Phenomenology: QCD

Tilman Plehn

University of Edinburgh

Graduiertenkolleg Freiburg, 11/2007

Outline

Hadron Colliders — Stars on the Physics Sky

QCD for New Physics Searchers

Collinear jets

QCD scales

Important Standard–Model Processes

Jet Radiation

Organization

5 1/2 hours on LHC phenomenology

- collider basics
- scales in QCD
- hard vs collinear jets
- merging jet descriptions
- why new physics?
- why supersymmetry?
- searches for new physics
- new–physics properties
- new–physics parameters
- why extra dimensions?

One way of teaching phenomenology

- let's try to get to current topics
- past colliders are physics history and PDG entries
- we'll all spend 10+ years in the shadow of LHC
- you ask — I'll try to answer
- ....

Signals for new particles

Real–particle production [gluon, top quark]

– produce searched–for particle

– observe decay [before hadronization]

– reconstruct decay products [(transverse) mass peak with side bins]

⇒ measure mass, spin, branching ratios beyond Standard Model

⇒ highest–energy colliders

Virtual–particle effects [gauge bosons W, Z, $b \to s\gamma$]

– produce and measure something else (like W, Z)

– compare to Standard-Model predictions

⇒ find deviations from Standard–Model relations

⇒ highest–precision colliders

Rare effect or rare decays [B physics, EDMs, LHC signatures?]

– produce something else (like B_s,...)

– find effect forbidden in Standard Model

⇒ observe effect beyond Standard Model

⇒ best–chosen experiment

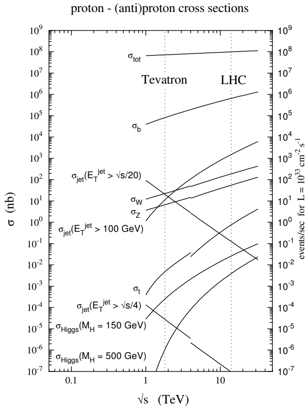
Collider basics

Most powerful colliders: hadron colliders

- inside 27 km LEP tunnel [used to be e^+e^- with 200 GeV, now pp with 14 TeV]
- proton–proton collisions [Tevatron: proton–antiproton at 2 TeV]
- hadronic c.m. energy divided into partons [first approximation $p = (uud)$]
- luminosity: $N = \sigma \mathcal{L}$ with $\mathcal{L} \propto f\, n_1 n_2 / a$ [measured in $\text{cm}^{-2}\text{s}^{-1} = 10^{-39}\text{fb}^{-1}\text{s}^{-1}$]

Everything you always wanted to know...

- signal: everything new, exciting and rare
  background: yesterday's signal
- Standard Model: theory of background
  QCD: evil background theory trying to kill us
- $N_\text{events} = \sigma \cdot \mathcal{L} \cdot \epsilon$
- trigger: no leptons/photons — not on tape
- jet: everything except for leptons/photons
  crucial: what is inside a jet [q, g, b, τ tagged?]
- discovery $N_S/\sqrt{N_B} > 5$



Collider basics

Computing what goes on at hadron colliders

– incoming protons resolved at TeV-scale energy

– to first approximation described by valence quarks (*uud*)

$$\sigma_{AB} = \sum_{a,b} \int_0^1 dx_a dx_b \; f_{a/A}(x_a) \; f_{b/B}(x_b) \;\; \hat{\sigma}_{ab}$$

(1) parton density $f_{a/A}(x_a)$:
probability to find parton a of momentum fraction x_a in proton A
kinematics of partons collinear with proton

– parton densities measured in many experiments [mostly HERA]

(2) partonic cross section $\hat{\sigma}_{ab}$:
just like e^+e^-, but with incoming quarks and gluons ['hard process']
defined perturbatively counting interaction vertices

