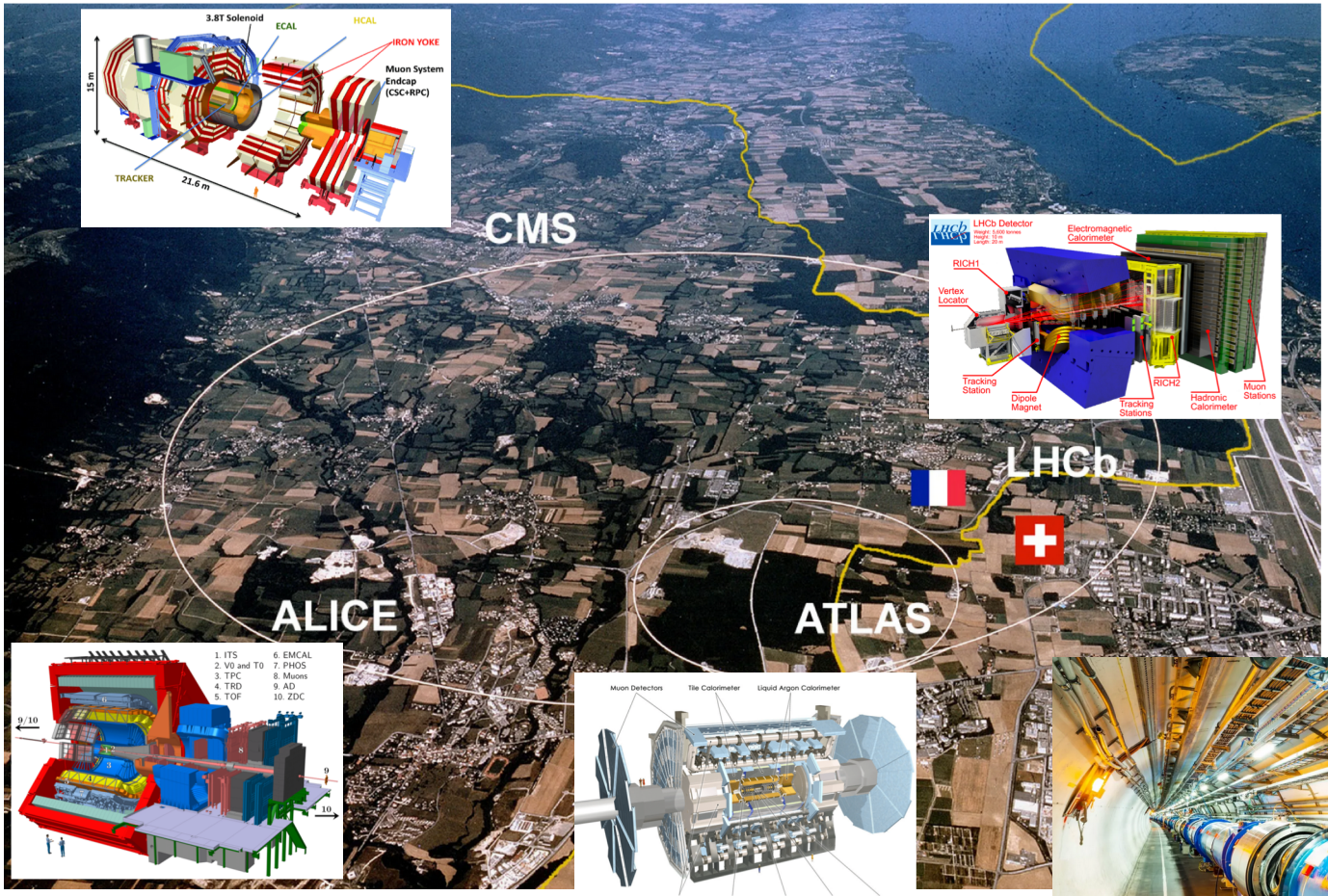
Particle Physics Summer School Aug 22-24, 2022

Collider Theory

Will cover `selected' basic to understand collider phenomenology

KAIST
Minho Son

Collider : restrict to Large Hadron Collider (LHC)





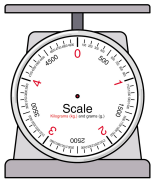
: proton- proton collision
Machine at c.o.m E of 13 TeV

Let us start with unit system

Non-relativistic Classical World

CGS







Length Mass Time

How about Relativistic Quantum World ?

Special Relativity

Lorentz symmetry

$$t \to \gamma(t - \beta x)$$
$$x \to \gamma(x - \beta t)$$

Time ↔ Length (space)

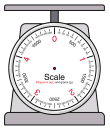
 = 

Quantum Mechanics

Wave-particle duality

$$\lambda \sim \frac{\hbar}{p}$$

Length ↔ Momentum

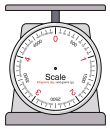
 = $\dfrac{1}{\text{} \times \dfrac{\text{}}{\text{}}}$

Natural Unit

$$c = \hbar = 1$$

Nature favors to have only one unit

Energy (mass) = 1/Time = 1/Length

 = $\dfrac{1}{\text{}} = \dfrac{1}{\text{}}$

Point-like particle or not :

Consider a particle of mass m





Uncertainty of length to claim a point-like particle

$$\Delta x \sim L$$

Uncertainty principle

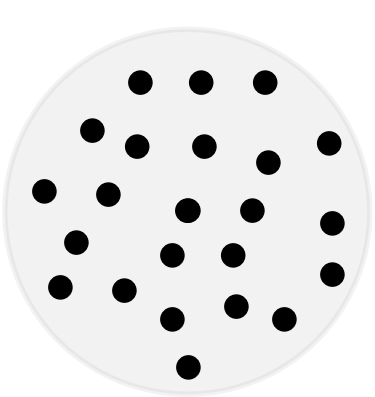
$$E \sim mc^2$$

$$\Delta p \sim \frac{1}{\Delta x} = \frac{1}{L} \rightarrow \qquad \Delta E \sim \Delta p \sim \frac{1}{L} \gtrsim m \rightarrow \qquad L \lesssim \frac{1}{m}$$

If one tries to resolve the particle to the better accuracy than $\Delta x \sim 1/m$, the energy violation big enough to create more particles are possible

Consider a particle of mass m

m



Min distance to treat as a point-like particle

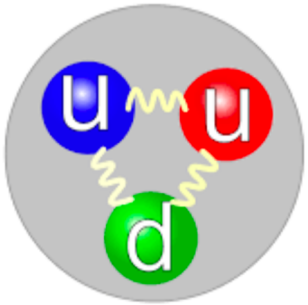
$$\lambda_{\text{compton}} \sim \frac{1}{m}$$

Uncertainty principle

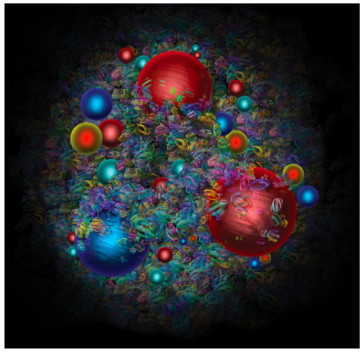
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Proton



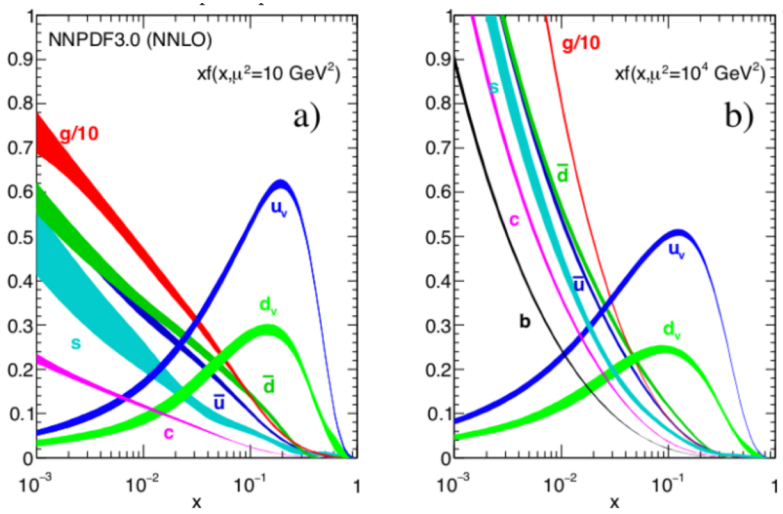
The reality is close to this



It is sort of soup : broth, carrot, potato etc …

Parton Model

Parton Distribution Function (PDF)



Collider Physics is about getting information from the data

Cross section for pp collision using NDA



$$\sigma \sim \pi r_p^2 \sim 3\ \text{fm}^2 = 3{\times}10^{-30}\ \text{m}^2 = 0.03\ \text{b}$$

1 barn (b) = $10^{-28}\ m^2$

$\Lambda_{QCD} \sim 200$ MeV

proton radius $r_p \sim 1$ fm

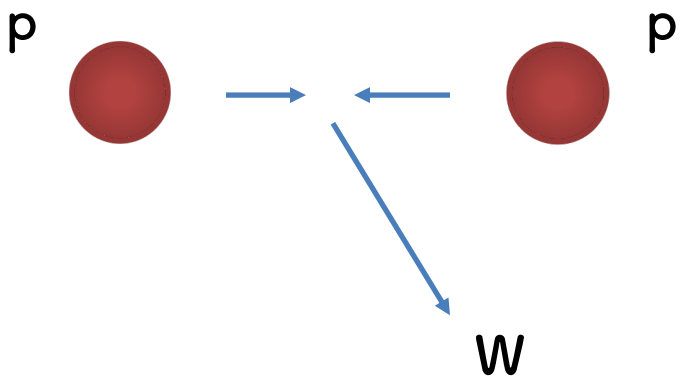
$$\frac{1}{\text{GeV}^2}\hbar^2 c^2 = 3.894 \times 10^{-32}\ m^2$$

, or simply $200\ \text{MeV} = \frac{1}{\text{fm}}$

Cross section for pp collision

$$\sigma \sim \pi r_p^2 \sim 3\ \text{fm}^2 = 3{\times}10^{-30}\ \text{m}^2 = 0.03\ \text{b} = 30\ \text{mb}$$

Scattering happens at the tens-of-milibarns level



$$\sigma(pp \to W) \sim \text{G}_\text{F}^2 \sim \frac{1}{(100\ \text{GeV})^2} = 10^{-6}\ \text{mb} = 1\ \text{nb}$$

Roughly 1 in a million proton collisions will produce a W boson

$$\sigma(pp \to h) \sim 10^{-3} \times \sigma(pp \to W) = 10^{-9}\ \text{mb} = 1\ \text{pb}$$

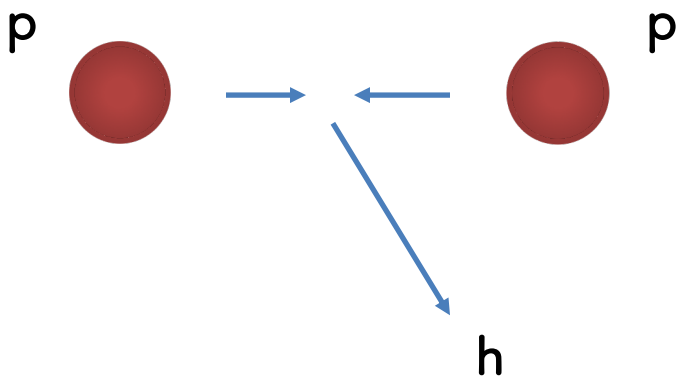
$$\sim \frac{1}{16\pi^2}$$

Need 1 billion proton collisions to produce a Higgs

Cross section for pp collision

$$\sigma \sim \pi r_p^2 \sim 3\ \text{fm}^2 = 3{\times}10^{-30}\ \text{m}^2 = 0.03\ \text{b} = 30\ \text{mb}$$

Scattering happens at the tens-of-milibarns level



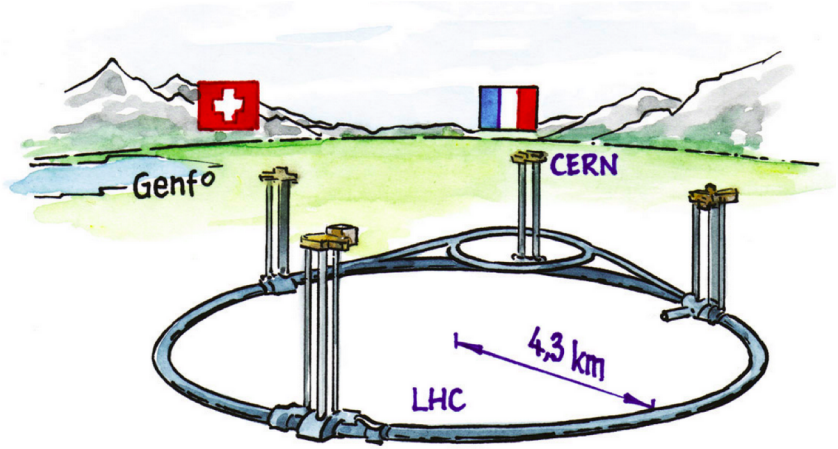
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Need 1 billion proton collisions to produce a Higgs

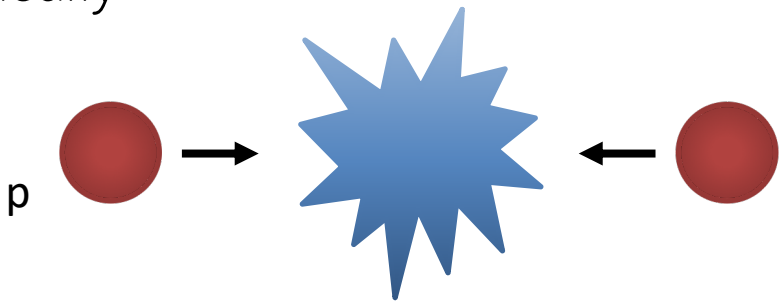
$$\frac{10^9\ \text{collisions}}{1\ \text{Higgs}} \times \frac{10^3\ \text{Higgs}}{h \to \gamma\gamma} \times \frac{1}{10^{-2}\ \text{eff}} \times \frac{100\ h \to \gamma\gamma}{\text{year}} \times \frac{\text{year}}{10^9\ \text{sec}} = 10^9\ \frac{\text{collisions}}{\text{sec}} = 1\ \text{GHz}$$

Need 1 billion proton collisions per second to produce 100 Higgs in a year

How Large Hadron Collider (LHC) discover the Higgs ?



Ideally



In reality



25 ns

$\sim$ 40 MHz

10^{11} protons per bunch

If each bunch manages to have 25 collisions per bunch crossing, we get 1 GHz (25 x 40 = 1000)

$$N_{\text{events}} = \left(10^{11}\,\frac{\text{protons}}{\text{bunch}}\right)^2 \frac{\sigma_{pp} = 10\text{ mb}}{\sigma_{\text{beam}} = (10\ \mu\text{m})^2} = 100\ \frac{\text{collisions}}{\text{bunch crossing}} \longrightarrow \frac{100}{25} = 4\text{ GHz}$$

Total collision rate

Luminosity : $\mathcal{L}$

: collision rate, e.g. how many times we repeat

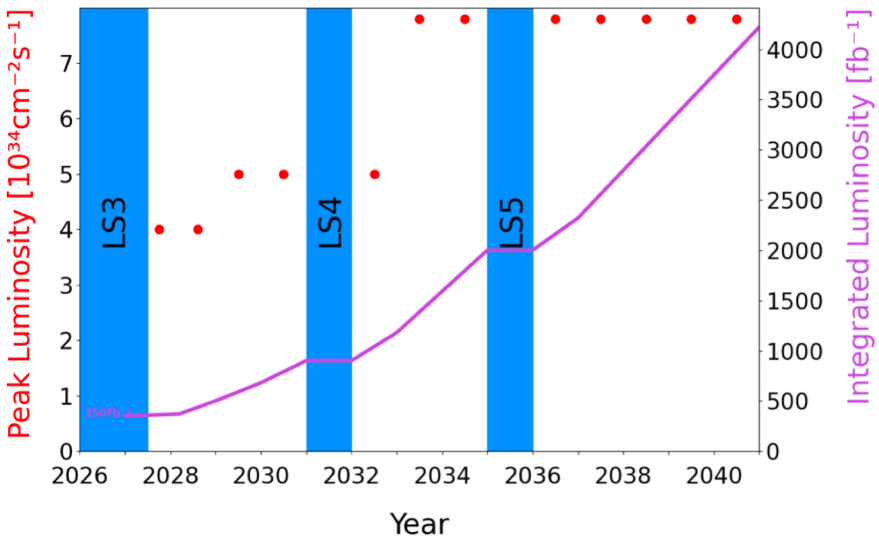
Instantaneous luminosity of the LHC, currently,

$$\mathcal{L}^{\text{inst}}_{@\text{LHC}} \sim 10\,\frac{\text{Hz}}{\text{nb}} = 10^{34}\,\frac{1}{\text{cm}^2 \cdot \text{s}}$$

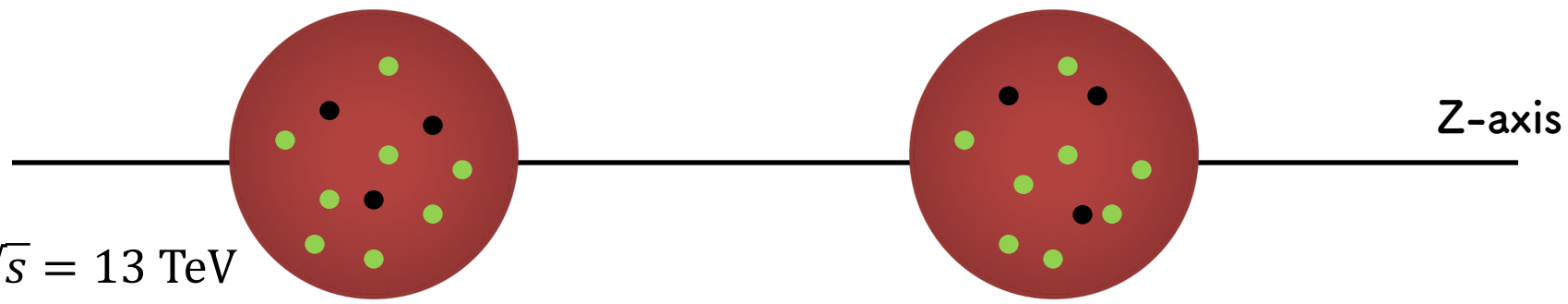
Integrating over time gives **Integrated** luminosity

$$\mathcal{L}^{\text{inst}}_{@\text{LHC}} \times 10\ \text{mb} = 10^{8}\ \text{Hz} = 0.1\ \text{GHz}$$

Luminosity at
High-Luminosity LHC



Kinematics



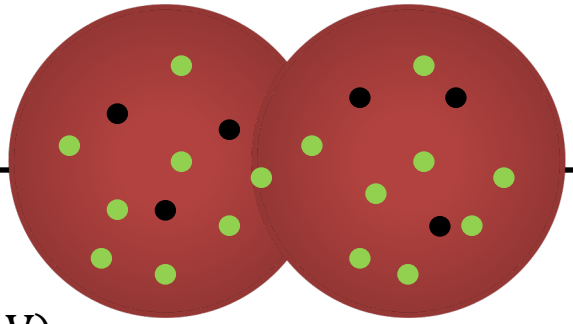
$@\ \sqrt{s} = 13\ \text{TeV}$

$P_1^\mu = (6.5\ \text{TeV}, 0, 0, 6.5\ \text{TeV})$

$P_2^\mu = (6.5\ \text{TeV}, 0, 0, -6.5\ \text{TeV})$

Kinematics

- Valence quarks
- Sea quarks and gluons



Z-axis

@ $\sqrt{s} = 13$ TeV

$P_1^\mu = (6.5\ \text{TeV}, 0, 0, 6.5\ \text{TeV})$

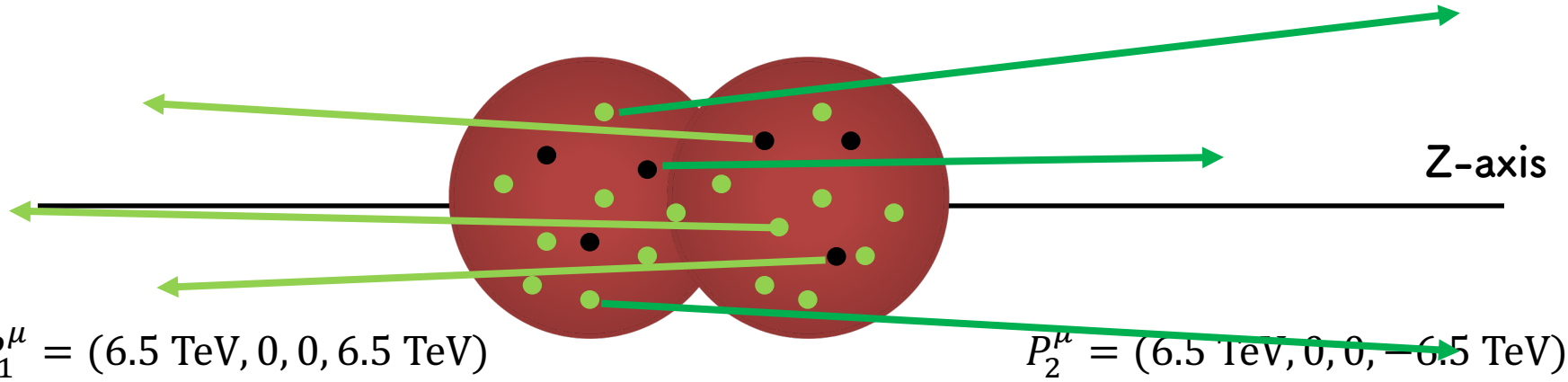
$P_2^\mu = (6.5\ \text{TeV}, 0, 0, -6.5\ \text{TeV})$

$p_1^\mu = x_1\, P_1^\mu \qquad p_2^\mu = x_2\, P_2^\mu$

Proton's momentum is distributed over each partons. Exact porton is given by PDF

For most of time

: they do not see each other



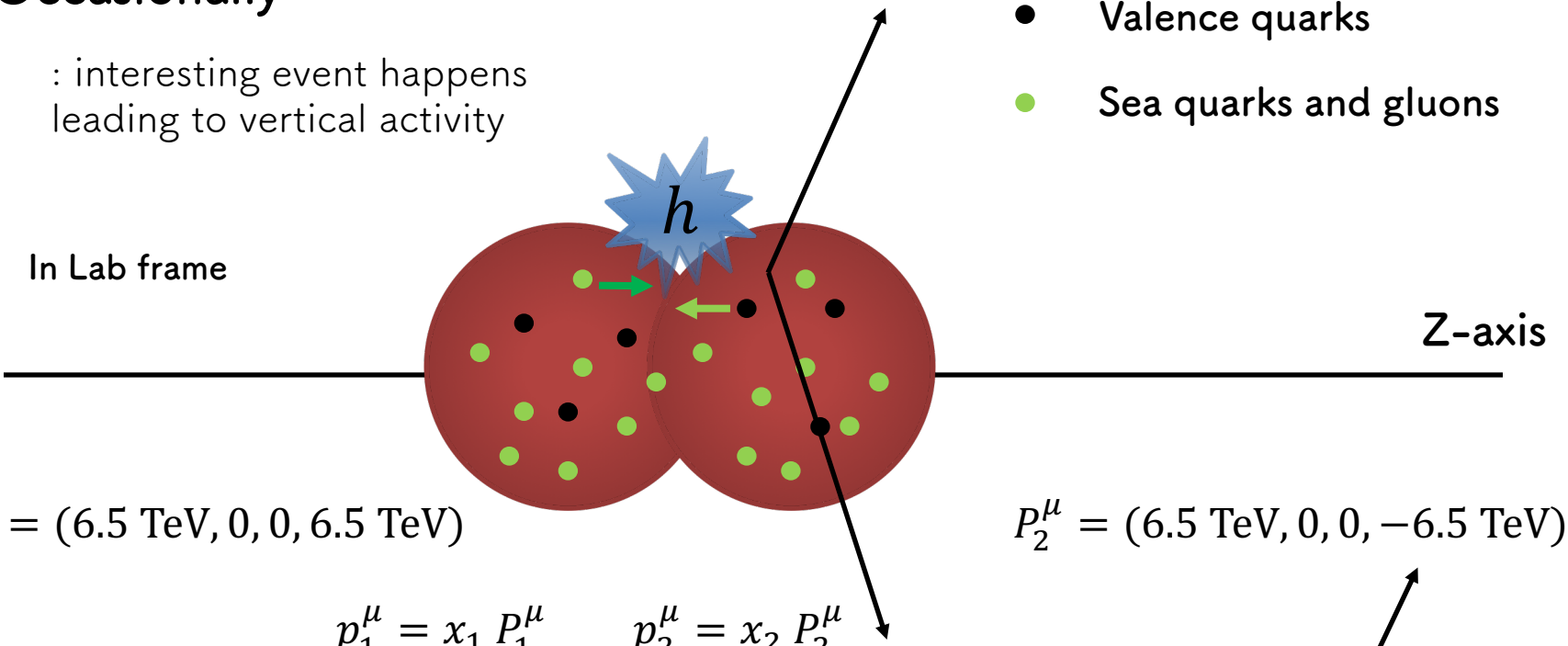
$P_1^\mu = (6.5\ \text{TeV}, 0, 0, 6.5\ \text{TeV})$

