QCD Lecture [Day 3]

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3rd France-Asia Particle Physics School (FAPPS11)
Les Houches, France, 14/Oct/2011

ÉCOLE DE PHYSIQUE
des HOUCHES

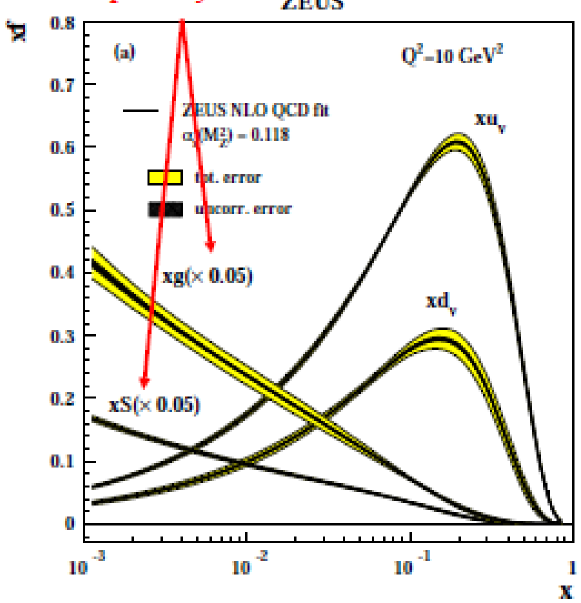
Plan for 3 days lectures

- Day-1: Basis of QCD
- Day-2: Proton structure @ lepton-hadron collision
- **Day-3: Jets @ hadron-hadron collision**

QCD knowledge necessary for doing physics at LHC

► Leant from Day-2:
-- Factorization into ME and PDF
-- How PDF is determined

Note that gluon and sea quarks are multiplied by 1/20



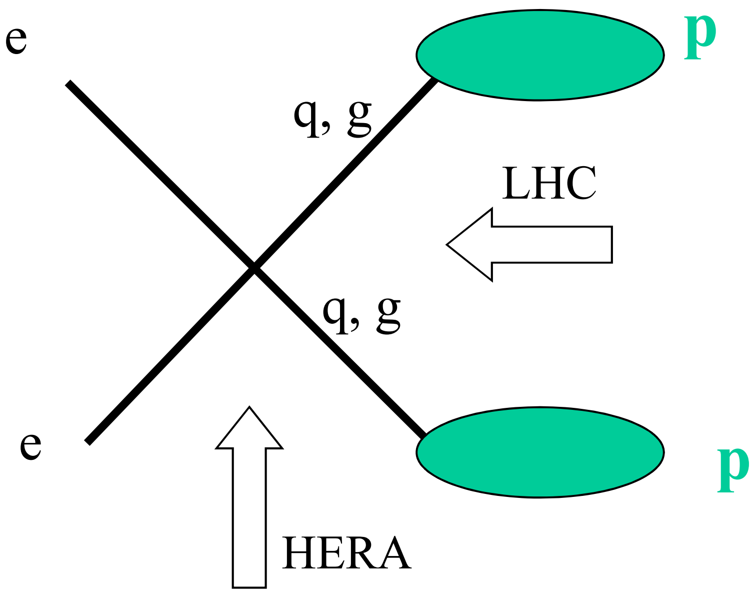
If any questions on Day-2 contents, please ask.

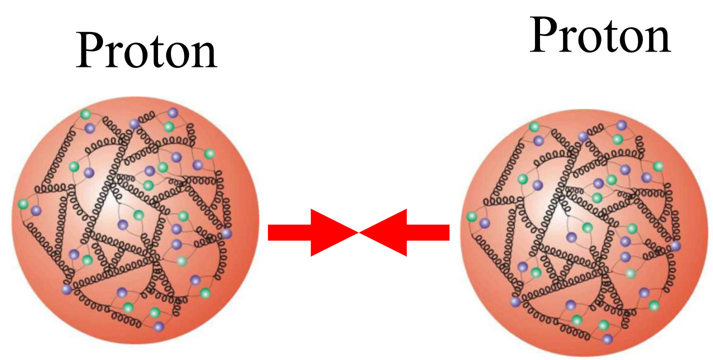
Day-3 is to use PDF for LHC physics

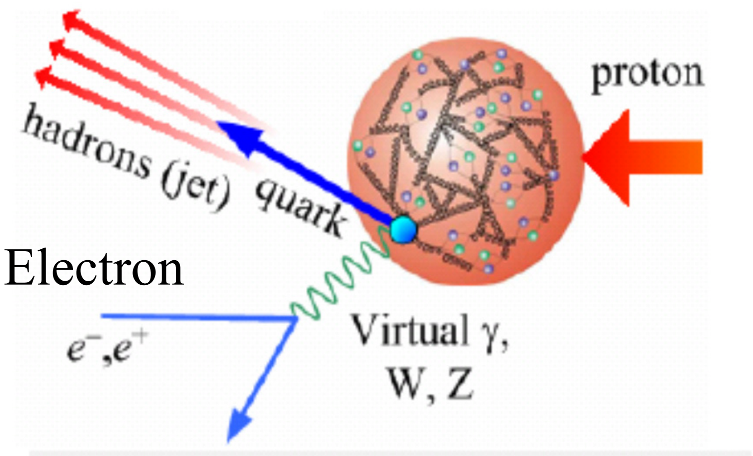
Introduction

- **Towards observables at LHC**

LHC and HERA







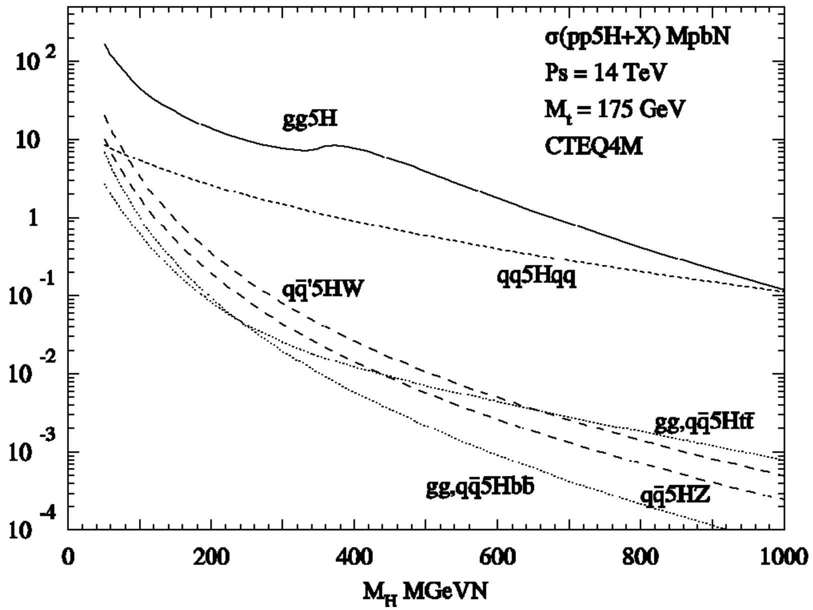
- ▶ HERA
  - -- Measure proton structure with electron as a probe
  - -- Search for new particle/physics in e-q elementary process
- ▶ LHC
  - -- Search for new particle/physics in q-q, q-g, g-g elementary process
  - -- Needs proton structure information as a mandatory input

Kimematics @ LHC

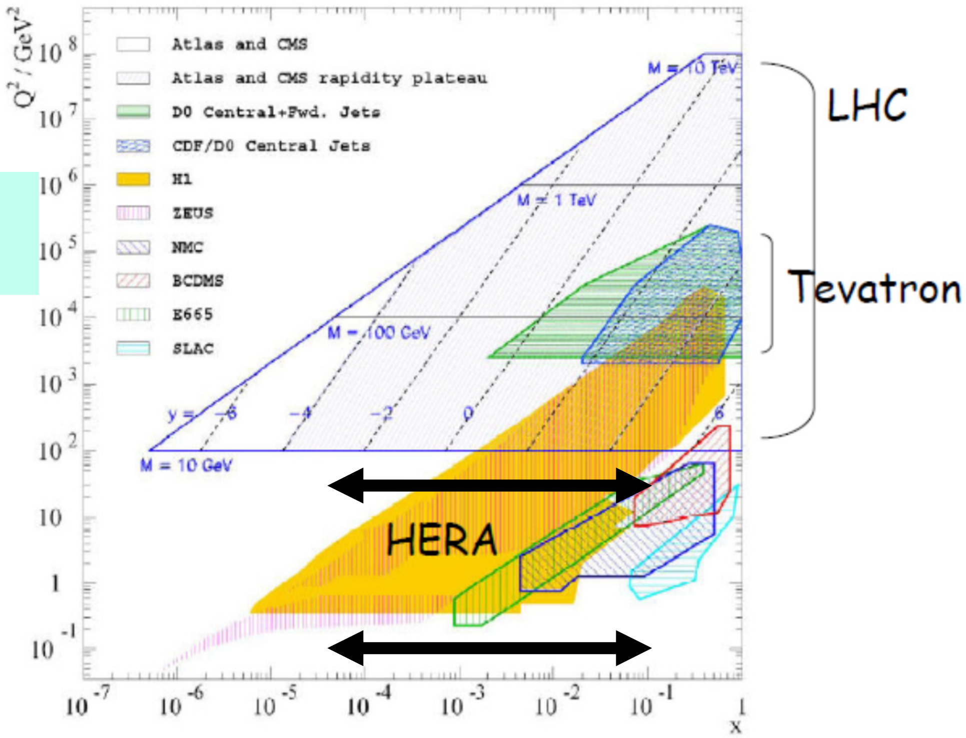
- Main x range is same between LHC and HERA

- Gluon is the main parton which contributes most to interactions at LHC
  -- HERA has provided gluon in this same x range!

Higgs production cross section at LHC



Q^2 (scale)



Bjorken x (momentum fraction)

Inputs are ready.

Kimematics @ LHC

- Main x range is same between LHC and HERA

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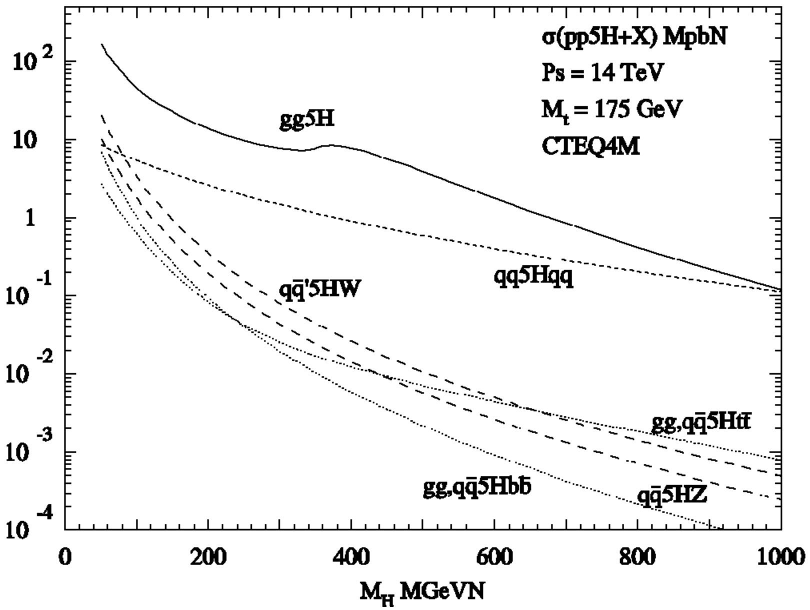
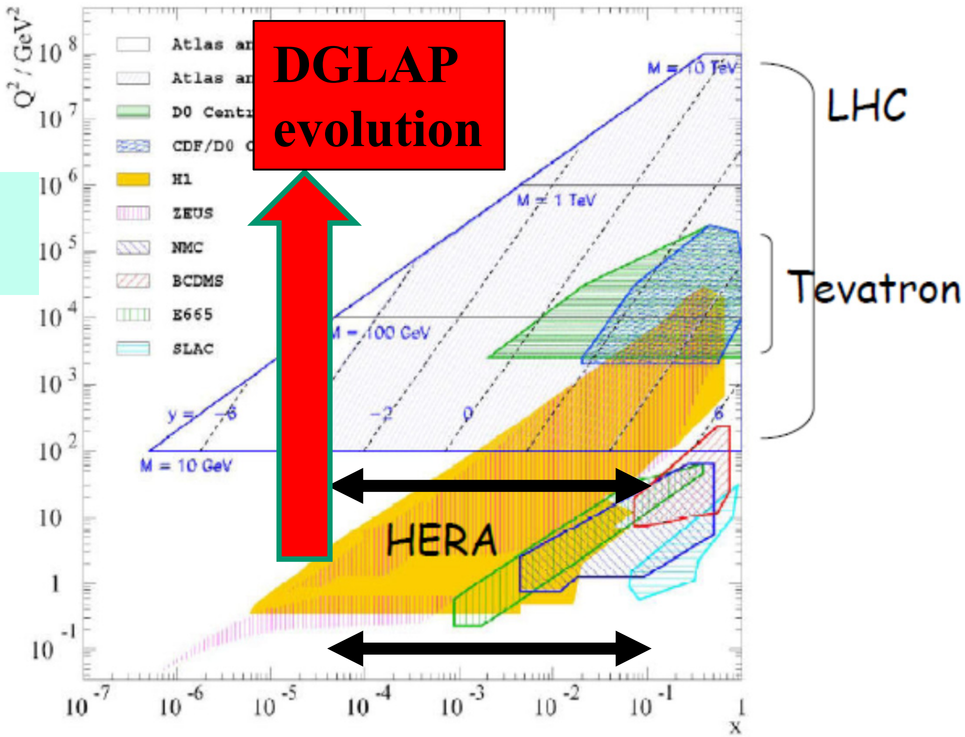
Q^2 (scale)

Higgs production cross section at LHC



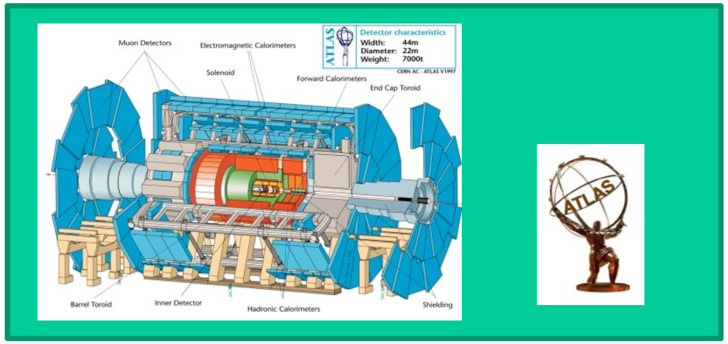


Inputs are ready.