– partonic cross section calculated (numerically) for any imaginable final state

Collider basics

Kinematics at a hadron collider

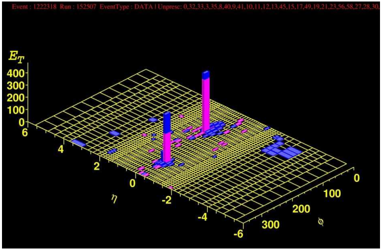
- incoming momenta in lab frame: $p_{a,b} = x_{a,b} \left(E_{A,B}, 0, 0, p_{A,B} \right)$ [partons massless]
- center-of-mass frame moving in z direction
- cylindrical coordinates $d^3\vec{p} = p_T d\phi \, dp_T \, dp_z$ [transverse momentum $p_T = \sqrt{p_x^2 + p_y^2}$]
- (1) usual event sample: ϕ symmetry

  (2) transverse momentum and mass: $E_T = \sqrt{p_T^2 + m^2}$

  (3) rapidity

$$y = \frac{1}{2} \log \frac{E + p_z}{E - p_z} \qquad y_{\text{boosted}} = y + y_{\text{z-shift}} \qquad |y_{\text{observed}}| \lesssim 5$$

- lego plot (p_T, y, ϕ) or (E_T, η, ϕ) [$\eta = \log \cot \theta / 2$]
- distance between two tracks $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$



Collider basics

Kinematics at a hadron collider

– incoming momenta in lab frame: $p_{a,b} = x_{a,b}\,(E_{A,B}, 0, 0, p_{A,B})$ [partons massless]

– center-of-mass frame moving in z direction

– cylindrical coordinates $d^3\vec{p} = p_T d\phi\, dp_T\, dp_z$ [transverse momentum $p_T = \sqrt{p_x^2 + p_y^2}$]

– (1) usual event sample: ϕ symmetry

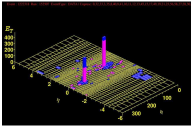
(2) transverse momentum and mass: $E_T = \sqrt{p_T^2 + m^2}$

(3) rapidity

$$y = \frac{1}{2}\log\frac{E + p_z}{E - p_z} \qquad y_\text{boosted} = y + y_\text{z-shift} \qquad |y_\text{observed}| \lesssim 5$$

– lego plot (p_T, y, ϕ) or (E_T, η, ϕ) [$\eta = \log\cot\theta/2$]

– distance between two tracks $\Delta R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$



Useful observables

– invariant mass $(p_{\ell,1} + p_{\ell,2})^2 = m_{\ell\ell}^2 \sim m_Z^2$

– transverse mass [massless invisible neutrino]

$$\begin{aligned} m_{e\nu}^2 &= (E_e + E_\nu)^2 - (\vec{p}_{T,e} + \vec{p}_{T,\nu})^2 - (\vec{p}_{z,e} + \vec{p}_{z,\nu})^2 \\ &> (E_{T,e} + E_{T,\nu})^2 - (\vec{p}_{T,e} + \vec{p}_{T,\nu})^2 \\ &= (E_{T,e} + |\vec{\not{p}}_T|)^2 - (\vec{p}_{T,e} + \vec{\not{p}}_T)^2 = m_{T,e\nu}^2 \end{aligned}$$

Collider basics

Trigger

– flood of data from each bunch crossing not manageable [event rate 1 GHz with 1 MB]

– use some prejudice to write 'interesting' events on tape [realistic 100 Hz]

– LHC is not built to test QCD! [interesting events $1/10^6$]

– soft jets, multiple interactions,... into trash

– leptons, photons, hard jets, missing momentum,... of high priority
open problems: invisible Higgs decays, stable particles, super-fast top jets,...

