Phenomenology at collider experiments [Part 1: QCD]

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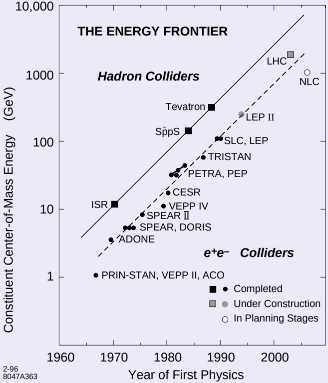
Outline

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, renormalizability, 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

Phenomenology at colliders

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

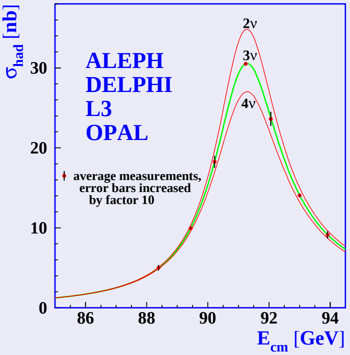
- 3 generations of matter fields:
  left-handed doublets, right-handed singlets

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

Setting the scene: How we know what we know

Generations



EW precision data

(from LEP EWWG public page)

Setting the scene

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 fb^{-1}/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..

LHC - The energy frontier

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, $\mathcal{L} = 10^{33}/\mathrm{cm}^2\mathrm{s} = 10^{-1}\mathrm{fb}^{-1}/\mathrm{y}$

Cross sections at hadron colliders

Master formula

Production cross section for final state Φ in AB collisions:

$$\sigma_{AB\to\Phi+X} = \sum_{ab}\int_0^1 \mathrm{d}x_1\mathrm{d}x_2\, f_{a/A}(x_1,\mu_F^2) f_{b/B}(x_2,\mu_F^2)\, \hat{\sigma}_{ab\to\Phi}(\hat{s},\mu_F^2,\mu_R^2)$$

where

- $x_{1,2}$ are momentum fractions w.r.t. the hadron, $\hat{s} = x_1x_2s$;
- $\hat{\sigma}_{ab\to\Phi}(\hat{s},\mu_F^2,\mu_R^2)$ is the parton-level cross section,
- and where $f_{a/A}(x,Q^2)$ is the parton distribution function (PDF).

PDFs and factorization

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 behavior 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)

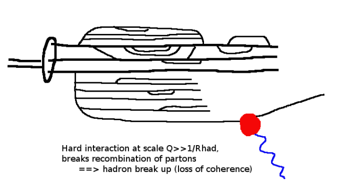
PDFs and factorization

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 color field - only one parton takes part.
- Other partons feel absence only when trying to recombine.
- Universality (process-independence) of PDFs.
- Collinear factorization.

PDFs and factorization

Determination of 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 and fit parameters (including α_S).
- Ensure sum rules (Gottfried, momentum, ...).

PDFs and factorization

Determination of PDFs: Data input

Example: MSTW parameterization 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 $35\mathrm{GeV} < E_T < 45\mathrm{GeV}$.

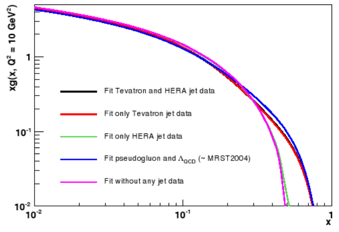
HERA inclusive jet data (in DIS).

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.

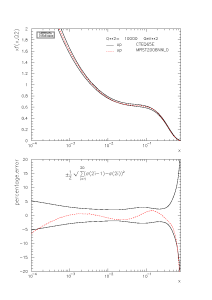


(From R.Thorne's talk at DIS 2007)

