Collider Phenomenology

YETI 2018

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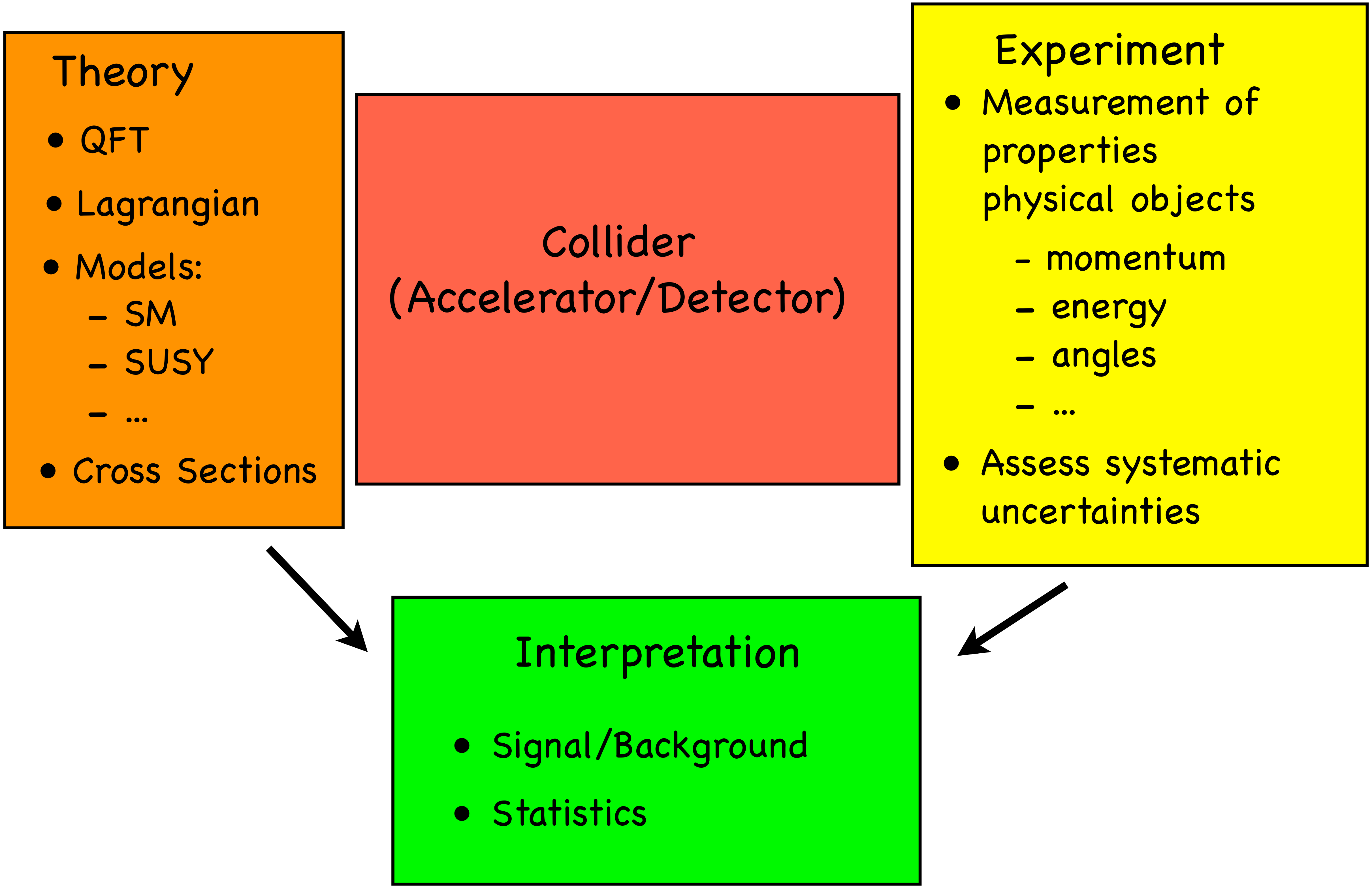
The purpose of collider physics is to test theoretical predictions experimentally in a controllable environment



Past and Present Particle Accelerators

Overview of accelerators: Major collider sites with center of mass energy > 10 GeV

e^+e^- colliders:

Name	Site	Energy	Discovery	Run Time
DORIS	DESY	10 GeV	B oscillation	1974-1993
PETRA	DESY	40 GeV	gluon	1978-1986
CESR	Cornell	12 GeV	B meson properties	1979-2002
SLC	SLAC	90 GeV	charm quark, tau lepton	1989-2004
LEP	CERN	208 GeV	Z,W boson properties	1989-2000
KEKB	KEK	10.6 GeV	B meson properties	1999-2009

e^-p collider:

HERA	DESY	318 GeV	Proton structure	1992-2007

hadron colliders:

Name	Site	Energy	Discovery	Run Time	
Super Proton Synchrotron	CERN	~ 550 GeV	W, Z boson	1981-1984	$p\bar{p}$
Tevatron	Fermilab	1.8 TeV 1.96 TeV	b, t quark	1992-1995 2001-2011	$p\bar{p}$
LHC	CERN	7/8/13 TeV	Higgs boson	2008-present	pp

Focus on particle colliders (no beam dumps/fixed targets)

Physics ratio for collider facilities

$A + B \to M$ production in 2-particle collisions: $M^2 = (p_1 + p_2)^2$

fixed target:

$$p_1 \simeq (E, 0, 0, E)$$
$$p_2 = (m, 0, 0, 0)$$

$$M \simeq \sqrt{2mE}$$

root increase in M

- root E law: large energy loss in E_{kin}
- dense target: large collision rate / luminosity

collider target:

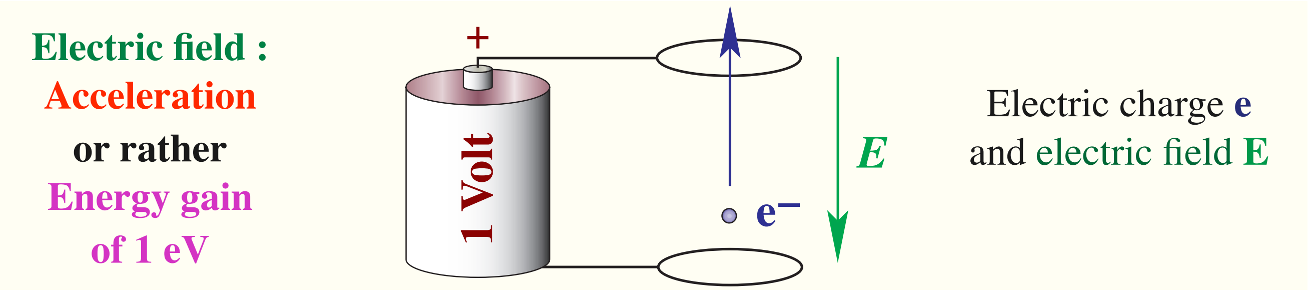
$$p_1 = (E, 0, 0, E)$$
$$p_2 = (E, 0, 0, -E)$$

$$M \simeq 2E$$

- linear E law: no energy loss
- less dense bunches: small collision rates

Collider characteristics

Energy: ranges from a few GeV to several TeV (LHC)



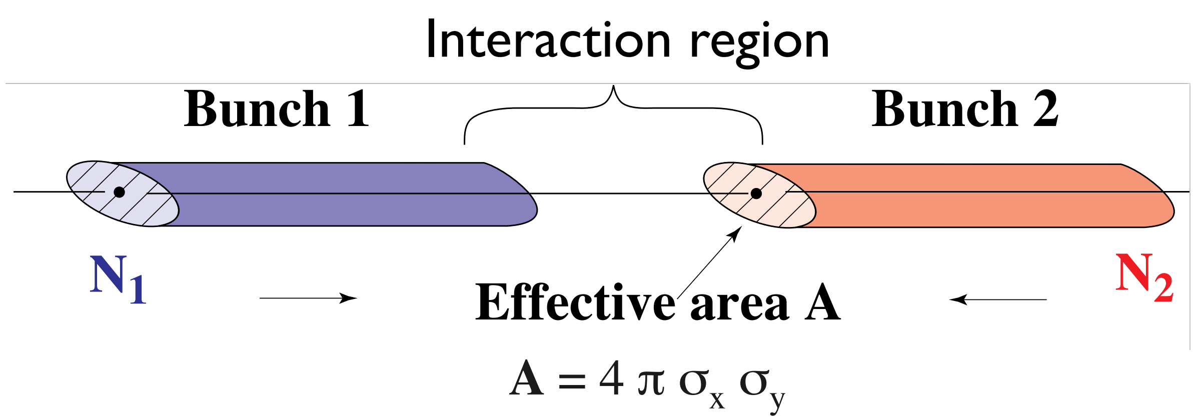
Luminosity: measures the rate of particles in colliding bunches

$N_i =$ number of particles in bunches

$A =$ transverse bunch area

$f =$ bunch collision rate

$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$



$\mathcal{L}\sigma =$ observed rate for process with cross section

LHC (at moment): $\mathcal{L} = 6.4 \cdot 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

LHC (targeted): $\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \longrightarrow 300\ \mathrm{fb}^{-1}$ in 3 years

Connecting Theory and experiment:
Scattering processes at hadron colliders

Master formula:

General process at proton-proton collider $\sigma(pp \to X)$

$$\sigma_{pp\to X} = \sum_{a,b} \int dx_1 dx_2 \; f_{a/p}(x_1,\mu_F) f_{b/p}(x_2,\mu_F) \; \hat{\sigma}_{a,b\to k}(\mu_F,\mu_R) \; \Theta(\text{Cuts}) \; D(k\to X)$$

where the partonic cross section is calculated by

$$\hat{\sigma}_{a,b\to k} = \frac{1}{2s} \int \left[\Pi_{i=1}^{n} \frac{d^3\vec{q}_i}{(2\pi)^3 2E_i}\right] \left[(2\pi)^4 \delta^4 \left(\sum_i q_i^\mu - (p_1+p_2)^\mu\right)\right] |\mathcal{M}_{ab\to k}(\mu_F,\mu_R)|^2$$

[flux factor] × [phase space (LiPS)] × [squared matrix element]

Crucial pieces for the calculation of the hadronic cross section are the **parton distribution functions** $f_{i/p}$ and the **squared matrix element** $|\mathcal{M}|^2$

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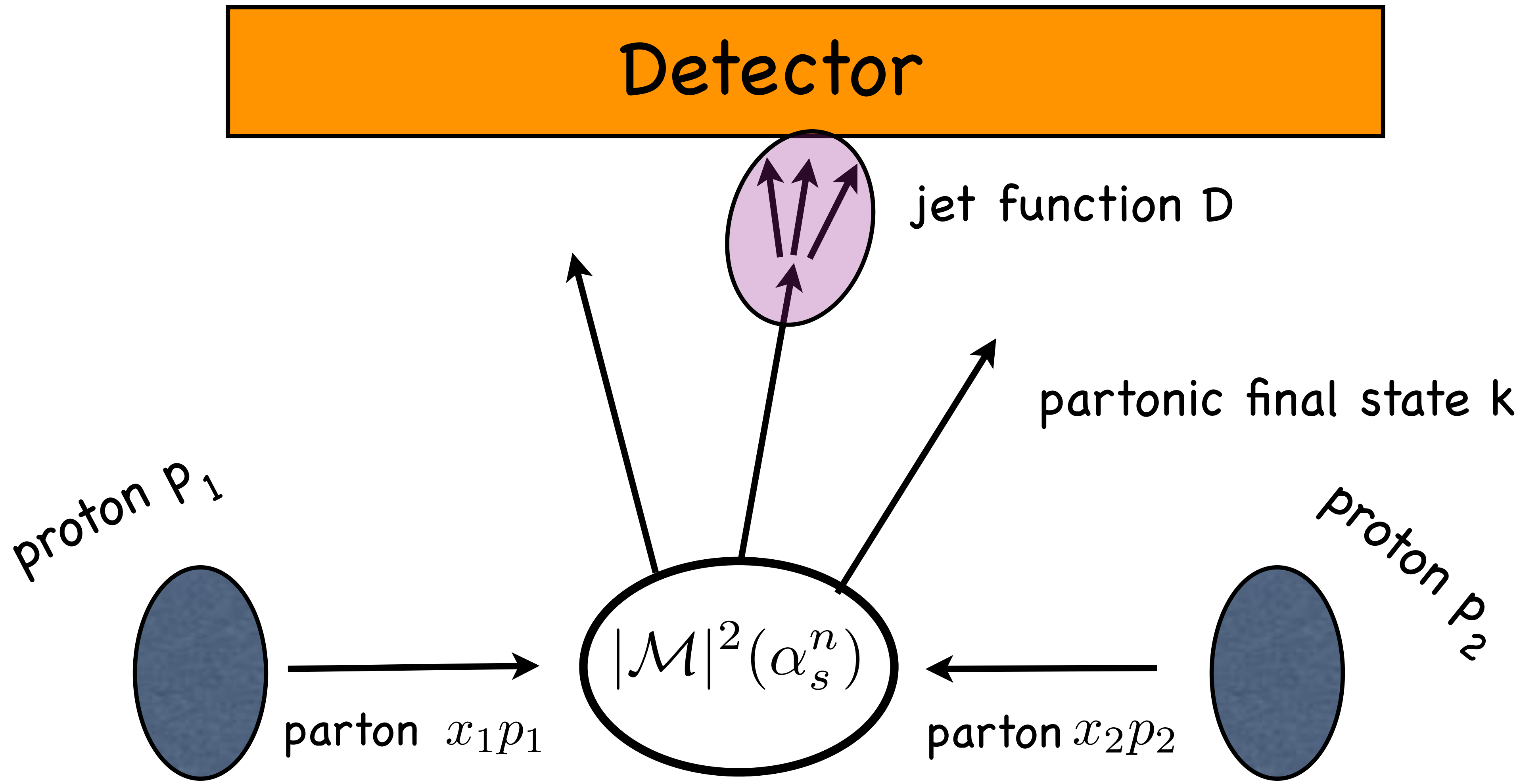
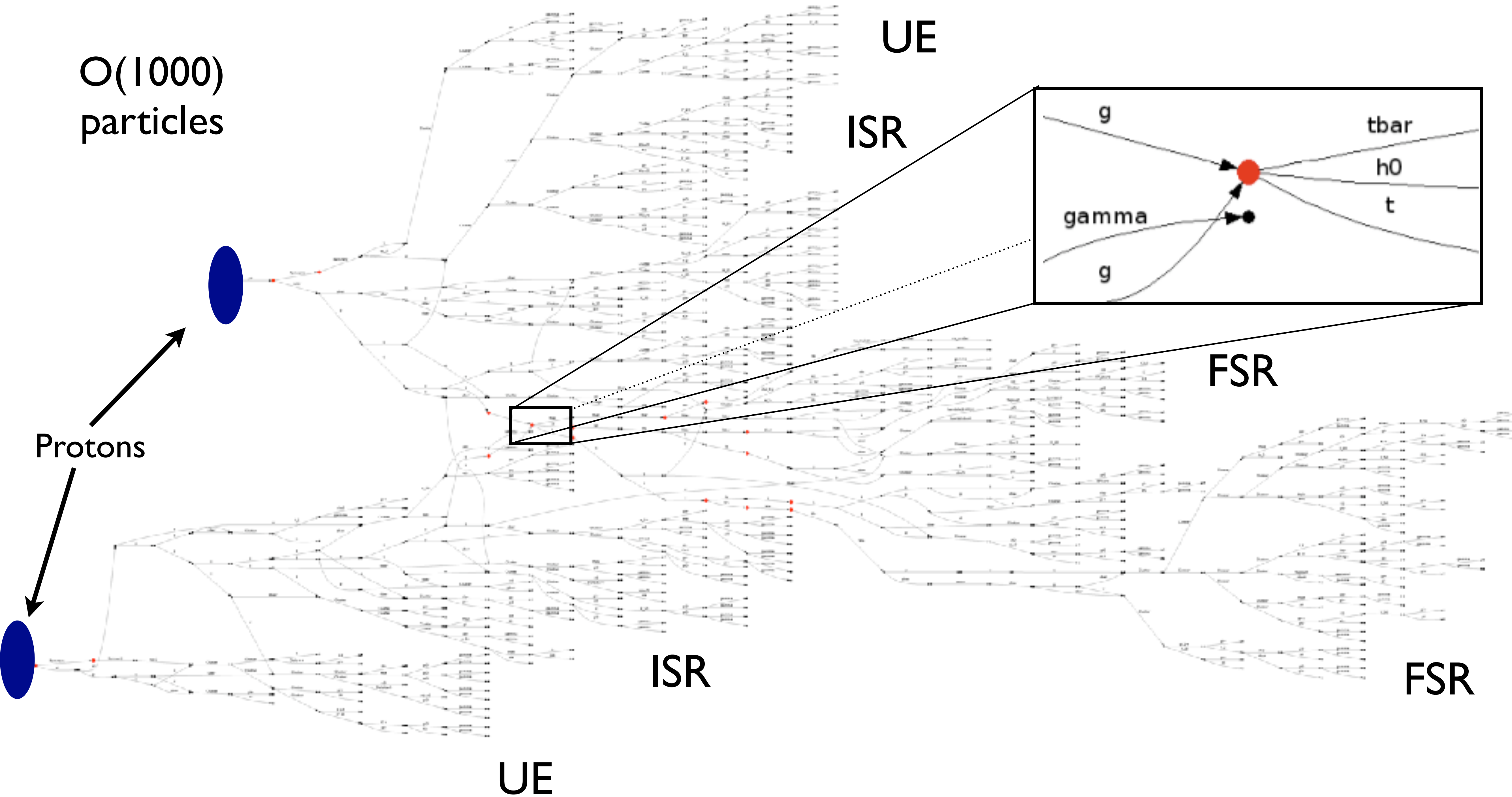
More detailed discussion of master formula

