Karlsruhe Institute of Technology

Particle Physics 1

Lecture 17: Jets and high p_T physics

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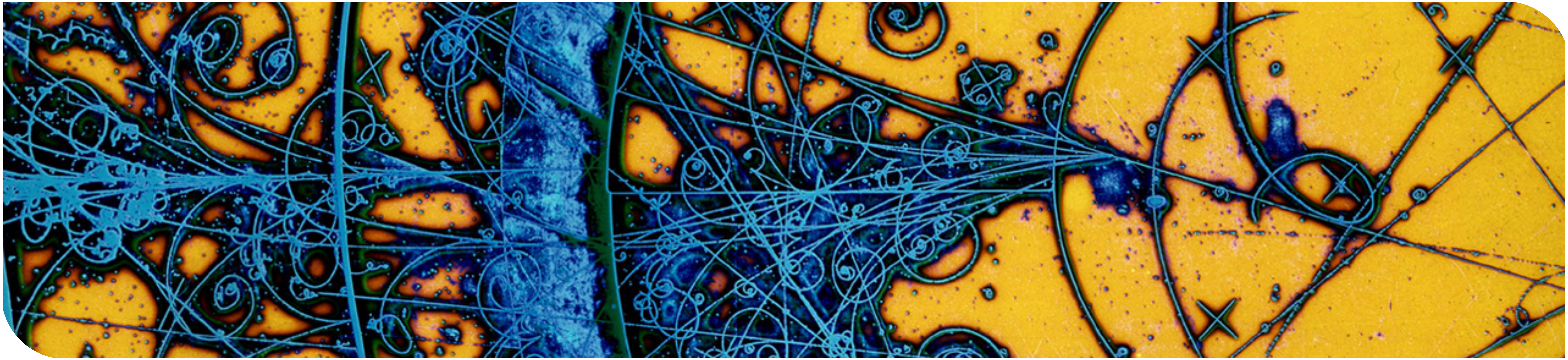
Wintersemester 2023/2024



Credit: CERN

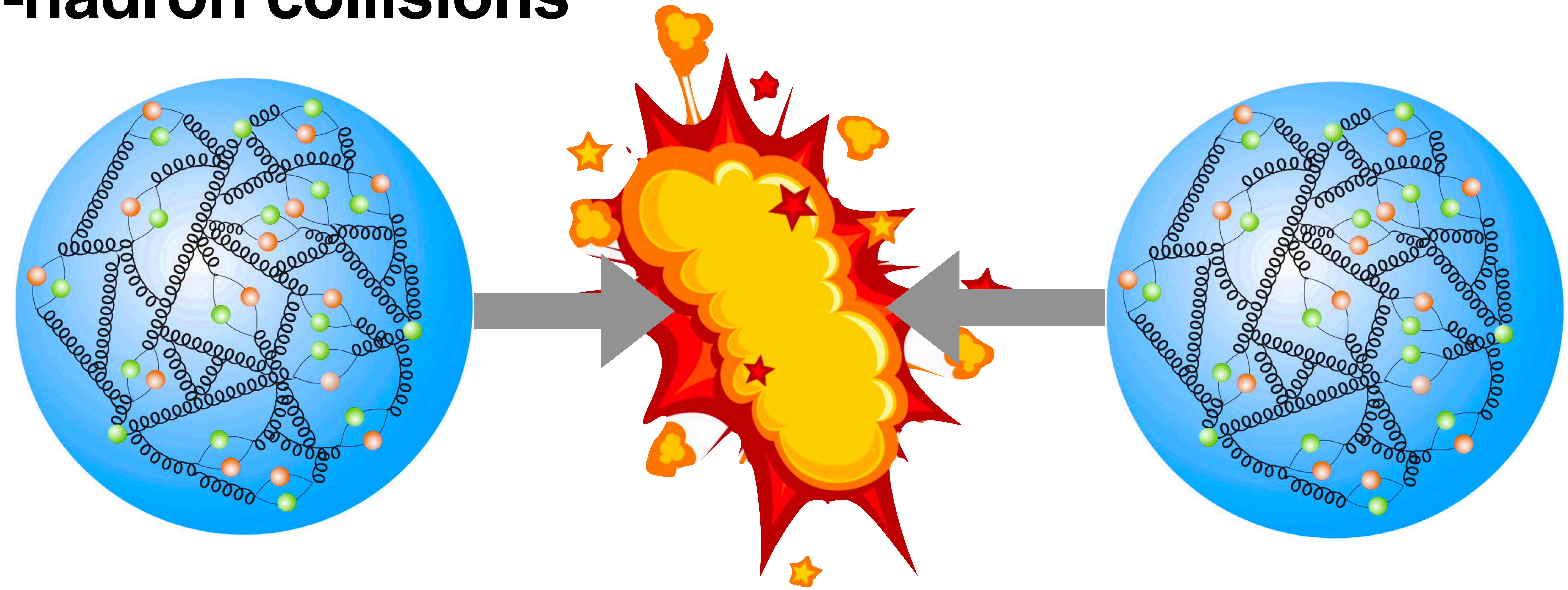
Learning goals

- What are jets?
- W production and properties
- Top production and properties

Introduction

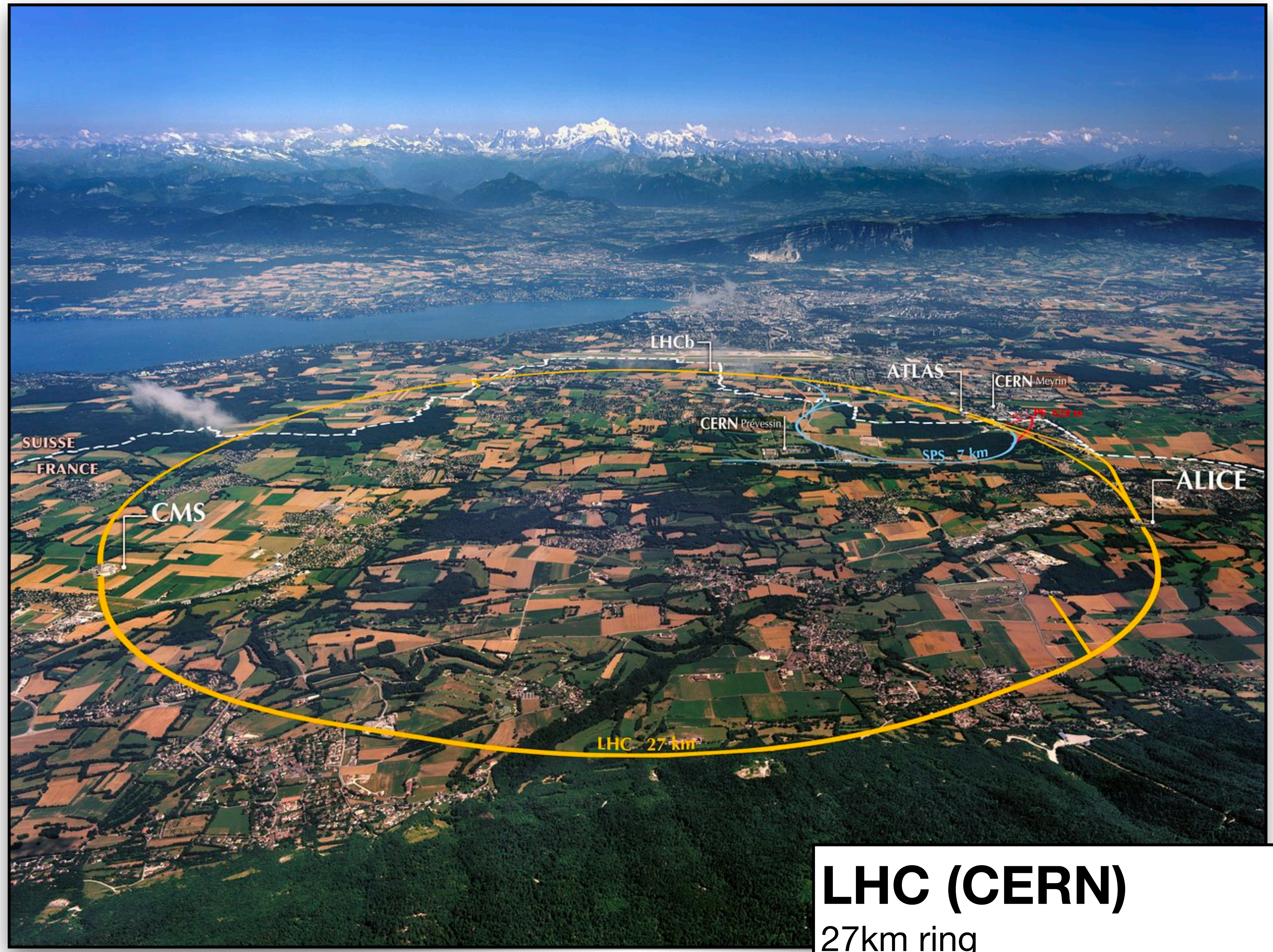
- What is high-pT physics?
  - Particle physics at very large momentum (transfer), often at hadron colliders
  - Most important analysis objects: jets originating from fragmentation and hadronization of quarks and gluons
  - Study of most massive particles of the standard model: W and Z bosons, top quarks, Higgs boson (later)

Hadron-hadron collisions



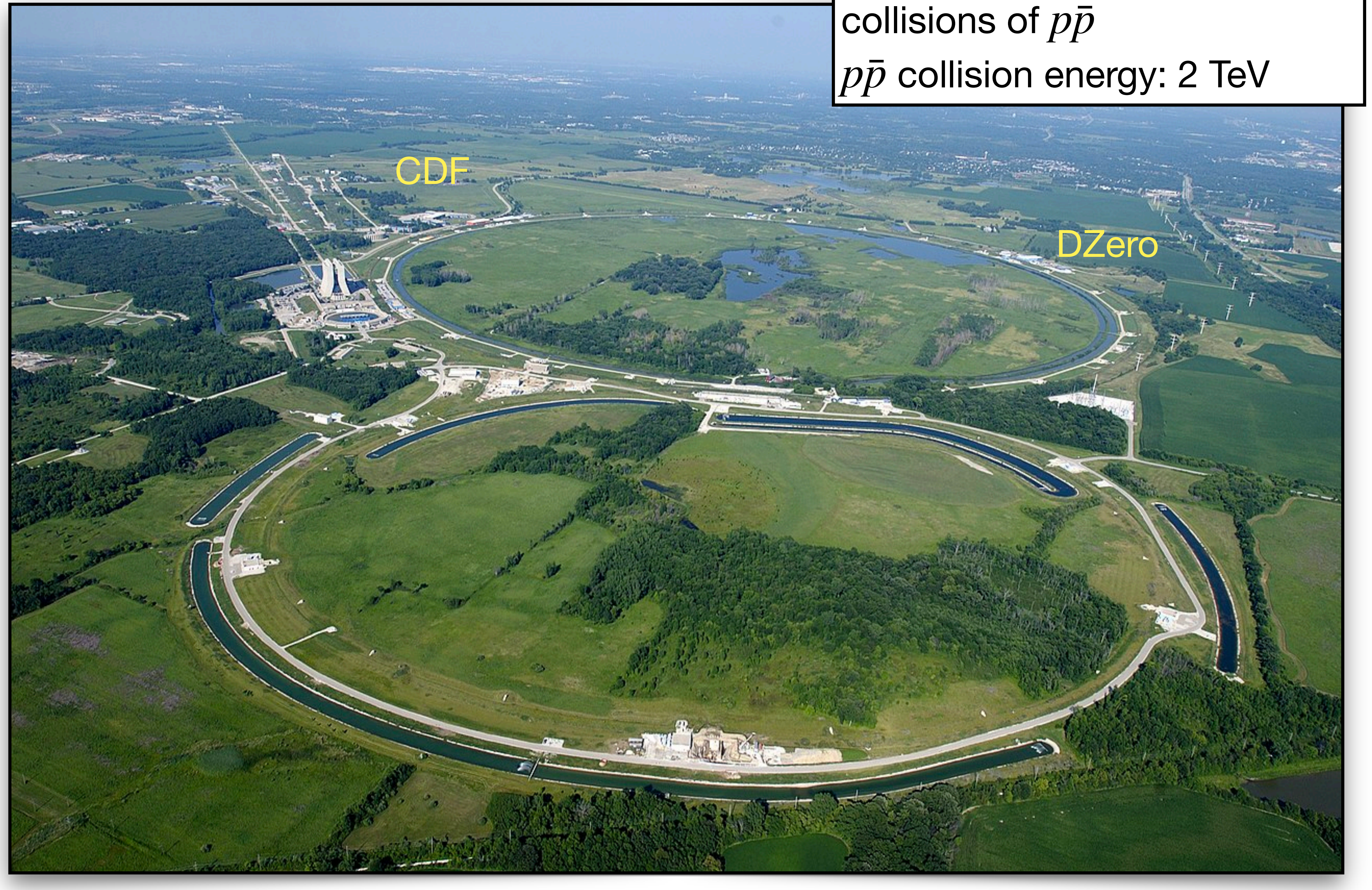
- No collision of point-like particles at fixed energy, but “broad-band” beam of various partons (quarks, gluons) with different color and energy
- Challenge: Reliable calculation of observables

Hadron-hadron collisions



Credit: Maximilien Brice (CERN)

LHC (CERN)
27km ring
collisions of pp and heavy ions
pp collision energy: 13.6 TeV

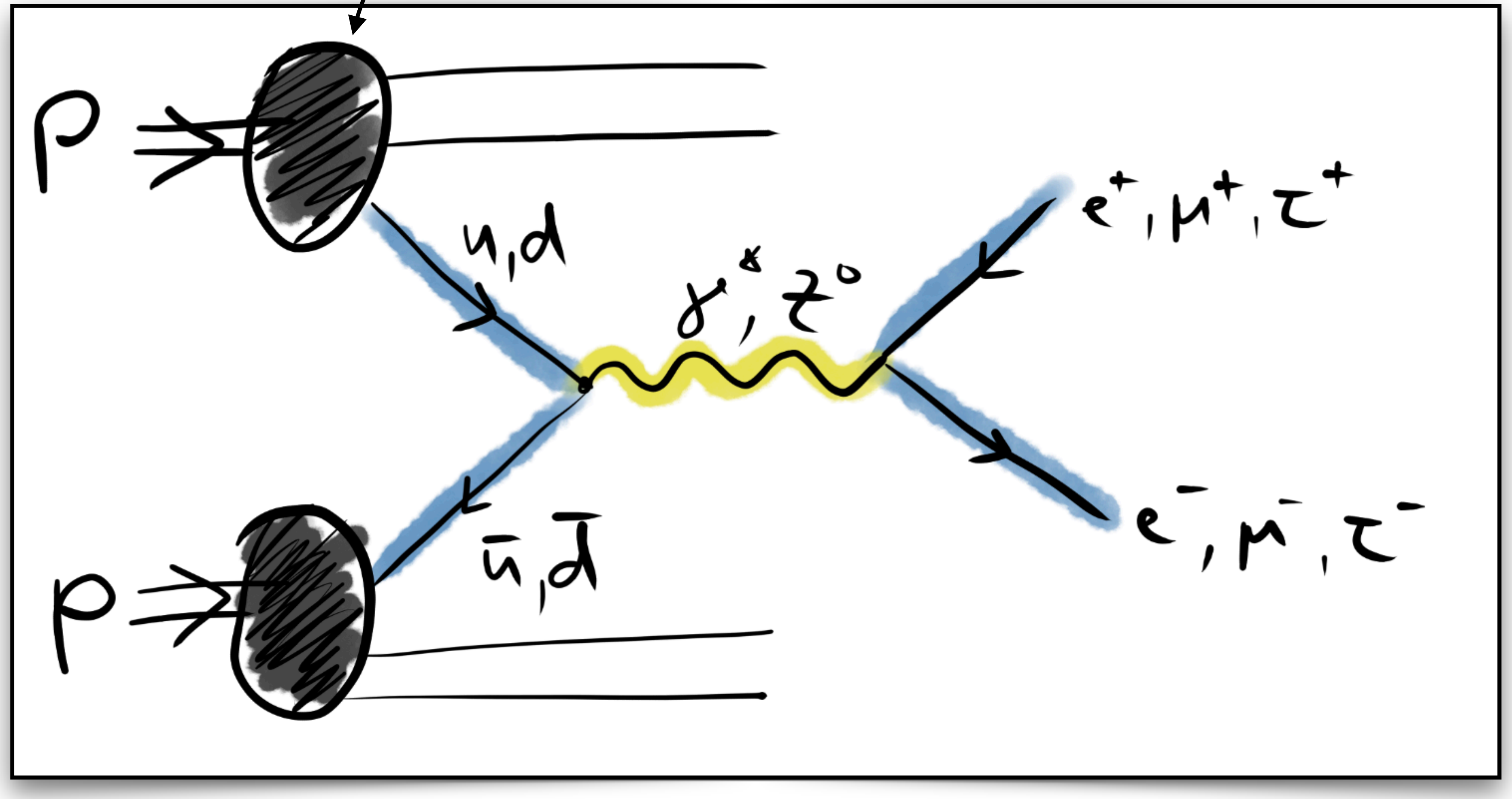


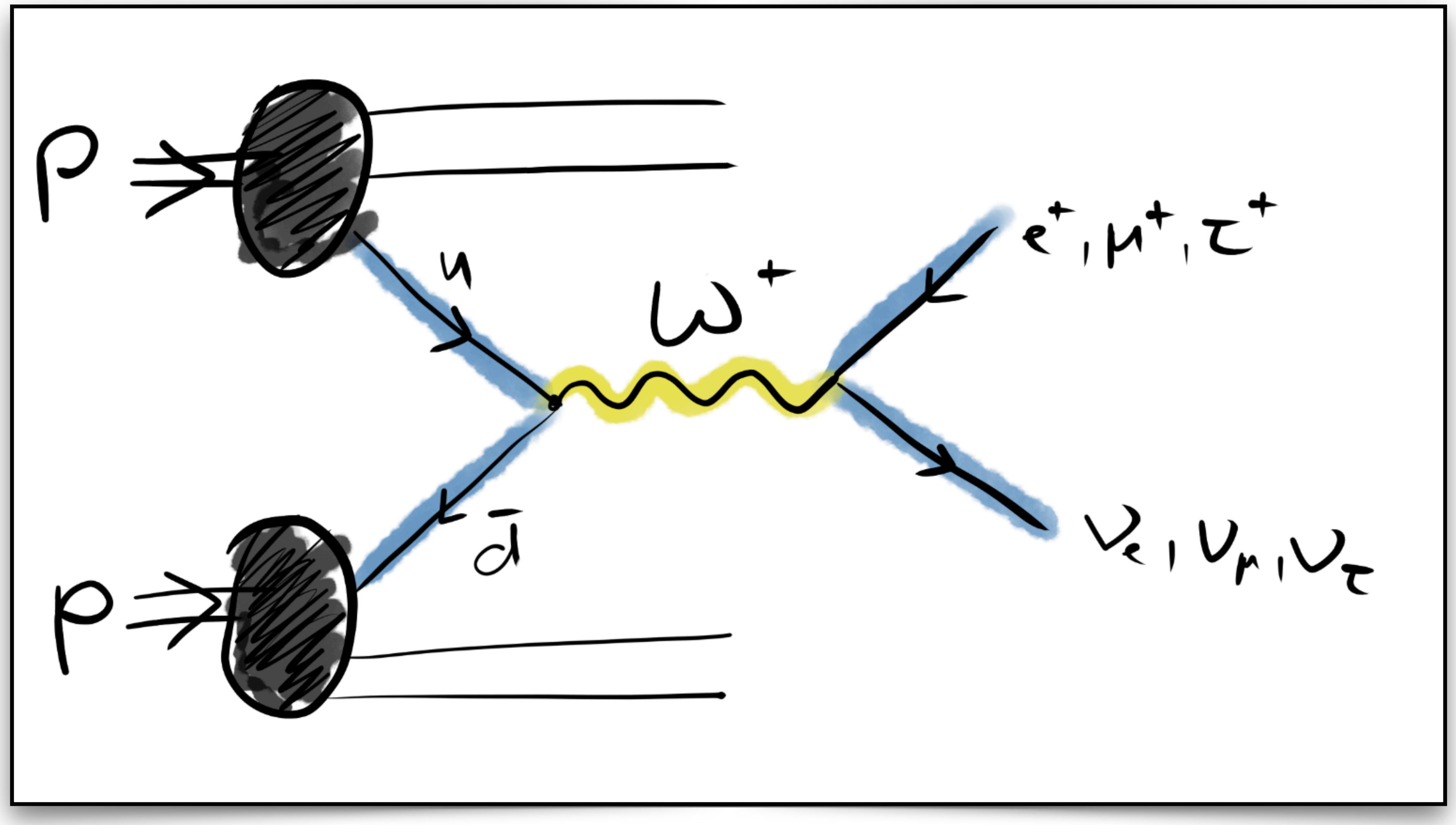
Tevatron (Fermilab)
6km ring
collisions of $p\bar{p}$
$p\bar{p}$ collision energy: 2 TeV

Example: Drell-Yan

- Drell-Yan: quark-antiquark annihilation into (virtual) photon, Z, or W into lepton pairs
  - $pp \rightarrow \gamma^*/Z \rightarrow \ell^+\ell^-$ or $pp \rightarrow W^\pm \rightarrow \ell^\pm \overset{(-)}{\nu}$
  - large center of mass energies with large momentum transfers
  - no hadronisation (apart from proton remnants)

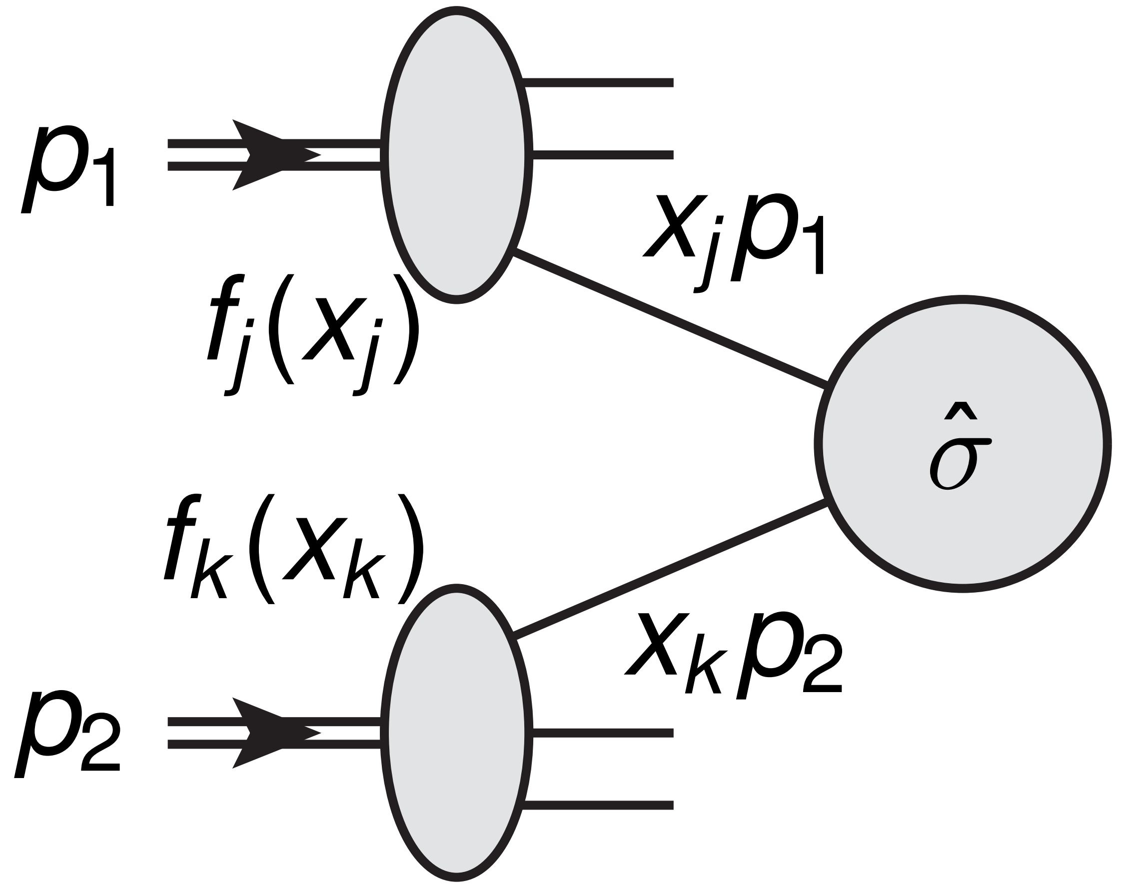
This is not a real Feynman diagram!





