Lecture 2: Introduction to Collider Physics

Zhao-Huan Yu（余钊焕）

ARC Centre of Excellence for Particle Physics at the Terascale,
School of Physics, the University of Melbourne
http://yzhxxzxy.github.io

Frontiers in Dark Matter, Neutrinos, and Particle Physics
Theoretical Physics Summer School

Sun Yat-Sen University, Guangzhou
July 27-28, 2017

THE UNIVERSITY OF MELBOURNE

CoEPP
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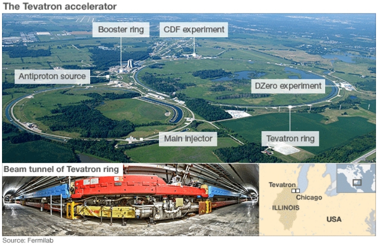
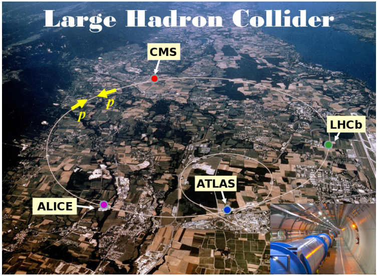
Past and Current High Energy Colliders

- **TEVATRON**: $p\bar{p}$ collider, 1987-2011
  Circumference: 6.28 km
  Collision energy: $\sqrt{s} = 1.96$ TeV
  Luminosity: $\mathcal{L} \sim 4.3 \times 10^{32}$ cm^{-2} s^{-1}
  Detectors: CDF, DØ
- **LEP**: e^+e^- collider, 1989-2000
  Circumference: 26.66 km
  Collision energy: $\sqrt{s} = 91 - 209$ GeV
  Luminosity: $\mathcal{L} \sim (2-10) \times 10^{31}$ cm^{-2} s^{-1}
  Detectors: ALEPH, DELPHI, OPAL, L3
- **LHC**: pp (pPb, PbPb) collider, 2009-
  Circumference: 26.66 km
  Collision energy: $\sqrt{s} = 7, 8, 13, 14$ TeV
  Luminosity: $\mathcal{L} \sim (1-5) \times 10^{34}$ cm^{-2} s^{-1}
  Detectors: ATLAS, CMS, ALICE, LHCb





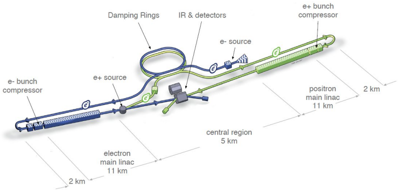
Future Projects

- **ILC**: International Linear Collider

  e^+e^- collider, $\sqrt{s} = 250$ GeV $- 1$ TeV

  $\mathcal{L} \sim 1.5 \times 10^{34}$ cm^{-2} s^{-1}

  Detectors: SiD, ILD



- **CEPC**: Circular Electron-Positron Collider (China)

  e^+e^- collider, $\sqrt{s} \sim 240 - 250$ GeV, $\mathcal{L} \sim 1.8 \times 10^{34}$ cm^{-2} s^{-1}

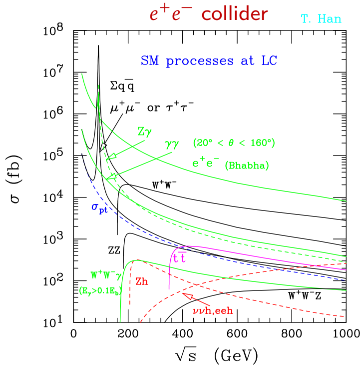
- **SPPC**: Super Proton-Proton Collider (China)

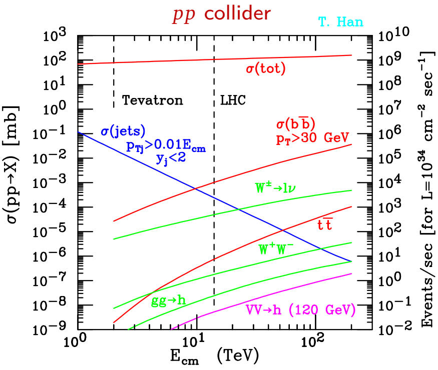
  pp collider, $\sqrt{s} \sim 50 - 70$ TeV, $\mathcal{L} \sim 2.15 \times 10^{35}$ cm^{-2} s^{-1}

- **FCC**: Future Circular Collider (CERN)
  - **FCC-ee**: e^+e^- collider, $\sqrt{s} \sim 90 - 350$ GeV, $\mathcal{L} \sim 5 \times 10^{34}$ cm^{-2} s^{-1}
  - **FCC-hh**: pp collider, $\sqrt{s} \sim 100$ TeV, $\mathcal{L} \sim 5 \times 10^{34}$ cm^{-2} s^{-1}

- **CLIC**: Compact Linear Collider, $\sqrt{s} \sim 1 - 3$ TeV, $\mathcal{L} \sim 6 \times 10^{34}$ cm^{-2} s^{-1}

Particle Production





[Han, arXiv:hep-ph/0508097]

- Units for **cross section** σ: 10^{-24} cm^2 $= 1$ b $= 10^{12}$ pb $= 10^{15}$ fb $= 10^{18}$ ab
- Units for **instantaneous luminosity** $\mathcal{L}$: 10^{34} cm^{-2} s^{-1} $\simeq 315$ fb^{-1} year^{-1}
- **Integrated luminosity** $\int \mathcal{L}(t)dt$ indicates the data amount
- For a process with a cross section σ, **event number** $N = \sigma \int \mathcal{L}(t)dt$

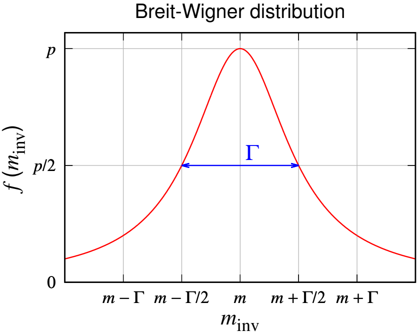
Particle Decay

- Particle **decay** is a **Poisson process**
- In the rest frame, the probability that a particle survives for time t before decaying is given by an exponential distribution:

$$P(t) = e^{-t/\tau} = e^{-\Gamma t},$$

where τ is the mean **lifetime**

- $\Gamma \equiv 1/\tau$ is called the **decay width**



- The mass of an unstable particle can be reconstructed by the total invariant mass of its products m_{inv}, which obeys a **Breit–Wigner distribution**

$$f(m_{\text{inv}}) = \frac{\Gamma}{2\pi} \frac{1}{(m_{\text{inv}} - m)^2 + \Gamma^2/4}$$

The central value m is conventionally called the **mass** of the parent particle

Partial Decay Width and Scattering Cross Section

- The probability that a decay mode j happens in a decay event is called the **branching ratio** $\mathrm{BR}(j)$, while $\Gamma_j = \Gamma \cdot \mathrm{BR}(j)$ is called the **partial width**

  Normalization condition: $\sum_j \mathrm{BR}(j) = \frac{1}{\Gamma}\sum_j \Gamma_j = 1$, *i.e.*, $\Gamma = \sum_j \Gamma_j$

- The partial width for an n-body decay mode j:

$$\Gamma_j = \frac{1}{2m}\int \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i}\, (2\pi)^4 \delta^{(4)}\Big(p^\mu - \sum_i p_i^\mu\Big)\, |\mathcal{M}_j|^2$$

- The cross section for a $2 \to n$ scattering process with initial states $\mathcal{A}$ and $\mathcal{B}$:

$$\sigma = \frac{1}{2E_{\mathcal{A}} 2E_{\mathcal{B}} |\mathbf{v}_{\mathcal{A}} - \mathbf{v}_{\mathcal{B}}|}\int \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i}\, (2\pi)^4 \delta^{(4)}\Big(p_{\mathcal{A}}^\mu + p_{\mathcal{B}}^\mu - \sum_i p_i^\mu\Big)\, |\mathcal{M}|^2$$

- The 4-dimensional **delta function** respects the 4-momentum conservation
- The **invariant amplitude** $\mathcal{M}$ is determined by the underlying physics model

