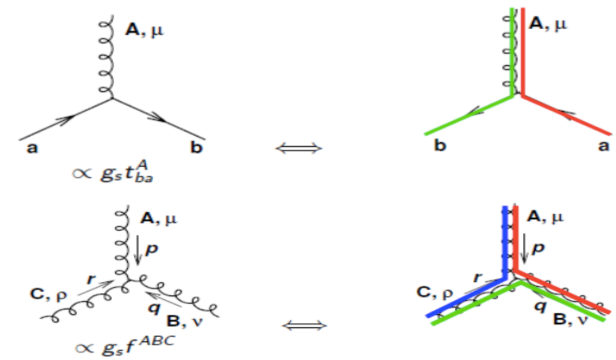
HASCO 2017

Introduction to QCD and Jet Physics

Vincenzo Cavasinni Universita’ di Pisa and INFN

Summary



Introduction to the QCD

-The color interaction

-Asymptotic freedom

-The QCD elementary cross sections

Jets

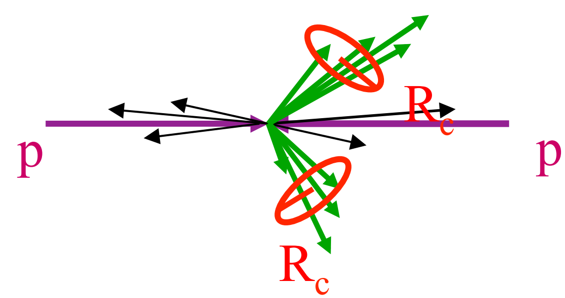
-Jet formation and reconstruction

-jet reconstruction algorithms

-jet energy calibration

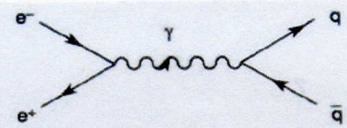
-jet cross sections measurement

-jets for searching new physics



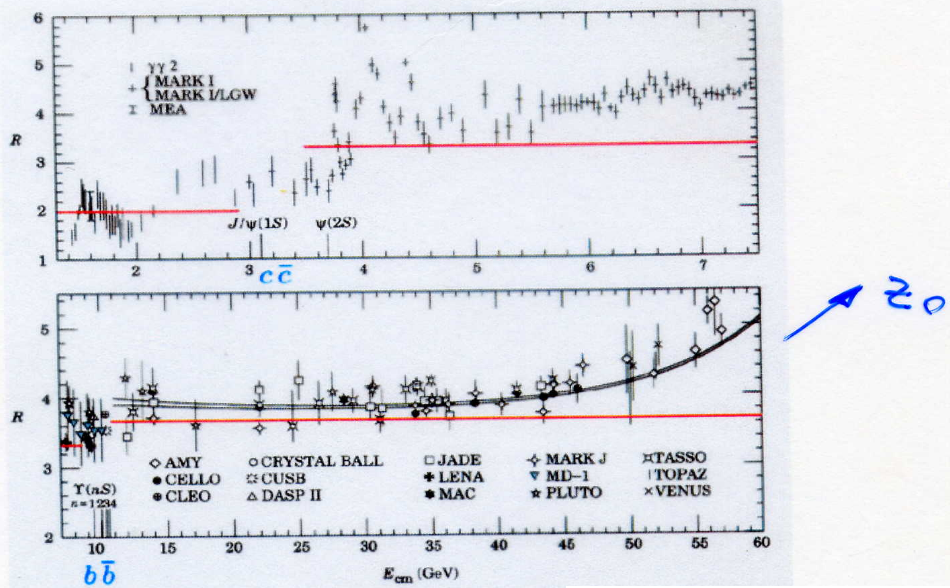
Evidence for a new quark interaction and a new quantum number: the color

$$Ratio: \frac{e^+e^- \to q(jet)\bar{q}(jet)}{e^+e^- \to \mu^+\mu^-}$$



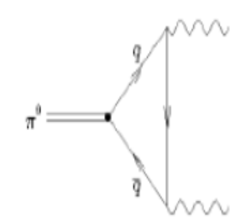
$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \approx \frac{\sum_q \sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} \approx N_C \sum_q Q_q^2$$

$$= \begin{cases} \frac{2}{3} N_C & , \quad (u,d,s) \\ \frac{10}{9} N_C & , \quad (u,d,s,c) \\ \frac{11}{9} N_C & , \quad (u,d,s,c,b) \end{cases}$$



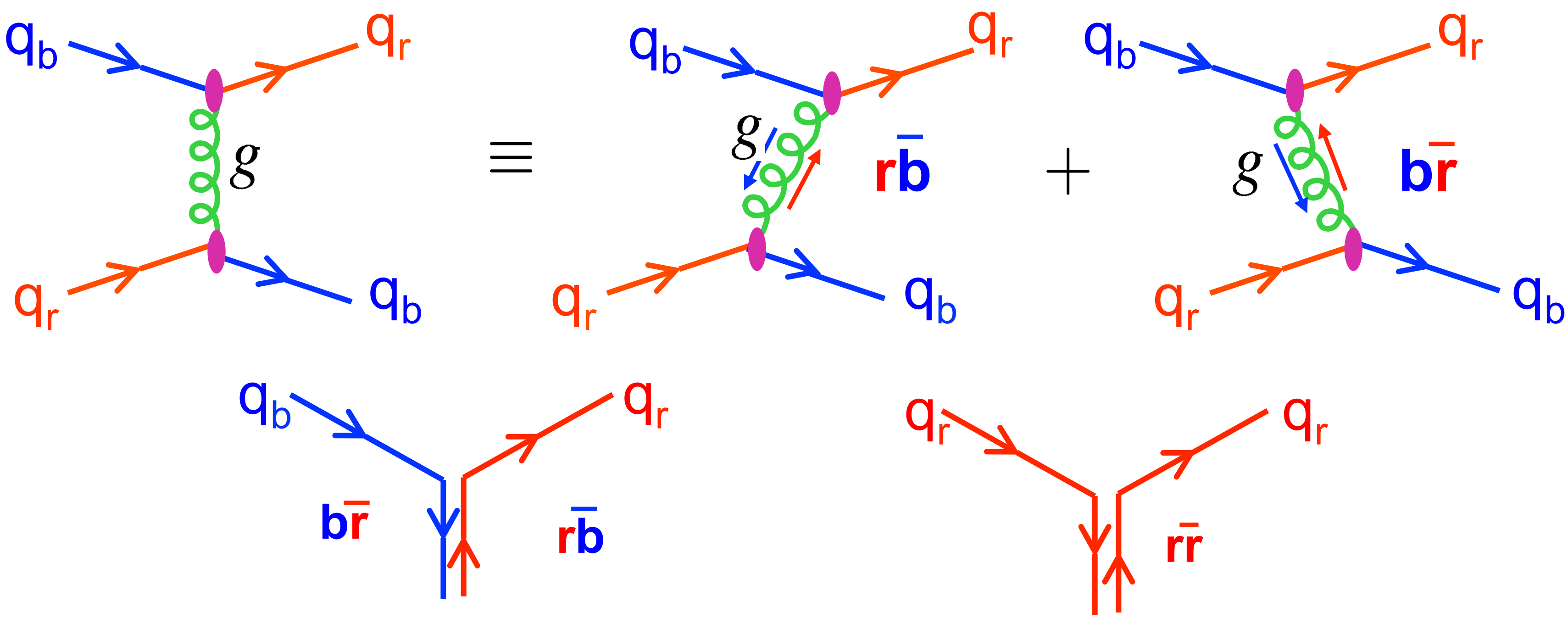
Several other evidences for color eg : $\Gamma(\pi^0 \to \gamma\gamma)$ decay $\pi^0 \to \gamma\gamma$ $\left[|\pi^0\rangle = \frac{1}{\sqrt{2}}(|u\bar{u}\rangle - |d\bar{d}\rangle \right.$

$$BR(\tau \to q\bar{q}'\nu)$$



Interaction between colored quarks: the Quantum Chromo Dynamics, QCD is mediated by a massless vector particle: the gluon

★ ex of exchange of colored gluon.



★We would expect 9 gluons: SU(3) algebra: 3 * 3= 8 + 1

octet $g\bar{b}$ $r\bar{b}$ $\frac{1}{\sqrt{2}}(r\bar{r}-g\bar{g})$ $\frac{1}{\sqrt{6}}(r\bar{r}+g\bar{g}-2b\bar{b})$ $r\bar{g}$ $b\bar{r}$ $b\bar{g}$

singlet: $\frac{1}{\sqrt{3}}(r\bar{r}+g\bar{g}+bb)$

★ **But color is confined**: and a singlet gluon would be not confined:

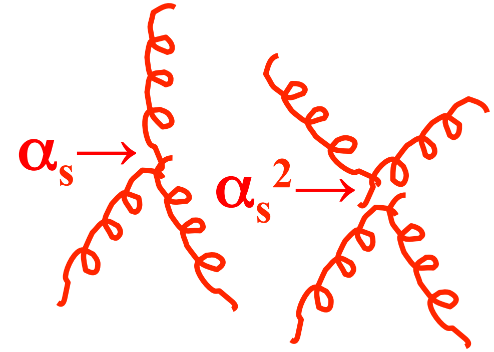
★-> long range force….

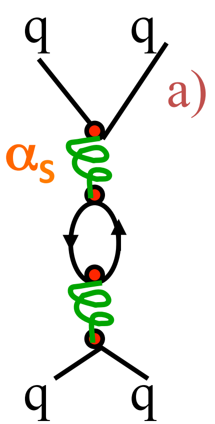
Implications of colored gluons

- Gluon can interact with itself

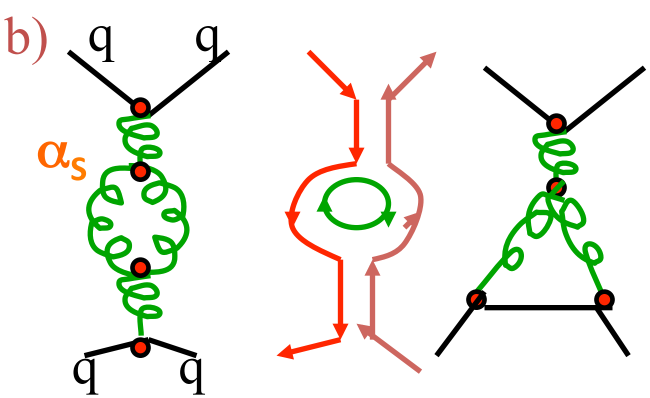
  (not the case for photons)

- Asymptotic freedom





As in QED there are effect from vacuum polarization:
the result into a shielding of the carge
the **<u>α_S decreases as $Q^2 \rightarrow 0$ (screening)</u>**



In QCD there are additional gluon loops:
Their effecs are ooposite to the vacuum polarization:
<u>The color charge is propagated (tube of charge).</u>
<u>As a result :</u>
<u>α_S increases as $Q^2 \rightarrow 0$ (antiscreening)</u>

<u>The antiscreening effects dominate</u>

$$\alpha_S(Q^2) = \alpha_S(\mu^2)\left[1 - \frac{\alpha_S(\mu^2)}{12\pi}(33 - 2f)\ln\frac{Q^2}{\mu^2} + \ldots\right]$$

David Gross,
Frank Wilczek and
David Politzer, 1973

gluon-loop effect

The vacuum polarization depends on the number of Active quarks f ($Q^2 > 4m_q^2$)

By summing up the leading log terms (geometric series: $\Sigma \ln^n \sim 1/(1-\ln)$):

$$\alpha_S(Q^2) = \frac{\alpha_S(\mu^2)}{1 + \frac{\alpha_S(\mu^2)}{12\pi}(33 - 2f)\ln\frac{Q^2}{\mu^2}} \Rightarrow$$ **QCD "running coupling constant"**

$$\boxed{\alpha_S(Q^2) \xrightarrow{Q^2 \to \infty} 0 \; (if\ 33 > 2f): The \text{ asymptotic freedom}}$$

Perturbation theory can be applied. But α_S=0.1-1 and, differently than α, It varies appreciably with Q^2.

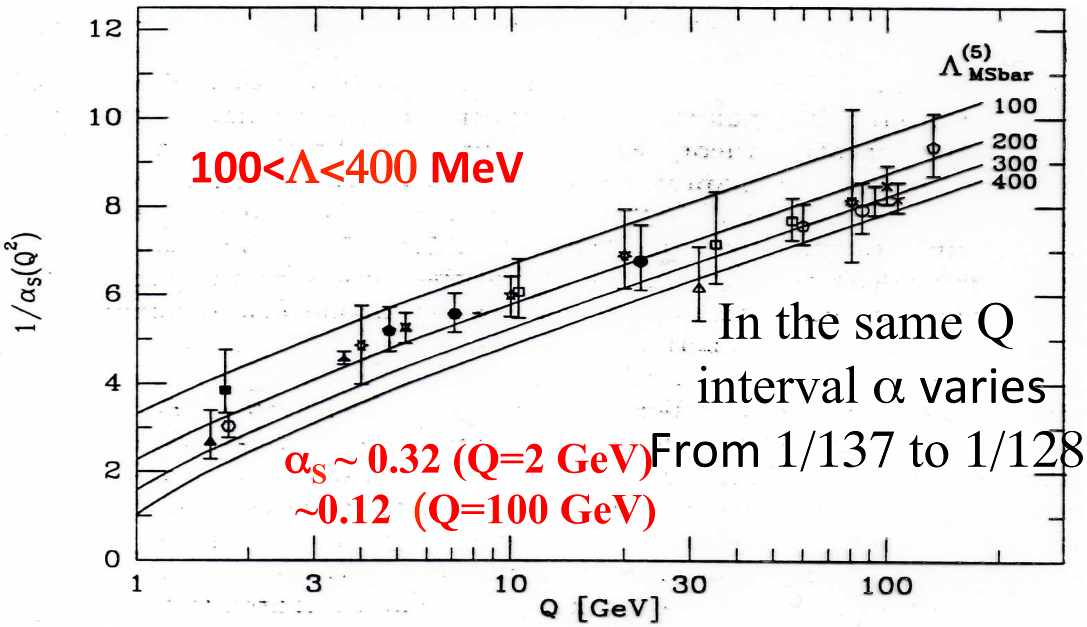
$$Defining \quad \ln\Lambda^2 = \ln\mu^2 - 12\pi/[(33 - 2f)\alpha_S(\mu^2)]$$

$$\alpha_S(Q^2) = \frac{12\pi}{(33 - 2f)\ln Q^2/\Lambda^2}$$

We have only 1 parameter : $\Lambda \sim 100-200$ MeV ~ 1 fm^{-1} to be extracted experimentally (QCD has not a natural scale as in QED (m_e)).

Conversely if $Q^2 \sim \Lambda^2$, α_S is large,>1: interaction becomes strong,confinement??

From α_S we can extract Λ, but with poor sensitivity



100<Λ<400 MeV

$\alpha_S \sim 0.32$ (Q=2 GeV)
~0.12 (Q=100 GeV)

In the same Q interval α varies From 1/137 to 1/128

Fig. 2.5. Measurements of α_S compared with predictions for various values of $\Lambda(5)$.

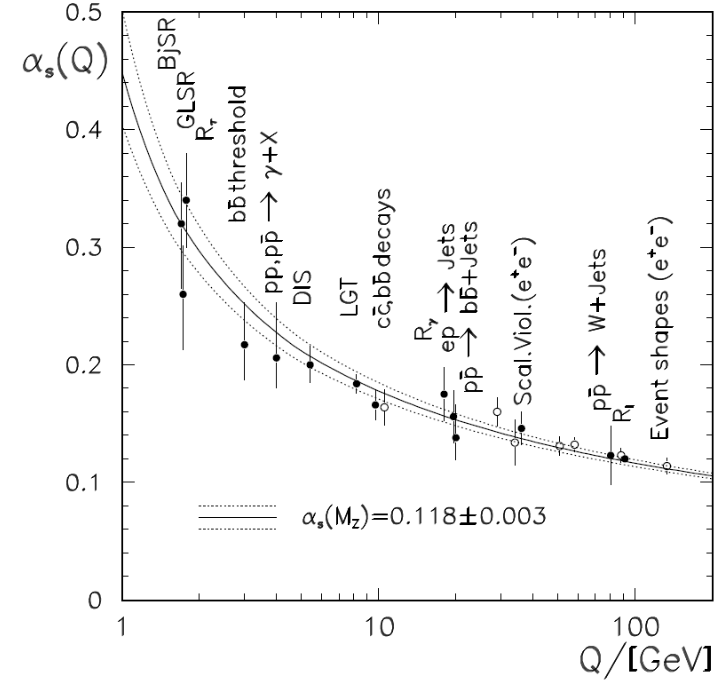
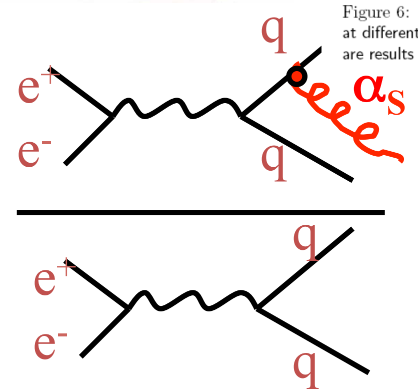
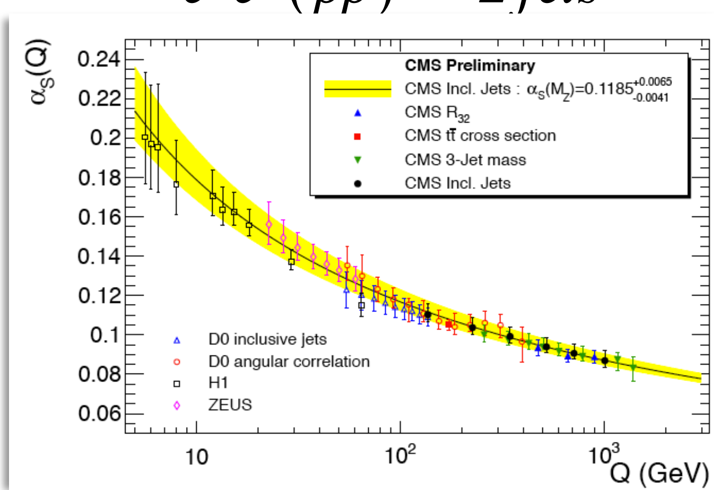


Figure 6: Running of the strong coupling constant established by various types of measurements at different scales, compared to the QCD prediction for $\alpha_s(M_Z) = 0.118 \pm 0.003$. The open dots are results based on global event shape variables.

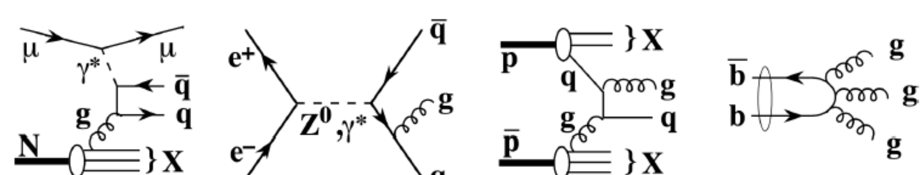
$$ex. \frac{e^+e^-(pp) \to 3\,jets}{e^+e^-(pp) \to 2\,jets} \propto \alpha_S$$



N.B. Λ depends on the active quark number

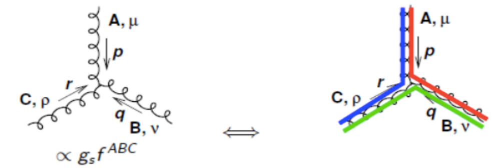


Other processes to extract α_S



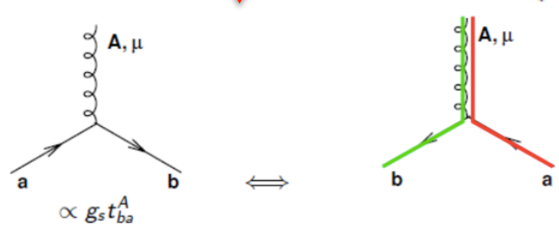
The Standard Model Lagrangian

Gauge boson (gluon) self interactions



$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
& +(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.}) && \text{(lepton dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T\begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right] && \text{(neutrino mass term)} \\
& +(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) && \text{(quark dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi}\begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] && \text{(down, strange, bottom mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T\begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right] && \text{(up, charmed, top mass term)} \\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)}
\end{aligned}
$$

Gauge boson (gluon)-quark interactions



QCD tree level cross sections

8 processes

PARTON PROCESS	$\|M\|^2$	F_M
$qq' \to qq'$ $q\bar{q}' \to q\bar{q}'$	$\frac{4}{9}\frac{s^2+u^2}{t^2}$	2.22
$qq \to qq$	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{s^2+t^2}{u^2}\right)-\frac{8}{27}\frac{u^2}{st}$	3.26
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\frac{t^2+u^2}{s^2}$	0.22
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{t^2+u^2}{s^2}\right)-\frac{8}{27}\frac{u^2}{st}$	2.59
$q\bar{q} \to gg$	$\frac{32}{27}\frac{u^2+t^2}{ut}-\frac{8}{3}\frac{u^2+t^2}{s^2}$	1.04
$gg \to q\bar{q}$	$\frac{1}{6}\frac{u^2+t^2}{ut}-\frac{3}{8}\frac{u^2+t^2}{s^2}$	0.15
$qg \to qg$	$-\frac{4}{9}\frac{u^2+s^2}{us}+\frac{u^2+s^2}{t^2}$	6.11
$gg \to gg$	$\frac{9}{2}\left(3-\frac{ut}{s^2}-\frac{us}{t^2}-\frac{st}{u^2}\right)$	$\boxed{30.4}$

They are in the ratio 64/9 (color)

Values at $\theta^*=90^o$

Combridge,
Kripfganz
Ranft (1977)
t,s,u of the incoming partons
(quarks or gluons)

$$t=-s(1-\cos\theta^*)/2,\; u=-s(1+\cos\theta^*)/2$$

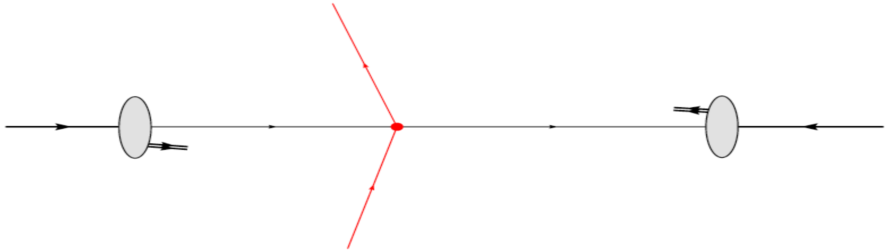
There is also the triple gluon vertex : ggg

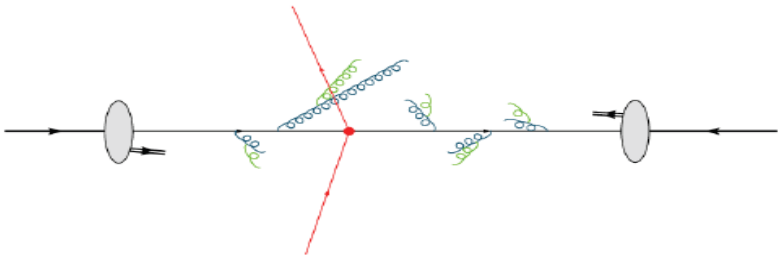
Absent in QED

$$\frac{d\sigma}{d\cos\theta^*}=\frac{\pi\alpha_S^2}{2s}|M|^2$$

$|M|^2$, averaged on initial <u>color</u> and spin and summed up on the final ones

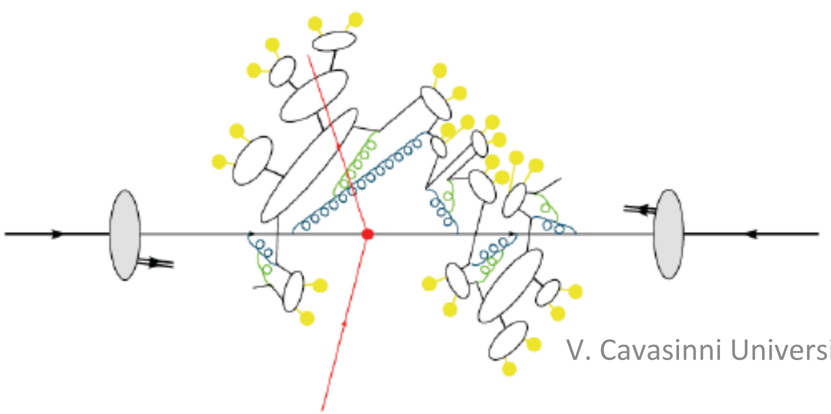
The elementary cross sections have to be weighted by the initial parton pdf's

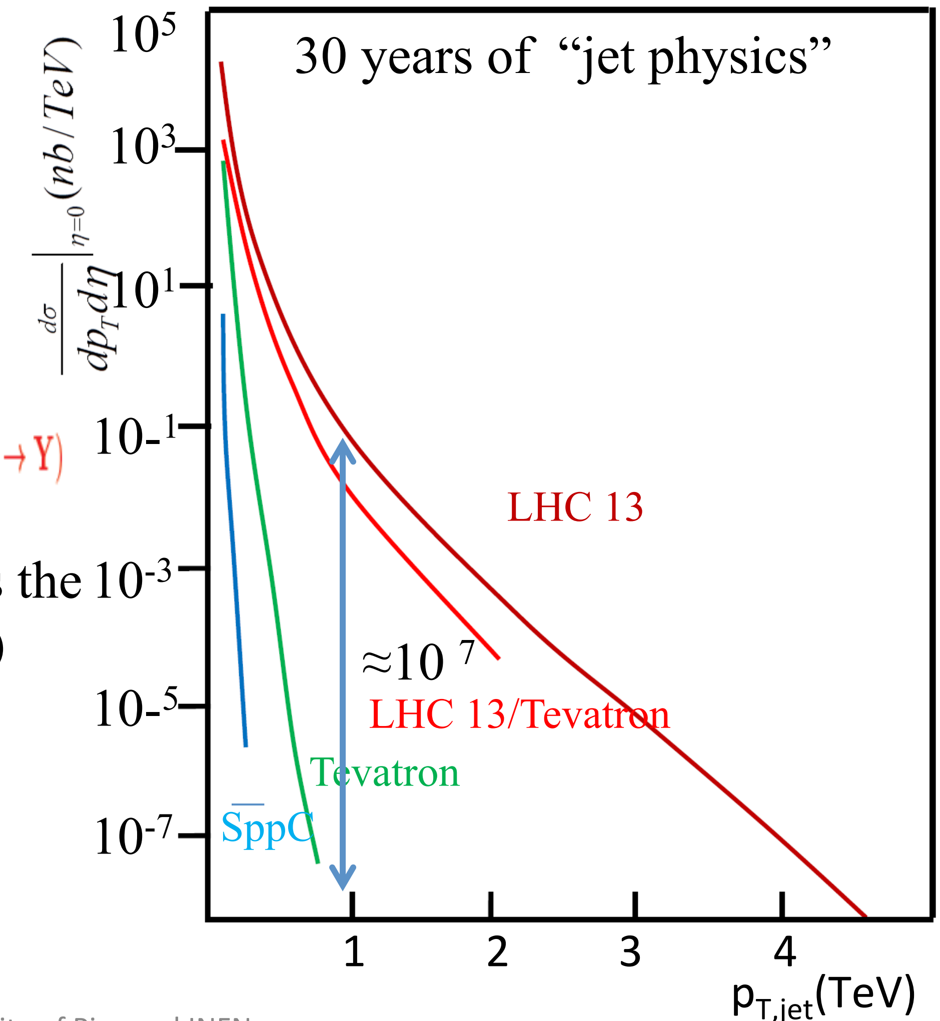




$$\sigma(p(P_1)+p(P_2)\rightarrow Y+X) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2)\cdot\sigma(q_f(x_1P)+\bar{q}_f(x_2P)\rightarrow Y)$$

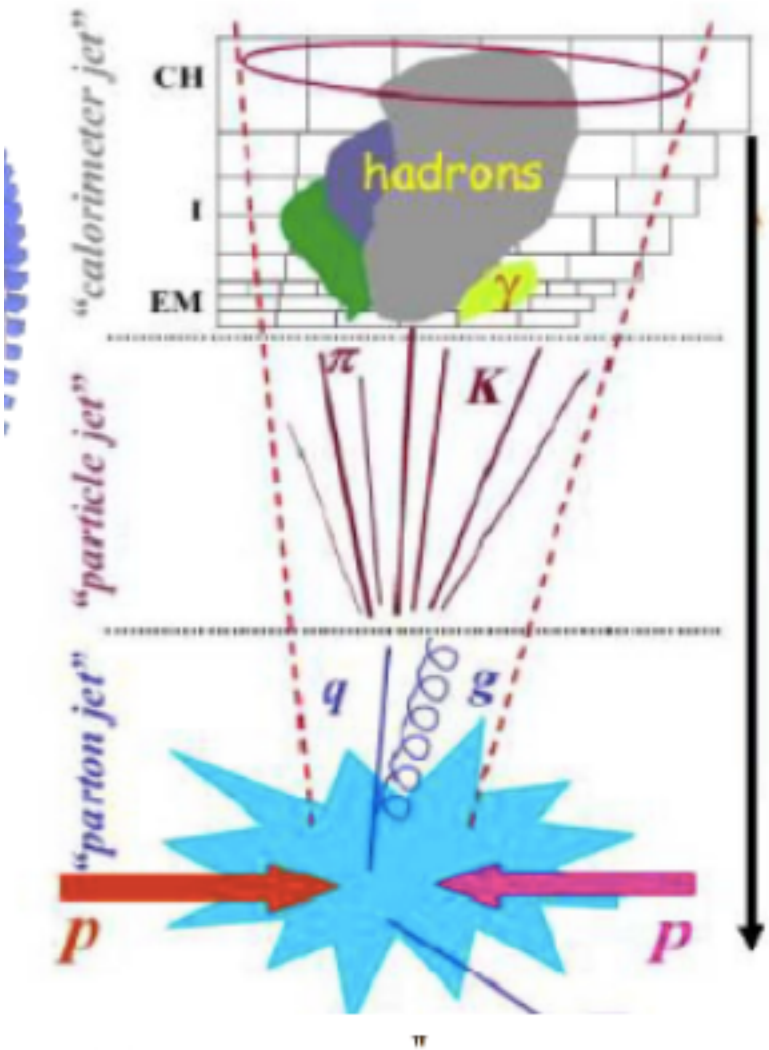
Partons, after the scattering, evolve towards the "parton showering" and hadronisation (jets)





Jet physics

What jets are?
QCD Interactions between quarks and gluons (proton constituents) yield quarks and gluons that, however, are not directly accessible (color confinement): in fact their fragment into a bunch of collimated hadrons (pion, kaons, neutros, protons,..): a "jet" of particles. So identifying and measuring jets, allows the reconstruction of the kinematics of the elementary QCD interactions.