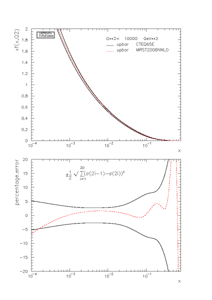
PDFs and factorization

Uncertainties of global PDFs: CTEQ6E vs. MRST2006 NNLO

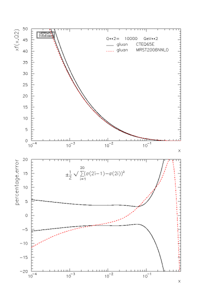
$xu(x,\ Q^2 = 10000\mathrm{GeV}^2)$



$x\bar{u}(x,\ Q^2 = 10000\mathrm{GeV}^2)$



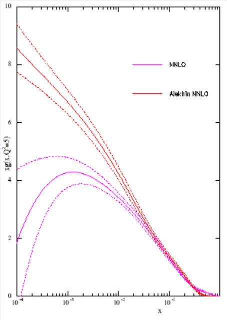
$xg(x,\ Q^2 = 10000\mathrm{GeV}^2)$



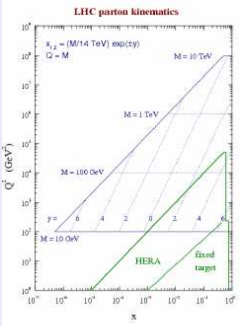
(From Hepdata base)

PDFs and factorization

MSTW vs. Alekhin (NNLO)



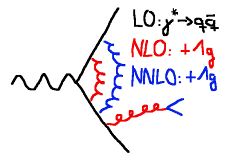
Kinematical coverage



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

Higher-order corrections

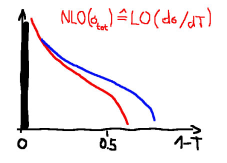
Specifying higher-order corrections: $\gamma^* \to$ hadrons



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

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

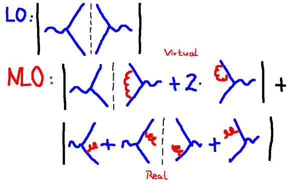
Counter-example: thrust distribution



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

Higher-order corrections

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 → renormalization
- But also: IR-divergences in real & virtual contributions
  Must cancel each other, non-trivial to see:
  N vs. $N+1$ particle FS, divergence in PS vs. loop

Higher-order corrections

Cancelling the IR divergences: Subtraction method

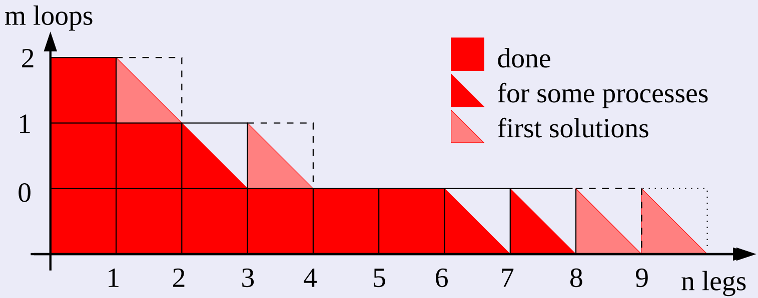
- Total NLO xsec: $\sigma_{\rm NLO} = \sigma_{\rm Born} + \int {\rm d}^D k |\mathcal{M}|^2_V + \int {\rm d}^4 k |\mathcal{M}|^2_R$
- IR div. in real piece $\longrightarrow$ regularize: $\int {\rm d}^4 k |\mathcal{M}|^2_R \longrightarrow \int {\rm d}^D k |\mathcal{M}|^2_R$
- Construct subtraction term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

Cross sections @ hadron colliders

Availability of exact calculations



Cross sections @ hadron colliders

Tree-level tools

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

Loop-level tools (one loop)

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

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.

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 hadronization)

Origin of radiation

Accelerated charges radiate

- Well-known: Accelerated charges radiate
- QED: Electrons (charged) emit photons
  Photons split into electron-positron pairs
- QCD: Quarks (colored) emit gluons
  Gluons split into quark pairs
- Difference: Gluons are colored (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").