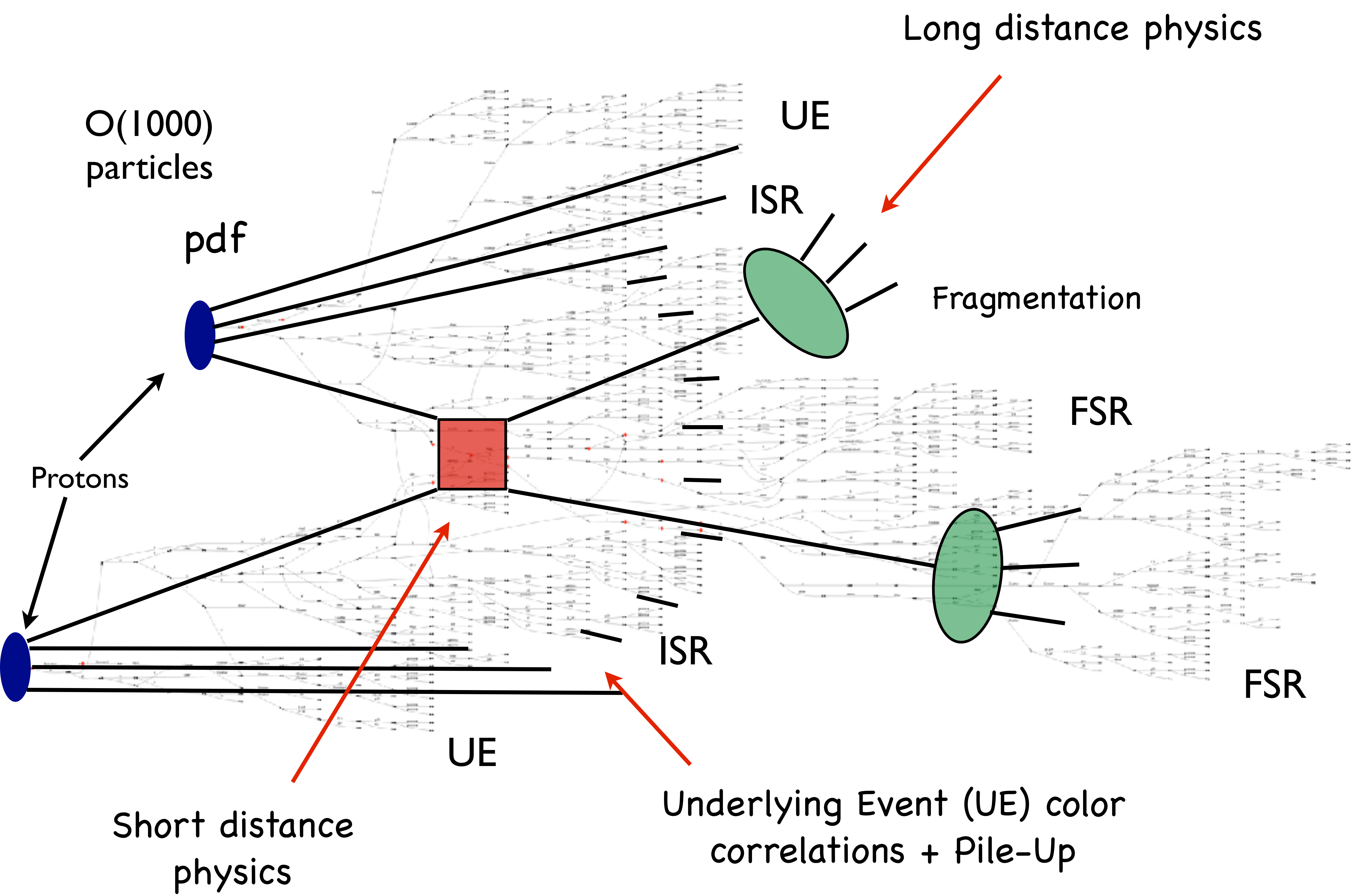
Pictorial description:



LHC hosts complex environment!



Tedious for theorists and experimentalists



Long distance physics
O(1000) particles
UE
ISR
pdf
Fragmentation
FSR
Protons
ISR
FSR
UE
Short distance physics
Underlying Event (UE) color correlations + Pile-Up

More detailed discussion of master formula

Partonic cross section $\hat{\sigma}$:

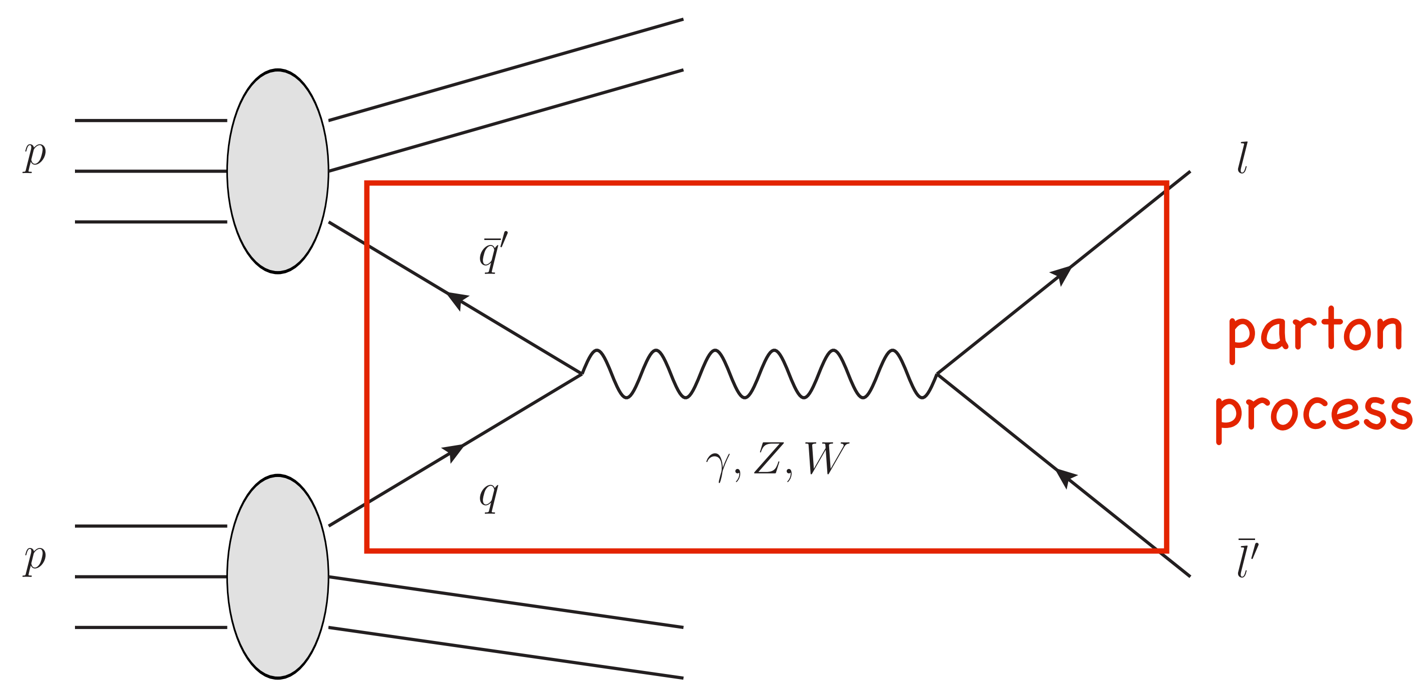
Partons (e.g. quarks) of incoming hadrons (e.g. protons) interact at short distance (large momentum transfer). Example Drell-Yan process: $\hat{\sigma}(q\bar{q} \to l^+ l^-)$

calculable with perturbation theory in powers of

$$\hat{\sigma}_{ab\to k} = \left[\hat{\sigma}_0 + \alpha_s(\mu_R^2)\hat{\sigma}_1 + \alpha_s^2(\mu_R^2)\hat{\sigma}_2 + \cdots\right]$$

Example: Drell-Yan Process

Leading-order diagram



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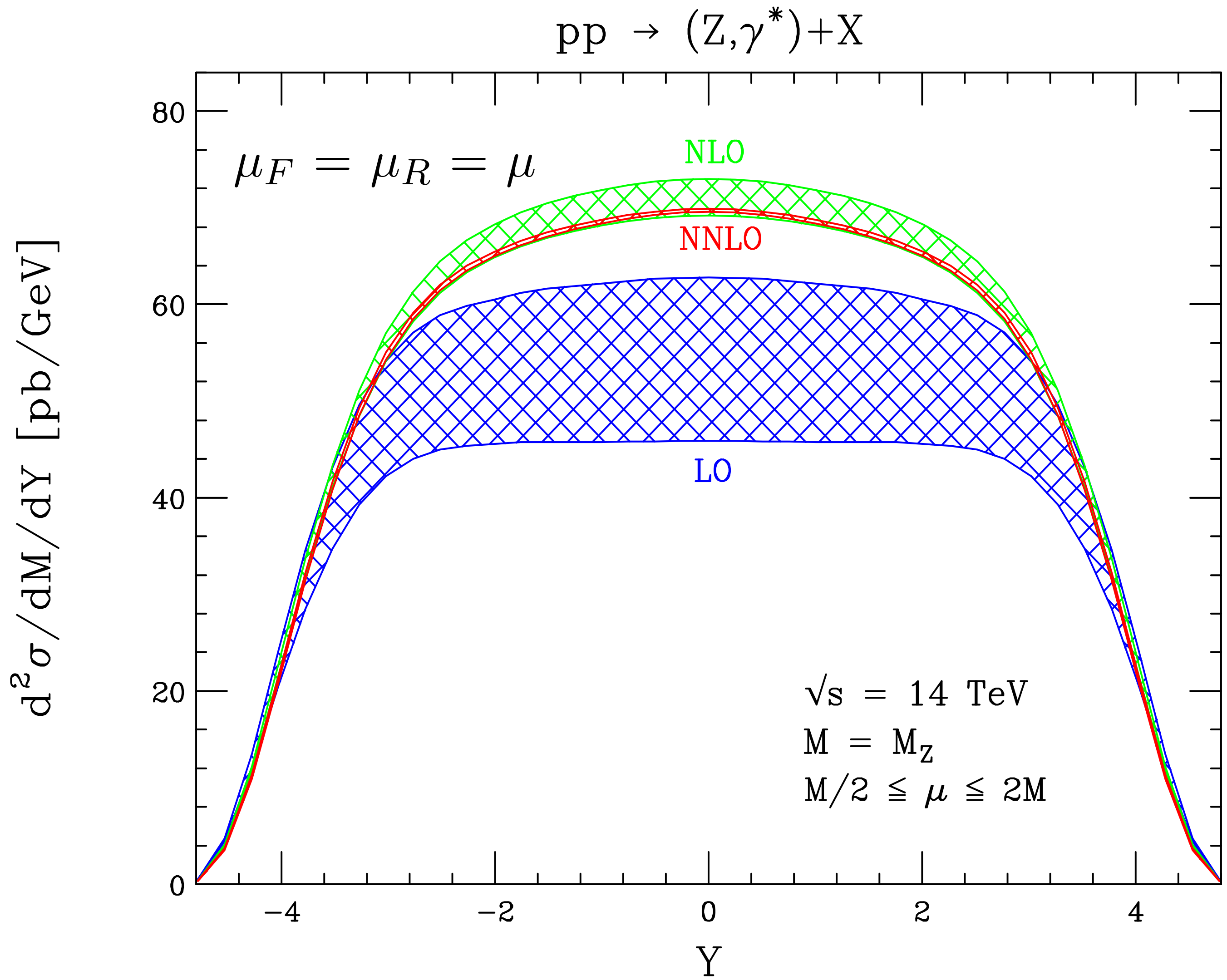
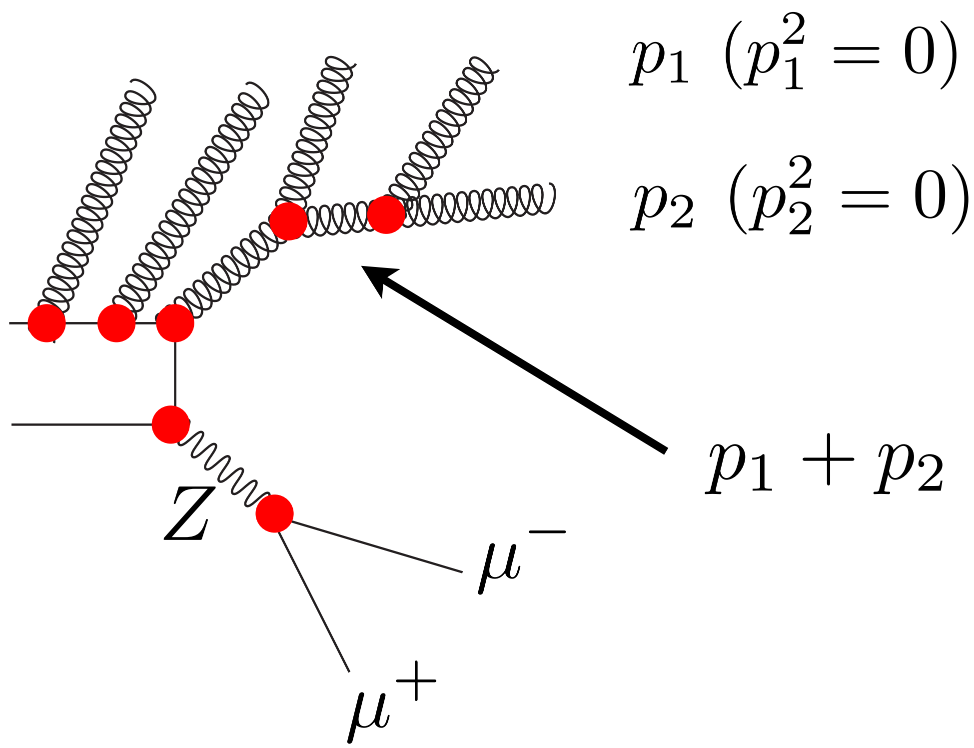
NLO contributions are important for precision



- NLO-K-factor is ratio between LO and NLO
- Higher-Order corrections important for phenomenology at colliders
- Rate determined by hard process and pdfs, but kinematic distributions highly affected by parton shower

The parton shower bridges the gap from the hard interaction scale down to the hadronization scale O(1) GeV



partons from the hard interaction emit other partons (gluons and quarks)

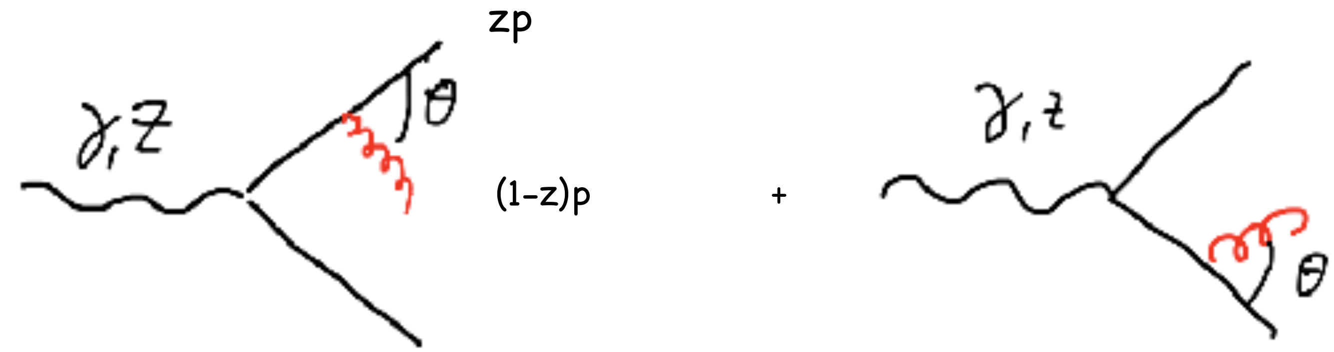
These emissions are enhanced if they are collinear and/or soft with respect to the emitting parton

Probability enhanced in soft and collinear region due to ~ $1/(p_1+p_2)^2$

- If $p_1 \to 0$, then $1/(p_1+p_2)^2 \to \infty$
- If $p_2 \to 0$, then $1/(p_1+p_2)^2 \to \infty$
- If $p_2 \to \lambda p_1$, then $1/(p_1+p_2)^2 \to \infty$

Parton shower theory

$e^+e^- \rightarrow 3$ jets



Collinear limit:

$$d\sigma_{ee\rightarrow 3j} \approx \sigma_{ee\rightarrow 2j} \sum_{j\in\{q,\bar{q}\}} \frac{\alpha_s}{2\pi} \frac{d\theta_{jg}^2}{\theta_{jg}^2} P(z)$$

$$P_{q\rightarrow qg} = C_F \frac{1+z^2}{1-z} \qquad P_{g\rightarrow gg} = C_A \frac{(1-z(1-z))^2}{z(1-z)} \qquad P_{g\rightarrow q\bar{q}} = T_R n_f (z^2 + (1-z)^2)$$