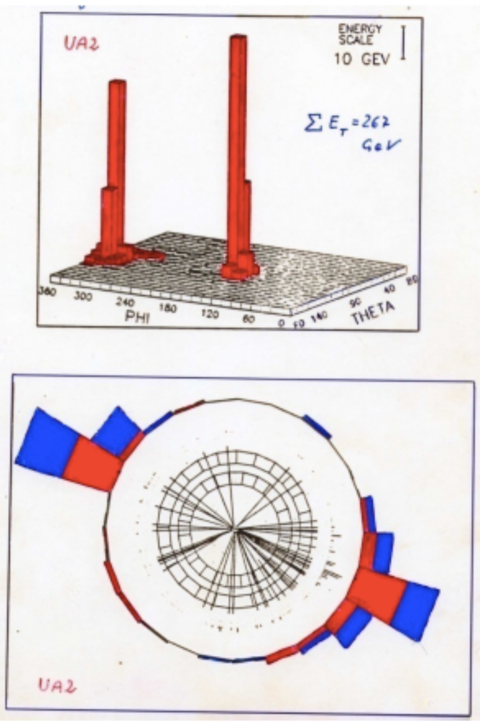


Credits to:
C.Roda – Lectures on "Jet Physics", Pisa University, 2017.

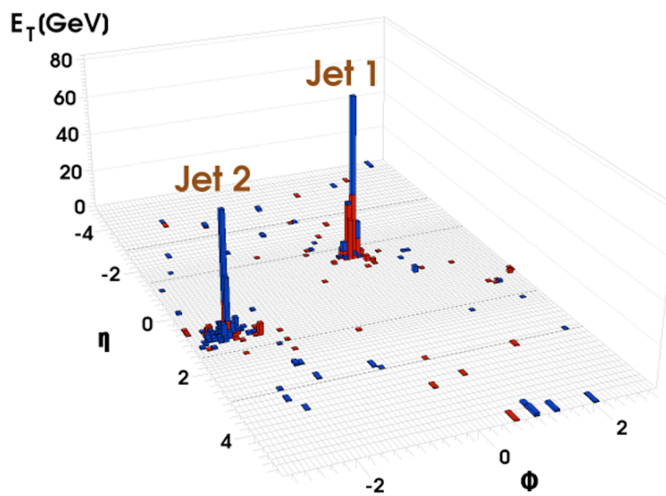
A dijet event at the p-pbar collider

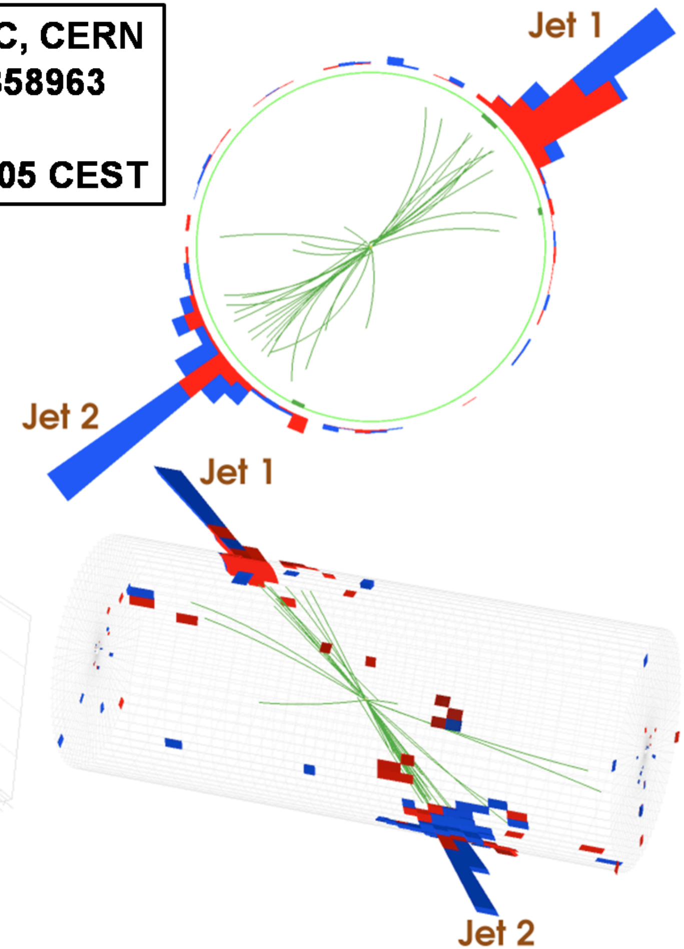
A dijet event at LHC

UA2 1983



CMS Experiment at LHC, CERN
Run 133450 Event 16358963
Lumi section: 285
Sat Apr 17 2010, 12:25:05 CEST





Notice that the two jets have to be balanced in Pt also in the lab, but not necessarily in longitudinal momentum (opposite rapidity) because the two primary interacting proton partons can have unbalanced momentum (pdf's)

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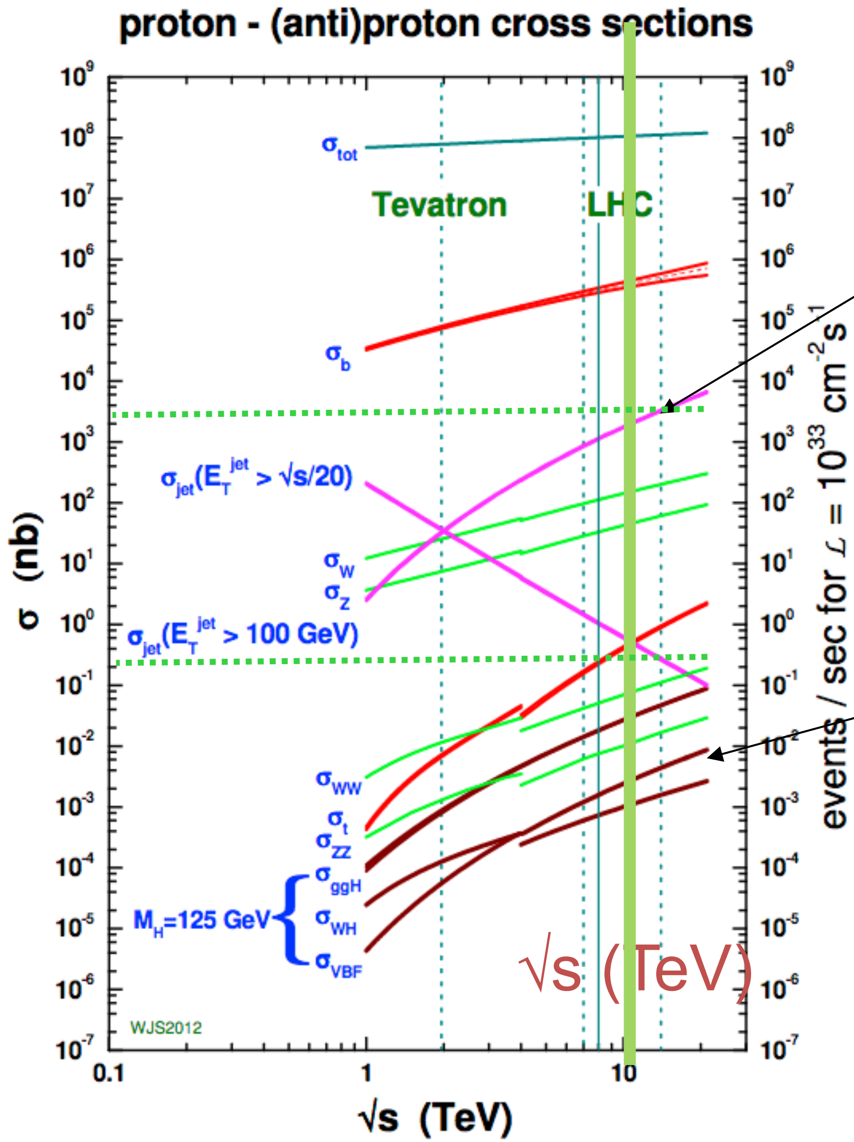
Why do we care about jets:

QCD studies

Background of many other physics processes



Jets will be the background for nearly all searches:

$\sigma(E_T>100$ GeV) ~ μb

Signal processes:

- SUSY involving heavy particles:

σ(squark-squark @ M~ 1 TeV)~ pb

- SM Higgs:

σ(Higgs @ M=125 GeV)~ 20 pb

QCD background is 5-6 order of magnitude higher than signals. Control of details of jet reconstruction and calibration is essential.

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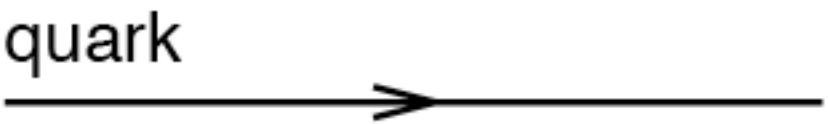
Part 1 – jet formation and reconstruction

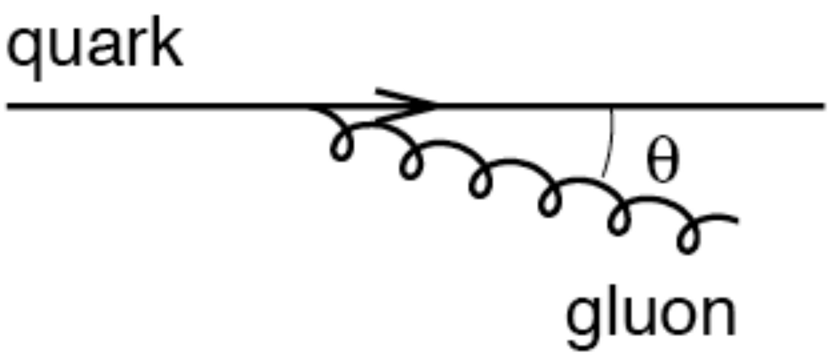
How a jet is generated



Gluon emission:

$$\int \alpha_s \frac{dE}{E}\frac{d\theta}{\theta} \gg 1$$

How a jet is generated



Probability to emit gluon

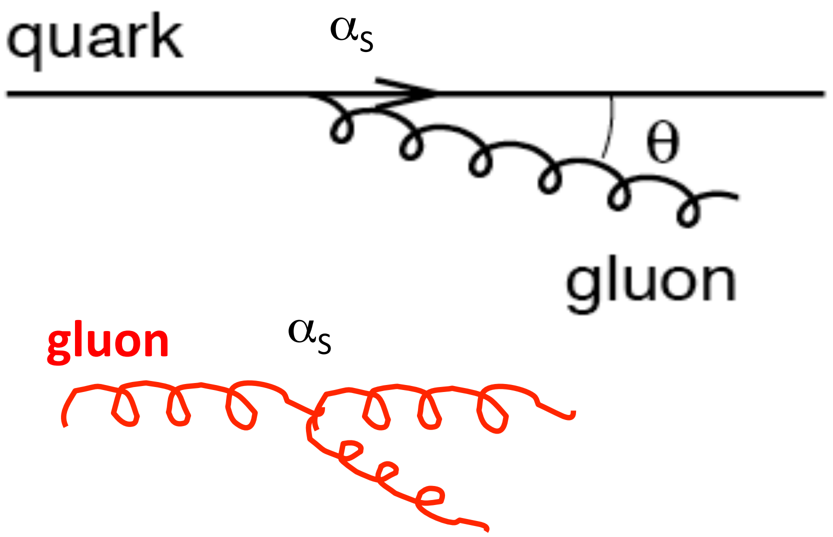
<u>Gluon emission:</u>

$$\int \alpha_s \frac{dE}{E}\frac{d\theta}{\theta} \gg 1$$

Integral is over energy of Gluon and angle of gluon

Integral diverges if E or theta are small…
QCD has to be renormalised.

In QCD quarks and gluons can radiate (α_S)



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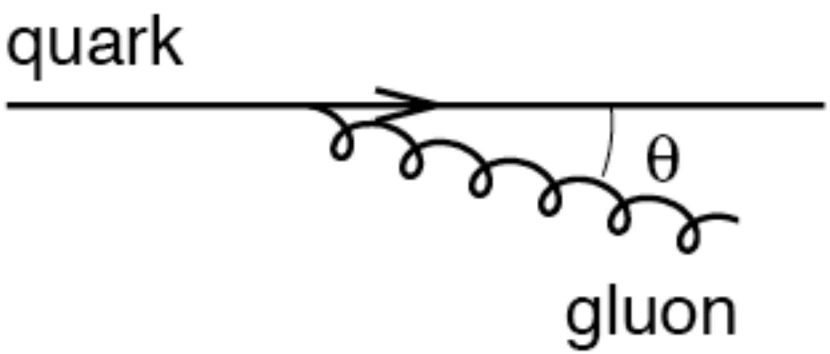
Jet generation



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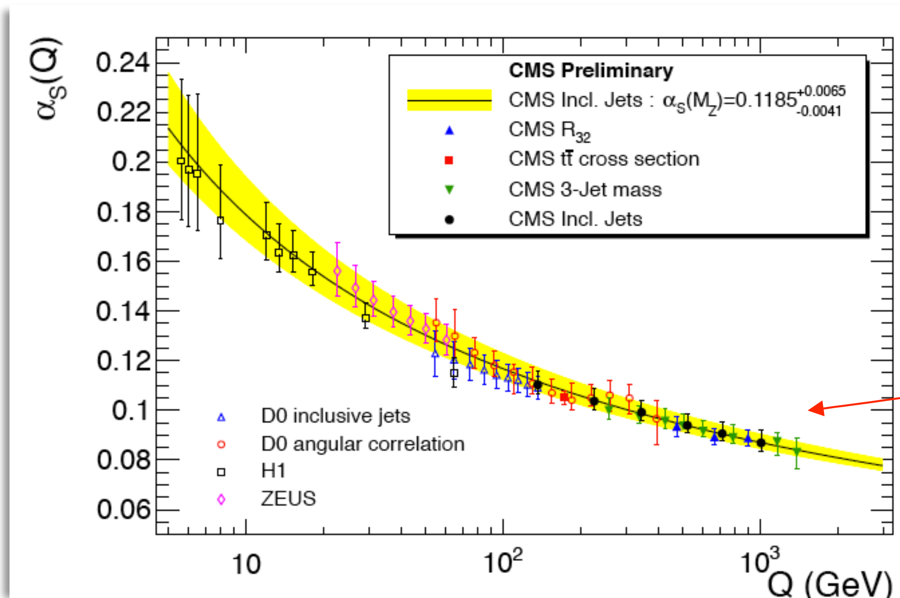
Gluon emission:

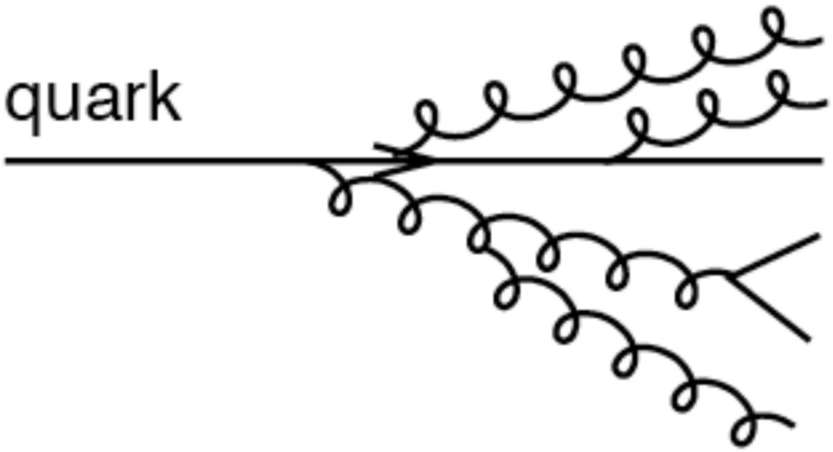
$$\int \alpha_s \frac{dE}{E}\frac{d\theta}{\theta} \gg 1$$

At low scales:

$$\alpha_s \to 1$$



Jet generation

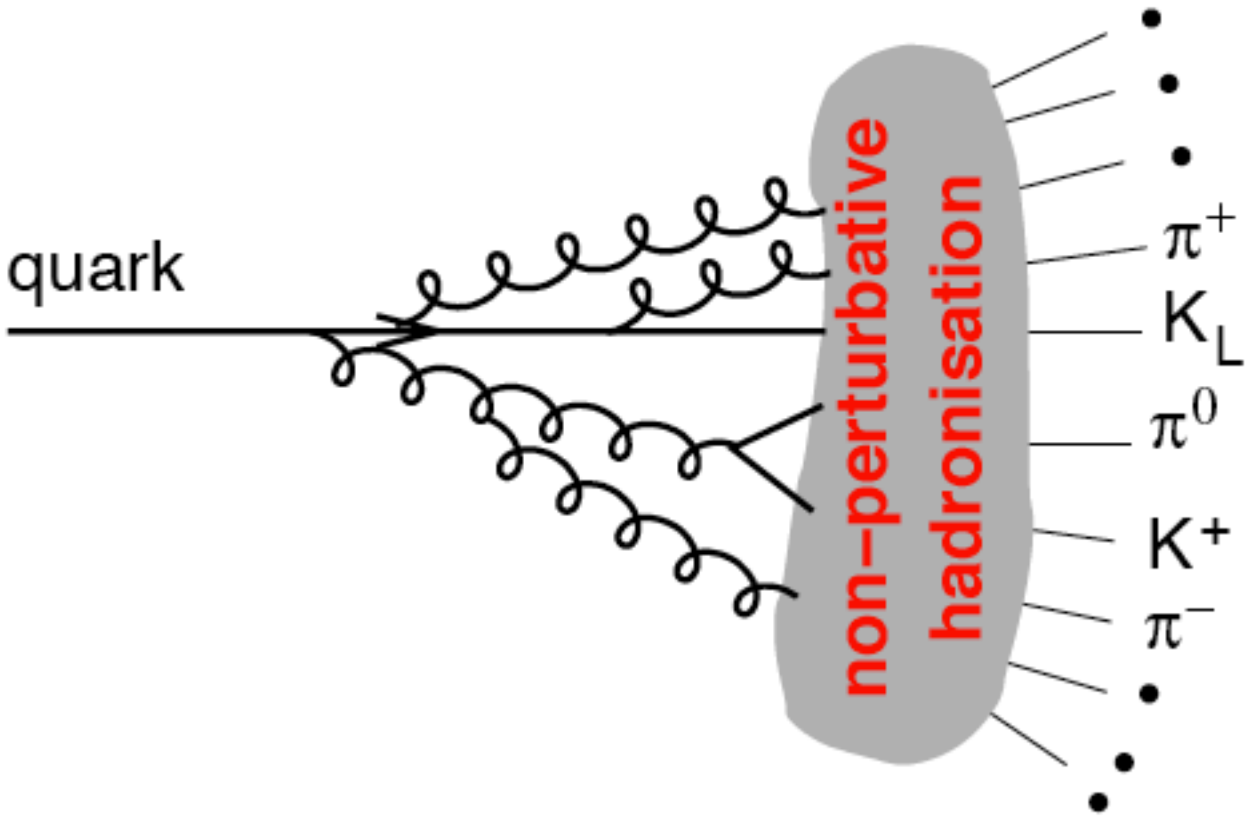


Gluon emission:

$$\int \alpha_s \frac{dE}{E} \frac{d\theta}{\theta} \gg 1$$

Gluon can turn into a quark-antiquark pair

Jet generation



Gluon emission:

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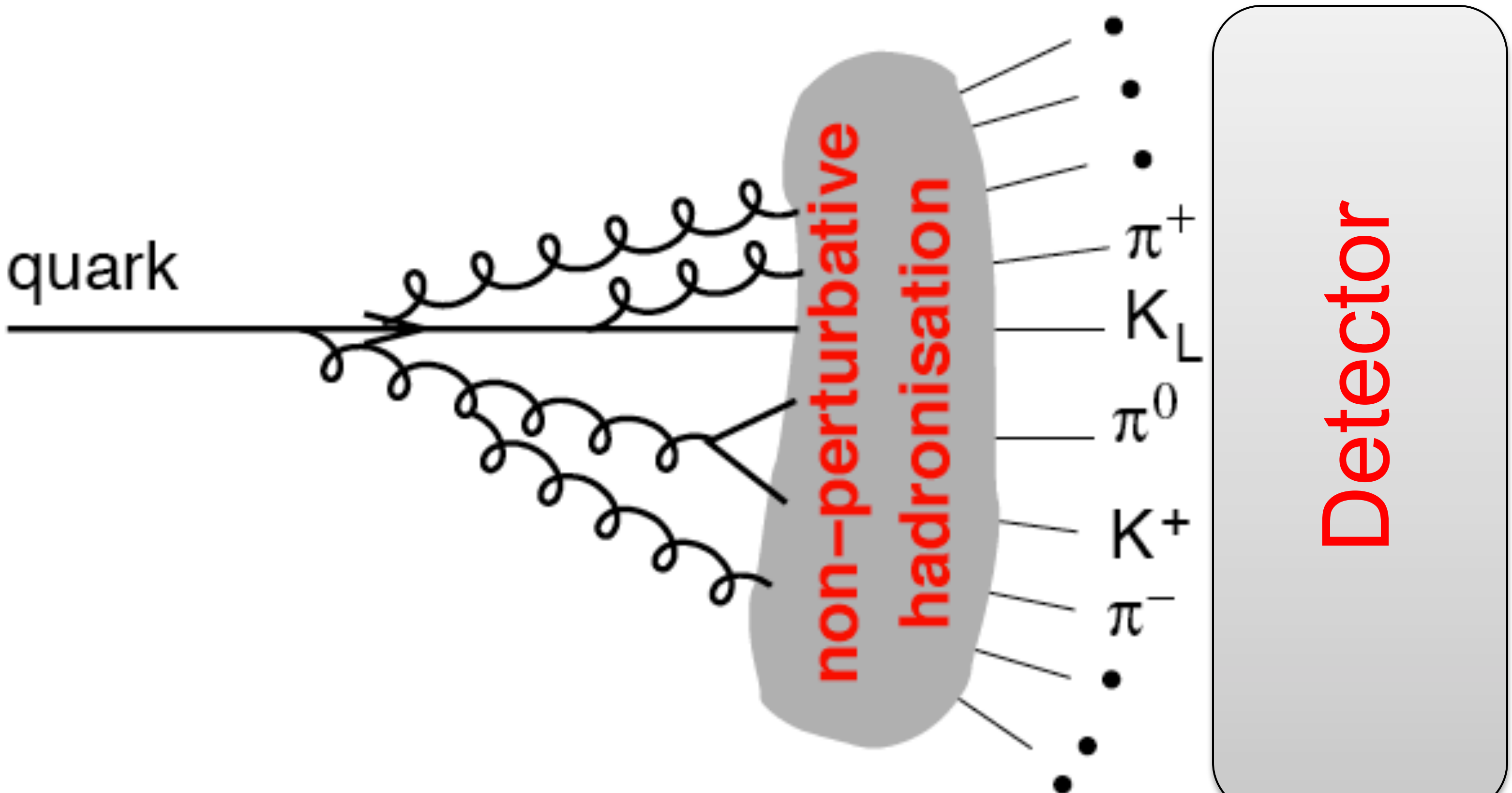
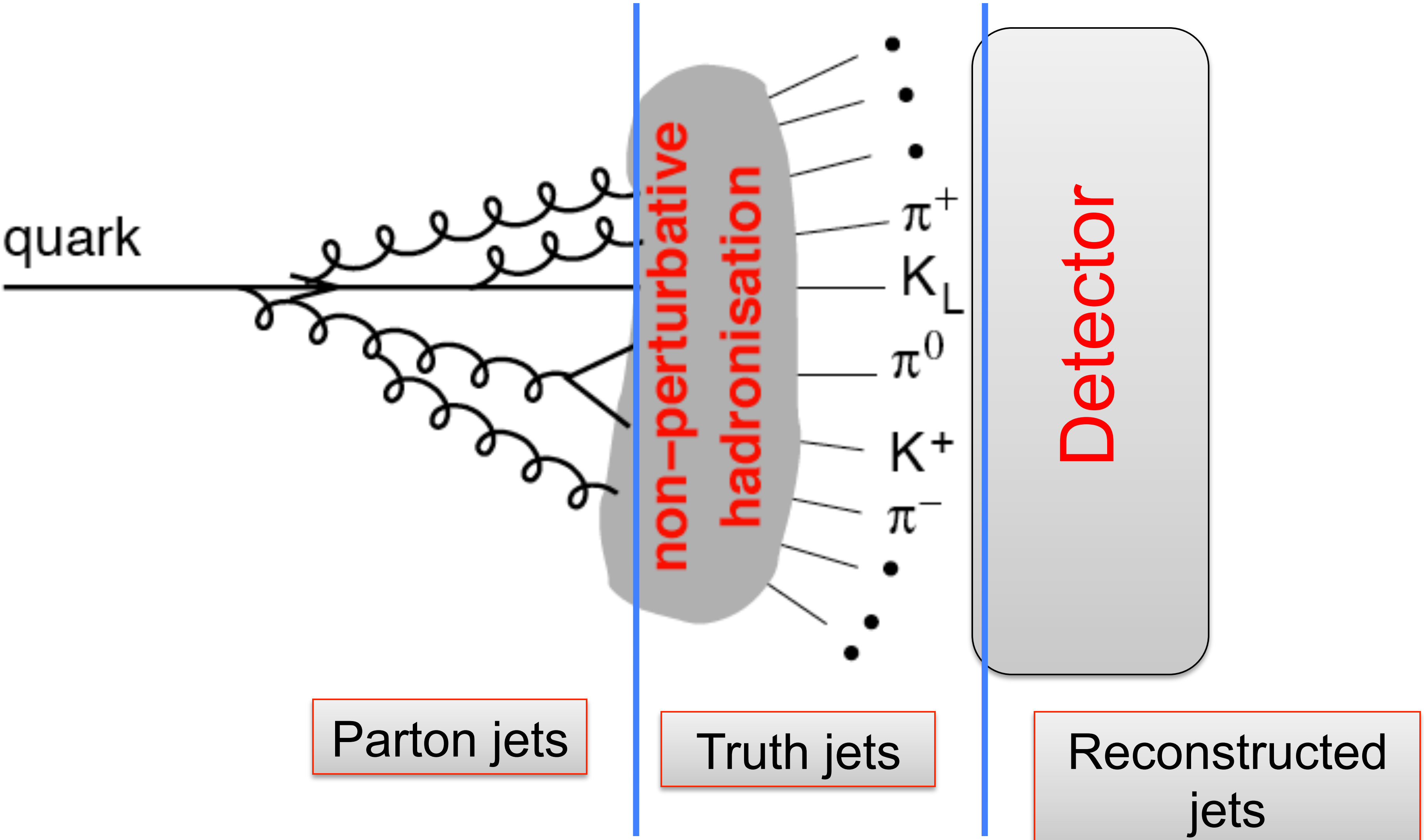
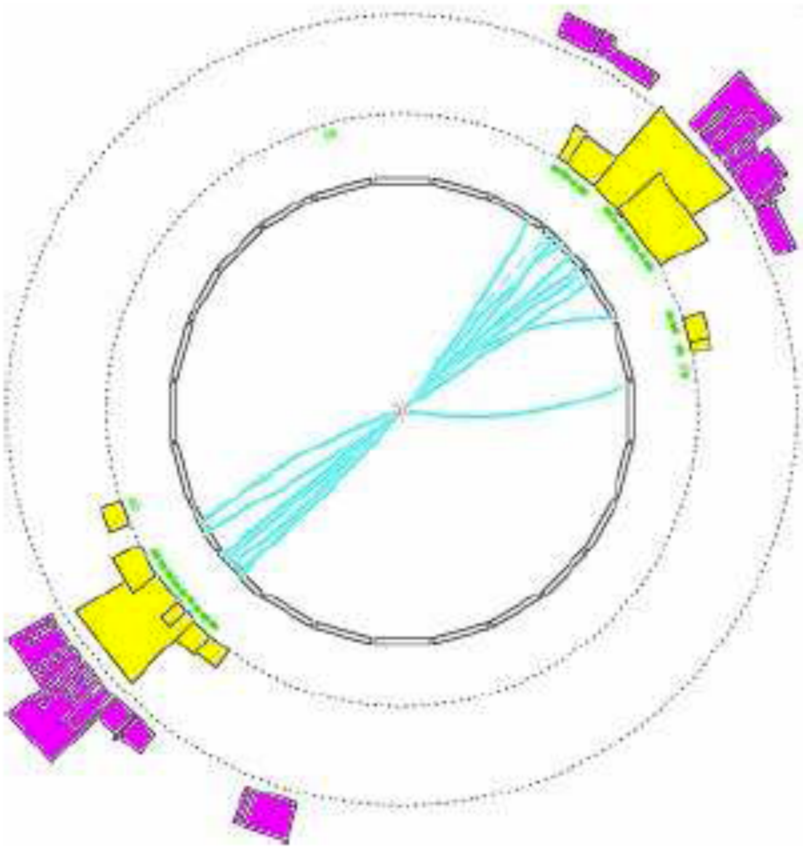
Jet generation and reconstruction



Jet generation and recontsruction



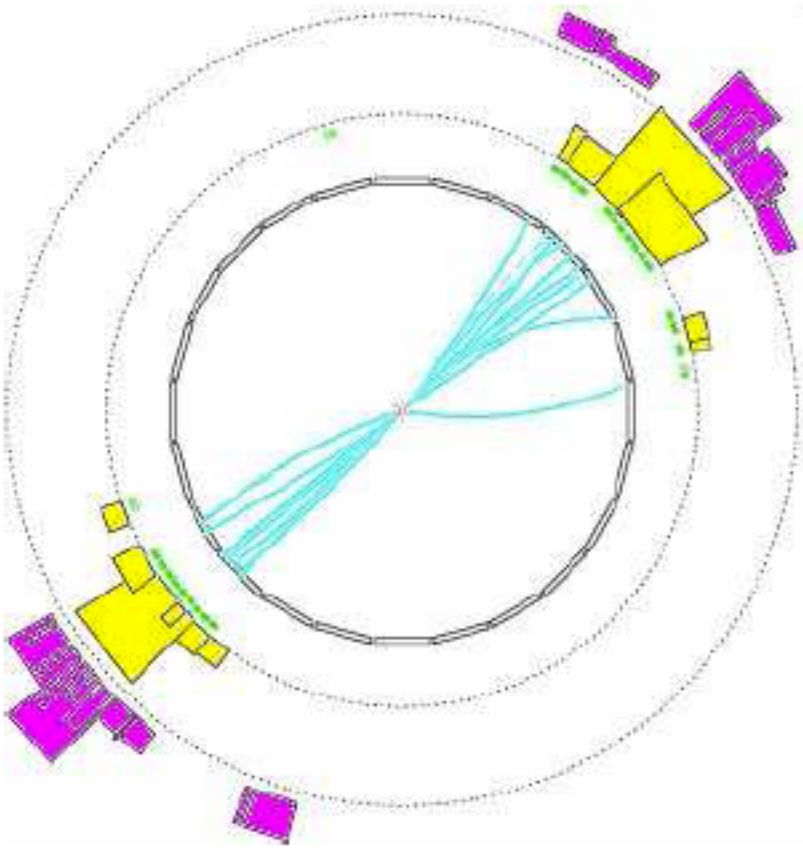
Jet identification



Transverse view of a collision e^+e^- ->hadrons (jets) the cleanest situation

How many jets in this event:
It is clear they are 2!