QCD factorization

- Factorization theorem (can be proven): cross section of Drell-Yan process can be calculated by factorizing hard/soft components:
  - Compute "hard" partonic sub-process in perturbative QCD, e.g. $q\bar{q} \to \mu^+\mu^-$
  - Weight cross section with probability to find these partons in hadrons (→ PDFs $f_i(x)$) and integrate over all partons and parton momenta
  - PDFs universal → measured independently, e.g. in DIS

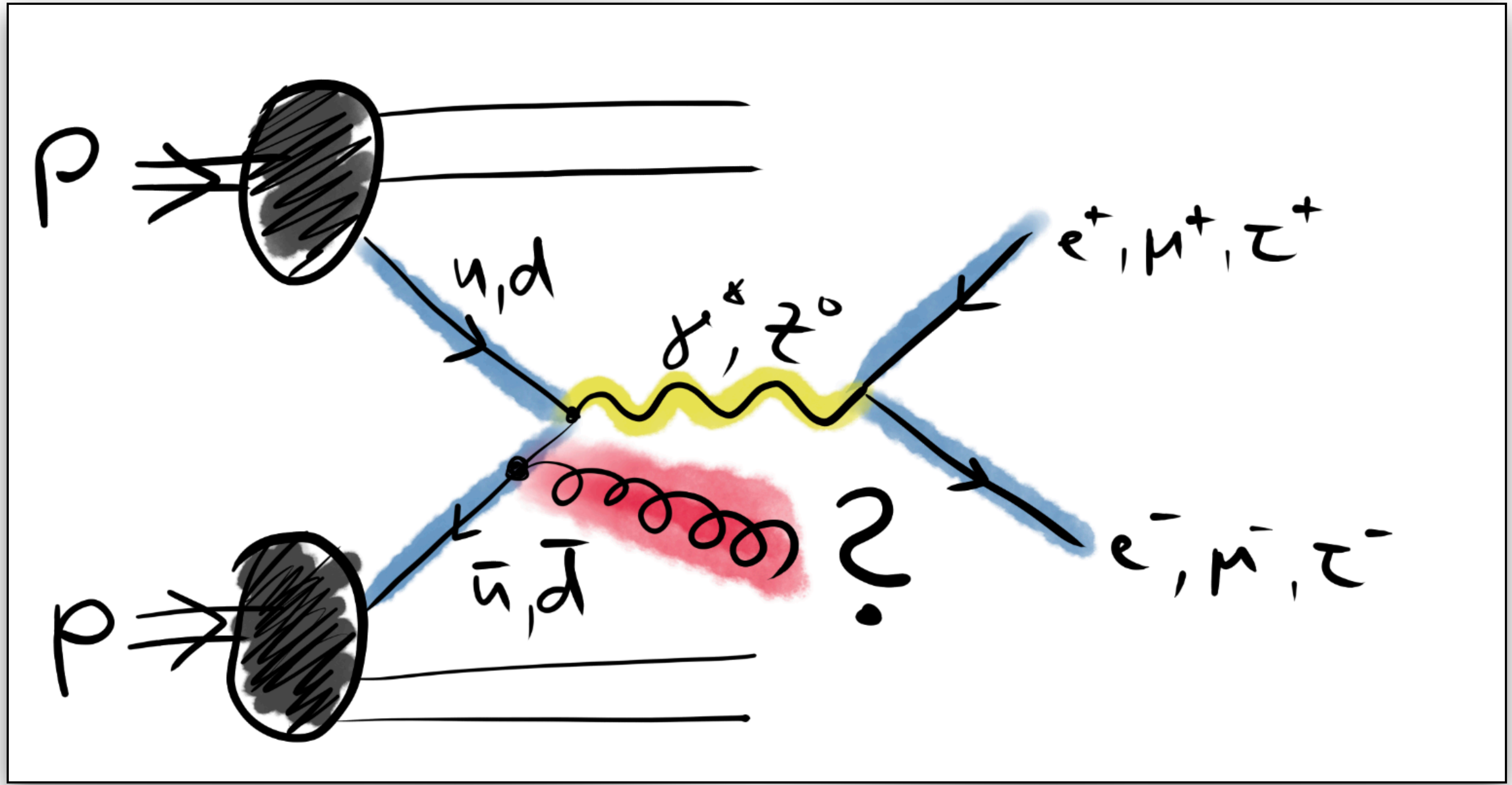


$$\sigma_{DY} = \underbrace{\sum_{jk} \int \mathrm{d}x_j\, \mathrm{d}x_k}_{\text{Summation over partons } j,\, k}\ \underbrace{f_j(x_j)\, f_k(x_k)}_{\text{Probabilities for partons with } x_j \text{ and } x_k} \cdot \underbrace{\hat{\sigma}(q_j q_k \to \ell^+\ell^-)}_{\text{Cross section for partonic sub-process}}$$

Fit to data

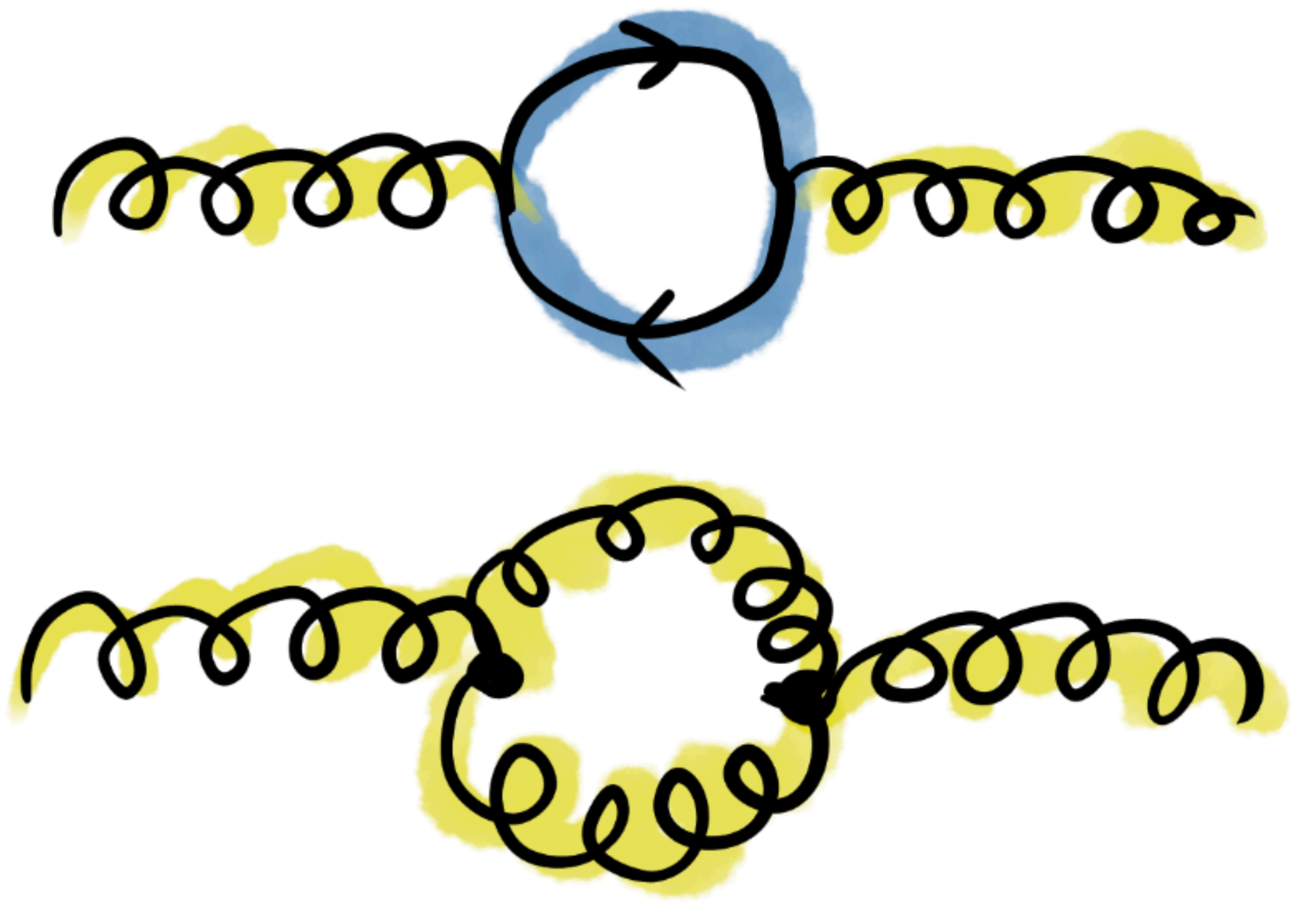
Calculation

Divergencies



Divergencies

- Ultraviolet divergencies:
  - Source: unbound momenta of particles in loops
  - Solution: **Renormalization (with scale μ_R)**; **UV divergencies absorbed in running coupling α_s**



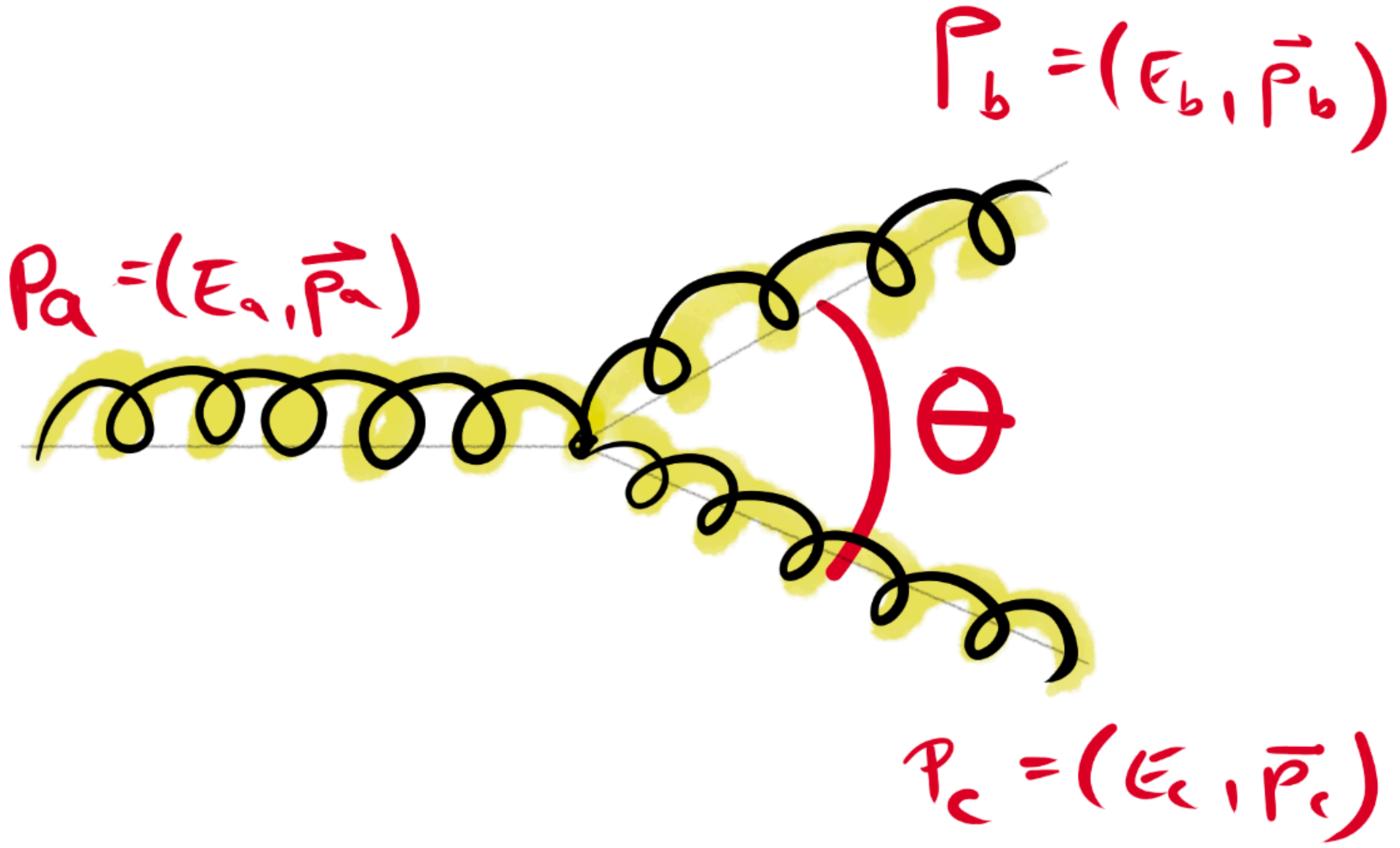
- Infrared divergencies:
  - Consider propagator of the incoming gluons $\sim 1/p_a^2$:

$$p_a^2 = (p_b + p_c)^2 = m_b^2 + m_c^2 + 2(E_b E_c - \mathbf{p}_b \cdot \mathbf{p}_c)$$

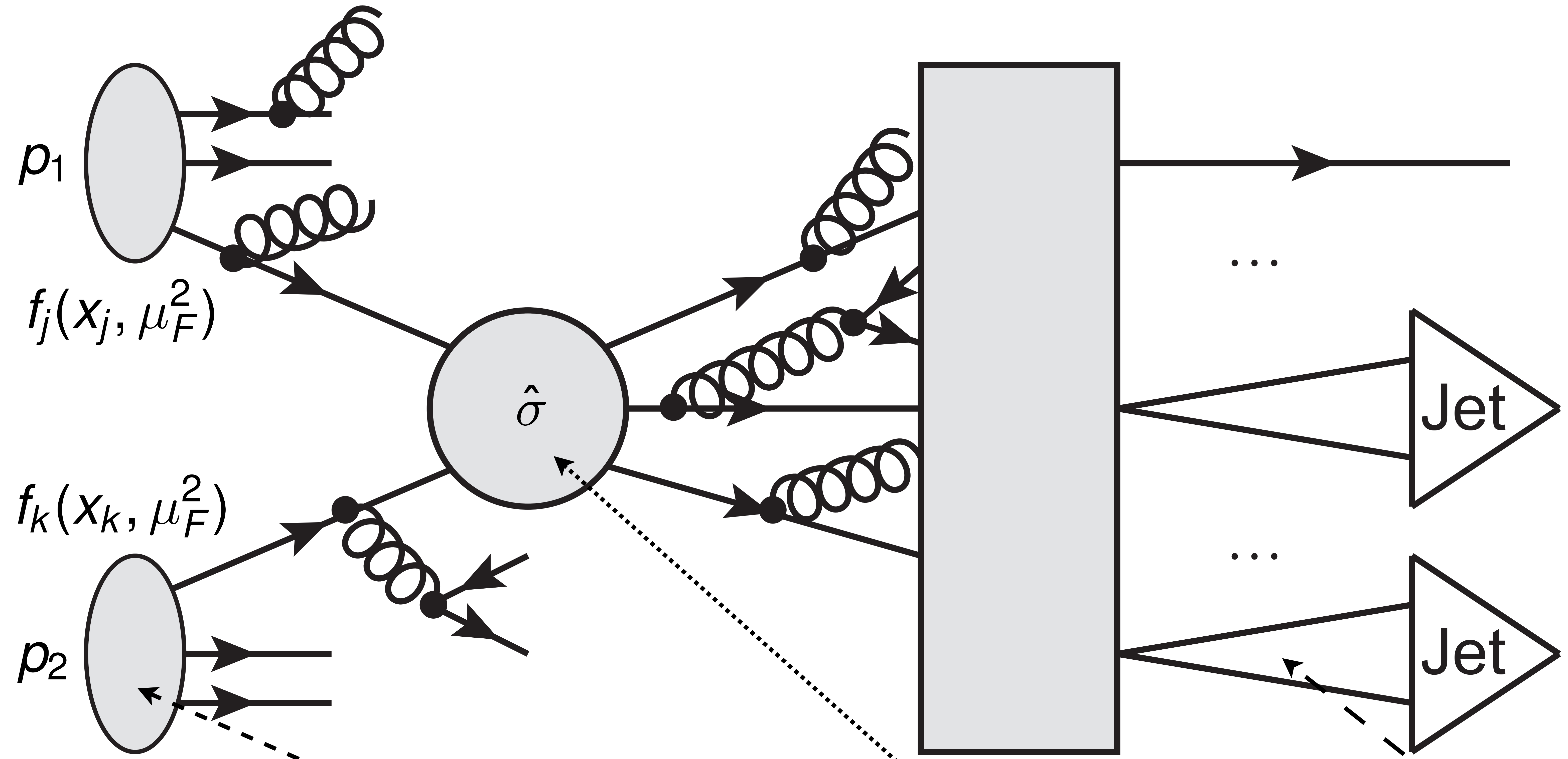
$$\underset{m_i=0}{=} 2E_b E_c(1 - \cos\theta) = 2E_a^2\, z(1 - z)(1 - \cos\theta)$$

Source: soft (z→ 0 or 1) or collinear (θ→0) gluons (→ large range, pQCD not valid)

  - Solution: **IR divergencies absorbed in PDFs** (the PDFs become scale dependent with **factorization scale μ_F**)



Cross section = PDFs ⊗ hard process ⊗ hadronization



$$\sigma_{\mathrm{QCD}} = \sum_{jk} \int \mathrm{d}x_j\, \mathrm{d}x_k\, \boxed{f_j(x_j, \mu_F^2)\, f_k(x_k, \mu_F^2)}\, \boxed{\hat{\sigma}(x_j x_k s, \mu_F^2, \alpha_S(\mu_R^2))} \otimes \boxed{\text{Hadronization}}$$

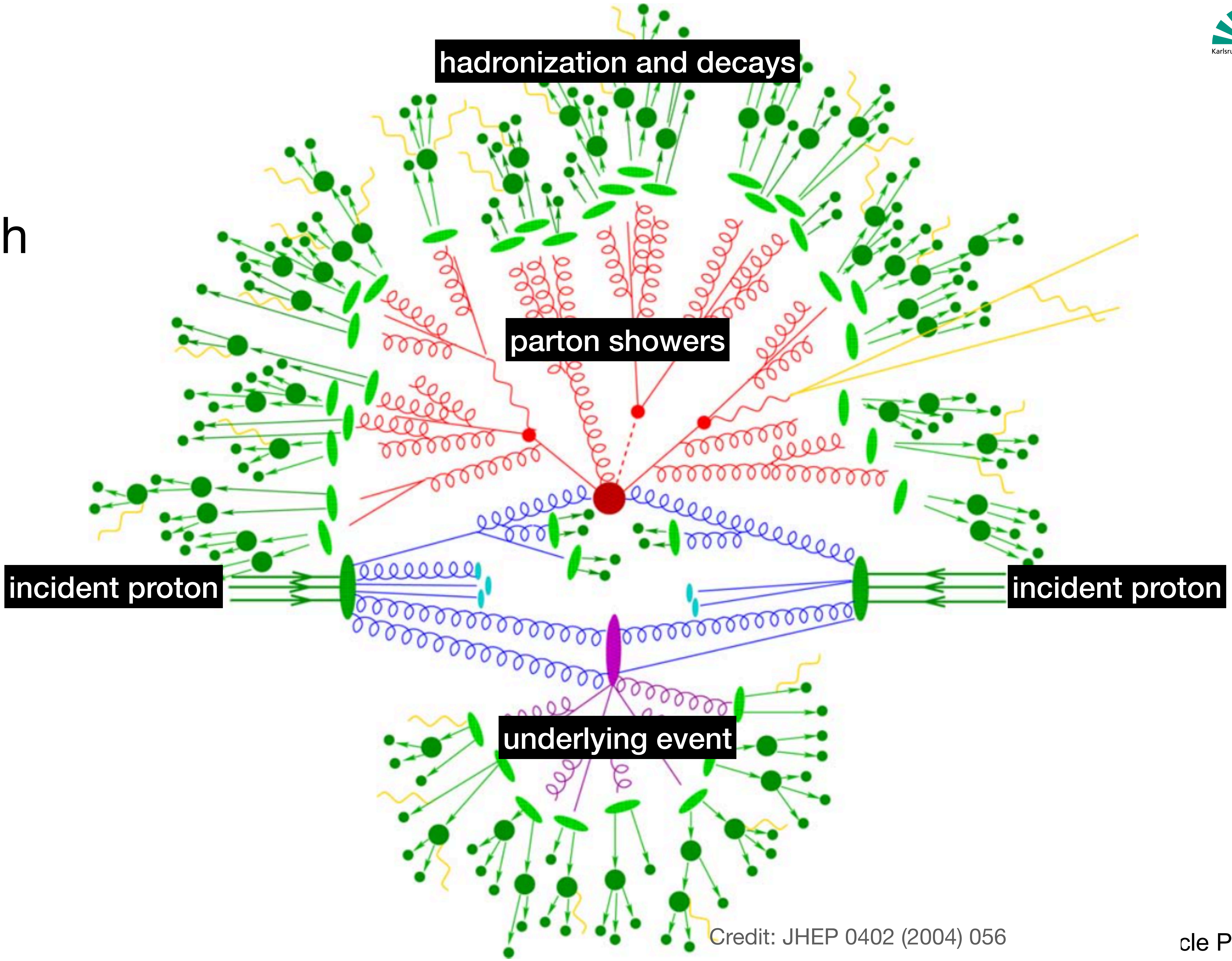
Credit: U. Husemann

What is a jet?

