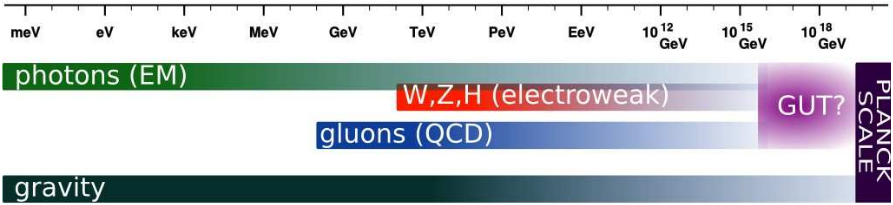
QCD and the LHC

Gavin Salam

CERN, Princeton & LPTHE/CNRS (Paris)

Rutgers University, February 15 2011

The scales at play



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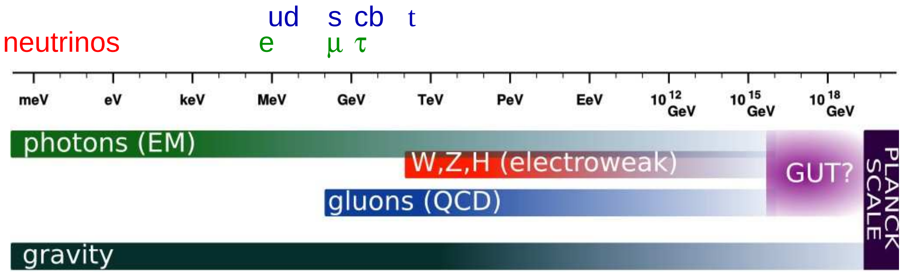

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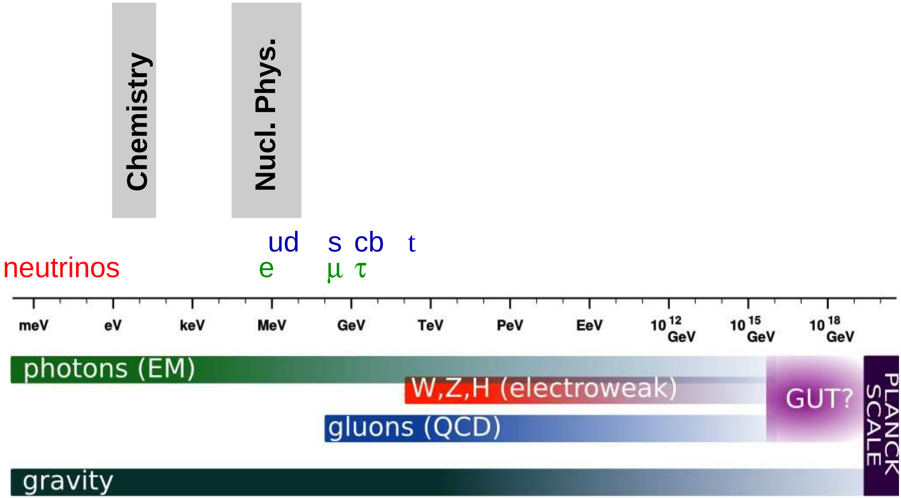

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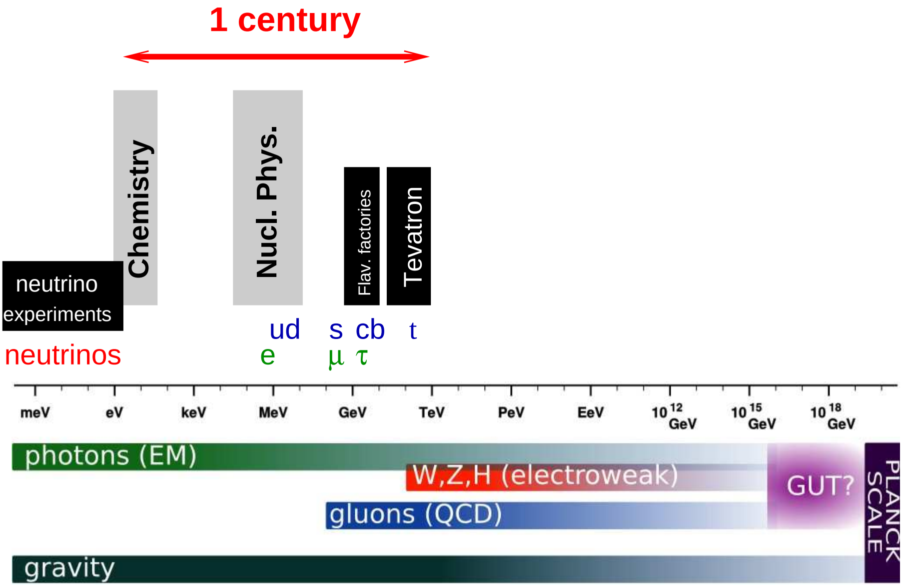

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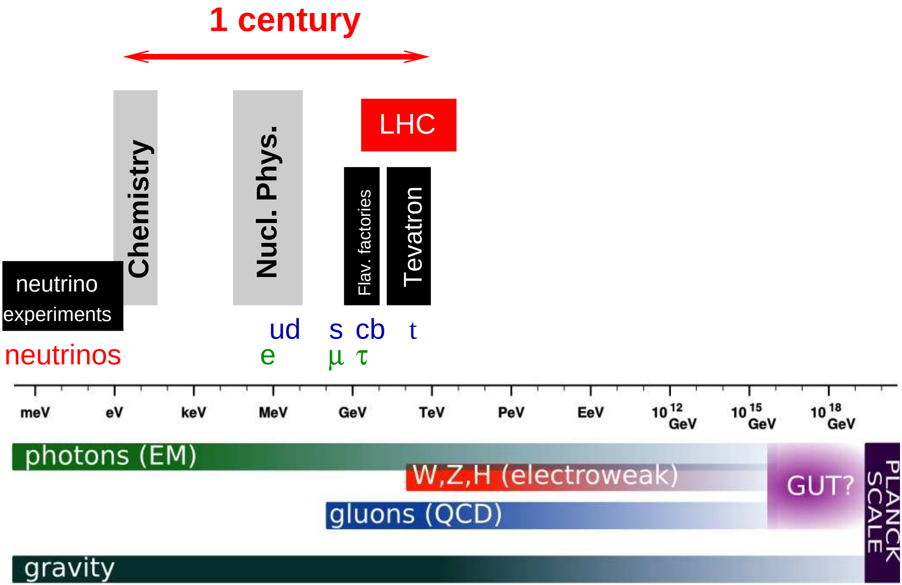

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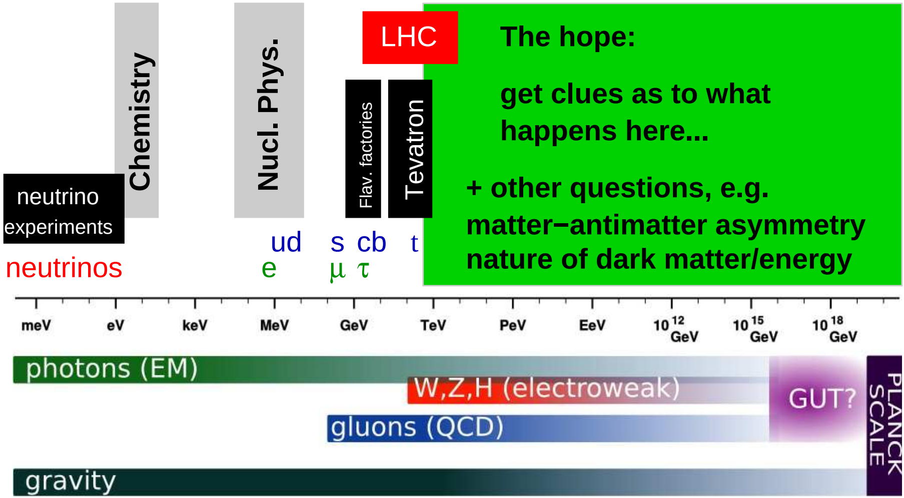

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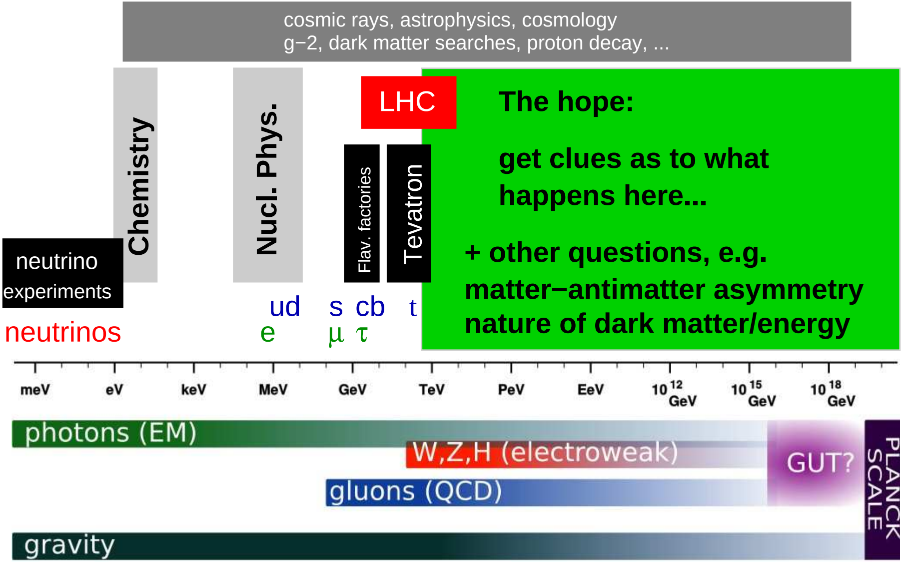