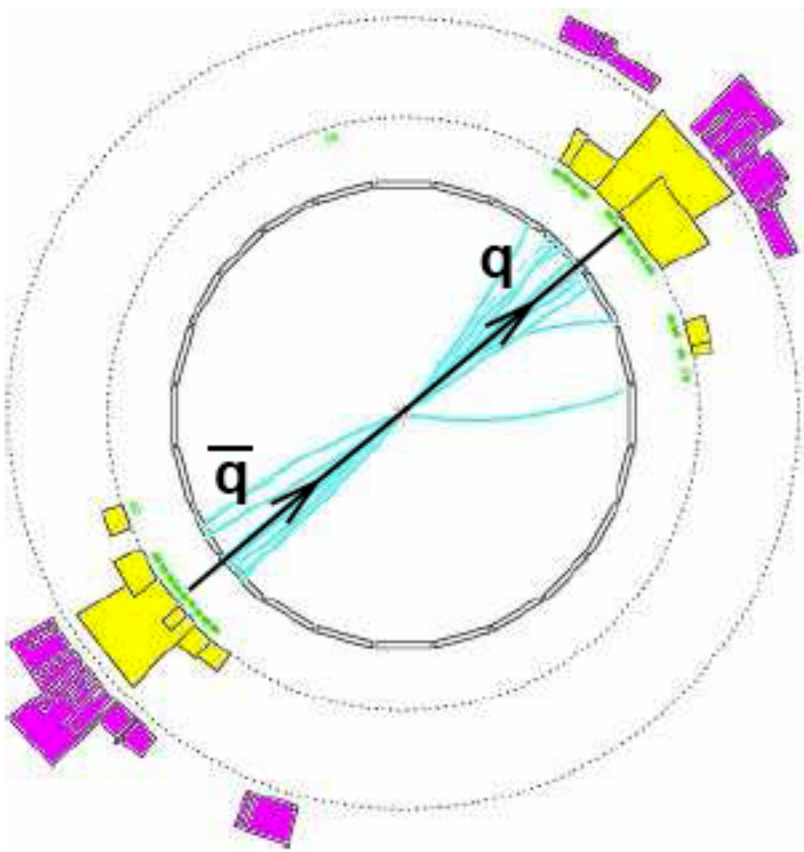
Jet identification



Transverse view of a collision e^+e^- -> hadrons (jets) the cleanest situation: only jets in final state

How many jets in this event:
It is clear they are 2!

Jet identification



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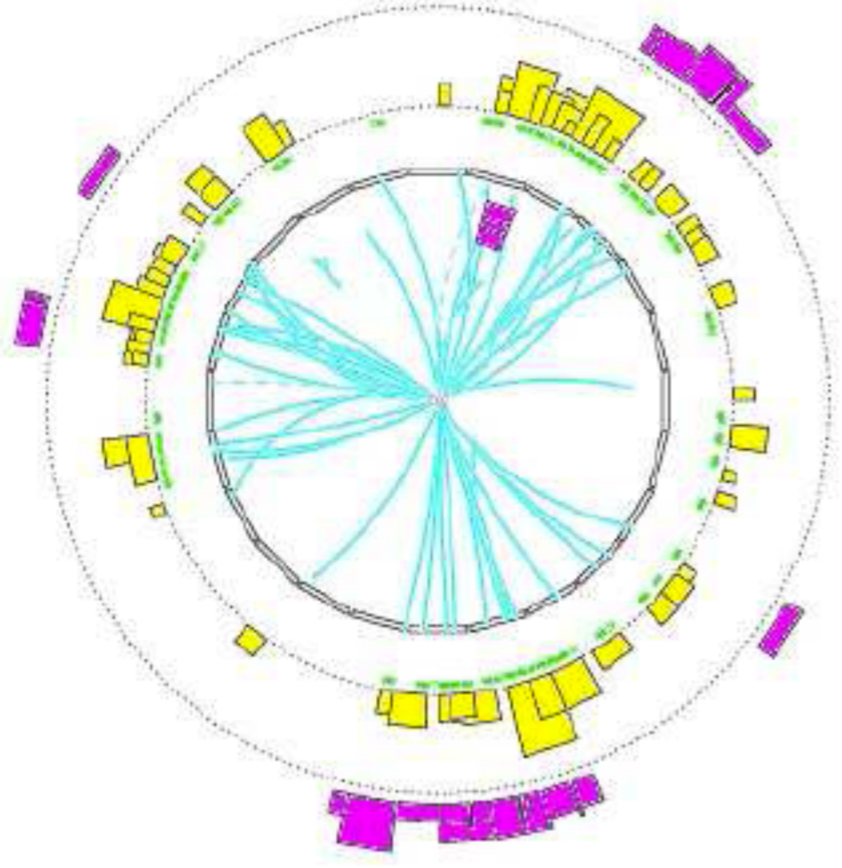
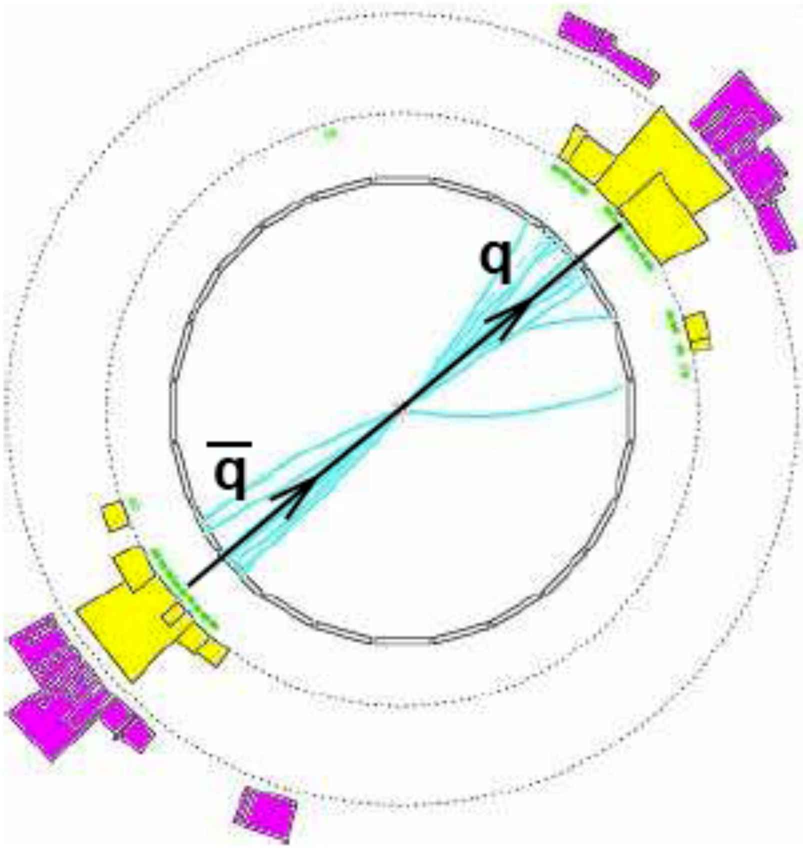


And in this one?

Jet identification



How many jets in this event:
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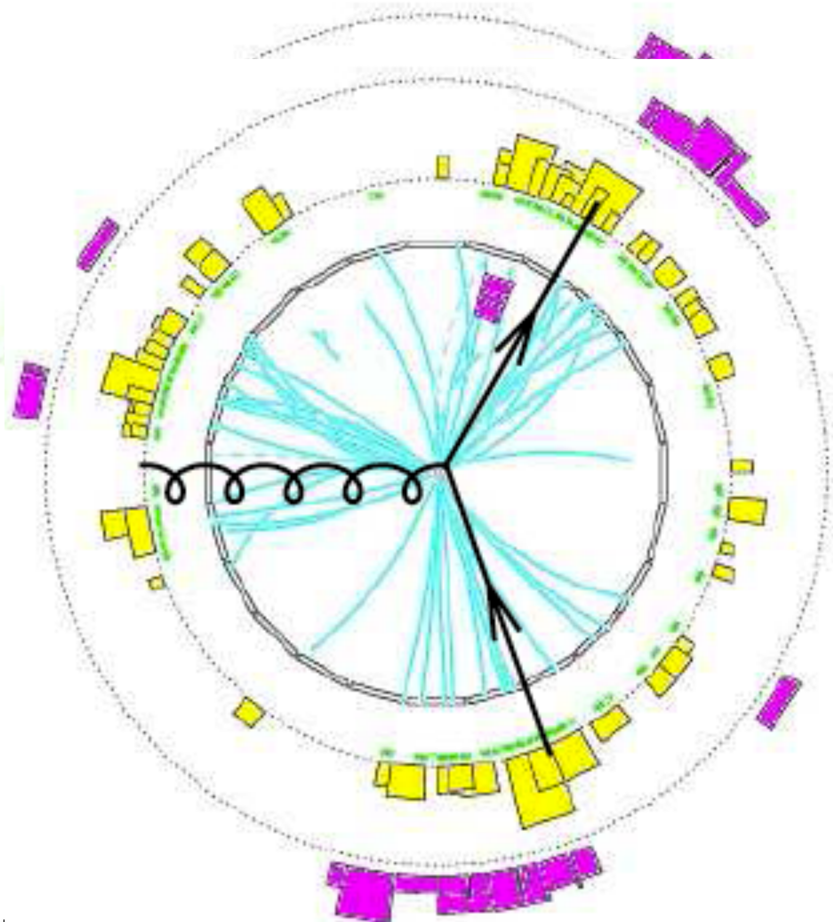
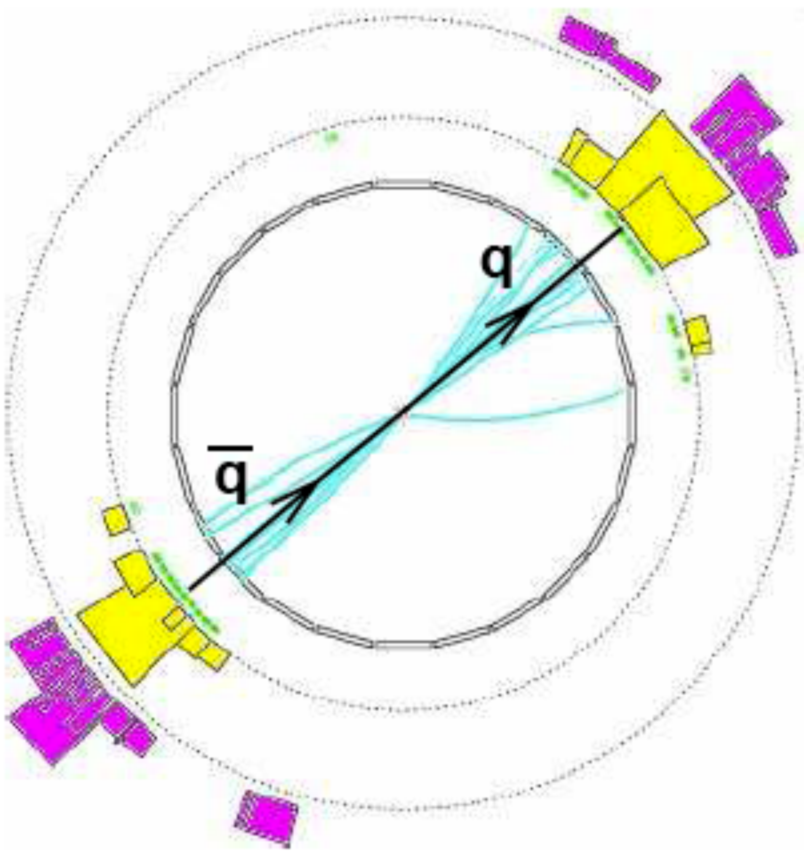
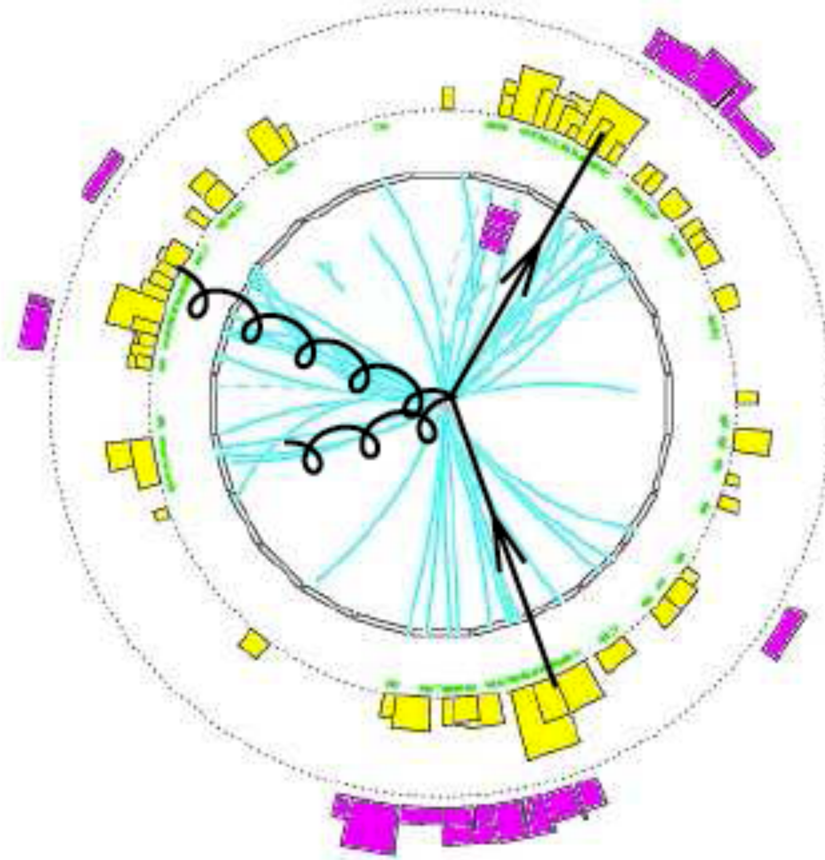


And in this one?

Jet identification



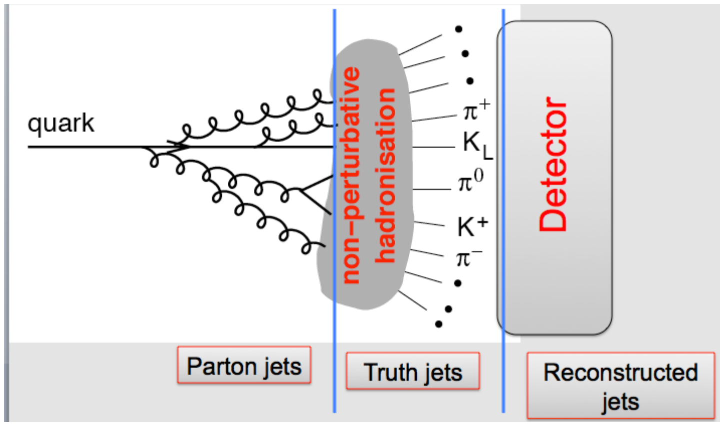
How many jets in this event:
It is clear they are 2!



And in this one?

It is necessay to implement a “jet algorithm” to identify jets in the event and consequently to measure their 4-momenta

Jet Algorithms



Jet algorithm: a set of rules that define how to "cluster" jets from a collection of input signals from calorimeters and tracking

O(1k) calorimetric signals (clusters, cells) → reconstructed jets
O(100) hadrons produced from fragmentation → truth jets
O(10) → parton jets

The different jet types give different *views* of the same event and allow to compare measurements (reconstructed jets) to predictions (truth jets, parton jets) → comparison between predictions and measurements.

Jet algorithm

- The physics results (new particle discoveries, coupling measurements, PDFs…)should not depend on the particular jet algorithm used
- Testing a measurement with different jet algorithms, or with different values of parameter for a jet algorithms is a very important test that allows to verify that the measurement is robust with respect to QCD radiations, hadronizations …
- Exception: the sensitivity of a measurement may depend on the "resolution" with which the event is investigated …

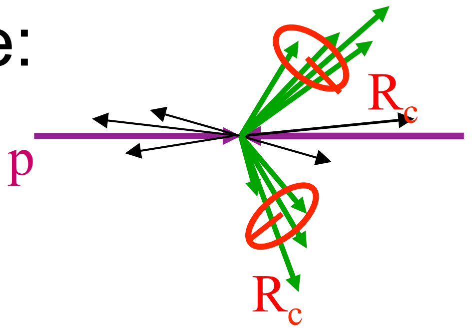
A dependence that we should avoid …. →

Jet algorithms

- **Two cathegories:**

- **Cone**: a cone is build with Lorentz invariant quantities: R_C and particles are collected within this cone:

$$R_C \approx \sqrt{\Delta\phi^2 + \Delta\eta^2}$$



- **Sequential:** start from single elements: track or, calorimetric cluster and try to recontruct back the branching effects due to the QCD showering and recombining the various elements with a “distance” algorithm between them.

The k_t algorithm family

•A family of sequential algorithms characterized by a specific "distance" definition used to join two tracks or calorimeter cluster

The general definition is`:

$$d_{ij} = \min(k_{ti}^{2\alpha}, k_{tij}^{2\alpha}) \cdot \frac{\Delta R^2}{R^2}$$

$$d_{iB} = k_{ti}^{2\alpha}$$

$k_{ti} = \textit{tranverse}$ momentum of the element i

$\mathrm{k}_{tij} = \textit{relative}$ transverse momentum between elements i,j

α = 1 → Inclusive k_t algorithm
α = 0 → only angular distances – Cambridge-Achen algorithm
α = -1 → Antikt algorithm

Antik$_t$

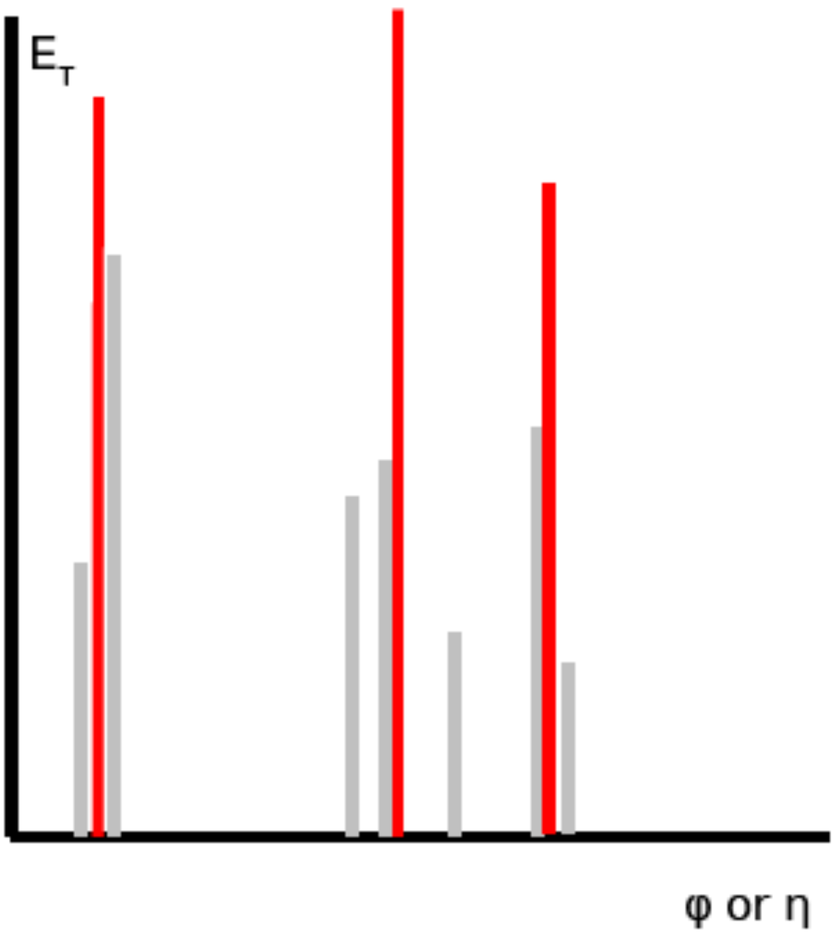
- At present the most popular at LHC

$$d_{ij} = \min\left(\frac{1}{k_{ti}^2}, \frac{1}{k_{tj}^2}\text{i}\right)\frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = \frac{1}{k_{ti}^2}$$

Cacciari, GPS & Soyez, '08 [+ Delsart unpublished]

-Recombination of collinear elements are privileged
-Large p_T elements lead the recombination sequence
-Produces regular shape jets

Example:



Clustering Algorithms:

Kt, AntiKt

- Define a distance d_{ij} between two objects i, j :

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

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

and a distance d_{iB} between one object i and the beam direction B:

$$d_{iB} = k_{ti}^{2\mathbf{p}}$$

- Find the smallest of d_{ij}, d_{iB} .

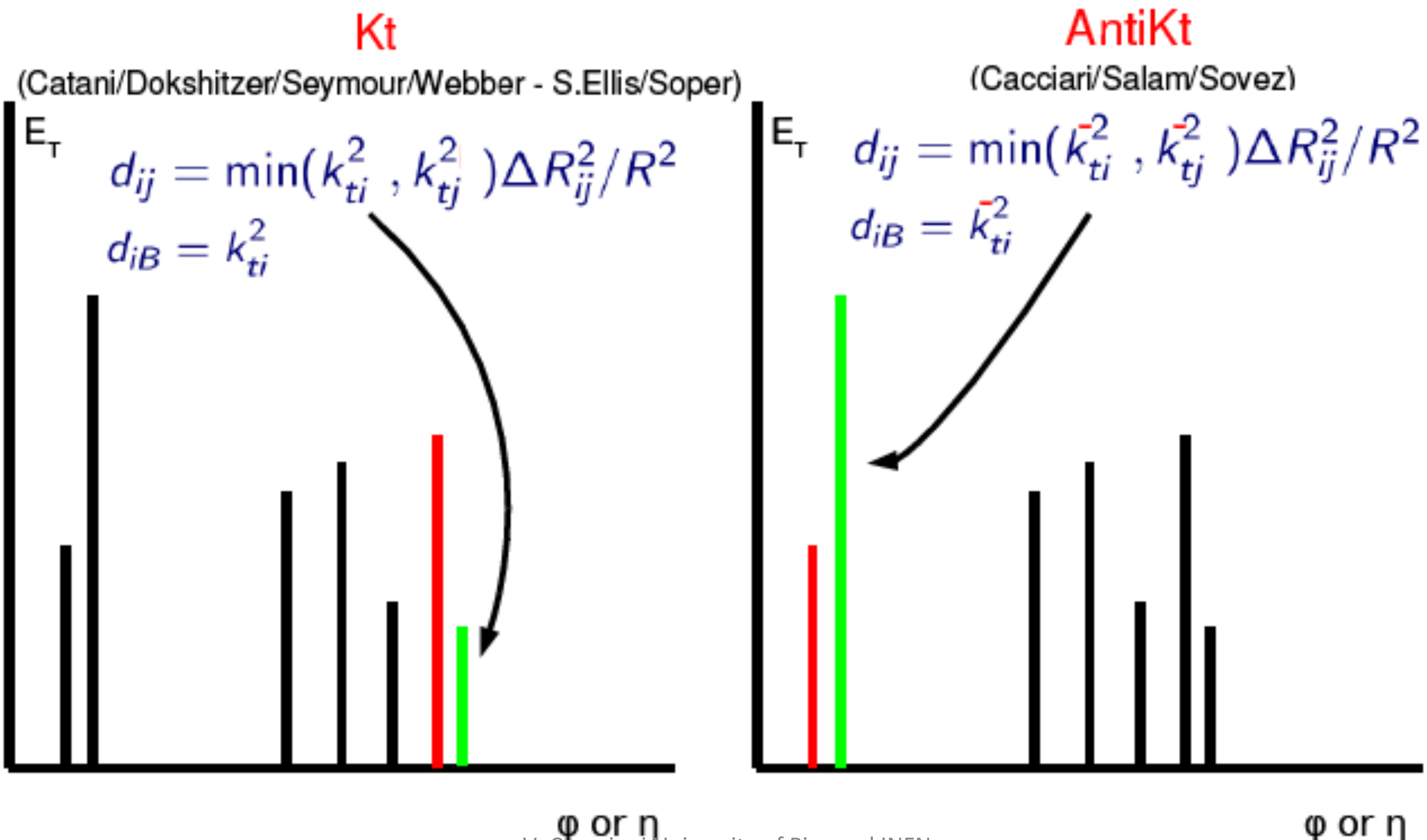
  If d_{ij} recombine i, j ;

  If d_{iB} , i is a jet.

