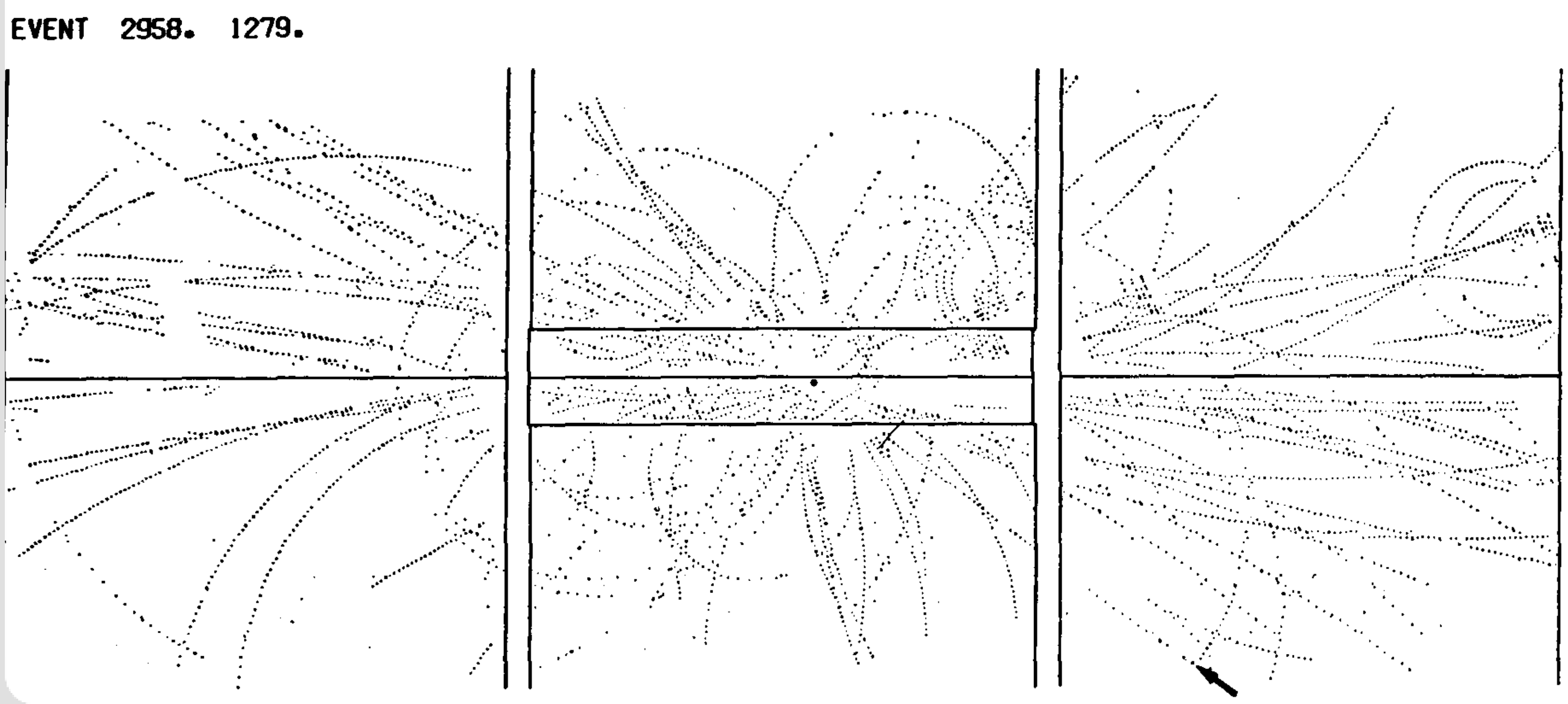
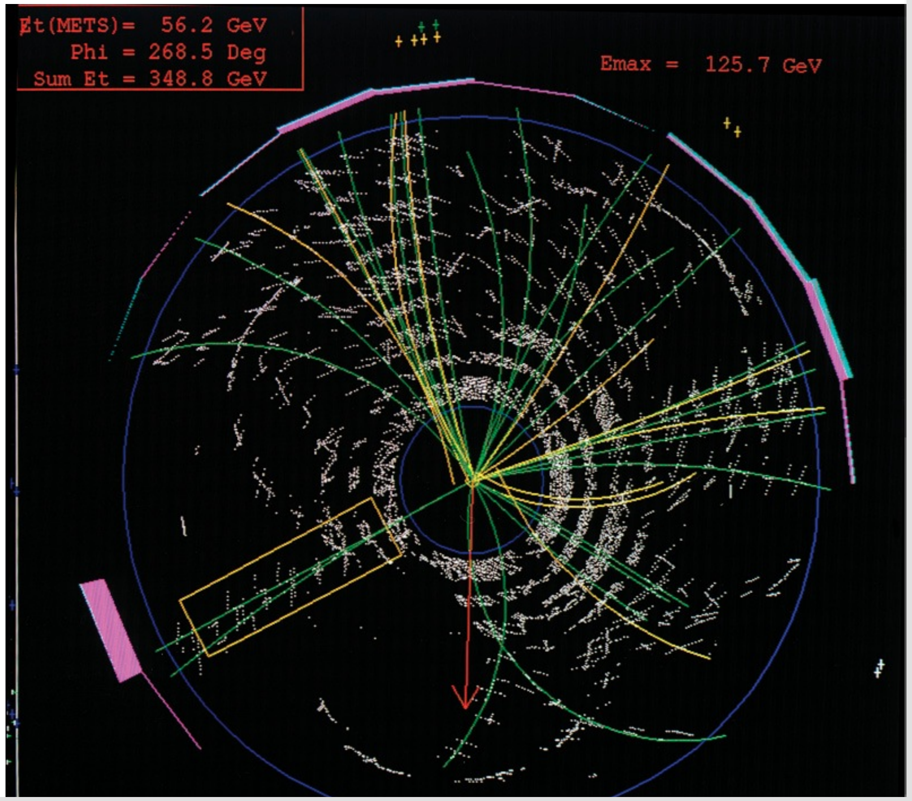
KSETA-Course: Accelelerator-Based Particle Physics

QCD and Jet Physics

Matthias Mozer, Roger Wolf
Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie



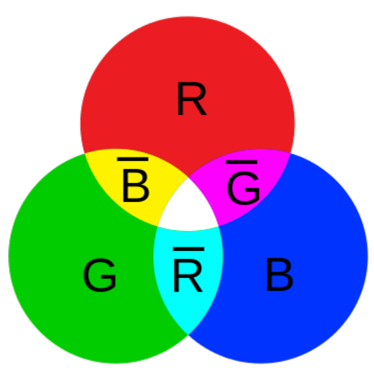


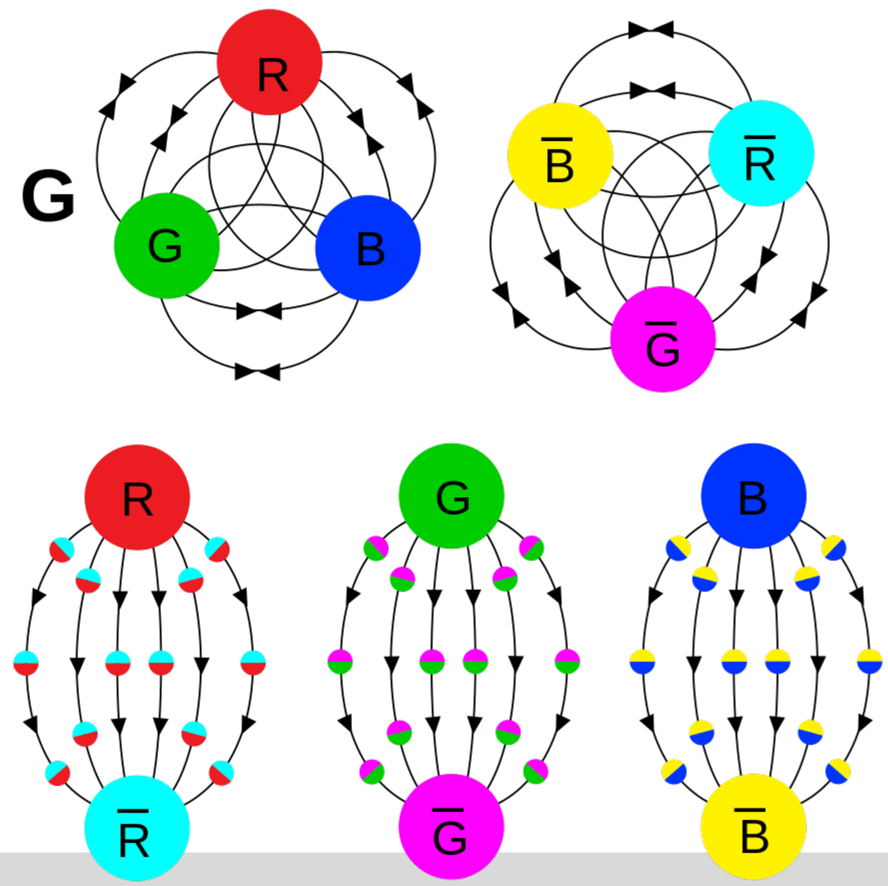
QCD Reminder

- Force between color-charged particles
  $\Rightarrow$ 6 quarks (with colors), 6 anti-quarks (with anti-colors)

- Coupling constant α_s

- Described in field theory by SU(3) group
  $\Rightarrow$ force carried by 8 gluons, each with one color + one anti-color
  $\Rightarrow$ non-abelian $\rightarrow$ gluon self-interactions





Strong Coupling

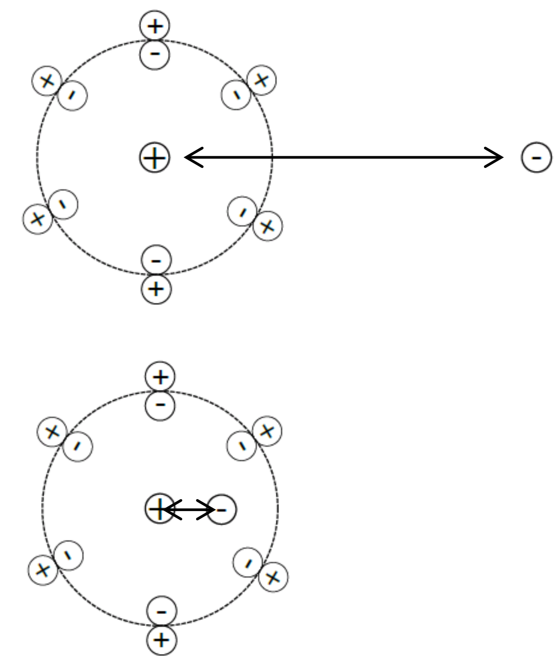
- Vacuum polarization effects:
  $\Rightarrow$ couplings depend on energy

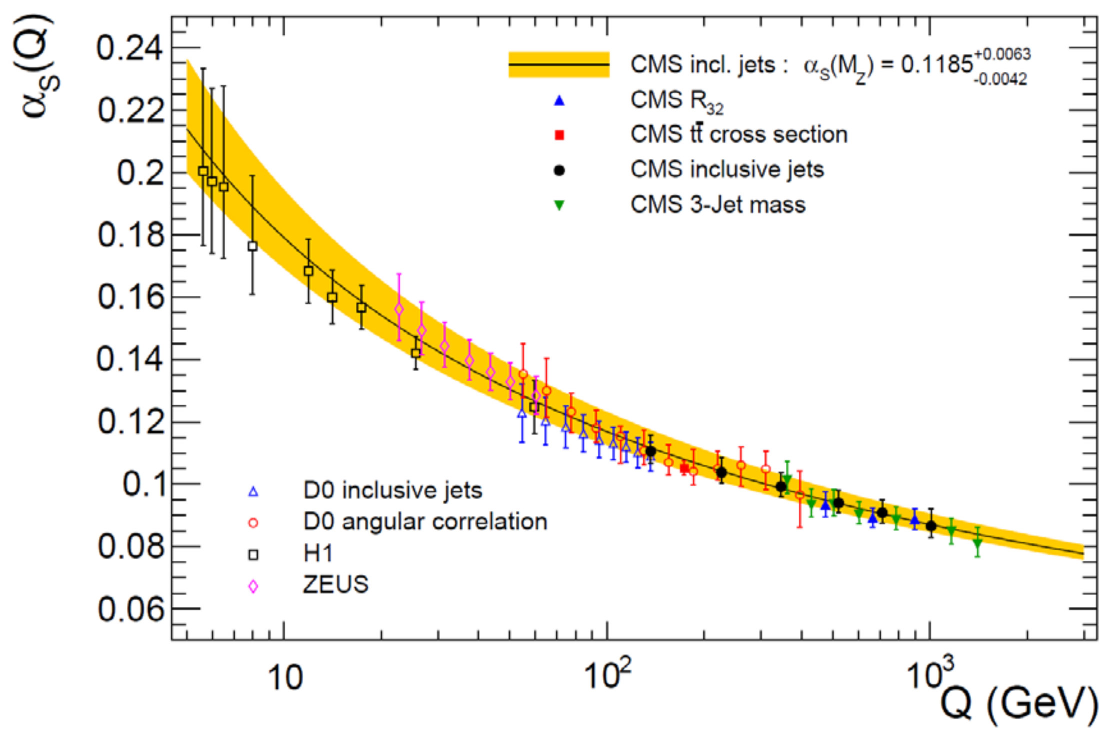
- EM: screening
  $\Rightarrow$ coupling stronger at higher energies