Parton Distribution Functions

Cross section for a **hadron scattering** process $h_1 h_2 \to X$:

$$\sigma(h_1 h_2 \to X) = \sum_{ij} \int dx_1 dx_2\, f_{i/h_1}(x_1, \mu_\mathrm{F}^2)\, f_{j/h_2}(x_2, \mu_\mathrm{F}^2)\, \hat{\sigma}_{ij\to X}(x_1 x_2 s, \mu_\mathrm{F}^2),$$

- $\hat{\sigma}_{ij\to X}$: cross section for a parton scattering process $ij \to X$
- $f_{i/h}(x, \mu_\mathrm{F}^2)$: **parton distribution function (PDF)** for a parton i emerging from a hadron h with $x \equiv p_i^\mu / p_h^\mu$ at a factorization scale μ_F
- 4-momentum conservation:

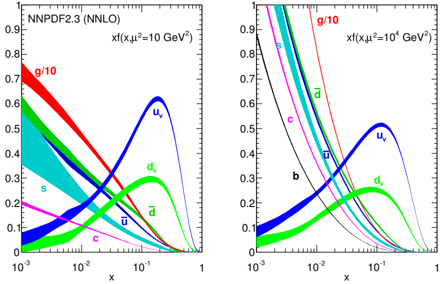
$$\int_0^1 dx \sum_i x f_{i/p}(x, \mu_\mathrm{F}^2) = 1$$

$$i = g, d, u, s, c, b, \bar{d}, \bar{u}, \bar{s}, \bar{c}, \bar{b}$$

- Valence quarks in a proton are uud:

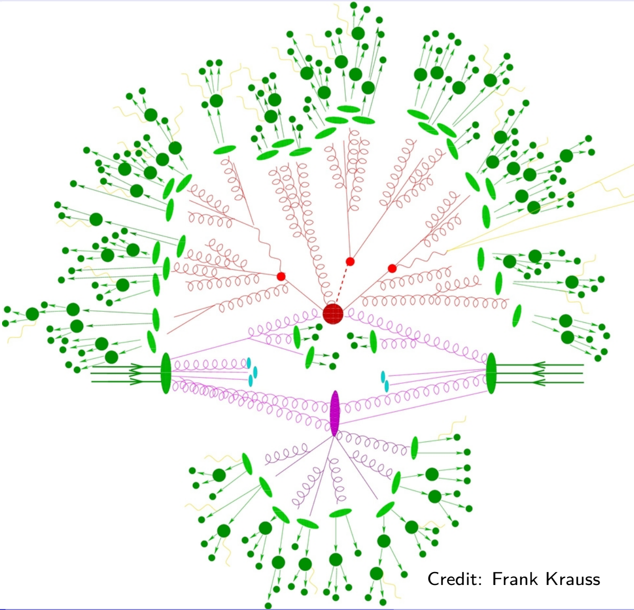
$$\int_0^1 dx [f_{u/p}(x, \mu_\mathrm{F}^2) - f_{\bar{u}/p}(x, \mu_\mathrm{F}^2)] = 2$$

$$\int_0^1 dx [f_{d/p}(x, \mu_\mathrm{F}^2) - f_{\bar{d}/p}(x, \mu_\mathrm{F}^2)] = 1$$



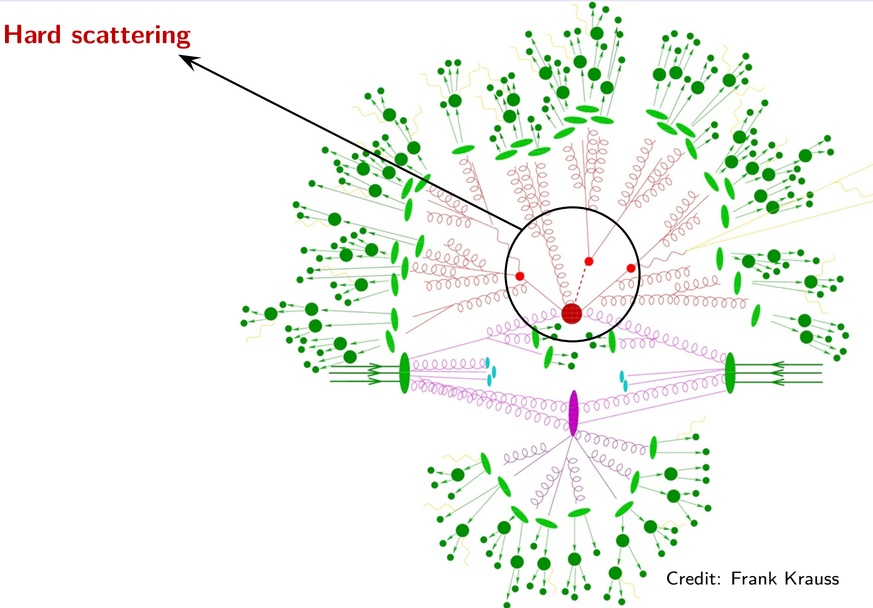
PDFs for proton [PDG 2014]

Typical Event



Credit: Frank Krauss

Typical Event



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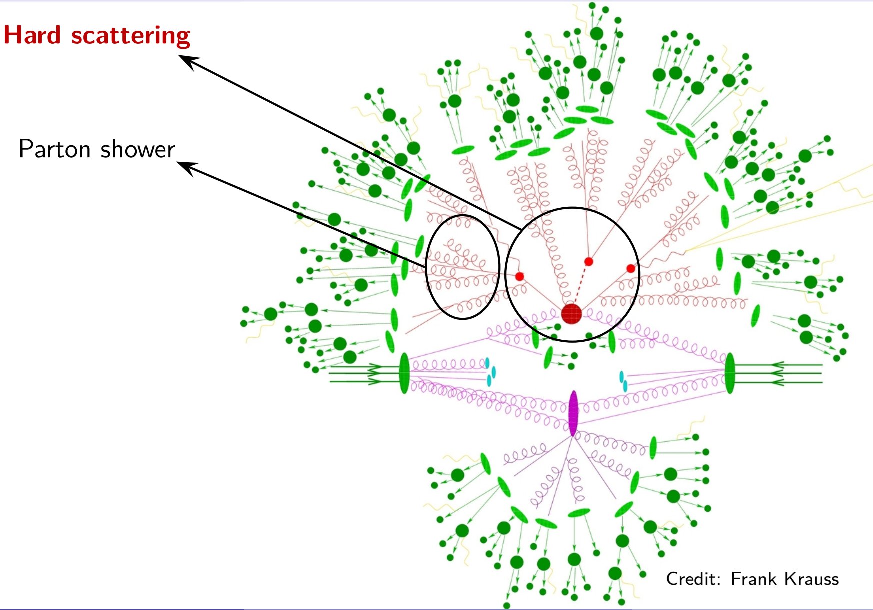
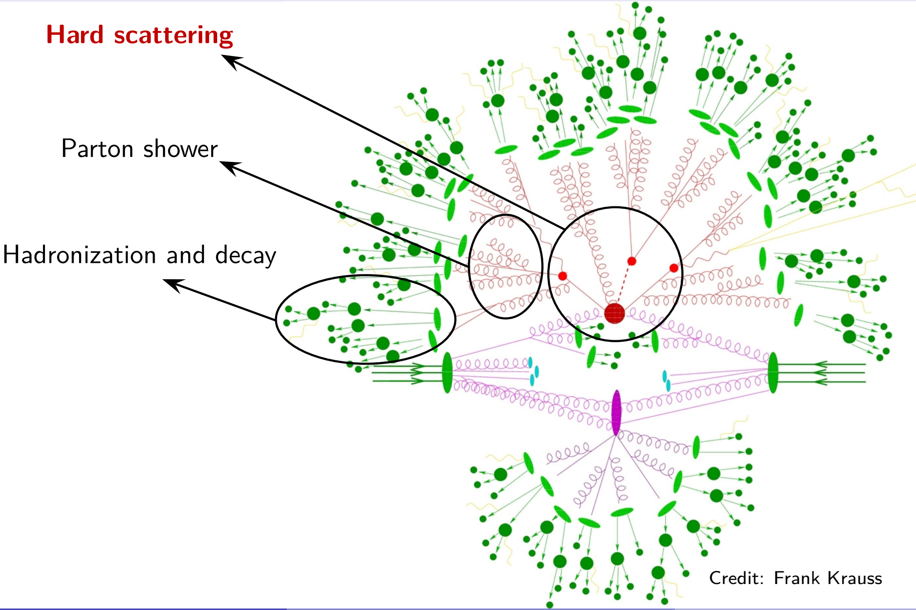
Typical Event



