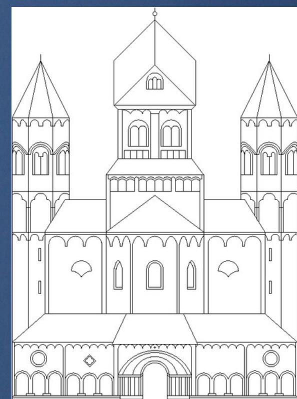
QCD and Jets at the LHC

V02 – From jet definition to prediction and measurement

Herbstschule Maria Laach



Klaus Rabbertz

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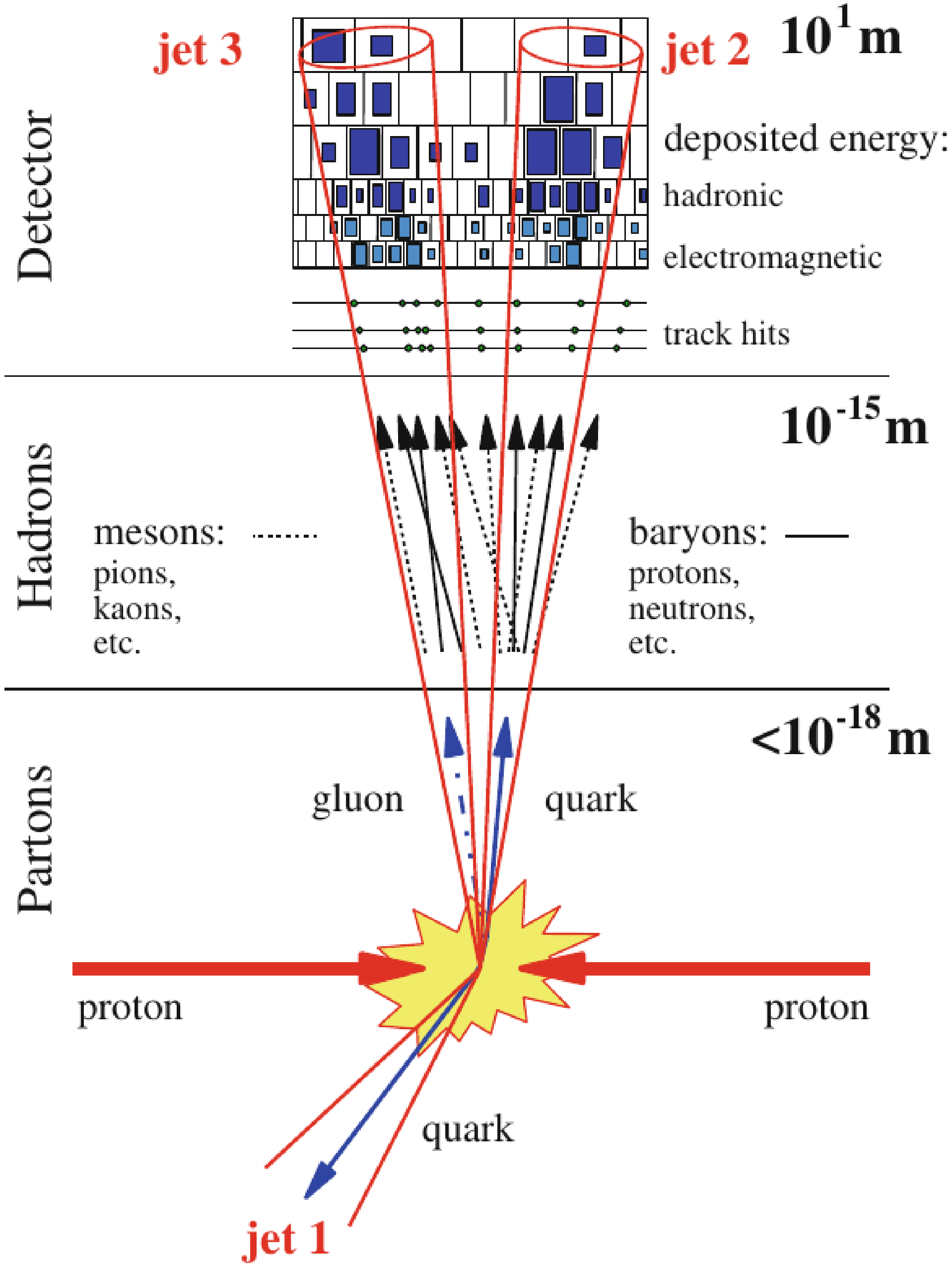
Outline

- **Jet algorithms at LHC**
- **DIS and PDFs**
- **Hadron-hadron collisions**
- **Jet reconstruction**

Tools in particle physics: Jets



Jet algorithms

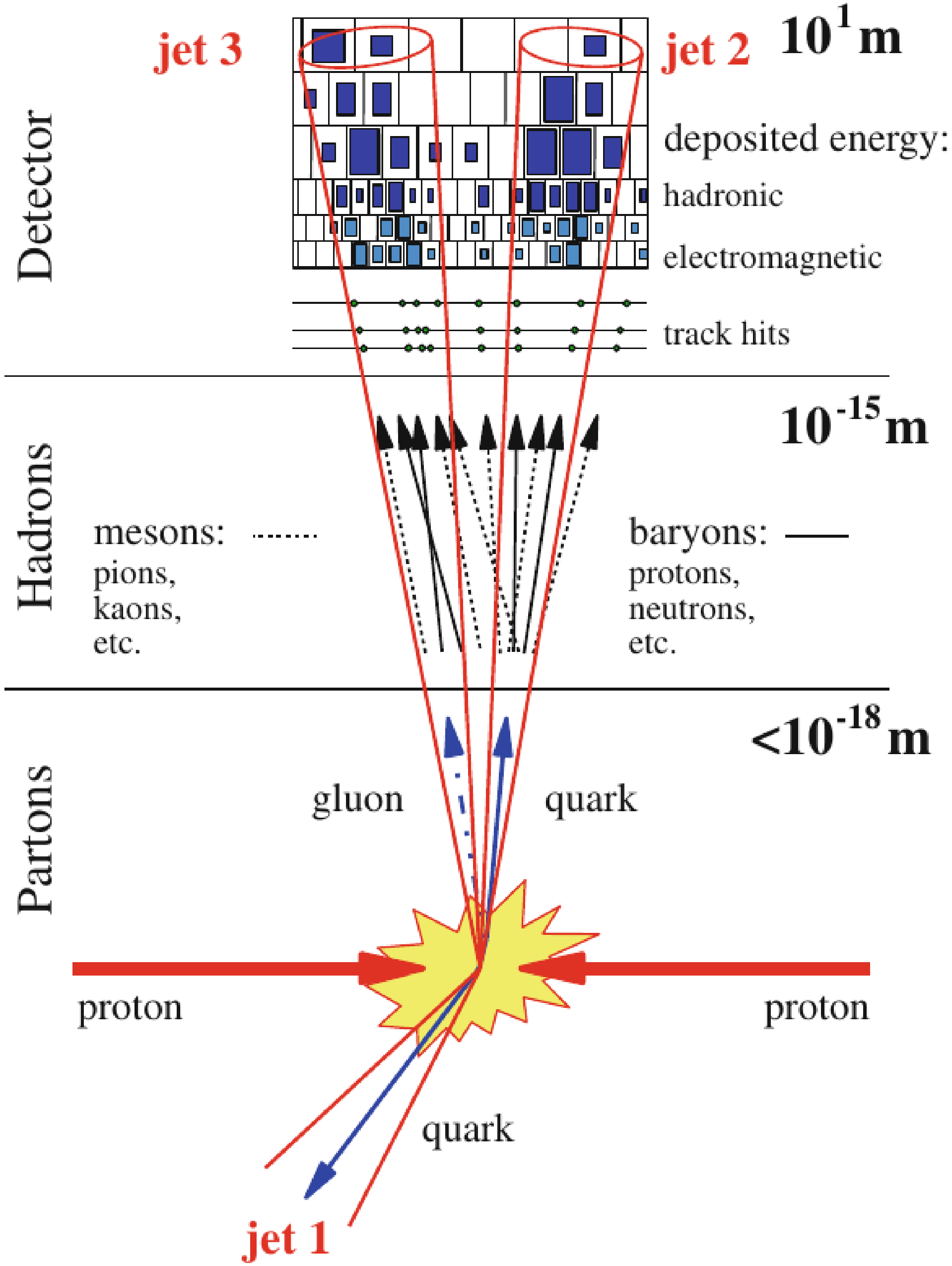
Primary goal:

Good correspondence among:
- **Detector measurements**
- **Particles in final state and**
- **"hard" partons**

Two classes of algorithms:

1. Cone algorithms: **"Geometrical" attribution of objects to the direction of largest energy flow in an event (First choice at hadron colliders)**

2. Sequential recombination: **Iterated combination of closest neighbors among all pairs of objects (First choice at e^+e^- & ep colliders)**



From e^+e^- to pp algorithm

- **No E_{vis} for normalisation**
  - **Drop E_{vis}, $y_{ij} \rightarrow d_{ij}$ has dimensions**

$$y_{ij}^{\mathrm{k_T}} = \frac{2\min(E_i^2, E_j^2)(1-\cos(\theta_{ij}))}{E_{\mathrm{vis}}^2}$$

e^+e^-

$$d_{ij} = 2\min(E_i^2, E_j^2)(1-\cos(\theta_{ij}))$$

From e^+e^- to pp algorithm

- **No E_{vis} for normalisation**
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- **Account for beam remnants**
  - **2nd distance measure**

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- **Longitudinal boost invariance**
  - Only use p_T, rapidity y, azimuth Φ

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$$d_{ij} = \min(p_{ti}^2, p_{tj}^2) \cdot \Delta R_{ij}^2 \qquad d_{iB} = p_{ti}^2$$

$$\Delta R_{ij}^2 = \Delta\phi_{ij}^2 + \Delta y_{ij}^2$$

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- **No absolute scale to define d_{cut}**
  - **Replace y_{cut} by angular size R**

$$y_{ij}^{\mathrm{k_T}} = \frac{2\min(E_i^2, E_j^2)(1-\cos(\theta_{ij}))}{E_{\mathrm{vis}}^2}$$ **e^+e^-**

$$d_{ij} = 2\min(E_i^2, E_j^2)(1-\cos(\theta_{ij}))$$

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$$d_{ij} = \min(p_{ti}^2, p_{tj}^2) \cdot \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{ti}^2$$

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  - 1. find smallest of all d_{ij}, d_{iB} in object list
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  - 4. iterate until only jets left

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$$d_{ij} = \boxed{\min(p_{ti}^2, p_{tj}^2)} \cdot \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{ti}^2$$

Inclusive k_T algorithm **pp**

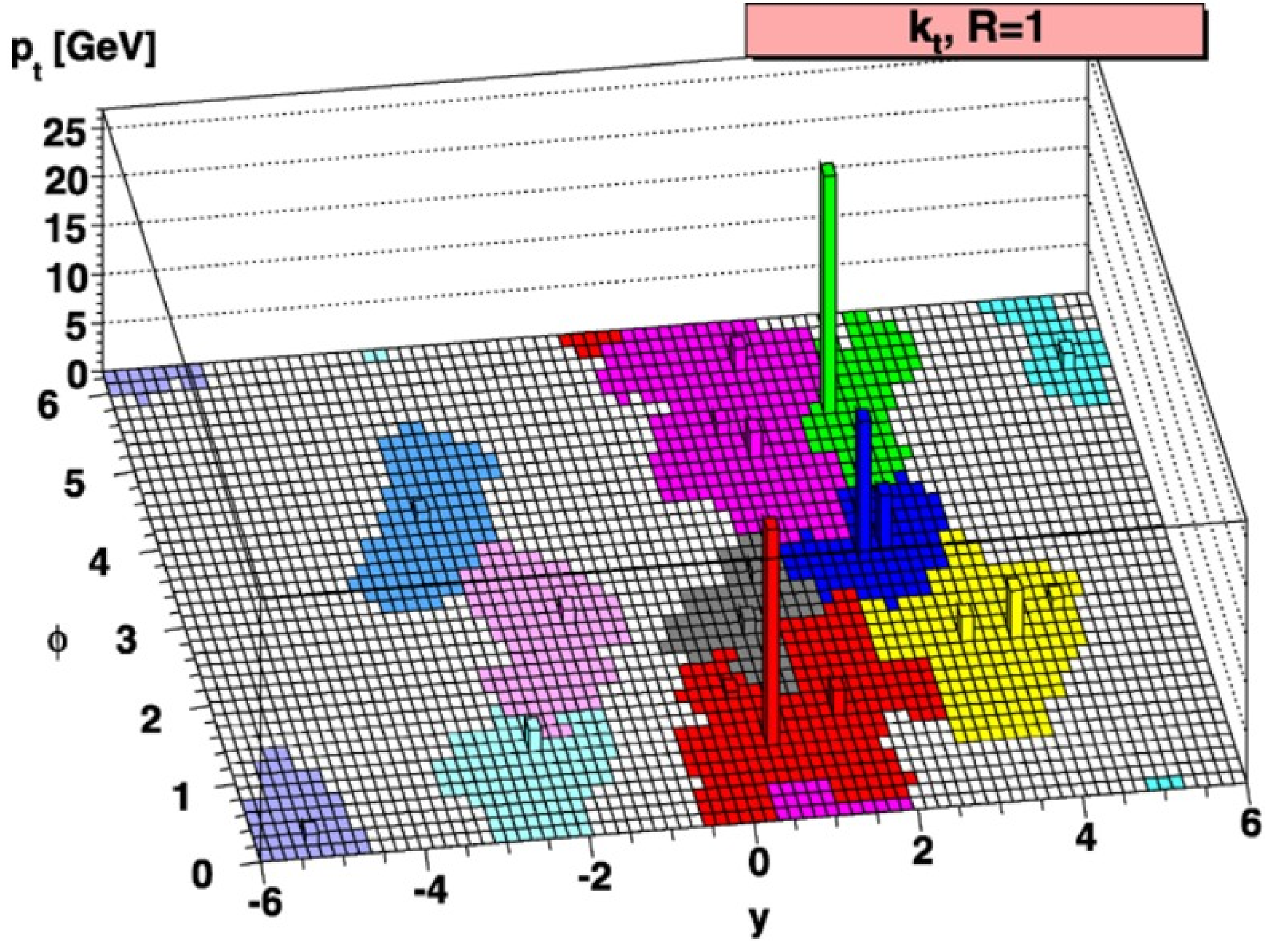
$$\boxed{\Delta R_{ij}^2 = \Delta\phi_{ij}^2 + \Delta y_{ij}^2}$$

Inclusive k_T

- **Character sheet**
  - **Clusters softest particles first**
  - **Irregular shape in y,Φ plane**
  - **Difficult to calibrate**
  - **Undoes QCD splittings**
  - **Meaningful clustering sequence**
  - **Suited for substructure analysis**
  - **Time per N particles ~ NlnN (originally thought to be ~ N^3)**

Cacciari, Salam, PLB 641 (2006) 57.

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2) \cdot \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{ti}^2$$



Ellis, Soper, PRD 48 (1993) 3160.

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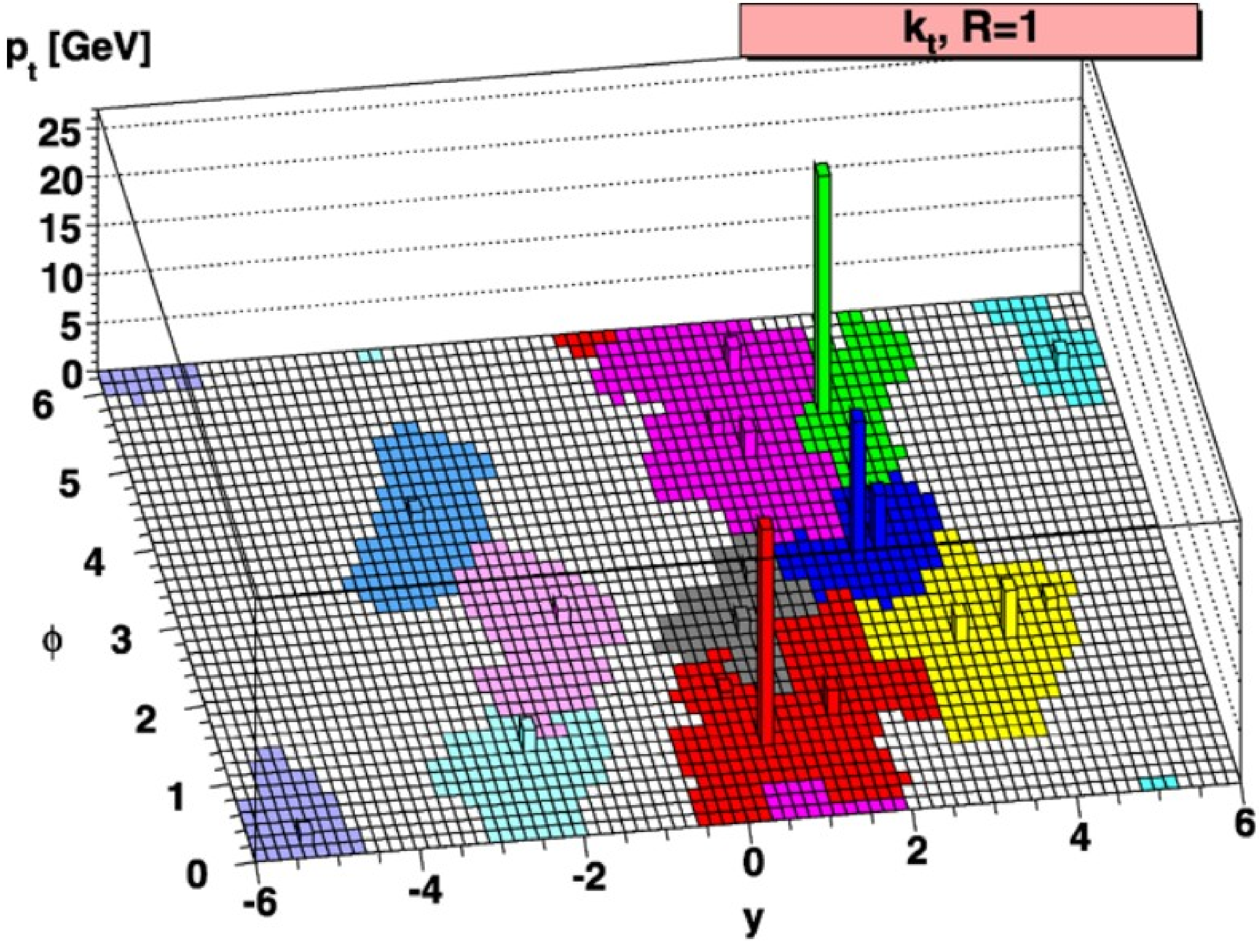


Remark:
For such plots tens of thousands of p_T ~ 0 dust or ghost particles are distributed oder the y,Φ plane and clustered into jets. This determines the coloring of the "jet areas" and only works with CI safe algorithms!

Cacciari, Salam, Soyez, JHEP04 (2008) 005.

Ellis, Soper, PRD 48 (1993) 3160.

