Tools in particle physics

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Wichtig!

Ab Montag, den 14.12., bis zum 23.12. werden Sie gebeten Online-Umfragen zu unseren Veranstaltungen auszfüllen. Bitte geben Sie Rückmeldung! Die Links finden Sie auch auf den ILIAS Seiten.

Link zur TP I Vorlesungsumfrage

Link zu TP I Praktikumsumfrage

Summary

- Strongly interacting particles ("hadrons") are composite objects.
- The pattern of hadrons is best described by introducing a new three-valued quantum number: "color"
- The constituents carrying color charges are named "quarks".
- Originally, two types of quarks, "up" and "down" with electrical charges +2/3 and -1/3 (never observed in nature freely …)
- Complemented with further quark types: strange, charm, bottom, top
- Hadrons come in two types:
  - Mesons are made of one quark and one anti-quark
  - (Anti-)Baryons are made of three (anti-)quarks
- Strong interactions are derived from local gauge invariance of color SU(3)
- Eight massless, self-interacting gluons are the carriers of the strong force
- In contrast to QED, quantum corrections lead to color forces decreasing with energy (asymptotic freedom) and increasing with distance (confinement)

Quark masses

- Formalism for quark masses more involved than for leptons:
  - All quarks **massive** (leptons: only charged leptons massive)
  - **Flavor mixing**: mass eigenstates (physical particles) $\neq$ eigenstates of interactions (particles coupling to gauge bosons)

- Classification into $SU(2)_L$ multiplets: left-handed doublet, right-handed singlets:

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad u_R, \quad d_R$$

- Mechanism: **Yukawa coupling to Higgs field** (first step: before SSB)
  - **Two separate terms** for masses of up-type and down-type quarks
  - In principle: require two separate Higgs doublets, but luckily $\tilde{\Phi} = i\tau^2\Phi^*$ works

$$\mathcal{L}_{\text{Yukawa}} = -f_d(\overline{Q}_L \Phi d_R) - f_u(\overline{Q}_L \tilde{\Phi} u_R) + \text{h.c.}$$

  - Flavor mixing for three generations: generalize to **matrix equation**

$$\mathcal{L}_{\text{Yukawa}} = -f_d^{\alpha\beta}(\overline{Q}_L^\alpha \Phi d_R^\beta) - f_u^{\alpha\beta}(\overline{Q}_L^\alpha \tilde{\Phi} u_R^\beta) + \text{h.c.} \quad \text{with } \alpha, \beta = 1, 2, 3$$

Quark interactions

- Sketch of next steps:
  - Replace Higgs field by Higgs VEV *v* and physical Higgs *h*(*x*) after SSB
  - Diagonalize mass matrix → **CKM mixing matrix** (later)

- **Charged currents** of quarks: **mixing** with CKM matrix V_{CKM}

$$J^{\mu,+}_{\mathrm{CC}} = (\overline{u}, \overline{c}, \overline{t}) \left(\gamma^\mu \frac{1}{2}(1-\gamma_5) V_{\mathrm{CKM}} \right) \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

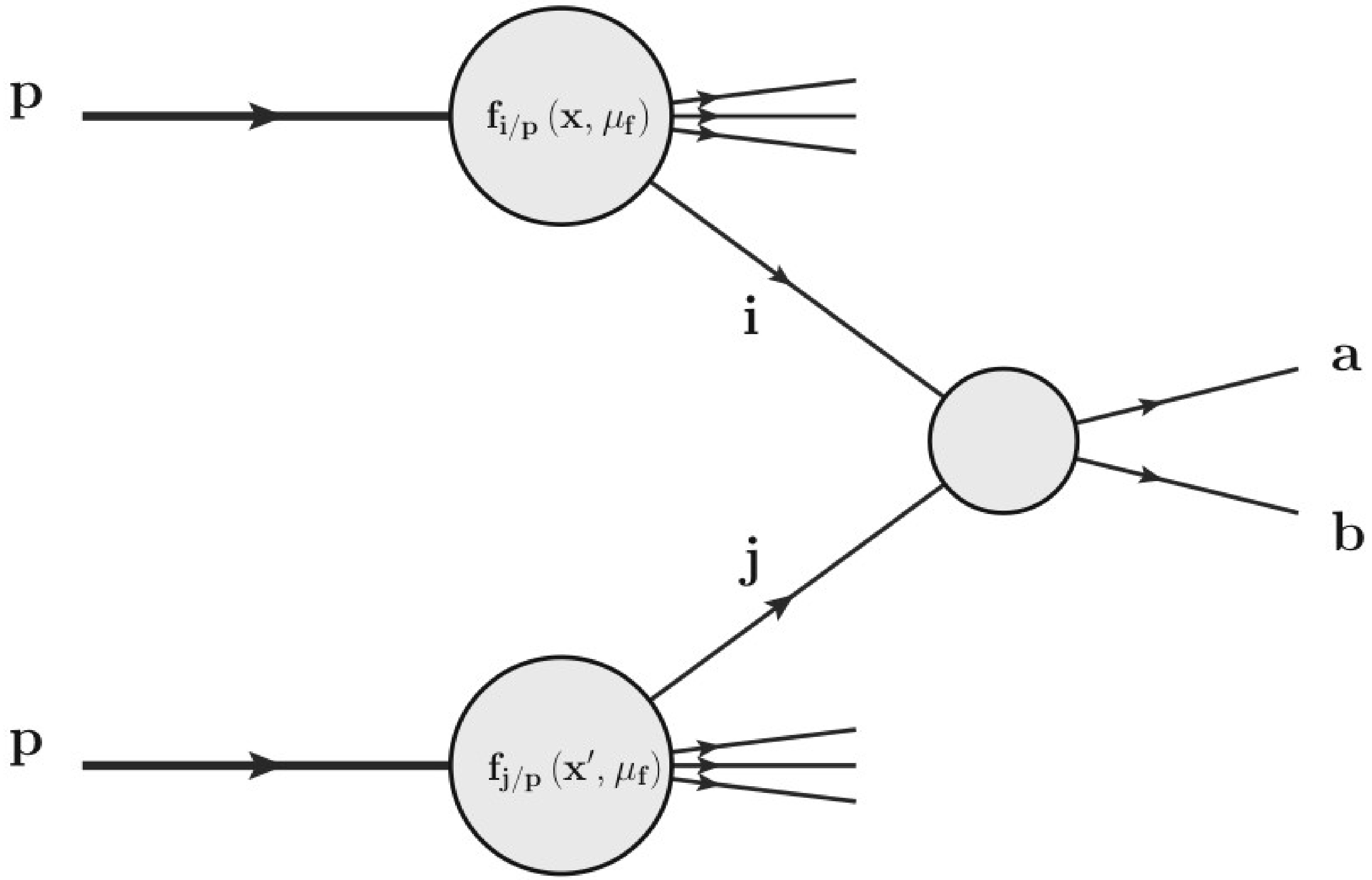
- **Neutral currents** of quarks: **no** mixing (“flavor diagonal”)

$$J^{\mu}_{\mathrm{NC}} = (\overline{u}, \overline{c}, \overline{t})\, \gamma^\mu \left[I_{3,u}(1-\gamma_5) - 2Q_u \sin^2\theta_W \right] \begin{pmatrix} u \\ c \\ t \end{pmatrix}$$

$$+ (\overline{d}, \overline{s}, \overline{b})\, \gamma^\mu \left[I_{3,d}(1-\gamma_5) - 2Q_d \sin^2\theta_W \right] \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Theory cross section

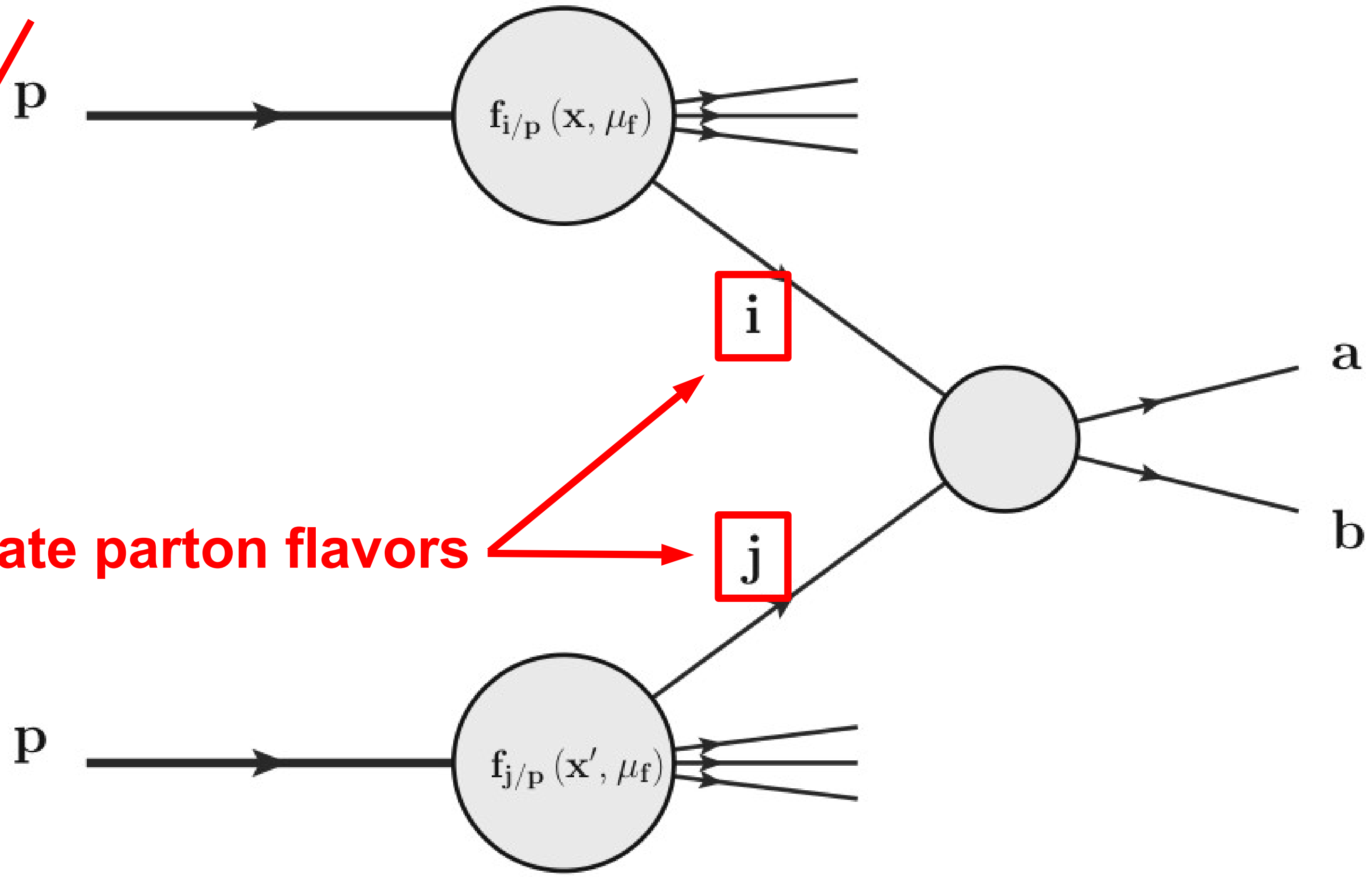
$$\mathrm{d}\sigma_{(pp\to X)} = \sum_{i,j} \int \mathrm{d}x\mathrm{d}x' f_{i/p}(x,\mu_f) \cdot f_{j/p}(x',\mu_f) \times \mathrm{d}\hat{s}_{(ij\to X)}(x,x',\mu_f,\mu_r,\alpha_s(\mu_r))$$



Theory cross section

$$d\sigma_{(pp\to X)} = \sum_{i,j} \int dx dx' f_{i/p}(x,\mu_f)\cdot f_{j/p}(x',\mu_f) \times d\hat{s}_{(ij\to X)}(x,x',\mu_f,\mu_r,\alpha_s(\mu_r))$$

sum over



initial state parton flavors

Theory cross section

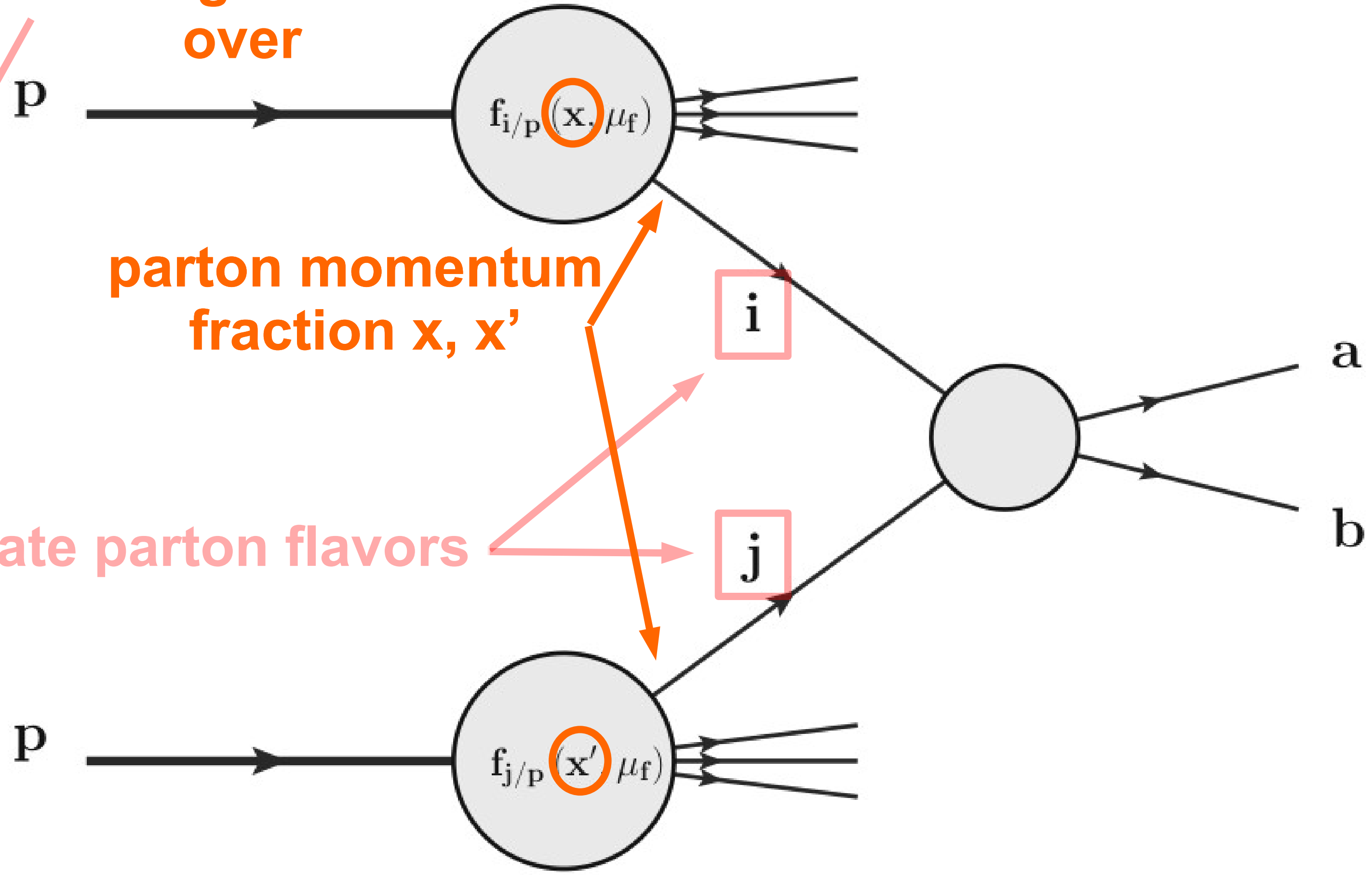
$$d\sigma_{(pp\to X)} = \sum_{i,j} \int dx dx' f_{i/p}(x,\mu_f) \cdot f_{j/p}(x',\mu_f) \times d\hat{s}_{(ij\to X)}(x,x',\mu_f,\mu_r,\alpha_s(\mu_r))$$

sum over

integration over

parton momentum fraction x, x'