Credit: Frank Krauss

Typical Event



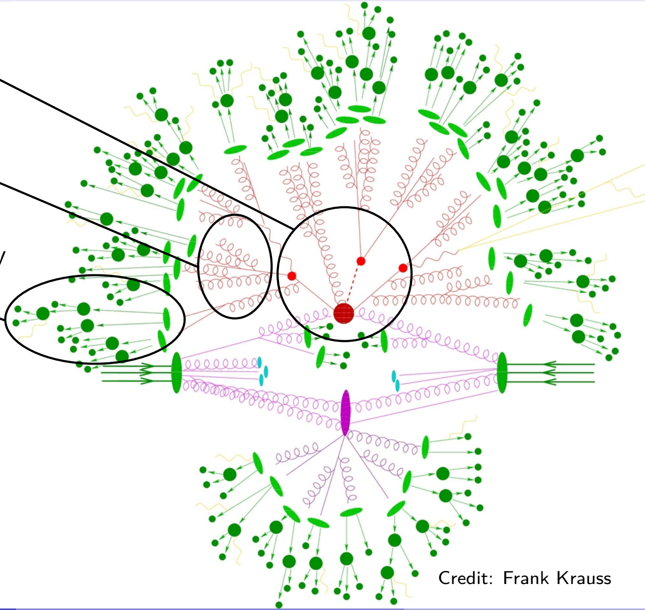
Credit: Frank Krauss

Typical Event

Hard scattering

Parton shower

Hadronization and decay



Collimated particles

⇓

Jet

⇓

Mimic to a hard parton

Credit: Frank Krauss

Typical Event

Hard scattering

Parton shower

Hadronization and decay

Collimated particles

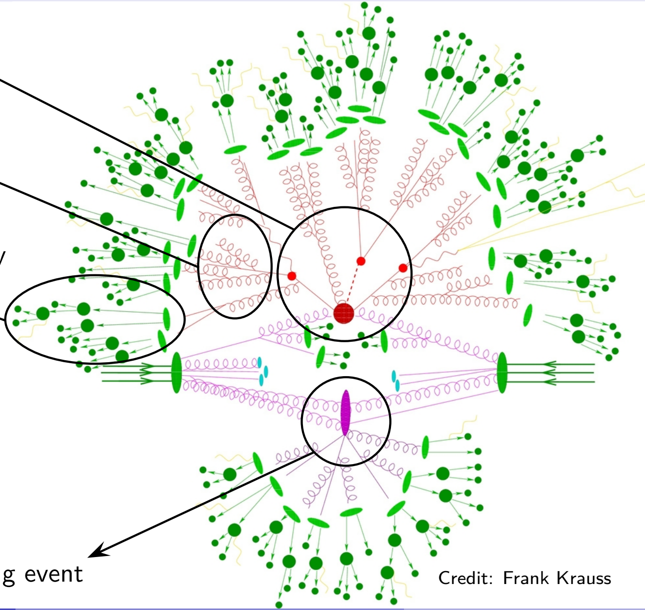
⇓

Jet

⇓

Mimic to a hard parton

Underlying event



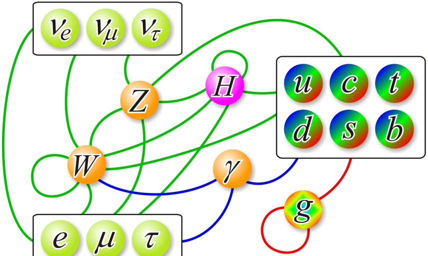
Credit: Frank Krauss

Elementary Particles

Elementary Particles in the Standard Model (SM)

- **Three families of fermions**
  - Charged leptons: electron (e), muon (μ), tau (τ)
  - Neutrinos: electron neutrino (ν_e), muon neutrino(ν_μ), tau neutrino (ν_τ)
  - Up-type quarks: up quark (u), charm quark (c), top quark (t)
  - Down-type quarks: down quark (d), strange quark (s), bottom quark (b)
- **Gauge bosons**
  - Electroweak: photon (γ), $W^\pm$, Z^0
  - Strong: gluons (g)
- **Scalar boson**: Higgs boson (H^0)

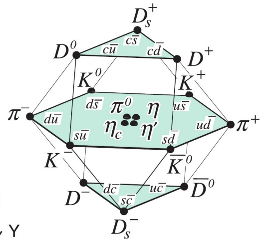
Interactions in the Standard Model:
strong interaction
electromagnetic (EM) interaction
weak interaction

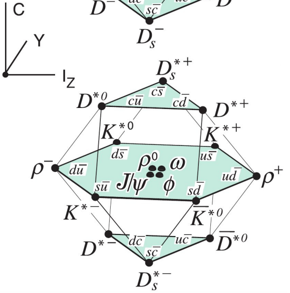


Composite Particles

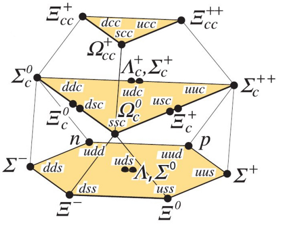
- **Nuclei**: composed of nucleons (p and n)
  E.g., nuclei of D, T, ^{3}He, and ^{4}He
- **Hadrons**: strongly interacting bound states composed of valence quarks
  - **Mesons**: composed of a quark and an antiquark
    E.g., $\pi^+(u\bar{d})$, $\pi^-(d\bar{u})$, $\pi^0\left[(u\bar{u}-d\bar{d})/\sqrt{2}\right]$
  - **Baryons**: composed of three quarks
    E.g., proton $p(uud)$, neutron $n(udd)$, $\Lambda^0(uds)$

Pseudoscalar meson 16-plet

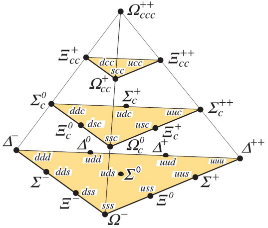




Vector meson 16-plet



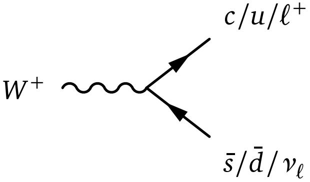
Spin-1/2 baryon 20-plet



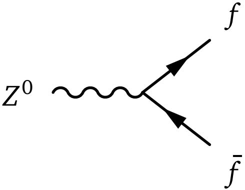
Spin-3/2 baryon 20-plet

Typical Decay Processes in the SM

1. $W^{\pm}$ **gauge boson**, $m = 80.4$ GeV, $\Gamma = 2.1$ GeV
   - **Weak decay** $W^+ \to c\bar{s}/u\bar{d}$, BR $= 67.4\%$
   - **Weak decay** $W^+ \to \tau^+ \nu_\tau$, BR $= 11.4\%$
   - **Weak decay** $W^+ \to e^+ \nu_e$, BR $= 10.7\%$
   - **Weak decay** $W^+ \to \mu^+ \nu_\mu$, BR $= 10.6\%$

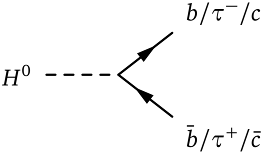


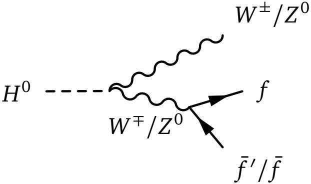
2. Z^0 **gauge boson**, $m = 91.2$ GeV, $\Gamma = 2.5$ GeV
   - **Weak decay** $Z^0 \to u\bar{u}/d\bar{d}/c\bar{c}/s\bar{s}/b\bar{b}$, BR $= 69.9\%$
   - **Weak decay** $Z^0 \to \nu_e\bar{\nu}_e/\nu_\mu\bar{\nu}_\mu/\nu_\tau\bar{\nu}_\tau$, BR $= 20\%$
   - **Weak decay** $Z^0 \to \tau^+\tau^-$, BR $= 3.37\%$
   - **Weak decay** $Z^0 \to \mu^+\mu^-$, BR $= 3.37\%$
   - **Weak decay** $Z^0 \to e^+e^-$, BR $= 3.36\%$