$P_2^\mu = (6.5\ \text{TeV}, 0, 0, -6.5\ \text{TeV})$

$p_1^\mu = x_1\, P_1^\mu \qquad p_2^\mu = x_2\, P_2^\mu$

Occasionally

: interesting event happens
leading to vertical activity



$P_1^\mu = (6.5\ \text{TeV}, 0, 0, 6.5\ \text{TeV})$

$P_2^\mu = (6.5\ \text{TeV}, 0, 0, -6.5\ \text{TeV})$

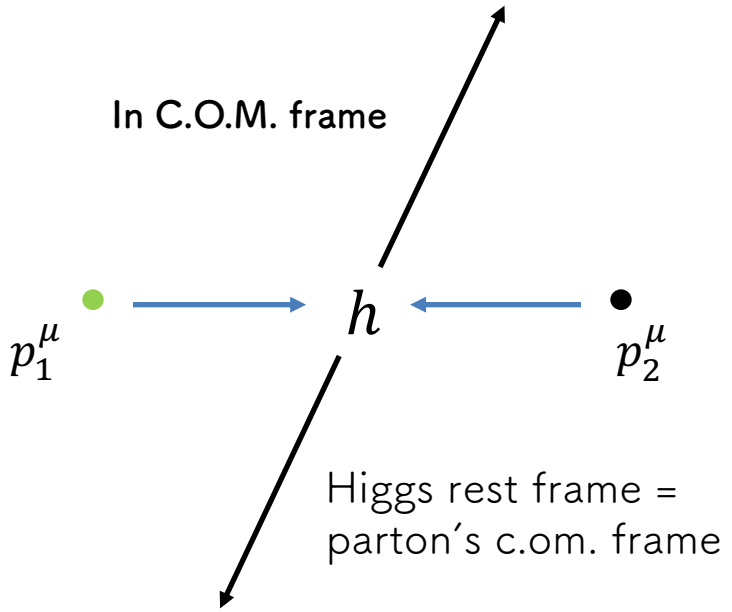
$p_1^\mu = x_1\, P_1^\mu \qquad p_2^\mu = x_2\, P_2^\mu$

$$p_1^\mu + p_2^\mu = \frac{\sqrt{s}}{2}(x_1 + x_2, 0, 0, x_1 - x_2)$$

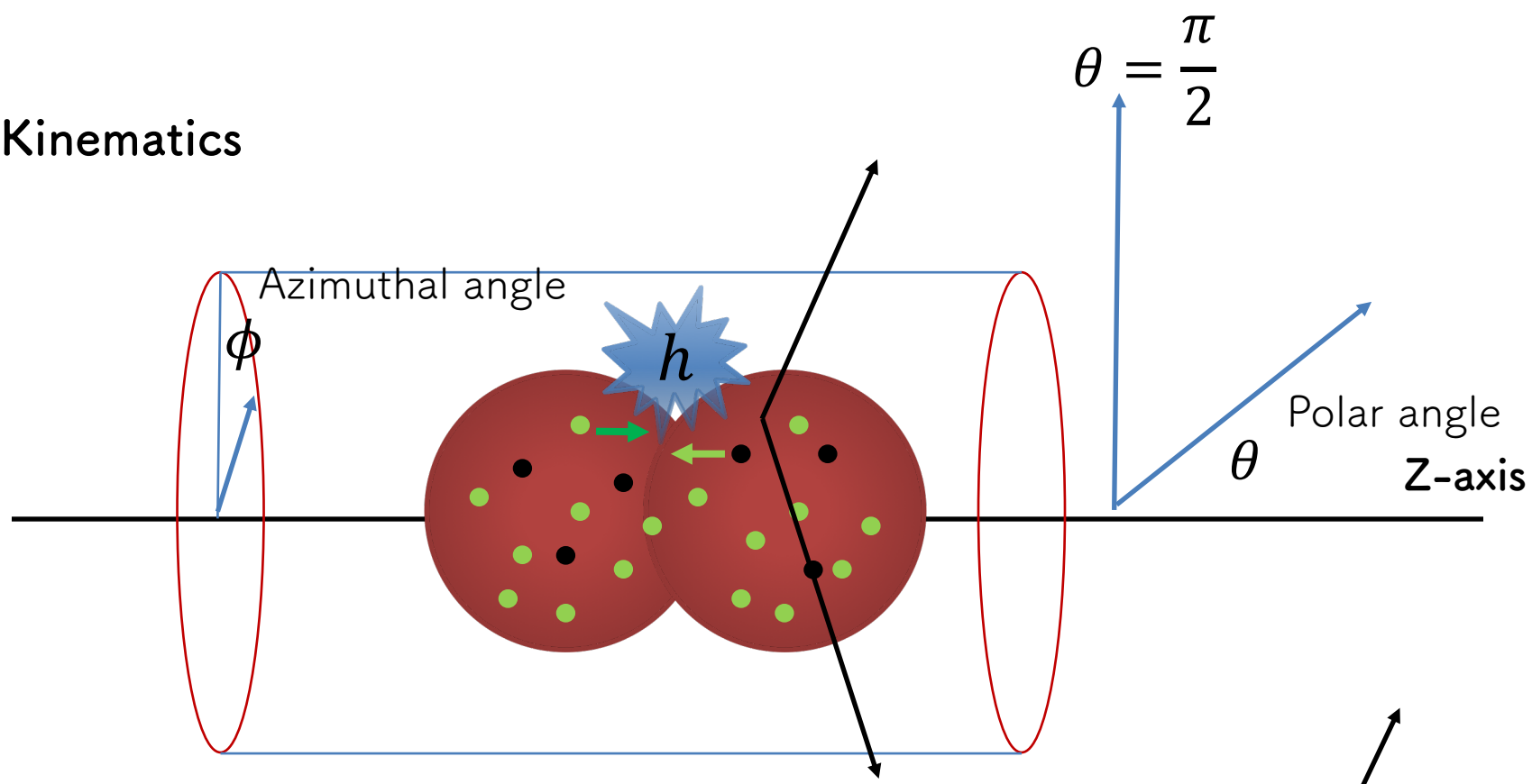
$$(p_1 + p_2)^2 = m_h^2$$

Boosting along the beam axis

In C.O.M. frame



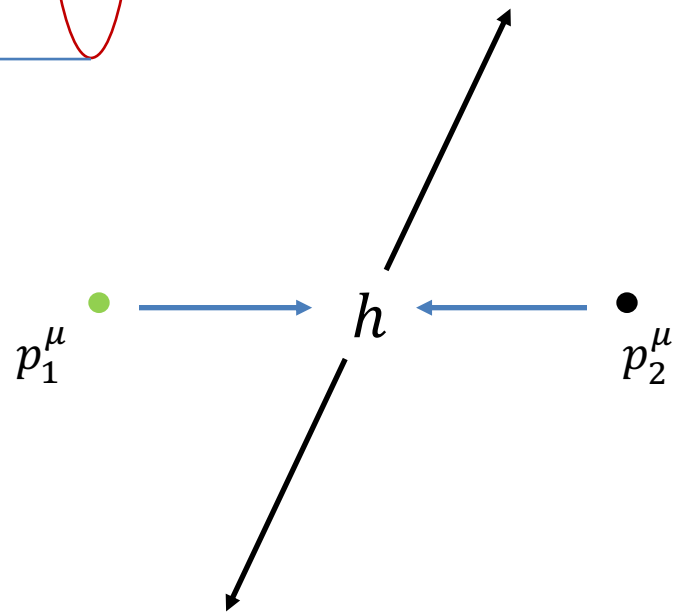
Kinematics



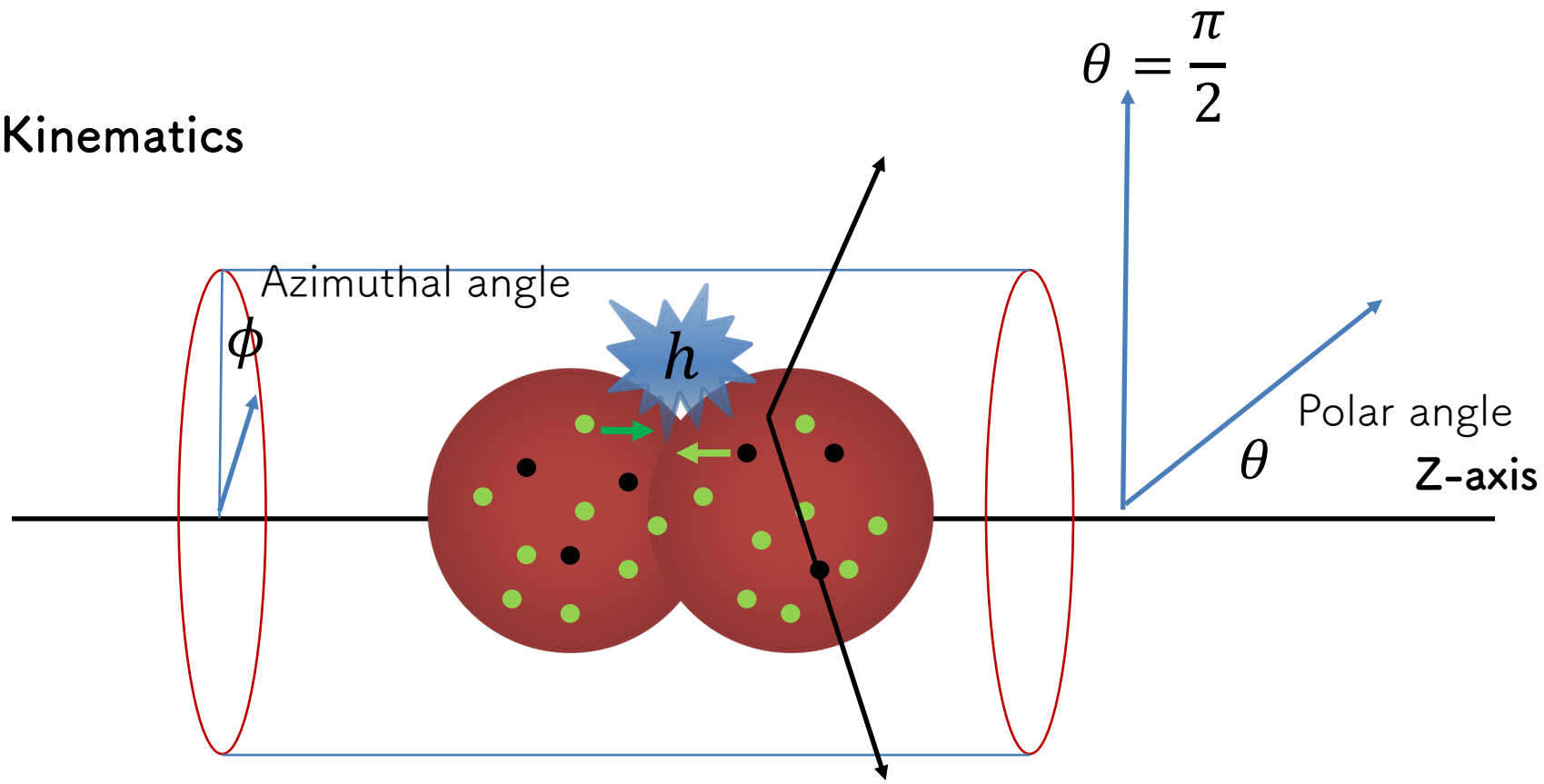
Under boost along the beam axis

$$p^\mu = (E, p_x, p_y, p_z)$$

$$E \to E\cosh\beta + p_z \sinh\beta$$
$$p_x \to p_x$$
$$p_y \to p_y$$
$$p_z \to p_z \cosh\beta + E\sinh\beta$$



Kinematics



Construct boost insensitive variables

$p^\mu = (E, p_x, p_y, p_z)$

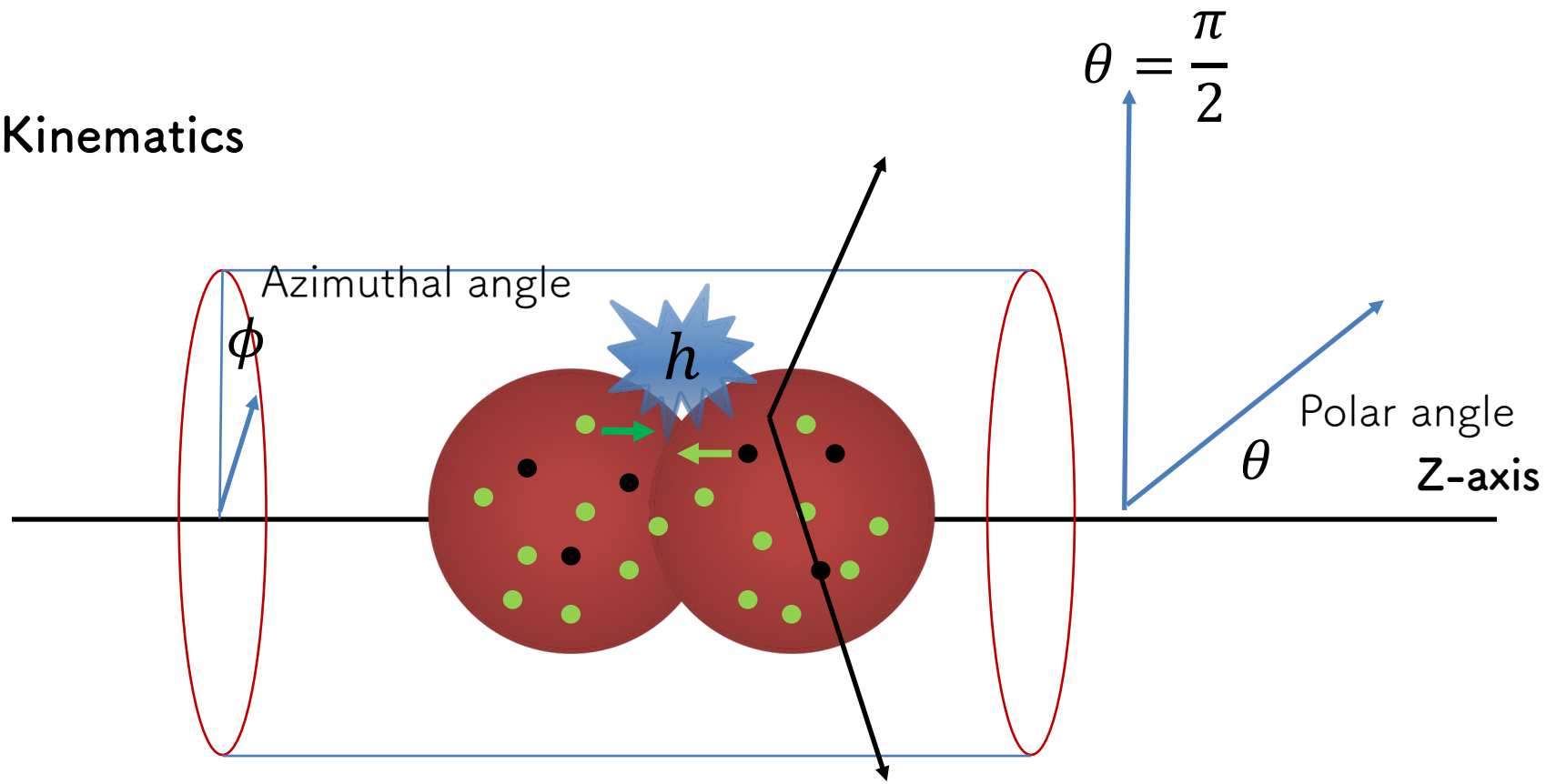
$E \to E\cosh\beta + p_z\sinh\beta$
$p_x \to p_x$
$p_y \to p_y$
$p_z \to p_z\cosh\beta + E\sinh\beta$

$\vec{p}_T = (p_x, p_y),\ p_T = |p_T|$: transverse momentum

$\phi = \tan^{-1}\frac{p_x}{p_y}$: azimuthal angle

$$\frac{E+p_z}{E-p_z} \to \frac{E(c+s)+p_z(c+s)}{E(c-s)-p_z(c-s)} \times \frac{c+s}{c+s} = \frac{E+p_z}{E-p_z}(c+s)^2$$

Kinematics



Construct boost insensitive variables

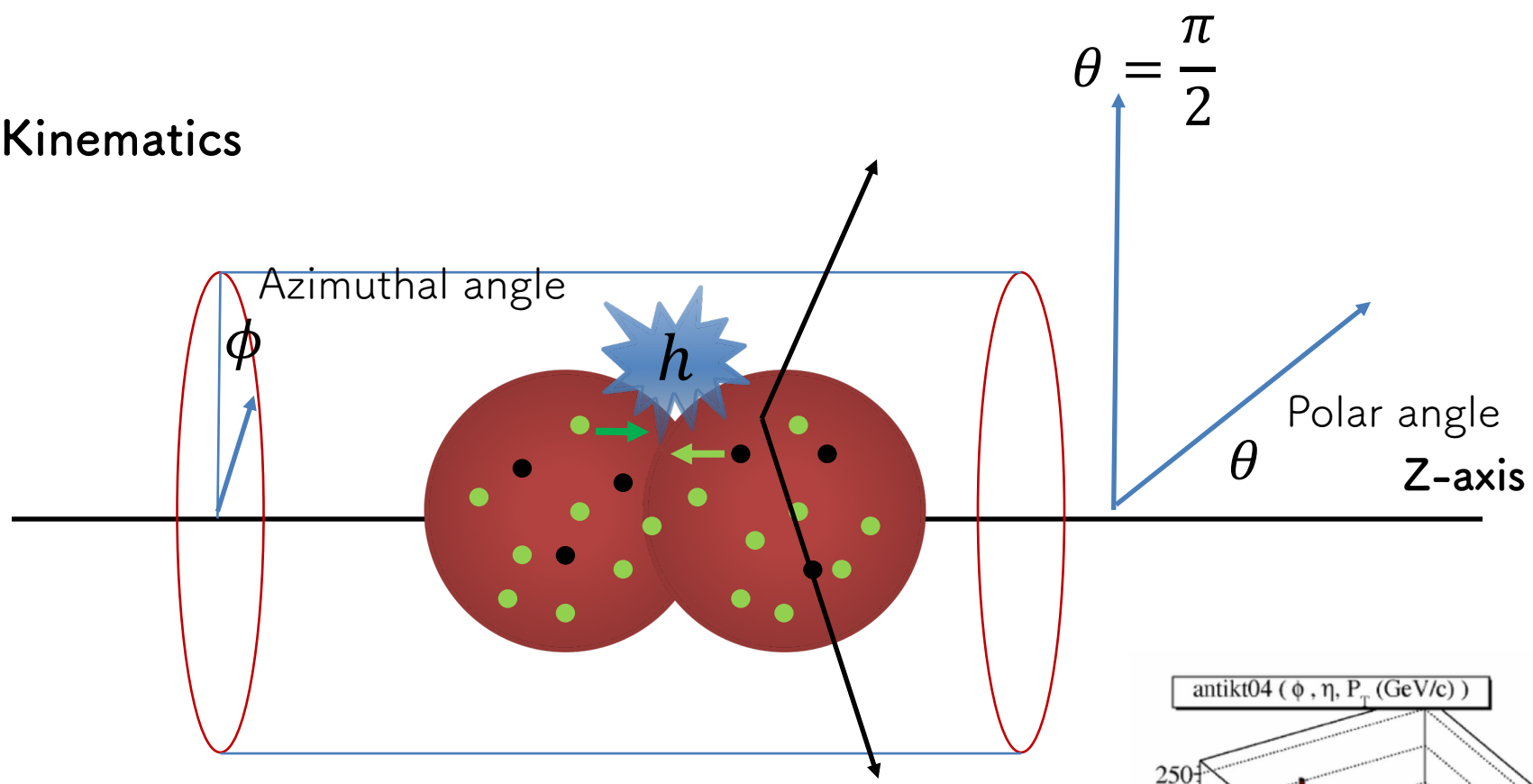
$\vec{p}_T = (p_x, p_y),\ p_T = |p_T|$: transverse momentum

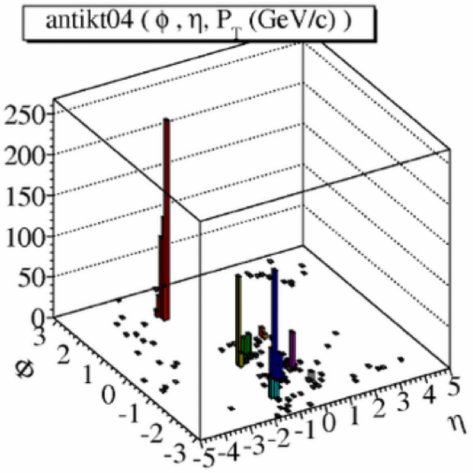
$\phi = \tan^{-1}\frac{p_x}{p_y},\quad y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$: rapidity (Δy is invariant)

Massless limit $\longrightarrow$ $\eta = \frac{1}{2}\ln\cot\frac{\theta}{2}$: pseudorapidity

$p^\mu = E(1, \sin\theta, 0, \cos\theta)$

Kinematics





Construct boost insensitive variables

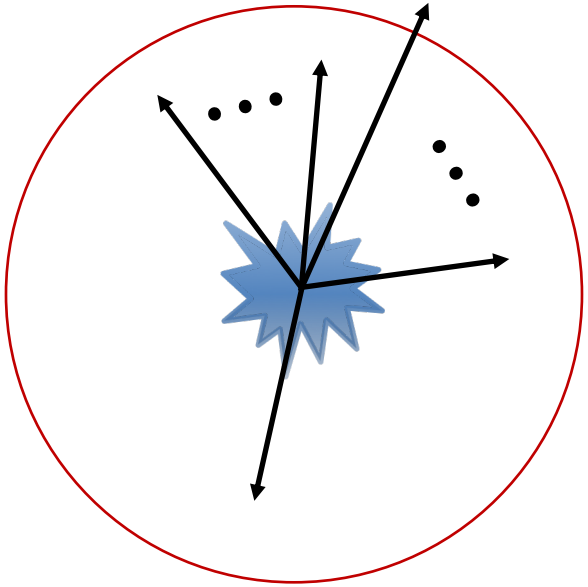
$\vec{p}_T = (p_x, p_y),\ p_T = |p_T|$: transverse momentum

$\phi = \tan^{-1}\frac{p_x}{p_y}, \quad y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$: ($\Delta y, \Delta\eta$ are invariant)

Angular distance is boost invariant : $dR = \sqrt{(\Delta\phi)^2 + (\Delta y)^2}$

We adopt $y, \phi, \vec{p}_T$, and we construct observables out of them

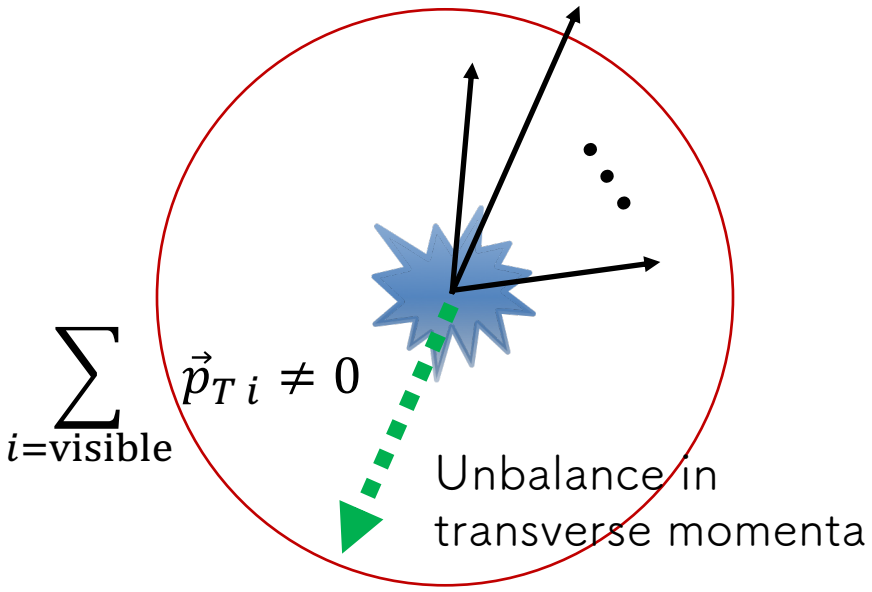
Overall hadronic activity



$$H_T = \sum_{\text{jets } j} \left|\vec{p}_T^{\,j}\right|$$

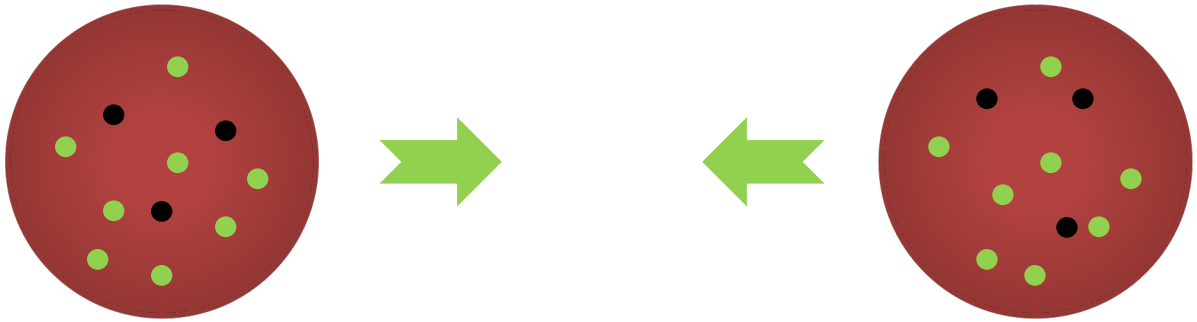
We adopt $y, \phi, \vec{p}_T$, and we construct observables out of them

Missing transverse momentum/energy



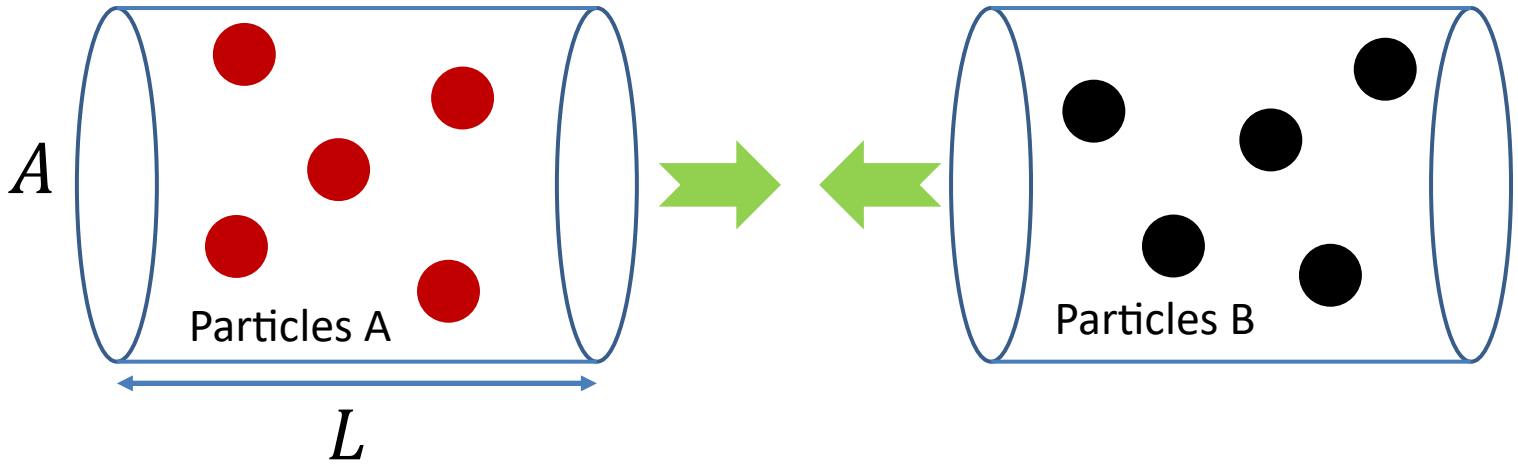
$$\not{\vec{p}}_T = -\sum_{\text{jets } j} \vec{p}_T^{\,j}$$