initial state parton flavors



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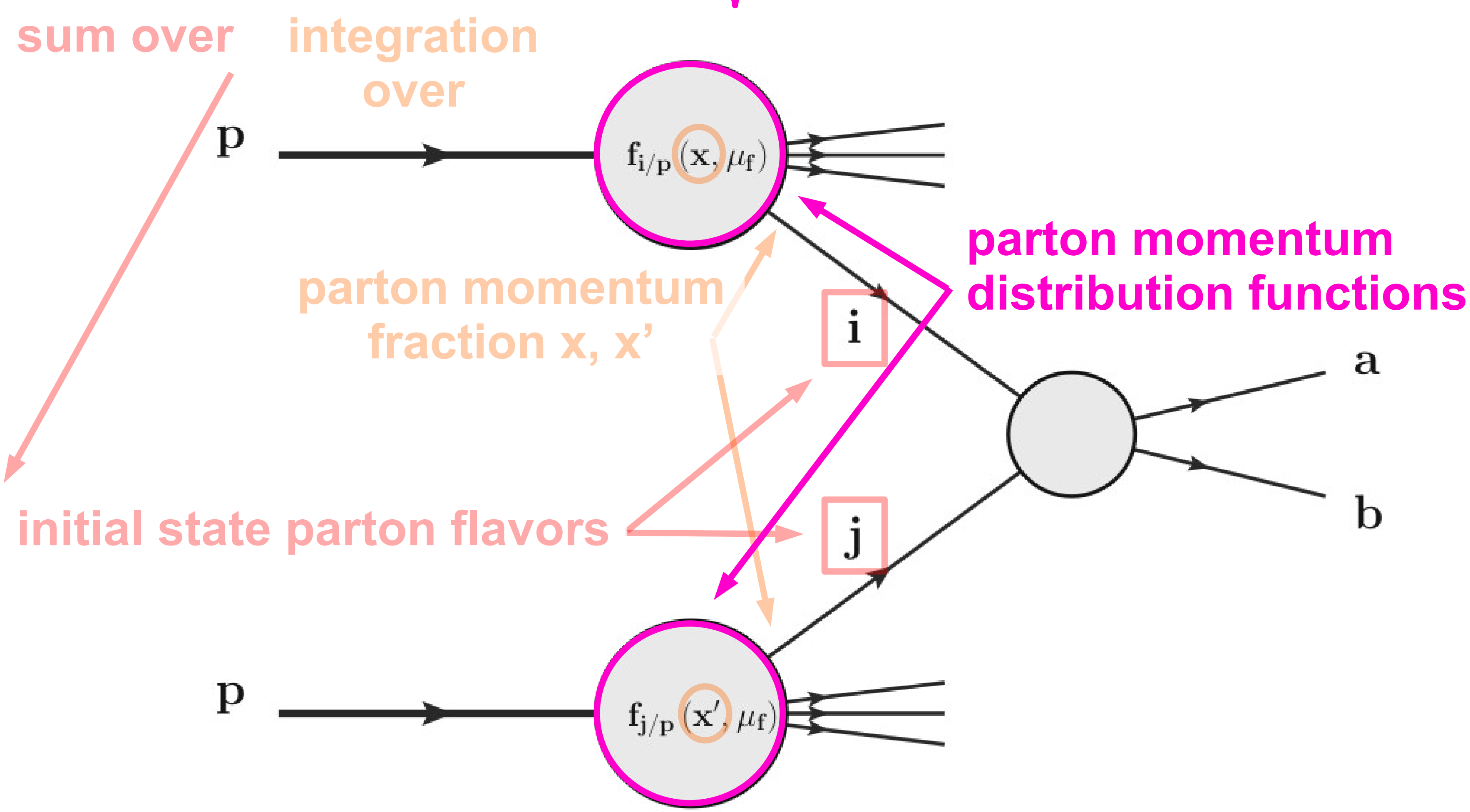

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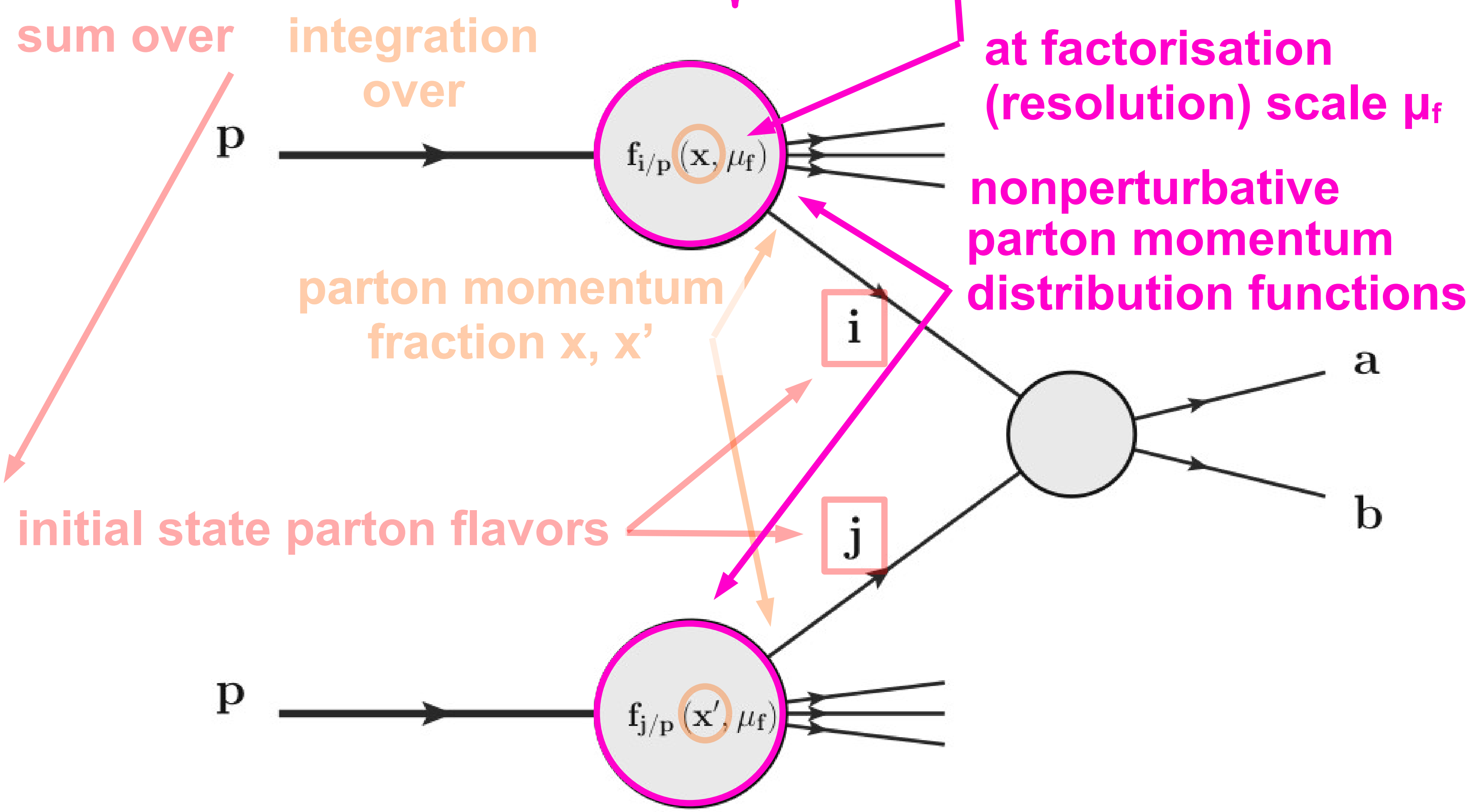

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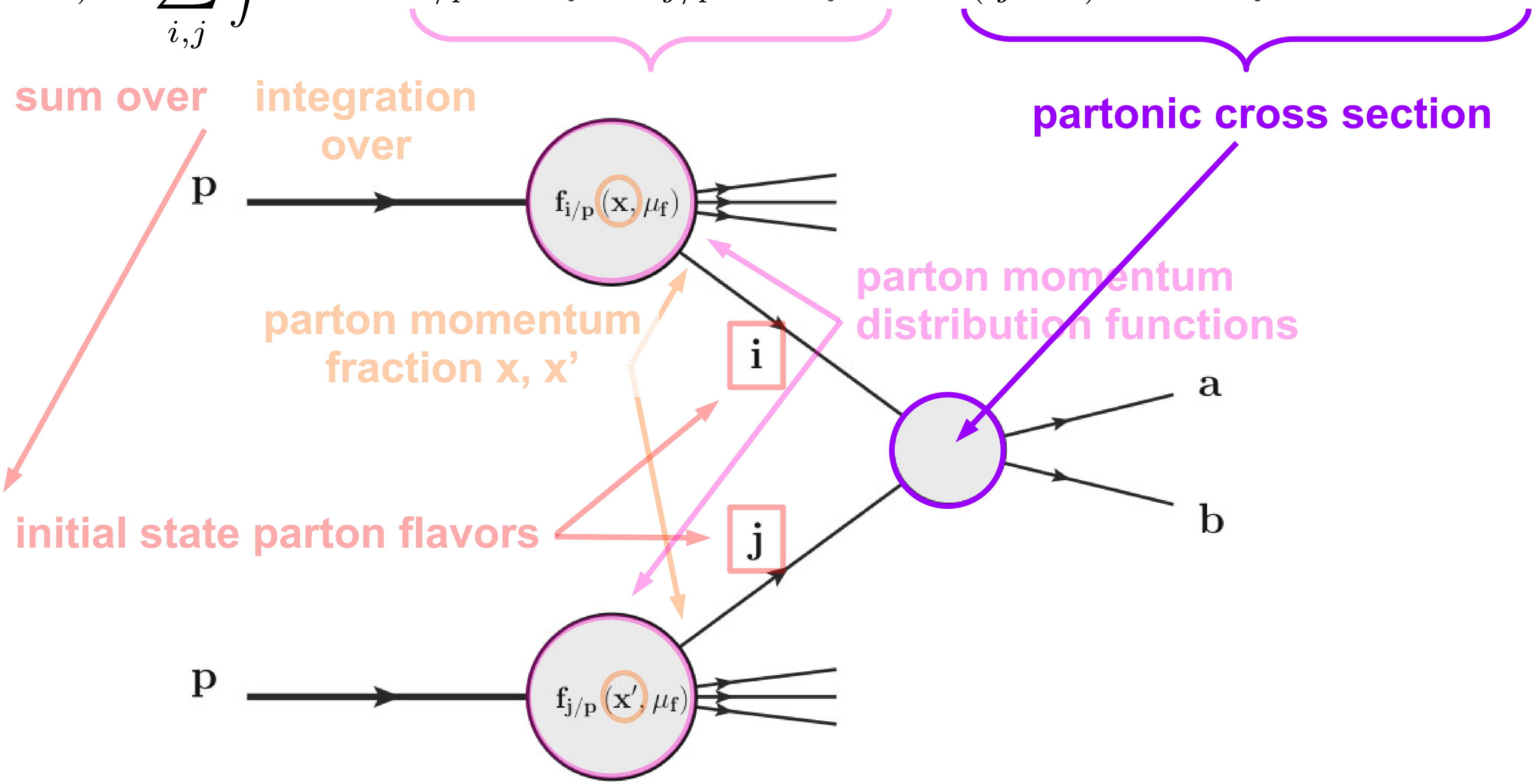