Pattern of radiation

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 $\bar{q}$):

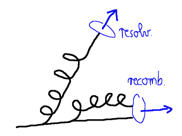
$$\mathrm{d}\sigma_{ee\to 3j} \approx \sigma_{ee\to 2j} \sum_{j\in\{q,\bar{q}\}} \frac{C_F\alpha_s}{2\pi} \frac{\mathrm{d}\theta^2_{jg}}{\theta^2_{jg}} P(z)\,,$$

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

Pattern of radiation

Leading logs: Parton resolution

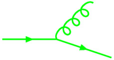
- What is a parton?
  Collinear pair/soft parton recombine!
- Introduce resolution criterion $k_\perp > Q_0$.



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

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

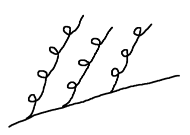
- Unitarity: Probabilities add up to one
  $\mathcal{P}(\text{resolved}) + \mathcal{P}(\text{unresolved}) = 1.$

 $+$  $=1.$

Occurrence of large logarithms

Many emissions: Parton parted partons

- Iterate emissions (jets)



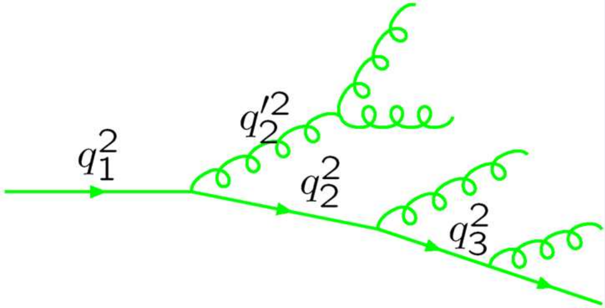
Maximal result for $t_1 > t_2 > \dots t_n$:

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

- How about Q^2? Process-dependent!

Occurrence of large logarithms

Ordering the emissions : Pattern of parton parted partons

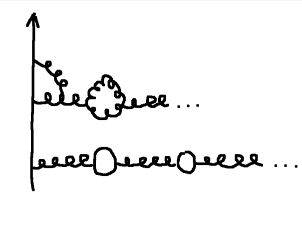


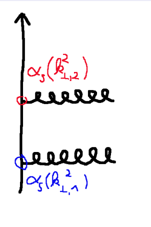
$$q_1^2 > q_2^2 > q_3^2,\ q_1^2 > {q_2'}^2$$

Inclusion of quantum effects

Running coupling

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



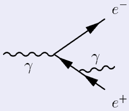


- Much faster parton proliferation, especially for small $k_\perp^2$.
- Must avoid Landau pole: $k_\perp^2 > Q_0^2 \gg \Lambda^2_{\rm QCD}$
  $\Longrightarrow Q_0^2 =$ physical parameter.

Inclusion of quantum effects

Soft logarithms : Angular ordering

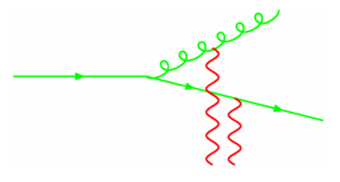
- In principle, independence on collinear variable: t (inv.mass), $k_\perp^2$, θ all lead to same leading logs
- But: Soft limit for single emission also universal
- Problem: Soft gluons come from all over (not collinear!) Quantum interference? Still independent evolution?
- Answer: Not quite independent.
  - 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: $\Delta b > \lambda_\perp^\gamma \implies \theta_{ee} > \theta$



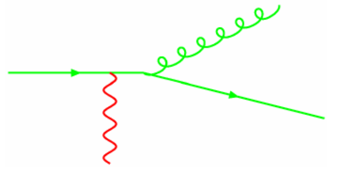
- Thus: Angular ordering takes care of soft limit.

Inclusion of quantum effects

Soft logarithms : Angular ordering



$\Longrightarrow$

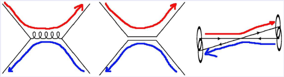


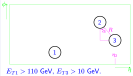
Gluons at large angle from combined color charge!

