LHC Theory

DESY Summer Students Lectures 2011

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LHC Theory 1

Zeuthen, 28 July 2011

HELMHOLTZ ASSOCIATION

DESY

Theory at the Large Hadron Collider

- Introduction to collider physics, QCD and basic LHC processes

  Thursday 28 July 2011

- Introduction to EW theory, Higgs physics and BSM physics

  Friday 29 July 2011

Today:

- ***Introduction to high energy collider physics***
- ***Basics of QCD***
- ***Perturbative QCD at colliders***
- ***Parton density functions***
- ***Jet cross sections***
- ***Important processes at the LHC***

High energy physics – what we know

Q What is the world made out of and what holds it together?

- What are the basic building blocks of matter?
- How do they interact?

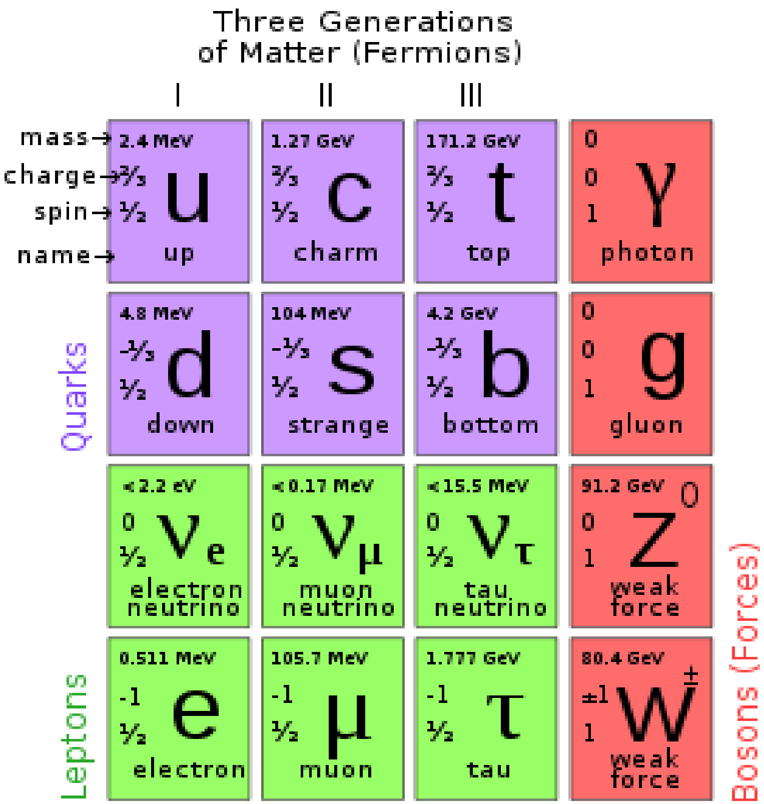
A Standard Model

- Fermions (constituents of matter, spin ½):

  quarks and leptons

- Bosons (force carriers, spin 1):

  photon, weak bosons, gluon

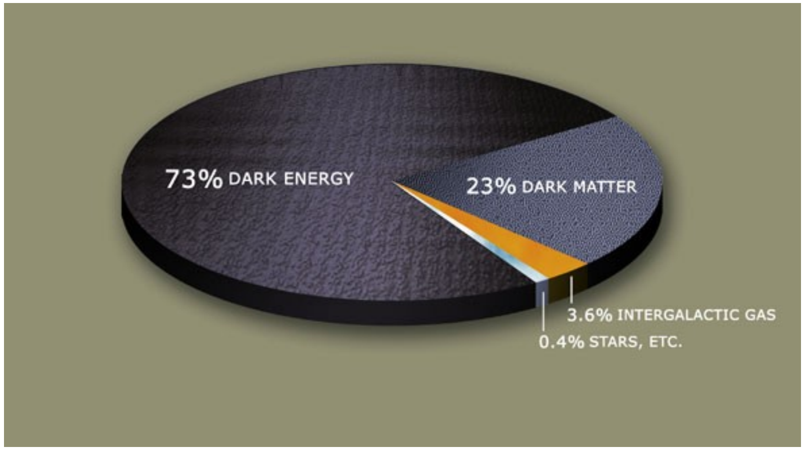


Q Is that it?

A Not quite...

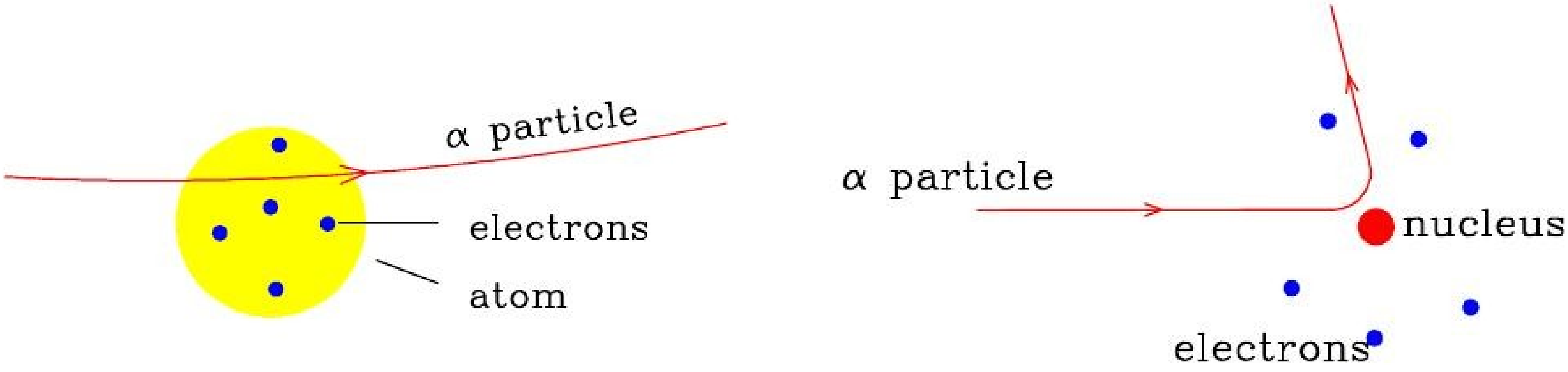
Open questions

- What is the mechanism of EW symmetry breaking?
  - Does the SM Higgs boson exist?
  - What is the origin of mass?
- Observations not addressed in SM
  - What is dark matter, dark energy?
  - Why is there matter-antimatter asymmetry?
  - Why are neutrinos heavy?
- Conceptual questions
  - Hierarchy problem
  - Why three forces?
  - Why three generations?
  - How to include gravity?



How to make progress?

- Scattering experiments!
- The prototype: Rutherford scattering



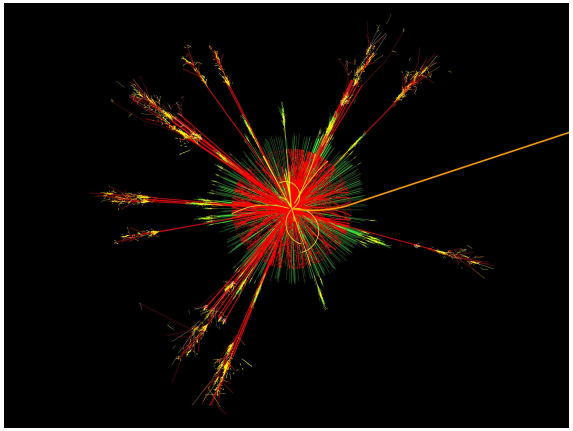
- Large angle distribution of α particles scattering on gold is consistent with the assumption that positive charge is concentrated in a small volume. This demonstrates the existence of the nucleus.
- Principle essentially unchanged at LHC, but resolving smaller scales requires larger energies.

The LHC

- Explicitly designed to study the electroweak symmetry breaking mechanism and as a discovery machine for processes with x-sec down to few fb in the range 100 GeV to 1-2 TeV.
- Hadron collider. The fundamental collisions between partons allow to span different order of magnitude in the CM energy.
- Nominal CM energy of $\sqrt{s} = 14\, TeV$. For $x_1, x_2 \approx 0.15 - 0.20$ one has partonic CM energy

$$\hat{s} = x_1 x_2 s \approx 1\, TeV$$

- Proton-proton collider, due to difficulties to accumulate high-intensity beams of anti-protons.
- Design luminosity $10^{34} cm^{-2} s^{-1}$, obtained with 2808 bunches per beam colliding every 25 ns.
- Easier to accelerate protons, energy loss due to synchroton radiation proportional to $\gamma^4 = (E/m)^4$.



LHC goals

- Two general purpose experiments

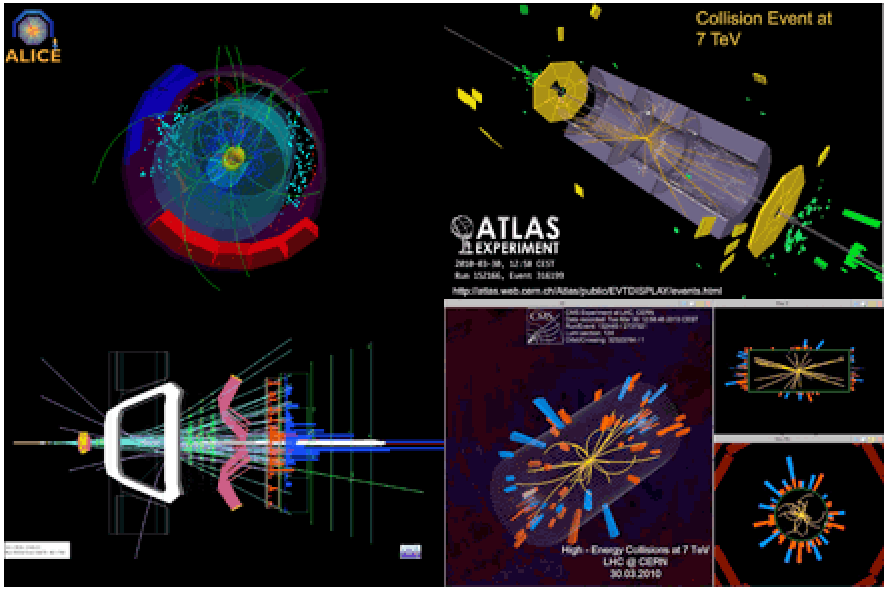
  ATLAS and CMS

- More specific ones

  LHCb, ALICE, TOTEM, LHCf

- Main goals of ATLAS and CMS:

- Study EW symmetry breaking mechanism. Search for Higgs boson in the 100 GeV – 1 TeV mass range.
  - If found, understand if SM Higgs or not
  - If not found, look for alternative models
- Search for new physics. SUSY particles with m < 3 TeV will be accessible. More exotic models have a mass reach of 5 TeV.
- Perform precision measurements of EW, QCD, CP and B sectors: $m_W, m_{top}, \sin^2\theta_W$ and triple gauge couplings.



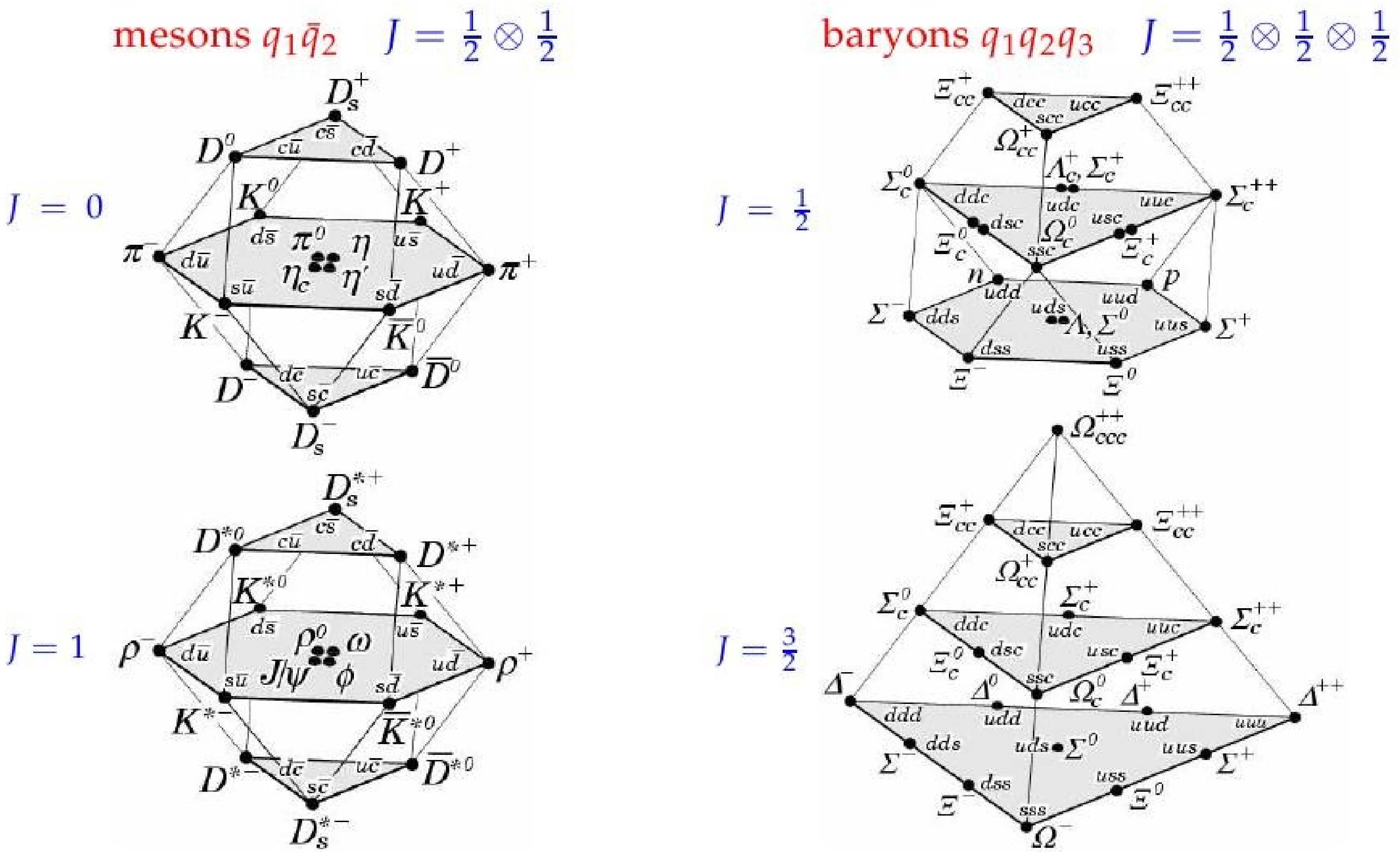
Collider phenomenology

- LHC will test the structure of matter at the shortest distances ever achieved in the laboratory. (Experiment)
- Literally hundreds of models have been proposed for what physics looks like beyond the SM, at the TeV scale. (Model building)
- Interpreting the huge volume of experimental data, looking for new physics beyond the SM and picking out the proper models requires precise theoretical predictions for both signal and background processes in SM and beyond. (Phenomenology)
  - Need to validate detectors, modeling, etc. by measuring known SM processes. This requires precise theoretical knowledge of standard processes (vector boson production, jet production, heavy quark production,...)
  - Look for deviations from SM. To do this, clearly we must know precisely what the SM predicts.
  - If deviations are found, determine which BSM physics models might explain these.
- Collider phenomenology: theoretical model → prediction for measurable quantity

Quantum chromodynamics (QCD)

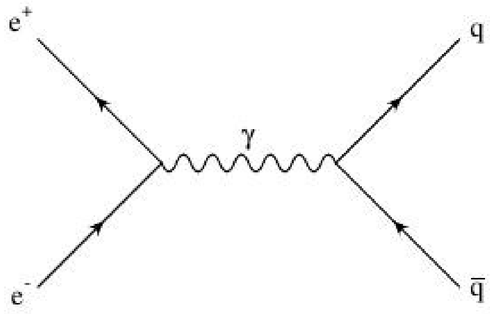
- The theory that describes quarks and gluons is QCD.
- Assumptions:
  - A quark is a point-like spin ½ particle that carries another quantum number: COLOR
  - Each quark can have one out of three different colors: ("red, green, blue")
  - The strong force is mediated by gluons, that also are colored. There can be 8 combinations, so there are 8 gluons. Notice: the photon doesn't carry any charge!
  - The coupling constant g_s is generally greater than the electromagnetic one: "strong" force!
- The theory is supported by the following experimental evidence:
  - Hadron spectrum can be classified according to quark content.
  - Observable hadrons are neutral in color.
  - Nevertheless, effects due to the presence of the color quantum number are observed!
  - At low energies quarks and gluons interact strongly.
  - At high energies quarks and gluons behave as free particles.