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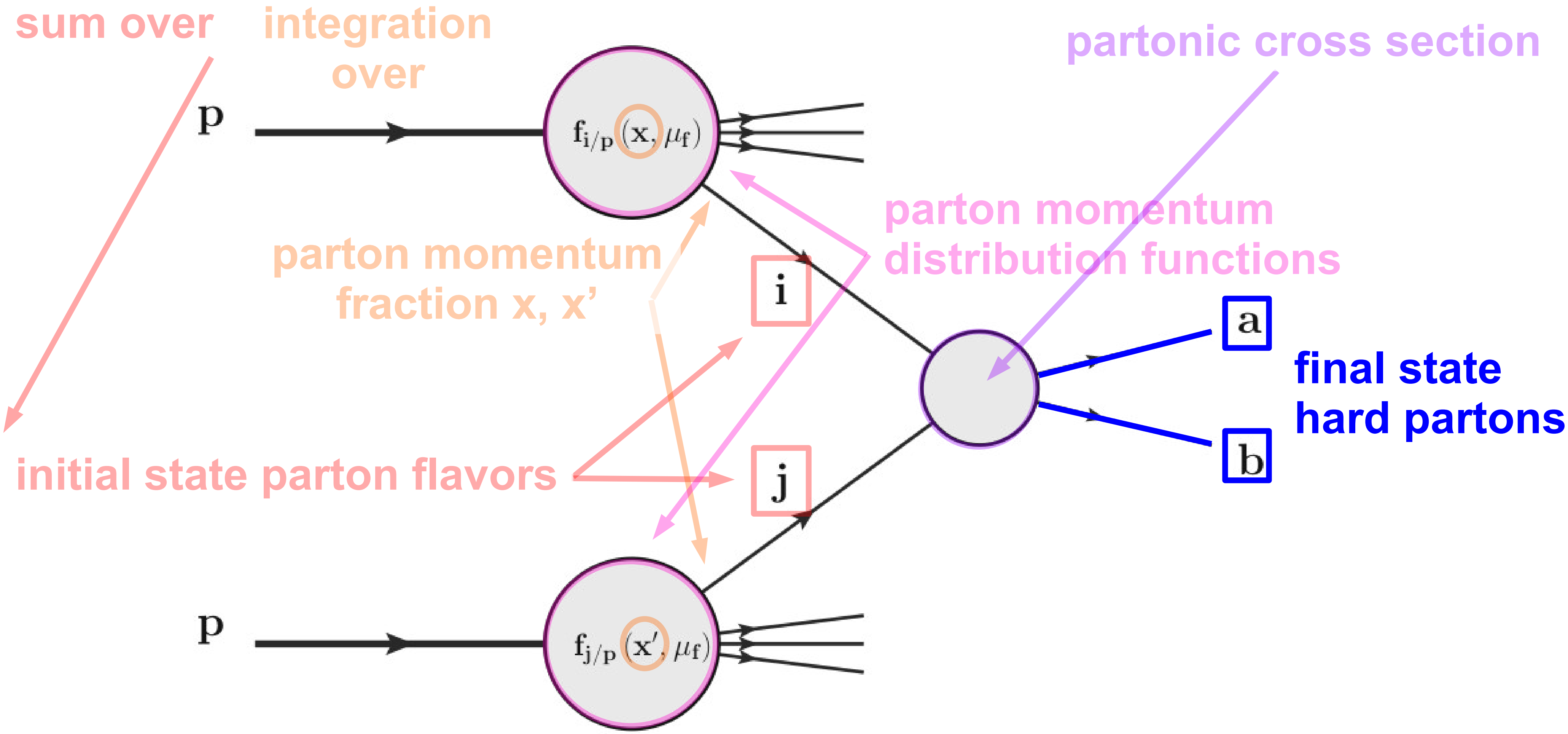
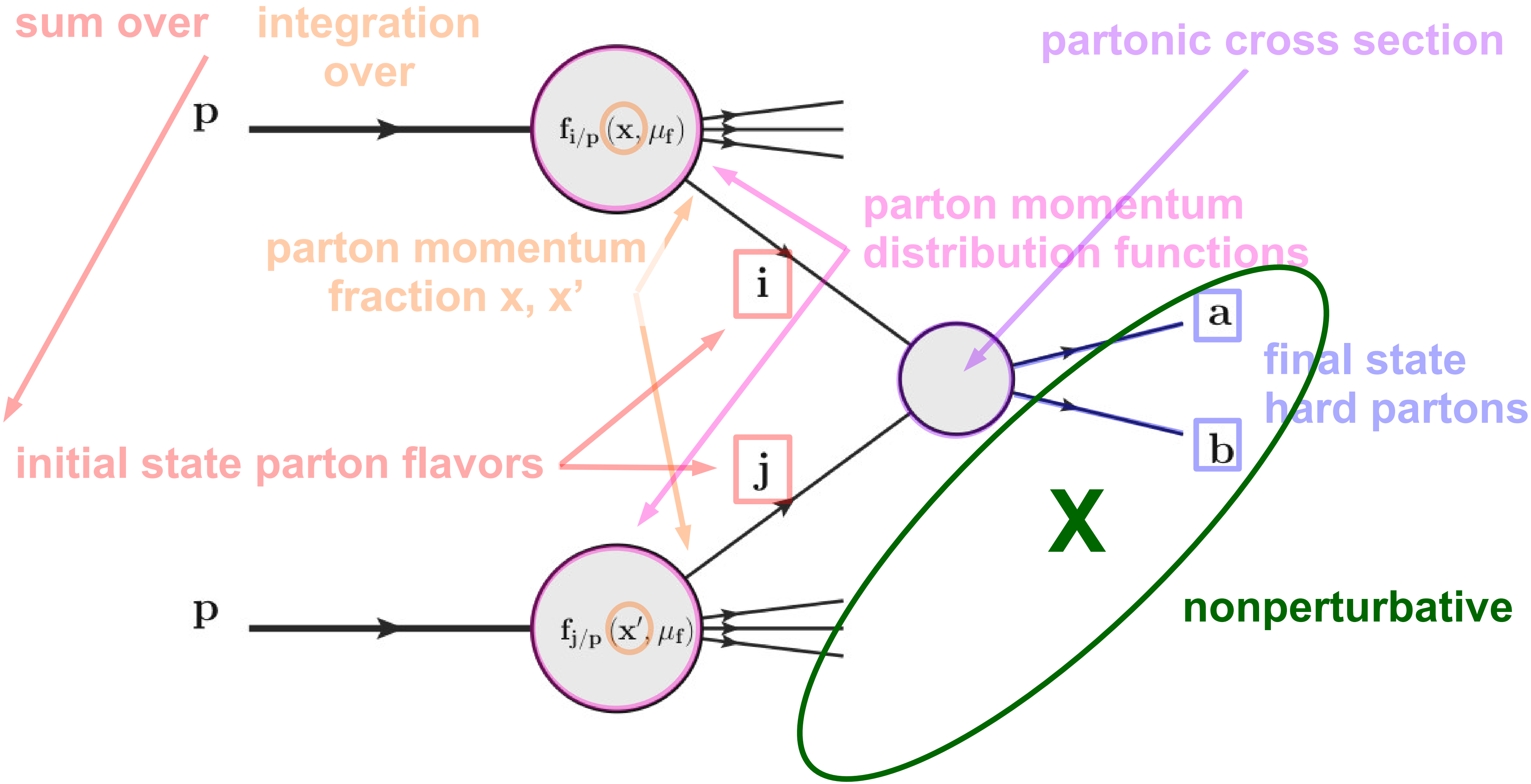
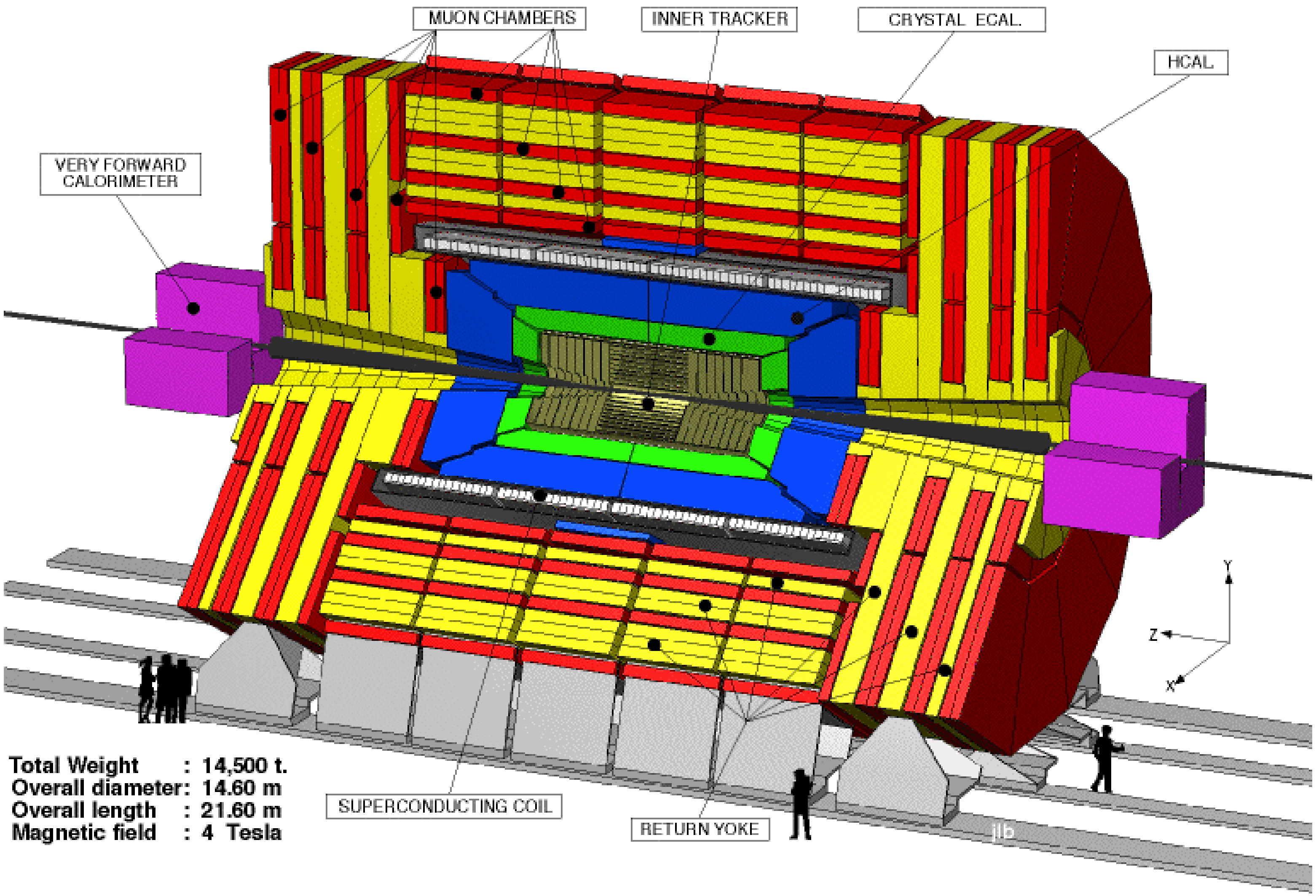


Theory cross section

$$\mathrm{d}\sigma_{(pp\to X)} = \sum_{i,j}\int \mathrm{d}x\mathrm{d}x'\, f_{i/p}(x,\mu_f)\cdot f_{j/p}(x',\mu_f)\times \mathrm{d}\hat{s}_{(ij\to X)}(x,x',\mu_f,\mu_r,\alpha_s(\mu_r))$$



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:

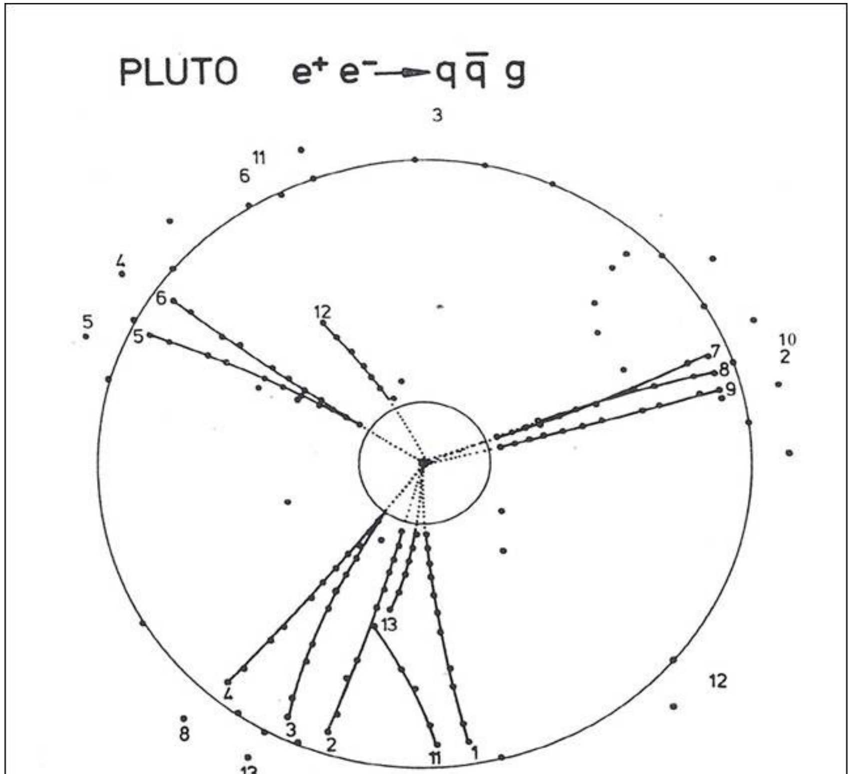
- Solenoid → 3.8T

Such complex detectors require detailed simulations –> GEANT, cf. previous lectures & GEANT exercise!

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

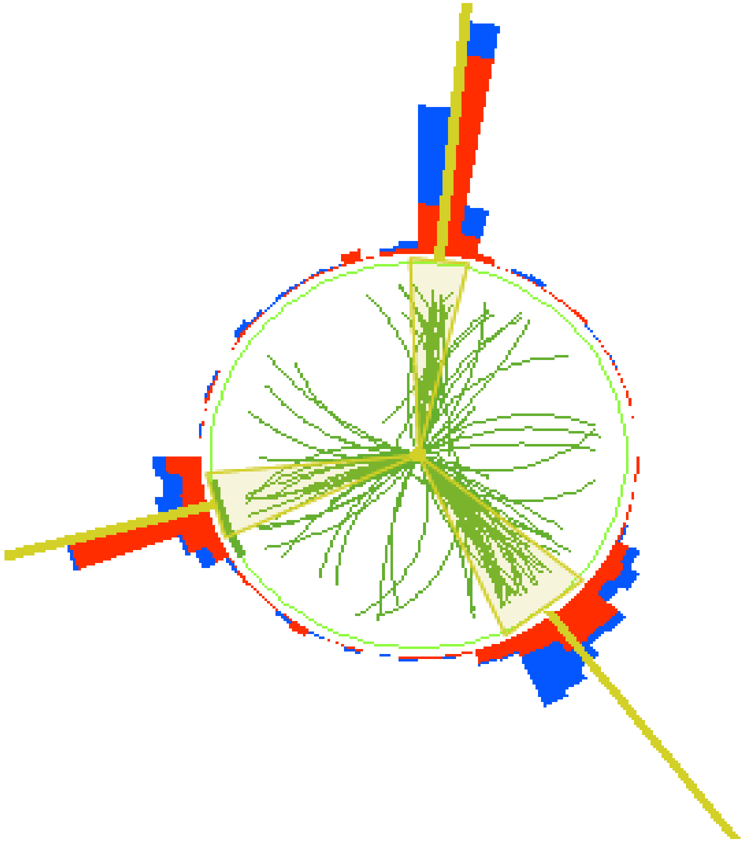
3-Jet events 1979 – 2010

PLUTO,1979
e^+e^-,$\sqrt{s}$ = 30 GeV
Multiplicity ~ 10



PLUTO(1979).

CMS, 2010
pp,$\sqrt{s}$ = 7000 GeV
Multiplicity ~ 100



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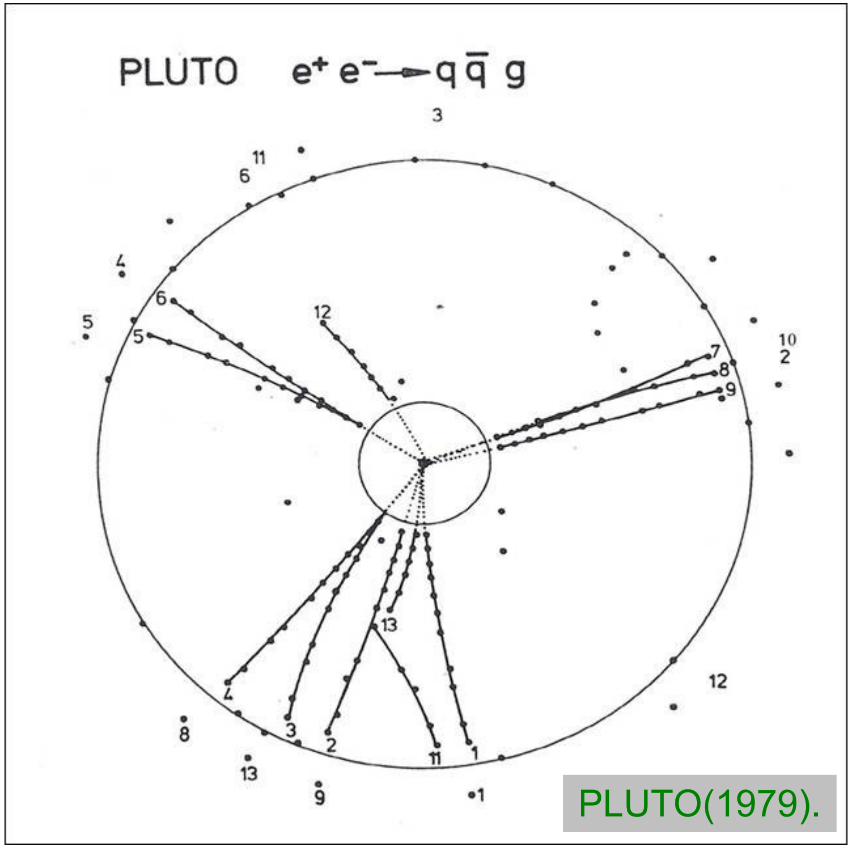

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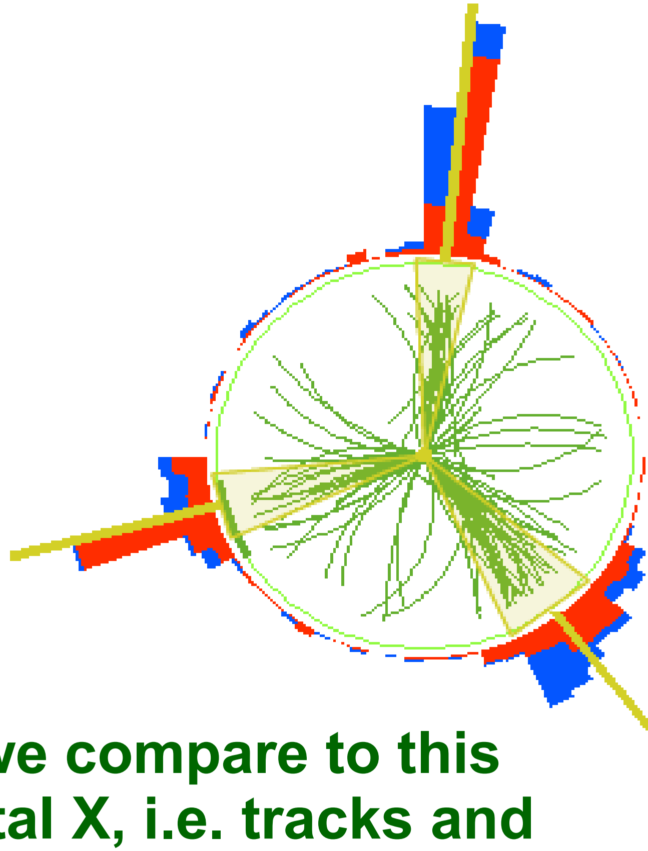
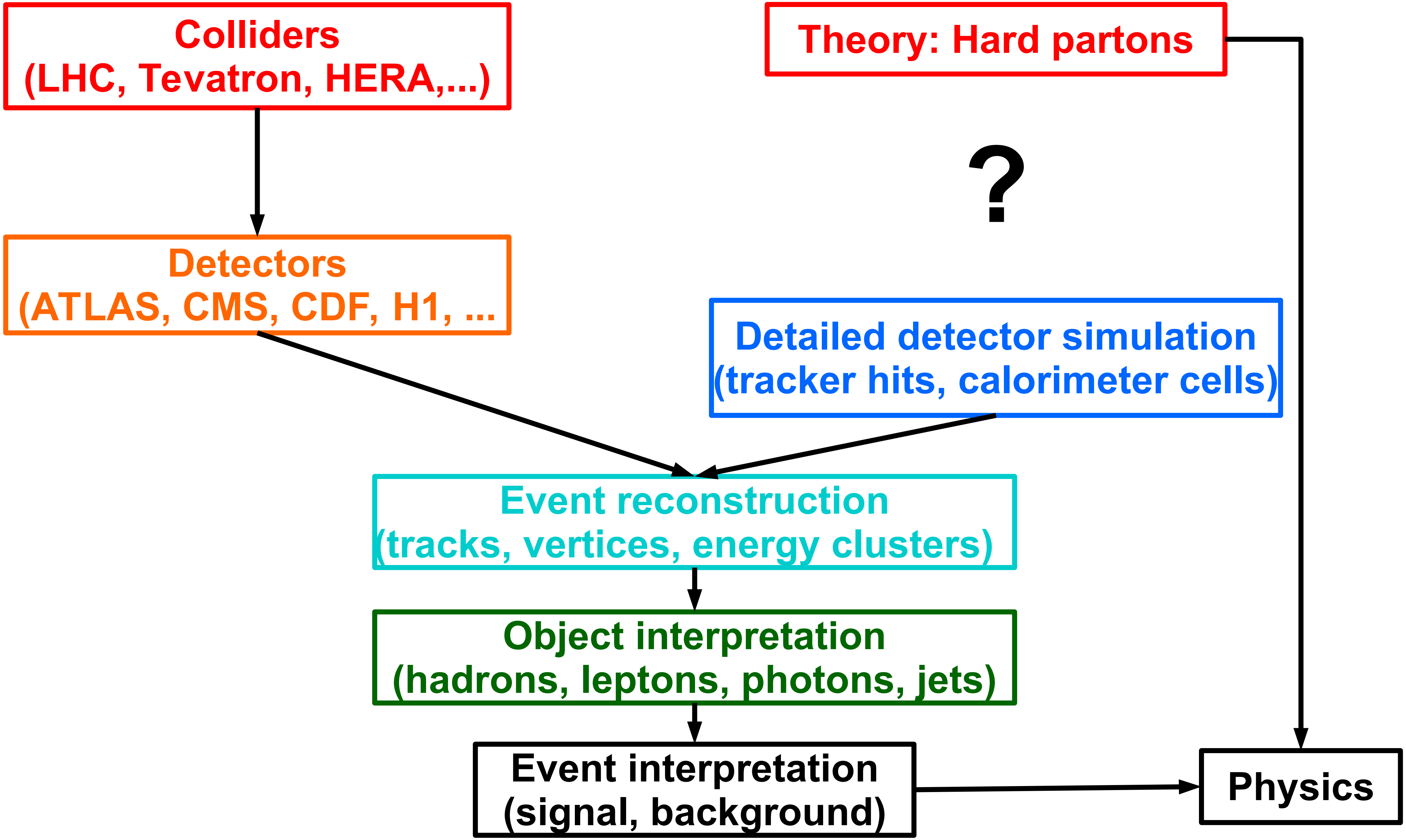