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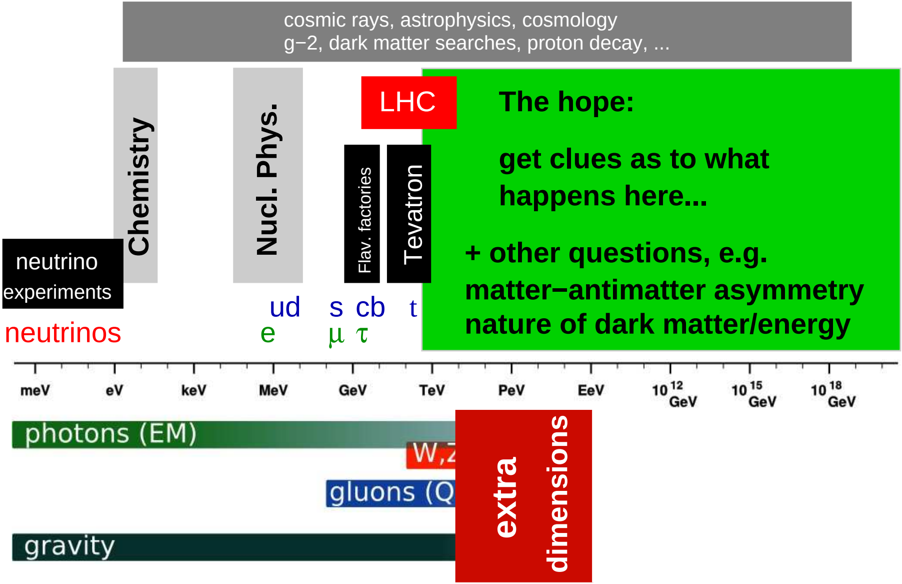
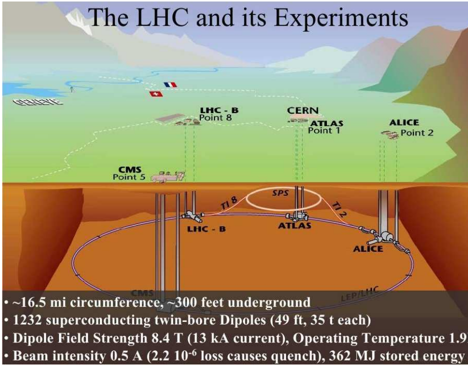


The Large Hadron Collider

The world's largest fundamental physics endeavour

Designed to be 7× more powerful than its predecessor, Tevatron

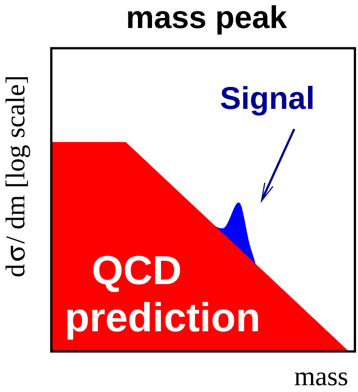
Involving $\mathcal{O}(10\,000)$ scientists
From about 60 countries
At a cost of several billion US$



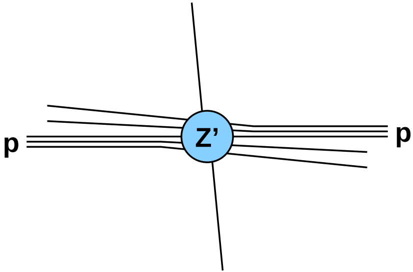
This talk is about one of the facets of discovery at the LHC:
The use of Quantum Chromodynamics, i.e. the theory that governs the behaviour of quarks and gluons

What does discovery look like?

What kinds of searches?

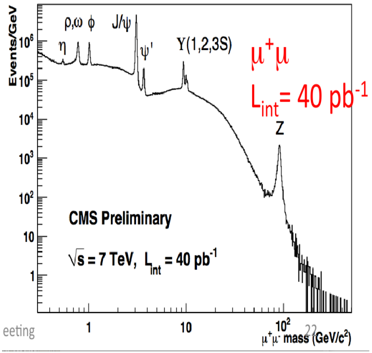


New resonance (e.g. Z') where you see all decay products and reconstruct an invariant mass



Sufficiently large, sharp signal emerges independently of any knowledge of backgrounds.

What kinds of searches?



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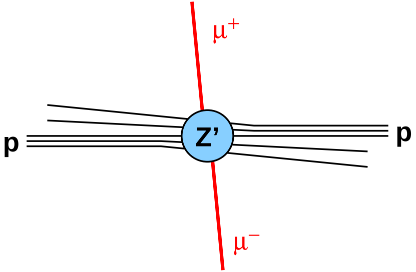

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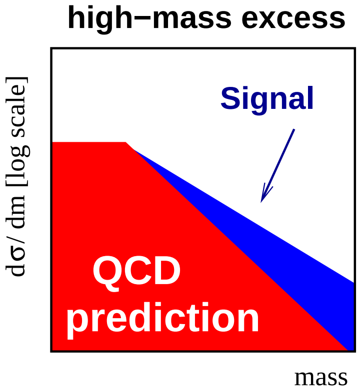
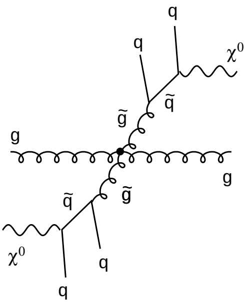


Unreconstructed SUSY cascade. Study *effective* mass (sum of all transverse momenta).



Broad excess at high mass scales.

Knowledge of backgrounds is crucial is declaring discovery.

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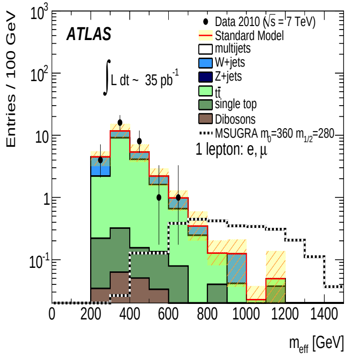

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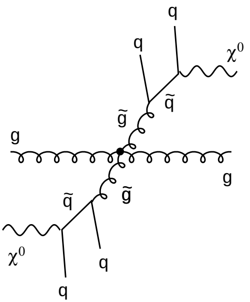

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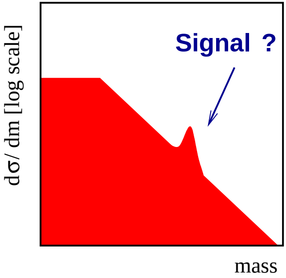

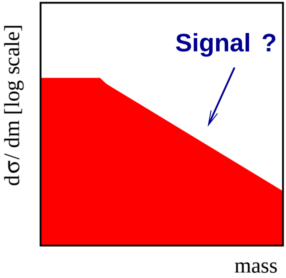

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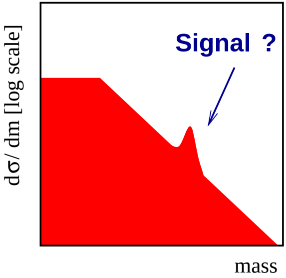

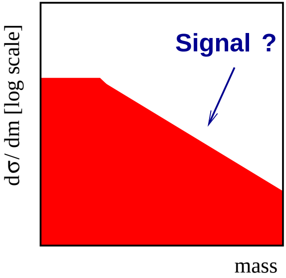

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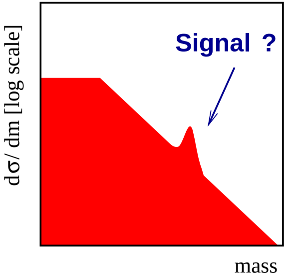

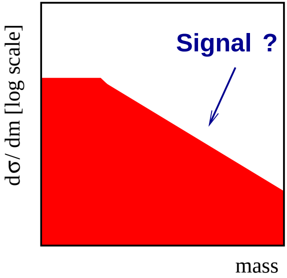

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How do you predict a background?

The LHC collides protons — made of quarks and gluons.

The theory that governs the behaviour of quarks and gluons is Quantum Chromodynamics (QCD)

QCD, an SU(3) Yang-Mills theory, gives the rules for the interaction of quark fields (ψ) with gluon fields ($\mathcal{A}$), and gluon fields with themselves. Most simply expressed in terms of the Lagrangian

$$\mathcal{L} = \bar{\psi}_a (i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m)\psi_b - \frac{1}{4} F^{\mu\nu}_A F^{A\,\mu\nu}$$

$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\nu - g_s\, f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu \qquad [t^A, t^B] = i f_{ABC}\, t^C$$

The QCD coupling

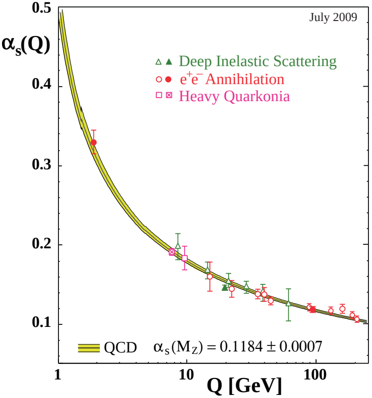
One key parameter: the strength of the interaction, i.e. the strong coupling 'constant' $\alpha_s = g_s^2/4\pi$

$$\alpha_s(Q) \simeq \frac{1}{b_0 \ln Q^2/\Lambda^2}$$

Nobel: Gross, Politzer & Wilczek

- strong interactions at proton (GeV) scale
- **weak interactions at LHC (TeV) scales:**

$$\alpha_s(1\text{ TeV}) \simeq 0.09$$



Bethke '09

QCD predictions

Given small coupling, the most widespread approach to making QCD predictions is **perturbation theory**.