Mesons and baryons



$SU(4) : u, d, s, c$

Color

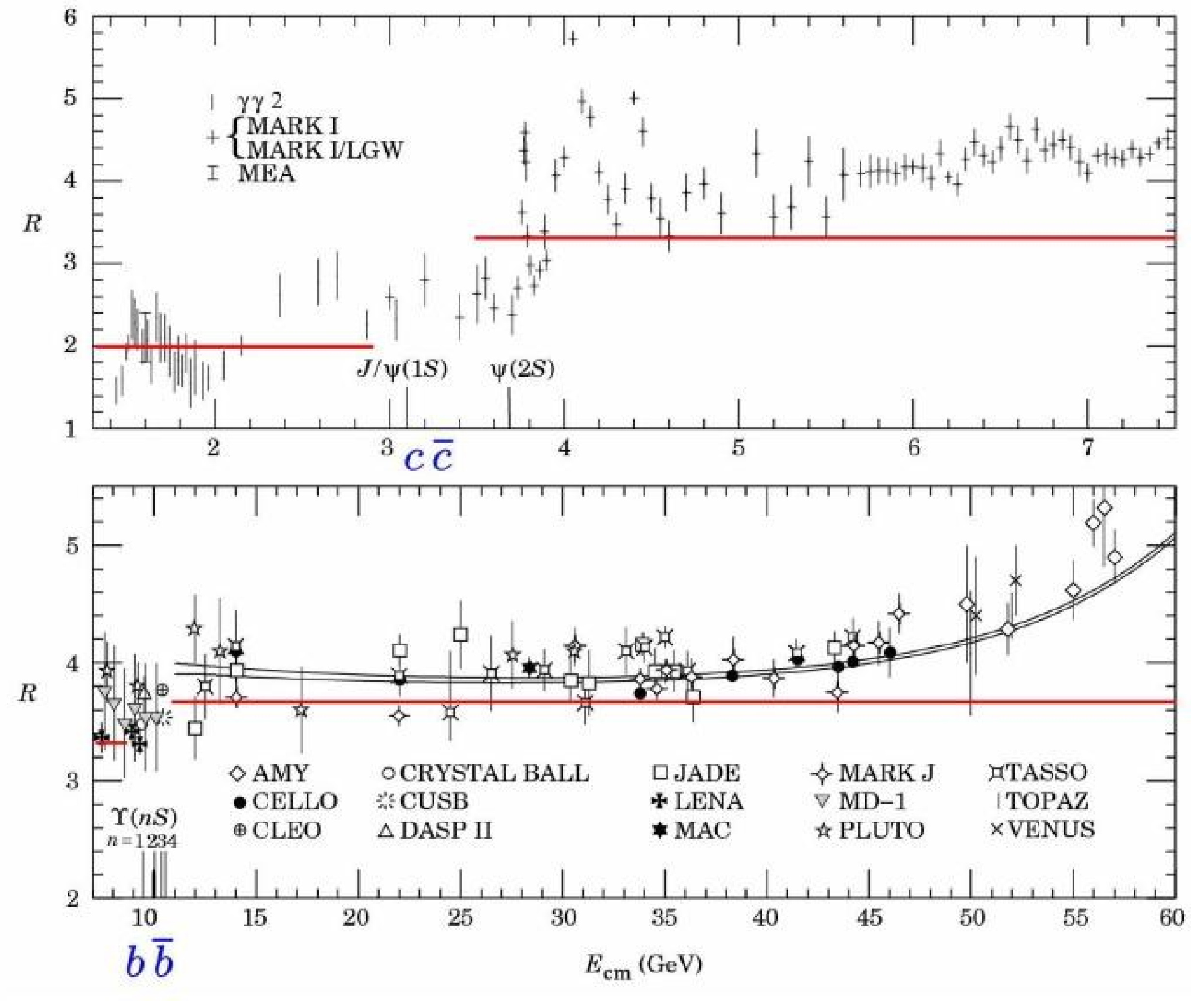


$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \sim \frac{\sum_q \sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} \sim N_c \sum_q Q_q^2$$

$$= \left\{ \begin{array}{ll} \frac{6}{9} N_c & (u,d,s) \\ \frac{10}{9} N_c & (u,d,s,c) \\ \frac{11}{9} N_c & (u,d,s,c,b) \end{array} \right\}$$

fractional charges!!

Color


γγ 2
MARK I
MARK I/LGW
MEA
R
J/ψ(1S)
ψ(2S)
$c\bar{c}$
AMY
CELLO
CLEO
CRYSTAL BALL
CUSB
DASP II
JADE
LENA
MAC
MARK J
MD–1
PLUTO
TASSO
TOPAZ
VENUS
Υ(nS)
n=1234
$b\bar{b}$
E_{cm} (GeV)

$N_c = 3$

Quantum Field Theory: (very) basic concepts

- The language in which the SM (hence QCD) is phrased is that of Quantum Field Theory (QFT). The basic setup of a QFT is as follows.
  - Prescribe the set of fields (↔ very roughly particles) of the theory.
  - Prescribe the set of symmetries (↔ very roughly interactions) of the theory. This constrains the form of interactions between the fields: some types of interactions may not be allowed by the symmetries.
  - Write the most general Lagrangian/action built out of the given fields that has the prescribed symmetries and is "renormalizable". This gives the "equations of motion".
- QCD as an example
  - Fields: for each flavor of quark, introduce a spinor field $(\Psi_f)^a{}_i$. Here f = u,d,s,c,b,t is the flavor index, and Ψ carries color index "a", and spinor index "i".
  - Symmetries: SU(3) "color" gauge symmetry. This is a generalization of the gauge symmetry of electrodynamics. It forces the existence of a gluon field $A^\alpha{}_\mu$, which carries a color index "α", and Lorentz index "μ". It also fixes the precise form of quark-gluon and gluon-gluon interactions.
  - QCD Lagrangian: $\sum_f \bar{\Psi}_f(\mathrm{i}\not{D} - m_f)\Psi_f - \frac{1}{4}\mathrm{tr}\, F^{\mu\nu}F_{\mu\nu}$

Quantum Field Theory: (very) basic concepts

- In principle, predictions for cross sections of scattering processes (e.g. $e^+e^- \to q\bar{q}$) may be computed perturbatively, i.e. as a series expansion in terms of the (running) coupling.
  - E.g.: $R = \sigma(e^+e^- \to q\bar{q})/\sigma(e^+e^- \to \mu^+\mu^-) = R_0\,[1 + 2\,(\alpha_S/2\pi) + 5.636\,(\alpha_S/2\pi)^2 + \ldots]$
- Feynman rules, Feynman graphs
  - The mathematical expressions of perturbation theory may be constructed from a set of graphical rules known as Feynman rules. These associate a set of graphs to a given process (at any order in PT), the Feynman graphs. The sum of graphs corresponds to the mathematical expression for the appropriate scattering matrix element.
  - In graphical terms, the perturbative expansion is essentially an expansion in the number of loops in Feynman-graphs.
- Fact: in QFTs the strength of interactions (usually) depends on the energy scale at which it is measured. We say that couplings "run".
  - Very roughly due to the fact that in QFT the vacuum is filled with particle-antiparticle pairs.
  - The running can be computed. The value at a particular energy needs to be fixed by experiment.

QCD Feynman rules

$$= \delta^{ab}\left[-g^{\alpha\beta} + (1-\lambda)\frac{p^\alpha p^\beta}{p^2+i\epsilon}\right]\frac{i}{p^2+i\epsilon}$$

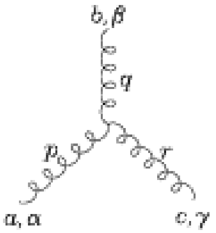
- Gluon propagator

$$= \delta^{ab}\frac{i}{p^2+i\epsilon}$$

- Ghost propagator

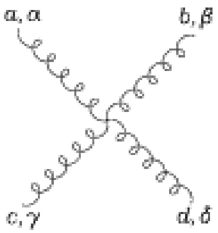
$$= \delta^{ik}\left.\frac{i}{\not p - m + i\epsilon}\right|_{mn}$$

- Quark propagator



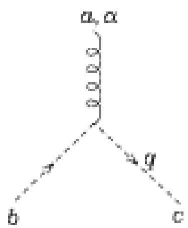
$$= -g_s f^{abc}\left[g^{\alpha\beta}(p-q)^\gamma + g^{\beta\gamma}(q-r)^\alpha + g^{\gamma\alpha}(r-p)^\beta\right]$$

- Triple gluon vertex



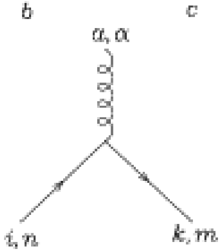
$$\begin{aligned} &= -ig_s^2 f^{xac} f^{xbd}\left(g^{\alpha\beta}g^{\gamma\delta} - g^{\alpha\delta}g^{\beta\gamma}\right) \\ &\quad -ig_s^2 f^{xad} f^{xbc}\left(g^{\alpha\beta}g^{\gamma\delta} - g^{\alpha\gamma}g^{\beta\delta}\right) \\ &\quad -ig_s^2 f^{xab} f^{xcd}\left(g^{\alpha\gamma}g^{\beta\delta} - g^{\alpha\delta}g^{\beta\gamma}\right) \end{aligned}$$

- Quadruple gluon vertex



$$= g_s f^{abc}\, q^\alpha$$

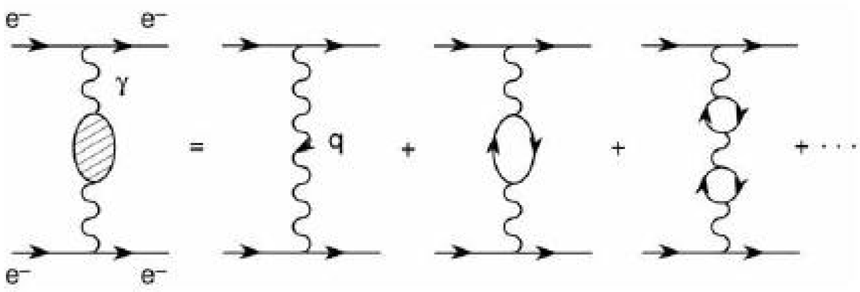
- Ghost-gluon vertex



$$= -ig_s t^a_{ki}\,\gamma^\alpha_{mn}$$

- Quark-gluon vertex

Running coupling in QED



Running coupling

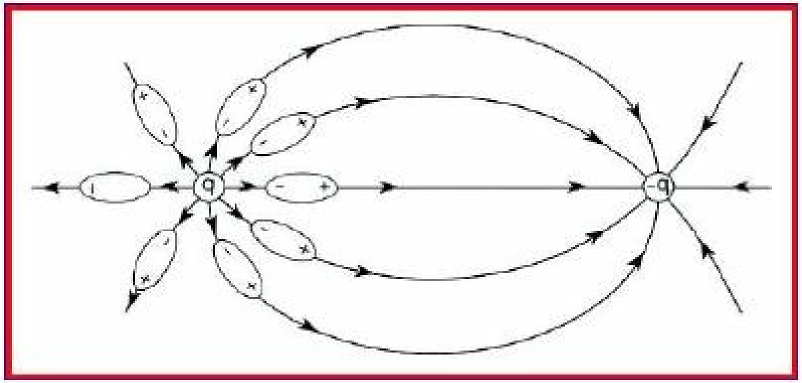
$$\alpha = e^2/(4\pi)$$

$$\alpha(q^2) = \frac{\alpha(m_e^2)}{1 - \frac{\alpha(m_e^2)}{3\pi}\log\left(\frac{q^2}{m_e^2}\right)}$$

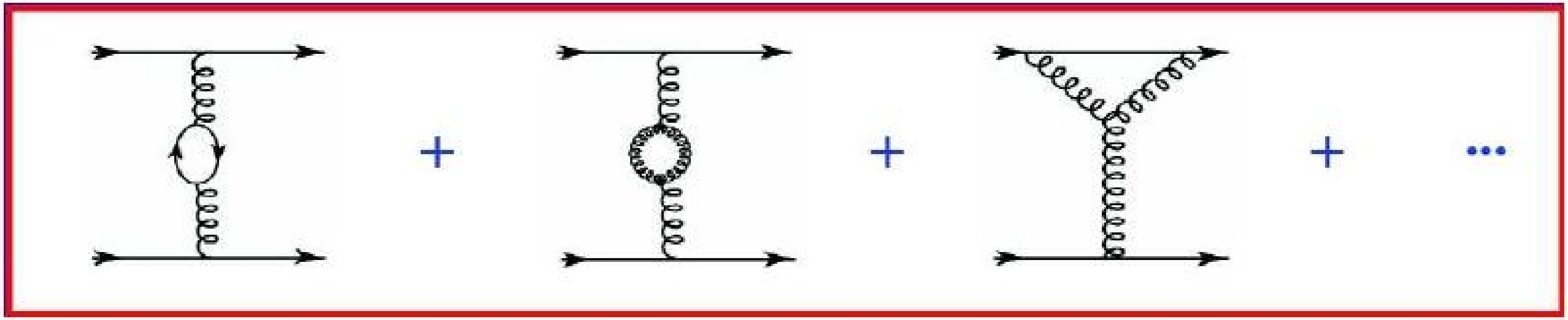
- $\alpha(q^2)$ increases with q^2
  $\alpha(q^2)$ decreases at large distances.
  The **electric charge** in **NOT** a **constant**.