- Relation between **properties of partons** (quarks and gluons) and objects measured in collider detector (jets)?
  - Unknown momentum fractions of interacting partons → **unknown Lorentz boost** of partonic center-of-mass frame relative to laboratory frame
  - Quarks and gluons carry color charge, jets are color neutral
    → **no unambiguous jet-parton assignment** possible
  - Working hypothesis (“local parton-hadron duality”): parton properties can be **inferred directly** from measurements of hadrons

Jets

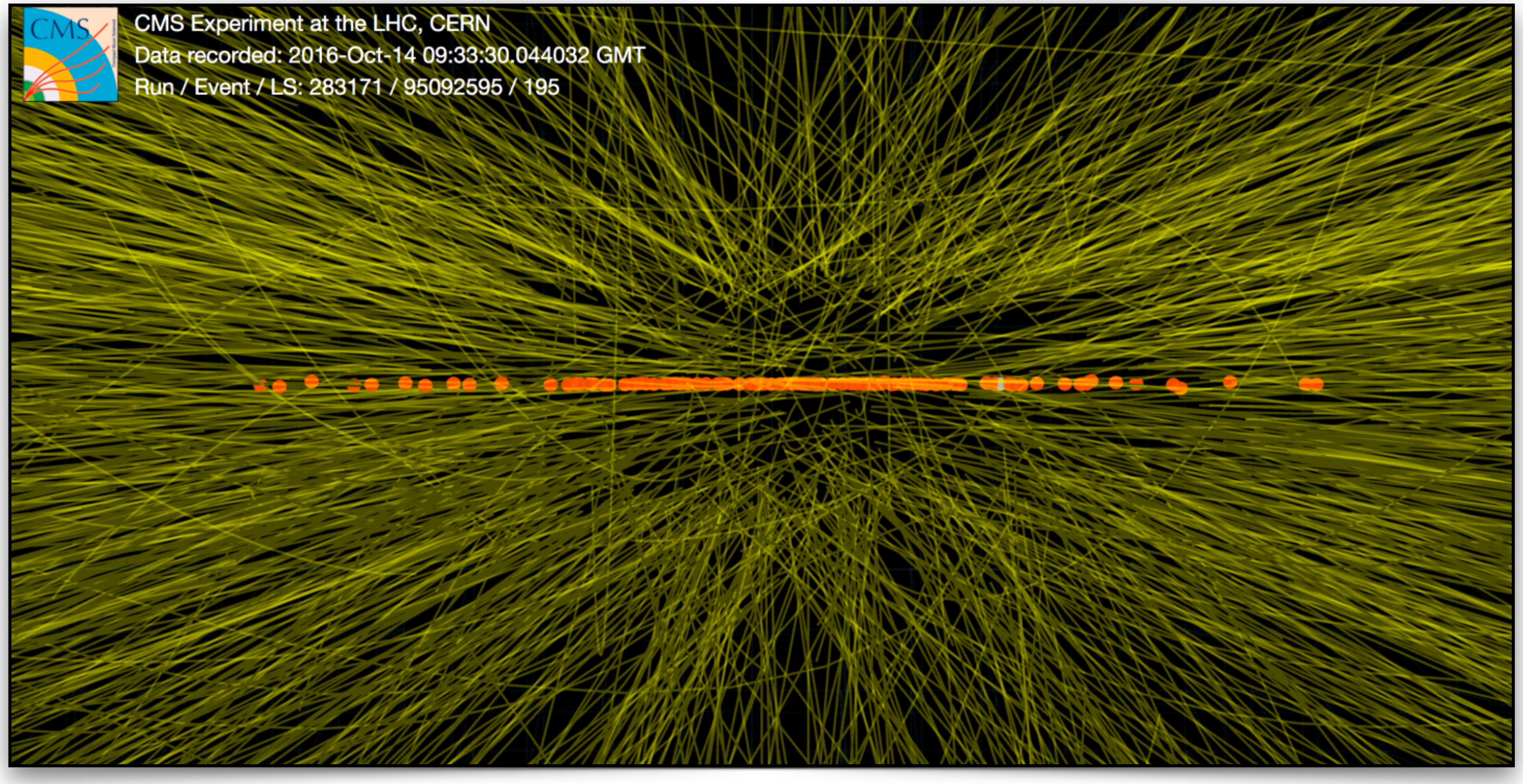
- Very complex process: Described with Monte Carlo



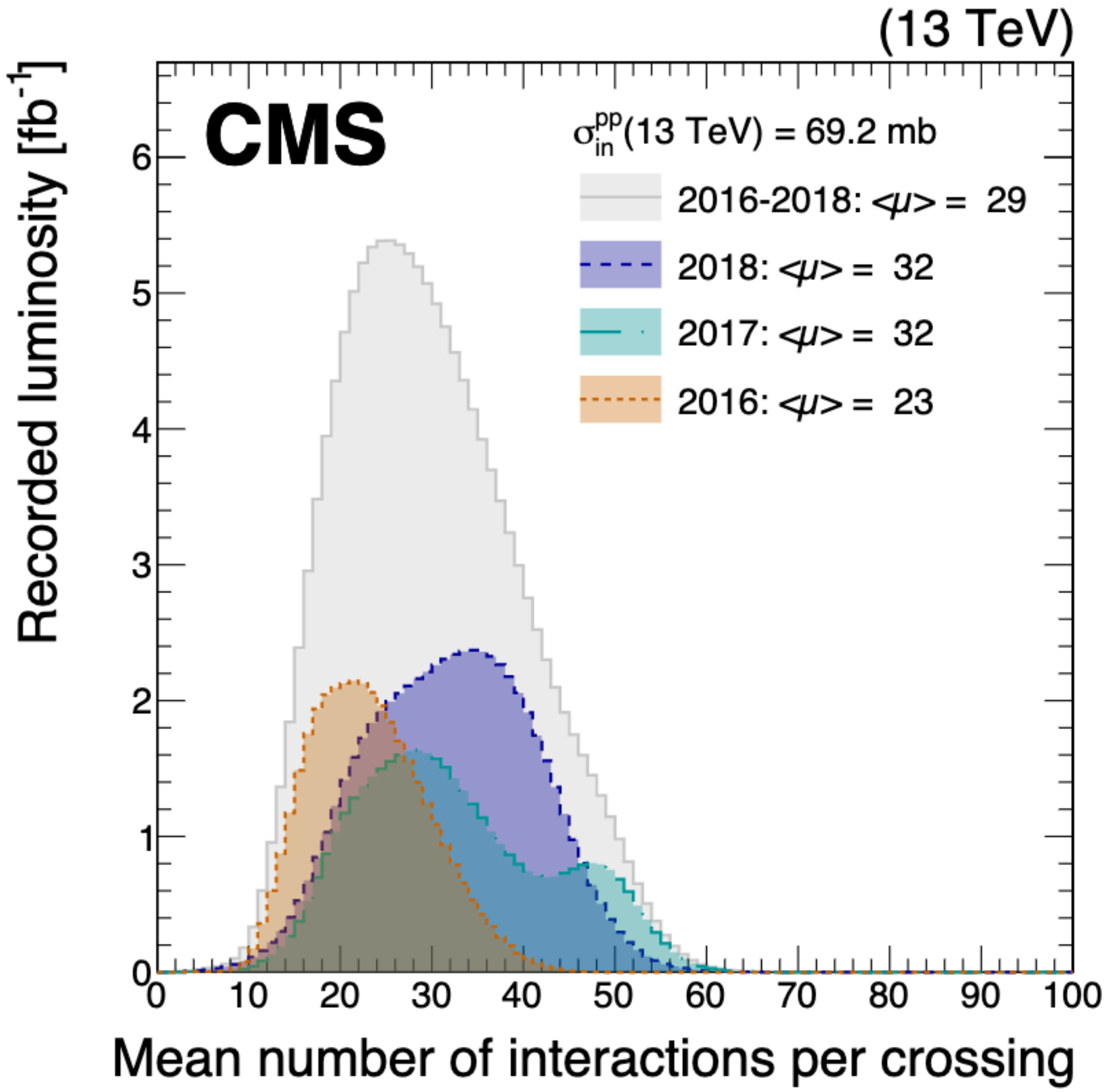
Credit: JHEP 0402 (2004) 056

Additional challenge: Pile up

- In addition to unwanted particles from the underlying event, in LHC pp collisions, more than one interaction occurs per bunch crossing



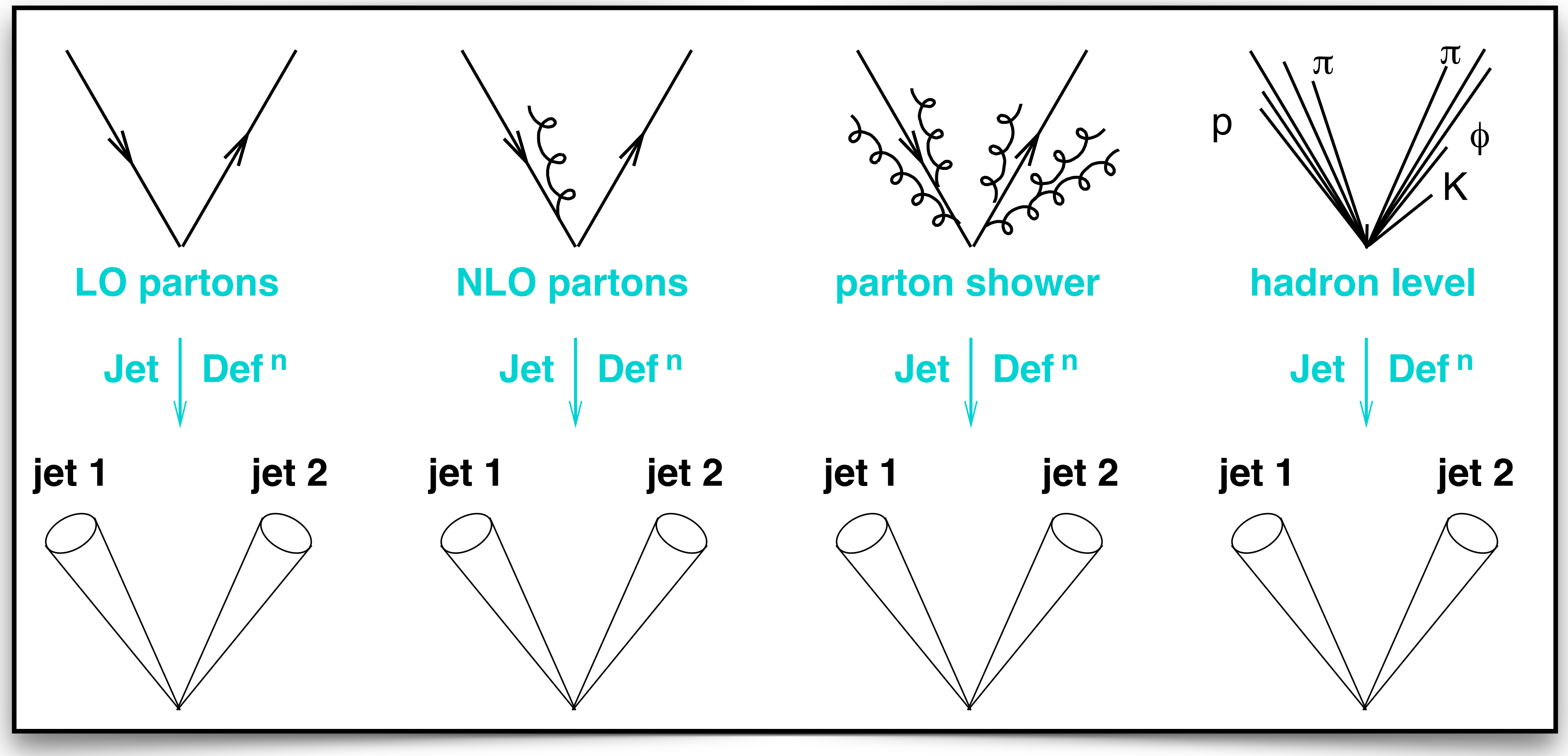
Credit: https://cds.cern.ch/record/2231915



Credit: https://arxiv.org/pdf/2003.00503.pdf

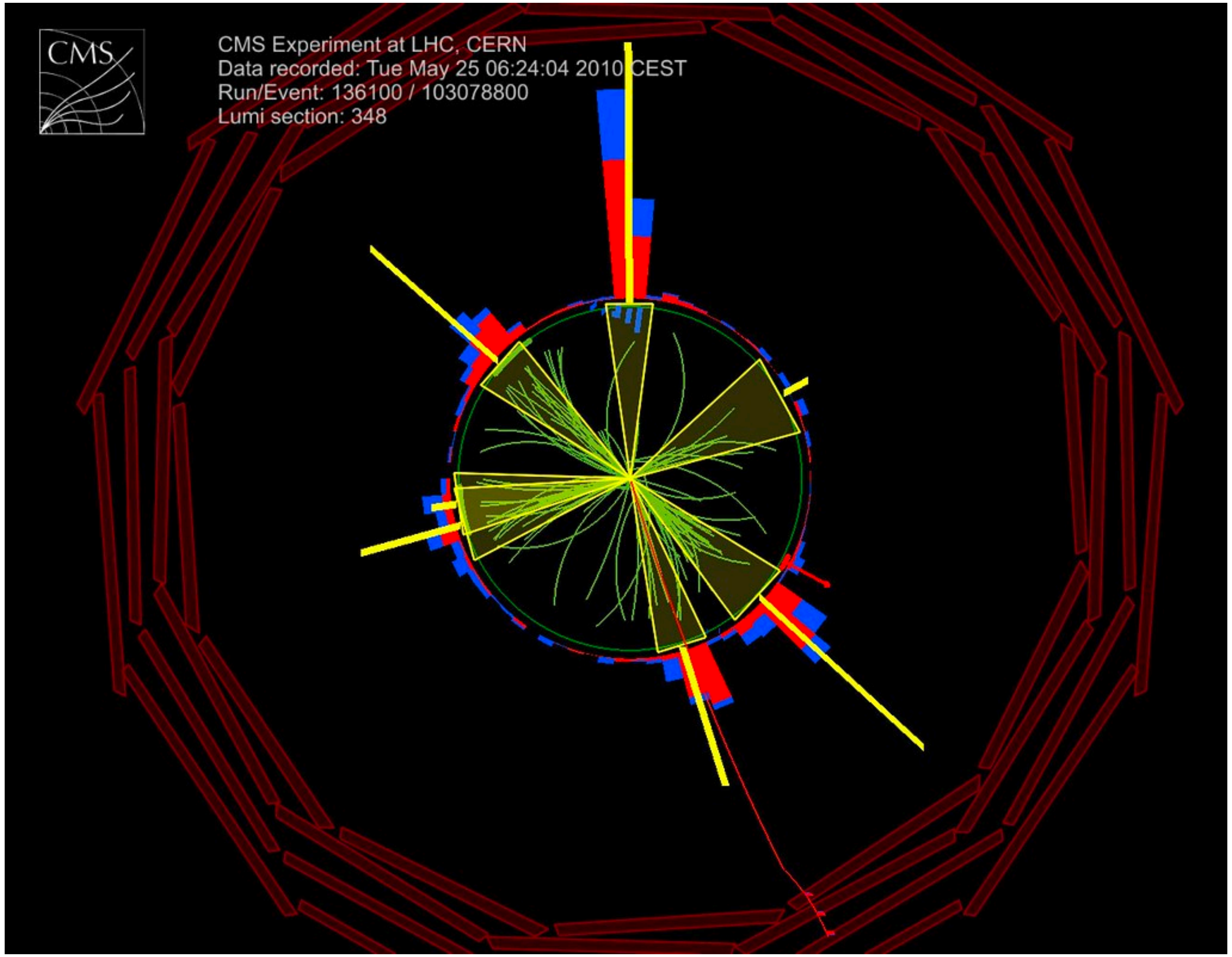
Jet reconstruction

- Jets can be defined on different technical levels:
  - Parton level: for calculations in perturbative QCD ("theory jets")
  - Particle level: jets reconstructed from stable hadrons
  - Detector level: jets reconstructed from energy deposits in calorimeter and/or tracks in tracking detectors
- Design of successful jet algorithms:
  - Independent of technical level
  - Invariant under Lorentz boosts
  - Comparison with theory: infrared and collinear safe → find same jet even after emitting soft/collinear radiation



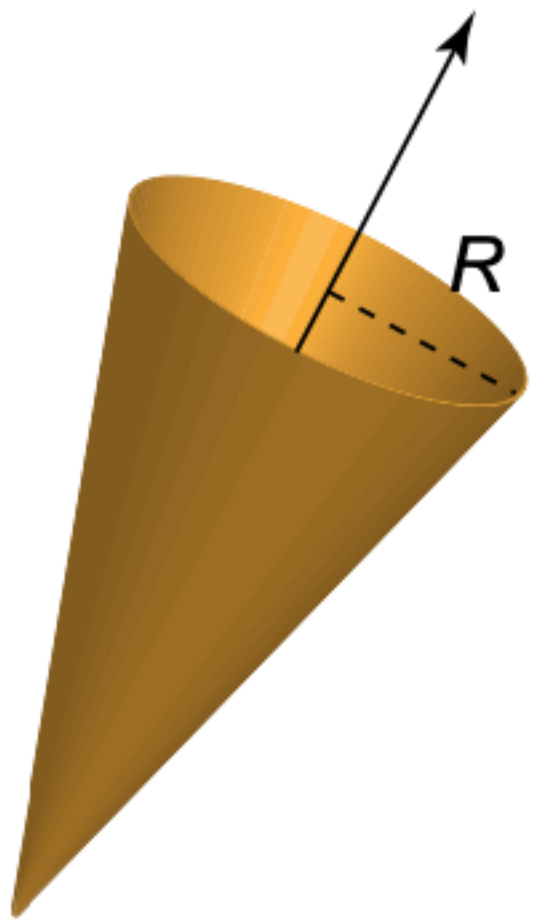
Credit: G. Salam

Jet example


CMS
CMS Experiment at LHC, CERN
Data recorded: Tue May 25 06:24:04 2010 CEST
Run/Event: 136100 / 103078800
Lumi section: 348

Jet reconstruction

- Fixed cone algorithms:
  - Start with high energy seed
  - collect all energy within a cone with radius
    $R = \sqrt{(\eta - \eta_0)^2 - (\phi - \phi_0)^2}$
  - Split/merge nearby clusters

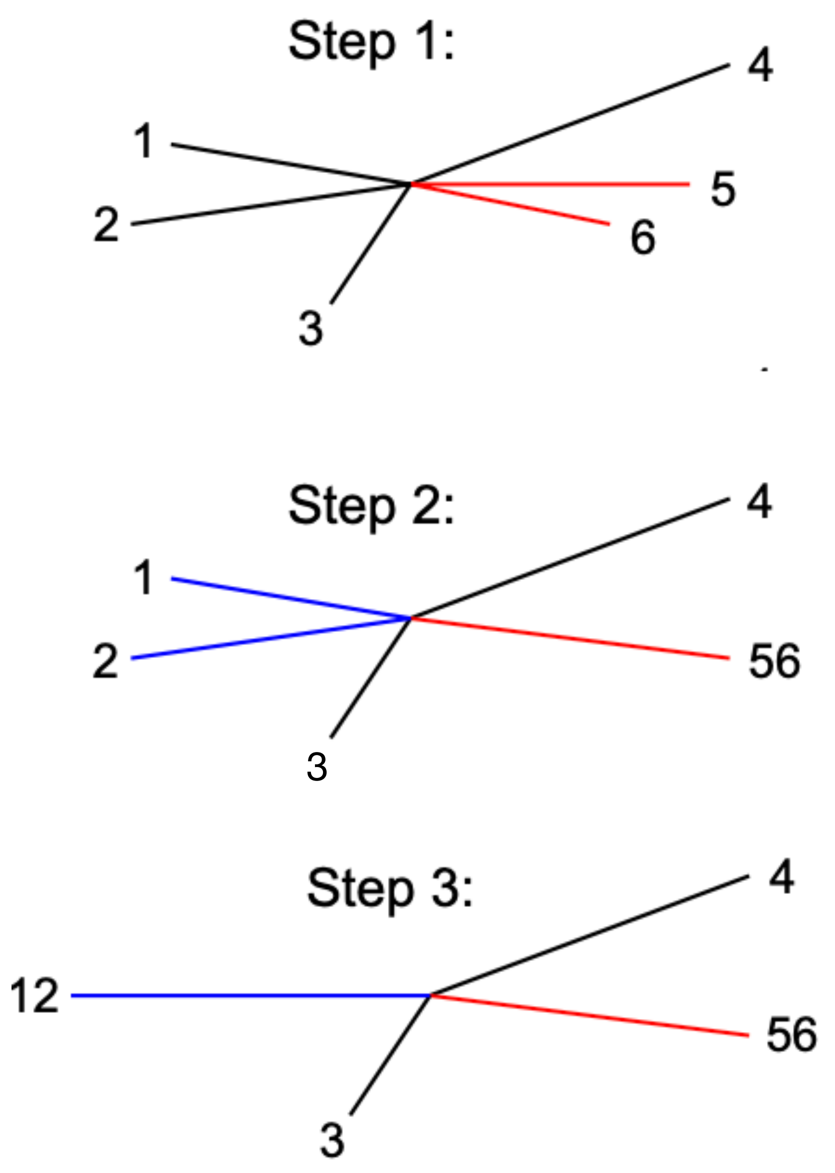


- Sequential recombination “anti-kt”:
  - compute distances ($R_{\text{LHC run 2}} = 0.4$):