$\Rightarrow$ trigger menue $T(t, k, \$)$ [a function of time, knowledge and money]

Level-1 trigger menue from Atlas [down to 10^5 Hz, always outdated]

	Atlas	
Objects	$\lvert\eta\rvert^{\max}$	$p_T^{\min}$ (GeV)
μ inclusive	2.4	6 (20)
e/photon inclusive	2.5	17 (26)
two e's or two photons	2.5	12 (15)
1-jet inclusive	3.2	180 (290)
3 jets	3.2	75 (130)
4 jets	3.2	55 (90)
τ/hadrons	2.5	43 (65)
$\not{p}_T$	4.9	100
jets+$\not{p}_T$	3.2, 4.9	50,50 (100,100)

QCD basics

Simple hadron collider process: $pp \to Z(+\text{jets})$

- Drell–Yan process: single gauge boson production [could be W, Z with $Z \to \ell\ell$]
- what is the final state in hadronic σ_{AB}?
- more specific: what about additional jets $\sigma(pp \to Z + \text{jets})$?
- to get an idea: compute $q\bar{q} \to Z$ and $q\bar{q} \to Zg$
- phase space integration over gluon IR divergent: soft — $E_g \to 0$
  collinear — $\theta_{gX} \to 0$

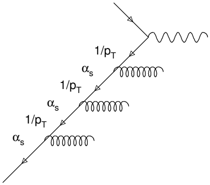
Similarly for initial–state radiation

- gluon off incoming quark with p_{Tj} [soft and collinear, needs virtual–gluon diagrams]
- same for incoming gluon splitting into quarks with p_{Tj} [$qg \to Zq$ only collinear]

$\Rightarrow$ partonic cross section $\hat{\sigma}_{Z+\text{jet}}$ IR divergent

$$\frac{d\sigma_{Zg}}{d\,p_{Tj}} \propto \frac{\alpha_s\; p_{Tj}}{p_{Tj}^2 + m_j^2} = \frac{\alpha_s}{p_{Tj}}$$

$$\Rightarrow \sigma_{Zg} \propto \alpha_s\; \log \frac{p_{Tj}^{\text{max}}}{p_{Tj}^{\text{min}}}$$



QCD basics

Simple hadron collider process: $pp \to Z(+\text{jets})$

– Drell–Yan process: single gauge boson production [could be W, Z with $Z \to \ell\ell$]

– what is the final state in hadronic σ_{AB}?

– more specific: what about additional jets $\sigma(pp \to Z + \text{jets})$?

– to get an idea: compute $q\bar{q} \to Z$ and $q\bar{q} \to Zg$

– phase space integration over gluon IR divergent: soft — $E_g \to 0$
collinear — $\theta_{gX} \to 0$

Similarly for initial–state radiation

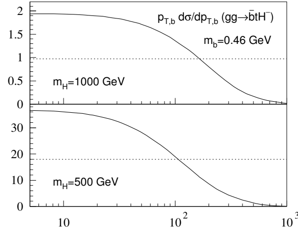
– gluon off incoming quark with p_{Tj} [soft and collinear, needs virtual–gluon diagrams]

– same for incoming gluon splitting into quarks with p_{Tj} [$qg \to Zq$ only collinear]

$\Rightarrow$ partonic cross section $\hat{\sigma}_{Z+\text{jet}}$ IR divergent

$$\frac{d\sigma_{Zg}}{d\,p_{Tj}} \propto \frac{\alpha_s\; p_{Tj}}{p_{Tj}^2 + m_j^2} = \frac{\alpha_s}{p_{Tj}}$$

$$\Rightarrow \sigma_{Zg} \propto \alpha_s \;\log \frac{p_{Tj}^{\text{max}}}{p_{Tj}^{\text{min}}}$$



QCD basics

Divergences, regularization and renormalization scale

– remember $q\bar{q} \to b\bar{b}$ via s-channel gluon to NLO

– including chain of (reducible) gluon self energies

– regularize gluon self–energy bubbles [$n = 4 - 2\epsilon < 4$]

$$\int \frac{d^4k}{(2\pi)^4} \;\to\; r_\epsilon(\mu_R) \int \frac{d^{4-2\epsilon}k}{(2\pi)^{4-2\epsilon}} \sim \mu_R^{2\epsilon} \int \frac{d^{4-2\epsilon}k}{(2\pi)^{4-2\epsilon}}$$

rewrite $\mu_R^\epsilon = \exp(\log \mu_R^\epsilon) = \exp(\epsilon \log \mu_R) = 1 + \epsilon \log \mu_R + \ldots$