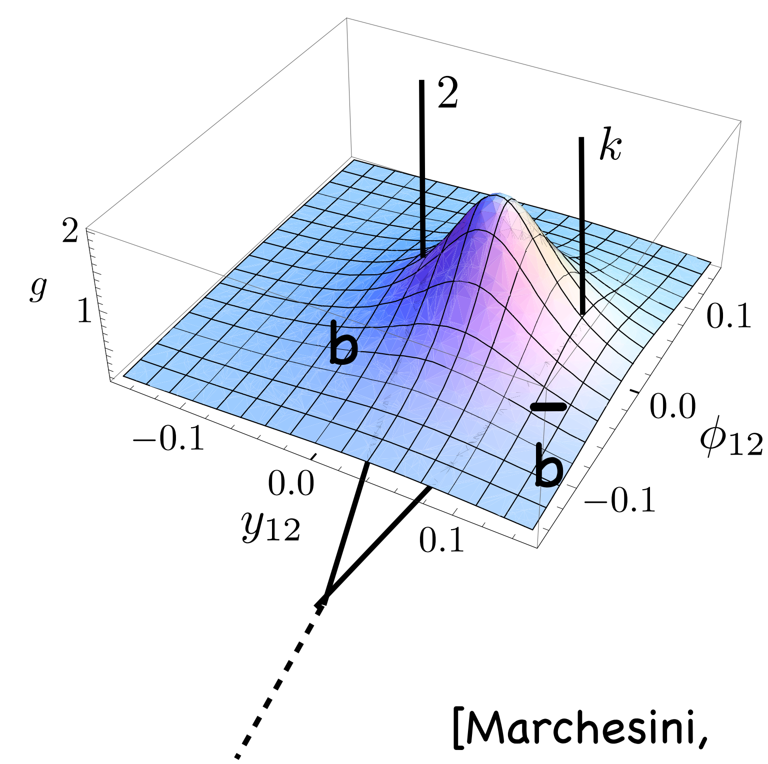
Soft limit: $E_g \rightarrow 0$ $\quad k^\mu \ll p_i^\mu$ the matrix element for

$e^+e^- \rightarrow \bar{q}qg$ factorizes (Eikonal Current)

↓ dipole

$$|\mathcal{M}_{q\bar{q}g}|^2 = |\mathcal{M}_{q\bar{q}}|^2 g_s^2 C_F \frac{2p_1 \cdot p_2}{p_1 \cdot k \; p_2 \cdot k}$$

In the large Nc limit most radiation occurs in a cone between colour partners



[Marchesini, Webber]

Factorization of emissions and Sudakov factors allow semiclassical approximation of quantum process:

Sudakov form factor:

$$\mathcal{P}_{\text{nothing}}(0 < t \leq T) = \lim_{n->\infty} \Pi_{i=0}^{n-1} \mathcal{P}_{\text{nothing}}(T_i < t \leq T_{i+1})$$

$$= \lim_{n\to\infty} \Pi_{i=0}^{n-1} \left(1 - \mathcal{P}_{\text{something}}(T_i < t \leq T_{i+1})\right)$$

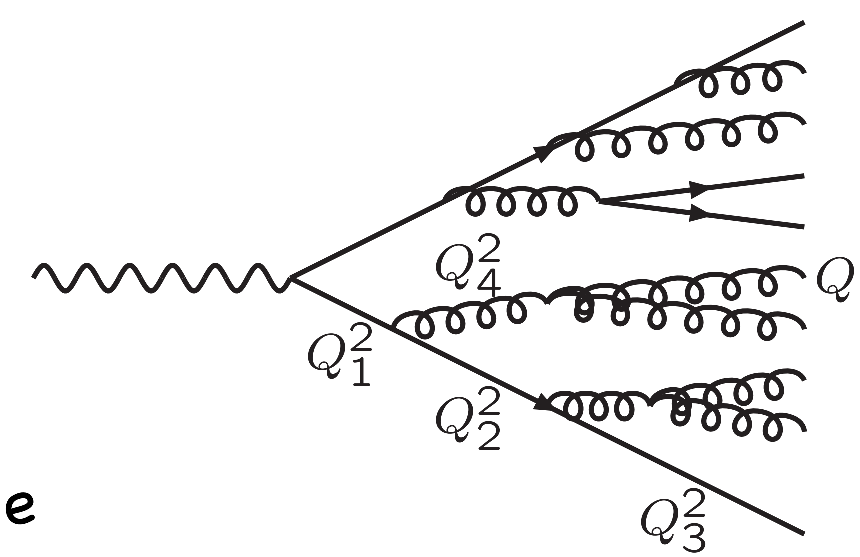
$$= \exp\left(-\int_0^T \frac{d\mathcal{P}_{\text{something}}(t)}{dt} dt\right)$$

$$\Rightarrow \quad d\mathcal{P}_{\text{first}}(T) = d\mathcal{P}_{\text{something}}(T) \exp\left(-\int_0^T \frac{d\mathcal{P}_{\text{something}}(t)}{dt} dt\right)$$

Sudakov form factor provides "time" ordering of shower:

$Q_1^2 > Q_2^2 > Q_3^2$

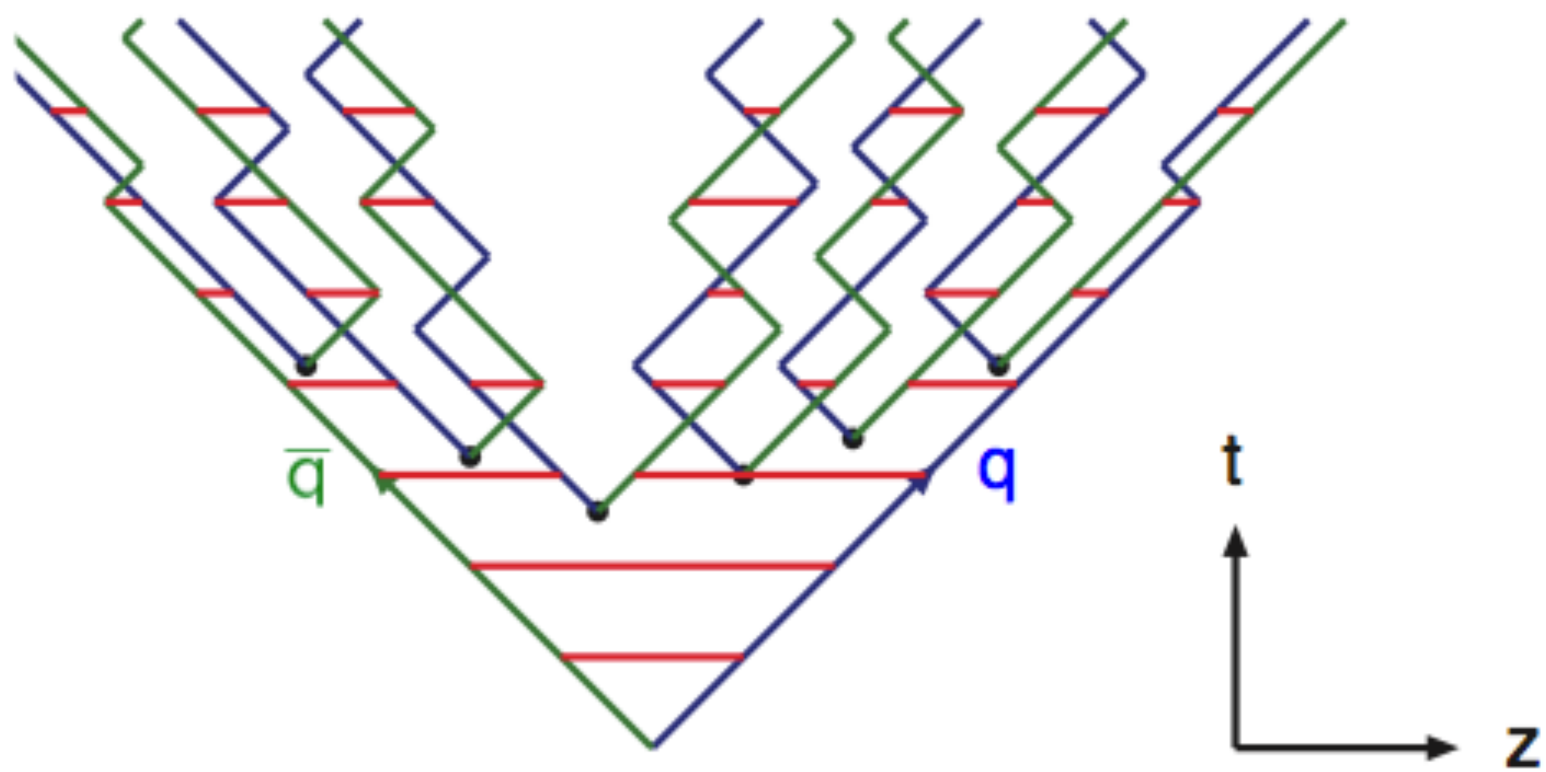
low Q^2 $\Leftrightarrow$ longer time



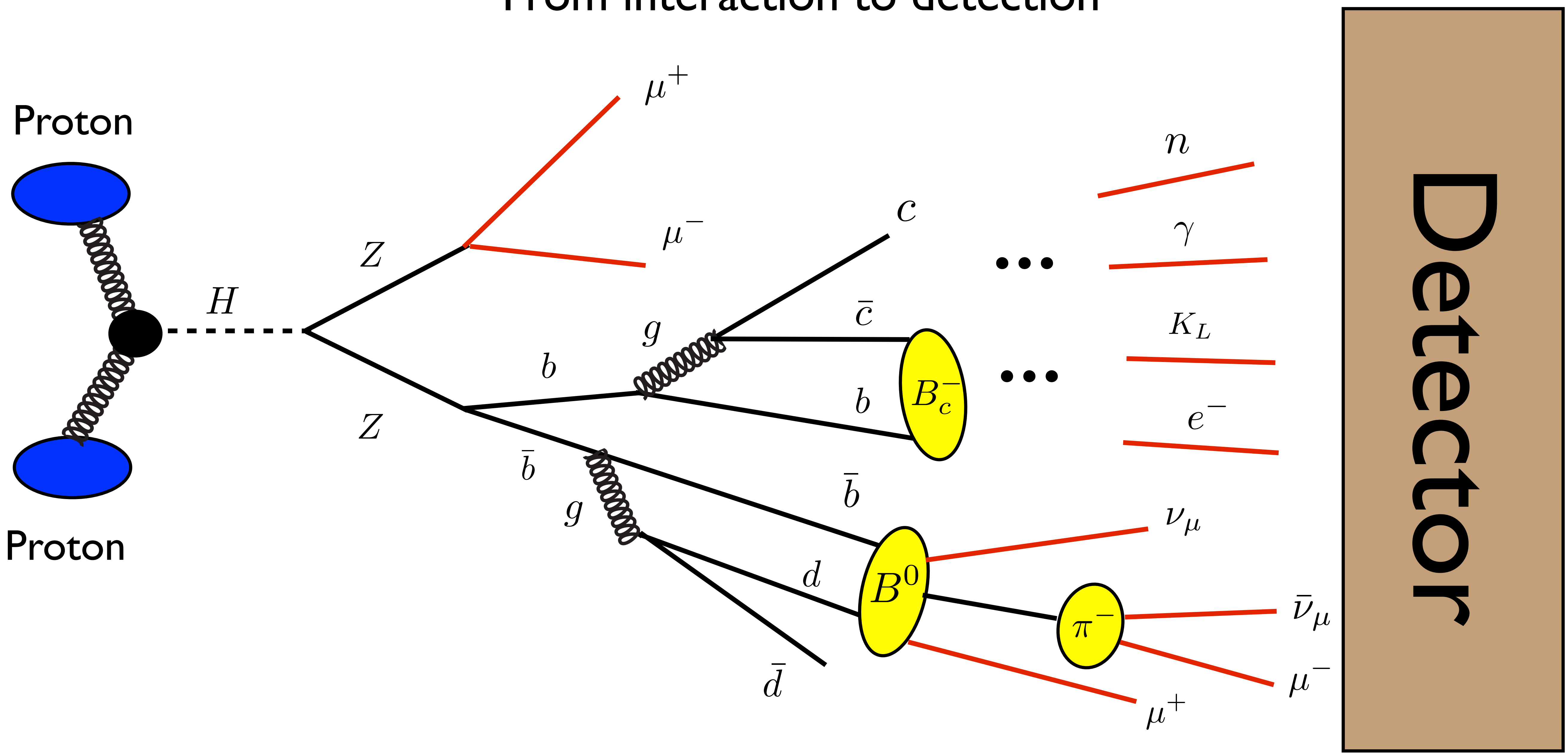
Hadronization

After the shower evolved from the hard interaction scale down to the hadronization scale ~O(1) GeV the coloured partons have to be rearranged into colour singlet bound states

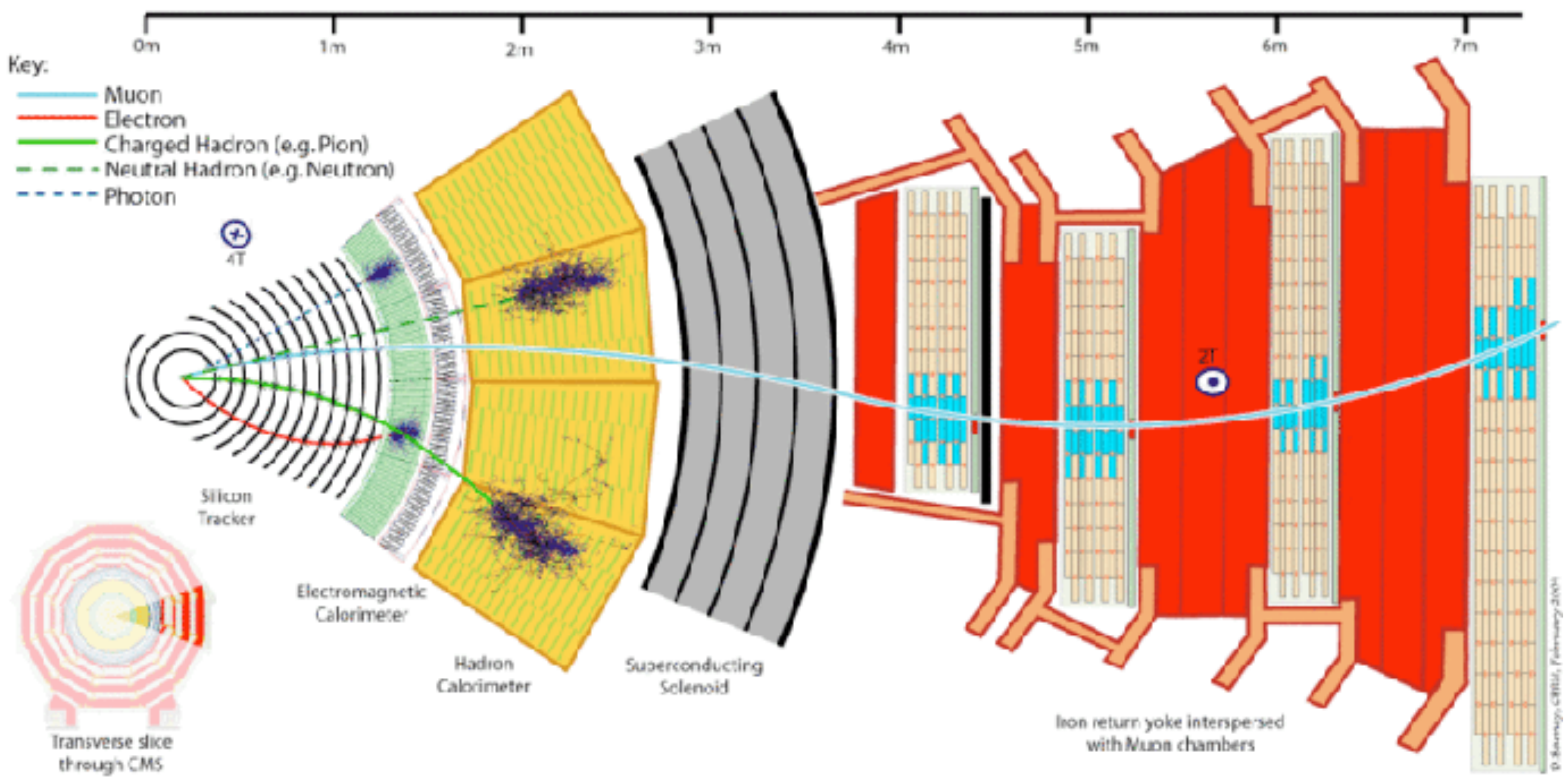
This process cannot be calculated using perturbation theory but has to be modeled. Different models are used, e.g. Independent Fragmentation, Lund String Model, Cluster Model.