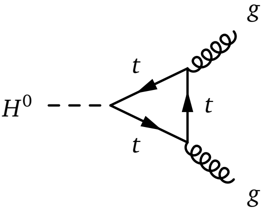


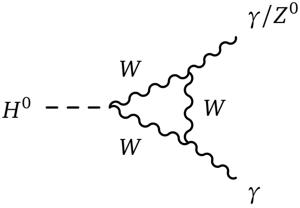
❸ Higgs boson H^0, $m = 125$ GeV, expected $\Gamma = 4$ MeV

- $H^0 \to b\bar{b}$, expected BR $= 58\%$
- $H^0 \to W^\pm W^{\mp *} (\to f\bar{f}')$, expected BR $= 21\%$
- $H^0 \to gg$, expected BR $= 8.2\%$
- $H^0 \to \tau^+\tau^-$, expected BR $= 6.3\%$
- $H^0 \to c\bar{c}$, expected BR $= 2.9\%$
- $H^0 \to Z^0 Z^{0*} (\to f\bar{f})$, expected BR $= 2.6\%$
- $H^0 \to \gamma\gamma$, expected BR $= 0.23\%$
- $H^0 \to Z^0\gamma$, expected BR $= 0.15\%$

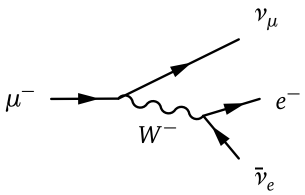




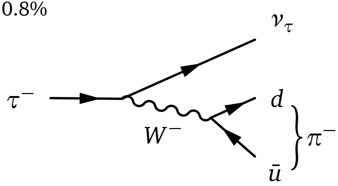




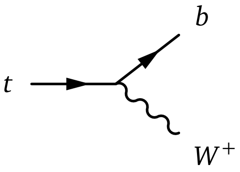
4. **Muon** $\mu^\pm$, $m = 105.66$ MeV, $\tau = 2.2 \times 10^{-6}$ s
    - **Weak decay** $\mu^- \to e^- \bar{\nu}_e \nu_\mu$, $\mathrm{BR} \simeq 100\%$

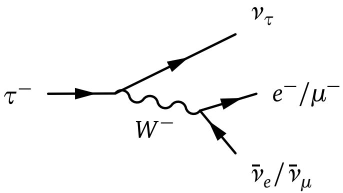


5. **Tau** $\tau^\pm$, $m = 1.777$ GeV, $\tau = 2.9 \times 10^{-13}$ s
    - **Weak decay** $\tau^- \to \mathrm{hadrons} + \nu_\tau$, $\mathrm{BR} = 64.8\%$
        - $\mathrm{BR}(\tau^- \to \pi^- \pi^0 \nu_\tau) = 25.5\%$, $\mathrm{BR}(\tau^- \to \pi^- \nu_\tau) = 10.8\%$
    - **Weak decay** $\tau^- \to e^- \bar{\nu}_e \nu_\tau$, $\mathrm{BR} = 17.8\%$
    - **Weak decay** $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$, $\mathrm{BR} = 17.4\%$

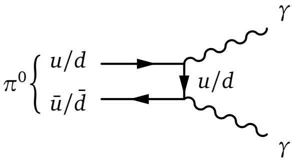


6. **Top quark** t, $m = 173$ GeV, $\Gamma = 1.4$ GeV
    - **Weak decay** $t \to bW^+$, $\mathrm{BR} \simeq 100\%$

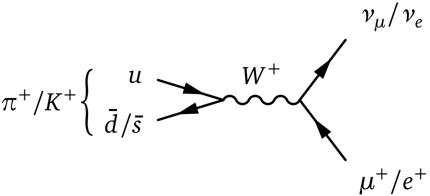


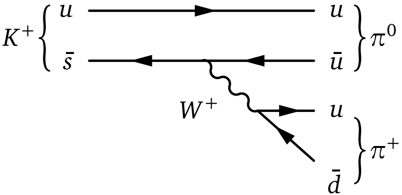


7. π^0 **meson** $\left[(u\bar{u}-d\bar{d})/\sqrt{2}\right]$,
$m = 135.0$ MeV, $\tau = 8.5\times 10^{-17}$ s
   - **EM decay** $\pi^0 \to \gamma\gamma$, $\mathrm{BR} = 98.8\%$
   - **EM decay** $\pi^0 \to e^+e^-\gamma$, $\mathrm{BR} = 1.2\%$



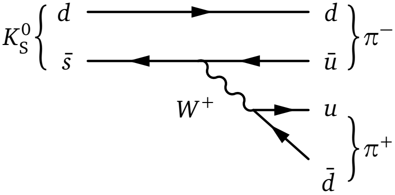
8. $\pi^\pm$ **meson** $[\pi^+(u\bar{d}),\ \pi^-(d\bar{u})]$, $m = 139.6$ MeV, $\tau = 2.6\times 10^{-8}$ s
   - **Weak decay** $\pi^+ \to \mu^+\nu_\mu$, $\mathrm{BR} = 99.9877\%$
   - **Weak decay** $\pi^+ \to e^+\nu_e$, $\mathrm{BR} = 0.0123\%$
9. $K^\pm$ **meson** $[K^+(u\bar{s}),\ K^-(s\bar{u})]$, $m = 493.7$ MeV, $\tau = 1.2\times 10^{-8}$ s
   - **Weak decay** $K^+ \to \mu^+\nu_\mu$, $\mathrm{BR} = 63.6\%$
   - **Weak decay** $K^+ \to \pi^+\pi^0$, $\mathrm{BR} = 20.7\%$

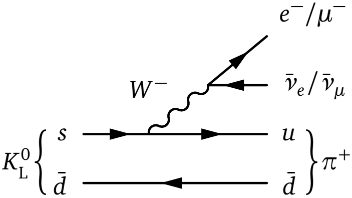




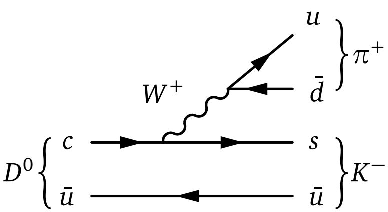
The $\bar{K}^0(s\bar{d})$ meson is the antiparticle of $K^0(d\bar{s})$, with the same mass 497.6 MeV. Under the CP transformation, $K^0 \leftrightarrow -\bar{K}^0$, so they can be mixed into two CP eigenstates: **CP-even state** $K_S^0 = (K^0 - \bar{K}^0)/\sqrt{2}$ and **CP-odd state** $K_L^0 = (K^0 + \bar{K}^0)/\sqrt{2}$. The CP conservation in weak interactions allows K_S^0 decaying into $\pi^+\pi^-$ and $\pi^0\pi^0$, but forbids K_L^0 decaying into $\pi^+\pi^-$ or $\pi^0\pi^0$, resulting in a short lifetime for K_S^0 and a long lifetime for K_L^0.