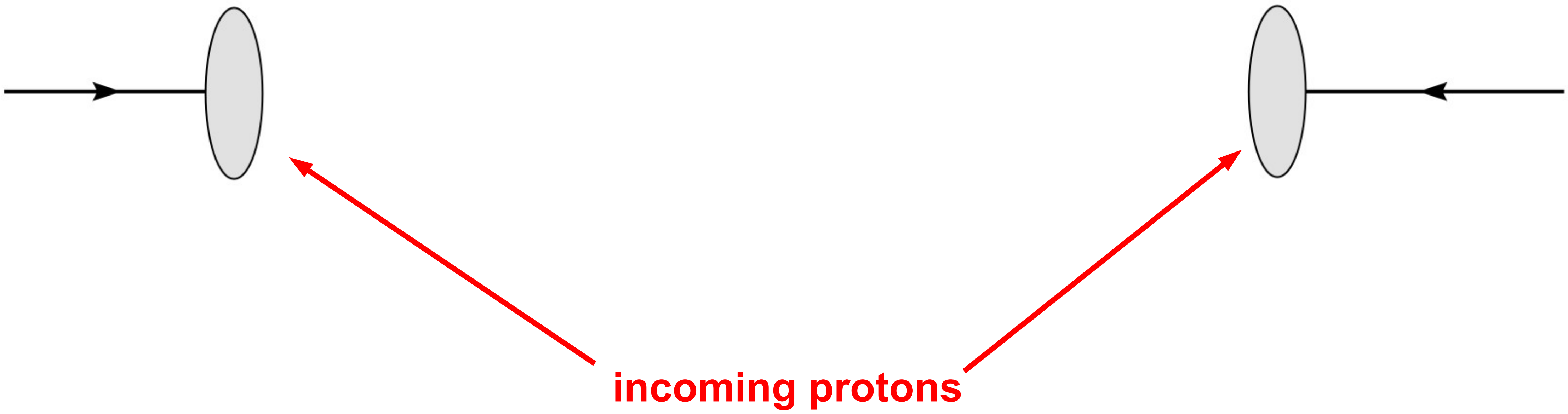
What can we compare to this experimental X, i.e. tracks and energy depositions?

X

What do we need?