Cambridge/Aachen

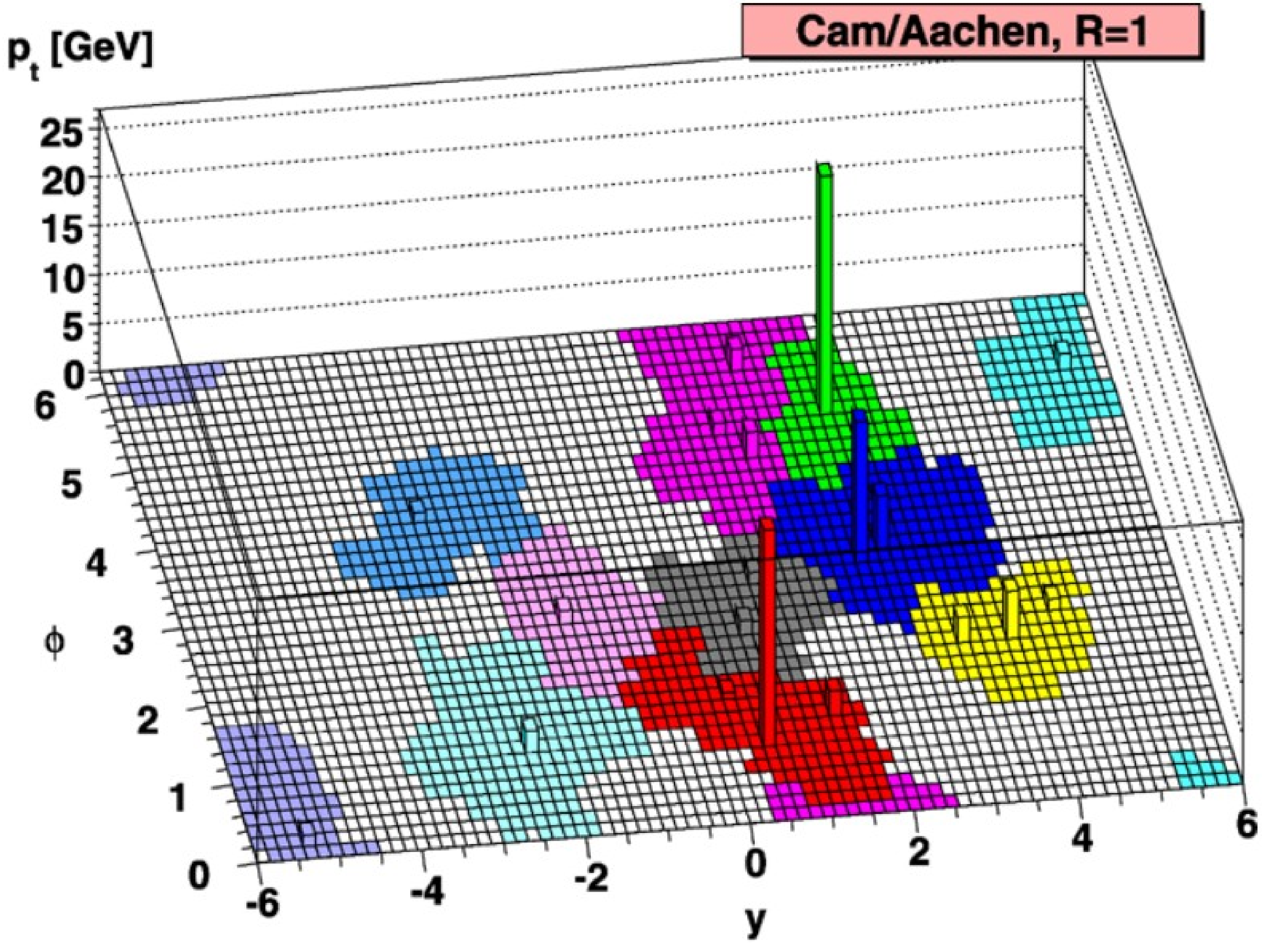
- **Character sheet**
  - Clusters particles closest in R
  - Irregular shape in y,Φ plane
  - Difficult to calibrate
  - Meaningful clustering sequence
  - Suited for substructure analysis
  - Time per N particles ~ NlnN

$$d_{ij} = \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = 1$$

Alternative:

- p_T dropped in distance
- Strictly angular ordering

$$p_{ti}^2 \rightarrow p_{ti}^0 = 1$$

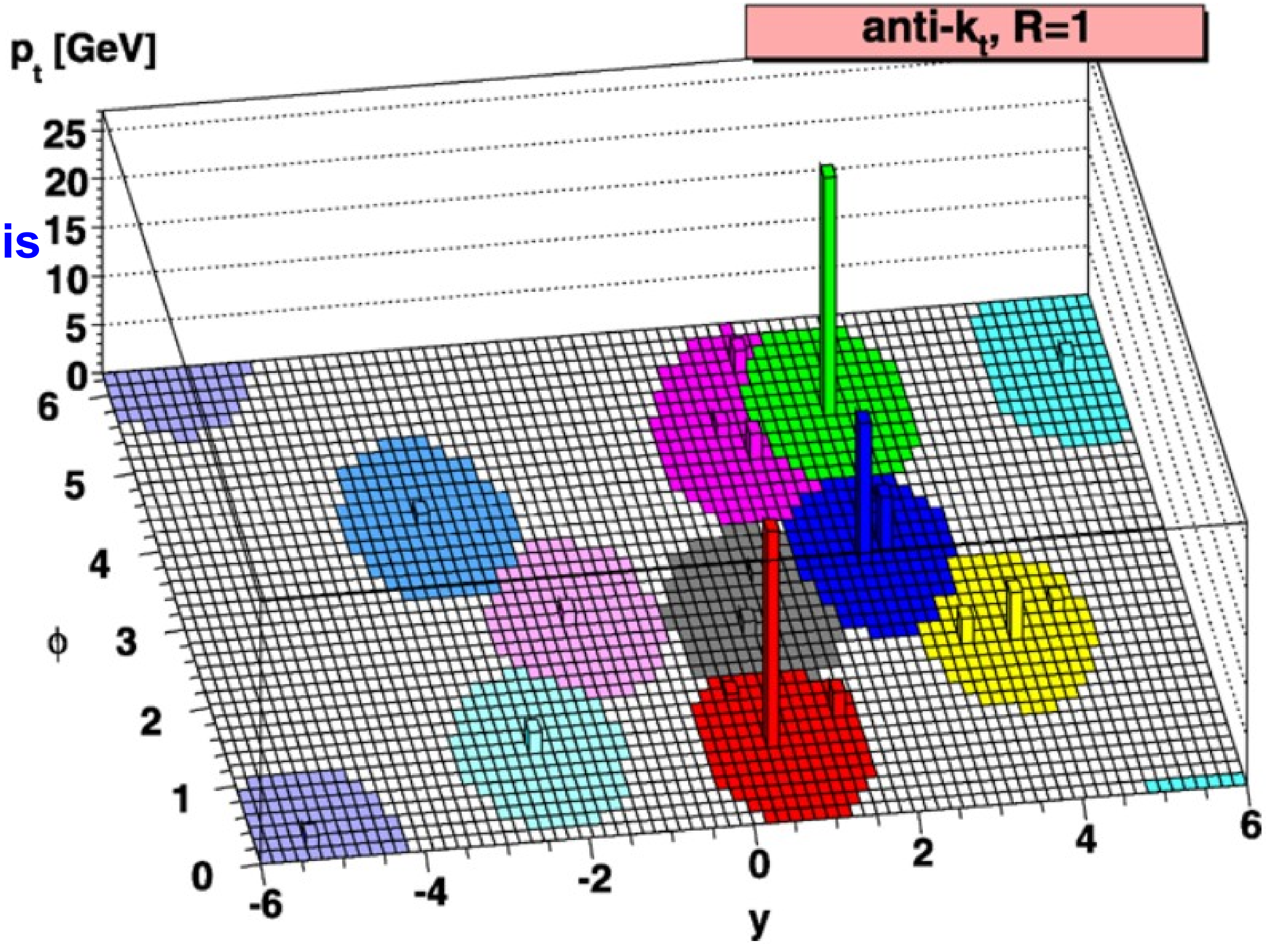


Dokshitzer et al., JHEP 08 (1997) 001,
Wobisch et al., Proceedings, MC Generators for HERA Physics (1998).

anti-k_T

- **Character sheet**
  - **Clusters hardest particles first**
  - **Cone-like shape in y,Φ plane**
  - **Simpler to calibrate**
  - **Clustering sequence not useful**
  - **Unsuited for substructure analysis**
  - **Time per N particles ~ $N^{3/2}$**

$$d_{ij} = \min(p_{ti}^{-2}, p_{tj}^{-2}) \cdot \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{ti}^{-2}$$



Alternative:

- **Use 1 / p^2_T in distance**

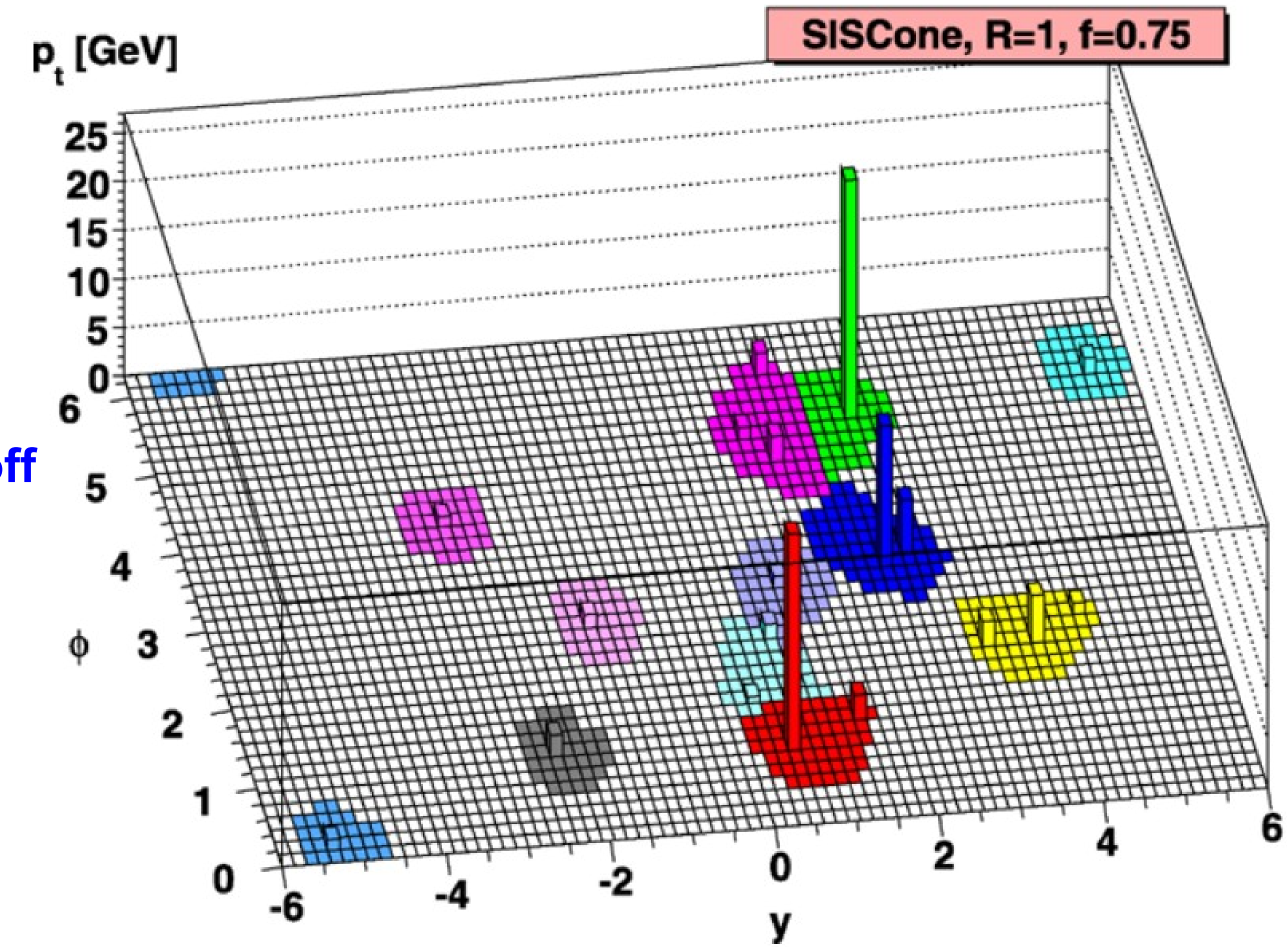
$$p_{ti}^2 \rightarrow p_{ti}^{-2} = \frac{1}{p_{ti}^2}$$

Cacciari, Salam, Soyez, JHEP 04 (2008) 063.

SISCone

- **Character sheet**
  - True cone algorithm
  - Does not use seeds (Seedless Infrared Safe)
  - Cone-like shape in y,Φ plane
  - Simpler to calibrate
  - Smaller jet size
  - Time per N particles ~ $N^2 lnN$
  - Used occasionally, never took off because of anti-k_T

e.g.: ZEUS, PLB 691 (2010) 127.



Salam, Soyez, JHEP 05 (2007) 086.

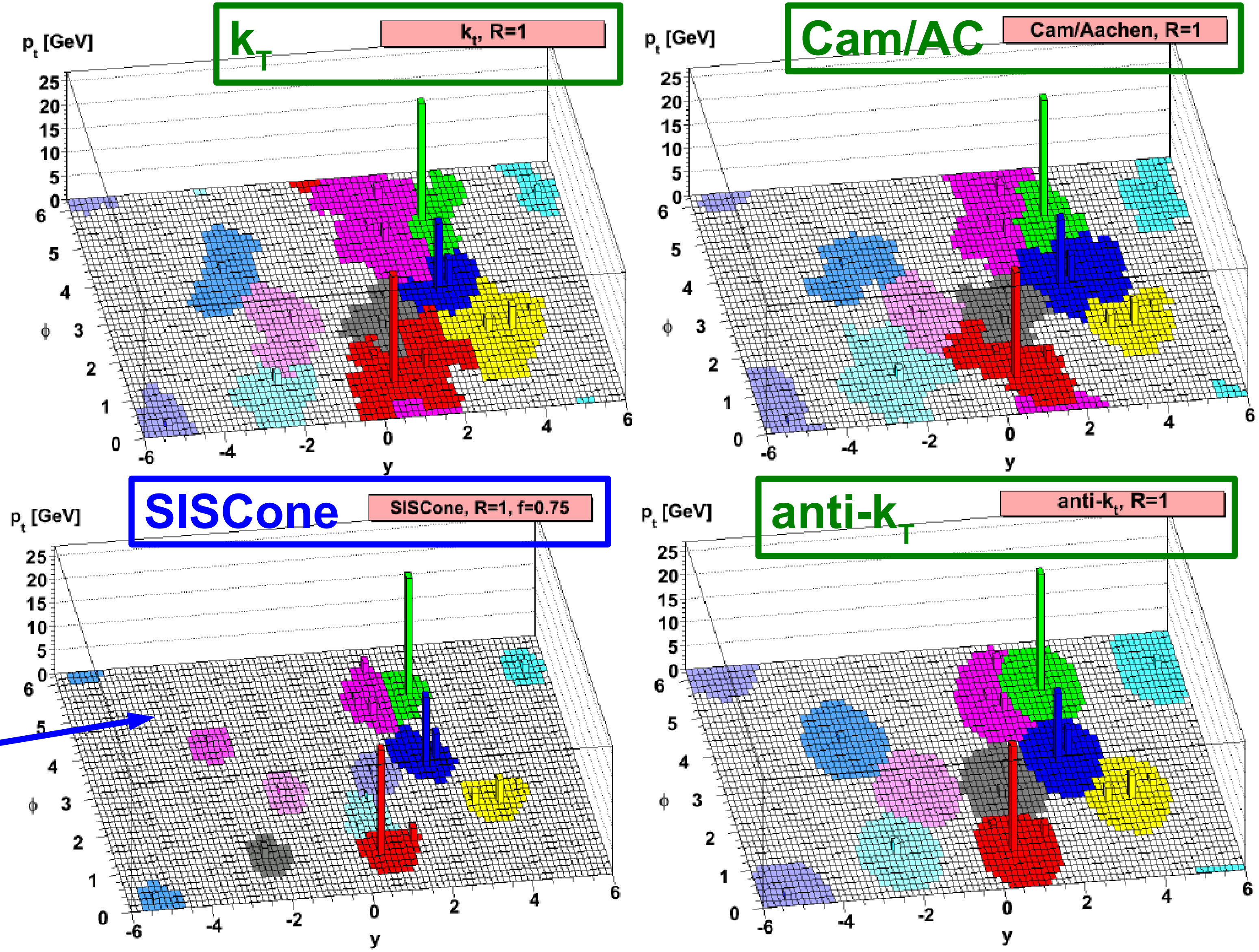
Jet algorithms for pp

Standard algorithm:

- **Anti-k_T:**
  ATLAS R = 0.4, 0.6
  CMS R = 0.5, 0.7
  (Run II: 0.4, 0.8)
- k_T
- SISCone ("real" cone algo)
- Cambridge/Aachen
  useful in jet substructure,
  e.g. for "boosted" top, t´, Z´

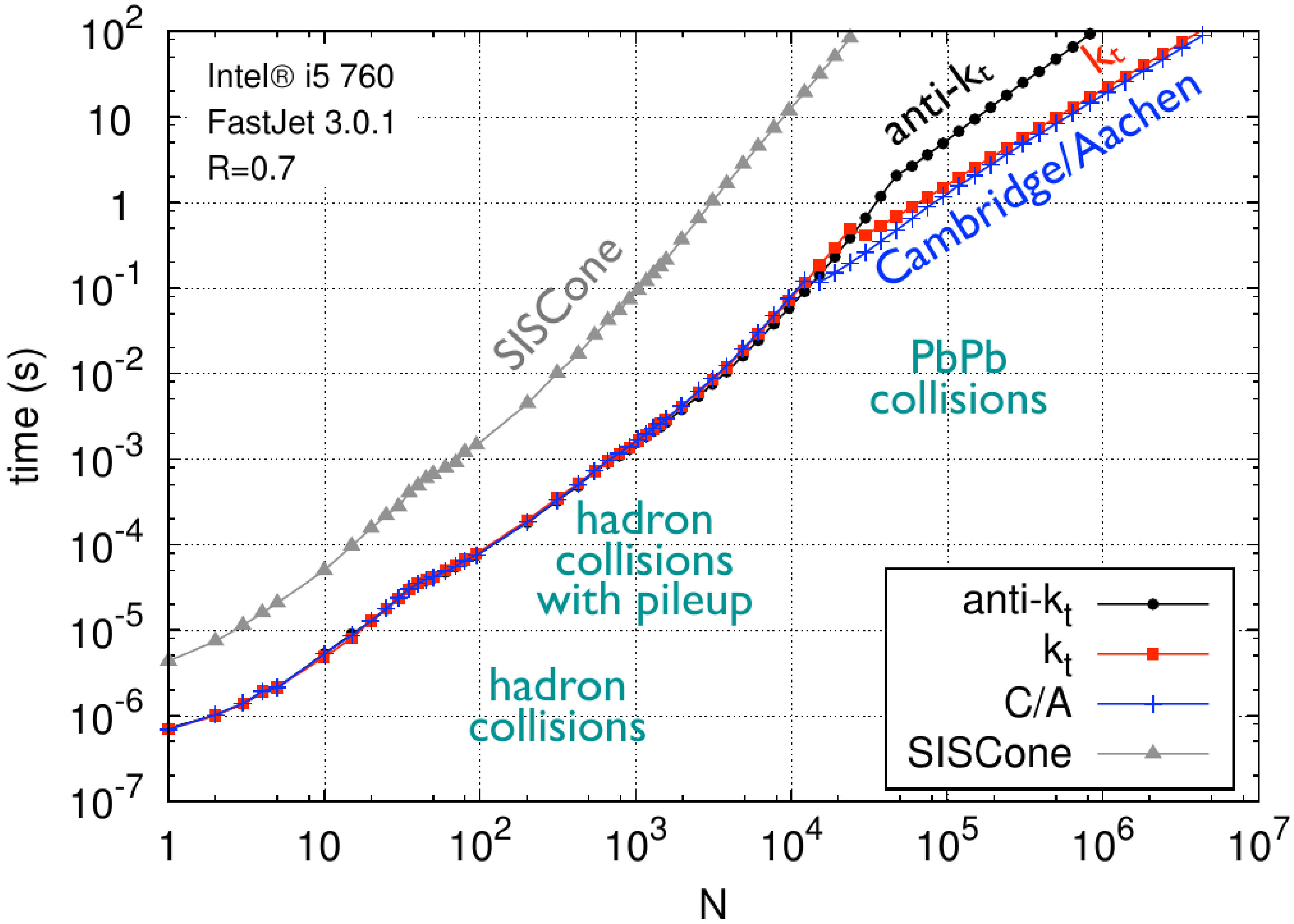
Often:
anti-k_T as baseline &
CamAC for substructure

Only "real" cone algorithm!



Timing comparison

Time to reconstruct an event with N particles



M. Caciari, PRISMA lectures, 2018

Desiderata – Theory

Jet Algorithm Desiderata (Theory):

- Infrared safety
- Collinear safety
  - never problem for e^+e^- or ep
  - long-standing issue at Tevatron
  - solved for LHC: k_T family of jets
- Longitudinal boost invariance (recombination scheme!)
- Boundary stability (→ 4-vector addition, rapidity y)
  - both solved with k_T family of jets
- Order independence (parton, particle, detector)
- Ease of implementation (standardized public code?)
  - solved thanks to fastjet package

Cacciari et al., EPJC72 (2012) 1896.

See also:
"Snowmass Accord", FNAL-C-90-249-E
Tevatron Run II Jet Physics, hep-ex/0005012
Les Houches 2007 Tools and Jets Summary , arXiv:0803.0678

Desiderata – Experiment

Jet Algorithm Desiderata (Experiment):

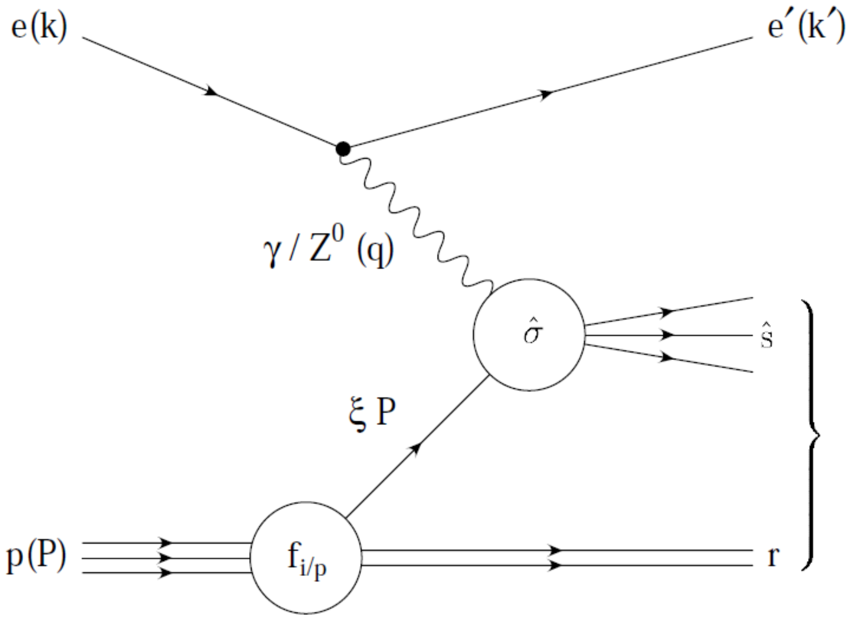
- **Computational efficiency and predictability**
  (use in trigger?, reconstruction times?) — mostly solved thanks to fastjet
- **Maximal reconstruction efficiency**
  (no dark jets) — solved with k_T family of jets
- **Minimal resolution smearing and angular biasing** — mostly solved by modern jet algorithms and unfolding
- **Insensitivity to pile-up**
  (mult. collisions at high luminosity ...) — no unique answer, question of required jet radius
- **Ease of calibration** — solved by anti-k_T "cone" jets
- **Detector independence**
- **Fully specified (no erroneous reimplementations)** (details?, code?)
- **Ease of implementation**
  (standardized public code?)