From interaction to detection



- Higgs boson generated in proton-proton collision with subsequent decay into Z bosons
- Z bosons decay into quarks (e.g. bottom quarks) or leptons (e.g. long-lived muons)
- After bottom quarks radiate gluons a process called hadronization starts. During hadronization the coloured partons are regrouped in colour-singlet mesons (2 quarks) or baryons (3 quarks)
- Most mesons/baryons are not stable and decay into long-lived hadrons or leptons before reaching the detector



- <u>Tracker:</u> Immediately around the interaction point the inner tracker serves to identify the tracks of individual particles and match them to the vertices from which they originated. The curvature of charged particle tracks in the magnetic field allows their charge and momentum to be measured.
- <u>Electromagnetic Calorimeter:</u> The Electromagnetic Calorimeter (ECAL) is designed to measure with high accuracy the energies of photons, charged leptons and hadrons.
- <u>Hadron Calorimeter:</u> The purpose of the Hadronic Calorimeter (HCAL) is both to measure the energy of individual hadrons produced in each event, and to be as near to hermetic around the interaction region as possible to allow events with missing energy to be identified.
- <u>Return yoke with muon chambers:</u> Its purpose is to identify muons and measure their momenta.

Watch also: <u>http://www.atlas.ch/multimedia/html-nc/feature-episode2.html</u>

Jet Physics

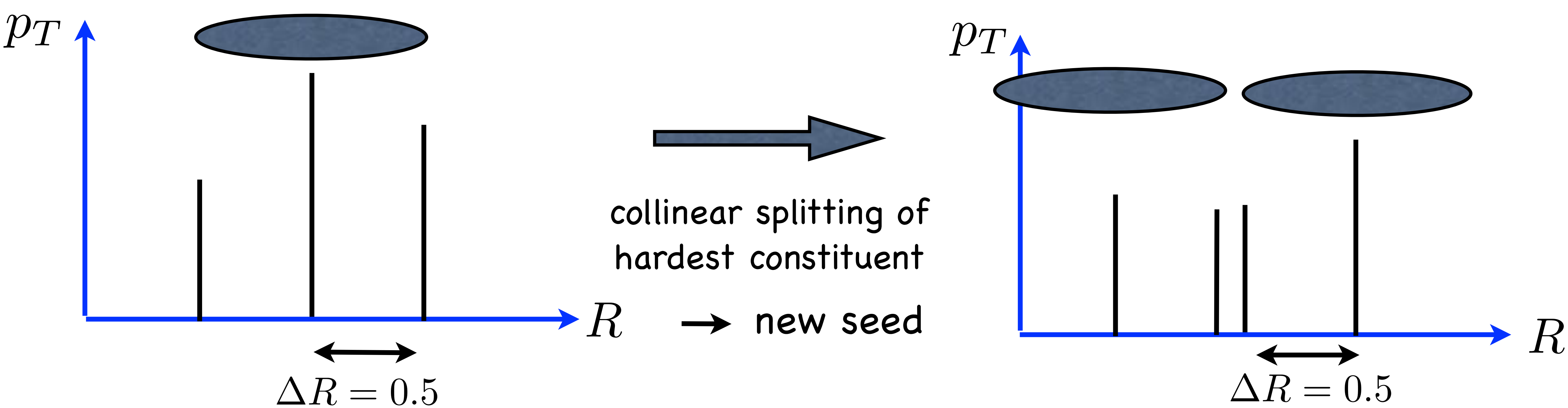
Jets are objects consisting of a collimated spray of particles (i.e. photons, long-lived mesons/baryons, leptons,...)

IR safe definition of jets:

Observables must be insensitive to modification of final state with respect to soft and/or collinear splitting

Seeded cone algorithms are infrared unsafe!
Example: Take the hardest constituent of event as seed for jet cone

Assume 3 constituents in event with cone size R=0.5



1-jet configuration

2-jet configuration

IR-safe sequential jet algorithms

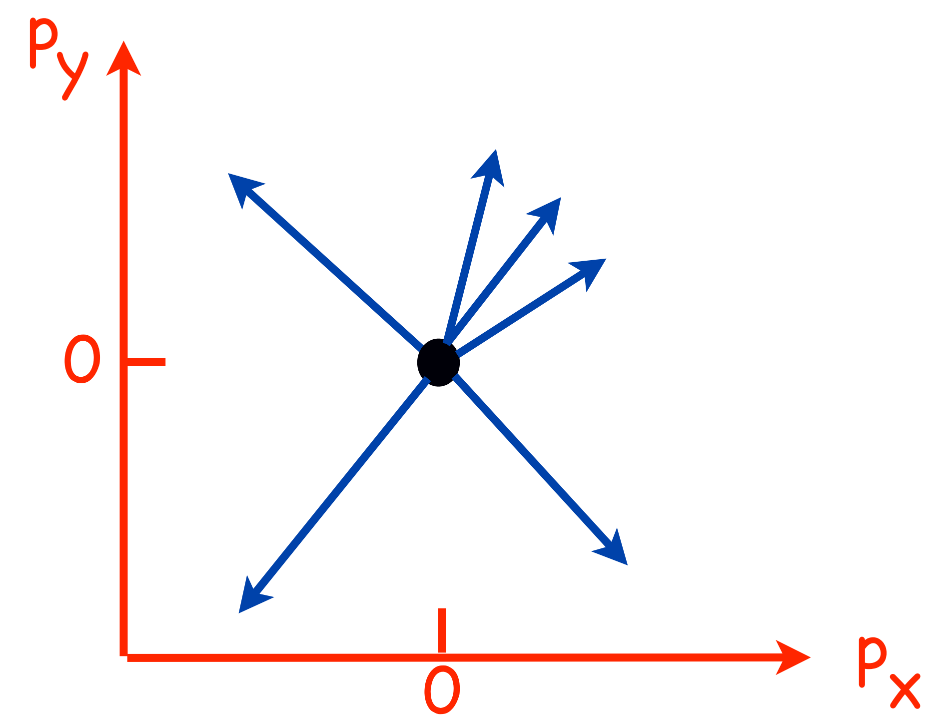
inclusive kT algorithm: [S.D. Ellis & Soper, '93; Catani et al. 93']

Distance measure

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{Ti}^2$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$



1. Find smallest of d_{ij} d_{iB}
2. if ij recombine them
3. if iB call i a jet and remove from list of particles
4. repeat from 1. until no particles left

Minimum distance between jets is R

Only number of jets above pt cut is IR safe

Cambridge/Aachen alg. - distance measure: $d_{ij} = \frac{\Delta R_{ij}^2}{R^2}$ $d_{iB} = 1$

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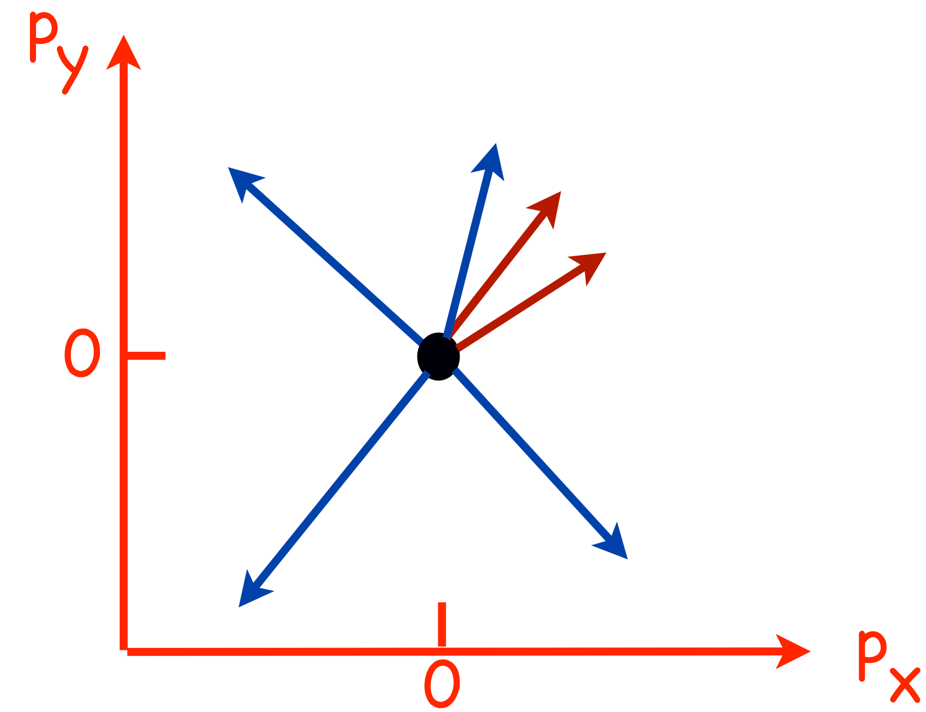

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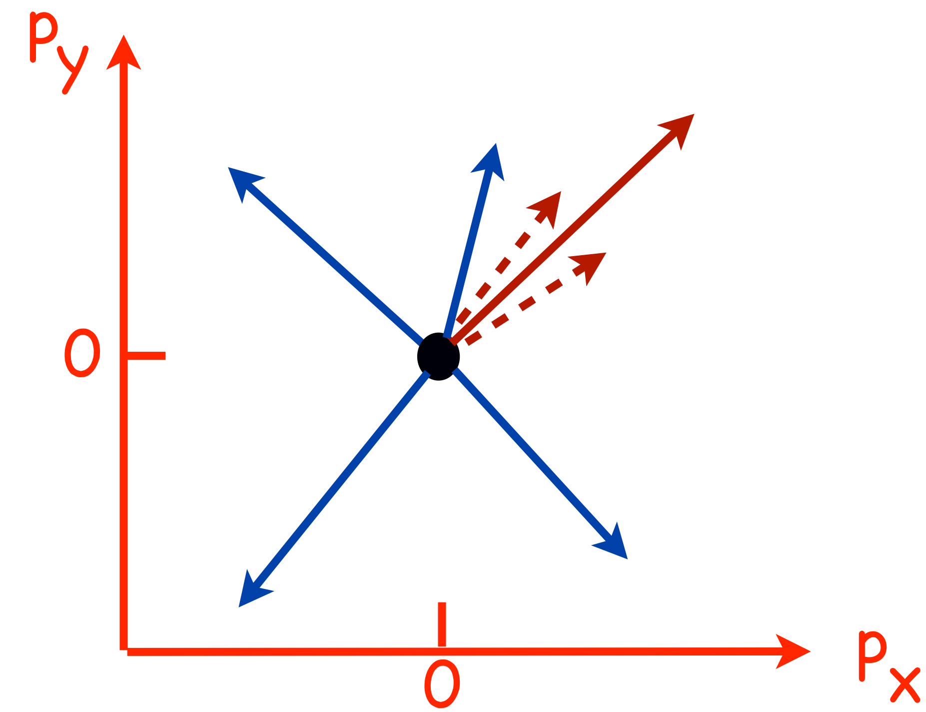

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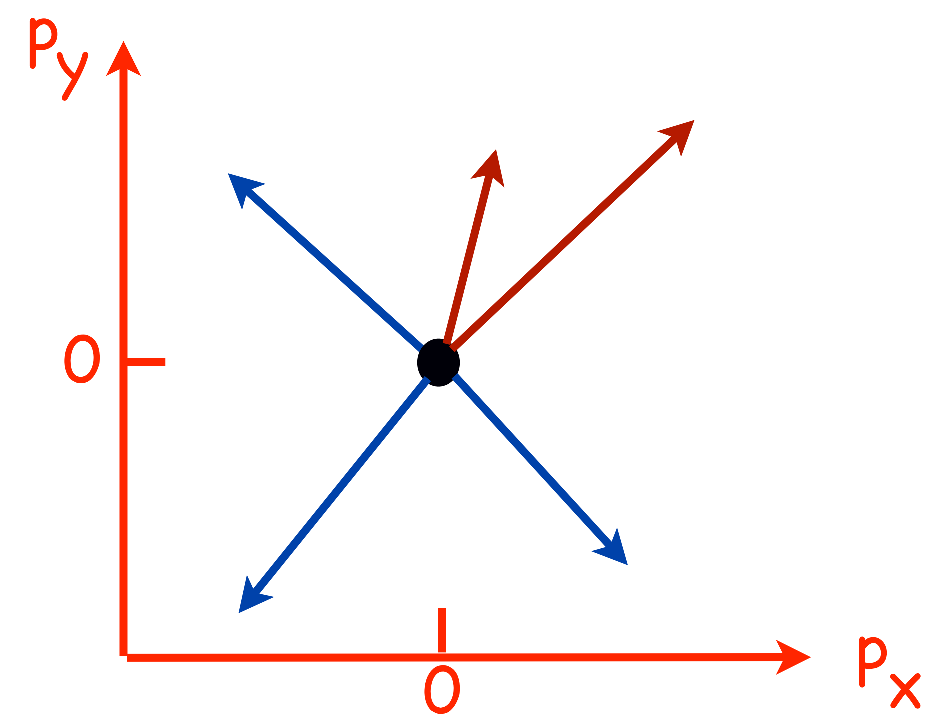

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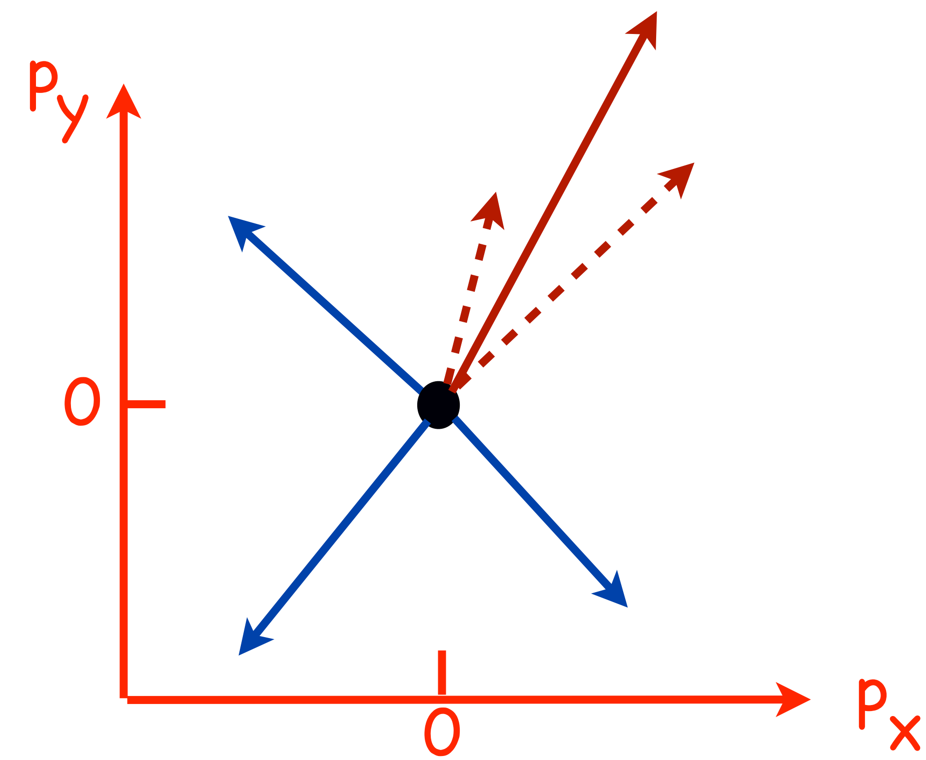

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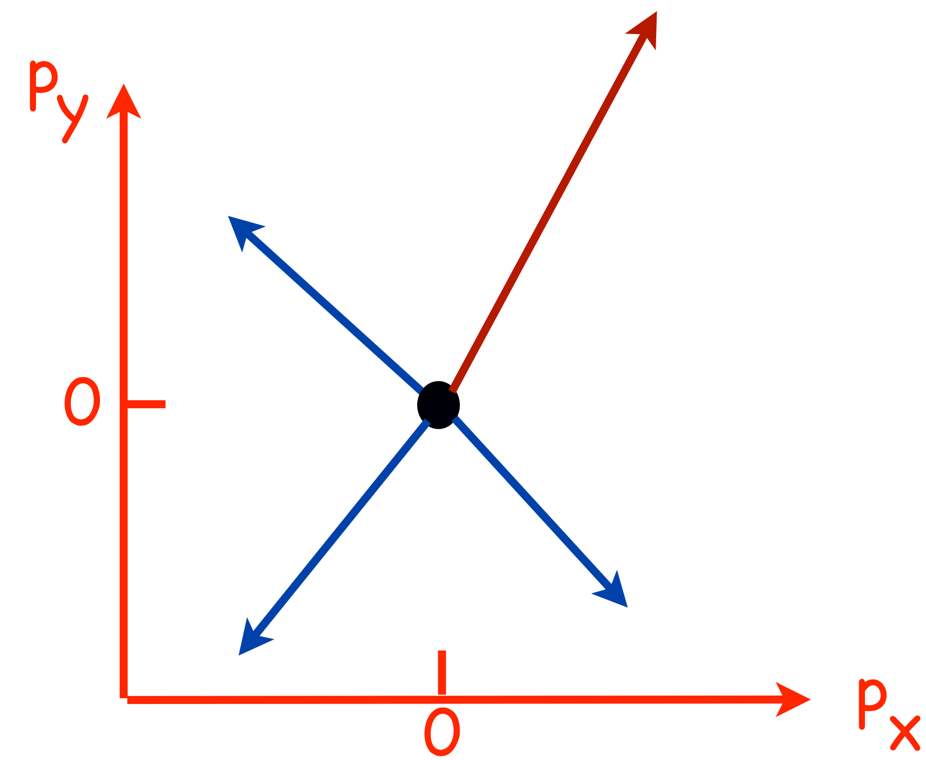