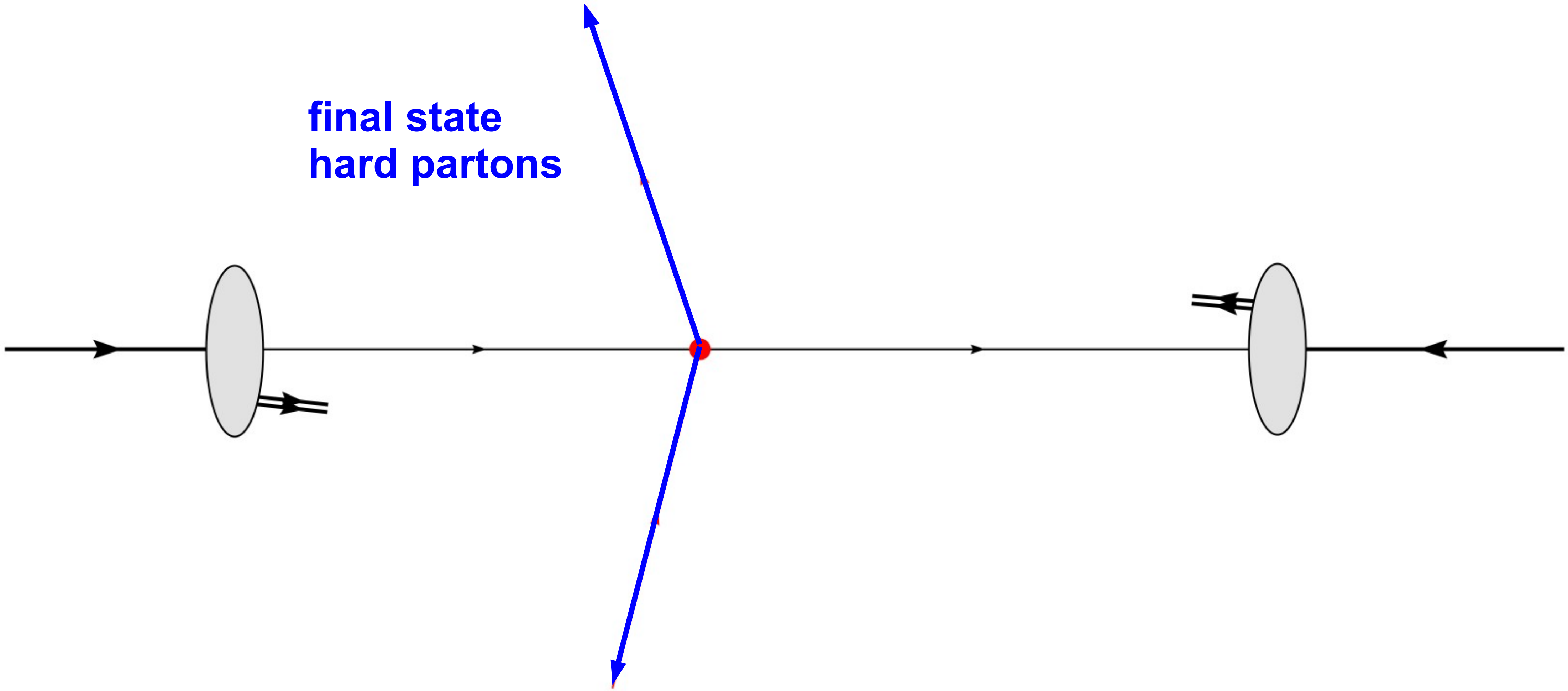


Tools: MC event generators

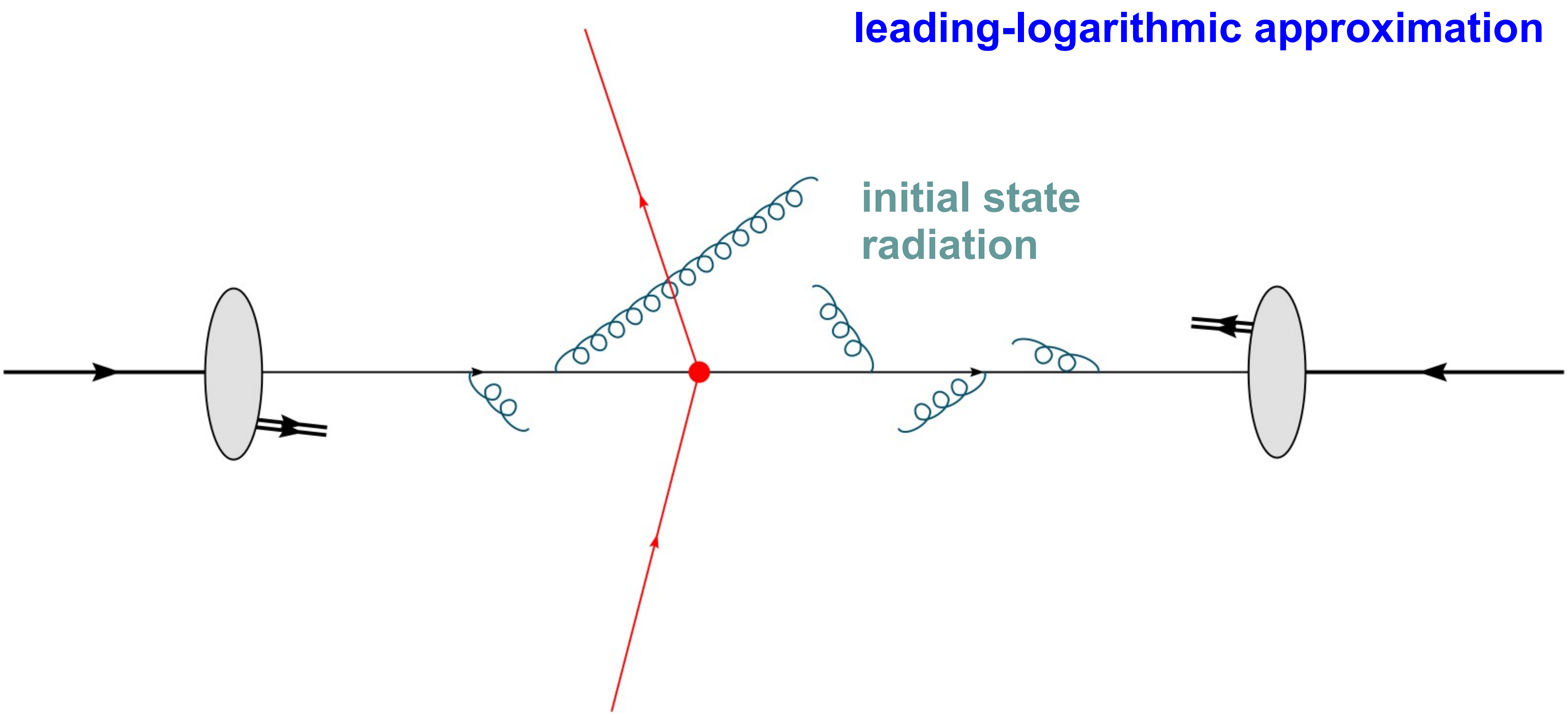


Tools: MC event generators

perturbative expansion

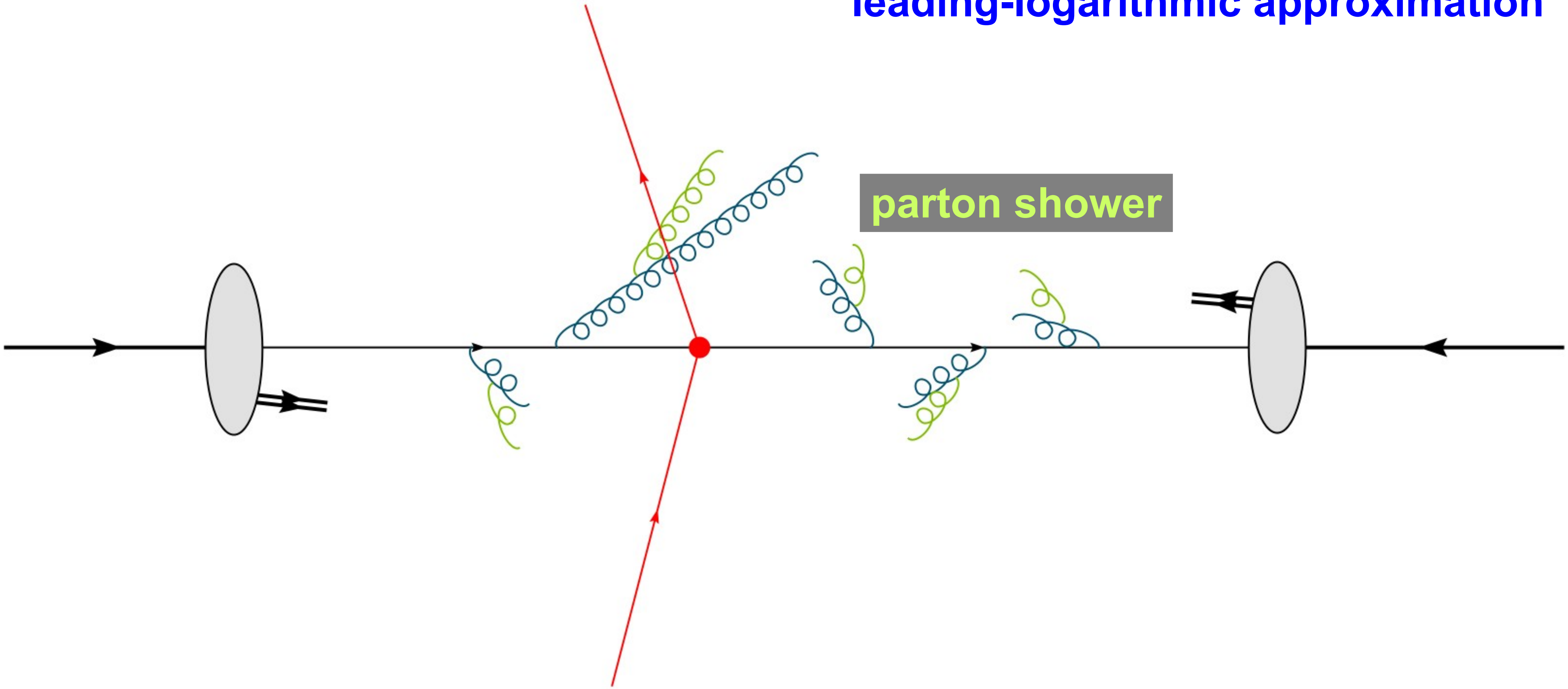


Tools: MC event generators

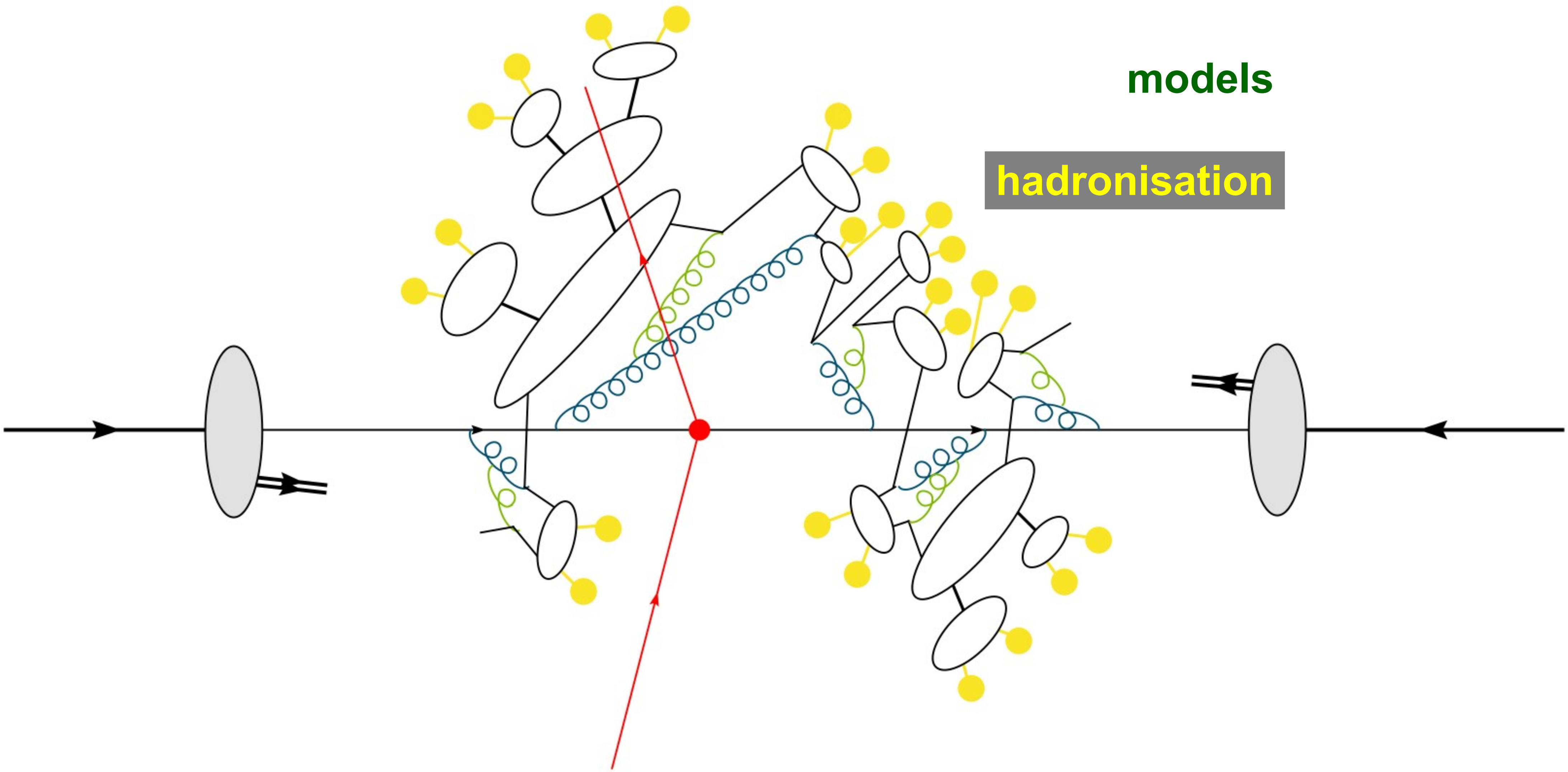


Tools: MC event generators

leading-logarithmic approximation



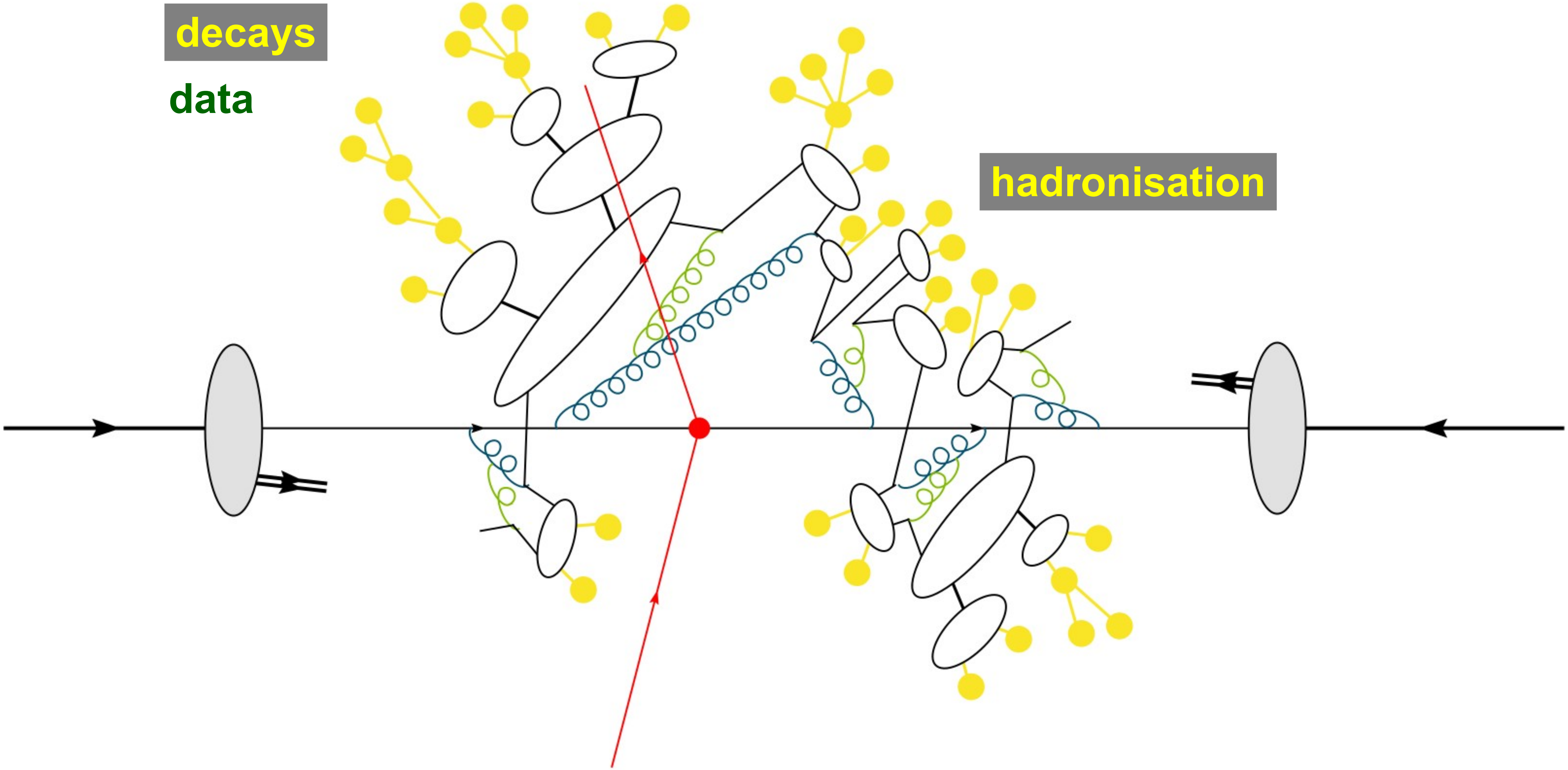
Tools: MC event generators



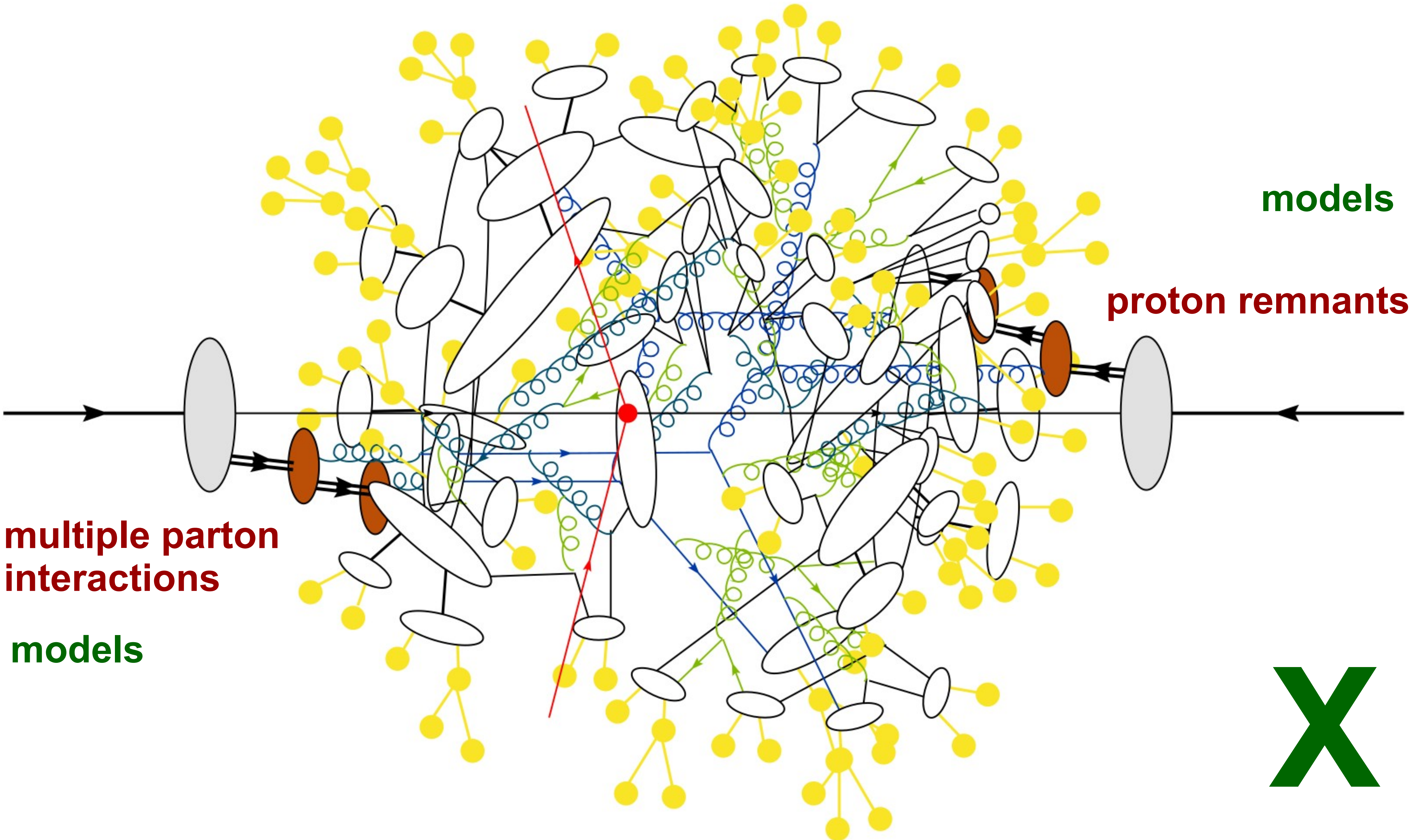
models

hadronisation

Tools: MC event generators



Tools: MC event generators



models

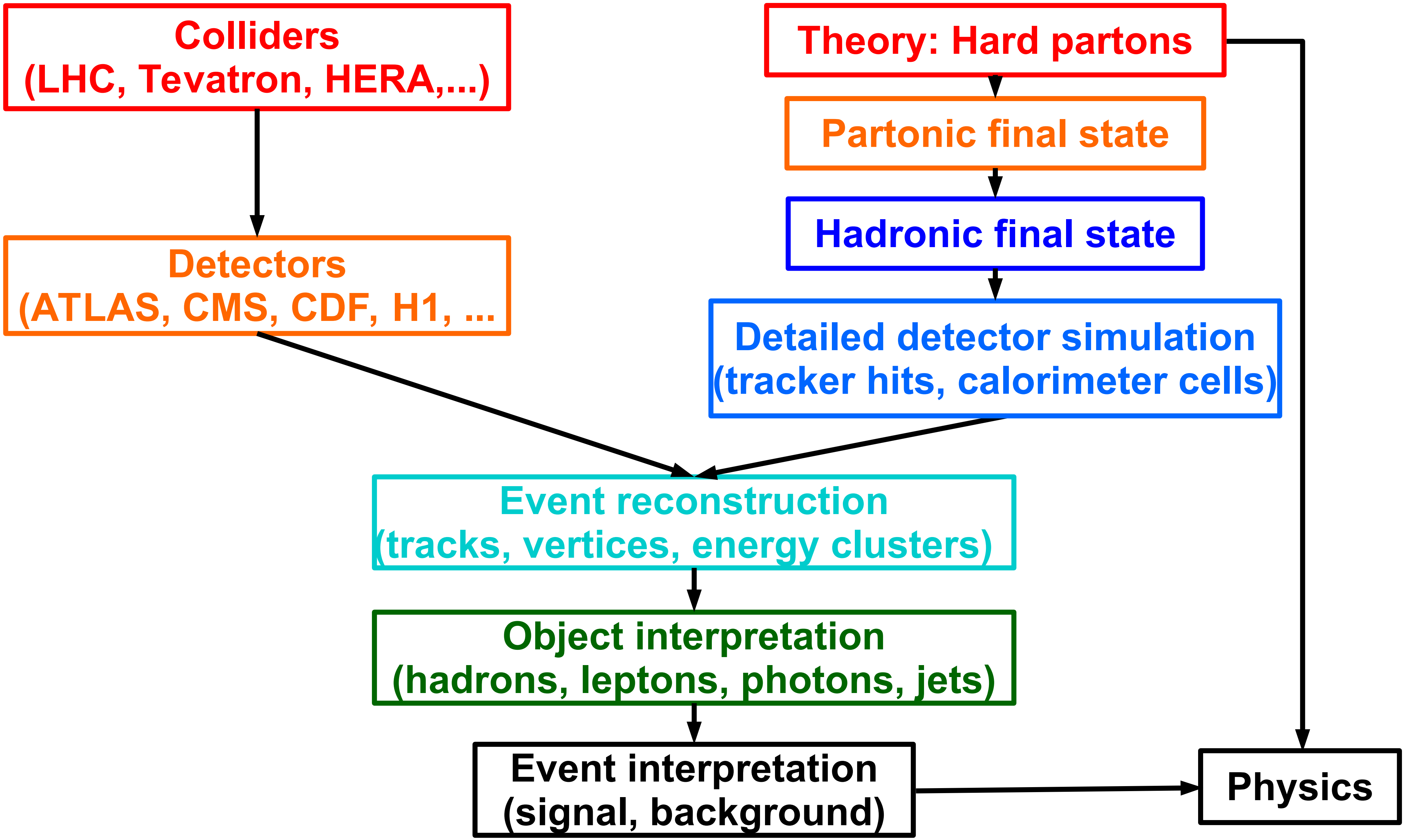
proton remnants

multiple parton interactions

models

X

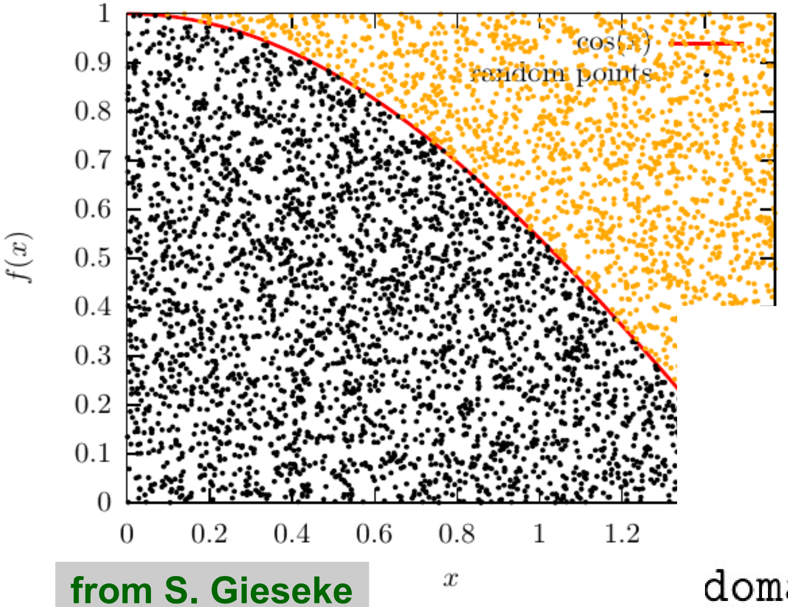
The whole picture



The MC in Monte Carlo event generators ...

- Theory leads to very complex multidimensional integrals
- corresponding to probability distributions
  - Integral inversion: Very efficient, possible only in the simplest cases
  - Numerical integrations mandatory:
    - Hit and miss: Widely applicable, but very inefficient
    - Simple MC integration: Still quite inefficient
    - MC integration with importance sampling: Much better
    - VEGAS: Automatic importance sampling, adaptive grids, robust
- Available general purpose MC event generators: Overview, Phys. Rept. 504 (2011) 145.
  - Herwig7 → see tomorrow's exercise — Herwig++, Eur. Phys. J. C 58 (2008) 639.
  - Pythia8 — Pythia8, Comput. Phys. Commun. 178 (2008) 852.
  - Sherpa — Sherpa, JHEP02 (2009) 007.