Bjorken x (momentum fraction)

Up to detector level

► Connection up to detector level (hadrons): we have inputs (PDF etc)
but it is still far up to outputs…

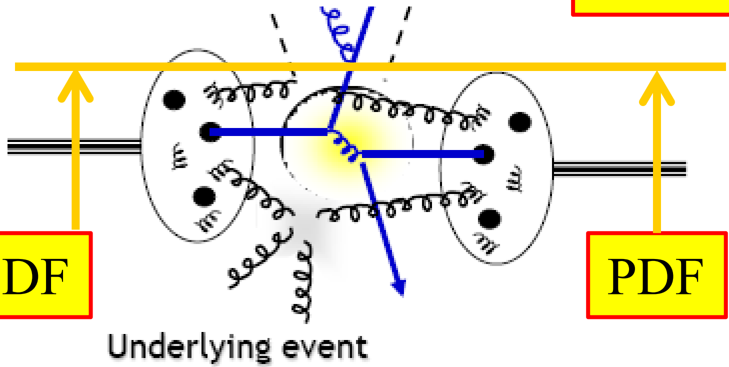


Detector level

Parturbative calc.

Factorization at μ_F^2

DGLAP equation



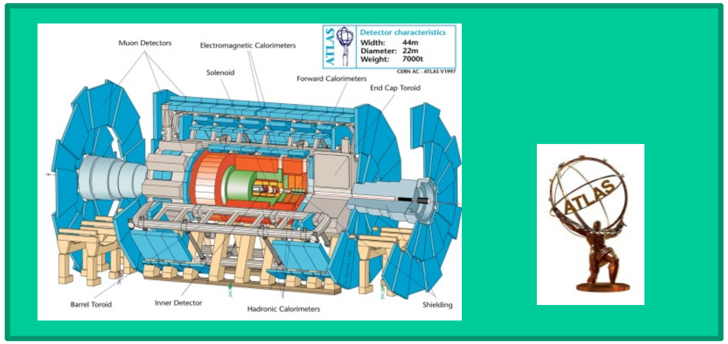
PDF

PDF

For more,
→ Lectures by
Prof. Kurihara

Up to detector level -cont'd-

► Connection up to detector level (hadrons): **Parton shower model**



Detector level

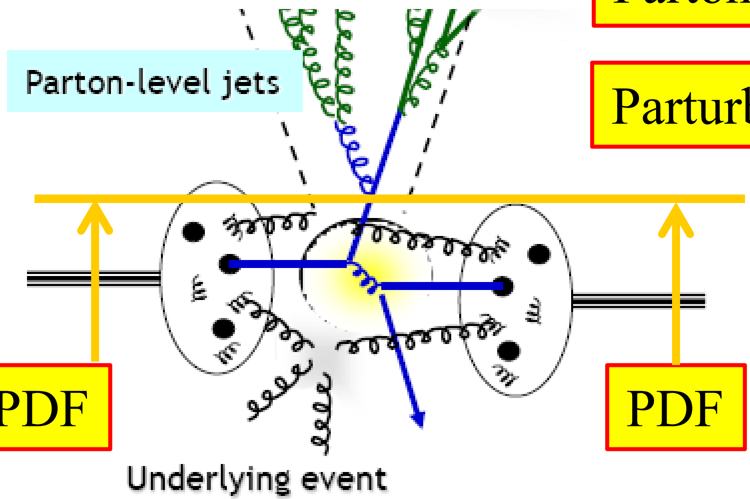
g→gg, q→qg raditions can be modeled as "Parton shower"

Parton shower model

Parturbative calc.

Factorization at μ_F^2

DGLAP equation



PDF

PDF

Up to detector level -cont'd-

For more,
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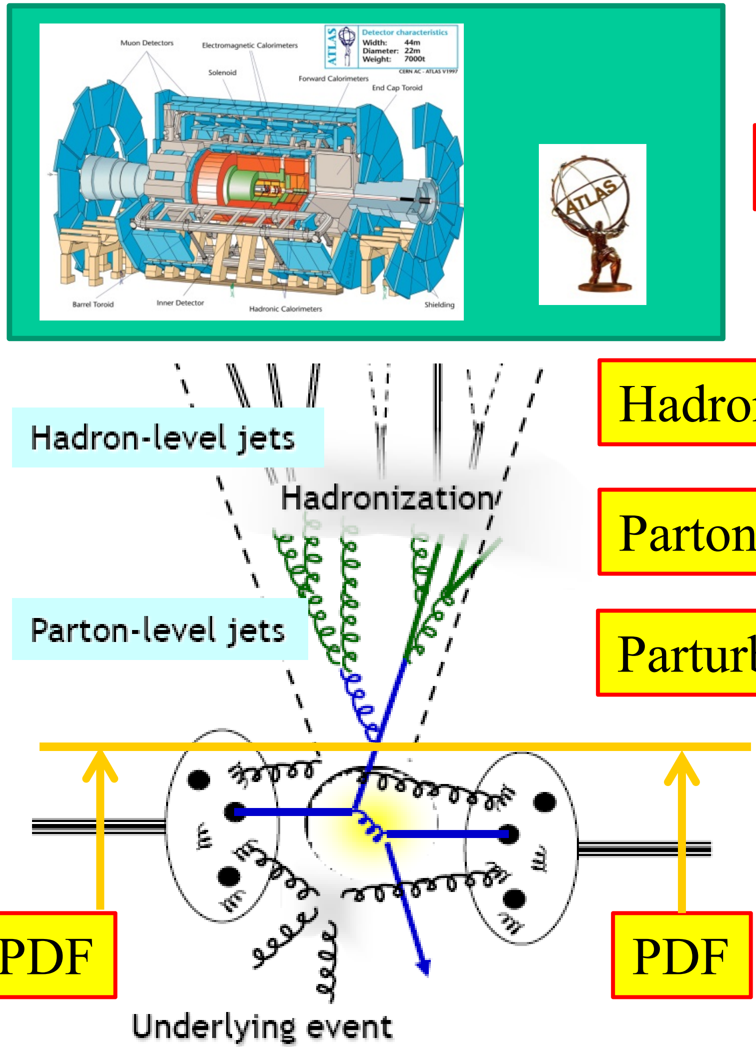
► Connection up to detector level (hadrons): Parton shower model
→ **Hadronization model**



Detector level

Quarks and gluons to form hadrons, mesons Cannot be perturbatively calculated; several models.

Hadronization model

Parton shower model

Parturbative calc.

Factorization at μ_F^2

DGLAP equation

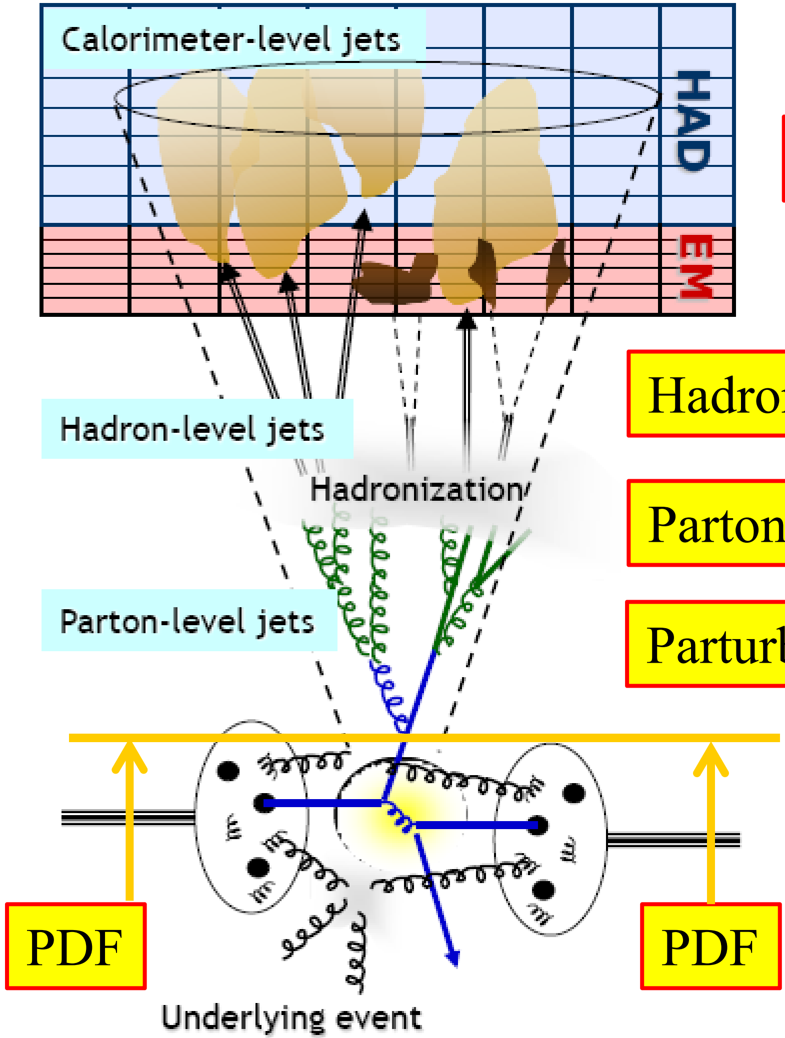
PDF

PDF

Have learned @ lecture by Prof. V. Ruhlman-Kleider

Up to detector level -cont'd-

► Connection up to detector level (hadrons): Parton shower model
→ Hadronization model



Detector level

Hadronization model

Parton shower model

Parturbative calc.

Factorization at μ_F^2

DGLAP equation

Particles detected in calorimeter, tracking devices etc.
-- Energies in calorimeter cell etc.

➔ Experimental technique to reconstruct objects as closer to particles as possible

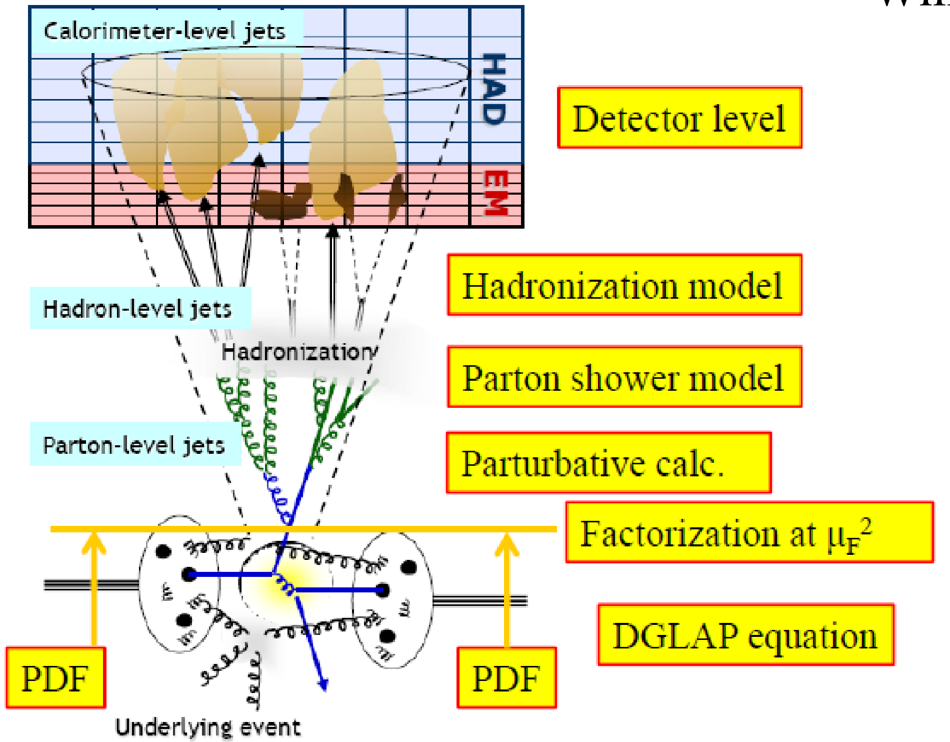
(Calorimeters, Particle Flow tech. etc.)

