QCD and Collider Phenomenology

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IPMU/KEK Lectures 2009

Lecture 2: Jet Fragmentation and Hadron-Hadron Processes

- Jet Fragmentation
  - Fragmentation functions
  - Coherent parton branching
  - Small-x fragmentation and average multiplicity
- Hadronization Models
  - General ideas
  - Cluster model
  - String model
- Hadron-Hadron Processes
  - Parton-parton luminosities
  - Lepton pair, jet and heavy quark production
  - Higgs boson production
- Survey of NLO Calculations for LHC

Jet Fragmentation

- Fragmentation functions $F_i^h(x,t)$ gives distribution of momentum fraction x for hadrons of type h in a jet initiated by a parton of type i, produced in a hard process at scale t.
- Like parton distributions in a hadron, $D_i^h(x,t)$, these are factorizable quantities, in which infrared divergences of PT can be factorized out and replaced by experimentally measured factor that contains all long-distance effects.
- In e^+e^- annihilation, for example, the hard process is $e^+e^- \longrightarrow q\bar{q}$ at scale equal to c.m. energy squared s; distribution of $x = 2p_h/\sqrt{s}$ is (for $s \ll M_Z^2$)

$$\frac{d\sigma}{dx} = 3\sigma_0 \sum_q Q_q^2 \left\{ F_q^h(x,s) + F_{\bar{q}}^h(x,s) \right\}$$

where σ_0 is $e^+e^- \longrightarrow \mu^+\mu^-$ cross section.

- Fragmentation functions satisfy DGLAP evolution equation

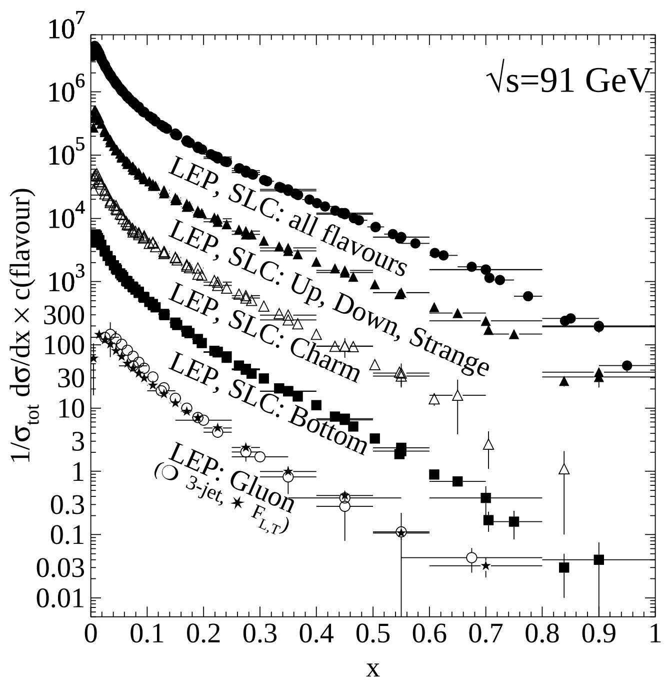
$$t\frac{\partial}{\partial t} F_i^h(x,t) = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_S}{2\pi} P_{ji}(z,\alpha_S) F_j^h(x/z,t) \ .$$

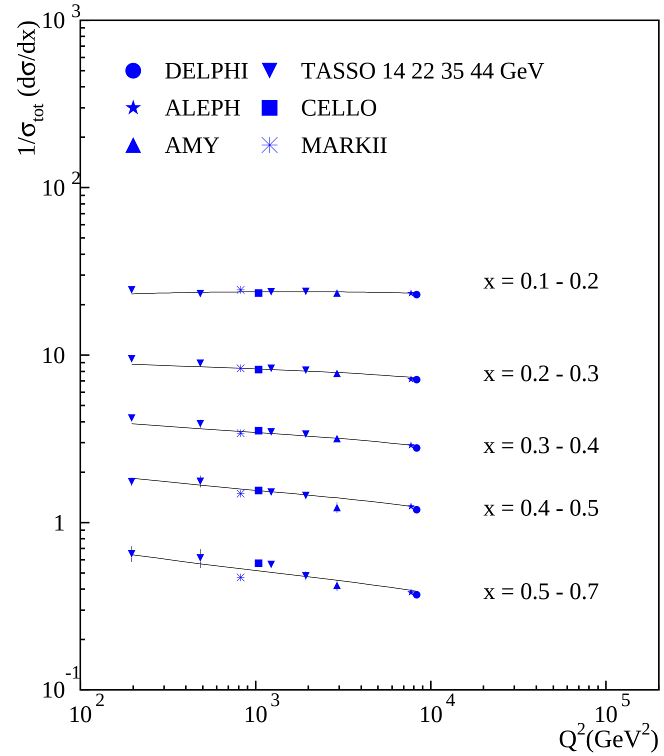
Splitting functions P_{ji} have perturbative expansions of the form

$$P_{ji}(z,\alpha_S) = P_{ji}^{(0)}(z) + \frac{\alpha_S}{2\pi} P_{ji}^{(1)}(z) + \cdots$$

Leading terms $P_{ji}^{(0)}(z)$ were given earlier. Notice that splitting function is P_{ji} rather than P_{ij} since F_j^h represents fragmentation of final parton j.

- Solve DGLAP equation by taking moments as explained for DIS. As in that case, scaling violation is clearly seen.





Soft Gluon Coherence

- Parton branching formalism discussed so far takes account of collinear enhancements to all orders in PT. There are also soft enhancements: When external line with momentum p and mass m (not necessarily small) emits gluon with momentum q, propagator factor is

$$\frac{1}{(p \pm q)^2 - m^2} = \frac{\pm 1}{2p \cdot q} = \frac{\pm 1}{2\omega E(1 - v\cos\theta)}$$

where ω is emitted gluon energy, E and v are energy and velocity of parton emitting it, and θ is angle of emission. This diverges as $\omega \longrightarrow 0$, for any velocity and emission angle.

- Including numerator, soft gluon emission gives a colour factor times universal, spin-independent factor in amplitude

$$F_{\text{soft}} = \frac{p \cdot \epsilon}{p \cdot q}$$

where ϵ is polarization of emitted gluon. For example, emission from quark gives numerator factor $N \cdot \epsilon$, where

$$\begin{aligned} N^\mu &= (\not{p} + \not{q} + m)\gamma^\mu u(p) \underset{\omega \to 0}{\longrightarrow} (\gamma^\nu \gamma^\mu p_\nu + \gamma^\mu m) u(p) \\ &= (2p^\mu - \gamma^\mu \not{p} + \gamma^\mu m) u(p) \; = \; 2p^\mu u(p) \; . \end{aligned}$$

(using Dirac equation for on-mass-shell spinor $u(p)$).

- Universal factor F_{soft} coincides with classical eikonal formula for radiation from current p^μ, valid in long-wavelength limit.

- No soft enhancement of radiation from off-mass-shell internal lines, since associated denominator factor $(p+q)^2 - m^2 \to p^2 - m^2 \neq 0$ as $\omega \to 0$.
- Enhancement factor in amplitude for each external line implies cross section enhancement is sum over all pairs of external lines $\{i, j\}$:

$$d\sigma_{n+1} = d\sigma_n \frac{d\omega}{\omega} \frac{d\Omega}{2\pi} \frac{\alpha_S}{2\pi} \sum_{i,j} C_{ij} W_{ij}$$

where $d\Omega$ is element of solid angle for emitted gluon, C_{ij} is a colour factor, and radiation function W_{ij} is given by

$$W_{ij} = \frac{\omega^2 p_i \cdot p_j}{p_i \cdot q \, p_j \cdot q} = \frac{1 - v_i v_j \cos\theta_{ij}}{(1 - v_i \cos\theta_{iq})(1 - v_j \cos\theta_{jq})} \, .$$

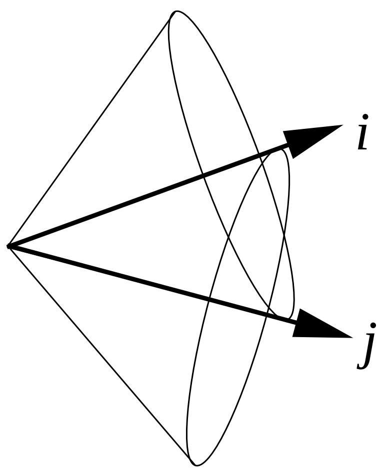
Colour-weighted sum of radiation functions $C_{ij} W_{ij}$ is antenna pattern of hard process.

- Radiation function can be separated into two parts containing collinear singularities along lines i and j. Consider for simplicity massless particles, $v_{i,j} = 1$. Then $W_{ij} = W_{ij}^i + W_{ij}^j$ where

$$W_{ij}^i = \frac{1}{2}\left(W_{ij} + \frac{1}{1-\cos\theta_{iq}} - \frac{1}{1-\cos\theta_{jq}}\right) \ .$$

- This function has remarkable property of angular ordering. Write angular integration in polar coordinates w.r.t. direction of i, $d\Omega = d\cos\theta_{iq}\, d\phi_{iq}$. Performing azimuthal integration, we find

$$\int_0^{2\pi} \frac{d\phi_{iq}}{2\pi} W_{ij}^i = \frac{1}{1-\cos\theta_{iq}} \quad \text{if } \theta_{iq} < \theta_{ij}, \text{ otherwise } 0.$$



Thus, after azimuthal averaging, contribution from W_{ij}^i is confined to cone, centred on direction of i, extending in angle to direction of j. Similarly, W_{ij}^j, averaged over ϕ_{jq}, is confined to cone centred on line j extending to direction of i.

Angular Ordering

- To prove angular ordering property, write

$$1 - \cos\theta_{jq} = a - b\cos\phi_{iq}$$

where

$$a = 1 - \cos\theta_{ij}\cos\theta_{iq}\ , \qquad b = \sin\theta_{ij}\sin\theta_{iq}\ .$$

Defining $z = \exp(i\phi_{iq})$, we have

$$I^i_{ij} \equiv \int_0^{2\pi}\frac{d\phi_{iq}}{2\pi}\frac{1}{1-\cos\theta_{jq}} = \frac{1}{i\pi b}\oint\frac{dz}{(z-z_+)(z-z_-)}$$

where z-integration contour the unit circle and

$$z_\pm = \frac{a}{b} \pm \sqrt{\frac{a^2}{b^2} - 1}\ .$$

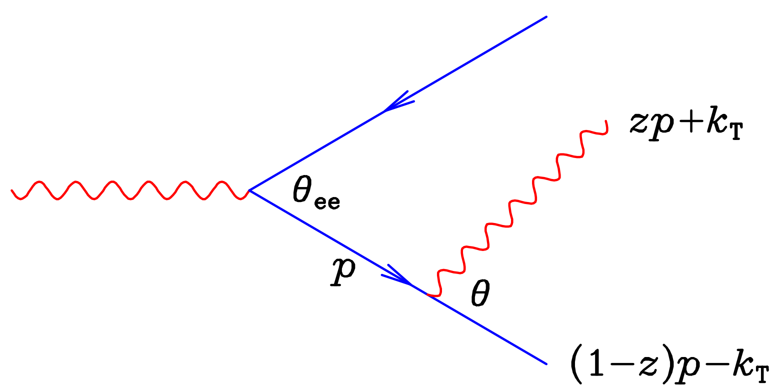
Now only pole at $z = z_-$ can lie inside unit circle, so

$$I^i_{ij} = \sqrt{\frac{1}{a^2 - b^2}} = \frac{1}{|\cos\theta_{iq} - \cos\theta_{ij}|}\ .$$

Hence

$$\int_0^{2\pi} \frac{d\phi_{iq}}{2\pi} W_{ij}^i = \frac{1}{2(1-\cos\theta_{iq})}[1 + (\cos\theta_{iq} - \cos\theta_{ij}) I_{ij}^i]$$
$$= \frac{1}{1-\cos\theta_{iq}} \quad \text{if } \theta_{iq} < \theta_{ij}, \text{ otherwise } 0.$$

- Angular ordering is coherence effect common to all gauge theories. In QED it causes Chudakov effect – suppression of soft bremsstrahlung from e^+e^- pairs, which has simple explanation in old-fashioned (time-ordered) perturbation theory.



- ❖ Consider emission of soft photon at angle θ from electron in pair with opening angle $\theta_{ee} < \theta$. For simplicity assume $\theta_{ee}, \theta \ll 1$.
- ❖ Transverse momentum of photon is $k_T \sim zp\theta$ and energy imbalance at $e \to e\gamma$ vertex is

$$\Delta E \sim k_T^2/zp \sim zp\theta^2 .$$

- Time available for emission is $\Delta t \sim 1/\Delta E$. In this time transverse separation of pair will be $\Delta b \sim \theta_{ee}\Delta t$.
- For non-negligible probability of emission, photon must resolve this transverse separation of pair, so

$$\Delta b > \lambda/\theta \sim (zp\theta)^{-1}$$

  where λ is photon wavelength.
- This implies that

$$\theta_{ee}(zp\theta^2)^{-1} > (zp\theta)^{-1} \ ,$$

  and hence $\theta_{ee} > \theta$. Thus soft photon emission is suppressed at angles larger than opening angle of pair, which is angular ordering.
- Photons at larger angles cannot resolve electron and positron charges separately – they see only total charge of pair, which is zero, implying no emission.

- More generally, if i and j come from branching of parton k, with (colour) charge $\boldsymbol{Q}_k = \boldsymbol{Q}_i + \boldsymbol{Q}_k$, then radiation outside angular-ordered cones is emitted coherently by i and j and can be treated as coming directly from (colour) charge of k.