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

  - combine pairs with $d_{ij} < k_{t,i}^{-2}$

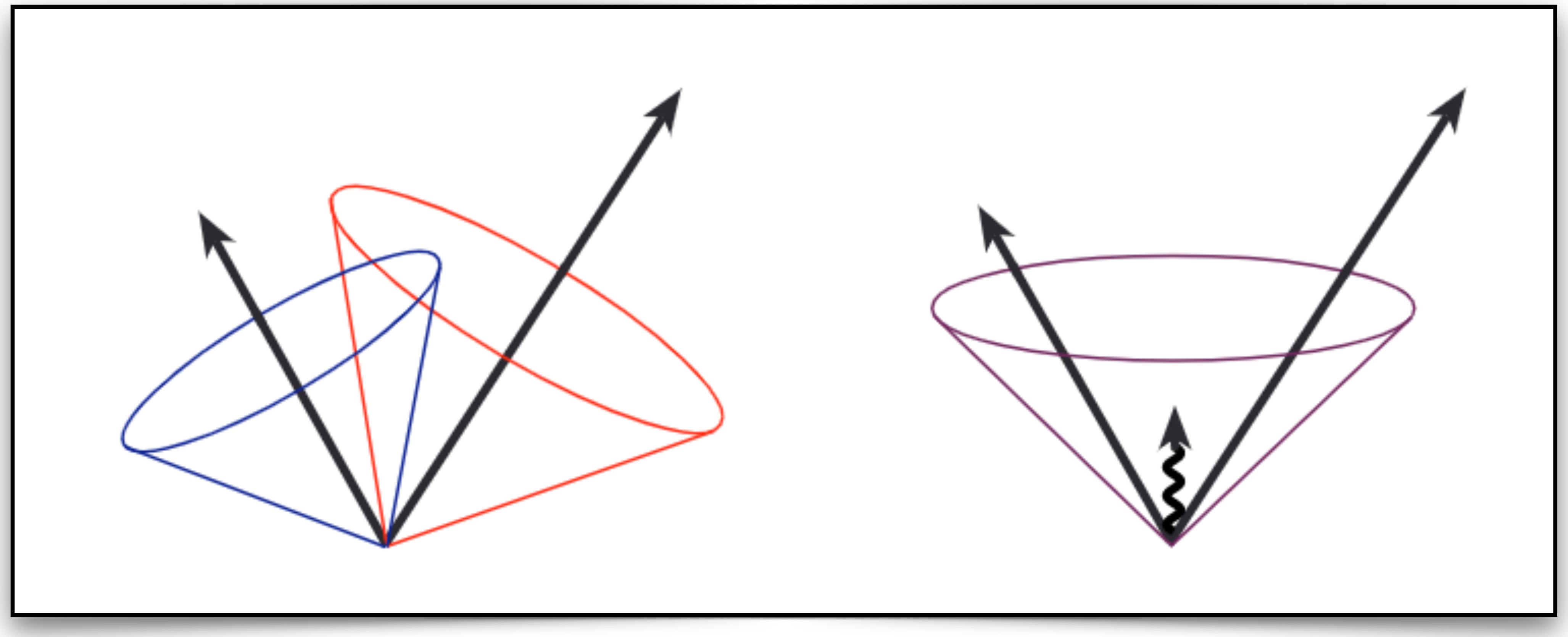
https://arxiv.org/abs/0802.1189

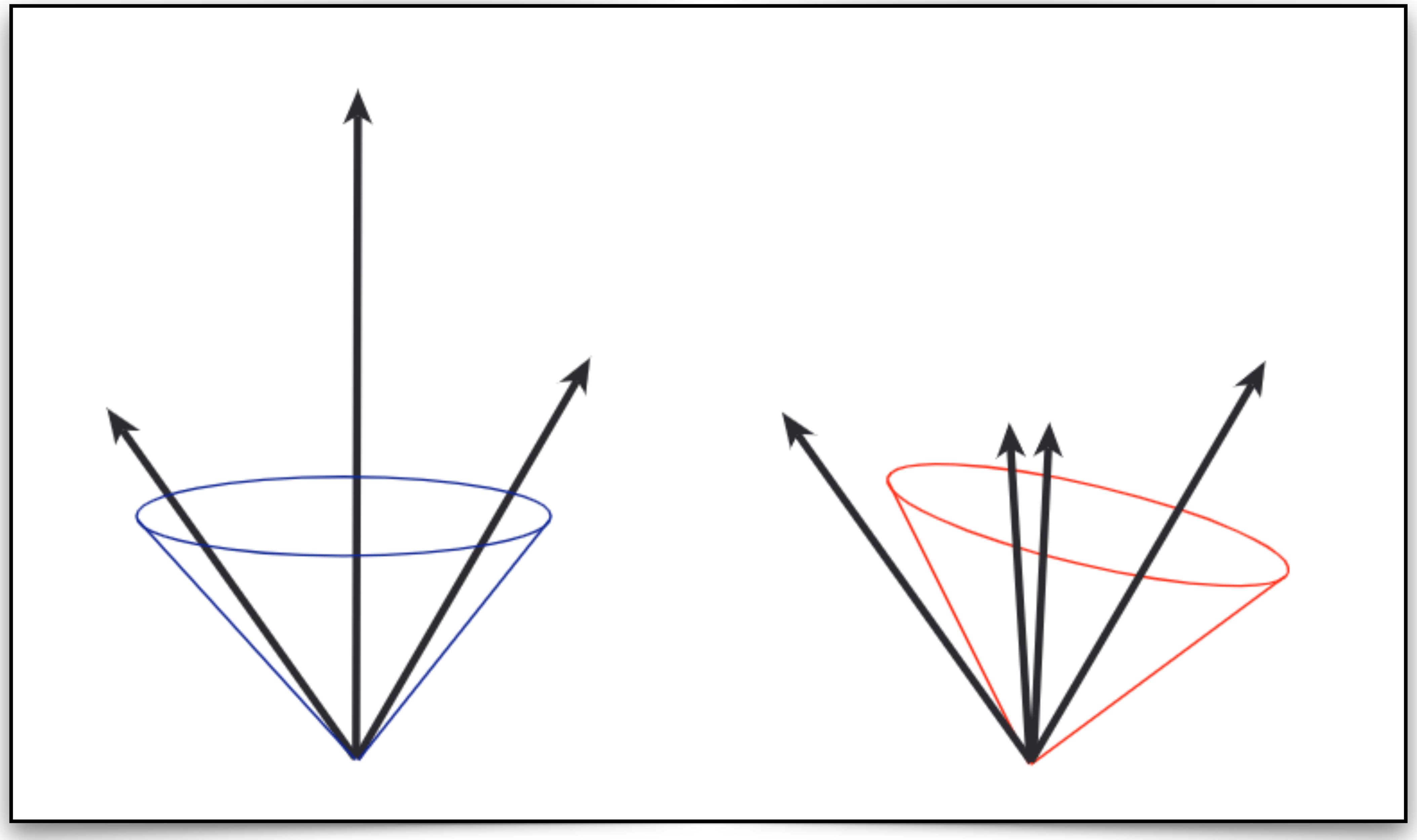


Jet reconstruction

Not save cone: Collinear problems

Not save cone: IR problems



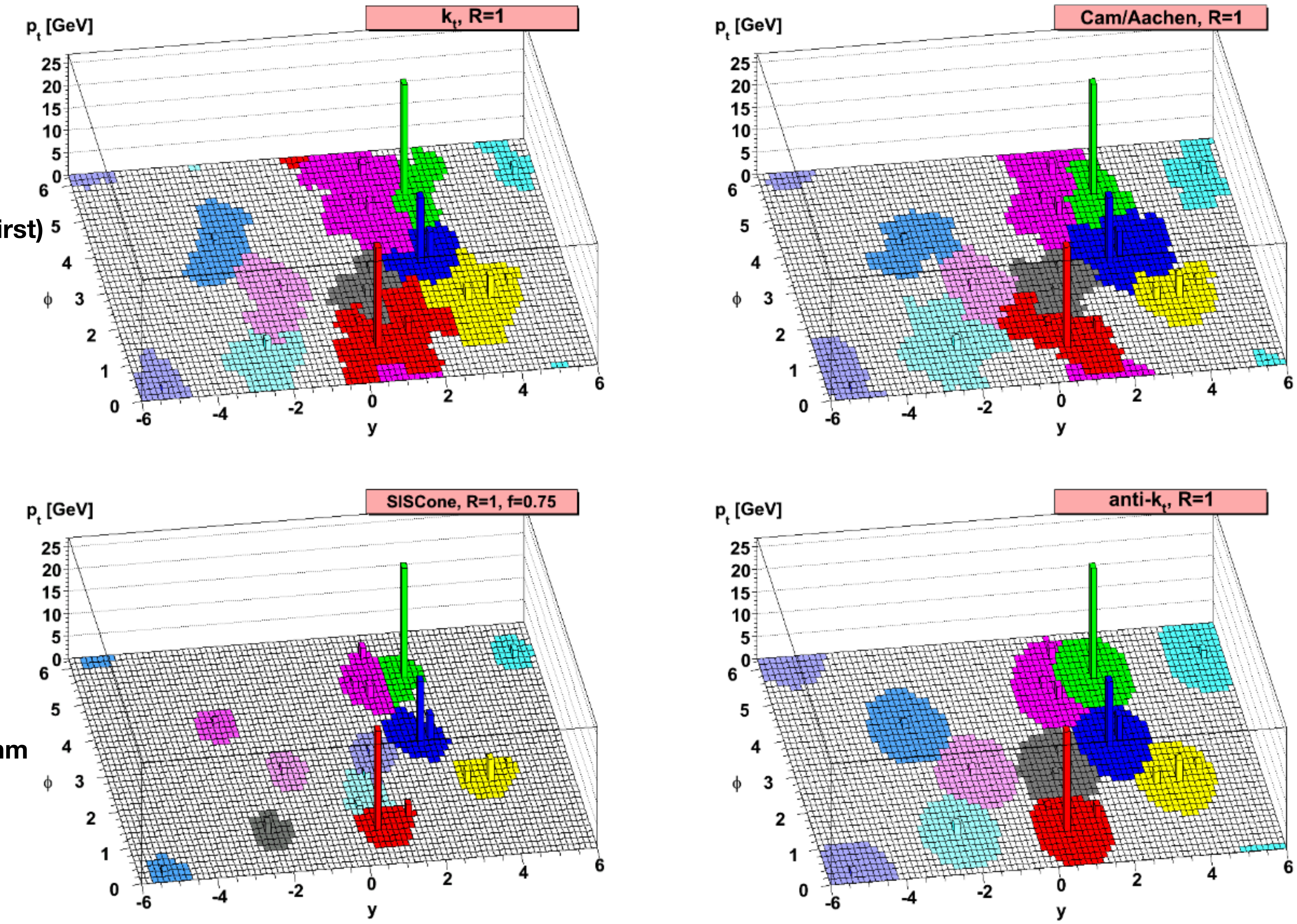


Source: S Catani

Jet reconstruction

kt algorithm (soft particles first)
→ patchwork

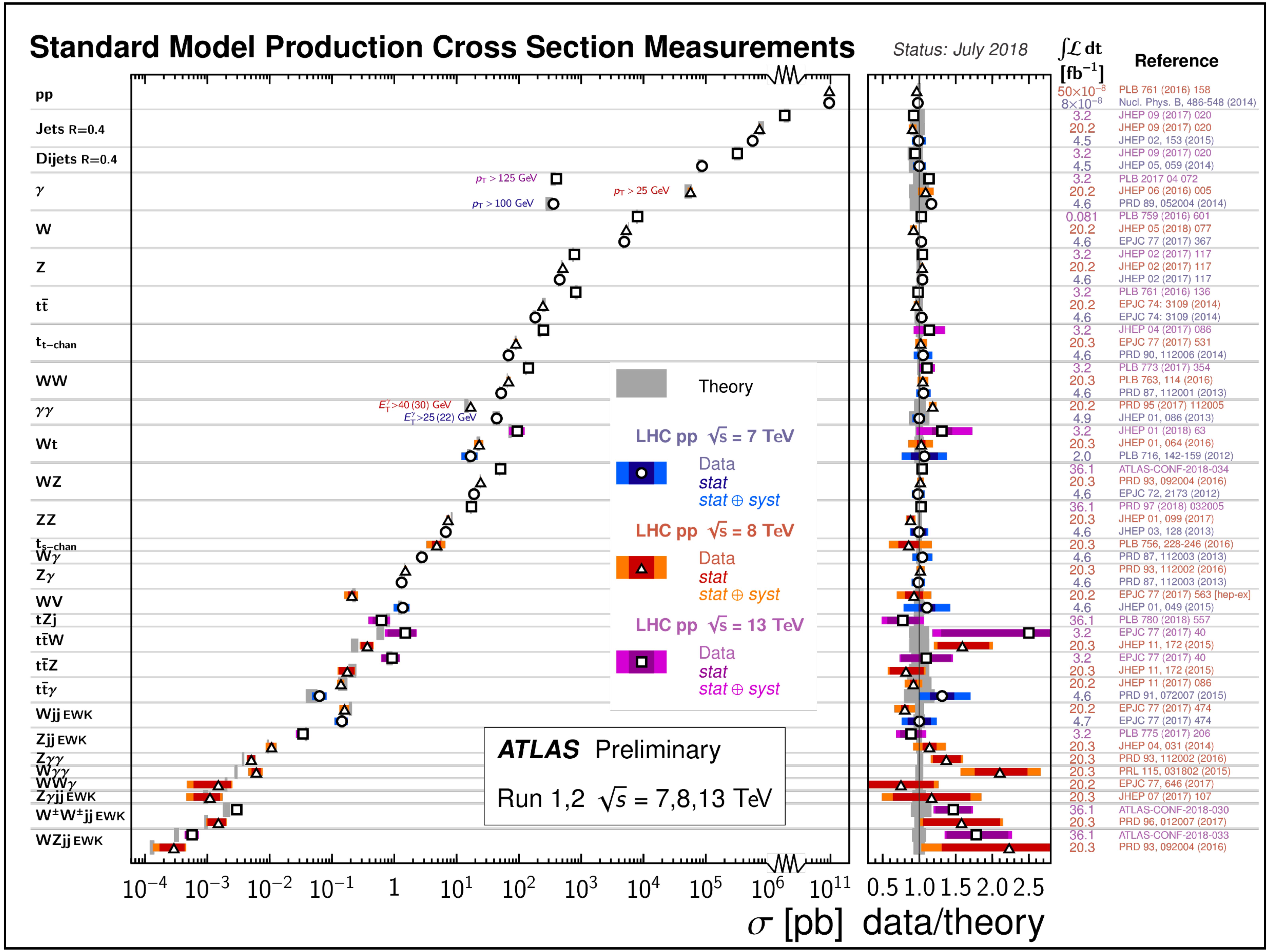
Advanced cone algorithm
→ jets cone-shaped



anti kt algorithm
→ jets cone-shape

https://arxiv.org/pdf/0802.1189.pdf

Jet cross section at the LHC



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/ATLAS_d_SMSummary_FiducialXsect_rotated/ATLAS_d_SMSummary_FiducialXsect_rotated.png

Jet production at the LHC

Total cross section

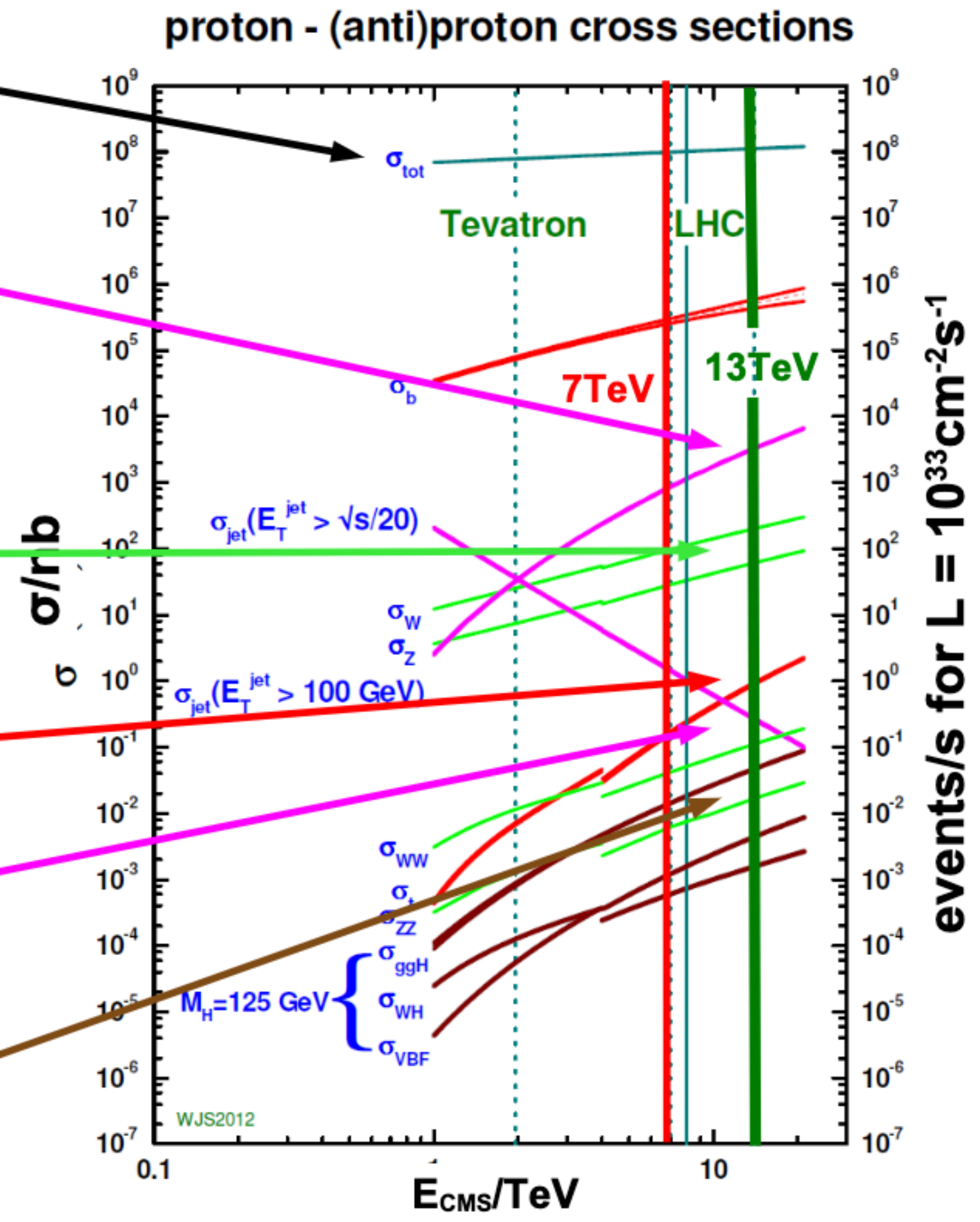
Jets: $\sigma_{jet}(E_T^{jet} > 100\,\mathrm{GeV})$
~ 2000 / s

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

Top quarks (σ_{tt})
~ 1 / s

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

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



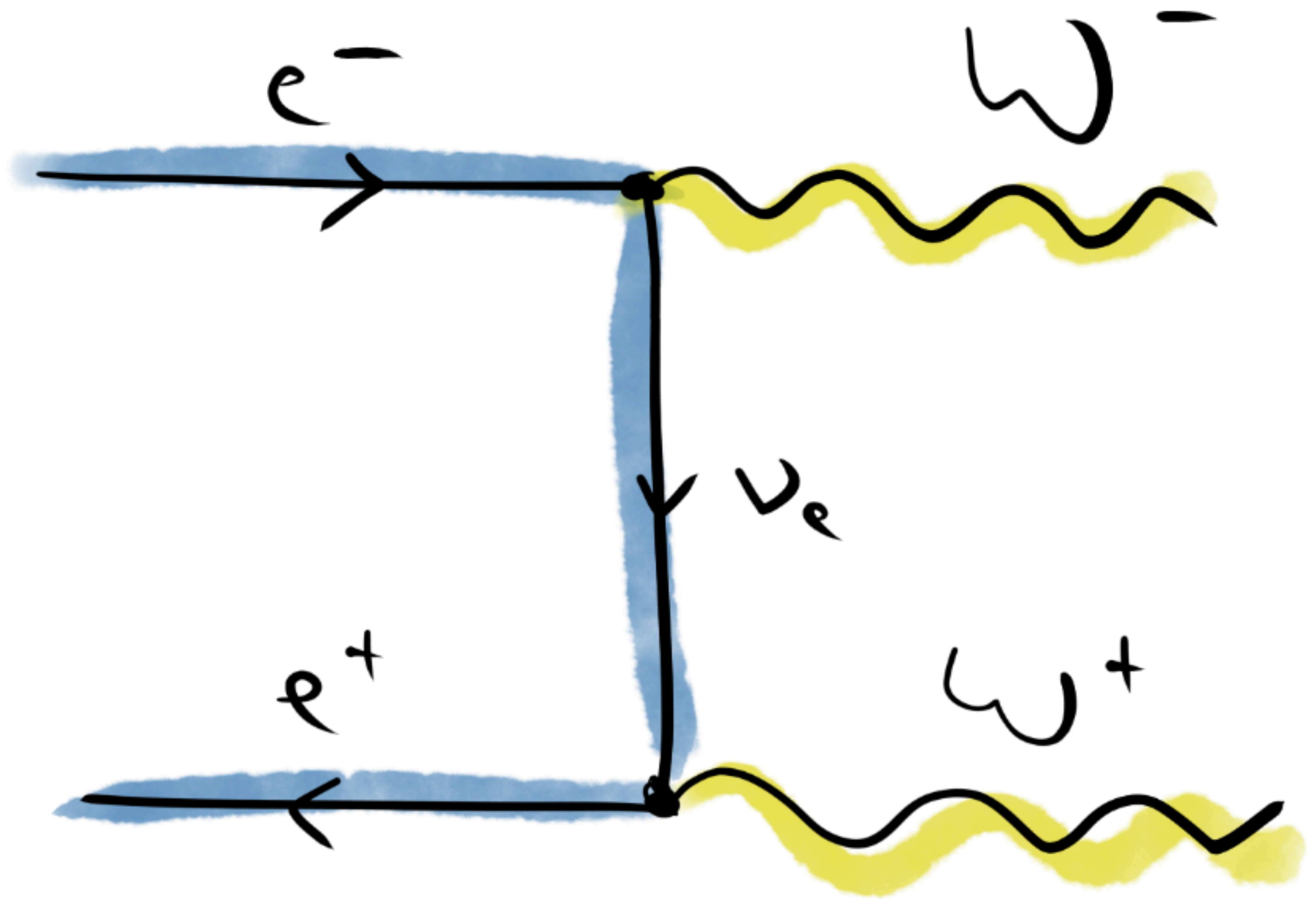
Credit: W. Stirling

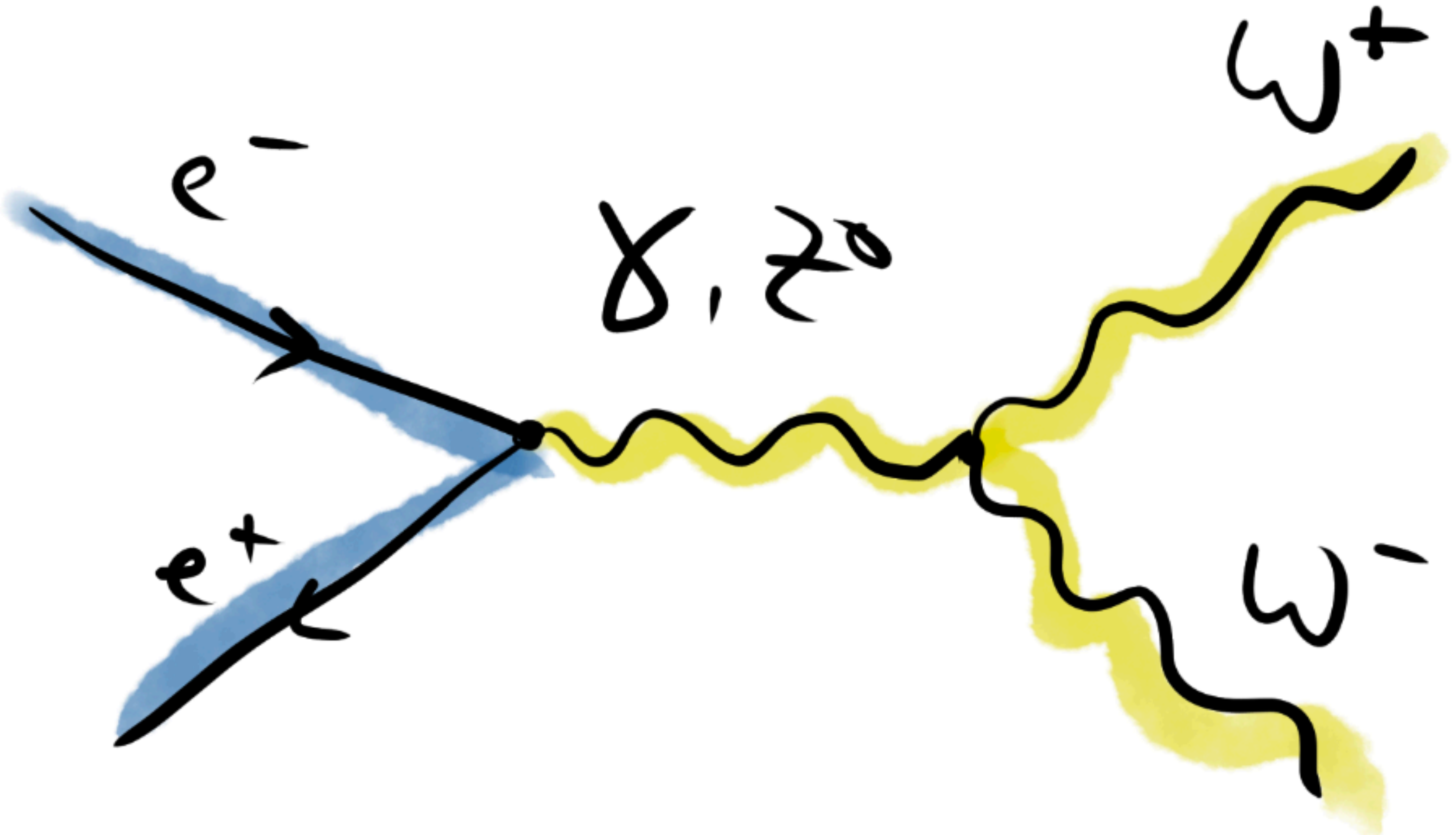
W-production at LEP2 (not at LEP!)