E.g. using Feynman diagrams; basic rules for QCD known for ∼40 years
recursive techniques for trees (late 80's); unitarity for loops (90's and 00's)

A cross section σ is written as a series in powers of α_s:

$$\sigma = \underbrace{\sigma_2\, \alpha_s^2}_{\text{leading order (LO)}}$$

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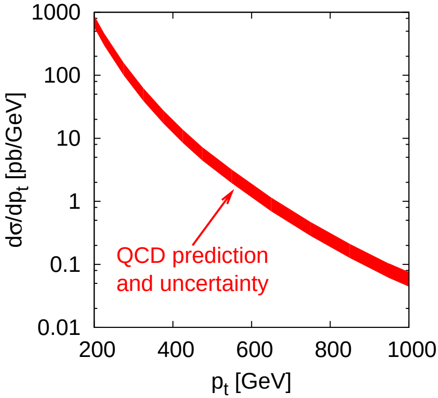
Controlling QCD for discovery

We can only **approximate** QCD (e.g. LO, NLO, etc.).

Discovery comes if you have an excess with respect to a QCD prediction **accounting for its uncertainties.**

Standard Model



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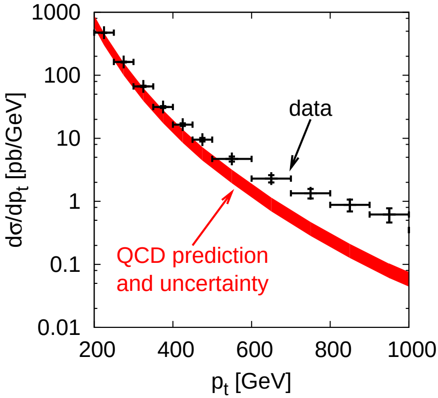

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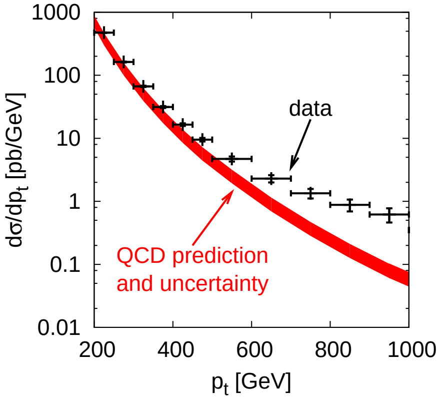
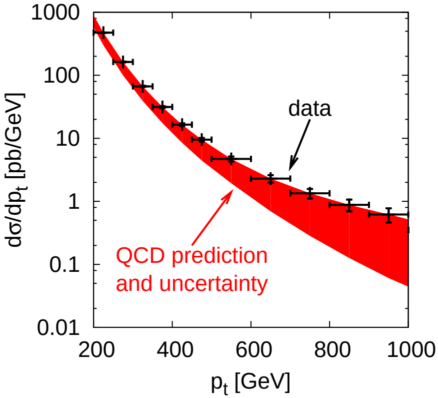


New Physics?



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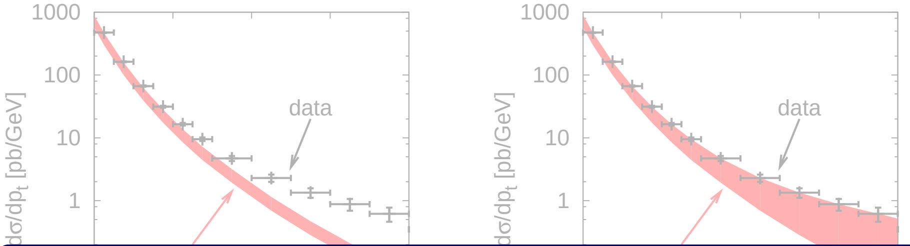
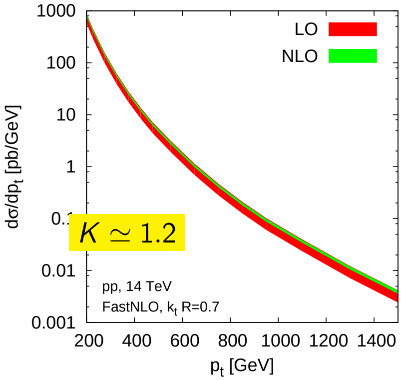


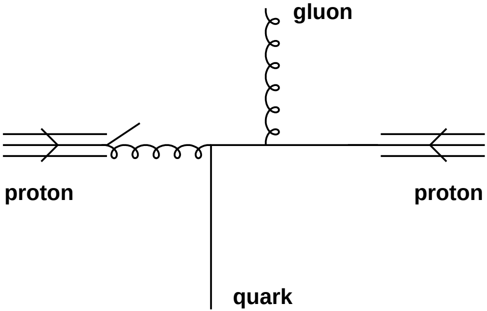
A non-issue?

Even for a basic leading-order approximation, with $\alpha_s \simeq 0.1$, expect $\sim$ 10% uncertainty from missing NLO(?)

How well does QCD perturbative series converge?

Consider LO, NLO and their ratio $K = \frac{\text{NLO}}{\text{LO}}$





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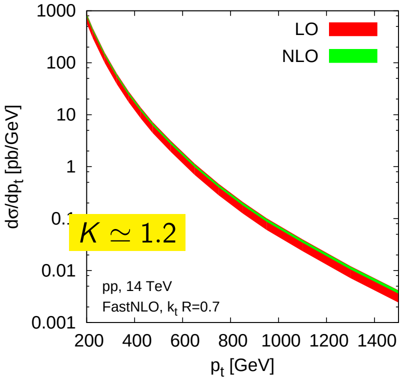
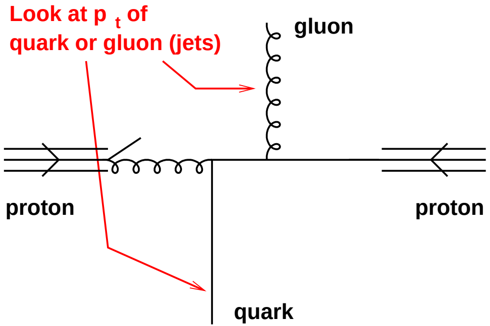


$K \simeq 1.2$



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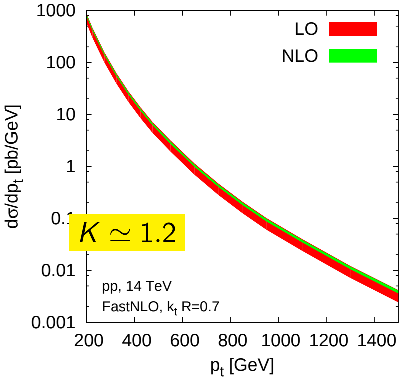

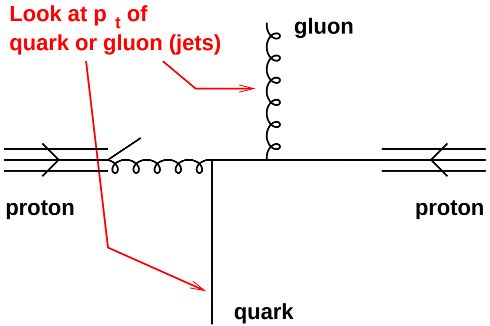

K of 1.2 is compatible with being $1 + \mathcal{O}(\alpha_s)$

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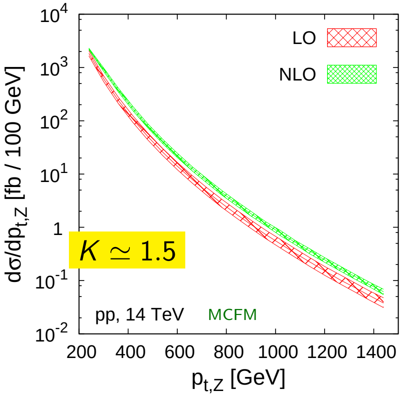

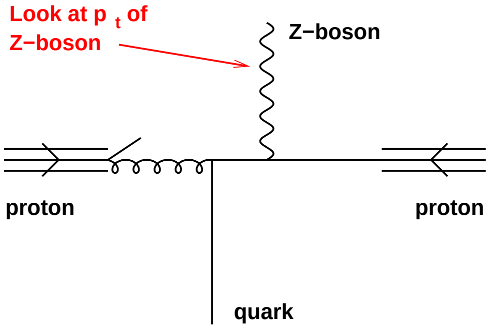

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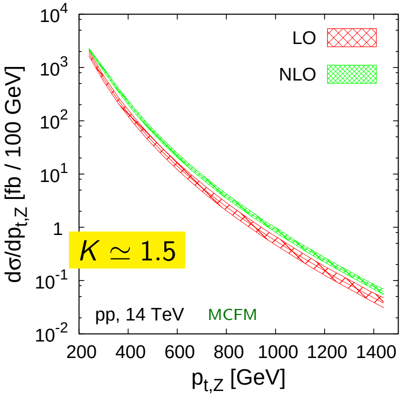