- QCD: anti-screening
  $\Rightarrow$ coupling weaker at higher energies

- Consequences:
  $\Rightarrow$ confinement
  $\Rightarrow$ asymptotic freedom

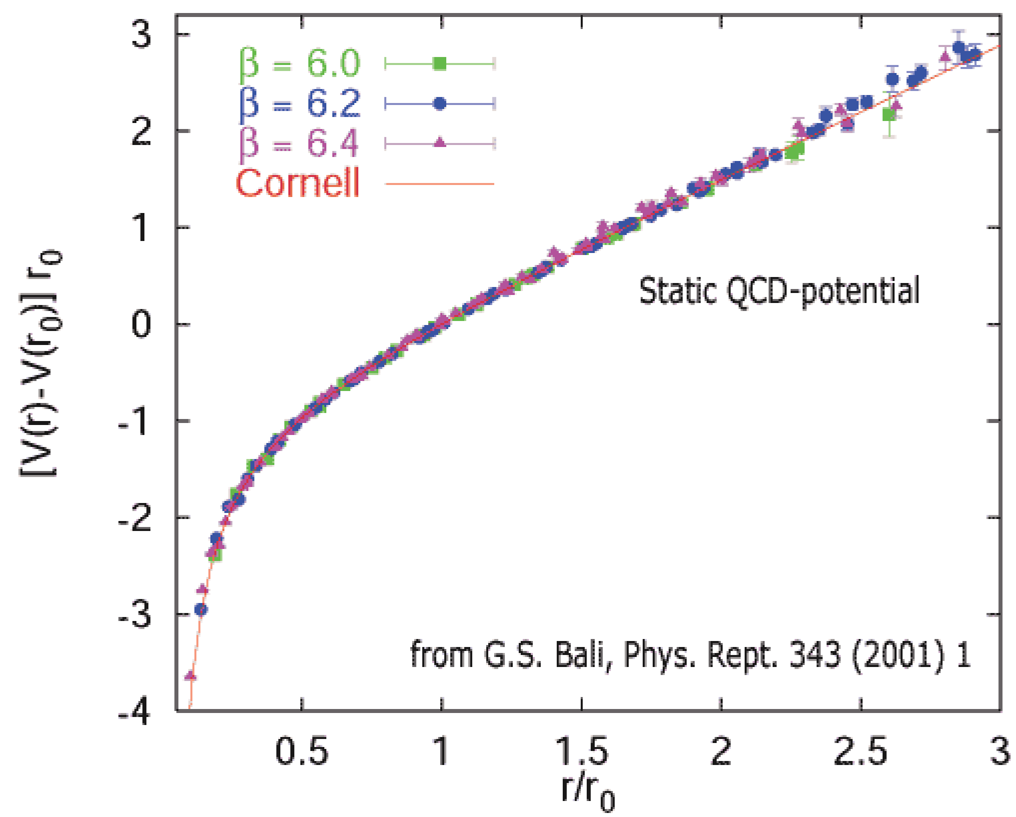
EM: Screening





QCD Reminder: Phenomenology

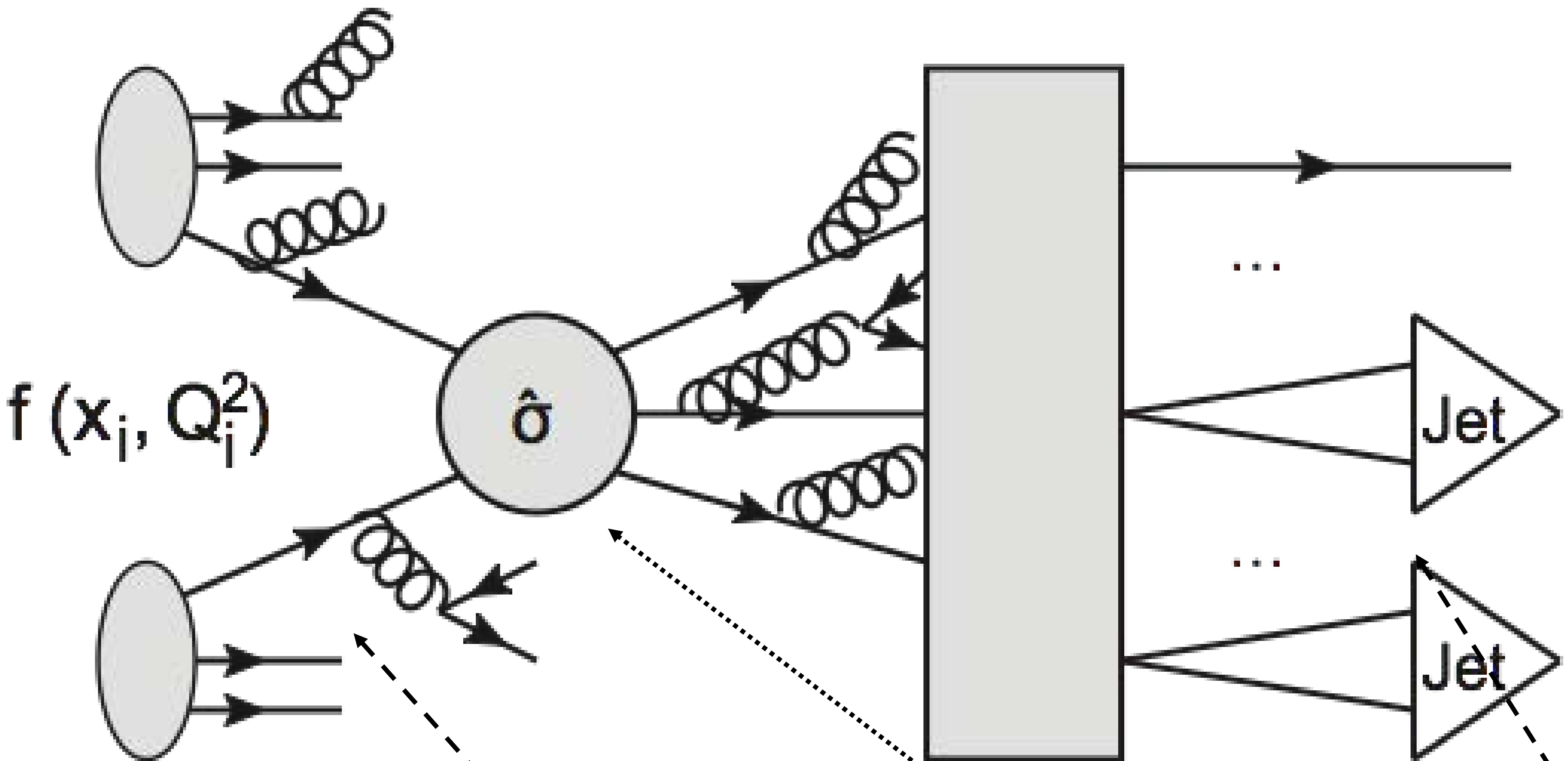
- Confinement:
  strong coupling increasing at
  low energies, large distances
  $\Rightarrow$ QCD potential rising infinitely
  $\Rightarrow$ no free color-charged particles
  observable, only hadrons



- Asymptotic freedom:
  coupling shrinking at high energy
  $\Rightarrow$ α_s small enough for perturbation theory
  $\Rightarrow$ collider strong physics framed as
  quark + gluon physics

Reminder: QCD-Factorisation

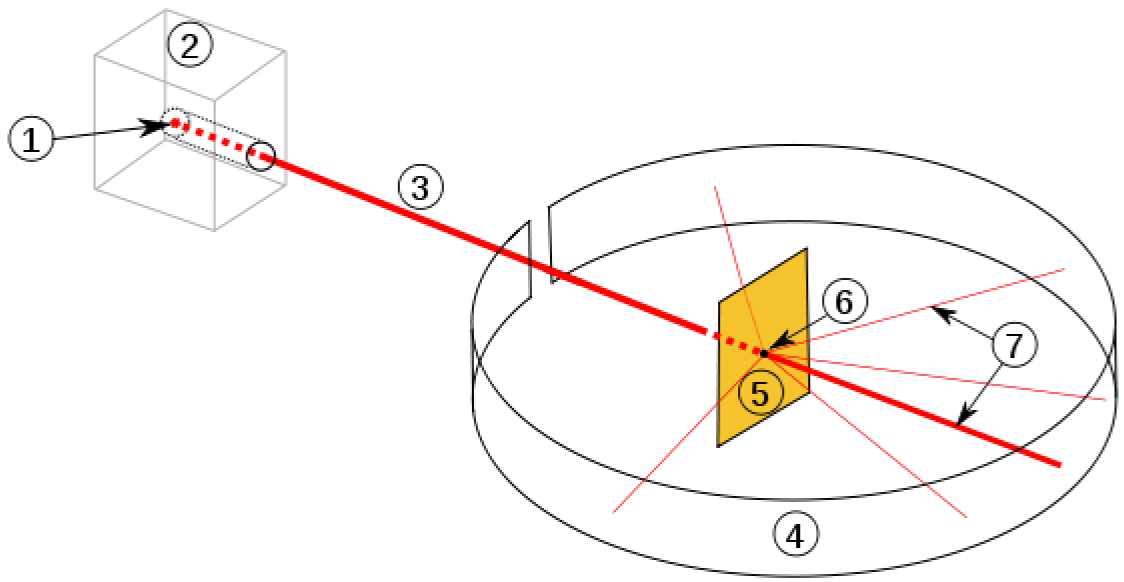
cross section = PDF $\otimes$ hard process $\otimes$ hadronisation



$$\sigma_{QCD} = \sum_{jk} \int dx_j\, dx_k\, \boxed{f_j(x_j, \mu_F^2)\, f_k(x_k, \mu_F^2)} \cdot \boxed{\hat{\sigma}(x_j x_k s, \mu_F^2, \mu_R^2)} \otimes \boxed{\text{hadronisation}}$$

Proton Structure

- Probe proton structure with scattering experiments
- Inspiration: Rutherford Scattering

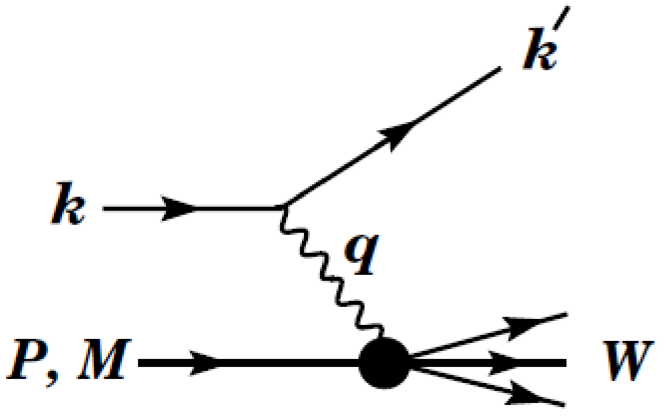


$\Rightarrow$ charge distribution within proton

- Add additional degree of freedom: inelastic scattering
  $\rightarrow$ scattering angle
  $\rightarrow$ energy loss

Deep Inelastic Scattering

- Kinematic variables:
  four-momentum transfer: $Q^2 = -q^2 = (k - k')^2$
  inelasticity: $y = \frac{P\cdot q}{P\cdot k} = \frac{E-E'}{E}$
  „scaling variable“ $x = \frac{Q^2}{2P\cdot q}$
  mass of scattered system: $W = (P+q)^2$

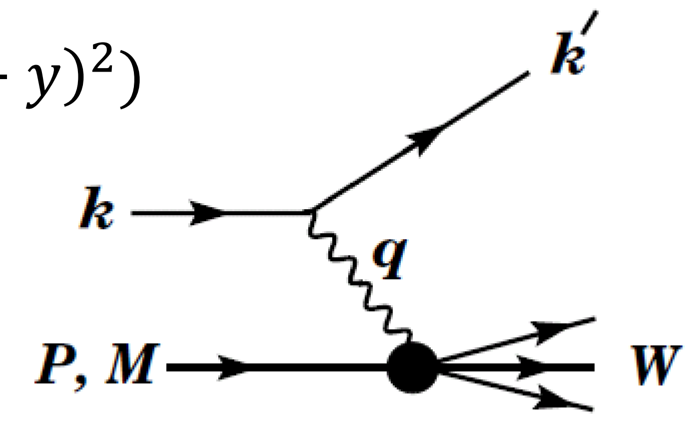


- Processes described by just two variables
  $Q^2 = xys$ (s = center-of-mass energy)
- Kinematics determined by electron kinematics alone
- „Deep Inelastic“ if W ≫ M

Structure Functions

- Scattering Process can be generically written as

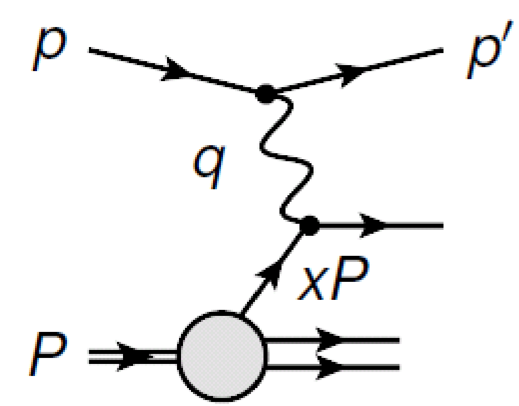
$$\frac{d\sigma^2_{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(Y_+ F_2 - y^2 F_L \mp Y_- x F_3\right) \qquad Y_\pm = (1 \pm (1-y)^2)$$



photon propagator
and em coupling factorize

with F_2, F_3, F_L intrinsic properties of the proton

- Interpret proton in the quark model ⇒ functions get meaning
  xP: momentum carried by struck quark

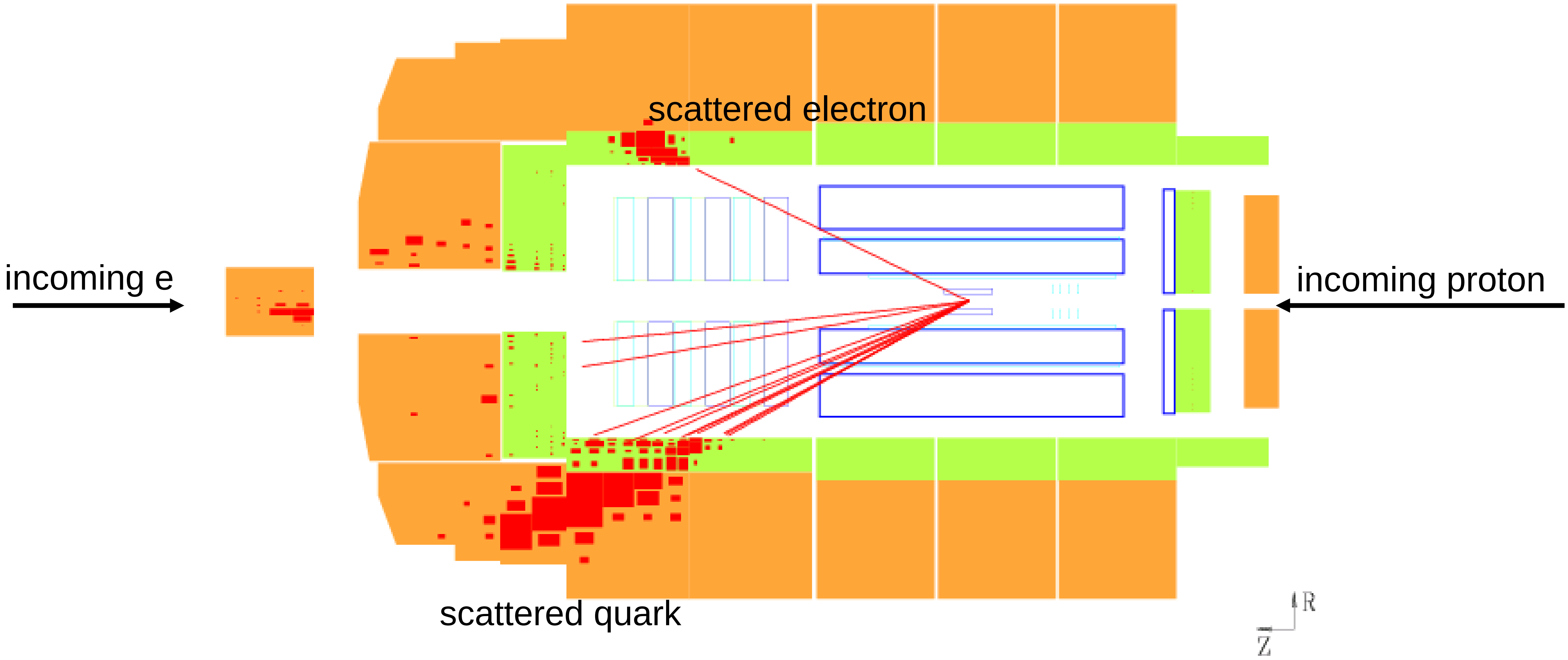


$$F_2(x,Q^2) = x\sum_q e_q^2\left(q(x,Q^2) + \bar{q}(x,Q^2)\right)$$

$$xF_3(x,Q^2) = x\sum_q e_q^2\left(q(x,Q^2) - \bar{q}(x,Q^2)\right)$$

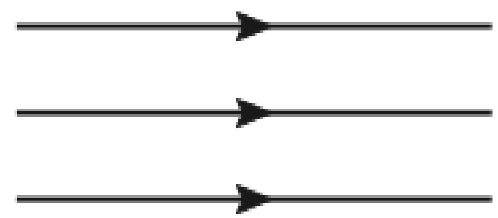
$F_L(x,Q^2) = 0$ (in leading order)