Jet algorithms

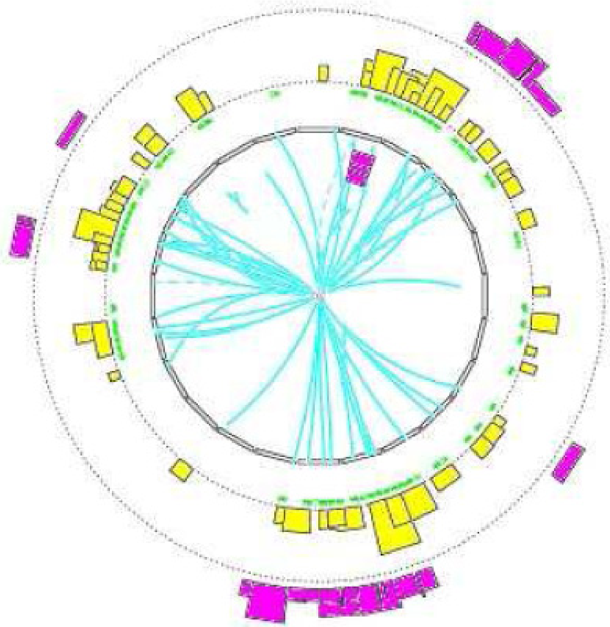
- We need a good observable which allows direct/robust comparison between theory and experiment

Jet

- ► Partons contributed to a hard scatter tend to form a spray of collinear hadrons;
  "Jets" → A good measure to relate detector level and parton-level hard scatter
  "Window for partons"



- ► To be precise, need a "well-defined" jet algorithm
  -- How to define jets



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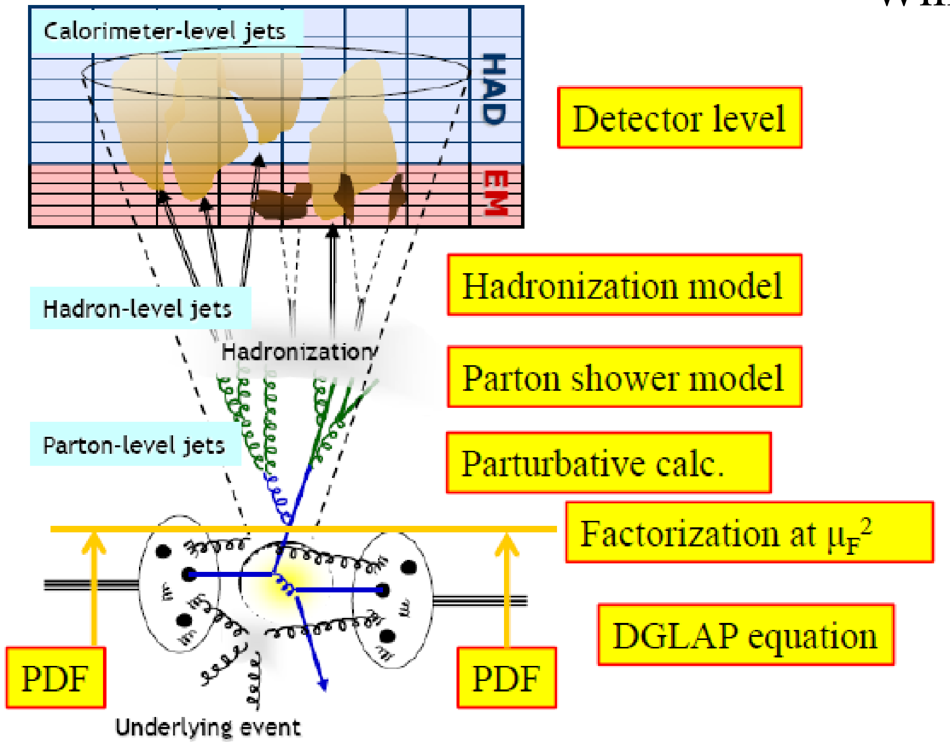

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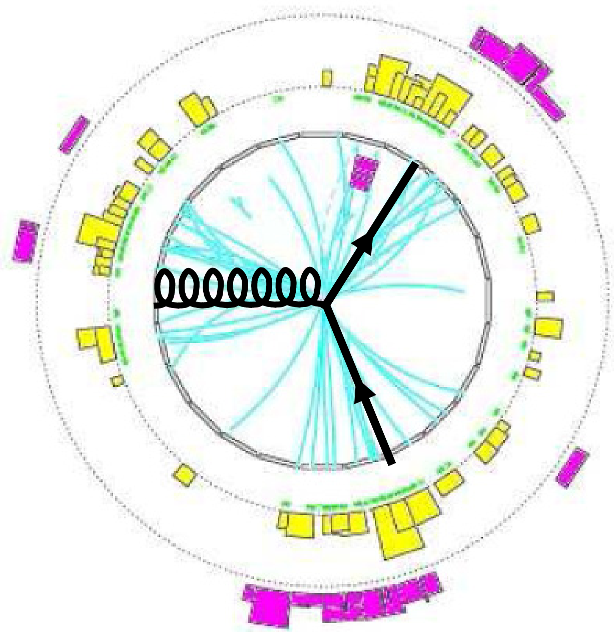

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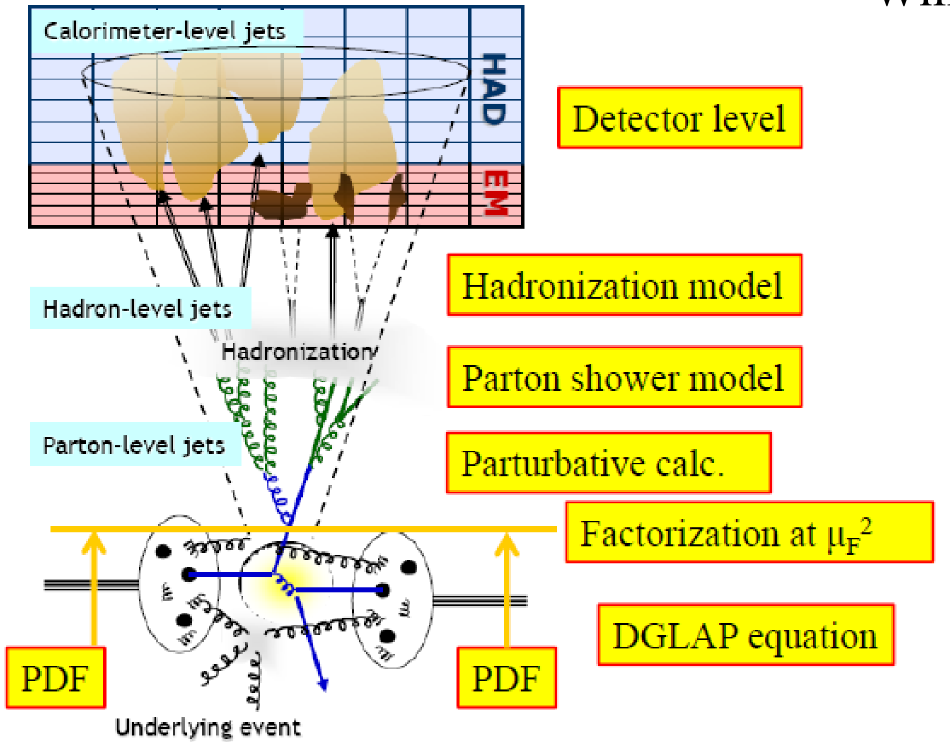

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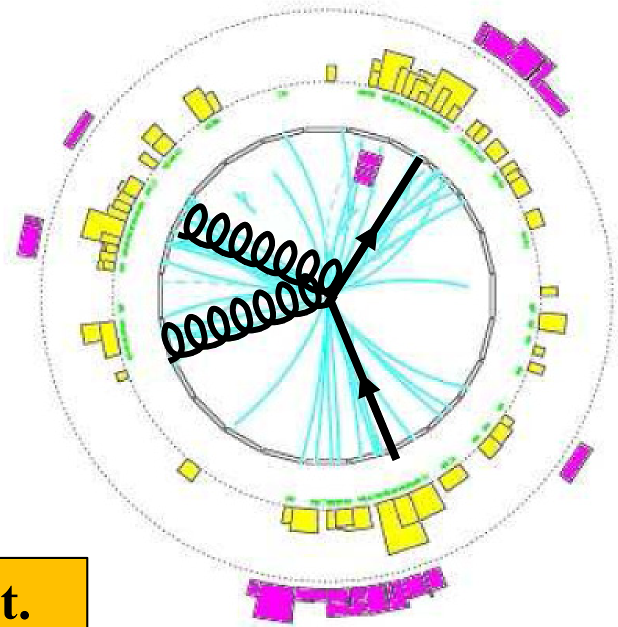
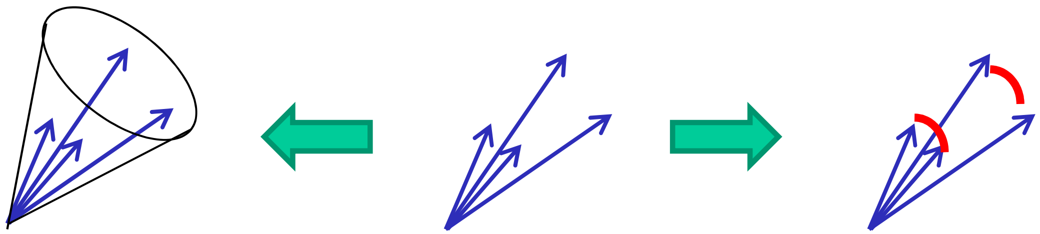


Definition of jet is algorithm dependent.

Jet algorithms

► Cone algorithms

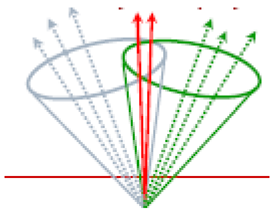
► Recombination algorithms



-- Search for a "cone" in which the vector sum particles inside the cone points to the center of the cone

-- Used at TEVATRON

- Pros
  -- Circular cone shape
- Cons
  -- Often **infrared unsafe** (except for SisCone)
  -- Overlapping cones handling



-- Successively find "closest" pair of particles and combine them

-- Used at e-e, e-p and LHC

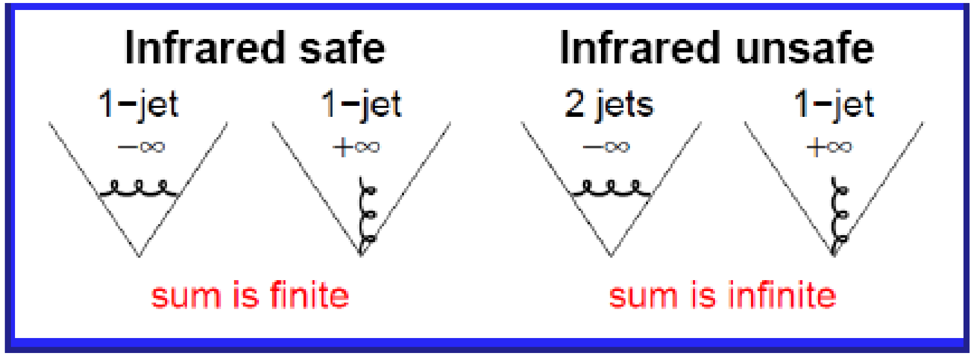
- Pros
  -- **Infrared safe**
- Cons
  -- Irregular shapes (except for Anti-kT)

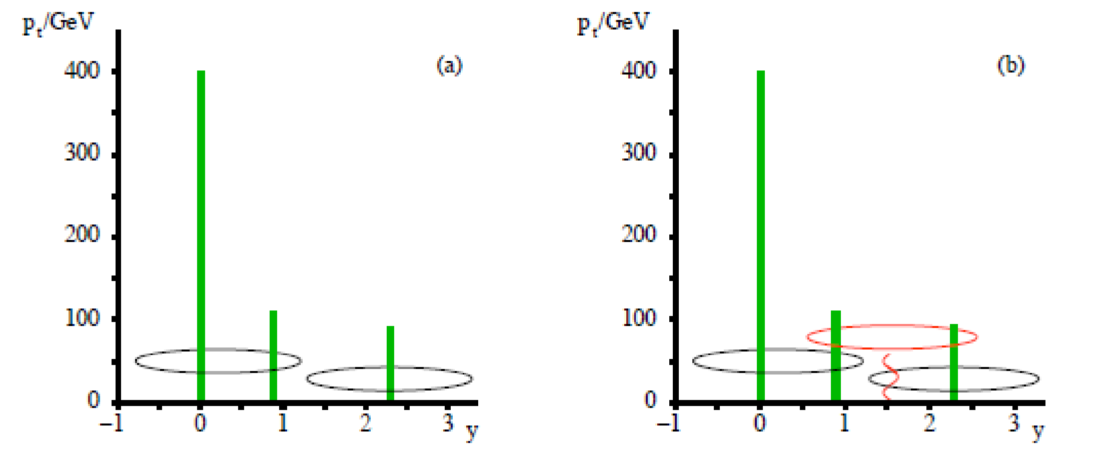
→ **Next page.**

In this lecture, concentrate on recombination algorithms.