- Kinematic production threshold:

$$\sqrt{s} \geq 2m_W$$

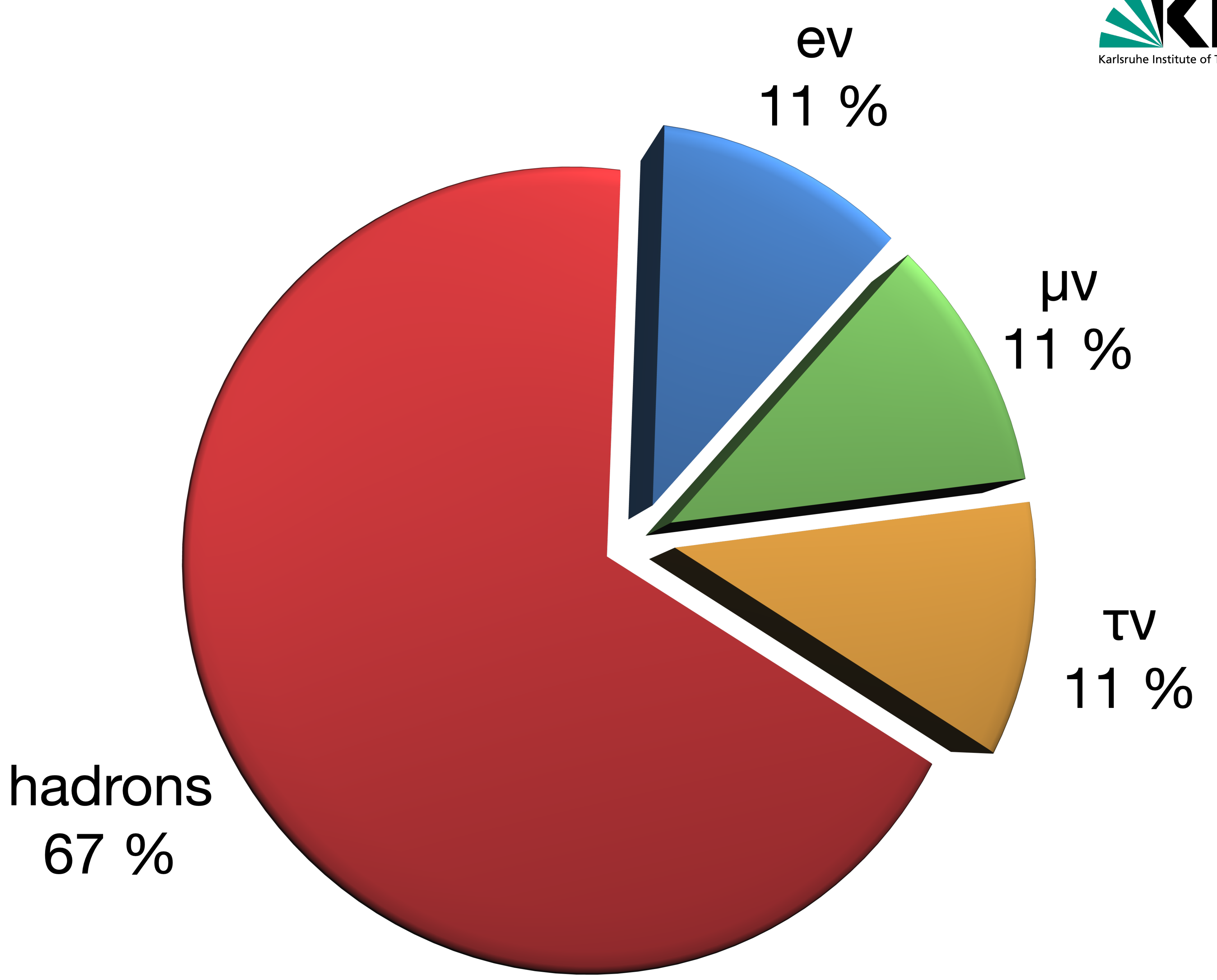
- **Threshold scan**: measure cross section as a function of $\sqrt{s}$ (scan of beam energies) → scattering matrix only unitary if both neutrino exchange and triple gauge boson (*ZWW*) vertex are considered





W decays

- Leptonic decay: $W \to \ell\nu_\ell$
  - Neutrino: missing transverse momentum
  - $\ell = e, \mu$: experimentally very clean
  - $\ell = \tau$: hadronic τ-decays → complicated
- Hadronic decay $W \to q\bar{q}$
  - Large QCD multijet background → complicated



- Isolated leptons are a clean experimental signature of W or Z decay
- QCD jets contain mostly non-isolated leptons from heavy quark decays inside the jet

PINGO

- **PINGO:**
  - Umfrage: Teilchenphysik 1 (WS 23/24)
  - Zugangsnummer: 434521
  - Link: https://pingo.coactum.de/events/434521

PINGO: QCD Jets

- Why is QCD jet production expected to be the most important background for the decay $W \rightarrow l\nu$?
  - Jets may be misidentified as charged leptons.
  - Jets always contain charged leptons.
  - Often QCD jet events contain large missing transverse momentum.
  - Detector noise may “fake” missing transverse momentum.
  - The production cross sections for W bosons and QCD jets are approximately of equal size.

PINGO: QCD Jets

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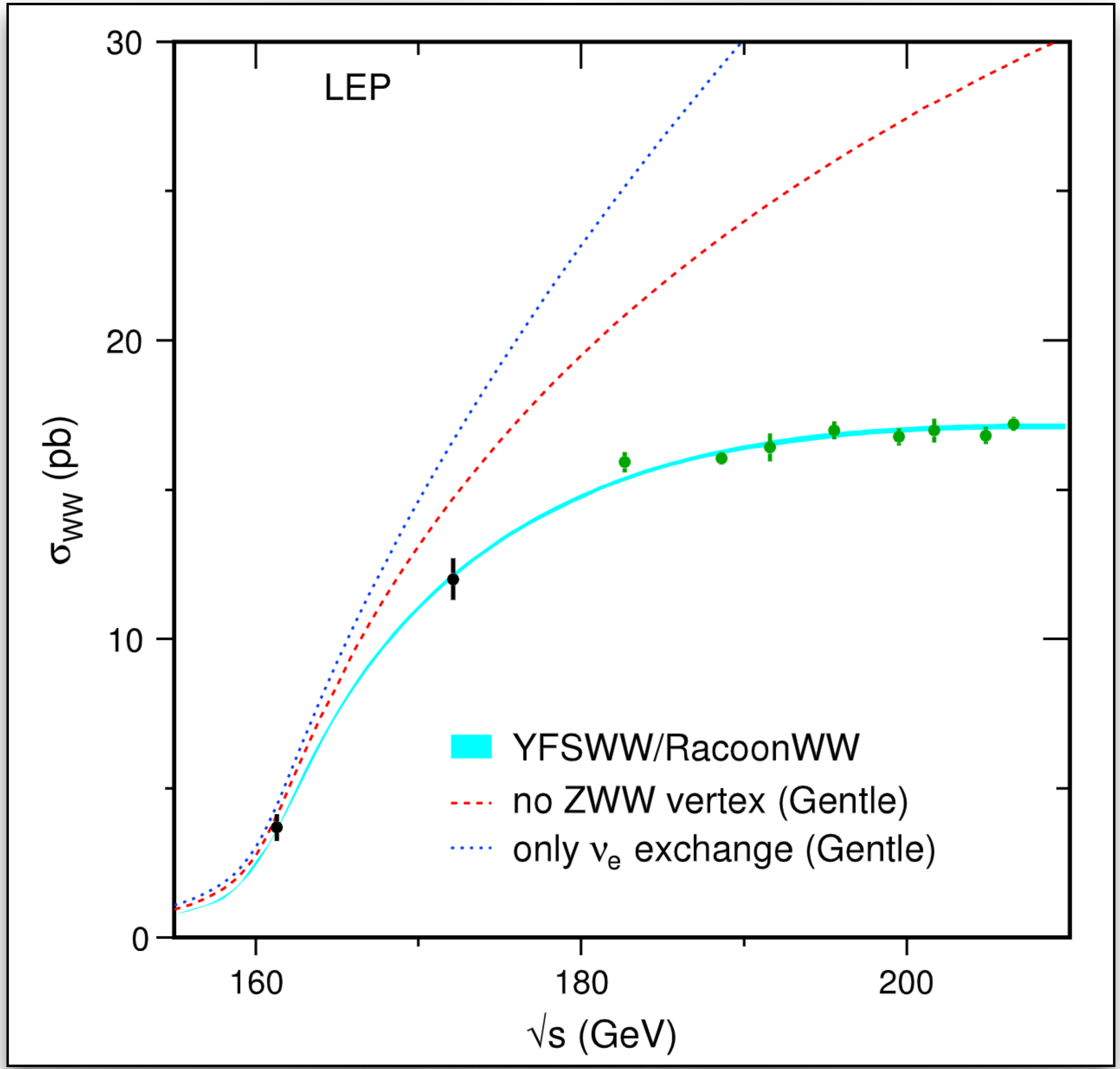
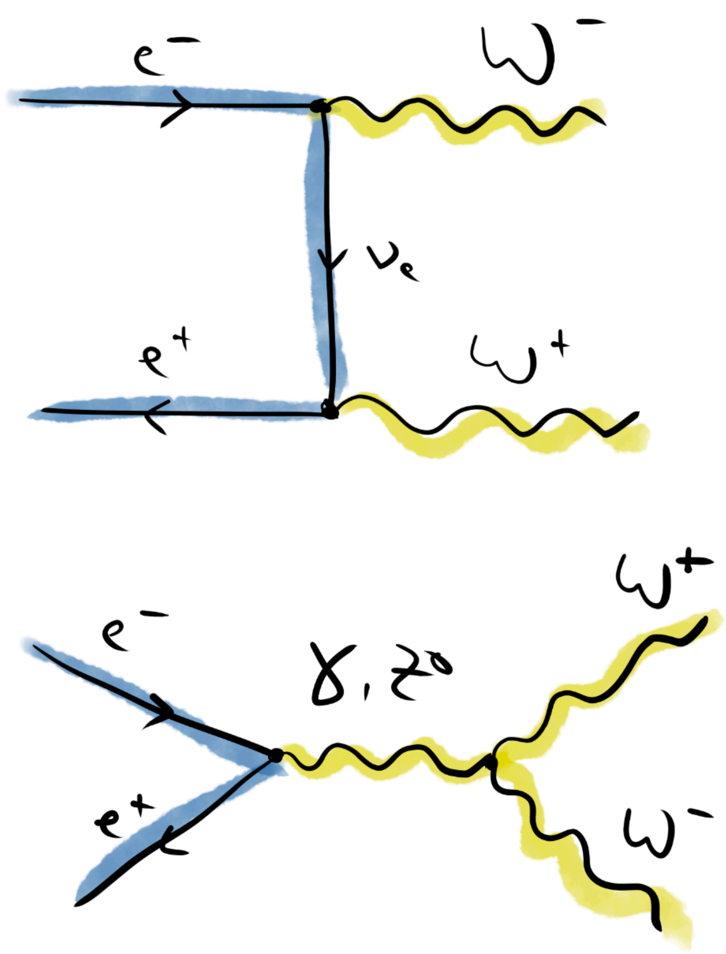
W-production at LEP2 (not at LEP!)





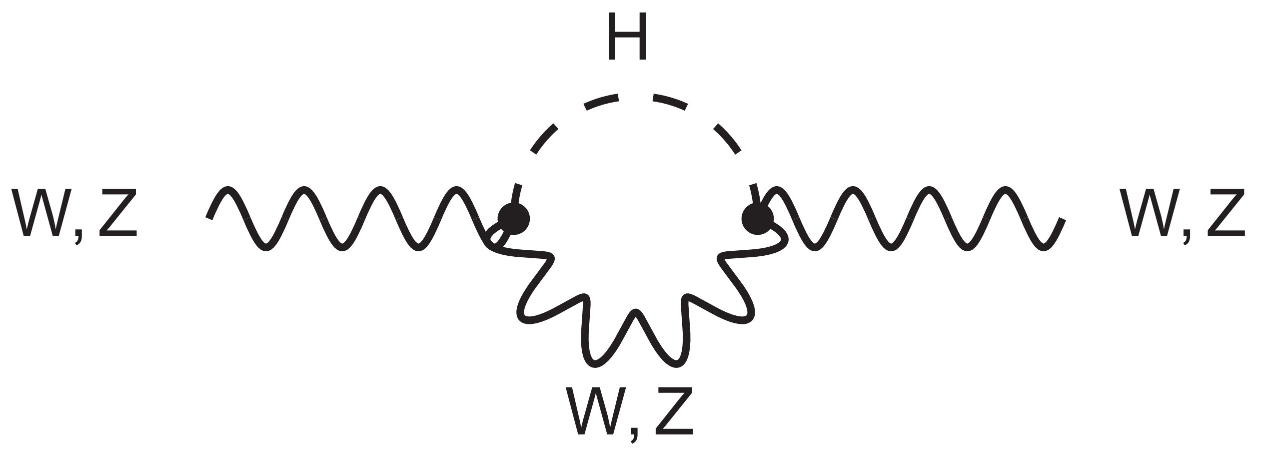
Source: http://www.sciencedirect.com/science/article/pii/S0370157313002706

Indirect W properties

- *W* and *Z* boson masses related through **weak mixing angle:**

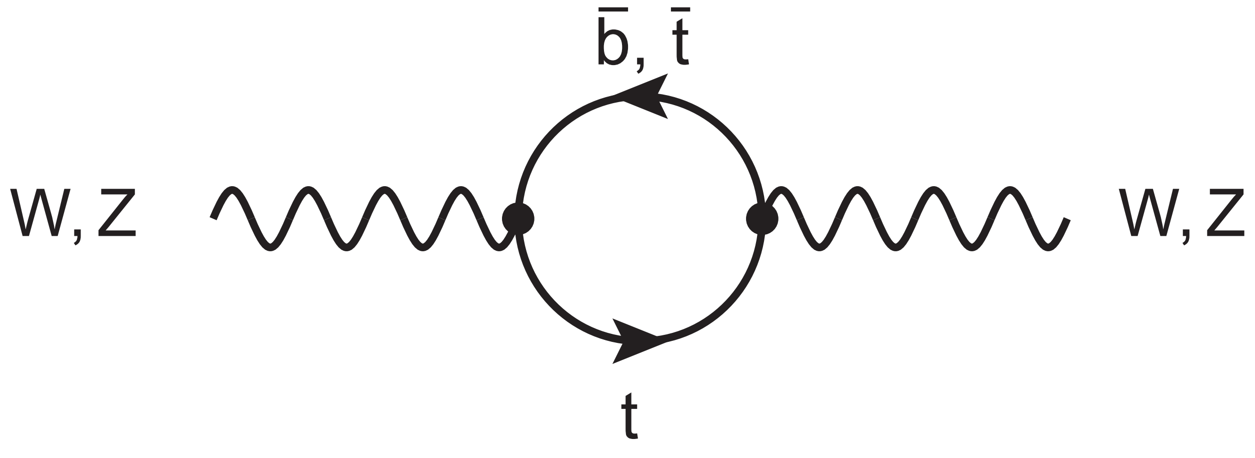
$$m_W^2 = \frac{g^2 v^2}{4}, m_Z^2 = \frac{v^2}{4}(g^2 + g'^2), \rho_0 = \frac{m_W^2}{m_Z^2 \cos\theta_W} = 1$$

- Relation with top-quark and Higgs-boson masses through loop corrections, e.g. *W* and *Z* boson “**self energy**”



$\sim g' \ln(m_H / m_W)$

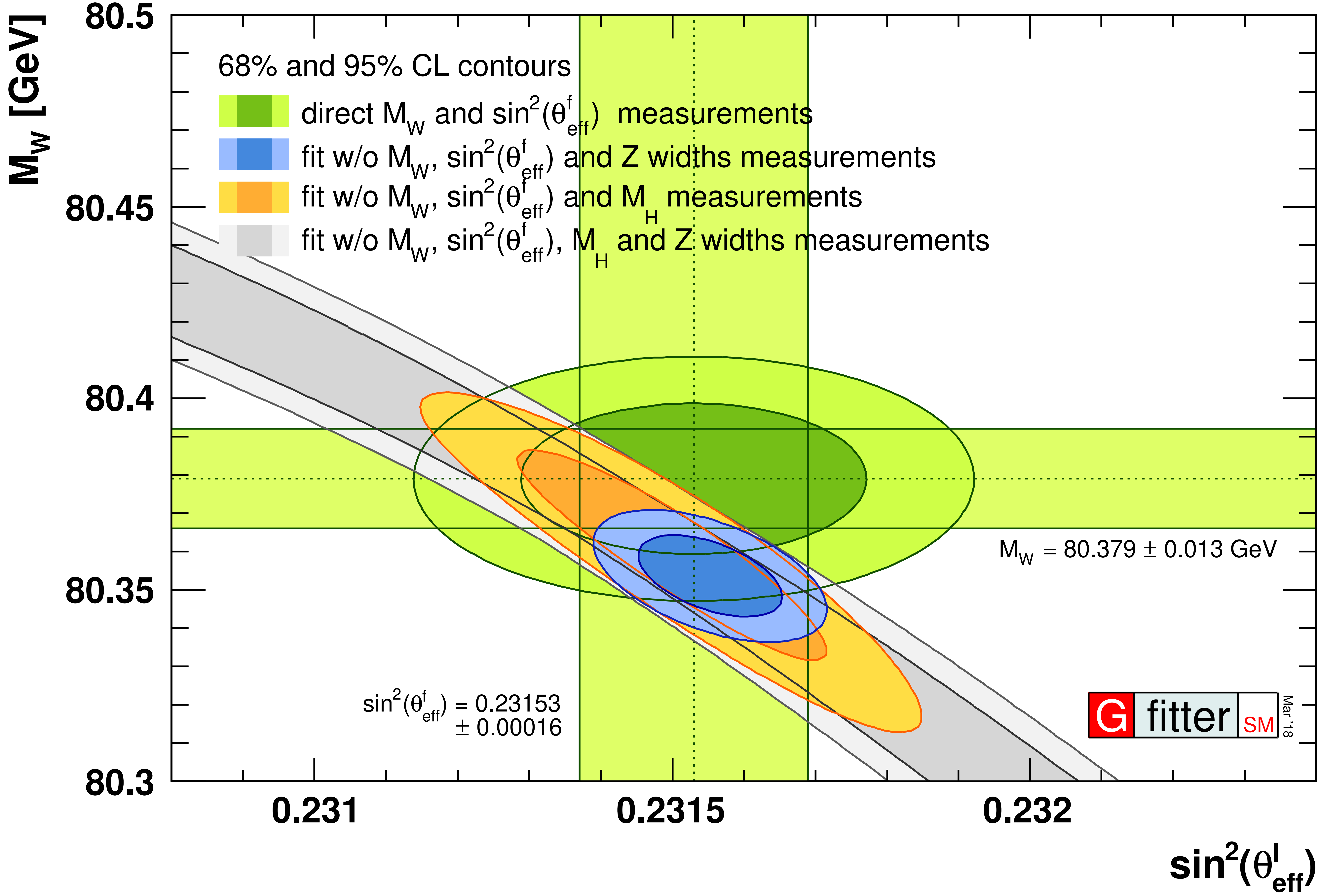
Weak dependence (logarithmic)



$\sim G_F\, m_t^2$

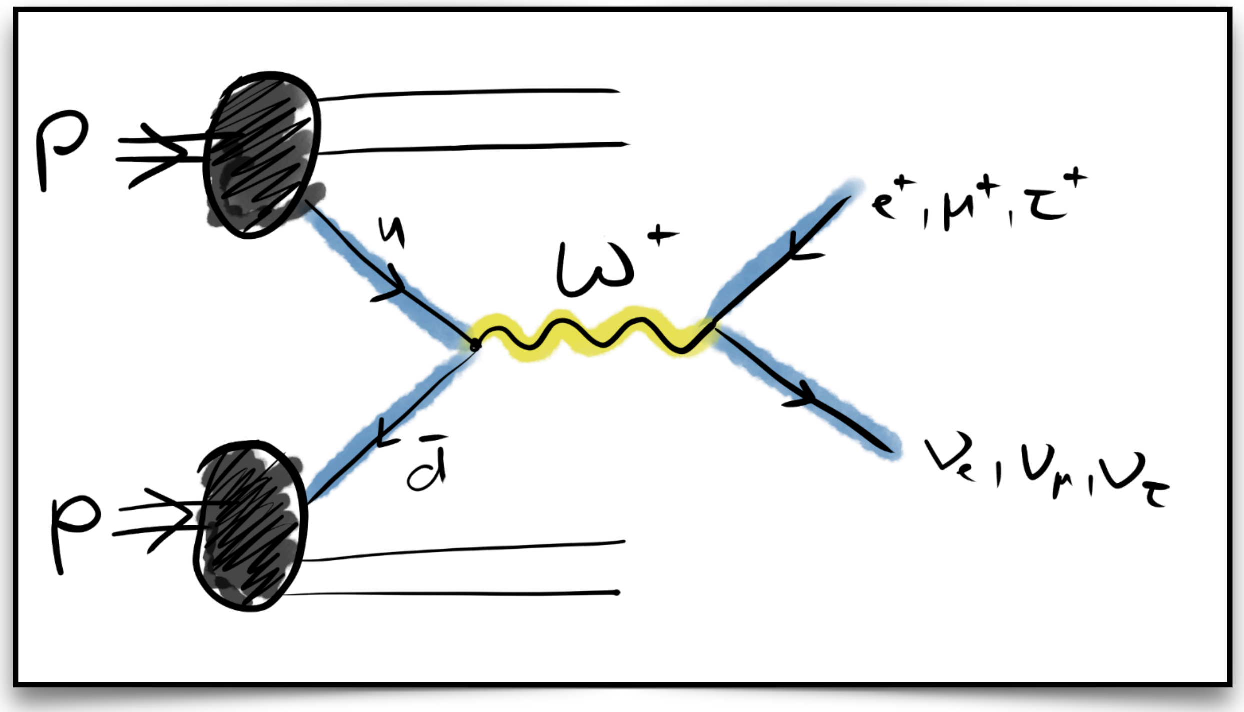
Strong dependence (quadratic)