Coherent Branching

- Angular ordering provides basis for coherent parton branching formalism, which includes leading soft gluon enhancements to all orders.
- In place of virtual mass-squared variable t in earlier treatment, use angular variable

$$\zeta = \frac{p_b \cdot p_c}{E_b\, E_c} \simeq 1 - \cos\theta$$

as evolution variable for branching $a \to bc$, and impose angular ordering $\zeta' < \zeta$ for successive branchings. Iterative formula for n-parton emission becomes

$$d\sigma_{n+1} = d\sigma_n \frac{d\zeta}{\zeta} dz \frac{\alpha_S}{2\pi} \hat{P}_{ba}(z) \; .$$

- In place of virtual mass-squared cutoff t_0, must use angular cutoff ζ_0 for coherent branching. This is to some extent arbitrary, depending on how we classify emission as unresolvable. Simplest choice is $\zeta_0 = t_0/E^2$ for parton of energy E.
- For radiation from particle i with finite mass-squared t_0, radiation function becomes

$$\omega^2 \left(\frac{p_i \cdot p_j}{p_i \cdot q\, p_j \cdot q} - \frac{p_i^2}{(p_i \cdot q)^2} \right) \simeq \frac{1}{\zeta} \left(1 - \frac{t_0}{E^2 \zeta} \right) \; ,$$

so angular distribution of radiation is cut off at $\zeta = t_0/E^2$. Thus t_0 can still be interpreted as minimum virtual mass-squared.

- With this cutoff, most convenient definition of evolution variable is not ζ itself but rather

$$\tilde{t} = E^2\zeta \geq t_0 \ .$$

Angular ordering condition $\zeta_b, \zeta_c < \zeta_a$ for timelike branching $a \to bc$ (a outgoing) becomes

$$\tilde{t}_b < z^2\tilde{t} \ , \quad \tilde{t}_c < (1-z)^2\tilde{t}$$

where $\tilde{t} = \tilde{t}_a$ and $z = E_b/E_a$. Thus cutoff on z becomes

$$\sqrt{t_0/\tilde{t}} < z < 1 - \sqrt{t_0/\tilde{t}} \ .$$

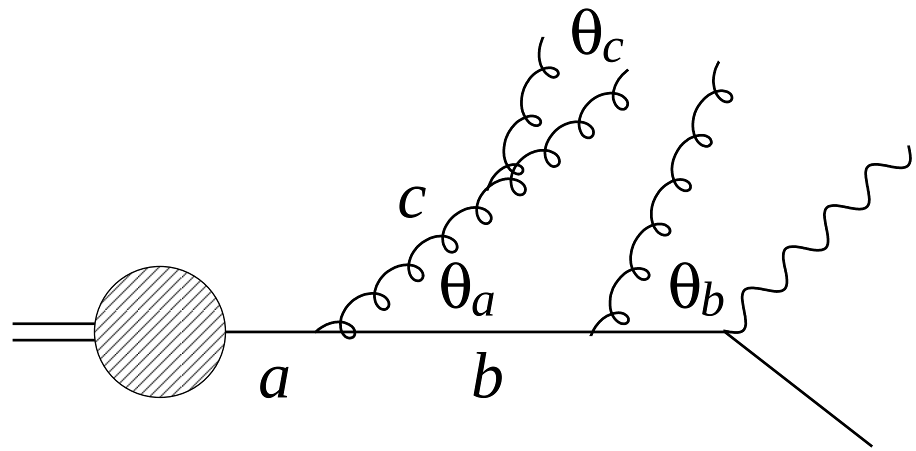
- Neglecting masses of b and c, virtual mass-squared of a and transverse momentum of branching are

$$t = z(1-z)\tilde{t} \ , \quad p_t^2 = z^2(1-z)^2\tilde{t} \ .$$

Thus for coherent branching Sudakov form factor of quark becomes

$$\tilde{\Delta}_q(\tilde{t}) = \exp\left[-\int_{4t_0}^{\tilde{t}} \frac{dt'}{t'} \int_{\sqrt{t_0/t'}}^{1-\sqrt{t_0/t'}} \frac{dz}{2\pi} \alpha_S(z^2(1-z)^2 t') \hat{P}_{qq}(z)\right]$$

At large $\tilde{t}$ this falls more slowly than form factor without coherence, due to the suppression of soft gluon emission by angular ordering.



- Note that for spacelike branching $a \to bc$ (a incoming, b spacelike), angular ordering condition is

$$\theta_b > \theta_a > \theta_c \; .$$

However, kinematics implies $E_b\theta_b > E_a\theta_a$ at small x and in this case $E_b < E_a$, so angular ordering does not impose an extra constraint on branching. Therefore gluon emission is not suppressed by coherence in spacelike branching at small x.

  - This permits the rapid rise of structure functions at small x.
  - We shall see that the production of low-momentum hadrons in *jet fragmentation* at small x, controlled by timelike branching, is quite different – strongly suppressed by QCD coherence.

Small-x fragmentation

- Evolution of fragmentation functions at small x sensitive to moments near $N = 1$. However, anomalous dimensions $\gamma_{gq}^{(0)}$, $\gamma_{gg}^{(0)}$ are not defined at $N = 1$: moment integrals for $N \leq 1$ are dominated by small z, where $P_{gi}(z)$ diverges due to soft gluon emission.
- At small z must take into account coherence effects. Recall evolution variable becomes $\tilde{t} = E^2[1 - \cos\theta]$, with angular ordering condition $\tilde{t}' < z^2\tilde{t}$. Thus, redefining t as $\tilde{t}$, evolution equation in integrated form is

$$\begin{aligned} F_i(x,t) &= F_i(x,t_0) \\ &\quad + \sum_j \int_x^1 \frac{dz}{z} \int_{t_0}^{z^2 t} \frac{dt'}{t'} \frac{\alpha_S}{2\pi} P_{ji}(z) F_j(x/z, t') \end{aligned}$$

or in differential form

$$t\frac{\partial}{\partial t} F_i(x,t) = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_S}{2\pi} P_{ji}(z) F_j(x/z, z^2 t) \; .$$

- Only difference from DGLAP equation is z-dependent scale on the right-hand side — not important for most values of x but crucial at small x.
- For simplicity, consider first α_S fixed and neglect sum over j. Taking moments as usual,

$$t\frac{\partial}{\partial t} \tilde{F}(N,t) = \frac{\alpha_S}{2\pi} \int_x^1 dz\, z^{N-1} P(z) \tilde{F}(N, z^2 t) \; .$$

❖ Try solution of form $F(N,t) \propto t^{\gamma(N,\alpha_S)}$. Then anomalous dimension $\gamma(N,\alpha_S)$ must satisfy

$$\gamma(N,\alpha_S) = \frac{\alpha_S}{2\pi}\int_0^1 z^{N-1+2\gamma(N,\alpha_S)} P(z) \; .$$

❖ For $N-1$ not small, we can neglect $2\gamma(N,\alpha_S)$ in exponent and obtain usual formula for anomalous dimension. For $N \simeq 1$, $z \to 0$ region dominates, where $P_{gg}(z) \simeq 2C_A/z$. Hence

$$\begin{aligned}
\gamma_{gg}(N,\alpha_S) &= \frac{C_A\alpha_S}{\pi}\frac{1}{N-1+2\gamma_{gg}(N,\alpha_S)} \\
&= \frac{1}{4}\left[\sqrt{(N-1)^2+\frac{8C_A\alpha_S}{\pi}}-(N-1)\right] \\
&= \sqrt{\frac{C_A\alpha_S}{2\pi}}-\frac{1}{4}(N-1)+\frac{1}{32}\sqrt{\frac{2\pi}{C_A\alpha_S}}(N-1)^2+\cdots
\end{aligned}$$

● To take account of running α_S, write

$$\tilde{F}(N,t) \sim \exp\left[\int^t \gamma_{gg}(N,\alpha_S)\frac{dt'}{t'}\right] \; ,$$

and note that $\gamma_{gg}(N, \alpha_S)$ should be $\gamma_{gg}(N, \alpha_S(t'))$. Use

$$\int^t \gamma_{gg}(N, \alpha_S(t')) \frac{dt'}{t'} = \int^{\alpha_S(t)} \frac{\gamma_{gg}(N, \alpha_S)}{\beta(\alpha_S)} d\alpha_S ,$$

where $\beta(\alpha_S) = -b\alpha_S^2 + \cdots$, to find

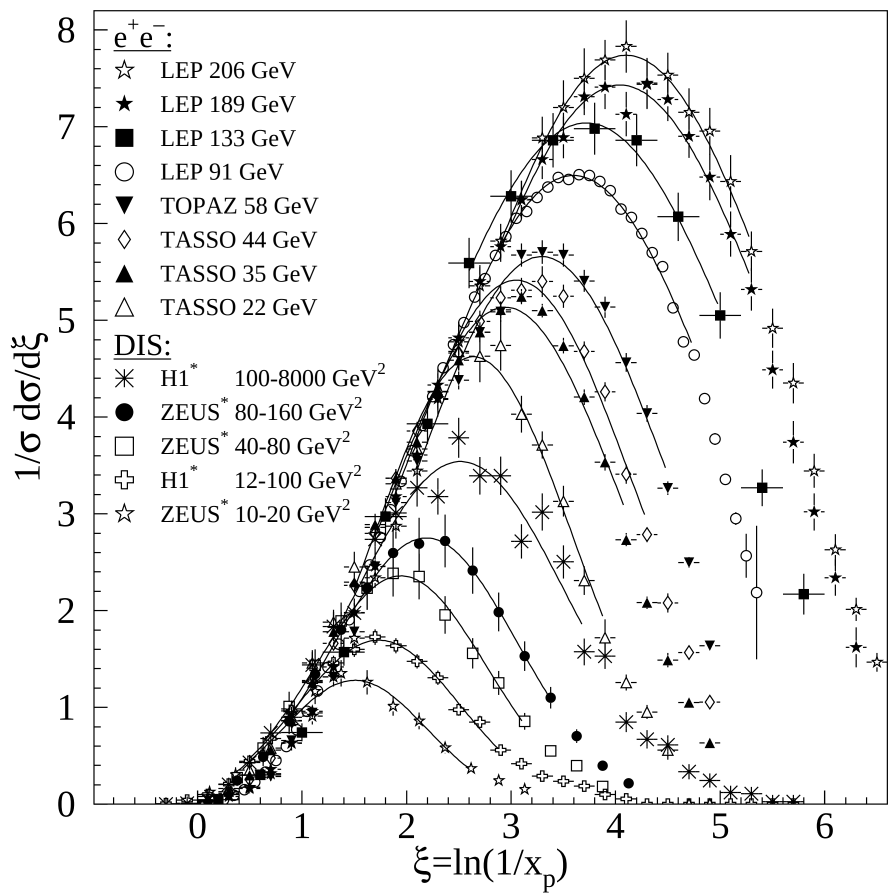
$$\begin{aligned} \tilde{F}(N,t) \quad &\sim \quad \exp\left[\frac{1}{b}\sqrt{\frac{2C_A}{\pi\alpha_S}} - \frac{1}{4b\alpha_S}(N-1)\right. \\ &+ \quad \left.\frac{1}{48b}\sqrt{\frac{2\pi}{C_A\alpha_S^3}}(N-1)^2 + \cdots\right]_{\alpha_S=\alpha_S(t)} . \end{aligned}$$

- In e^+e^- annihilation, scale $t \sim s$ and behaviour of $\tilde{F}(N,s)$ near $N = 1$ determines form of small-x fragmentation functions. Keeping terms up to $(N-1)^2$ in exponent gives Gaussian function of N which transforms into Gaussian function of $\xi \equiv \ln(1/x)$:

$$xF(x,s) \propto \exp\left[-\frac{1}{2\sigma^2}(\xi - \xi_p)^2\right] ,$$

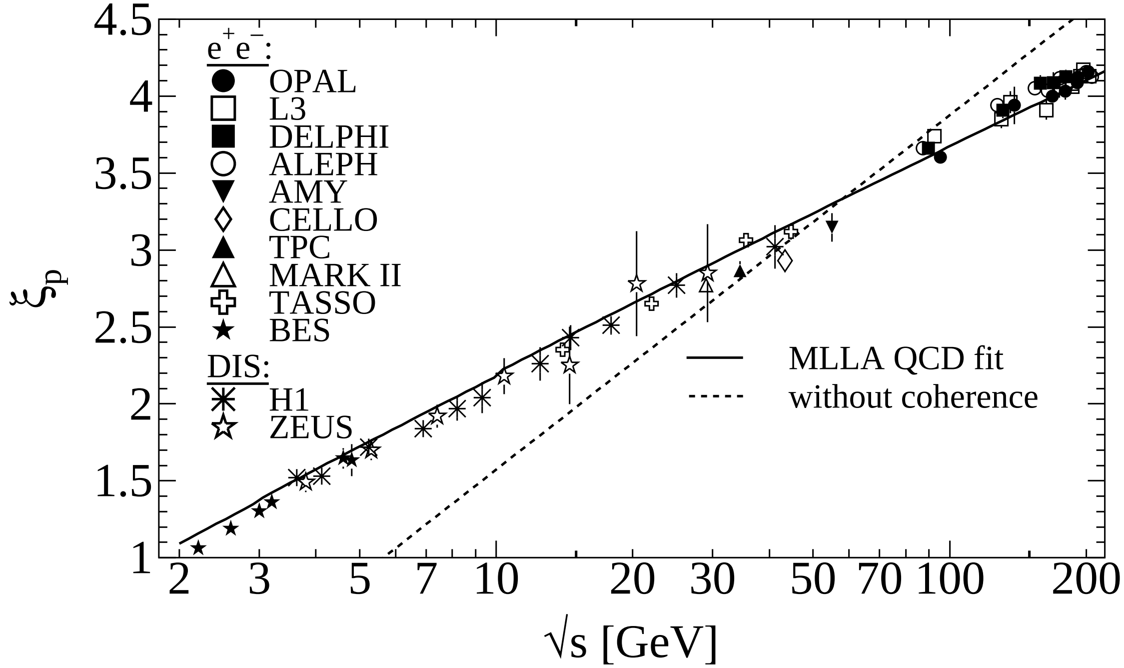
- Width of distribution

$$\sigma = \left(\frac{1}{24b}\sqrt{\frac{2\pi}{C_A\alpha_S^3(s)}}\right)^{\frac{1}{2}} \propto (\ln s)^{\frac{3}{4}} \; .$$