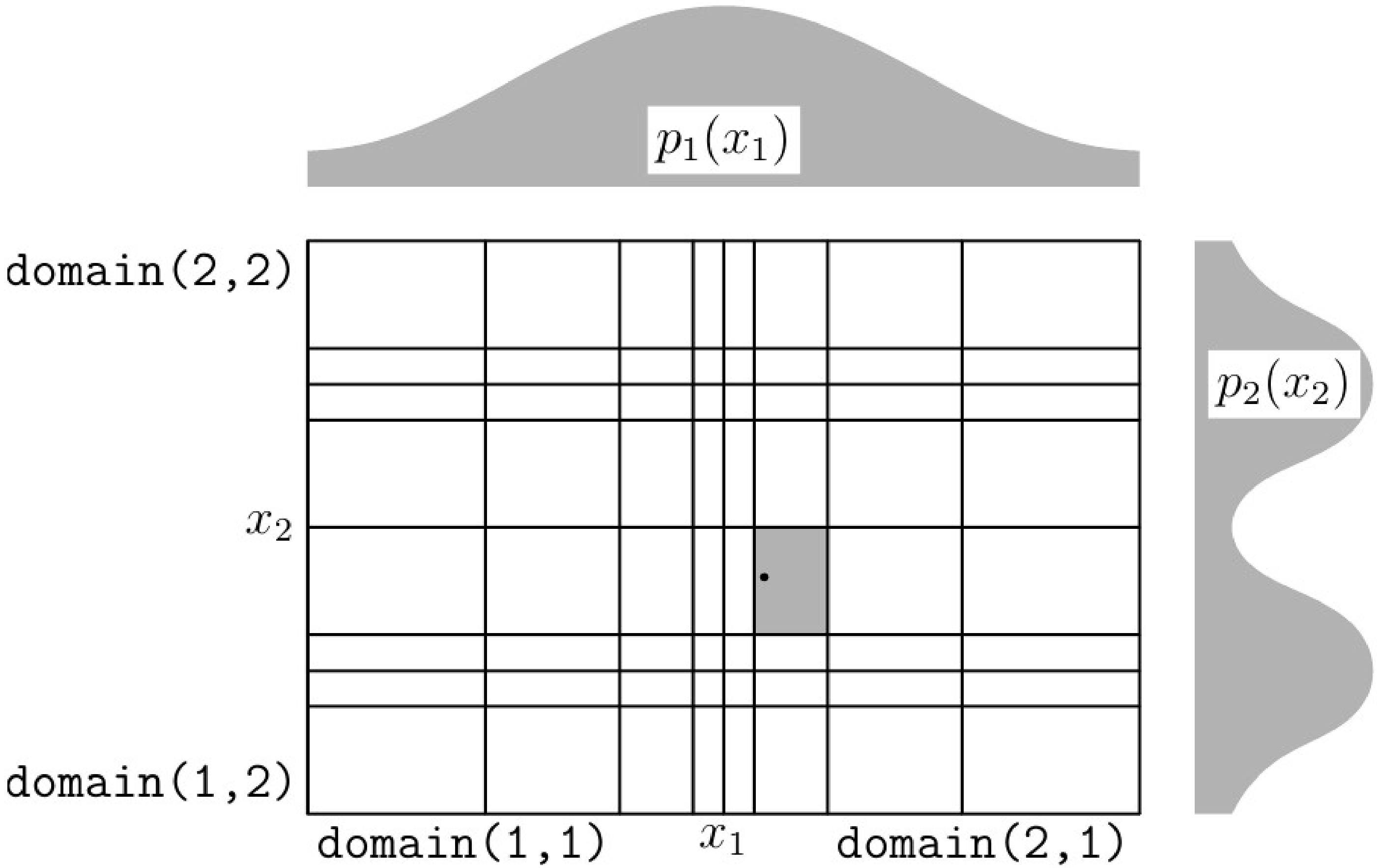
Numerical integration



from S. Gieseke

Hit and miss

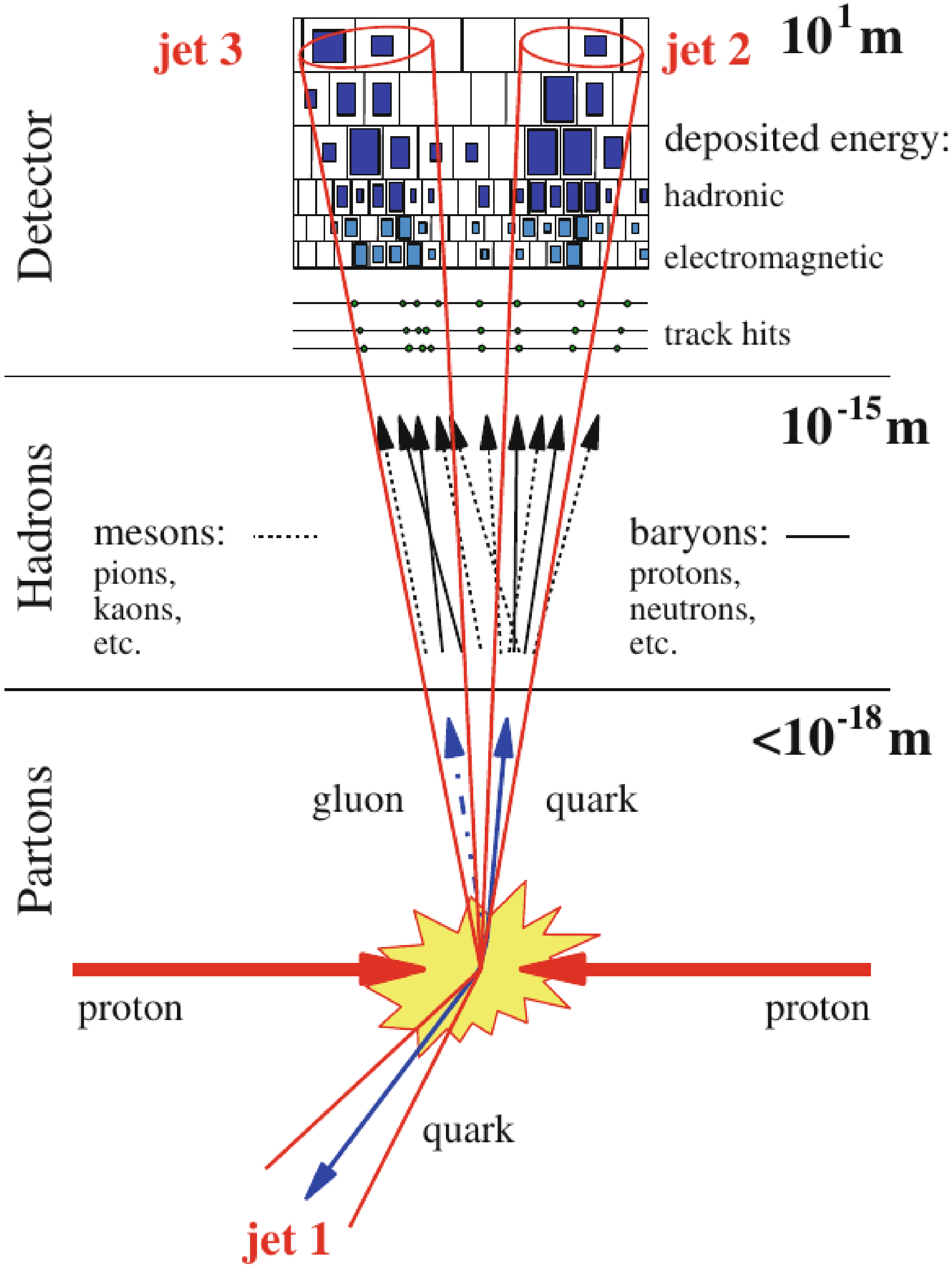
VEGAS like adaptation



[from T. Ohl, VAMP]

Merits lectures of its own!

Tools: Jets

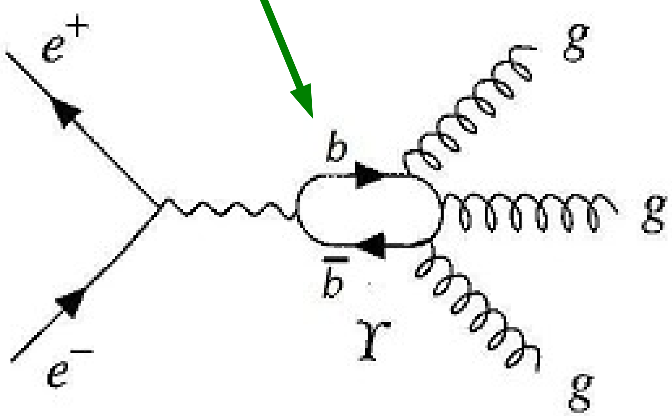


jet 3
jet 2
10^1 m
Detector
deposited energy:
hadronic
electromagnetic
track hits
10^{-15} m
Hadrons
mesons: pions, kaons, etc.
baryons: protons, neutrons, etc.
$<10^{-18}$ m
Partons
gluon
quark
proton
proton
quark
jet 1

PLUTO @ DORIS, 1978

$\sqrt{s}$ = 9.46 GeV

Ypsilon resonance



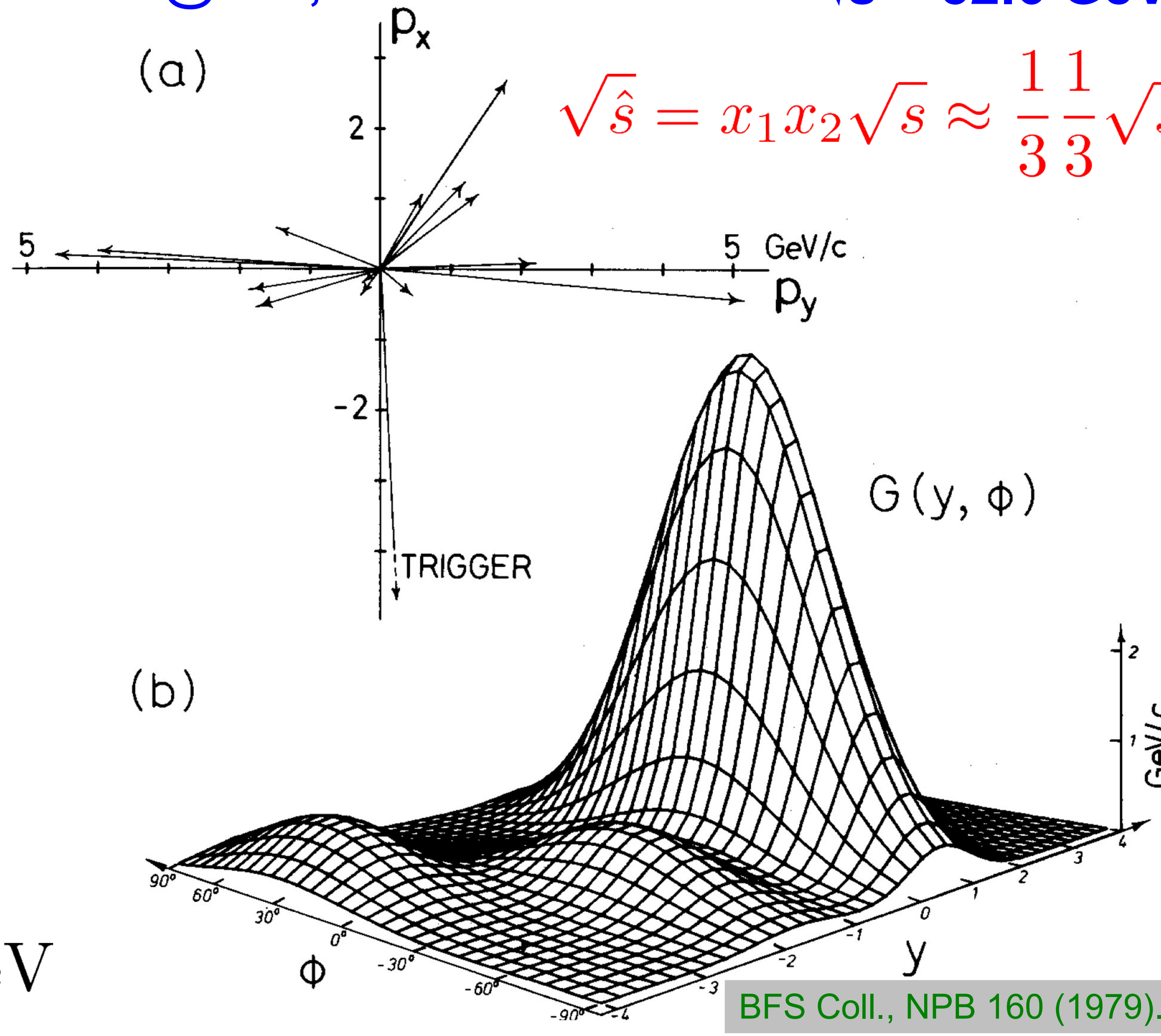
Energy for particle production should be larger than typical hadronisation effects with:

$$E \gg p_{\mathrm{T,had}} \approx \Lambda \approx 300\mathrm{MeV}$$

BFS @ ISR, 1979

$\sqrt{s}$ = 52.6 GeV

$$\sqrt{\hat{s}} = x_1 x_2 \sqrt{s} \approx \frac{1}{3}\frac{1}{3}\sqrt{s}$$

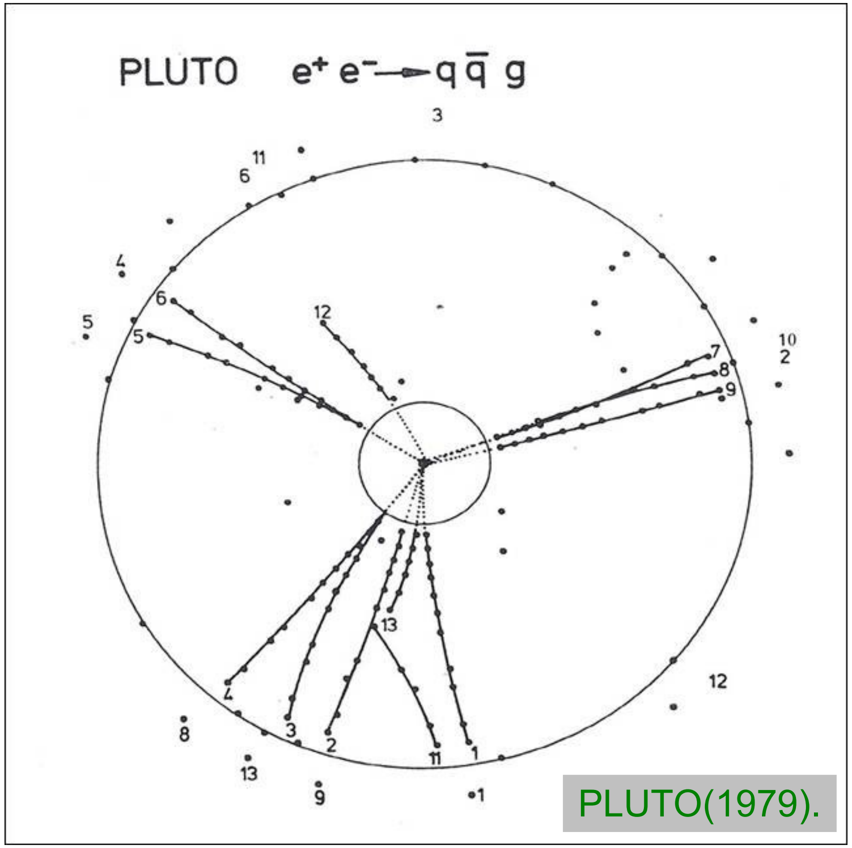


BFS Coll., NPB 160 (1979).