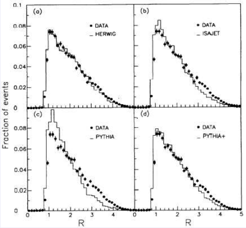
Inclusion of quantum effects

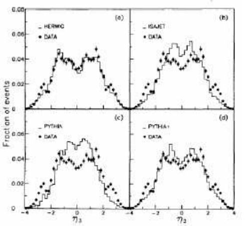
Experimental manifestation of angular ordering

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.

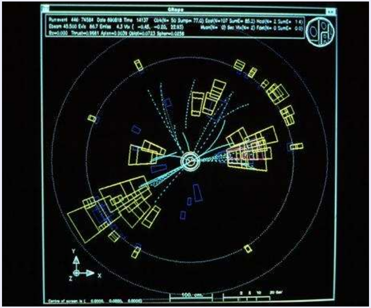
Parton showers

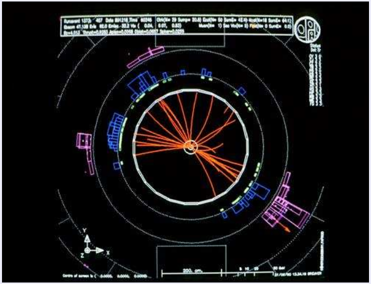
Tools

	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	3 showers: t and $2\times k_\perp^2$	varying	C++

What are jets?

Jets = collimated hadronic energy

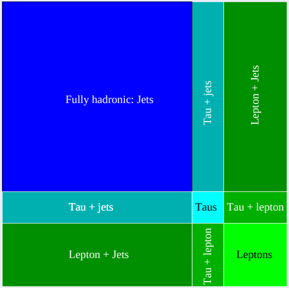




The need for jets

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

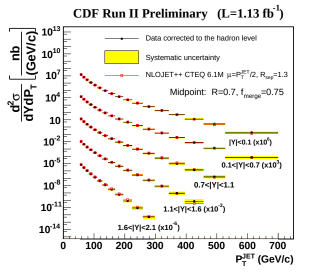
$p_\perp^{\rm jet} > 60$ GeV, $\theta_{ij} > \pi/6$, $|y_i| < 3$

Draggiotis, Kleiss & Papdopoulos '02

Linking partons and detector signals

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 & hadronization 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!

Jet definitions

Robustness

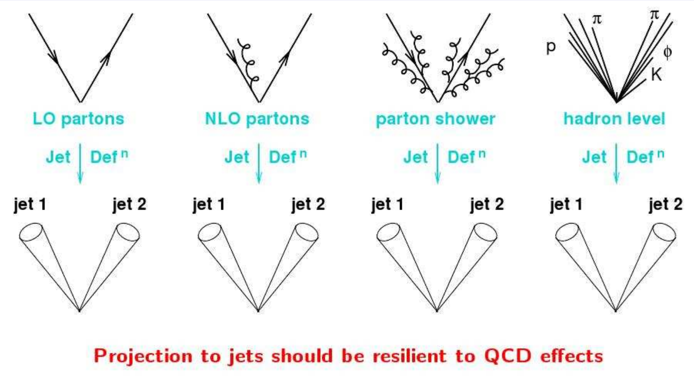


Figure from G.Salam

Jet definitions

Collinear/infrared safety

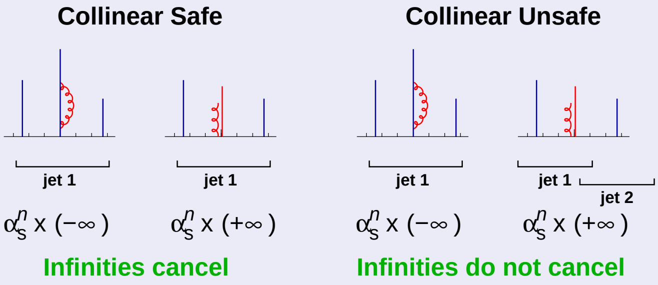
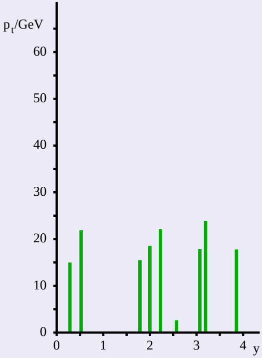