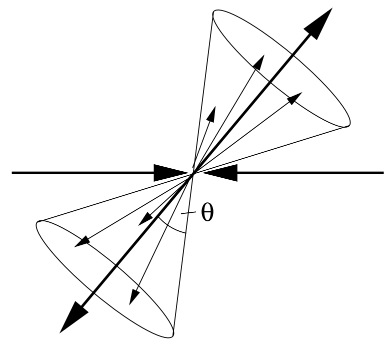
- Peak position

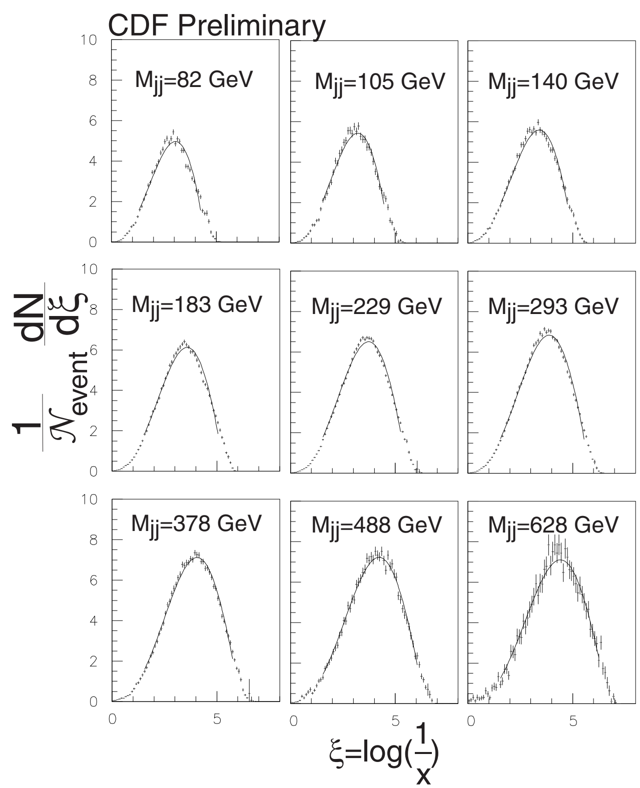
$$\xi_p = \frac{1}{4b\alpha_S(s)} \sim \frac{1}{4} \ln s$$

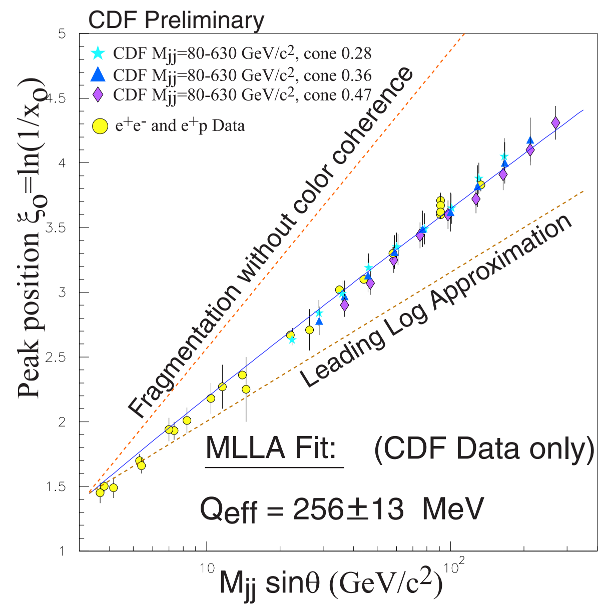


- Energy-dependence of the peak position ξ_p tests suppression of hadron production at small x due to soft gluon coherence. Decrease at very small x is expected on kinematical grounds, but this would occur at particle energies proportional to their masses, i.e. at $x \propto m/\sqrt{s}$, giving $\xi_p \sim \frac{1}{2} \ln s$. Thus purely kinematic suppression would give ξ_p increasing twice as fast.

- In $p\bar{p} \longrightarrow$ dijets, $\sqrt{s}$ is replaced by $M_{JJ} \sin\theta$ where M_{JJ} is dijet mass and θ is jet cone angle.


θ


CDF Preliminary
Mjj=82 GeV
Mjj=105 GeV
Mjj=140 GeV
Mjj=183 GeV
Mjj=229 GeV
Mjj=293 GeV
Mjj=378 GeV
Mjj=488 GeV
Mjj=628 GeV
ξ=log(1/x)


CDF Preliminary
CDF Mjj=80-630 GeV/c2, cone 0.28
CDF Mjj=80-630 GeV/c2, cone 0.36
CDF Mjj=80-630 GeV/c2, cone 0.47
e+e- and e+p Data
Fragmentation without color coherence
Leading Log Approximation
MLLA Fit: (CDF Data only)
Qeff = 256±13 MeV
Peak position ξ0=ln(1/x0)
Mjj sinθ (GeV/c2)

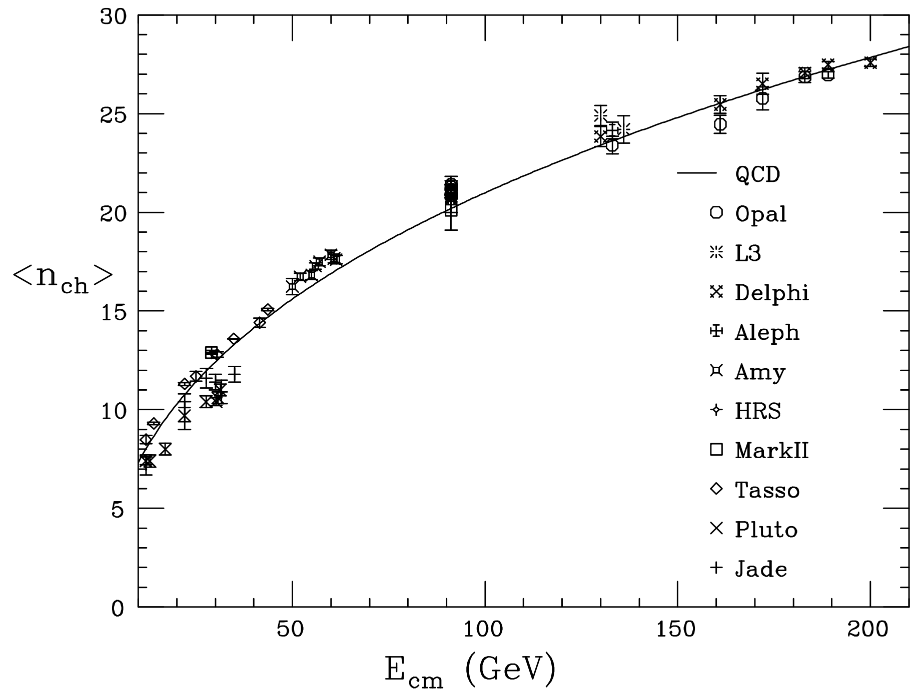
Average Multiplicity

- Mean number of hadrons is $N = 1$ moment of fragmentation function:

$$\langle n(s) \rangle = \int_0^1 dx\, F(x,s) = \tilde{F}(1,s)$$

$$\sim \exp \frac{1}{b}\sqrt{\frac{2C_A}{\pi\alpha_S(s)}} \sim \exp \sqrt{\frac{2C_A}{\pi b} \ln\left(\frac{s}{\Lambda^2}\right)}$$

(plus NLL corrections) in good agreement with data.



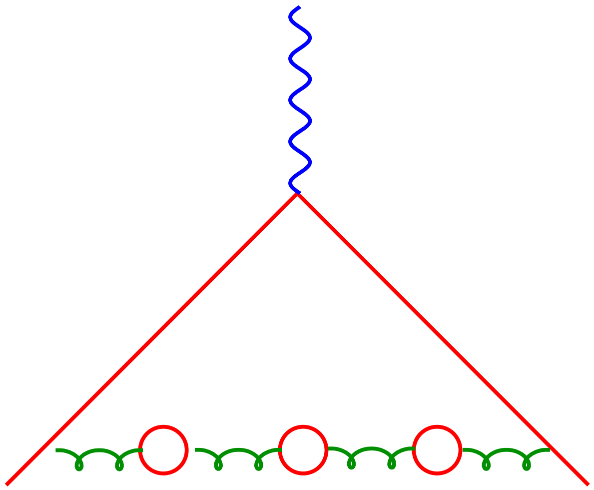
General ideas

- Local parton-hadron duality
  - Hadronization is long-distance process, involving small momentum transfers. Hence hadron-level flow of energy-momentum, flavour should follow parton level.
  - Implicit in earlier discussion of jet fragmentation.
  - Results on spectra and multiplicities support this.
- Universal low-scale α_S
  - PT works well down to very low scales, $Q \sim 1$ GeV.
  - Assume $\alpha_S(Q)$ defined (non-perturbatively) for all Q.
  - Good description of heavy quark spectra, event shapes.

Universal low-scale α_S

- Infrared renormalon

$$\begin{aligned} F &\sim \int_0^Q \frac{dp_t}{Q} \alpha_S(p_t) \\ &= \alpha_S(Q) \sum_n \int_0^Q \frac{dp_t}{Q} \left[b\alpha_S(Q) \ln \frac{Q^2}{p_t^2} \right]^n \\ &= \alpha_S(Q) \sum_n n! [2b\alpha_S(Q)]^n \end{aligned}$$



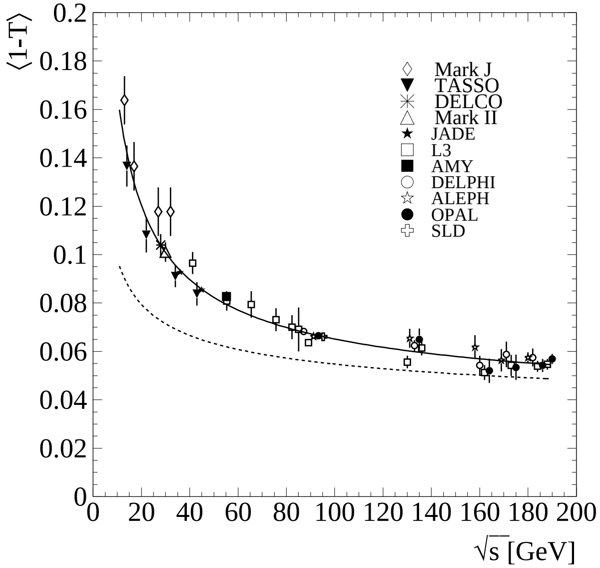
- Divergent series: truncate at smallest term ($n_m = [2b\alpha_S(Q)]^{-1}$) $\Rightarrow$ uncertainty in F

$$\delta F \sim n_m! [2b\alpha_S(Q)]^{n_m} \sim e^{-n_m} = \frac{\Lambda}{Q}$$

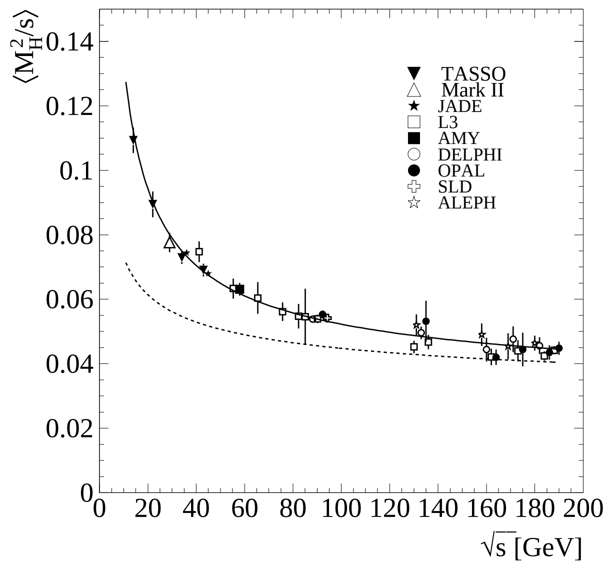
- Renormalon is due to infrared divergence of α_S
  - ❖ Postulate universal infrared-regular α_S. Then $1/Q$ power corrections depend on

$$\alpha_0(\mu_I) = \frac{1}{\mu_I} \int_0^{\mu_I} \alpha_S(p_t)\, dp_t$$

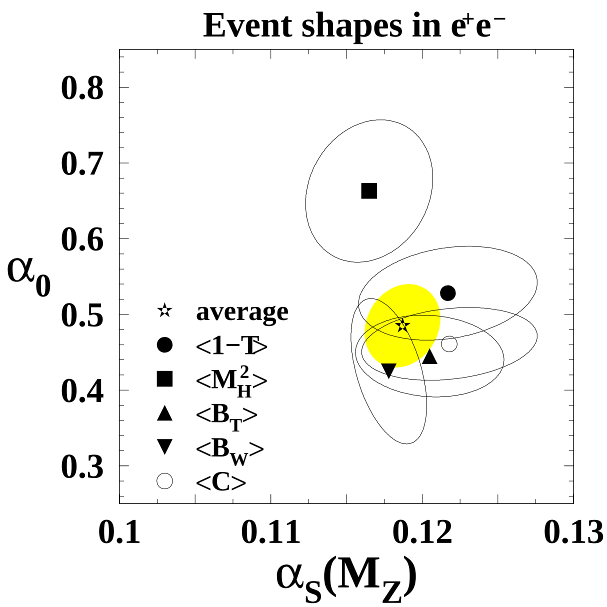
  - ❖ Match PT and NP at $\mu_I \sim 2$ GeV



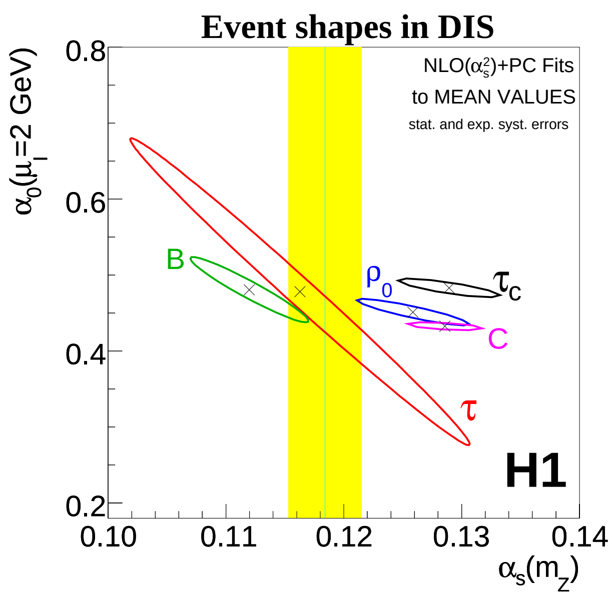
⟨1-T⟩
Mark J
TASSO
DELCO
Mark II
JADE
L3
AMY
DELPHI
ALEPH
OPAL
SLD
√s [GeV]