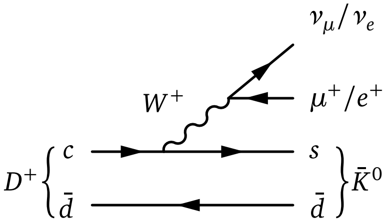
10. **K_S^0 meson**, $CP = +$, $m = 497.6$ MeV, $\tau = 9.0 \times 10^{-11}$ s
    - **Weak decay** $K_S^0 \to \pi^+\pi^-$, $\mathrm{BR} = 69.2\%$
    - **Weak decay** $K_S^0 \to \pi^0\pi^0$, $\mathrm{BR} = 30.7\%$
11. **K_L^0 meson**, $CP = -$, $m = 497.6$ MeV, $\tau = 5.1 \times 10^{-8}$ s
    - **Weak decay** $K_L^0 \to \pi^\pm e^\mp \nu_e / \pi^\pm \mu^\mp \nu_\mu$, $\mathrm{BR} = 67.6\%$
    - **Weak decay** $K_L^0 \to \pi^0\pi^0\pi^0 / \pi^+\pi^-\pi^0$, $\mathrm{BR} = 32.1\%$



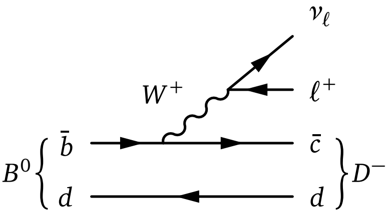


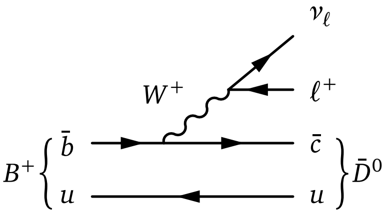
12. D^0 **meson** $(c\bar{u})$, $m = 1.865$ GeV, $\tau = 4.1 \times 10^{-13}$ s
    - **Weak decay** $D^0 \to K^- + \text{anything}$, $\text{BR} \simeq 54.7\%$
    - **Weak decay** $D^0 \to \bar{K}^0/K^0 + \text{anything}$, $\text{BR} \simeq 47\%$
    - **Weak decay** $D^0 \to \bar{K}^*(892)^- + \text{anything}$, $\text{BR} \simeq 15\%$
13. $D^\pm$ **meson** $[D^+(c\bar{d}),\ D^-(d\bar{c})]$, $m = 1.870$ GeV, $\tau = 1.0 \times 10^{-12}$ s
    - **Weak decay** $D^+ \to \bar{K}^0/K^0 + \text{anything}$, $\text{BR} \simeq 61\%$
    - **Weak decay** $D^+ \to K^- + \text{anything}$, $\text{BR} \simeq 25.7\%$
    - **Weak decay** $D^+ \to \bar{K}^*(892)^0 + \text{anything}$, $\text{BR} \simeq 23\%$
    - **Weak decay** $D^+ \to \mu^+ + \text{anything}$, $\text{BR} \simeq 17.6\%$



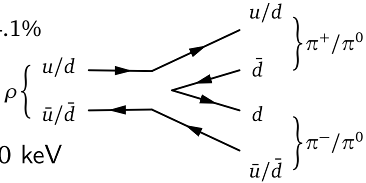


14. B^0 **meson** $(d\bar{b})$, $m = 5.280$ GeV, $\tau = 1.5 \times 10^{-12}$ s
    - **Weak decay** $B^0 \to K^\pm + \text{anything}$, BR $\simeq 78\%$
    - **Weak decay** $B^0 \to \bar{D}^0 X$, BR $\simeq 47.4\%$
    - **Weak decay** $B^0 \to D^- X$, BR $\simeq 36.9\%$
    - **Weak decay** $B^0 \to \ell^+ \nu_\ell + \text{anything}$, BR $\simeq 10.33\%$
15. $B^\pm$ **meson** $[B^+(u\bar{b}),\ B^-(b\bar{u})]$, $m = 5.279$ GeV, $\tau = 1.6 \times 10^{-12}$ s
    - **Weak decay** $B^+ \to \bar{D}^0 X$, BR $\simeq 79\%$
    - **Weak decay** $B^0 \to \ell^+ \nu_\ell + \text{anything}$, BR $\simeq 10.99\%$
    - **Weak decay** $B^+ \to D^- X$, BR $\simeq 9.9\%$
    - **Weak decay** $B^+ \to D^0 X$, BR $\simeq 8.6\%$

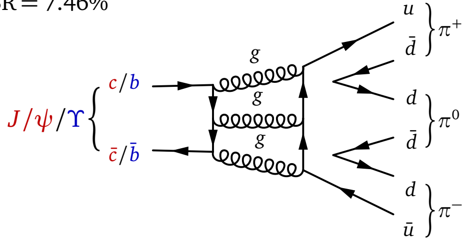




16. $\rho(770)$ **meson** $[(u\bar{u}-d\bar{d})/\sqrt{2}]$, $m = 775$ MeV, $\Gamma = 149$ MeV
    - **Strong decay** $\rho \to \pi^+\pi^-/\pi^0\pi^0$, BR $\simeq 100\%$
17. $J/\psi(1S)$ **meson** $(c\bar{c})$, $m = 3.097$ GeV, $\Gamma = 92.9$ keV
    - **Strong decay** $J/\psi \to ggg \to$ hadrons, BR $= 64.1\%$
    - **EM decay** $J/\psi \to \gamma^* \to$ hadrons, BR $= 13.5\%$
    - **EM decay** $J/\psi \to e^+e^-/\mu^+\mu^-$, BR $= 11.9\%$
18. $\Upsilon(1S)$ **meson** $(b\bar{b})$, $m = 9.460$ GeV, $\Gamma = 54.0$ keV
    - **Strong decay** $\Upsilon \to ggg \to$ hadrons, BR $= 81.7\%$
    - **EM decay** $\Upsilon \to e^+e^-/\mu^+\mu^-/\tau^+\tau^-$, BR $= 7.46\%$

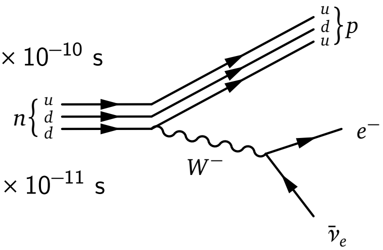


The **Okubo-Zweig-Iizuka (OZI) rule**: any strong decay will be suppressed if, through only the removal of internal gluon lines, its diagram can be separated into two disconnected parts: one containing all initial state particles and one containing all final state particles.



19 **Neutron** n (udd), $m = 939.6$ MeV, $\tau = 880$ s

- **Weak decay** $n \to p e^- \bar{\nu}_e$, BR $\simeq 100\%$



20 Λ^0 **baryon** (uds), $m = 1.116$ GeV, $\tau = 2.6 \times 10^{-10}$ s

- **Weak decay** $\Lambda^0 \to p\pi^-$, BR $= 63.9\%$
- **Weak decay** $\Lambda^0 \to n\pi^0$, BR $= 35.8\%$

21 Σ^+ **baryon** (uus), $m = 1.189$ GeV, $\tau = 8.0 \times 10^{-11}$ s

- **Weak decay** $\Sigma^+ \to p\pi^0$, BR $= 51.6\%$
- **Weak decay** $\Sigma^+ \to n\pi^+$, BR $= 48.3\%$

22 Σ^- **baryon** (dds), $m = 1.197$ GeV, $\tau = 1.5 \times 10^{-10}$ s

- **Weak decay** $\Sigma^- \to n\pi^-$, BR $= 99.85\%$

23 Σ^0 **baryon** (uds), $m = 1.193$ GeV, $\tau = 7.4 \times 10^{-20}$ s

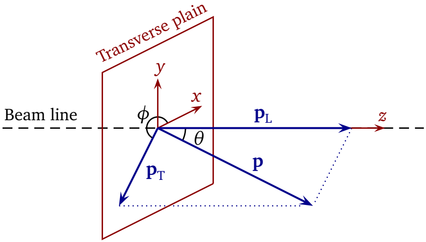
- **EM decay** $\Sigma^0 \to \Lambda^0\gamma$, BR $\simeq 100\%$

24 $\Delta^0(1232)$ **baryon** (udd), $m = 1.232$ GeV, $\Gamma = 117$ MeV

- **Strong decay** $\Delta^0 \to n\pi^0/p\pi^-$, BR $= 99.4\%$

Coordinate System in the Laboratory Frame

- The 3-momentum of a particle, $\mathbf{p}$, can be decomposed into a component p_L, which is parallel to the beam line and a transverse component p_T
- The $\mathbf{p}$ direction can be describe by a polar angle $\theta \in [0, \pi]$ and an azimuth angle $\phi \in [0, 2\pi)$