P= 1: Kt (Catani/Dokshitzer/Seymour/Webber-S.Ellis/ Soper)

P= -1: AntiKt (Cacciari/Salam/Soyez)

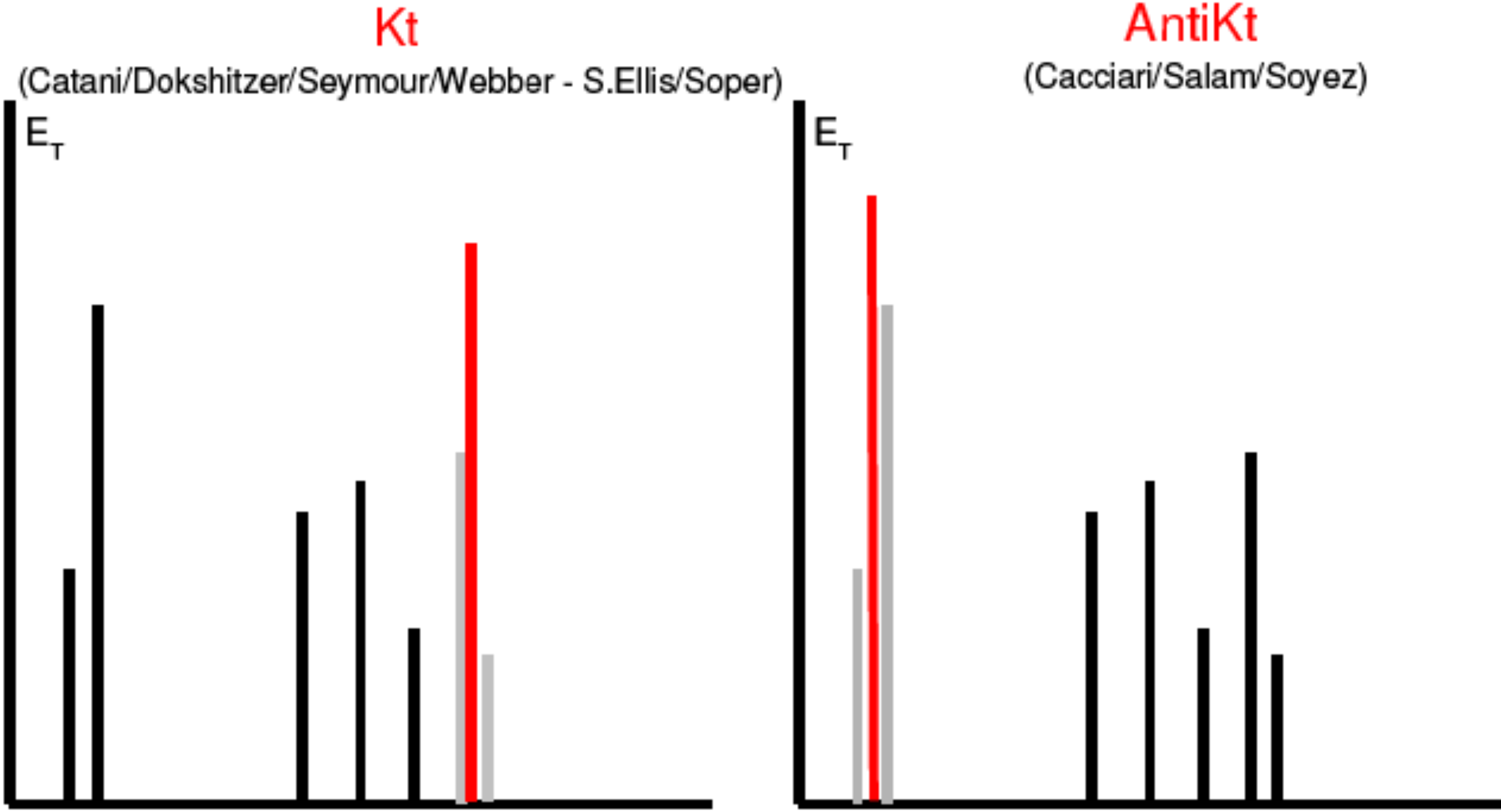
AntiKt



Kt
(Catani/Dokshitzer/Seymour/Webber - S.Ellis/Soper)
E_T
$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$
$d_{iB} = k_{ti}^2$
φ or η
AntiKt
(Cacciari/Salam/Sovez)
E_T
$d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\Delta R_{ij}^2/R^2$
$d_{iB} = k_{ti}^{-2}$
φ or η

AntiKt

CTEQ-MCnet school 2008
Gavin Salam Lectures on Jets



AntiKt

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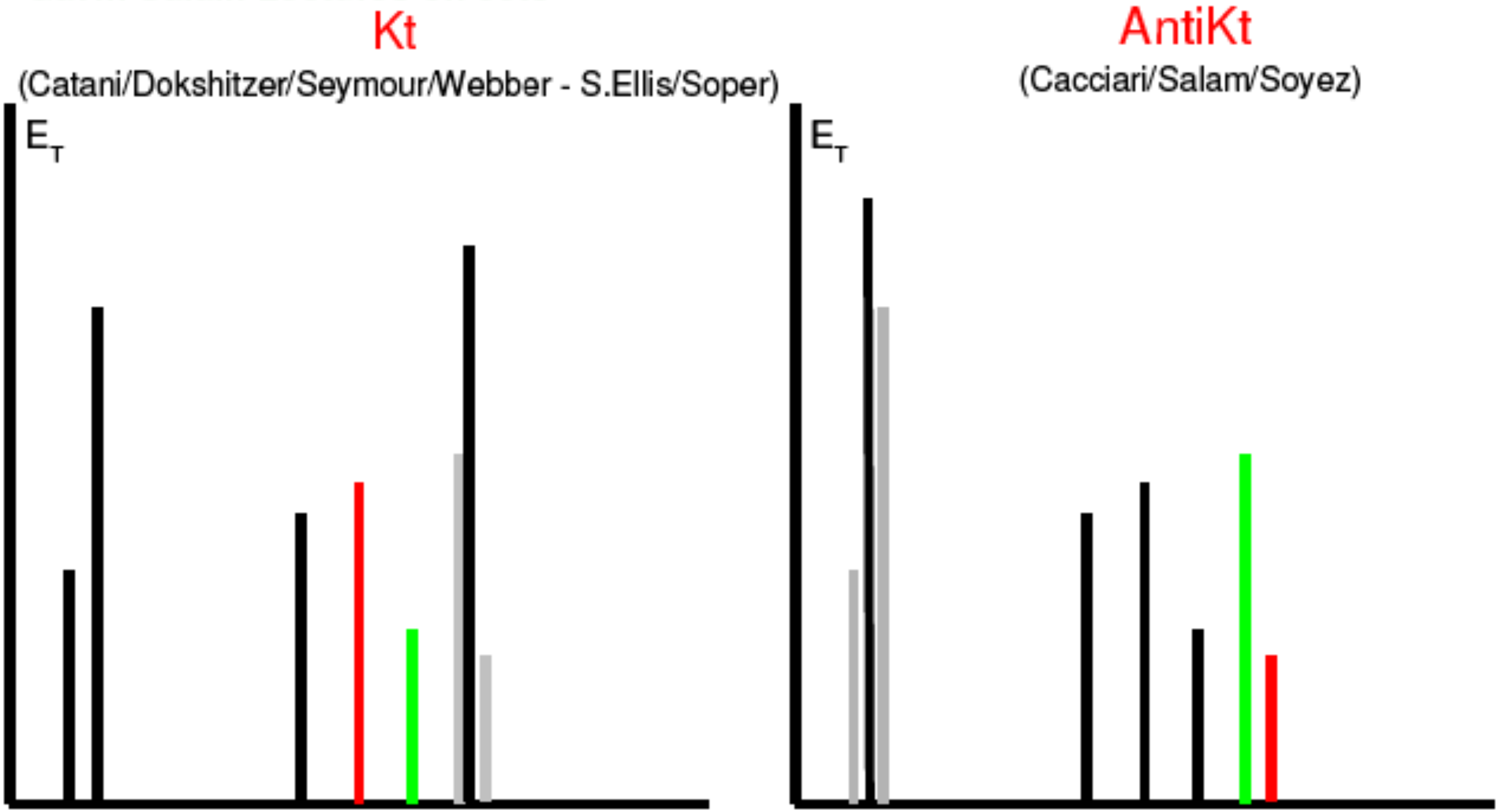
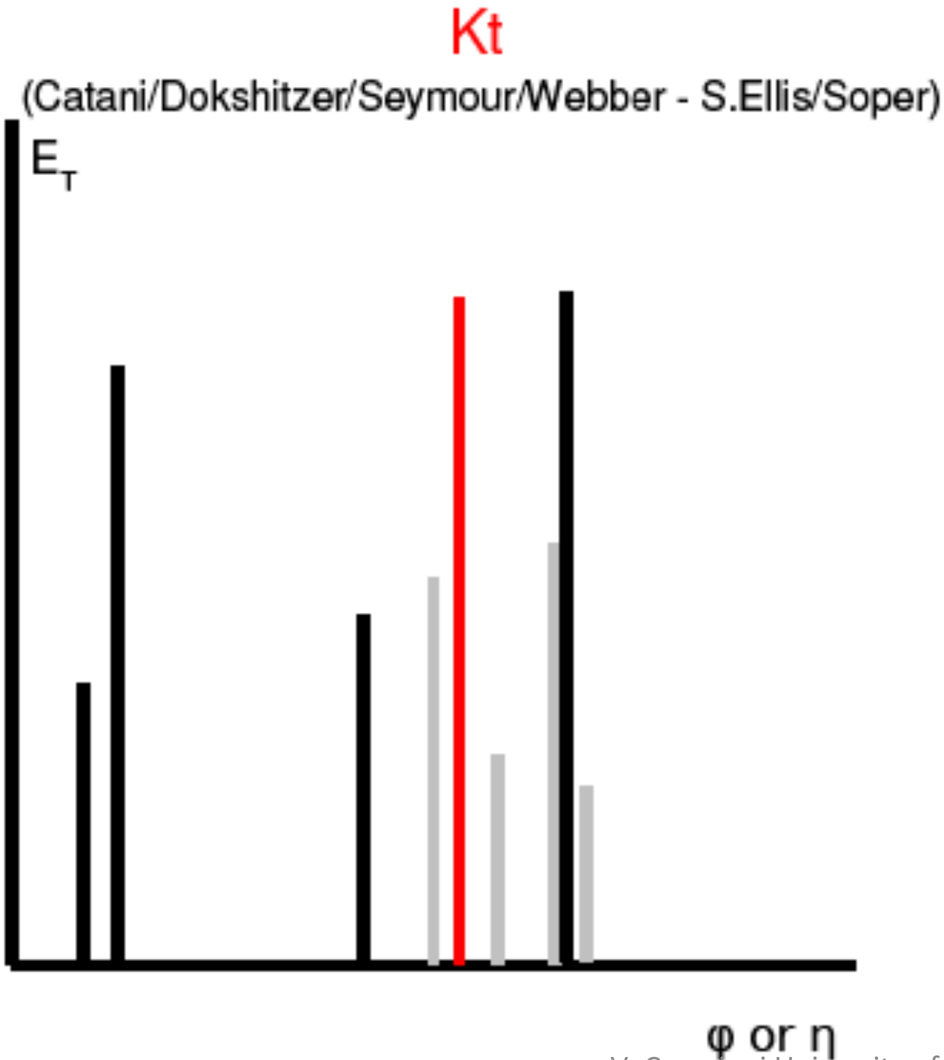
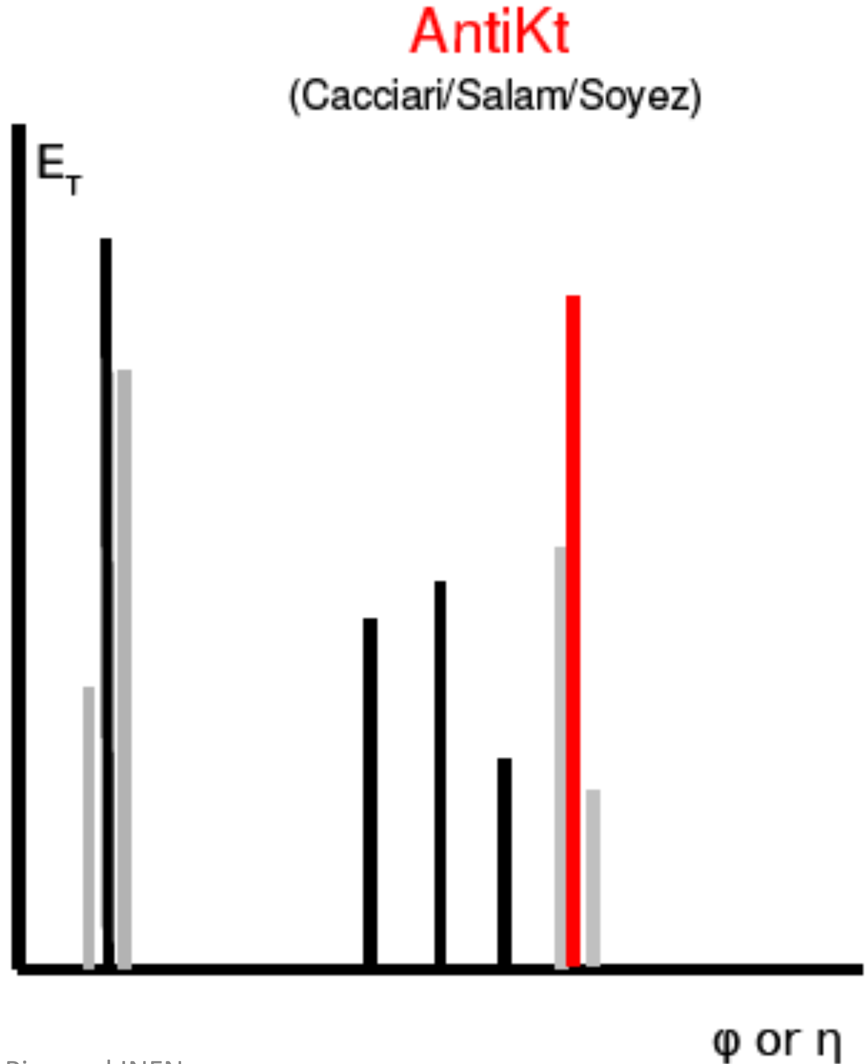


AntiKt

CTEQ-MCnet school 2008
Gavin Salam Lectures on Jets





AntiKt

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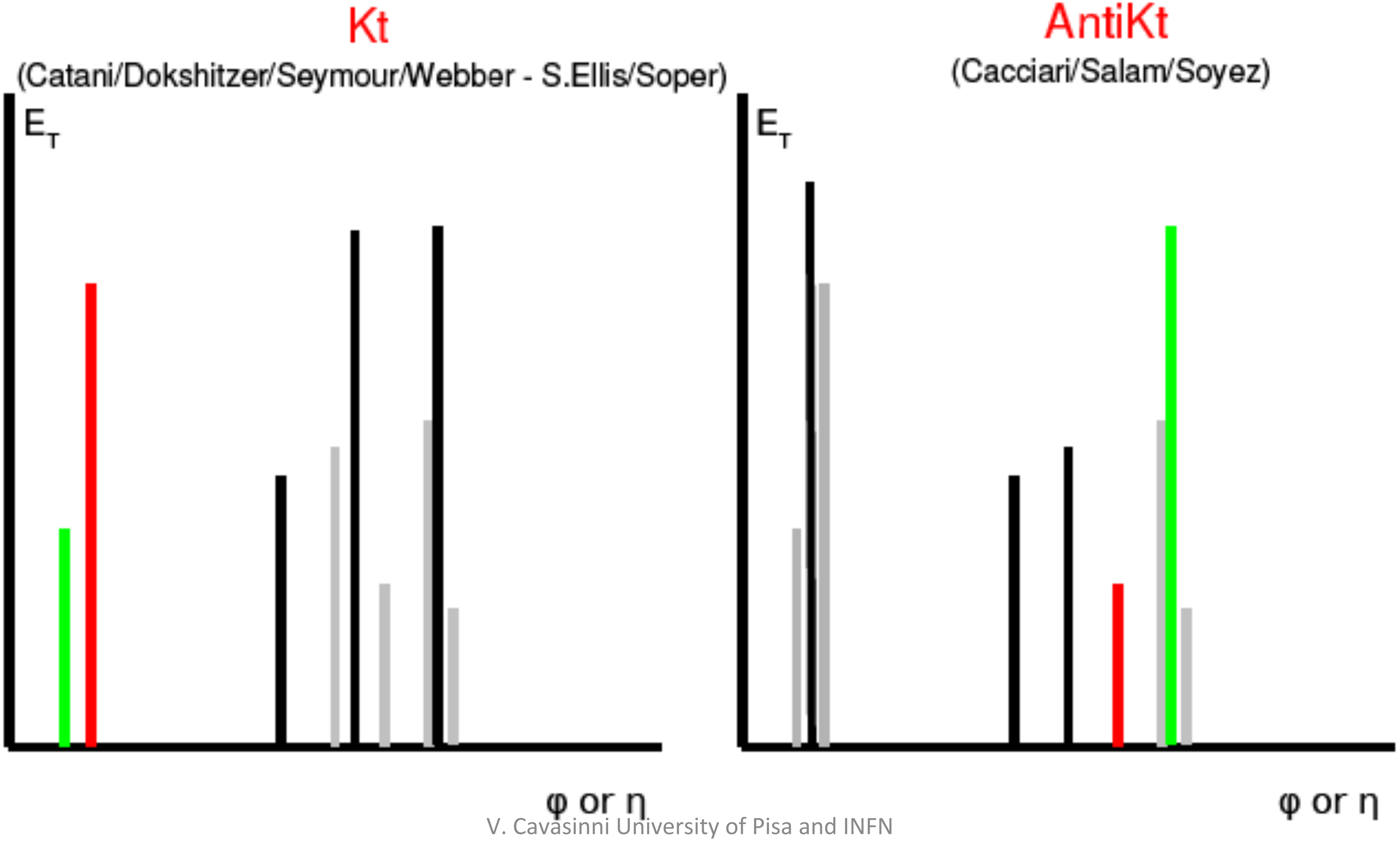

AntiKt

CTEQ-MCnet school 2008
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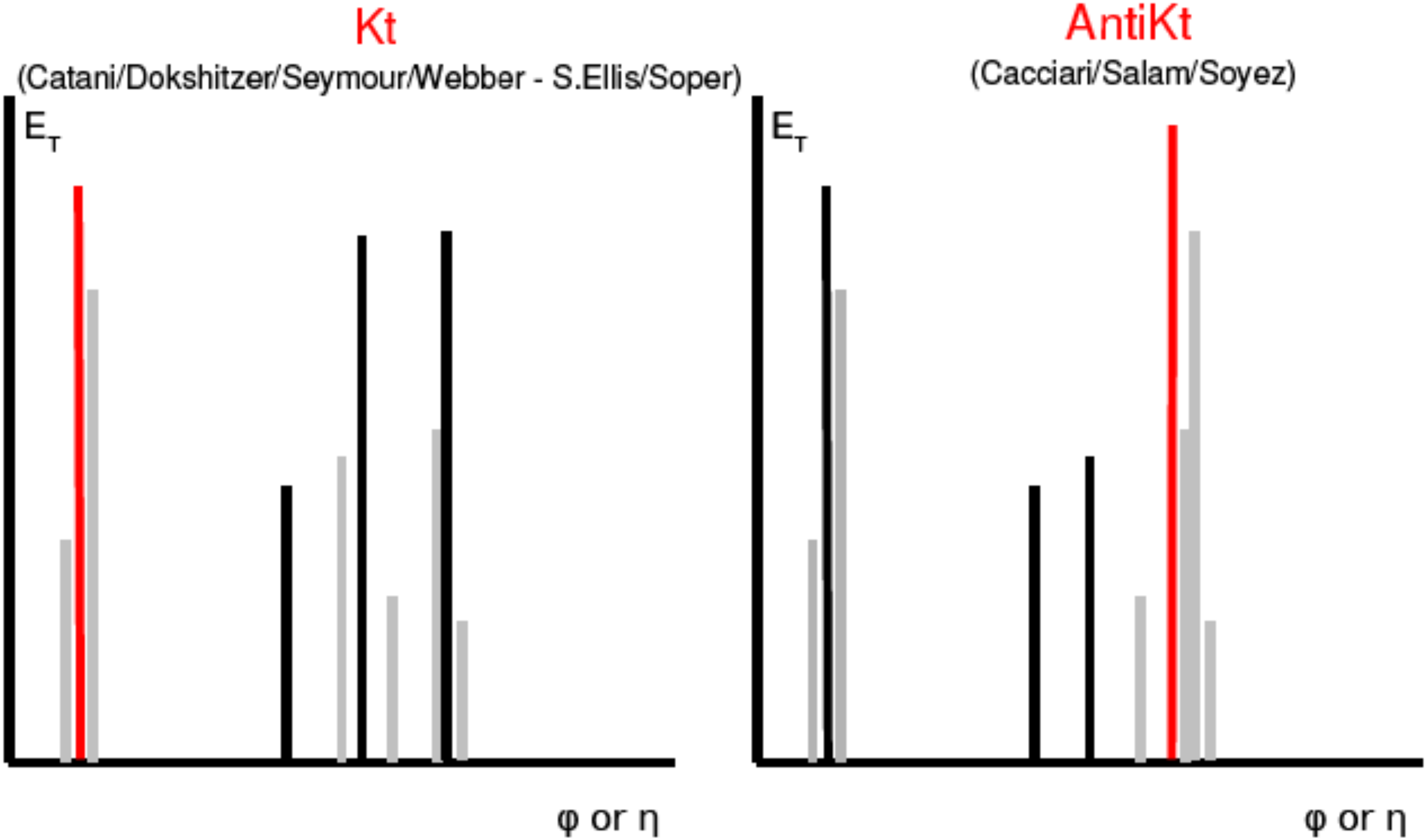

AntiKt

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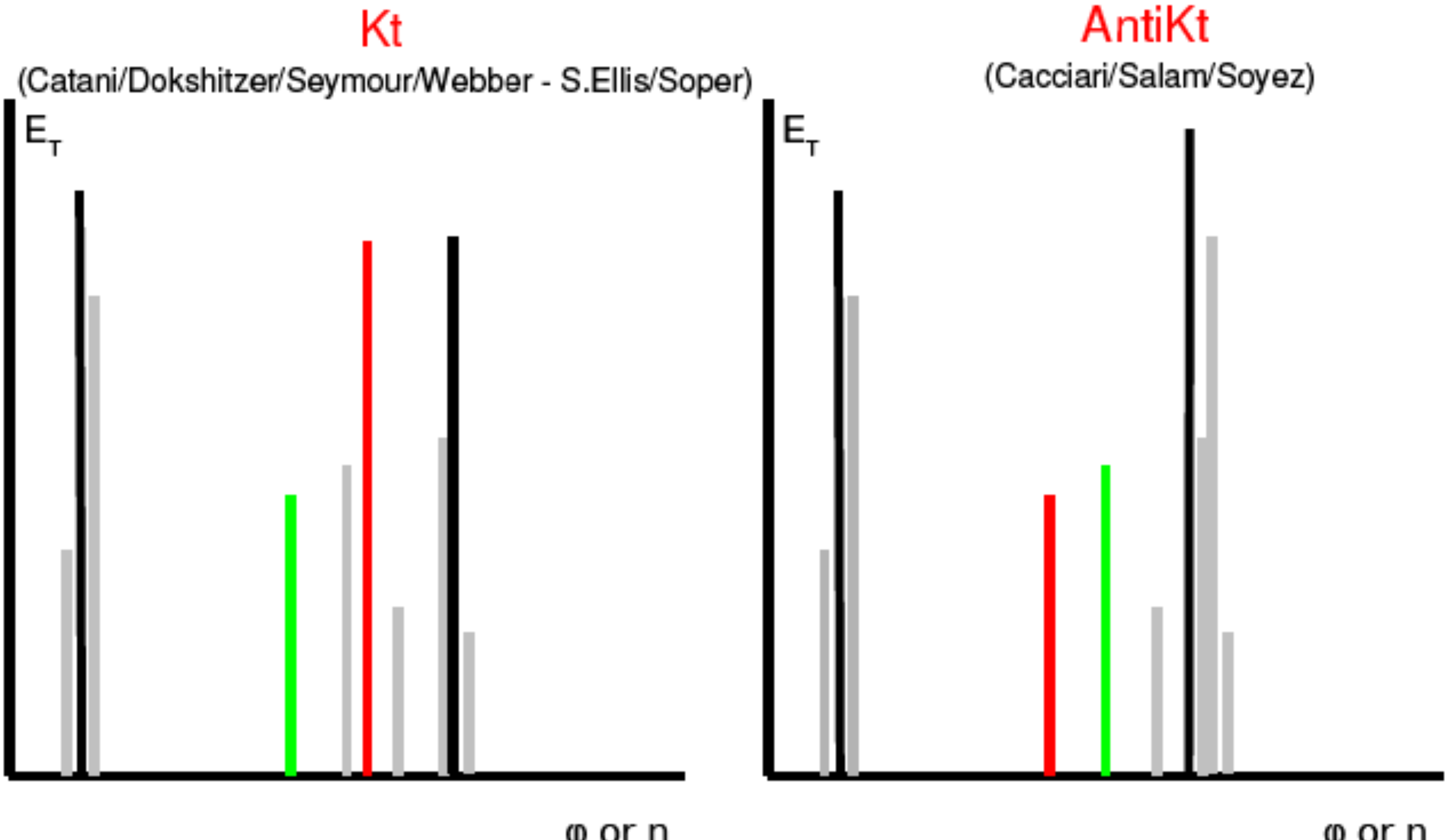

AntiKt

CTEQ-MCnet school 2008
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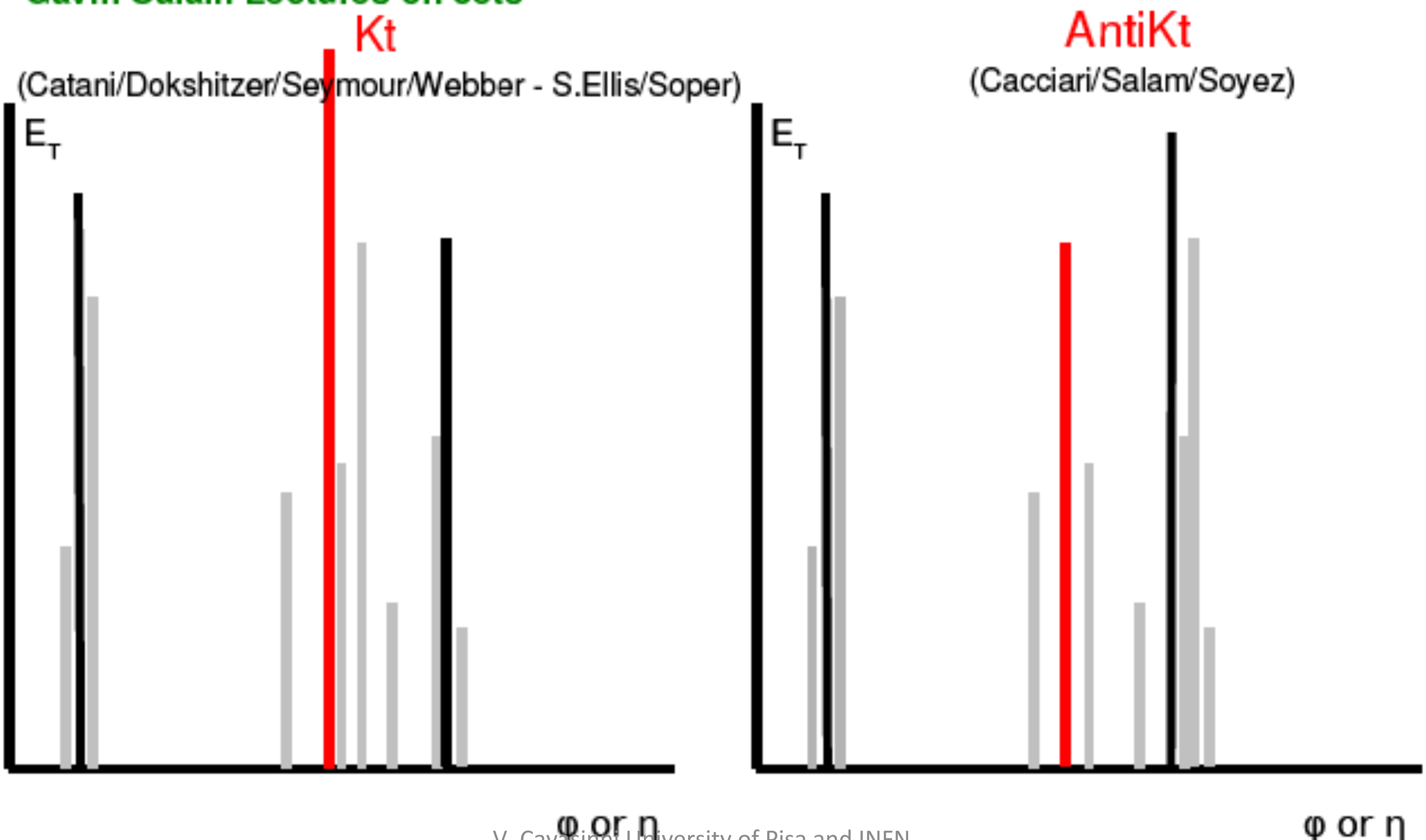

AntiKt

CTEQ-MCnet school 2008
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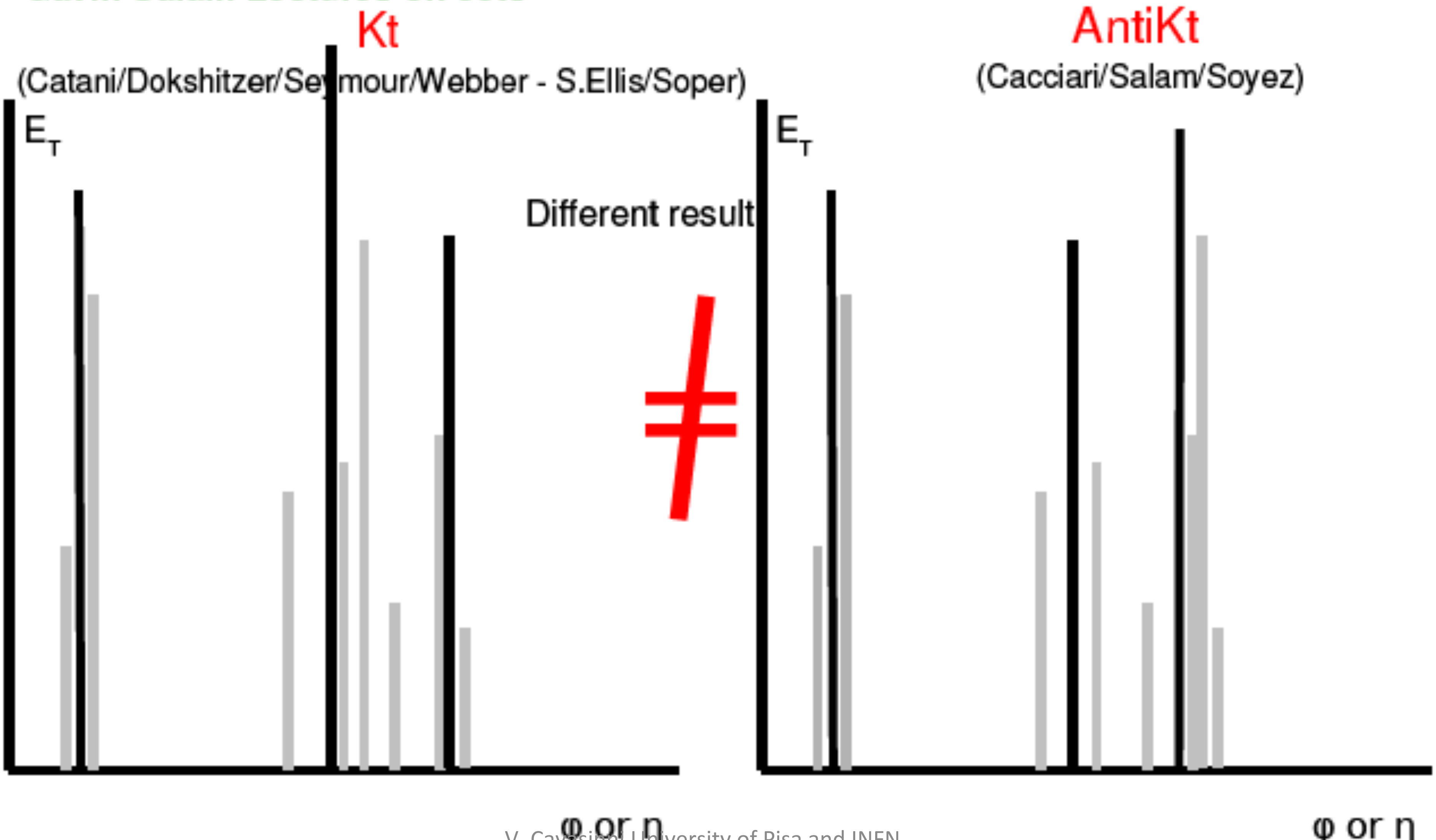
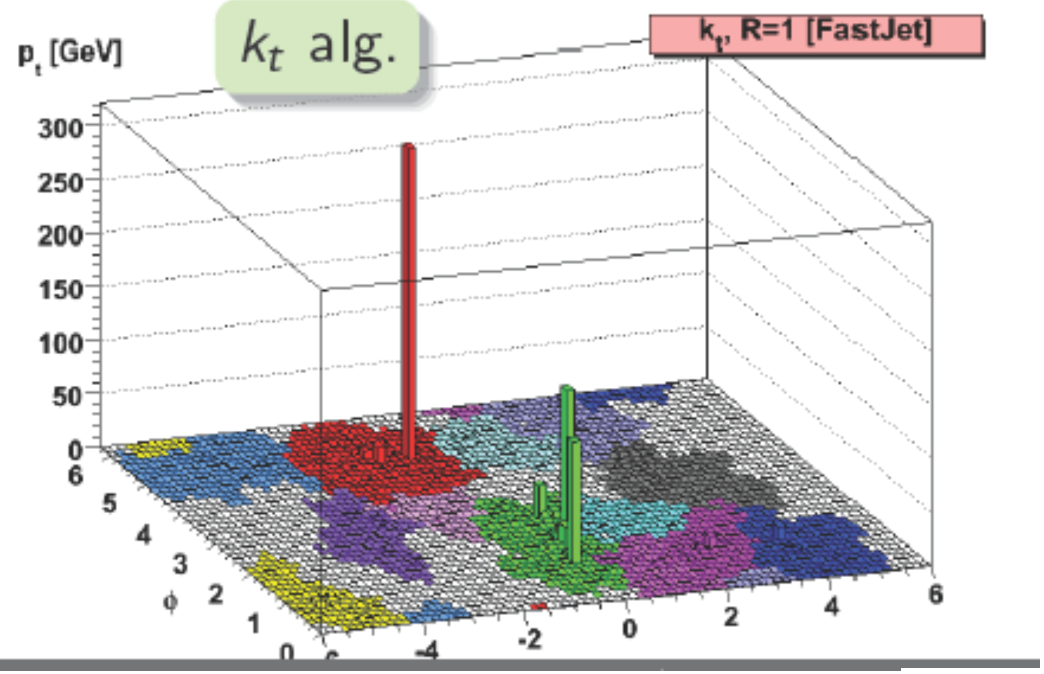
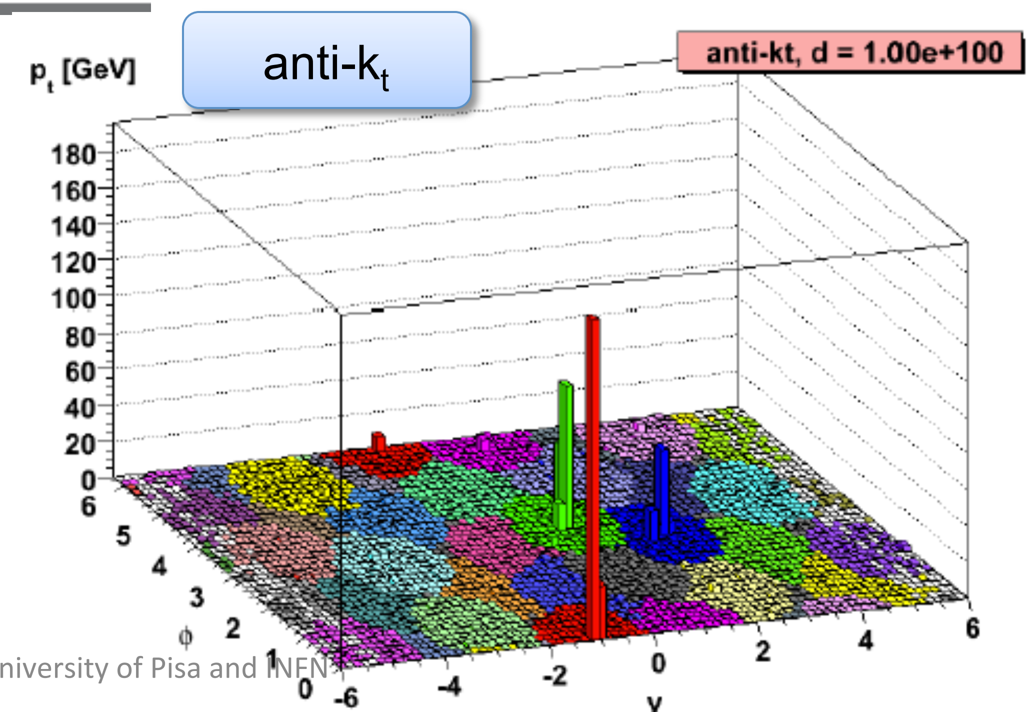