$\langle M_H^2/s \rangle$
TASSO
Mark II
JADE
L3
AMY
DELPHI
OPAL
SLD
ALEPH
√s [GeV]



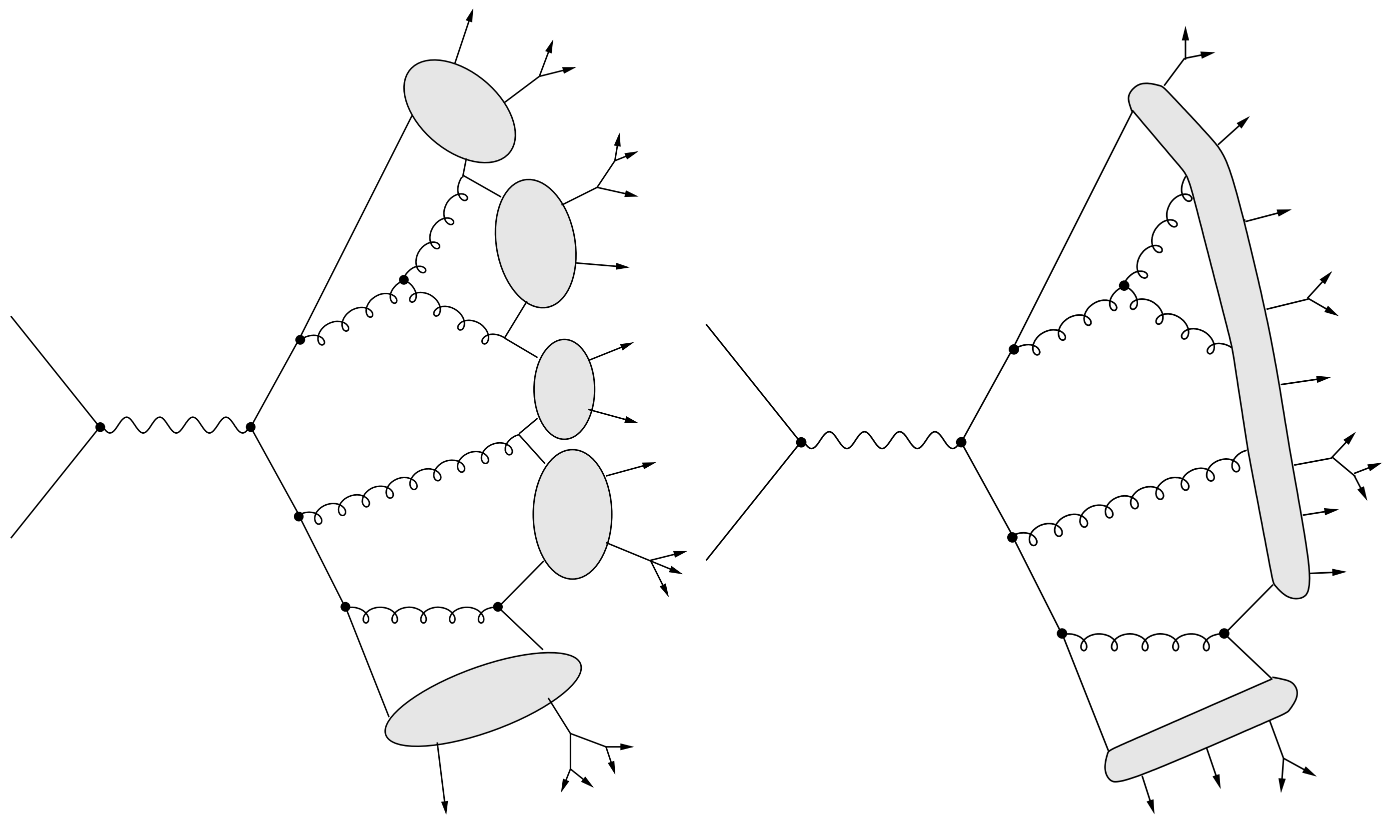
Event shapes in e^+e^-
α_0
average
<1−T>
$\langle M_H^2 \rangle$
$\langle B_T \rangle$
$\langle B_W \rangle$
<C>
$\alpha_S(M_Z)$



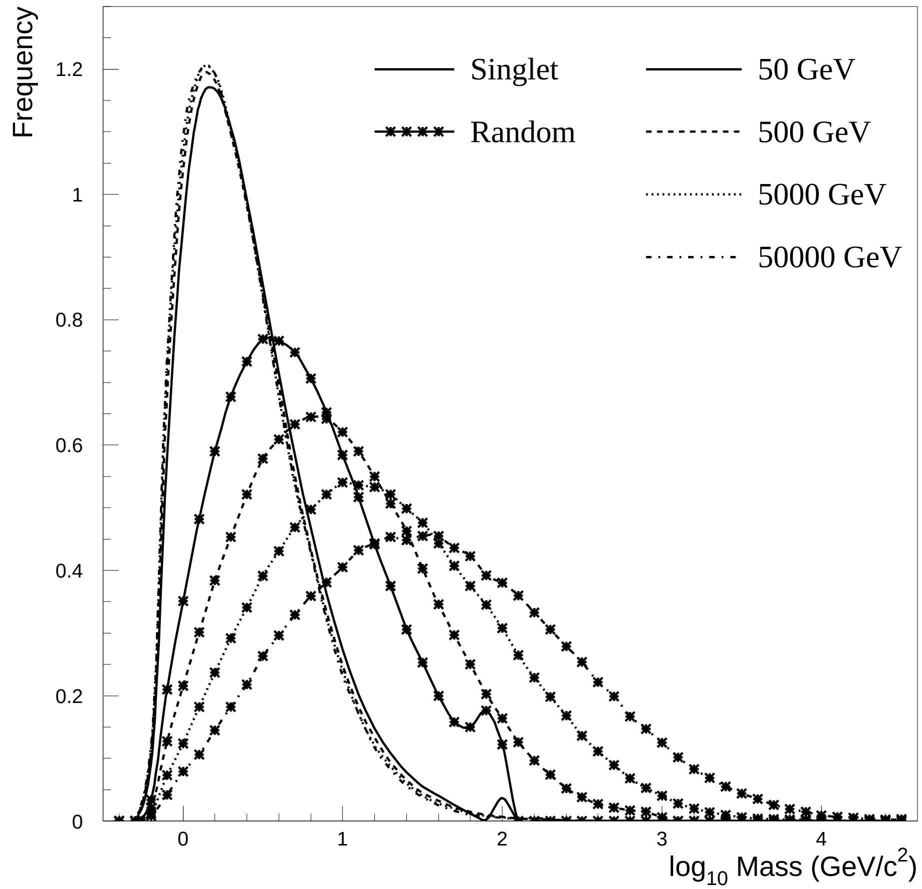
Event shapes in DIS
NLO(α_s^2)+PC Fits
to MEAN VALUES
stat. and exp. syst. errors
$\alpha_0(\mu_I=2$ GeV)
B
ρ_0
τ_c
C
τ
H1
$\alpha_s(m_Z)$

Specific Hadronization Models

- General ideas do not describe hadron formation. Main current models are cluster and string.

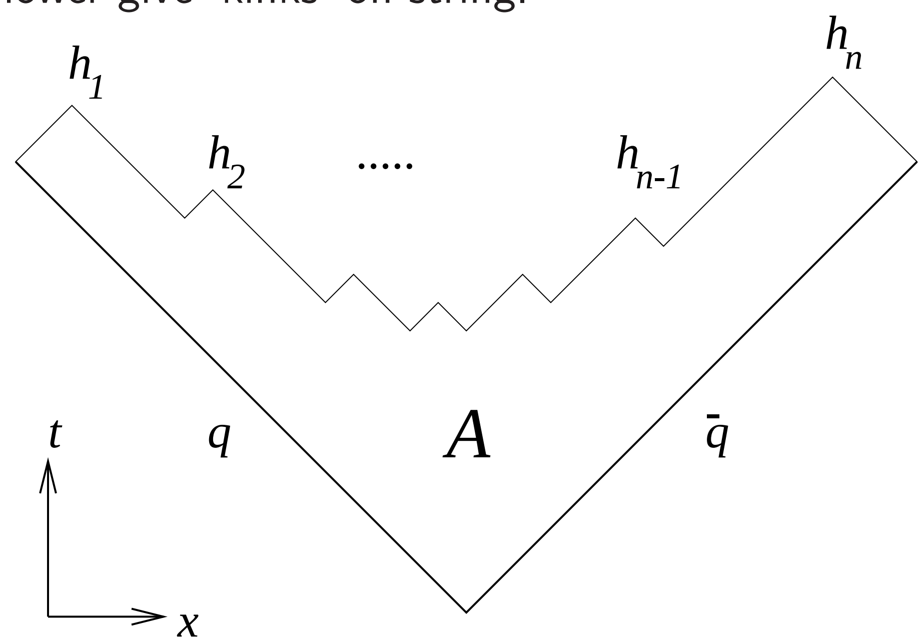


- Cluster (HERWIG)
  - Non-perturbative $g \longrightarrow q\bar{q}$ splitting after parton shower.
  - Colour singlet $q\bar{q}$ clusters have lower mass due to preconfinement property of parton shower.



  - Clusters decay according to 2-hadron density of states.
  - Few parameters: natural p_T and heavy particle suppression
  - Problems with massive clusters, baryons, heavy quarks

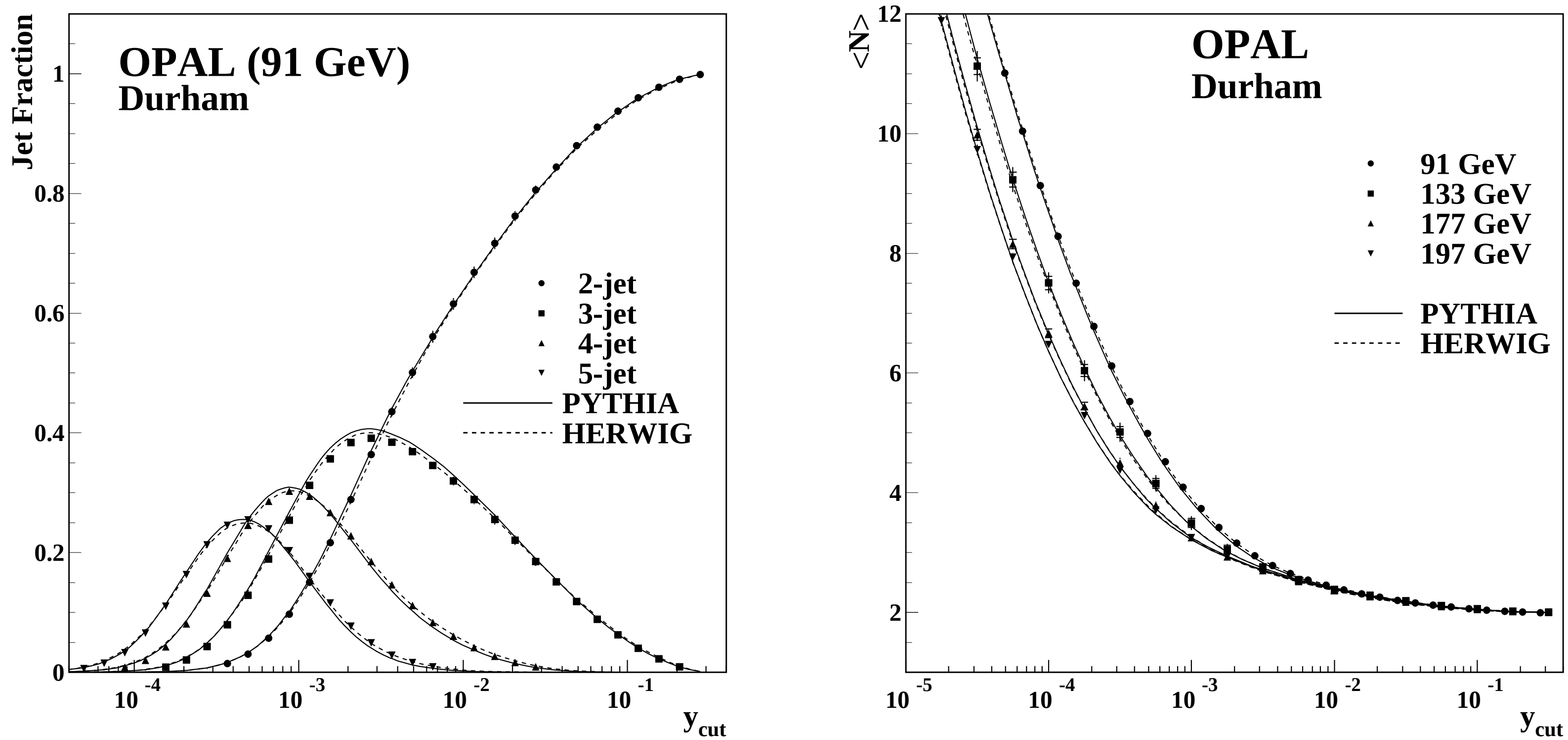
- String (PYTHIA)
  - Uses string dynamics: colour string stretched between initial $q\bar{q}$ breaks up into hadrons via $q\bar{q}$ pair production.
  - String gives linear confinement potential, area law for matrix elements.
  - Gluons produced in shower give 'kinks' on string.