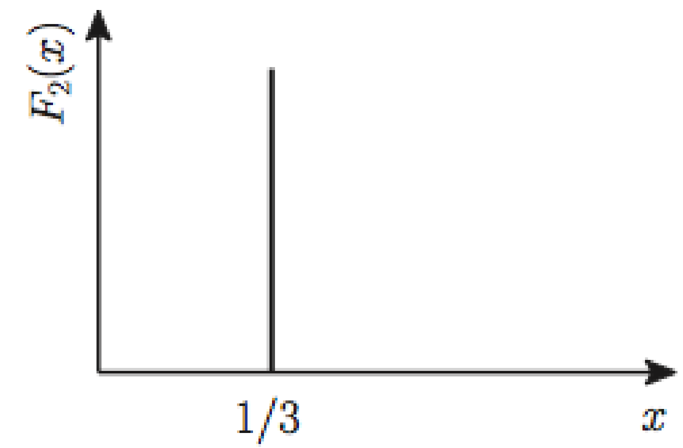
Deep Inelastic Scattering



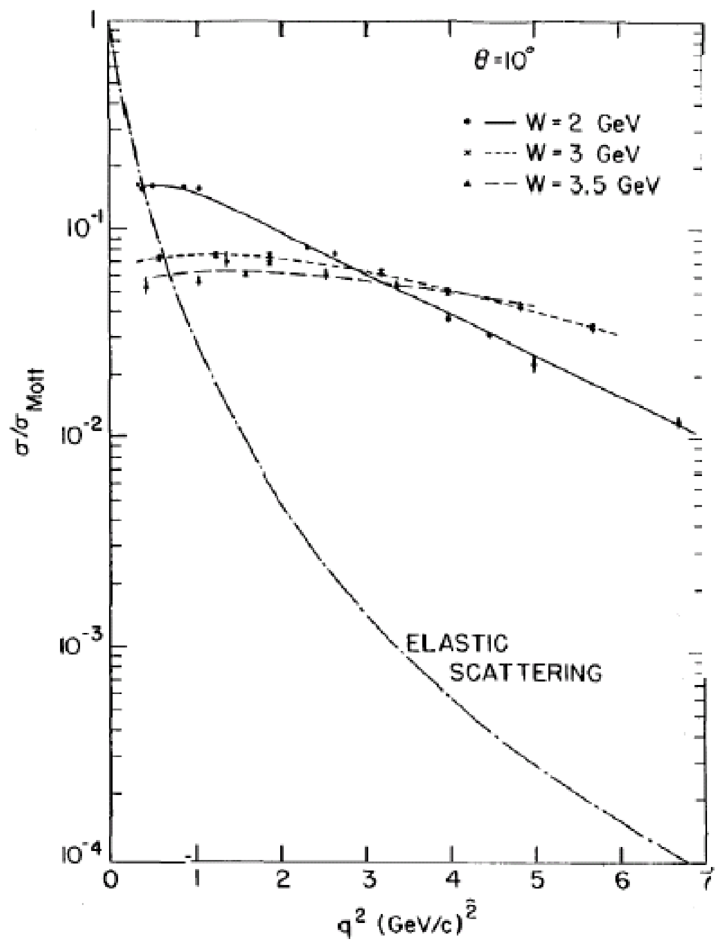
Bjorken Scaling

- Naive assumption: pointlike constituents: $F_2(x,Q^2) \rightarrow F_2(x)$
- 1969: SLAC+MIT experiments
- Quarks are real!
- looks like scaling

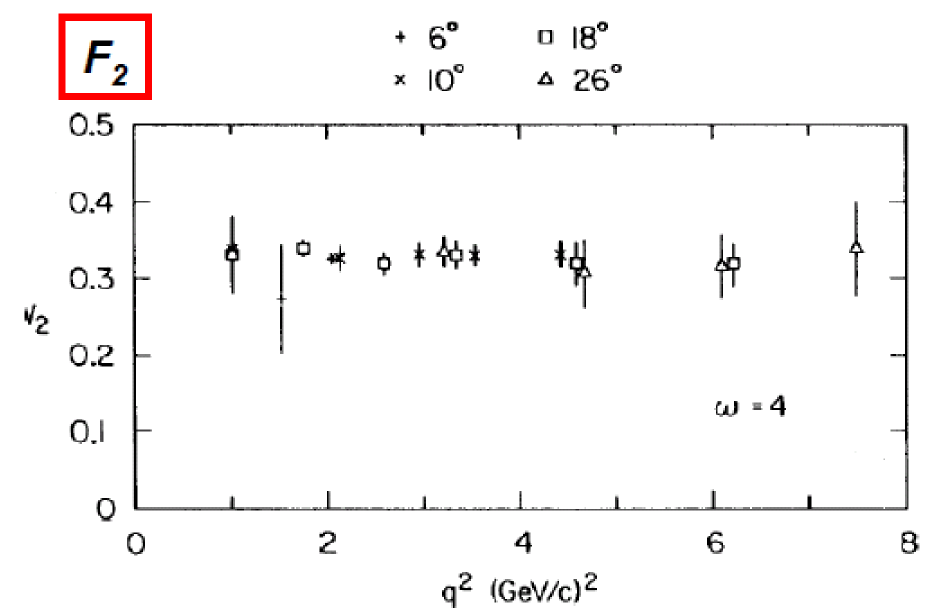




Deep-inelastic scattering (DIS)

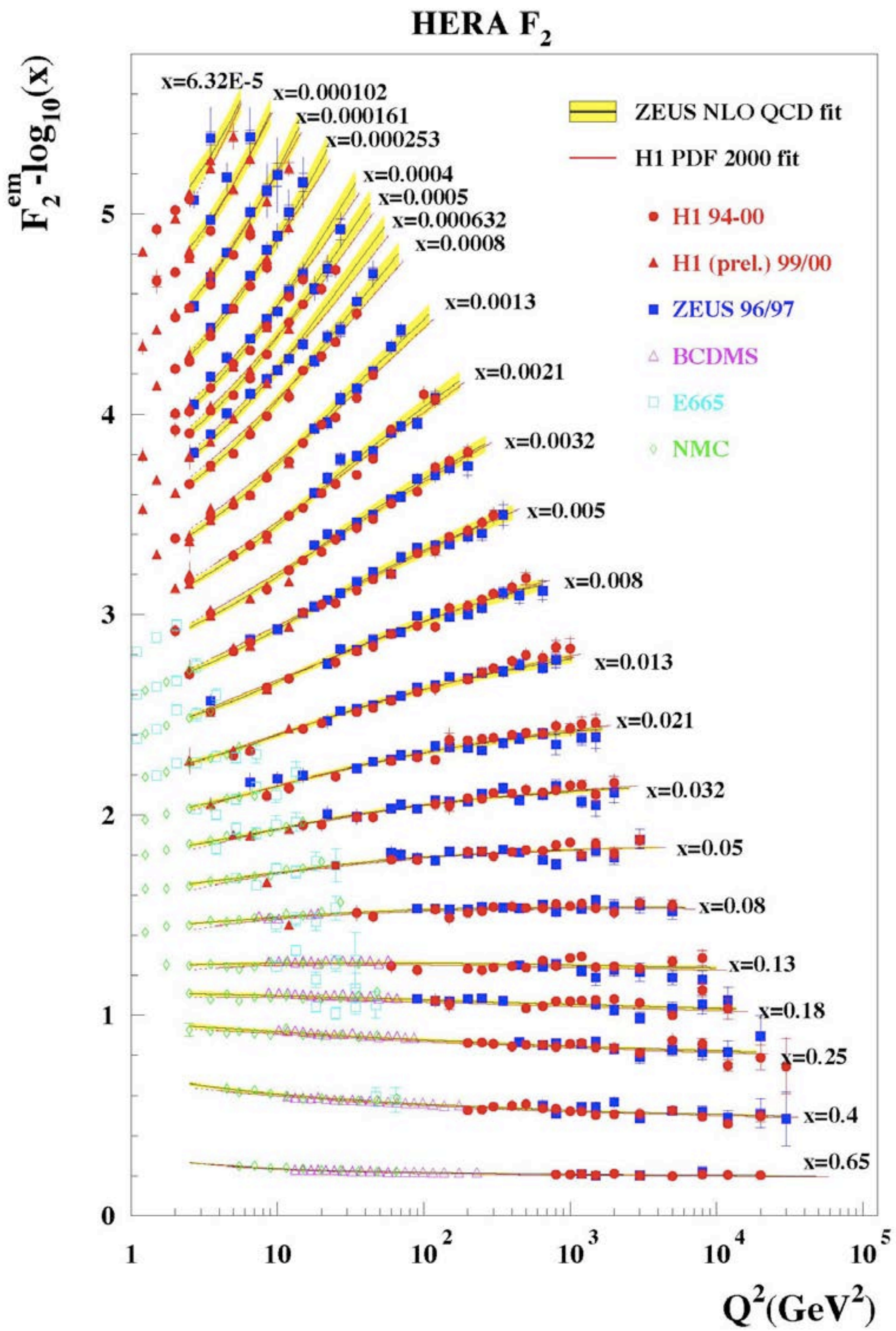


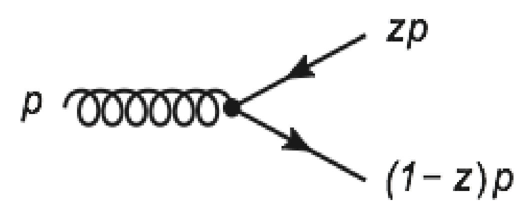
Scaling behavior



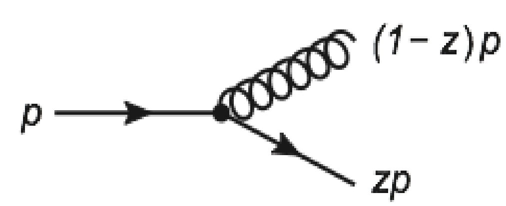
$\omega = 1/x$

Scaling Violations





low x:
Gluon splitting enhances quark density
$\Rightarrow$ F_2 rises with Q^2



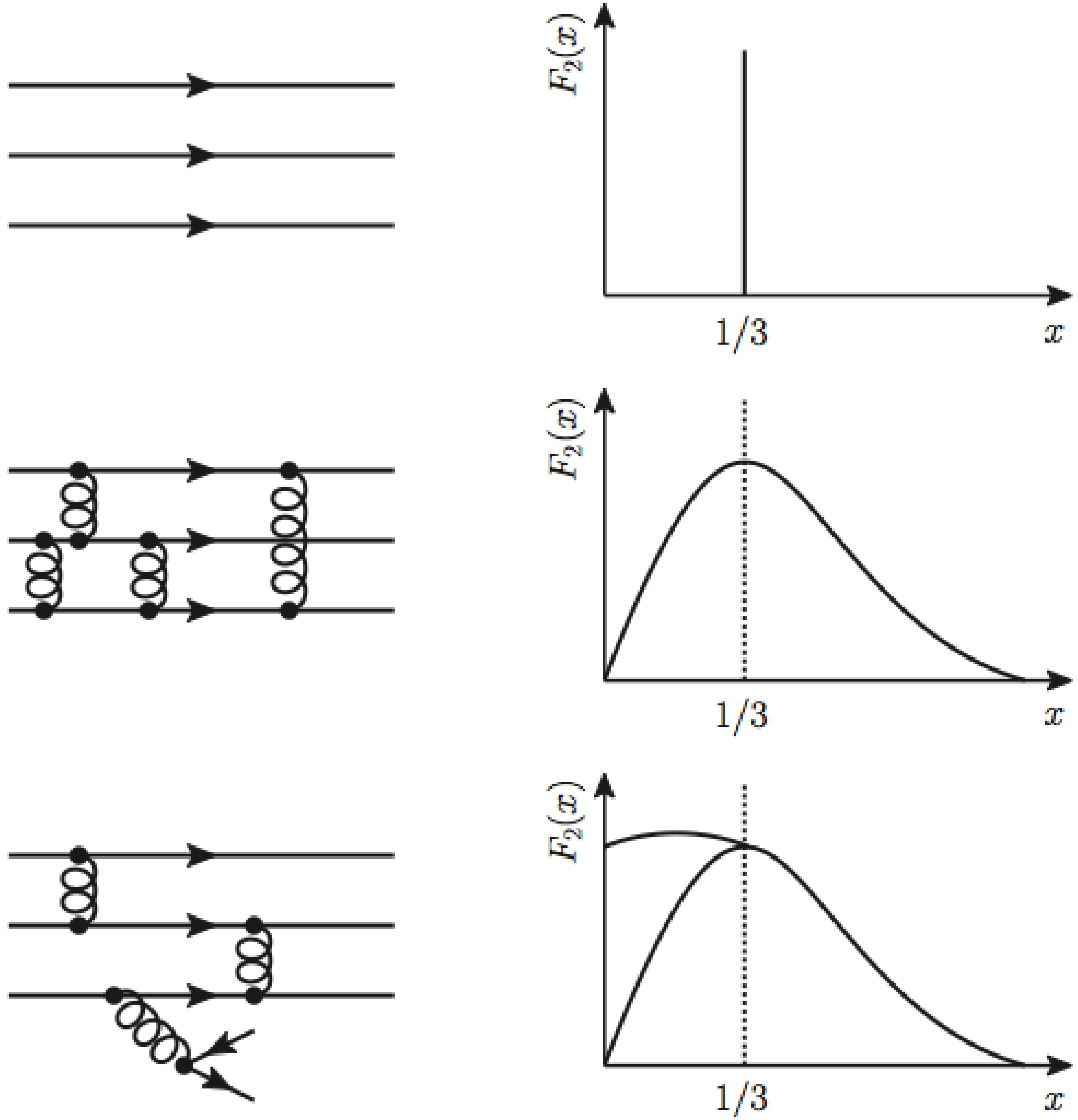
high x:
Gluon radiation shifts quark to lower x
$\Rightarrow$ F_2 falls with Q^2

Parton-Model and PDFs

- „Naive” parton model: Proton described by structure function F_2

$$F_2(x) = \sum_i q_i^{\,2}\, x\, f_i(x)$$

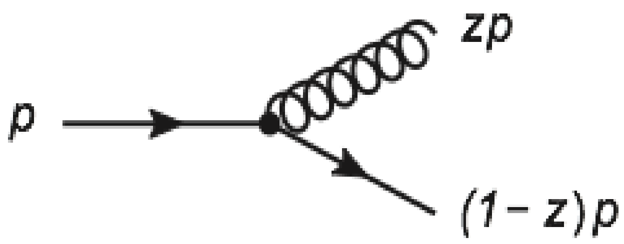
- Simple Model: three valence quarks → $F_2 = 1/3$
- Gluon-exchange between valence quarks → smearing
- Gluon-exachnge and Gluon-radiation → sea quarks



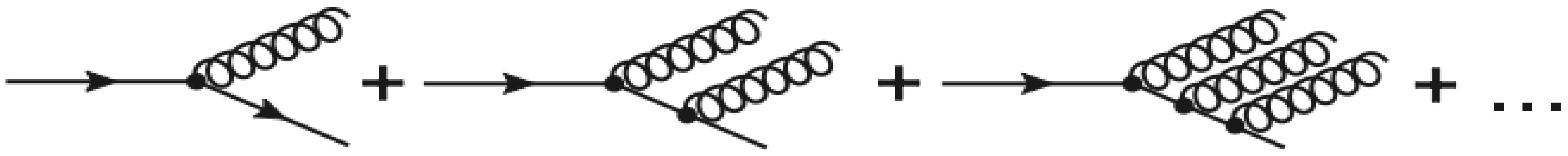
[nach: Halzen, Martin, Quarks & Leptons]

QCD-Evolution of PDFs

- PDFs depend on energy transfer:
  - concept: Parton content of the proton changes with energy transfer Q^2, e.g. more sea-quarks adn gluons from radiation at high Q^2



  - Theoretical desription: Resumming of all collinear parton radiation
    → DGLAP-equation
    (renormalization group equation)

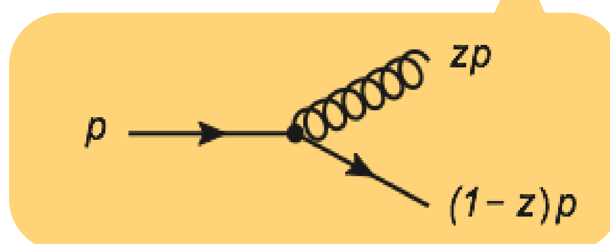


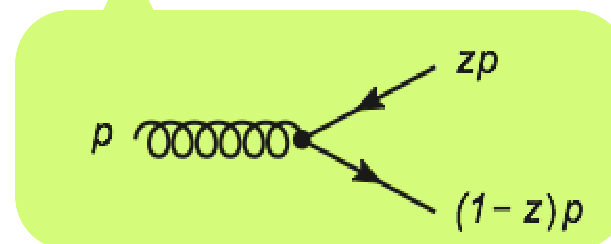
- Starting point: PDFs measurements at starting energy scale
  - non-perturbative process: not calculable ab initio
  - measurement in many processes, e. g. deep inelastic scattering, jet production (HERA, Tevatron, LHC, Fixed Target, Neutrinos)