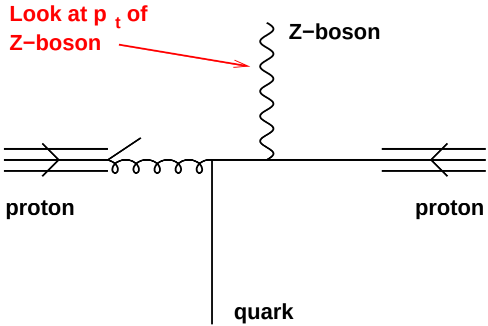

K of 1.5 is compatible with being $1 + C \times \alpha_s$, with quite large C

To date, no generalised understanding of size of C when in range $5 - 10$

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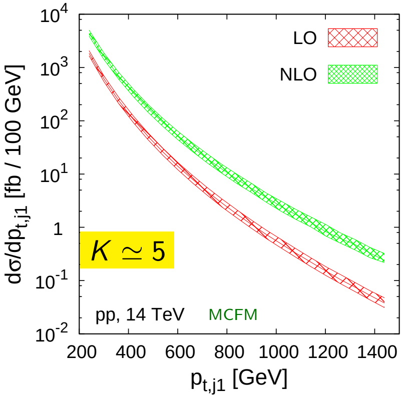

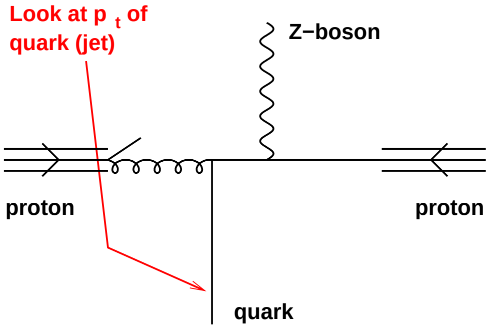

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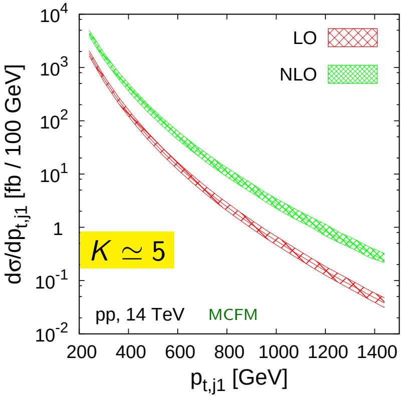

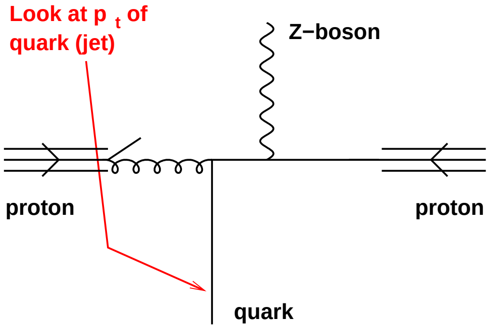

Butterworth, Davison, Rubin & GPS '08
Bauer & Lange '09; Denner et al '09

K of 5?!!! Found by several groups.

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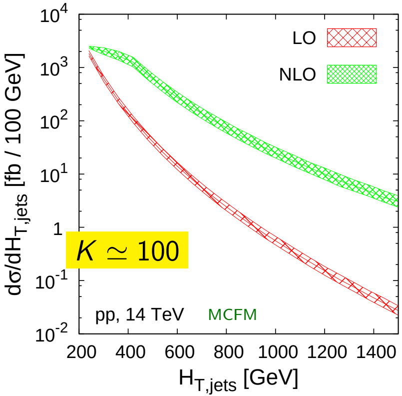

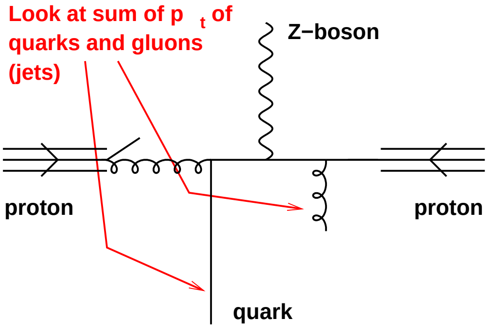

Rubin, GPS & Sapeta '10

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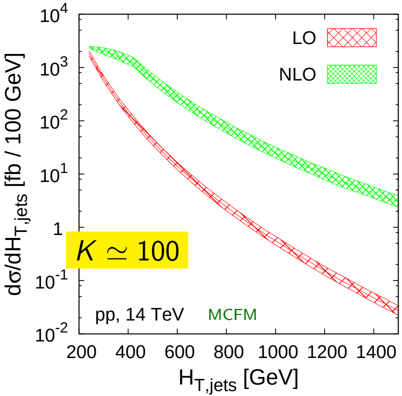
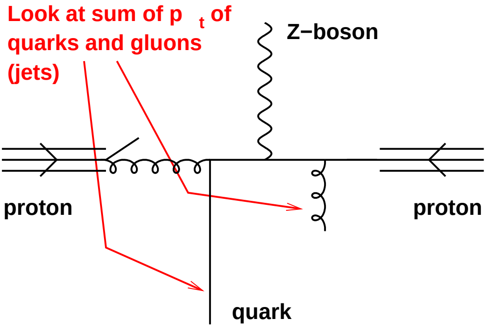




Rubin, GPS & Sapeta '10

What can it possibly mean to do perturbation theory if the "$\mathcal{O}(\alpha_s)$" NLO correction is so much larger than LO?

So what happens at the next order, NNLO?

The last examples are somewhat extreme. In such cases, it's fair to ask the question:

What happens at the next order? Does QCD converge?

Despite over 10 years' work by many people, not a single NNLO calculation exists for a hadron-collider process with coloured particles in the final state.

Several groups working on NNLO for this and related processes; maybe Z+jet jet process will be completed in a year or two or …?

Gehrmann family, Glover, Heinrich & al

Weinzierl

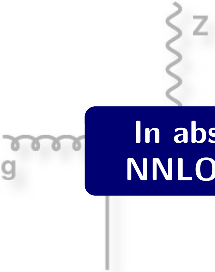
Somogyi, Trocsanyi, Del Duca, et al.

Czakon, Mitov, et al.

etc.

Why the large K-factor from LO to NLO?

Leading Order	Next-to-Leading Order



In absence of a full calculation at NNLO, try to gain physical insight

$\alpha_s \alpha_{EW}$

$\alpha_s^2 \alpha_{EW}$

LHC probes scales well above EW scale, $\sqrt{s} \gg M_Z$.
EW bosons are light.
New (logarithmically enhanced) topologies appear.

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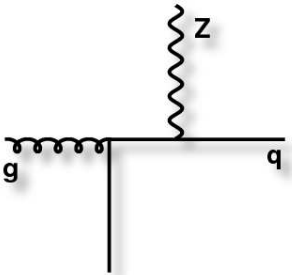
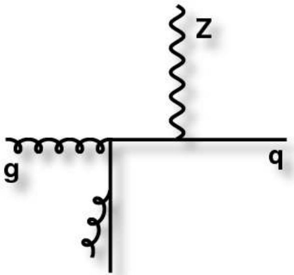
Leading Order



$\alpha_s \alpha_{EW}$

Next-to-Leading Order



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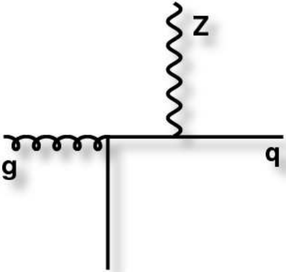

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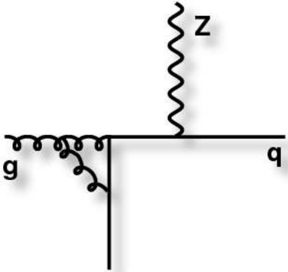
Next-to-Leading Order



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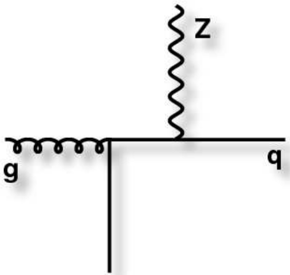

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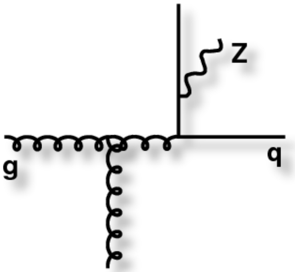

$\alpha_s^2 \alpha_{EW} \ln^2 \frac{p_t}{M_Z}$

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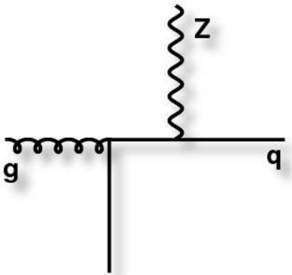
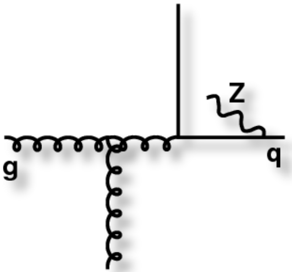
Leading Order



$\alpha_s \alpha_{EW}$

Next-to-Leading Order



$\alpha_s^2 \alpha_{EW} \ln^2 \frac{p_t}{M_Z}$

LHC probes scales well above EW scale, $\sqrt{s} \gg M_Z$.
EW bosons are **light**.
New (logarithmically enhanced) topologies appear.