$$|M(q\bar{q} \to h_1 \cdots h_n)|^2 \propto e^{-bA}$$

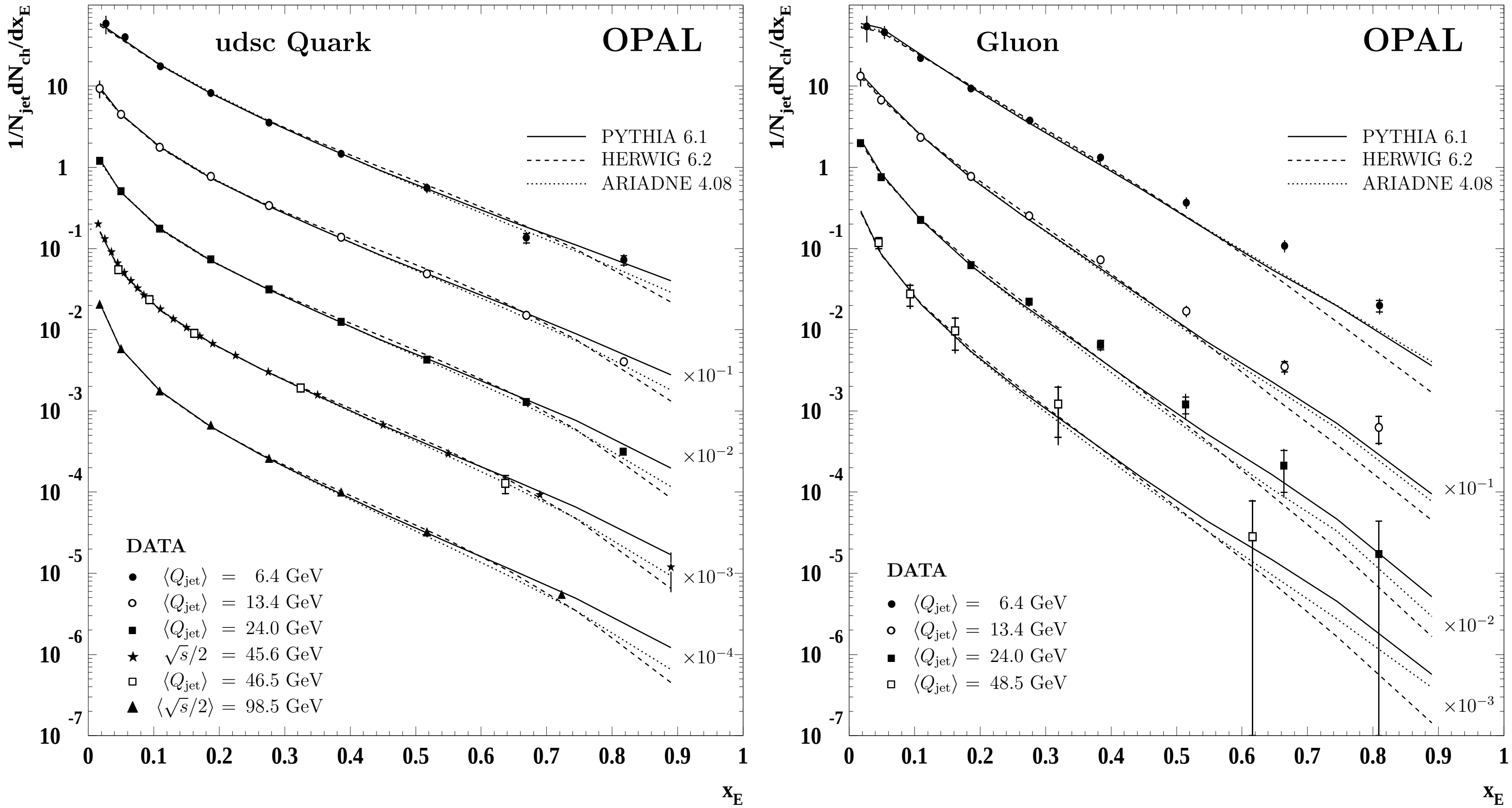
  - Extra parameters for p_T and heavy particle suppression.
  - Some problems with baryons.
- Both models describe e^+e^- data well . . .

- Jet rates and mean number of jets



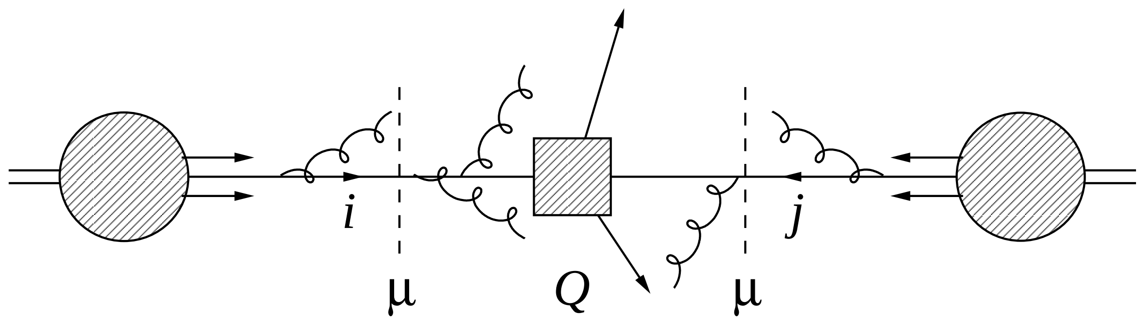
- k_T or Durham algorithm:
  - Define jet resolution y_{cut} (dimensionless).
  - For final-state momenta p_i, p_j define $y_{ij} = 2\min\{E_i^2, E_j^2\}(1 - \cos\theta_{ij})/s$
  - If $y_{IJ} = \min\{y_{ij}\} < y_{\text{cut}}$, combine I, J into one object K with $p_K = p_I + p_J$.
  - Repeat until $y_{IJ} > y_{\text{cut}}$. Then remaining objects are jets.

- Light quark and gluon fragmentation functions



Hadron-Hadron Processes

- In hard hadron-hadron scattering, constituent partons from each incoming hadron interact at short distance (large momentum transfer Q^2).



- For hadron momenta P_1, P_2 $(S = 2P_1 \cdot P_2)$, form of cross section is

$$\sigma(S) = \sum_{i,j} \int dx_1 dx_2 D_i(x_1, \mu) D_j(x_2, \mu) \hat{\sigma}_{ij}(\hat{s} = x_1 x_2 S, \alpha_S(\mu), Q/\mu)$$

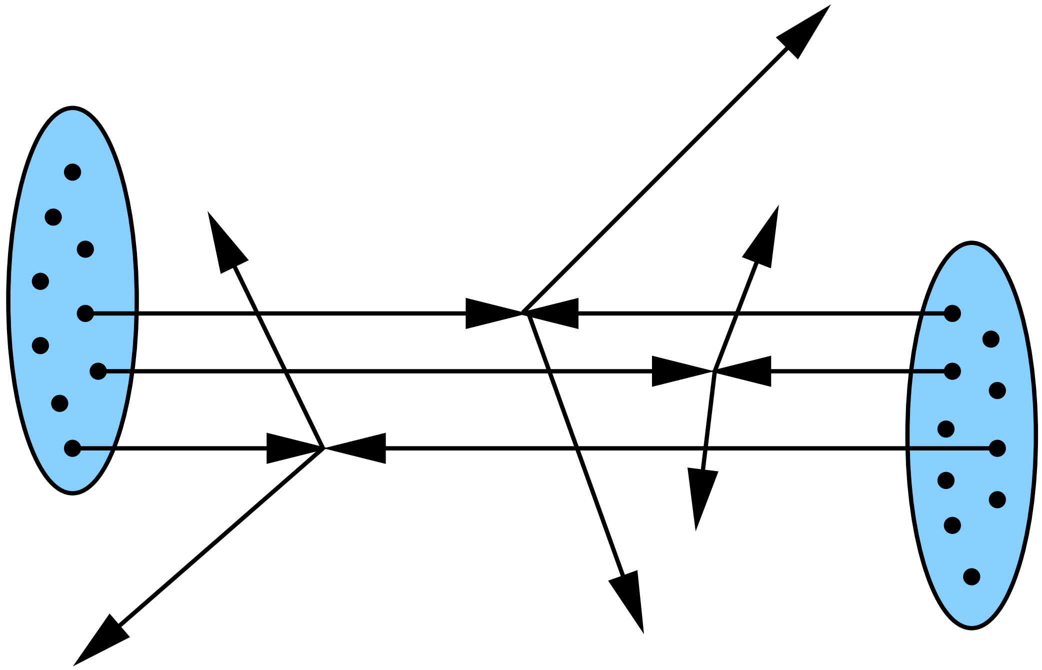
where μ is factorization scale and $\hat{\sigma}_{ij}$ is subprocess cross section for parton types i, j.

❖ Factorization scale is in principle arbitrary: it affects only what we call part of subprocess or part of initial-state evolution (parton shower).

❖ Rapidity of subprocess c.m. frame $p^\mu = p_1^\mu + p_2^\mu$:

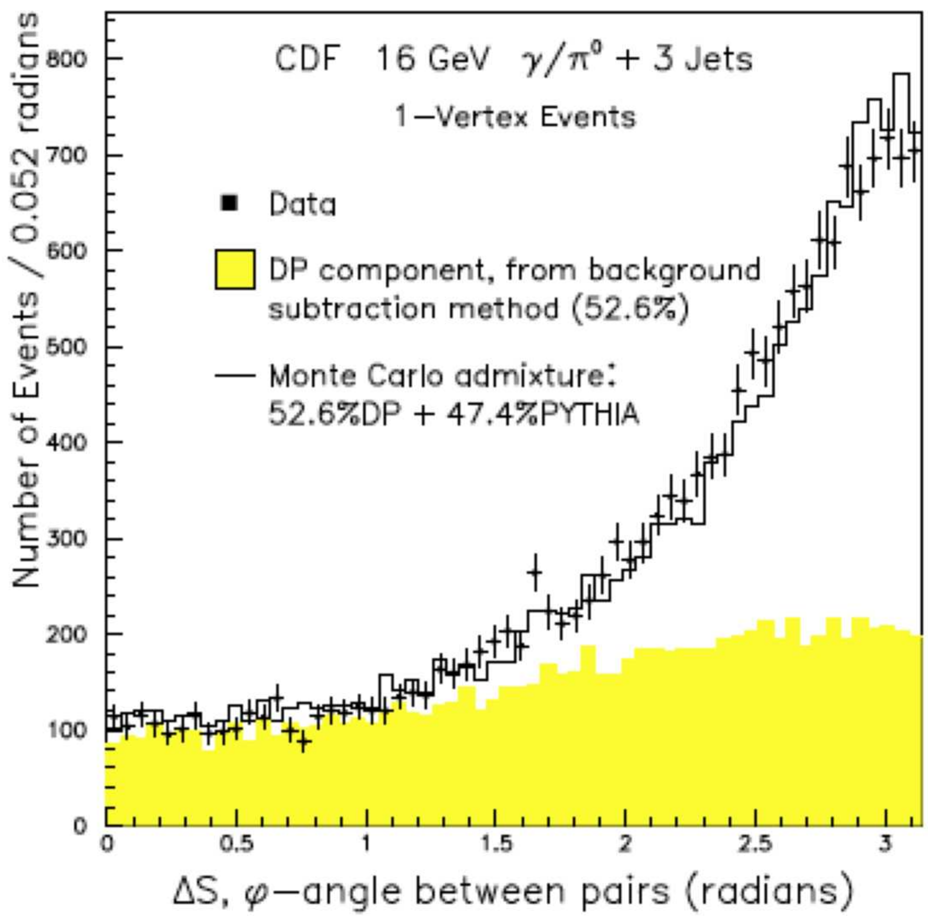
$$y \equiv \frac{1}{2} \ln \left[(p^0 + p_3)/(p^0 - p_3) \right] = \frac{1}{2} \ln (x_1/x_2)$$

- Unlike e^+e^- or ep, we may have interaction between spectator partons, leading to *soft underlying event* and/or *multiple hard scattering*.



Double Parton Scattering

- CDF Collaboration [PR D56 (1997) 3811] studied $\gamma+$ 3 jets.
  - DPS has 'best-balanced' ($\gamma+$ jet) and dijet uncorrelated in azimuth.

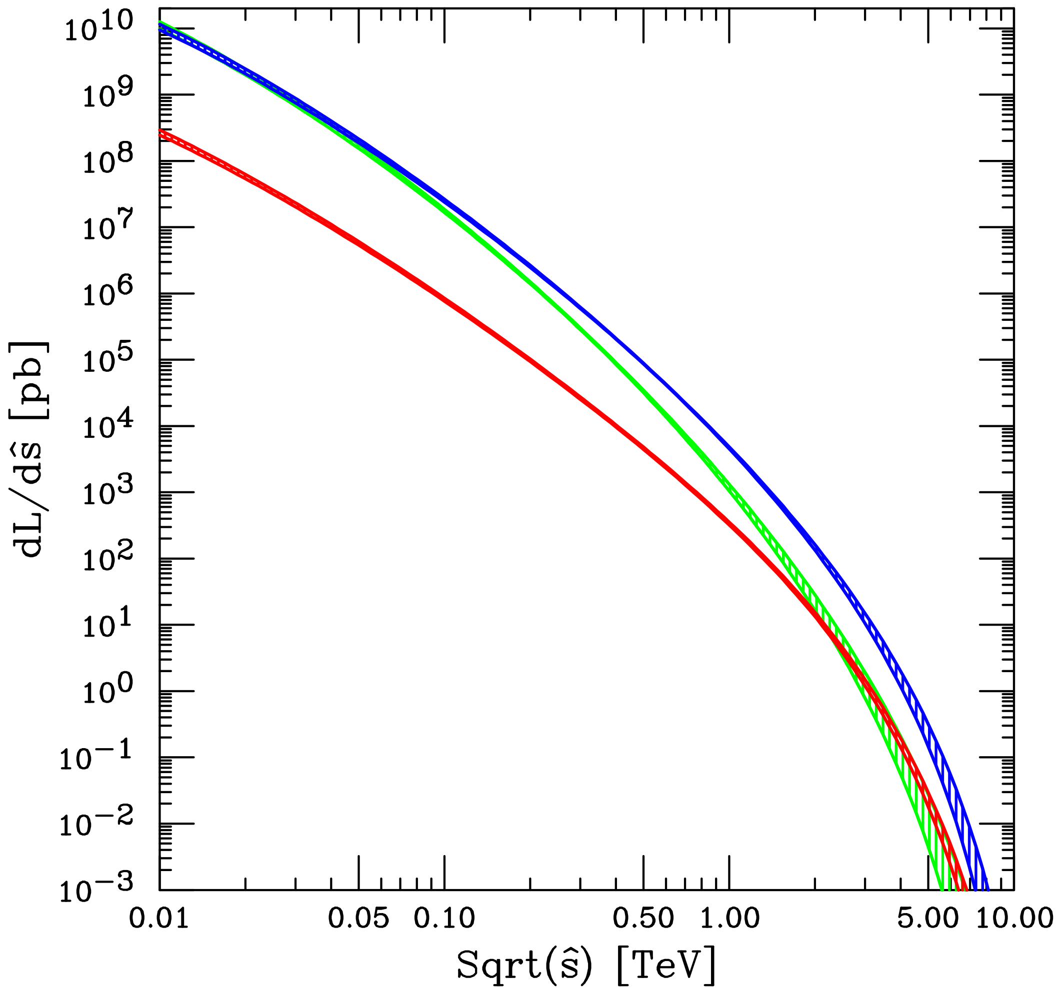


  - They found $\sigma_{\rm DPS} = \sigma_{\gamma j}\sigma_{jj}/\sigma_{\rm eff}$ where $\sigma_{\rm eff} = 14 \pm 1.7^{+1.7}_{2.3}$ mb