- The vacuum behaves like a polarized dielectric medium

- $\alpha(m_e^2) = 1/137.03599911(46)$
  $\alpha(m_Z^2) = 1/128.95 \pm 0.05$



Asymptotic freedom in QCD



The strong coupling $\alpha_s = g_s^2/(4\pi)$ "runs" according to

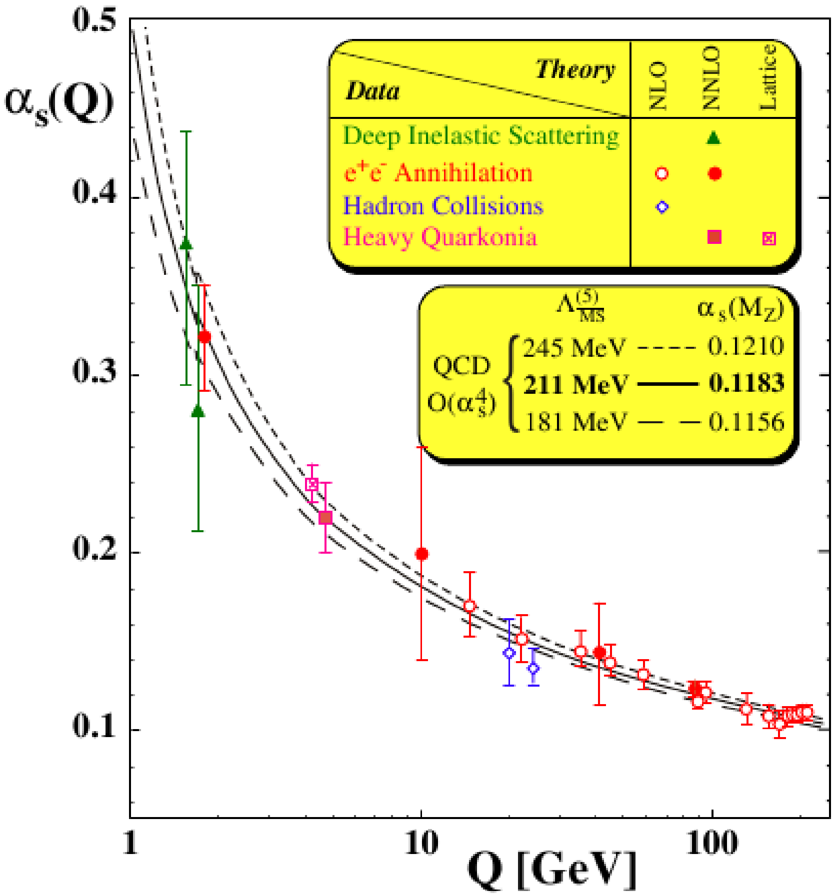
$$\alpha_s(q^2) = \frac{\alpha_s(q_0^2)}{1 + \beta_0\,\alpha(q_0^2)\log\left(\frac{q^2}{q_0^2}\right)}$$

where

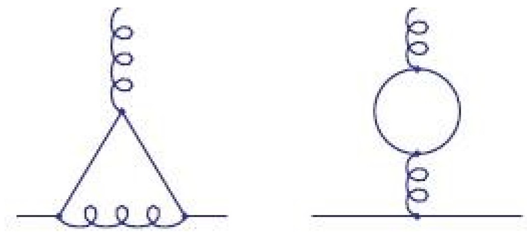
$$\beta_0 = \frac{11N_c - 2n_f}{12\pi} > 0 \qquad N_c = 3 \qquad n_f = 6$$

$\alpha_s(q^2)$ decreases at short distances $\Longrightarrow$ **asymptotic freedom**

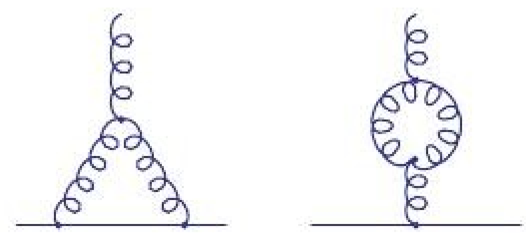
Asymptotic freedom



- Asymptotic freedom is due to the non-abelian nature of QCD (gluon self-interactions)
  - Screening (as in QED)

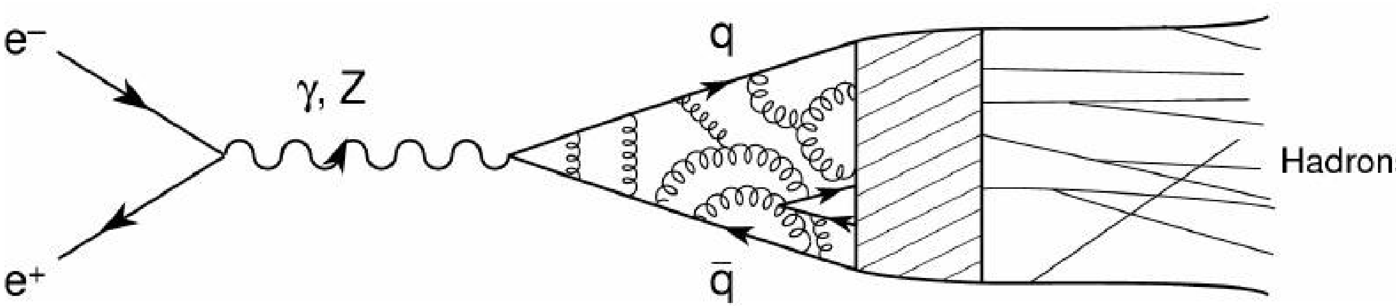


  - Anti-screening

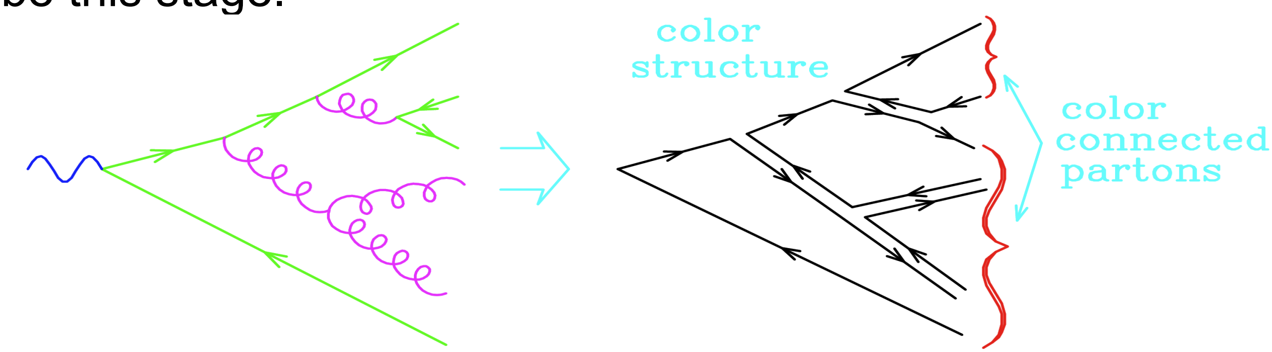


- It allows the use of perturbation theory at high energies – short distances

Confinement and hadronization



- The growing of $\alpha_S(q^2)$ at low energies eventually give rise to the confinement of quarks and gluons into hadrons. This results in colorless hadrons observed!
- The mathematical foundations of confinement are still lacking. It cannot be explained within perturbative QCD. Only by solving QCD “fully”, for example discretizing space-time (lattice), can one gain some insight!
- Phenomenological models of hadronization, based on low energy data, are used to describe this stage.

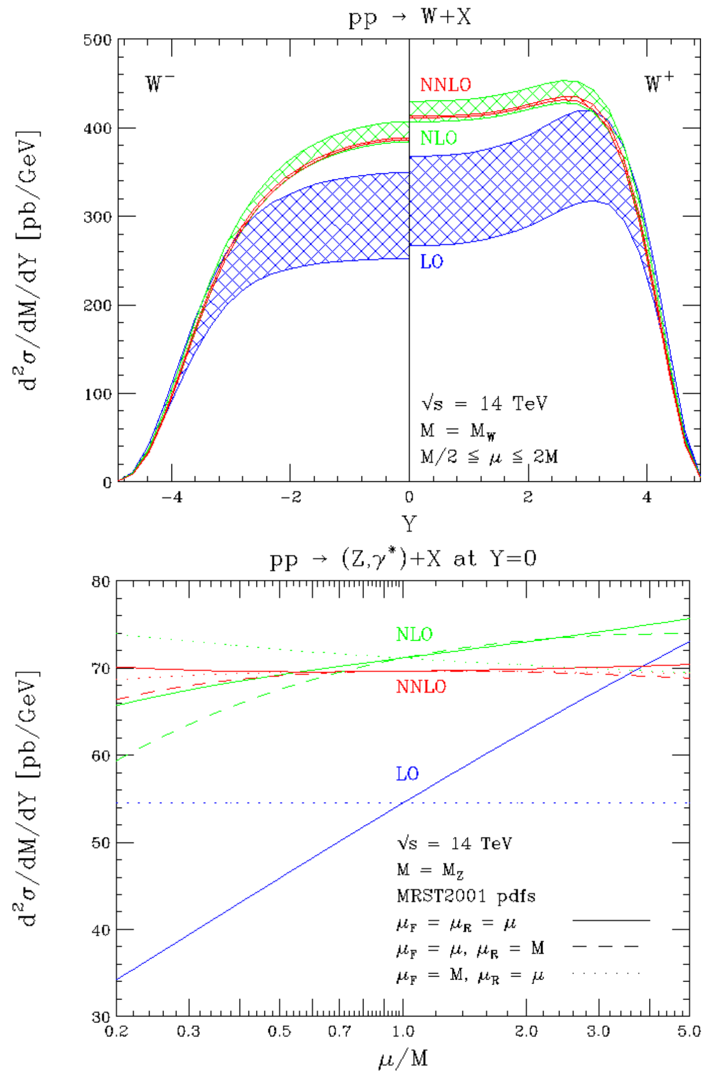


Perturbative QCD at hadron colliders

- QCD is the background to everything! Precise knowledge of cross sections is needed to study any new physics!

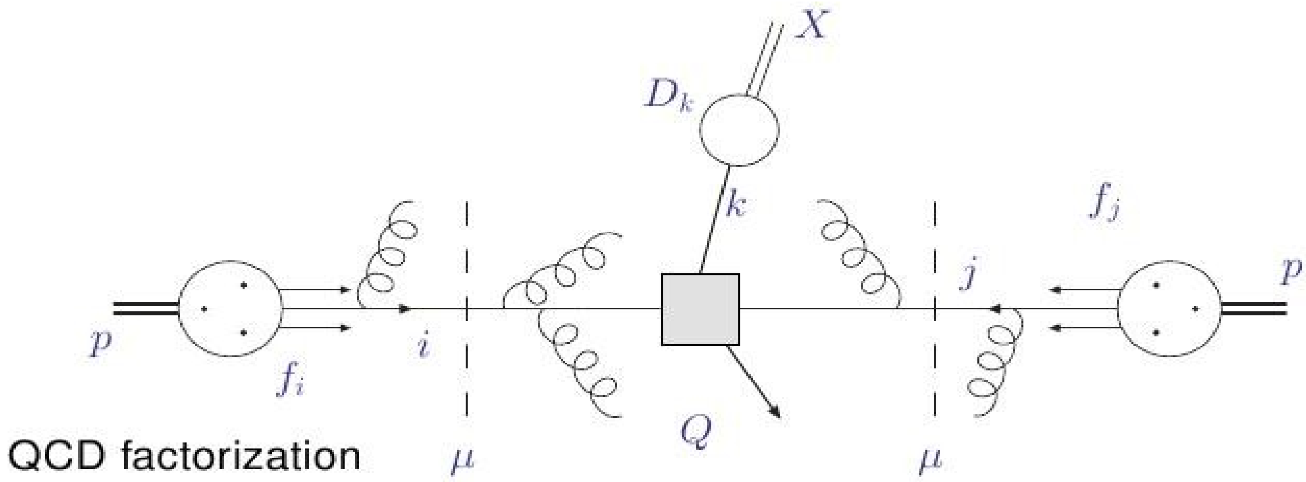
  New Physics = Signal – Background

- The calculation of x-secs in PT is based on “QCD factorization”.
- Leading order (LO) pQCD predictions are only order-of-magnitude est's.
- Going to higher orders (next-to-leading order, NLO) mandatory
  - Increases the accuracy, reducing the theoretical uncertainty due to dependence on unphysical scale μ.
  - It is possible to have more accurate distributions to compare with data!
  - Last but not least, test convergence of PT!



QCD factorization

- Hard hadron collisions: collisions between constituents at high energy



- QCD factorization theorems: the key insight is that it is possible to separate the hard dynamics (i.e. parton-parton scattering), calculable in pQCD, from the soft (e.g. the problem of proton binding).
  - This makes it possible to predict hadronic x-secs without having to solve the full QCD first!
  - Note how this separation introduces a more-or-less arbitrary and unphysical scale, the factorization scale, μ_F. Very roughly, scales above μ_F are hard, scales below are soft.

Hadronic cross sections

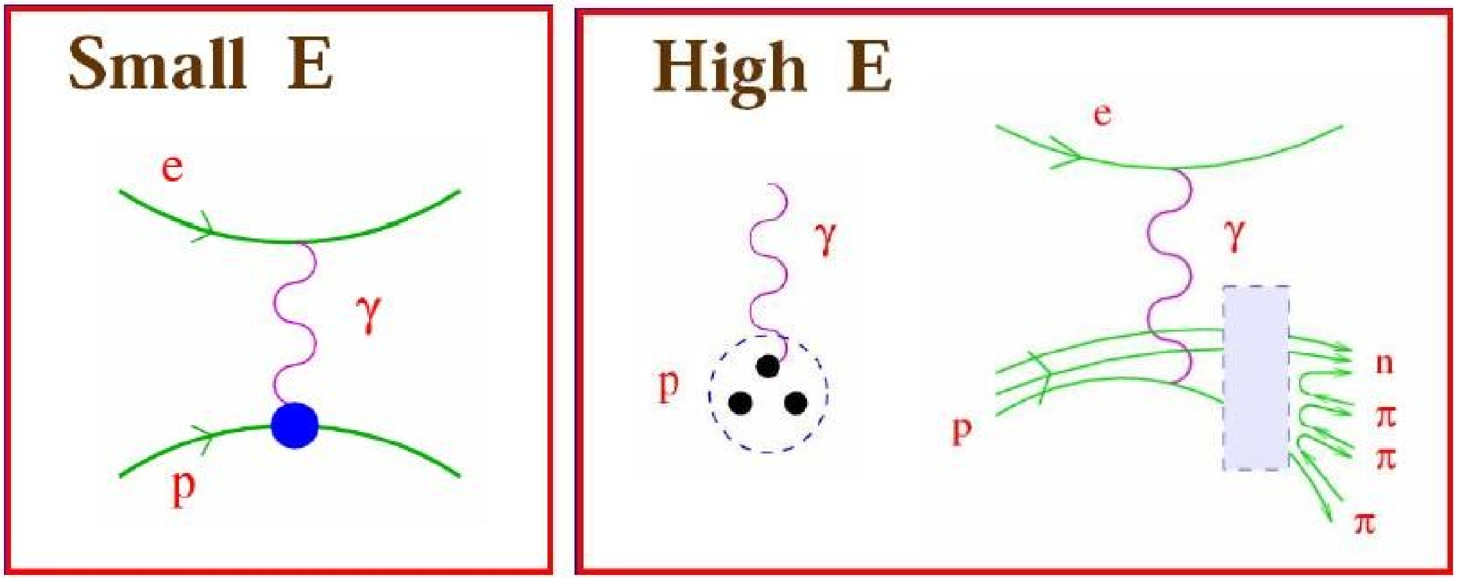
- Hadronic cross sections are written as convolutions:

$$\sigma_{pp\to X} = \sum_{ijk} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to k}\left(\alpha_s(\mu^2), Q^2, \mu^2\right) \otimes D_{k\to X}(\mu^2)$$

- Ingredients: pdf's hard partonic x-sec frag. fcn's
- Parton density functions
  - They essentially describe the makeup of the incoming hadron (e.g. proton). Very roughly, $f_i(x,\mu)$ gives the probability to find a parton of flavor “i” carrying a fraction x of the total momentum inside the hadron (proton), at scale μ.
  - Not calculable in pQCD, but process independent, i.e. they can be determined from one experiment, and used to make predictions for another.
- Hard partonic cross section
  - Describes the hard parton-parton scattering.
  - Process dependent, but calculable in pQCD involving only quarks and gluons.
- Fragmentation functions
  - Very roughly, $D_{k\to X}$ gives the probability for parton k to “fragment” into hadron X.

Looking inside the proton - Deep Inelastic Scattering

- Repeat the Rutherford experiment with electrons scattering off protons!
- Directly we cannot “see” the constituents of the proton (quarks) because of confinement (i.e. cannot free quarks from the proton).



- Nevertheless, at SLAC ('68) it was discovered that the distribution of scattered electrons is compatible with collisions with almost free particles of spin ½, with dimensions much smaller that the proton!