- both solved thanks to fastjet package

Scale invariance

- **Inelastic >> elastic cross section**
- **Inelastic cross section ~ const. * Mott x section**
  - **approximately independent of resolution ~ q^2**
  - **scale invariant, i.e. no natural length scale**
  - **like scattering at point-like objects**

Deep-inelastic scattering (DIS)

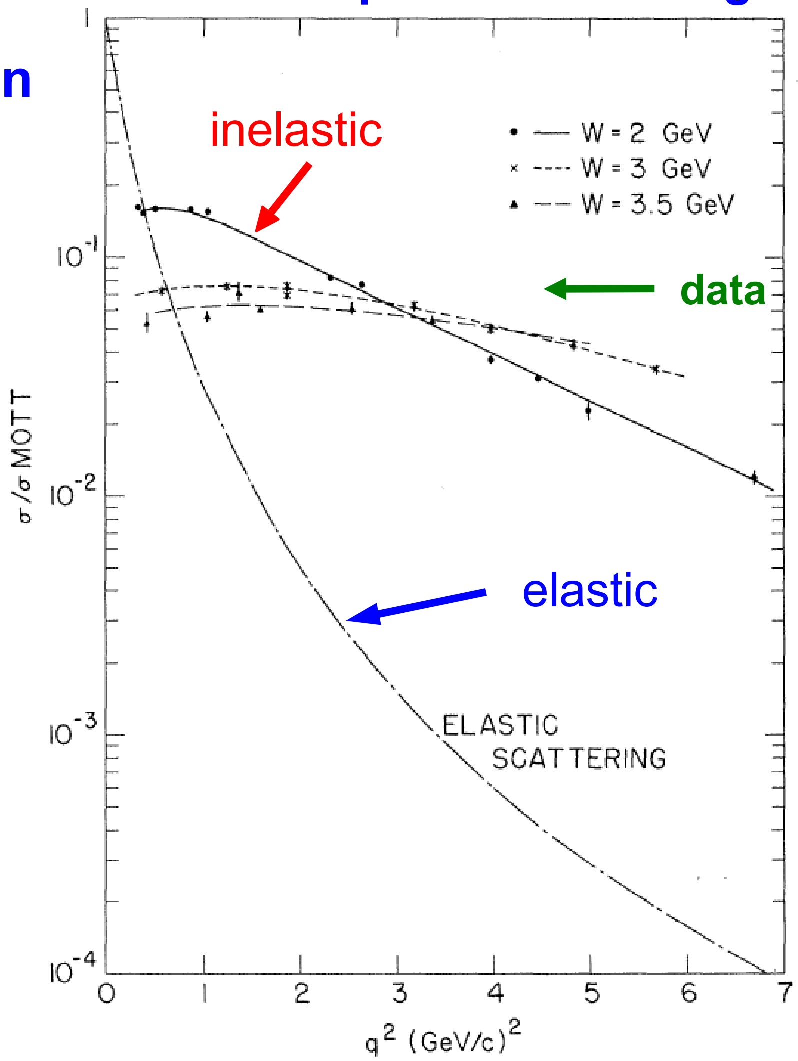


Scattered electron

Many Hadrons

X(h)

electron-proton scattering



PRL 23 (1969) 935.

DIS kinematics

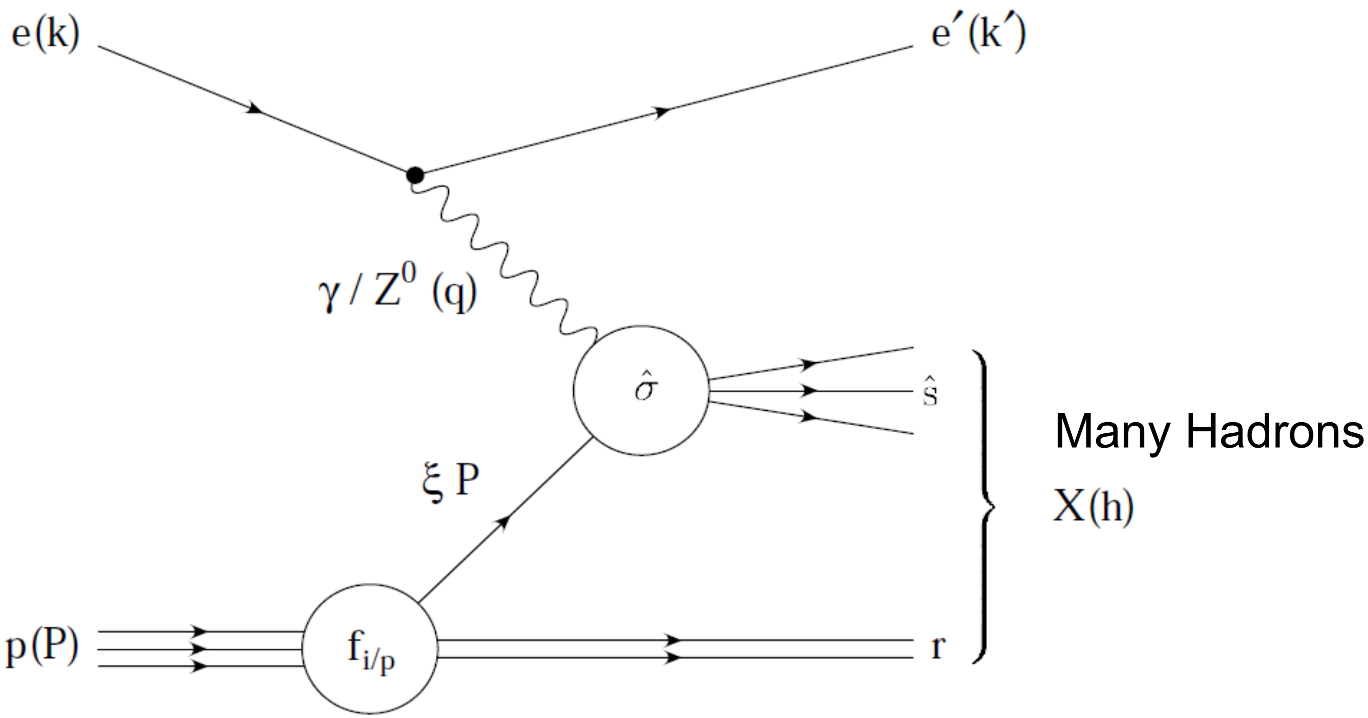
Neglect electron and proton masses: $M_p = M_e = 0$

Center-of-mass energy: $s = (k+P)^2 = 2k \cdot P = 4E_e E_p$

Elastic → one independent variable:

$$Q^2 = -q^2 = (k-k')^2 = 2k \cdot k' = 2E_e E_{e'}(1+\cos(\theta_{e'}))$$

Deep-inelastic scattering (DIS)



Inelastic → 2nd variable:

$$W^2 = (q+P)^2 = 2P \cdot q - q^2$$

Alternative:

Bjorken scaling variable: $x = \frac{Q^2}{2P \cdot q}$

Inelasticity: $y = \frac{P \cdot q}{P \cdot k}$

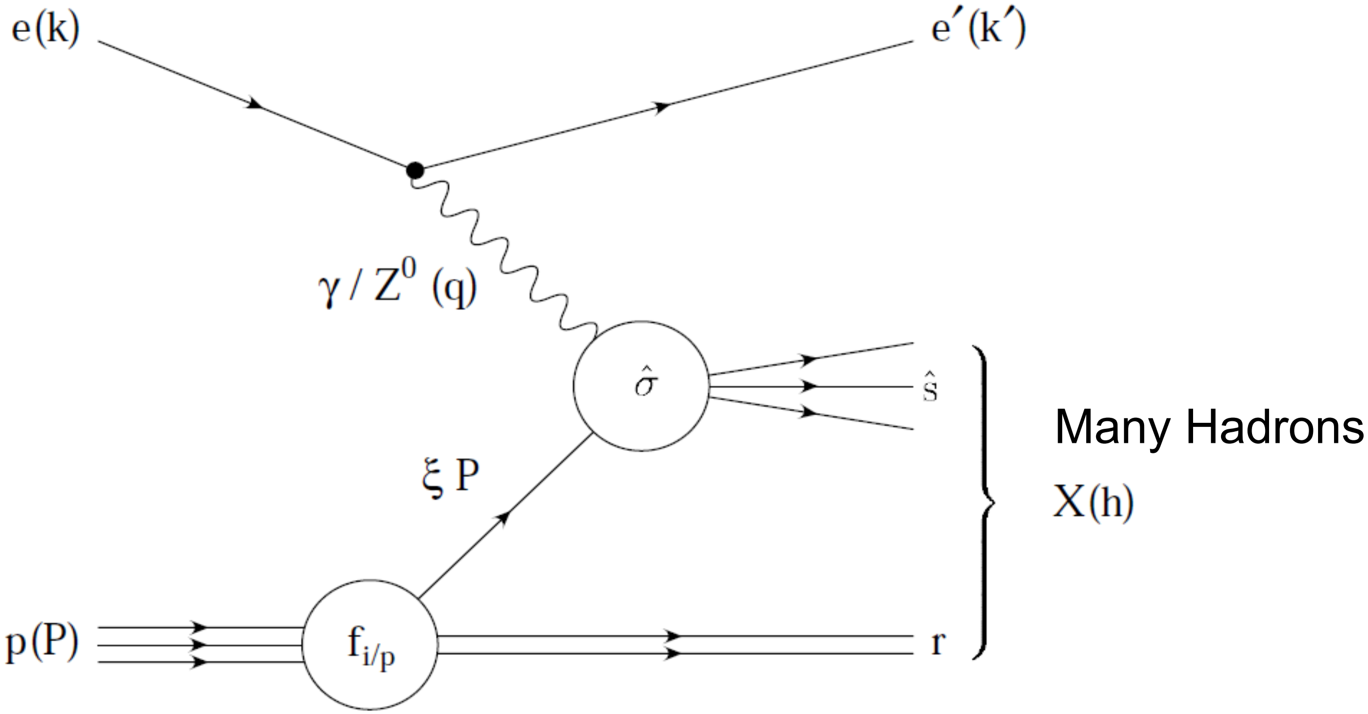
$$0 \le (x, y) \le 1$$

Infinite momentum frame

Proton equals collinear stream of fast moving "partons", masses negligible
→ factorised incoherent partonic scatter

$$\hat{s} = (q + \xi P)^2 = 2\xi q \cdot P - Q^2 = \left(\frac{\xi}{x} - 1\right) Q^2$$

Deep-inelastic scattering (DIS)



$$x = \frac{Q^2}{2P \cdot q}$$

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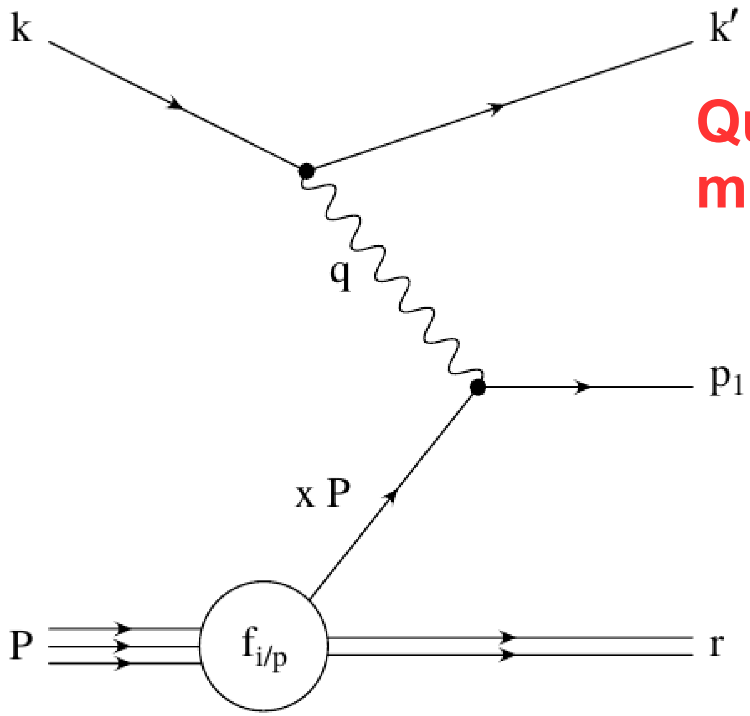
Deep-inelastic scattering (DIS) at LO $\hat{s} = 0 \rightarrow \xi = x$ $\xi = \left(1 + \frac{\hat{s}}{Q^2}\right) x$



One parton

Quark parton model (QPM) → scaling variable x: momentum fraction of struck parton in proton

$$x = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$

$$0 \leq (x, y) \leq 1$$

Infinite momentum frame

Proton equals collinear stream of fast moving "partons", masses negligible
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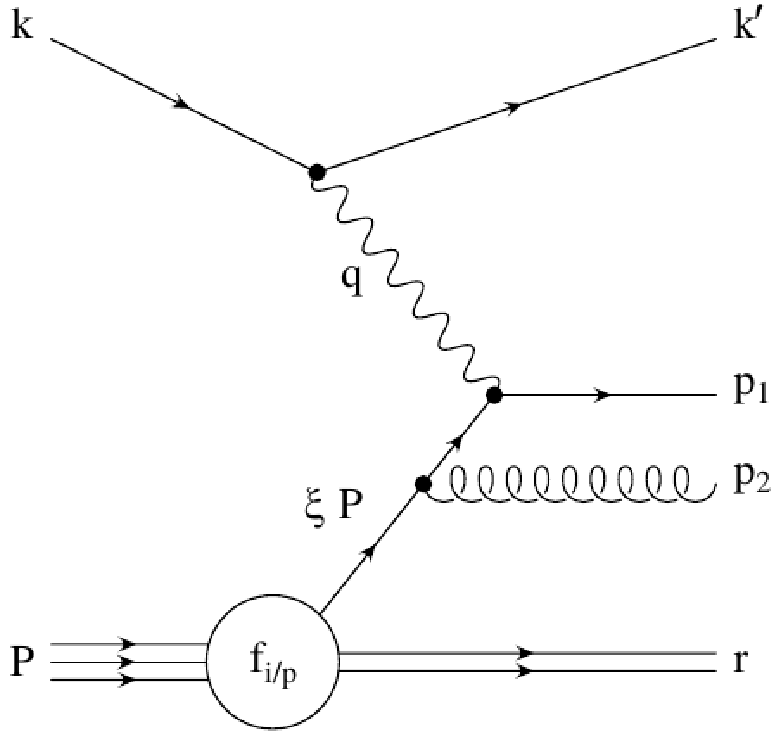
Deep-inelastic scattering (DIS) at NLO $x \leq \xi \leq 1$ $\xi = \left(1 + \frac{\hat{s}}{Q^2}\right) x$



More partons

$$x = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$

$$0 \leq (x, y) \leq 1$$

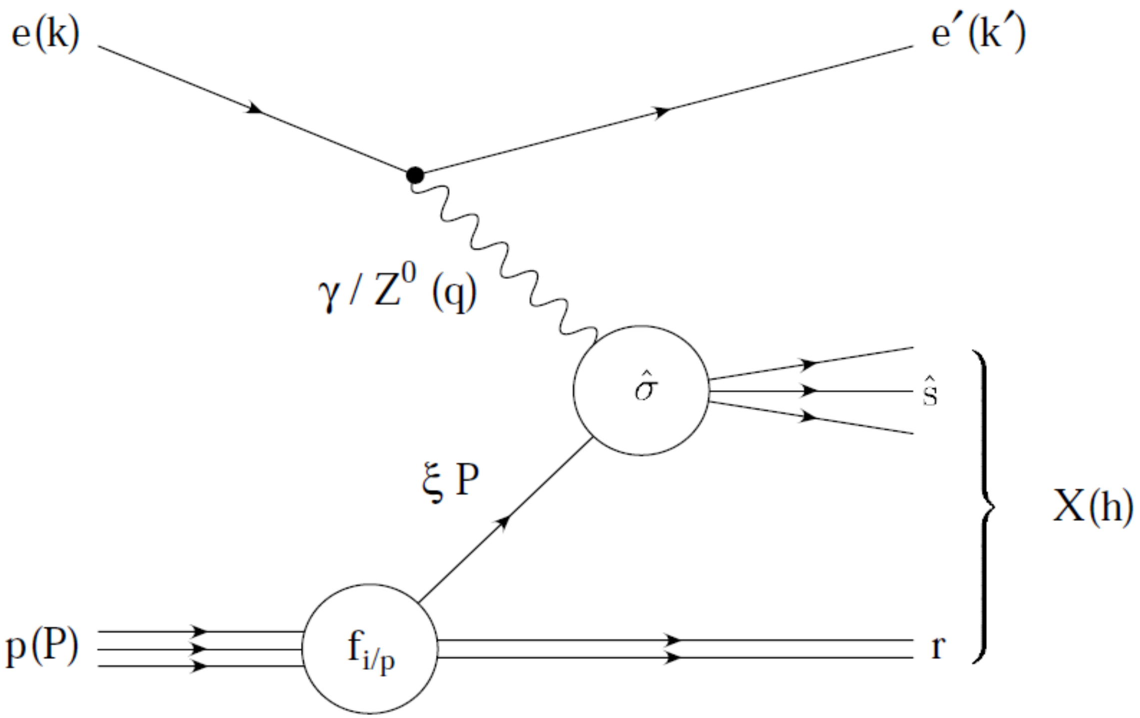
Target rest frame

Inelasticity y is relative energy loss of electron in target rest frame:

$$y = \frac{E_e - E_{e'}}{E_e}$$

Only two of the four invariant variables are independent!

Deep-inelastic scattering (DIS)



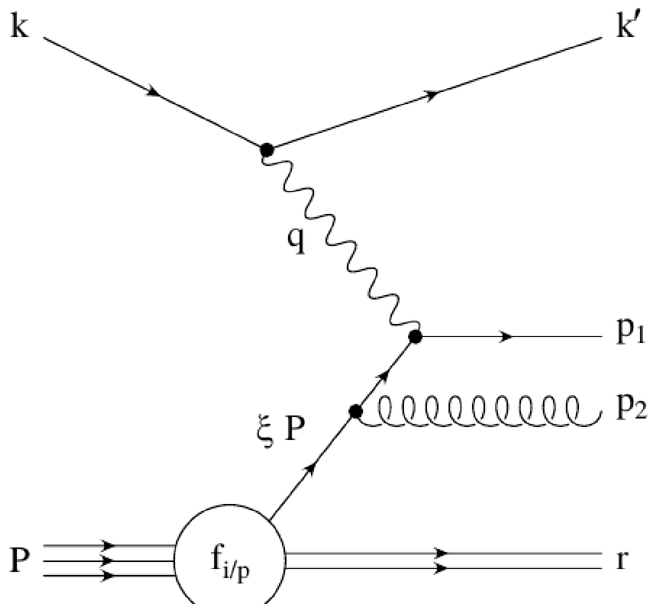
Conversion formulae

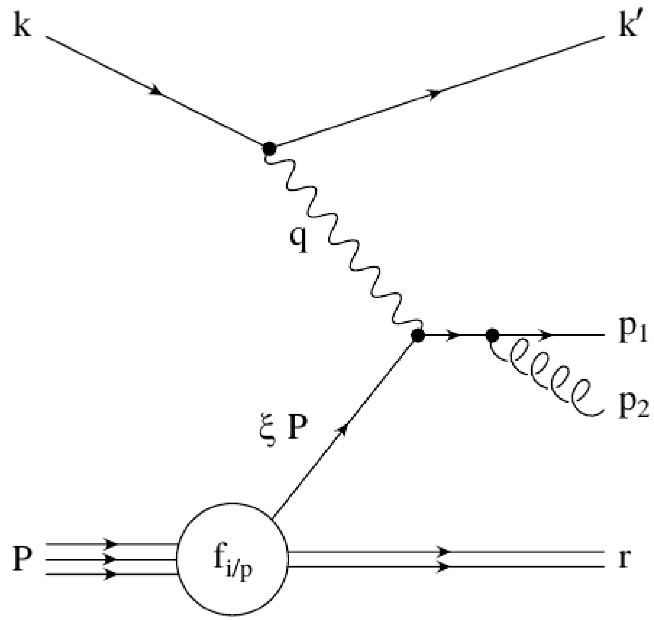
$$x = \frac{Q^2}{Q^2 + W^2} \qquad y = \frac{Q^2 + W^2}{s}$$