- The pseudorapidity $\eta \in (-\infty, \infty)$ is commonly used instead of θ

$$\eta \equiv -\ln\left(\tan\frac{\theta}{2}\right), \quad \theta = 2\tan^{-1} e^{-\eta}, \quad -\eta = -\ln\left(\tan\frac{\pi-\theta}{2}\right)$$

η	0	0.5	1	1.5	2	2.5	3	4	5	10
θ	90°	62.5°	40.4°	25.2°	15.4°	9.4°	5.7°	2.1°	0.77°	0.005°

- The 4-momentum of an on-shell particle can be described by $\{m, p_T, \eta, \phi\}$
- Particles with higher p_T are more likely related to hard scattering, so p_T, rather than the energy E, is generally used for **sorting** particles or jets

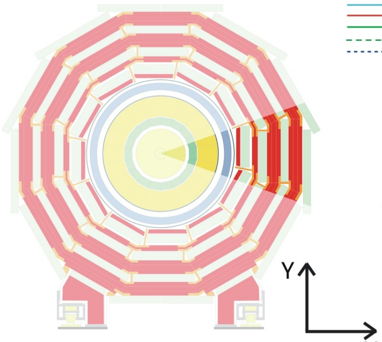
Particle Stability

Mean **decay length** of a relativistic unstable particle:

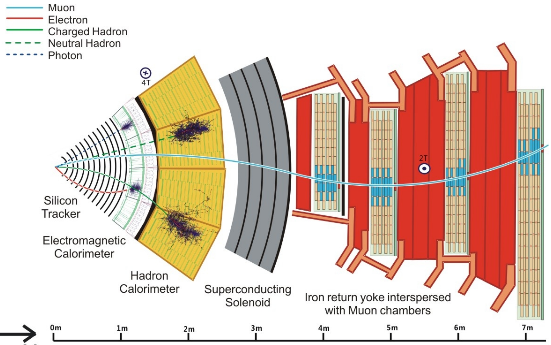
$$d = \beta\gamma\tau \simeq \gamma\left(\frac{\tau}{10^{-12}\ \mathrm{s}}\right) 300\ \mu\mathrm{m}, \quad \gamma = \frac{E}{m} = \frac{1}{\sqrt{1-\beta^2}}$$

- **Stable particles**: p, $e^\pm$, γ, ν_e, ν_μ, ν_τ, dark matter particle
- **Quasi-stable particles** ($\tau \gtrsim 10^{-10}$ s): $\mu^\pm$, $\pi^\pm$, $K^\pm$, n, Λ^0, K_L^0, *etc.*
  These particles may travel into outer layer detectors
- **Particles with** $\tau \simeq 10^{-13} - 10^{-10}$ s: $\tau^\pm$, K_S^0, D^0, $D^\pm$, B^0, $B^\pm$, *etc.*
  These particles may travel a distinguishable distance ($\gtrsim 100\ \mu$m) before decaying, resulting in a displaced secondary vertex
- **Short-lived resonances** ($\tau \lesssim 10^{-13}$ s): $W^\pm$, Z^0, t, H^0, π^0, ρ^0, $\rho^\pm$, *etc.*
  These particles will decay instantaneously and can only be reconstructed from their decay products

Particle Detectors at Colliders

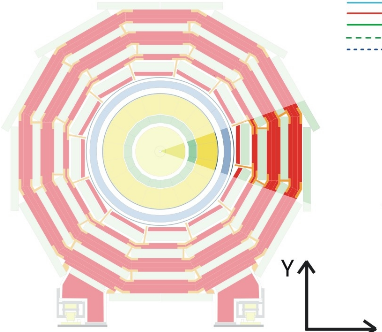


CMS detector

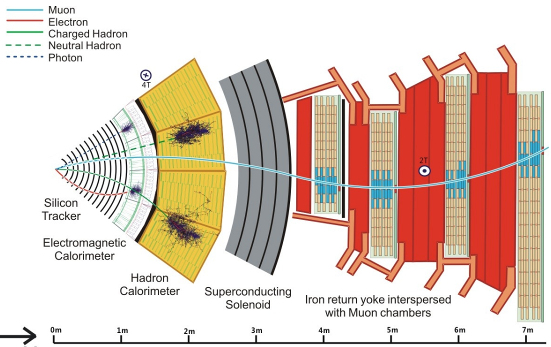


	γ	$e^\pm$	$\mu^\pm$	Charged hadrons	Neutral hadrons	ν, DM
Tracker, $\lvert\eta\rvert \lesssim 2.5$	×	√	√	√	×	×
ECAL, $\lvert\eta\rvert \lesssim 3$			√	√	×	×
HCAL, $\lvert\eta\rvert \lesssim 5$	×	×	×			×
Muon detectors, $\lvert\eta\rvert \lesssim 2.4$	×	×	√	×	×	×

Particle Detectors at Colliders



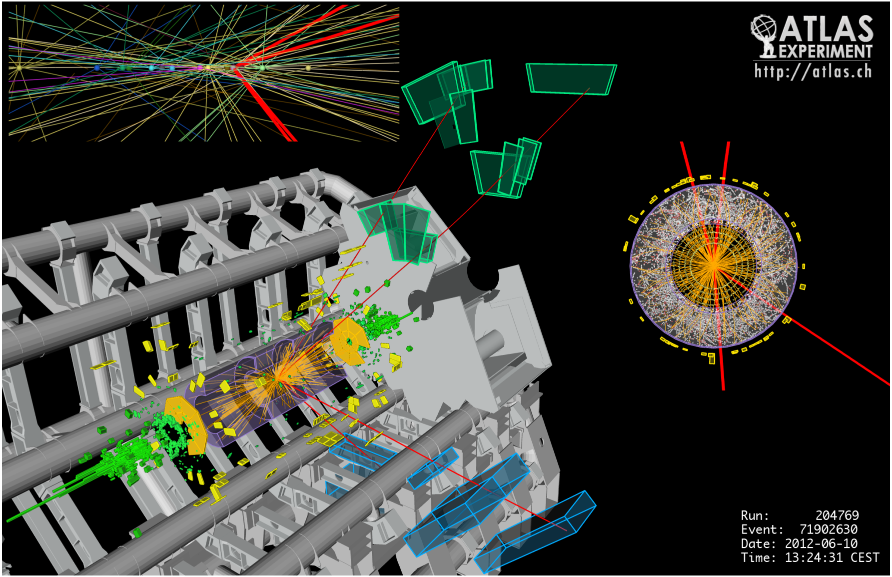
CMS detector



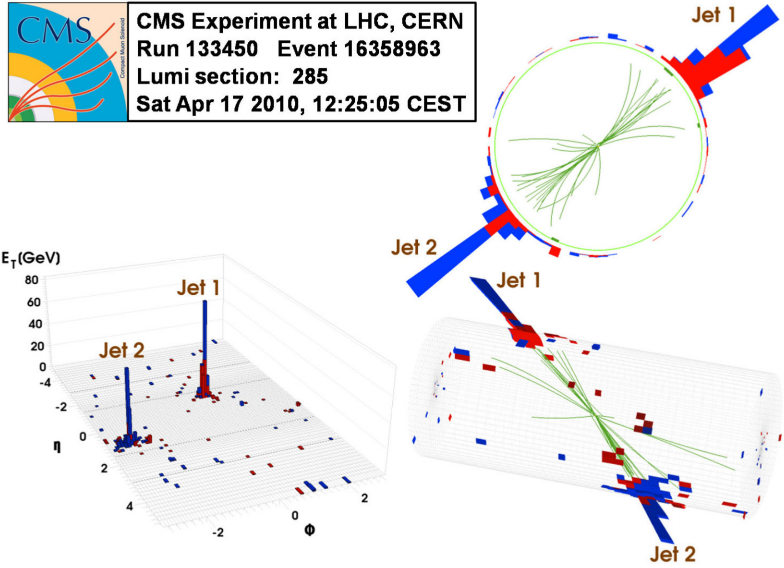
	γ	$e^{\pm}$	$\mu^{\pm}$	Charged hadrons	Neutral hadrons	ν, DM
Tracker, $\lvert\eta\rvert \lesssim 2.5$	×	√	√	√	×	×
ECAL, $\lvert\eta\rvert \lesssim 3$			√	√		×
HCAL, $\lvert\eta\rvert \lesssim 5$	×	×	×			×
Muon detectors, $\lvert\eta\rvert \lesssim 2.4$	×	×	√	×	×	×