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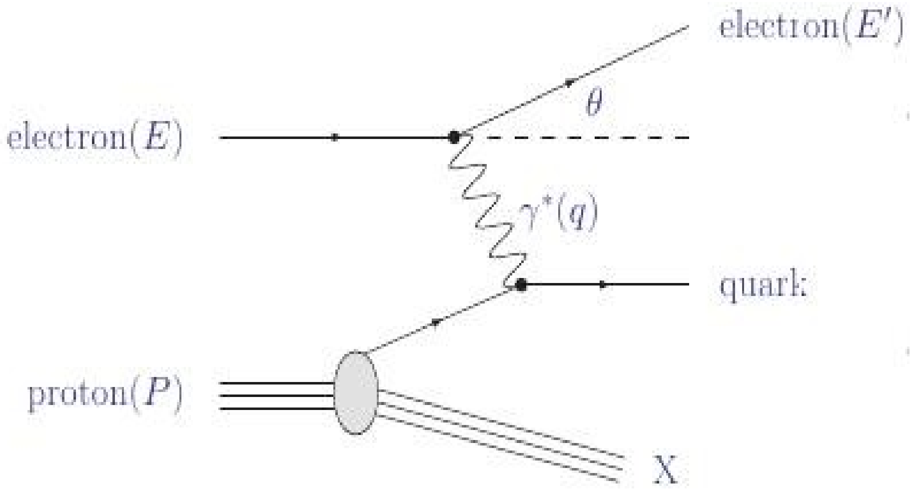
Deep Inelastic Scattering

- Scattering between a high energy electron and a hadron
- Resolution ↔ photon virtuality

$$Q^2 \equiv -q^2 = 4EE' \sin^2(\theta/2)$$



- Inelasticity ↔ Bjorken x_{Bj}

$$x = \frac{Q^2}{2P\cdot q} < 1$$

- Structure functions parametrize the structure of the proton as "seen" by γ^*

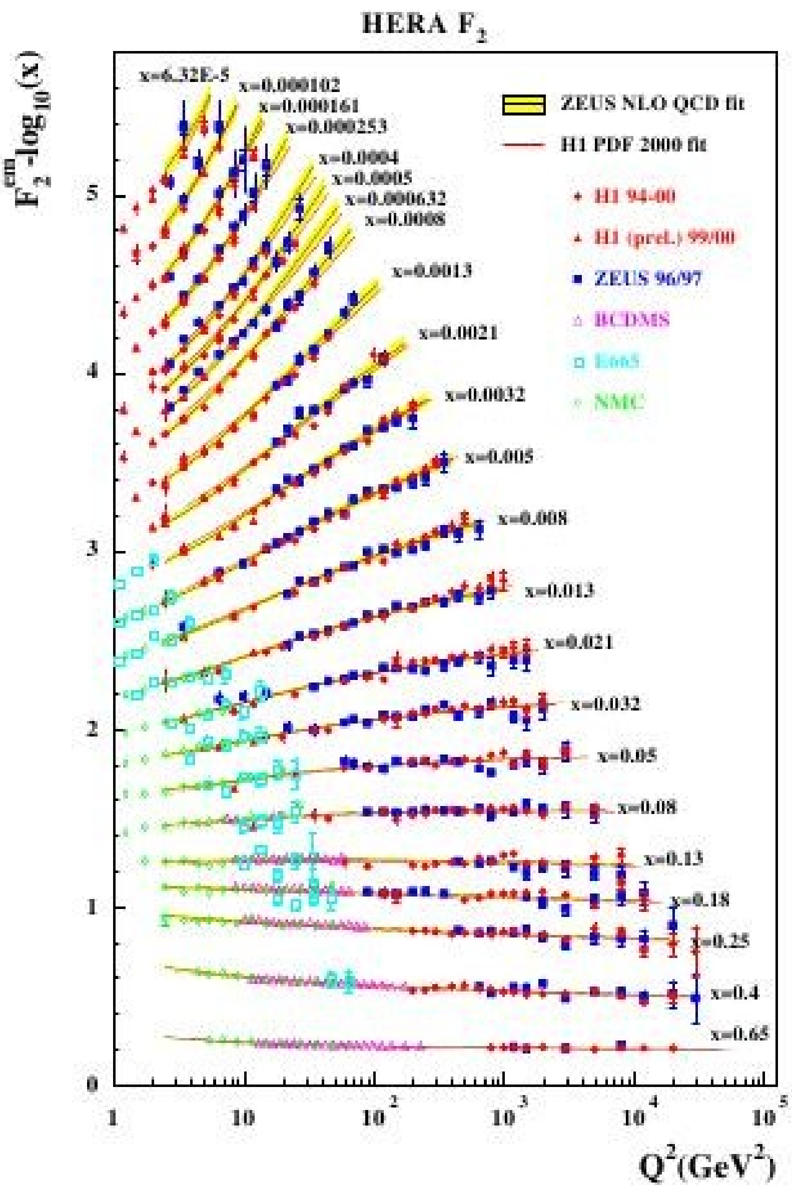
$$(E-E')\frac{d\sigma}{d\Omega\, dE'} \stackrel{\text{lab}}{=} \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} \left\{ F_2^p(x,Q^2) + \tan^2\frac{\theta}{2}\, F_1^p(x,Q^2) \right\}$$

- Deviation from Mott's formula: protons are not point-like objects

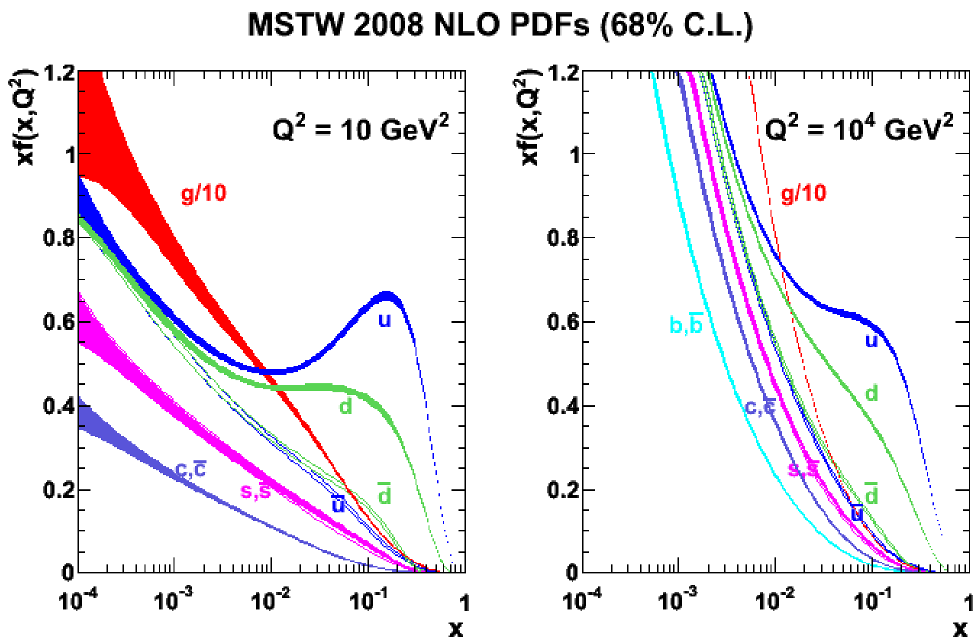
Deep Inelastic Scattering - Naive Parton Model

- Bjorken limit : $Q^2 \to \infty$ and x fixed
- Structure functions obey a *scaling* law
  - $F_2(x,Q^2) \simeq F_2(x) = \sum_i e_i^2 \, x f_i(x)$
  - They depend only on one single variable. This means that the photon scatters off *point-like* objects! (No Q/Q_0 dependence)
  - Callan-Gross relation: $F_2 = 2xF_1$. Quarks are spin ½ particles.
- We have assumed the Parton Model
  - hadrons contain constituents ("partons") which carry a longitudinal fraction x of their momenta.
  - $f_i(x)dx$ is the probability to find a parton of species i with momentum $[x,x+dx]$.
  - These are the pdf's in the naive parton model.
- PDF's and structure functions have been measured in collider experiments with increasing precision since the late '60's.

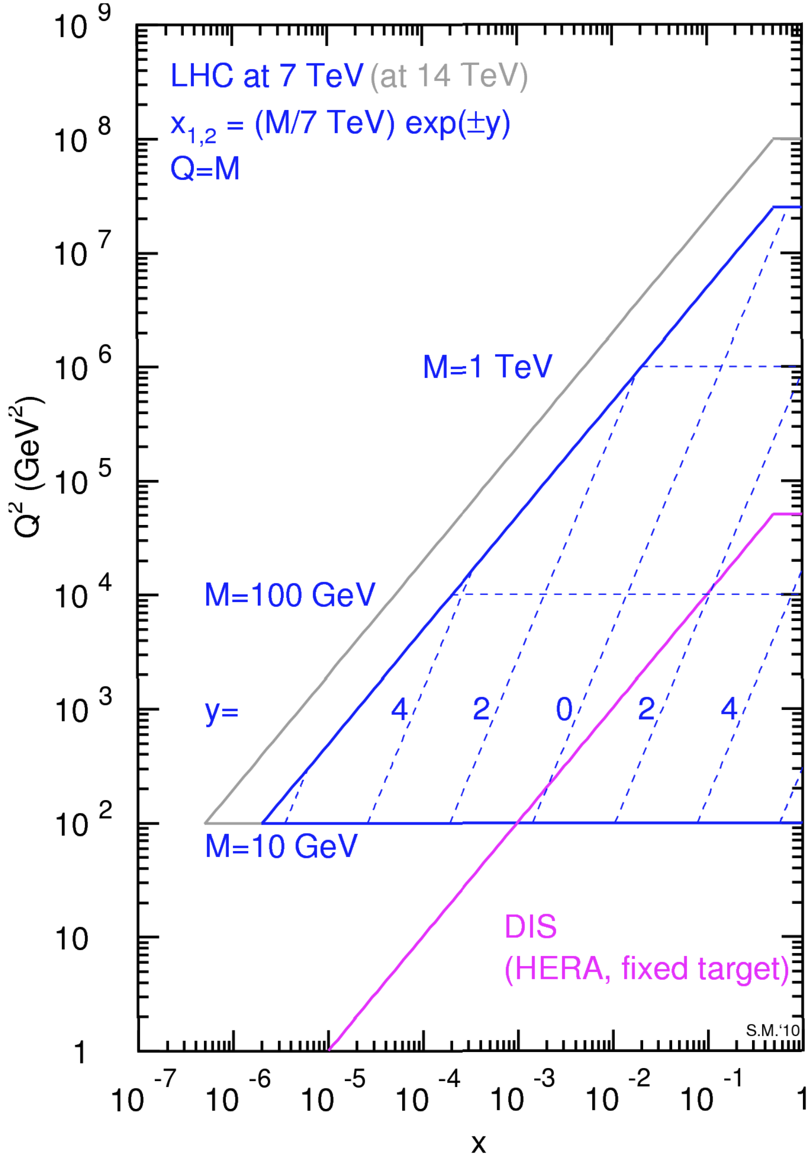
Improved parton model



- Violations of scaling for decreasing x.
- The parton model needs to be improved, including also the correct treatment of transverse momentum of partons inside hadrons.
- The parton density functions become scale dependent.



More on parton density functions



- The scale dependence of PDF's can be predicted by the theory (DGLAP equation)

$$\frac{d}{d\ln\mu^2} f_i(x,\mu^2) = \sum_k \left[P_{ik}(\alpha_s(\mu^2)) \otimes f_k(\mu^2)\right](x)$$

- Splitting kernels are calculable in perturbative QCD

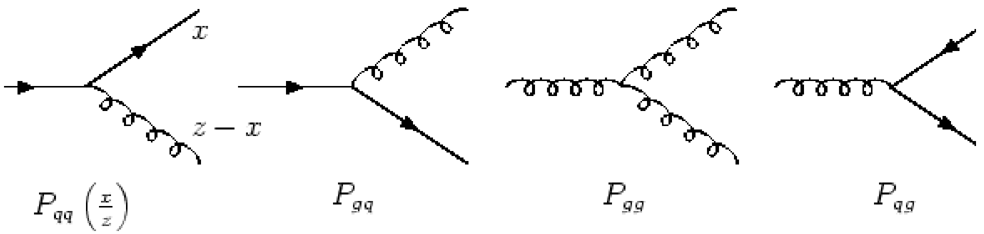
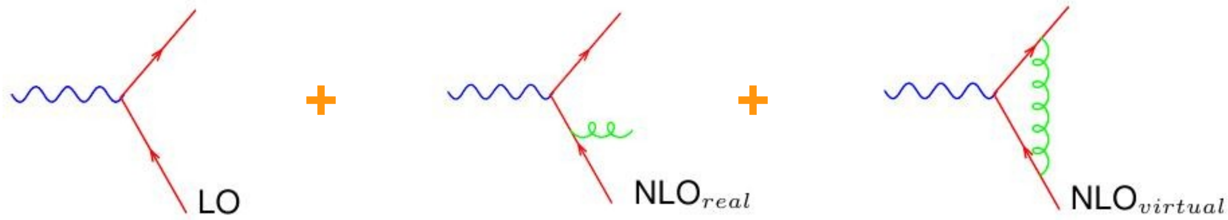


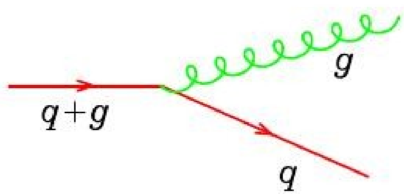
Figure 1.1: *The processes related to the lowest order QCD splitting functions. Each splitting function $P_{p'p}(x/z)$ gives the probability that a parton of type p converts into a parton of type p', carrying fraction x/z of the momentum of parton p*

Hard partonic x-sec - outline of an NLO calculation

- Sum all contributions at the given order (NLO) in PT: virtuals and reals



- Virtual and real corrections are separately IR divergent, but their sum *after* phase space integrations is finite.



$$\frac{1}{(q+g)^2 - m_q^2} = \frac{1}{2E_g E_q(1-\beta_q \cos\theta_{qg})}$$

Soft divergence if $E_g \to 0$
collinear if $\theta_{qg} \to 0$ (only if $m_q = 0$)

- KLN theorem: Sum of reals + virtuals yields finite partonic cross sections for so-called IR safe (sometimes called IR and collinear safe) obs's.
  - An IR safe observable is one whose value does not change if we add a soft or collinear parton to the event. Such a parton is also called “unresolved”.