Cross section : precise version



$N_{\text{events}} = ?$ for interesting processes

Cross section : precise version



$$\sigma = \pi(r_A + r_B)^2$$

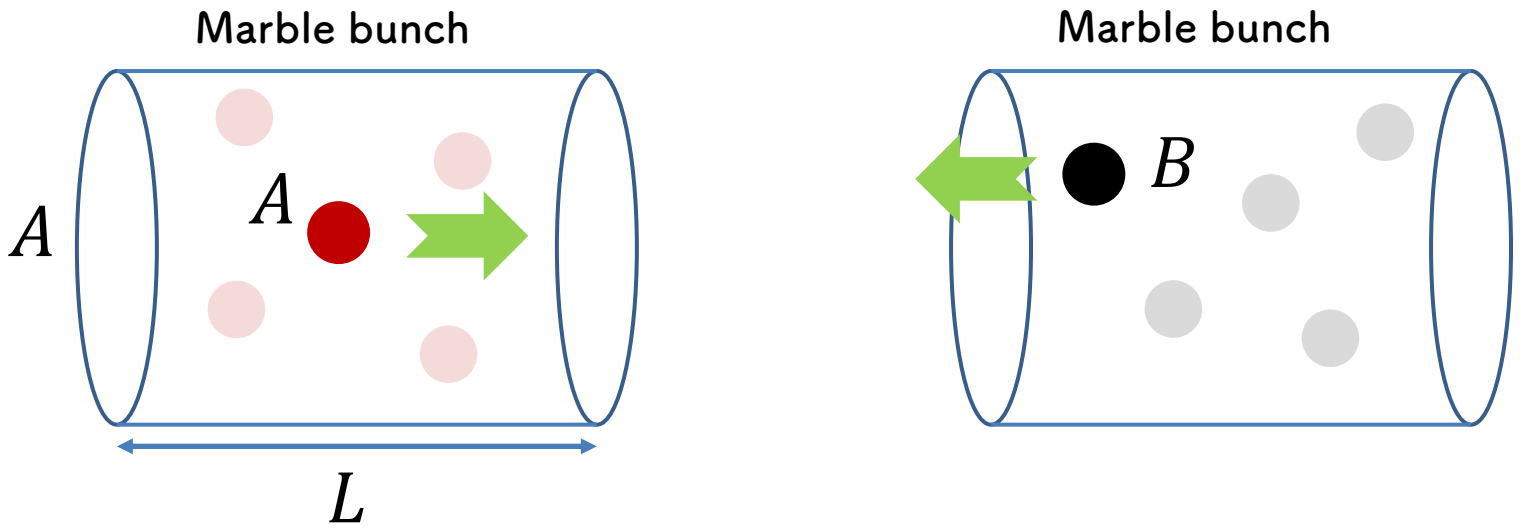
$$\mathcal{P}_{\text{a collision}} = \frac{\sigma \times (\#\text{ of } B's)}{A}$$

$$N_{\text{events}} = \frac{(\#\text{ of } A's) \times (\#\text{ of } B's) \times \sigma}{A} = \frac{(\rho_A A L_A)(\rho_B A L_B)}{A}\sigma = \frac{N_A N_B \sigma}{A}$$

$$\sigma = A\frac{N_{\text{events}}}{N_A N_B} = A \cdot \mathcal{P}_{\text{scattering}}$$

We want to generalize this notion of cross sectional area to a cross section in QM system

Cross section : precise version



$$\sigma = \pi(r_A + r_B)^2$$

In practice, it is very unlikely to collide more than two particles at a time, thus we focus on a 2-to-n process, e.g. initial state is two particle state.

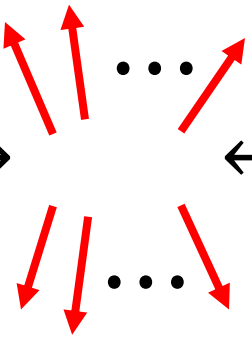
$$\sigma(\ A \bullet \rightarrow \quad \leftarrow \bullet B\ ) \times \text{Luminosity} = N_{\text{events}}$$

n-particles

: How many times we repeat 2-to-n experiments

In practice, it is very unlikely to collide more than two particles at a time, thus we focus on a 2-to-n process, e.g. initial state is two particle state.

$$\sigma(\ A\bullet\rightarrow \quad \leftarrow\bullet B\ )\times \text{Luminosity} = N_{\text{events}}$$



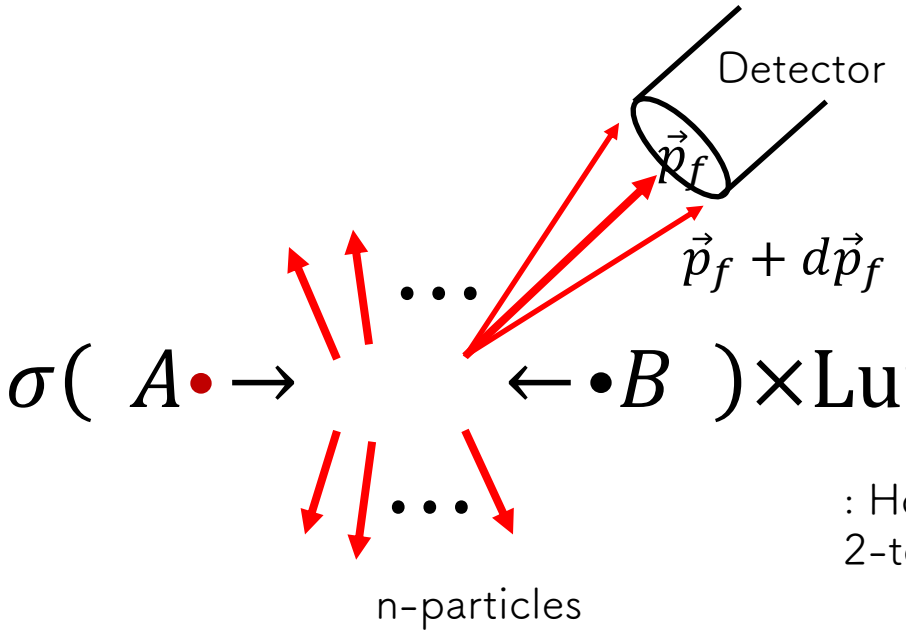
n-particles

: How many times we repeat 2-to-n experiments

For a single flux (for either particle)

$$1 = N = \rho V = \rho L A = \rho v T A = \Phi T A \qquad \rightarrow A = \frac{1}{\Phi T} \qquad , \Phi = \rho v = \frac{1}{V} v \rightarrow \frac{|\vec{v}_A - \vec{v}_B|}{V}$$

In c.o.m frame



$$\sigma(\ A\bullet\rightarrow \quad \leftarrow\bullet B\ )\times \text{Luminosity} = N_{\text{events}}$$

: How many times we repeat 2-to-n experiments

For a single flux (for either particle)

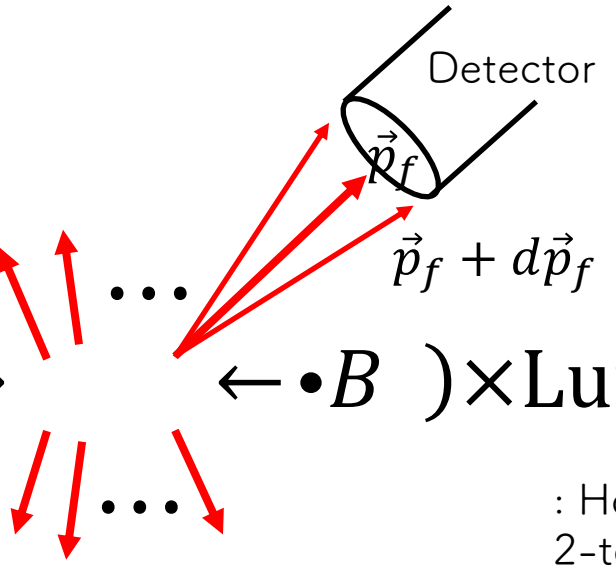
$$1 = N = \rho V = \rho L A = \rho v T A = \Phi T A \qquad \rightarrow A = \frac{1}{\Phi T} \qquad , \Phi = \rho v = \frac{1}{V} v \rightarrow \frac{|\vec{v}_A - \vec{v}_B|}{V}$$

In experiment, we measure differential cross section as a function of angles and energies of final state particles

In c.o.m frame

$$d\sigma = \frac{1}{\Phi T} d\mathcal{P}_{\text{scattering}} = \frac{V}{T} \frac{1}{|\vec{v}_A - \vec{v}_B|} d\mathcal{P}_{\text{scatt}}$$

$$\frac{d\mathcal{P}_{\text{scatt}}}{d\Pi} = \frac{|\langle f|S|i\rangle|^2}{\langle f|f\rangle\langle i|i\rangle}$$



$$\sigma(\ A\bullet\rightarrow\ \cdots\ \leftarrow\bullet B\ )\times\text{Luminosity} = N_{\text{events}}$$

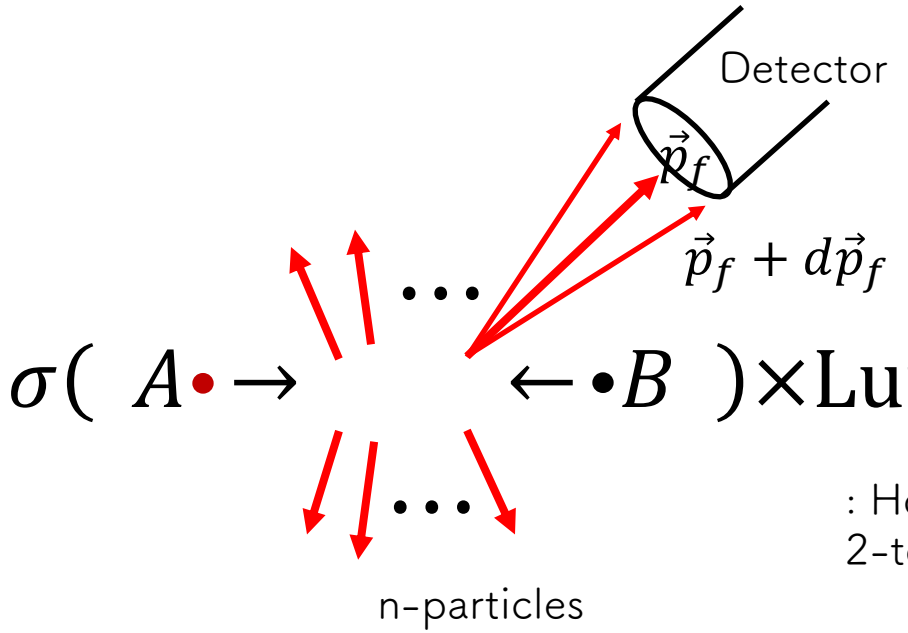
: How many times we repeat 2-to-n experiments

$$d\sigma = A d\mathcal{P}_{\text{scattering}} = \frac{1}{\Phi T} d\mathcal{P}_{\text{scattering}} = \frac{V}{T}\frac{1}{|\vec{v}_A - \vec{v}_B|} d\mathcal{P}_{\text{scatt}}$$

$$= \frac{V}{T}\frac{1}{|\vec{v}_A - \vec{v}_B|}\frac{|\langle f|S|i\rangle|^2}{\langle f|f\rangle\langle i|i\rangle} d\Pi$$

$$S = 1 + iT : \text{S-matrix}$$

$$T = (2\pi)^4 \delta^{(4)}(\sum p) i\mathcal{M}$$



$$\sigma(\ A\bullet\rightarrow \quad \leftarrow\bullet B\ ) \times \text{Luminosity} = N_{\text{events}}$$

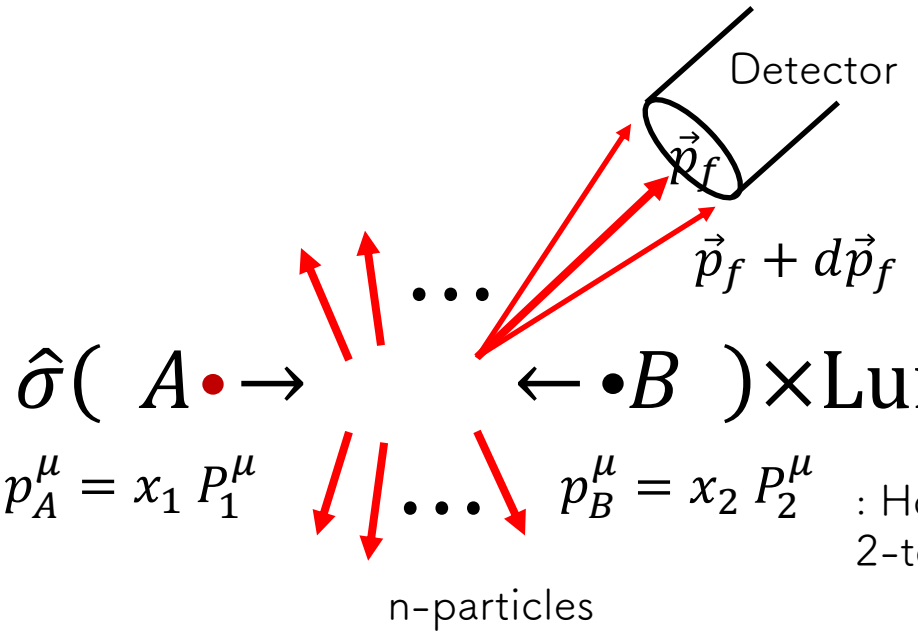
: How many times we repeat
2-to-n experiments

$$d\sigma = A d\mathcal{P}_{\text{scattering}} = \frac{1}{\Phi T} d\mathcal{P}_{\text{scattering}} = \frac{V}{T}\frac{1}{|\vec{v}_A - \vec{v}_B|} d\mathcal{P}_{\text{scatt}}$$

$$= \frac{V}{T}\frac{1}{|\vec{v}_A - \vec{v}_B|}\frac{|\langle f|S|i\rangle|^2}{\langle f|f\rangle\langle i|i\rangle} d\Pi$$

$$= \frac{V}{T}\frac{1}{|\vec{v}_A - \vec{v}_B|}\frac{|\langle f|\mathcal{M}|i\rangle|^2 VT\delta^{(4)}(\sum p)(2\pi)^4}{(2E_A V)(2E_B V)\prod_{j=1}^{n}(2E_j V)}\prod_{f=1}^{n}\frac{V}{(2\pi)^3} d^3\vec{p}_f$$

$$= \frac{1}{(2E_A)(2E_B)|\vec{v}_A - \vec{v}_B|}|\langle f|\mathcal{M}|i\rangle|^2(2\pi)^4\delta^{(4)}(\sum p)\prod_{f=1}^{n}\frac{d^3\vec{p}_f}{(2\pi)^3}\frac{1}{2E_f}$$



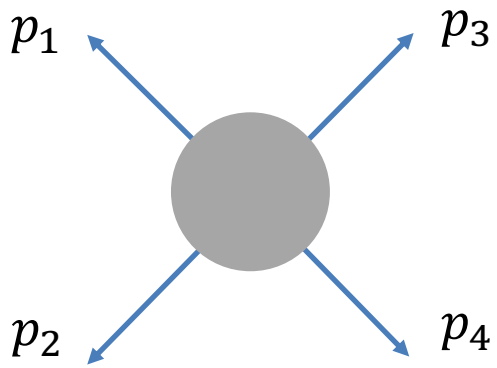
$$\sigma_{\text{had}} = \int_0^1 dx_1 \int_0^1 dx_2 \sum f_i(x_1,\mu) f_j(x_2,\mu)\, \hat{\sigma}_{ij}(\mu)$$

$$d\hat{\sigma}_{ij} = \frac{1}{(2E_A)(2E_B)|\vec{v}_A - \vec{v}_B|} |\langle f|\mathcal{M}|i\rangle|^2 (2\pi)^4 \delta^{(4)}(\sum p) \prod_{f=1}^{n} \frac{d^3\vec{p}_f}{(2\pi)^3} \frac{1}{2E_f}$$

$$\sigma_{\text{had}} = \int_0^1 dx_1 \int_0^1 dx_2 \sum f_i(x_1,\mu) f_j(x_2,\mu)\, \hat{\sigma}_{ij}(\mu)$$

$$d\hat{\sigma}_{ij} = \frac{1}{(2E_A)(2E_B)|\vec{v}_A - \vec{v}_B|} |\langle f|\mathcal{M}|i\rangle|^2 (2\pi)^4 \delta^{(4)}(\sum p) \prod_{f=1}^{n} \frac{d^3\vec{p}_f}{(2\pi)^3} \frac{1}{2E_f}$$

Most interesting (and likely dominant) event happens at 2-to-2 process



Mandelstam variables :

$$\hat{s} = (p_1 + p_2)^2 = (p_3 + p_4)^2 = 4E^2, m^2$$

$$\hat{t} = (p_1 + p_3)^2 = (p_2 + p_4)^2 = -2p^2\,(1 - \cos\theta)$$

$$\hat{u} = (p_1 + p_4)^2 = (p_2 + p_3)^2 = -2p^2\,(1 + \cos\theta)$$

$\hat{s} + \hat{t} + \hat{u} = 4m^2$ for same particles

$$\hat{\sigma}_{2\to2} = \hat{\sigma}_{2\to2}(\hat{s},\hat{t},\hat{u})$$

$$= \hat{\sigma}_{2\to2}(\hat{s},\theta)$$

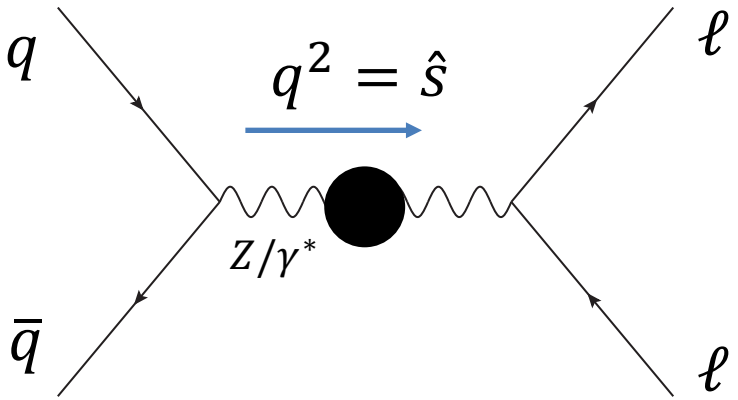
$$\frac{d\hat{\sigma}_{2\to2}}{d\hat{s}}, \frac{d\hat{\sigma}_{2\to2}}{d\hat{t}} \to \frac{d\hat{\sigma}_{2\to2}}{dm_{34}^2}, \frac{d\hat{\sigma}_{2\to2}}{d\cos\theta} \sim \frac{d\hat{\sigma}_{2\to2}}{dp_T}$$

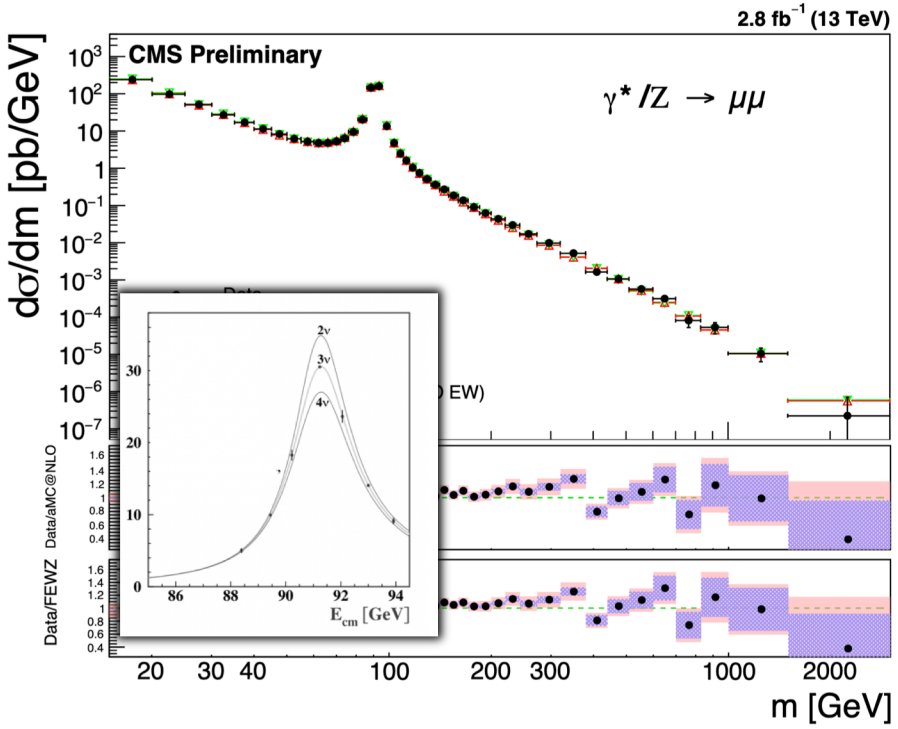
Observables

Resonance peak

$$\frac{d\hat{\sigma}}{d\hat{s}} \rightarrow \frac{d\hat{\sigma}(q\bar{q} \rightarrow Z \rightarrow \ell^+\ell^-)}{dm^2_{\ell\ell}} \sim \left|\frac{g^2}{\hat{s} - m_Z^2 + i\mathrm{m_Z}\Gamma_Z}\right|^2 = \frac{g^4}{(\hat{s} - m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$

Breit-Wigner form





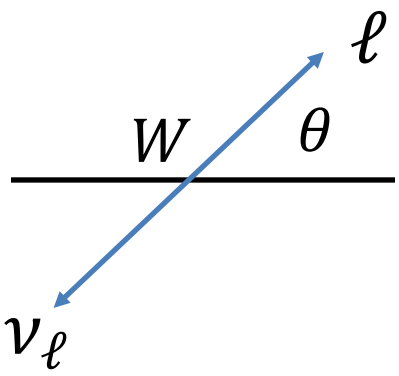
Observables

Jacobian peak at $p_T \sim \frac{m_W}{2}$

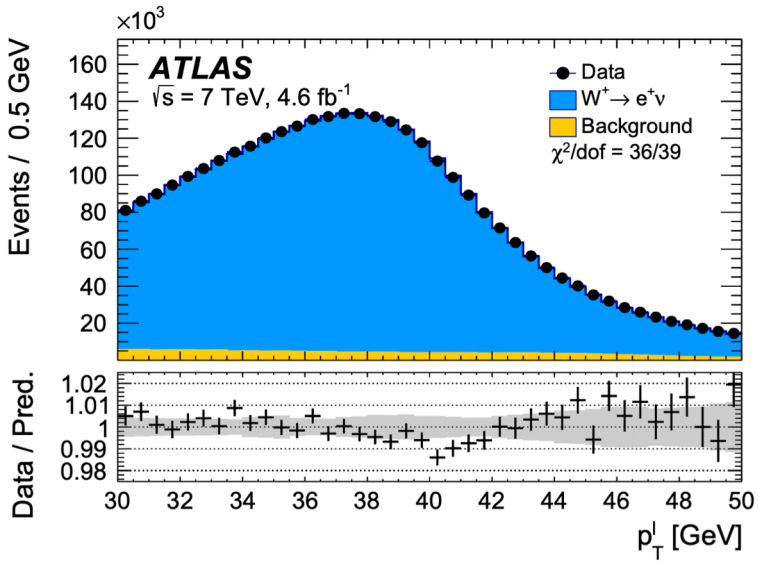
$$\sim 1 + \cos^2\theta$$

$$\frac{d\hat{\sigma}}{d\hat{t}} \rightarrow \frac{1}{\sigma_0}\frac{d\hat{\sigma}\,(q\bar{q} \rightarrow W \rightarrow e^-\nu)}{dp_T} = \frac{3}{m_W^2}\frac{p_T}{\sqrt{1-\frac{4p_T^2}{m_W^2}}}\left(1-\frac{2p_T^2}{m_W^2}\right)$$

$$\cos\theta = \frac{p_z}{|\vec{p}|} = \sqrt{1-\frac{4p_T^2}{m_W^2}}$$



Position of peak gives W mass.
Sensitive to NLO effect

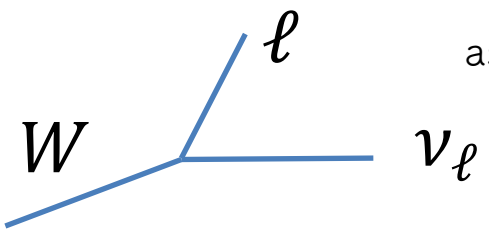


Observables

Transverse mass (mass in 2+1 dimension)

$$m_T = \sqrt{(E_{eT} + E_{\nu T})^2 - (\vec{p}_{Te} + \vec{p}_{T\nu})^2}$$

where $m^2 = E^2 - \vec{p}^2 \equiv E_T^2 - \vec{p}_T^2$



as opposed to full invariant mass

$$m = \sqrt{(E_e + E_\nu)^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 - (p_{ez} + p_{\nu z})^2} \geq m_T$$

$$\frac{1}{\sigma_0}\frac{d^2\hat{\sigma}\,(q\bar{q} \to W \to e^-\nu)}{dm^2 dm_T^2} \propto \frac{\Gamma_W m_W}{(m^2 - m_W^2)^2 + \Gamma_W^2 m_W^2}\frac{1}{m\sqrt{m^2 - m_T^2}}$$

endpoint

$m_T < m_W$

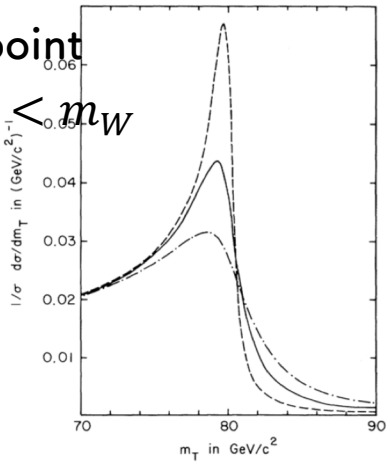
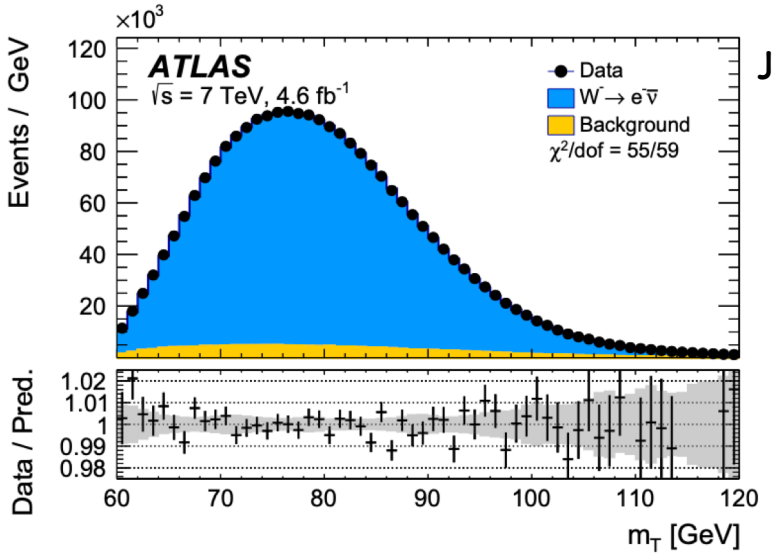


FIG. 2. $\sigma^{-1}d\sigma/m_T$ for $M = 80$ GeV/c^2 and $p_T{}^W = 0$ GeV/c^2. The dashed, solid, and dot-dashed lines refer to $\Gamma = 1$, 2.5, and 5 GeV/c^2, respectively.