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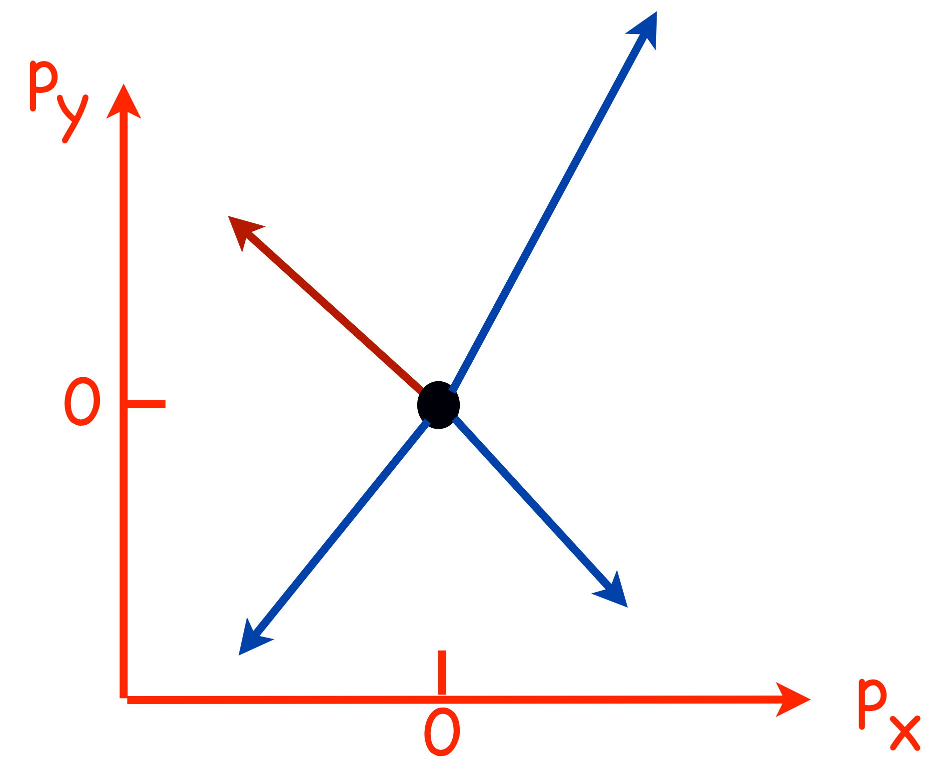

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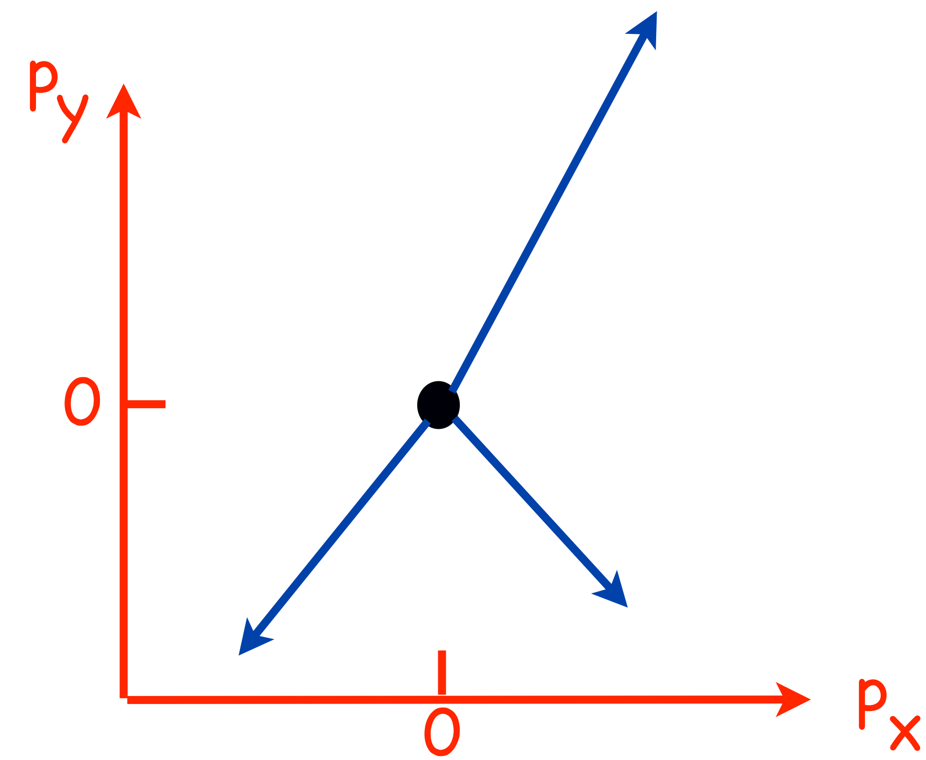

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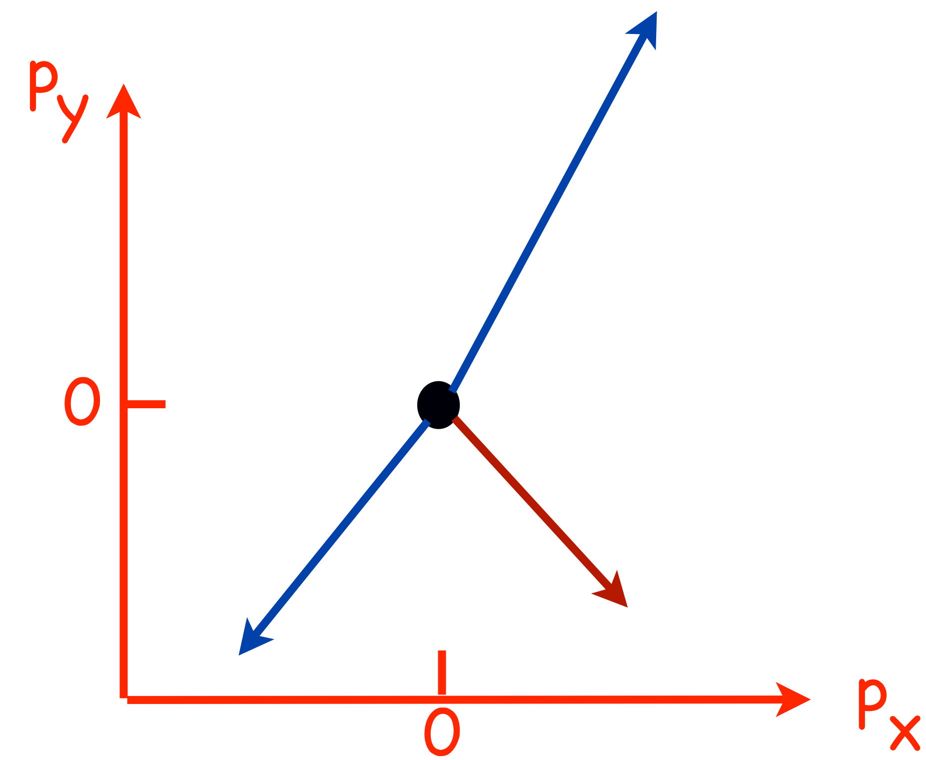

1. Find smallest of d_{ij} d_{iB}
2. if ij recombine them
3. if iB call i a jet and remove from list of particles
4. repeat from 1. until no particles left

Minimum distance between jets is R

Only number of jets above pt cut is IR safe

Cambridge/Aachen alg. - distance measure: $d_{ij} = \frac{\Delta R_{ij}^2}{R^2}$ $d_{iB} = 1$

anti-kT alg. - distance measure: $d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\frac{\Delta R_{ij}^2}{R^2}$ $d_{iB} = p_{Ti}^{-2}$

IR-safe sequential jet algorithms

inclusive kT algorithm: [S.D. Ellis & Soper, '93; Catani et al. 93']

Distance measure

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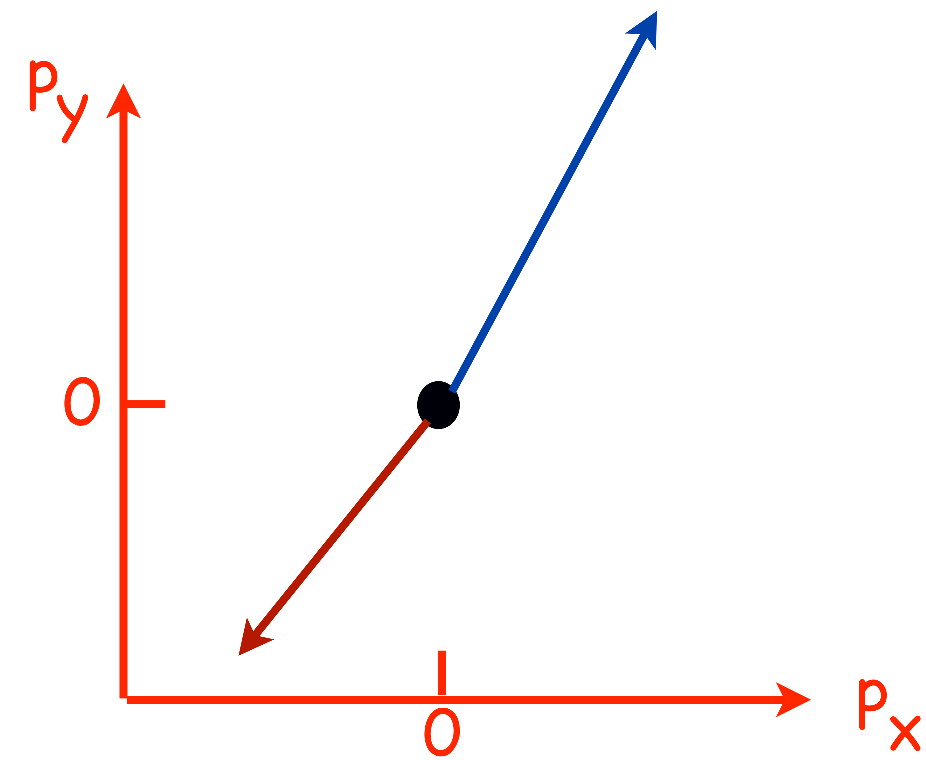

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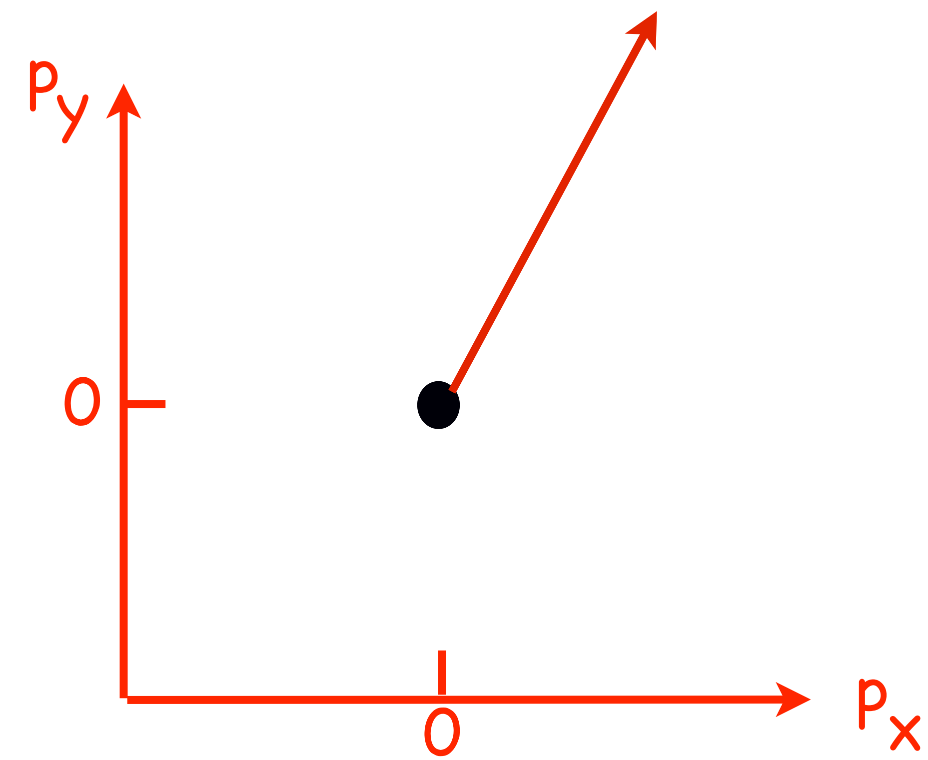

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inclusive kT algorithm: [S.D. Ellis & Soper, '93; Catani et al. 93']

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1. Find smallest of d_{ij} d_{iB}
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3. if iB call i a jet and remove from list of particles
4. repeat from 1. until no particles left

Found 4 Jets

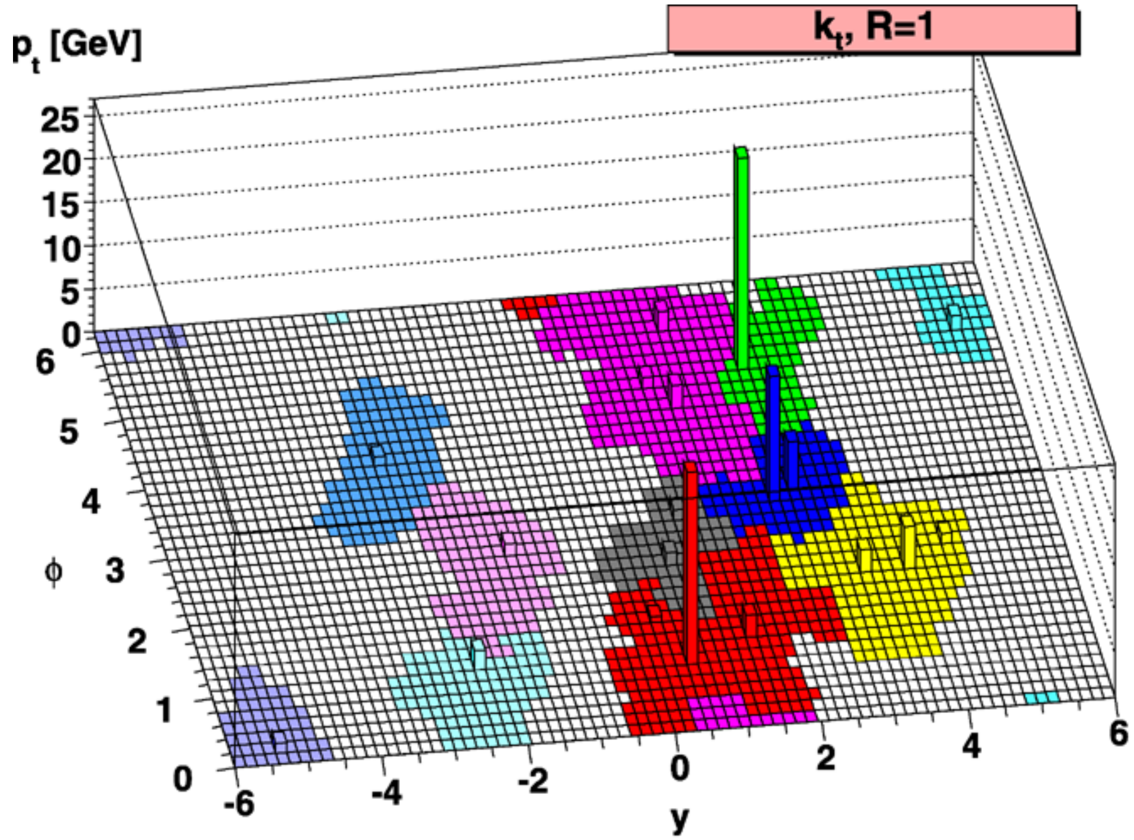
Minimum distance between jets is R

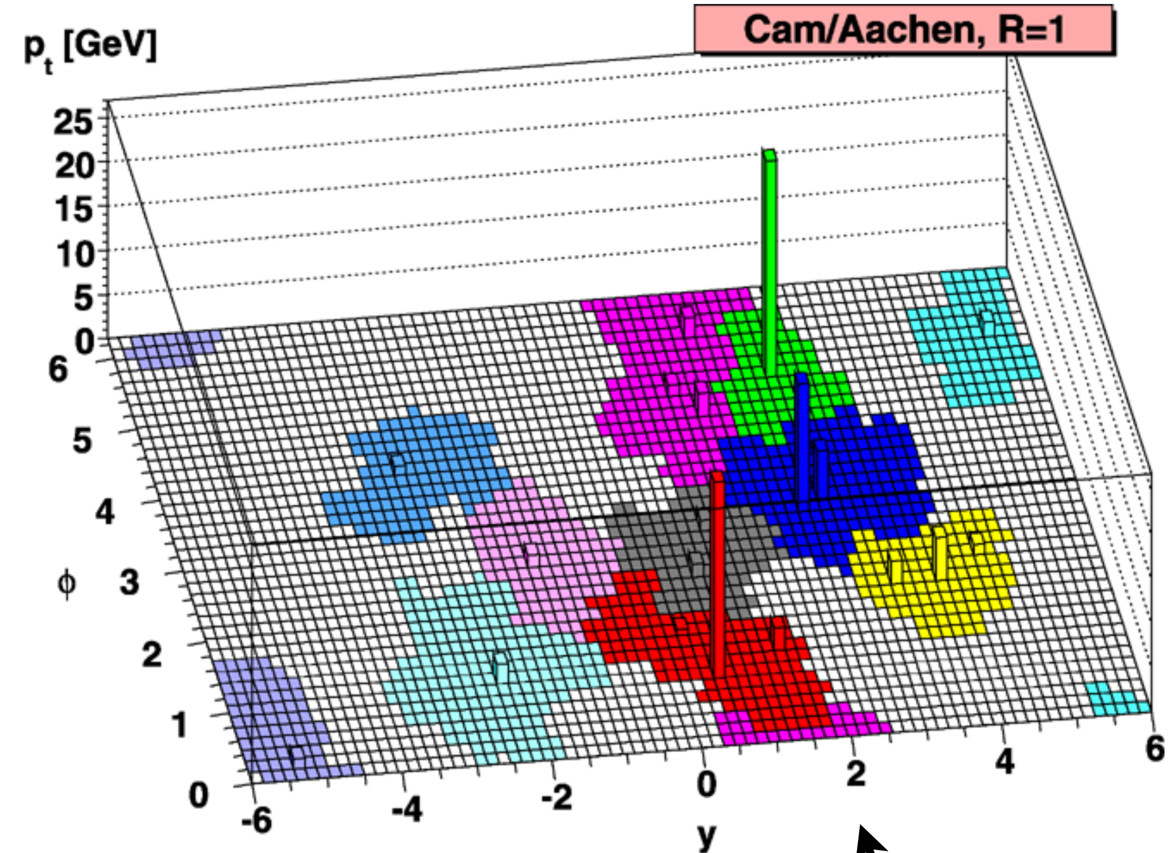
Only number of jets above pt cut is IR safe