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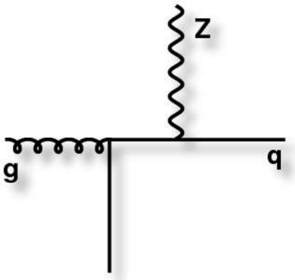

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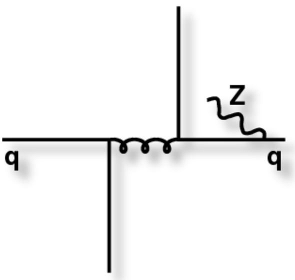

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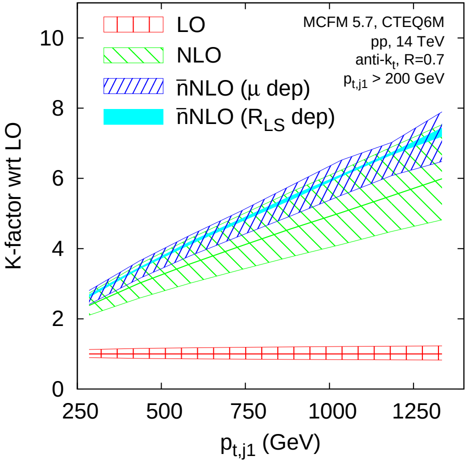
Physical understanding → better predictions

Since dominant contribution comes from Z+2 partons, try combining NLO Z+parton with NLO Z+2 partons.

LoopSim: Rubin, GPS & Sapeta '10

Never achieved previously

p_t of jet 1



We call this $\bar{n}$NLO

Not quite full NNLO

But has many of its qualities

- p_{tj} distribution seems to converge at $\bar{n}$NLO
- scale uncertainties reduced by $\sim$ factor 2

Physical understanding → better predictions

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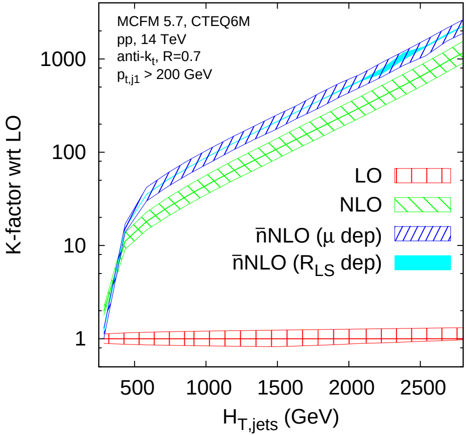
$$H_{T,jets} = \sum_{jets} p_{t,j}$$



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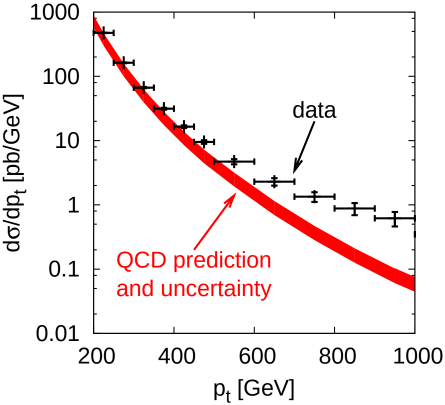
- Signficiant further enhancement for $H_{T,jets}$
- $\bar{n}$NLO brings clear message:

$H_{T,jets}$ is not a good observable!



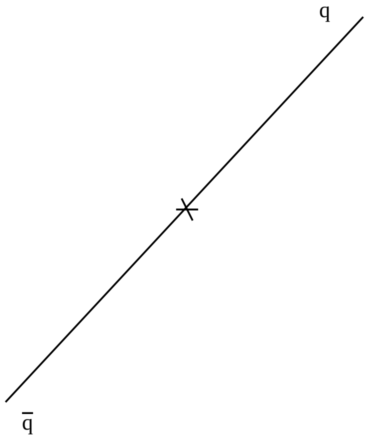
Really New Physics?

What went into the QCD prediction?

As if "giant" K-factors weren't bad enough...

How about **infinite** K-factors?

Quarks & gluons? You never see them



Start off with quark and anti-quark, $q\bar{q}$

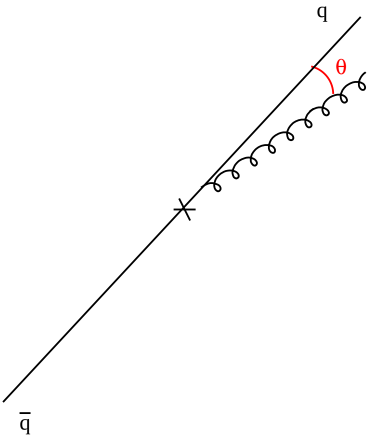
Quarks & gluons? You never see them

In perturbative quantum chromodynamics (QCD), probability that a quark or gluon emits a gluon:

$$\sim \frac{dE}{E}\frac{d\theta}{\theta}$$

Diverges for small gluon energies E

Diverges for small angles θ



A quark never survives unchanged

it always emits a gluon (usually low-energy, at small angles)

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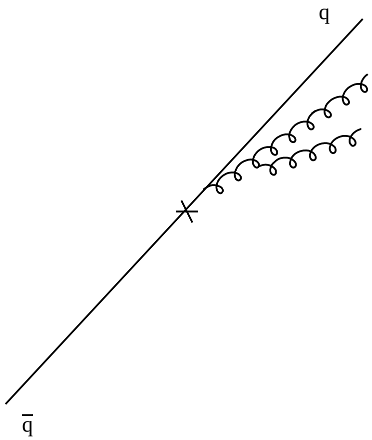

Each gluon radiates a further gluon

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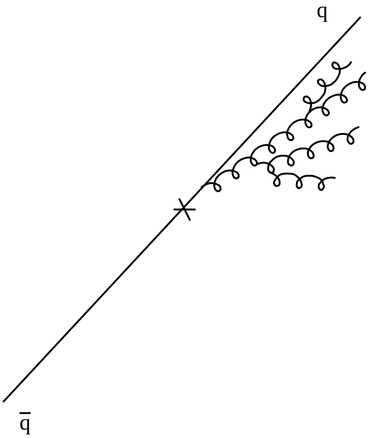

And so forth

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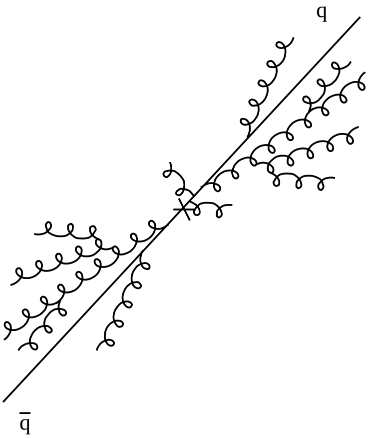

Meanwhile the same happens on other side of event

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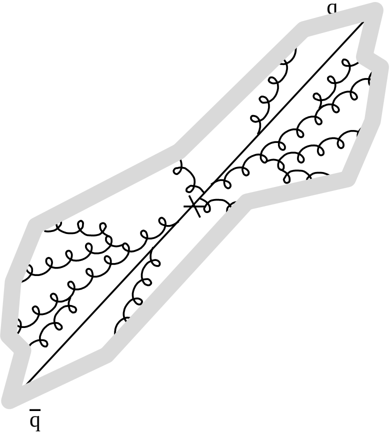
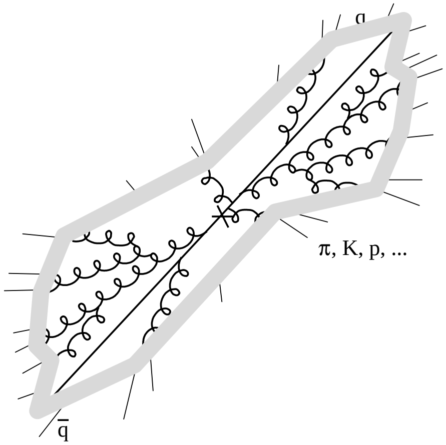


And then a non-perturbative transition occurs

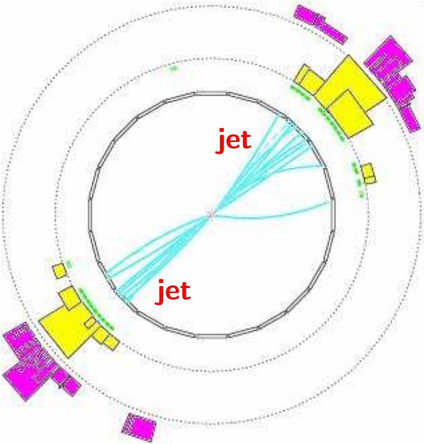
Quarks & gluons? You never see them

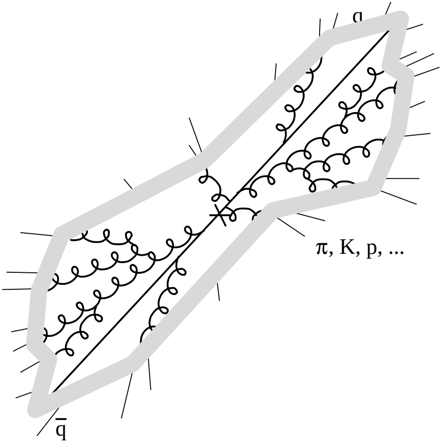


Giving a pattern of hadrons that "remembers" the gluon branching

Hadrons mostly produced at small angle wrt $q\bar{q}$ directions or with low energy

Quarks & gluons? You never see them





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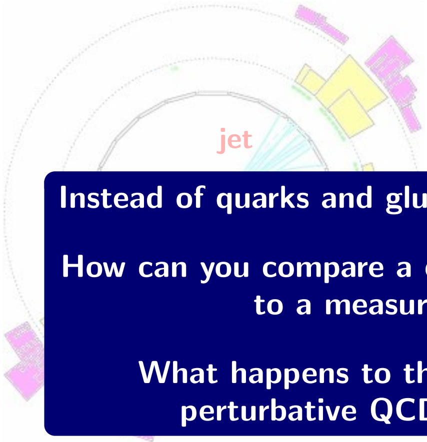
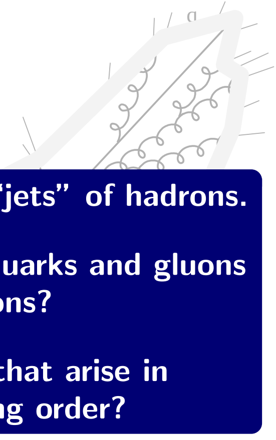




Instead of quarks and gluons, one sees “jets” of hadrons.