Parton-Parton Luminosities

- Useful to define the differential parton-parton luminosity $dL_{ij}/d\hat{s}\,dy$ and its integral $dL_{ij}/d\hat{s}$:
$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{S}\frac{1}{1+\delta_{ij}}\left[D_i(x_1,\mu)D_j(x_2,\mu) + (1 \leftrightarrow 2)\right].$$
Factor with Kronecker delta avoids double-counting when partons are identical.
- We have $d\hat{s}\,dy = S\,dx_1\,dx_2$ and hence
$$\begin{aligned}\sigma &= \sum_{i,j}\int d\hat{s}\,dy\left(\frac{dL_{ij}}{d\hat{s}\,dy}\right)\hat{\sigma}_{ij}(\hat{s})\\ &= \sum_{i,j}\int d\hat{s}\left(\frac{dL_{ij}}{d\hat{s}}\right)\hat{\sigma}_{ij}(\hat{s})\end{aligned}$$
- This can be used to estimate the production rate for subprocesses at LHC.

- Figure shows parton-parton luminosities at $\sqrt{s} = 14\,\mathrm{TeV}$ for various parton combinations, calculated using the CTEQ6.1 parton distribution functions and scale $\mu = \sqrt{\hat{s}}$. Widths of curves estimate PDF uncertainties.



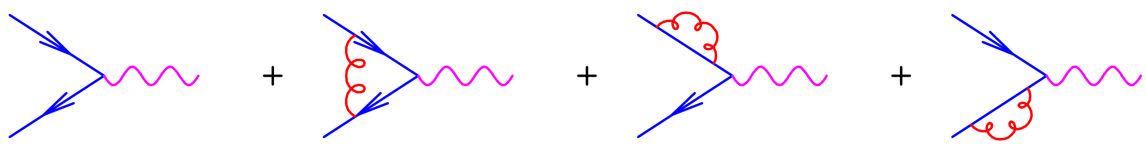
Green $= gg$, Blue $= gq + g\bar{q} + qg + \bar{q}g$, Red $= q\bar{q} + \bar{q}q$ $(q = d + u + s + c + b)$.

Lepton Pair Production

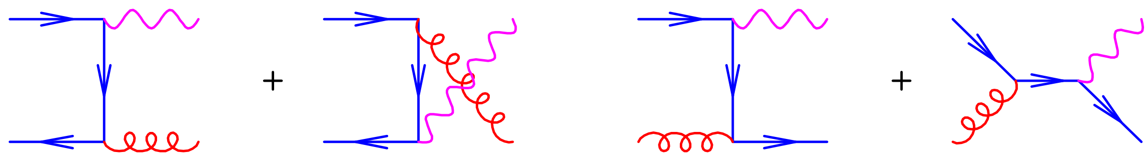
- Inverse of $e^+e^- \longrightarrow q\bar{q}$ is Drell-Yan process. At $\mathcal{O}(\alpha_S^0)$, mass distribution of lepton pair is given by

$$\frac{d\hat{\sigma}}{dM^2}(q\bar{q} \to \gamma^* \to l^+l^-) = \frac{4\pi\alpha^2}{\hat{s}}\frac{1}{3}Q_q^2\,\delta(M^2 - \hat{s})$$

❖ Factor of $1/3 = 1/N$ instead of $3 = N$ because of *average* over colours of incoming q.

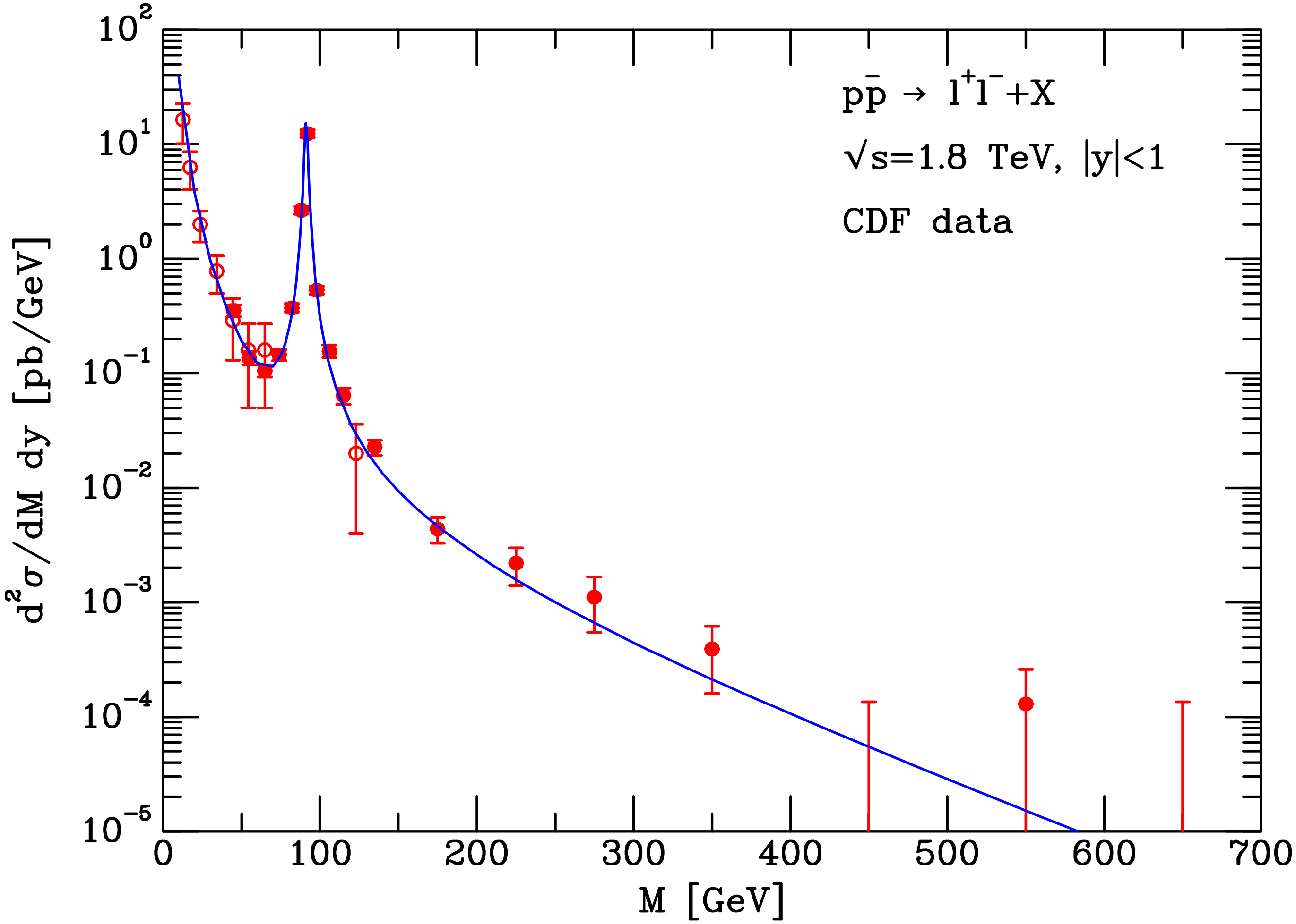


(a)



(b) **(c)**

❖ In higher orders *vertex corrections* (a) have $M^2 = \hat{s}$,
gluon emission (b) and *QCD Compton* (c) diagrams give $M^2 < \hat{s}$.

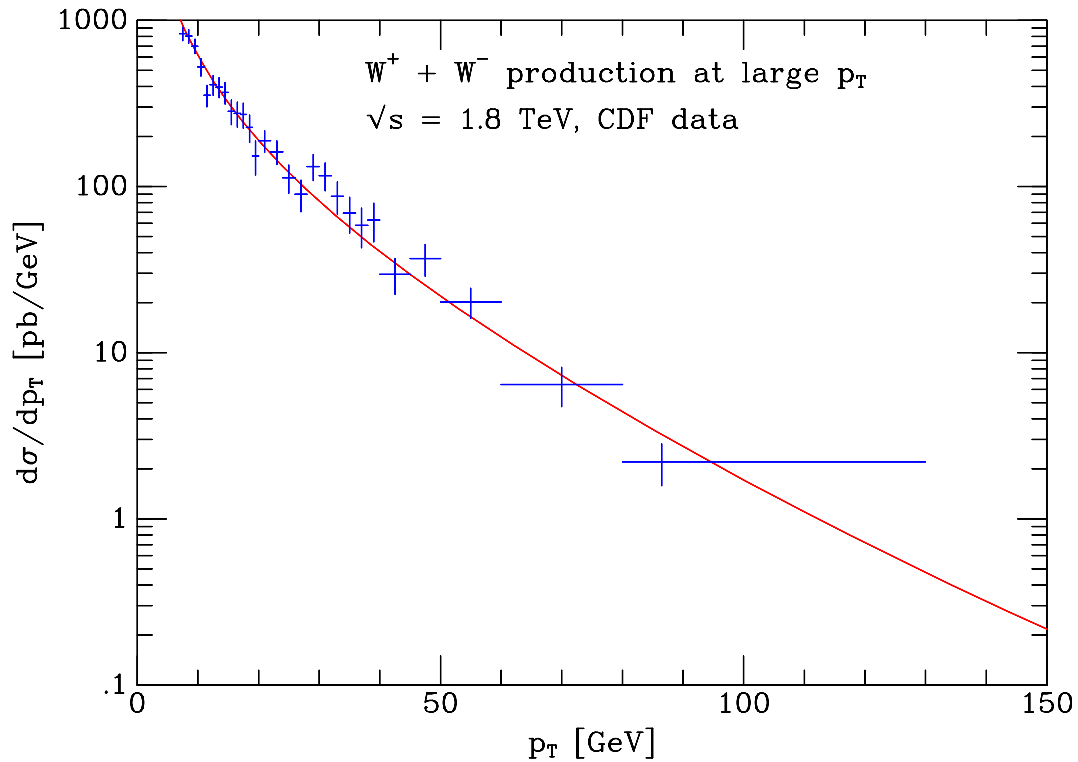


$p\bar{p} \rightarrow l^+l^- + X$
$\sqrt{s}$=1.8 TeV, |y|<1
CDF data
$d^2\sigma/dM\ dy$ [pb/GeV]
M [GeV]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
100
200
300
400
500
600
700

- $W^{\pm}$ boson production is similar, except sensitive to different parton distributions, e.g.

$$u\bar{d} \to W^+ \to l^+\nu_l$$

- Transverse momentum of lepton pair, p_T measures net transverse momentum of colliding partons plus any *intrinsic* p_T:

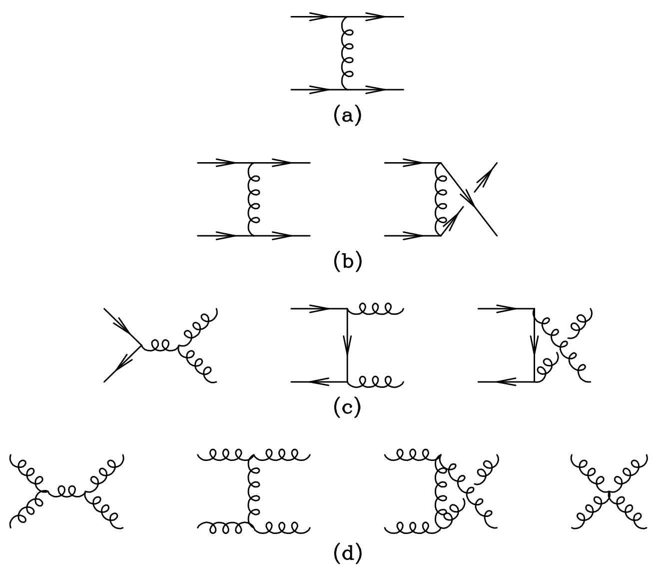


Jet Production

- Lowest-order subprocess for purely hadronic jet production is $2 \longrightarrow 2$ scattering $p_1 + p_2 \longrightarrow p_3 + p_4$

$$\frac{d\hat{\sigma}}{d\Phi_{34}} \equiv \frac{E_3 E_4 d^6\hat{\sigma}}{d^3\boldsymbol{p}_3 d^3\boldsymbol{p}_4} = \frac{1}{32\pi^2\hat{s}}\overline{\sum}|\mathcal{M}|^2\,\delta^4(p_1+p_2-p_3-p_4)\ .$$

- Many processes even at $\mathcal{O}(\alpha_S^2)$:



- Single-jet inclusive cross section obtained by integrating over one outgoing momentum:

$$\frac{Ed^3\hat{\sigma}}{d^3\boldsymbol{p}} = \frac{d^3\hat{\sigma}}{d^2\boldsymbol{p}_T dy} \longrightarrow \frac{1}{2\pi E_T}\frac{d^3\hat{\sigma}}{dE_T\, d\eta}$$
$$= \frac{1}{16\pi^2\hat{s}}\overline{\sum}|\mathcal{M}|^2\,\delta(\hat{s}+\hat{t}+\hat{u})$$

where (neglecting jet mass)