Cambridge/Aachen alg. - distance measure: $d_{ij} = \frac{\Delta R_{ij}^2}{R^2}$ $d_{iB} = 1$

anti-kT alg. - distance measure: $d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\frac{\Delta R_{ij}^2}{R^2}$ $d_{iB} = p_{Ti}^{-2}$

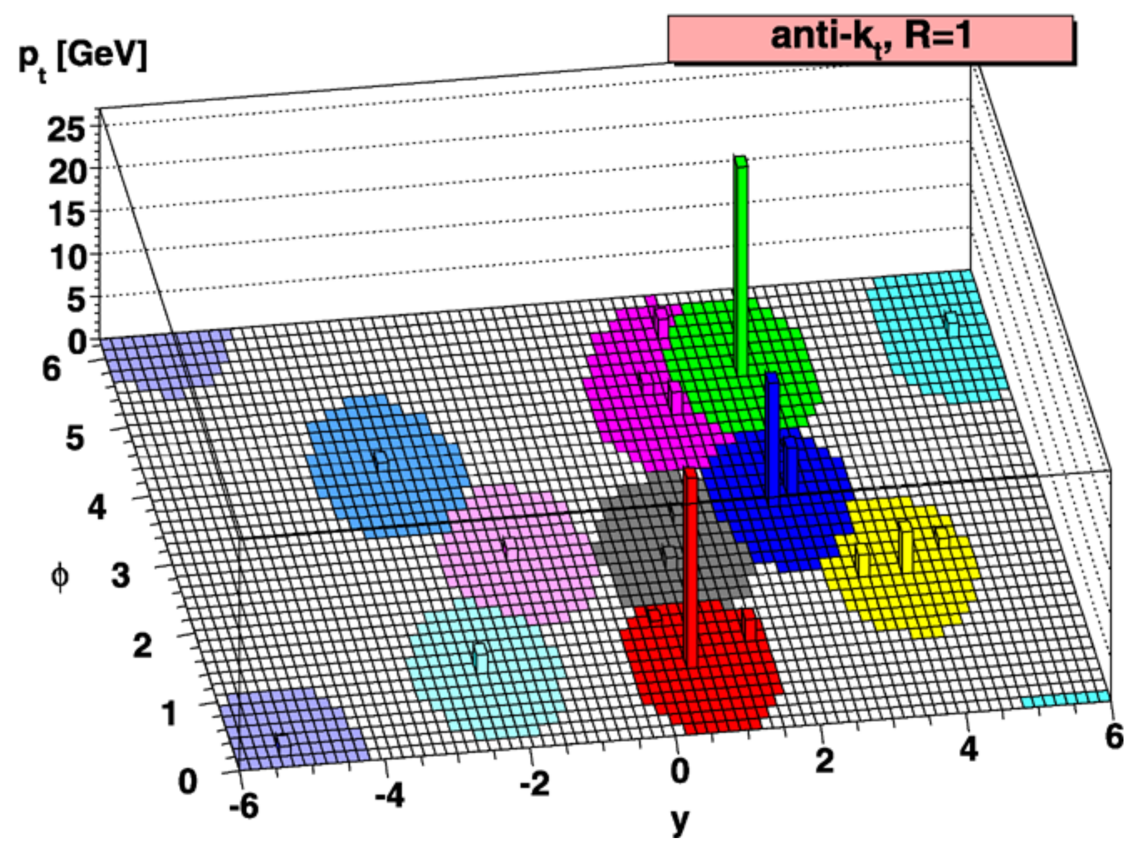
[G. Salam, Towards Jetography]





soft jet
more
circular

shape independent
of jet pT

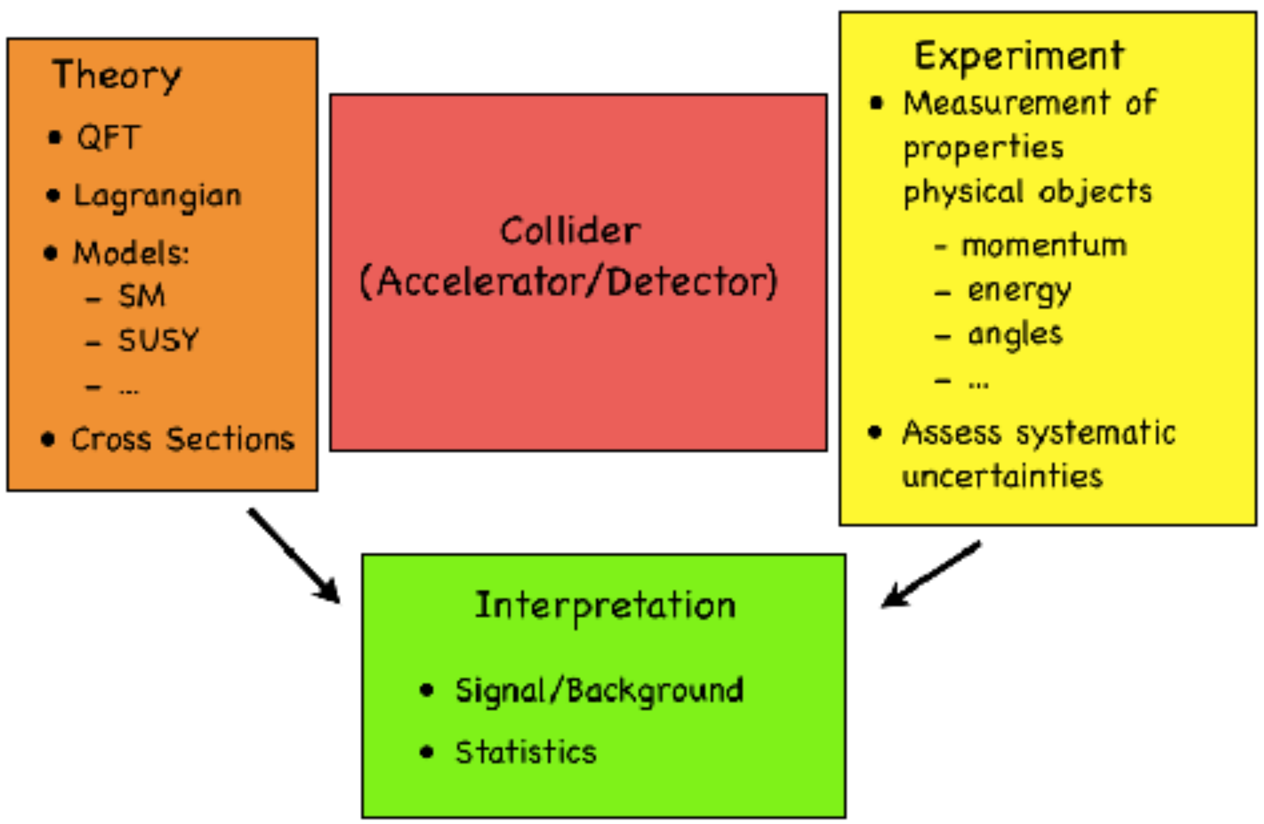


hard jet
more
circular

Finally!

We now how to **reconstruct objects** in a detector and we know how to **calculate theory predictions**

→ Next step: **Interpretation**



Example: Higgs boson as window to new physics

Higgs mechanism a brief review

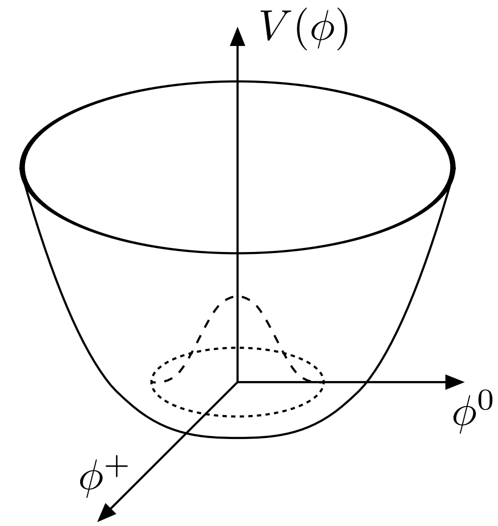
Purpose: explain existence of massive particles consistence with gauge invariance

Symmetry of the Lagrangian

$$SU(2)_L \times U(1)_Y$$

Higgs doublet

$$\Phi = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$



$$V(\Phi) = \lambda \left[\Phi^\dagger \Phi - \frac{v^2}{2} \right]^2$$

Symmetry of the vacuum

$$U(1)_{em}$$

vacuum expectation value

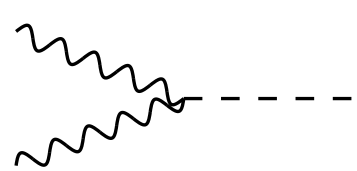
$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$v = 246 \text{ GeV}$$

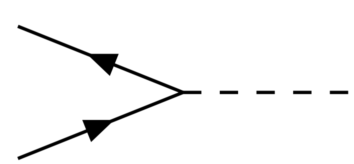
Higgs mass: $m_H = \sqrt{2\lambda} v$

couplings to

gauge bosons $\quad g_{VVH} = \dfrac{2m_V^2}{v}$

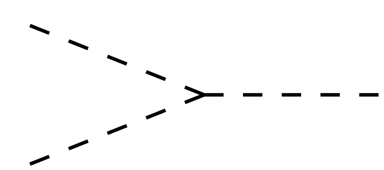


fermions $\quad g_{f\bar{f}H} = \dfrac{m_f}{v}$

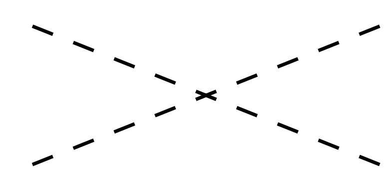


Higgs selfcouplings

$$\lambda_{HHH} = -3\frac{m_H^2}{v}$$



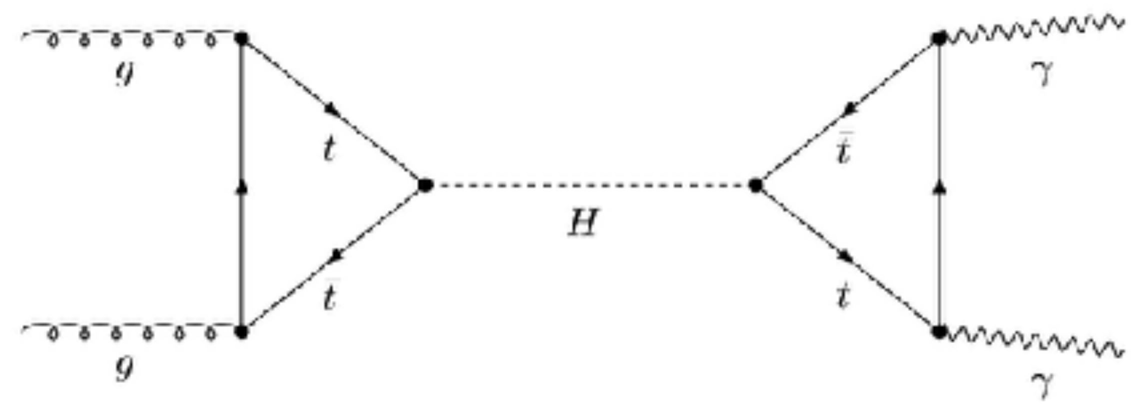
$$\lambda_{HHHH} = -3\frac{m_H^2}{v^2}$$



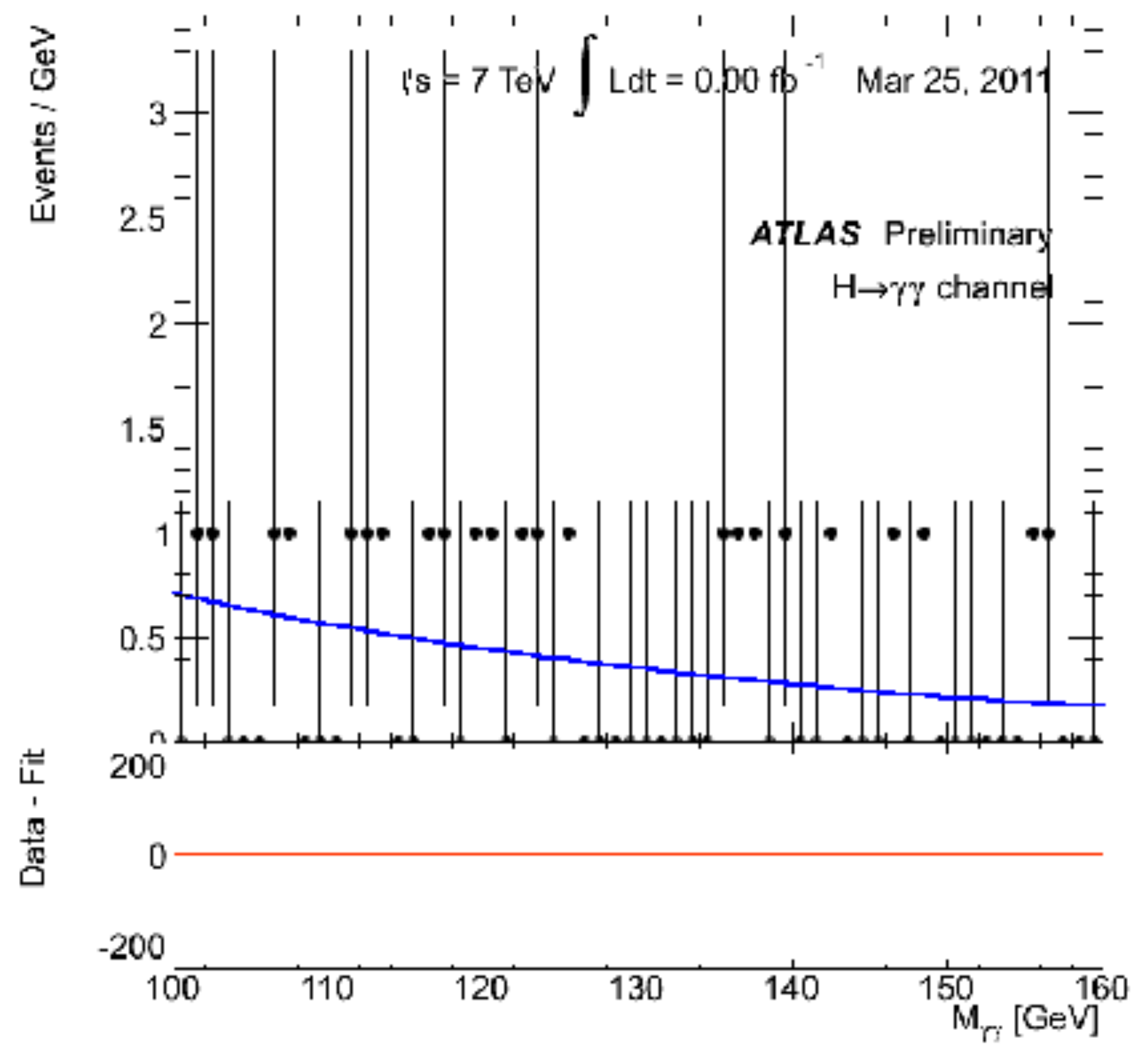
Need to test SM predictions for deviations!