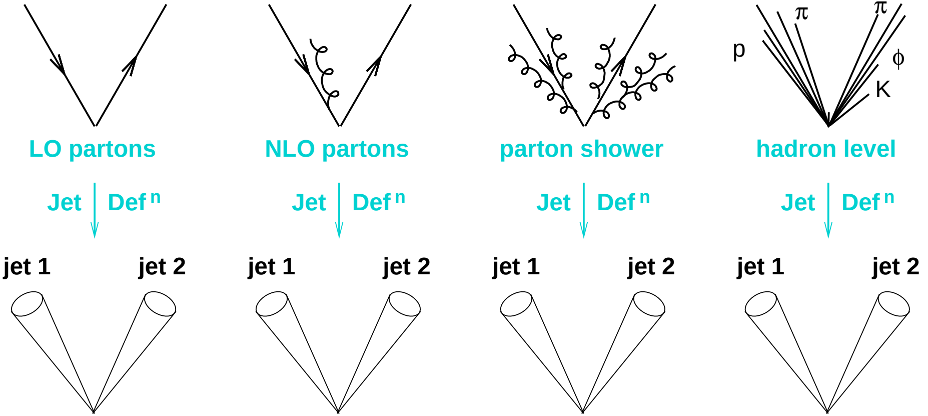
How can you compare a calculation of quarks and gluons to a measurement of hadrons?

What happens to the divergences that arise in perturbative QCD beyond leading order?

Giving a pattern of hadrons that “remembers” the gluon branching

Hadrons mostly produced at small angle wrt $q\bar{q}$ directions or with low energy

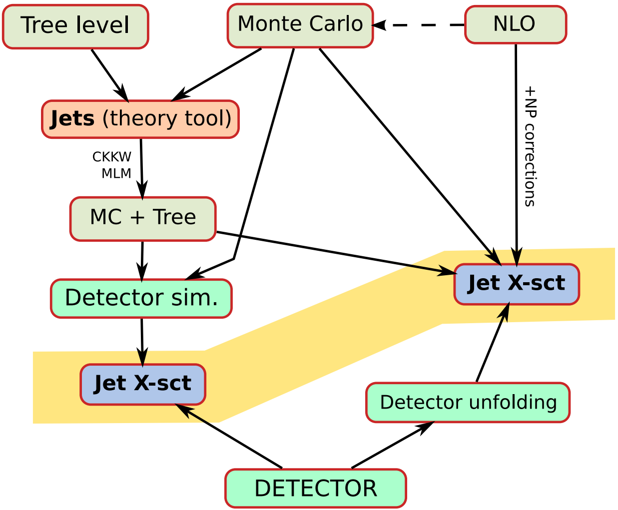
Jets made systematic: jet definitions



LHC events may be discussed in terms of quarks, quarks+gluon, or hadrons

A **jet definition** provides common representation of different "levels" of event complexity.

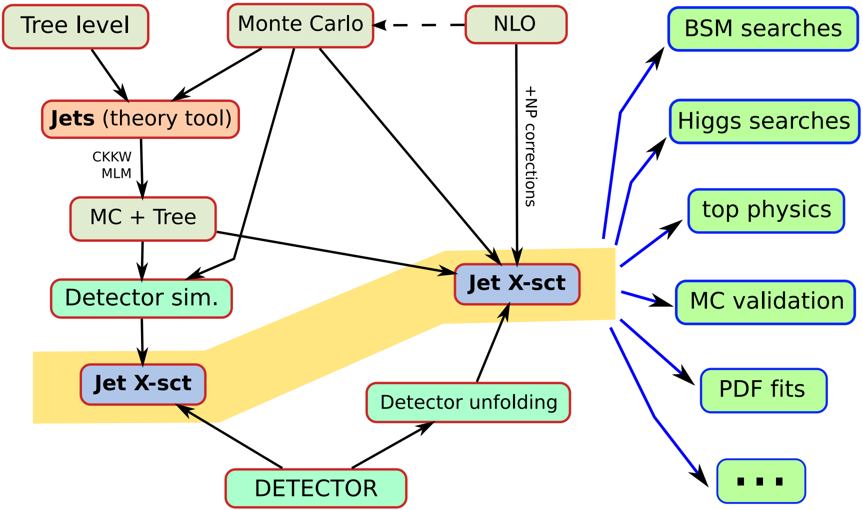
QCD jets flowchart



Jet (definitions) provide central link between expt., "theory" and theory

And jets are an input to almost all analyses

QCD jets flowchart



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A $100 000 000, 20-year old problem

A significant community of QCD theorists has spent the past ten years making accurate calculations of signals and backgrounds at the LHC (with remarkable advances in field theory on the way)

$\mathcal{O}(100)$ people $\times$ 10 years $\simeq$ $100 000 000

Problem 1: the jet definitions previously used by LHC experiments were not compatible with these calculations — they "leaked" infinities:

$$\sigma = c_1\,\alpha_s + c_2\,\alpha_s^2 + \boldsymbol{\infty}\,\alpha_s^3 + \cdots$$

Problem 2: the jet definitions advocated by theorists since 1990's had been mostly shunned by proton-collider experiments

a) bad response to experimental noise

b) severe computational issues (1 minute/event $\times 10^{10}$ recorded events)

Solving the jets problem

Discovered a link between QCD jet-finding and problems of 2D computational geometry

Cacciari & GPS '05

Many techniques could be carried over from comp. geom field

Developed a theory of the interplay between jet-finding, QCD radiation and experimental noise

Cacciari, GPS & Soyez '08

A crucial element was linearity of response

Proposed a new jet-definition based on what we'd learnt

anti-k_t

Cacciari, GPS & Soyez '08

How anti-k_t works:

- Define pairwise i–j distances

$$d_{ij} = \min\left(\frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2}\right) \Delta R_{ij}^2$$

- Define single-particle distances

$$d_{iB} = \frac{1}{p_{ti}^2}$$

  - If smallest is d_{ij} merge i and j
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A non-intuitive successor to k_t alg of Catani et al. '91

You can cluster anything

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Island Beach State Park

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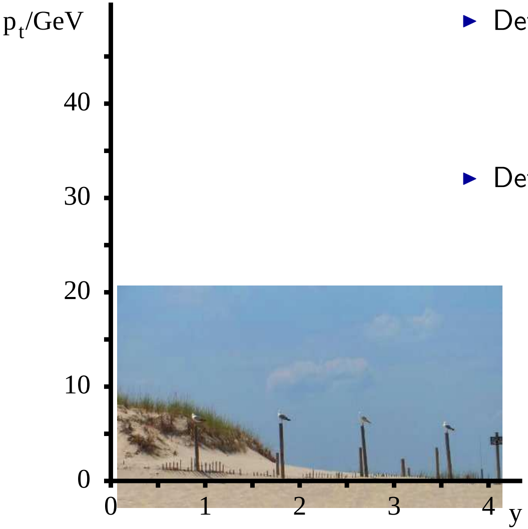

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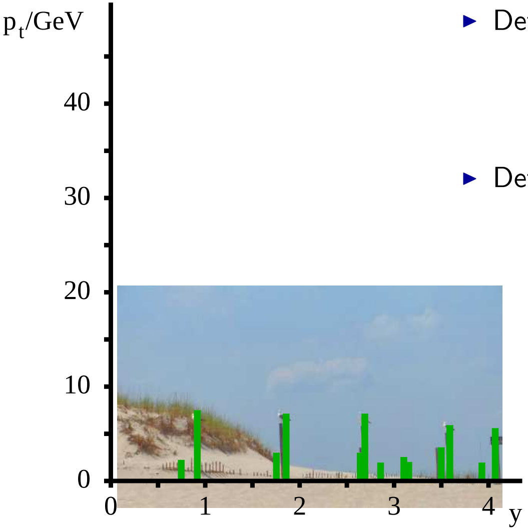

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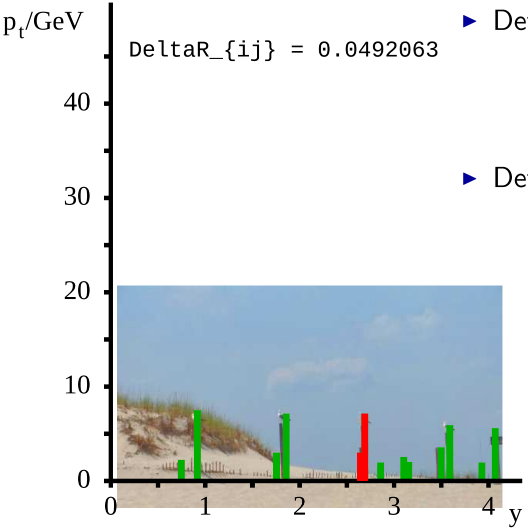