Infrared safety

- ► Invariance against infrared emission: "Infrared safe"
  - -- Adding a soft parton should not change the jet algorithm result





Three hard particles clustered into **two** cones

Addition of a **soft** particles changes the hard jets configuration: **three** stable cones are found

M. Cacciari @ FRIF, 2008

Otherwise, real-virtual cancellation is lost (infinities will not cancel) → divergent results

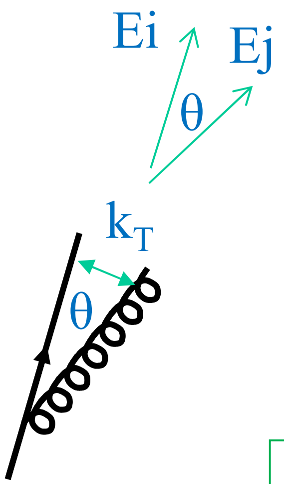
Kt(Durham) algorithm for e^+e^-

► Metric

$$y_{ij} = \frac{2\min(E_i^{\,2}, E_j^{\,2})(1-\cos\theta_{ij})}{Q^2} \approx \frac{\min(E_i^{\,2}, E_j^{\,2})\theta_{ij}^{\,2}}{Q^2} \approx \frac{k_T^{\,2}}{Q^2}$$

Relative p_T between particles

Normalization with interaction scale Q^2



Majority of QCD branching is soft & collinear
➔ Take pair with strongest divergence (p_T~0) between them; which is most likely to belong together

1. Calculate y_{ij} for all pairs among all particles
2. Find minimum y_{ij}
   -- If > y_{cut}, stop clustering
   -- Otherwise recombine i and j and repeat from 1.

1 parameter in the algorithm

y_{cut} : sets minimum relative p_T^2 between any pair of jets

Kt for hadron collider

► Metric

ee : $$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{Q^2} \approx \frac{\min(E_i^2, E_j^2)\theta_{ij}^2}{Q^2} \approx \frac{k_T^2}{Q^2}$$

pp : $$y_{ij} = \frac{\min(p_{t,i}^2, p_{t,j}^2)\Delta R_{ij}^2}{R^2}$$

Longitudinally invariant by using p_T, y (rapidity), φ

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

$$\eta = \frac{1}{2}\ln\frac{p+p_z}{p-p_z} = -\log(\tan(\theta/2))$$

($\eta = y$ when a particle is massless)

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

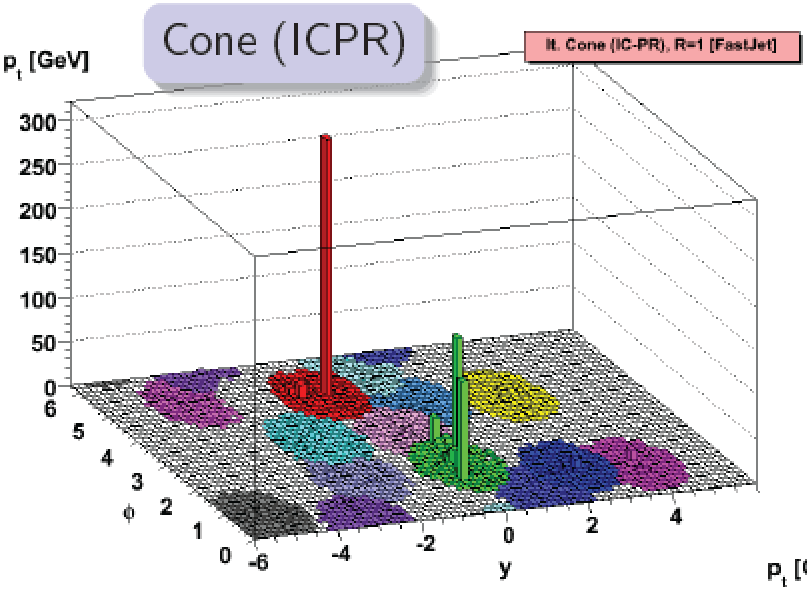
New parameter

$$y_{ii} = p_{t,i}^2$$

1. Calculate y_{ij} for all pairs among all particles
2. Find minimum y_{ij}
   -- If ij, recombine them
   -- If ii, call i a jet and remove from list of particle
3. Repeat from step 1 until no particle left.

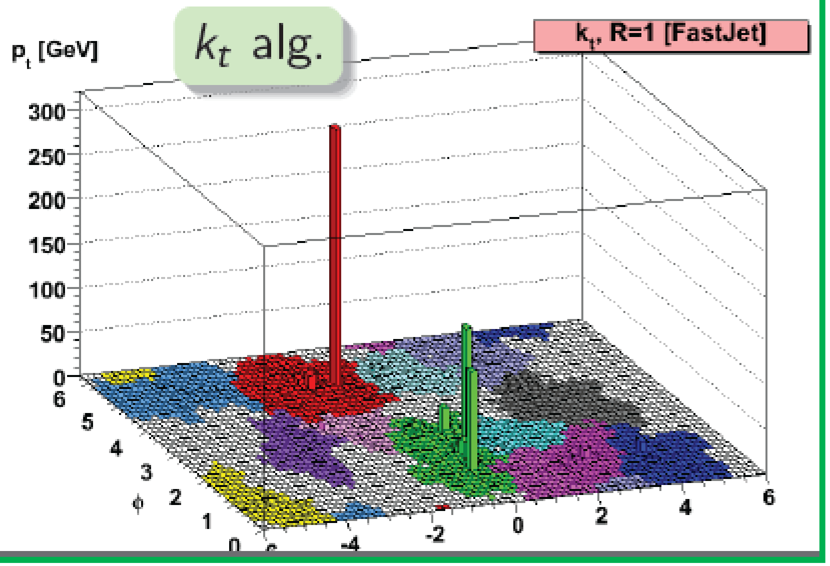
- R : sets minimum separation ΔR^2 between any pair of jets
- pt cut on the jets

Shapes of Kt jets



(Some) cone algorithms give **circular** jets in $y - \phi$ plane

Much appreciated by experiments e.g. for acceptance corrections



k_t jets are **irregular**

Because soft junk clusters together first:

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2$$

Regularly held against k_t

➔ Is there any non cone-based jet algorithm that can obtain circular jets ?

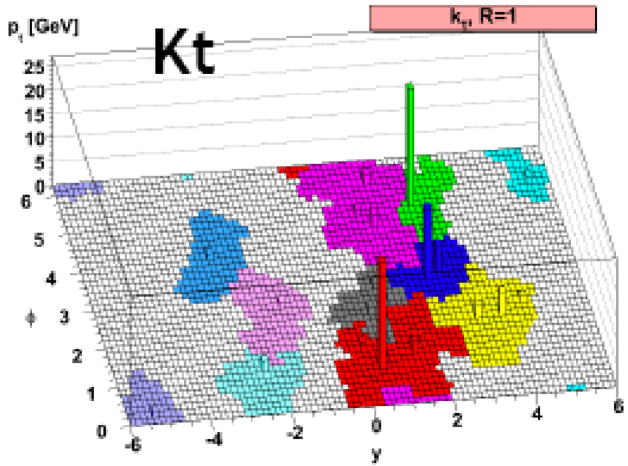
Anti-Kt algorithm

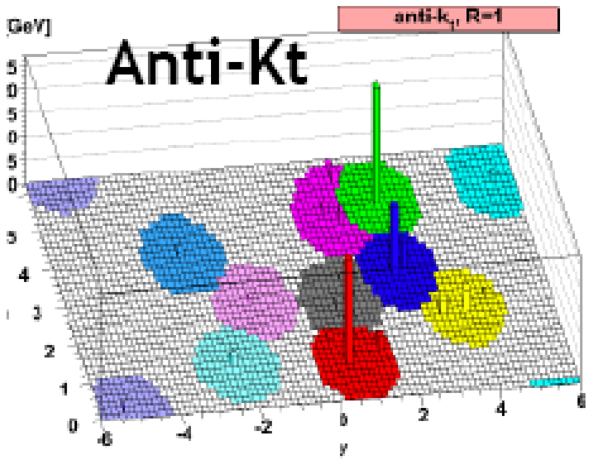
► kT → Anti-kT

$$y_{ij} = \frac{\min(p_{t,i}{}^2, p_{t,j}{}^2)\Delta R_{ij}{}^2}{R^2} \quad \Rightarrow \quad y_{ij} = \frac{\Delta R_{ij}{}^2}{\max(p_{t,i}{}^2, p_{t,j}{}^2) R^2}$$

-- Soft stuff clusters with nearest neighbor

-- Hard stuff clusters with nearest neighbor

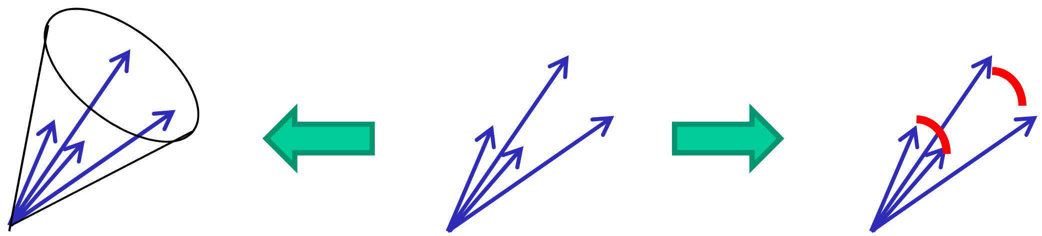




Jet algorithms

▶ Cone algorithms

▶ Recombination algorithms



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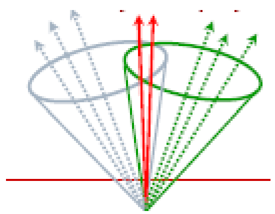

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Anti-kT is used as default in ATLAS, CMS

For more,
→ Lectures by
Prof. Kurihara

Parton shower and resummation

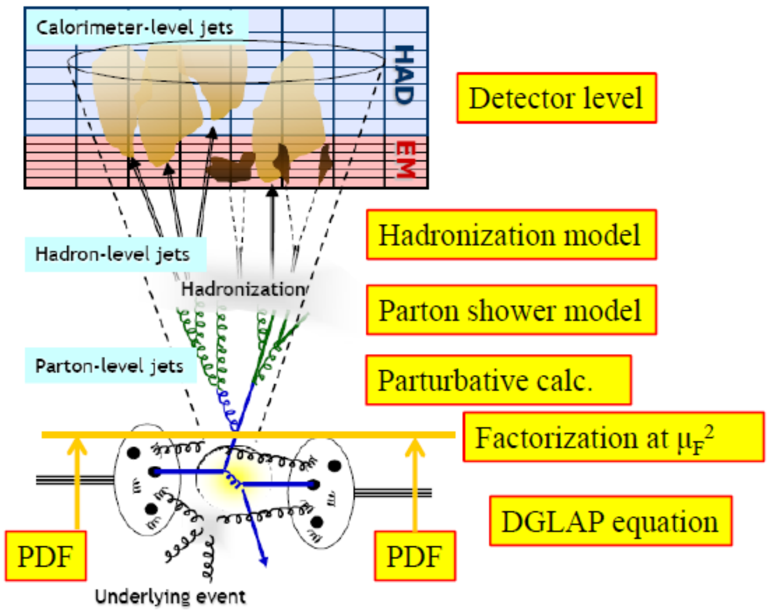
- **Now we have a robust jet definition.**
- **Next, we need more to connect: ME+PDF → hadron**
    - **-- Parton shower**
    - **-- Hadronization**

Just to get a rough overview on the technique of this connection.
For more details → Event Generator lecture by Prof. Kurihara

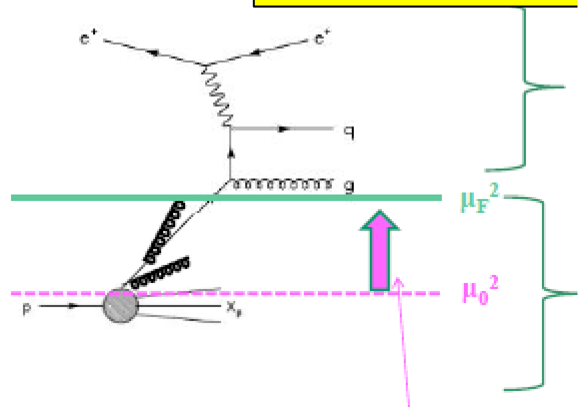
Parton shower (PS) model

For more,
→ Lectures by
Prof. Kurihara

- QCD branching



-- Quite similar to the DGLAP evolution



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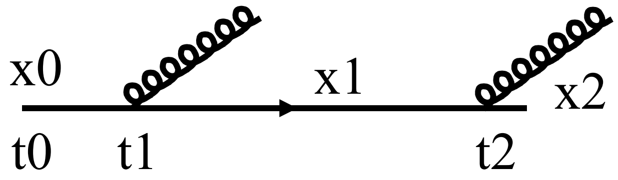
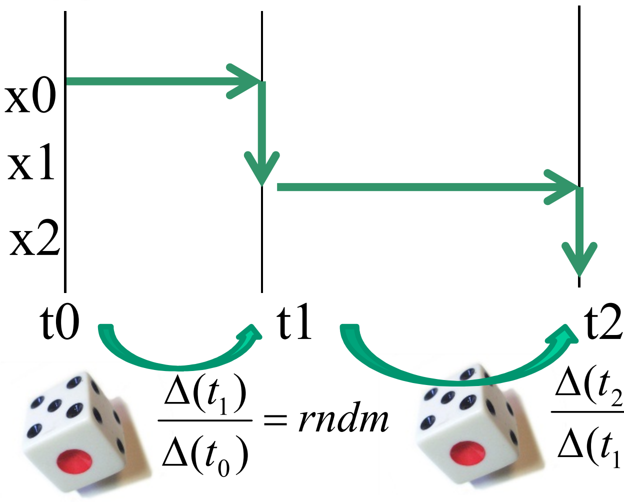
For computer simulation, it is instead convenient to define "**Sudakov form factor**"

$$\Delta(t)$$

→ Survival probability





$$\frac{\Delta(t_1)}{\Delta(t_0)} = rndm \qquad \frac{\Delta(t_2)}{\Delta(t_1)} = rndm$$

Prediction with computer simulation

ME-PS matching

For more,
→ Lectures by
Prof. Kurihara

- Matrix-Element calculation (hard scatter)
  - -- Excellent in simulating: well separated, hard partons, while
  - -- problems with collinear/soft partons

- Parton shower
  - -- Hard, wide-angle emissions are poorly approximated, while
  - -- soft/collinear emissions are well described

Clearly, it would be desirable to combine
ME and PS approaches, however,
it is not a trivial work…

(To understand this)
Let's look a bit more on PS
what it is actually doing.