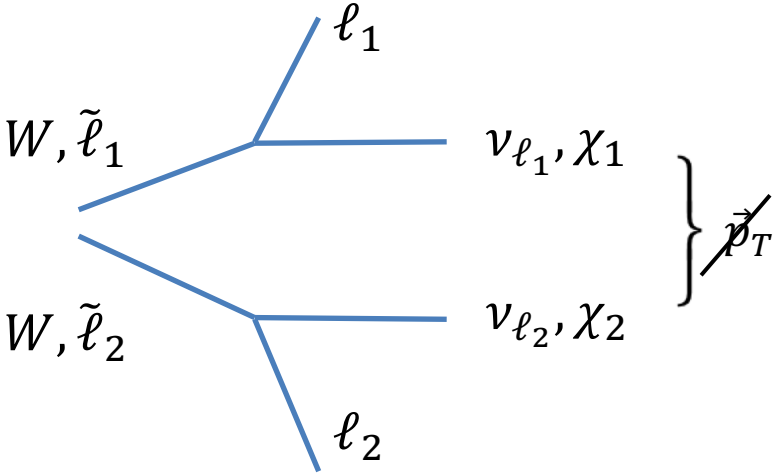


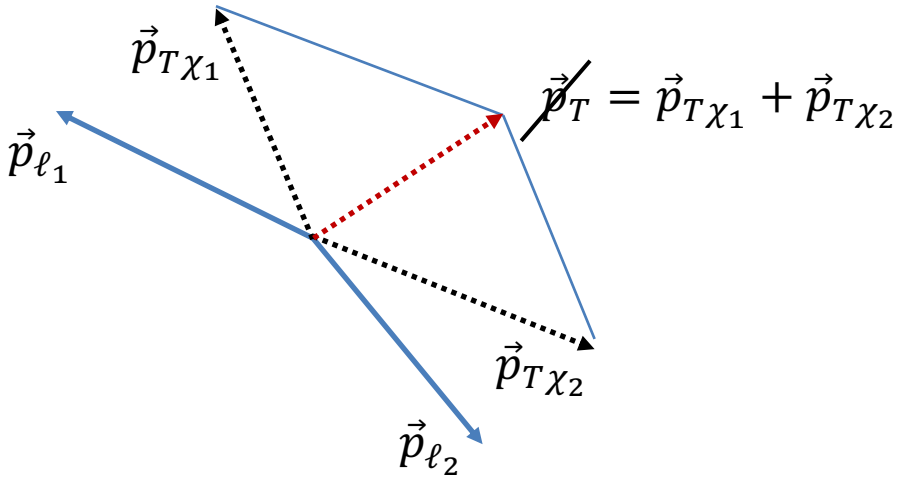
Jacobian peak at

$m_T \sim m_W$

Transverse mass m_{T2}

When involving more than one unmeasured particles





$$m_{T2} = \min\left[m_T(\vec{p}_{T\ell_1}, \vec{p}_{T\chi_1}, m_{\ell_1}, m_{\chi_1}), m_T(\vec{p}_{T\ell_2}, \vec{p}_{T\chi_2}, m_{\ell_2}, m_{\chi_2})\right]$$

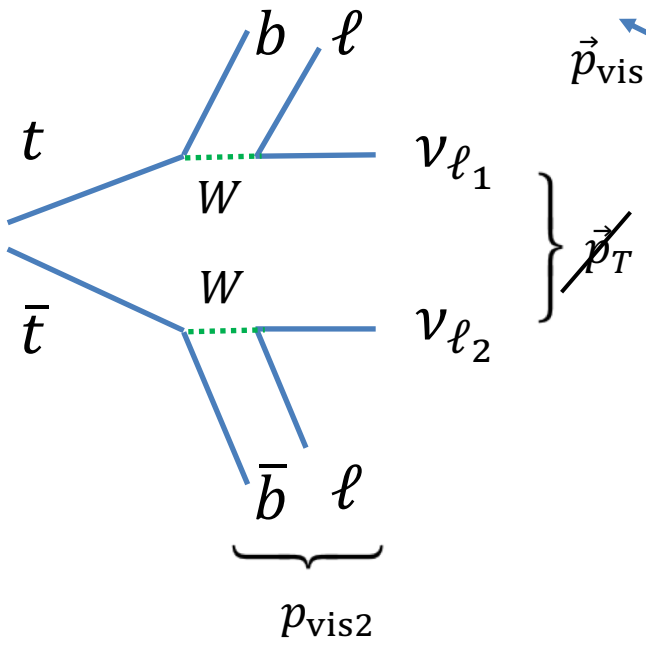
$$\not{\vec{p}}_T = \vec{p}_{T\chi_1} + \vec{p}_{T\chi_2}$$

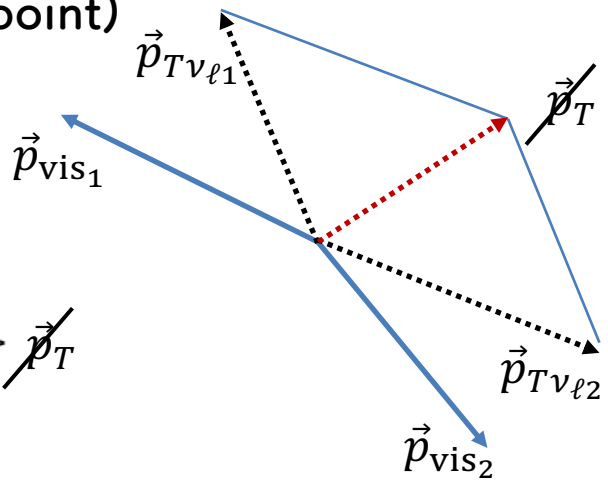
: m_{T2} has an end point at $m_{T2} = m_{\tilde{\ell}}$ when m_χ is correctly chosen

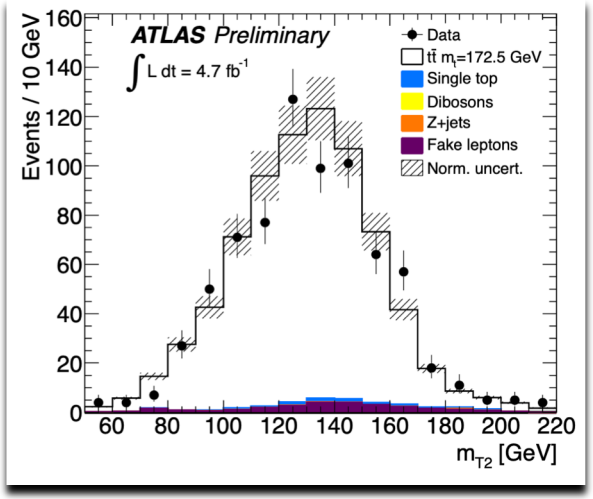
$$m_{T2}^{\max} = \max m_{T2}$$

: has a kink when m_χ is correctly chosen

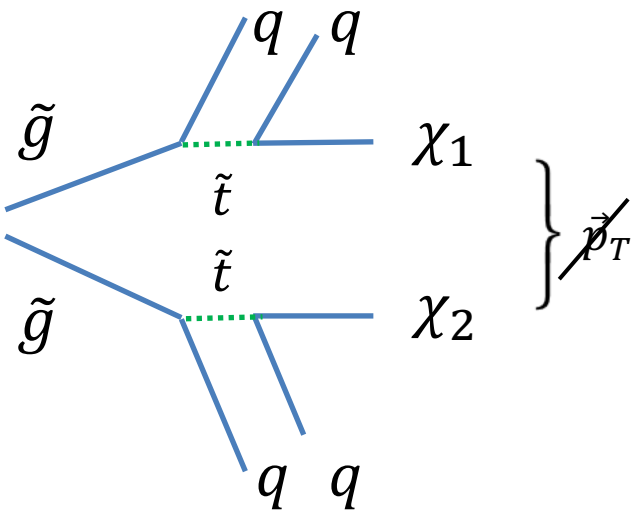
m_{T2} in dileptonic ttbar (endpoint)

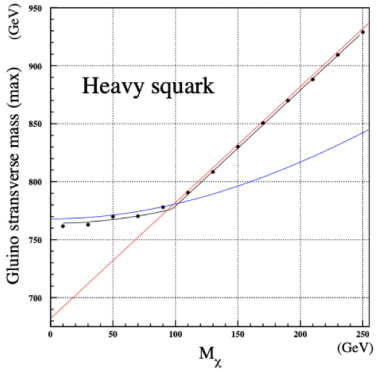






m_{T2} in gluino pair production (kink)

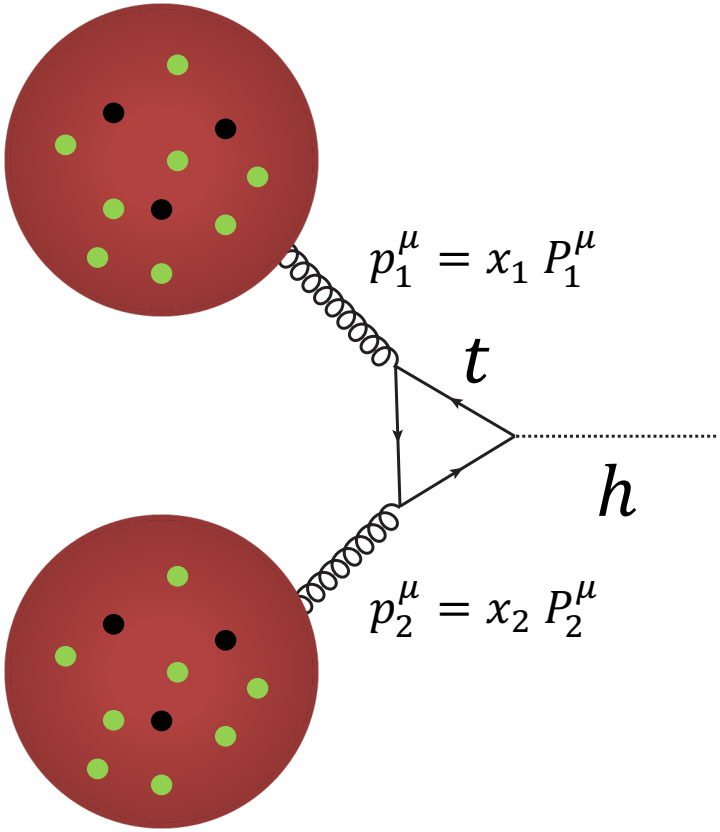




Cho, Choi, Kim, Park, 2007

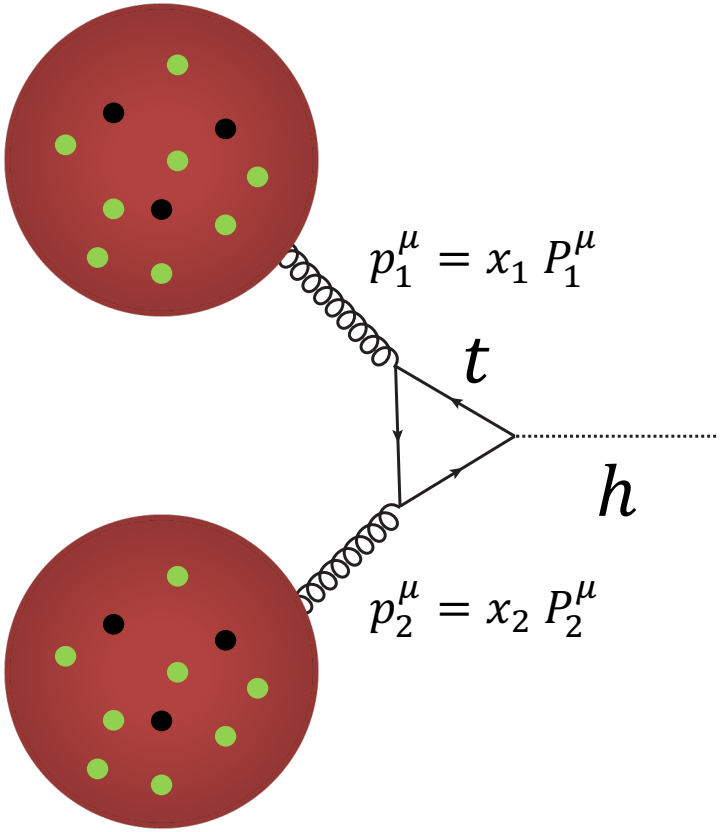
FIG. 2: $m_{T2}^{\max}$ *as a function of the trial LSP mass* m_χ *for the benchmark point of mAMSB with heavy squarks.*

Single Higgs production revisited



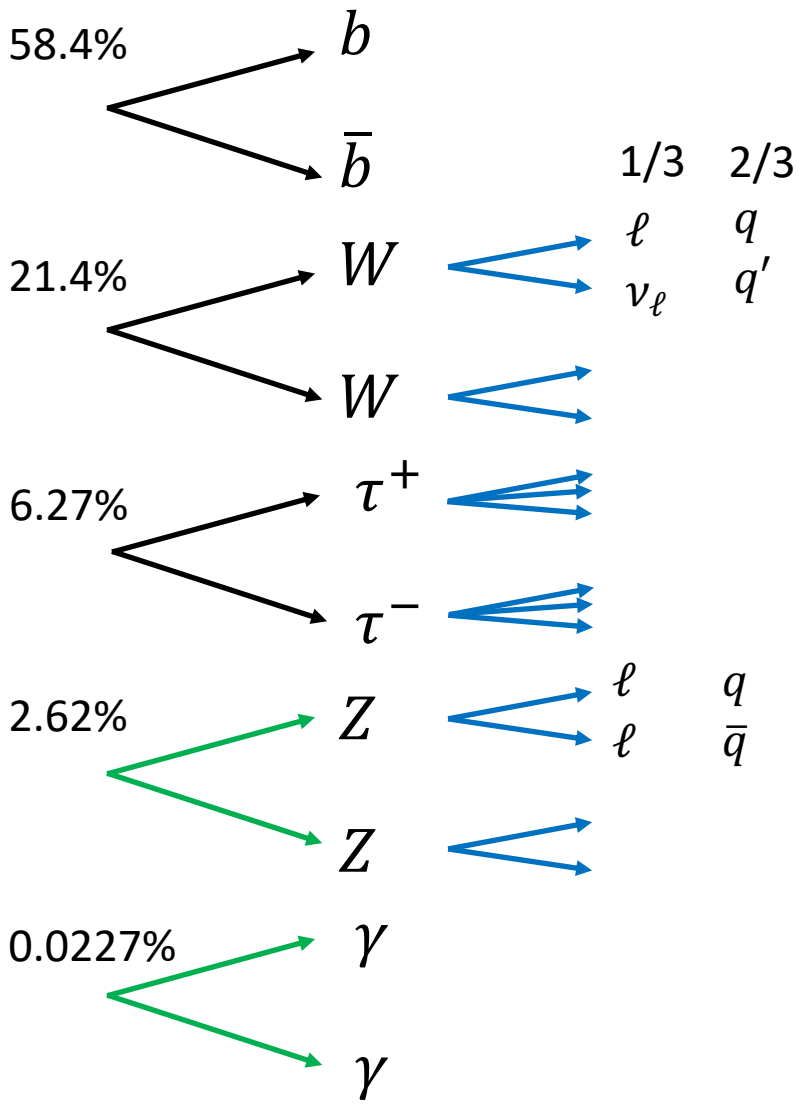
$$\sigma(gg \to h) = 44.1\ \text{pb}$$

Single Higgs production revisited



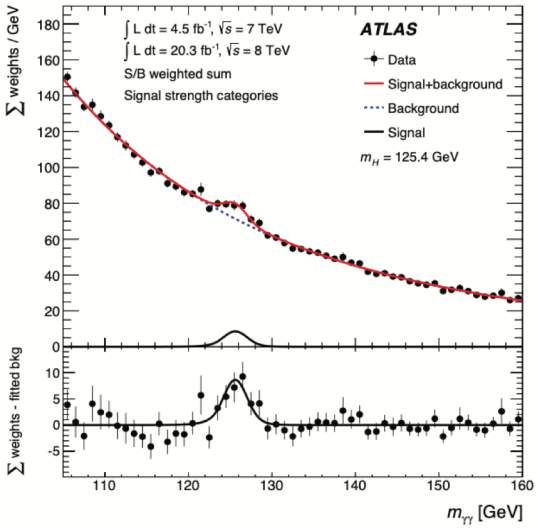
$\sigma(gg \to h) = 44.1\ \text{pb}$

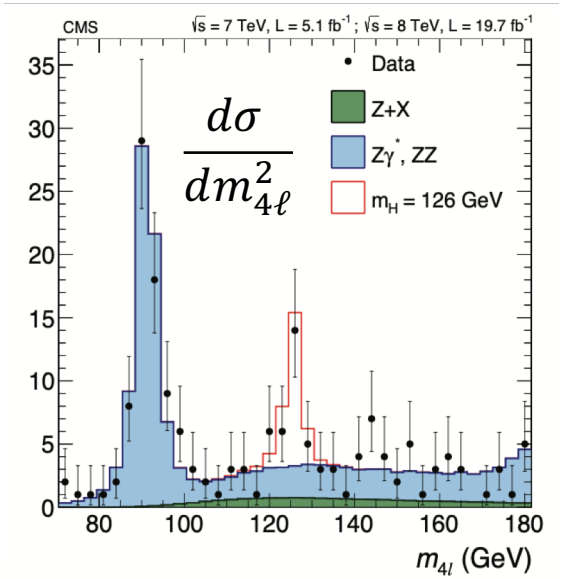
$\times$



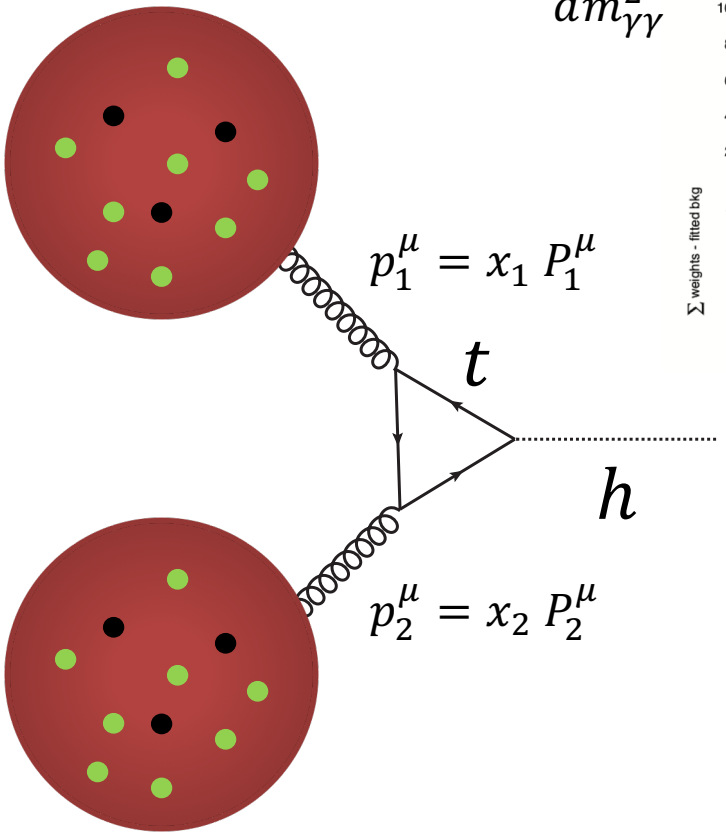
Single Higgs production rev

$$\frac{d\sigma}{dm_{\gamma\gamma}^2}$$





$$\frac{d\sigma}{dm_{4\ell}^2}$$



$$p_1^\mu = x_1\, P_1^\mu$$

$$p_2^\mu = x_2\, P_2^\mu$$

$$\sigma(gg \to h) = 44.1\ \text{pb}$$

$$\times$$

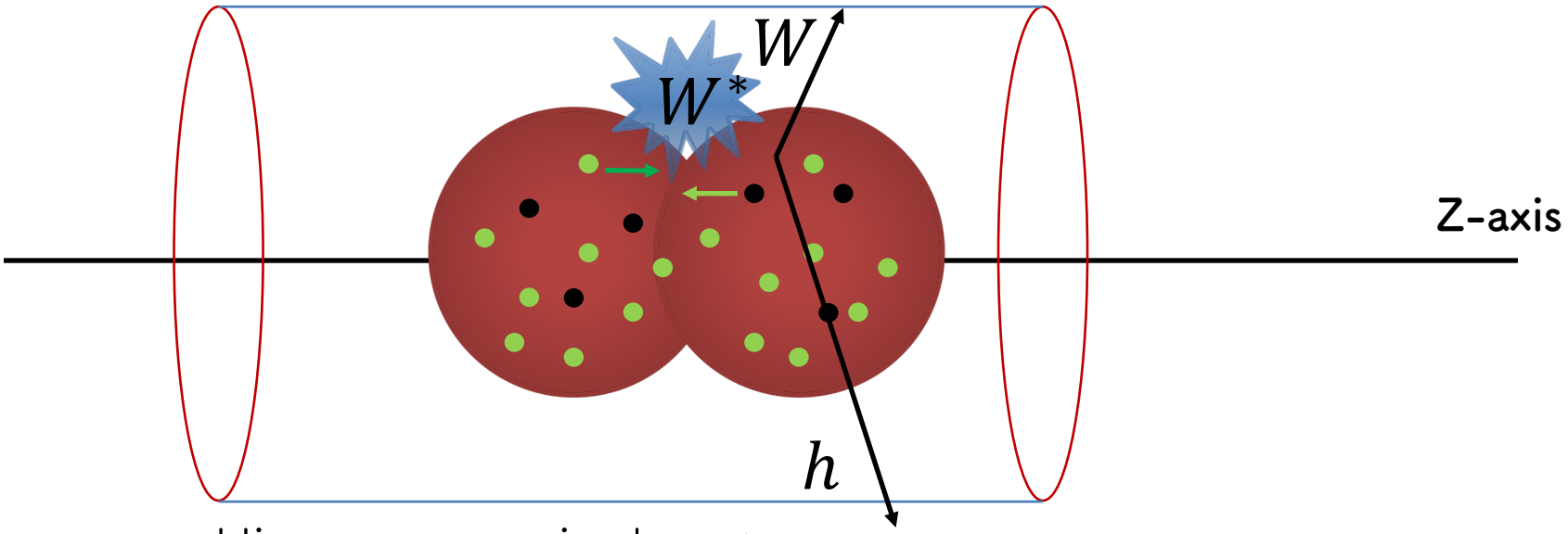
$$m_{\ell\ell\ell\ell}^2 = (p_{\ell 1} + p_{\ell 2} + p_{\ell 3} + p_{\ell 4})^2$$