The k_t algorithm builds jets of irregular shape driven by the clusterization of soft element

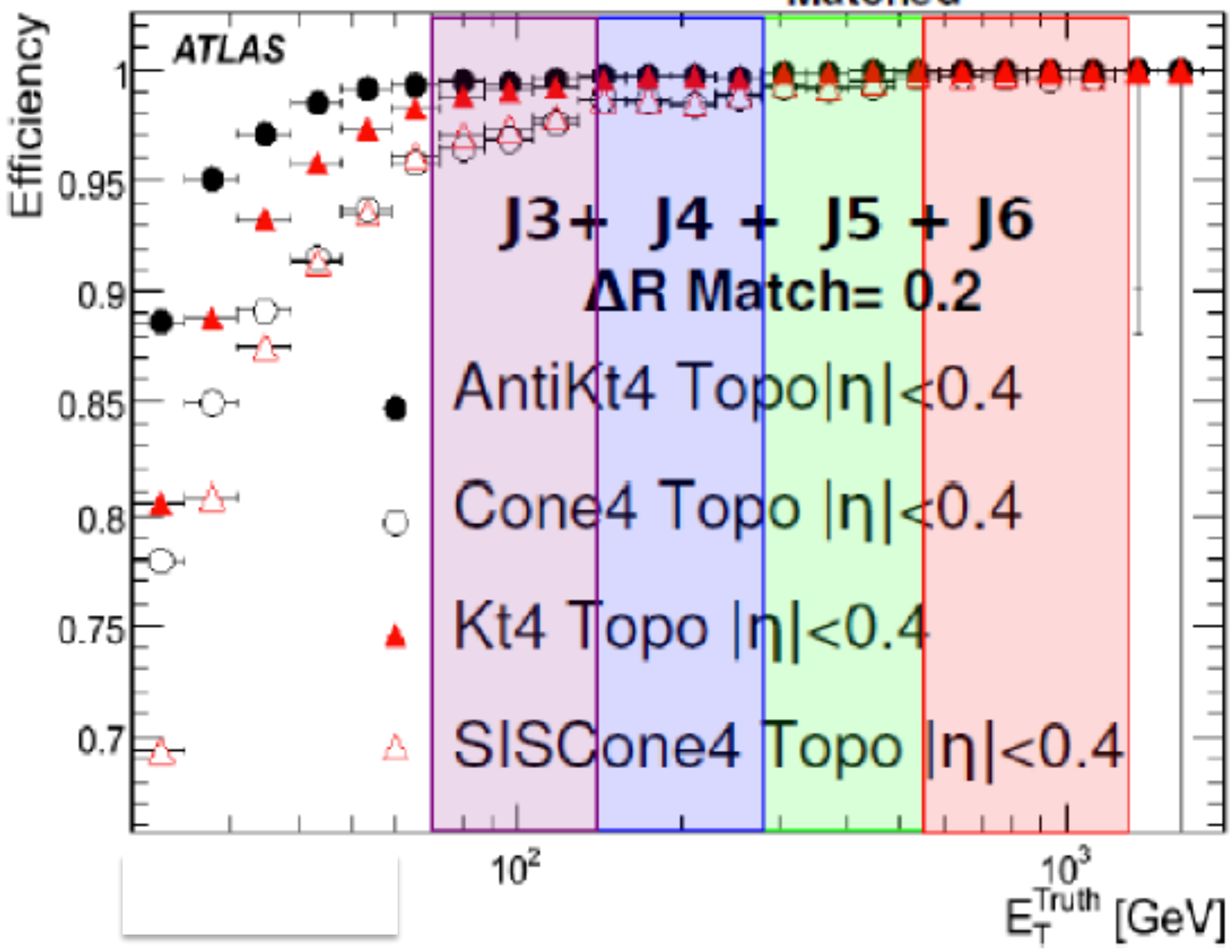
Thew anti-k_t is driven by the highest p_T elements and produces regular (cone) jets:

-Easier to manage experimentally
- corrections can be linear



Jet reconstruction and matching efficiency

$$\text{Efficiency} = N^{\text{Truth}}_{\text{Matched}} / N^{\text{Truth}}$$



As good as, or better than all previous experimentally-favoured algorithms.

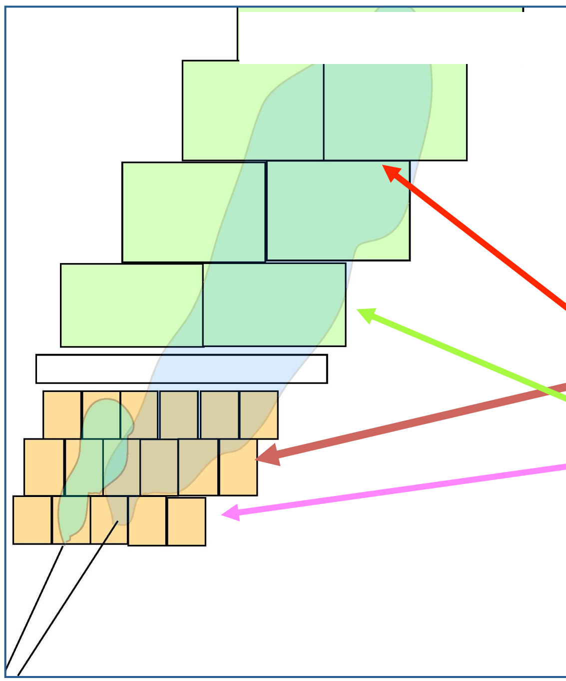
Essentially because anti-k_t has linear response to soft particles.

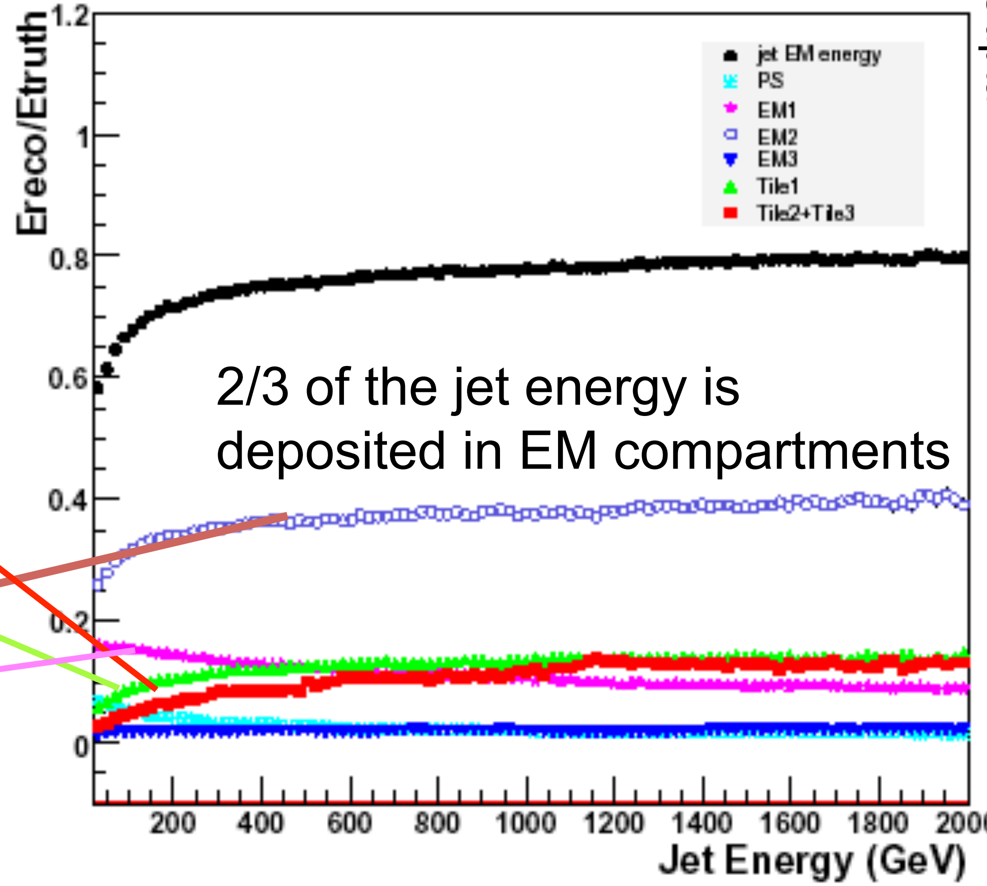
And it's also infrared and collinear safe (needed for theory calcs.)

Where the jet energy is? (ATLAS)

A.Gupta

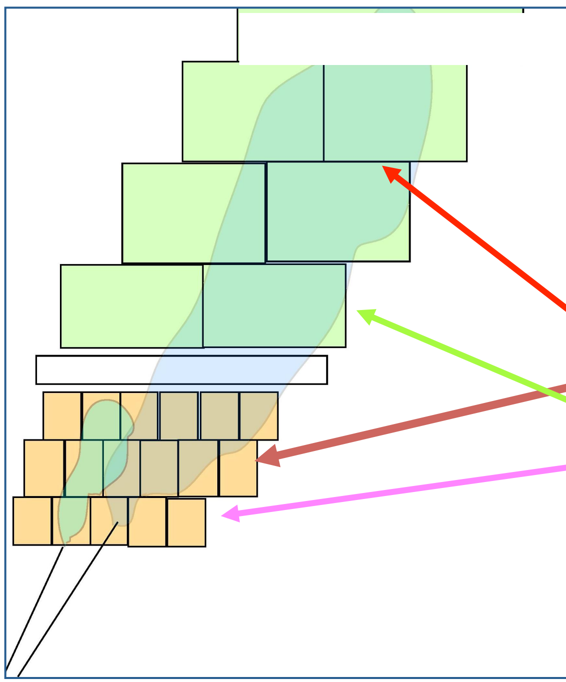
Central calorimeter region

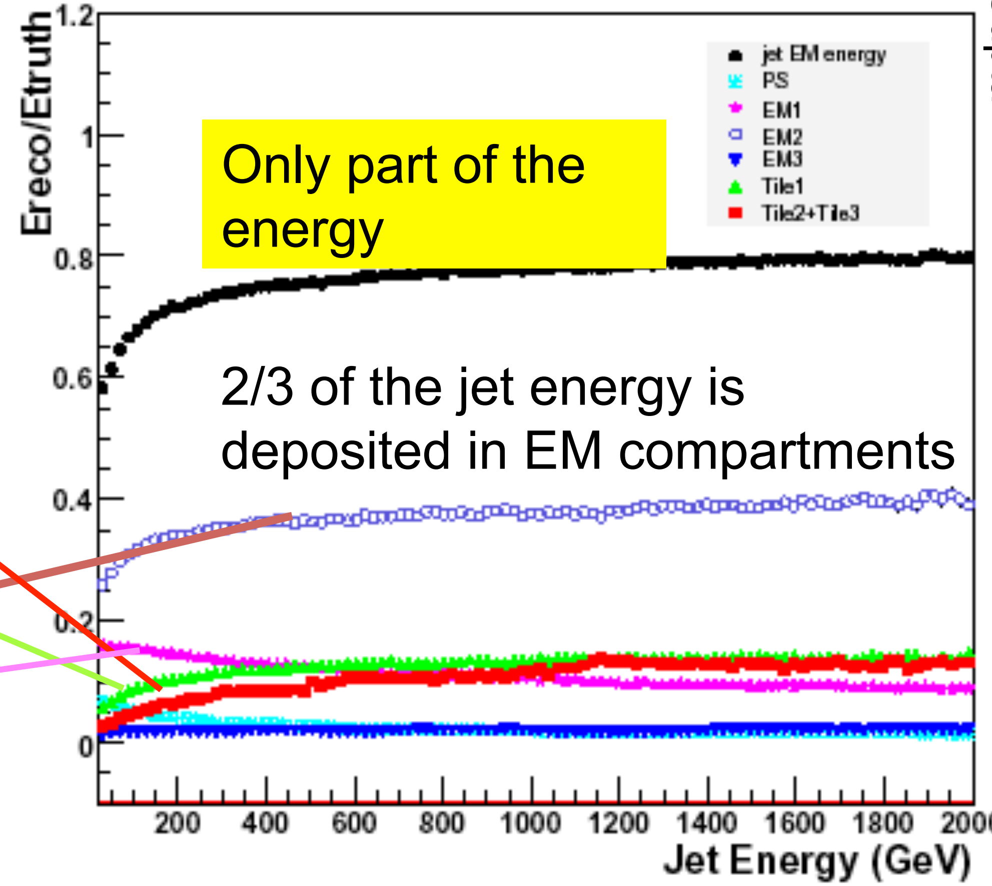




Where the jet energy is? (ATLAS)

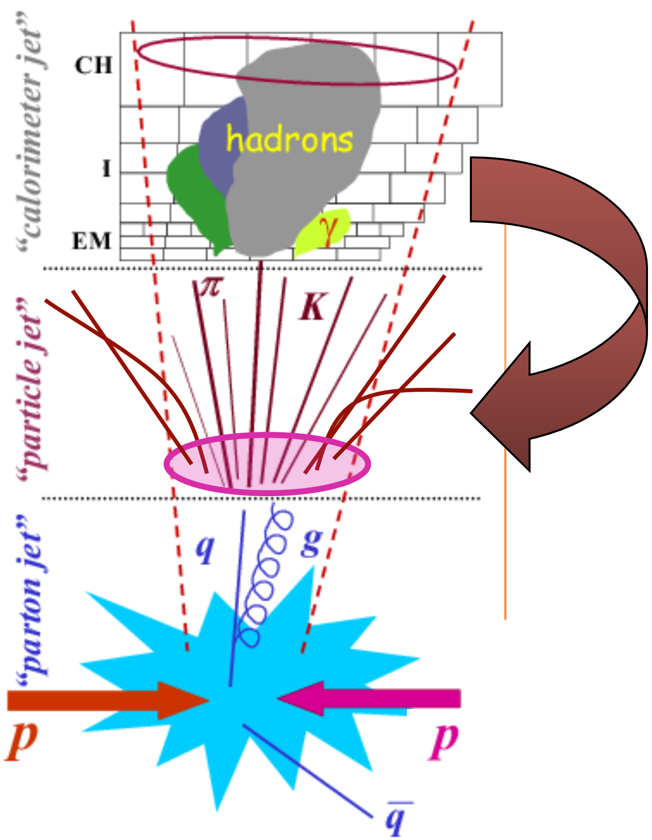
Central calorimeter region





A.Gupta

Jet calibration



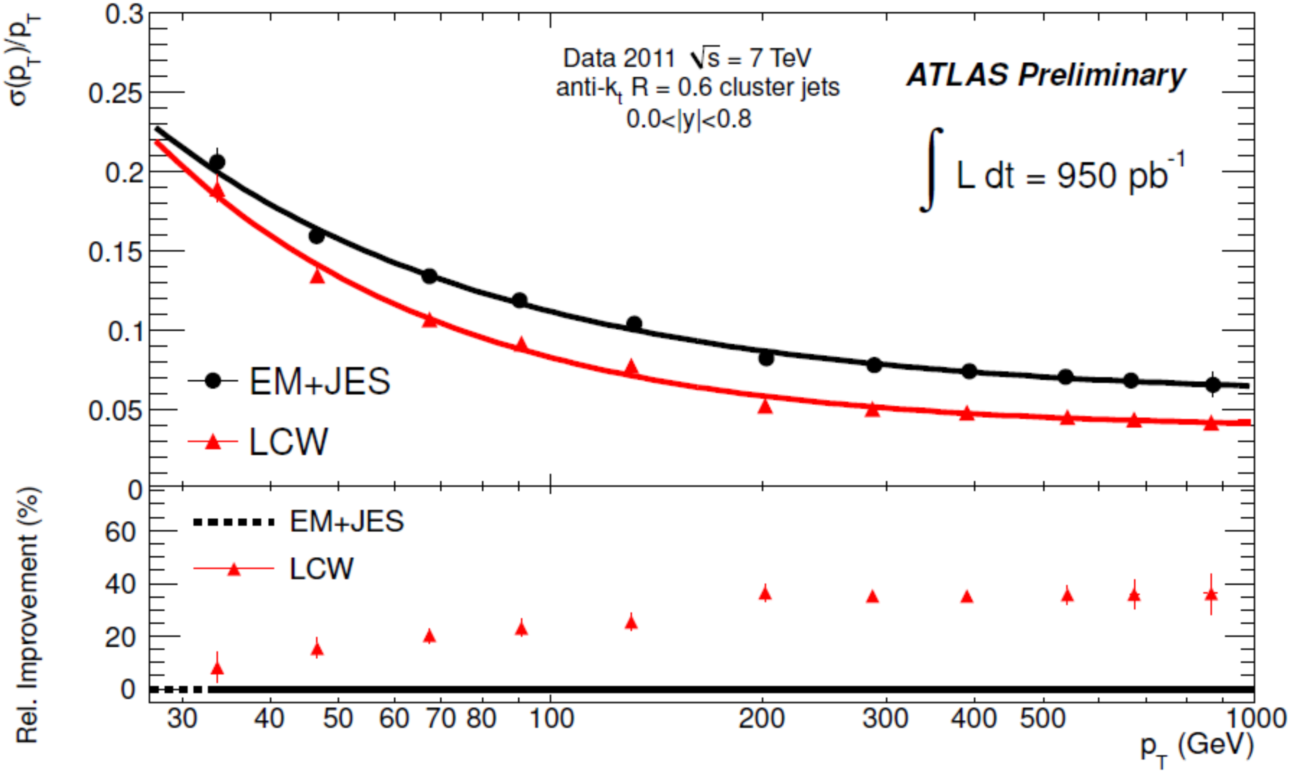
Correction of the detector effects to be considered to obtain the "true jet"

:

- uncompensation of calorimeters (e/h)
- effect of cracks, dead material, losses in material in fron of the calorimeters
- longitudinal leakage
- magnetic field effect. Truths contain the particles swept off from B field (p_T<350 MeV do not reach the calorimeter entrances)
- Pile-up contributions

Jet energy resolution

Jet energy resolution affects the unfolding/evaluation of the jet distributions: systematics
"unfolding" is the technique to reconstruct back from the measured jet distribution
the "parton" distribution (QCD)



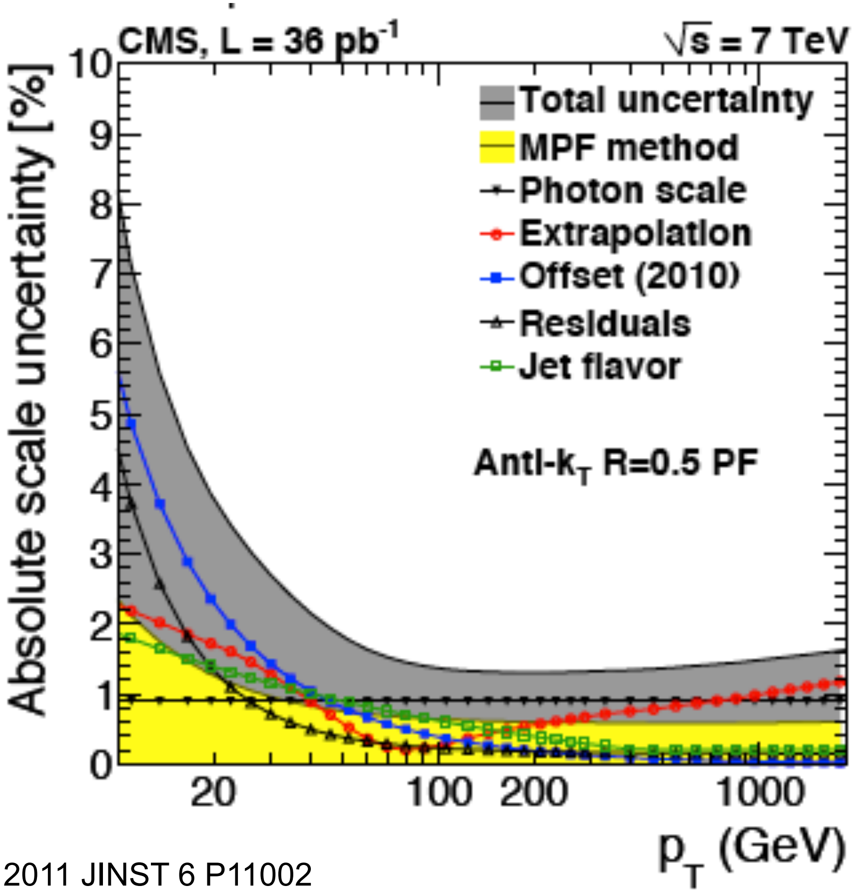
Up to **30% improvement** if using refined calibration techniques
(e.g. Local Cluster Weighting)

Jet Energy Scale Uncertainty

- This is NOT the resolution: it is a systematic error on the absolute jet energy
- Many physics measurements are largely affected by th JES (jet cross sections, jet-jet resonances, , limits on new physics)

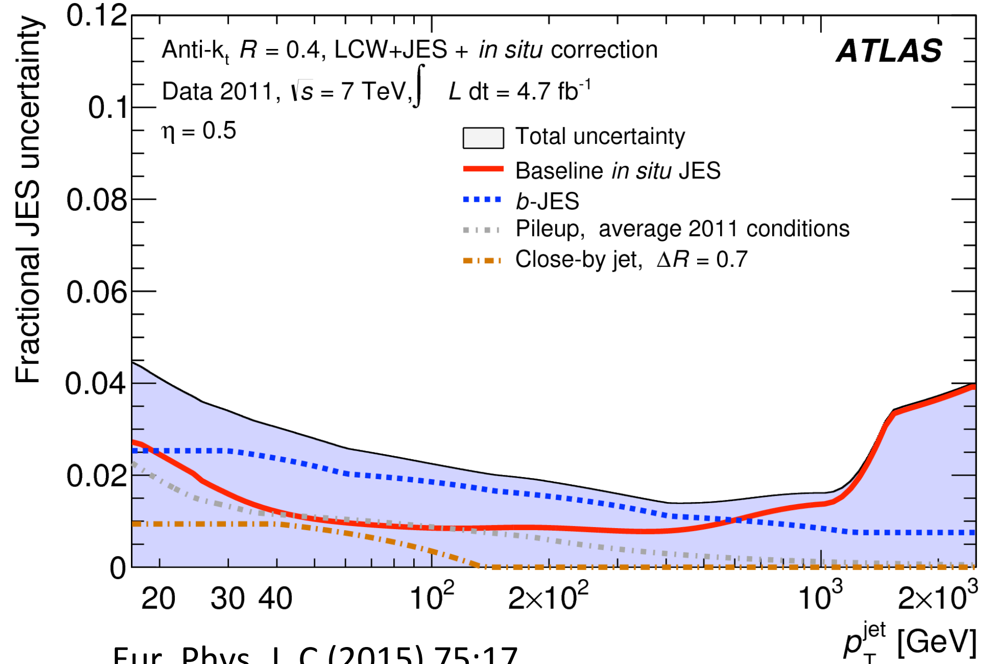
Jet Energy Scale Uncertainty

CMS



2011 JINST 6 P11002

ATLAS



Eur. Phys. J. C (2015) 75:17

JES uncertainty ranges between 2 and 5 % for $p_T > 20$ *GeV*

V. Cavasinni University of Pisa and INFN

Part III – Physics results

Why bother ?

Understanding/testing the QCD theory of SM
in a new kinematic range never explored before (LHC)

Our level of understanding and modeling of the QCD interactions has direct impact on the potential we have for precision measurements and discovery

-QCD jets are often the largest backgrounds in many Higgs decay channels eg:

$$H \rightarrow \vec{b}b;\ H \rightarrow \tau(had)\tau(had),..$$

-W/Z+jet is often one of the largest background to top-quark, SUSY, Higgs and exotic searches.