Resummation: when "logs" are not so small

► Reminder: factorization, perturbation

Perturbation expansion

$$O = \phi \otimes \hat{O} + P_0 \qquad \hat{O} = \sum_n C_n \alpha_s^{\,n} + R_n$$

Observable **PDF** **Partonic observable** **Cn often includes "log"s**

► Generally, partonic observable behaves:

$$\hat{O} = 1 + \alpha(L^2 + L + 1) + \alpha^2(L^4 + L^3 + L^2 + L + 1)\ldots$$

"L": represents "log"
"1": represents π, 2 etc…

→ If L is not so small, calculation only with αL^2 will not be a good approx.

► "Resummation" : re-organize / re-sum such that

$$\begin{aligned}\hat{O} &= 1 + \alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \ldots \\ &= \exp\left(\underbrace{\underbrace{Lg_1(\alpha_s L)}_{LL} + g_2(\alpha_s L)}_{NLL} + \alpha_s g_3(\alpha_s L) + \ldots\right)\underbrace{C(\alpha_s)}_{\text{constants}} \\ &\quad + \text{ suppressed terms}\end{aligned}$$

"LL": Leading Log

$$\alpha^n L^{2n}$$

"NLL": Next-to-Leading Log

$$\alpha^n L^{2n-1}$$

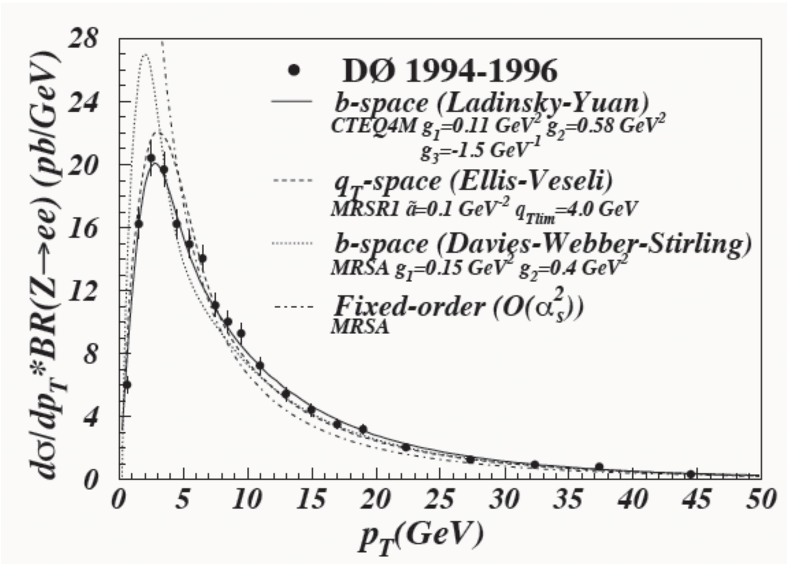
When "log"s become not so small ?

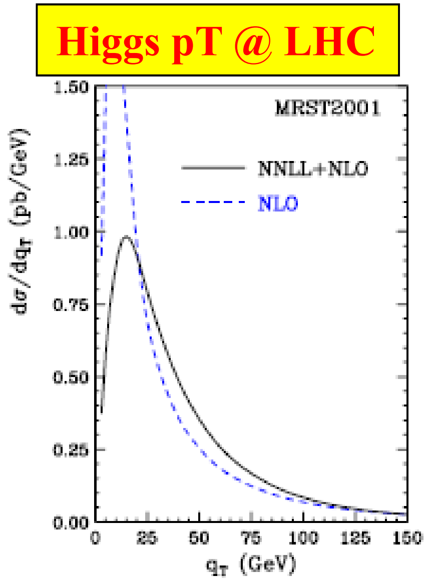
► Generally speaking, when there are > 1 typical scales in the process

-- If there is only one scale, e.g. inclusive DIS as Q^2: $\ln Q^2/\mu^2$

- Recoil logs

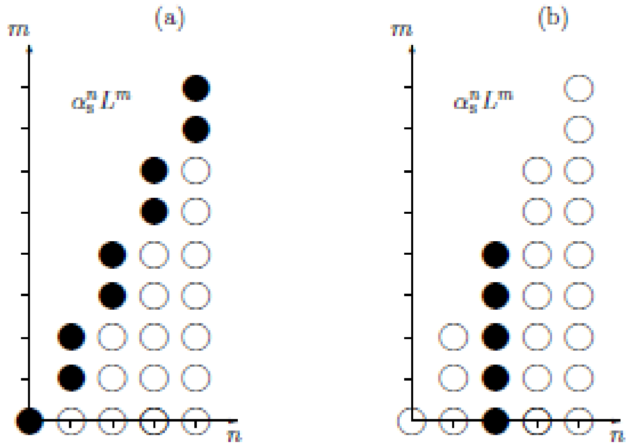
-- E.g. Z production in p-p, Z's p_T distribution → $L = \ln \frac{p_T^{\ 2}}{m_Z^{\ 2}}$





Resummation -cont'd-

- ► A pictorial view



Resummation up to NLL

Full coefficients from α^2

$$\hat{O} = 1 + \alpha_s(L^2 + L + 1) + \alpha_s^2 \boxed{(L^4 + L^3 + L^2 + L + 1)} + \ldots$$

$$= \exp\left(\underbrace{\underbrace{L g_1(\alpha_s L)}_{LL} + g_2(\alpha_s L)}_{NLL} + \alpha_s g_3(\alpha_s L) + \ldots \right) \underbrace{C(\alpha_s)}_{\text{constants}}$$

$$+ \ \text{suppressed terms}$$

"LL": Leading Log

$$\alpha^n L^{2n}$$

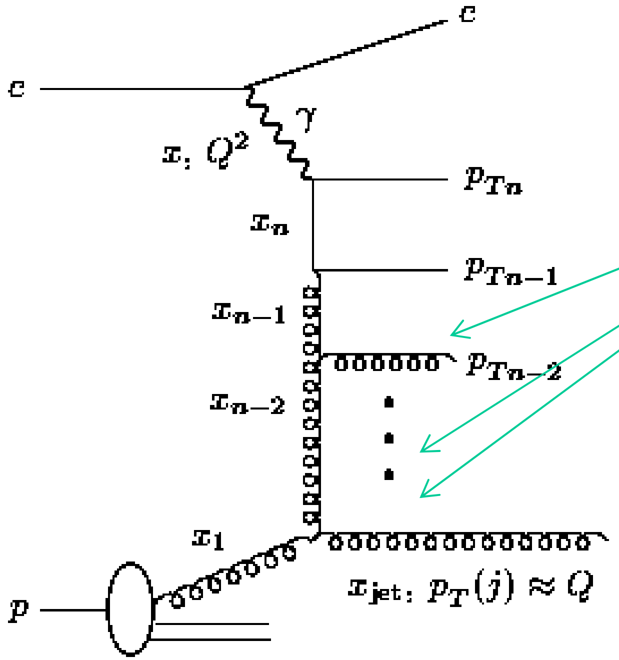
"NLL": Next-to-Leading Log

$$\alpha^n L^{2n-1}$$

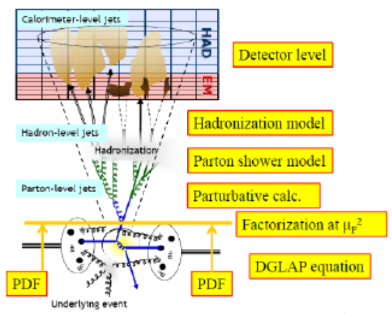
This is actually what we have done with PS, DGLAP

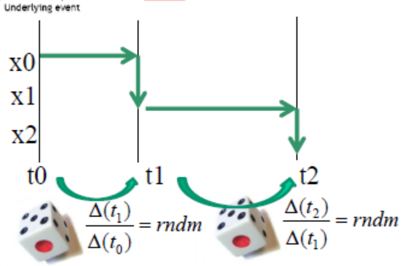
► DGLAP is a derivative equation → When we are solving it numerically from μ_0^2 to μ^2

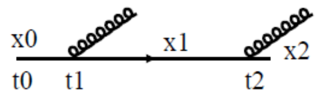
-- By numerically transferring it with many steps at μ_1^2, μ_2^2, μ_3^2… we are effectively summing up all logs of αL from μ_0^2 to μ^2



► Parton shower is also resummation







ME+PS matching -cont'd-

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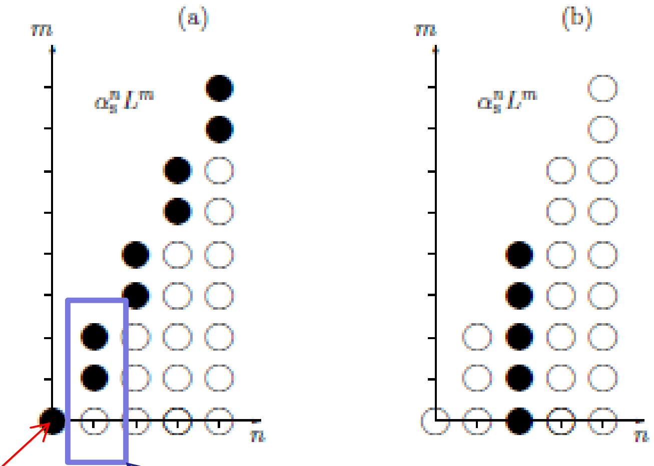
Prof. Kurihara

► A pictorial view



Resummation up to NLL

NLO ME

Not so straightforward to combine ME and PS (overlaps etc.)

$$
\begin{aligned}
\hat{O} &= 1 + \boxed{\alpha_s(L^2+L+1)} + \alpha_s^2(L^4+L^3+L^2+L+1) + \ldots \\
&= \exp\left(\underbrace{\underbrace{Lg_1(\alpha_s L)}_{LL} + g_2(\alpha_s L)}_{NLL} + \alpha_s g_3(\alpha_s L) + \ldots\right)\underbrace{C(\alpha_s)}_{\text{constants}} \\
&\quad + \text{ suppressed terms}
\end{aligned}
$$

"LL": Leading Log

$$\alpha^n L^{2n}$$

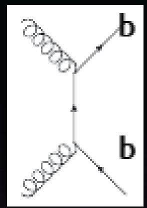
"NLL": Next-to-Leading Log

$$\alpha^n L^{2n-1}$$

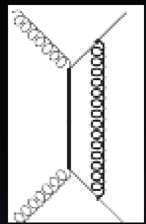
ATLAS EXPERIMENT http://atlas.ch

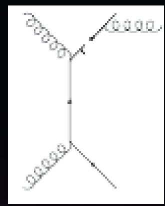
QCD predictions (and postdictions)

LO
lowest order in α_s

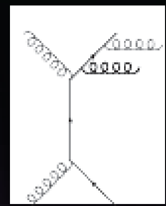


NLO
up to 1 loop





+ parton shower



Emits as many gluons you can, but in the soft or collinear approximation (larger contribution)

LO MC — Pythia, Herwig LO process + showering + fragmentation + particle decays. Tuned on data to get best agreement (often good prediction of shapes, large deviation in absolute values)

NLO parton level — only partons or gluons in the final state (Just compute the pQCD part of the process): NLOJet++, MCFM, DIPHOX, JETPHOX

NLO MC + parton shower — Hard process computed at NLO, showering performed by PYTHIA or HERWIG.

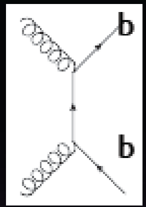
NLO + resummation — FONLL(QQ, NLO + NLL), RESBOS (Drell Yan, NLO+NNLL; di-photons) The soft and collinear emission is computed analytically at higher orders.