Missing energy
$\not{E}_{\mathrm{T}}$

A Candidate Event for $H^0 \to ZZ^* \to \mu^+\mu^-\mu^+\mu^-$

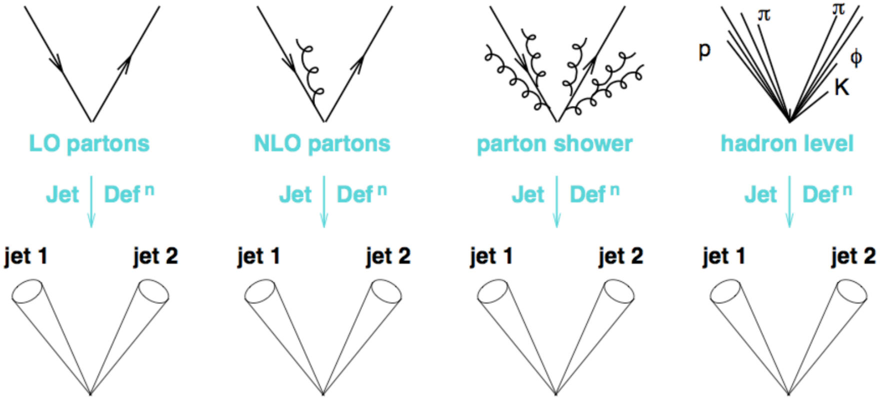


A Dijet Event



Partons and Jets

A **jet** is a collimated bunch of particles (mainly hadrons) flying roughly in the same direction, probably originated from a **parton** produced in hard scattering

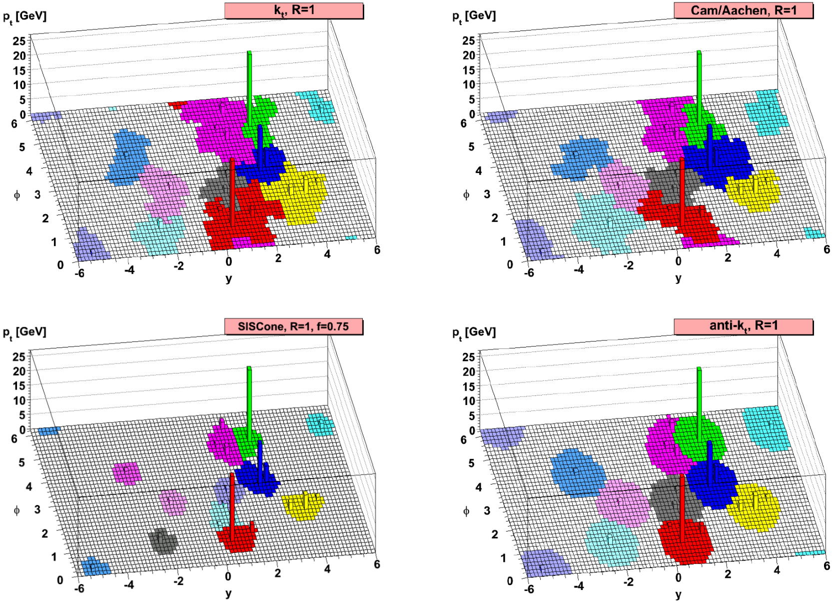


[From M. Cacciari's talk (2013)]

Jet Clustering Algorithms

An observable is **infrared and collinear (IRC) safe** if it remains **unchanged** in the limit of a **collinear splitting** or an **infinitely soft** emission

- **Cone algorithms**: find coarse regions of energy flow
  Combine particles i and j when $\Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} < R$, and find stable cones with a radius R
  - **Cone algorithms with seeds**: find only some of the stable cones; **IRC unsafe**
  - **SISCone algorithm**: seedless; find all stable cones; **IRC safe**
- **Sequential recombination algorithms**: starting from closest particles
  Distance $d_{ij} = \min\left(k_{\mathrm{T},i}^{2p}, k_{\mathrm{T},j}^{2p}\right)\left(\frac{\Delta R_{ij}}{R}\right)^2$ for transverse momenta $k_{\mathrm{T},i}$ and $k_{\mathrm{T},j}$
  - **k_T algorithm**: $p = 1$; starting from soft particles; **IRC safe**
  - **Cambridge-Aachen algorithm**: $p = 0$; starting from close directions; **IRC safe**
  - **Anti-k_T algorithm**: $p = -1$; starting from hard particles; **IRC safe**

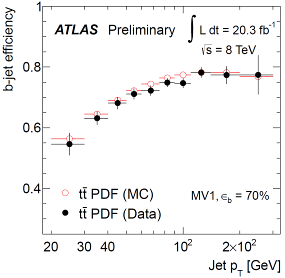


[Cacciari, Salam, Soyez, arXiv:0802.1189, JHEP]

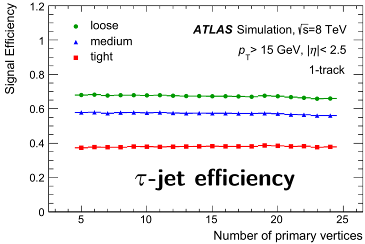
b-jets and τ-jets

Jets originated from b **quarks** and **tau leptons** can be distinguished from jets originated from **light quarks and gluons** via tagging techniques using various discriminating variables

- **b-jets**: tagging efficiency $\sim 70\%$
  - B mesons (*e.g.*, B^0, $B^\pm$) result in displaced vertices
  - Numbers of soft electrons and soft muons are more than other jets
- **τ-jets** from hadronically decaying taus
  - 1-prong modes ($\mathrm{BR} = 50\%$): 1 charged meson in the decay products, medium tagging efficiency $\sim 60\%$
  - 3-prong modes ($\mathrm{BR} = 15\%$): 3 charged mesons in the decay products, medium tagging efficiency $\sim 40\%$

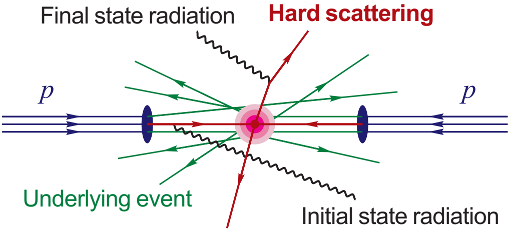


[ATLAS coll., CONF-2014-004]



[ATLAS coll., arXiv:1412.7086, EPJC]

Monte Carlo Simulation

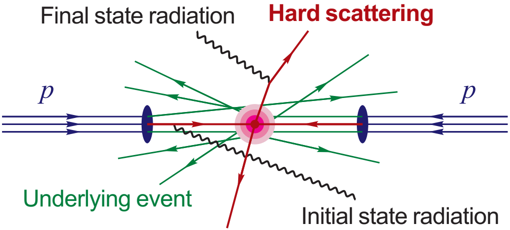


Monte Carlo Simulation

Partical physics model

↓

FeynRules



Monte Carlo Simulation

Partical physics model

↓

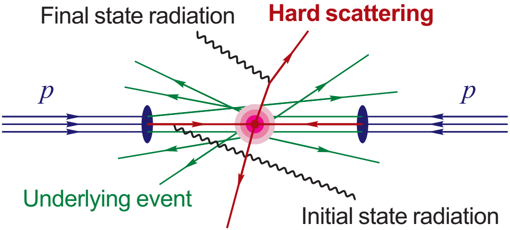
FeynRules

↓

Matrix element (ME)
MadGraph

↓

Parton shower (PS)
PYTHIA



Monte Carlo Simulation

Partical physics model

↓

FeynRules

↓

Matrix element (ME)
MadGraph

↓

Parton shower (PS)
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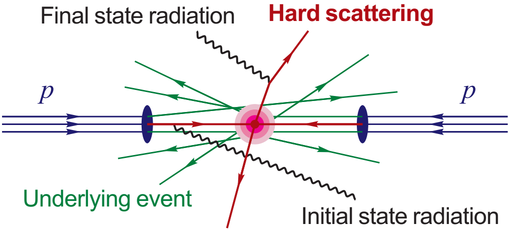