Figure from G.Salam

Jet definitions

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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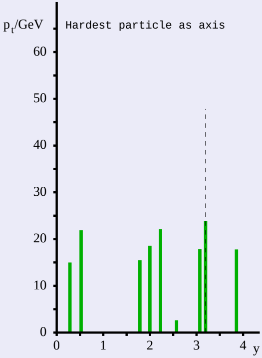

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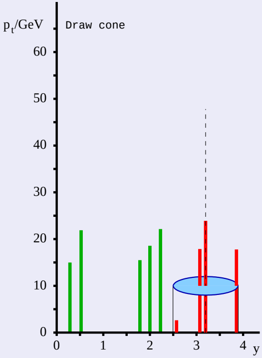

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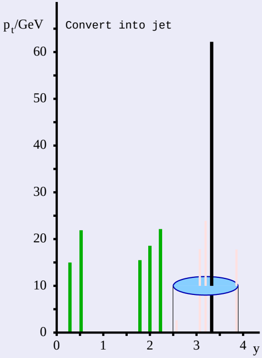

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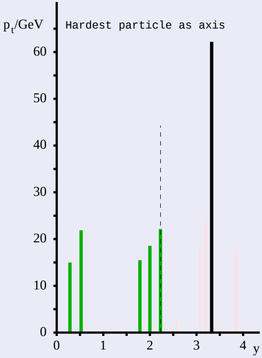

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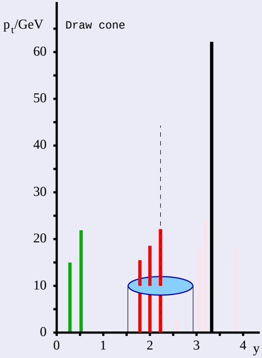

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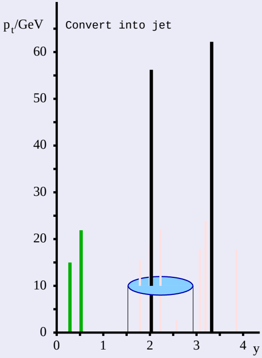

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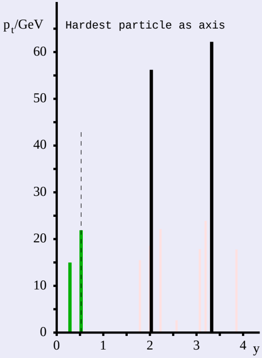

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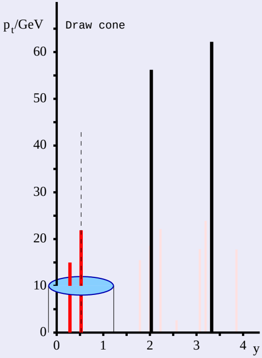

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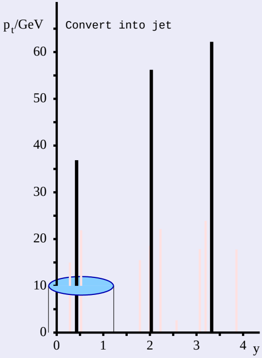

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Jet definitions

$k_\perp$ 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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- "Cone-size" D.
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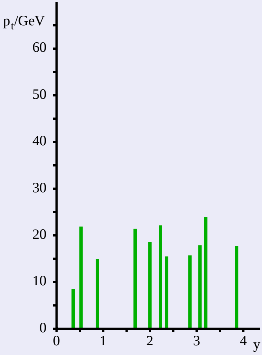

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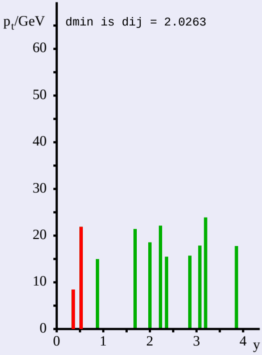