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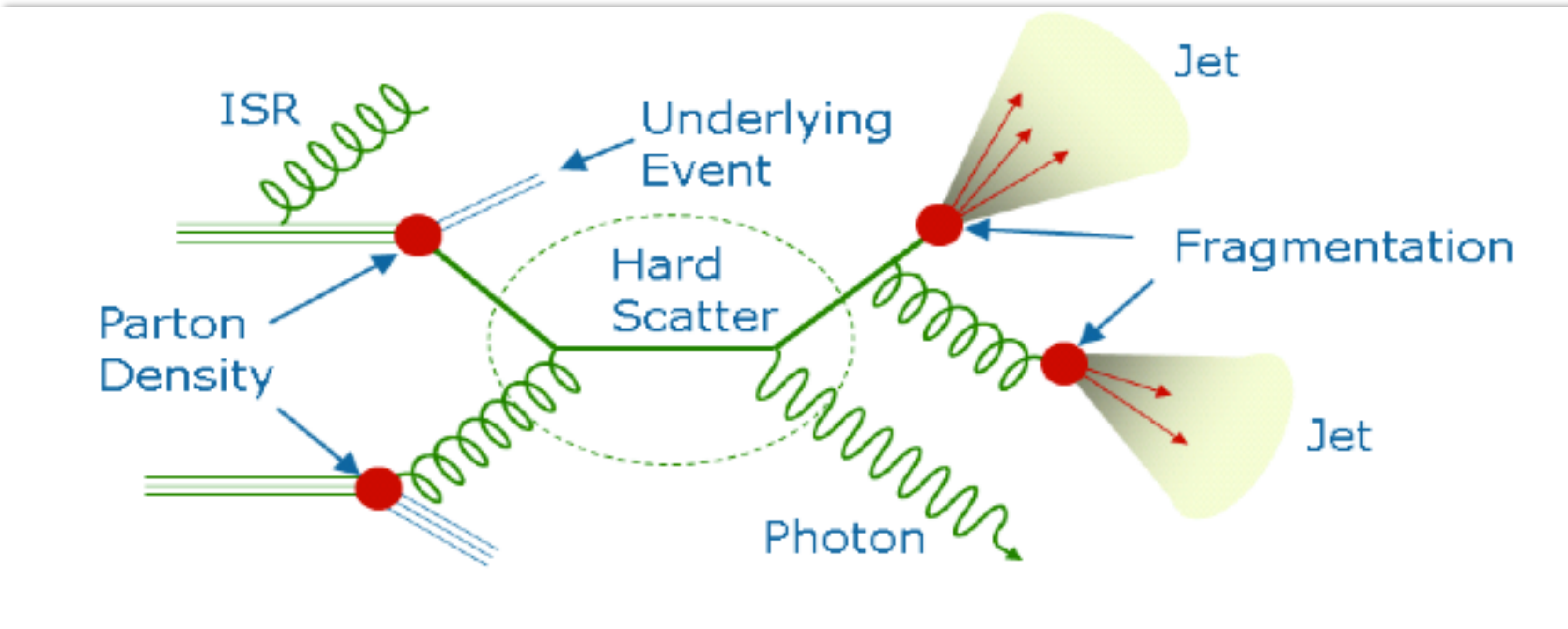
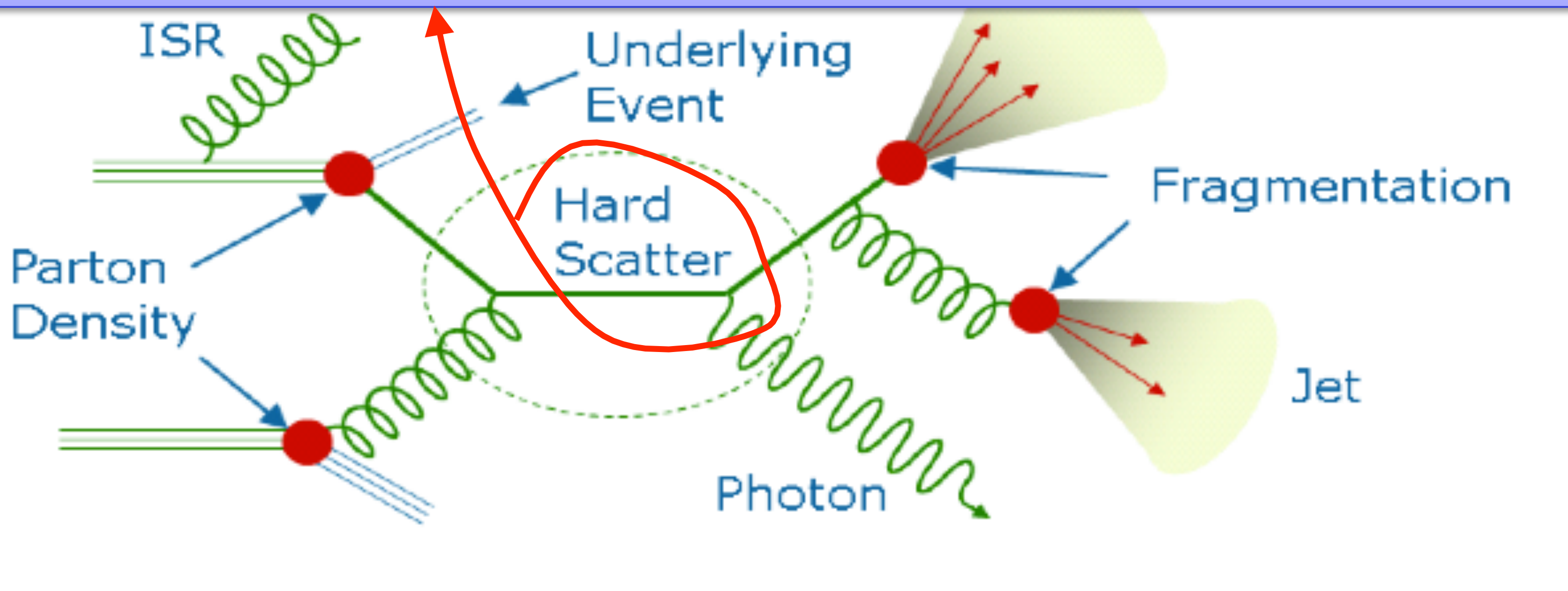
and INFN

The ingredients in the predictions…



The ingredients in the predictions…

Hard Scattering and parton shower: fixed order NLO partonic calculations (NLOJET++,MCFM,BlackHat), LO+PS (Pythia, Herwig), High multi. LO+PS (Alpgen, Sherpa, Madgraph,…). State of the art: **NLO+PS (MC@NLO+PS, POWHEG+PS, MEPS@NLO)**



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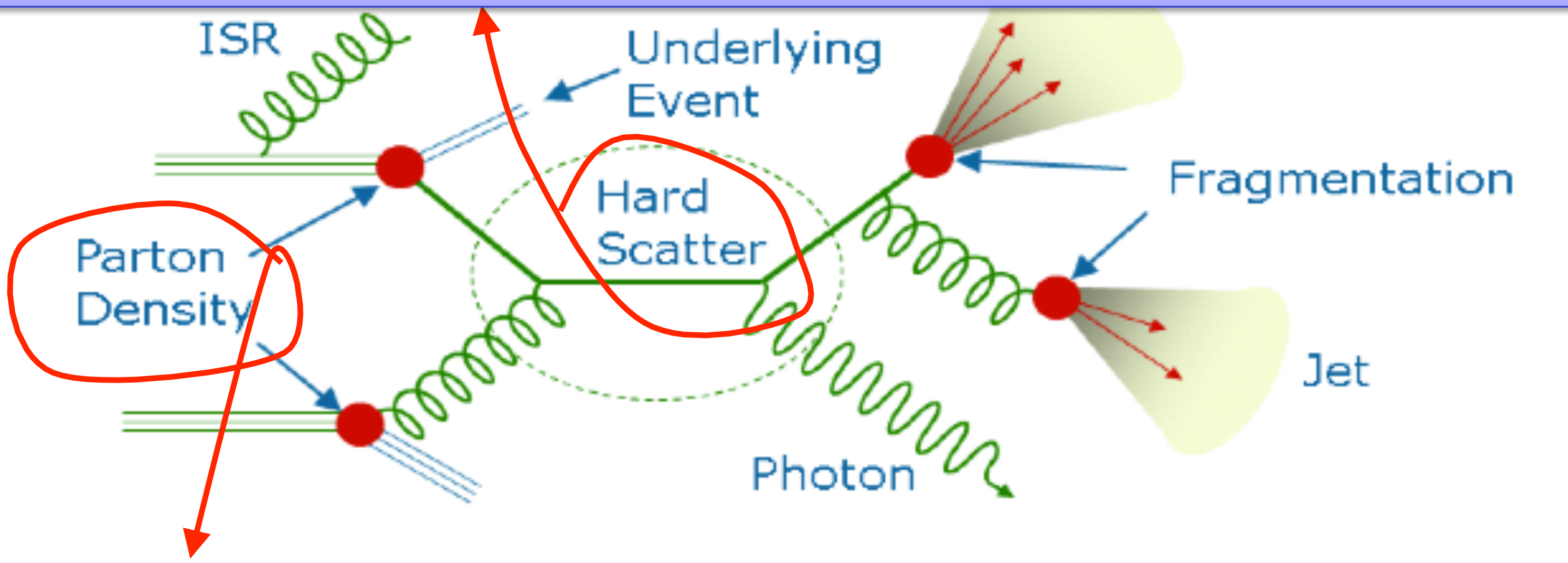

PDF: CTEQ/CT, NNPDF, MSTW, ABM, HERAPDF…
Differences: data used the fit, α_s value, treatment of errors, parameterization…

The ingredients in the predictions…

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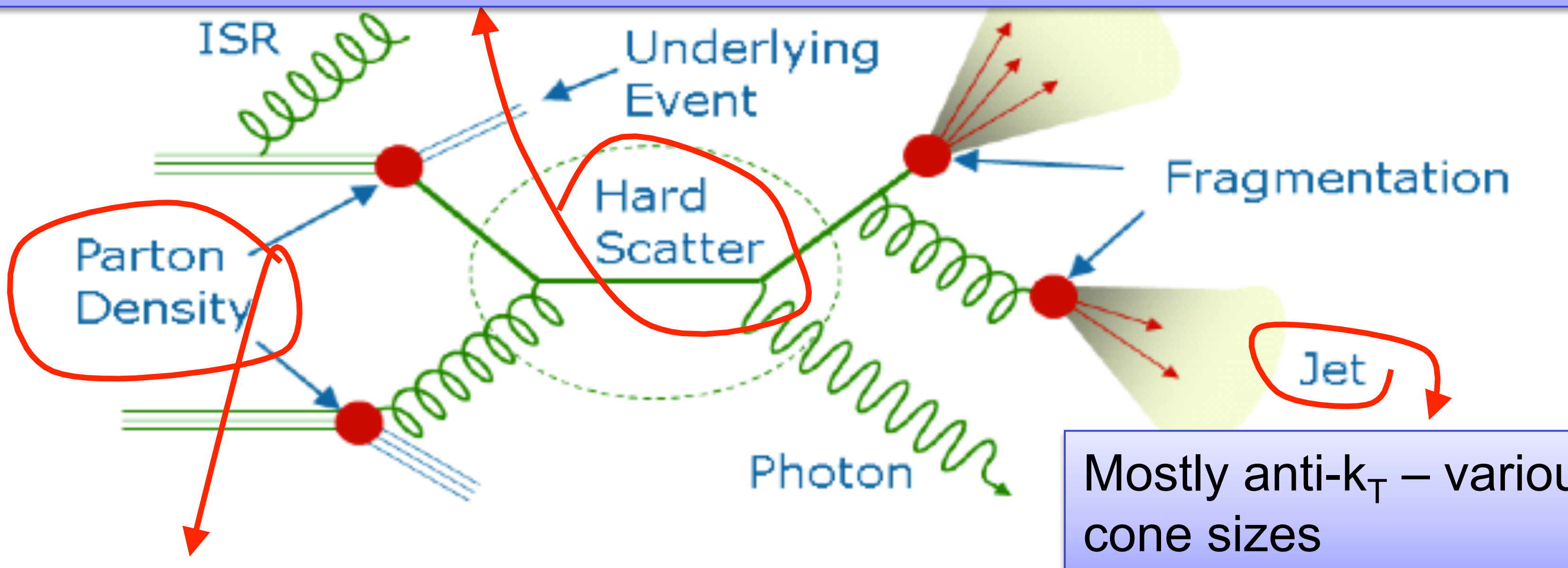

Mostly anti-k_T – various cone sizes

PDF: CTEQ/CT, NNPDF, MSTW, ABM, HERAPDF…
Differences: data used the fit, α_s value, treatment of errors, parameterization…

Measurements are unfolded at particle level to be compared with predictions

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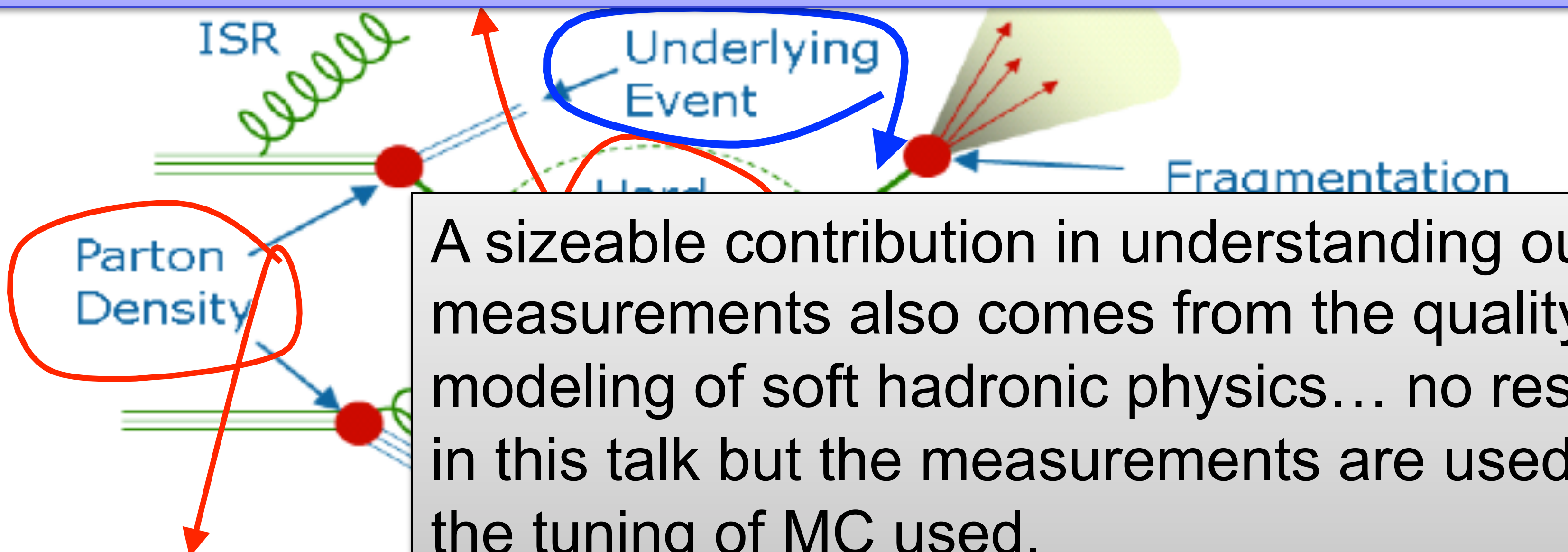


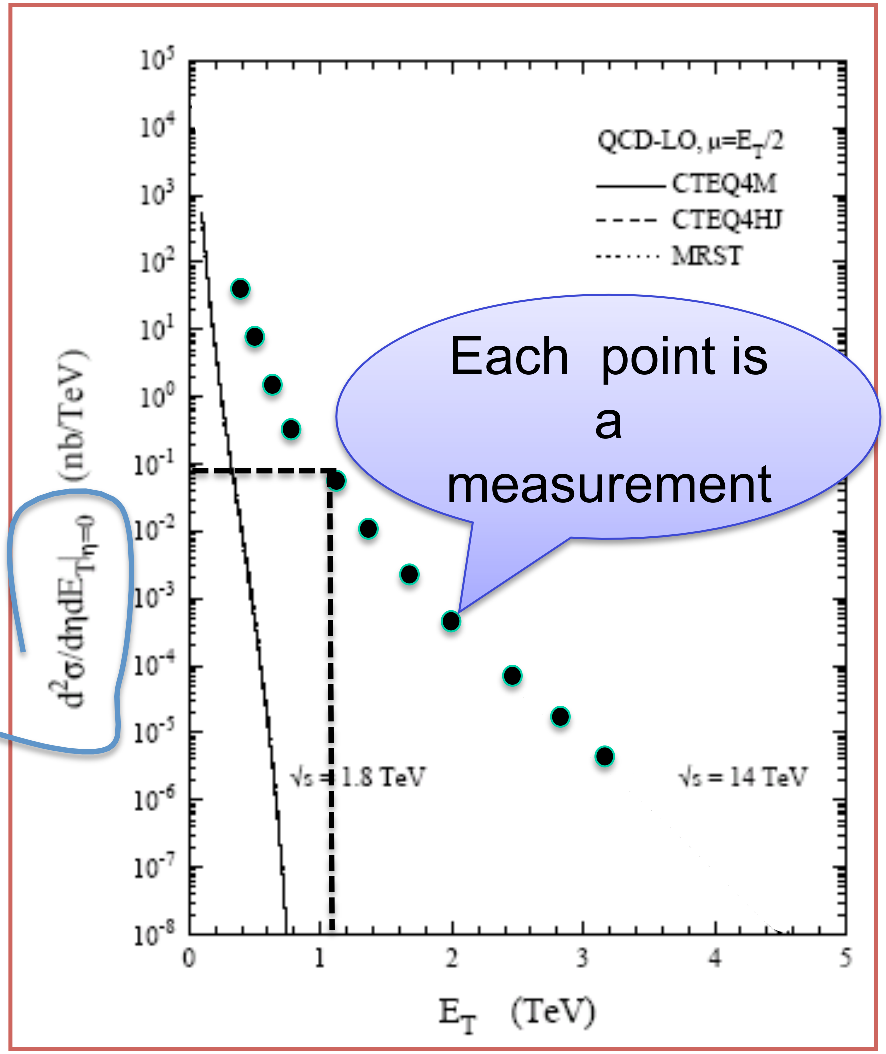
A sizeable contribution in understanding our measurements also comes from the quality of modeling of soft hadronic physics… no results in this talk but the measurements are used for the tuning of MC used.

PDF: CTEQ/CT, NNPDF, MSTW, AMB, HERAPDF…
Differences: data used the fit, α_s value, treatment of errors, parameterization…

Measurements are unfolded at particle level to be compared with predictions

Inclusive Jet cross-section

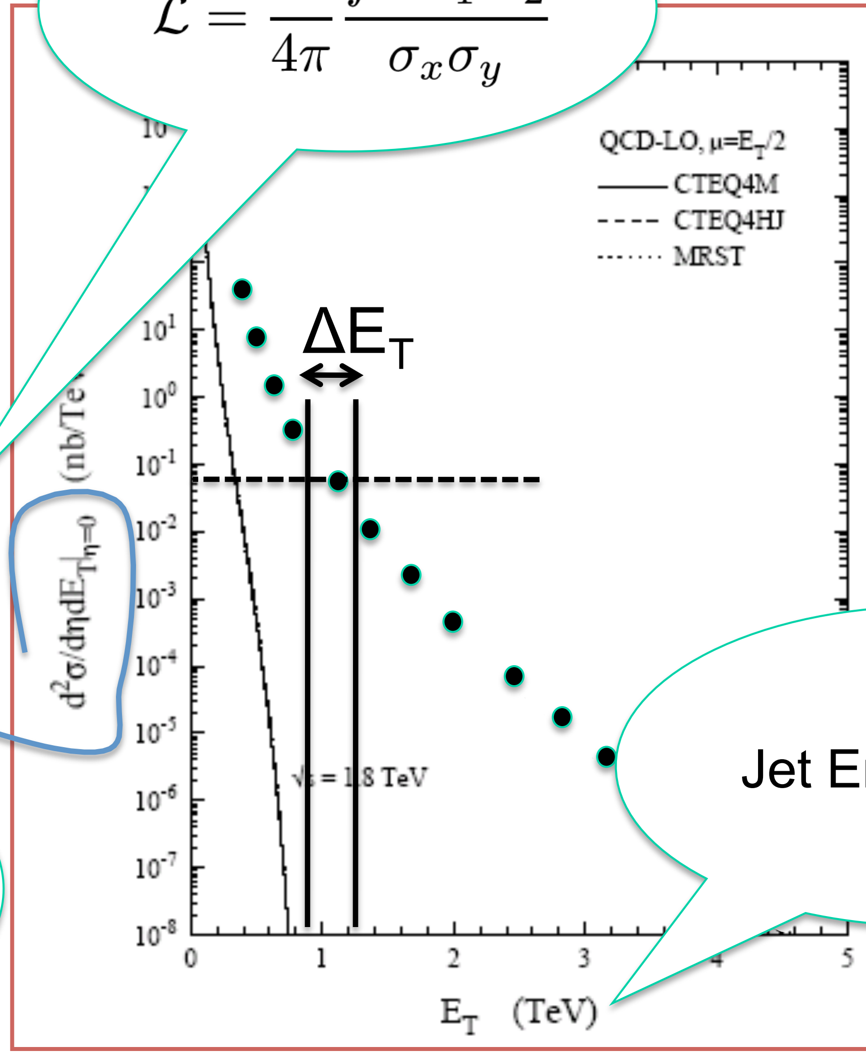
$$\left\langle \frac{\mathrm{d}^2\sigma}{\mathrm{d}E_T\mathrm{d}\eta} \right\rangle = \frac{N}{\Delta E_T \Delta\eta\, \epsilon\, \mathcal{L}}$$



N = Number of jets in the $\Delta E_T\Delta\eta$ range

$$\mathcal{L} = \frac{1}{4\pi}\frac{f k N_1 N_2}{\sigma_x \sigma_y}$$

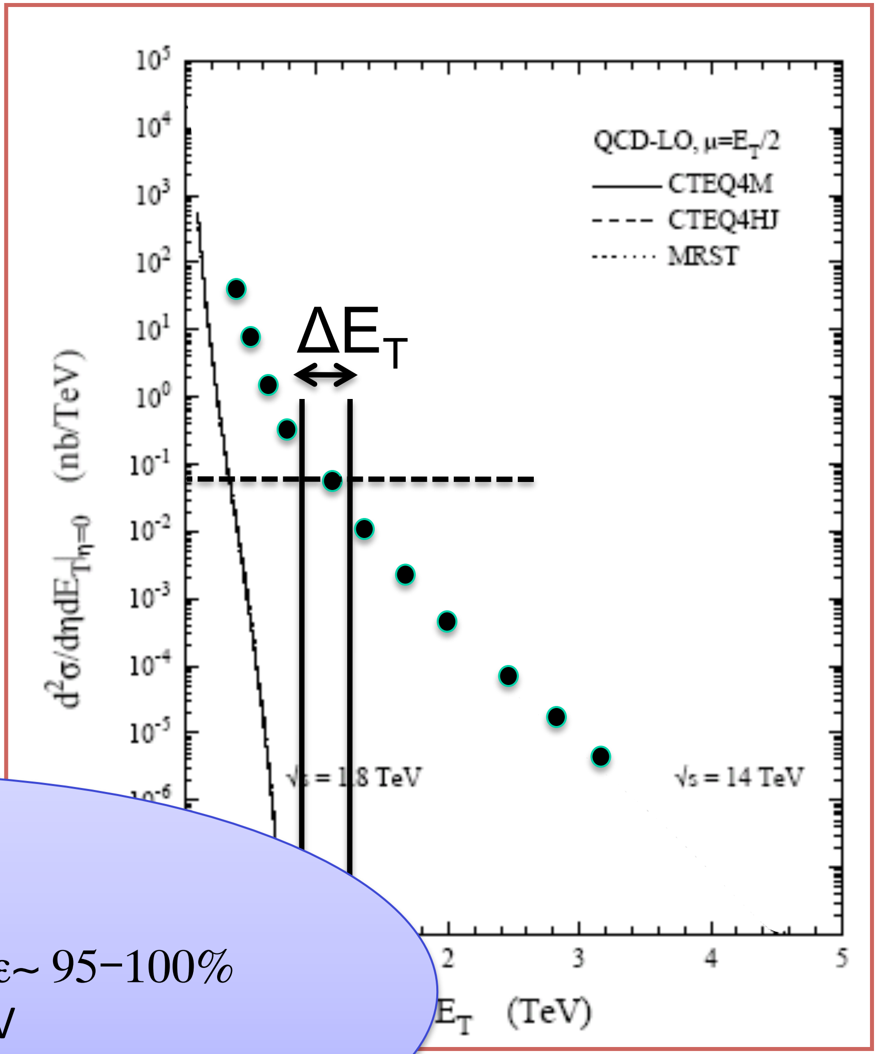
$$\left\langle \frac{\mathrm{d}^2\sigma}{\mathrm{d}E_T\mathrm{d}\eta} \right\rangle = \frac{N}{\Delta E_T \Delta\eta\, \epsilon\, \mathcal{L}}$$



ΔE_T ($\Delta\eta$, Δy)

Jet Energy (TeV

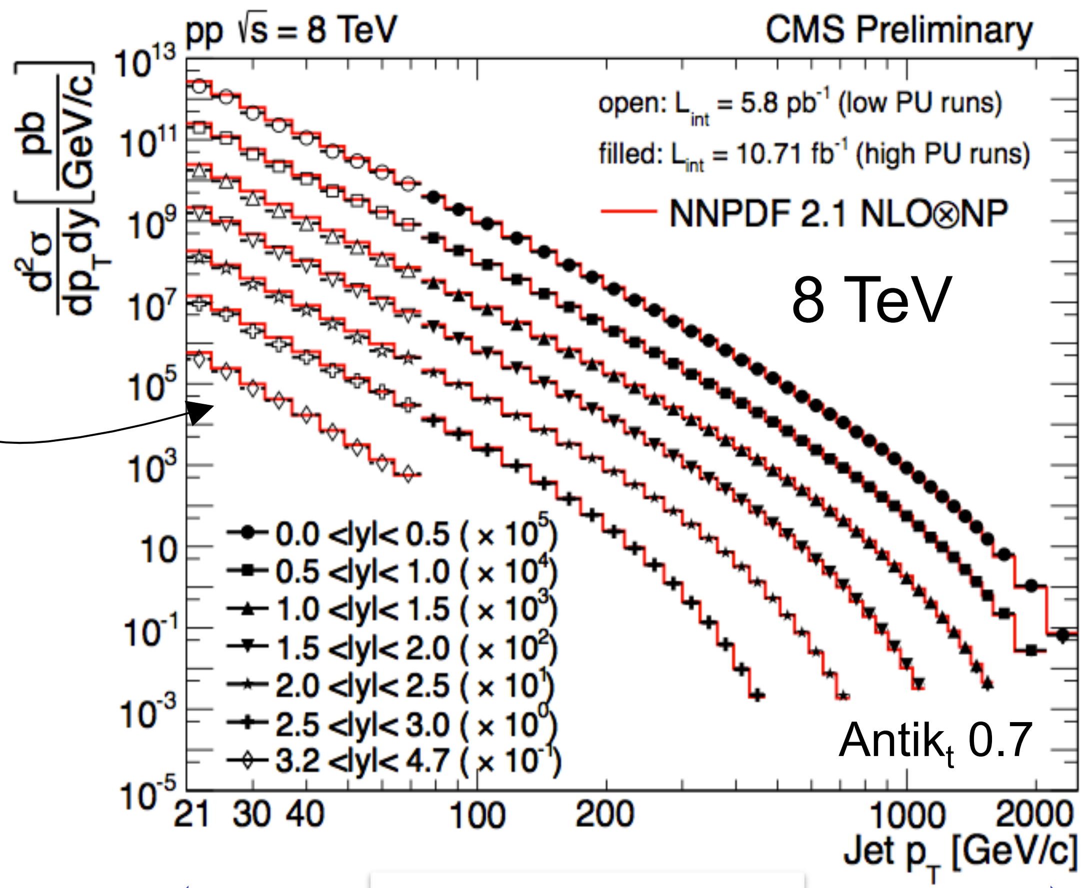
$$\left\langle \frac{\mathrm{d}^2\sigma}{\mathrm{d}E_T\mathrm{d}\eta} \right\rangle = \frac{N}{\Delta E_T \Delta\eta\, \epsilon\, \mathcal{L}}$$



Jet detection efficiency. ε~ 95−100%
at pT> 20GeV

STDM-2013-11 CMS-PAS-FSQ-12-031 CMS-PAS-SMP-12-012

Inclusive cross-section @ 8 TeV



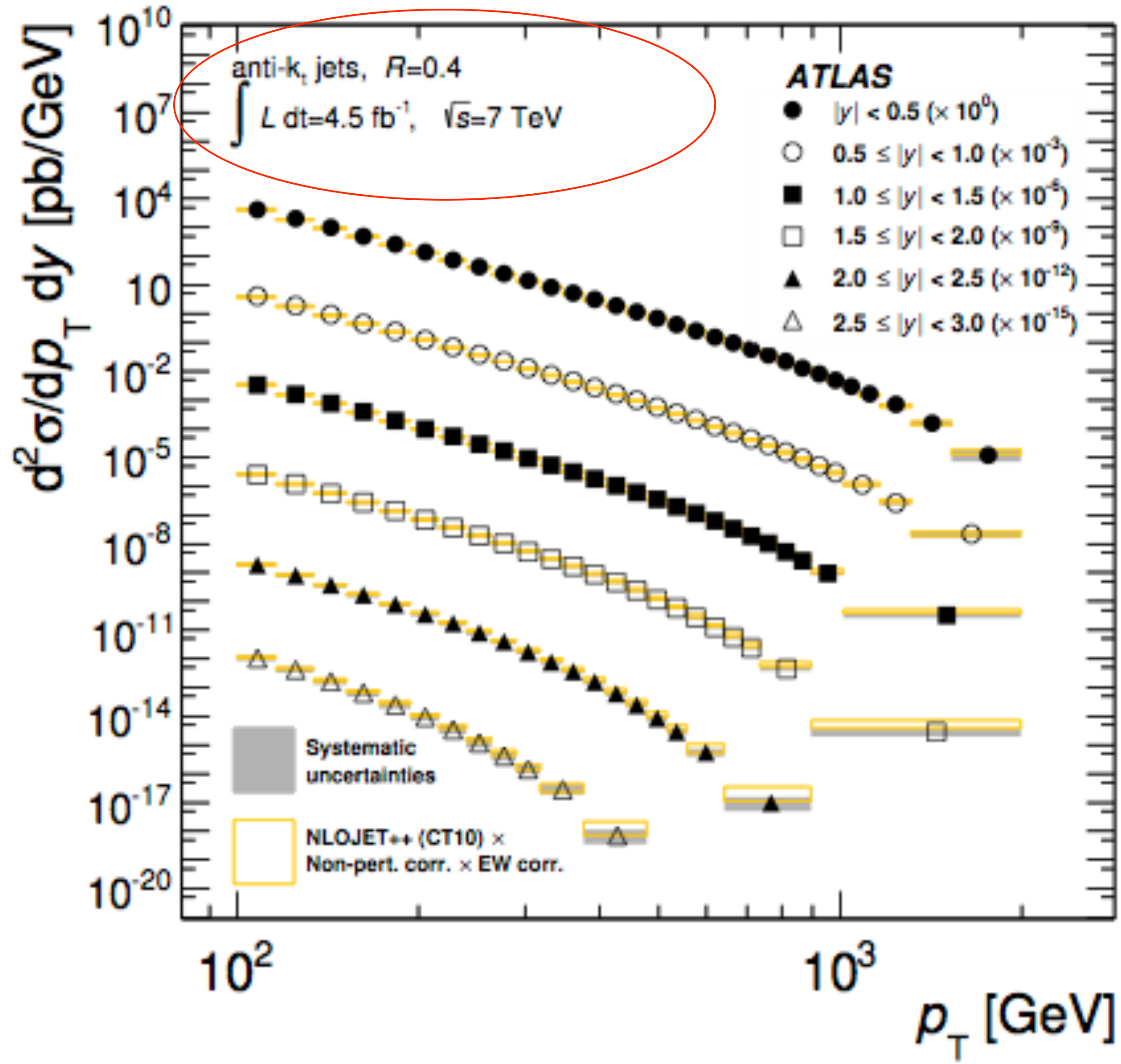
Low pile-up data to extend to the low p_T range down to 20 GeV and $|y|<4.7$