2.62% → $Z \to \ell\ell$, $Z \to \ell\ell$

0.0227% → $\gamma\gamma$

$$m_{\gamma\gamma}^2 = (p_{\gamma 1} + p_{\gamma 2})^2$$

Associated Higgs production

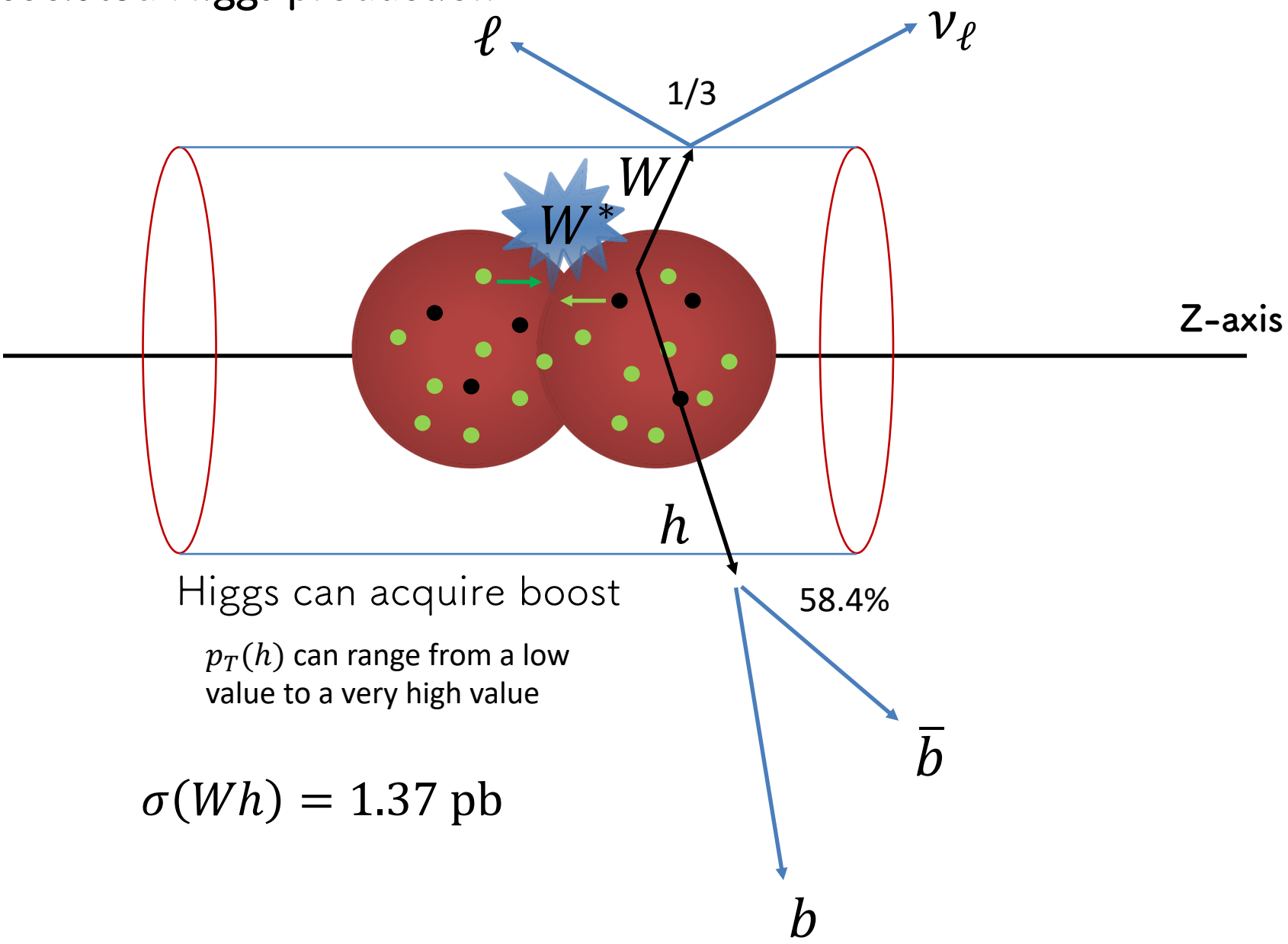


Higgs can acquire boost

$p_T(h)$ can range from a low value to a very high value

$$\sigma(Wh) = 1.37 \text{ pb}$$

Associated Higgs production

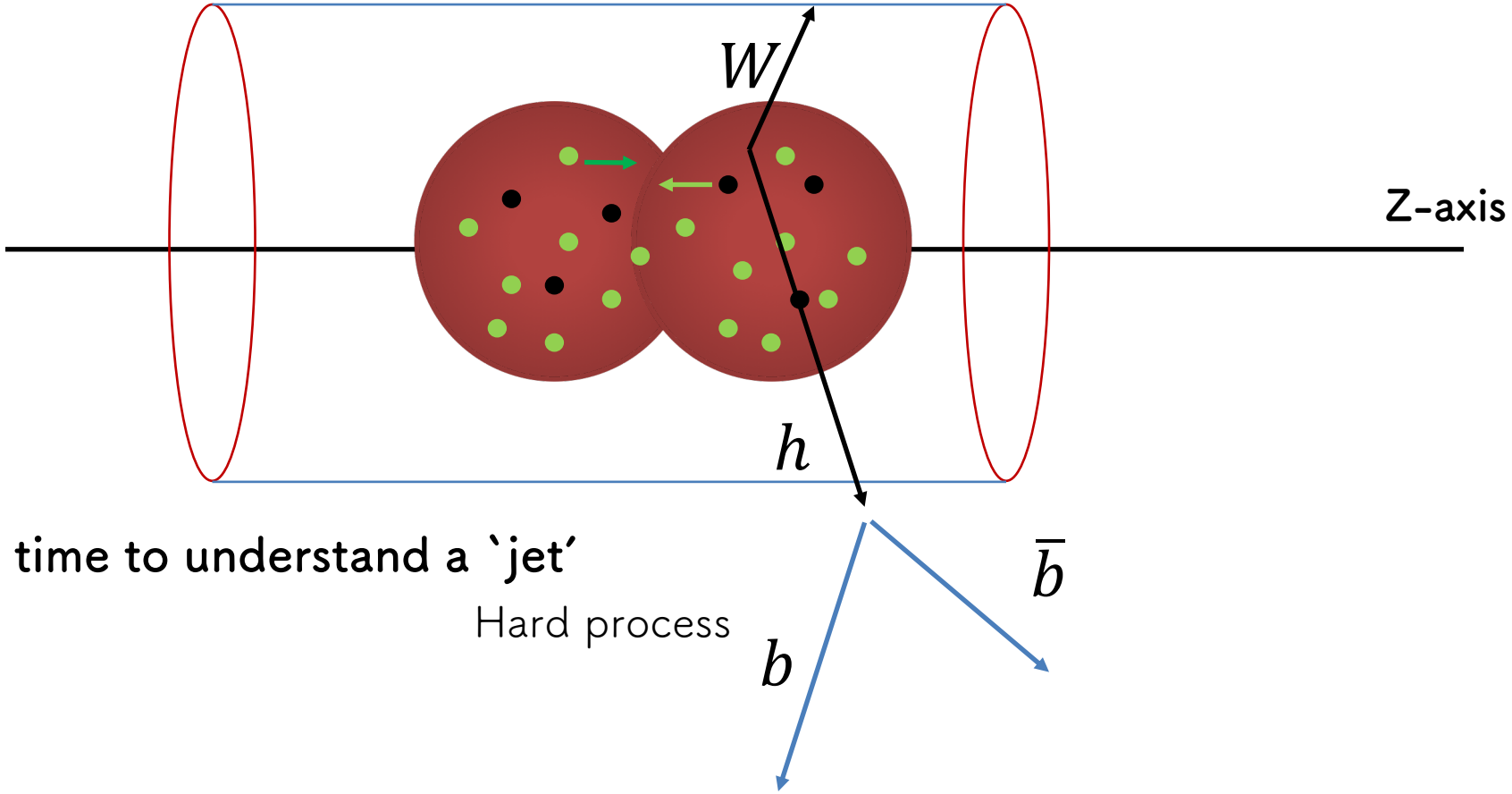


Higgs can acquire boost

$p_T(h)$ can range from a low value to a very high value

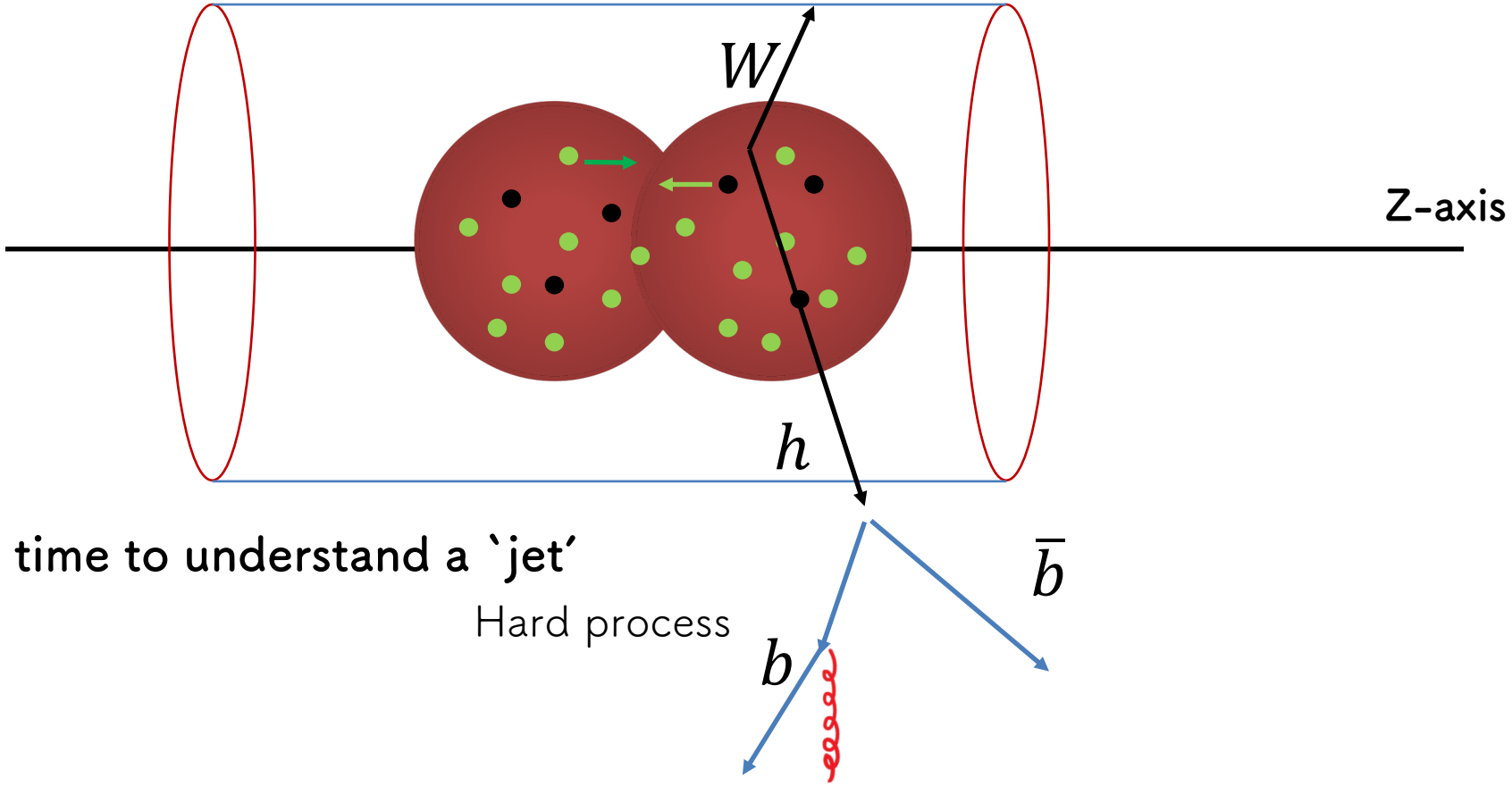
58.4%

$\sigma(Wh) = 1.37$ pb



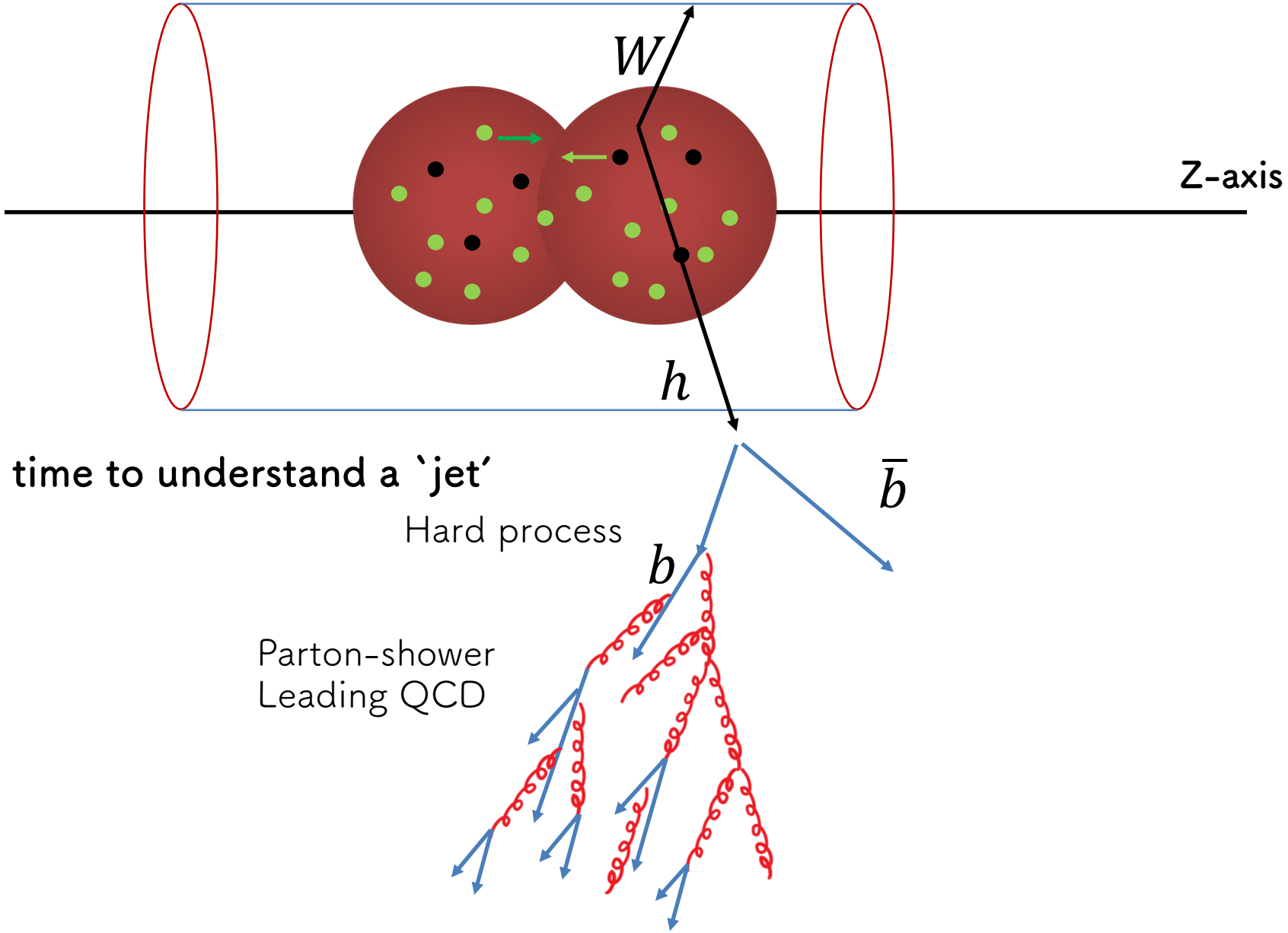
It's time to understand a `jet'

Hard process

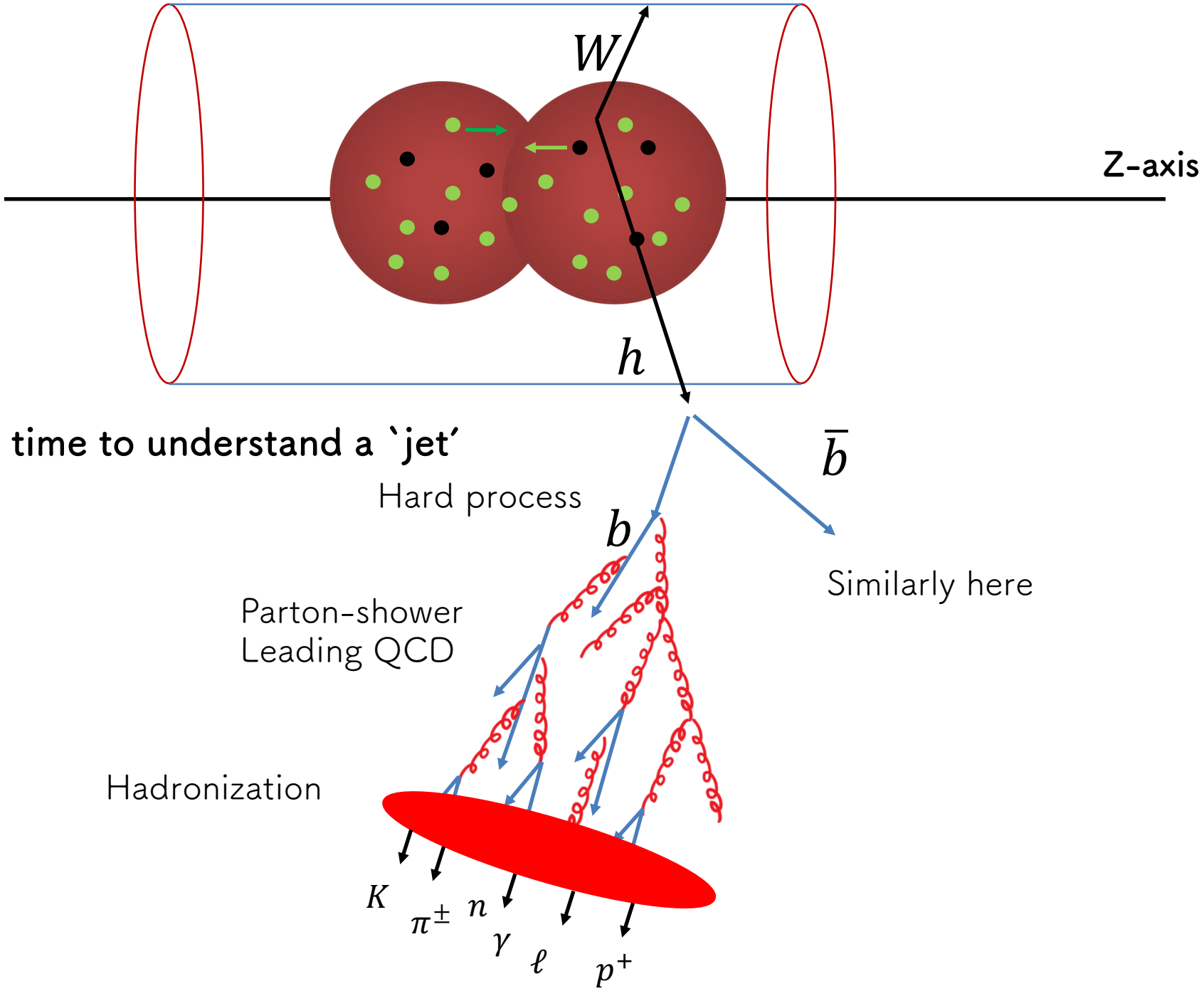


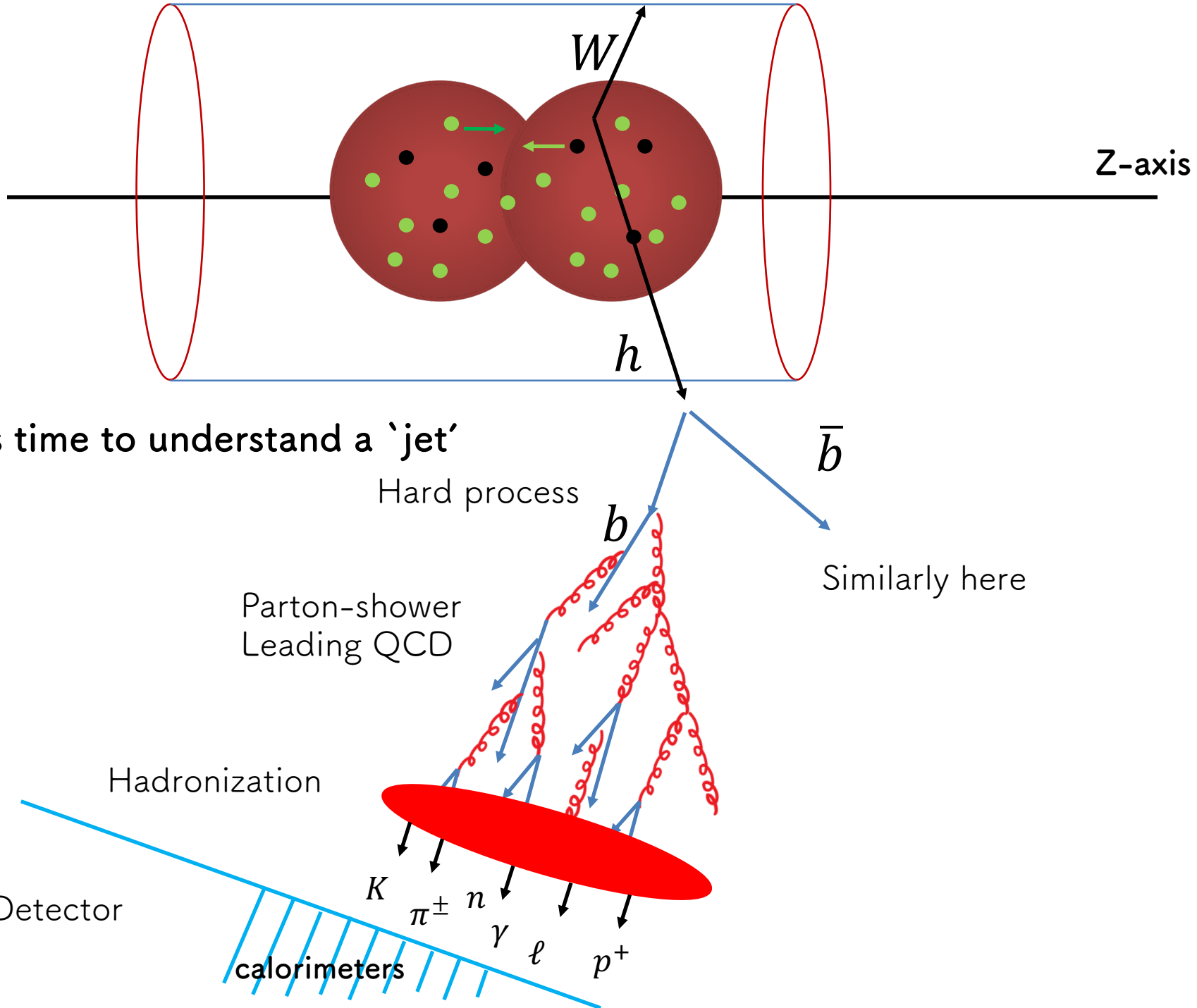
It's time to understand a `jet'

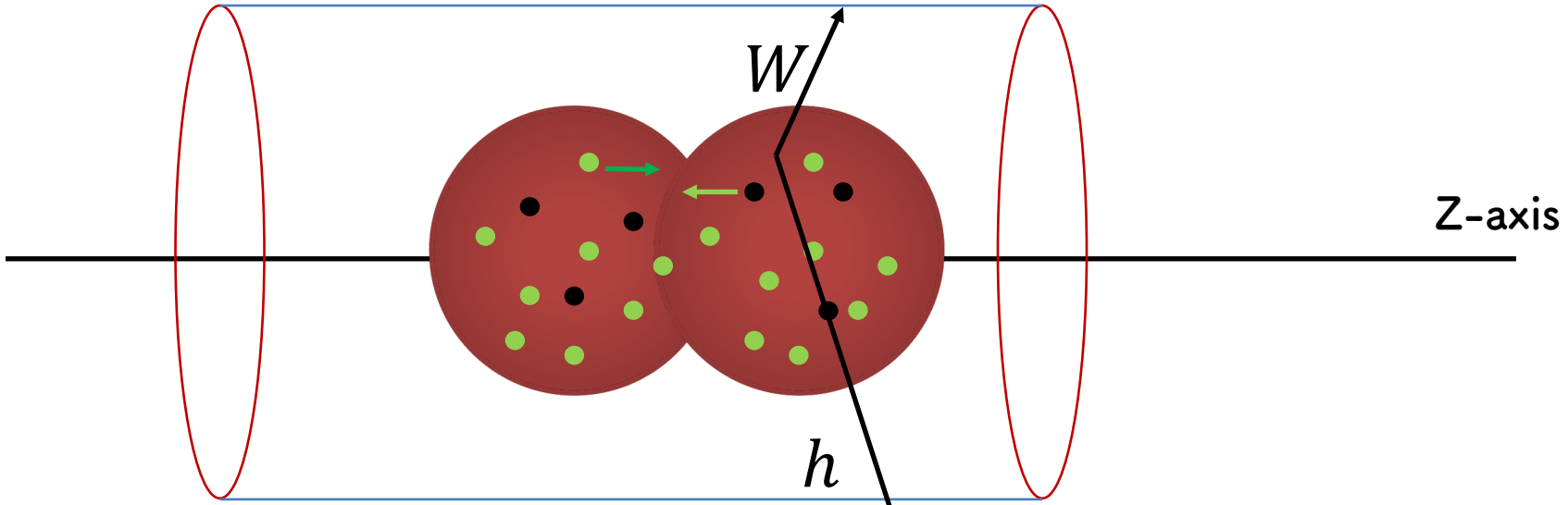
Hard process



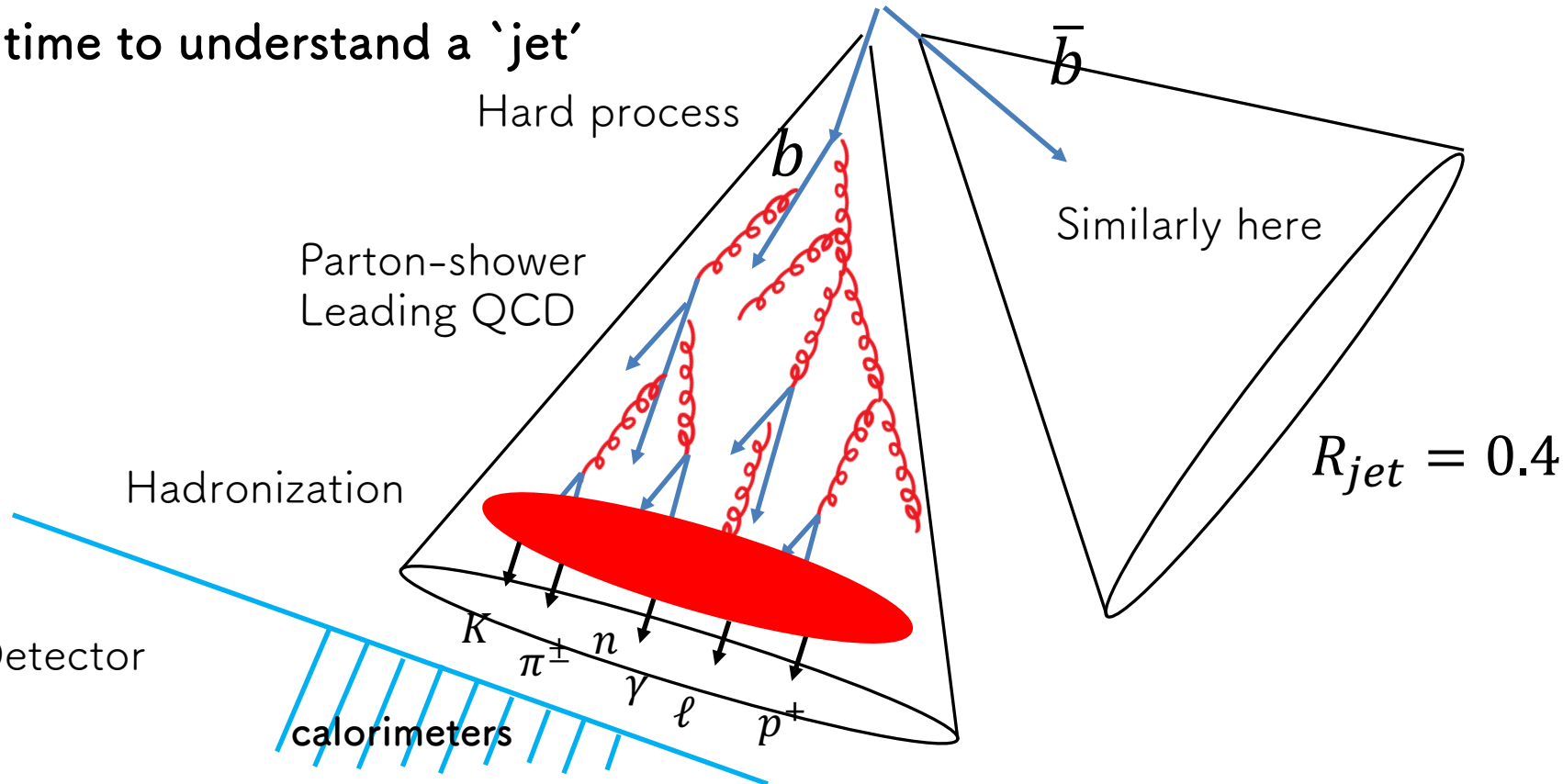
It's time to understand a `jet'