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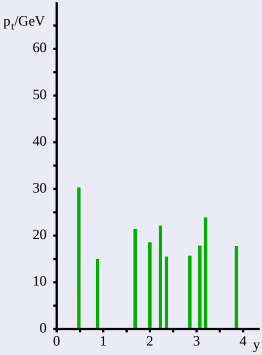

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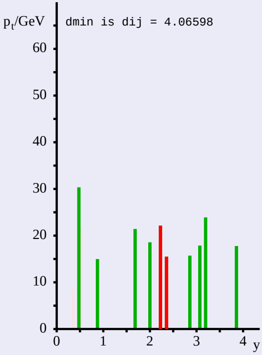

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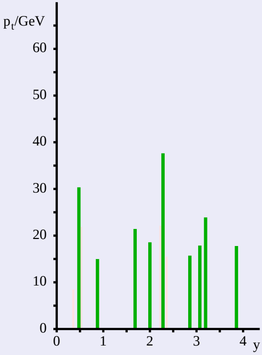

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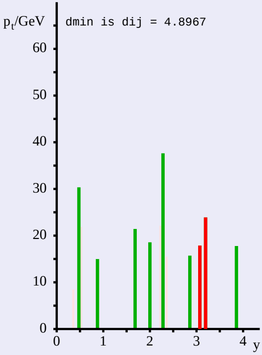

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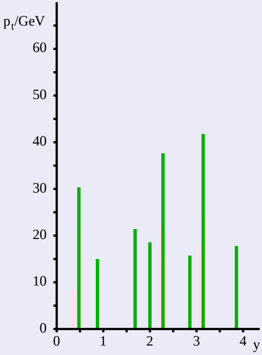

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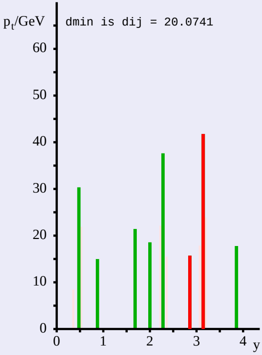

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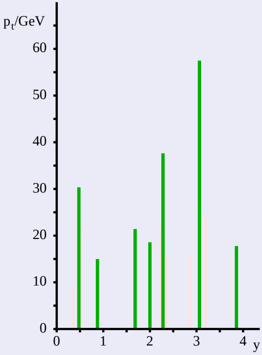

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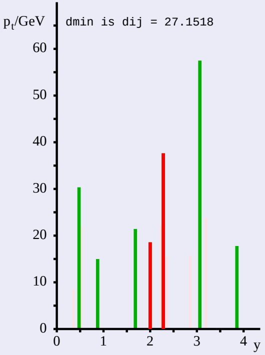

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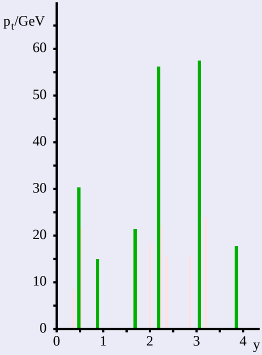

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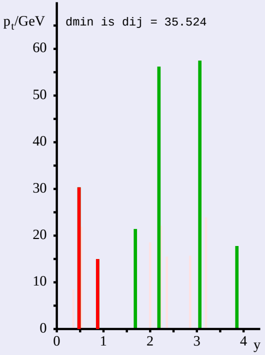

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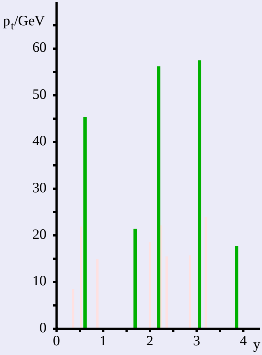