Discovery of a shiny resonance

- Channel with largest significance for Higgs boson discovery



- QFT at work: Counter-intuitive coupling to **massless** gluons and photons



- Data-driven background subtraction and signal bump-hunt

→ $5.6\ \sigma$ with full run-1 CMS data-set

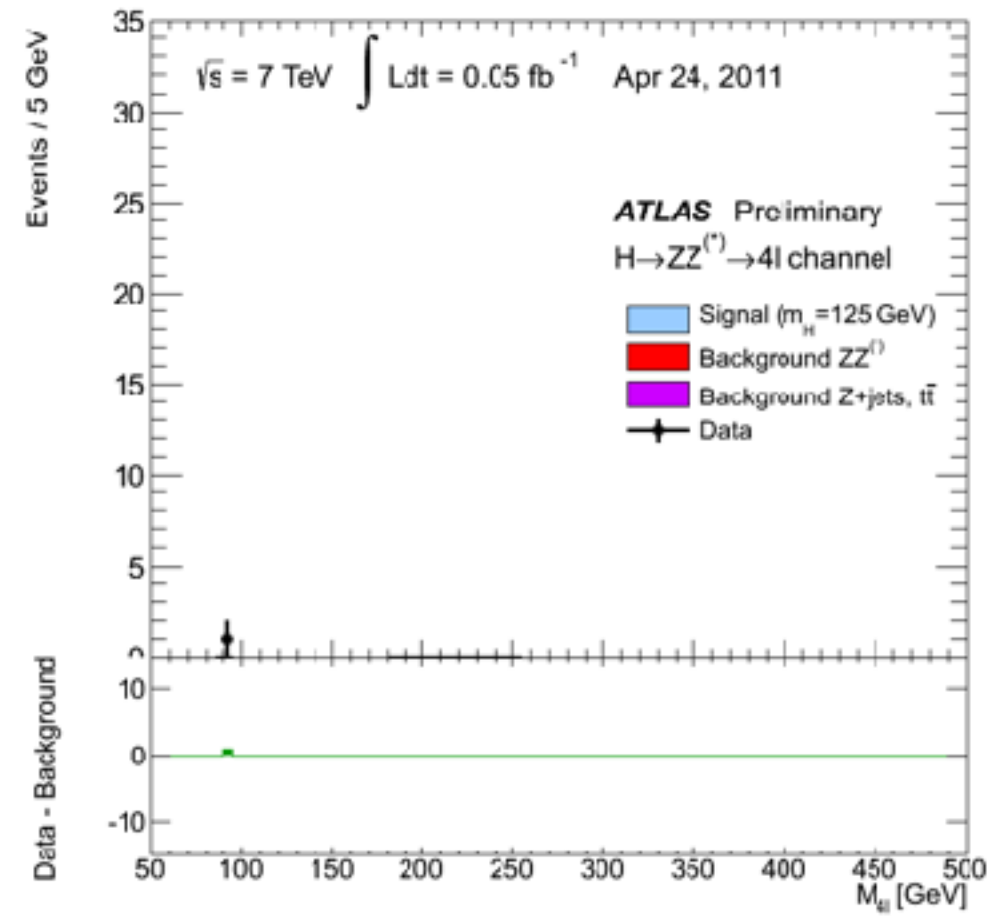
Observation in many other channels

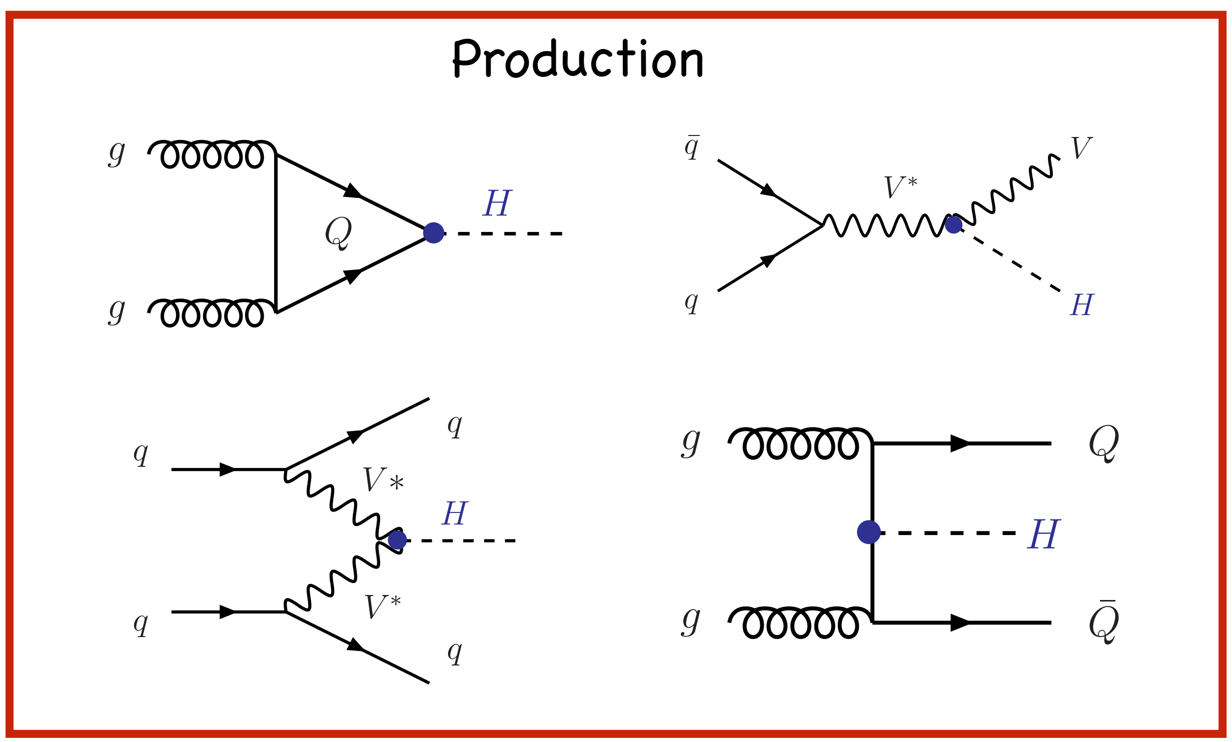
- Early confirmation that new resonance couples to gauge bosons in

$$H \to ZZ^* \quad \text{and} \quad H \to WW^*$$

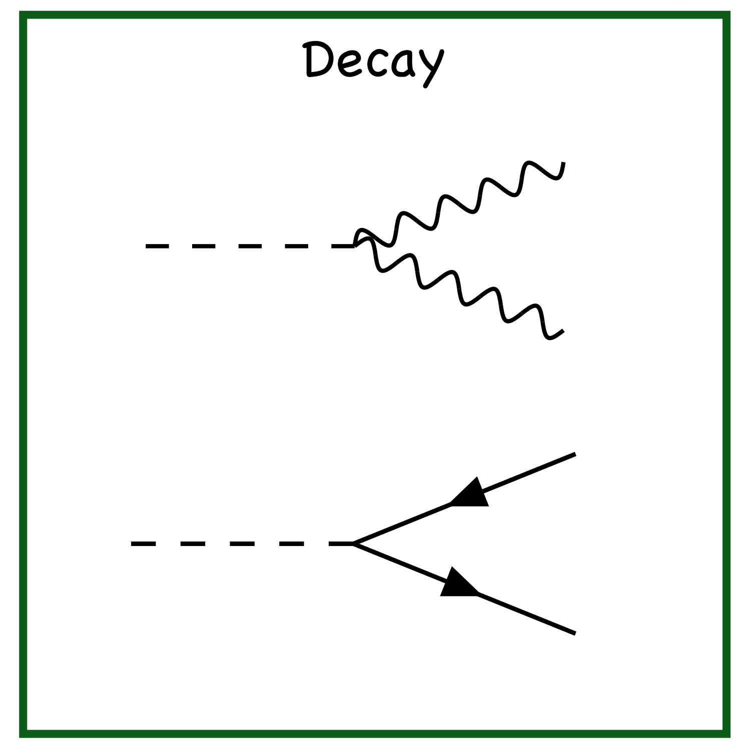
- Important channels to confirm Higgs can unitarize longitudinal gauge-boson scattering

- Many other channels observed too:

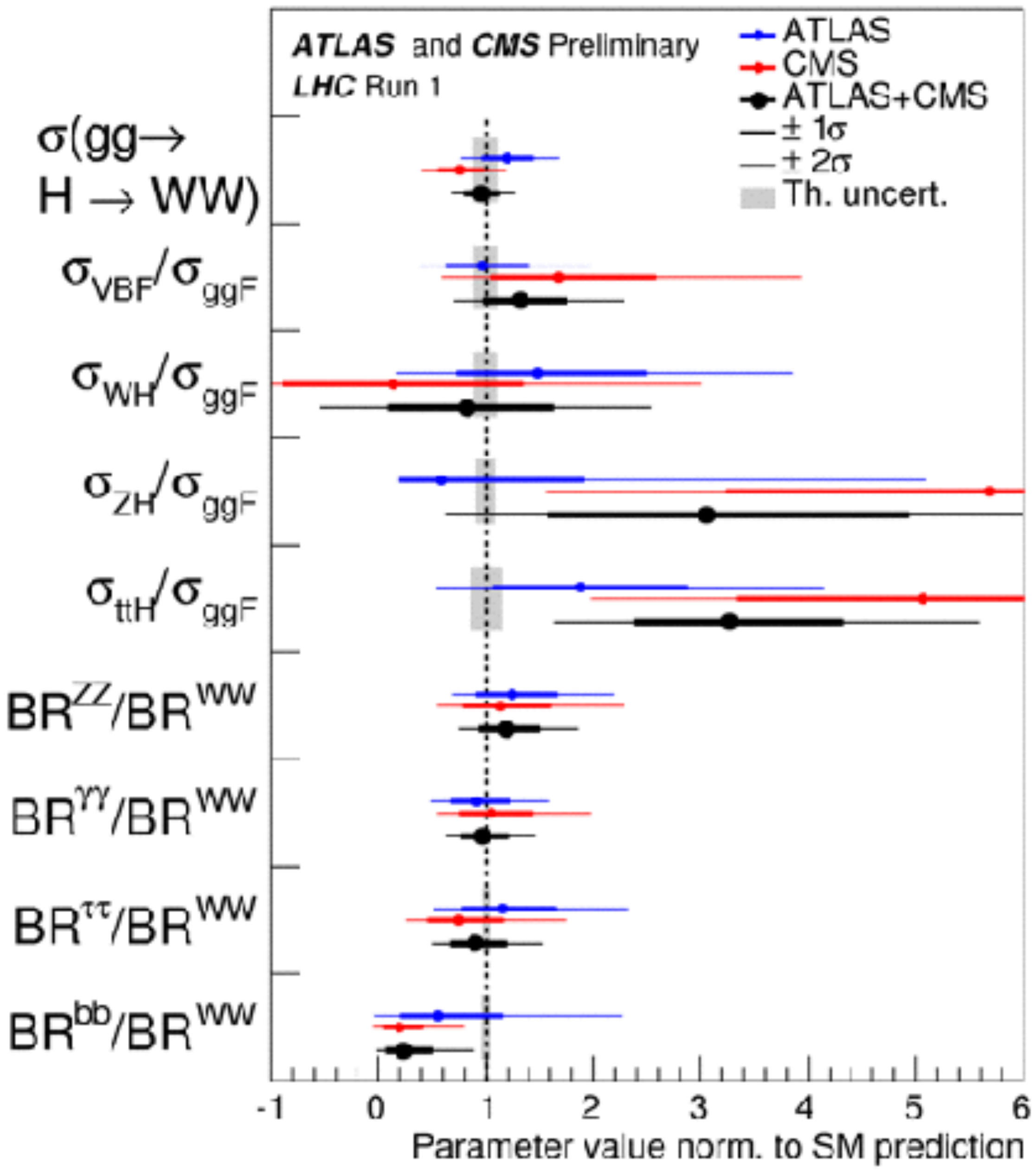


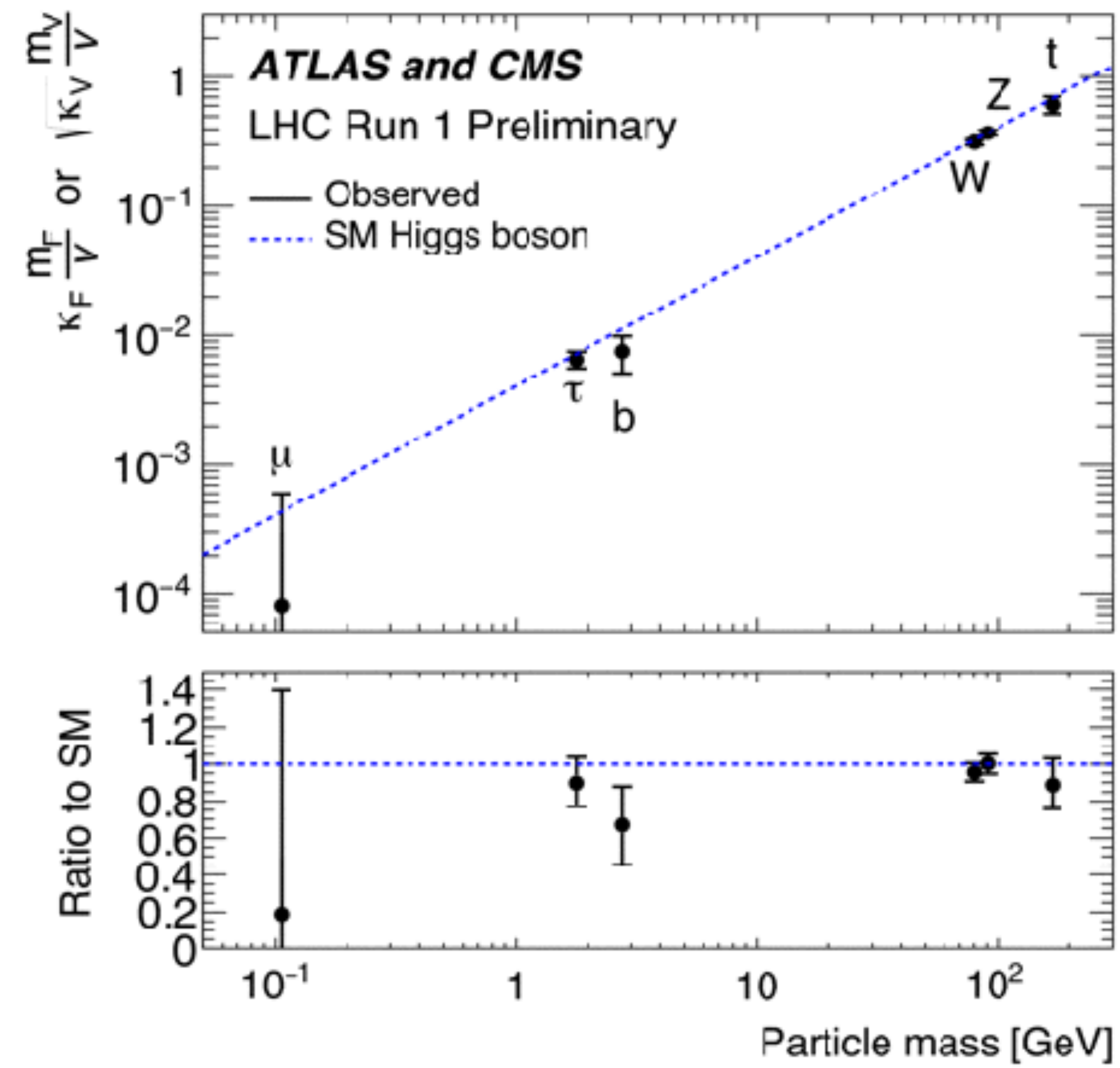


$\otimes$



Higgs couplings after run 2



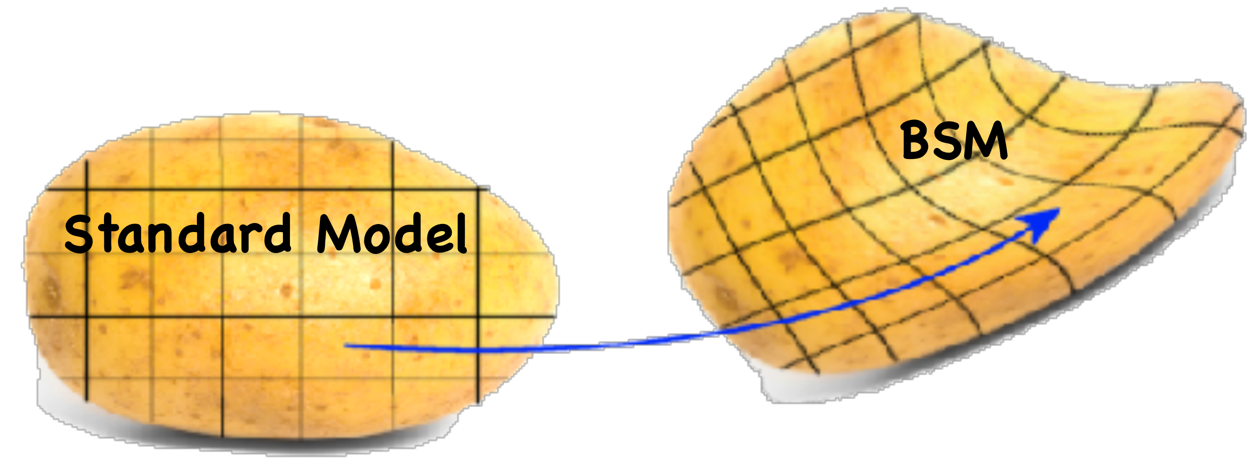


Within current precision,

Higgs properties in good agreement with Standard Model predictions

Improved/Unified way of interpretation of measurements

- interpretation of any measurement model dependent
- interpretation requires communication between different scales as well as theorists and experimentalists