– naked divergent gluon self energy

$$\frac{\Sigma^{\mu\nu}(p^2)}{p^2} = \frac{\alpha_s}{4\pi} \, \frac{r_\epsilon(\mu_R)}{\epsilon} \left(\frac{4T_R N_F}{3} - \frac{5C_A}{3} \right) \left(-g^{\mu\nu} + \frac{p^\mu p^\nu}{p^2} \right)$$

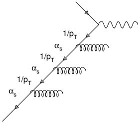
– add chains of one, two, three,.... one–loop bubbles [will show in detail later]
call the resulting scale–dependent coupling $\alpha_s(p^2)$ [$\overline{\text{MS}}$ scheme]

$$\frac{1}{\alpha_s(p^2)} = \frac{1}{\alpha_s(\mu_R^2)} + \frac{1}{4\pi} \left(\frac{11C_A}{3} - \frac{4T_R N_F}{3} \right) \log \frac{p^2}{\mu_R^2}$$

$$\Leftrightarrow \; \frac{\partial \alpha_s(\mu^2)}{\partial \log \mu^2} = -\frac{\alpha_s^2}{4\pi} \left(\frac{11C_A}{3} - \frac{4T_R N_F}{3} \right) + \ldots$$

$\Rightarrow$ renormalization group sums chains of divergent diagrams

Collinear jets

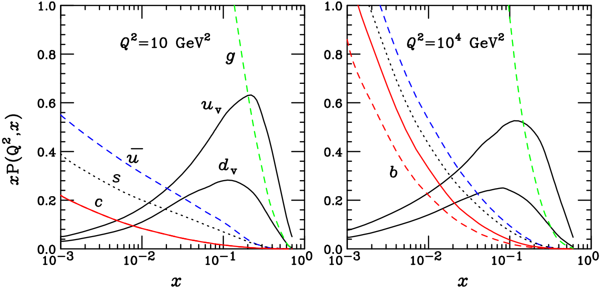


Initial–state gluon radiation

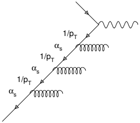
- back to multiple gluon radiation off incoming quark
- each splitting $\alpha_s \log p_{Tj}^{\max} / p_{Tj}^{\min}$ [also possible as $1/\epsilon$]
- IR–divergent in collinear limit
- geometric series just like multiple gluon self energies [IR problem instead of UV problem]

⇒ sum diagrams and absorb in running of parton density [DGLAP]

$$\frac{d f_{a/A}(x,\mu_F)}{d \log \mu_F^2} = \sum_B \int_x^1 \frac{dz}{z} P_{a\leftarrow b}\left(\frac{x}{z},\alpha_s\right) f_{b/A}(z,\mu_F)$$



Collinear jets



Initial–state gluon radiation

– back to multiple gluon radiation off incoming quark

– each splitting $\alpha_s \log p_{Tj}^{\max}/p_{Tj}^{\min}$ [also possible as $1/\epsilon$]

– IR–divergent in collinear limit

– geometric series just like multiple gluon self energies [IR problem instead of UV problem]

$\Rightarrow$ sum diagrams and absorb in running of parton density [DGLAP]

$$\frac{df_{a/A}(x,\mu_F)}{d\log\mu_F^2} = \sum_B \int_x^1 \frac{dz}{z} P_{a\leftarrow b}\left(\frac{x}{z},\alpha_s\right) f_{b/A}(z,\mu_F)$$

– with universal collinear splitting kernels [means factorization]

$$P_{q\leftarrow q}(x) = C_F \frac{1+x^2}{1-x} \qquad P_{q\leftarrow g}(x) = T_R\left(x^2+(1-x)^2\right)$$

$$P_{g\leftarrow q}(x) = C_F \frac{1+(1-x)^2}{x} \qquad P_{g\leftarrow g}(x) = C_A\left(\frac{x}{1-x}+\frac{1-x}{x}+x(1-x)\right)$$

– jet radiation absorbed into collinear pdf [jet distributions for $p_{Tj} < \mu_F$ from parton shower]

– divergence $p_{Tj}^{\min} \to 0$ removed, $p_{Tj}^{\max} \equiv \mu_F$ artifical parameter [smart choice?]