$$Q^2 = sxy \qquad W^2 = s(1-x)y$$

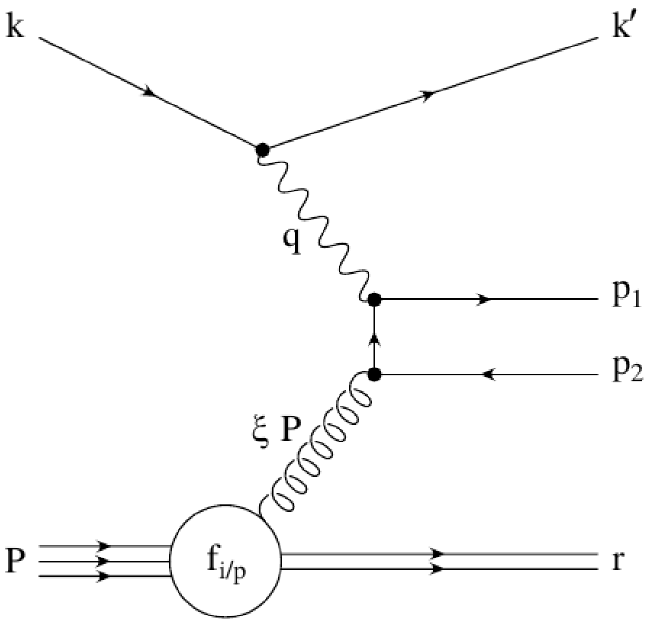
NLO

QCD-Compton

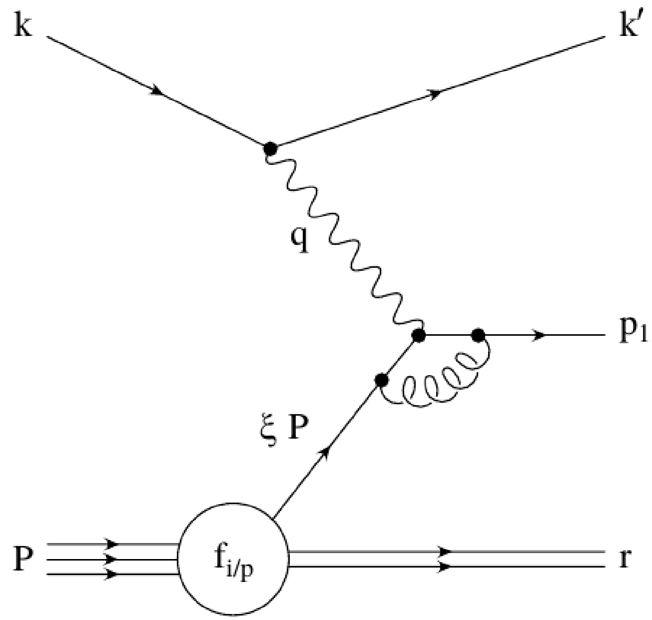




Boson-gluon fusion

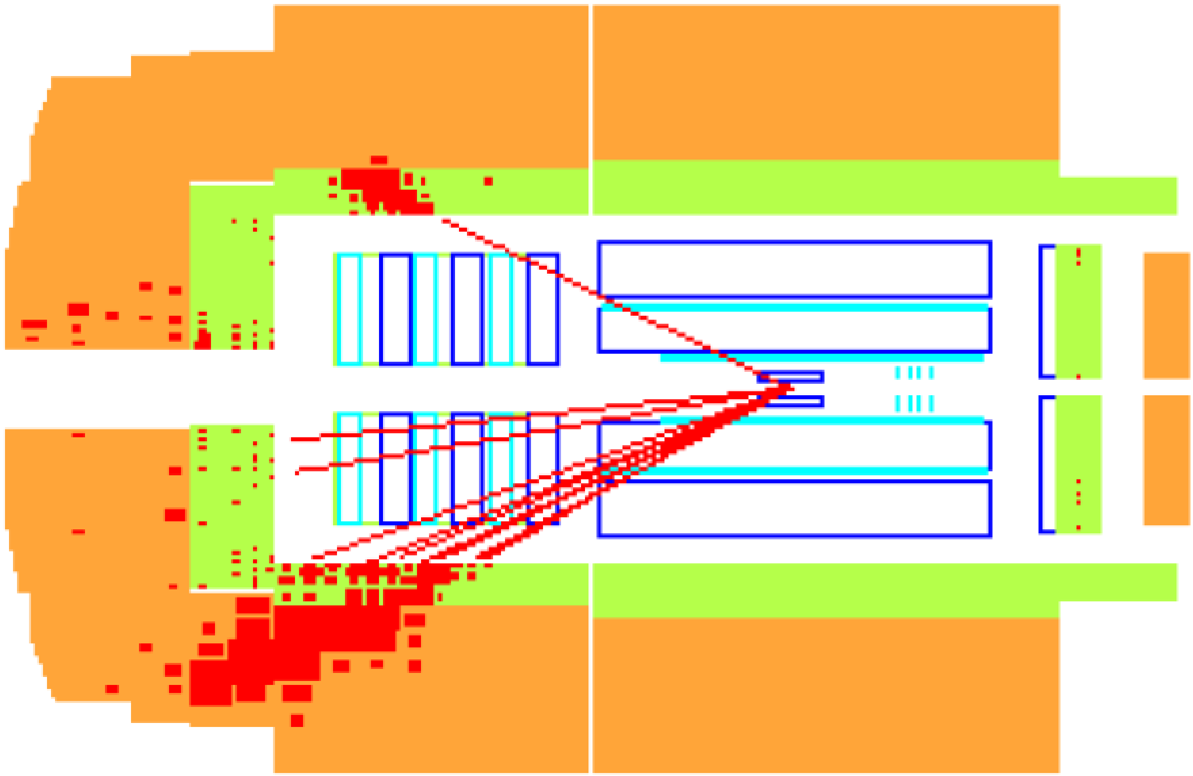


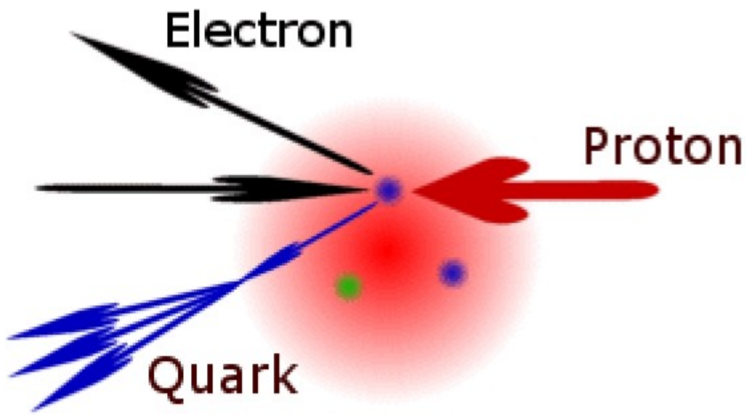
Virtual correction



Electromagnetic reaction:
Backscattering of electron off charged proton constituent

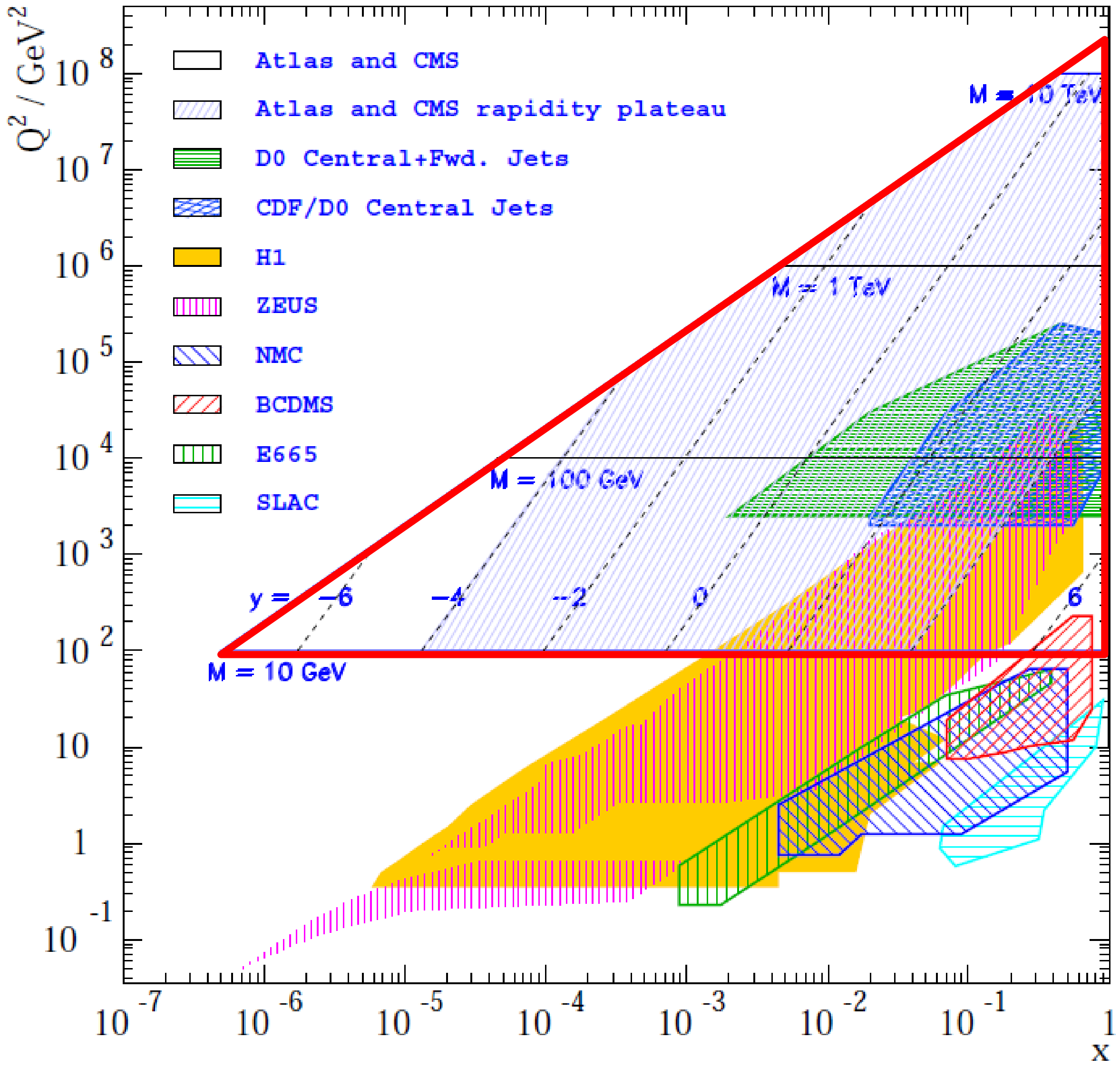
H1 Detector



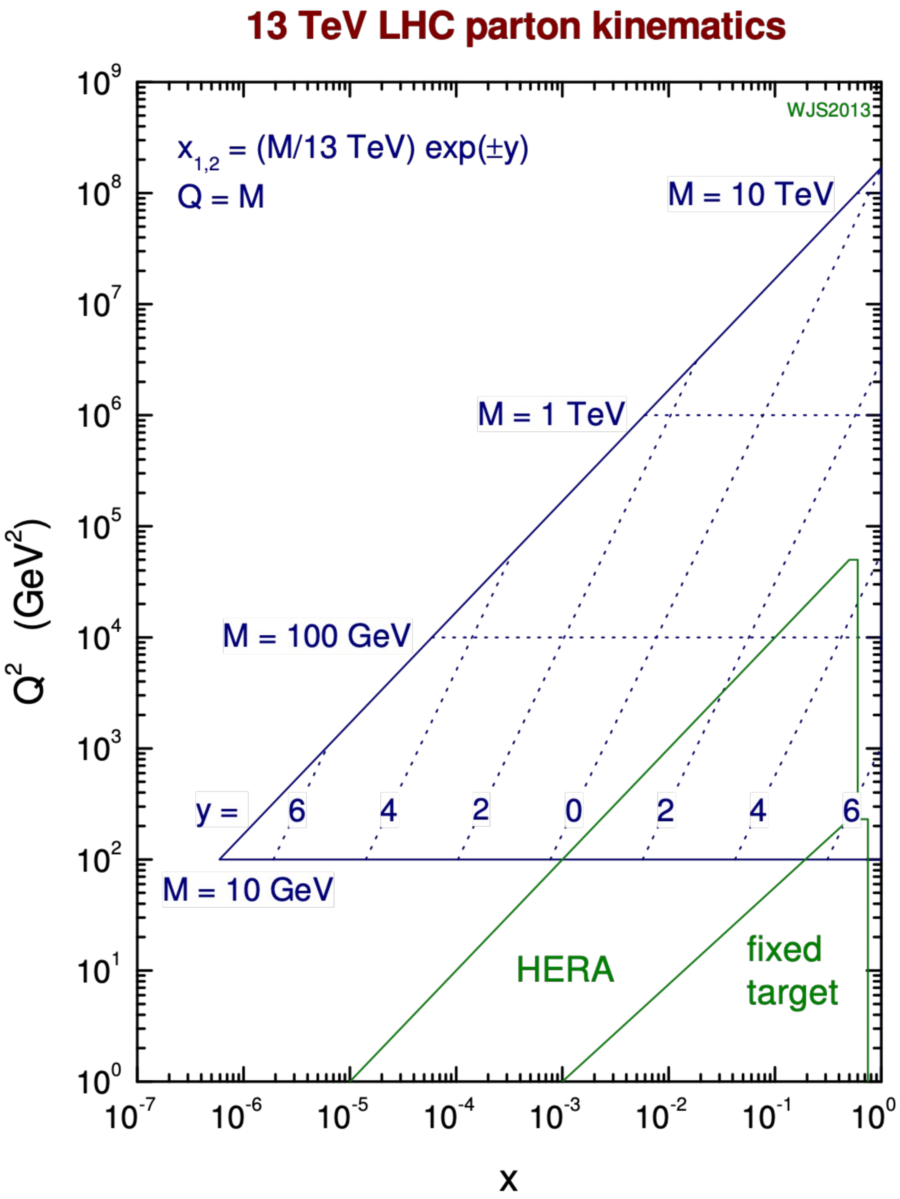


H1 Event Tutorial, J Meyer, DESY (2005)

Phase space in x and Q^2



S. Glazov, Braz.J.Ph. 37 (2007) 793.



W.J. Stirling

DIS cross section

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right] \qquad Q^2 \gg M_p^2 y^2$$

$F_1(x,Q^2)$ and $F_2(x,Q^2)$ are structure functions incorporating the form factors (and kinematic ones, τ), but cannot be related to Fourier transforms any more since dependent on x.

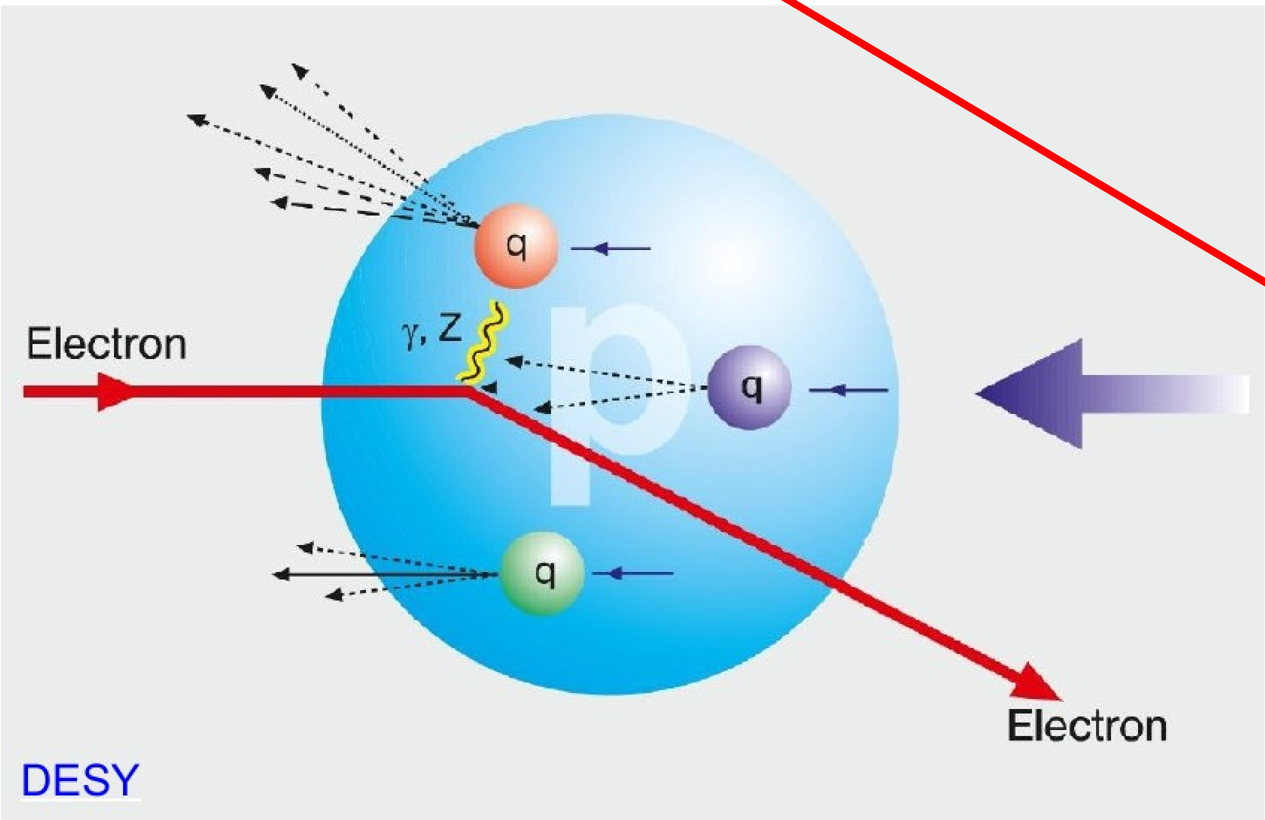
Still, $F_1(x,Q^2)$ is of purely magnetic origin, while $F_2(x,Q^2)$ originates from both, electric and magnetic effects.

What do they mean?

Quark-Parton-Model

J.D. Bjorken, R.P. Feynman 1969:

- Infinite momentum frame
  - incoherent superposition of elastic scatterings with point-like “partons”
  - scale invariant, i.e. independent of resolution ~ q^2, no natural length scale
  - partons have spin 1/2



Bjorken scaling:

$$F_1(x, Q^2) \to F_1(x)$$
$$F_2(x, Q^2) \to F_2(x)$$

Callan-Gross relation:

$$F_1(x) = \frac{F_2(x)}{2x}$$

Spin 0 would give:

$$F_1(x) = 0$$

Quark-Parton-Model

Modern writing:

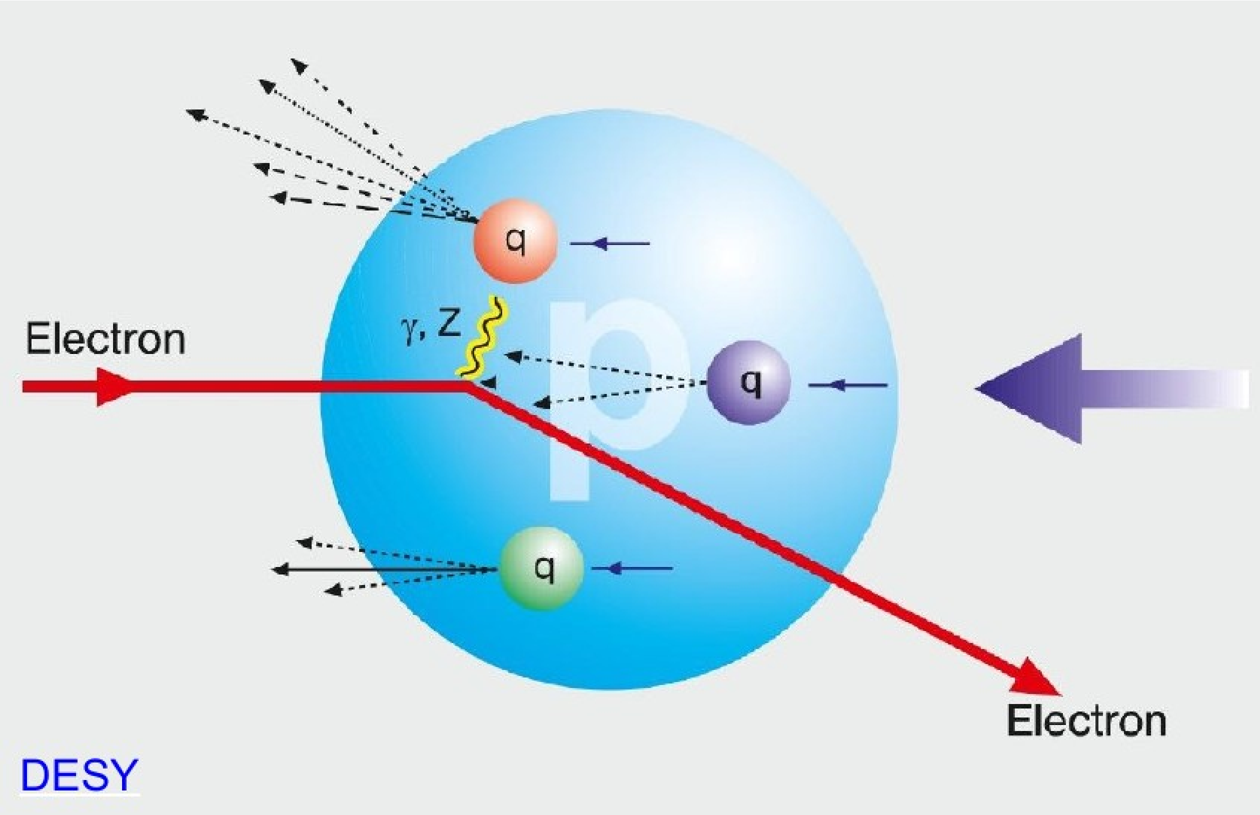
$$F_2(x) = x \sum_i e_i^2 \, [q_i(x) + \overline{q}(x)]$$

quark charges

anti-quark momentum distribution

quark momentum distribution

q_i : parton distribution functions (PDFs)



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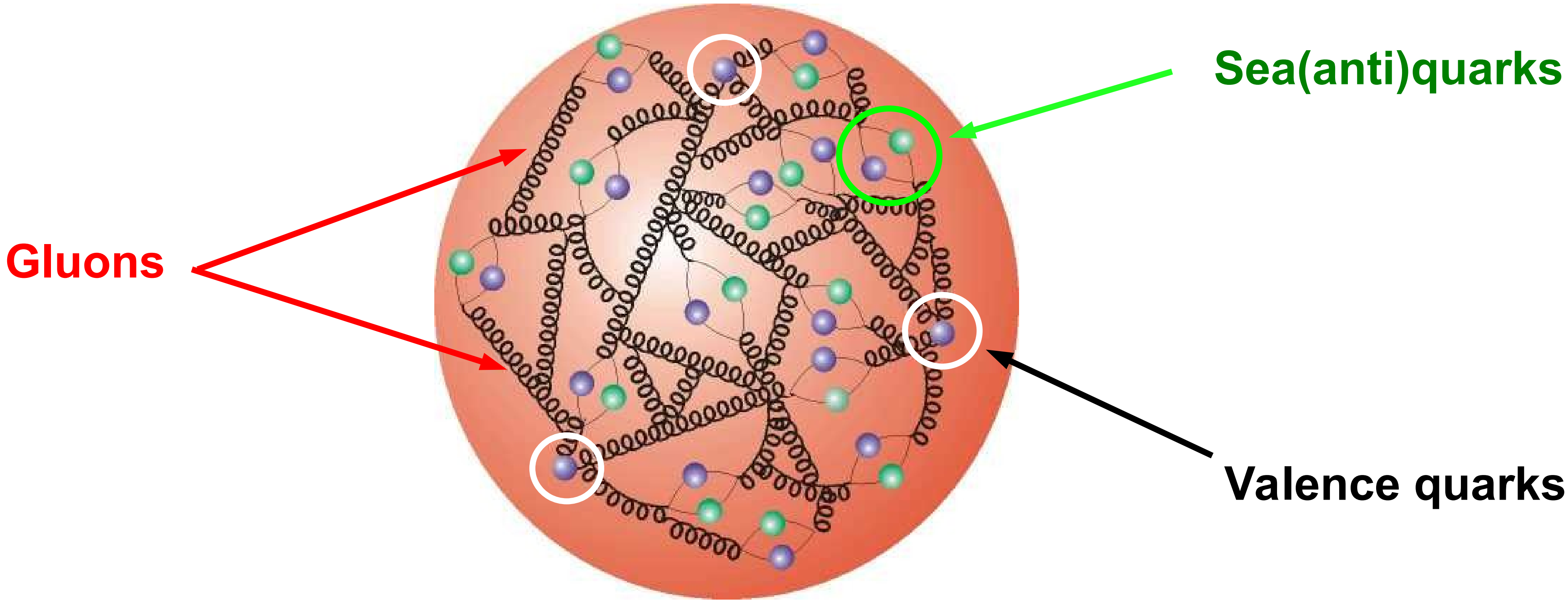
$$F_1(x) = 0$$