Indirect W properties



Differential W production cross section

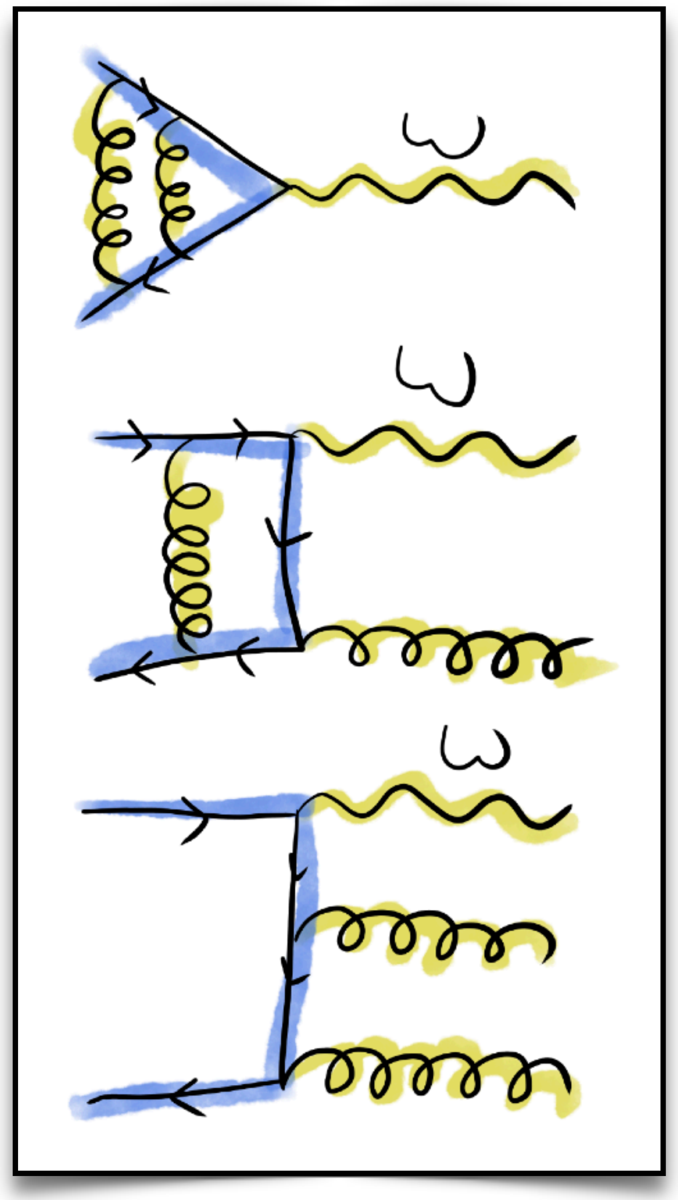
- W boson production via quark-antiquark annihilation



- Partonic cross section (leading order):

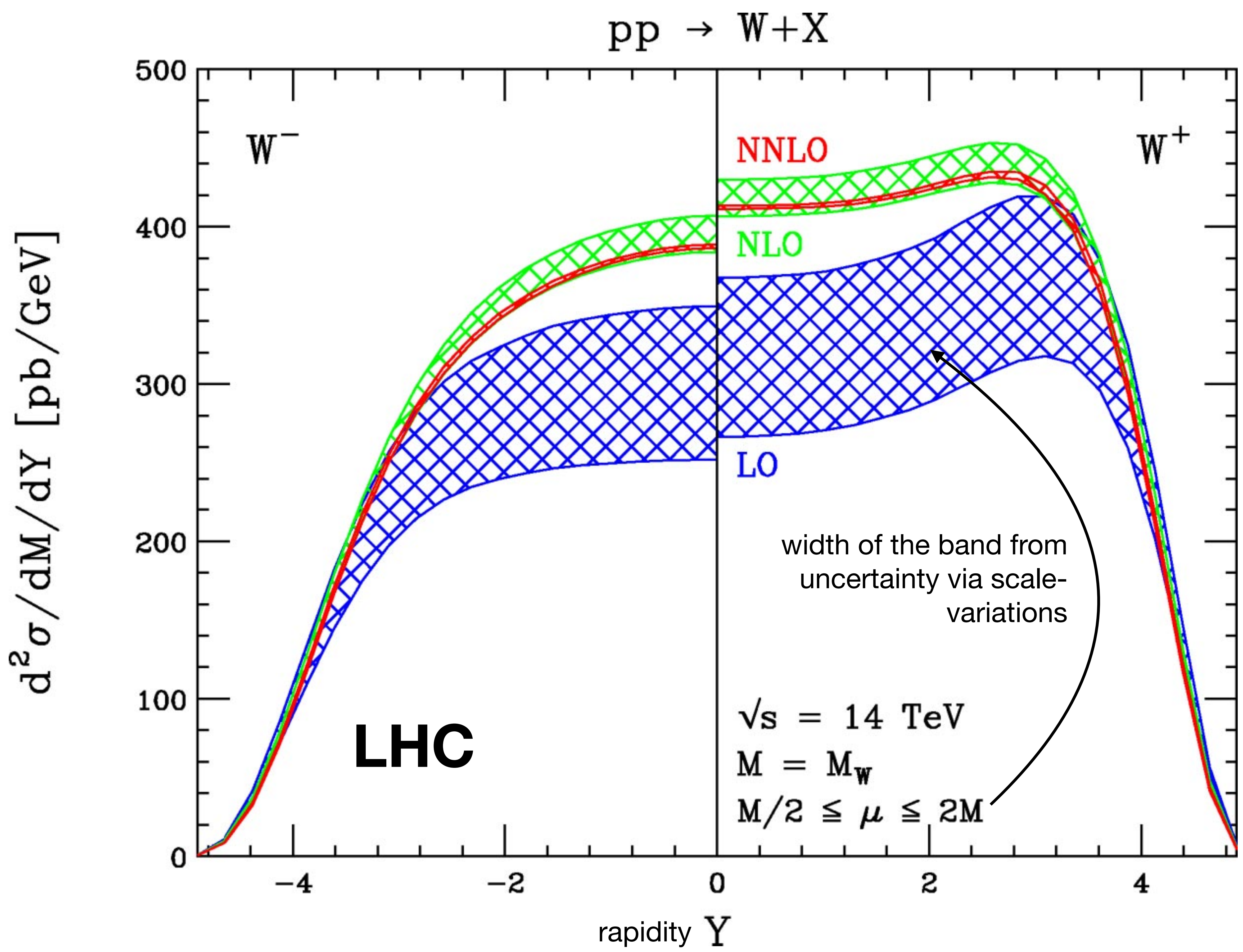
$$\hat{\sigma}(q\bar{q}' \to W) = \frac{\pi}{3}\sqrt{2}G_F m_W^2 |V_{q\bar{q}'}|^2 \delta(\hat{s} - m_W^2)$$

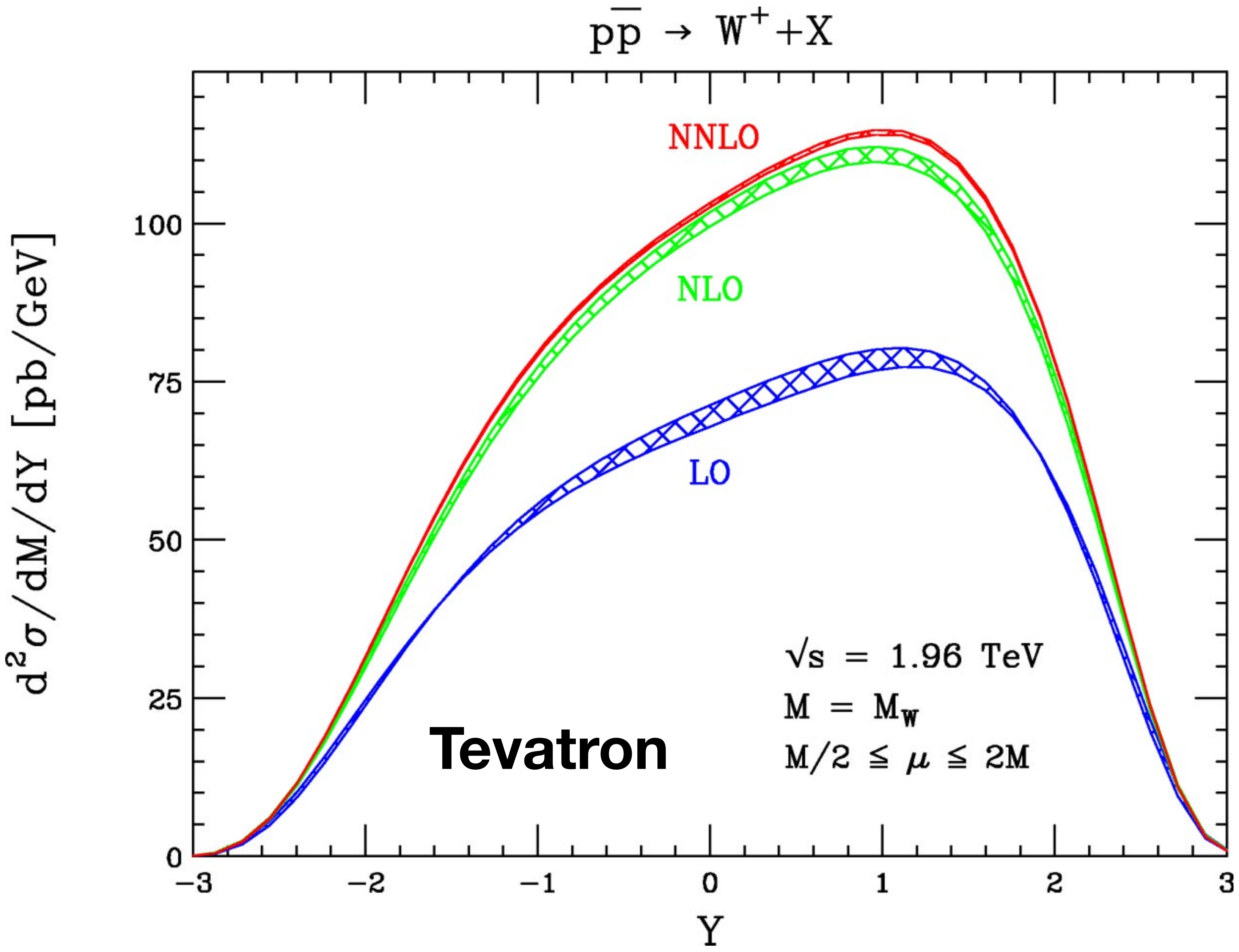
- Differential cross sections known theoretically up to next-to-next-to-leading order (NNLO) (next slide)



Differential W production cross section

Source: Phys. Rev. D 69, 094008 (2004)





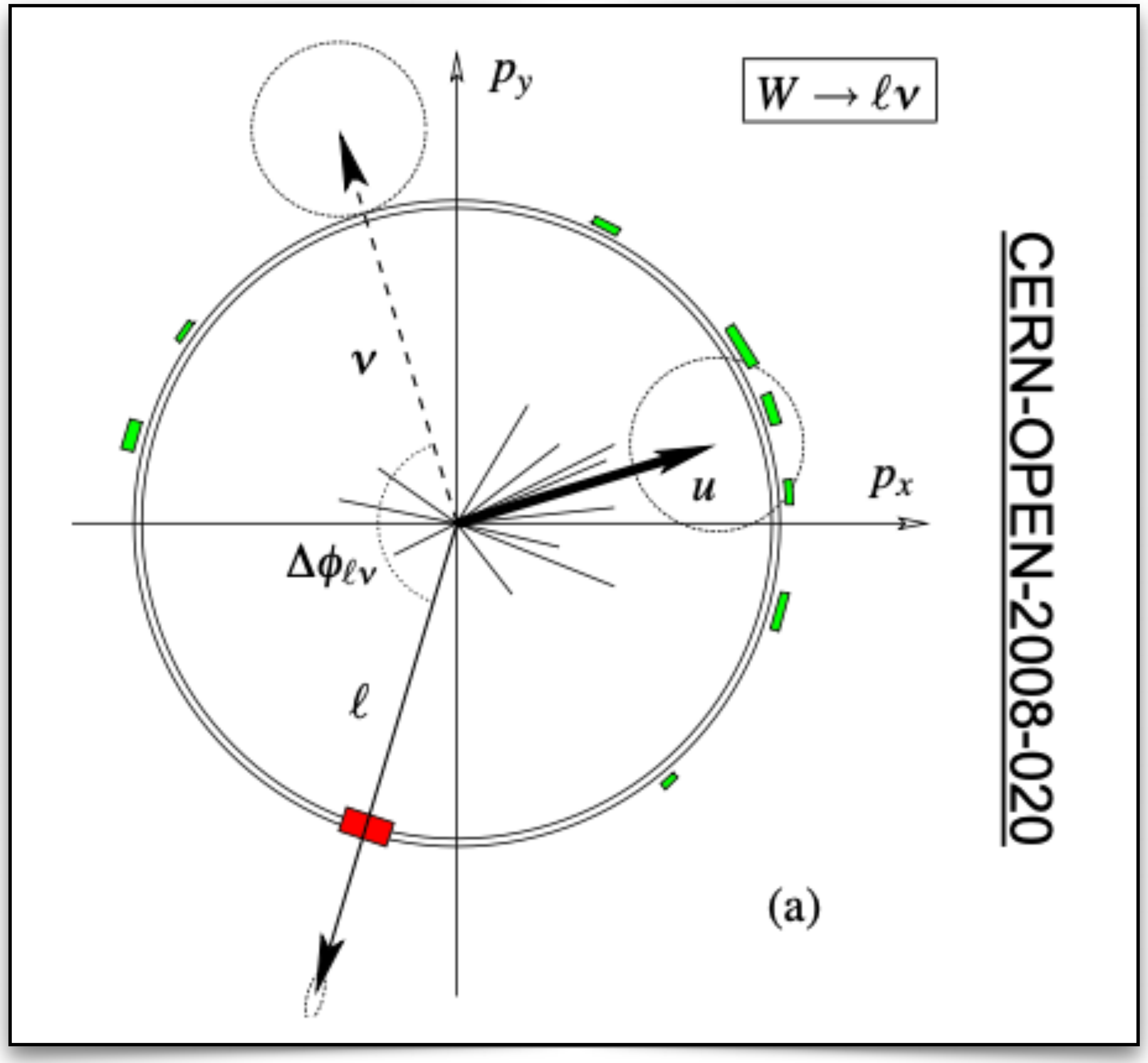
W^+ preferably moving in proton direction

W^- (not shown here) preferably moving in antiproton direction

W boson mass at hadron colliders

- Use muonic $W^+ \to \mu^+ \nu_\mu$ decays
  - Signature: isolated, high-pt lepton
  - Often additional hadronic activity
  - Neutrino is invisible energy
- Define observable "transverse mass":

$$m_T^2 = (E_T^\ell + E_T^\nu)^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2$$
$$\approx 2\,|\vec{p}_T^\ell|\,|\vec{p}_T^\nu|\,(1 - \cos\Delta\phi_{\ell\nu})$$



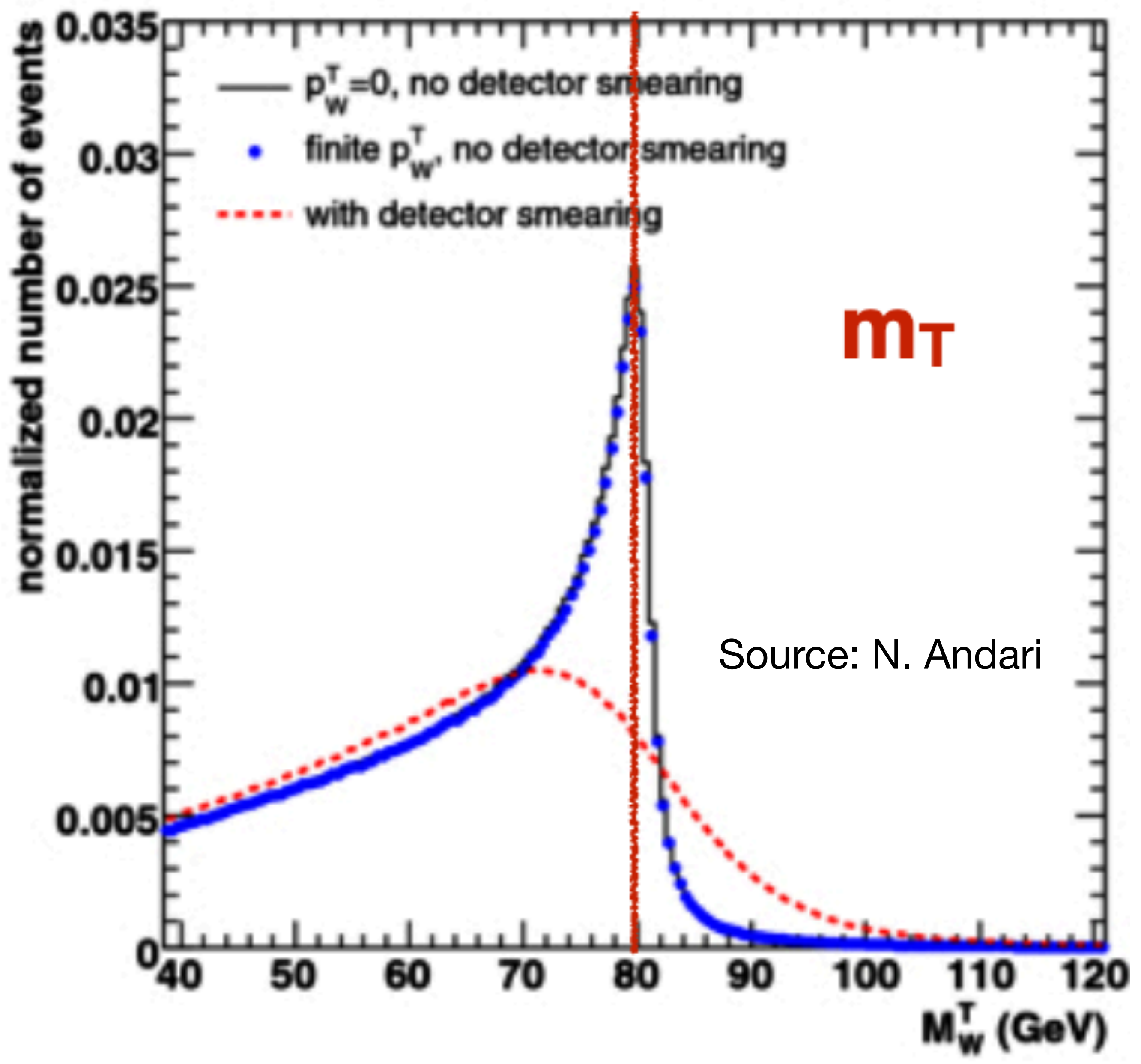
CERN-OPEN-2008-020

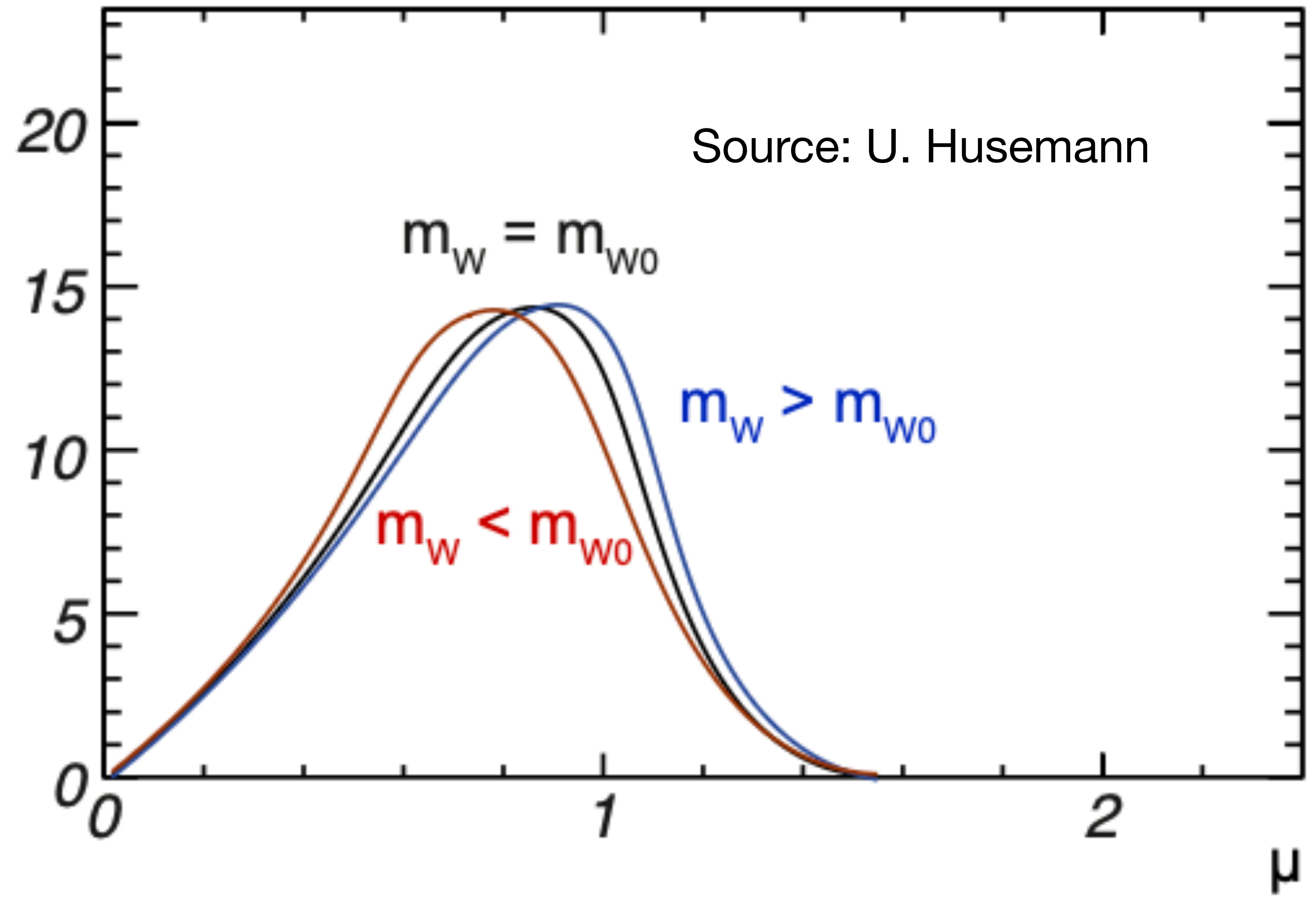
W boson mass at hadron colliders

- Exploit significant feature in kinematic distributions: **Jacobian edge**
- Two-body decay kinematics:
  - $p_T^\ell = p_T^\nu = \frac{m_W}{2} \sin\theta$
  - $\cos\Delta\phi_{\ell\nu} = -1$ ("back-to-back", 180°)
  - $m_T^2 \approx 2|\vec{p}_T^{\,\ell}||\vec{p}_T^{\,\nu}|(1-\cos\Delta\phi_{\ell\nu})$
    - $\rightarrow m_T = m_W \sin\theta$, define $\mu = \frac{m_T}{m_W}$ and with $\cos^2\theta = 1 - \sin^2\theta \rightarrow \cos\theta = \sqrt{1-\mu^2}$
- $$\frac{d\sigma}{d\mu} = \frac{d\sigma}{d\cos\theta}\left|\frac{d\cos\theta}{d\mu}\right| = \frac{d\sigma}{d\cos\theta}\left|\frac{d\sqrt{1-\mu^2}}{d\mu}\right| = \frac{d\sigma}{d\cos\theta}\left|\frac{-\mu}{\sqrt{1-\mu^2}}\right|$$