Higher order tree level MC. — Exact computation of all tree level diagrams, but missing loop contribtions, avoid double counting by requiring that all hard jets match a parton ALPGEN, SHERPA(+ parton shower)

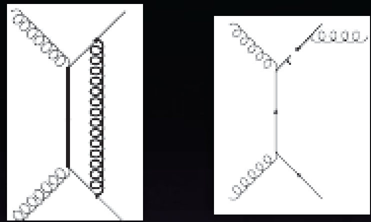
NNLO parton level — FEWZ, DYNNLO, HNNLO,...

QCD predictions (and postdictions)

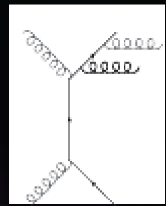
LO
lowest order in α_s



NLO
up to 1 loop



+ parton shower



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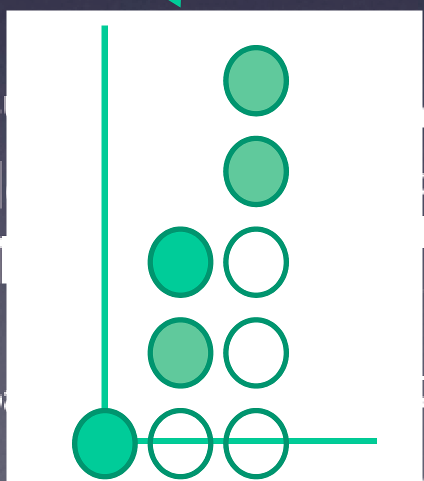
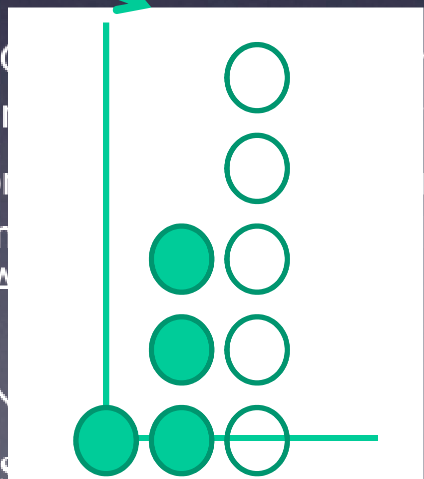
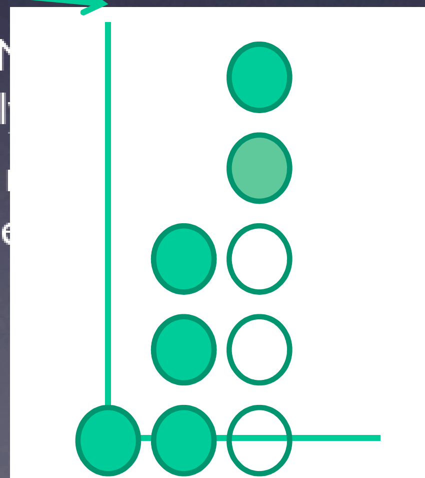






NLO + resu… …Q, NLO… …ell Yan, N… …s) …d collin… …ted anal… …s.

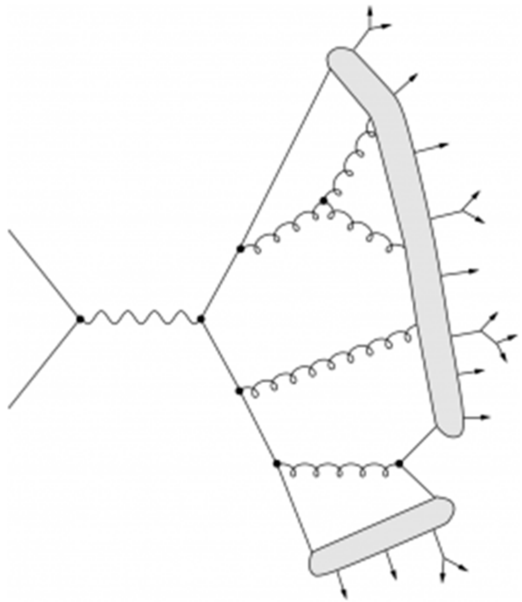
Higher ord… level M… …putation… …ms, but … …ns, …e coun… …ll hard je… HERPA…

NNLO pa… …Z, DYN…

Hadronization models

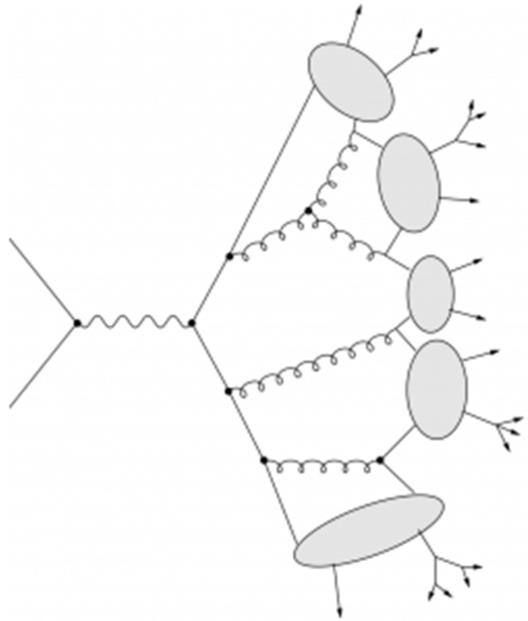
For more,
→ Lectures by
Prof. Kurihara

► String model



Prediction
with computer
simulation

► Cluster model



-- "String" representing color flux stretched from initial state
-- Gluon produces "kinks" in the string
-- Gluon splitting into quarks produce another string.
➔ Strings break up into hadrons

PYTHIA/JETSET

-- After parton shower, gluons are split into quark-antiquark
-- Color singlet ("white") combinations to form cluster
➔ Clusters undergo isotropic decay into pairs of hadrons

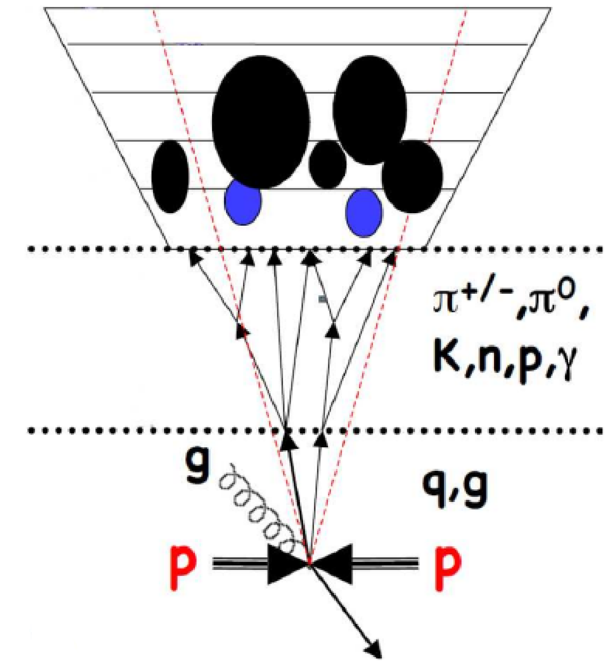
HERWIG

Jets @ LHC

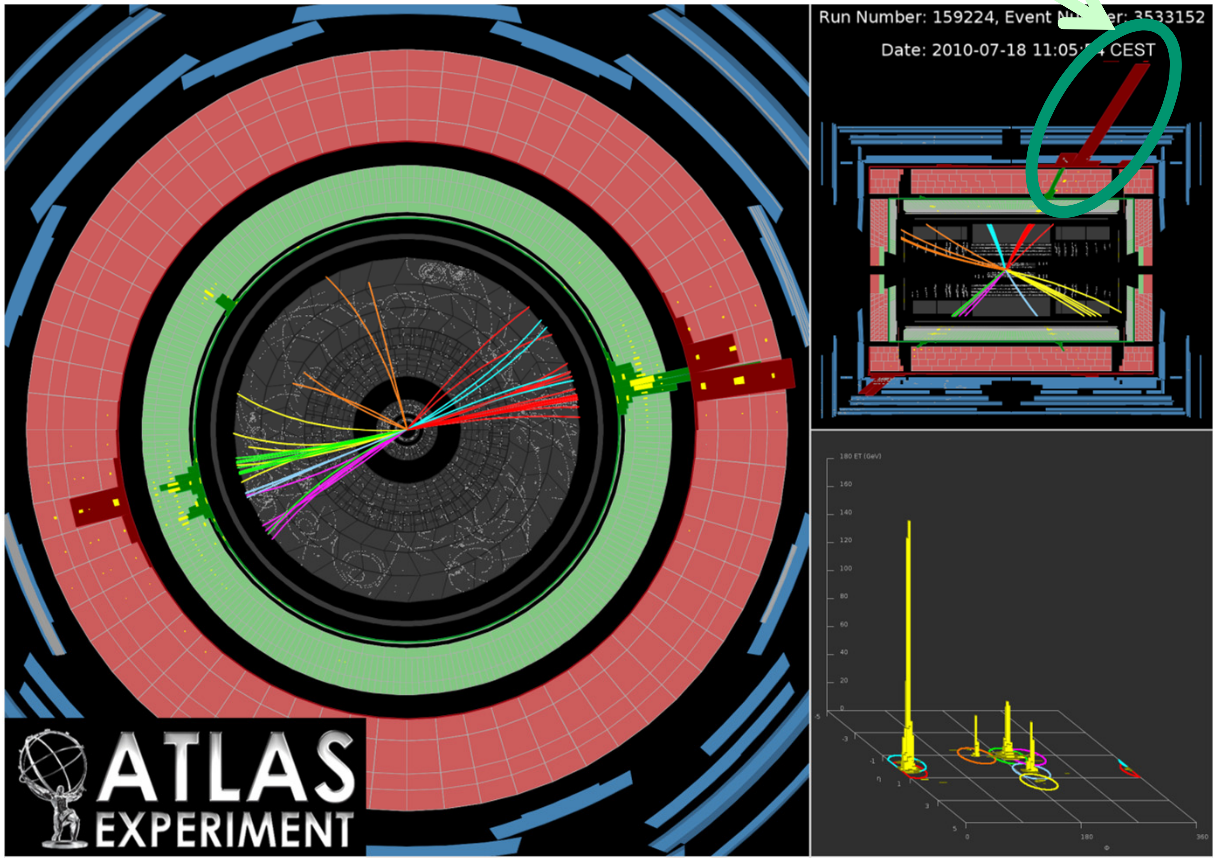
- **Now we have various theoretical predictions.**
  ➔ Let's see how LHC data are

Jets @ LHC

- QCD validation at unexplored kinematic phase space
  -- We are seeing $p_T \geq 1$ TeV and di-jets with $M_{jj} \geq 3$ TeV !