QCD-Evolution of PDFs

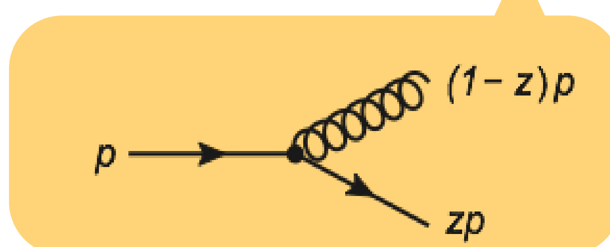
- Dokshitzer-Gribov-Lipatov-Altarelli-Parisi-equation (DGLAP)

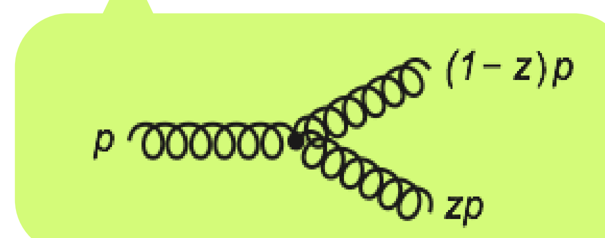
Quarks: $$\frac{dq(x,Q^2)}{d\ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\left\{q\otimes P_{qq} + g\otimes P_{qg}\right\}$$





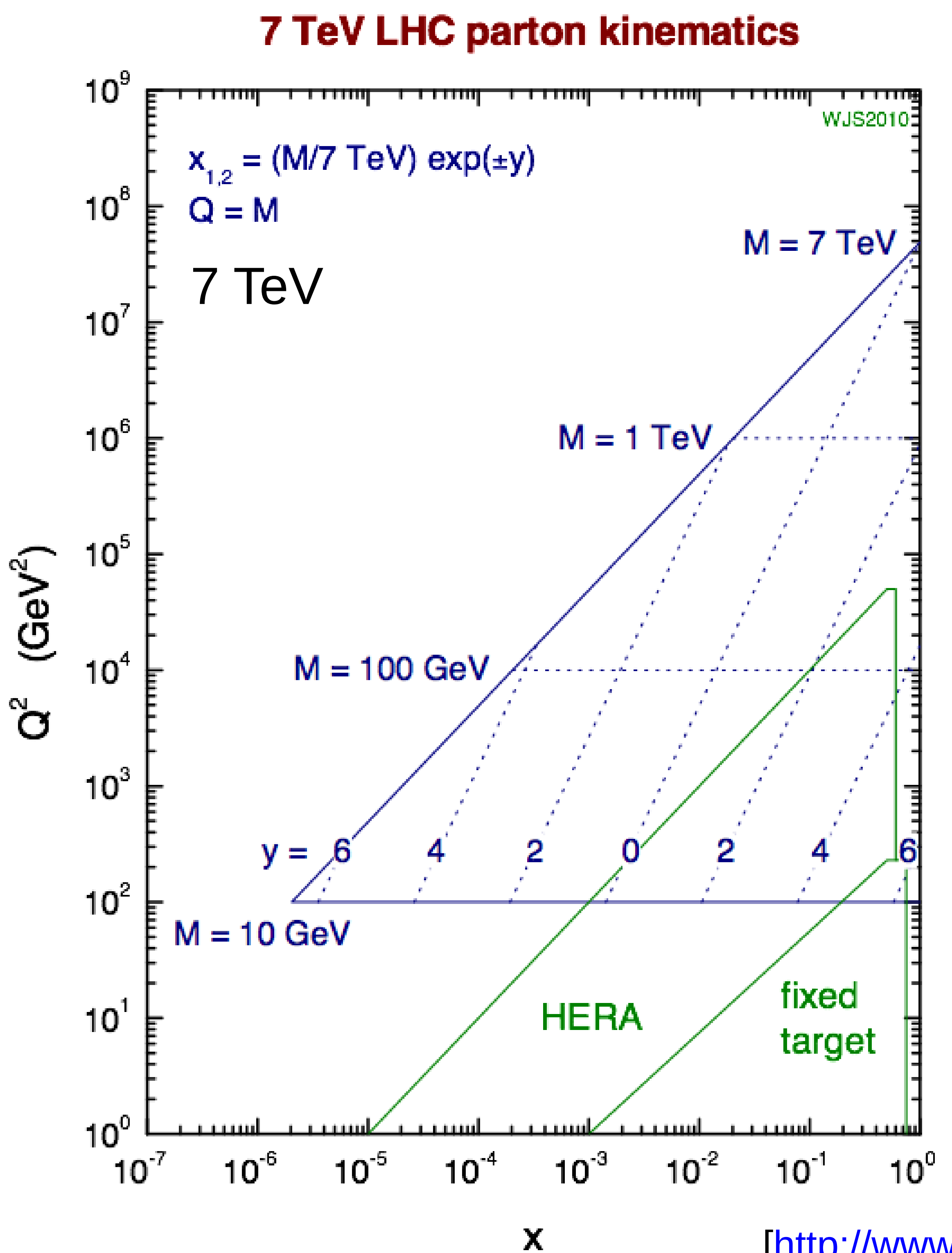
Gluons: $$\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\left\{q\otimes P_{gq} + g\otimes P_{gg}\right\}$$

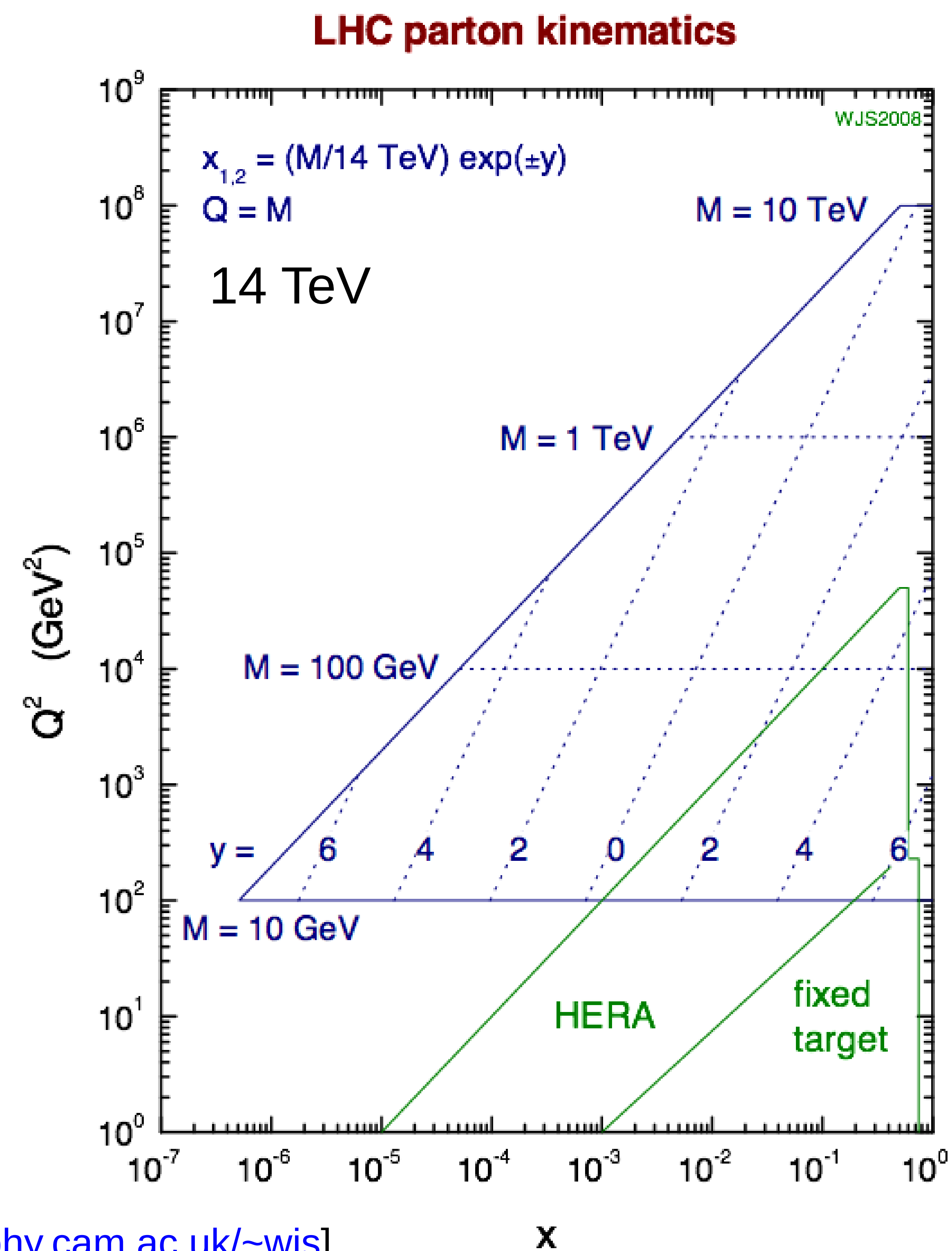




- P_{ij}: universal splitting function, e.g. in LO $P_{gq} = \frac{4}{3}\frac{1+(1-z)^2}{z}$
- Interpretation: get additional quarks with momentum fraction x at energy scale Q^2 by splitting q → qg or g → qq from larger x

Kinematic (x, Q^2)-Plane

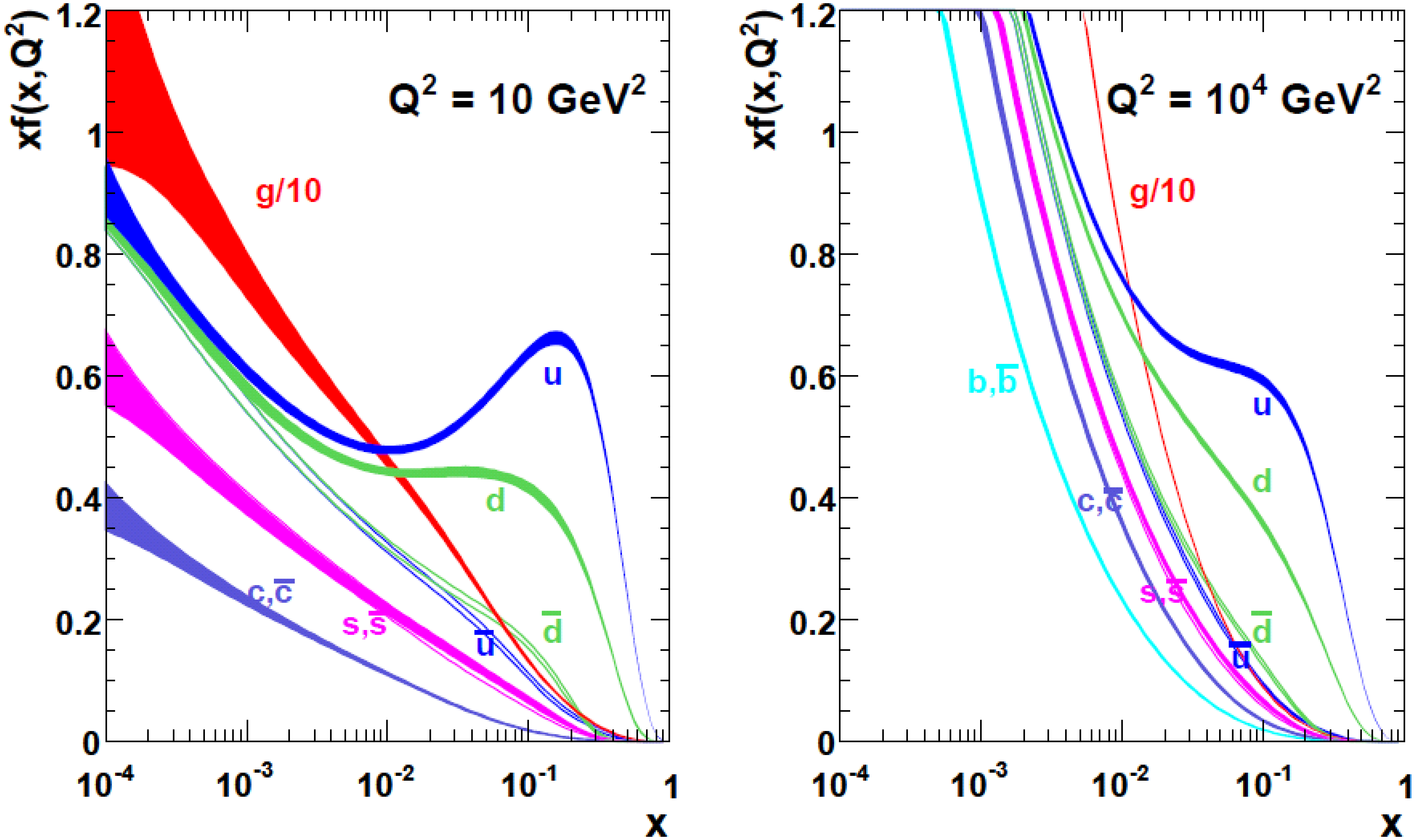




[http://www.hep.phy.cam.ac.uk/~wjs]

PDFs

MSTW 2008 NLO PDFs (68% C.L.)

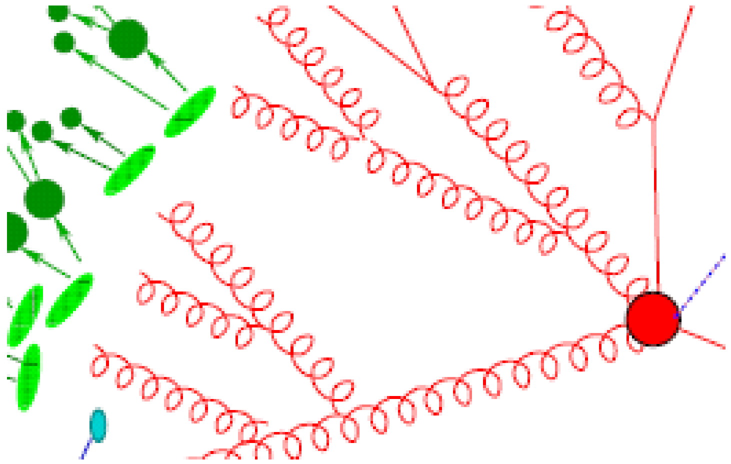


- Gluon-density steeply with falling x
  ⇒ high cross sections for gluon induced processes at the LHC

- Heavy quarks at high momentum transfer
  ⇒ proton effectively „contains“ quarks heavier than itself

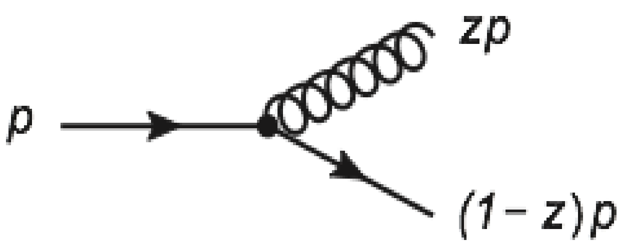
Parton Shower

- Fragmentation of partons:
  - partons can split into more partons („parton splitting“) → parton shower
  - parton shower: probabilistic modell for fragmentation, aequivalent to resumming



- Described with Sudakov form factor
  - Probability for the splitting on a parton i in j: splitting function P_{ji}
  - Solve DGLAP-equation for parton shower: Sudakov form factor

$$\Delta_i(t) = \exp\left[-\sum_j \int_{t_0}^{t} \frac{dt'}{t'} \int_0^1 dy \, \frac{\alpha_S}{2\pi} P_{ji}(y)\right]$$



  - Interpretation: probability that no splitting occurs

Parton Shower Algorithms

- Sudakov picture of parton shower well suited for MC-simulation

- Basic algorithm: Markov-chain
  → Each step only based on information from previous step
  - Start: Virtuality t_1, momentum fraction of parton x_1
  - Randomly generate new virtuality t_2 with random number $R_t \in [0,1]$ with

$$\frac{\Delta(t_2)}{\Delta(t_1)} = R_t$$

  - Randomly generate new momentum fraction x_2 with $R_x \in [0,1]$

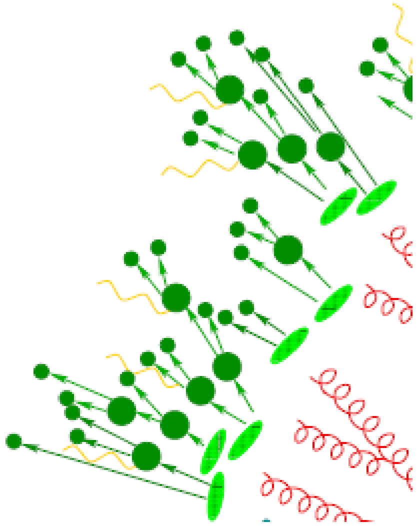
$$\frac{\int_0^{x_2/x_1} \mathrm{d}z \, \frac{\alpha_S}{2\pi} P(z)}{\int_0^1 \mathrm{d}z \, \frac{\alpha_S}{2\pi} P(z)} = R_x$$