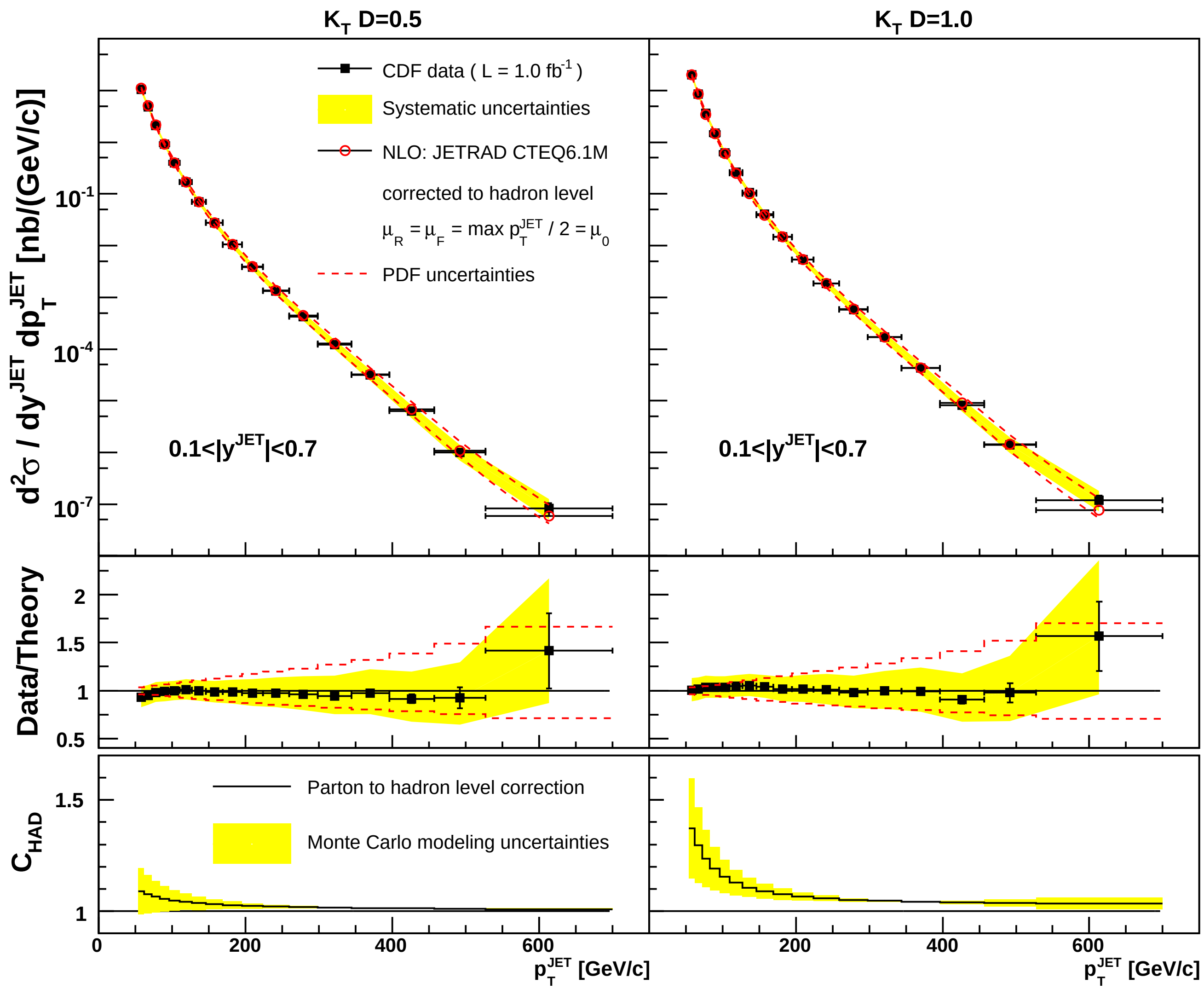
$$E_T \equiv E\sin\theta = |\boldsymbol{p}_T|\;, \qquad \eta \equiv -\ln\tan(\theta/2)\; = \; y\;.$$

- Jets can be defined by the k_T algorithm:
  - For each final-state momentum p_i and each pair of final-state momenta p_i, p_j, define

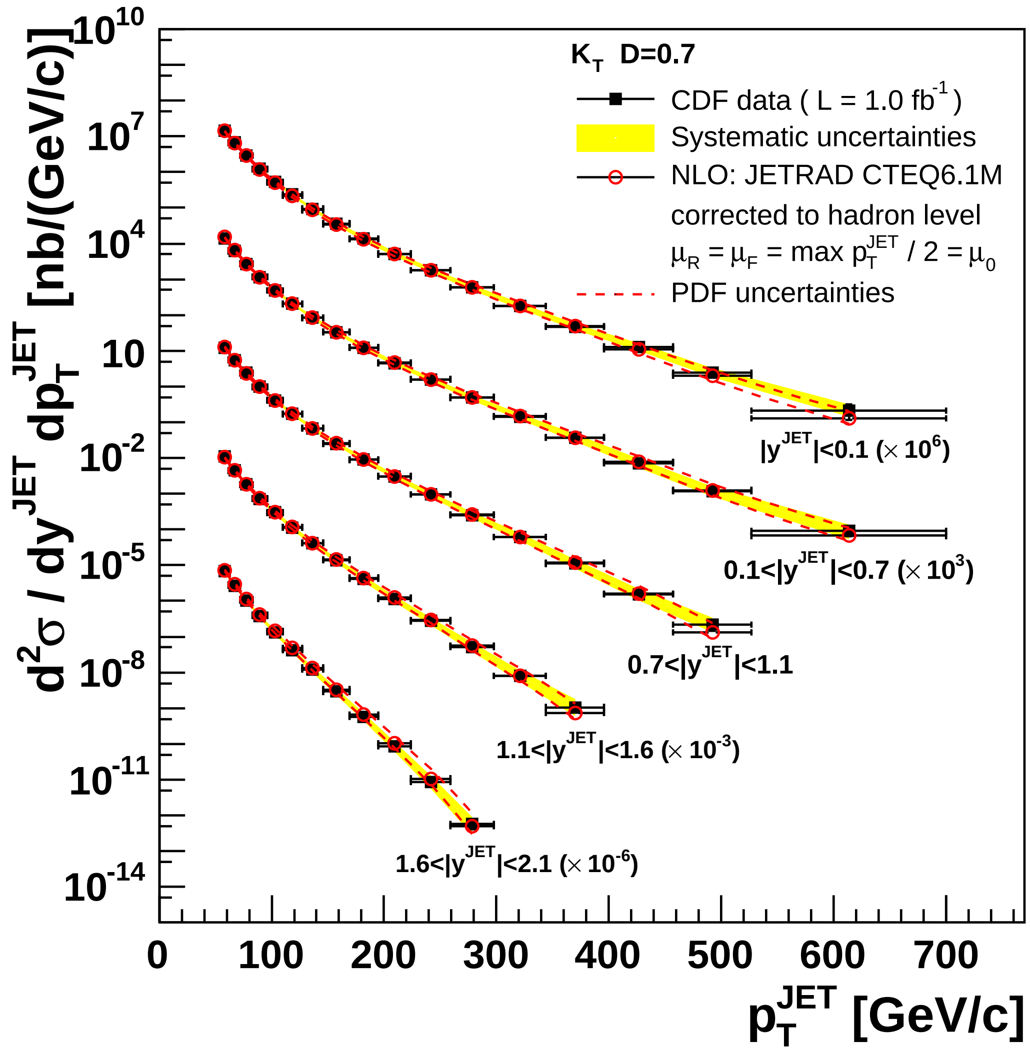
    $$k_{Ti} = E_{Ti}\;, \quad k_{Tij} = \min\{E_{Ti}, E_{Tj}\}\Delta R_{ij}/D$$

    where $\Delta R_{ij} = \sqrt{(\eta_i-\eta_j)^2+(\phi_i-\phi_j)^2}$ and $D =$ dimensionless parameter for angular size of jets ($D = 0.5 - 1.0$)
  - If k_{TI} is the smallest in the list of $\{k_{Ti}, k_{Tij}\}$, define I as a jet and remove from list.
  - If k_{TIJ} is the smallest, combine I, J into one object K with $p_K = p_I + p_J$.
  - Repeat until list is empty.
- Use η rather than θ for invariance under longitudinal boosts: $x_1 \to ax_1$, $x_2 \to x_2/a$ gives $\eta_i \to \eta_i + \ln a$, so $\eta_i - \eta_j$ is invariant.

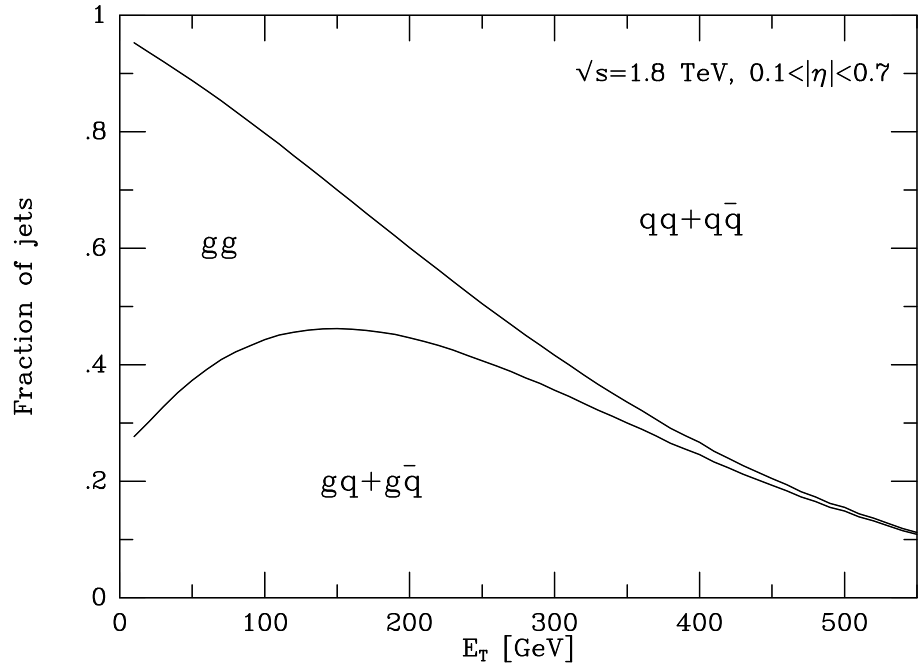
- NLO predictions and data agree very well:



- Rapidity dependence:



- Contribution of different parton combinations determined by subprocess cross sections and parton distributions.

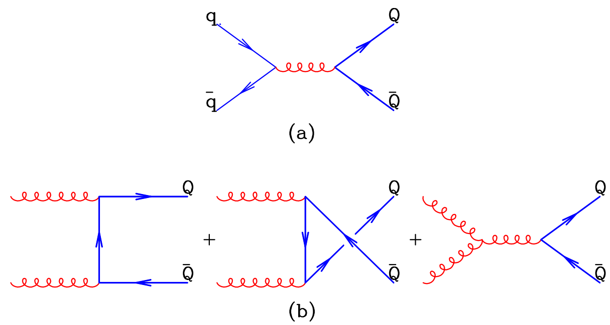


- Quarks dominate at large E_T since this selects large $x_{1,2}$:

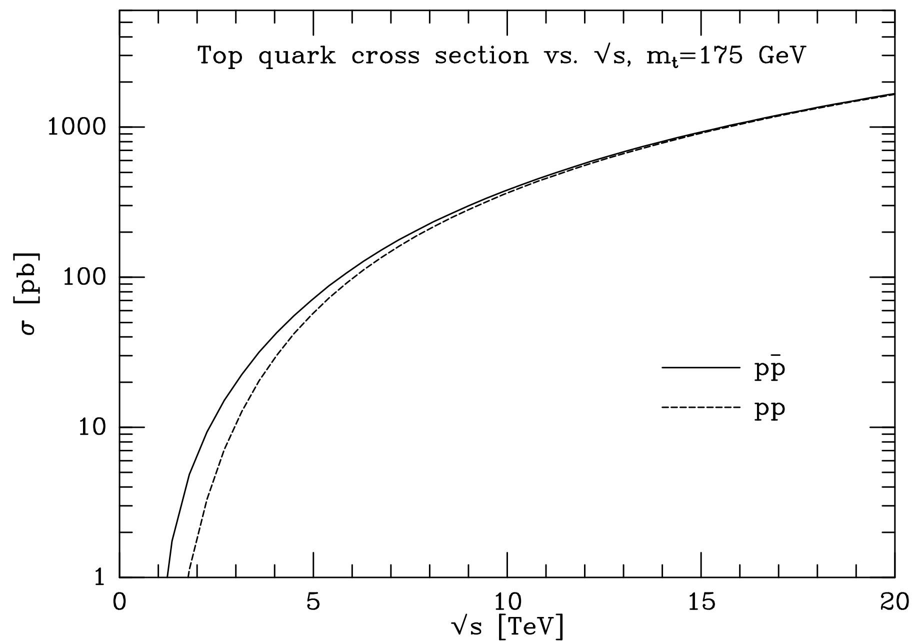
$$\hat{s} = x_1 x_2 S > 4E_T^2$$

Heavy Quark Production

- Lowest-order subprocesses for heavy quark production are (a) light quark-antiquark annihilation (10% at LHC) and (b) gluon-gluon fusion (90% at LHC)