Jet with $p_T \geq 1$ TeV



ATLAS-CONF-2011-047

Inclusive jet cross sections

► Anti-k_T, R=0.4

-- p_T(jet)>20 GeV to 1.5 TeV

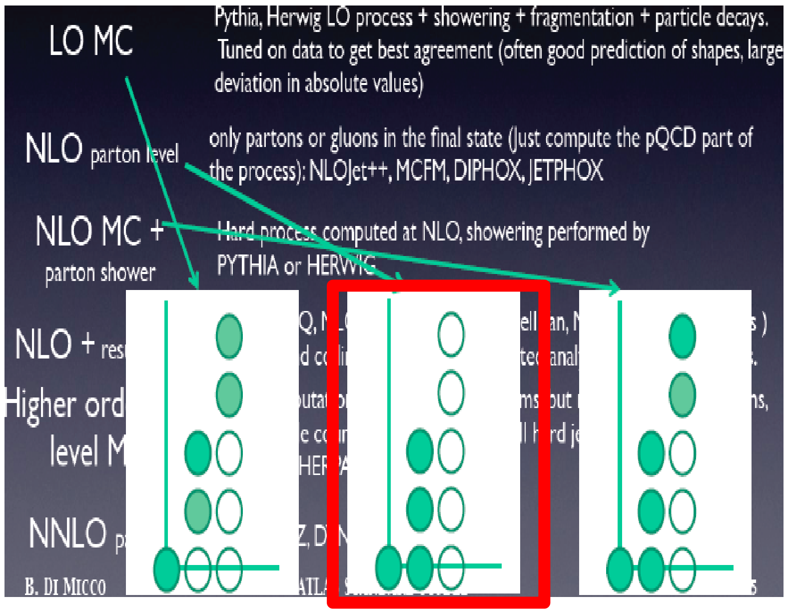
-- $|y_{jet}|$ up to 4.4

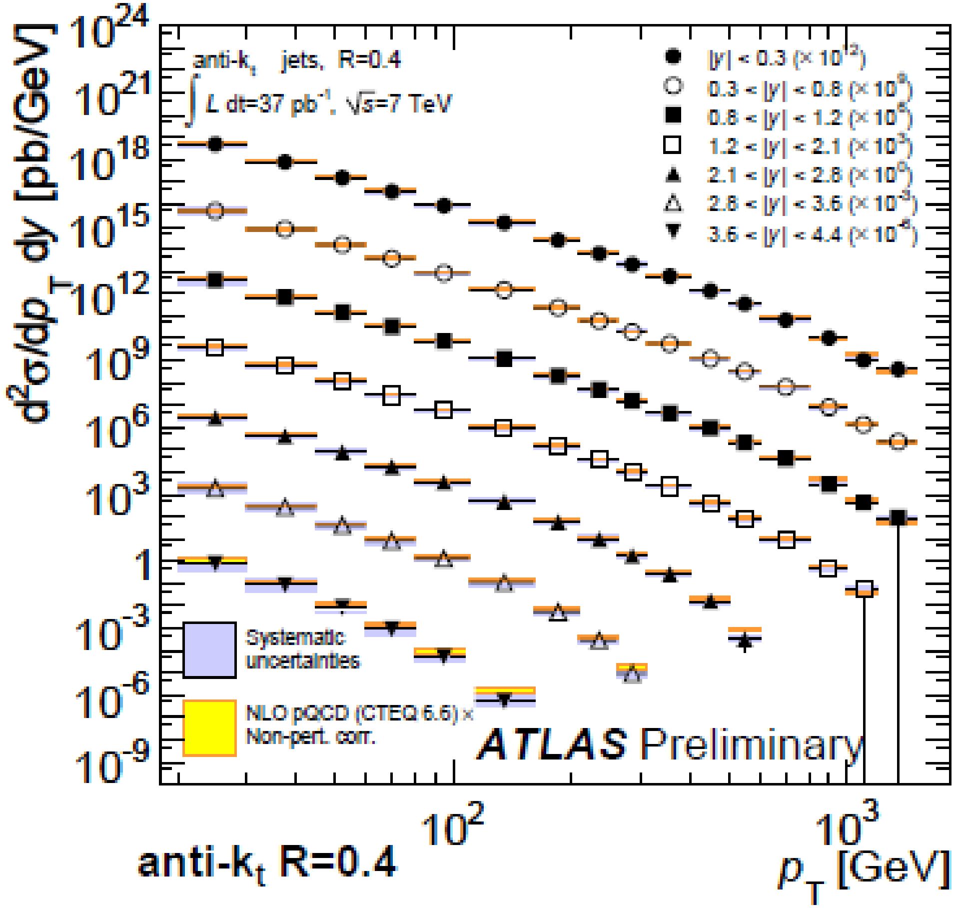
"NLO pQCD × Non-pert corr"

→ NLO @ parton level (NLOjet++)

×

$$f = \frac{\text{with hadronization (Pythia)}}{\text{without hadronization (Pythia)}}$$





QCD prediction works over > ~10 orders of magnitude.

Inclusive jet cross sections -cont'd-

▶ Anti-k_T, R=0.4

-- p_T(jet)>20 GeV to 1.5 TeV

-- $|y_{jet}|$ up to 4.4

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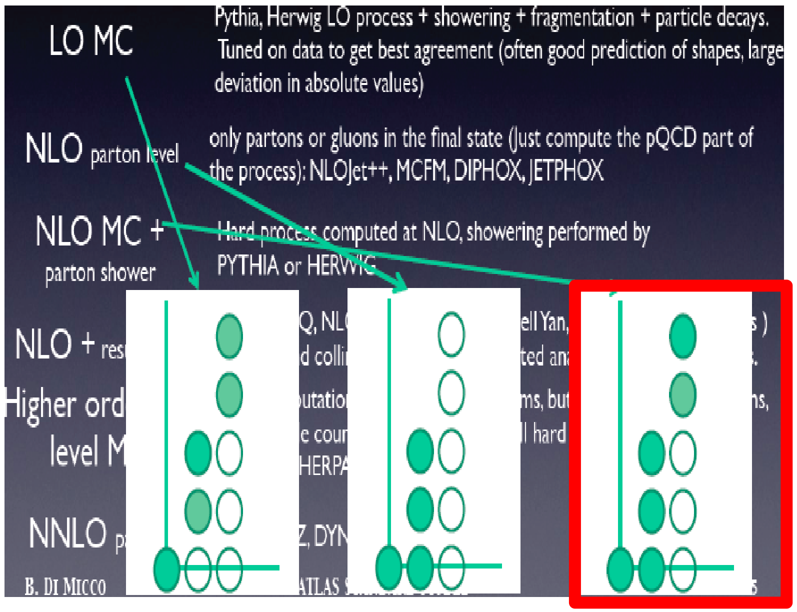
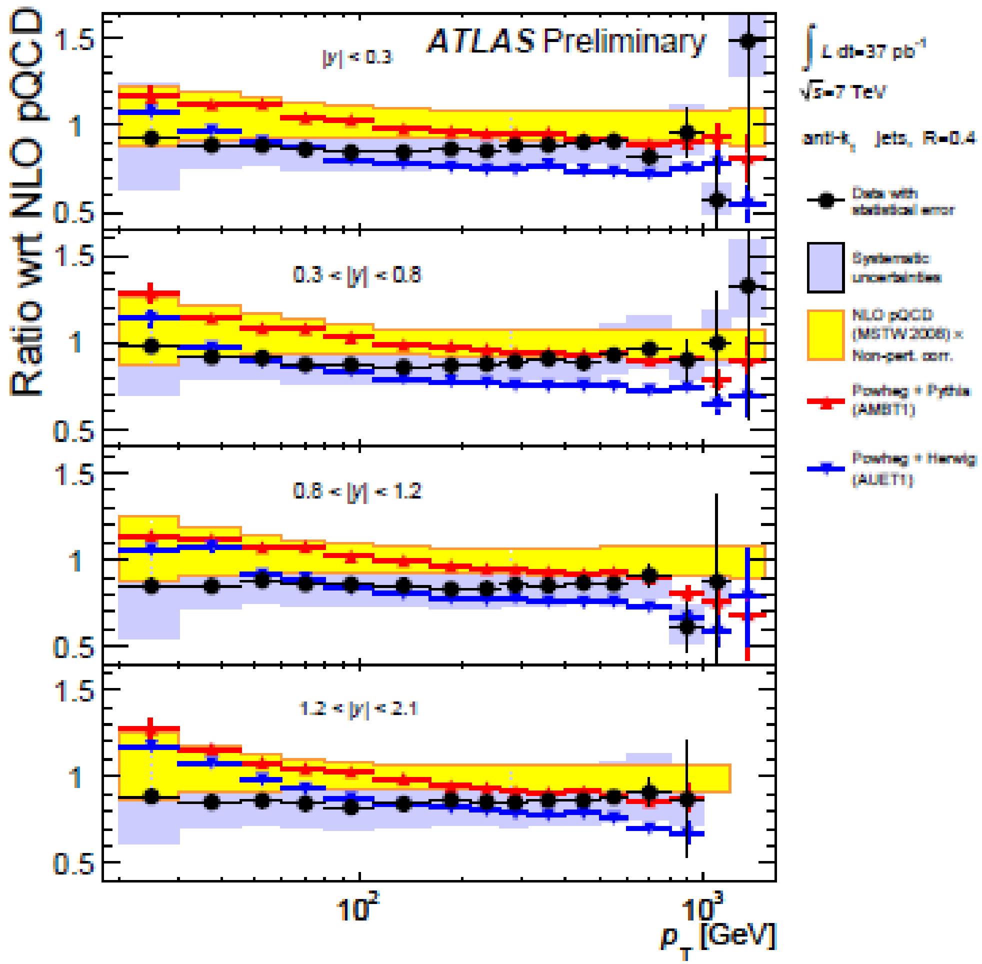




- **POWHEG predictions are in agreement with data within uncertainties**

Di-jet cross sections

► Anti-k_T, R=0.4

-- p_T(jet)>30, 20 GeV

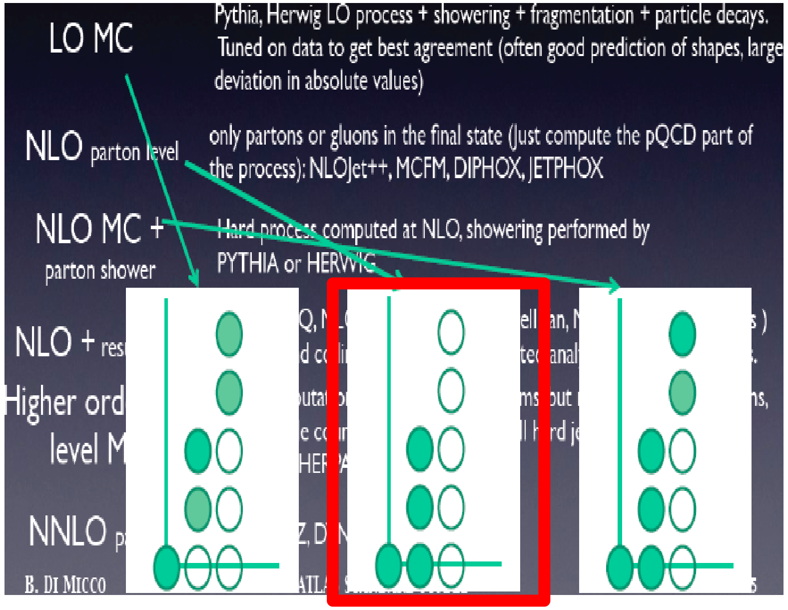
-- $|y_{jet}| < 2.8$

"NLO pQCD × Non-pert corr"

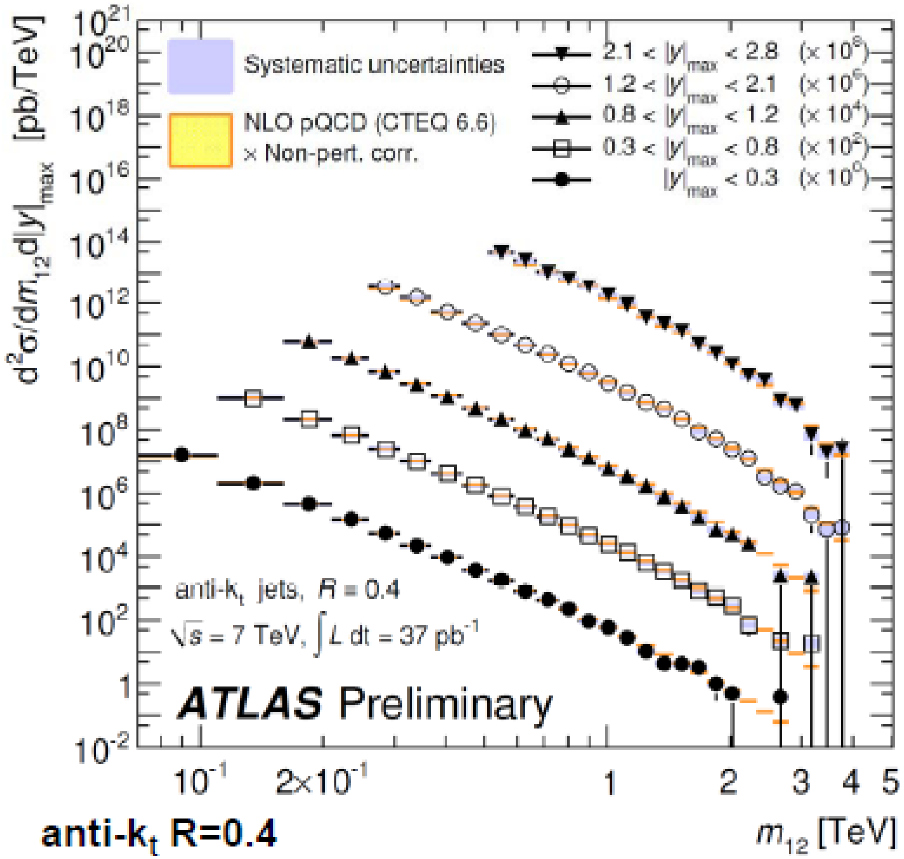
→ NLO @ parton level (NLOjet++)

×

$$f = \frac{\text{with hadronization (Pythia)}}{\text{without hadronization (Pythia)}}$$