  - randomly generate azimuthal angle $\Phi \in [0,2\pi]$
  - iterate until virtuality reaches threshold

Hadronisation Models

- Transition from partons to hadrons: not perturbative
  → phaenomenologic models

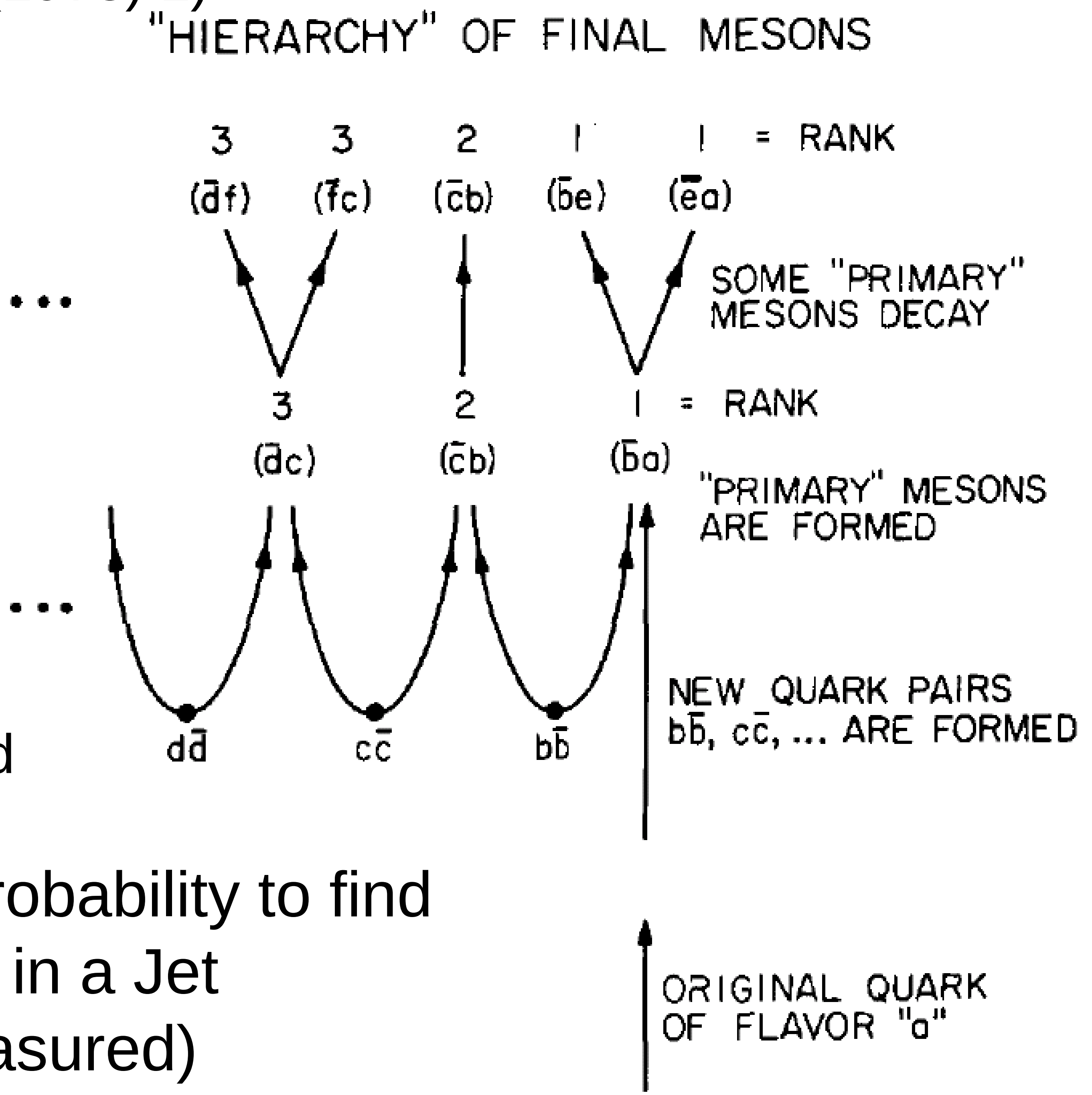
- Monte-Carlo models quite successful
  - Complete final state predictions → directly applicable to experiments
  - Disadvantage: many ad-hoc-parameters
    → Requires optimization
    → may hide actual physics effects



- Most common models
  - Independent fragmentation (historical)
  - Lund string model (Pythia)
  - Cluster model (Herwig, Sherpa)

Independent Fragmentation

- Ansatz: each parton fragments independently
  (Field, Feynman, Nucl. Phys. B136 (1978) 1)
- Algorithm
  - Start: original quark
  - Quark-antiquark-pairs created from vacuum → primary Meson with energyfraction z
  - New starting point: remaining quark with energyfraction 1 – z
  - Stop: at a lowert energy-threshold
- Fragmentation-funktion D(z): Probability to find a Hadron with energy fraction z in a Jet (not perturbative, has to be measured)

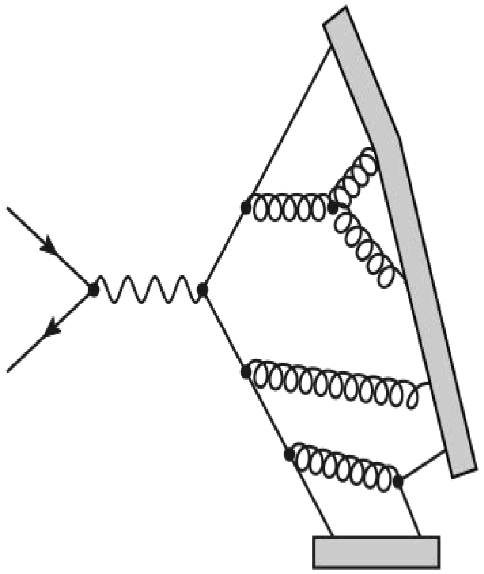


Lund String Model

- Ansatz: quark-antiquark-pairs form strings
  (Andersson et al., Lunds universitet, Phys. Rept 97 (1983) 31)
  - QCD potential: At large distances like a tensioned string

$$V(r) = -\frac{4}{3}\frac{\alpha_S(1/r^2)}{r} + kr$$

  - Quark-antiquark-pairs form strings
  - Strings break, when V(r) large enough
    → new quark-antiquark-pairs
  - Gluons: „kinks” in strings
  - Create hadrons at a lower energy threshold

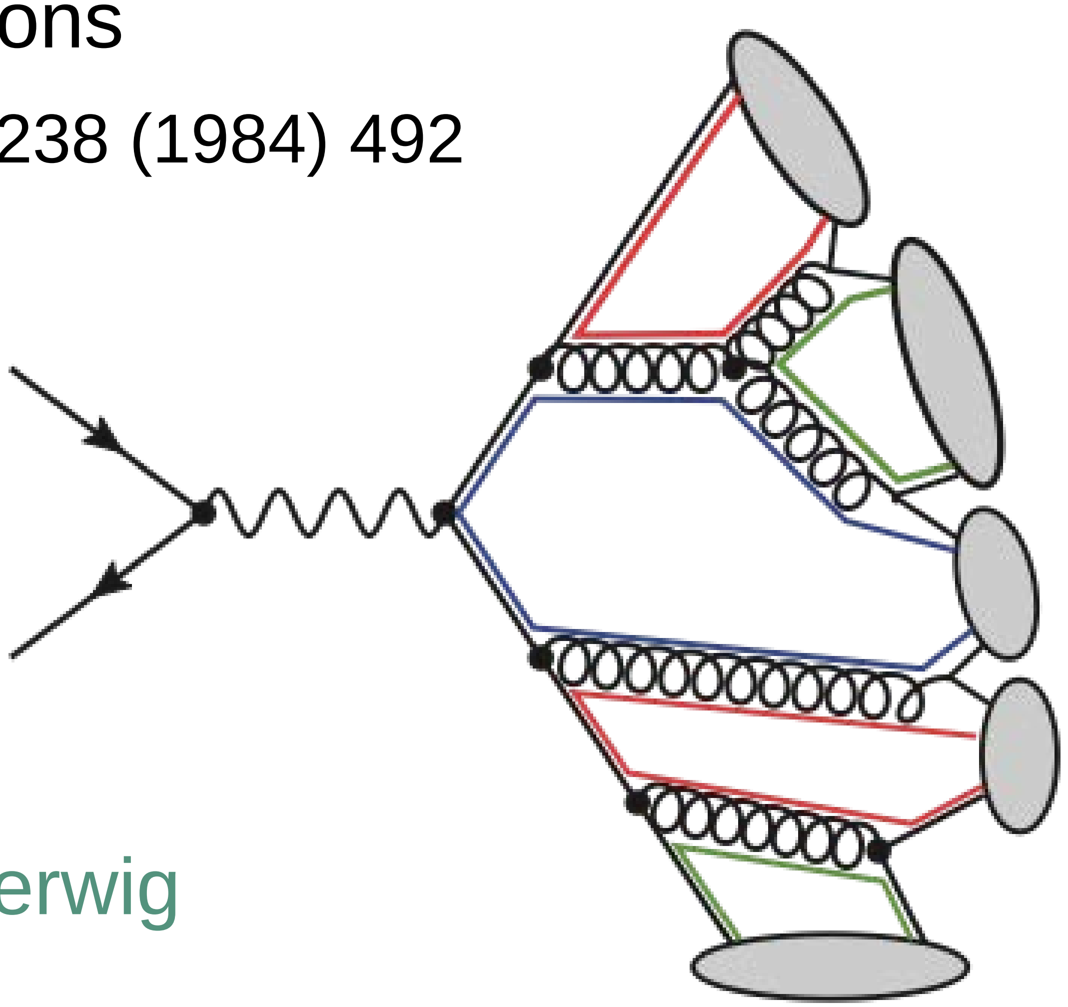


- Commonly used implementation: Pythia

[nach: Ellis et al., QCD and Collider Physics]

Cluster Model

- Ansatz: Colorflow during hadronization subject to confinement
  → form colorneutral clusters of partons
  - original paper: Webber, Nucl. Phys. B238 (1984) 492
  - Gluons (color + anticolor charge):
    split into quark-antiquark-Pairs
  - Decay von clusters according to
    available phase-space
- Advantage: no free parameters
- Commonly used implementation: Herwig

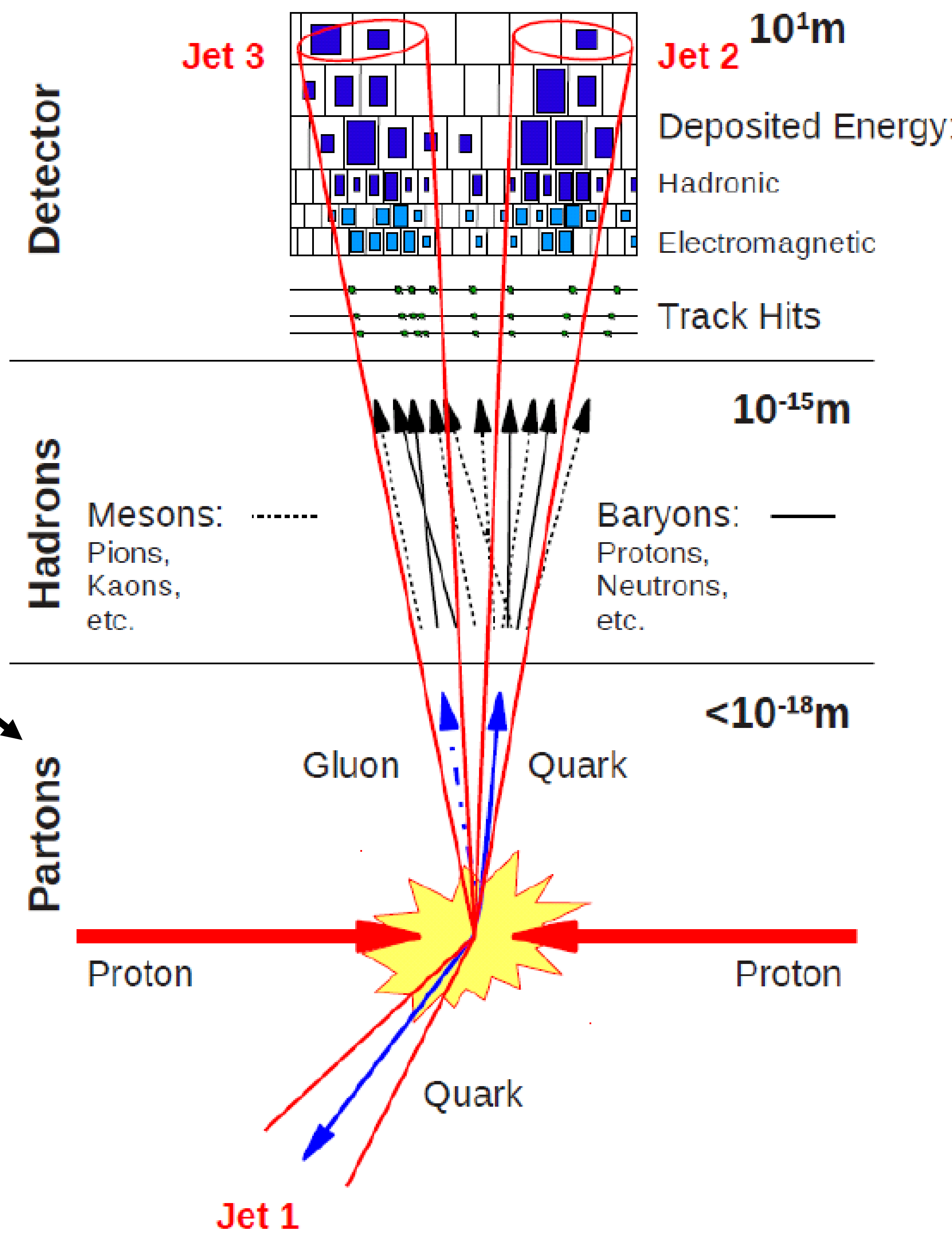


[nach: Ellis et al., QCD and Collider Physics]

Jet Algorithms

- Primary goal:
  establish correspondence between
  → detector signals
  → final state particles
  → hard partons

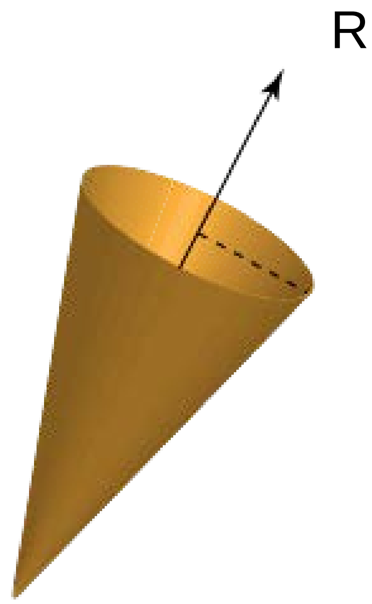
- Two classes of algorithms
  → Cone algorithms
  geometrically combine closeby objects
  → Sequential recombination
  combine two closest objects in some distance measure and iterate