Proton structure

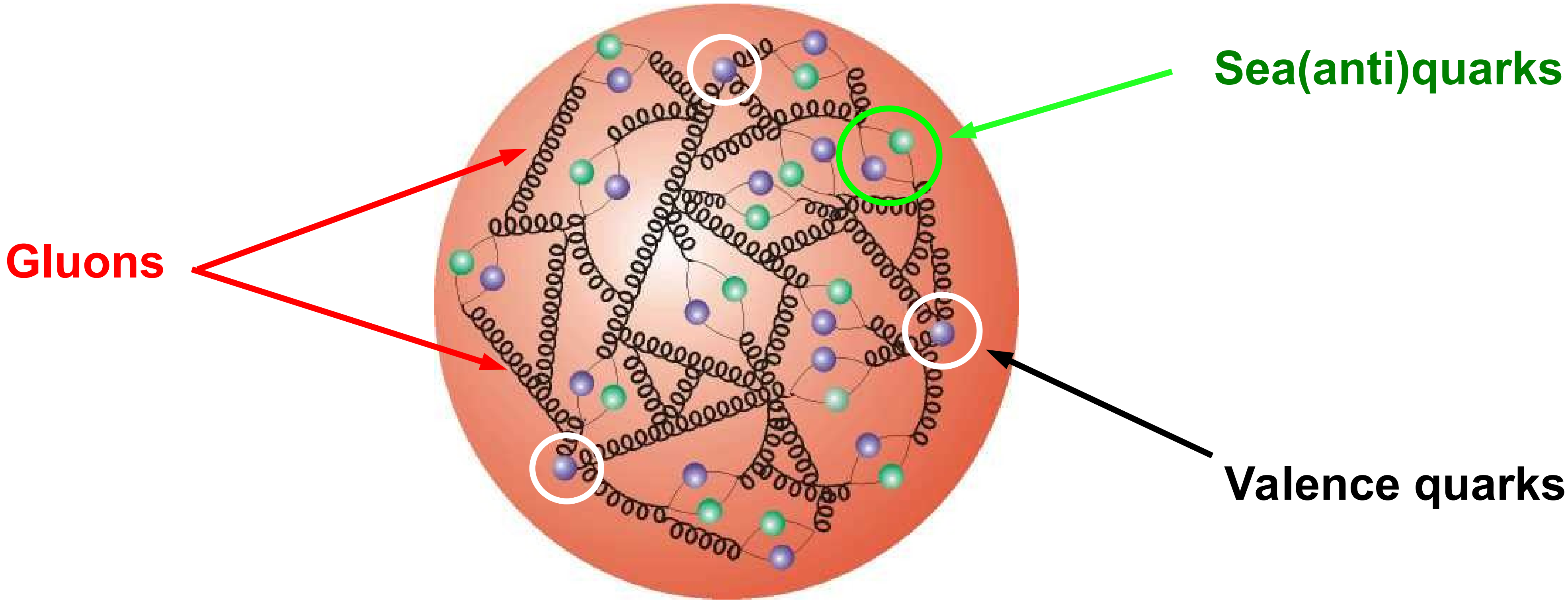


- Example of generic functional form of proton structure:

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

Normalisation — Behaviour for $x \to 0$ — Behaviour for $x \to 1$ — Middle region largest variability

Proton structure



$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

- non-perturbative in nature
- allow description of hadron collisions
- x-dependence extracted from measurements, e.g. DIS
- also depend on factorisation scale μ_F
- μ_F dependence given by perturbative QCD (DGLAP)

Proton structure à la HERAPDF

- **Typical parametrisation of the proton structure:**

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

Normalisation (A) — **Behaviour for x → 0** (B) — **Behaviour for x → 1** (C) — **Middle region largest variability** (D, E)

- **And this for all flavours … here an example from HERAPDF:**

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}$$

Gluon

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v}x+E_{u_v}x^2)$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$

Valence quarks $q_v = q - \bar{q}$

only while Δσ calc. (for D_{u_v})

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}$$

Sea quarks

→ 19 parameters

$\bar{U} = \bar{u}$ $\bar{D} = \bar{d} + \bar{s}$

Scale dependence given by pQCD

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations:

Scale dep. μ_f^2

PDFs

$$\mu_f^2 \frac{\partial f_i(x,\mu_f)}{\partial \mu_f^2} = \sum_{j=\{q,\bar{q},g\}} \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P_{ij}(z) f_{j/p}(x/z,\mu_f)$$

Momentum fractions z

LO Altarelli-Parisi (AP) splitting functions:

$$P_{qq}(z) = C_F \left(\frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z) \right)$$

quark → quark splitting

$$P_{gq}(z) = C_F \left(\frac{1+(1-z)^2}{z} \right)$$

quark → gluon splitting

$$P_{qg}(z) = T_F \left(z^2 + (1-z^2) \right)$$

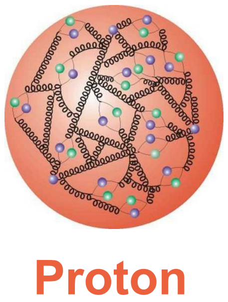
gluon → quark splitting

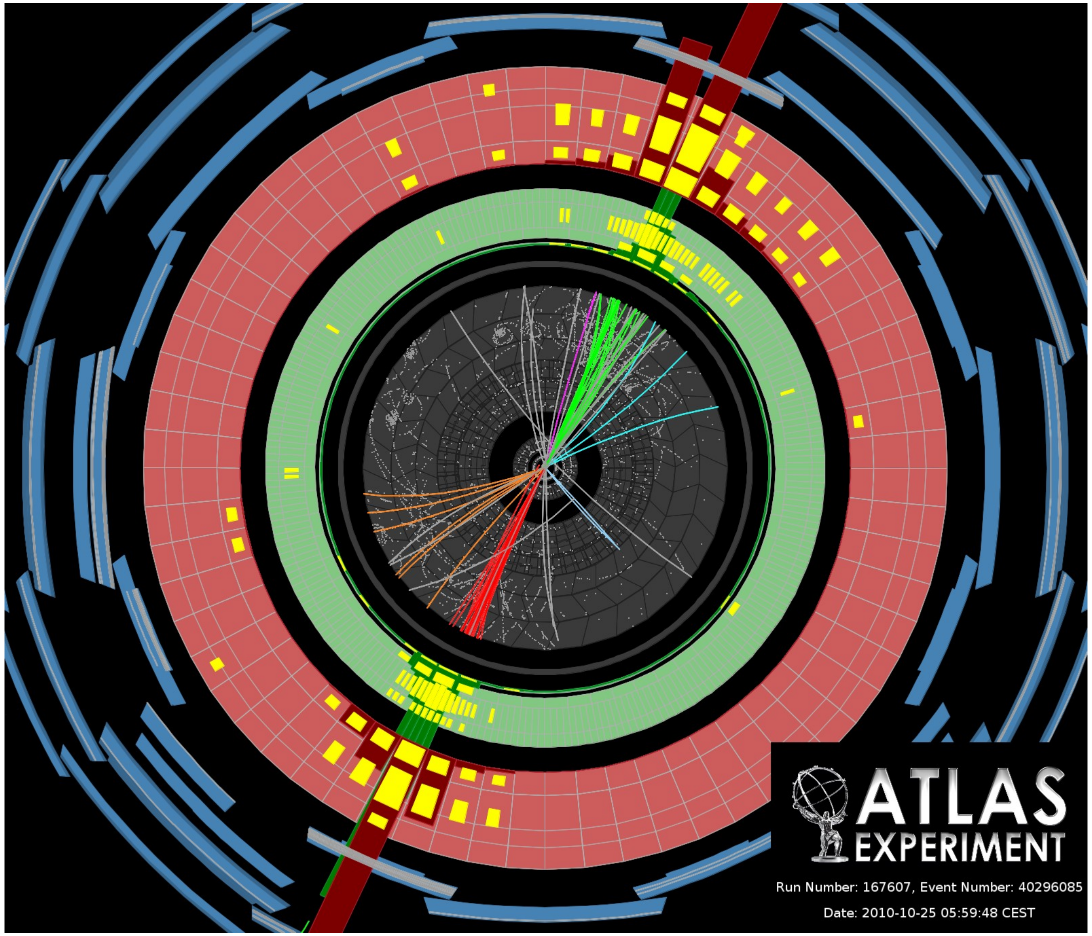
$$P_{gg}(z) = 2C_A \left(\frac{z}{(1-z)_+} + \frac{1-z}{z} + z(1-z) \right) + \delta(1-z) \frac{11C_A - 4N_F T_F}{6}$$

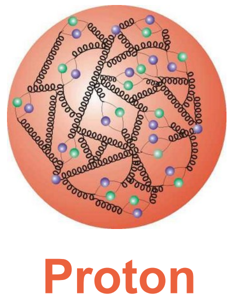
gluon → gluon splitting

QCD SU(3)

“Broadband beams” of various parton types with various energies
→ QCD parton collider!





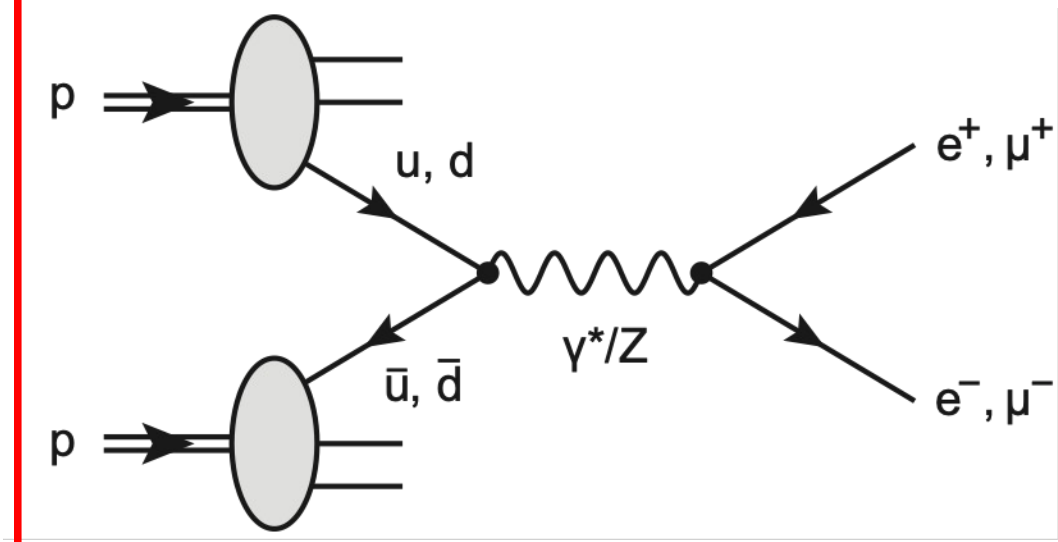


Challenge: Reliable calculations of observables

Prototype process: Drell-Yan

$pp \rightarrow l^+l^- + X$

- **Hadro-production of lepton pairs**
  - **at large center-of-mass energies**
  - **with large invariant mass**
  - **color-neutral final state (except proton remnants) → no hadronisation**



Not a Feynman diagram

Prototype process: Drell-Yan

$pp \to l^+l^- + X$

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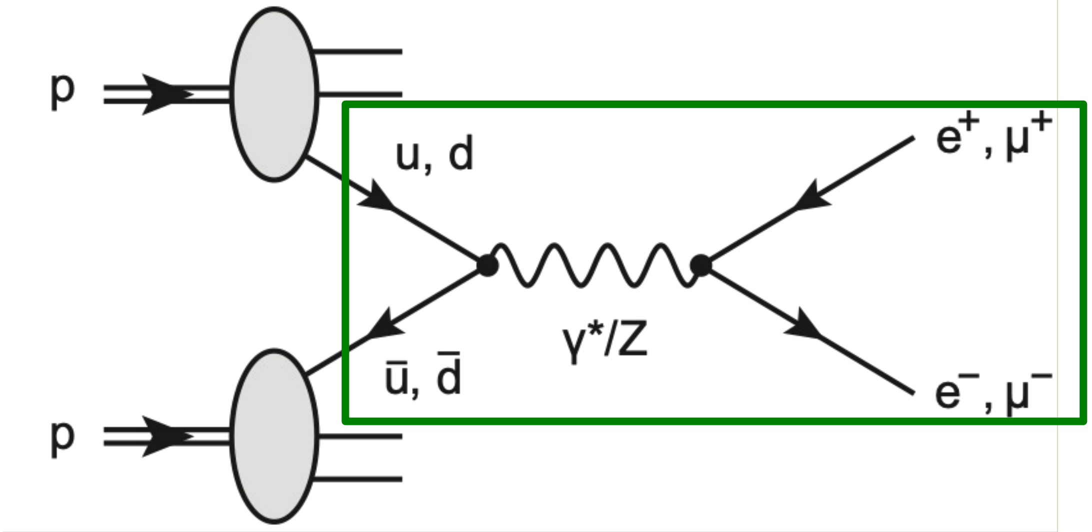
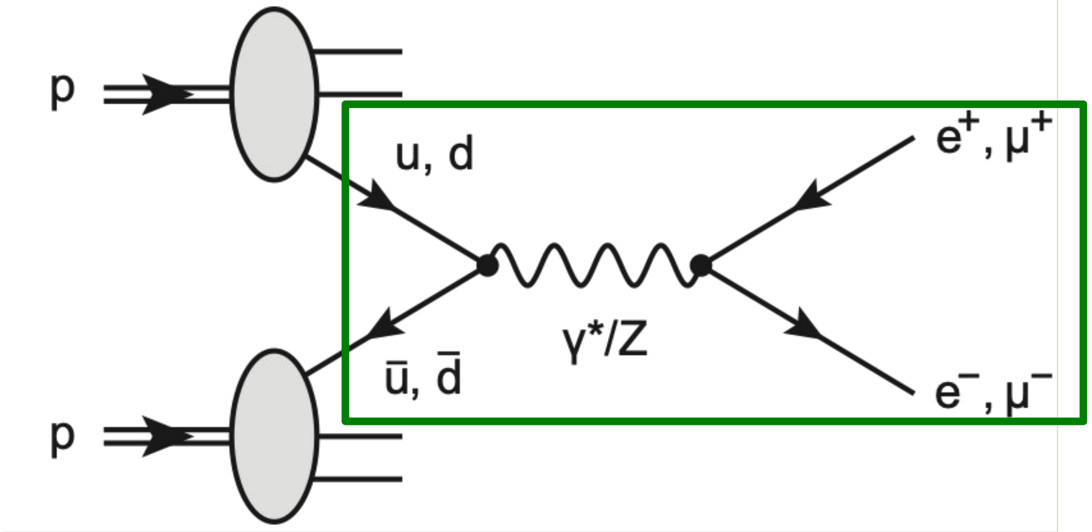


Partonic Feynman diagram
→ calculable in perturbative QCD

Prototype process: Drell-Yan

$pp \to l^+ l^- + X$

- **Hadro-production of lepton pairs**
  - at large center-of-mass energies
  - with large invariant mass
  - color-neutral final state (except proton remnants) → no hadronisation



- **Factorisation theorem of QCD:**
  - Process can be calculated by factorising "hard" and "soft" components
    - Calculate hard partonic subprocess
    - Weight cross section with probability to find partons with momenta x_1, x_2 inside hadrons
    - Integrate over all possible parton momenta
    - Sum over all possible parton flavors

Prototype process: Drell-Yan

$pp \to l^+ l^- + X$

- **Factorisation theorem of QCD:**
  - **Process can be calculated by factorising “hard” and “soft” components**
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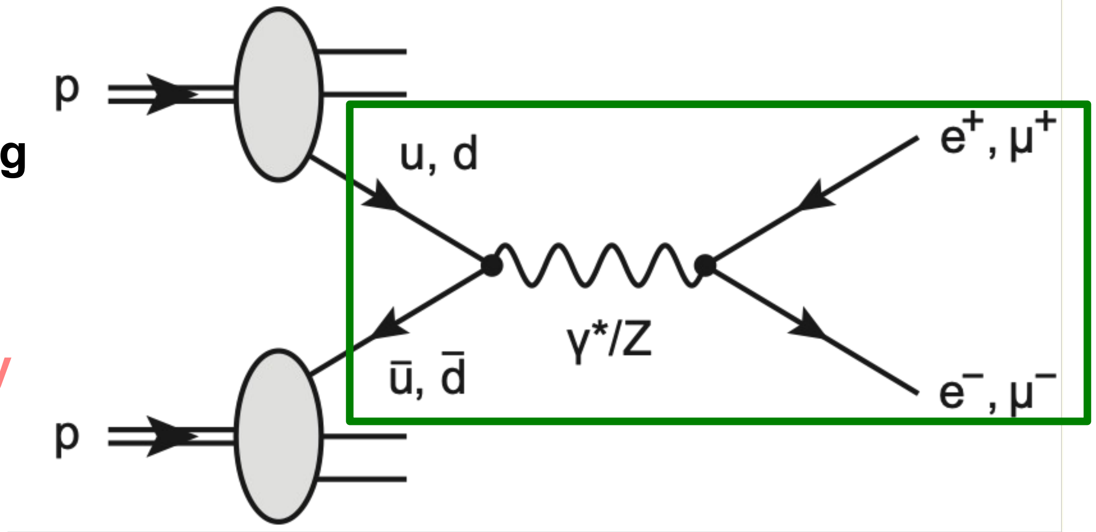
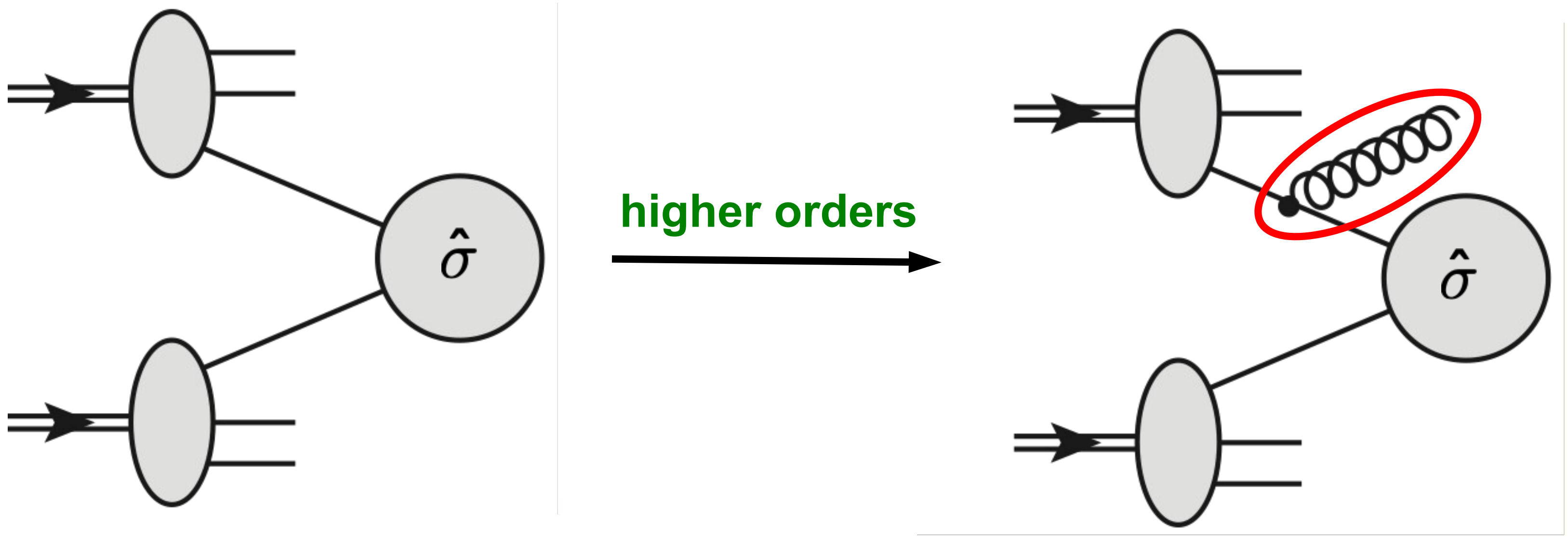


$$\sigma_{\mathrm{DY}} = \sum_{i,j} \int \mathrm{d}x_i \mathrm{d}x_j f_i(x_i) f_j(x_j) \cdot \hat{\sigma}(q_i q_j \to l^+ l^-)$$

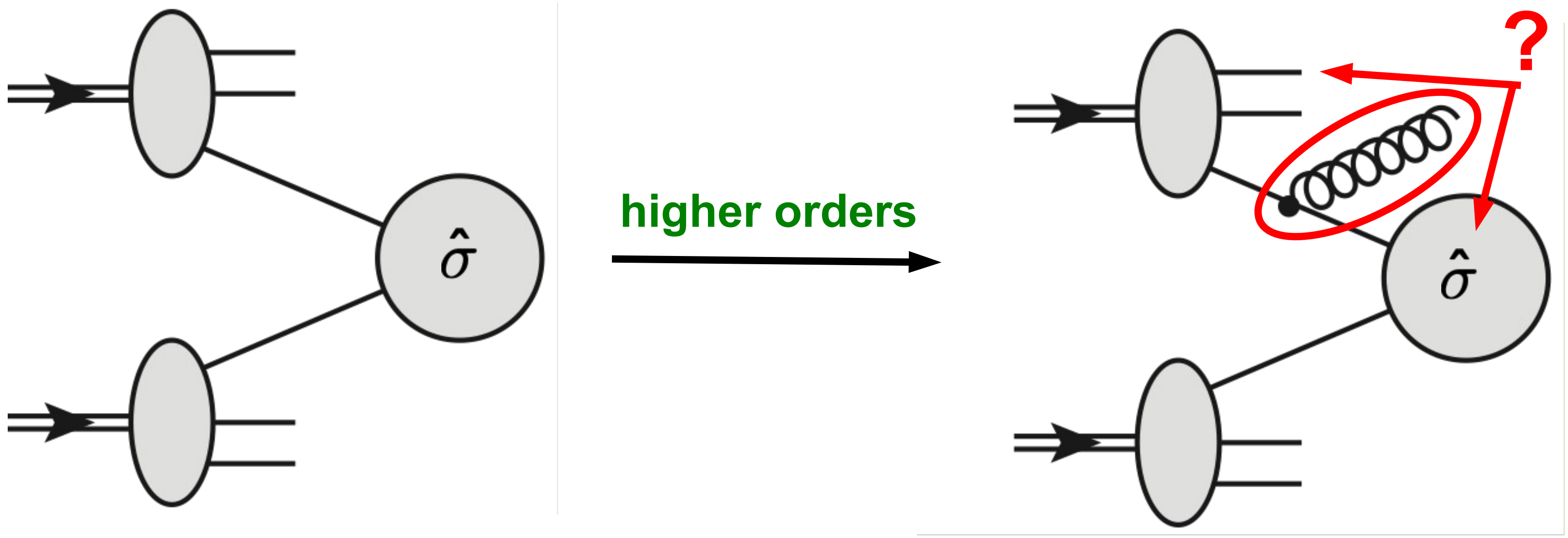
PDFs $f_i(x_i)$ are universal; can be measured independently e.g. in DIS!