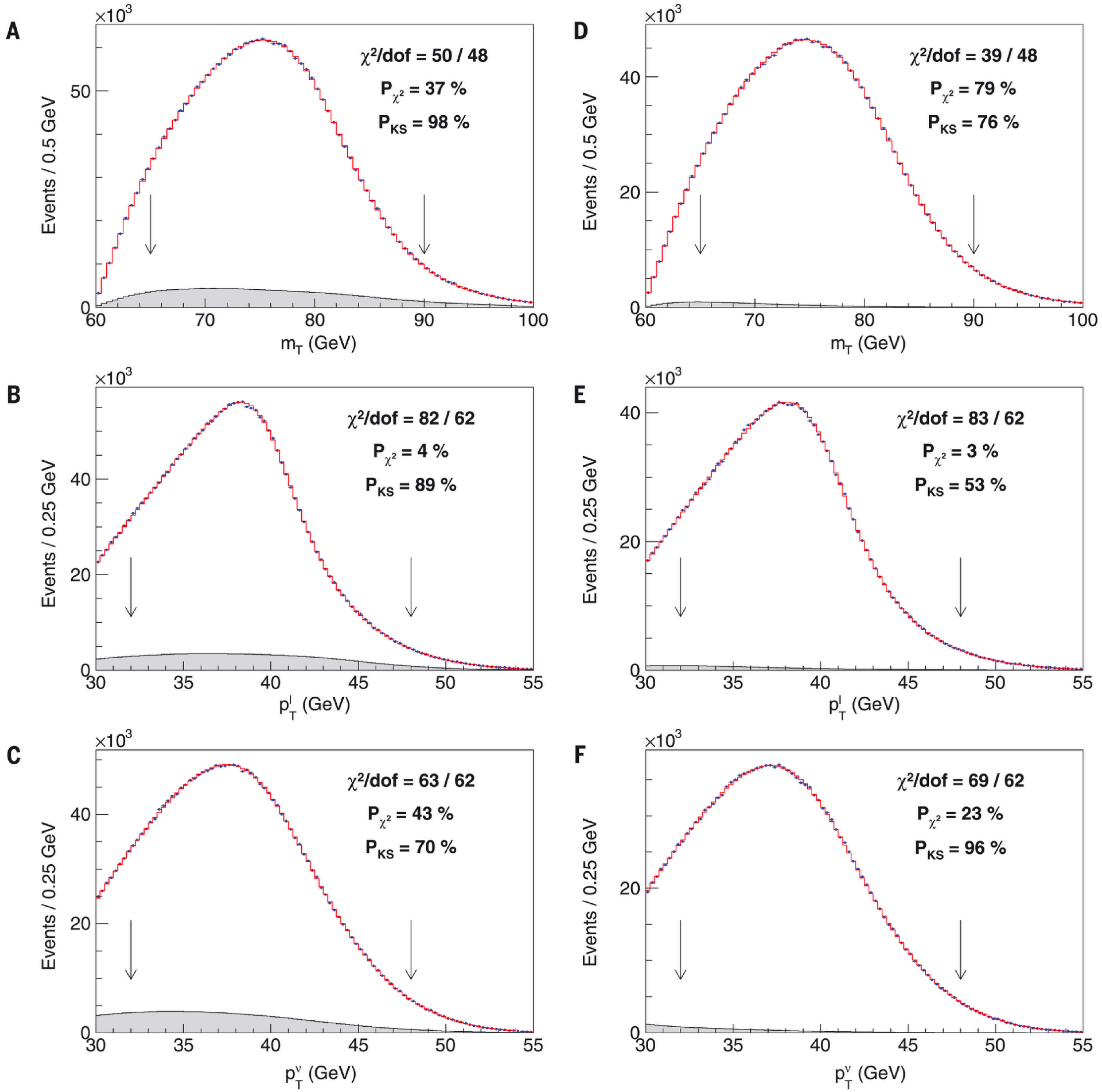
W boson mass at hadron colliders

- Finite W-width (~2 GeV) and detector effects smear peak significantly
- Analysis: Maximum-likelihood fit used templates (from full detector simulations) for different W masses
- Precision traditionally limited by systematic effects (at CDFII statistical uncertainty ~ systematics)





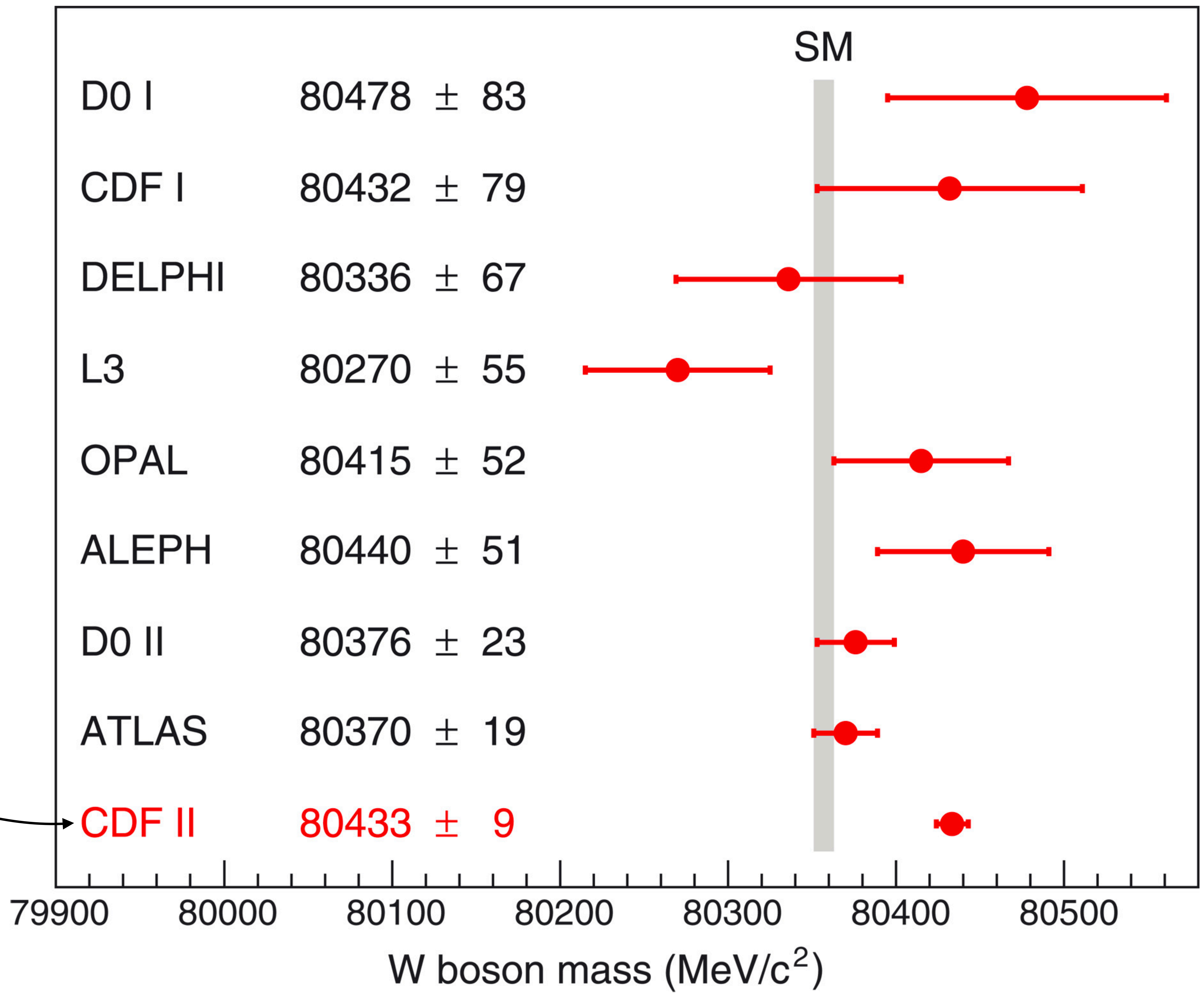
W boson mass at hadron colliders



Source: https://www.science.org/doi/10.1126/science.abk1781

W boson mass summary

hadron collider
(Tevatron)

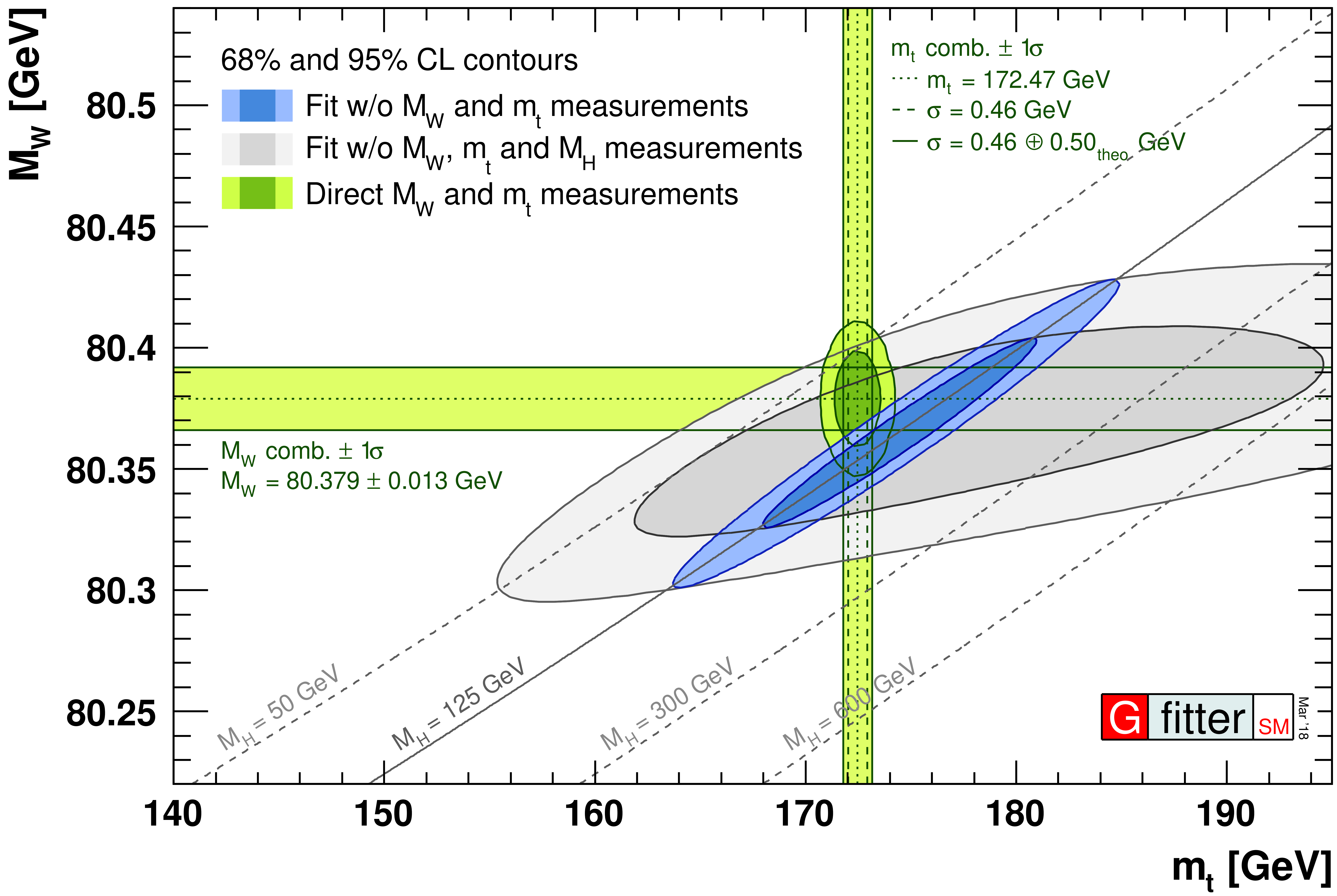


Source: https://www.science.org/doi/10.1126/science.abk1781

Top quark

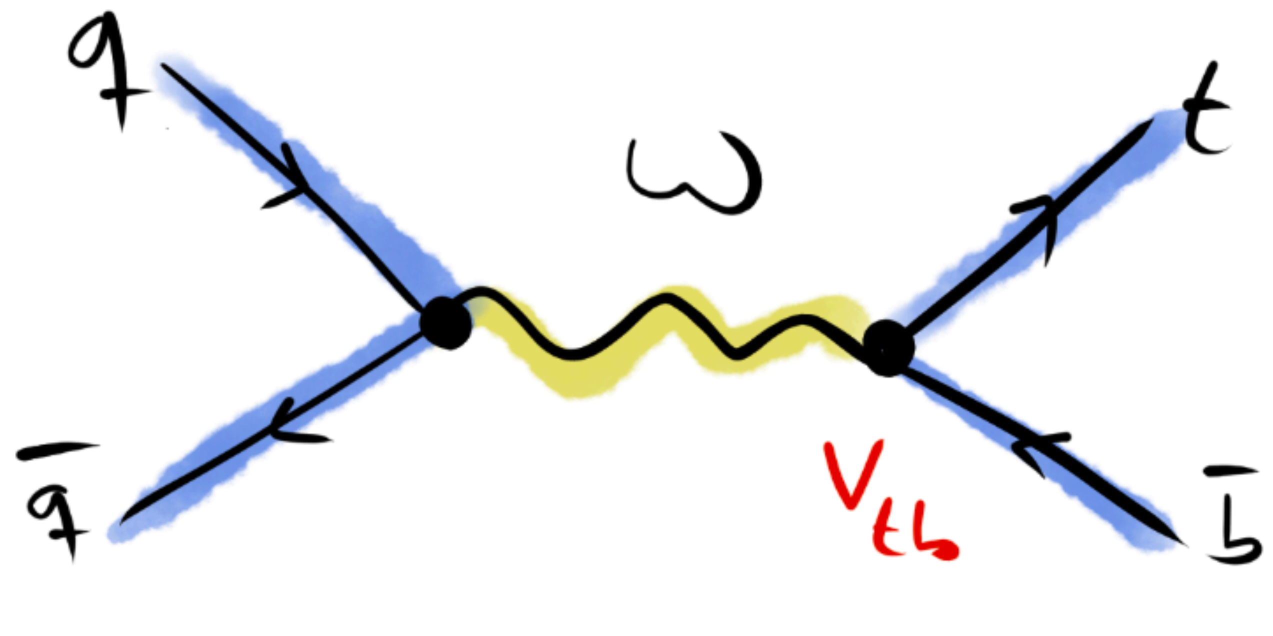
- 1973: three quark generations required for CP violation (Kobayashi & Maskawa)
- 1977: bottom quark discovery → first third-generation quark
- 1980s: search for “light top quarks” in decay W → tb, indirect hints for “heavy tops” from B-mixing
- 1992: first direct indications for “heavy tops” in decay t → Wb at the Tevatron
- 1995: Tevatron experiments CDF and DØ publish discovery of the top quark with a mass of about 175 GeV

Indirect top properties

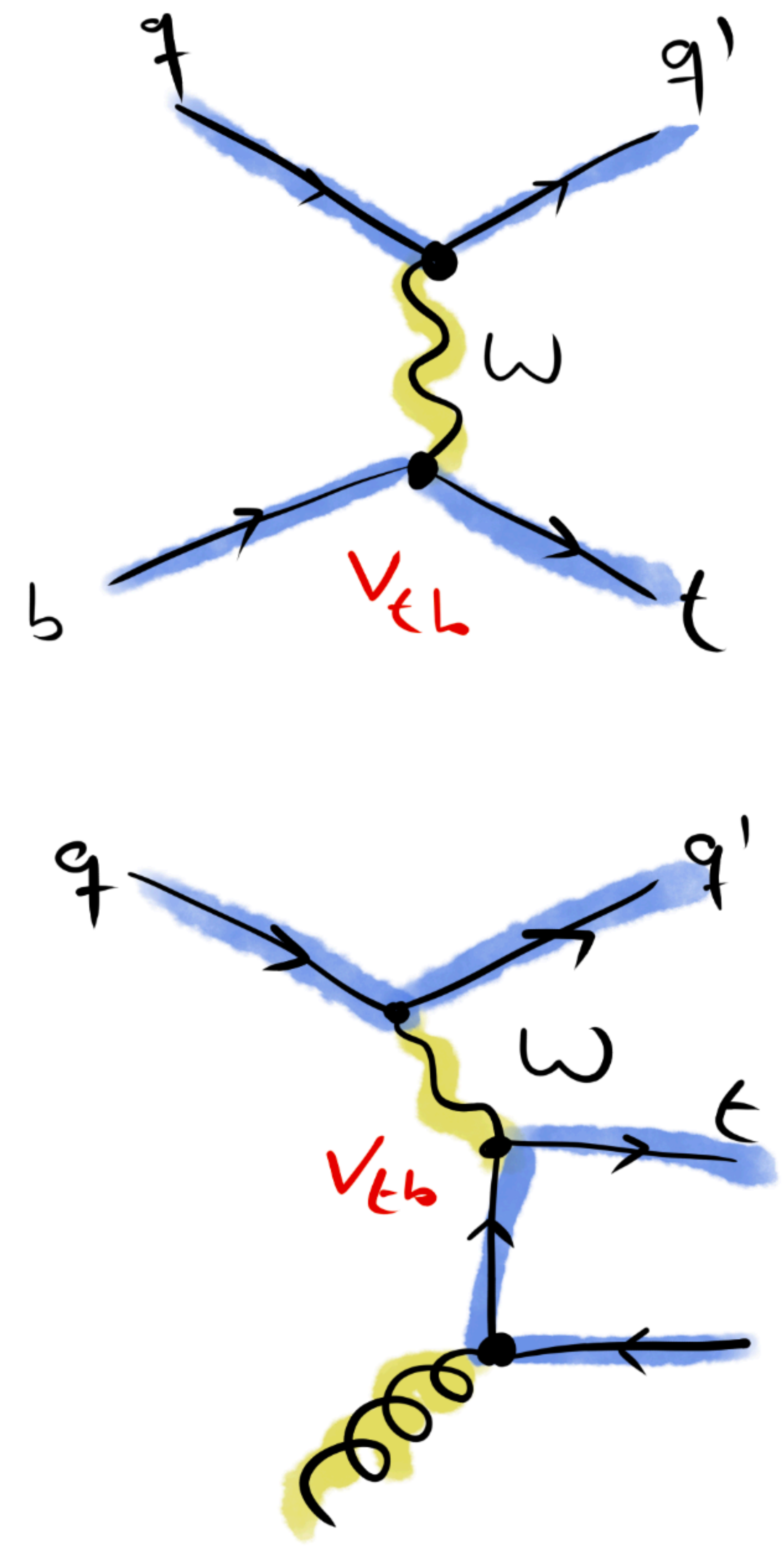


Single top production

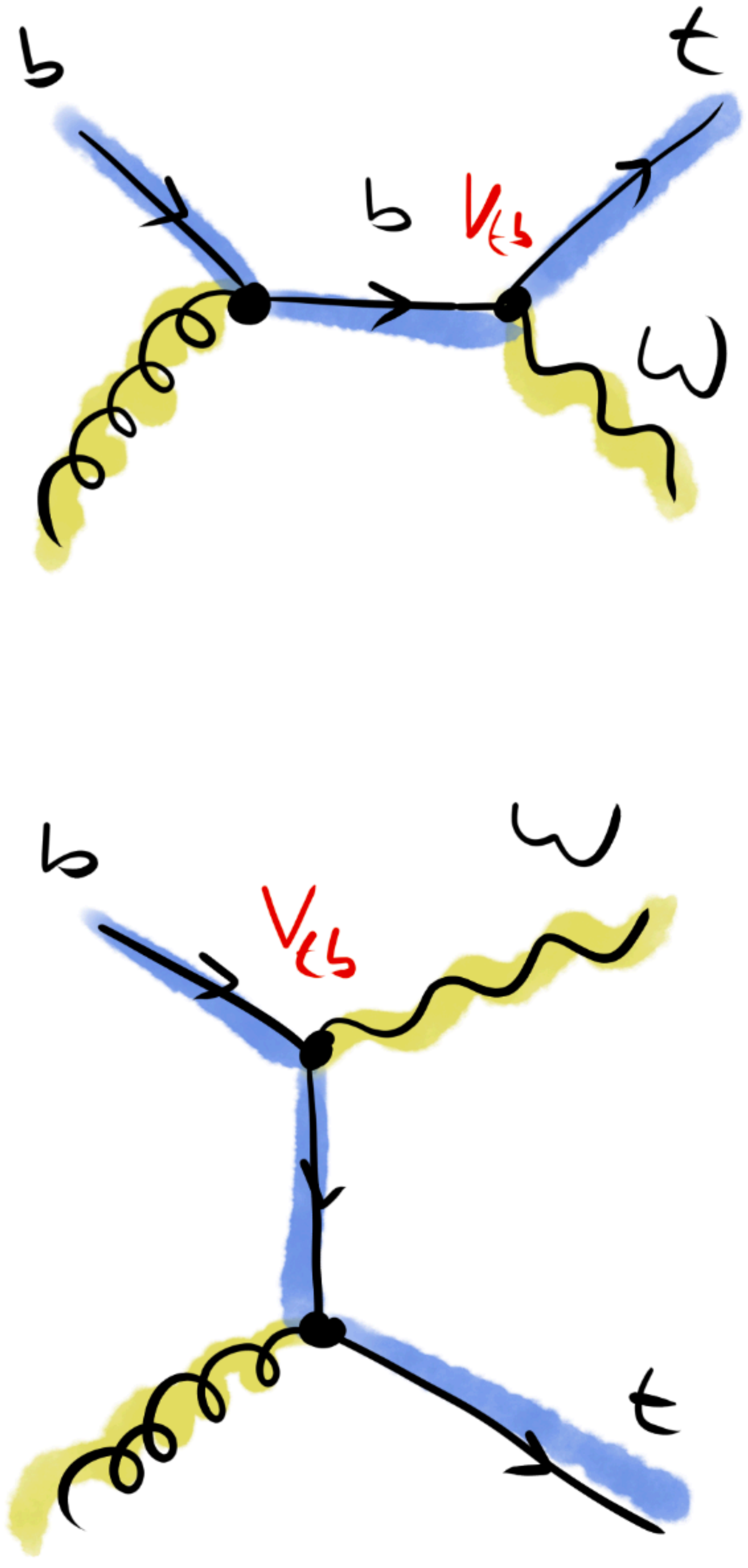
s-channel



t-channel (dominant)