Cone Algortihms

- Iterative cone algorithms: Jet = energy flow in cone of radius R in (y,ϕ)- or (η,ϕ)-space

$$R = \sqrt{(y - y_0)^2 + (\phi - \phi_0)^2}$$

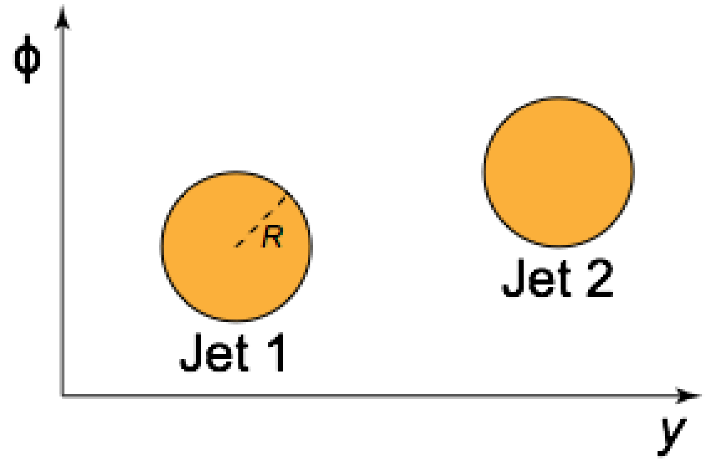


- Algorithm: Find all stable cones
  - Include in jet, if distance from center

$$\Delta_{iC} = \sqrt{(y_i - y_C)^2 + (\phi_i - \phi_C)^2} \leq R$$

  - Recompute center
  - Iterate until cone is stable

jet cone in (y,ϕ)-space



- Starting point ("seed")
  - Fixed seeds (e.g. calorimeter cluster above threshold): not IR safe
  - try all possible seeds
    → gain IR safety
    → can be numerically intensive

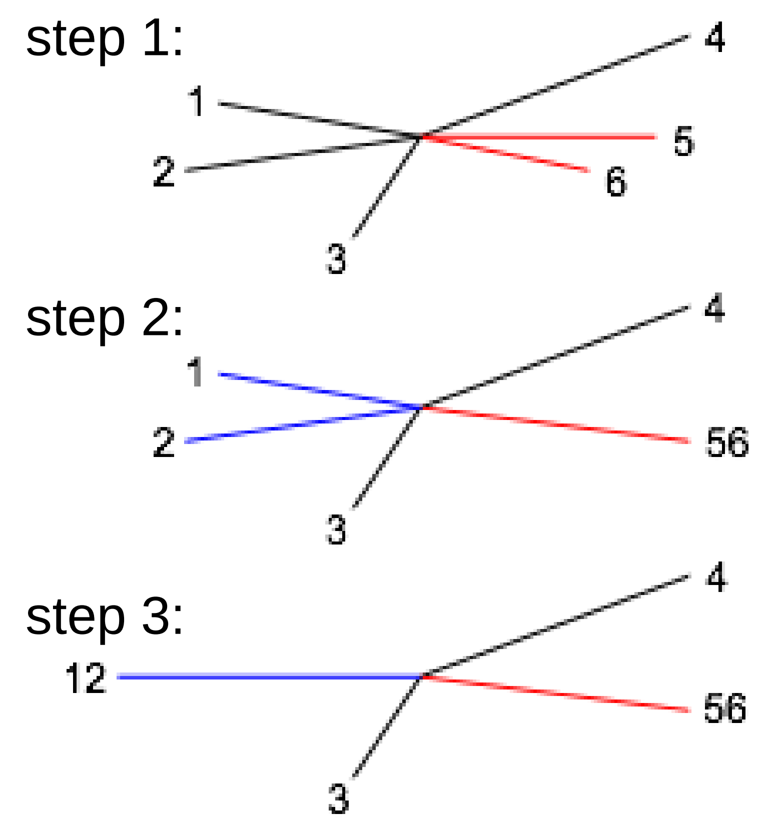
Sequential Recombination

- Main class: k_t-algorithms
  - Define distance measure d_{ij} between transverse momenta k_t e

$$d_{ij} = \min(k_{t,i}^{2n}, k_{t,j}^{2n}) \frac{\Delta R_{ij}}{R}$$

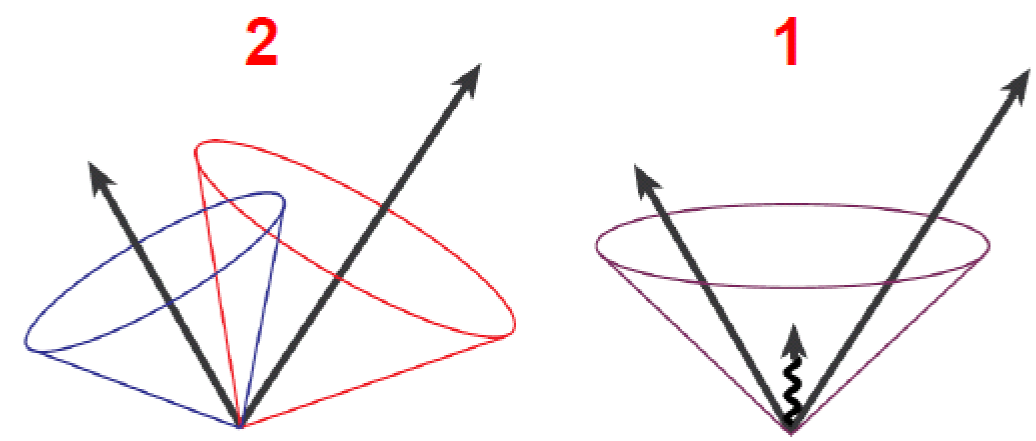
  - Define distance to beam: $d_{iB} = k_{t,i}^{2n}$
  - Compute d_{ij} for all pairs of particles
  - Jet found, if d_{iB} smallest d_{ij}
  - Otherwise: combine particles i and j
- Variants
  - n = 1: k_t-algorithm → combine similar k_t first
  - n = 0: Cambridge/Aachen-(C/A-)algorithm (d_{iB} = 1)→ purely geometrical
  - n = –1: anti-k_t-algorithm (LHC-Standard, ATLAS: R = 0.4, CMS: R = 0.4) → combine all low k_t around „hard" particle first

sequential recombination

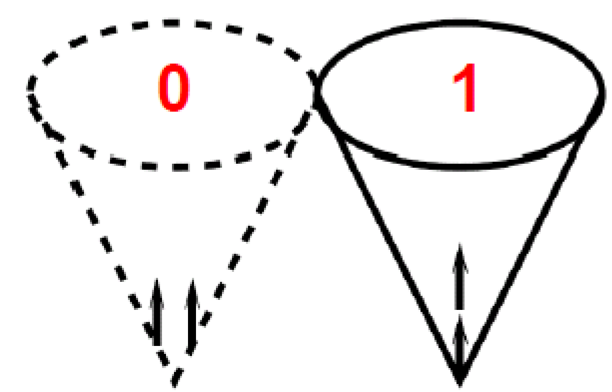


Desireable Properties

- IR-safety:
  soft gluon radiation has high probability
  → shouldn't matter for jet
- Collinear safety:
  parton splitting probability divergent
  → shouldn't matter for jet
- Boost invariance:
  at hadron colliders cms-frame not known
  → shouldn't matter for jet
- Compute Performance:
  need to reconstruct jets in finite time
- Shape regularity
  how to subtract noise/pileu-up
  → prefer regular shape, less greedy algo.
  (mostly a concern for hadron colliders)

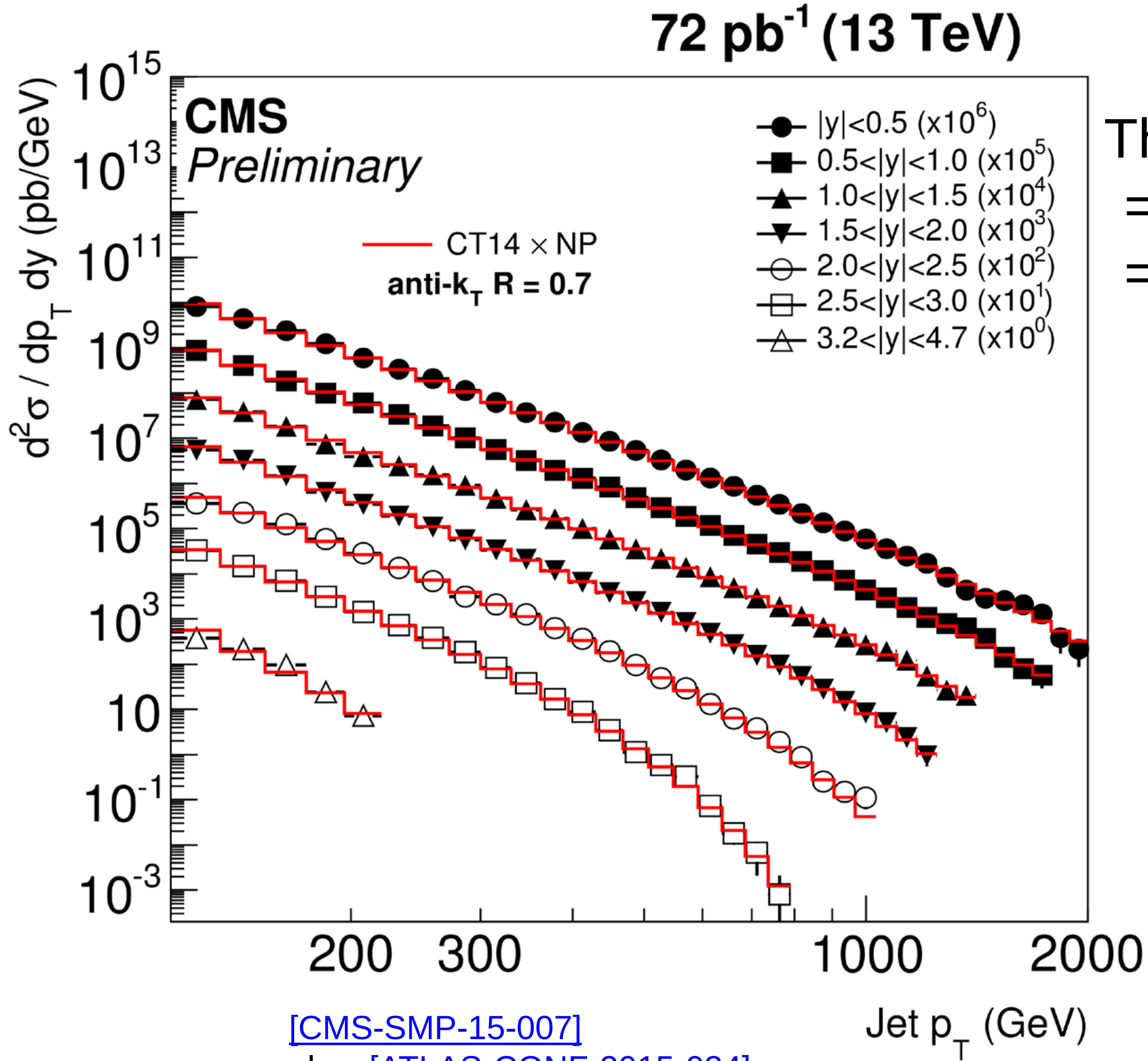


IR unsafe: Sensitive to the addition of soft particles



Coll. unsafe: Sensitive to the splitting of a 4-vector (seeds!)

Jet Production



[CMS-SMP-15-007]
also: [ATLAS-CONF-2015-034]

The dream analysis
=> Basically background free
=> Unlimited statistics

$$\sigma = \frac{N_{sel} - \overset{\sim 0}{N_{bkg}}}{\underset{\sim 1}{\varepsilon A} \int \mathcal{L}}$$

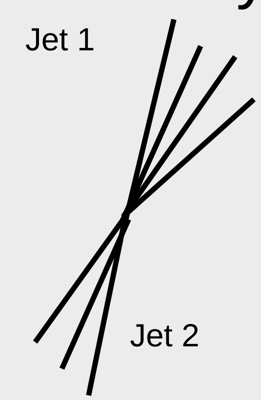
Challenges with Jets

- Huge statistical precision: Dream or nightmare?
- Systematic effects are everywhere:
  => Jet energy scale/resolution
  => Jet energy corrections depend on parton type/flavor
  => Pileup effects
  => …
- Theory uncertainties not negligible
  => QCD is hard to compute
  => PDFs not precisely known
  => Non-perturbative effects at low p_T

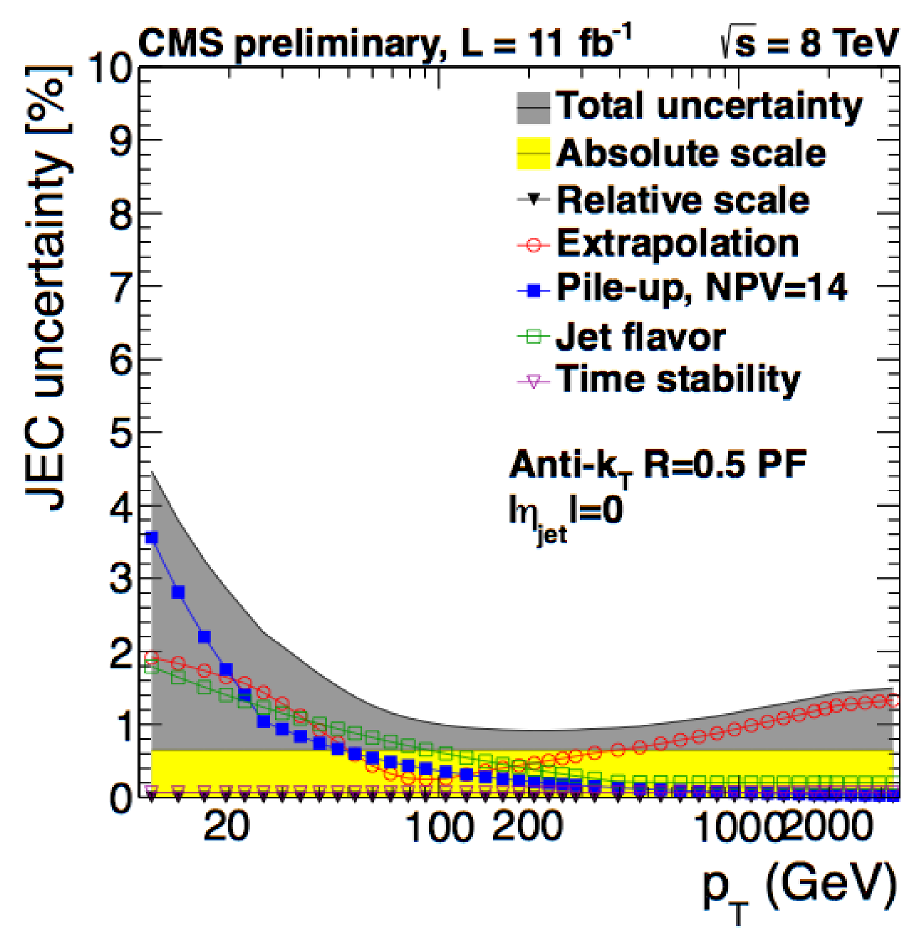
Jet Energy Calibration

- Determine parton energy from „raw" detector measurement → calibration jet energy scale (JES)
  - Calorimeter cells: equalize response, mask at high noise
  - Calorimeter (whole): correct for different response to EM particles and hadrons („compensation")
  - Additional energy in the jet, e. g. pile-up
  - Particles not caught by the jet algorithm („out of cone")
  - Differences in jet shapes for jets from gluons, udsc-quarks, b-Quarks