$\Rightarrow$ jet radiation below factorization scale ($p_{Tj} < \mu_F$) included in pdf

QCD scales

Scales in QCD processes

gluon propagator in s channel	initial–state jet radiation
UV divergence $1/(n-4)$ absorbed into counter term (renormalization) universality: renormalizability	IR divergence $\log p_T^{\text{min}}$ absorbed into parton densities (mass factorization) universality: factorization
running coupling $\alpha_s(\mu_R)$ renormalization scale μ_R evolution by beta function of α_s 'physics choice' $\mu_R \sim p_{T,j}$	running parton density $f_{a/A}(x,\mu_F)$ factorization scale μ_F evolution by DGLAP equation 'physics choice' $\mu_F \sim p_{T,j}^{\text{max}}$
all scales artificial parameters not unique for multy–scale problems scale dependence vanishing including all orders	

QCD scales

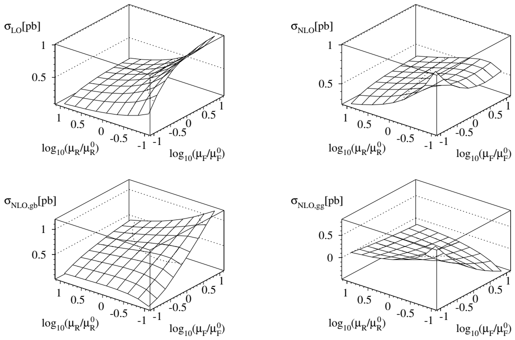
Error estimates in QCD

- QCD at colliders always perturbative in α_s [plus possibly logs]
- let's hope, large logarithms identified and summed
- all observables function of scales $O = O(\mu_F, \mu_R)$

$\Rightarrow$ scales artifact of perturbation theory, so vanish at all orders

$\Rightarrow$ scale dependence (only?) measure of theoretical uncertainty

Example: $pp \to tH^-$



QCD scales

Error estimates in QCD

– QCD at colliders always perturbative in α_s [plus possibly logs]

– let's hope, large logarithms identified and summed

– all observables function of scales $O = O(\mu_F, \mu_R)$

$\Rightarrow$ scales artifact of perturbation theory, so vanish at all orders

$\Rightarrow$ scale dependence (only?) measure of theoretical uncertainty

Caveats

– total cross section with jets $\sigma(\mu_F, \mu_R)$

(1) asymptotic freedom: $\sigma(\mu_R \to 0) = \infty$ and $\sigma(\mu_R \to \infty) = 0$
(2) p_T size of proton: $\sigma(\mu_F \to 0) = 0$ and $\sigma(\mu_F \to \infty) = \infty$

$\Rightarrow$ scale dependences can cancel [more on DY process later]

– there is no 'correct' scale, but there are idiotic scales [introducing large logs]

QCD scales

Error estimates in QCD

– QCD at colliders always perturbative in α_s [plus possibly logs]
– let's hope, large logarithms identified and summed
– all observables function of scales $O = O(\mu_F, \mu_R)$
⇒ scales artifact of perturbation theory, so vanish at all orders
⇒ scale dependence (only?) measure of theoretical uncertainty