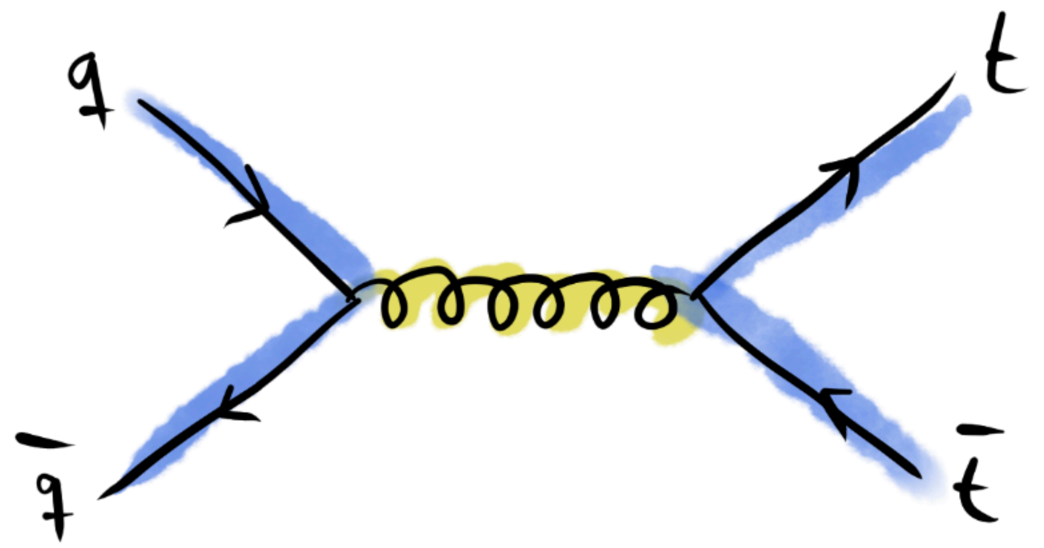


Wt-channel

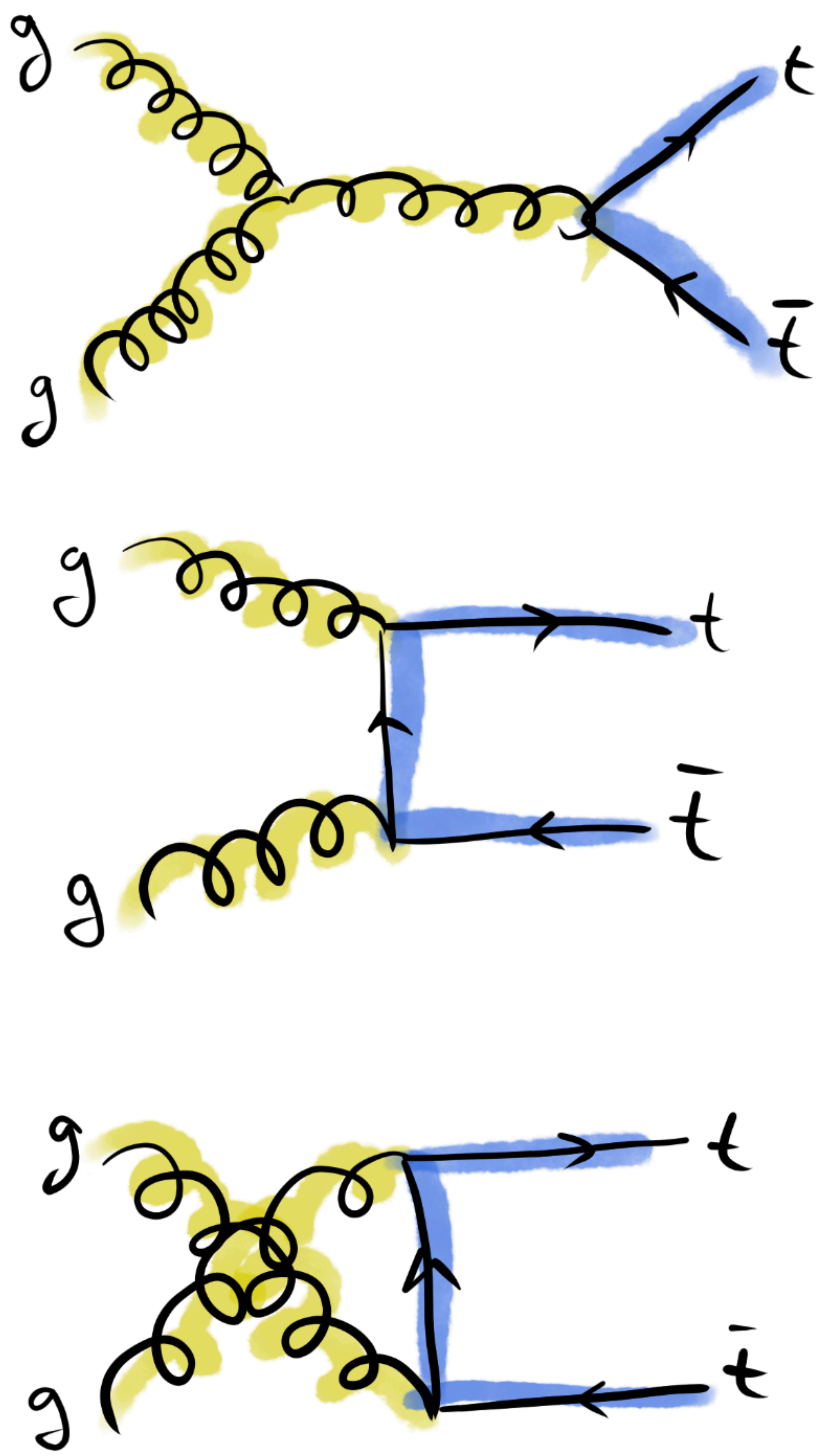


Top pair production

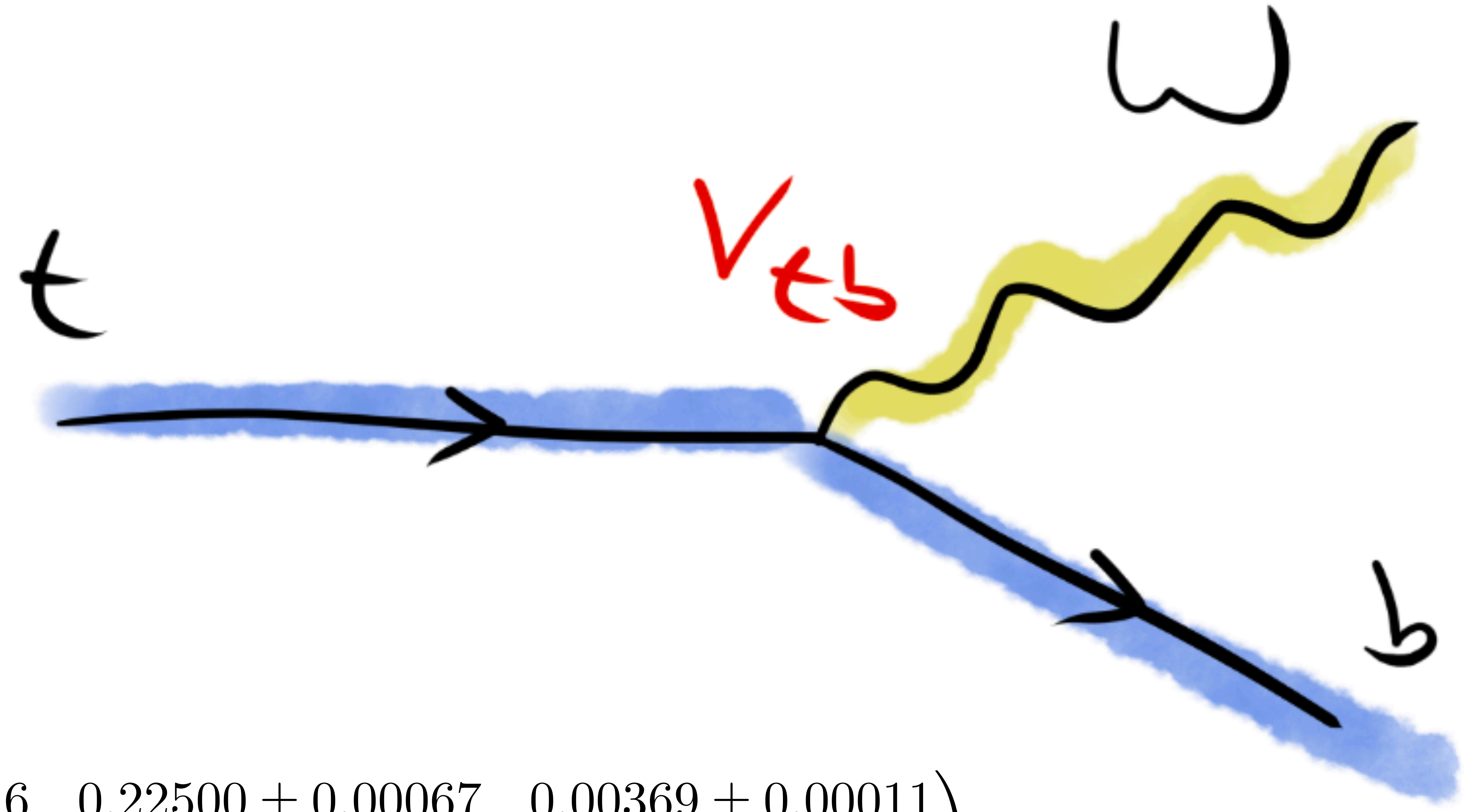
quark -antiquark annihilation (10% at LHC)



gluon-gluon fusion (90% at LHC)



Top decay(s): ~100% via one electroweak decay

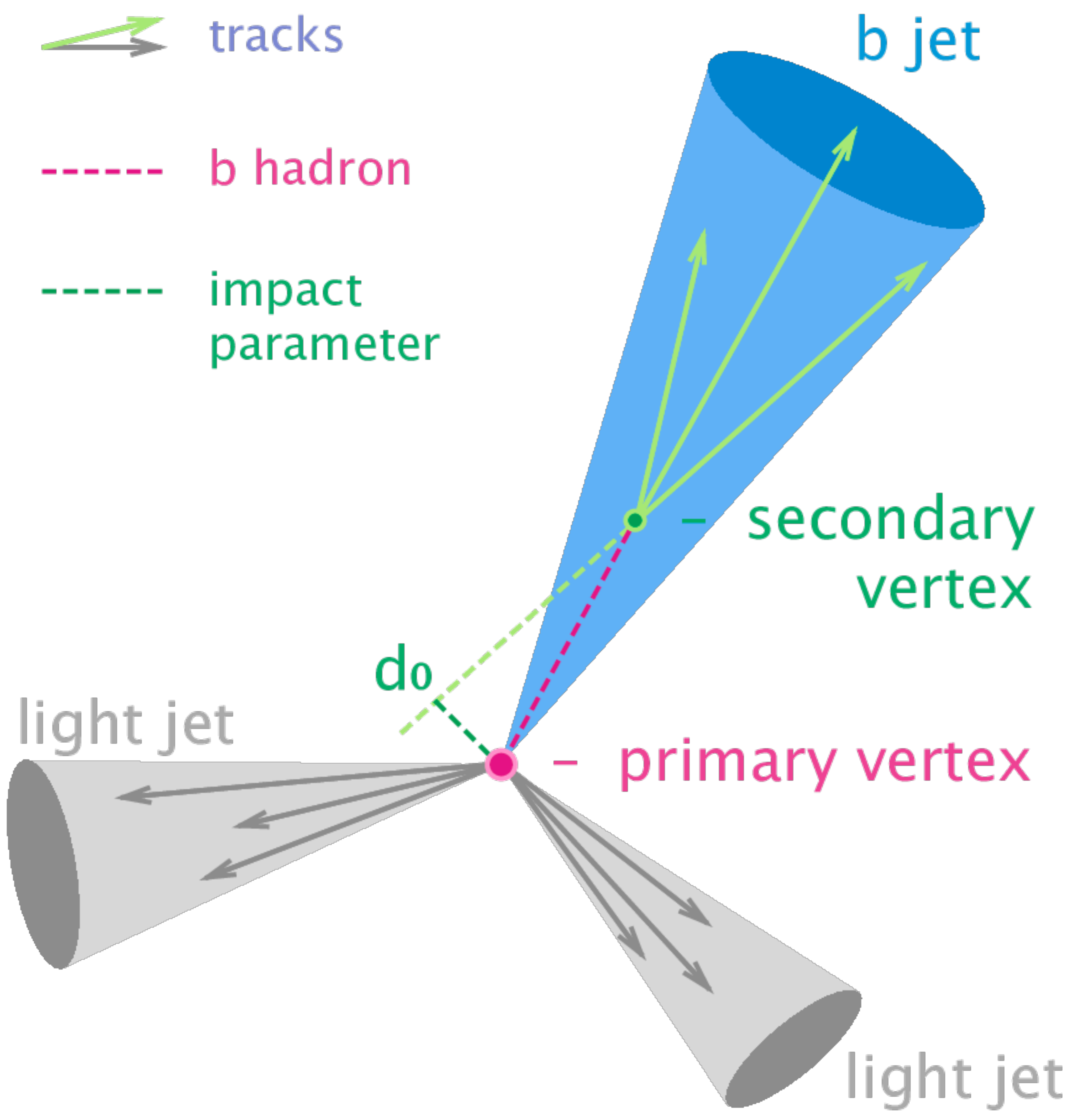


$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix}$$

Source: PDG 2022

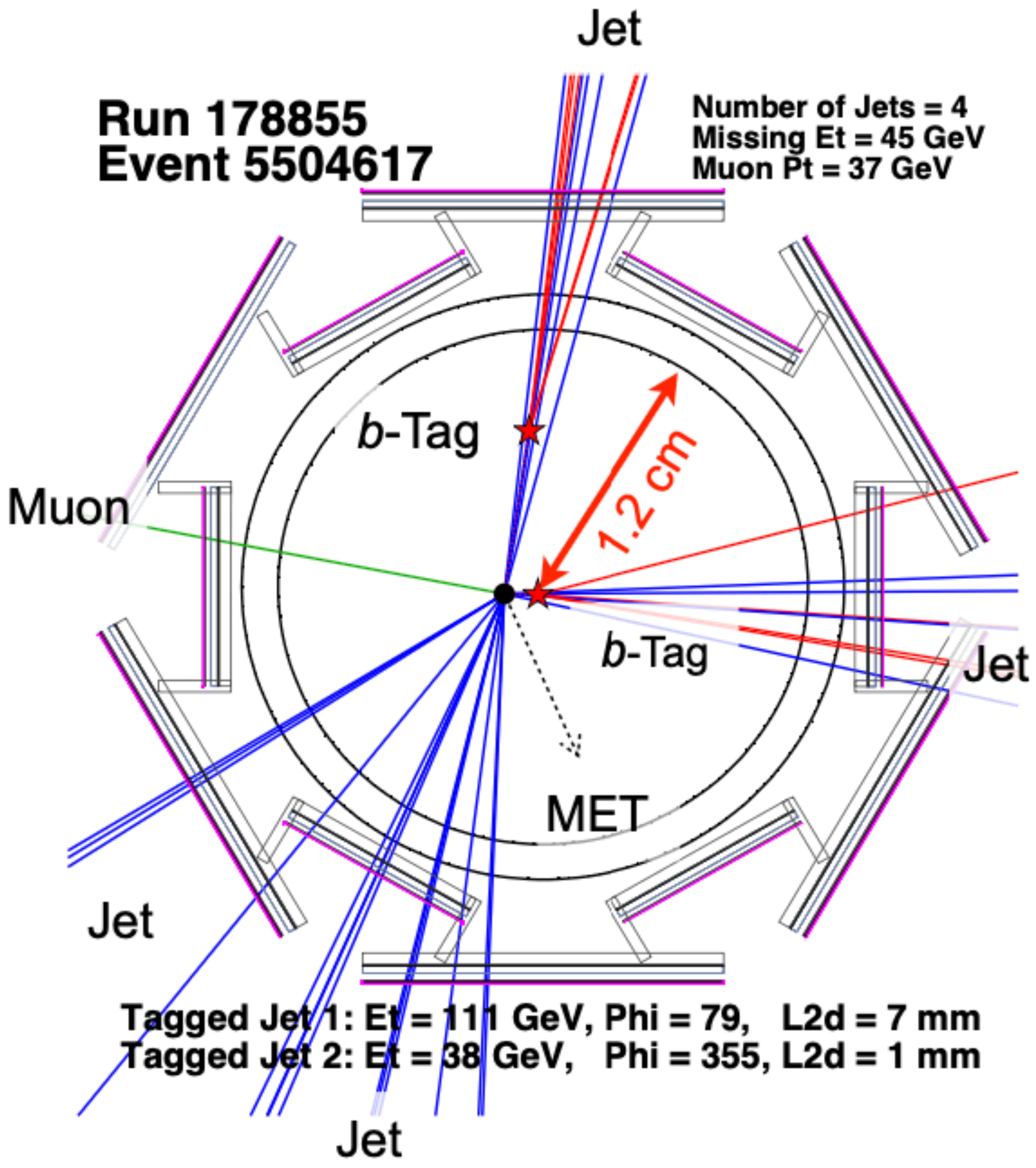
B-tagging

- SM decay $t \rightarrow Wb$: $t\bar{t}$ events have two b quarks → b identification is critical
- Lifetime-based b-tagging:
  - $b \rightarrow c$ transition CKM-suppressed:
    - $B^{\pm}$ proper lifetime: $c\tau$ = 491 μm
    - Tracks with large impact parameters
    - Displaced secondary vertex
- Decay-based b-tagging:
  - Semileptonic decays: $B \rightarrow l\nu X$
  - Signature: jets containing non-isolated "soft leptons"



Credit: Nazar Bartosik - http://bartosik.pp.ua/hep_sketches/btagging

B-tagging



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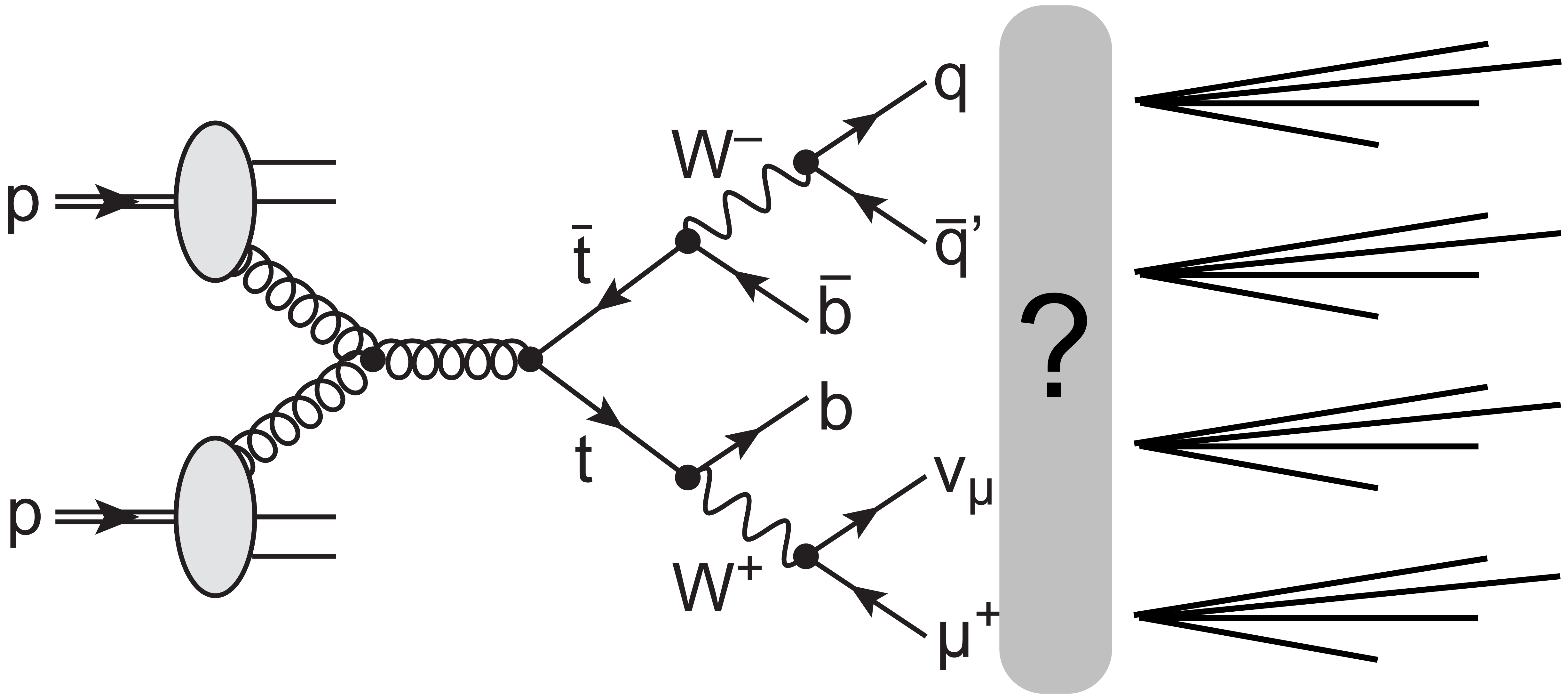
Top mass from kinematics

- Direct measurement of top-quark mass: top-quark reconstruction → mass from event kinematics
- Example lepton+jets: kinematics overdetermined
  - One unknown: neutrino p_Z
  - ≥1 possible constraints: e.g. mass of leptonically decaying W
- Challenge: combinatorics of jet-parton assignment (4 jets → 24 combinations) → which combination is the “best”?



Top summary

- Top-quark mass m_t:
  - Important standard-model parameter, ambiguities in definition (loop corrections)
  - Several complementary methods to determine m_t (e.g. template fit)
    → $m_t \simeq$ 172.5 GeV (0.3% precision)
- Further properties of the top quark:
  - Large total decay width (1.3 GeV) → lifetime shorter than typical time scale of hadronization
    → top quark is the only “free” quark
  - Standard model: top quark acquires mass through Yukawa coupling to Higgs boson: only quark with coupling constant of order one
  - *V–A* decay $t \to Wb$: source of polarized *W* bosons (70% longitudinal polarization, 30% left-handed polarization)

What questions do you have?