Factorisation scale



Where does this belong to?

Factorisation scale



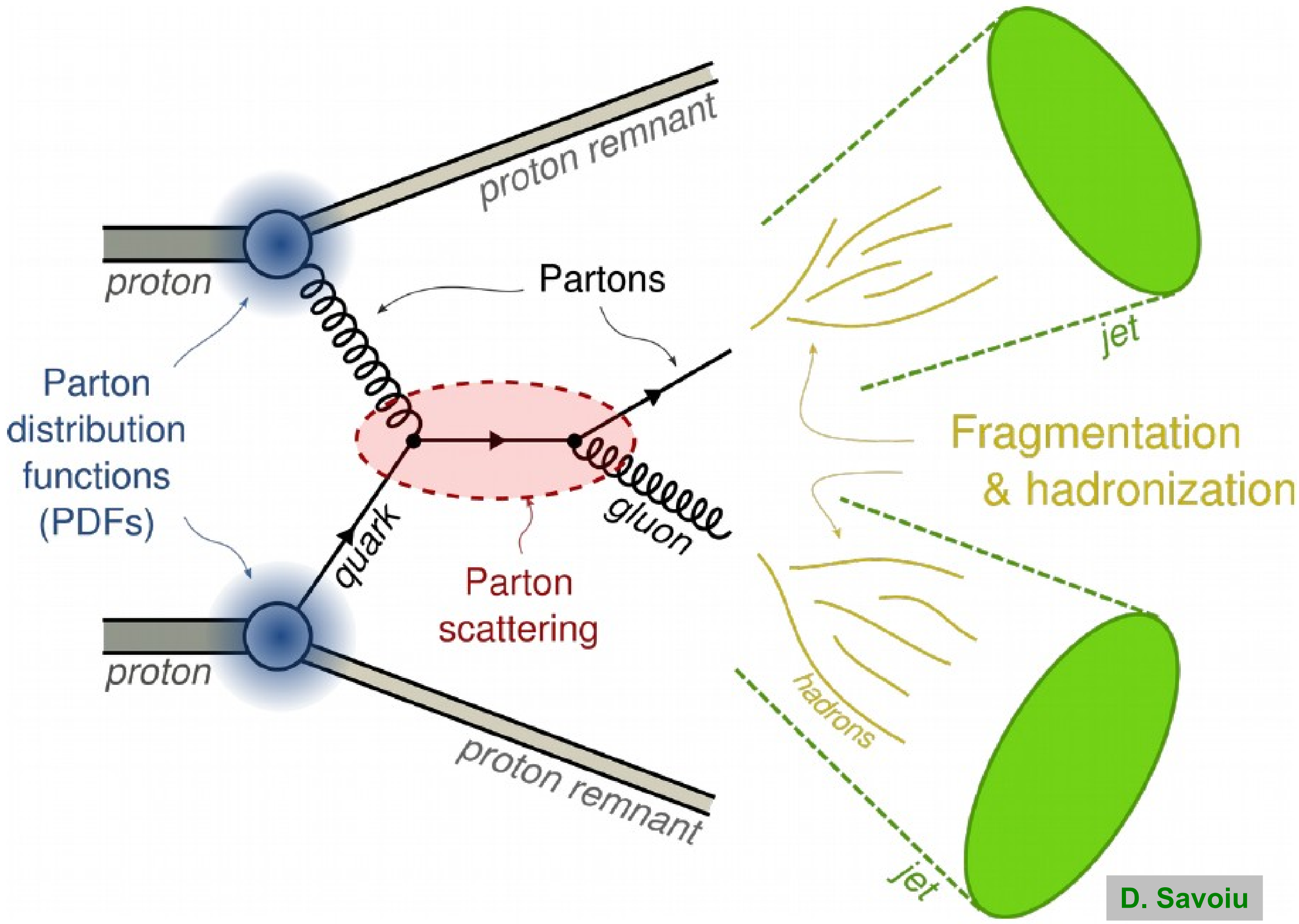
- **Attribution ambiguous:**
  - **Leads to soft and/or collinear divergences (long-distance effects!)**
  - **Solution: Introduce a new scale to separate short- and long-distance effects**
    - **Factorisation scale μ_f**
    - **All soft and collinear divergences (long-distance effects) are absorbed into the PDFs determined from experimental measurements**

$$f_i(x_i) \to f_i(x_i, \mu_f^2)$$

$$\hat{\sigma}_{ij}(x_i, x_j, \mu_r^2, \alpha_s(\mu_r^2)) \to \hat{\sigma}_{ij}(x_i, x_j, \mu_f^2, \mu_r^2, \alpha_s(\mu_r^2))$$

Hadron-hadron cross sections

Factorisation successful also for more general final states, e.g. jet production!



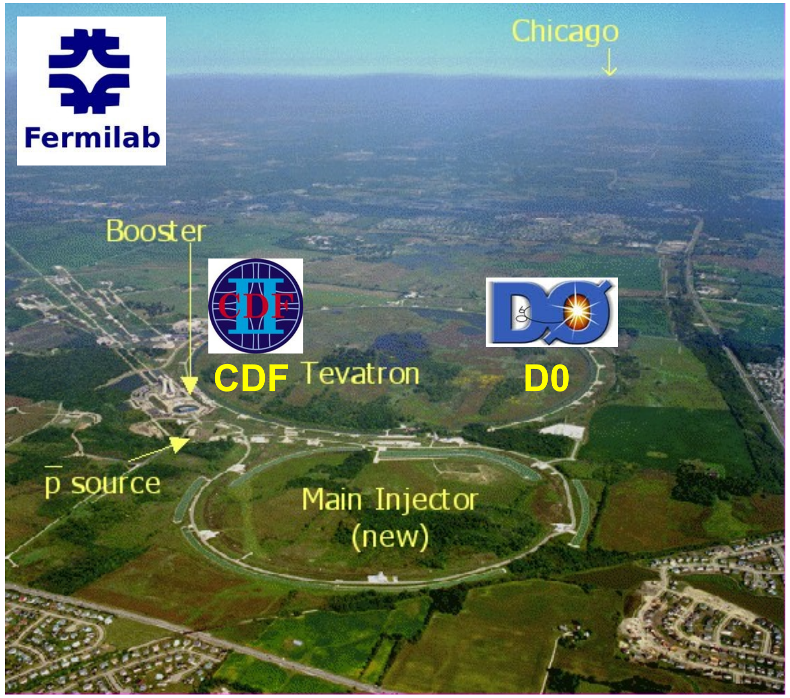
Hadron colliders

Tevatron: 1986 – 2011

Collisions of p anti-p

Run II: E_{cms} =1.96 TeV

Run II: Record luminosity: 4.3 x 10^{32} $cm^{-2}s^{-1}$



LHC: 2009 – present

Collisions of p-p, Pb-Pb, and p-Pb

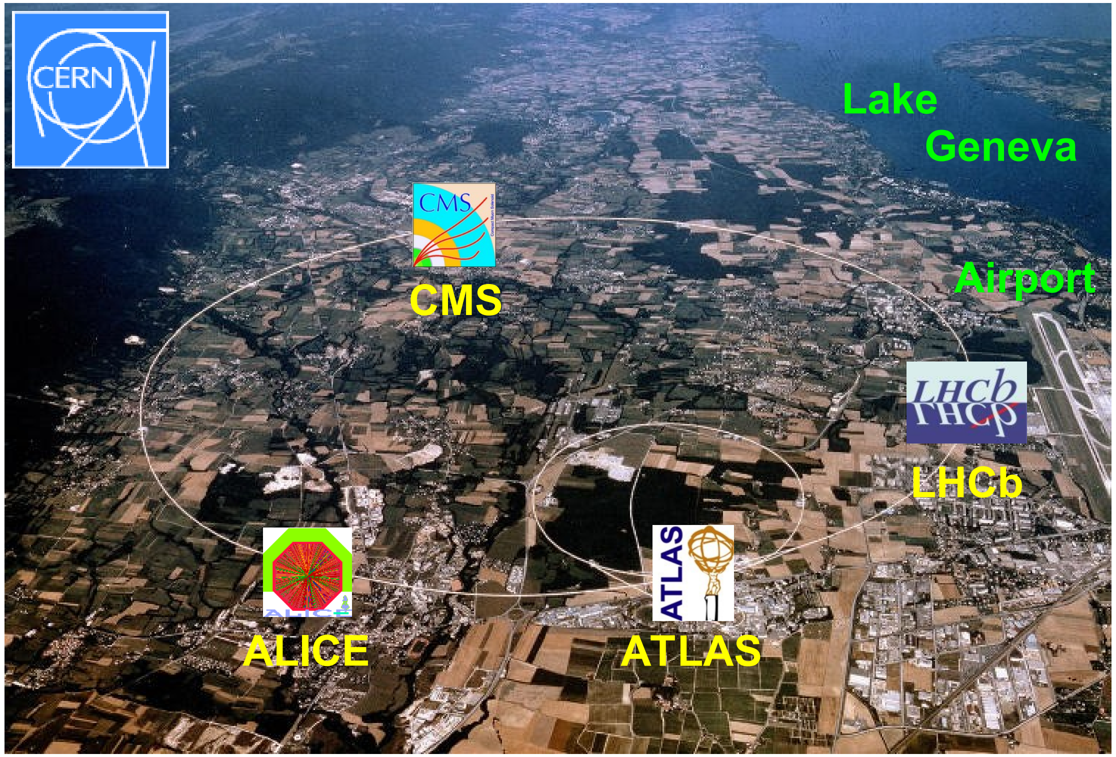
E_{cms} = 0.9, 2.36, 2.76, 5.02, 7, 8, 13 TeV

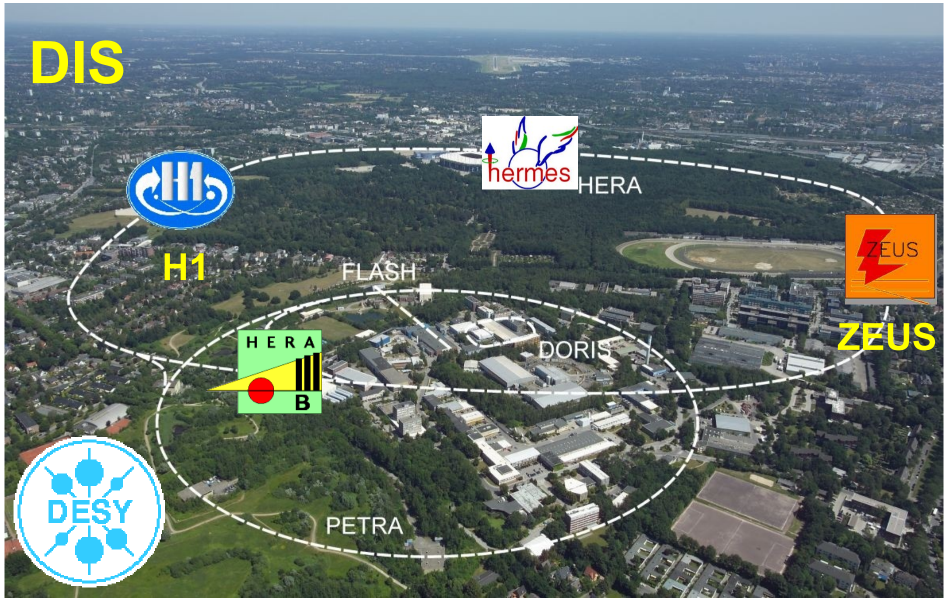
Peak inst. Luminosity: ~ 2 x 10^{34} $cm^{-2}s^{-1}$

HERA: 1992 – 2007

Collisions of e^{+}-p, e^{-}-p

HERA II: E_{cms} = 319 GeV





Event rates at the LHC

Total cross section

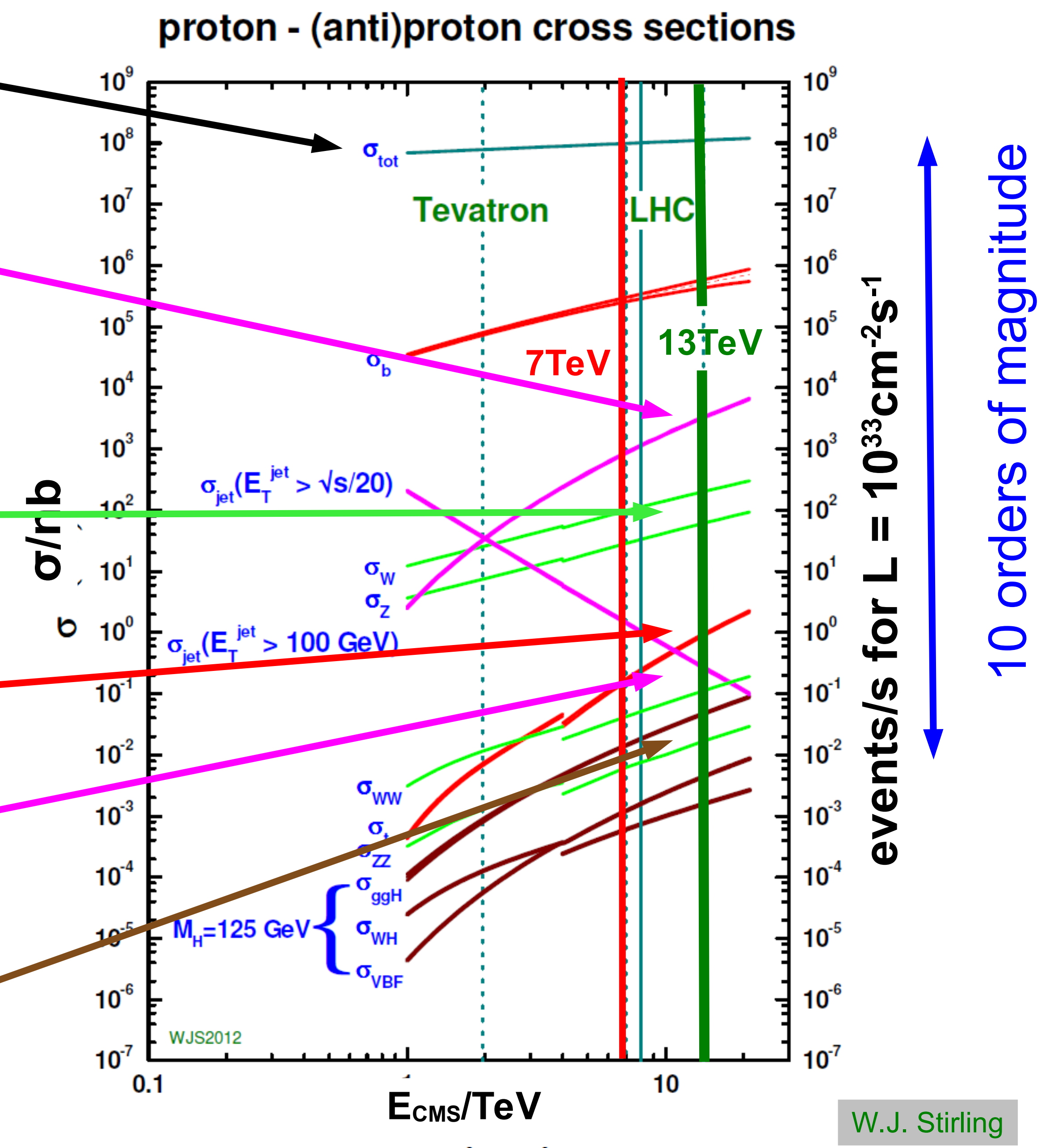
Jets: $\sigma_{jet}(E_T^{jet} > 100\text{GeV})$
~ 2000 / s

W & Z bosons: σ_W, σ_Z
~ 200 / s, 50 / s

Top quarks (σ_{tt})
~ 1 / s

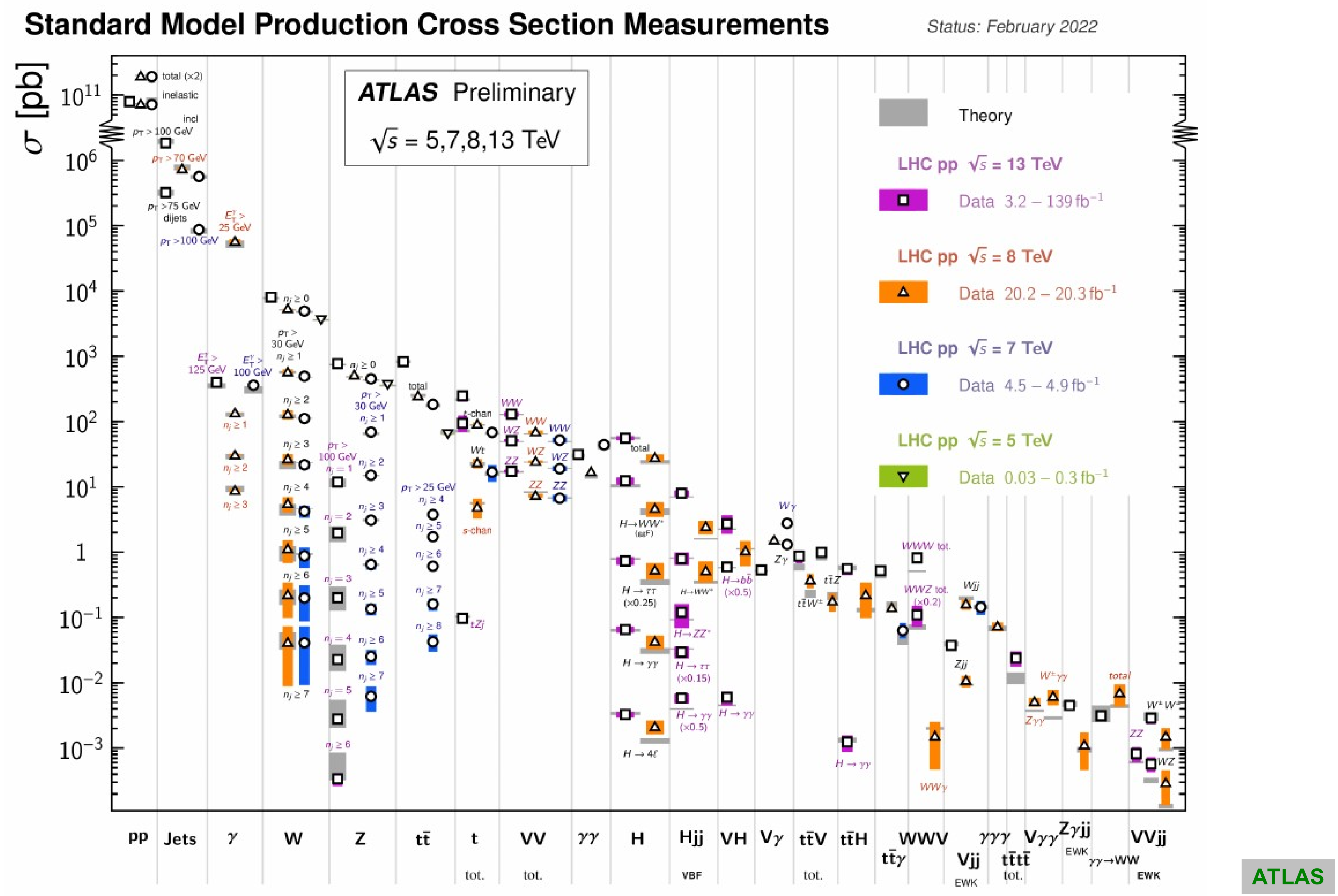
Jets: $\sigma_{jet}(E_T^{jet} > 650\text{GeV})$
~ 18 / min