Physics of wrong scales

– μ_F defining p_T-size of parton, perturbative part $f_{a/A} \propto \log \mu_F$
– large μ_F means (too) many collinear jets included LO
corrected by correct NLO jet radiation: $K = \sigma_{\text{NLO}}/\sigma_{\text{LO}} \ll 1$
small μ_F means (too) few jets included in LO
corrected by correct NLO jets: $K \gg 1$
– μ_R defining scale in coupling constants or masses $\propto \log \mu_1/\mu_2$
– $\alpha_s(\mu_R)$ leading higher–order contributions, but NLO with explicit argument $\log Q/\mu_R$ explicitely contributing to K
– known trick: mimick soft jet radiation using $\alpha_s(p_{Tj})$

Jets

Definition of jets

- jet–parton duality $\Leftrightarrow$ partons in detector
- jet-rich environment at (hadron) colliders [mostly but not only soft or collinear]

$\Rightarrow$ need jet algorithm to decide what comes from one parton

- stable w.r.t inclusion of soft or collinear jet [IR save]
- crucial for m_{qq} searching for $Z' \to q\bar{q}$, etc
- even more crucial if likelihood $|\mathcal{M}|^2$ of interest

Should be standard: k_T algorithm [experts: exclusive with $R = 1$]

- define a distance jet–jet d_{kl} and jet–beam d_{kB}
  only requirement: $d_{kl} \sim k^2_{T,kl}$ for $\theta_{kl} \to 0$ [e.g. $d_{kB} = E_k^2 \theta_k^2$]
- (0) define resolution d_cut [or number of jets]
  (1) find minimum $d_\text{min} = \min_{kl}(d_{kl}, d_{kB})$
  (2a) if $d_\text{min} > d_\text{cut}$ all objects are jets
  (2b) if $d_\text{min} = d_{kl} < d_\text{cut}$ combine k and l, go to (1)
  (2c) if $d_\text{min} = d_{kB} < d_\text{cut}$ remove k from list, go to (1)

$\Rightarrow$ d_cut separating hard from soft–collinear physics

- if pheno analysis requires jet algorithms, you'll likely get it wrong

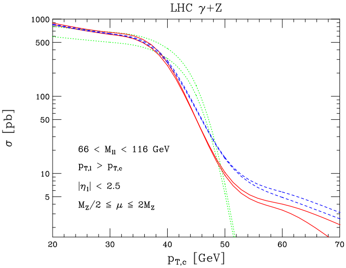
Processes

Example processes everyone will need

– total cross section (coupling) measurements need luminosity
– effectively: normalization to standard candle
– simple (leptonic) final state
well-controlled QCD corrections
high–precision Monte–Carlo [NNLO if possible]

$\Rightarrow$ Drell–Yan production $pp \to \mu^+\mu^-$

Example: Drell-Yan at LO, NLO, NNLO [error from scales?]



Processes

Example processes everyone will need

– new physics usually including bottom jets, lepton, missing momentum

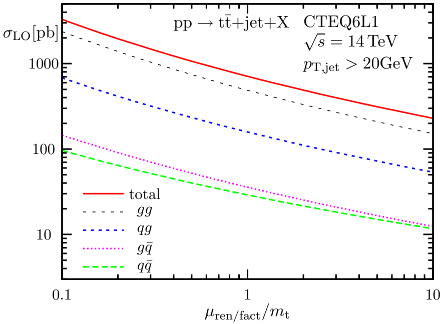
⇒ main background $t\bar{t}$+jets

– background rate after cuts problematic [phase space fragmented]

– NLO corrections to $pp \to t\bar{t}$ available in MC@NLO

– exclusive NLO corrections to $pp \to t\bar{t}j$ almost done

Example: $pp \to ttj$ at LO



Jet radiation

Hard jets [remember $Z+g$ example]

- strictly perturbative, no large logarithms
- described by matrix elements [finite at given order in α_s, e.g. $q\bar{q} \to Z+g+b+\bar{b}+g$]

Soft and collinear jets [no technical details here]

- perturbation theory spoiled by collinear logarithm [fixed-order divergence]
- total cross sections: defined only jet–inclusively [collinear jets always part of pdf]
- collinear jet distributions by parton shower [SCET with improved theoretical description?]