11 orders of magnitude

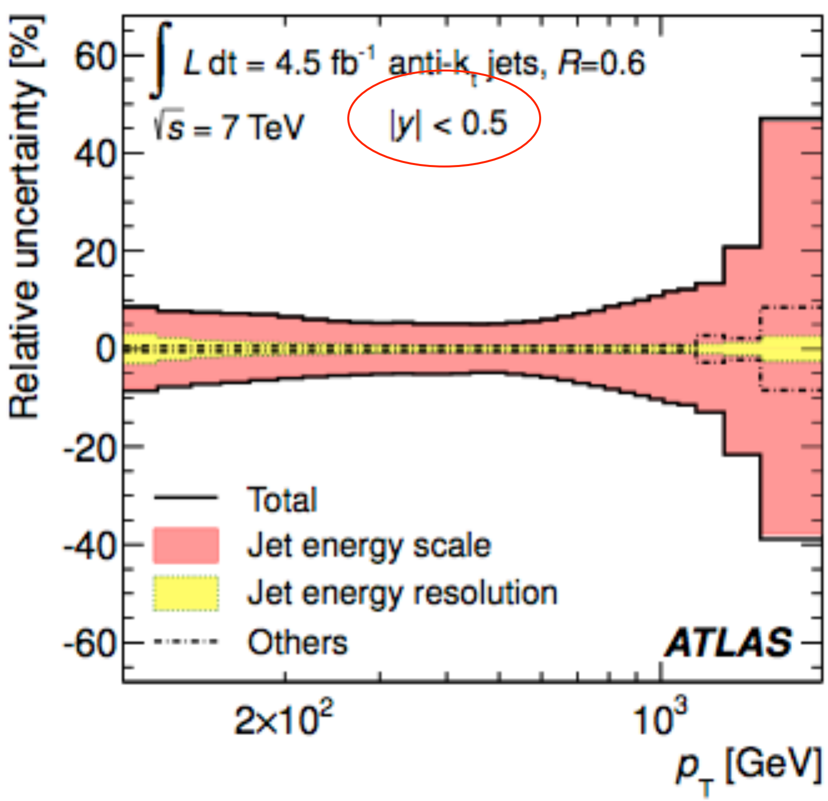
20 Gev – 2 TeV

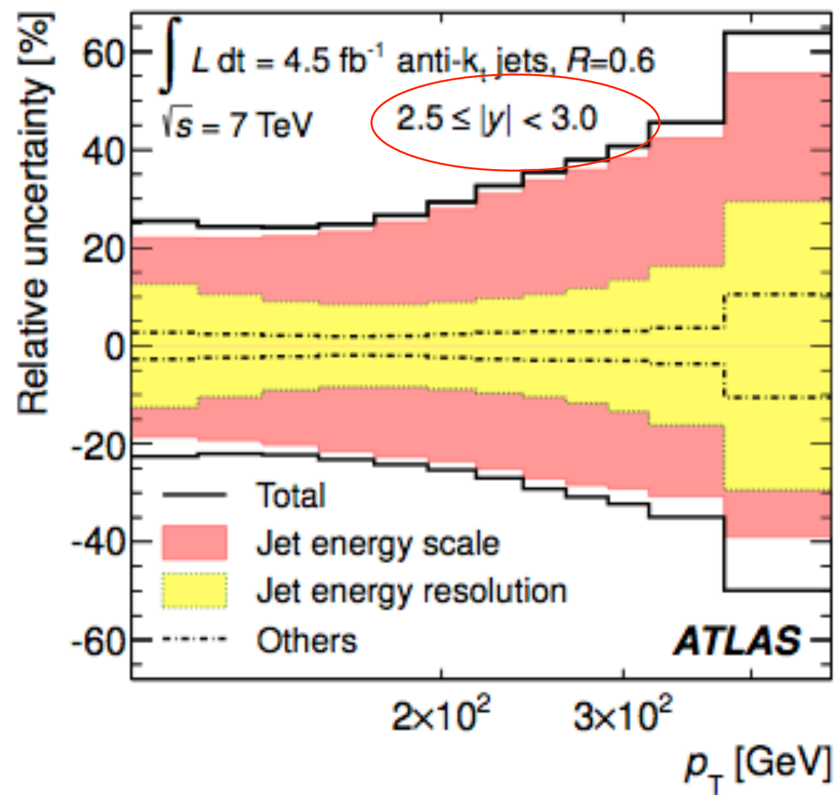
LHC data allows pQCD tests in a new kinematic regime – extended in p_T and y
Covers 11 orders of magnitude / two jet sizes

and INFN

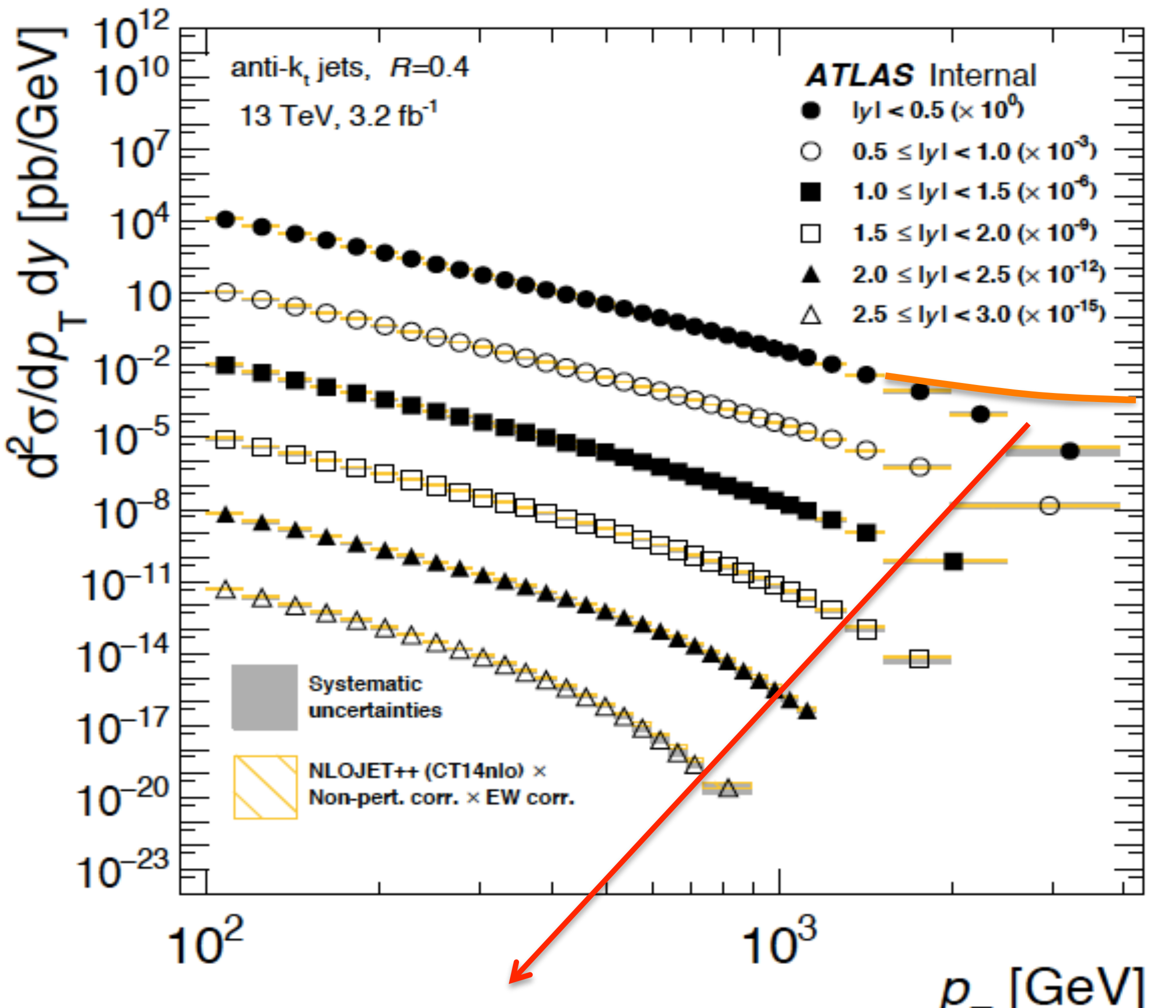

anti-k$_t$ jets, R=0.4
$\int L\,dt$=4.5 fb^{-1}, $\sqrt{s}$=7 TeV
ATLAS
$|y|$ < 0.5 (× 10^0)
0.5 ≤ $|y|$ < 1.0 (× 10^{-3})
1.0 ≤ $|y|$ < 1.5 (× 10^{-6})
1.5 ≤ $|y|$ < 2.0 (× 10^{-9})
2.0 ≤ $|y|$ < 2.5 (× 10^{-12})
2.5 ≤ $|y|$ < 3.0 (× 10^{-15})
Systematic uncertainties
NLOJET++ (CT10) ×
Non-pert. corr. × EW corr.
$d^2\sigma/dp_T\,dy$ [pb/GeV]
p_T [GeV]

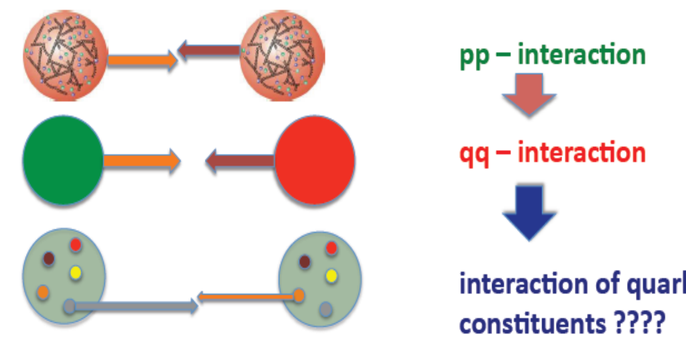
Measurements uncertainties





Inclusive jet measurement at 13 TeV (preliminary)





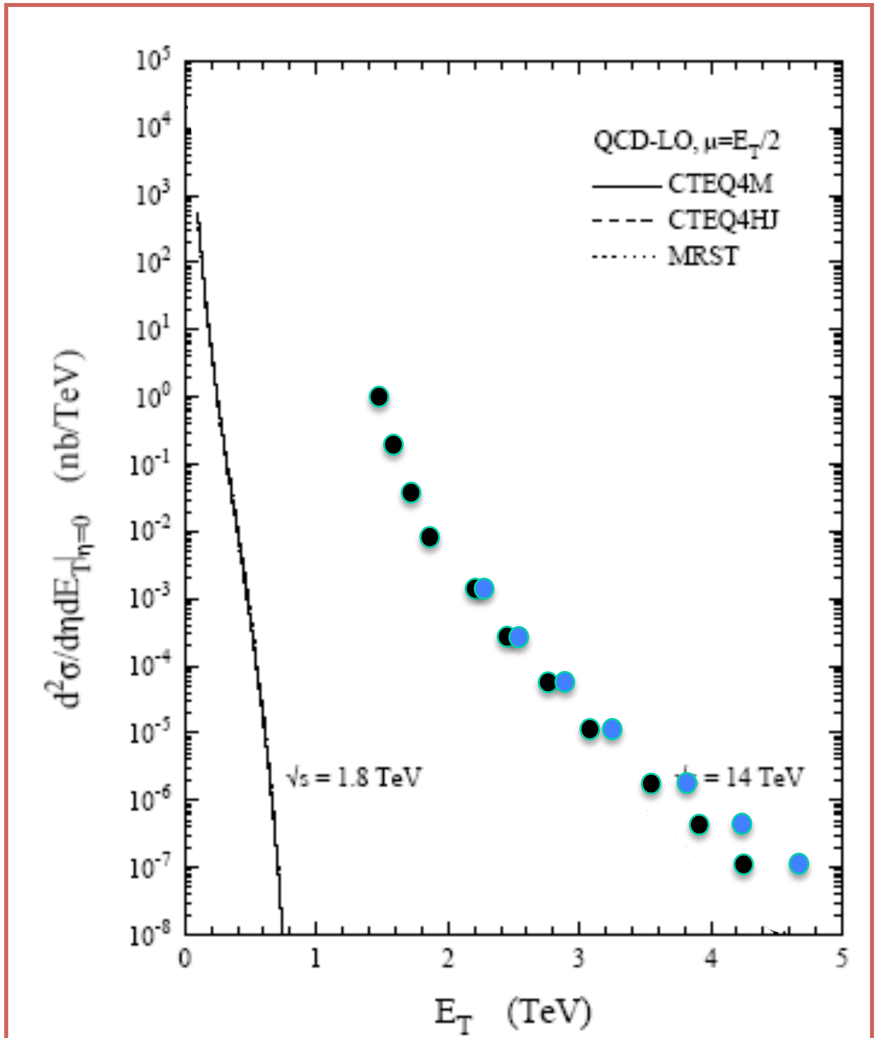
$$\mathcal{L}_{qqqq}(\Lambda) = \frac{\xi g^2}{2\Lambda_q^2}\bar{\Psi}_q^L\gamma^\mu\Psi_q^L\bar{\Psi}_q^L\gamma_\mu\Psi_q^L$$

Quark compositness parametrised as a current-current contact interaction (a la Fermi) with a cutoff "Λ": present limits: $\Lambda >\sim 10 TeV$

$\rightarrow$ substructure dimension d $<\sim 10^{-18} cm$

The existence of substructures of quarks (preons??) would show up as a discrepancy between the data and the QCD predictions ("Rutherford effect")

Jet energy scale uncertainty effect



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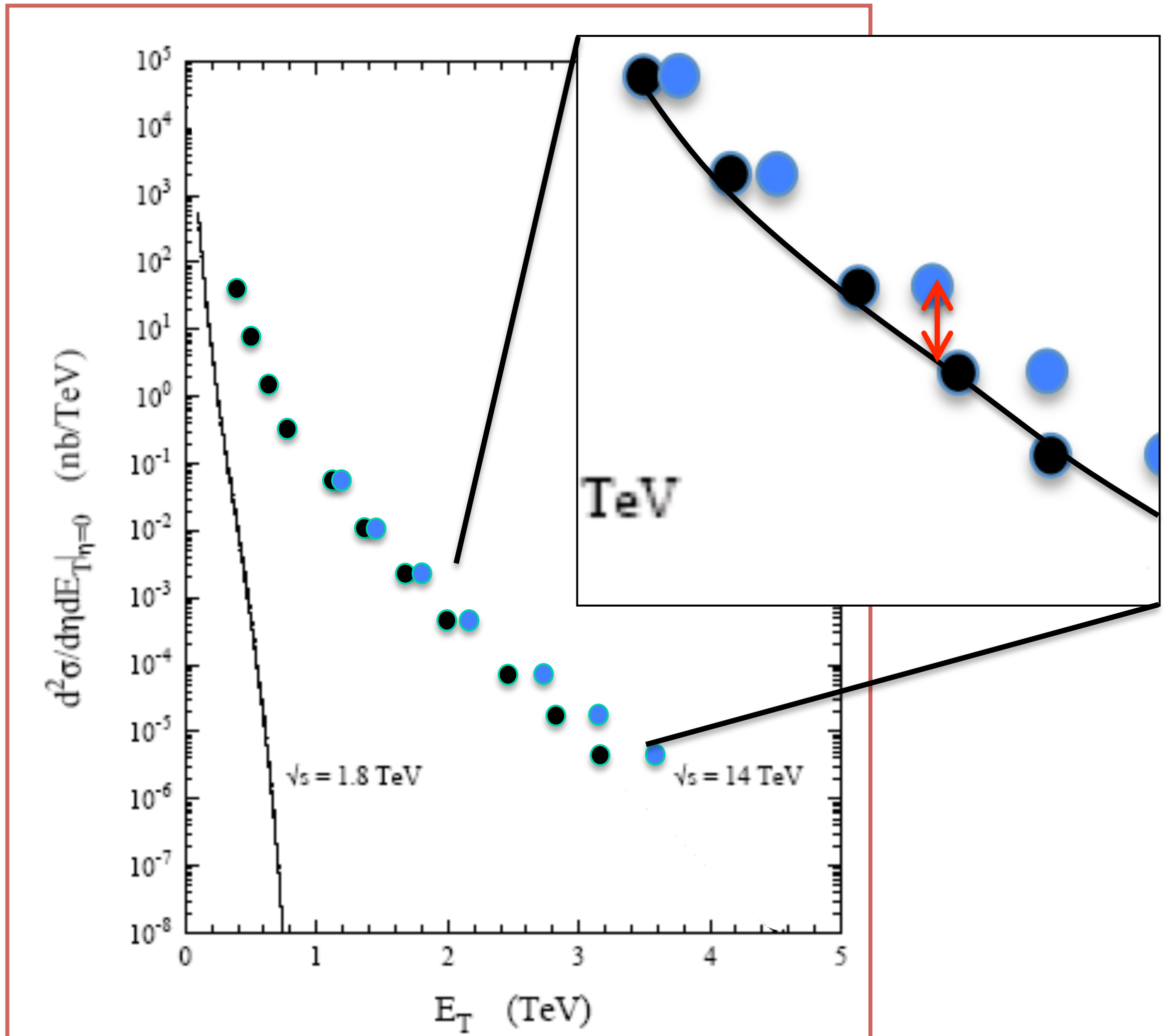
Jet energy scale uncertainty effect

Uncertainty 5% on E_T → 30% 30% error on cross section



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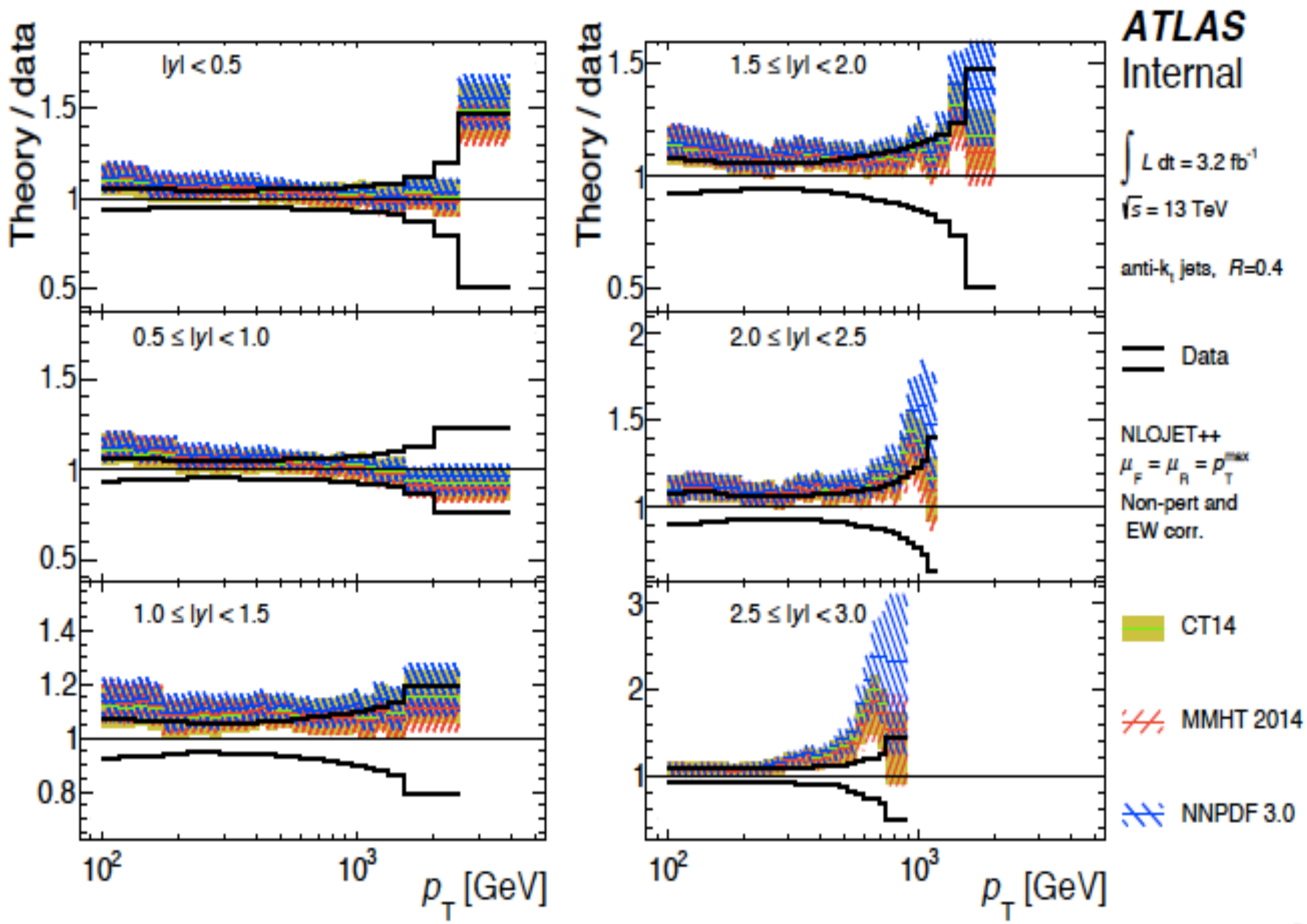
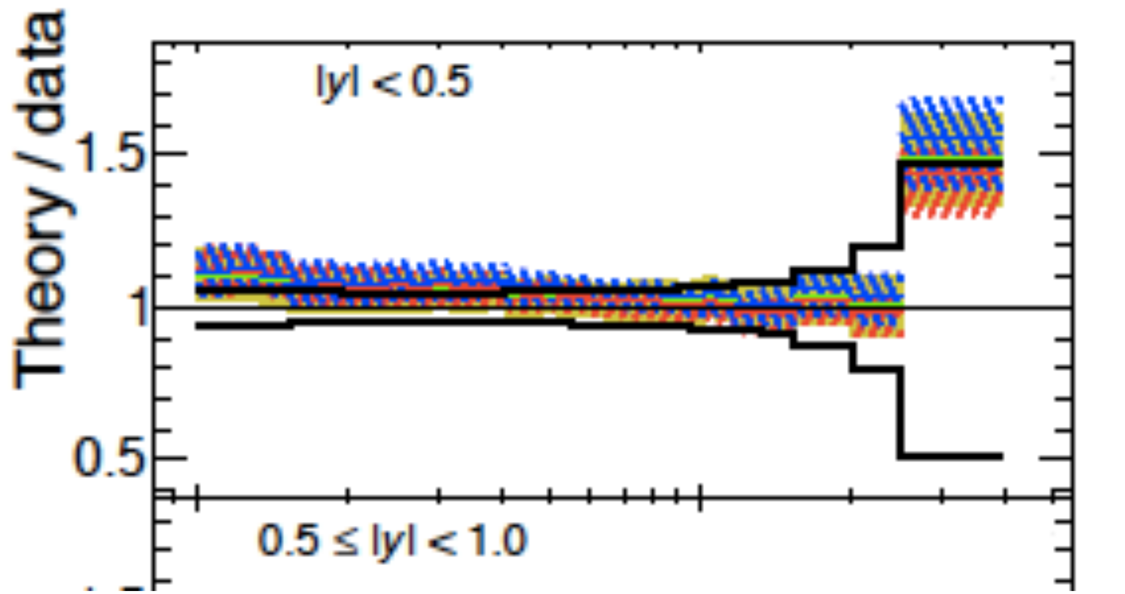
Ratio predictions/data



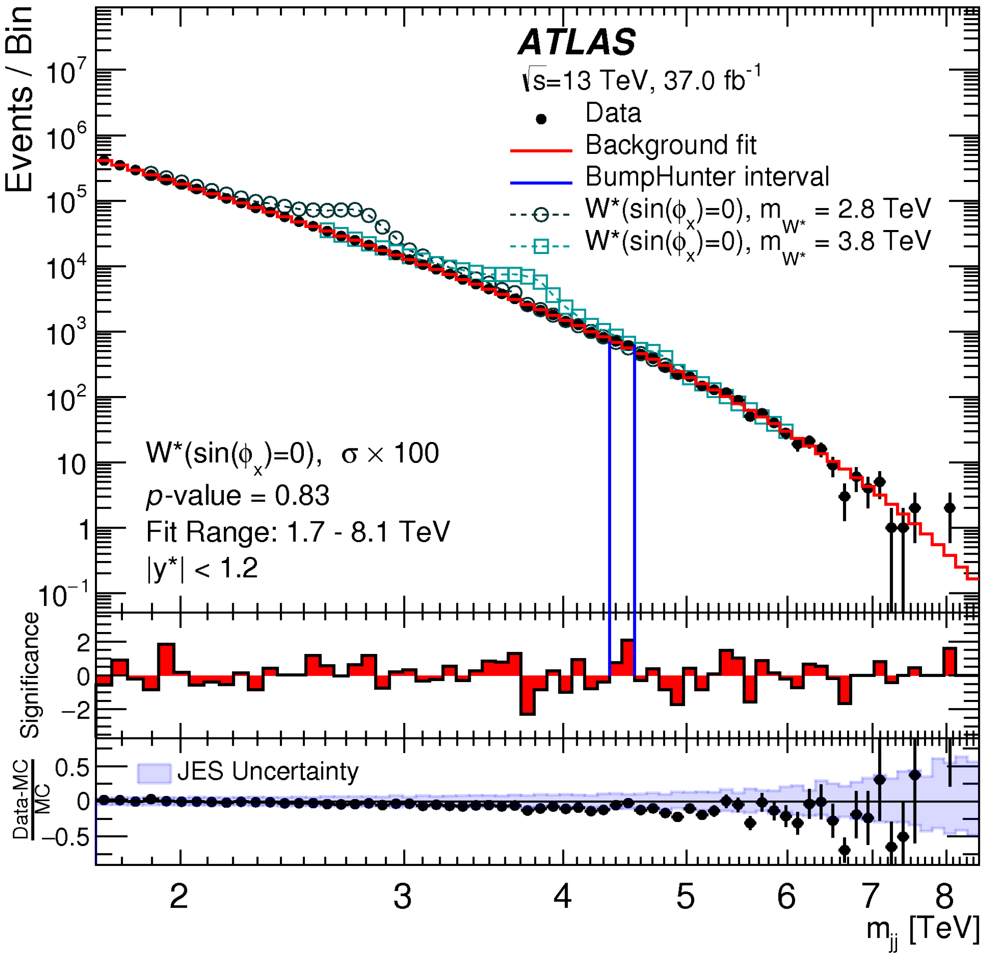
Ratio predictions/data



- interval between the black lines→ total uncertainty of data(statistical + systematic)
- colored band width→theoretical uncertainties from various PDF parametrizations.
- Agreement between theory and experiment within ~ 10-20% at p_T<1 TeV

Jets for new physics..

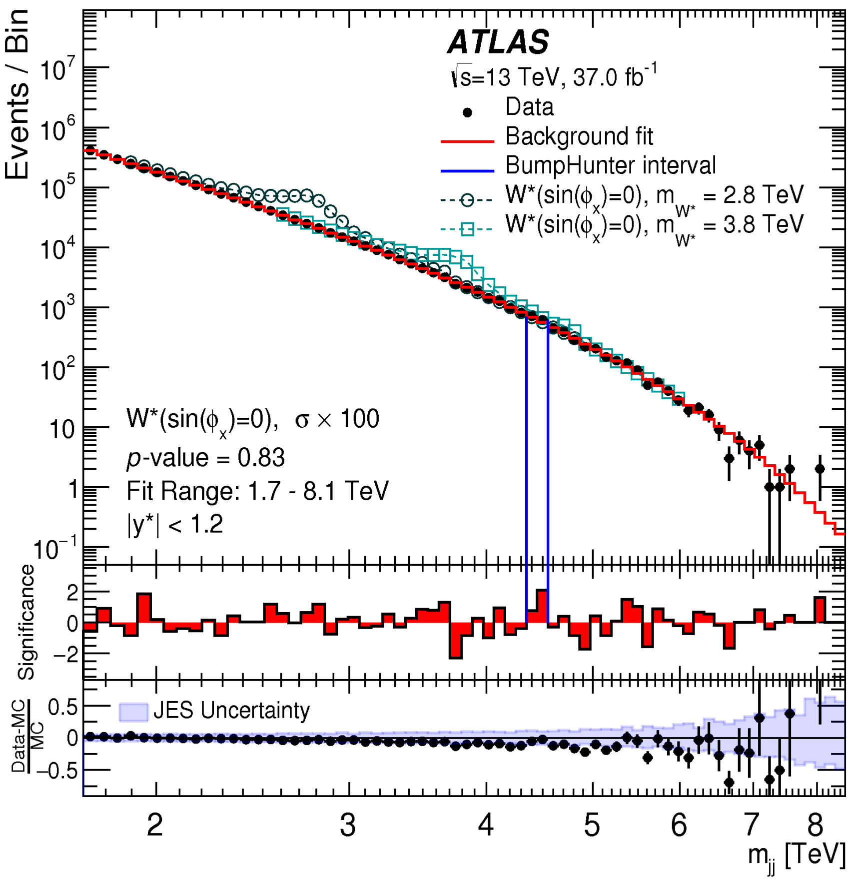
qq,gg,qg (jet-jet) resonance search

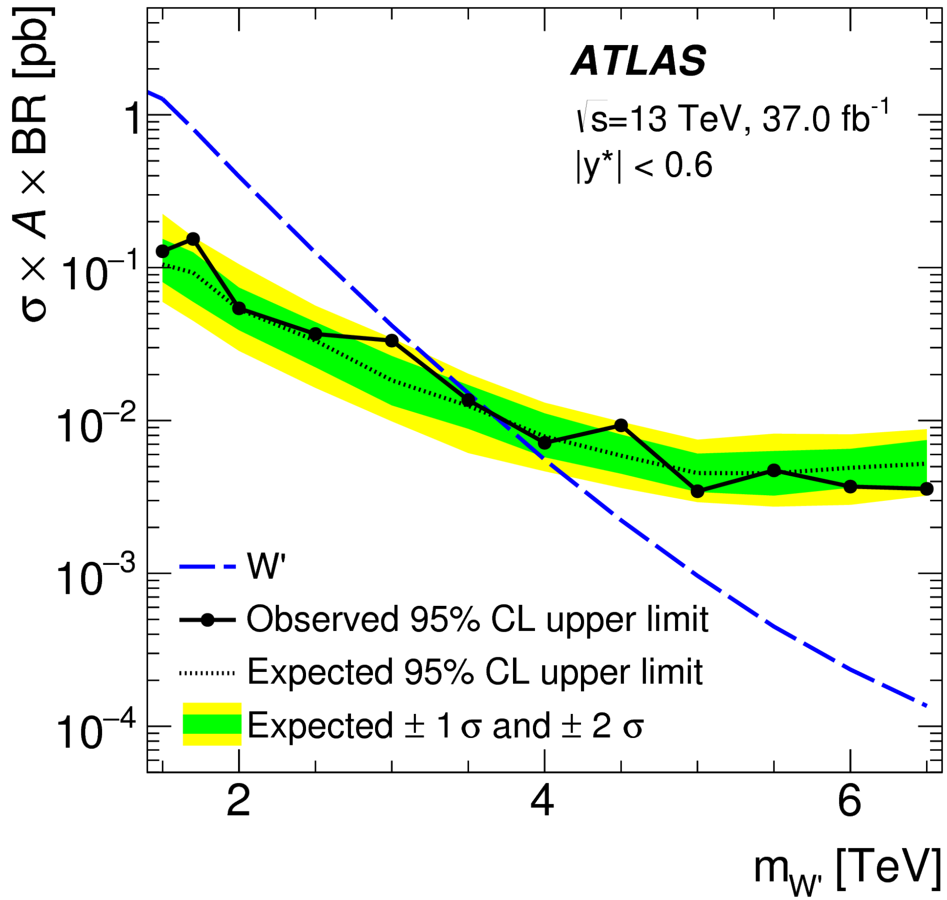


Ex: W’→ q$\bar{q}$’ → jet jet

Limit on CrossSectionxBRxA compared to model predictions

Resonance search in qq,gg,qg





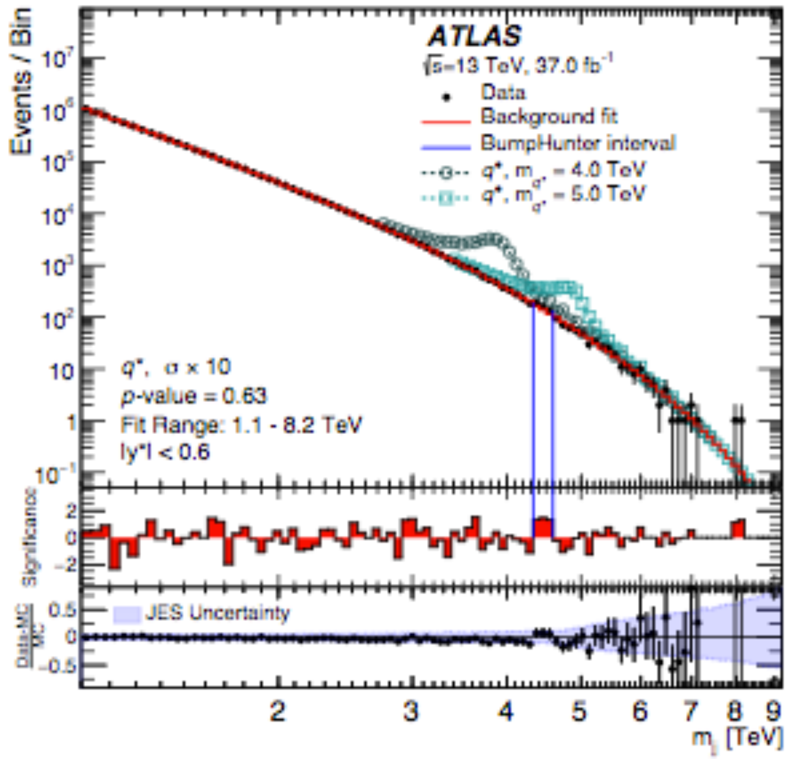
Generic Limits on a new signal CrossSectionxBRxA compared with model expectations