Higgs Bosonen (σ_{ggH}, σ_{WH}, σ_{VBF})
~ 150 / h

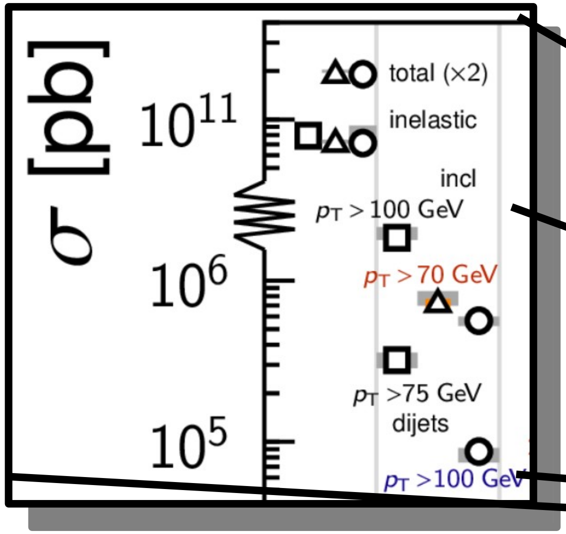


W.J. Stirling

SM cross section data vs. theory



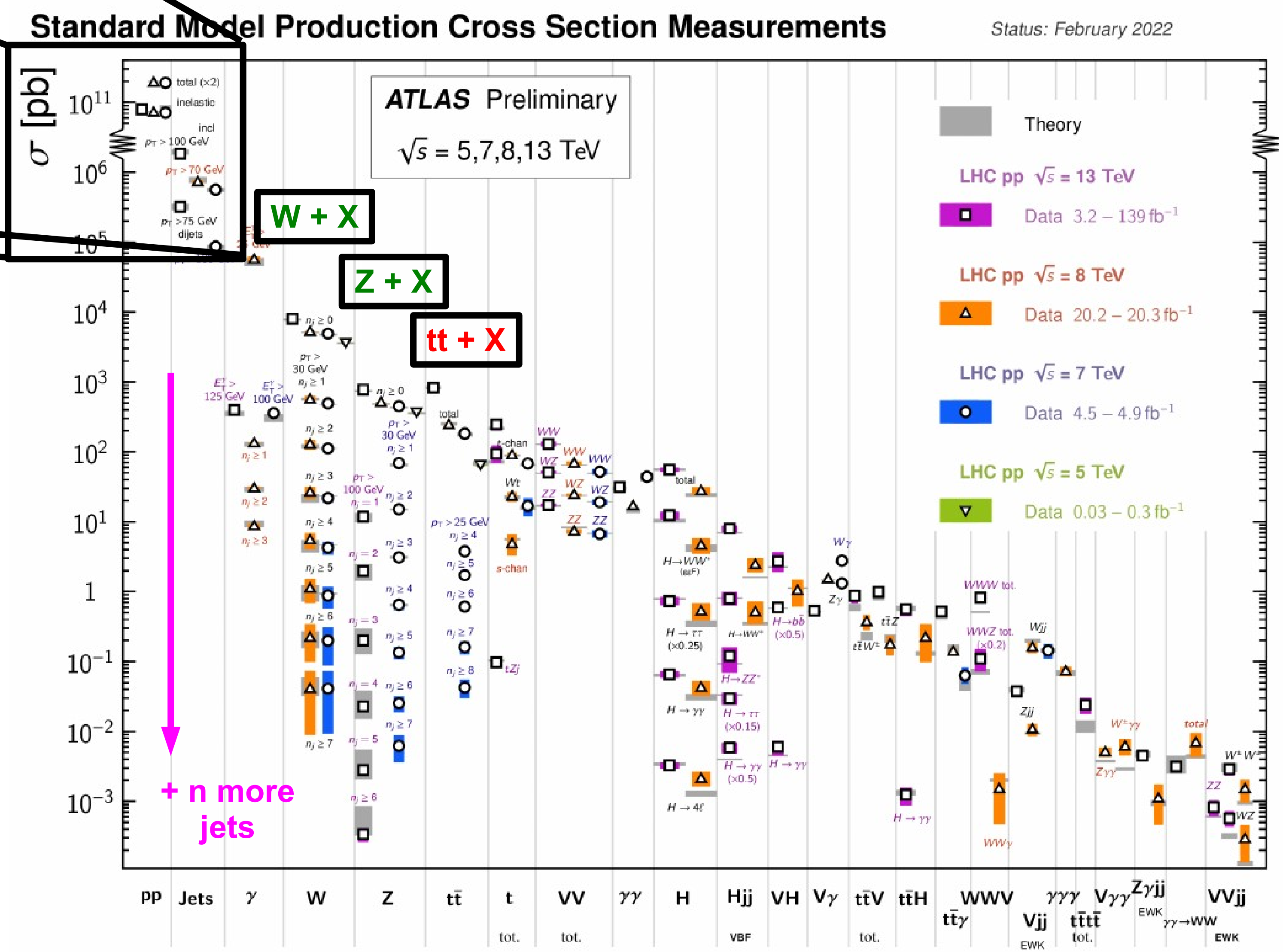
Many jets at the LHC



Inclusive jets: >= 1 jet
Inclusive dijets: jet jet + X

W+X: up to W + 7j + X
Z+X: up to Z + 7j + X

tt+X: up to tt + 8j + X



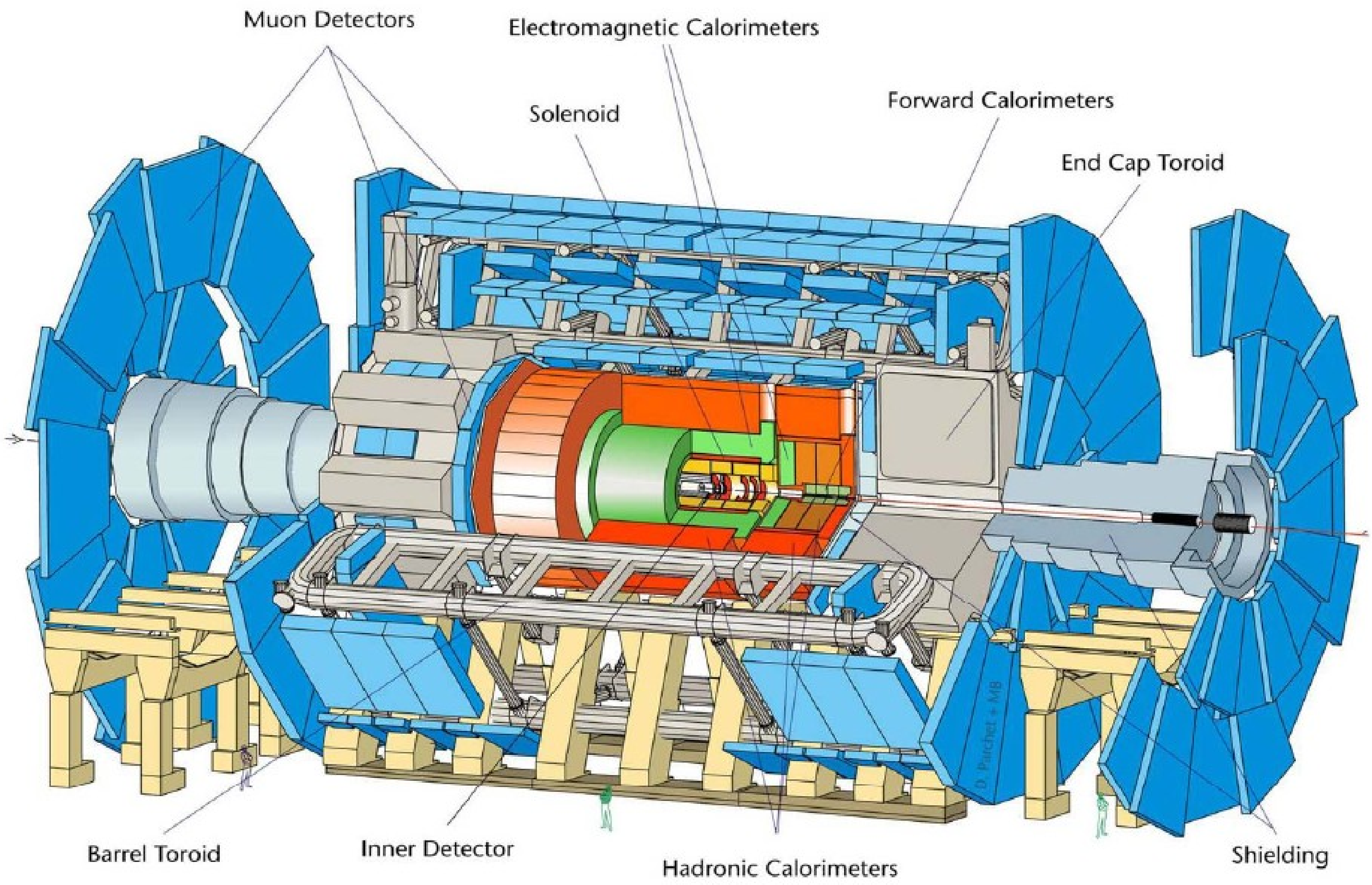
The ATLAS Detector

Inner Detector (ID) tracker:
- Si pixel and strip + transition rad. tracker
- $\sigma(d_0)$ = 15μm@20GeV
- $\sigma/p_T \approx 0.05\% p_T \oplus 1\%$

Calorimeter
- Liquid Ar EM Cal, Tile Had.Cal
- EM: $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
- Had: $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$

Muon spectrometer
- Drift tubes, cathode strips: precision tracking +
- RPC, TGC: triggering
- $\sigma/p_T \approx$ 2-7%

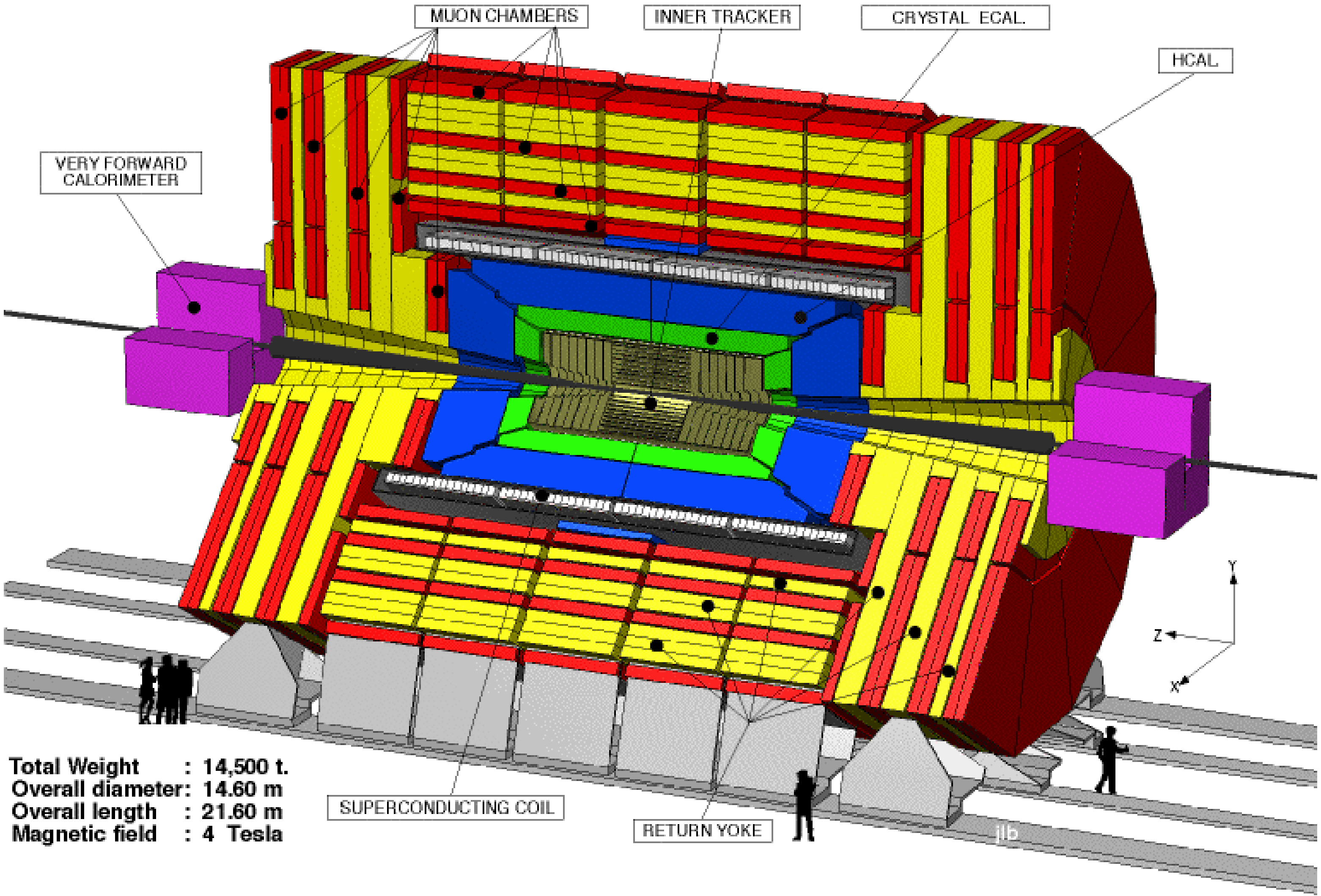
Magnets
- Solenoid (ID) → 2T
- Air toroids (muon) → up to 4T



Full coverage for |η|<2.5, calorimeter up to |η|<5

See also JINST 3 2008 S08003

The CMS Detector



Inner detector (tracker):
- Si pixel & strip tracker
- $\sigma/p_T \approx$ 1-2% (μ at 100 GeV)

Calorimeter:
- PbWO4 crystal ECAL, brass/scintillator HCAL
- ELM: $\sigma_E/E = 2.8\% /\sqrt{E} + 0.3\%$
- HAD: $\sigma_E/E = 100\% /\sqrt{E} + 5\%$

Muon system:
- Drift tubes, cathode strips, resistive plate chambers
- $\sigma/p \approx$ 10 – 50% (muon alone)
- $\approx$ 0.7 – 20% (with tracker)

Magnet:
- Solenoid → 3.8T

See also:
PTDR I LHCC-2006-001,
JINST 3 2008 S08003

Jet analysis uncertainties

- Experimental uncertainties (~ in order of importance):
  - Jet Energy Scale (JES)
    - Noise treatment
    - Pile-Up treatment
  - Luminosity (1 - 4%)
  - Jet Energy Resolution (JER)
  - Trigger efficiencies
  - Resolution in rapidity
  - Resolution in azimuth
  - Non-Collision background
  - • • •

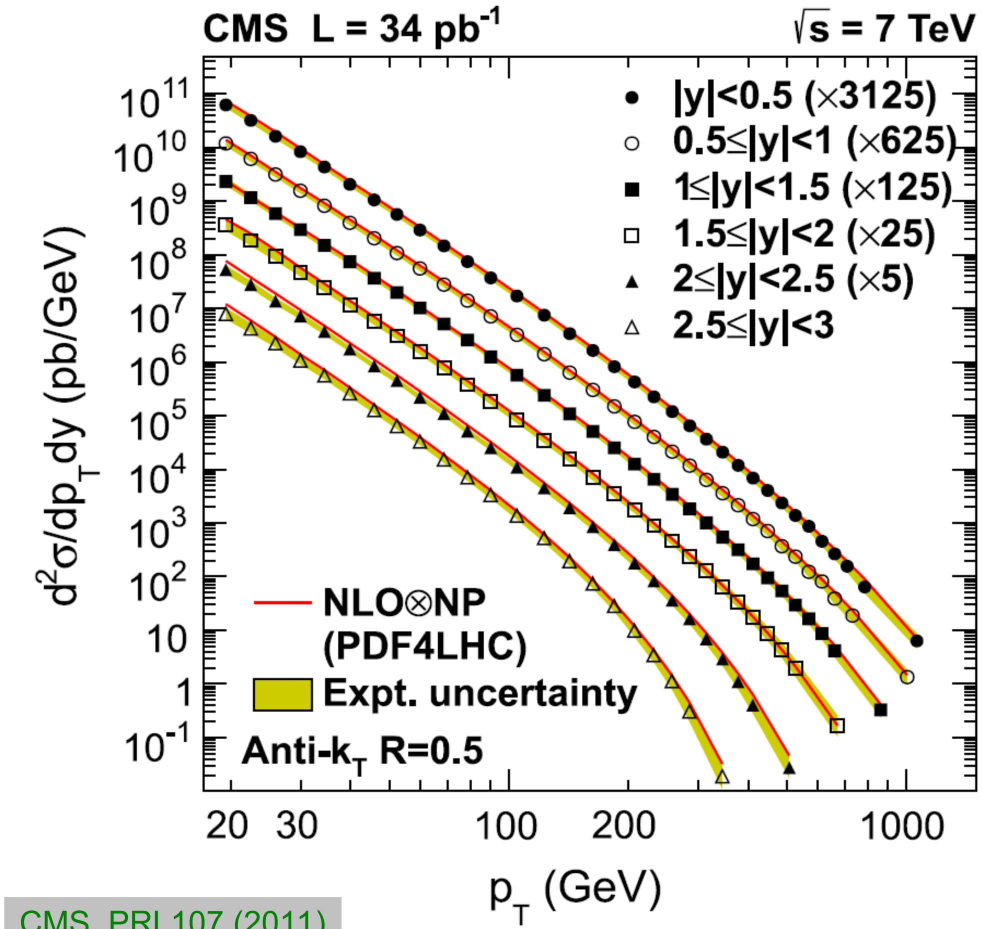
- Theoretical uncertainties:
  - MHOU (scale variation)
  - PDF uncertainty
  - Non-perturbative corrections
  - Electroweak corrections
  - PDF parameterization
  - Knowledge of $\alpha_s(M_Z)$
  - • • •

Why are JEC so important?

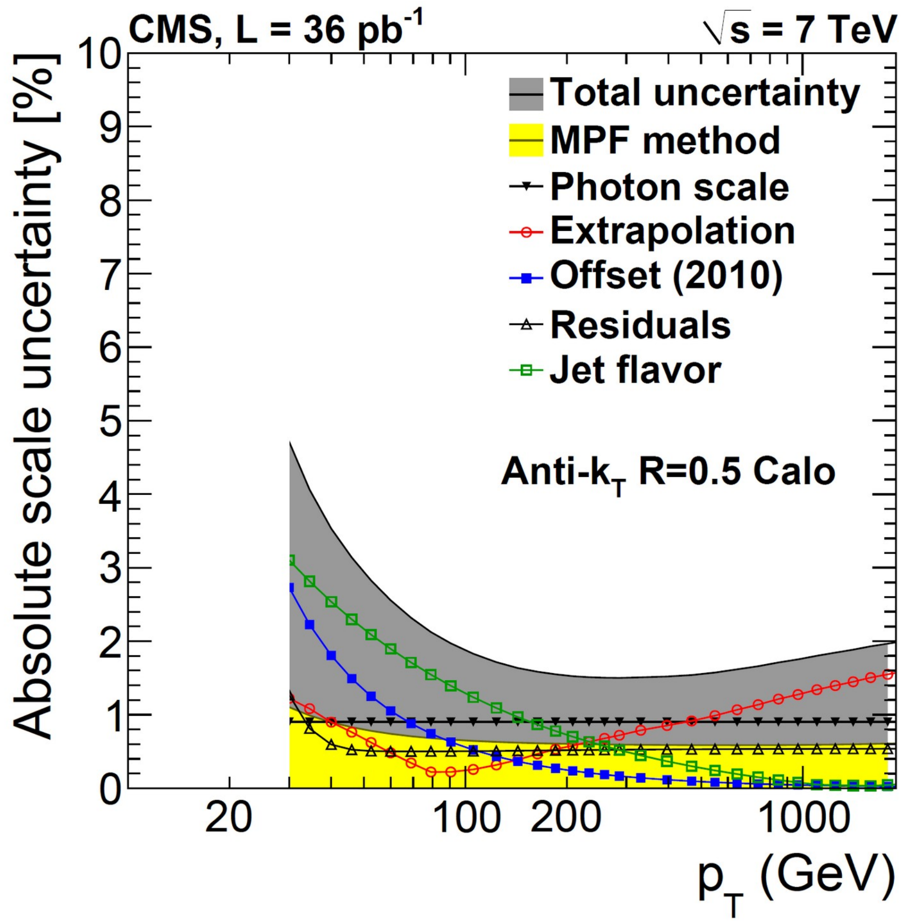
Steeply falling spectrum

$$\frac{d^2\sigma}{dp_T dy} \propto \frac{1}{p_T^{5-6}}$$

Factor 5 – 6 on uncertainty in energy scale, e.g. 2% → 10%



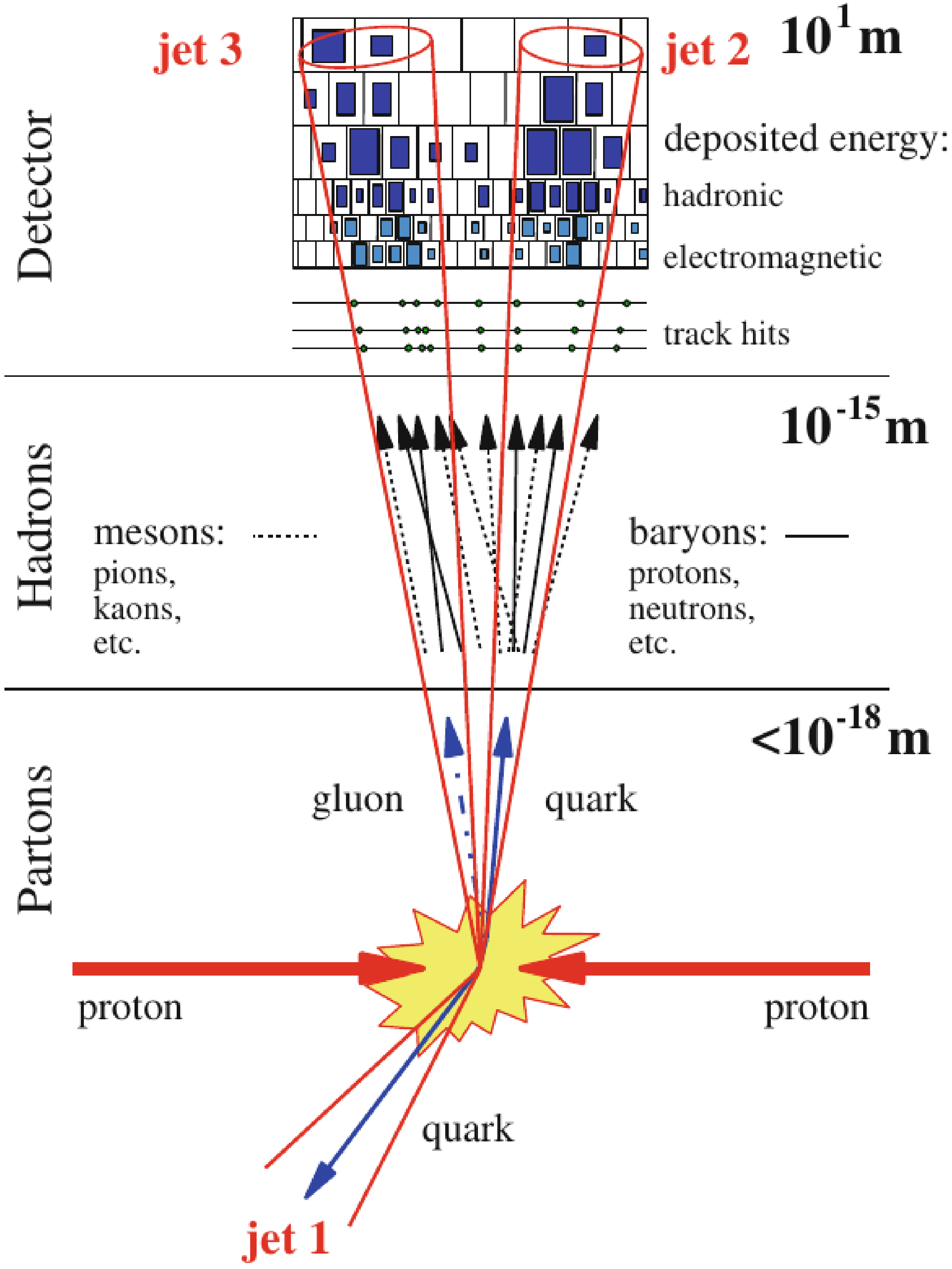
CMS, PRL107 (2011)