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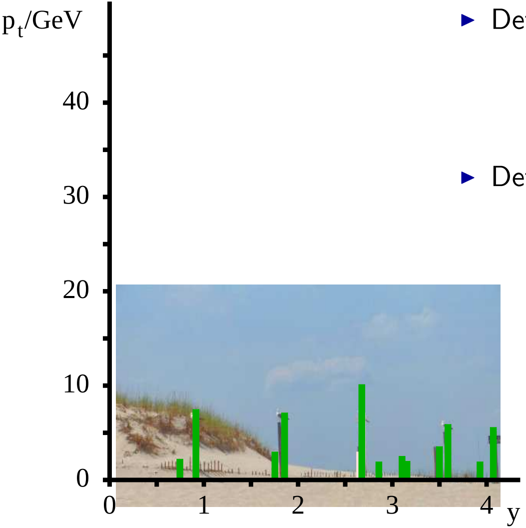

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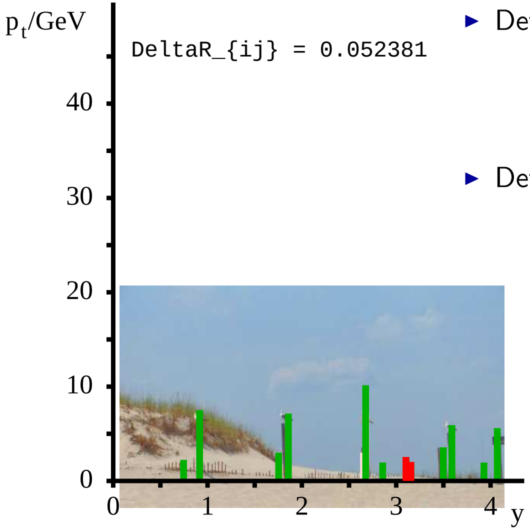

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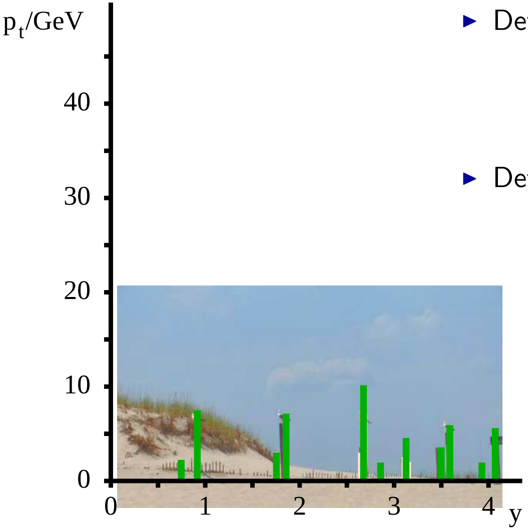

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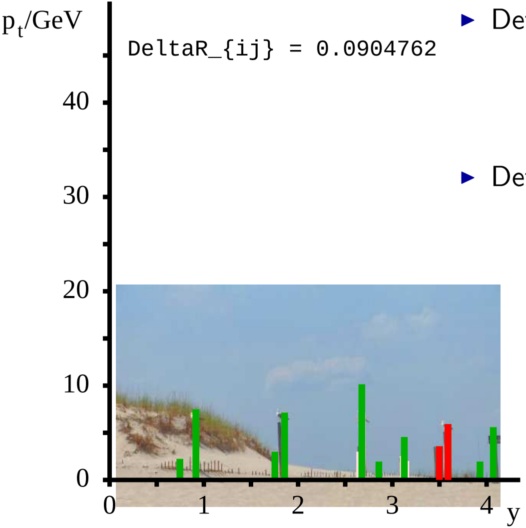

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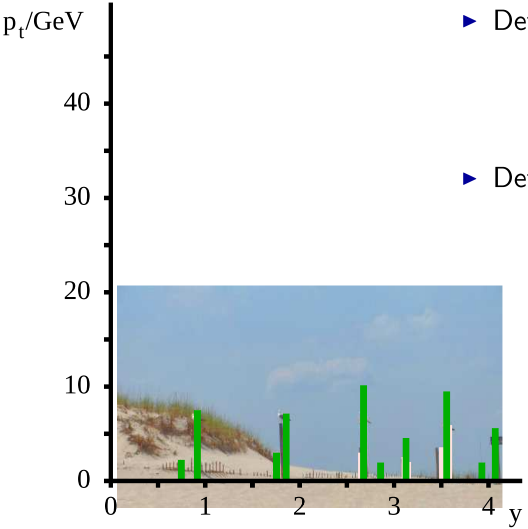

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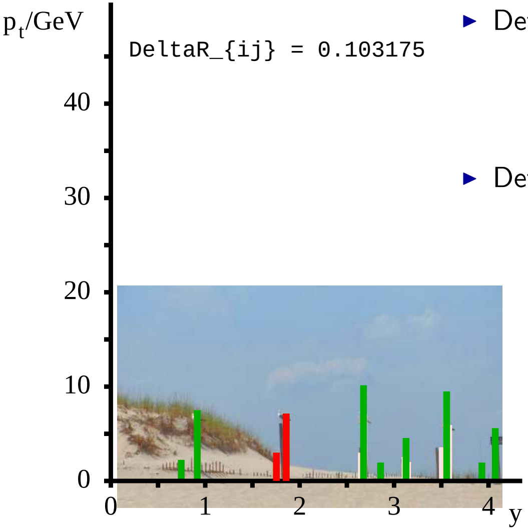

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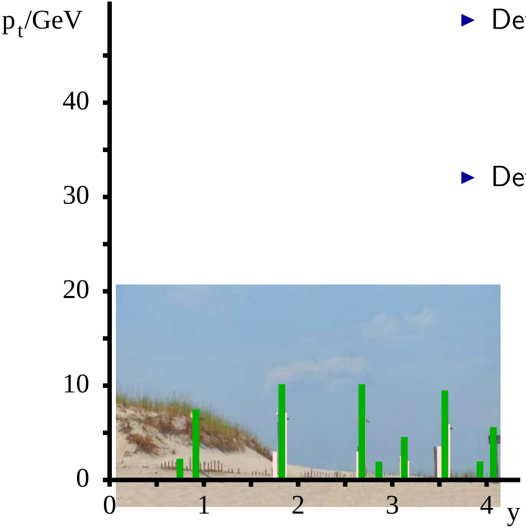

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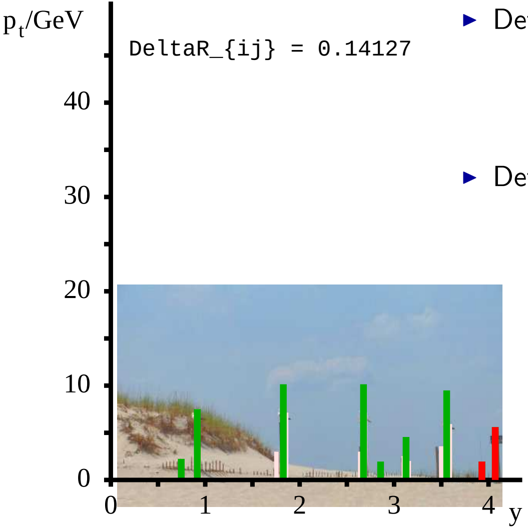

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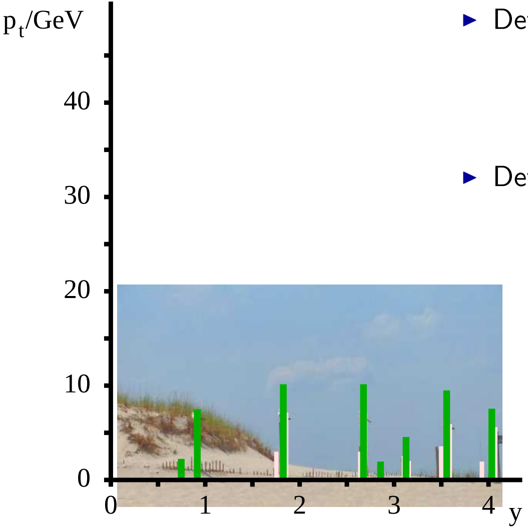

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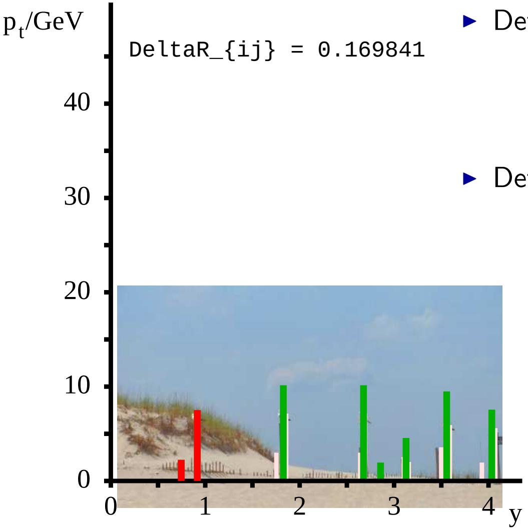

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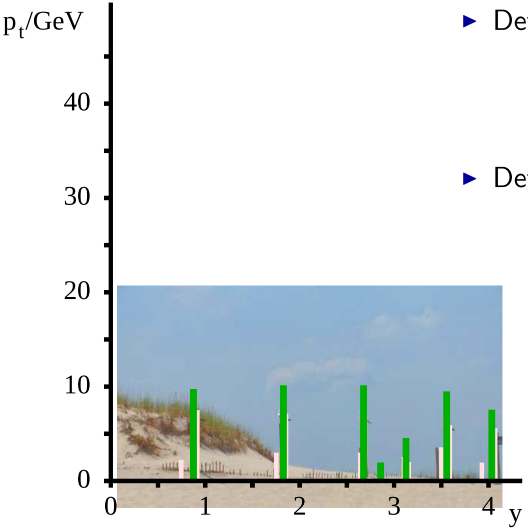