Summary

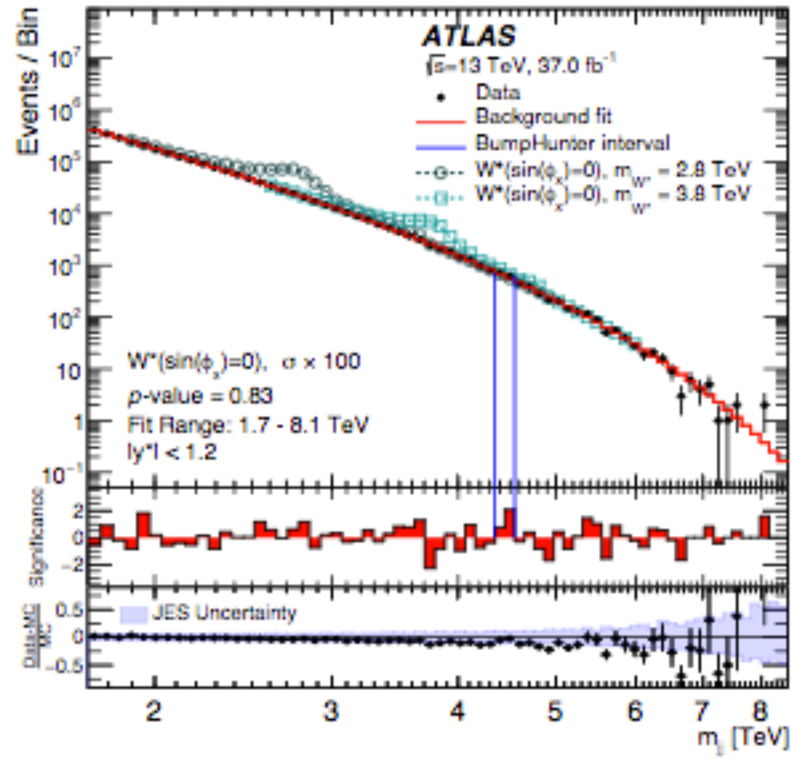
- Jets are the experimental manifestations of parton (quark, gluon) production;
- Jets are complex objects and need a definition of an algorithm and a recombination scheme;
- In order to compare predictions to experimental measurements a complex procedure of calibration needs to be applied;
- Often the systematic uncertainty on the energy scale of jets is the largest source of experimental uncertainty on a measurement;
- Skipped lots of important items: calorimeter, energy calibration, how to calculate systematics, jet substructure techniques

  (more in Gerald Eigen lecture)

Jets are complicated objects but they are fundamental components of the standard model and represent also an important tool to search for new physics!



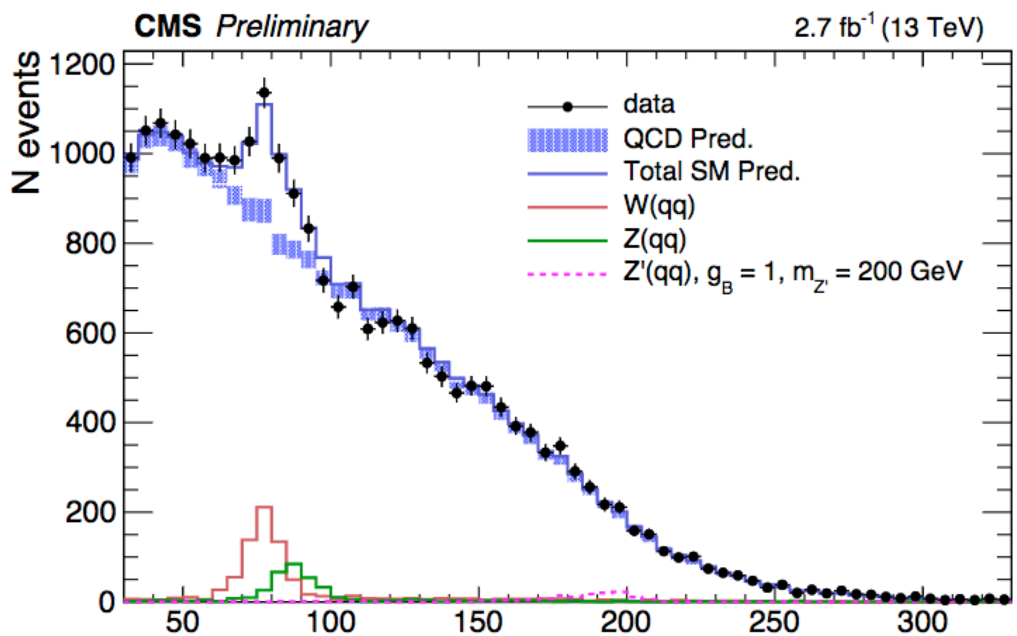
(a) $|y^{*}| < 0.6$ selection



(b) $|y^{*}| < 1.2$ selection

Figure 1: The reconstructed dijet mass distribution m_{jj} (filled points) is shown for events with $p_{\mathrm{T}} > 440$ (60) GeV for the leading (subleading) jet. The spectrum with $|y^{*}| < 0.6$ is shown in (a) for events above $m_{jj} = 1.1$ TeV while the selection with $|y^{*}| < 1.2$ is shown in (b) for events above $m_{jj} = 1.7$ TeV. The solid line depicts the background prediction from the sliding-window fit. Predictions for benchmark signals are normalized to a cross-section large enough to make the shapes distinguishable above the data. The vertical lines indicate the most discrepant interval identified by the BumpHunter algorithm, for which the p-value is stated in the figure. The middle panel shows the bin-by-bin significances of the data–fit differences, considering only statistical uncertainties. The lower panel shows the relative differences between the data and the prediction of Pythia 8 simulation of QCD processes, corrected for NLO and electroweak effects, and is shown purely for comparison. The shaded band denotes the experimental uncertainty in the jet energy scale calibration.

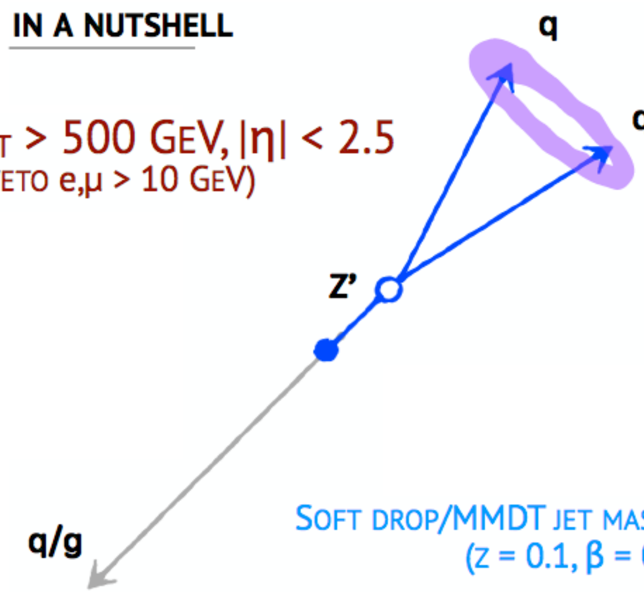
The potential of jet substructure — hadronic W & Z peaks



Nhan Tran @ Boost 2016

IN A NUTSHELL

$P_T > 500$ GeV, $|\eta| < 2.5$
(VETO e,μ > 10 GeV)

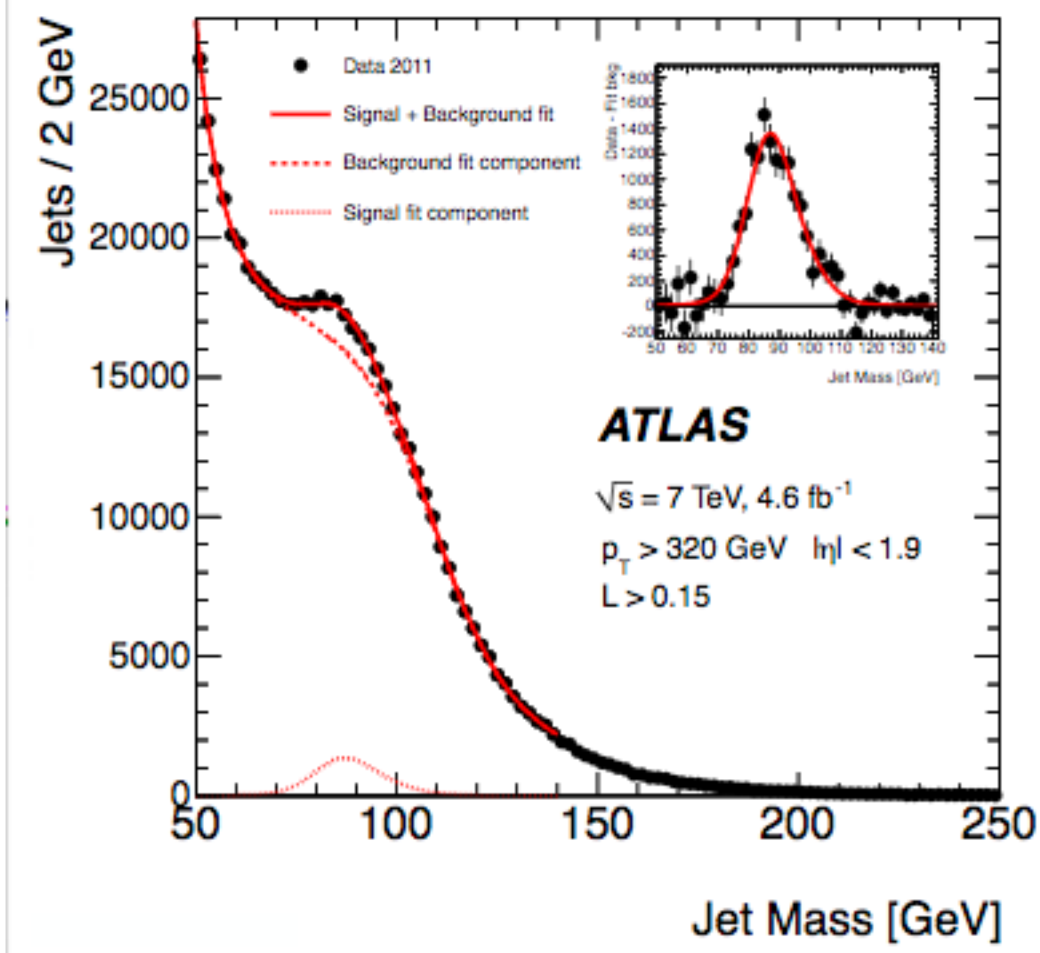


SOFT DROP/MMDT JET MASS
($z = 0.1, \beta = 0$)

$\tau_{21}^{DDT} < 0.38$

[PUPPI'ED INPUTS]

V. Cavasinni University of Pisa
and INFN



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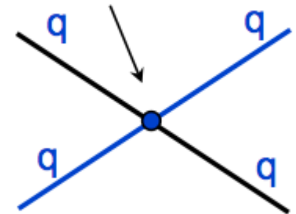
and INFN

Contact interactions & Dijet Angular Distributions

$d\sigma \sim$ [QCD + Interference + Compositeness]

$$\alpha_s^2(\mu^2)\frac{1}{\hat{t}^2} \qquad \alpha_s(\mu^2)\frac{1}{\hat{t}}\cdot\frac{\hat{u}^2}{\Lambda^2} \qquad \left(\frac{\hat{u}}{\Lambda^2}\right)^2$$



$\sqrt{\hat{s}} << \Lambda$

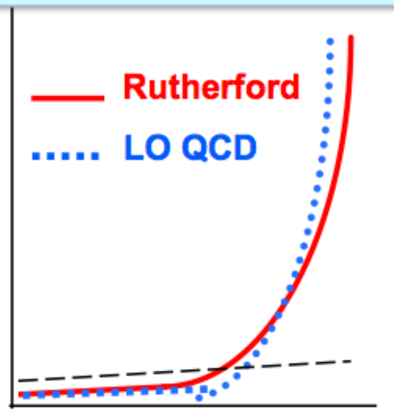
$d\sigma \sim 1/(1-\cos\theta^*)^2$

$d\sigma \sim (1+\cos\theta^*)^2$

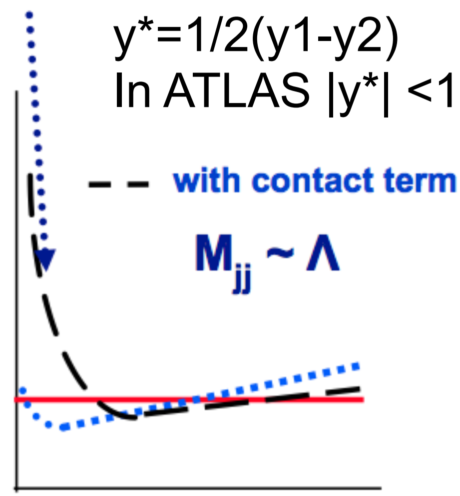
$$\chi = \frac{1+\cos\theta^*}{1-\cos\theta^*} = \exp\left(2\left|y^*\right|\right)$$

Instead of $\cos\theta^*$, use:
$dN/d\chi$ sensitive to contact interactions

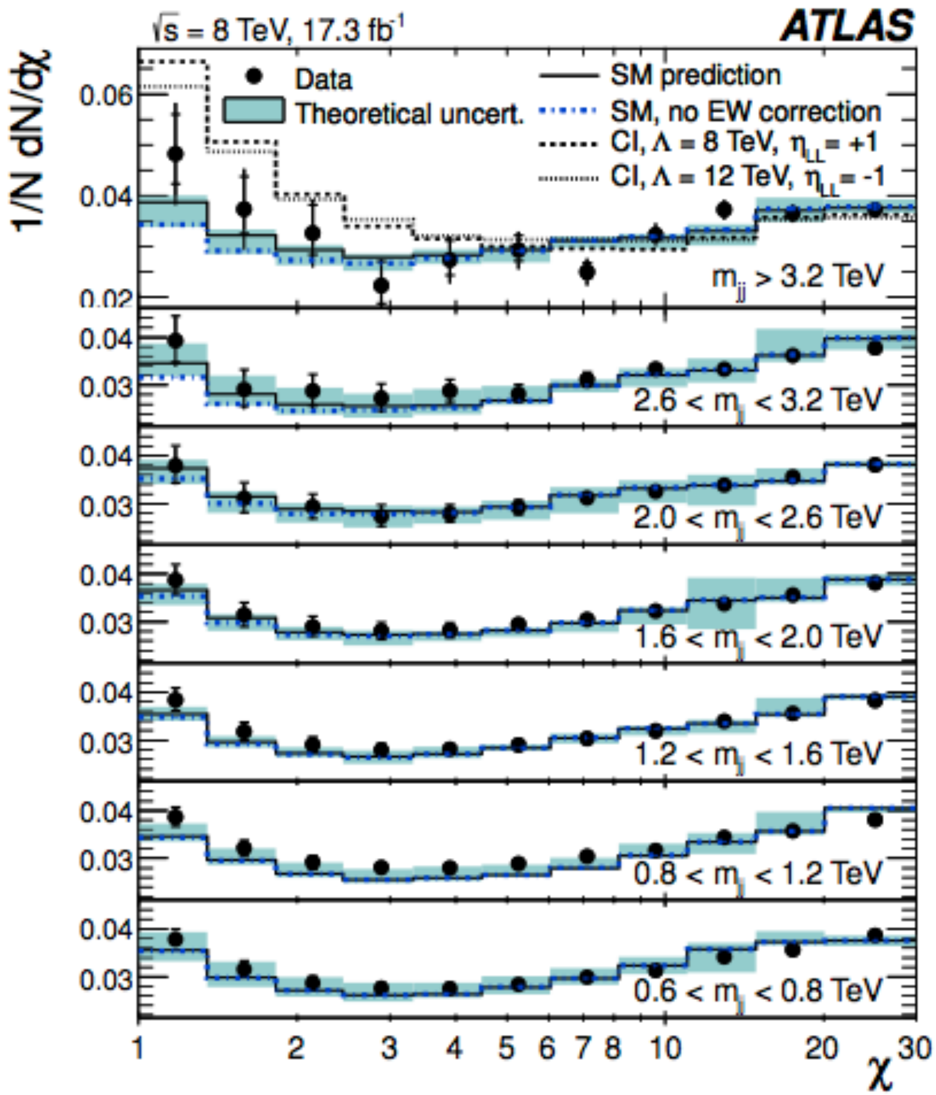
$y^*=1/2(y1-y2)$
In ATLAS $|y^*| < 1.7 \rightarrow \chi < 30$



$\Longrightarrow$



Compositness search with χ variable

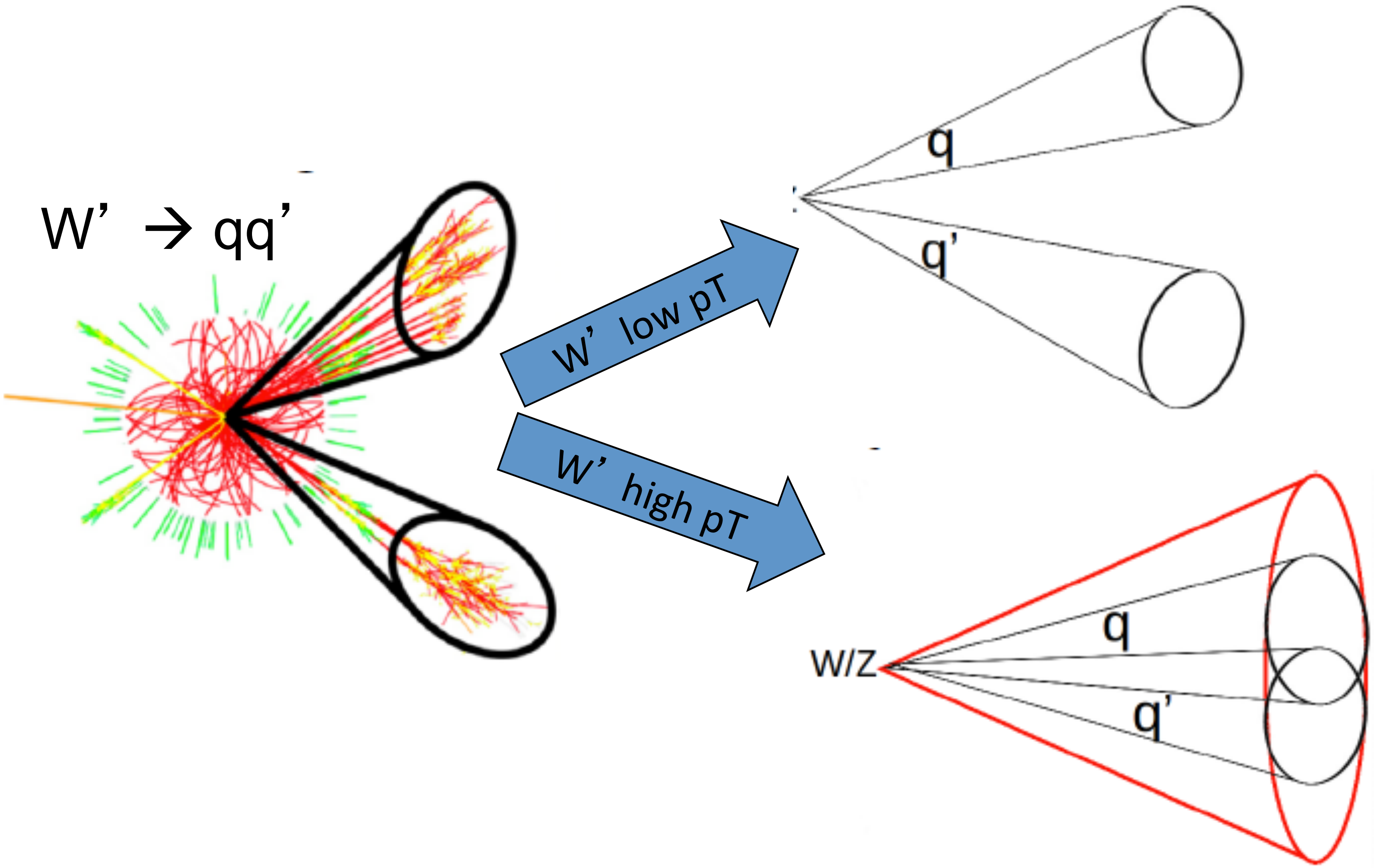


X is compositness sensitive especially at low values. X is less sensitive to the JES uncertainty.

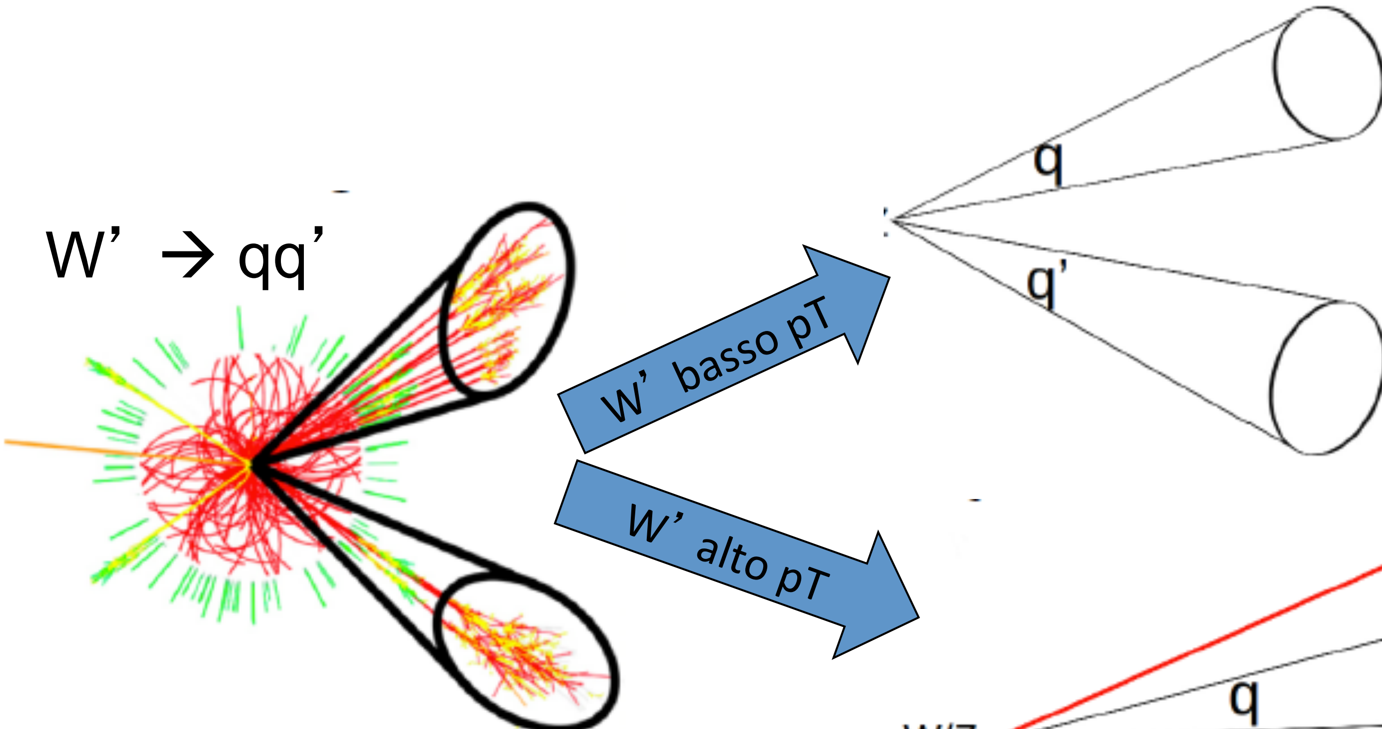
$$\chi = \frac{1+\cos\theta^*}{1-\cos\theta^*} = \exp\left(2\left|y^*\right|\right)$$

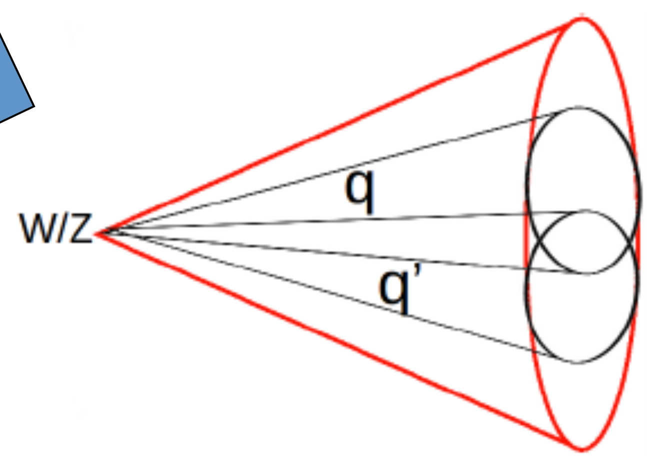
Present limit on the compositness scale:
Λ > 8.1TeV @ 95%C.L.

Resonance search at very high pT



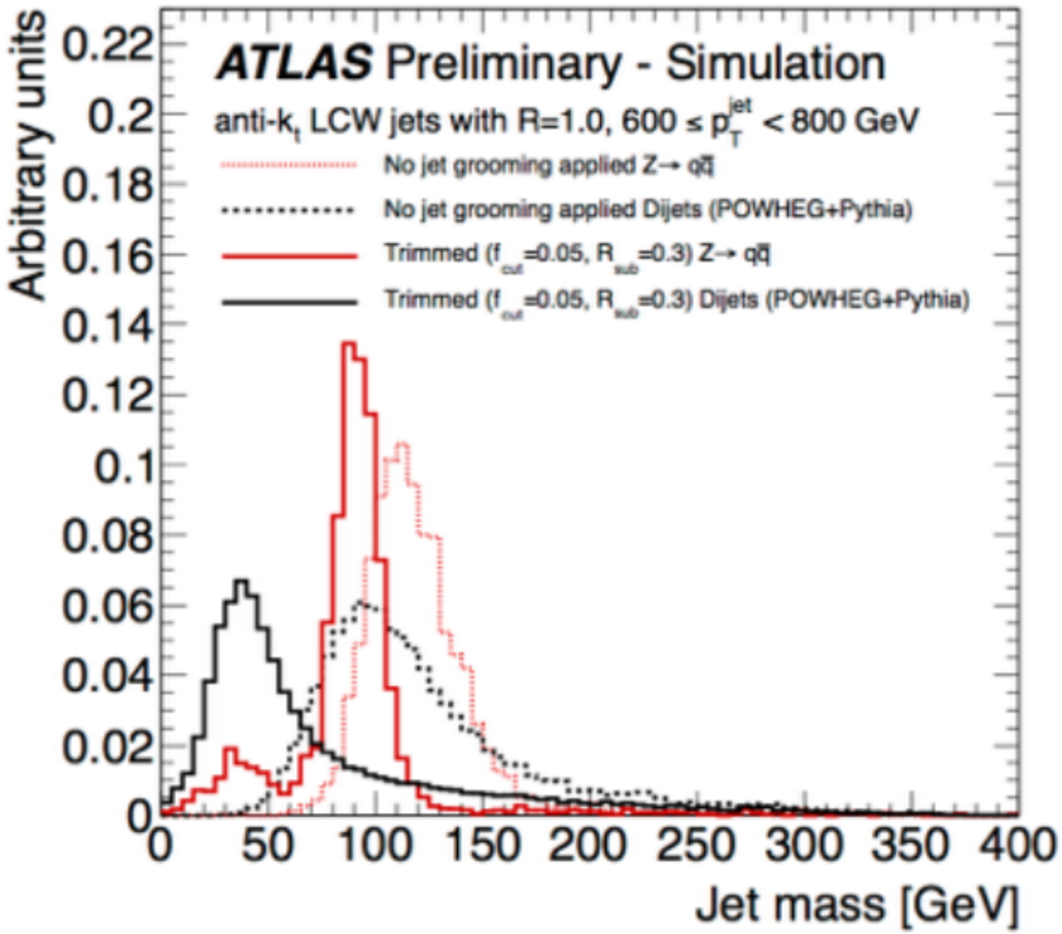
Resonance search at very high pT





In the last years new algorithms have been developed to extract substructures inside a large R

Invariant mass from jet sub-structure



One example:
Z → jj

Red: Z→ jj
Black: multi-jet bkg

Pre grooming

Post grooming

Jet sub-structure tecniques are in rapid evolution and allow to extend the energy reach for new physics studies.