Deformation of the Standard Model within different frameworks

Kappa Framework

- NP models simple rescaling of couplings
- No new Lorentz -structures or kinematics

EFT

- SM degrees of freedom and symmetries
- New kinematics/ Lorentz structures

Simplified Models

- EFT but new low-energy degrees of freedom
- Subset of states of full models, reflective at scale of measurement

Full (UV) Model

- Very complex and often high-dimensional parameter space
- Allows to correlate high-scale and low-scale physics

→ Complexity/Flexibility

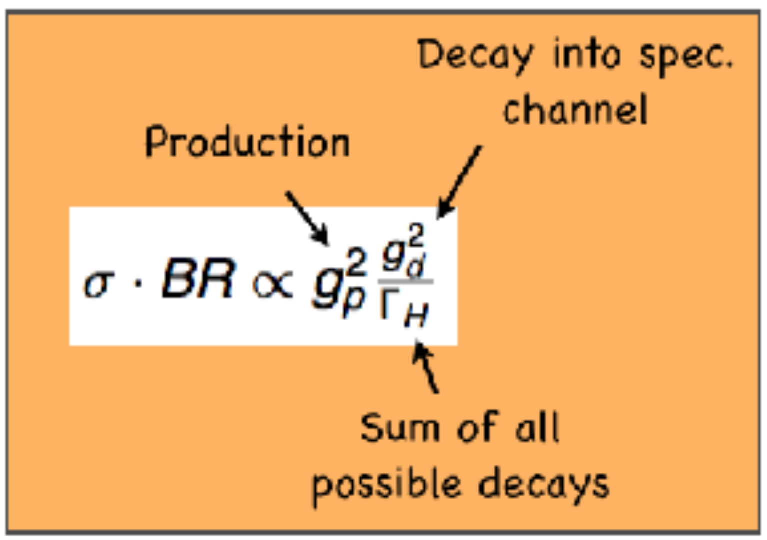
Kappa framework used in most coupling measurements to date

kappa is ratio of couplings:

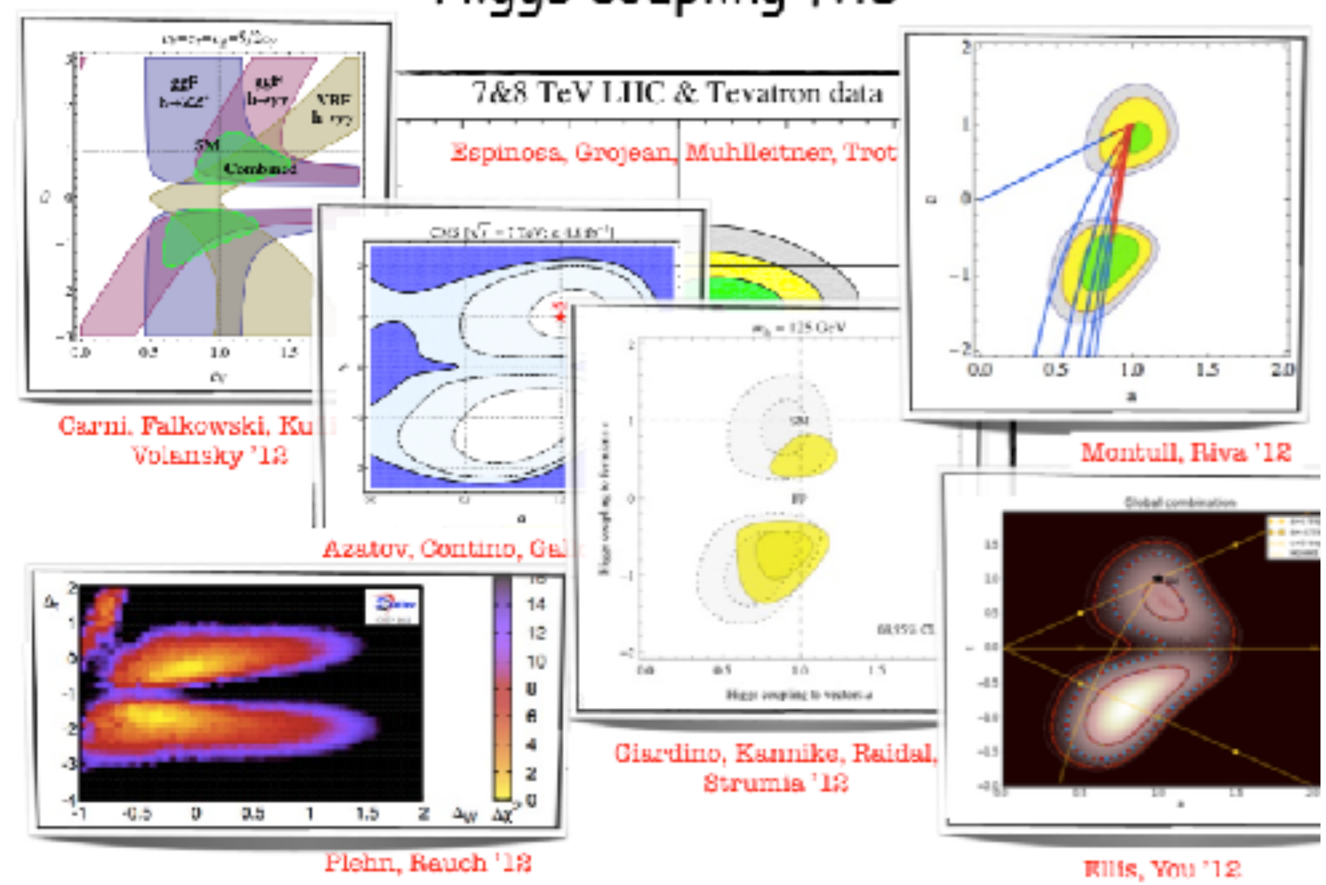
$$\kappa_i = \frac{g_i}{g_{i,SM}}$$

so-called

$\sigma(g_p) \times \mathrm{BR}(g_d)$ physics



Higgs coupling fits

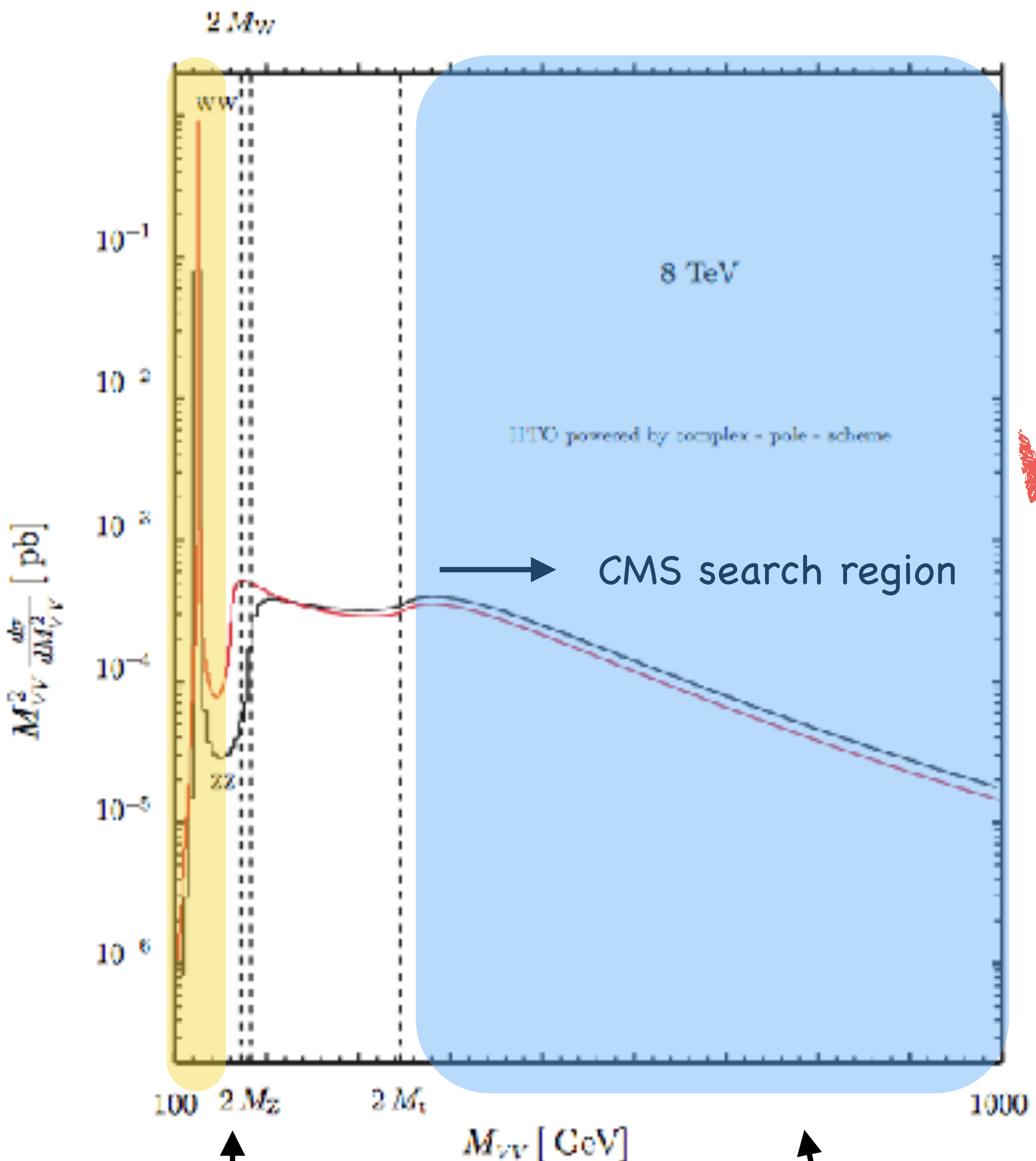


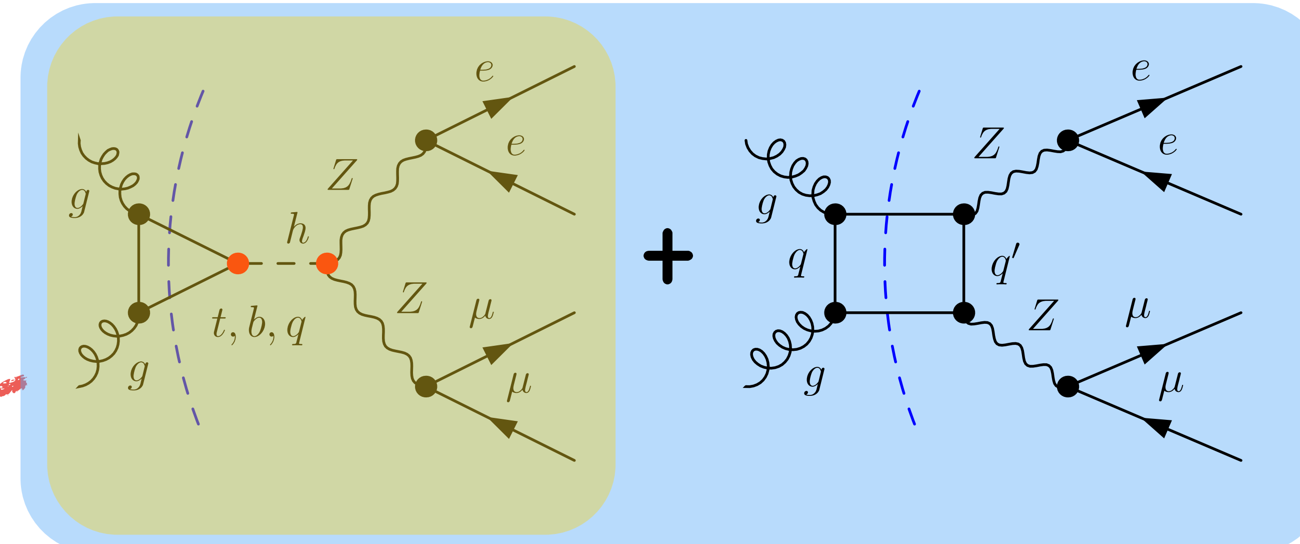
- try to over-constrain couplings basis
- Higgs width of particular importance

→ Higgs coupling fits based on total rates... no dynamics

→ No new Lorentz structures, limited applicability for new physics

Interesting property: measurement of Higgs-width





I. Count events in on-shell region

→ fix signal strength $\mu_{i,j} = \sigma_{H,i} \times BR_j \sim \frac{g_{ggH}\, g_{HZZ}}{\Gamma_H}$

II. measure $g^2_{ggH}\, g^2_{HZZ}$ in off-shell region using angular correlations of 4l decay products

III. insert off-shell coupling measurement in on-shell signal strength to bound width

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{\Gamma_H}$$

$$\sigma^{\text{off-peak}}_{gg\to H\to ZZ} \sim g^2_{ggH}\, g^2_{HZZ}$$

→

Obs.(exp.) @95% C.L:

$\Gamma_H < 4.2\,(8.5)\ \Gamma_H^{SM}$

$\Gamma_H < 17.4\ (35.3)$ MeV

[Kauer, Passarino 2011]

[Caola, Melnikov 2013] [Campbell, Ellis, Williams 2013]

Example 'width-measurement'

Measure coupling off-shell -> limit denominator on-shell

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{\Gamma_H} \quad \longleftrightarrow \quad \sigma^{\text{off-peak}}_{gg\to H\to ZZ} \sim g^2_{ggH}\, g^2_{HZZ}$$

Kappa Framework ✓

- Assuming global coupling rescaling

EFT ✓

- Assuming valid and no flat directions

↓

Coupling assumptions strong
LEP limits stronger than LHC

$$0.73\;\Gamma_{SM} \lesssim \Gamma_h \lesssim 1.87\;\Gamma_{SM}$$

[Englert, McCullough, MS '15]

Simplified Models ⚡

- Eg. **Higgs portal**, NP can contribute on-shell but not off-shell [Englert, MS '14]
- Eg. **Higgs triplet**, new scalar below measurement range cancels on-shell enhancement [Logan '15]

Full (UV) Model ⚡

- Uninteresting width not a free parameter of the theory

width derived and fully determined

What will the future hold?

Assumed scenario: Higgs boson is only window to New Physics

Discussed future collider concepts:

- HL-LHC, HE-LHC, FCC(hh)
- LHCeC
- Muon-Collider (125 GeV)
- ILC250, ILC500, FCC-ee-240, FCC-ee-350, CLIC1400, CEPC

General considerations:

<u>proton vs electron/positron vs muon</u>

- only protons and electrons/positrons stable
- bremsstrahlung energy loss pronounced for light particles $\Delta E \sim E^4 R^{-1} m^{-4}$
- cleaner final states for electrons/muons

<u>circular vs linear collider</u>

- charged particles in circular motion: permanently accelerated towards center -> emitting photons as synchrotron light $\Delta E \sim E^4 R^{-1} m^{-4}$
- large loss of energy [hypothetical TeV collider at LEP: $\Delta E \simeq E$ per turn]
- no-more sharp initial state energy
- larger luminosity for continuously accelerated particle bunches

Comparison precision for Higgs couplings [Thanks to Keith Ellis for slides]

Parameter	HL-LHC	FCC-ee	FCC-ee	ILC	CLIC	CEPC	μ-Coll
$\sqrt{s}$[TeV]	14	350	240	250	1400	240	125
Lum/IP[E34]	5	1.9	8.5	1.35	1.5	2	0.01?
total[ab^{-1}]	3+(3)	1.3+1.3	5+5	2	1.5	2+2	0.002?
years[Sn'm'ss]	6	6.8	5.9	15	10	10	2?
Δm_h[MeV]	$\sim$ 100			14	47	5.9	0.06
Γ_h[%]	-	1.2	2.4	3.9	3.7	2.7	3.6
Δg_{hZZ}[%]	4	0.15	0.16	0.38	0.8	0.26	
Δg_{hWW}[%]	4.5	0.19	0.85	1.8	0.9	1.2	2.2
Δg_{hbb}[%]	11	0.42	0.88	1.8	1.0	1.3	2.3
$\Delta g_{h\tau\tau}$[%]	9	0.54	0.94	1.9	1.7	1.4	2.3
$\Delta g_{h\gamma\gamma}$[%]	4.1	1.5	1.7	1.1	5.7	4.7	5
Δg_{hcc}[%]	-	0.71	0.71	2.4	2.3	1.7	10
Δg_{hgg}[%]	6.5	0.8	0.80	2.2	1.8	1.5	-
Δg_{htt}[%]	8.5	-	-	-	4.2	-	-
$\Delta g_{h\mu\mu}$[%]	7.2	6.2	6.4	5.6	14.1	8.6	2.1
$\Delta\Gamma_{\text{invis}}$[%]	$\sim$10			0.32			
Δg_{hhh}[%]	-400,1200	-	-	-	40	-	
References	ATL-PHYS-PUB -2014-016	1308.6176	1308.6176	1710.07621 1711.00568	1608.07538	IHEP-CEPC-DR -2015-01	1304.5270 1308.2143

(take numbers with grain of salt)

Summary

- Collider physics only way to study high-energy interactions in controlled environment
- Strong interplay between theory and experiment necessary
- Higgs boson window to new physics - even more so at future colliders

Literature for further reading:

"QCD and Collider Physics"

Ellis, Stirling, Webber

"The Black Book of Quantum Chromodynamics"

Campbell, Huston, Krauss