First indications of jets

Even gluons … but not as free particles, but:

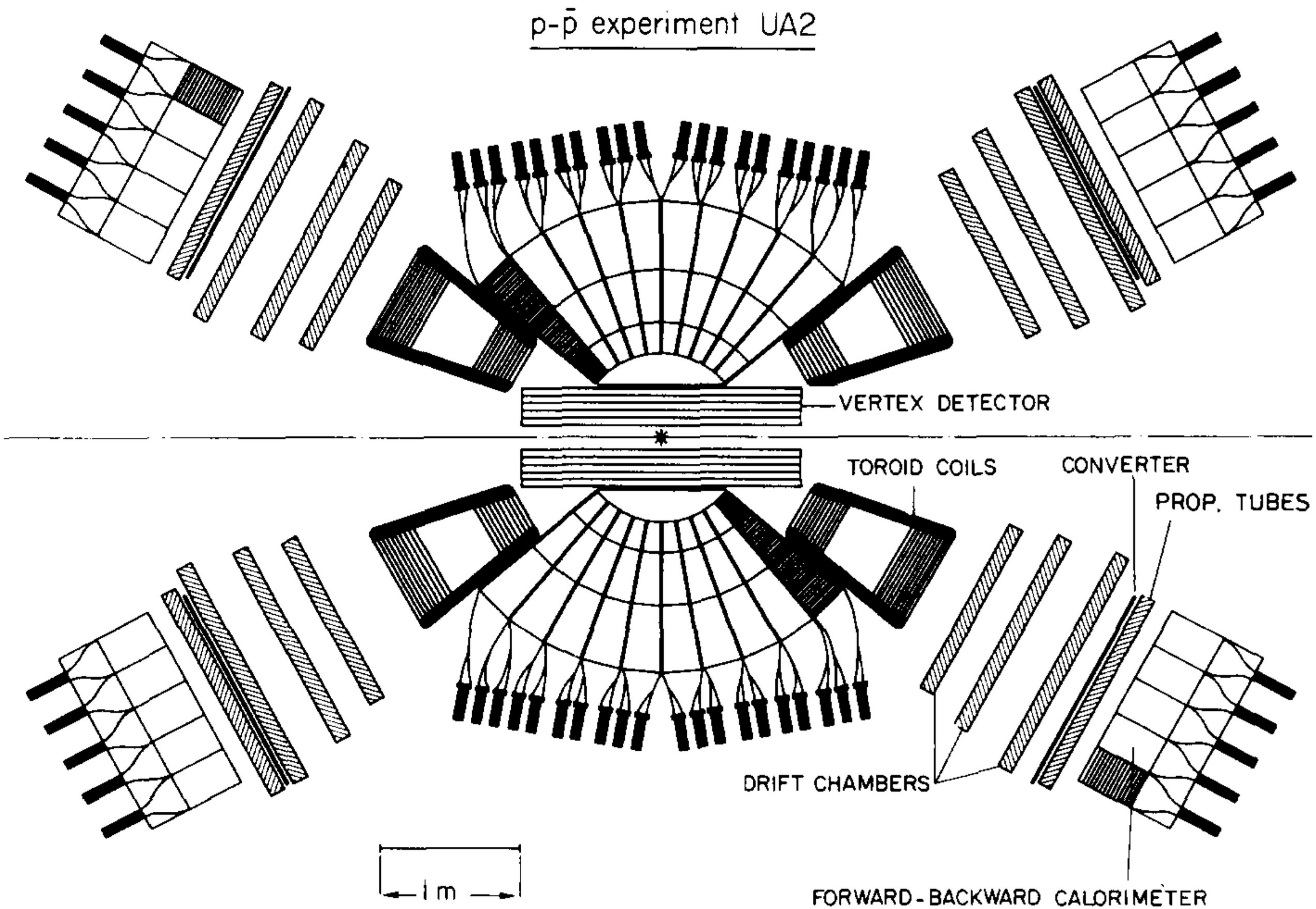
PLUTO @ PETRA, 1979
$\sqrt{s}$ = 27.7 – 30 GeV



PLUTO(1979).

- **Particle jets:**
  Collimated stream of particles with
  - **small transverse momenta (~ Λ) in comparison to principal direction of movement**

The UA2 experiment



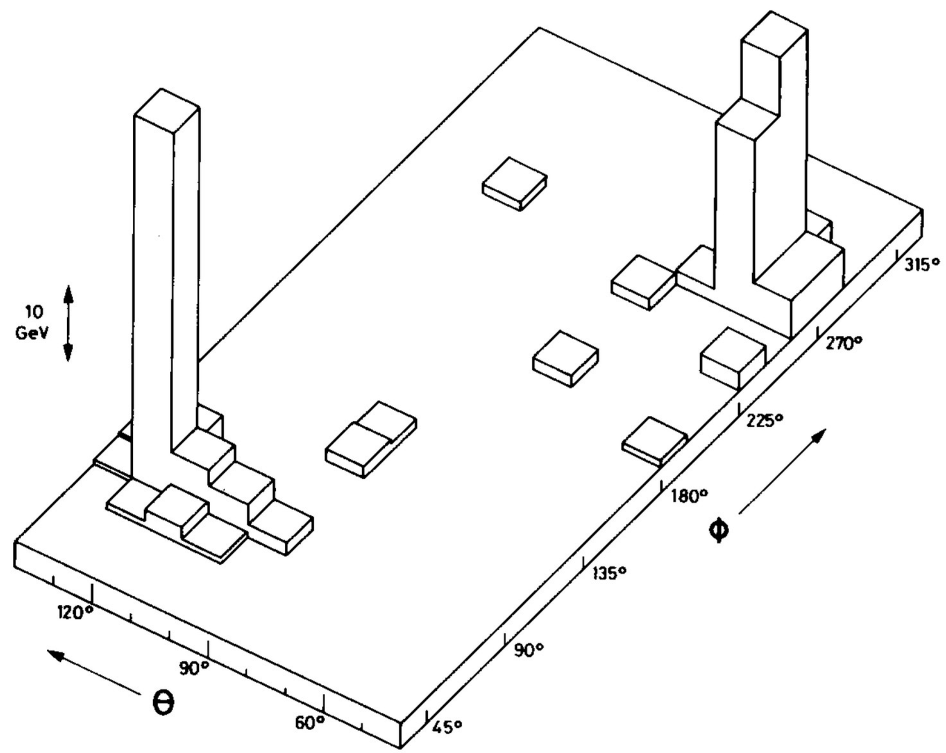
$\sqrt{s}$ = 540 GeV
Jet pT → 60 GeV

UA2, PLB 118 (1982).

Di-jet event with clearly separated energy depositions

'Jet algorithm' based on cell structure of the calorimeters (UA1 & UA2)

UA1 later also cone algorithm!



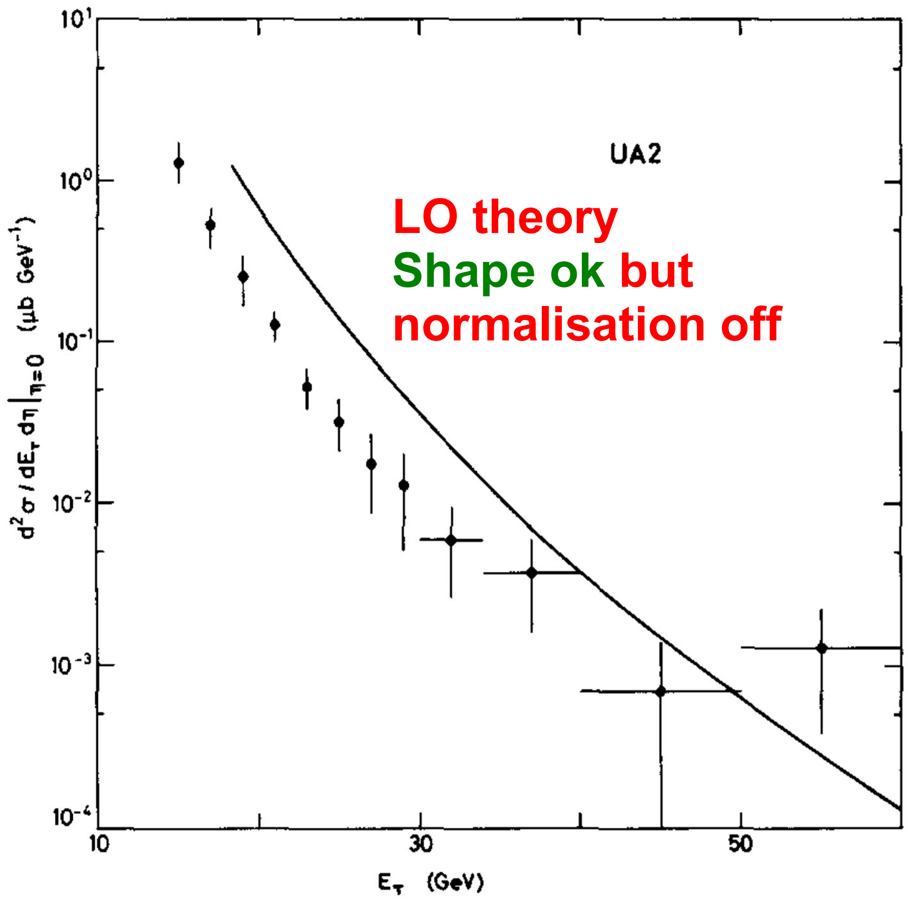
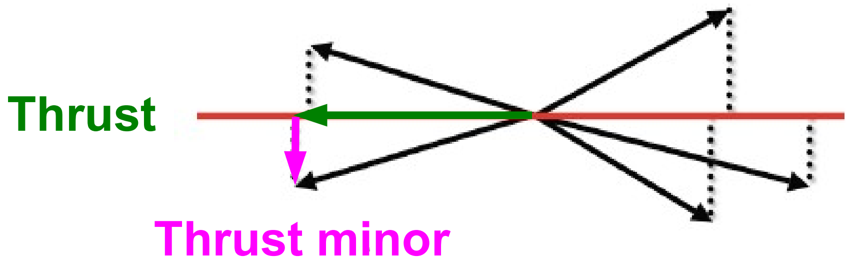


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

UA2, PLB 118 (1982).

Event Shapes

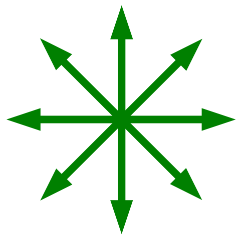
Definition:
Transverse global thrust



Similar as Event Shapes in e^+e^- and ep

- **In praxis, need to restrict rapidity range: $|\eta| < \eta_{max}$ →**
  Transverse central thrust
- **Less sensitive to JES & JER uncertainty**
- **No luminosity uncertainty**
- **Useful for MC tuning**
- **Comparison to perturbative QCD & resummation possible**

$$T_{\perp,g} = \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$



linear ~ dijet | **spherical ~ multijet**

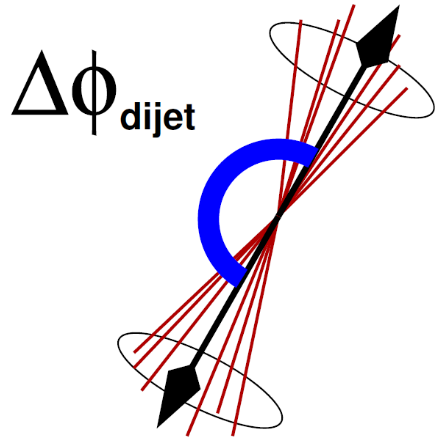
T ⟶ 0 | T ⟶ 2/π

Redefine to get $\tau_{\perp,g} \equiv 1 - T_{\perp,g}$ ⟶ 0 in LO dijet case

See e.g. A. Banfi, G. Zanderighi et al., JHEP06, 2010

Cone algorithms

- **First definition of G. Sterman, and S. Weinberg, PRL 39 (1977):**
  - **Specifically for dijet production in e+e- with opposite double cones**
  - **Theoretically 'well defined' in perturbation theory, avoids problems with singularities**
  - **Hadron production and multiplicity in general NOT perturbatively calculable (but cf. fragmentation functions ...)**
- **UA1 Collaboration at CERN SppS, PLB 123 (1982):**
  - **Cluster algorithm around cells with more than 2.5 GeV energy ('seed')**
  - **Distance criterium in (pseudo-)rapidity and azimuthal angle wrt. cell (or jet) → cone in (Φ,η) space**
  - **4-vector addition to combine**
  - **Further criteria to add less energetic cells**



$$R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

M. Wobisch

Sequential recombination algorithms

- **JADE Collaboration at DESY PETRA, ZPhysC 33 (1986):**
  - **Algorithm with sequential recombination**
  - **No treatment of proton remainder**
  - **1. Define metric for distance between two objects i and j via their 4-vectors**
  - **2. Calculate the distances for all pairwise combinations i, j**
  - **3. Compare the smallest distance to a threshold y_{cut}**
  - **4. If smaller → combine both objects i, j to a new one → iterate step 2**
  - **5. If larger → stop algorithm and declare all remaining 4-vectors to jets!**

$$y_{ij}^{\mathrm{J}} = \frac{2E_iE_j(1-\cos(\theta_{ij}))}{E_{\mathrm{vis}}^2}$$

$$y_{i,j;\mathrm{min}} < y_{\mathrm{cut}}$$

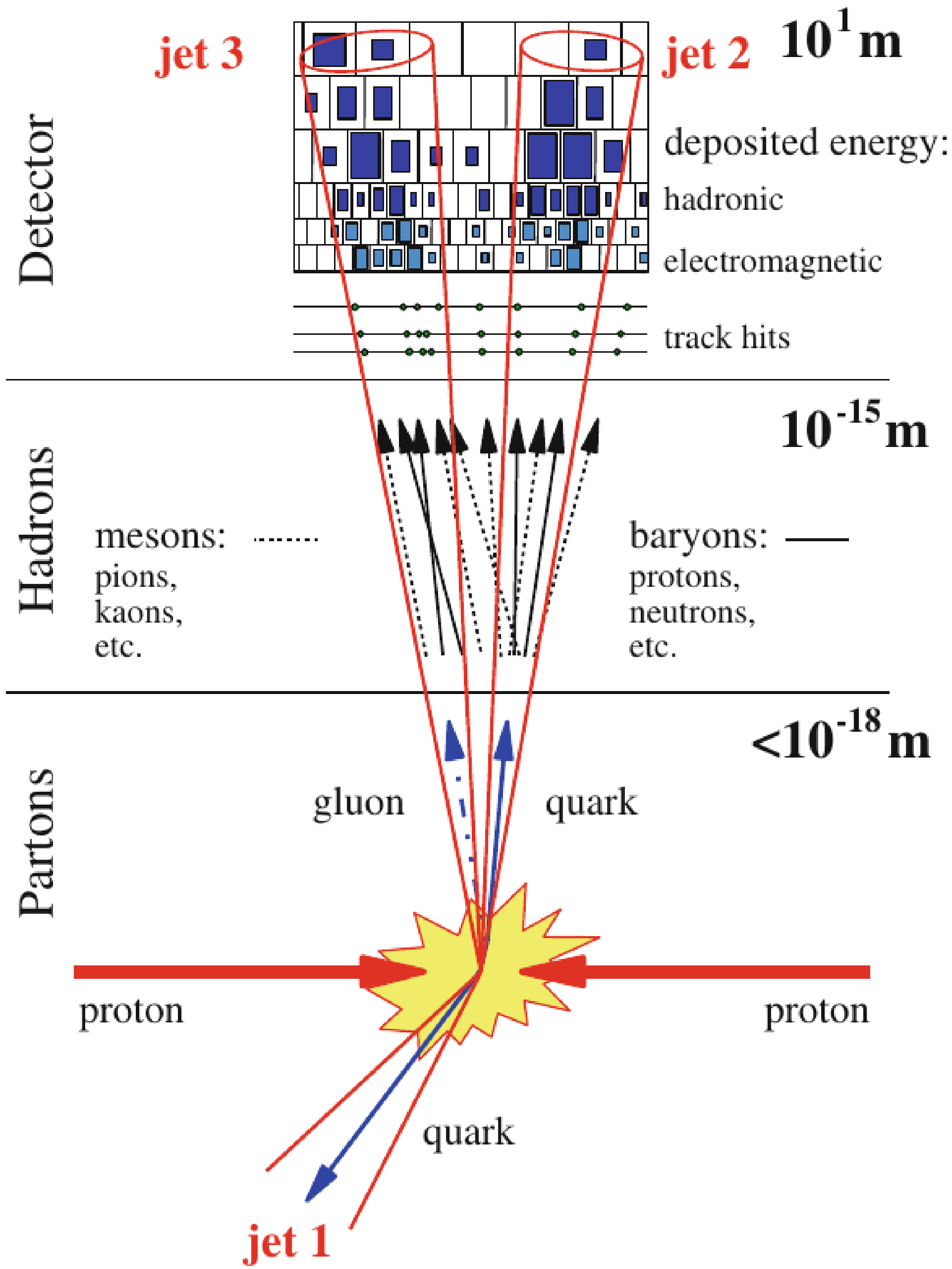
Jet algorithms

Primary goal:

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

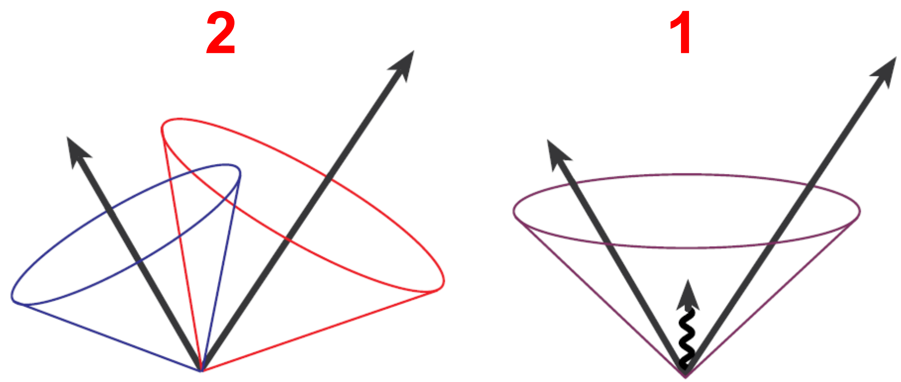
Two classes of algorithms:

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)

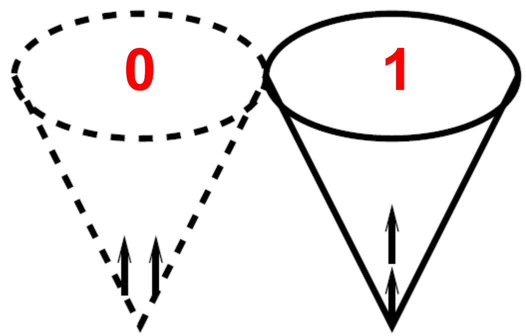


Desiderata – Theory

- **Jet Algorithm Desiderata (Theory):**
  - **Infrared safety**
  - **Collinear safety**
  - **Longitudinal boost invariance**
    (recombination scheme!)
  - **Boundary stability**
    (→ 4-vector addition, rapidity y)
  - **Order independence**
    (parton, particle, detector)
  - **Ease of implementation**
    (standardized public code?)