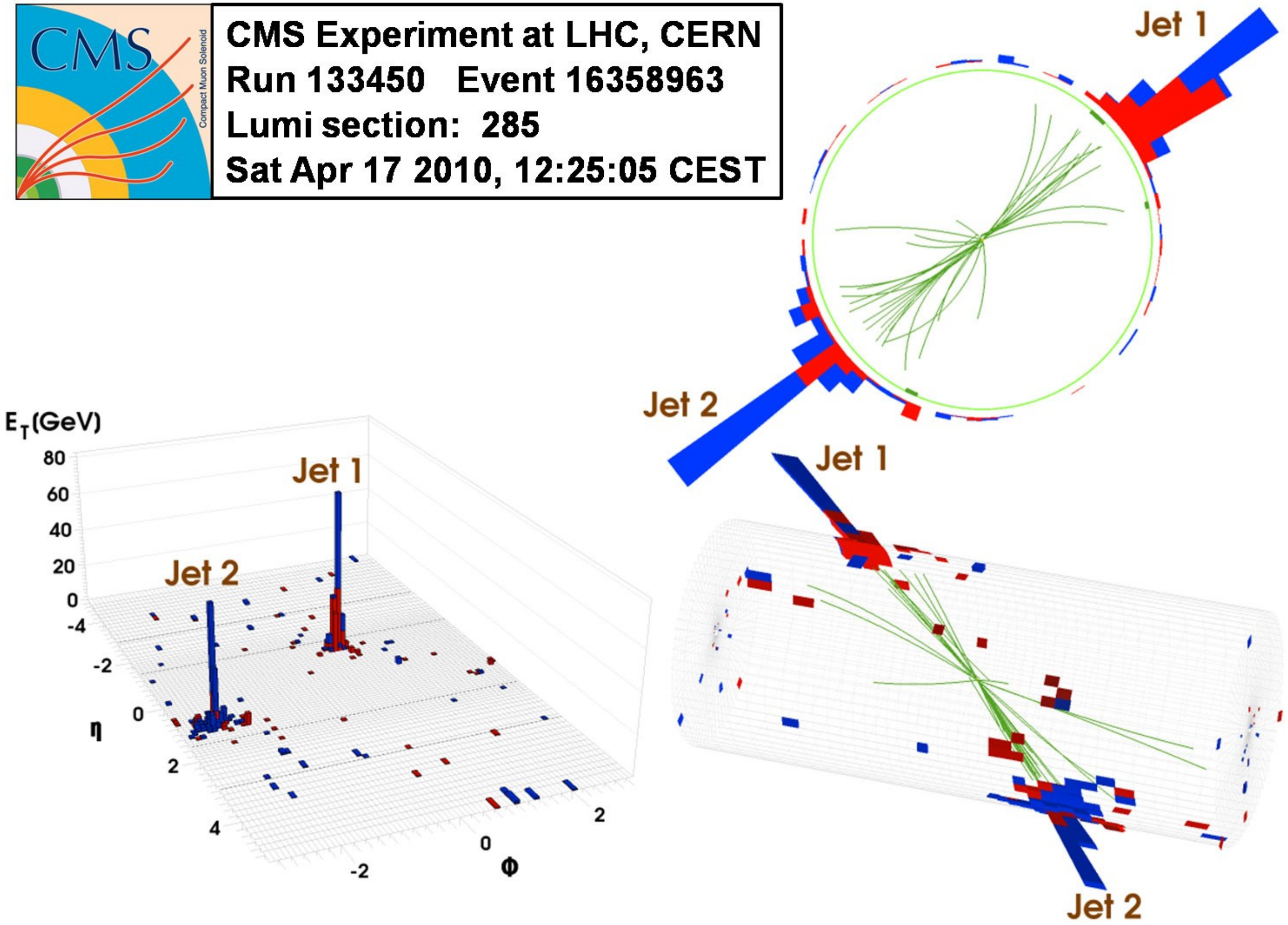
Outline of an NLO calculation

- We must nevertheless deal with the IR singularities present in intermediate stages of the calculation.
- The standard solution is to employ a *subtraction scheme*. The basic idea is to reshuffle the IR singularities between reals and virtuals by subtracting and adding back counterterms.
  - Subtract counterterms that regulate IR divergencies of reals before PS integration
  - Add back the same terms but integrated over the PS of the unresolved parton
  - Now both the reals and the virtuals are separately finite!
- Convolution with PDF's and (MC) integration over phase space.
- The bottleneck until very recently was the calculation of the virtuals (one-loop matrix elements).
- New methods (OPP, generalized unitarity, one-loop recursion,…) lead to dramatic improvements in computing one-loop matrix elements, fully automated NLO calculators on the way!

Jets in hadron collisions

- Notice: QCD talks about quarks and gluons, experiments observe hadrons.
  - How can we identify a cross section for producing quarks and gluons with one for producing hadrons?
  - Why is the cross section computed in pQCD any good if free quarks are not observed?
- Are there other quantities, apart from total x-sec, calculable in perturbative QCD?
- YES! A large class of these are the so-called *jet cross sections*.
  - Heuristically, jets are collimated bunches of hadrons.
  - Jet dynamics are usually related to parton dynamics.
  - Hence jets are our window on partons.
  - Jets can be used as tools to extract properties of the final state.
  - If properly defined, jet cross sections can be safely computed in pQCD.

Jets at LHC


CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Run 133450 Event 16358963
Lumi section: 285
Sat Apr 17 2010, 12:25:05 CEST
Jet 1
Jet 2
E_T(GeV)
80
60
40
20
0
-4
-2
0
η
2
4
-2
0
2
Φ
Jet 1
Jet 2
Jet 1
Jet 2

Jets in hadron collisions

- Experimentally, we see collimated bunches of hadrons in the detector (tracer, calorimeter towers,...). Hence, the event has “global” structure.
- Jet cross sections are meant to capture this global structure, while the fine details of particles inside the bunches is neglected.
- A jet definition is a fully specified set of rules for projecting information form 100's of hadrons/1000's of calorimeter towers onto a handful of objects.
- The resulting objects (jets) used for many things
  - Reconstructing decaying heavy particles.
  - Constraining pdf's
  - Theoretical tool to attribute structure to the event.
- You loose much information in projecting the event onto jet-like structures
  - Sometimes information you had no idea how to use.
  - Sometimes information you may not trust, or of no relevance.

Jet definitions at hadron colliders

- Two main classes for “modern” IR safe algorithms:
  - Sequential recombination: Choose a distance measure, combine particle starting from closest ones, iterate recombination until few objects left, call them jets

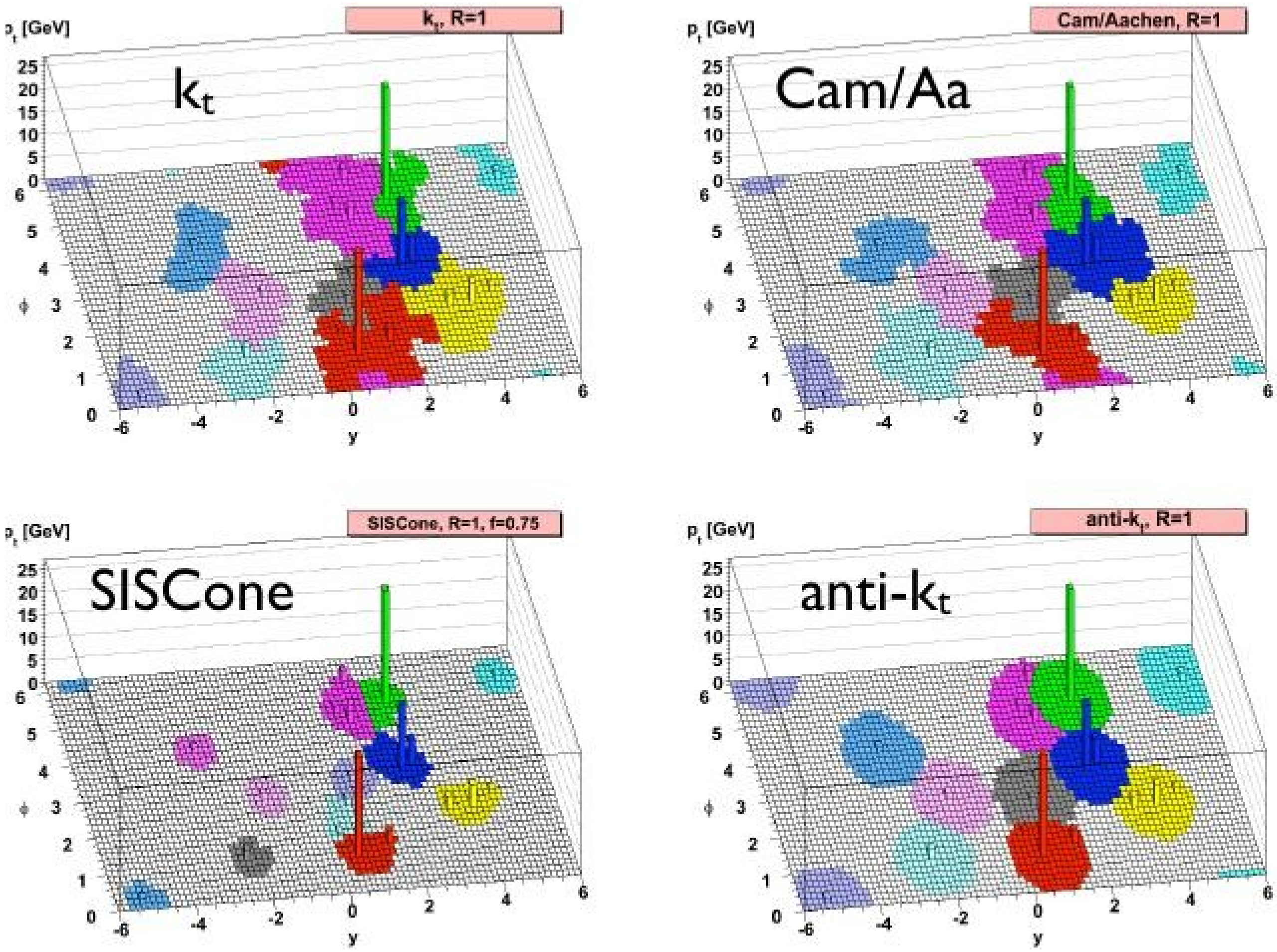
$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2} \qquad d_{iB} = k_{ti}^{2p}$$

    - » *p=1* k_T algorithm
    - » *p=0* *Cambridge-Aachen* algorithm
    - » *p=-1* *anti-*k_T algorithm

  - Cone algorithm: Define cones around most energetic particles and start adding other particles until cones are stable (cone axis is the sum of momenta inside a cone).
    - » SIScone (Seedless Infrared Safe)

- Implementation not straightforward, speed is an important issue: N lnN, N^2 lnN, $N^{3/2}$ vs N^3! (Use FASTJET.)
- Recall: IR safety means the algorithm is resilient to QCD effects like soft and collinear radiation (also detector effects), i.e. the overall jet structure of the event is insensitive to the presence of extra soft and collinear particles.

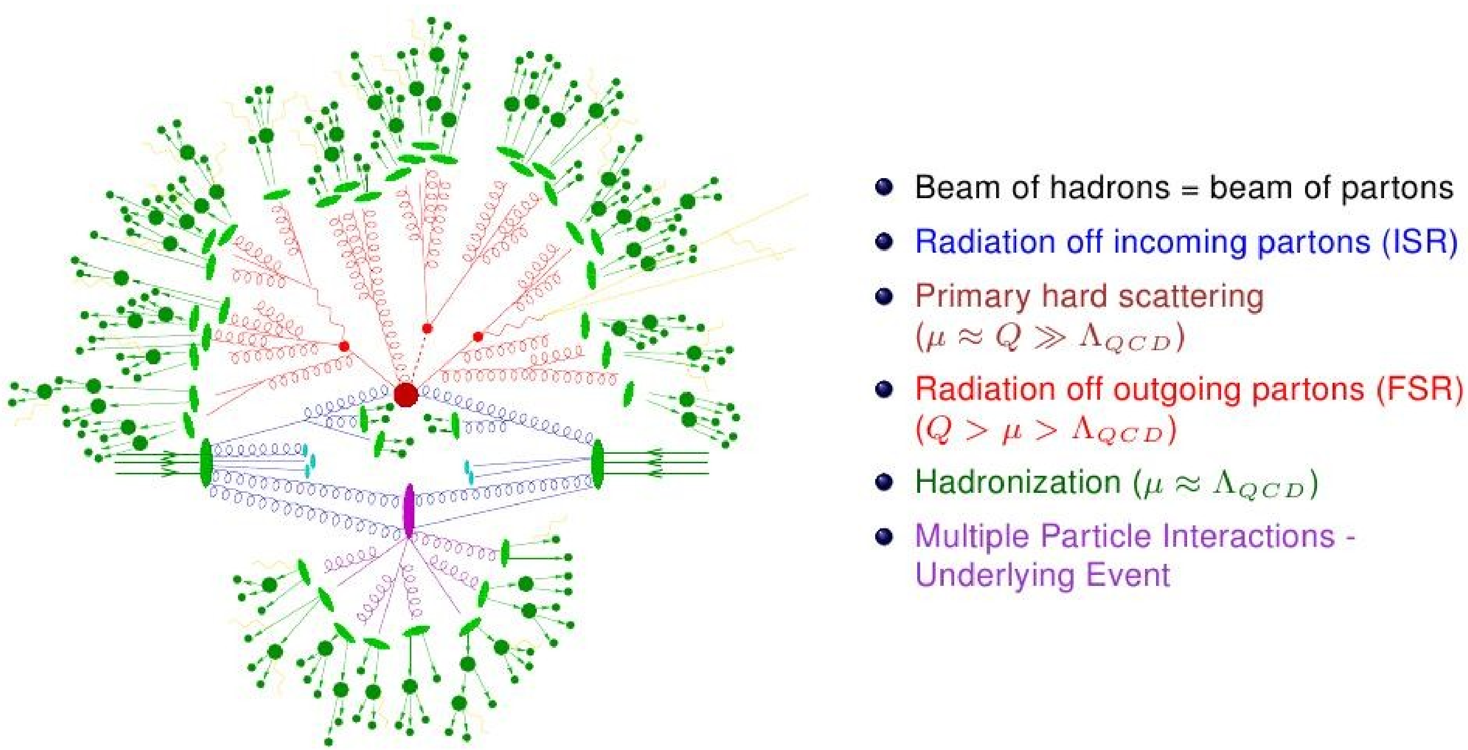
Jet definitions



Calculation of hadronic cross sections: tools

> Leading Order

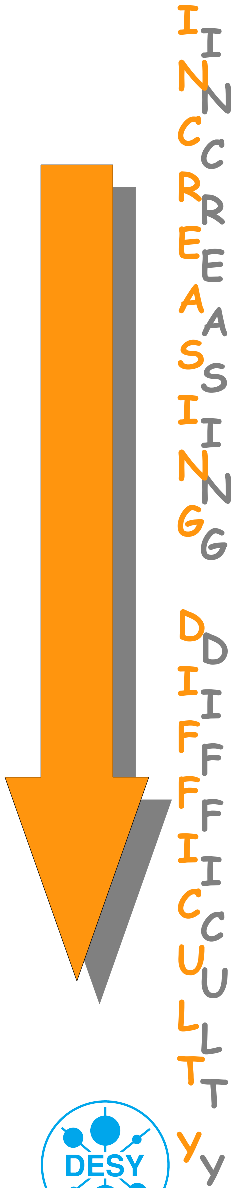
- Automated tree-level calculators for the SM and beyond (MADGRAPH, ALPGEN, SHERPA, COMPHEP,...)
- Shower Monte Carlo programs (LO + parton shower)



INCREASING DIFFICULTY

Calculation of hadronic cross sections: tools

- Leading Order
  - Automated tree-level calculators for the SM and beyond (MADGRAPH, ALPGEN, SHERPA, COMPHEP,...)
  - Shower Monte Carlo programs (LO + parton shower)
- Next to Leading Order
  - Analytical results known for many processes
  - Automatization of subtraction techniques
  - Complete automatization on the horizon
  - Parton level Monte Carlo integrators for many processes available (MCFM, NLOJET++,...)
  - NLO + parton shower matching recent achievement (MC@NLO, POWHEG)



Calculation of hadronic cross sections: tools

Leading Order

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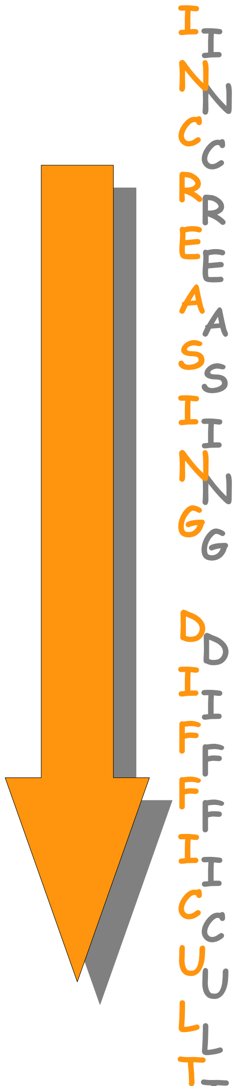
Next to Next to Leading Order