$\Rightarrow$ holy grail of QCD at colliders: combine the two

Sudakov factors

- Poisson statistics: event with expected p hits occuring n times

$$f(n;p) = \frac{p^n\, e^{-p}}{n!} \qquad \text{no event:} \quad f(0;p) = e^{-p}$$

- collinear gluon/photon radiation described by energy-dependent probability

$$dP(x) = \frac{\alpha_s}{2\pi}\, P(x)\, dx \qquad f(0;x_{\text{min}},x_{\text{max}}) = \exp\left(-\int_{x_{\text{min}}}^{x_{\text{max}}} dP(x)\right)$$

$\Rightarrow$ Sudakov giving probability of no radiation/splitting

Jet radiation: MC@NLO

MC@NLO approach

- one hard jet correctly described by exclusive NLO corrections
- soft and collinear jet radiation for all jets from parton shower

Bryan Webber's toy model

- observable for photon radiated with energy $0 < x < 1$

$$\langle O \rangle = \mu_F^{2\epsilon} \int_0^1 dx \, \frac{O(x)}{x^{2\epsilon}} \left[\left. \frac{d\sigma}{dx} \right|_B + \left. \frac{d\sigma}{dx} \right|_V + \left. \frac{d\sigma}{dx} \right|_R \right]$$

with Born, virtual, real contributions [$\lim_x R(x) = B$, a: coupling]

$$\left. \frac{d\sigma}{dx} \right|_B = B \, \delta(x) \qquad \left. \frac{d\sigma}{dx} \right|_V = a \left(\frac{B}{2\epsilon} + V \right) \delta(x) \qquad \left. \frac{d\sigma}{dx} \right|_R = a \frac{R(x)}{x}$$

- usual subtraction to cancel IR divergence in photon emission

$$\begin{aligned} \langle O \rangle_R = & a \, B \, O(0) \int_0^1 dx \, \frac{1}{x^{1+2\epsilon}} + a \int_0^1 dx \, \frac{R(x)O(x) - BO(0)}{x^{1+2\epsilon}} \\ = & - a \frac{B \, O(0)}{2\epsilon} + a \int_0^1 dx \, \frac{R(x)O(x) - BO(0)}{x} \end{aligned}$$

Jet radiation: MC@NLO

MC@NLO approach

– one hard jet correctly described by exclusive NLO corrections
– soft and collinear jet radiation for all jets from parton shower

Bryan Webber's toy model

– finite NLO Monte-Carlo

$$\langle O \rangle = B\, O(0) + a\, V\, O(0) + a \int_0^1 dx \frac{R(x)\, O(x) - B\, O(0)}{x}$$

– generating functional with additional photon–emission probability $d\sigma/dx|_{PS} = B\; aQ(x)/x$

$$\int_0^1 dx \left[F \left(B + aV - \frac{aB}{x} \right) + F \frac{a\, R(x)}{x} \right]$$
$$\to \int_0^1 dx \left[F \left(B + aV - \frac{aB}{x} + \frac{aBQ(x)}{x} \right) + F\, a \frac{R(x) - BQ(x)}{x} \right]$$

– now: two subtraction terms, new one not at $x = 0$ [harder in practice!]

⇒ MC@NLO subtraction scheme with proper non–collinear subtraction term

Jet radiation: MC@NLO

MC@NLO approach

– one hard jet correctly described by exclusive NLO corrections

– soft and collinear jet radiation for all jets from parton shower

Comments

+ first hard jet correct

+ normalization correct strictly to NLO

+ available from Herwig authors

– additional jets only via parton shower

– subtraction terms not easy or universal

– possible negative weights [why a problem?]