IR unsafe: Sensitive to the addition of soft particles

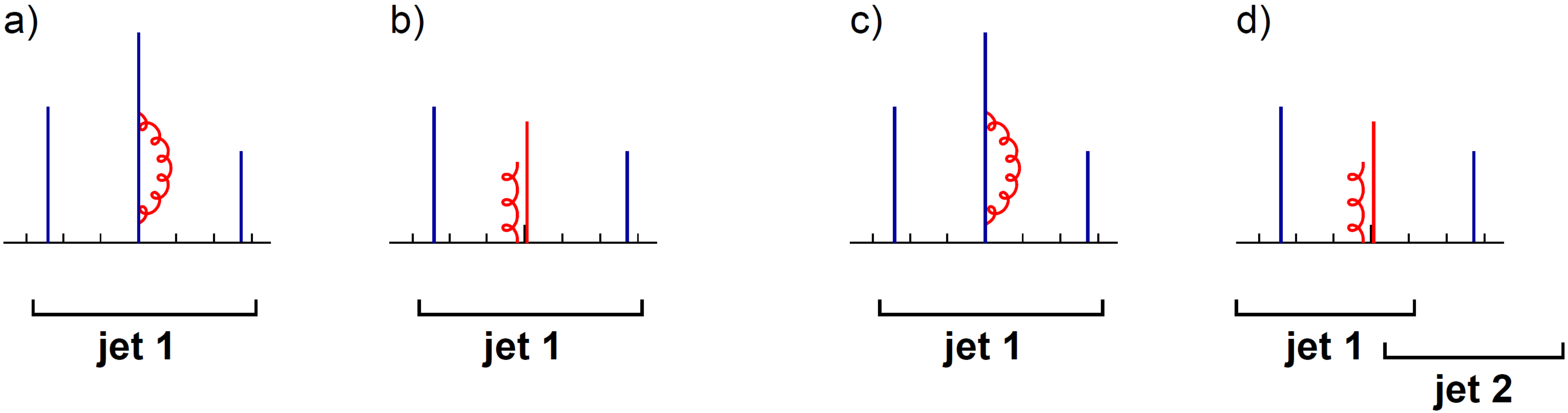


Coll. unsafe: Sensitive to the splitting of a 4-vector (seeds!)

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

Collinear safety

Collinear safe jet alg. | Collinear unsafe jet alg



α_s^n x $(-\infty)$ α_s^n x $(+\infty)$ α_s^n x $(-\infty)$ α_s^n x $(+\infty)$

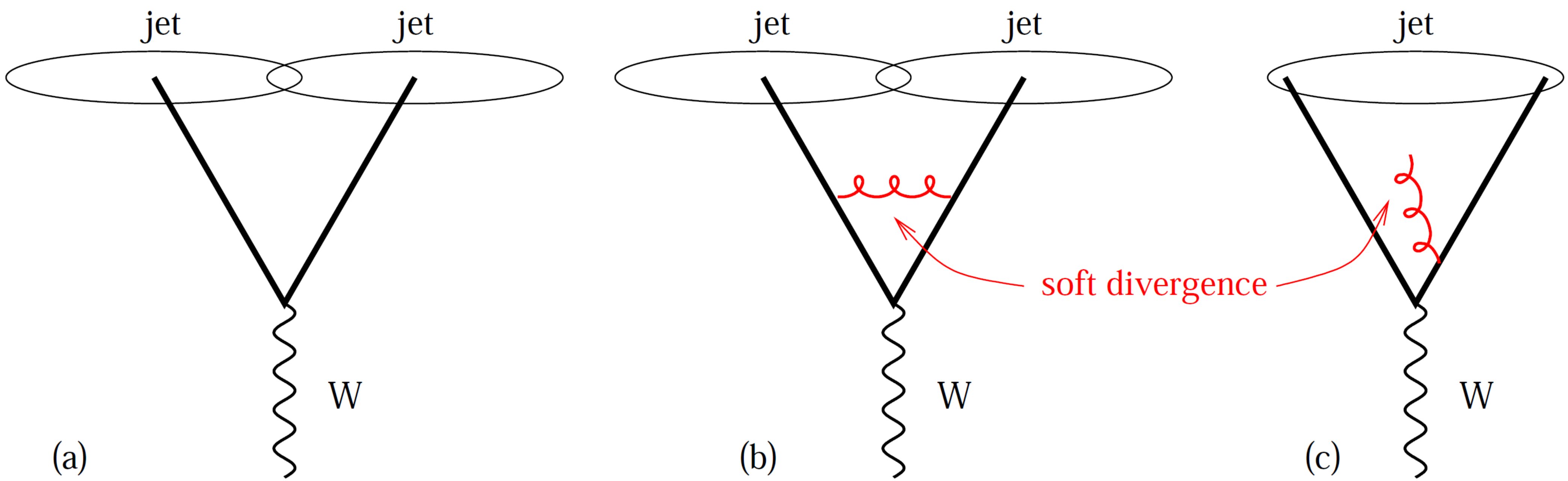
Infinities cancel | **Infinities do not cancel**

Jetography, G. Salam, hep-ph/0906.1833

Infrared safety

Iterative cone with Split/Merge:

- → not all objects end in jets, e.g. if no starting cone close by (dark Jets)
- → collinear unsafe because of minimal pT on cone seeds
- → infrared unsafe ...



Trial to fix issue: MidPoint Cone → Investigate add. all middle points between seeds
→ also unsafe, becomes apparent only for more complexe topologie
Discovered rather late: Real safe algorithm Seedless Infrared-Safe Cone (SISCone)
→ rarely used because of 2 orders of magnitude larger computing needs

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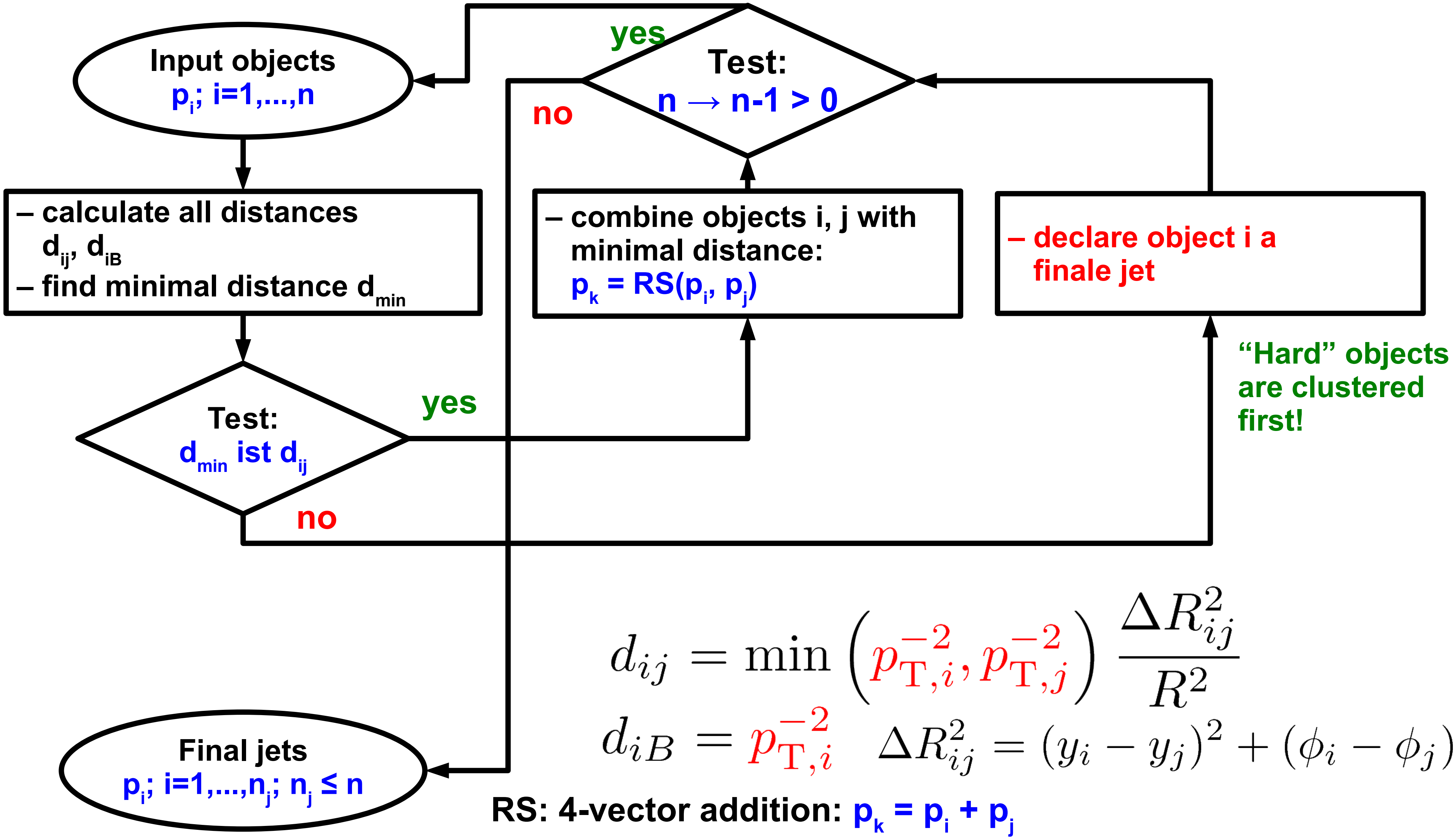
anti-k_T – hh



$$d_{ij} = \min\left(p_{\mathrm{T},i}^{-2}, p_{\mathrm{T},j}^{-2}\right) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{\mathrm{T},i}^{-2} \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

RS: 4-vector addition: $p_k = p_i + p_j$

Cacciari, Salam, Soyez, JHEP04 (2008).

Jet algorithms at the LHC

Standard algorithm:

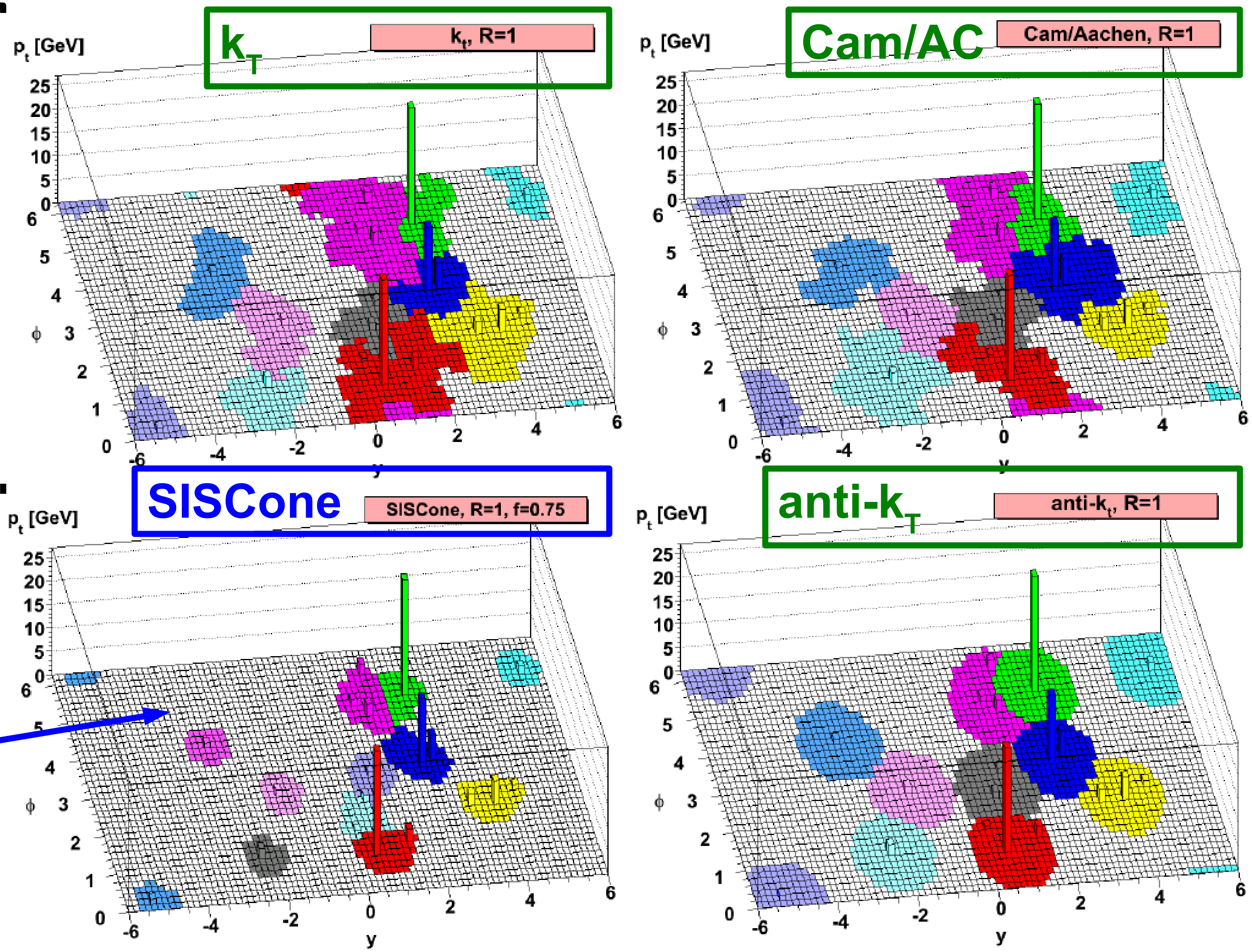
- **Anti-k_T:**

  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´

In general: Interest in all four!

Only "real" cone algorithm!



Fast kT, Cacciari/Salam, PLB641, 2006
SISCone, Salam/Soyez, JHEP05, 2007
anti-kT, Cacciari et al., JHEP04, 2008

Summary

- Quantum corrections lead to energy (distance) dependent couplings
- QED coupling increases with energy → Coulomb potential ~ 1/r
- QCD coupling decreases with energy → asymptotic freedom
- QCD coupling increases with distance (confinement) → string potential ~ r
- Perturbation theory gives free (anti-)quarks or gluons, but not measurable
- Need MC event generators to model transition from partons to hadrons
- Subsequent simulation of events in detector essential for understanding
- Must relate partonic foot print of hard interaction (not measurable) to experimental measurements
  - Energy flow pattern in events, “event shapes”
  - Streams of collimated particles, “jets”
- Jet definition (event shape, too) requires algorithm that is infrared- and collinear-safe to compare with perturbative predictions

Backup