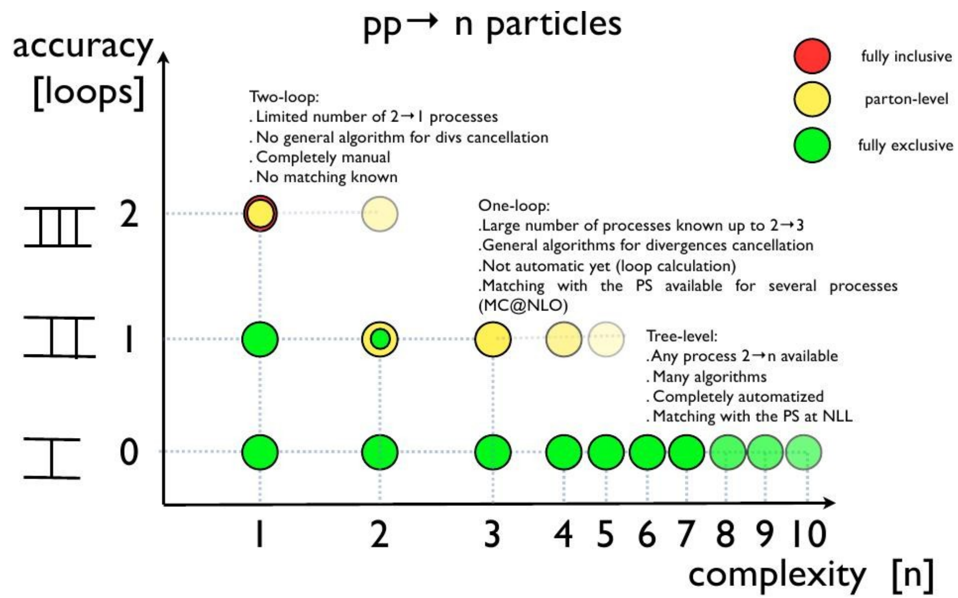
- Extremely complicated calculations!
- Only few results available for 2 → 1 processes. (E.g. pp → H)



State of the art – Les Houches wish list

> Present situation:

Relative order	$2 \to 1$	$2 \to 2$	$2 \to 3$	$2 \to 4$	$2 \to 5$	$2 \to 6$
1	LO					
α_s	NLO	LO				
α_s^2	NNLO	NLO	LO			
α_s^3		NNLO	NLO	LO		
α_s^4			NNLO	NLO	LO	
α_s^5				NNLO	NLO	LO

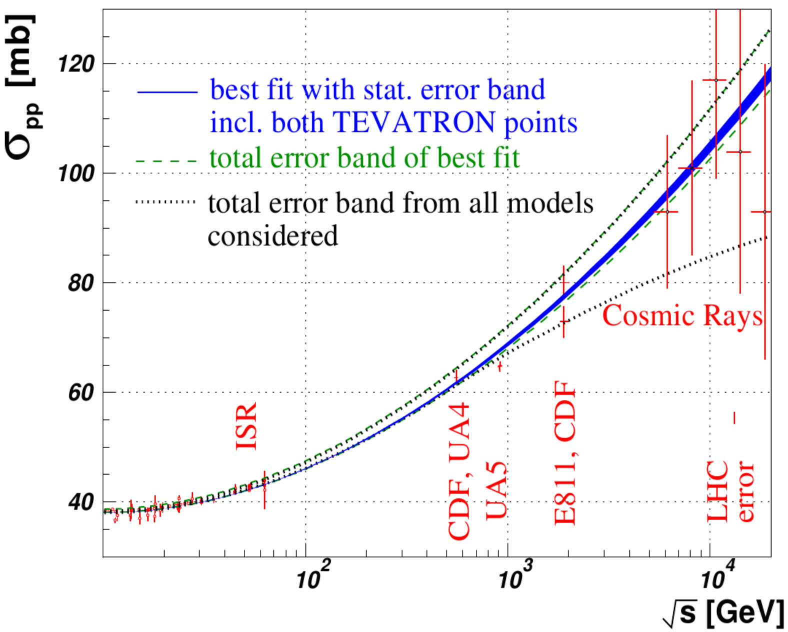


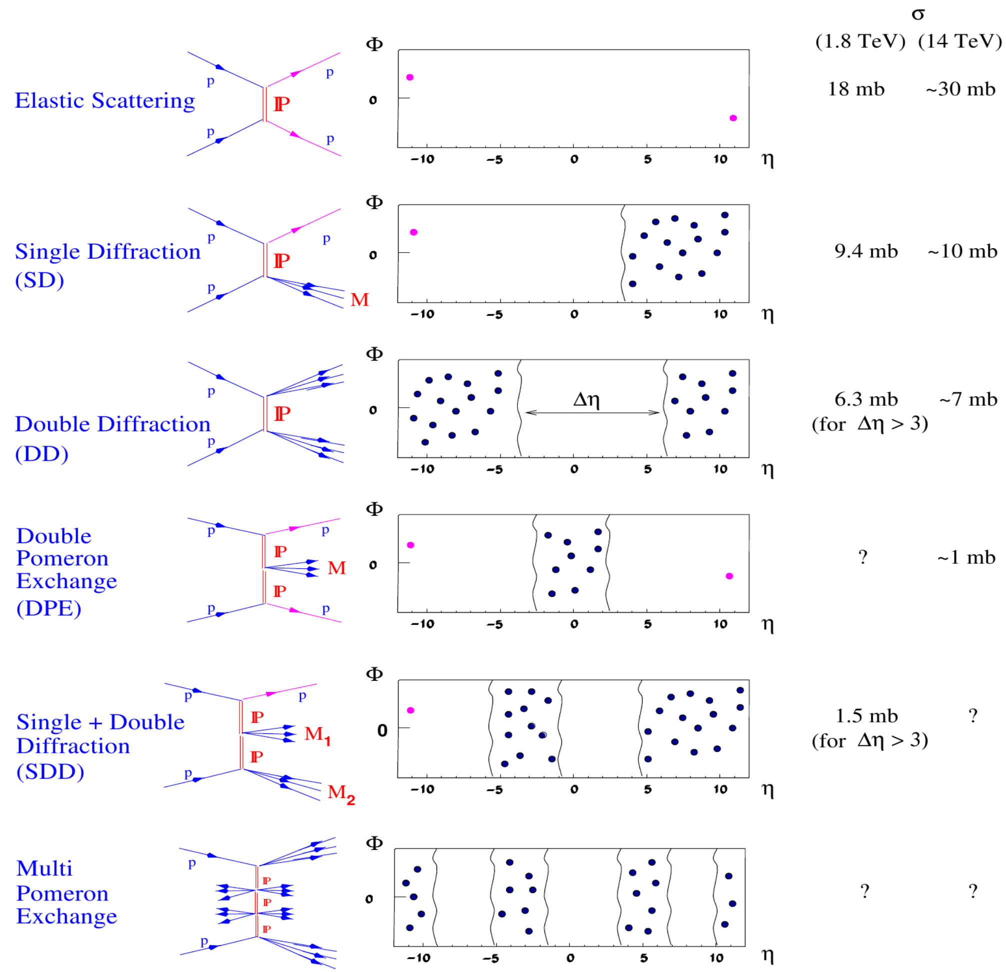
> 2009 wish list – done!

Process ($V \in \{Z, W, \gamma\}$)	Comments	Motivation
pre Les Houches 2007	(completed)	
1. $pp \to VV$jet	$V = Z$ cases missing, W-decays included	Higgs background
2. $pp \to$ Higgs+2jets	NLO QCD+EW to VBF	
3. $pp \to V\,V\,V$	γ cases missing	new physics background
4. $pp \to t\bar{t}\,b\bar{b}$	$m_b = 0$, no t-decay	background for $t\bar{t}H$
5. $pp \to W$+3jets	W-decay included	new physics background
Les Houches 2007	(in progress)	
6. $pp \to t\bar{t}$+2jets		relevant for $t\bar{t}H$
7. $pp \to WW\,b\bar{b}$,		relevant for $t\bar{t}$ benchmark process
8. $pp \to VV$+2jets	V-decays useful	VBF $\to H \to VV$
9. $pp \to b\bar{b}b\bar{b}$		Higgs and new physics signatures
	two-loop observables	
10. $gg \to W^*W^*$	NLO QCD	Higgs background
11. $pp \to t\bar{t}$	NNLO QCD	benchmark process
12. $pp \to Z/\gamma$+jet	NNLO QCD	pdf, jet-energy measurements
13. $pp \to W/Z$	NNLO QCD $\oplus$ NLO EW	benchmark process
Les Houches 2009		
14. $pp \to W$+3jets	W-decay included	new physics background
15. $pp \to W b\bar{b} j$	$m_b = 0$ sufficient (?)	Higgs search
16. $pp \to jjjj$		new physics background
17. $pp \to t\bar{t}t\bar{t}$		new physics background
18. $pp \to W jjjj$	leading color sufficient (?)	new physics background
19. $H \to f\bar{f}f'\bar{f}'$	NLO EW+QCD (completed)	Higgs search
	(two-loop)	
20. $gg \to H$	NLO EW (completed)	Higgs search
21. $pp \to VV$	NNLO	benchmark process
22. $pp \to Hj$	NNLO ($m_t \to \infty$)	Higgs search

LHC theoretical predictions: total cross section

> Event classification:

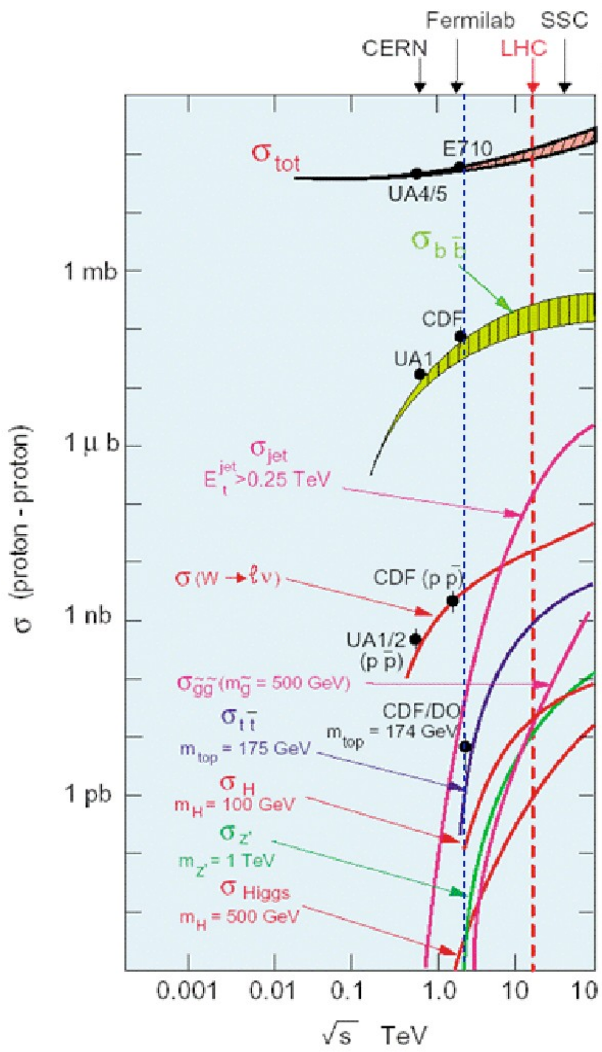


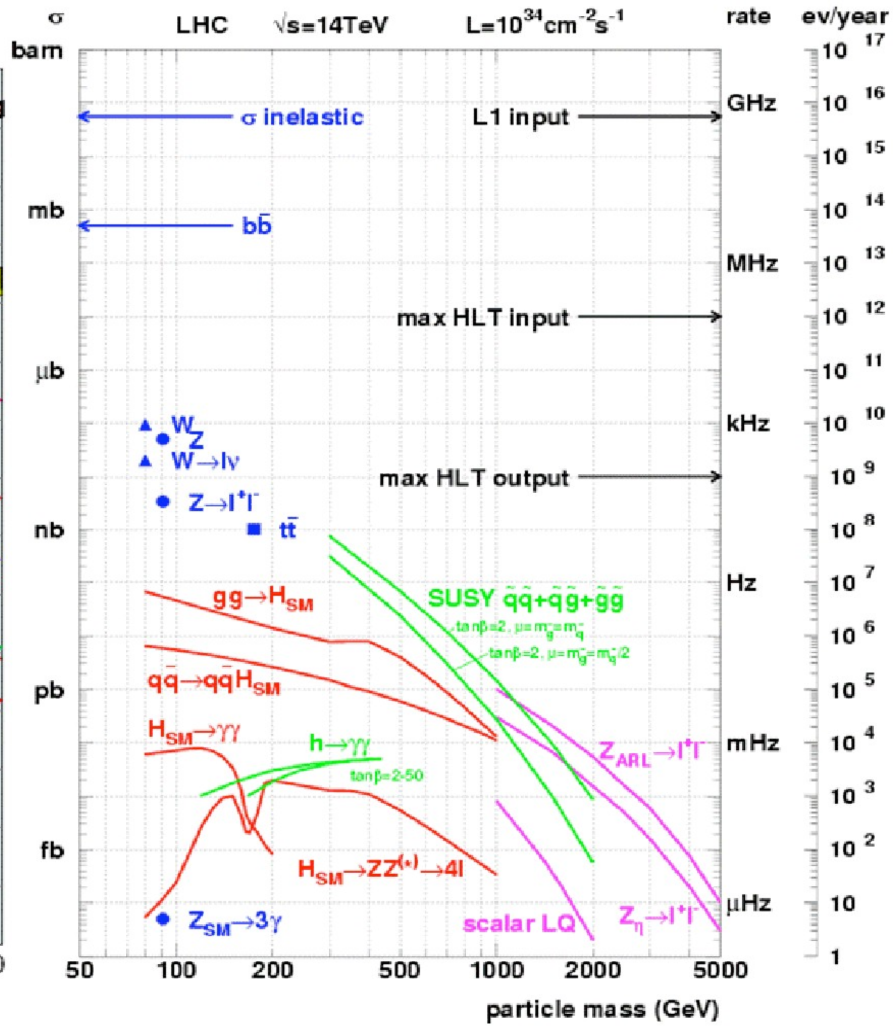


> Mainly interested in hard scattering events

DESY

LHC cross sections: theoretical predictions

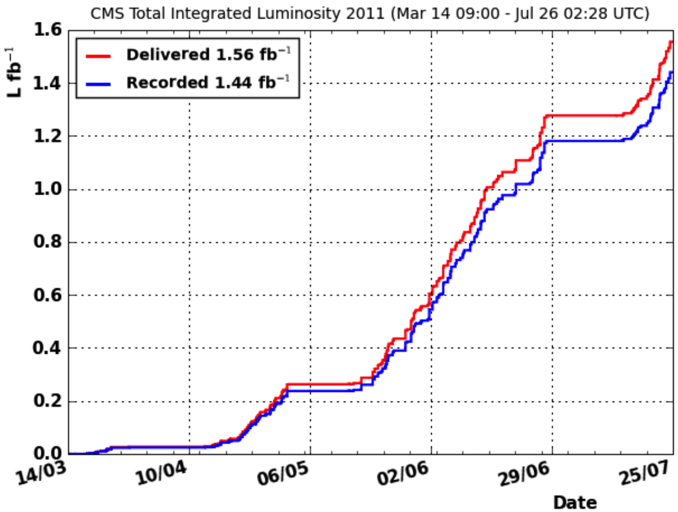




LHC: rates and current status

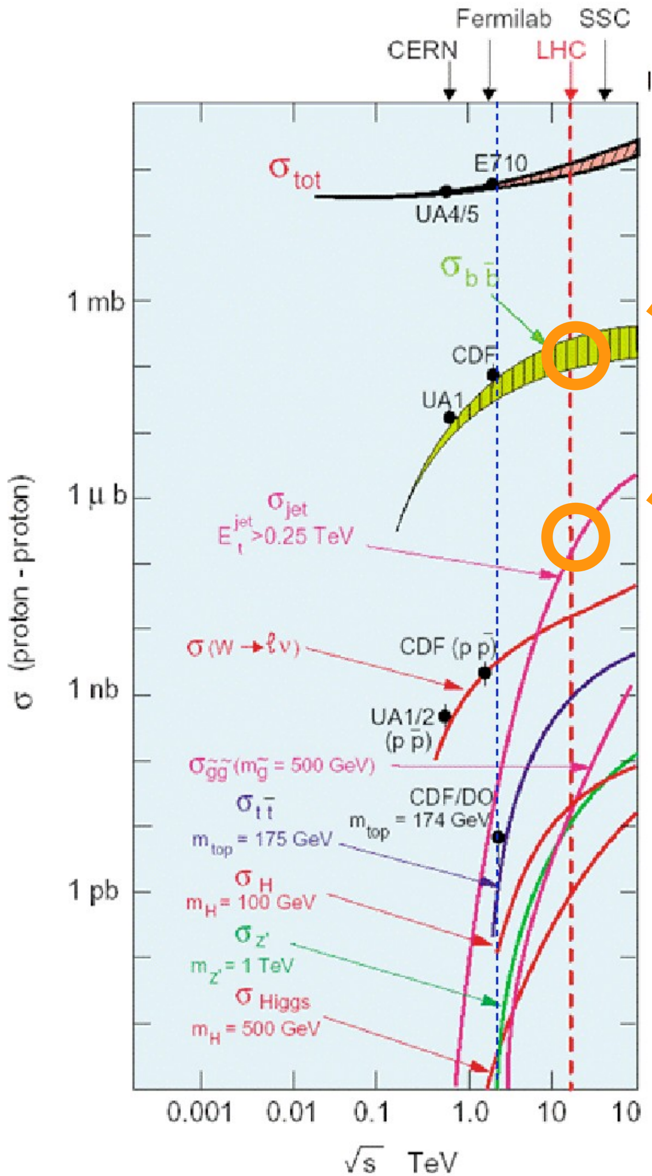
- The LHC allows to have interesting events with unprecedented rates, even in the “low” luminosity phase (10^{33} cm^{-2} s^{-1})