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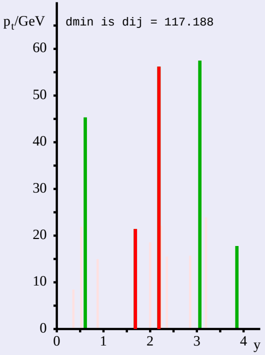

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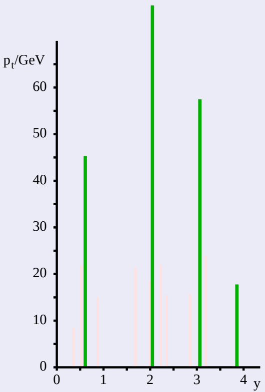

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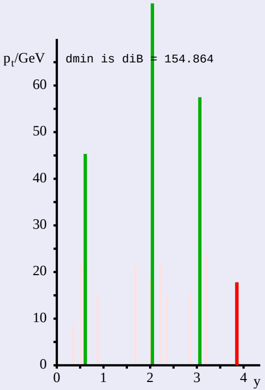

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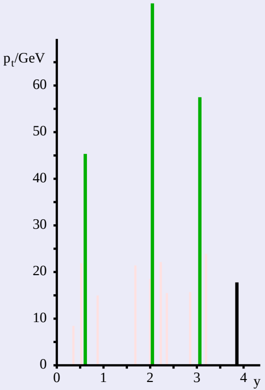

(from G.Salam)

Jet definitions

$k_\perp$ jets

- Main idea: Sequential recombination
- Distance between two objects i and j:
$$d_{ij} = \min\{p^2_{i,\perp},\, p^2_{j,\perp}\}\Delta R_{ij},$$
$$R_{ij} = [\cosh^2\Delta\eta_{ij} + \cos^2\Delta\phi_{ij}]/D^2.$$
- "Cone-size" D.
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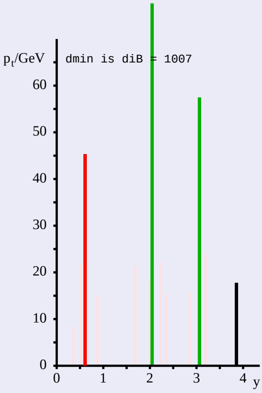

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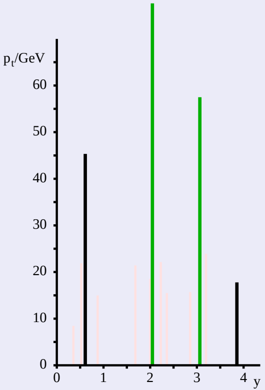

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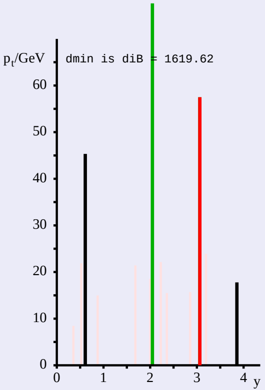

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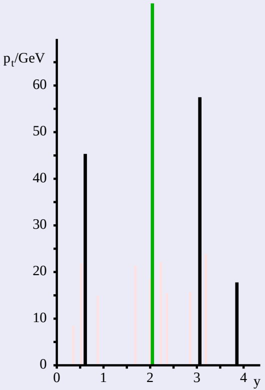

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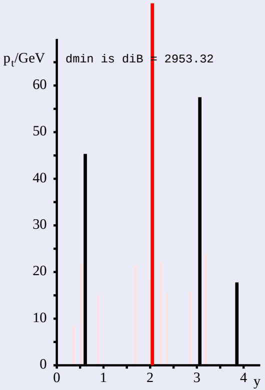

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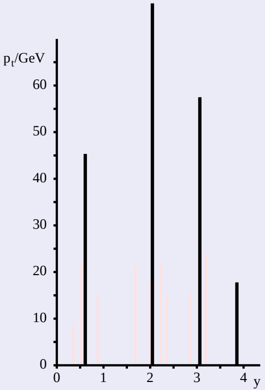

(from G.Salam)

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 hadronization
- 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