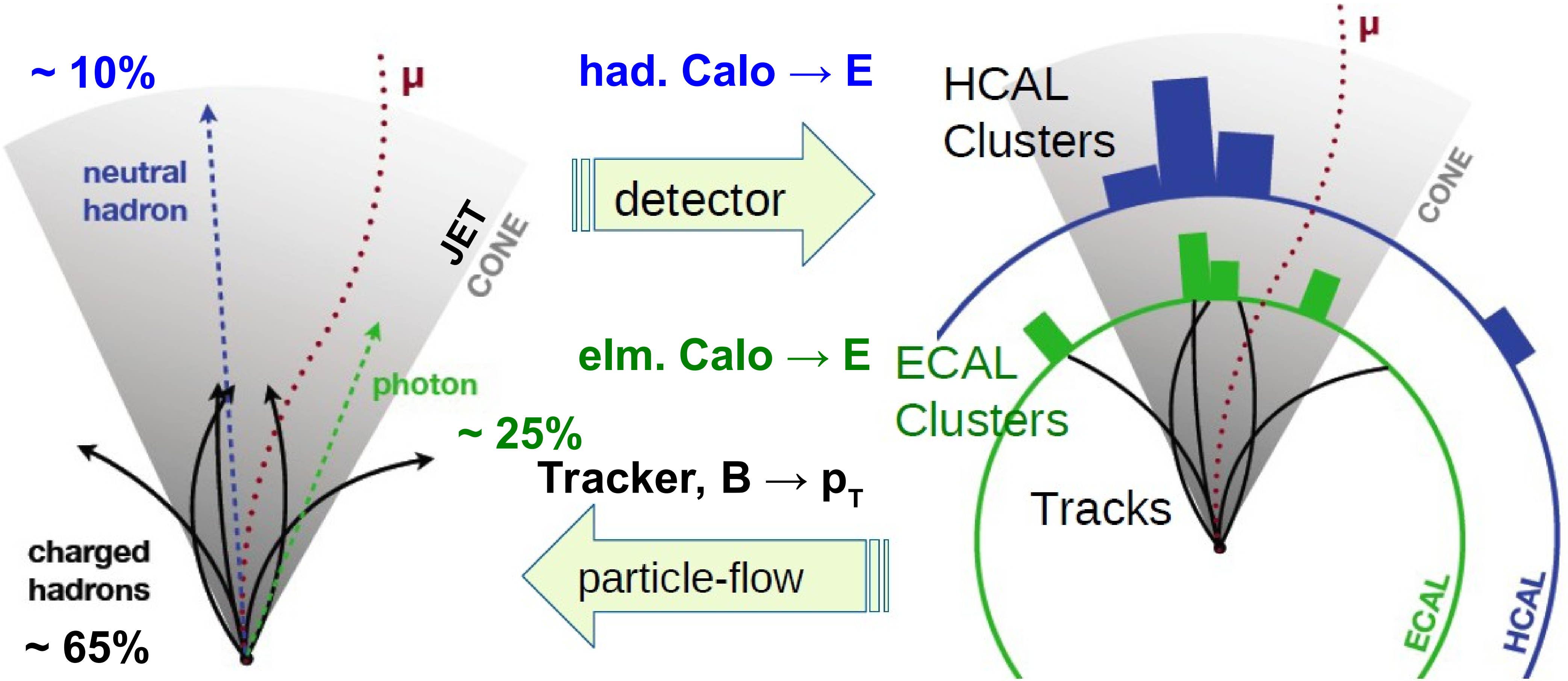
Jet content:
- Tracks
- elm. calorimeter cells/clusters
- had. calorimeter cells/clusters

How to combine to get good estimate of original energy?

How to calibrate away remaining differences?



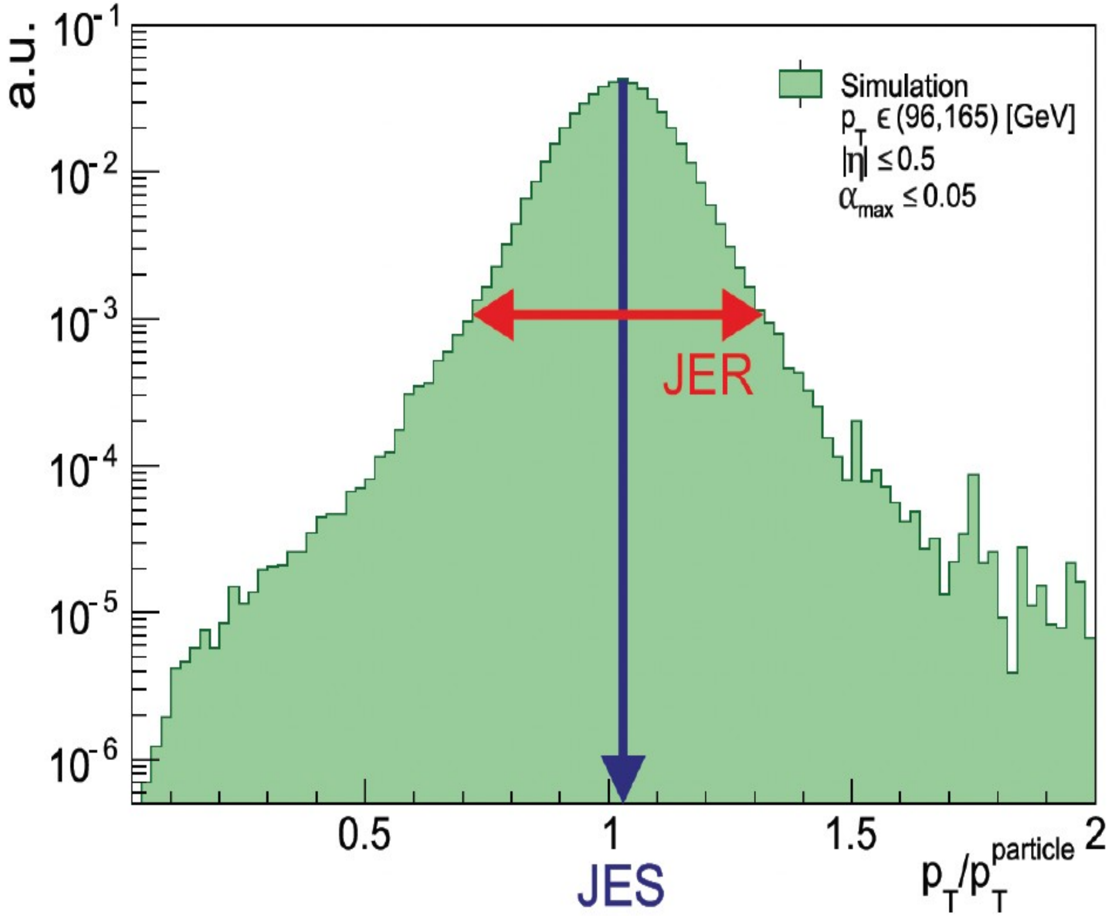
"Particle Flow" concept



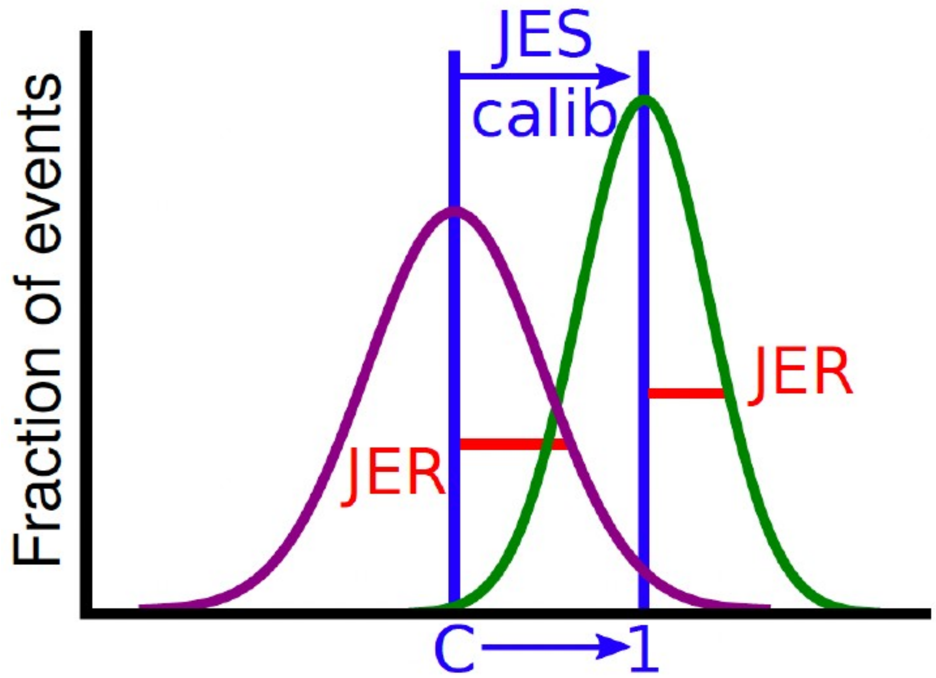
- Combine measurements of various detector components
- Consider specific detector properties wrt. particle type

Undo detector distortions

Use simulation to determine net shift and smearing of jet energies.
Use real data to correct for residual Biases.



S. Schramm, PreFit School 2020



Question:
What kind of real data can we take for this purpose?

Absolute calibration

- **Method 1: pT-balance against better known reference**
  - **Requires nicely balanced events**
  - **Insensitive to less well calibrated detector regions**
  - **Sensitive to additional high-pT activity in events (2nd jets etc.)**

$$R_{\mathrm{jet,pT}} = \frac{p_{\mathrm{T,jet}}}{p_{\mathrm{T,ref}}}$$

Z-jet-balance

Example picked up from ATLAS

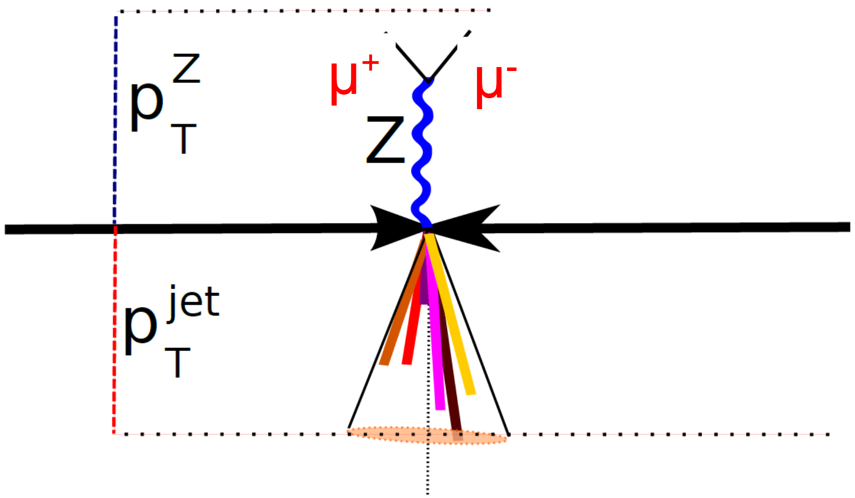
In-situ techniques used to validate JES and its uncertainty

- use well calibrated object(s) as reference for jet p_T
- compare balance of calibrated jets in data and Monte Carlo simulation

Techniques used in ATLAS:

- **Track-jets**: Compare calorimeter jets to track-jets
- **MPF method**: Employ MET projection to check γ and recoil balance
- **Photon-jet balance**: Balance p_T of γ and recoiling jet
- **Z-jet balance** (2011): Balance p_T of $Z \to ee$ with recoil jet [ATLAS-CONF-2011-159]
- **Multi-jet balance**: Balance high p_T jet with recoil system

Z-jet balance



Most precise method

Absolute calibration

- **Method 1: pT-balance against better known reference**
  - Requires nicely balanced events
  - Insensitive to less well calibrated detector regions
  - Sensitive to additional high-pT activity in events (2^{nd} jets etc.)

$$R_{\mathrm{jet,pT}} = \frac{p_{\mathrm{T,jet}}}{p_{\mathrm{T,ref}}}$$

- **Method 2: Missing transverse momentum projection fraction (MPF)**
  - No constraint to balanced events
  - Requires reasonable calibration everywhere (except object to be calibrated)

$$R_{\mathrm{jet,MPF}} = 1 + \frac{\vec{p}_{\mathrm{T,miss}} \cdot \vec{p}_{\mathrm{T,ref}}}{(p_{\mathrm{T,ref}})^2}$$

MPF method

Example picked up from ATLAS

In-situ techniques used to validate JES and its uncertainty

- use well calibrated object(s) as reference for jet p_T
- compare balance of calibrated jets in data and Monte Carlo simulation

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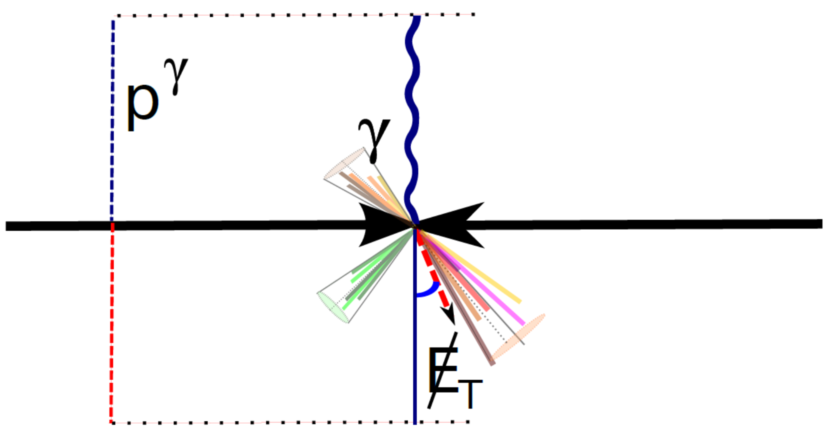
MPF method



Absolute calibration

- **General data-based principle usually the same:**

  Comparison of less precisely known with better known object!

  - **Detector measurements are most precise for:**
    - **Combination of inner tracker and outer muon tracks → muons (pT > 3-5GeV)**
    - **Inner tracker alone → isolated charged hadrons**
      (pT not too small → loops, or to large wrt. B field → straight tracks)
    - **Inner tracker and electromagnetic calorimeter → electrons**
    - **Electromagnetic calorimeter alone → photons**
  - **Propagation of more precise measurements:**
    - **From medium to lower or higher pT:**
      Best precision with Z(→ μμ) + 1 jet → abs. calibration in central detector
    - **From central detector outwards, from high event rates to areas with small event numbers:**
      Best "statistics" (Number of events) with jets →
      dijet extrapolation from central detector → towards higher rapidities
    - **Only possibility at highest pT →**
      Balance of two or more low pT jets against one high-pT jet

Take home message

- **General data-based principle usually the same:**

  Comparison of less precisely known with better known object!

  - Detector measurements are most precise for:
    - Combination of inner track… …ons (pT > 3-5GeV)
    - Inner track… (pT not too … large wrt. B field → straight tracks)
    - Inner tracker and electromagnetic calorimeter → electrons
    - Electromagnetic calorimeter alone → photons

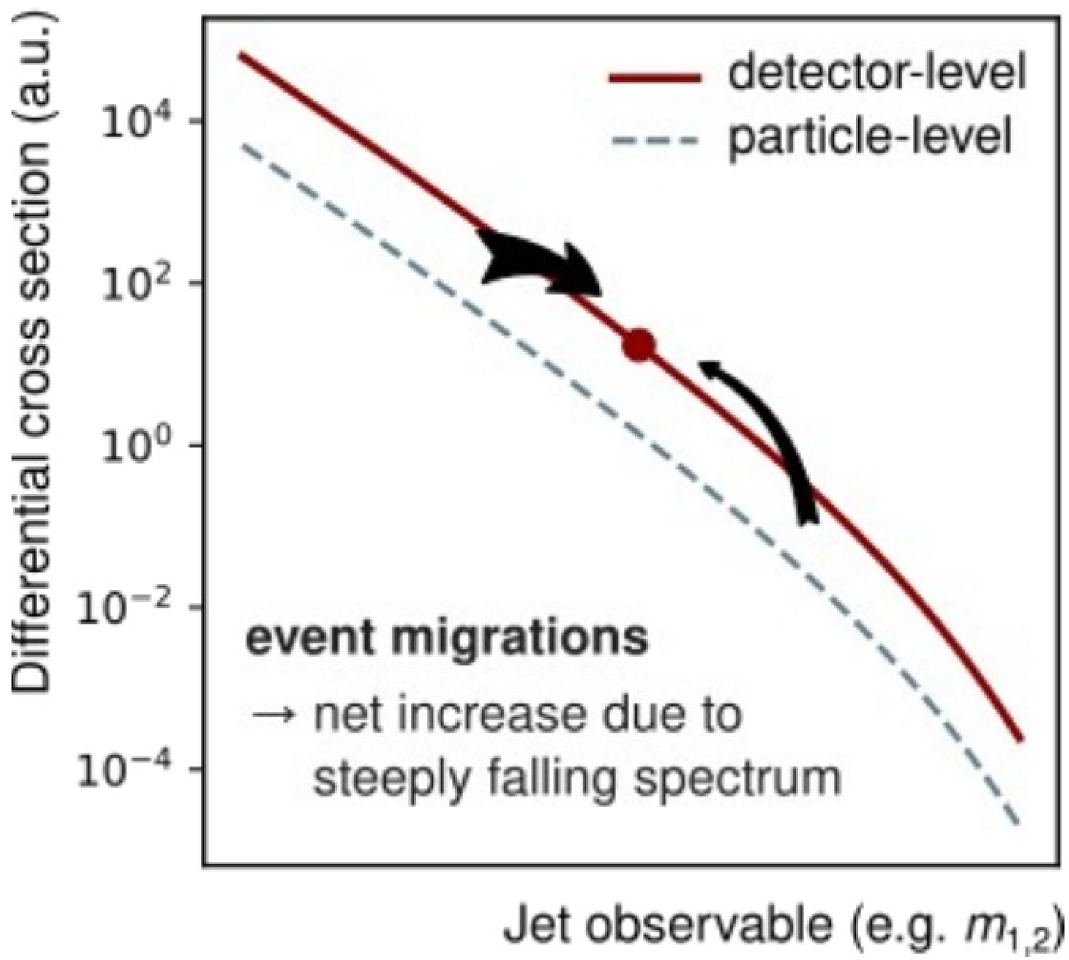
Calibrate less precisely measured object against more precisely measured one!

  - Propagation of more precise measurements:
    - From medium to lower or higher pT:
      Best prec… …μμ) + 1 jet → abs. calibration in central detector
    - From cen… …event rates to areas with small event numbers:
      Best "statistics" (Number of events) …
      dijet extrapolation from central detector → towards … rapidities
    - Only possibility at highest pT →
      Balance of two or more low pT jets against one high-pT jet

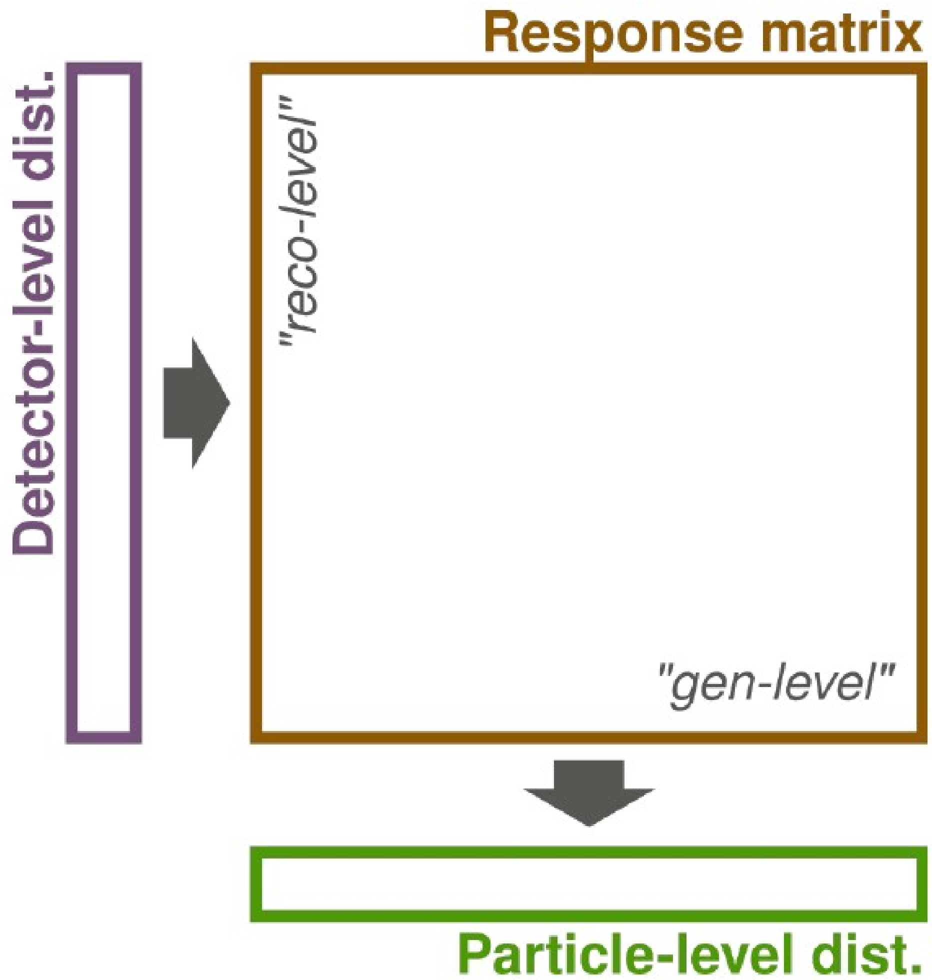
Calibrate less well-calibrated detector region against better calibrated one!

Jet energy resolution

Net effect of JER often looks like increase in cross section



Use response matrix from MC simulation to unfold the smearing.



Response matrix