Process	σ	Events/sec	Events/year	Other machine
$W \to e\nu$	20 nb	15	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	2 nb	1.5	10^7	10^7 LEP
$t\bar{t}$	1 nb	0.8	10^7	10^5 Tevatron
$b\bar{b}$	0.8 mb	10^5	10^{12}	10^8 Belle/BaBar
$\tilde{g}\tilde{g}$ (m = 1 TeV)	1 pb	0.001	10^4	
H (m = 0.8 TeV)	1 pb	0.001	10^4	
H (m = 0.2 TeV)	20 pb	0.01	10^5	

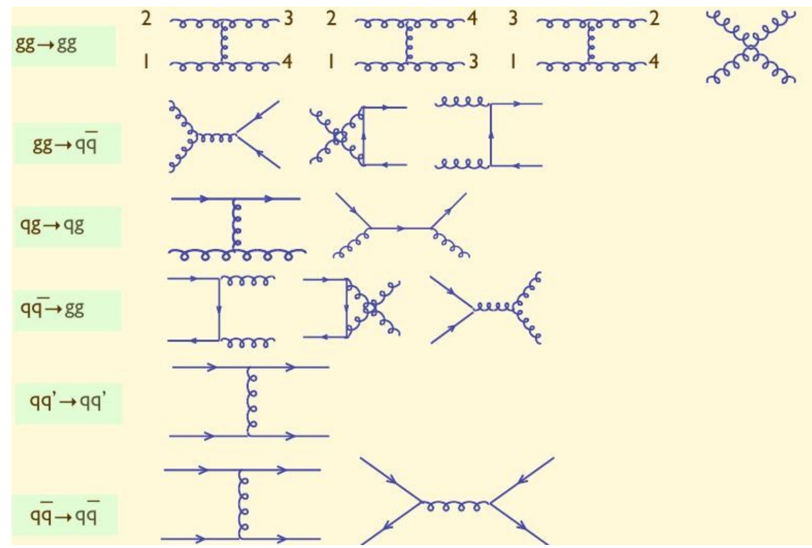


- Now running at 7 TeV CM energy with peak luminosity ~10^{33} cm^{-2} s^{-1}.
- Already delivered > 1 fb^{-1} (this was the plan for all of 2011)!
- Good efficiency in recording by experiments!

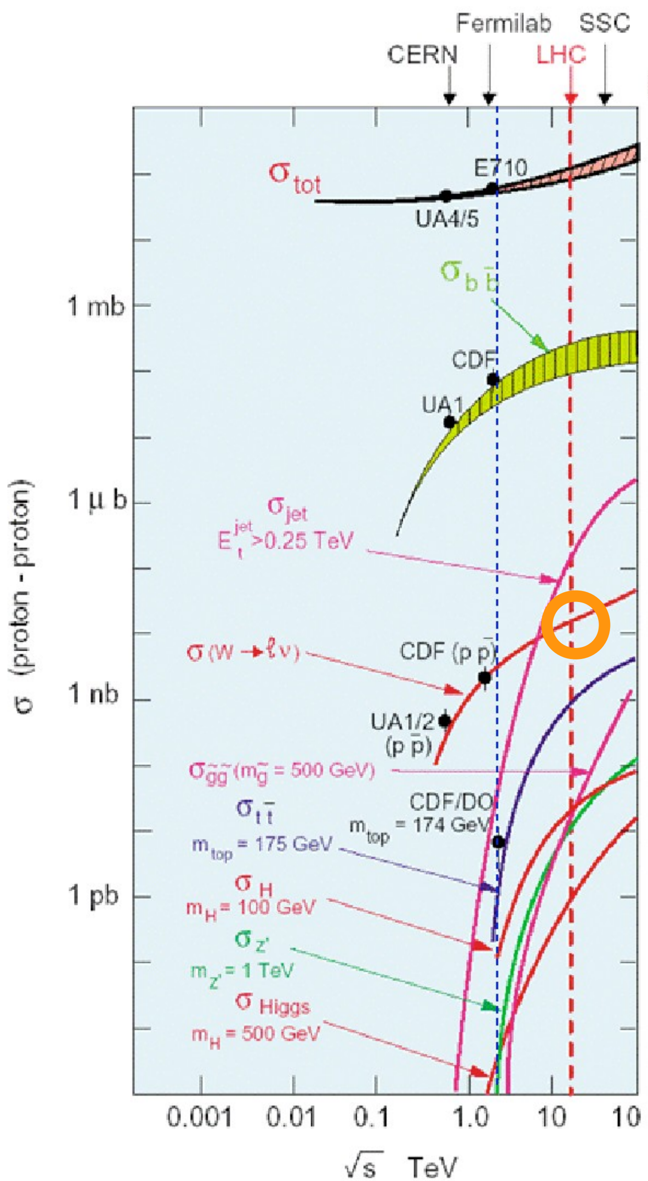
LHC cross sections



- B-quark pairs (i.e. b-jets in the detector): $\sigma_{b\bar{b}} \approx 500\,\mu b$
- Light quarks, (i.e. jets in the detector)
  - Depends on precise jet definition, i.e. jet cut!
  - Production mechanism:



LHC cross sections

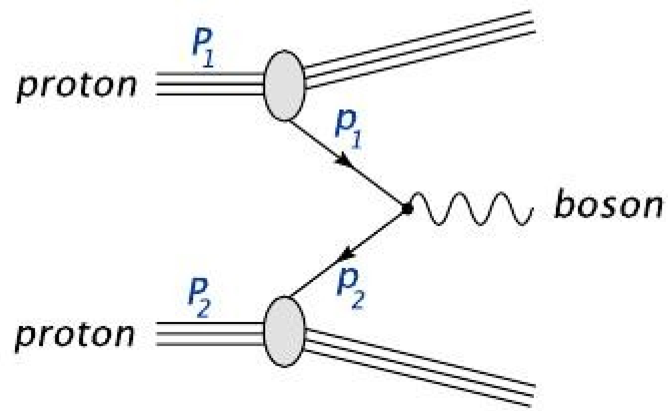


- W boson: $\sigma_W \approx 150-200\,nb$

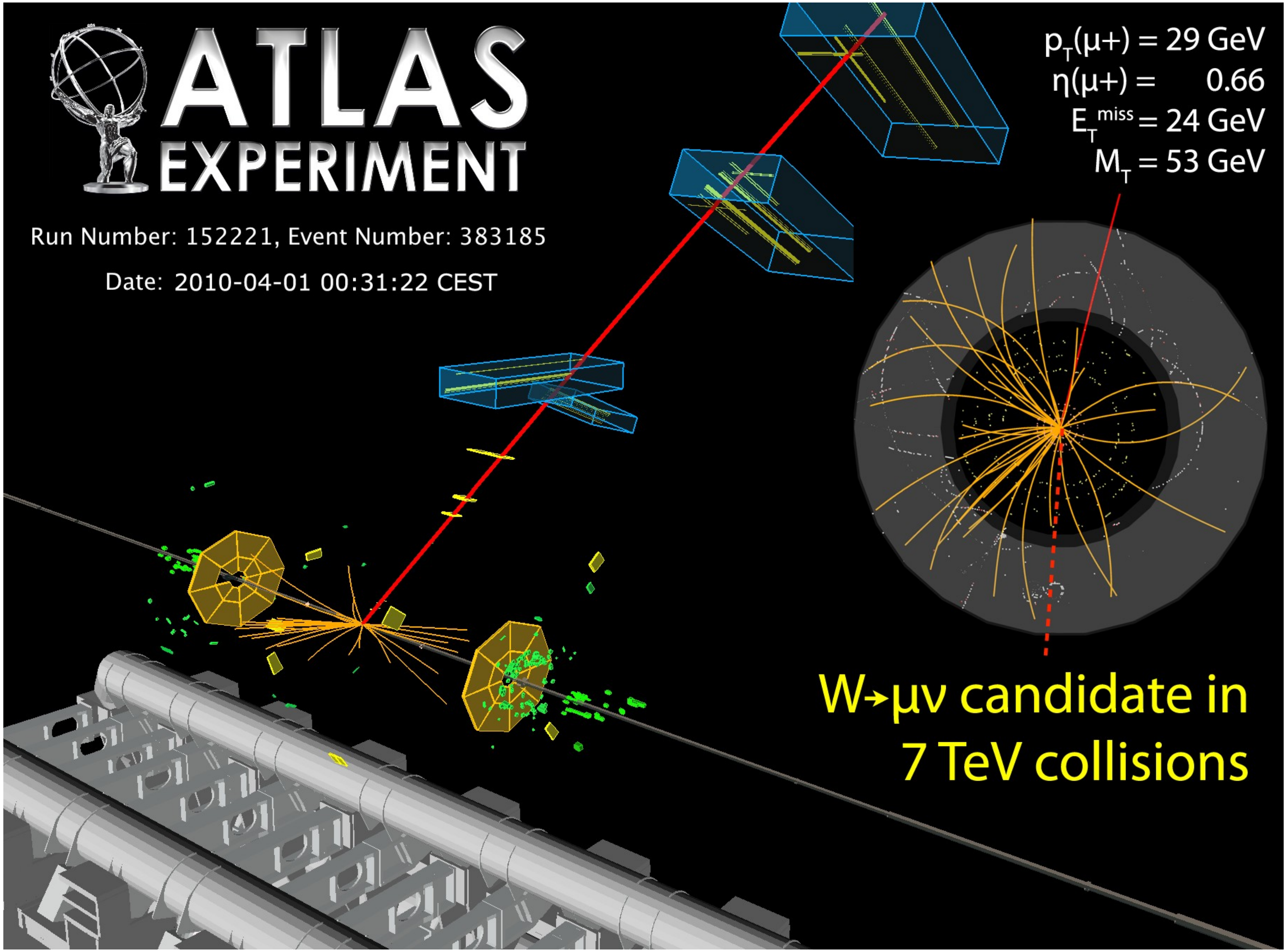
  $BR(W \rightarrow e\nu_e) = 0.108$

- Z boson: $\sigma_Z \approx 50-60\,nb$

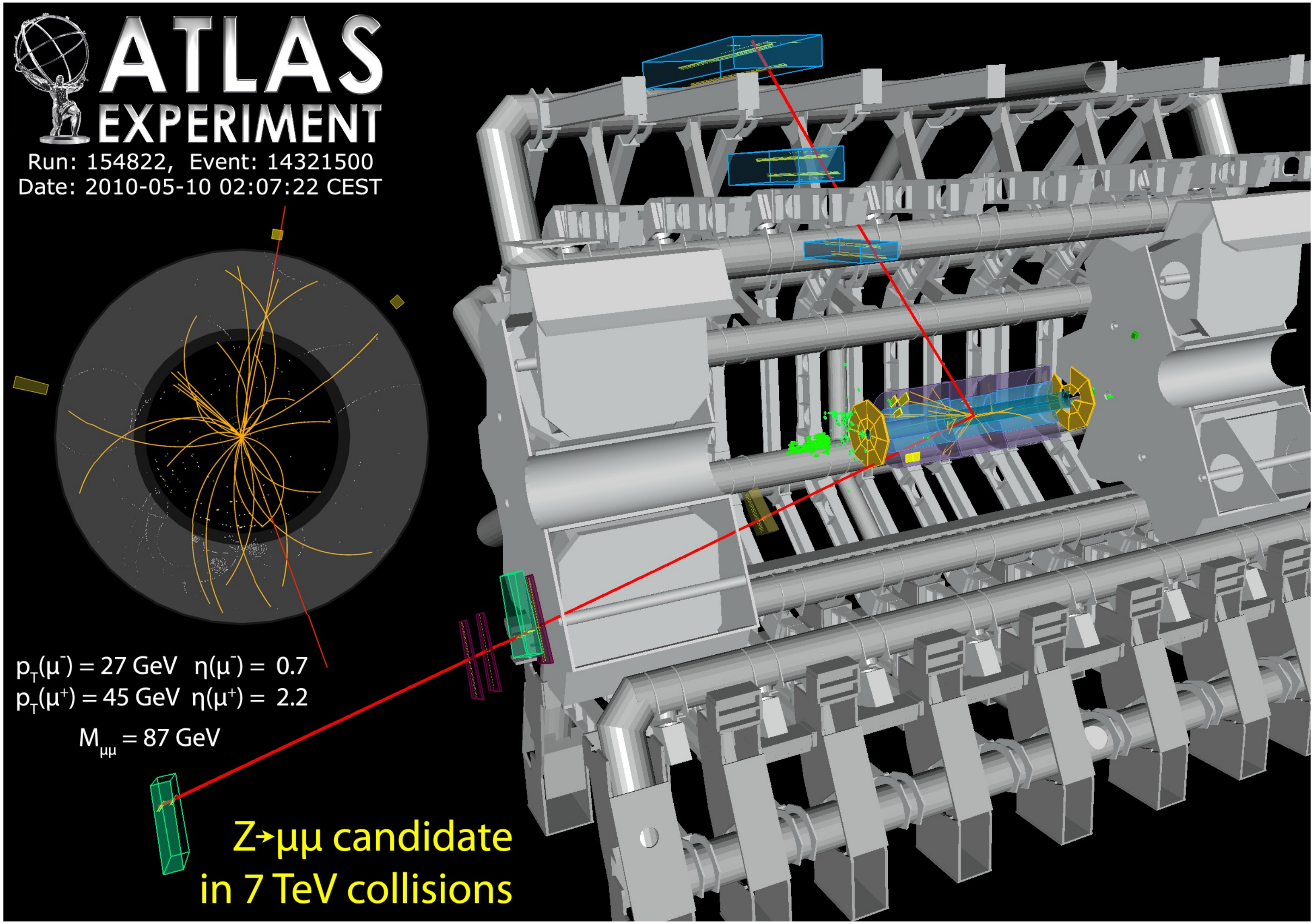
  $BR(W \rightarrow e^+ e^-) = 0.033$



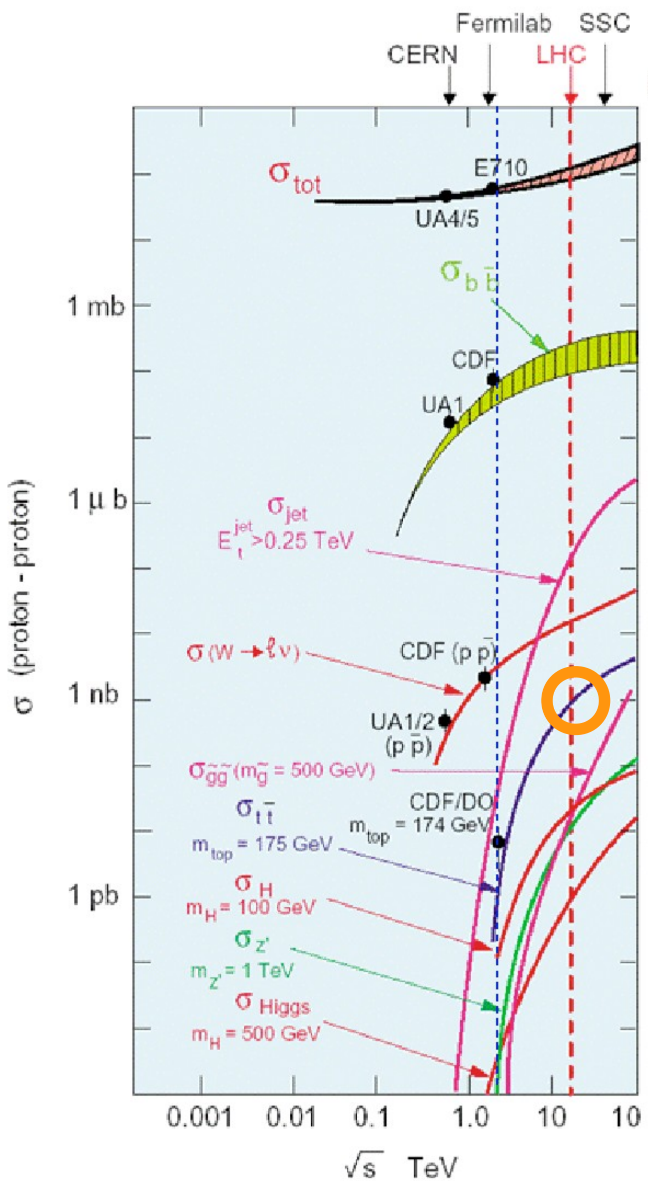
LHC events: W


ATLAS
EXPERIMENT
Run Number: 152221, Event Number: 383185
Date: 2010-04-01 00:31:22 CEST
$p_T(\mu+) = 29$ GeV
$\eta(\mu+) = 0.66$
$E_T^{miss} = 24$ GeV
$M_T = 53$ GeV
W→μν candidate in
7 TeV collisions

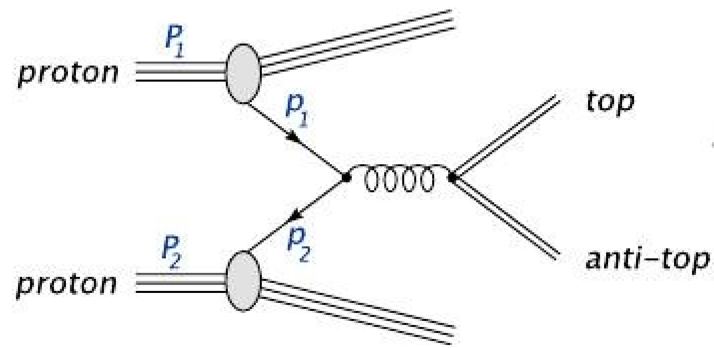
LHC events: Z


ATLAS
EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-)$ = 27 GeV $\eta(\mu^-)$ = 0.7
$p_T(\mu^+)$ = 45 GeV $\eta(\mu^+)$ = 2.2
$M_{\mu\mu}$ = 87 GeV
Z→μμ candidate
in 7 TeV collisions

LHC cross sections

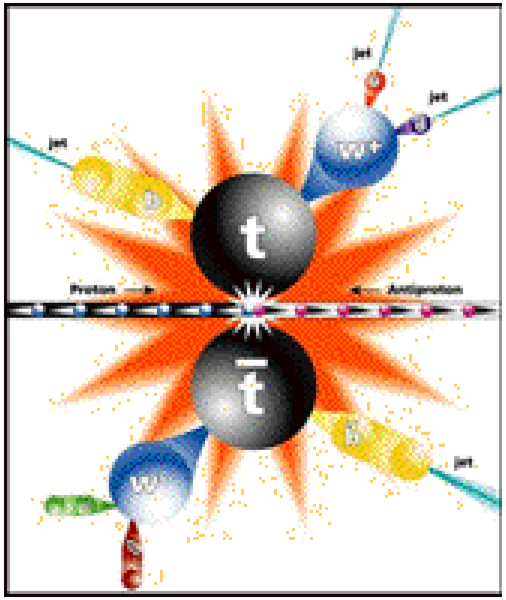


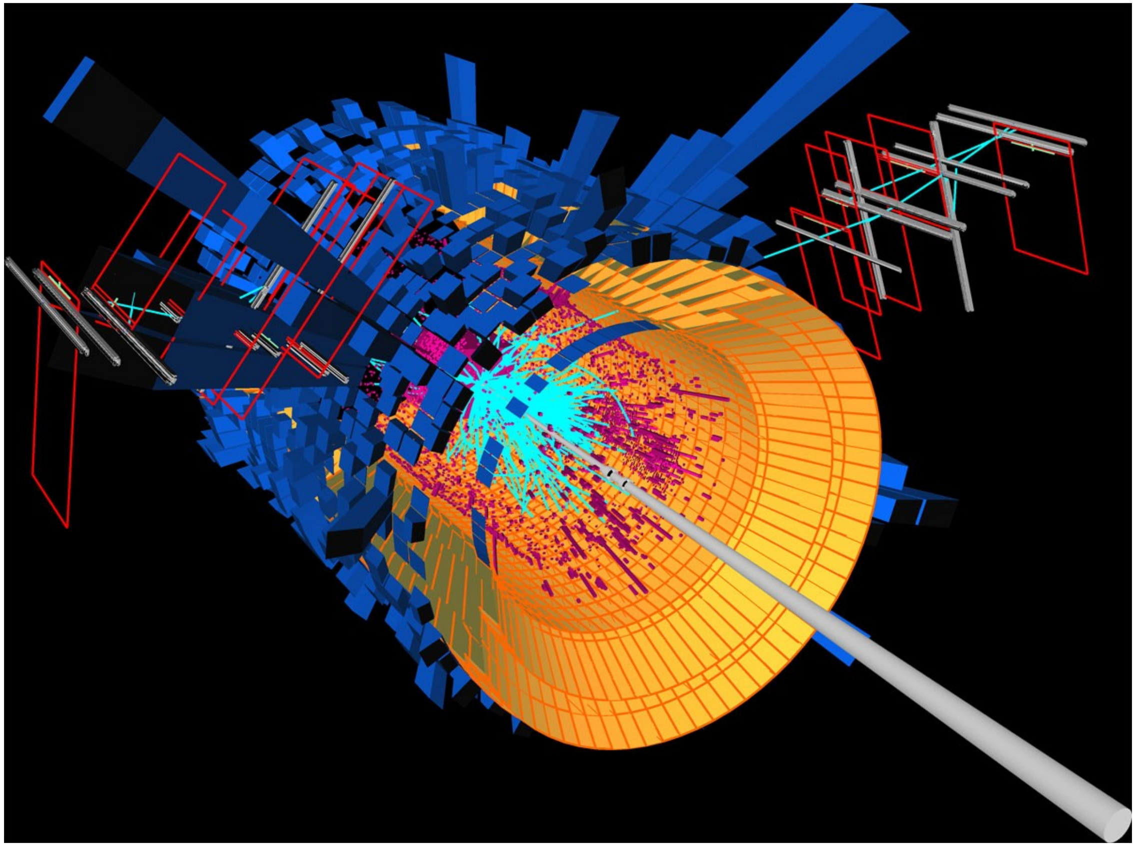
- Top pairs: $\sigma_{t\bar{t}} \approx 800\ pb,$
  $t \to (W \to e\nu_e) b,$
  $t \to (W \to q q') \to b$

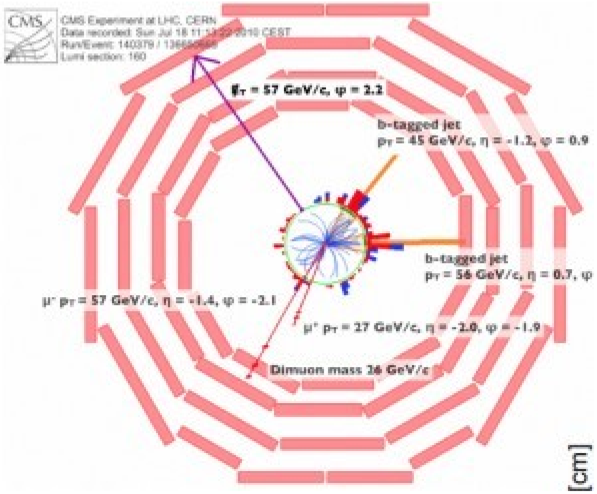


- New Physics: $\sigma_{NP} \approx 1 - 10\ pb$
  - Higgs
  - SUSY
  - New resonances
  - Extra dimensions

LHC events: $t\,\bar{t}$

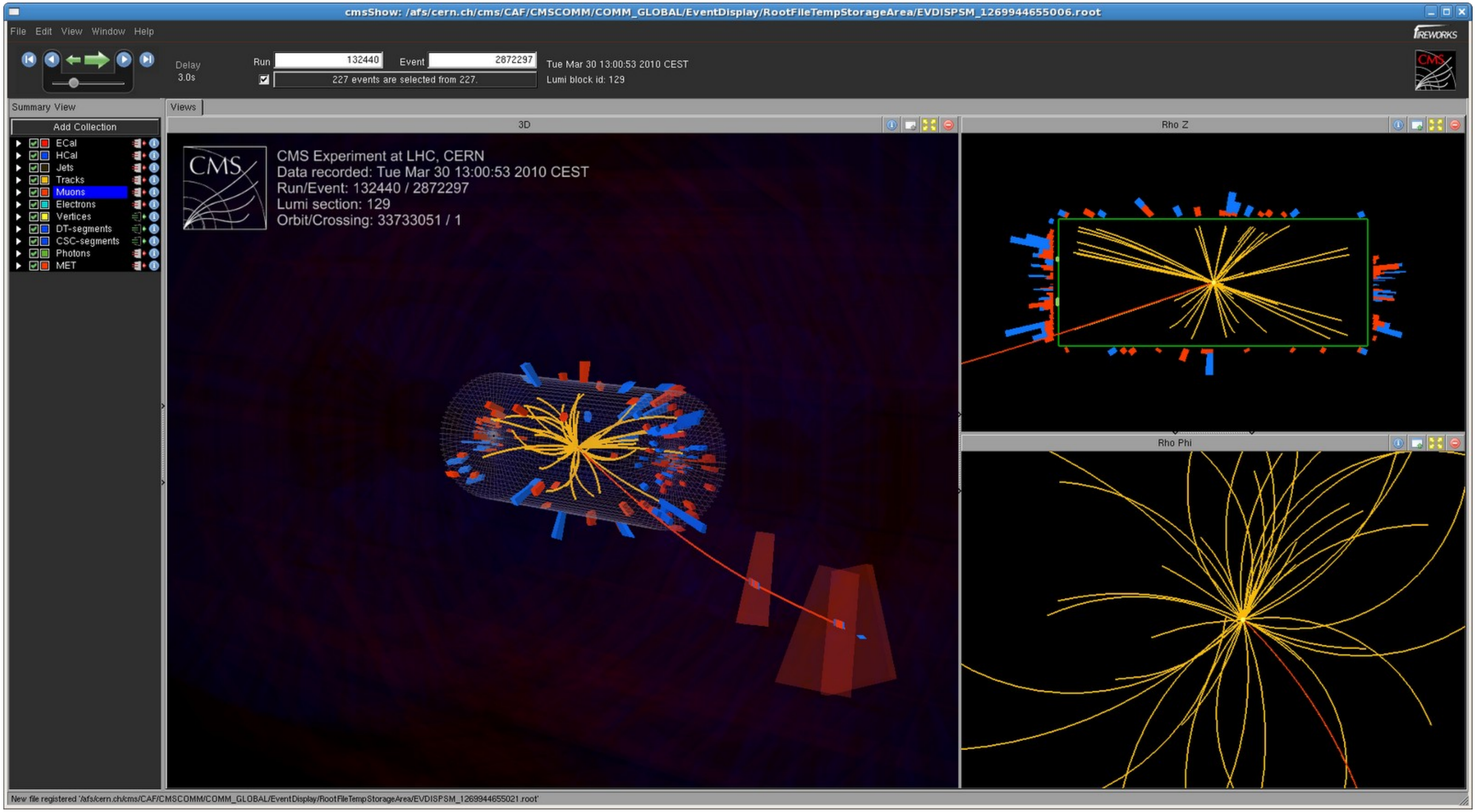






LHC events: new physics

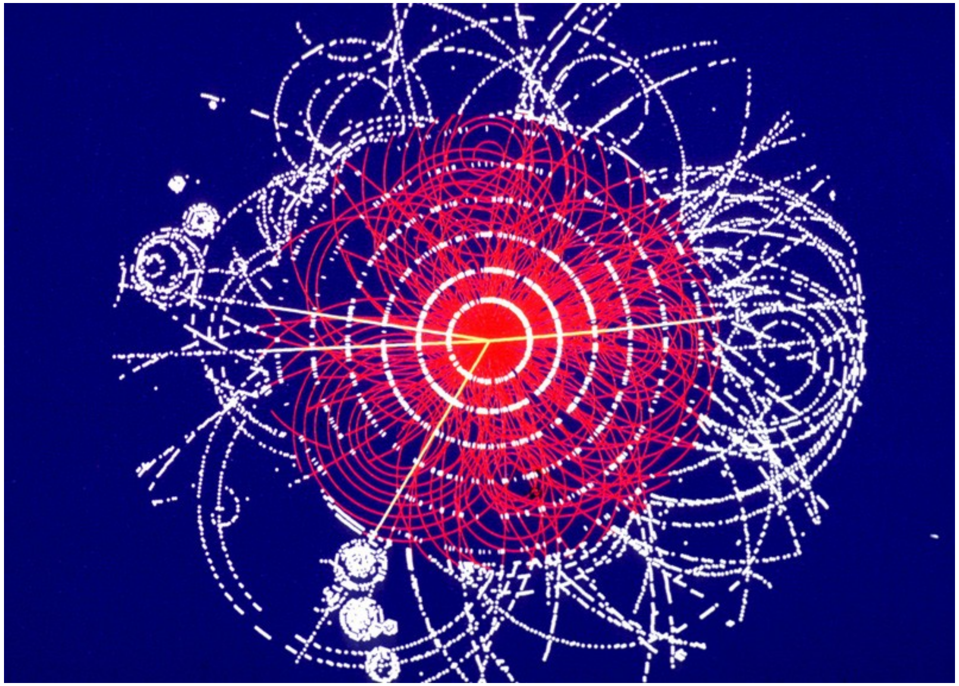
- NP signatures: highly energetic leptons, many jets and missing E_T



- Of course, this is only a muon :-)

Summary

- *Introduction to high energy physics at colliders*
- *Basics of QCD*
- *Perturbative QCD at colliders*
  - *factorization for hard processes*
  - *Parton density functions*
  - *Jet cross sections*
- *Important processes at the LHC*



Tomorrow

- *Higgs, Supersymmetry and beyond*