→ ME-PS matching
CKKW or MLM scheme

↓

Hadronization, decay, and underlying event
PYTHIA

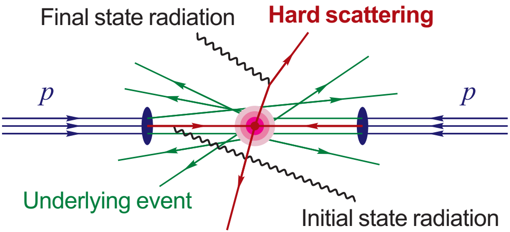
Monte Carlo Simulation

Partical physics model

FeynRules

Matrix element (ME)
MadGraph

Parton shower (PS)
PYTHIA



ME-PS matching
CKKW or MLM scheme

Hadronization, decay, and underlying event
PYTHIA

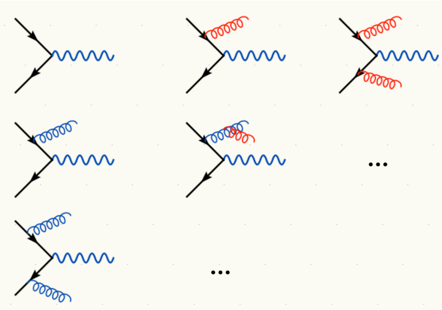
Fast detector simulation
PGS/Delphes

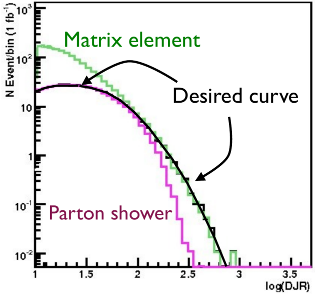
ME-PS Matching

- **Matrix element:** fixed order calculation for hard scattering diagrams
  Valid when partons are **hard and well separated**
- **Parton shower:** process-independent calculation based on QCD
  Valid when partons are **soft and/or collinear**
- **ME-PS Matching:** **avoids double counting** to yield correct distributions

PS →

ME ↓





[From J. Alwall's talk]

Kinematic Variables

Although the same final states may come from various processes, we can use many **kinematic variables**, each of which catches a particular feature, to discriminate among different processes in data analyses

1. **Invariant mass** $m_{\text{inv}} \equiv \sqrt{(p_1 + p_2 + \cdots + p_i)^2}$

   m_{inv} is commonly used to reconstruct the mass of an unstable particle from its decay products

2. **Recoil mass** m_{rec} at e^+e^- colliders

   - For a process $e^+ + e^- \to 1 + 2 + \cdots + n$, the recoil mass of Particle 1 is constructed by $m_{1,\text{rec}} \equiv \sqrt{[p_{e^+} + p_{e^-} - (p_2 + \cdots + p_n)]^2}$
   - For mass measurement of a particle at e^+e^- colliders, we can utilize not only its decay products, but also the associated produced particles

3. **Missing transverse energy** $\not{E}_{\text{T}} \equiv |\not{\mathbf{p}}_{\text{T}}|, \quad \not{\mathbf{p}}_{\text{T}} \equiv -\sum_i \mathbf{p}_{\text{T}}^i$

   $\not{E}_{\text{T}}$ is genuinely induced by **neutrinos** or **DM particles**, but may also be a result of imperfect detection of visible particles

4. **Scalar sum of $p_{\rm T}$ of all jets** $H_{\rm T} \equiv \sum_i p_{\rm T}^{j_i}$

   $H_{\rm T}$ characterizes the energy scale of jets from hard scattering

5. **Effective mass** $m_{\rm eff} \equiv \not{E}_{\rm T} + H_{\rm T}$

   $m_{\rm eff}$ characterizes the energy scale of hard scattering processes that involve both jets and genuine $\not{E}_{\rm T}$ sources, *e.g.*, supersymmetric particle production

6. **Transverse mass** $m_{\rm T}$ for **semi-invisible decays**

   - For a 2-body decay process $P \to v + i$ with a visible product v and an invisible product i (*e.g.*, $W \to \ell\nu_\ell$ and $\tilde{\chi}_1^\pm \to \pi^\pm \tilde{\chi}_1^0$), define

   $$m_{\rm T} \equiv \sqrt{m_v^2 + m_i^2 + 2(E_{\rm T}^v E_{\rm T}^i - \mathbf{p}_{\rm T}^v \cdot \mathbf{p}_{\rm T}^i)} \quad \text{with} \quad E_{\rm T}^{v,i} \equiv \sqrt{m_{v,i}^2 + |\mathbf{p}_{\rm T}^{v,i}|^2}$$

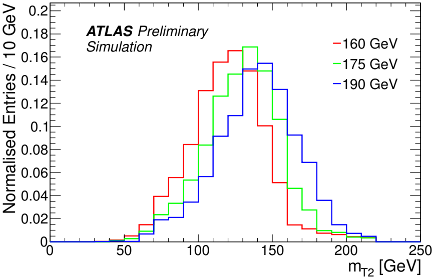
   and $\mathbf{p}_{\rm T}^i = \not{\mathbf{p}}_{\rm T}$, and thus $m_{\rm T}$ will be bounded by m_P: $m_{\rm T} \leq m_P$
   - In practice, m_v is often small, while m_i is usually either zero or unknown; thus a commonly used $m_{\rm T}$ definition is $m_{\rm T} = \sqrt{2(p_{\rm T}^v \not{E}_{\rm T} - \mathbf{p}_{\rm T}^v \cdot \not{\mathbf{p}}_{\rm T})}$
   - For a 3-body decay process with only one invisible particle, the transverse momenta of the two visible particles should be firstly combined, and then $m_{\rm T}$ will be well-defined

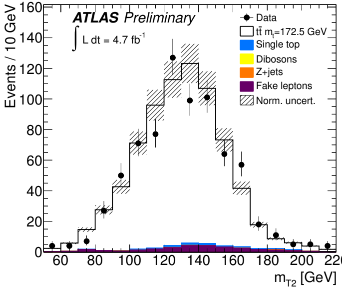
7 "Stransverse mass" m_{T2} for double semi-invisible decays

- For decays of a particle-antiparticle pair $P\bar{P} \to v_1 v_2 i \bar{i}$ with two visible products v_1 and v_2 and two invisible products i_1 and i_2, define

$$m_{\mathrm{T2}}(\mu_i) = \min_{\mathbf{p}_{\mathrm{T}}^1 + \mathbf{p}_{\mathrm{T}}^2 = \not{\mathbf{p}}_{\mathrm{T}}} \left\{ \max\left[m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{v_1}, \mathbf{p}_{\mathrm{T}}^1; m_{v_1}, \mu_i), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{v_2}, \mathbf{p}_{\mathrm{T}}^2; m_{v_2}, \mu_i) \right] \right\},$$

where μ_i is a trial mass for i and can be set to 0 under some circumstances
- m_{T2} is the minimization of the larger m_{T} over all possible partitions
- If μ_i is equal to the true mass of i, m_{T2} will be bounded by m_P: $m_{\mathrm{T2}} \leq m_P$





[ATLAS coll., CONF-2012-082]

Homework

1. Draw one or two more Feynman diagrams for decay modes of every hadron listed in Pages 15–19
2. Show that the $\pi^+\pi^-$ and $\pi^0\pi^0$ systems have $CP = +$, and explain how the CP conservation affects the lifetimes of the K_S^0 and K_L^0 mesons, as mentioned in Page 15
3. Explain how the OZI rule significantly reduces the widths of the J/Ψ and Υ mesons, whose decay modes listed in Page 18
4. Proof that the pseudorapidity η defined in Page 20 is the relativistic limit of the rapidity $y \equiv \tanh^{-1}(p_L/E)$
5. Express every component of the 4-momentum of an on-shell particle, $p^\mu = (p^0, p^1, p^2, p^3)$, as a function of $\{m, p_T, \eta, \phi\}$ defined in Page 20
6. Proof the statement $m_T \leq m_P$ in Page 32