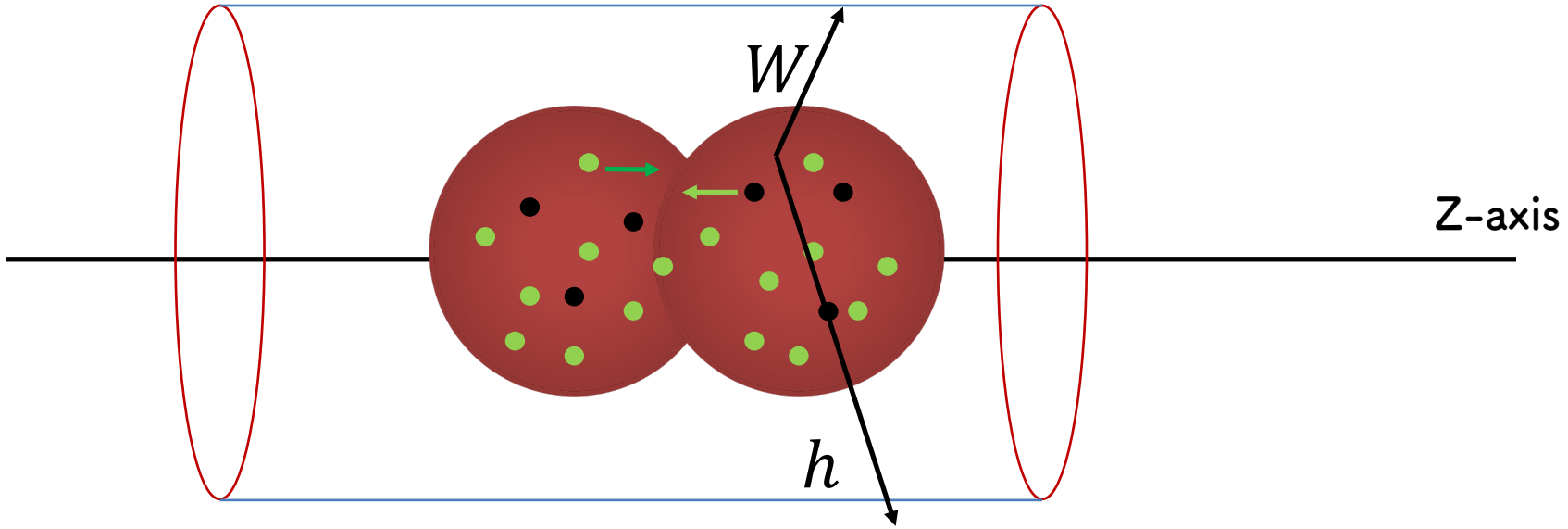

W
Z-axis
h
It's time to understand a `jet'
$\bar{b}$
Hard process
b
Similarly here
Parton-shower
Leading QCD
Hadronization
K
$\pi^{\pm}$
n
γ
ℓ
p^{+}


W
Z-axis
h
It's time to understand a `jet'
$\bar{b}$
Hard process
b
Similarly here
Parton-shower
Leading QCD
Hadronization
Detector
K
$\pi^{\pm}$
n
γ
ℓ
p^{+}
calorimeters

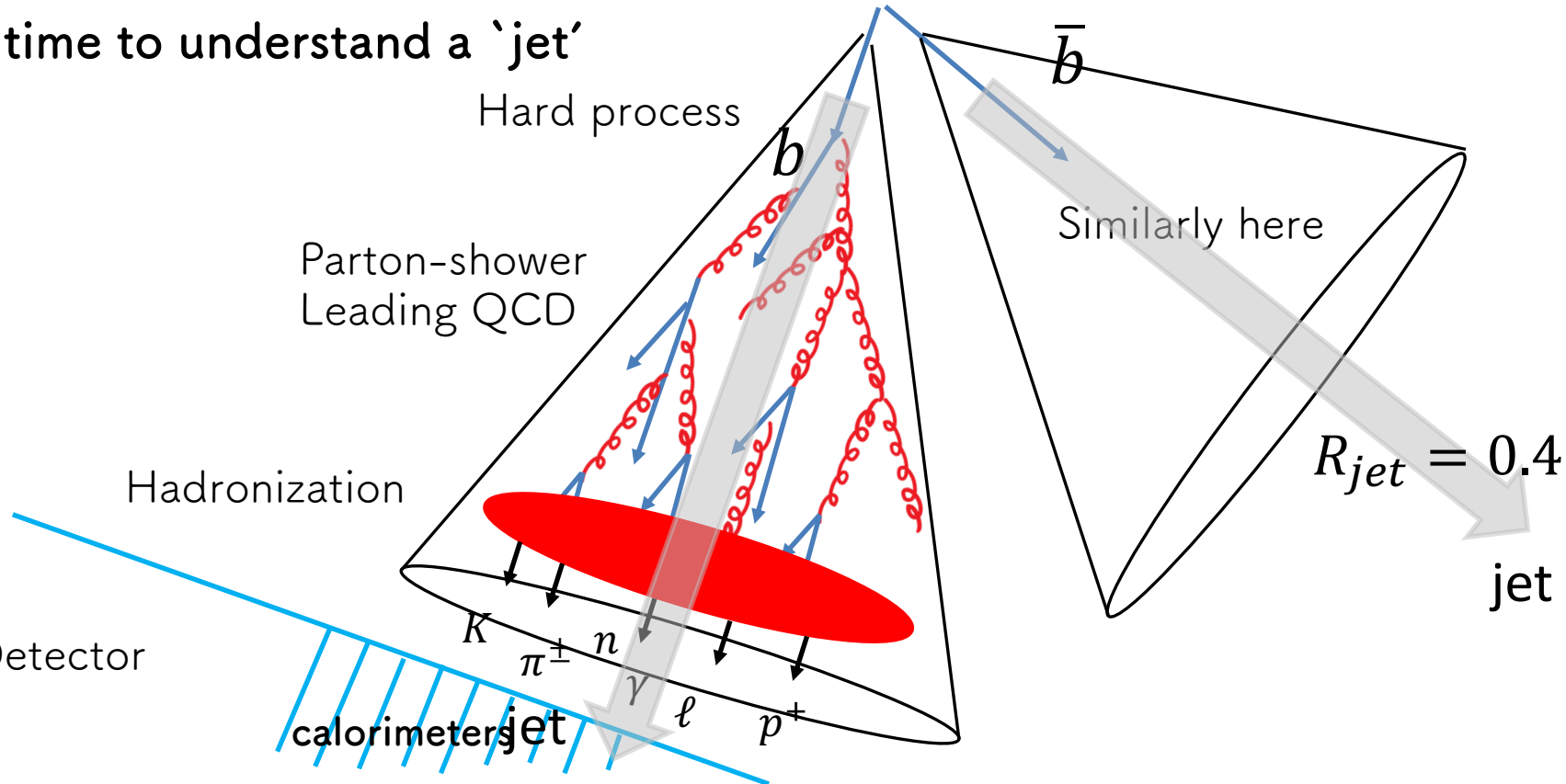


It's time to understand a `jet'

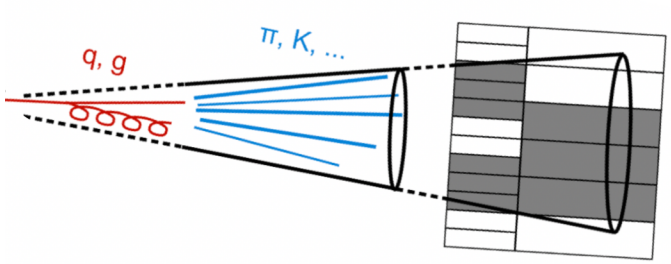




It's time to understand a `jet'

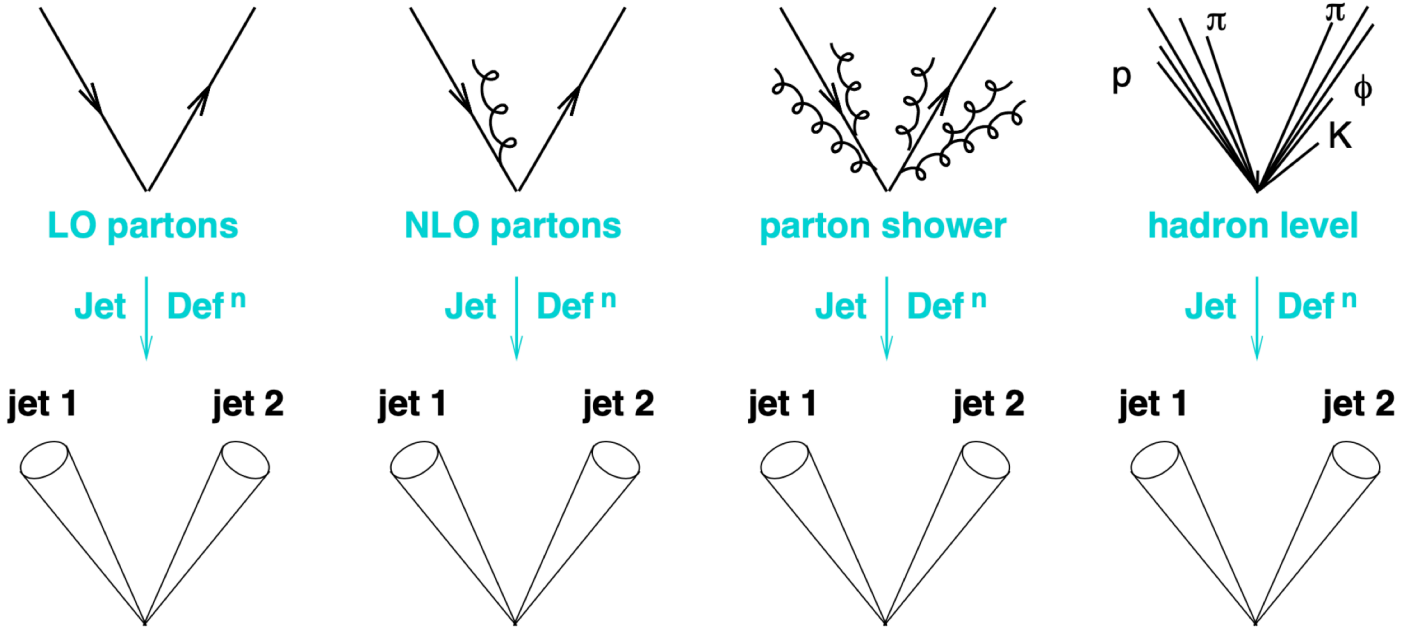


Jets



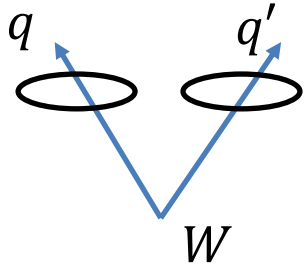
quarks ⟵ Jets

We want this to be correct



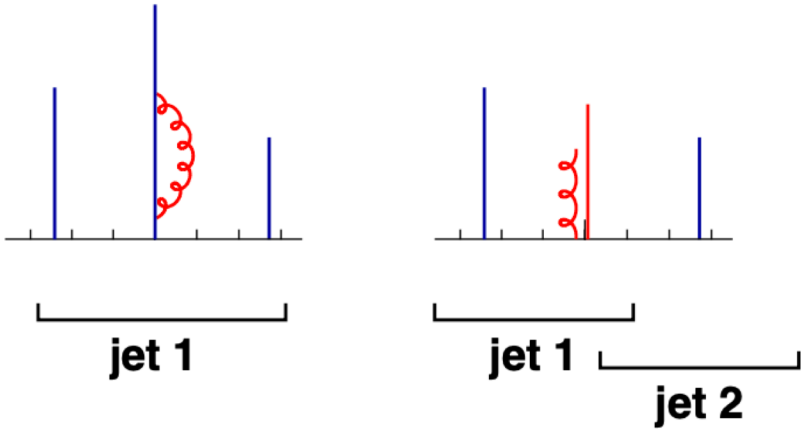
Seeded Cone jet algorithm

Leading Order(LO)



Next-to-Leading Order (NLO)





Virtual correction **Real emission** **Virtual correction** **Real emission**

∞ $-\infty$ ∞ $-\infty$

Virtual and real soft gluons contribute to two jets and one jet cross sections

Virtual and real soft gluons contribute to one jet and two jets cross sections

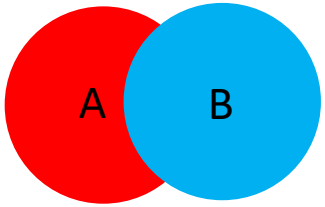
IR-divergences do not cancel ! (destroys the perturbative calculation)

Infrared safe jet algorithms

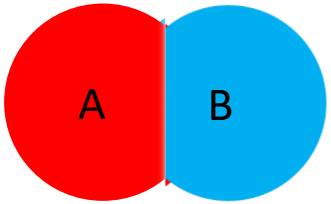
$$d_{ij} = \min(k_{ti}^{2n}, k_{tj}^{2n}) \frac{\Delta_{ij}^2}{R^2} \qquad d_{iB} = k_{ti}^{2n}$$

$$\Delta_{ij} = \sqrt{(\Delta\phi)^2 + (\Delta y)^2}$$

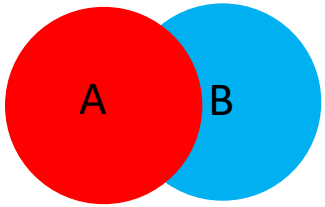
$n = 1$ k_T algorithm



$n = 0$ Cambridge/Aachen algorithm



$n = -1$ Anti-k_T algorithm



Jet area

$p_T(j_A) > p_T(j_B)$

SISCone jet algorithm

Infrared safe jet algorithms

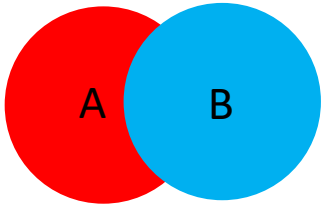
$$d_{ij} = \min(k_{ti}^{2n}, k_{tj}^{2n}) \frac{\Delta_{ij}^2}{R^2} \qquad d_{iB} = k_{ti}^{2n}$$