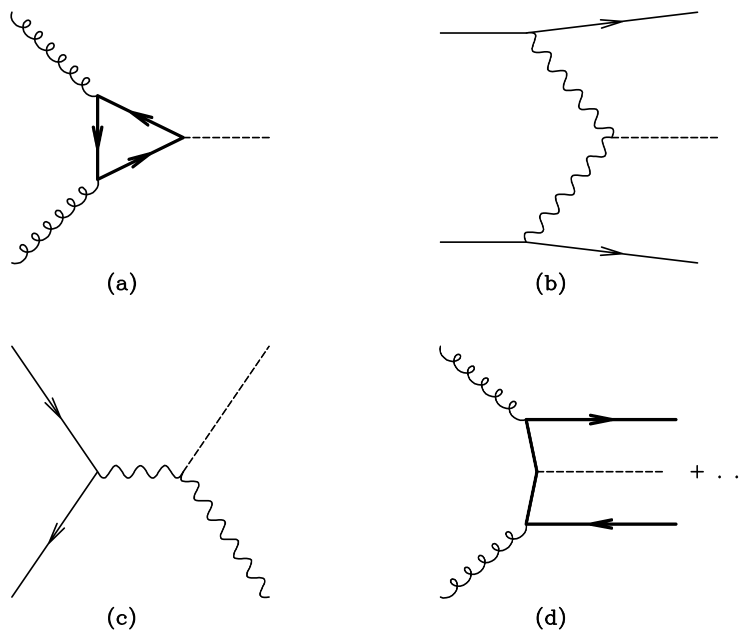


- NLO top quark cross section = 840±30(scale)±20(pdf) pb at LHC

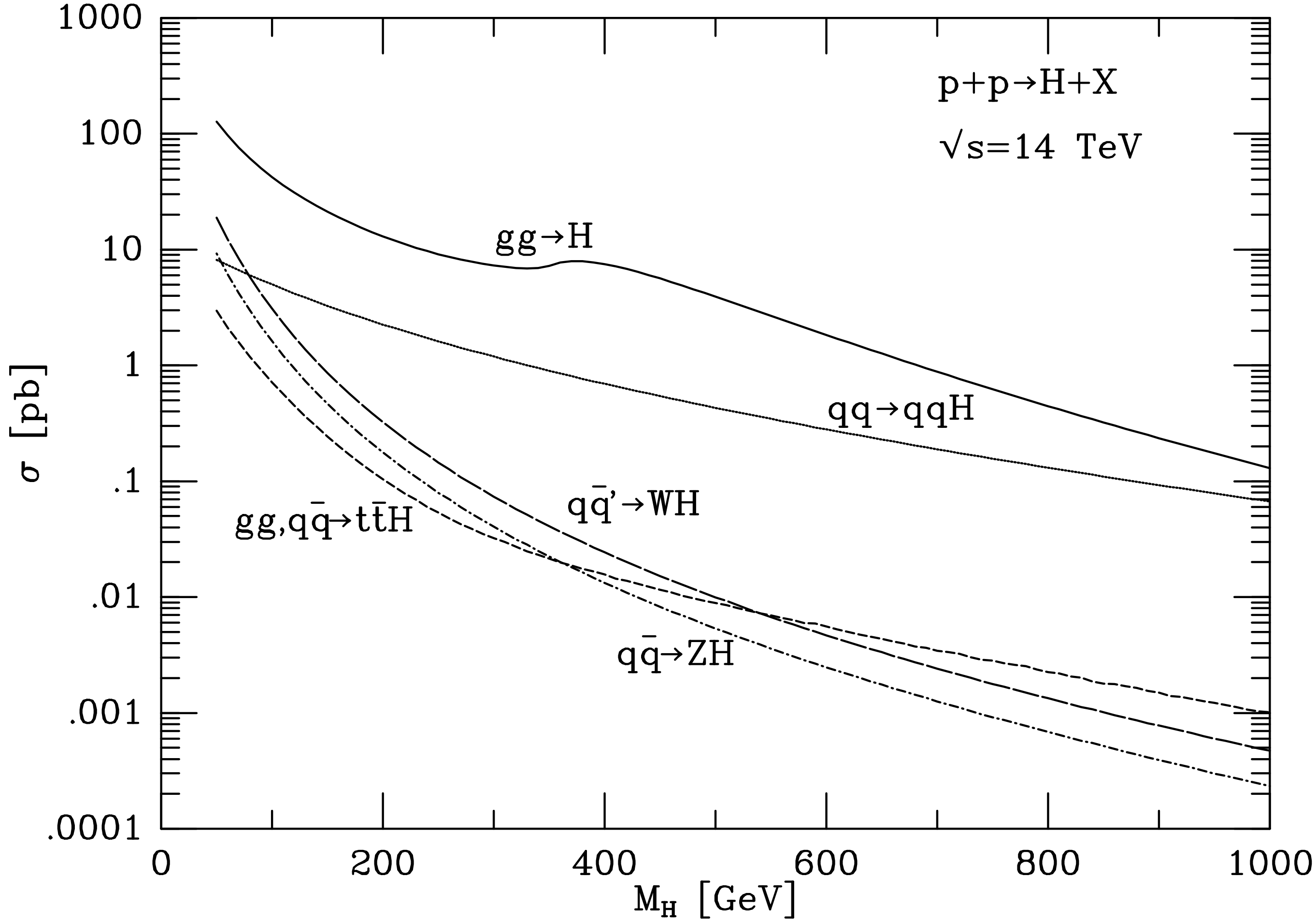


Standard Model Higgs Boson Production

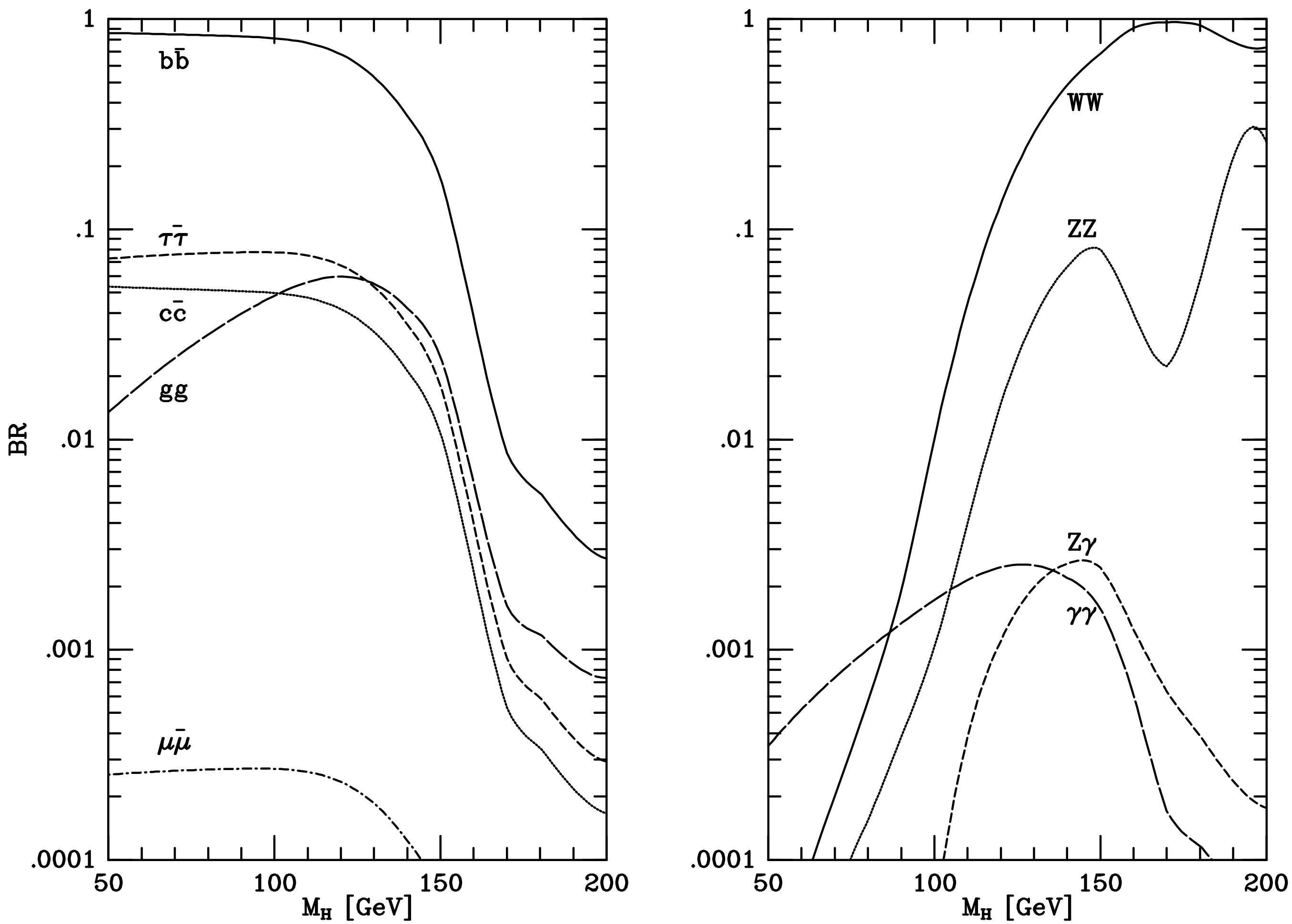
- Lowest-order subprocesses for Higgs boson production at hadron colliders:
  (a) Gluon-gluon fusion (via top loop)
  (b) Vector boson fusion
  (c) Associated production with W, Z boson
  (d) Associated production with $t\bar{t}$.



- NLO Higgs cross sections



- Discovery decay channels depend on Higgs mass



Status of NLO Calculations for LHC (2007)

- $2 \longrightarrow 2$ parton processes — all available, e.g. in MCFM (CaEl*)
- $2 \longrightarrow 3$ parton processes

Final State	Authors*	Comments
3 jets	KuSiTr,BerDixKo,GiKi,Na	Public code available
$V+$ 2 jets	ElCa,CaGlMi	Public code available
$V\,b\,\bar{b}$	ElCa	Massless b quarks
$V\,b\,\bar{b}$	ReFeWa	Massive b quarks
$H+$ 2 jets	FiOlZep	Vector boson fusion
$H+$ 2 jets	CaElZa	Gluon fusion
$V\,V+$ 2 jets	JaOlZep	Vector boson fusion
$\gamma\gamma$ jet	deFKu,DelMalNaTr,BiGuMah	
$t\bar{t}H$, $b\bar{b}H$	ReDaWaOr,BeeDitKrPlSpZer	
$t\bar{t}$ jet	DitUwWe	
$H\,H\,H$	PlRa,BiKarKauRu	
$W\,W$ jet	DiKalUw	
$Z\,Z\,Z$	LaMePe	

*Beenakker,Bern,Binoth,Campbell,Dawson,deFlorian,DelDuca,Dittmaier,Dixon,Ellis,FebresCordero,Figy, Giele,Glover,Guillet,Jager,Kallweit,Karg,Kauer,Kilgore,Kramer,Kosower,Kunszt,Lazopoulos,Mahmoudi, Maltoni,Melnikov,Miller,Nagy,Oleari,Orr,Petriello,Plehn,Plumper,Rauch,Reina,Ruckl,Signer,Spira, Troscsanyi,Uwer,Wackeroth,Weinzierl,Zanderighi,Zeppenfeld,Zerwas

NLO Update (Glover, LP2009)

Final State	Authors*	Comments
$W+$ 3 jets	BBDFFGIKM[a]	
$V V\, b\, \bar{b}$	vHPP[b]	
$H+$ 3 jets	FHZ[c]	Vector boson fusion
$t\bar{t}b\bar{b}$	BDDP[d], BCPPW[e]	
$t\bar{t}Z$	LMMP[f]	
VVV	BOPP[g]	WZZ, WWZ, WWW
multijets	GZ[h]	$gg \rightarrow$ up to 20 gluons

[a] Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre

[b] van Hameren, Papadopoulos, Pittau

[c] Figy, Hankele, Zeppenfeld

[d] Bredenstein, Denner, Dittmaier, Pozzorini

[e] Bevilacqua, Czakon, Papadopoulos, Pittau, Worek

[f] Lazopoulos, McElmurry, Melnikov, Petriello

[g] Binoth, Ossola, Papadopoulos, Pittau

[h] Giele, Zanderighi

- Les Houches 2007 wish list of "feasible" NLO calculations

Final State	Relevance	Progress?
$V\,V$ jet	$t\bar{t}H$, new physics	$VV = \gamma\gamma, WW$
$V\,V\,V$	SUSY trilepton	Done
$V\,V\,b\bar{b}$	VBF$\rightarrow H \rightarrow VV$, $t\bar{t}H$, new physics	Done
$V\,V + 2$ jets	VBF$\rightarrow H \rightarrow VV$	VBF
$V + 3$ jets	various new physics signatures	$W+$ 3 jets
$t\bar{t} + 2$ jets	$t\bar{t}H$	$t\bar{t}Z$
$t\bar{t}\,b\bar{b}$	$t\bar{t}H$	Done
$b\bar{b}\,b\bar{b}$	$t\bar{t}H$	
4 jets	various new physics signatures	$gg \rightarrow gggg$

- "Done" does not necessarily mean a (parton-level) event generator exists
  - Time for matrix element generation?
  - Sum over spins and colours?
  - Decays of unstable particles (with spin correlations)?
  - Efficient phase space generation and unweighting?
  - Interfacing to parton showers and hadronization?

Summary of Lecture 2

- Jet fragmentation functions also obey DGLAP evolution equations.
  - Scaling violation seen in e^+e^-.
  - Soft gluon coherence $\Rightarrow$ angular-ordered branching.
  - Small-x fragmentation sensitive to coherence effects.
  - Gaussian peak in $\ln(1/x)$, peak position shows coherence.
  - Average hadron multiplicity predicted.
- Hadronization models needed for simulation of full final states.
  - General ideas describe spectra and event shapes.
    - Local parton-hadron duality $\Rightarrow$ small-x hadron spectra.
    - Universal low-scale $\alpha_S \Rightarrow \langle \alpha_S(q < 2\ \mathrm{GeV}) \rangle \sim 0.5$.
  - Specific models needed for hadron distributions.
    - String model (PYTHIA).
    - Cluster model (HERWIG).
- In hadron-hadron processes, factorization permits cross section calculations.
  - Parton-parton luminosities important: uncertainties $\sim 10-20\%$.
  - Lepton-pair, jet, top and Higgs production reliably predicted (NLO or NNLO).
  - All $2 \to 2$ and many $2 \to 3$ subprocesses predicted to NLO.