Calibration, for example by jet pair balance

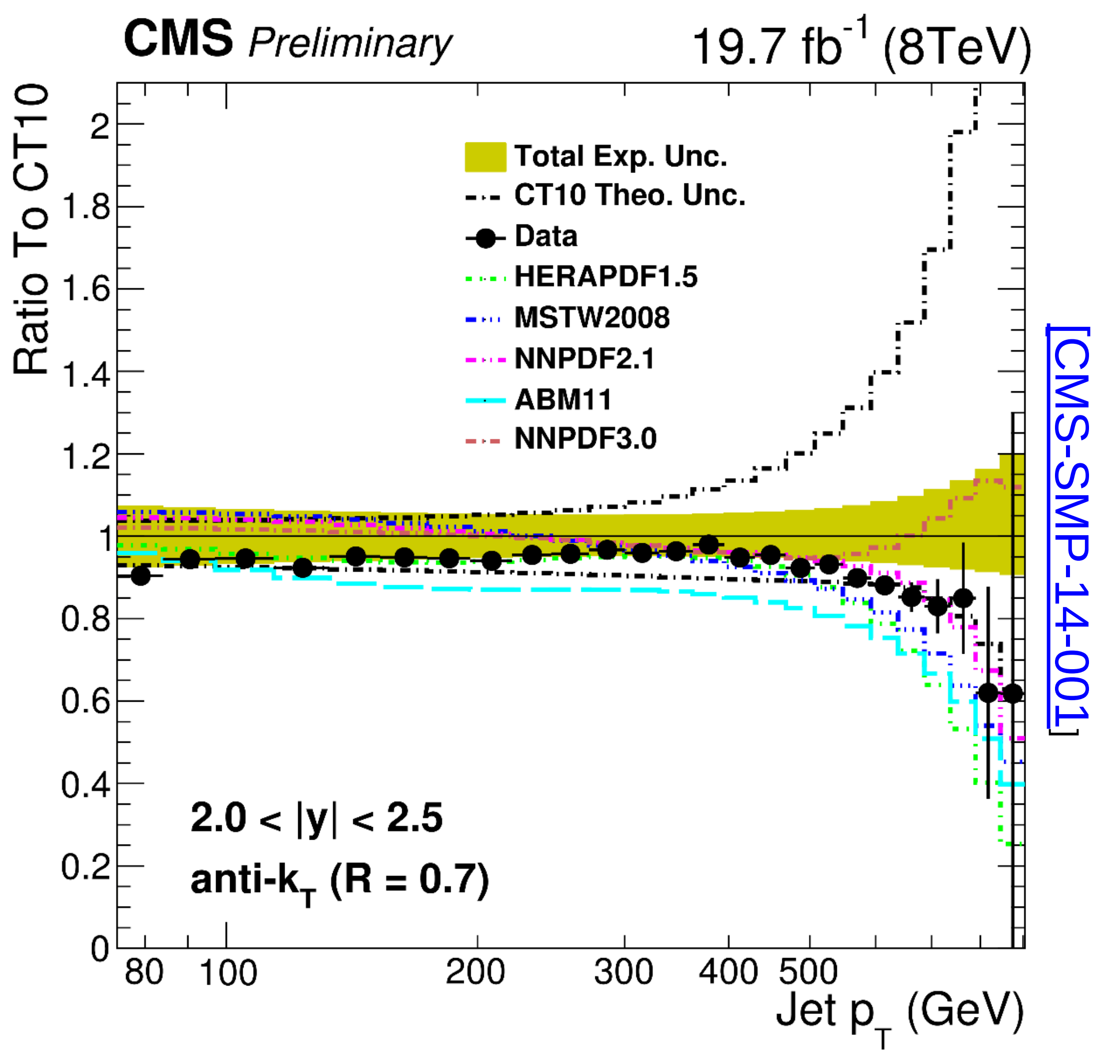


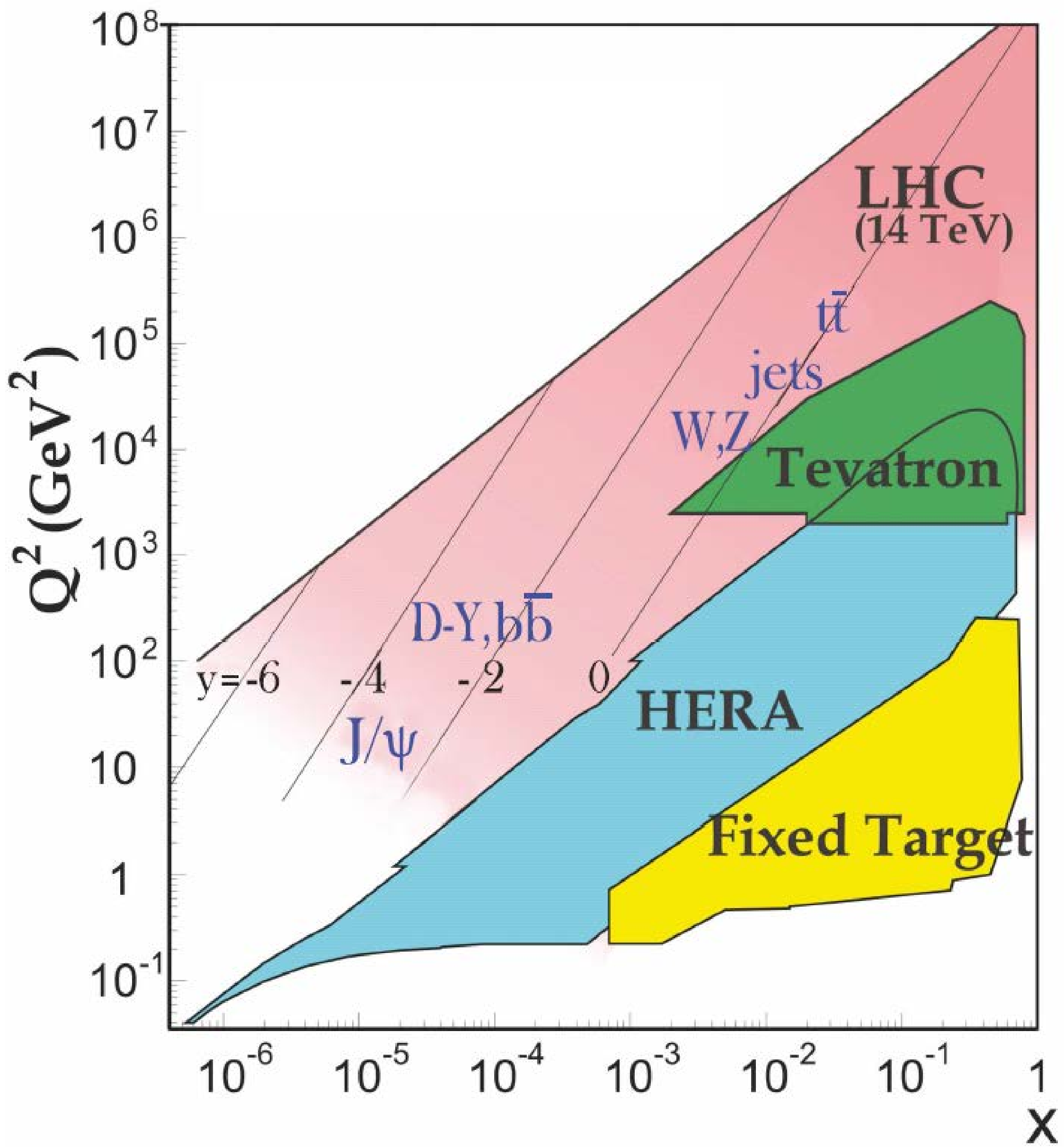
$$f = \frac{p_{T,1} - p_{T,2}}{(p_{T,1} + p_{T,2})/2}$$



[https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME2013JEC]

Theory Uncertainties



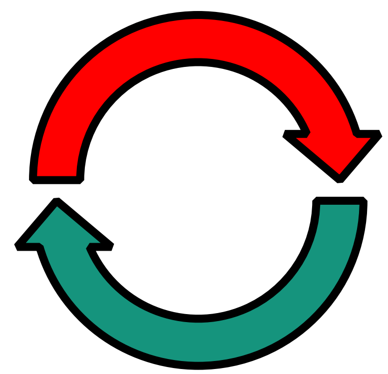


- Large theory uncertainties at high jet p_T
- Large extrapolation from HERA data
- Large x gluon density not that well constrained

Turning the tables

KIT Karlsruher Institut für Technologie

Measurement interpretation limited by theory uncertainties

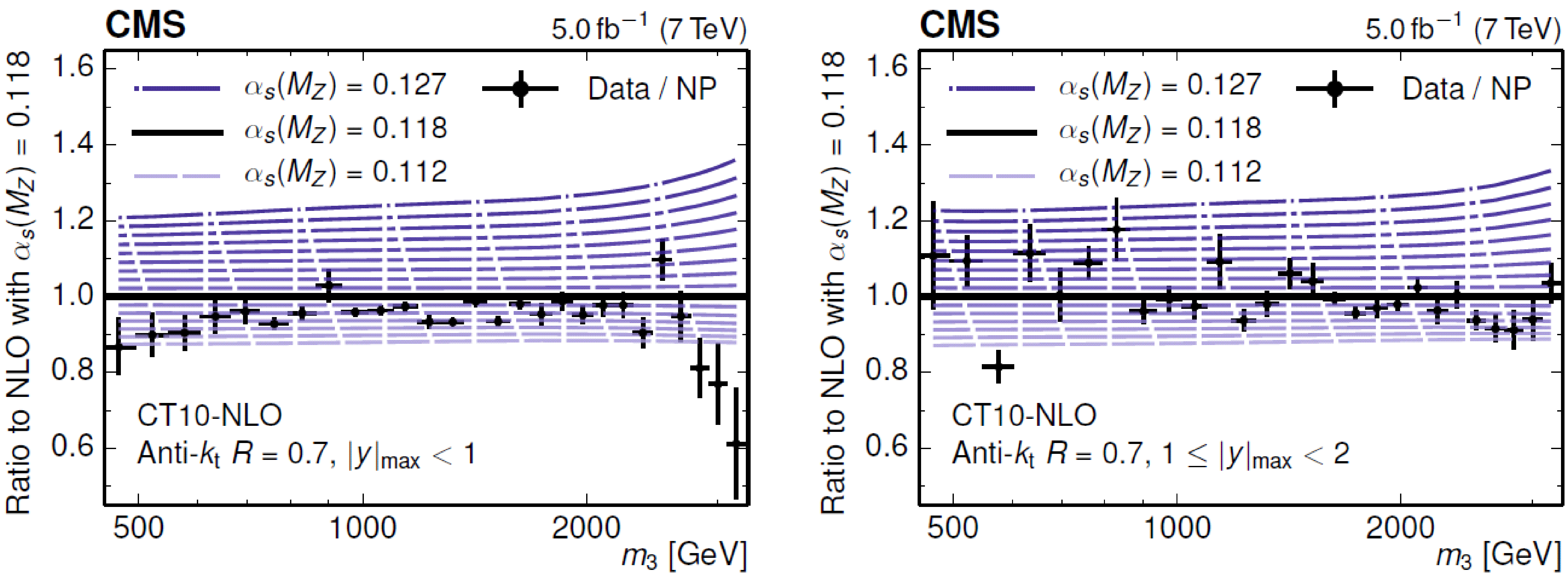


Measurements constrain theory parameters

=> Parton densities (PDFs)
=> Strong coupling (α_s)

Systematics are critical
=> some 7TeV studies still current

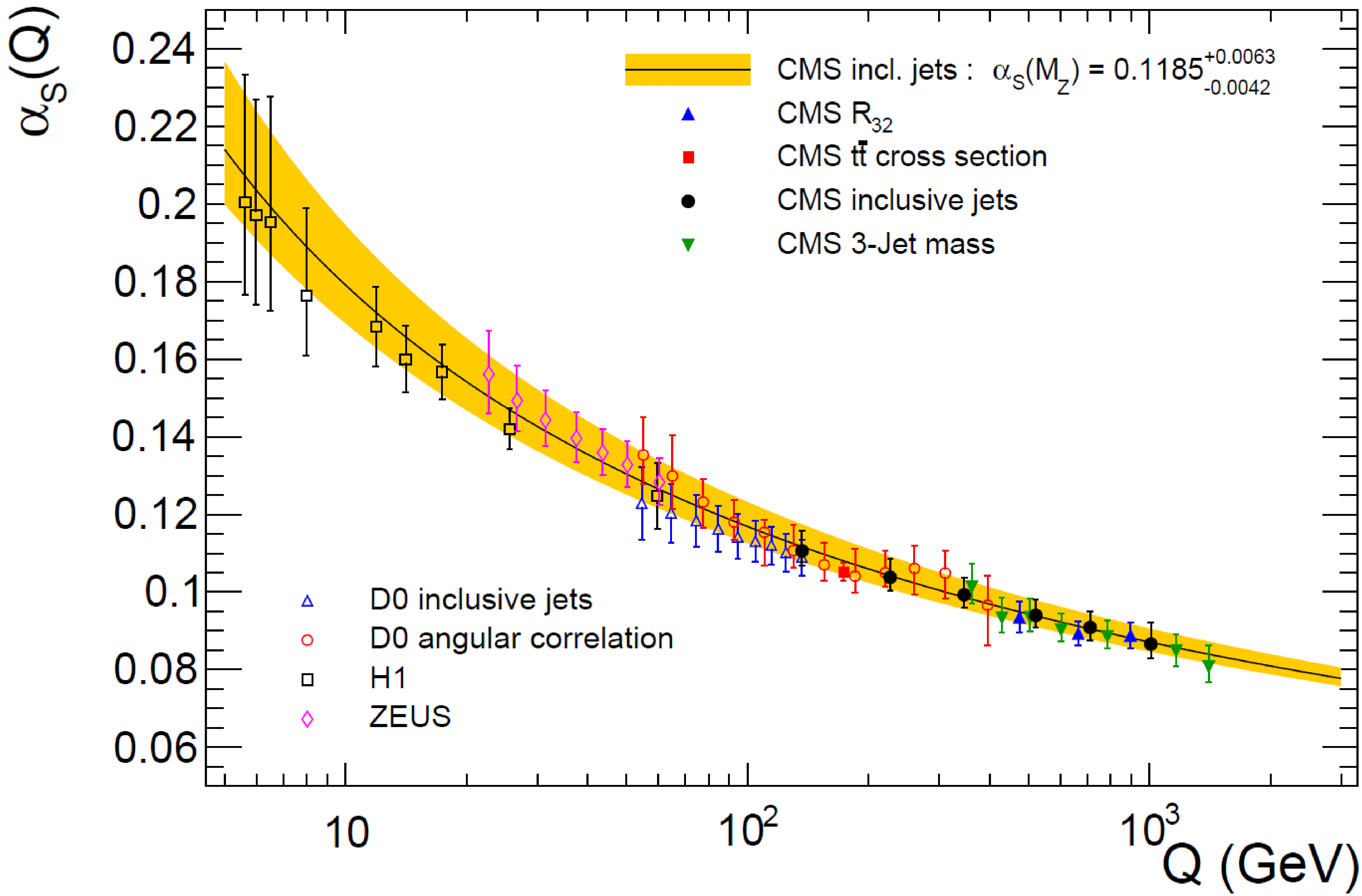
α_s: 3-jet mass



[Eur. Phys. J. C 75 (2015) 186]

- More jets in the final state => higher power of α_s
- Tricky theory calculation (NLO available)
- Correlated with PDFs => requires tuned PDF-sets