$$\Delta_{ij} = \sqrt{(\Delta\phi)^2 + (\Delta y)^2}$$

Default at LHC

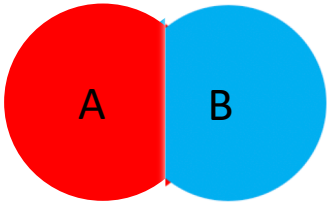
$n = 1$

k_T algorithm



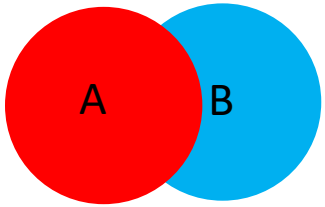
$n = 0$

Cambridge/Aachen algorithm



$n = -1$

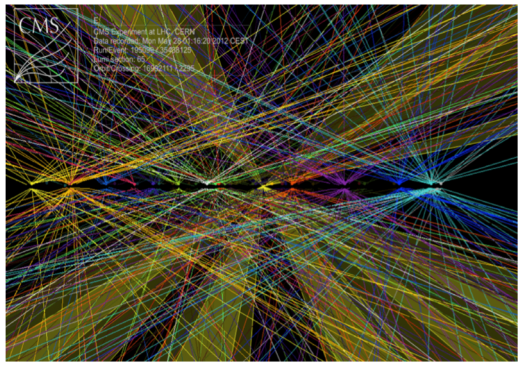
Anti-k_T algorithm



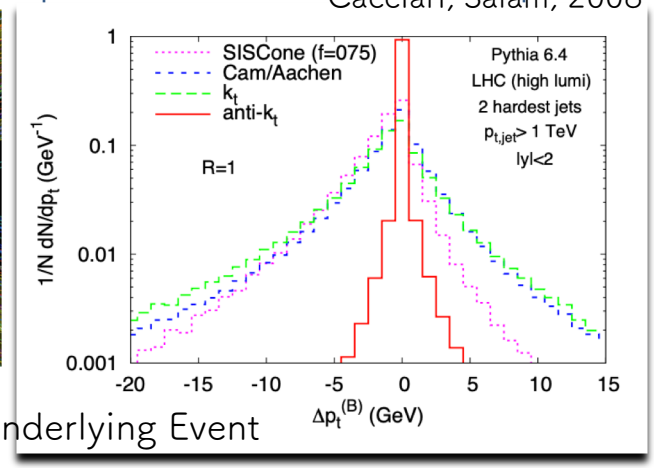
Jet area

$p_T(j_A) > p_T(j_B)$

SISCone jet algorithm



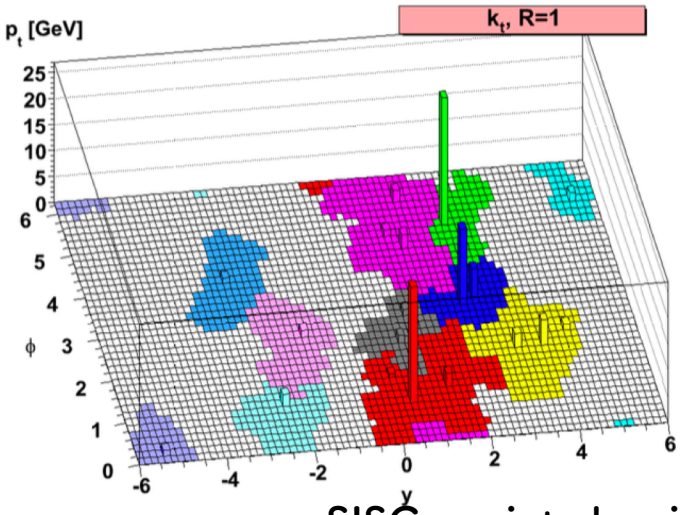
Cacciari, Salam, 2008



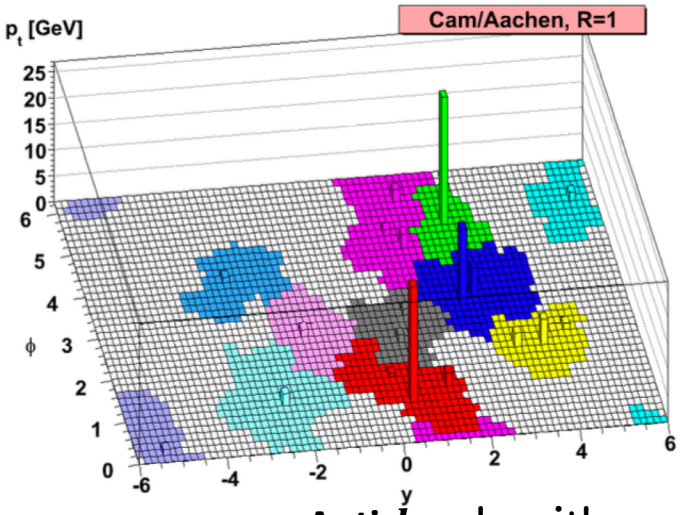
Insensitive to Pileup, Underlying Event

Jet algorithm

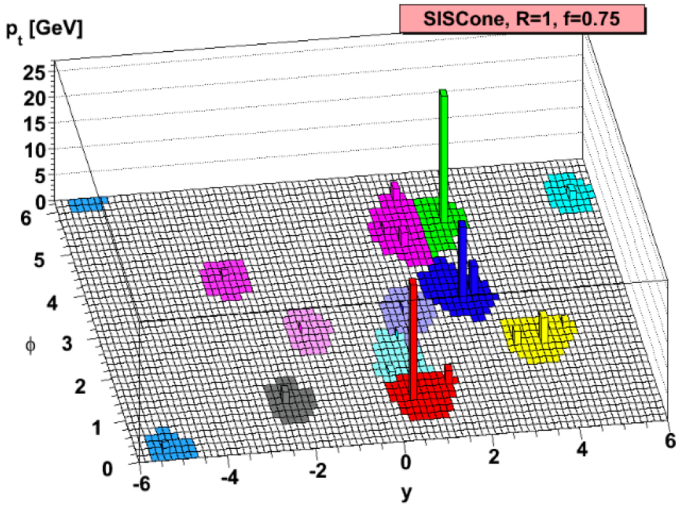
k_T algorithm



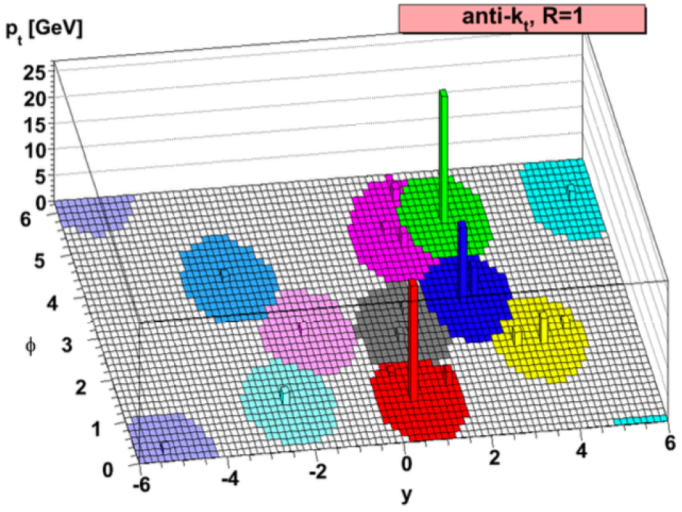
Cambridge/Aachen algorithm



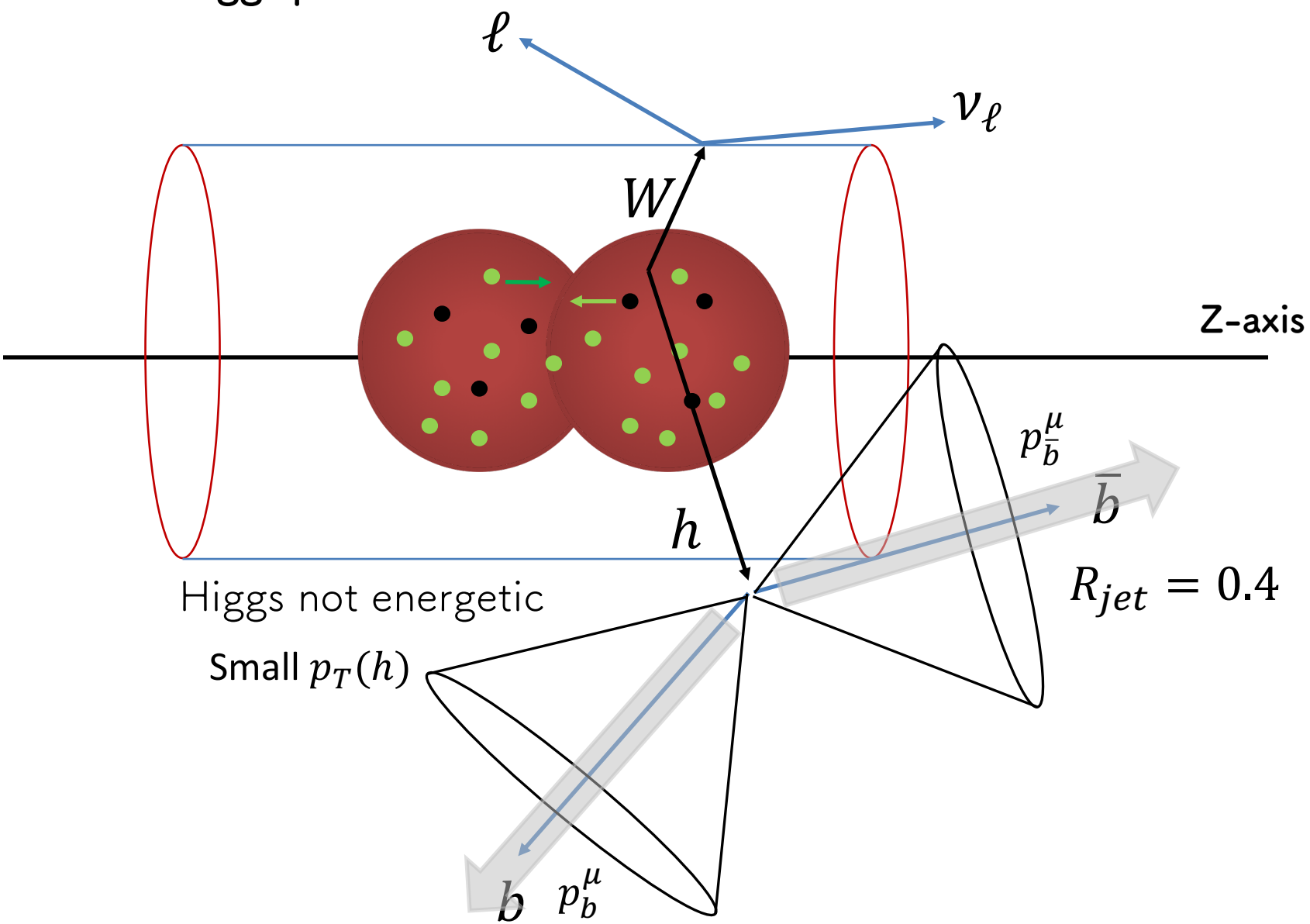
SISCone jet algorithm



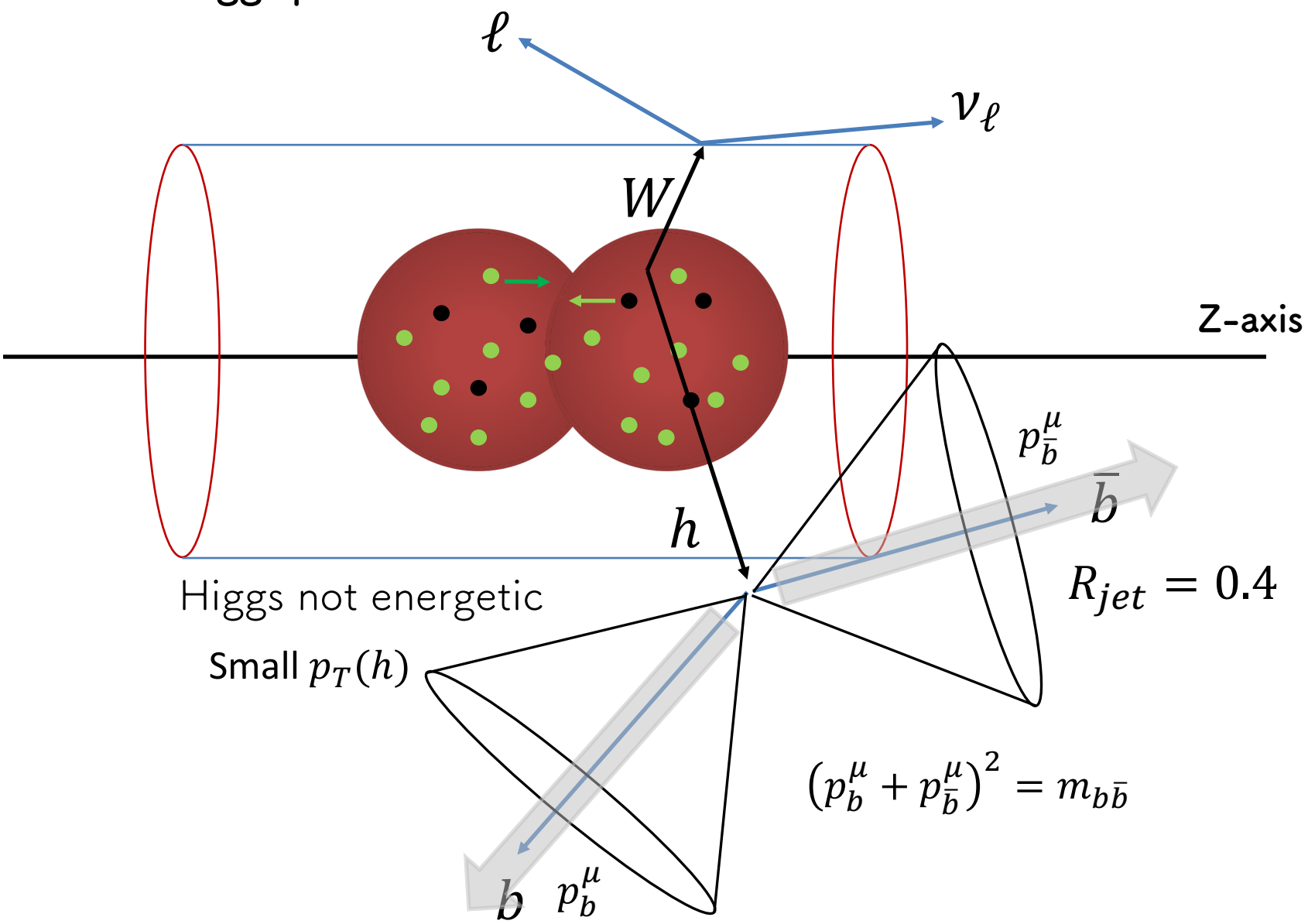
Anti-k_T algorithm



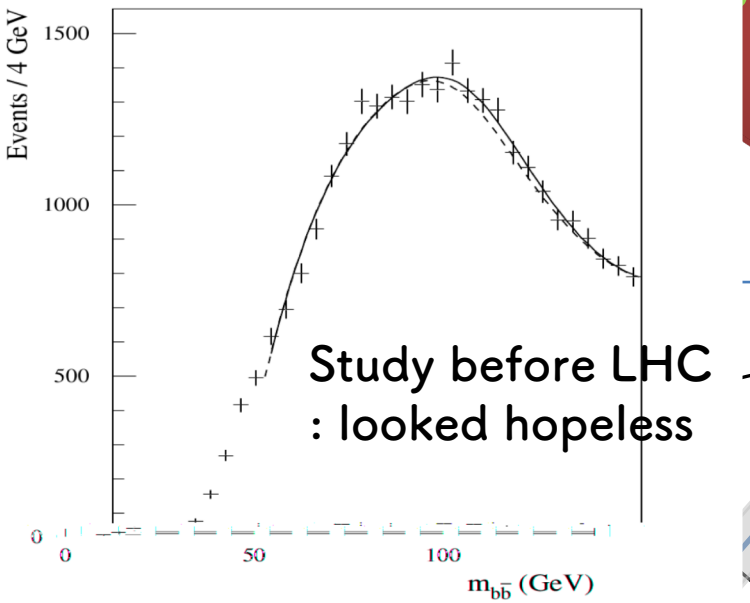
Associated Higgs production



Associated Higgs production



Associated Higgs production



Higgs bump on top of artificial bump

Study before LHC
: looked hopeless

ℓ

ν_ℓ

W

h

Z-axis

$p_{\bar{b}}^{\mu}$

$\bar{b}$

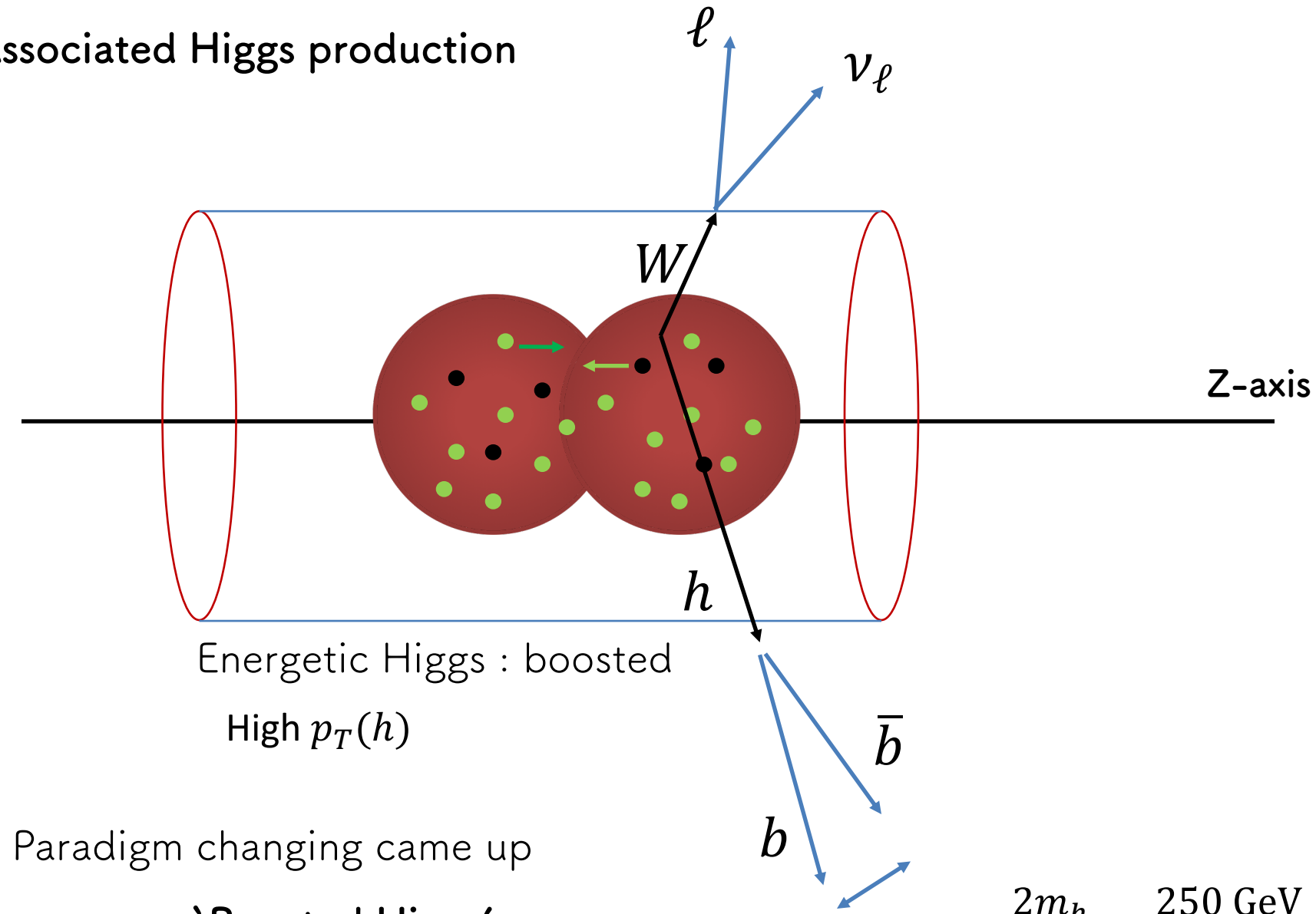
$R_{jet} = 0.4$

$\left(p_b^{\mu} + p_{\bar{b}}^{\mu}\right)^2 = m_{b\bar{b}}$

$* \; m_{b\bar{b}} \propto p_{Tb} p_{T\bar{b}} \Delta R$

FIGURE 1. Background (dashed line) plus Higgs signal (solid line) for a Higgs boson with $m_H = 100\,\text{GeV}$ in the $pp \to WH$, $W \to \ell^{\pm}\nu$ and $H \to b\bar{b}$ channel, as found in the ATLAS TDR study [3] for $30\,\text{fb}^{-1}$.

Associated Higgs production



Energetic Higgs : boosted

High $p_T(h)$

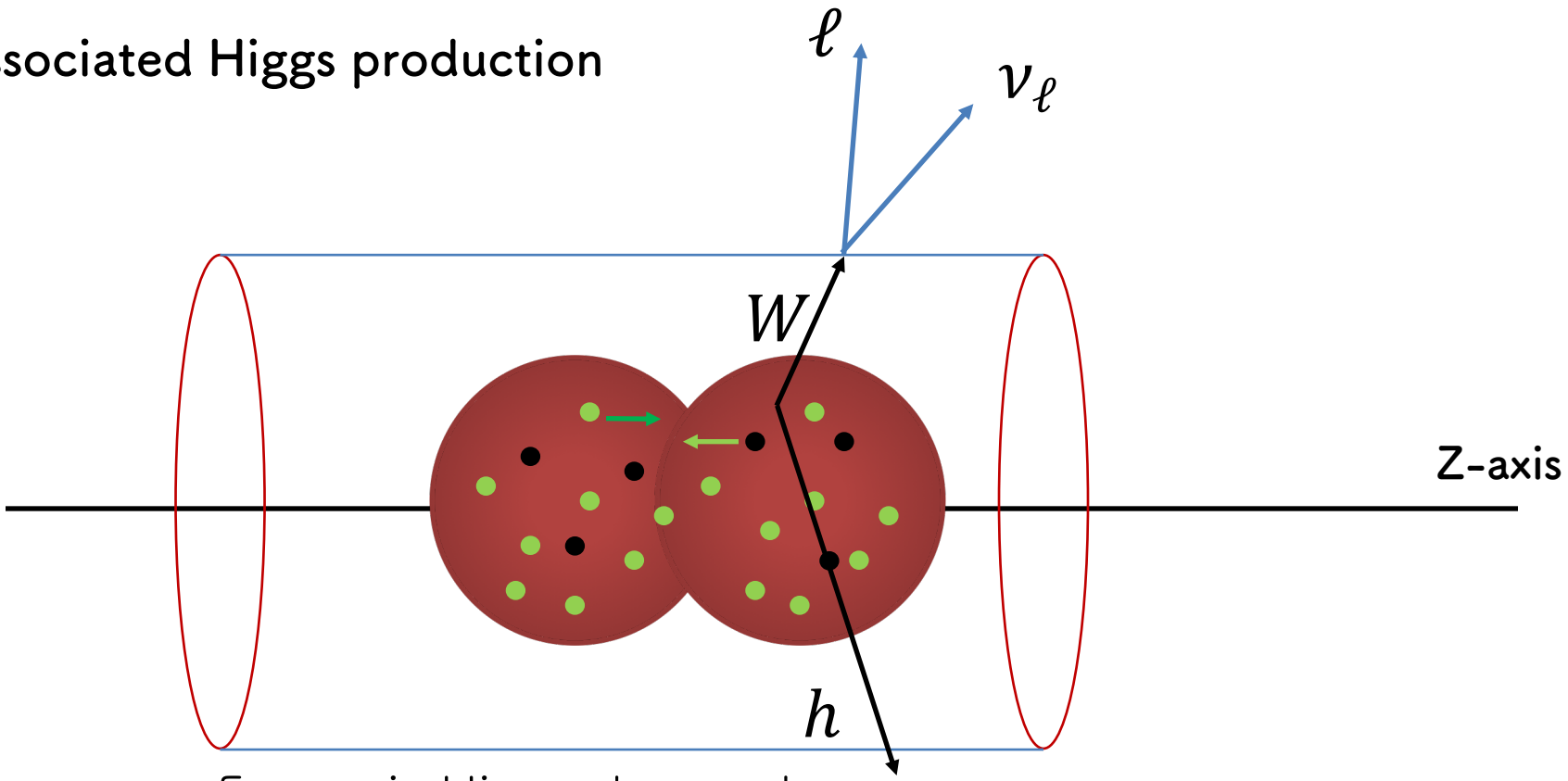
Paradigm changing came up

`Boosted Higgs'

Birth of **BOOST** workshop

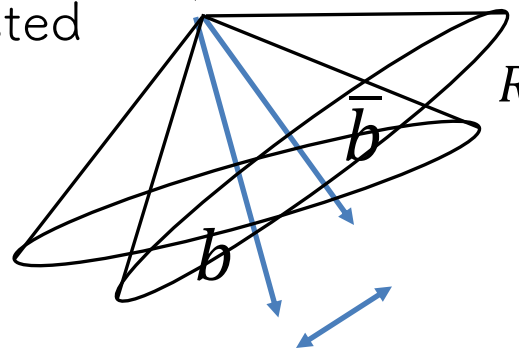
$$\Delta R \sim \frac{2m_h}{p_T(h)} = \frac{250\ \text{GeV}}{p_T(h)}$$

Associated Higgs production



Energetic Higgs : boosted

High $p_T(h)$



$R_{jet} = 0.4$

: traditional jet size

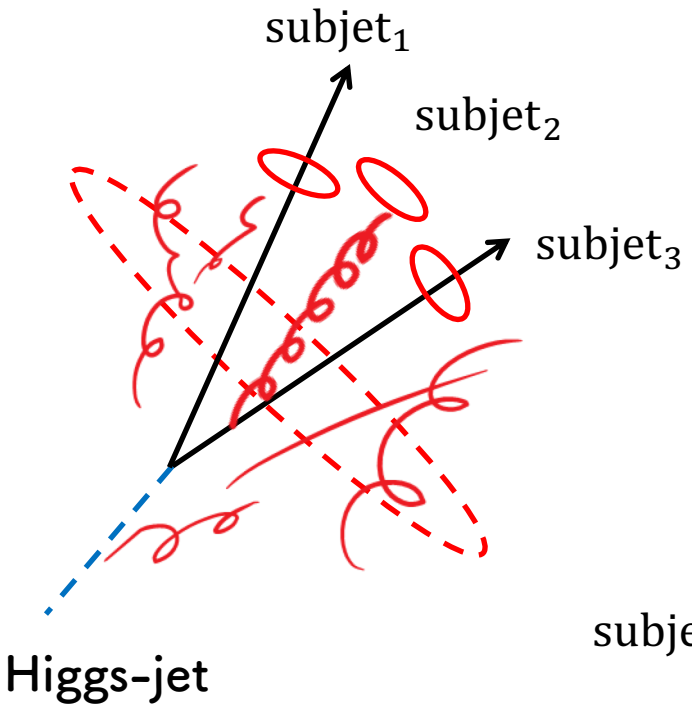
But traditional way could not handle

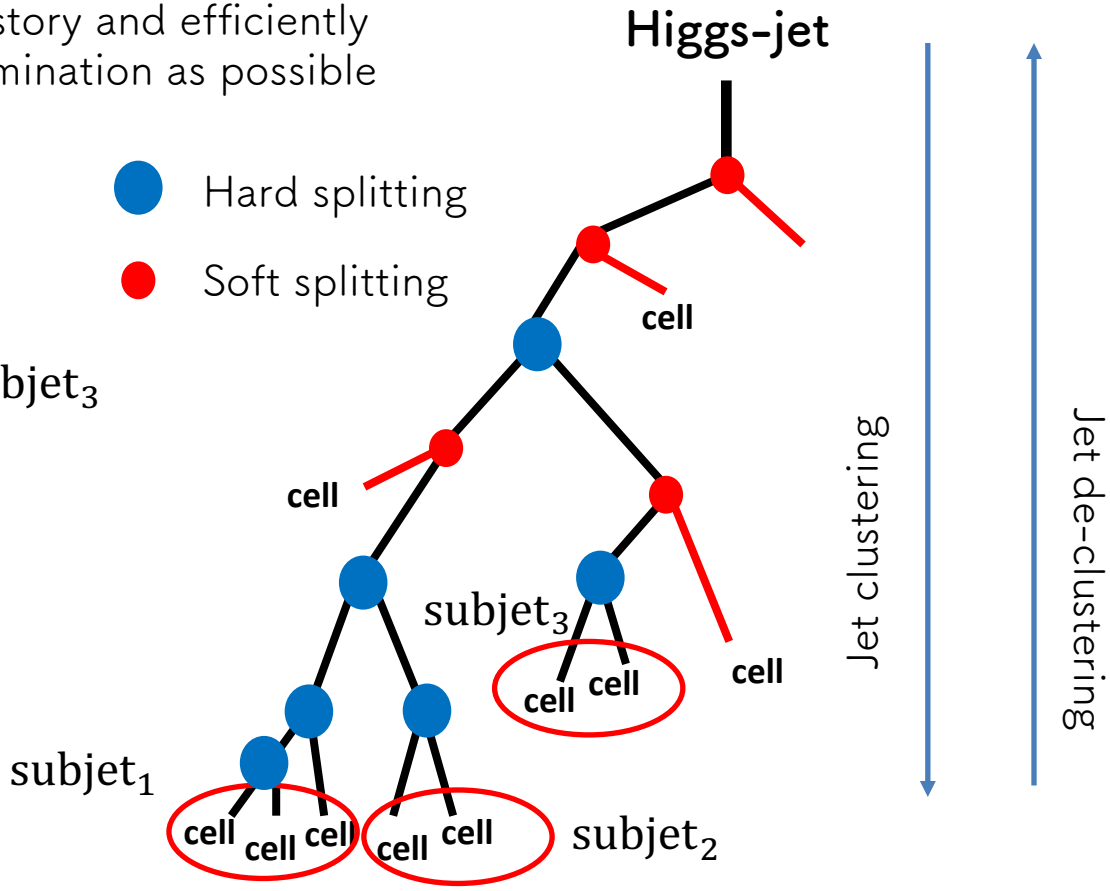
`Boosted Higgs'

$$\Delta R \sim \frac{2m_h}{p_T(h)} = \frac{250\ \text{GeV}}{p_T(h)}$$

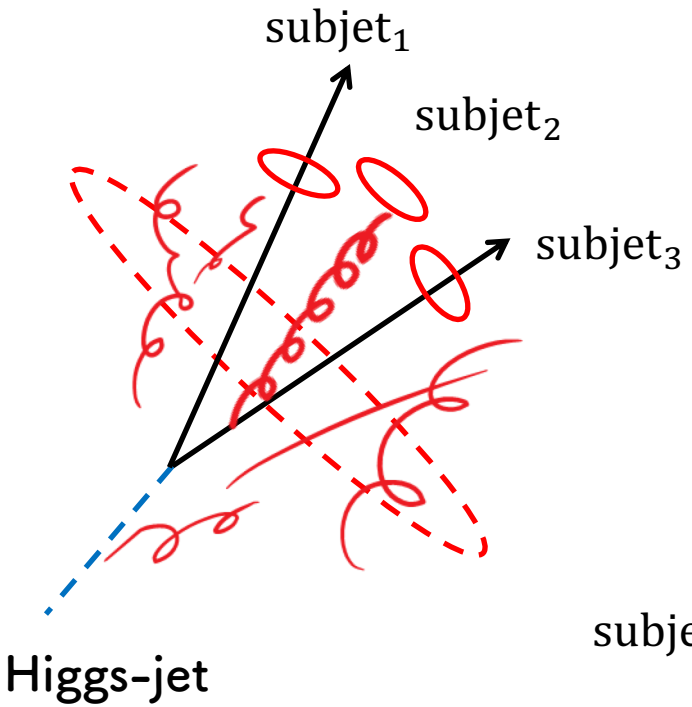
No reason for previous problem to get disappeared too

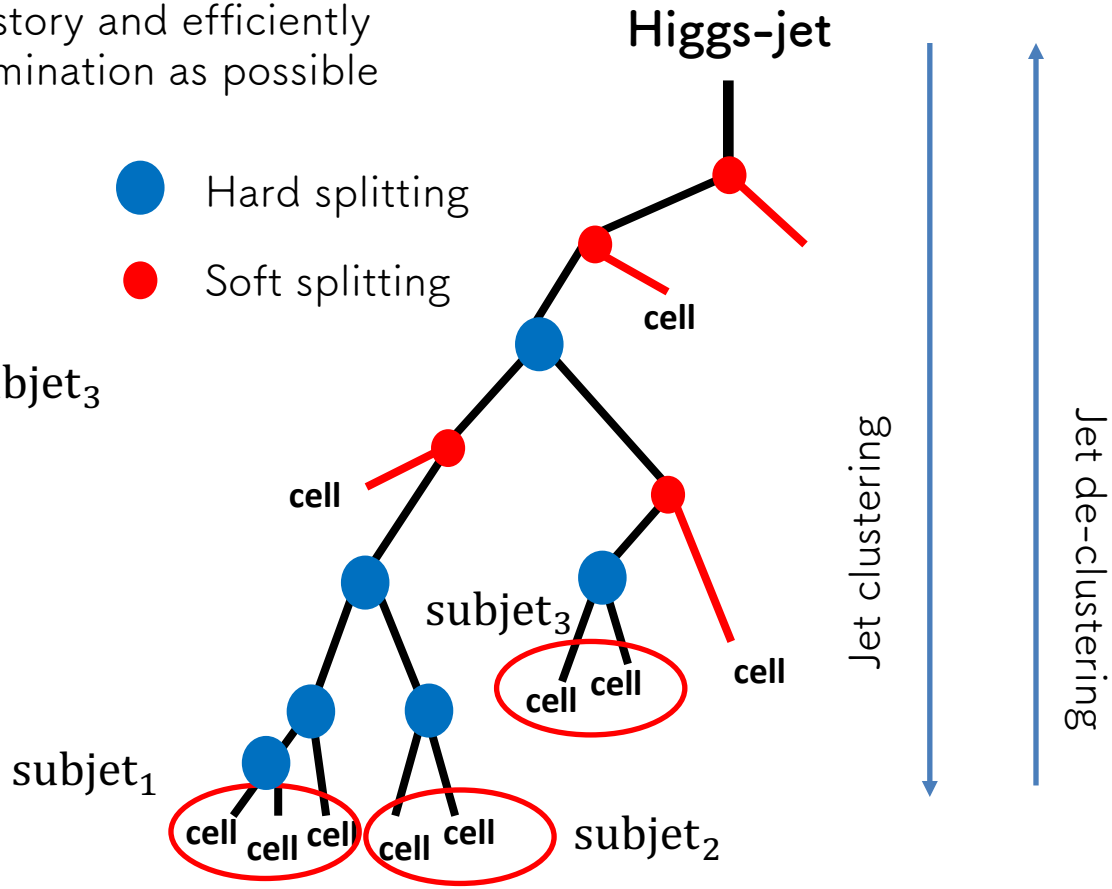
After identifying the region of interest, we're looking backward in the clustering history and efficiently filtering as much QCD contamination as possible

