)

$k_\perp$ jets

- Main idea: Sequential recombination
- Distance between two objects i and j:
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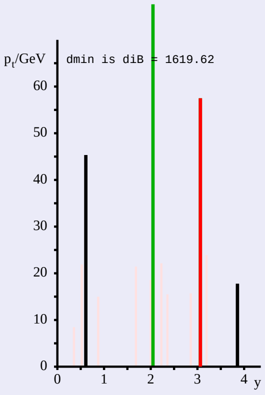

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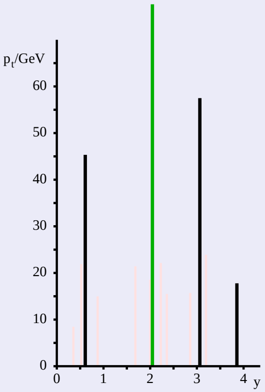

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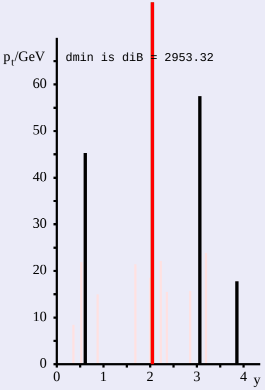

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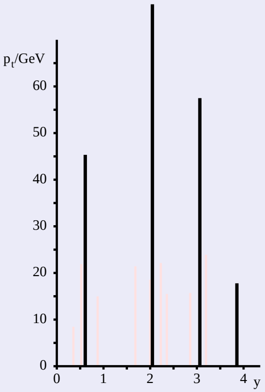
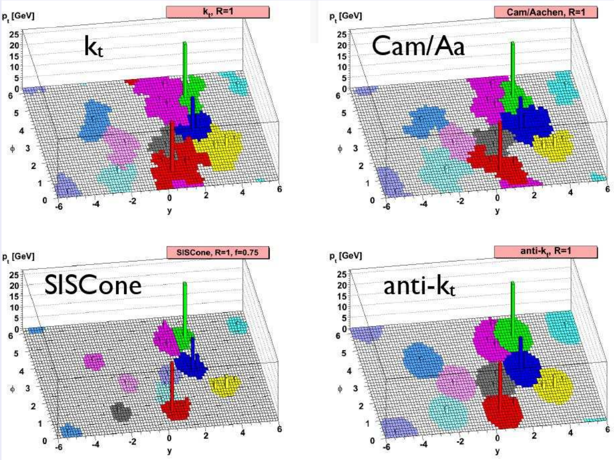


(from G.Salam)

Different jet algorithms

(stolen from M.Cacciari)



To take home

LHC, the QCD machine

- There are no LHC events without QCD!!!
- Perturbative expansion in α_S sufficiently well understood, but: hard to calculate beyond (N)LO.
- Important input to xsec calculations: PDFs
  Must be taken from data, only scaling from QCD
- Order of an calculation is observable-dependent
  make sure you know what you're talking about.

To take home

Parton-parted partons

- QCD radiation (bremsstrahlung) important
- Dominated by collinear & soft emissions
- Universal pattern of QCD bremsstrahlung
- Fills the phase space between large scales of signal creation and low scales of hadronisation
- Well understood in leading log approximation, gives rise to a probabilistic picture: parton showers.

To take home

A jet is (not) a jet is (not) a jet

- Jets are direct result of QCD in hard reactions - your primary experimental QCD entities.
- But: A parton is not a jet - a jet is what it is defined to be
- Jet definitions must match experimental and theoretical needs otherwise meaningless for comparison
- Infrared safety is a theoretical key requirement
- Many jet algorithms, presumably the "best" one does not exist