α_s: Results



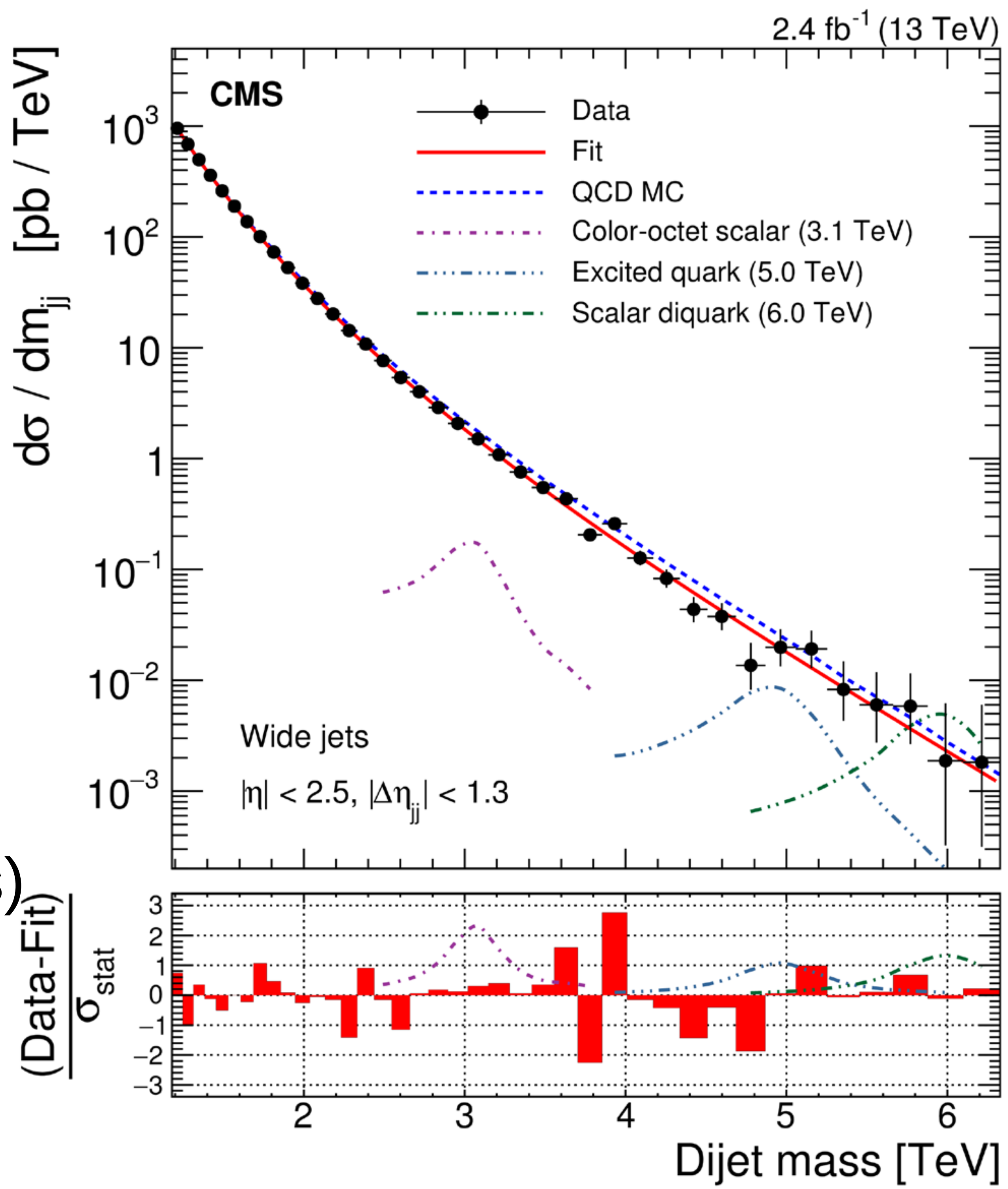
Exotic Physics with Jets

- Why use jets with huge backgrounds?
  $\Rightarrow$ quark final state implies possible strong production
  $\Rightarrow$ huge cross sections

  $\Rightarrow$ if several decays are possible quarks can be common
  (5/6 flavors x 3 colors)
  $\Rightarrow$ can have large branching Ratios
- Typical things to look for:
  - Excited quarks (possible if quarks are composite)
    $\Rightarrow$ decay to quark + gluon
  - Extended Gauge groups: Z', W'
    $\Rightarrow$ high BR to quarks if extra bosons are similar to SM bosons

Dijet Resonance

- Very high jet energies (TeV!)
  $\Rightarrow$ "soft" gluon radition
  not so soft any more
  $\Rightarrow$ R=0.4 jets not sufficient
  $\Rightarrow$ add all other jets within
  R=1.1
- Fit with:
  - Smooth curve (SM hypothesis)
  - Smooth curve + bump
    (signal + background hypothesis)
  - Limit from Likelihood ratio

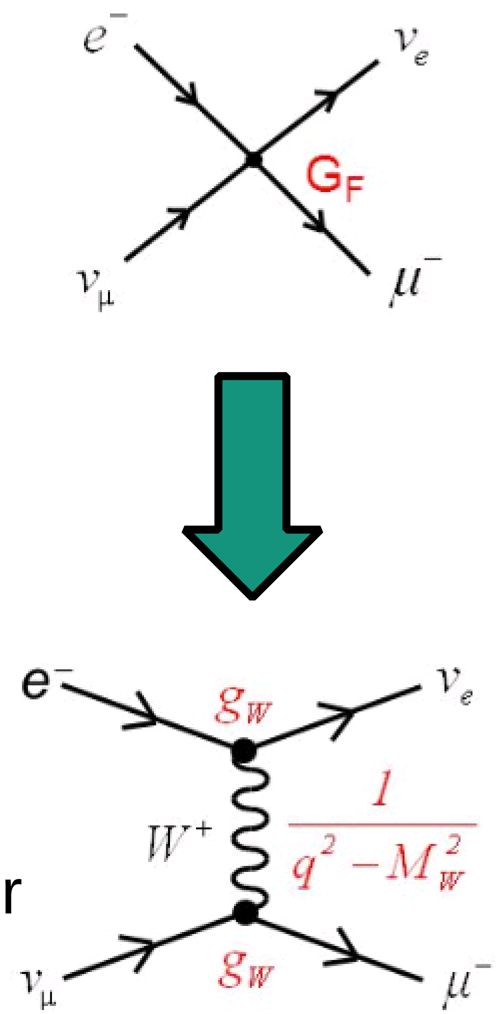


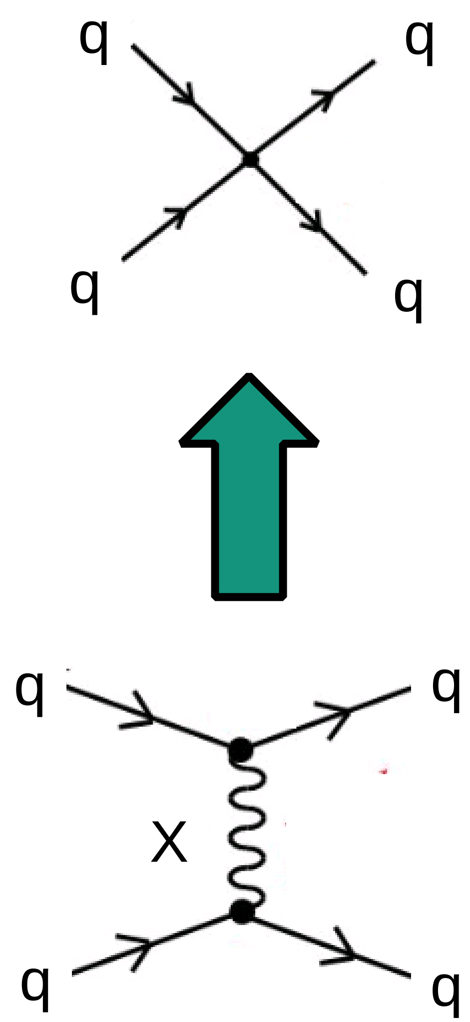
Contact Interactions

- What if the resonance is too heavy
- Analogy: Fermi theory of weak interaction

ad-hoc description
of weak interaction
with quartic vertex

is the low energy
approximation
of the W-propagator



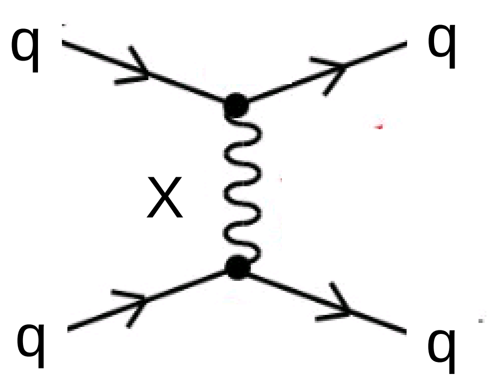


Integrate out heavy
particles
$\Rightarrow$ effective contact
interaction

Invent new theory
with heavy particle X

Contact Interactions

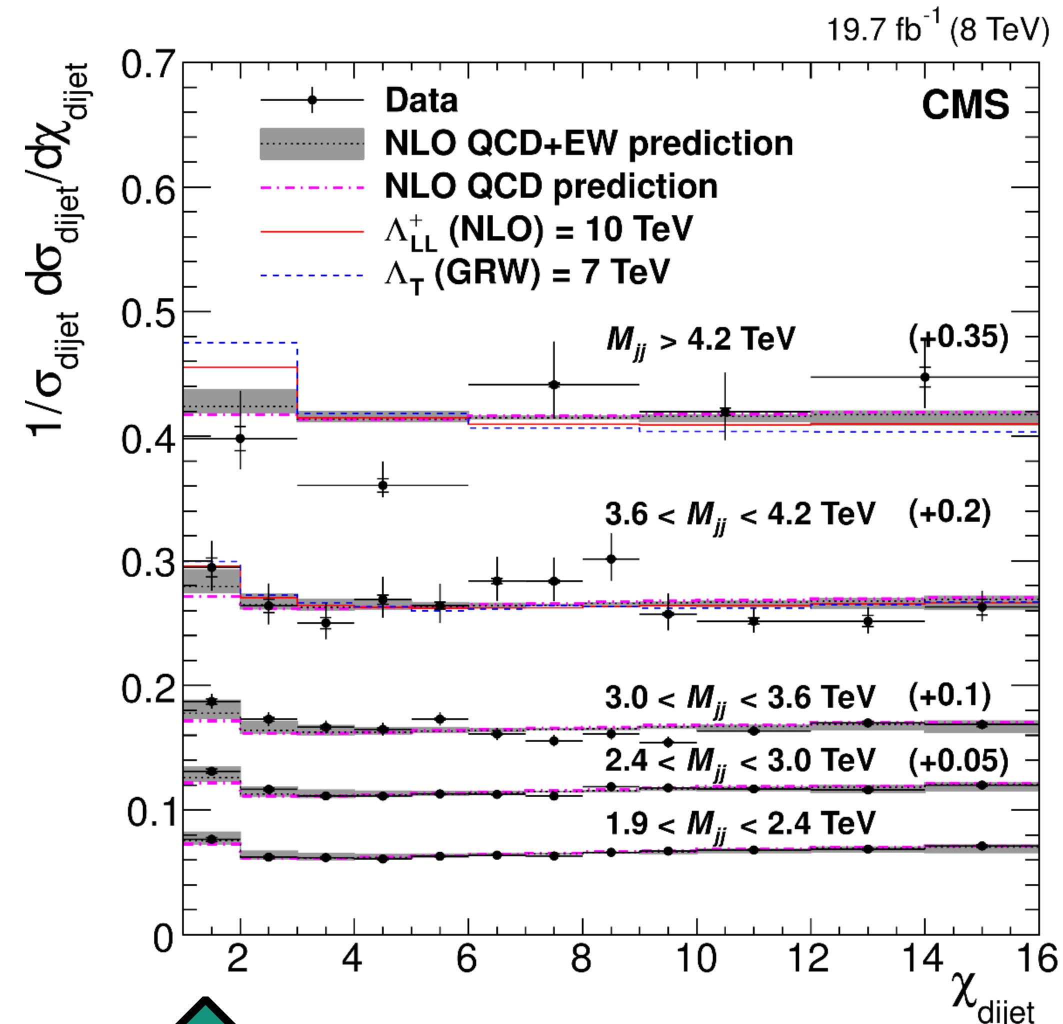
- Signal (contact interaction)
  $\Rightarrow$ roughly isotropic
- biggest background:
  t-channel processes



low momentum transfer
most likely:
$\Rightarrow$ jets mostly forward

- Look at angular distribution
  to find signal

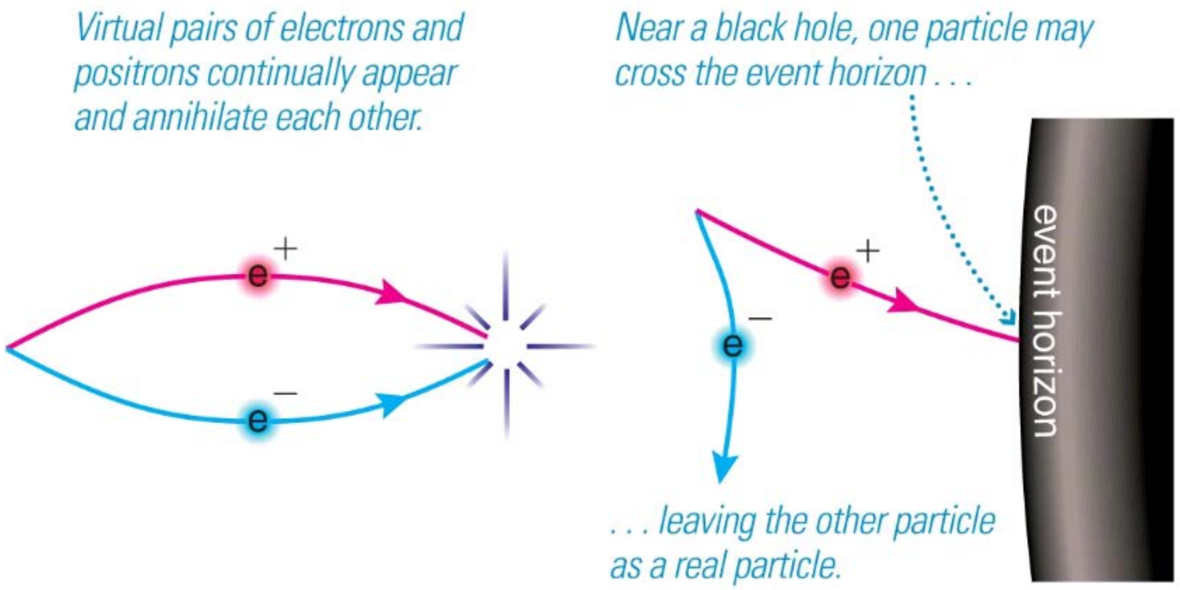
$$\chi = \exp(|\eta_1 - \eta_2|) = \frac{1+|\cos(\hat{\theta})|}{1-|\cos(\hat{\theta})|}$$



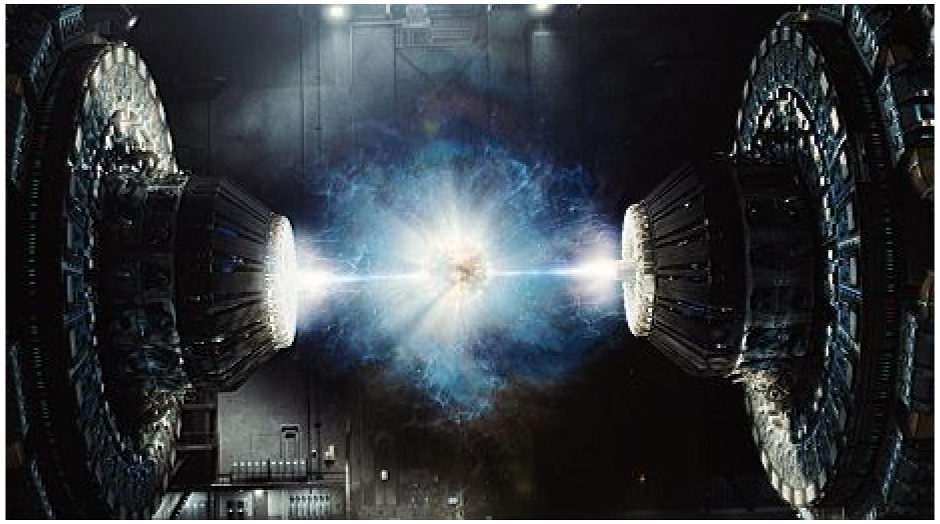
signal at low χ
jets central $\Rightarrow$ $\cos(\theta) \sim 0$

Black Holes

- Black holes decay via Hawking radiation:
  $\Rightarrow$ Black-Body spectrum with
  $$T_H = \frac{\hbar c^3}{8\pi G M k_B}$$
  $\Rightarrow$ $\tau \sim 5{\cdot}10^{-27}\mathrm{s}{\cdot}M^3$ (in g)
  $\Rightarrow$ astronomical black holes essentially stable



- Microscopic black holes producible?
  $\Rightarrow$ unclear, requires theory of quantum gravity
  $\Rightarrow$ usually expect lower limit on BH mass of 10^{-5}g
  $\Rightarrow$ but could be lower for exotic scenarios (extra dimensions)



Black Holes

- Hawking radiation is “democratic”
  - $\Rightarrow$ all particles with same probability
  - $\Rightarrow$ 6x3 = 18 quarks
  - $\Rightarrow$ expect many jet final state
- Impractical to study jets separately
  - $\Rightarrow$ us scalar sum of all jet p_t
  - $\Rightarrow$ expect black hole decays at high masses
- None found yet!