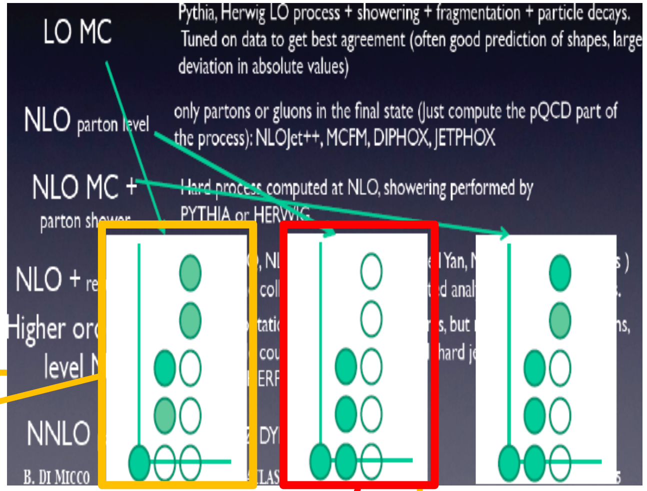


Dijet cross section as a function of invariant mass



QCD prediction works up to m(jet-jet) < 4 TeV

Multi-jet cross sections; test of complex QCD final states

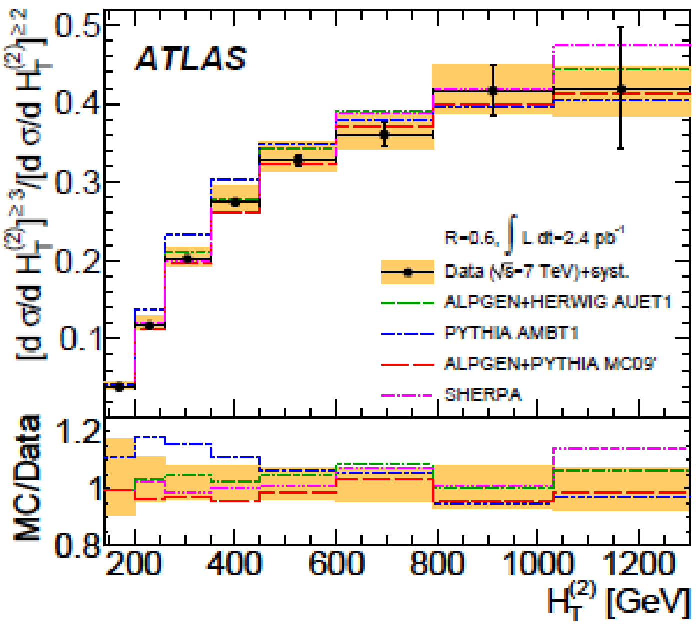


S. Shimizu @ DIS, 2011

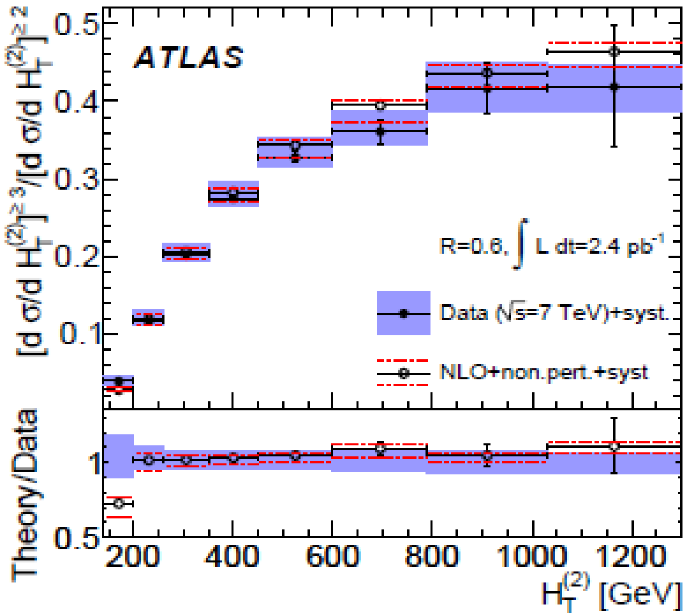
Ratio of 3-jet cross section to 2-jet cross section

- $H_T^{(2)}$: sum of the p_T of 2 leading jets

Comparison with LO MCs

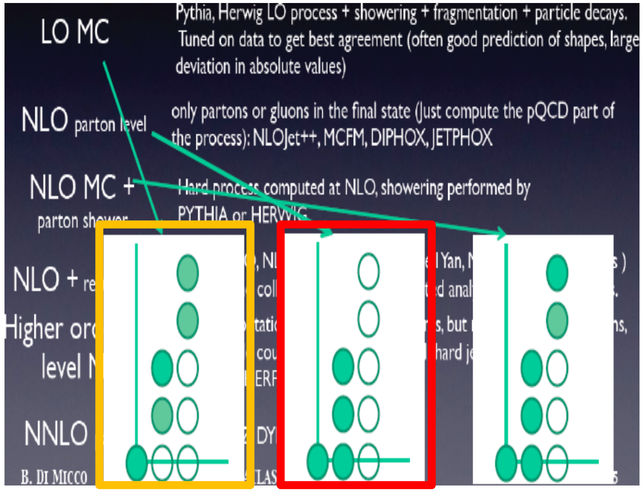


Comparison with NLO pQCD prediction (NLOJet++ with non-pert. correction)

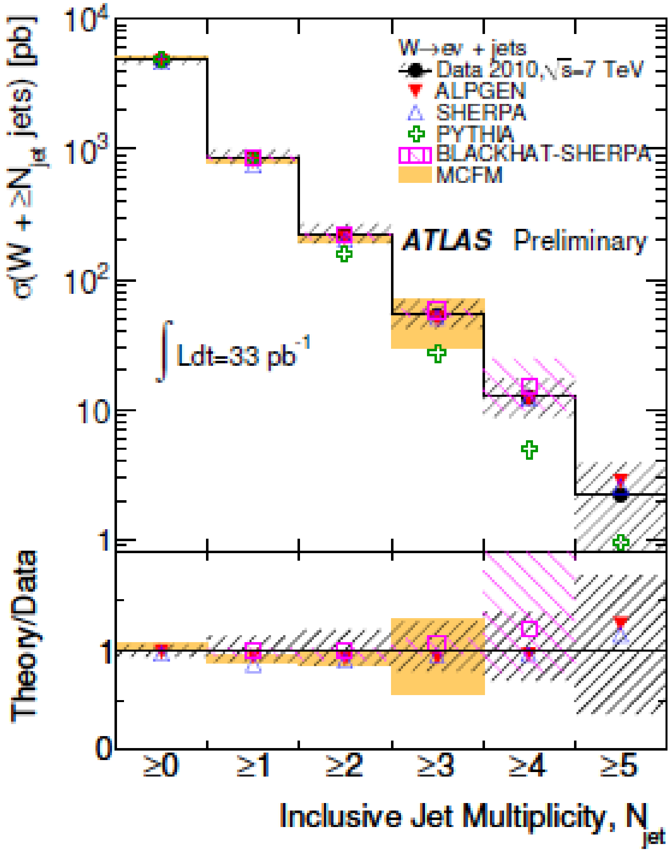


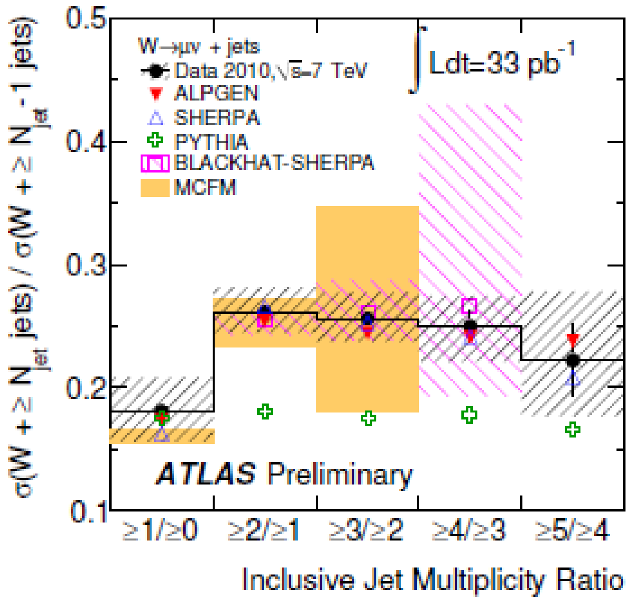
- Alpgen describes the data well, while Pythia overestimates 3-jet at $200 < H_T^{(2)} < 400$ GeV
- NLO pQCD prediction describes the data well, except for the lowest $H_T^{(2)}$ bin.

W+nJets



- ▶ pp → W + nJets
  - -- Potentially major backgrounds for new physics searches, e.g. H→WW





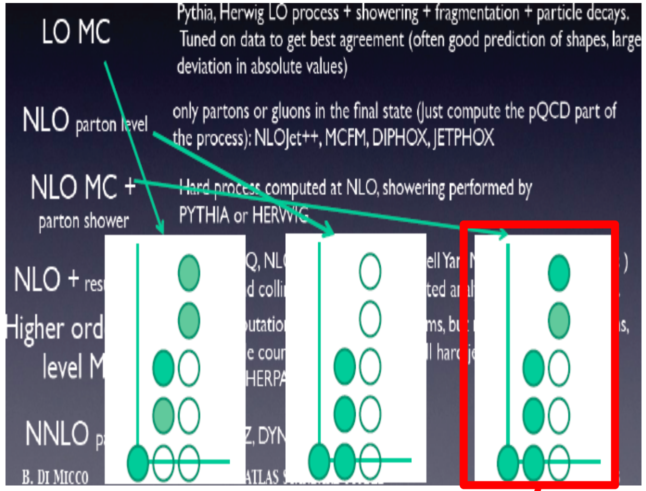
LO ME insufficient to describe many hard pT partons

- Pythia (LO + PS) does not describe # of jets correctly

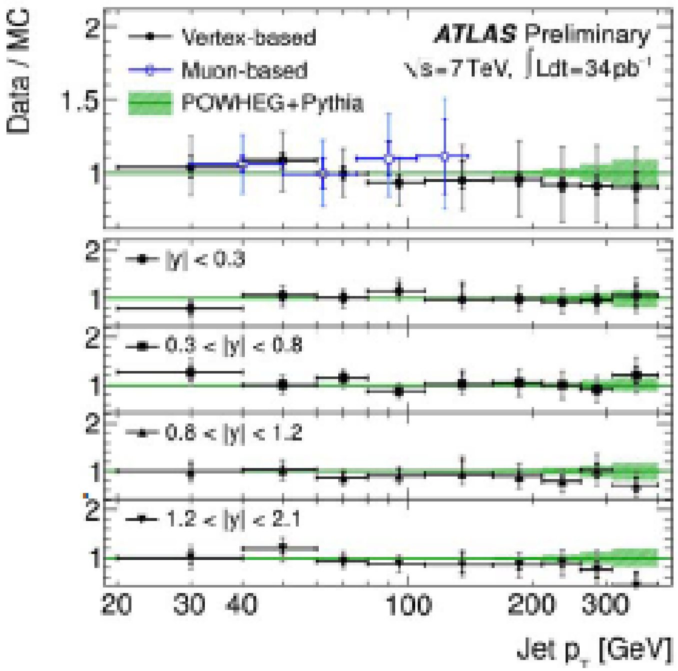
- Alpgen, BlackHat-Sherpa (NLO) describe data well.

➔ Pythia + K-factor approach does not work at at such phase space; be careful e.g if you are requiring >=3 jets in your new physics search

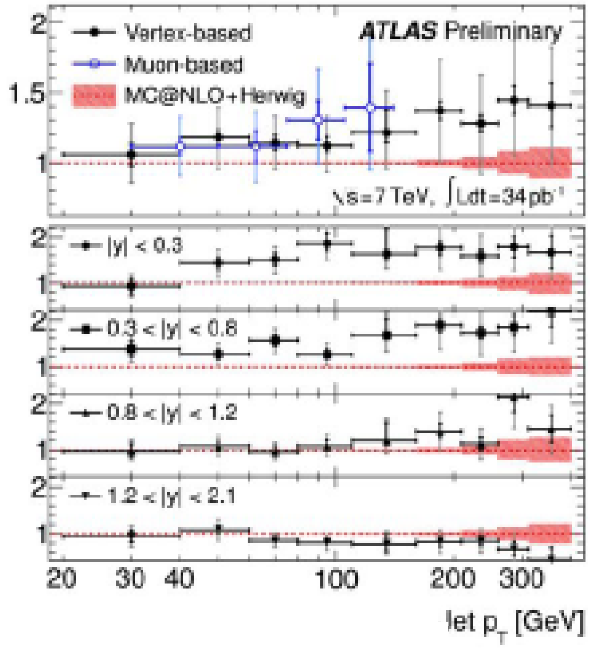
Jets with heavy quarks



- ▶ pp → b-jet
  - -- b-jet tagged with sec Vertex
  - -- Cross checked with SL Muon-tag



Data / POWHEG +Pythia



Data / MC@NLO +Herwig

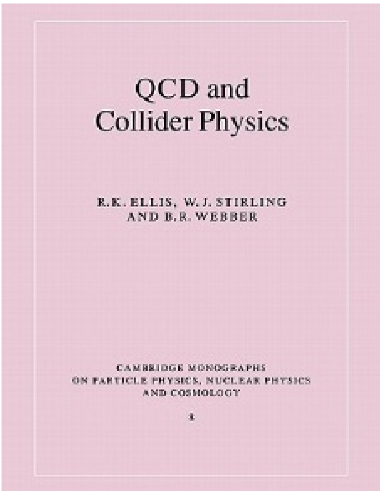
- POWHEG (NLO MC) + Pythia prediction shows good agreement.
- MC@NLO (NLO MC) + Herwig prediction shows different rapidity distribution

Wrap up

Topics discussed

► Jet clustering algorithms: Anti-kT, kT, Cone etc…
► Parton shower: leading log resummation
► Various QCD predictions
  -- LO + PS (Pythia etc.): difficult to simulate "nJets"
  -- NLO(NLOJet++), NLO + PS MC (POWHEG),
   LO + HOtree (Alpgen) : reasonably ok
→ Be aware the QCD phase space you are working.

References



- QCD and Collider Physics (Cambridge press)
  -- R.K.Ellis, W.J.Stirling, B.R.Webber
- arXiv:1101.2599 (Review of MC generators)
- Summary talks (e.g. at DIS 2011 conf.)
  -- S. Hoeche: "Status of MC generators"
  -- S. O.Moch: "Hard QCD at higher orders"
- Recent talks by Atlas/CMS ☺

End of Day-3

Z/W recoil pT @ LHC