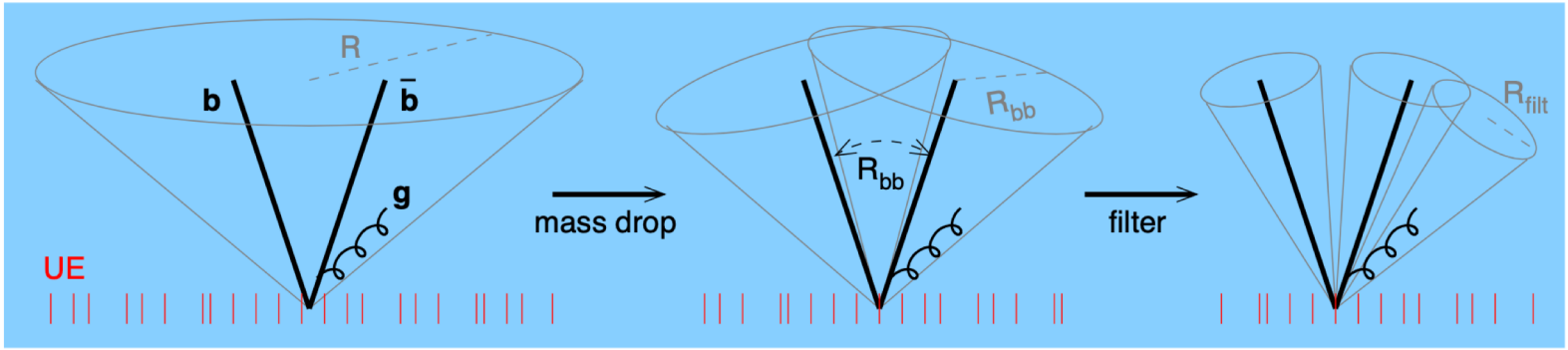




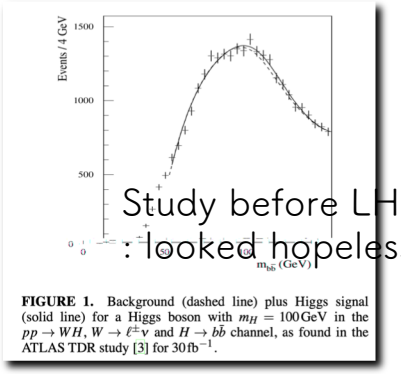
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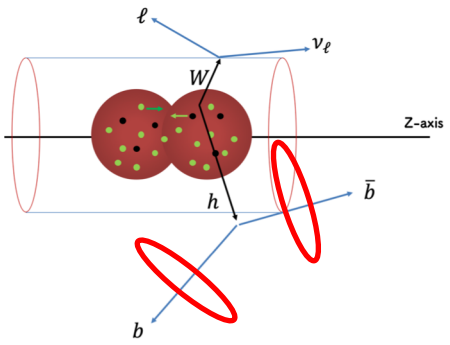


Ancient depressing story

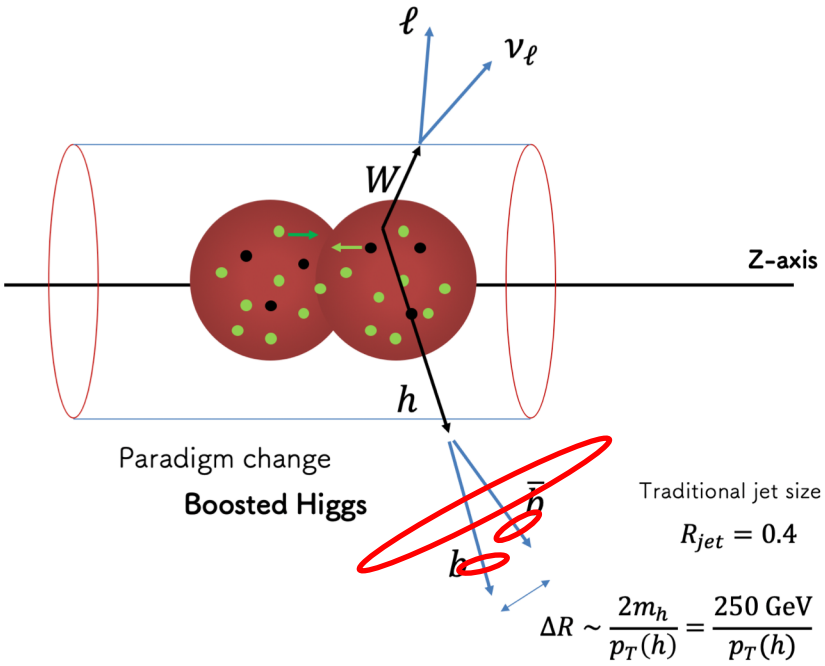


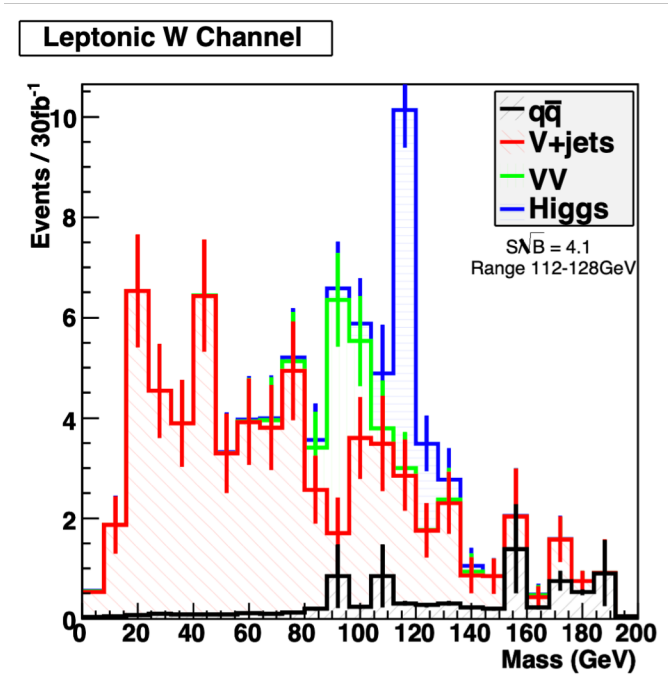
Study before LHC
: looked hopeless

FIGURE 1. Background (dashed line) plus Higgs signal (solid line) for a Higgs boson with $m_H = 100\,\text{GeV}$ in the $pp \to WH$, $W \to \ell^{\pm}\nu$ and $H \to b\bar{b}$ channel, as found in the ATLAS TDR study [3] for $30\,\text{fb}^{-1}$.



After jet-substructure 2008

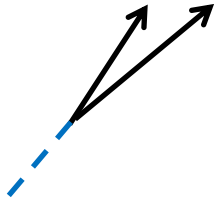




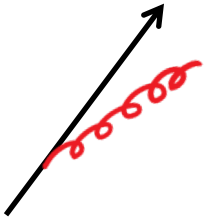
Birth of jet-substructure

Butterworth, Davison, Rubin, Salam (BDRS) 2008

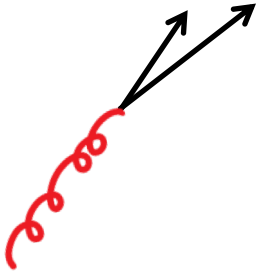
New classification of W/Z/H/top-jets which look similar to QCD-jets



W/Z/Higgs

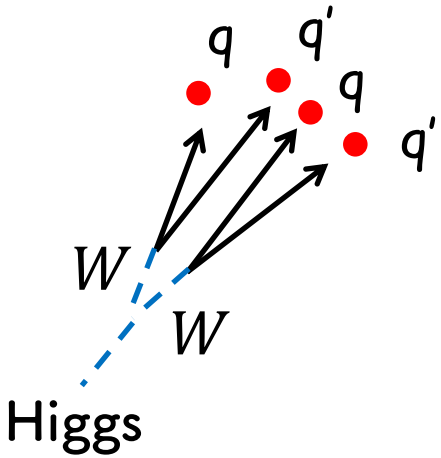


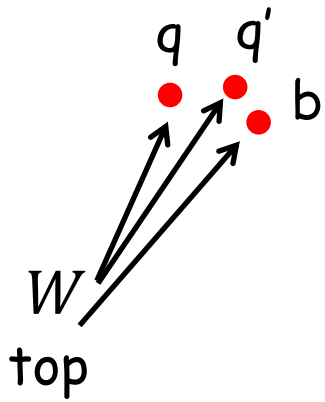
quark



gluon

Similarly for top, other Higgs decay

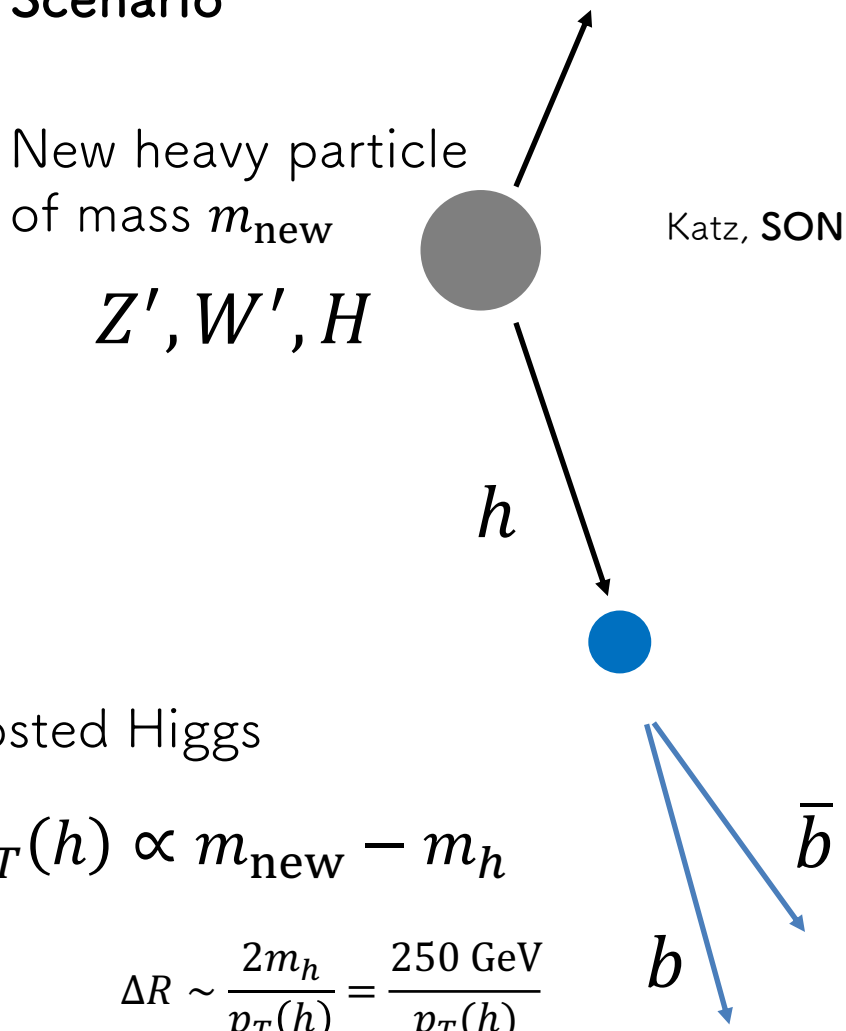




They look similar, but they are not same in physics-wise

Traditional jet definition is not suitable for disentangling the apparent resemblance

Boosted Higgses are more common in New Particle Scenario



Katz, **SON**, Tweedie 2010

Boosted Higgs

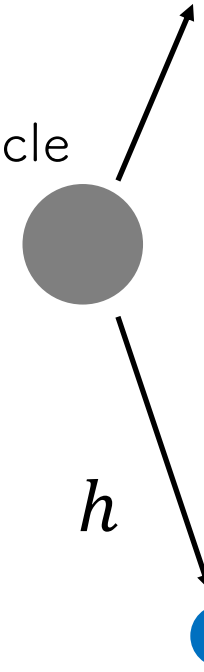
$$p_T(h) \propto m_{\mathbf{new}} - m_h$$

$$\Delta R \sim \frac{2m_h}{p_T(h)} = \frac{250\ \mathrm{GeV}}{p_T(h)}$$

Boosted Higgses are more common in New Particle Scenario

New heavy particle of mass $m_{\mathbf{new}}$

Z', W', H



Katz, **SON**, Tweedie 2011

h

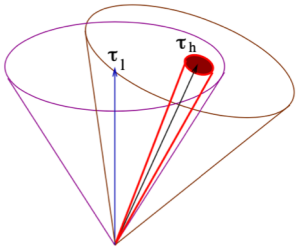
Boosted Higgs

$p_T(h) \propto m_{\mathbf{new}} - m_h$

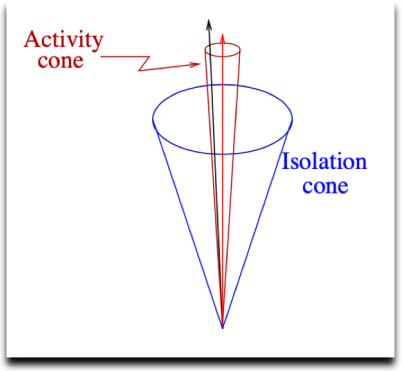
τ

τ

Ditau-jet



Tau is a tricky object to tag



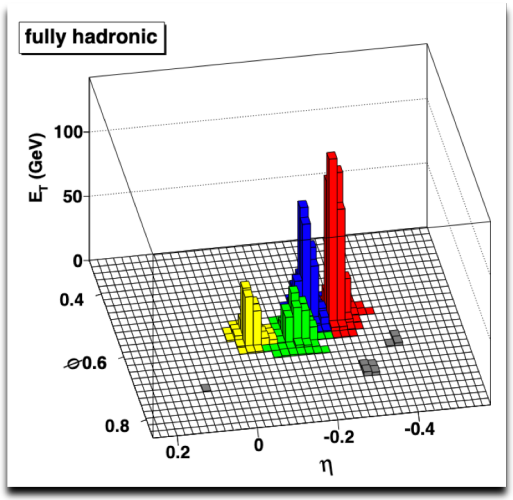
Boosted Higgses are more common in New Particle Scenario

New heavy particle of mass m_{new}

$$Z', W', H$$

h

SON, Spethman, Tweedie 2012



Boosted Higgs

$$p_T(h) \propto m_{\text{new}} - m_h$$

W

W

q'

q

q

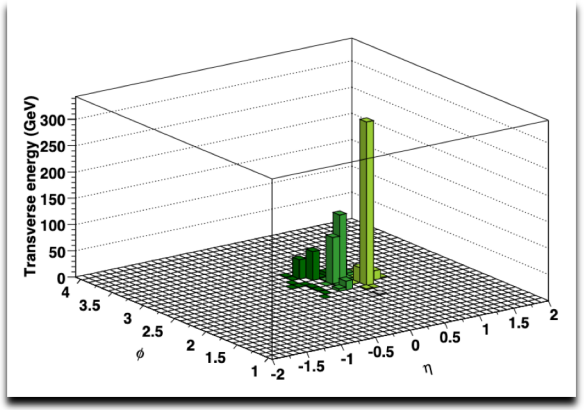
q'

Diboson-jet

Boosted Higgses are more common in New Particle Scenario

New heavy particle of mass m_{new}

Z', W', H



Kaplan, Rethermann, Schwartz, Tweedie 2008

top

Boosted top

$p_T(top) \propto m_{\text{new}} - m_{top}$

W

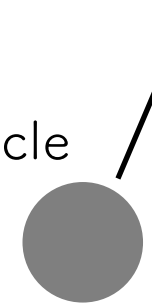
b q q'

Top-jet

Boosted Higgses are more common in New Particle Scenario

New heavy particle of mass m_{new}

Z', W', H



N-subjettiness

$$\tau_N \equiv \frac{\min\left[\sum p_T(i)\,\min\left\{\Delta R\left(i,\widehat{j_1}\right),\ldots..,\Delta R\left(i,\widehat{j_N}\right)\right\}\right]}{\sum p_T(i)\,R}$$

: exploits radiation pattern around N subjet axes

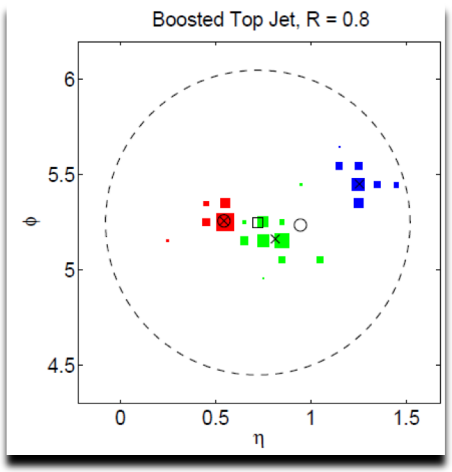
top

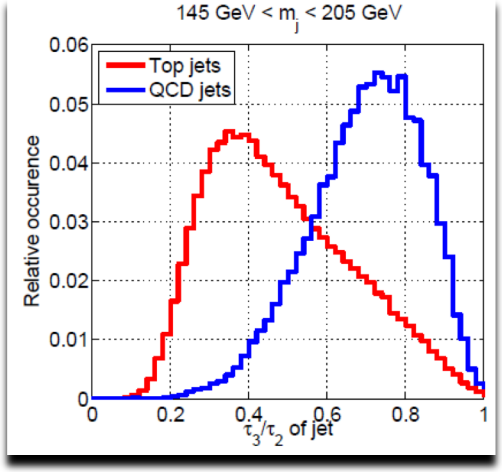


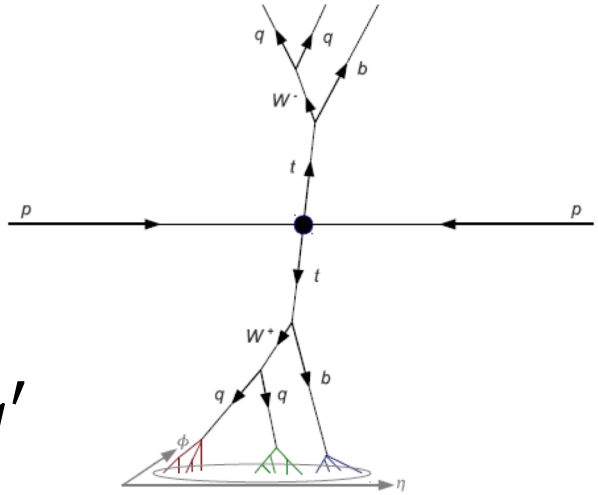
W

$b \quad q \quad q'$

Top-jet

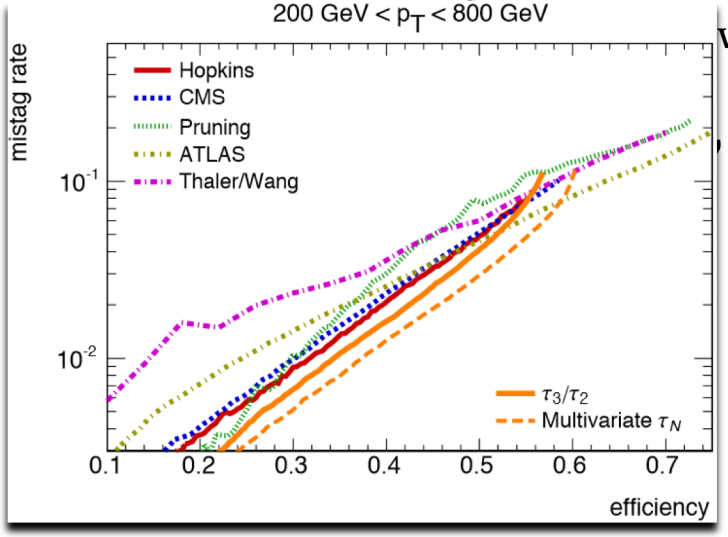






Boosted Higgses are more common in New Particle Scenario

New heavy particle



W

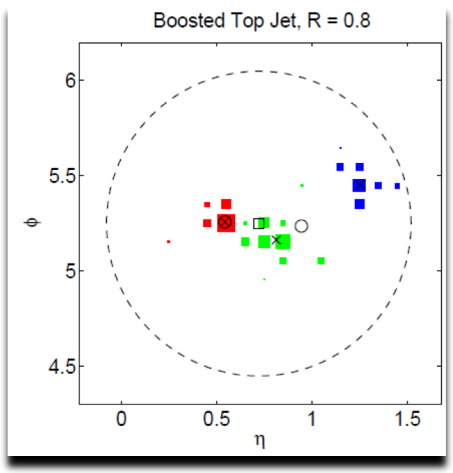
H

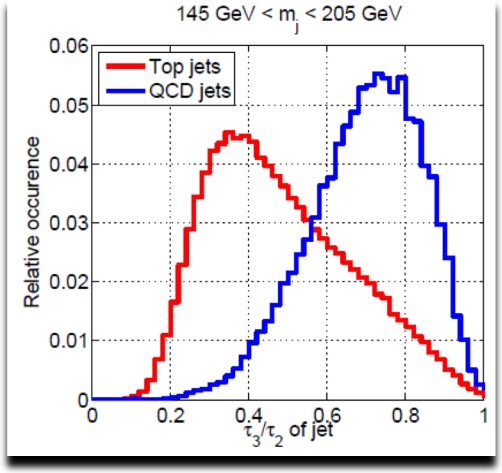
top

N-subjettiness

$$\tau_N \equiv \frac{\min\left[\sum p_T(i)\,\min\left\{\Delta R\left(i,\widehat{j_1}\right),\ldots..,\Delta R\left(i,\widehat{j_N}\right)\right\}\right]}{\sum p_T(i)\,R}$$

: exploits radiation pattern around N subjet axes

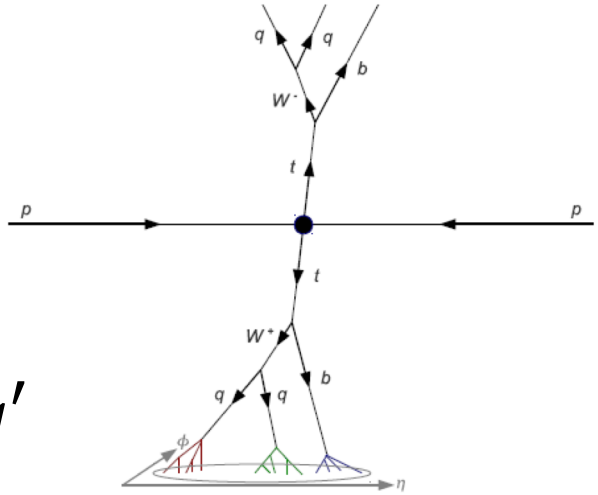




W

$b \quad q \quad q'$

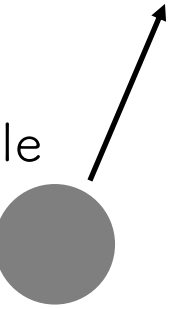
Top-jet



Boosted Higgses are more common in New Particle Scenario

New heavy particle of mass m_{new}

Z', W', H



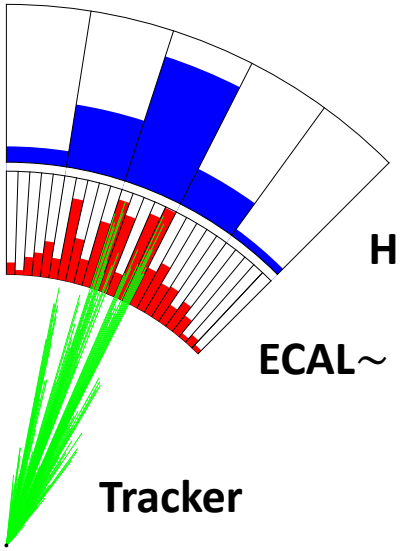
top

W

b q q'

Top-jet

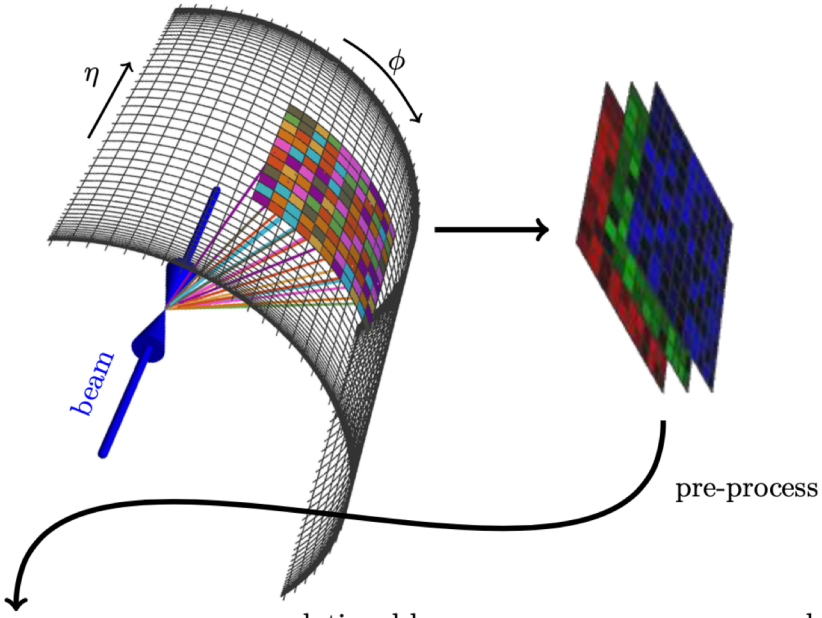
Pseudo-CMS type Event of ultra-boosted tops

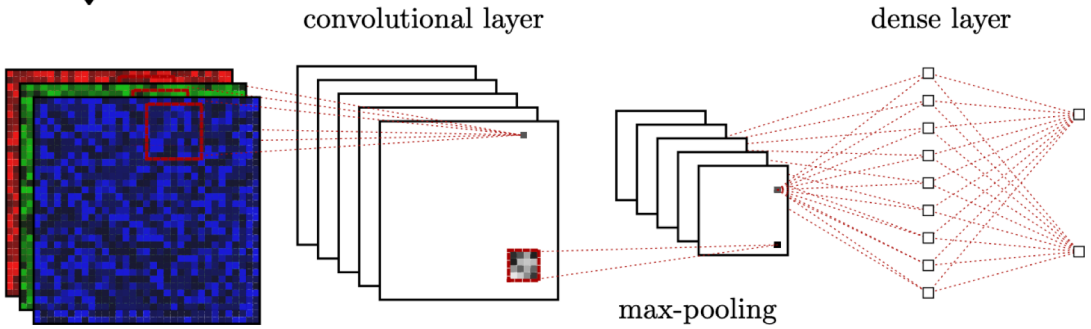


We are approaching extreme phase space

New paradigm change ongoing

Currently we are going through another paradigm changing in collider physics





`signal'-like

`background'-like

Concluding remark

For last 10 years, we have been applying our collider techniques to data at the state of art level. Unfortunately finding nothing. We are forced to look into rare phase space where our traditional and even new techniques are getting hard and hard to deal with

Some people now look into cosmology, astro-particle, neutrinos, gravitational waves etc. But be aware of that if LHC finds nothing, any other fields will likely have a hard time. We are all connected

On the other hand, do not forget we haven't figured out inflation, baryon asymmetry, dark matter, flavor etc. There ARE new physics, but somewhere that we do not know. Get excited !

Or There are nothing….