Jet radiation: CKKW

CKKW approach

- combine leading–order $X + j, X + jj, X + jjj, X + jjjj$ matrix elements
- avoid double counting between hard matrix elements
- avoid double counting with parton shower for collinear radiation

Combining jet–inclusive matrix elements

- for example 2-jet and 3-jet final state $g \to q\bar{q}(g)$
- complete splitting probabilities in terms of virtuality

$$\Gamma_q(Q_\text{out}, Q_\text{in}) \equiv \Gamma_{q\leftarrow q}(Q_\text{out}, Q_\text{in}) = \frac{2C_F}{\pi} \frac{\alpha_s(Q_\text{out})}{Q_\text{out}} \left(\log \frac{Q_\text{in}}{Q_\text{out}} - \frac{3}{4} \right)$$

$$\Gamma_g(Q_\text{out}, Q_\text{in}) \equiv \Gamma_{g\leftarrow q}(Q_\text{out}, Q_\text{in}) = \frac{2C_A}{\pi} \frac{\alpha_s(Q_\text{out})}{Q_\text{out}} \left(\log \frac{Q_\text{in}}{Q_\text{out}} - \frac{11}{12} \right)$$

$$\Delta_{q,g}(Q_\text{out}, Q_\text{in}) = \exp \left[- \int_{Q_\text{out}}^{Q_\text{in}} dq \; \Gamma_{q,g}(Q_\text{out}, Q_\text{in}) \right]$$

- 2 jets only: $[\Delta_q(Q_1, Q_2)]^2$ [gluon splitting at Q_2; parton shower below Q_1]
- 3 jets only: $\Gamma_q(Q_2, Q_q) \, [\Delta_q(Q_1, Q_2)]^2 \, \Delta_g(Q_1, Q_g)$ [gluon/quark after splitting: $Q_{g,q}$]
- 4 jets only....

$\Rightarrow$ additional Sudakov factors with simple algebra

Jet radiation: CKKW

CKKW approach

– combine leading–order $X+j, X+jj, X+jjj, X+jjjj$ matrix elements
– avoid double counting between hard matrix elements
– avoid double counting with parton shower for collinear radiation

Preparing event sample

(1) compute hard n–jet samples and cross sections [set of momenta with resolution d_{cut}]
(2) choose jet multiplicty n according to

$$p_n = \frac{\sigma_n}{\sum_{k=0} \sigma_k} \qquad \text{with} \qquad \sigma_k = \sigma_k(d_{\text{cut}})$$

(3) compute $|\mathcal{M}|^2$ and virtualities at splitting points [k_T algorithm]
(4) apply Sudakov correction factors to weight, re-weight α_s
MLM scheme: veto events instead of Sudakovs
Madevent scheme: test splitting with matrix elements
(5) use parton shower for soft/collinear end [indepenent of matching point!]
(6) normalize total rate to highest known order
$\Rightarrow$ CKKW: combine exclusive n–jet rates with parton shower

Jet radiation: CKKW

CKKW approach

– combine leading–order $X + j, X + jj, X + jjj, X + jjjj$ matrix elements

– avoid double counting between hard matrix elements

– avoid double counting with parton shower for collinear radiation

Comments

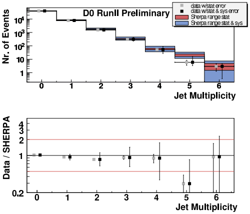
+ all additional jets correct

+ available from Sherpa, Madevent, Alpgen authors

– normalization of different processes with leading–order error

– over-all normalization unknown

Sherpa–CKKW and Tevatron data



QCD Outlook

LHC physicists need to know QCD [model builders too]

– not all collider events can be analysed: trigger
– perturbative QCD is not perfect, but the best we have
– some processes need to be known precisely: luminosity, backgrounds
– renormalization/factorization scales from higher orders
– collinear jets described by parton shower
– hard jets described by fixed–order matrix elements
– jets properly described: ME-PS matching

$\Rightarrow$ next: what LHC can do with that

Apologies...

...to the people I did not cite, because it is a lecture

...to you for not explaining things like parton shower

...to those for whom I went to fast

...to those I bored to death