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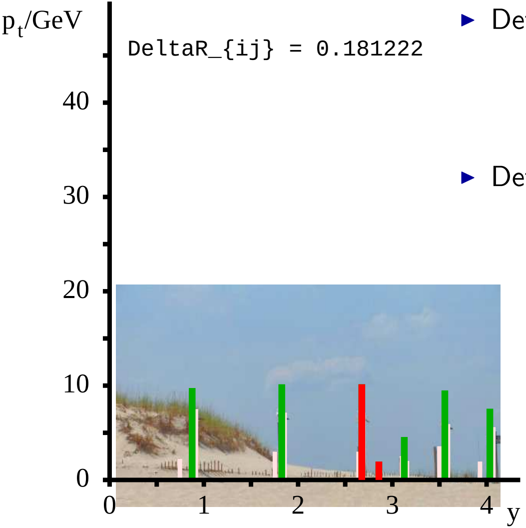

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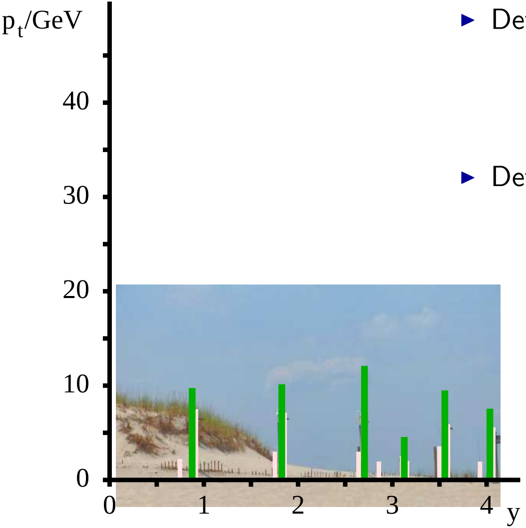

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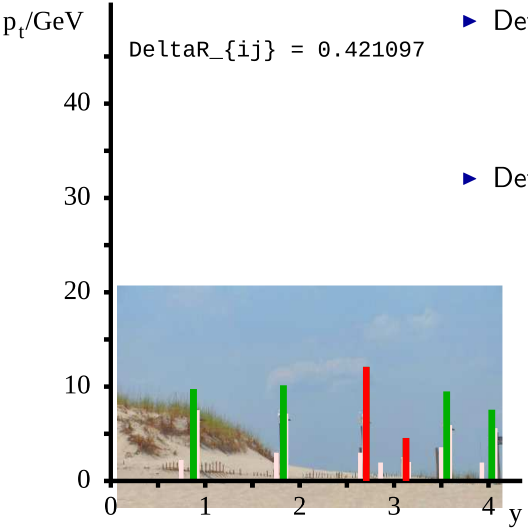
A non-intuitive successor to k_t alg of Catani et al. '91

You can cluster anything



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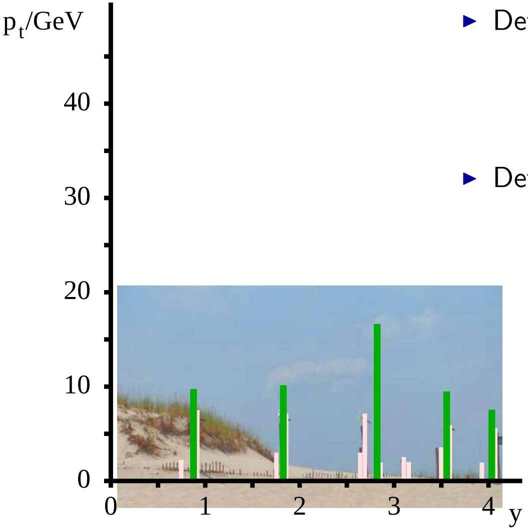

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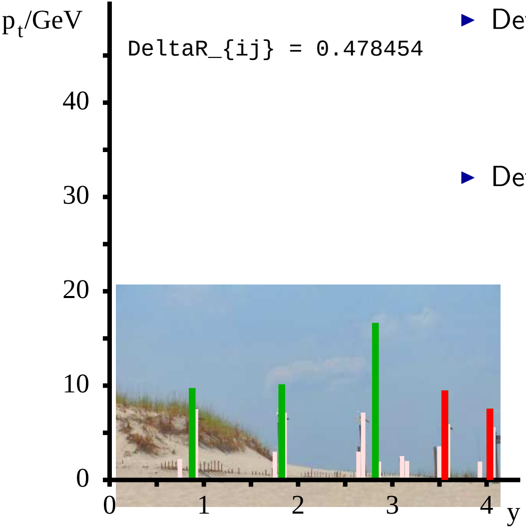

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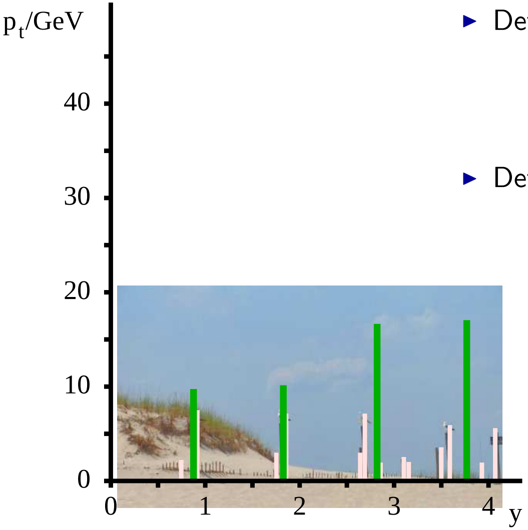

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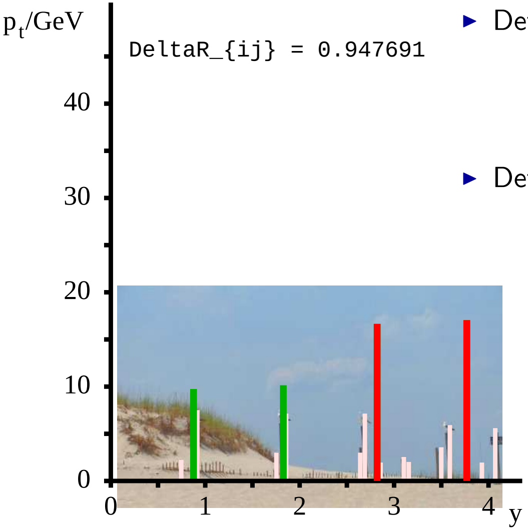

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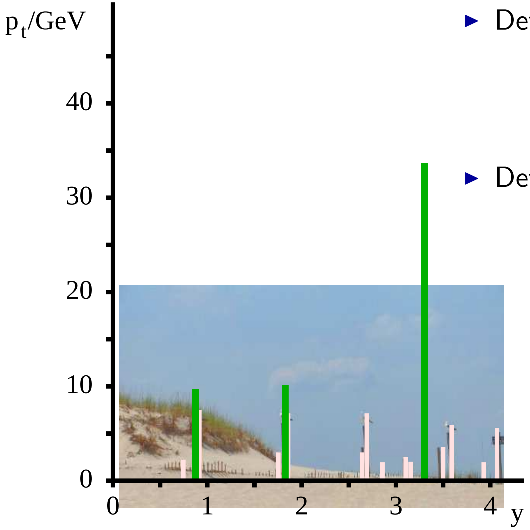

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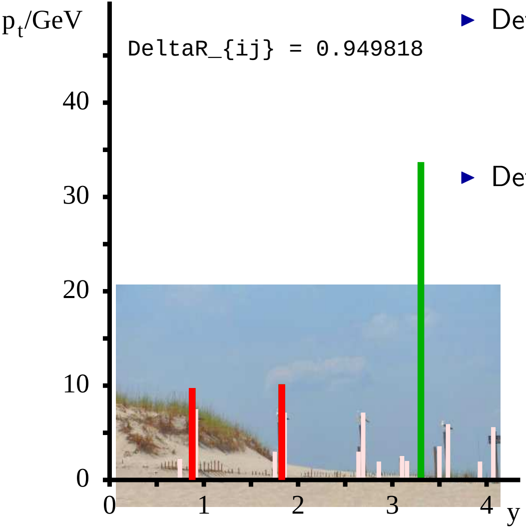

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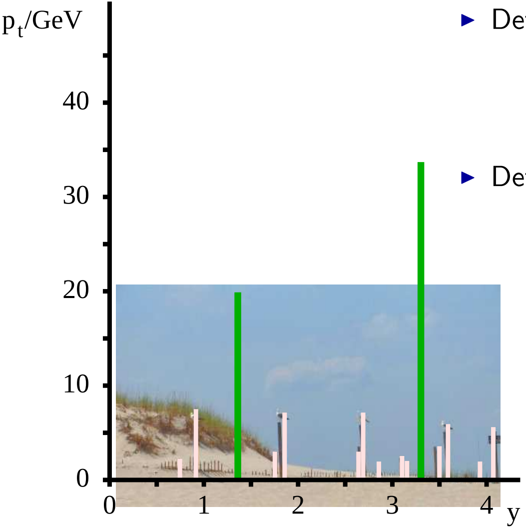

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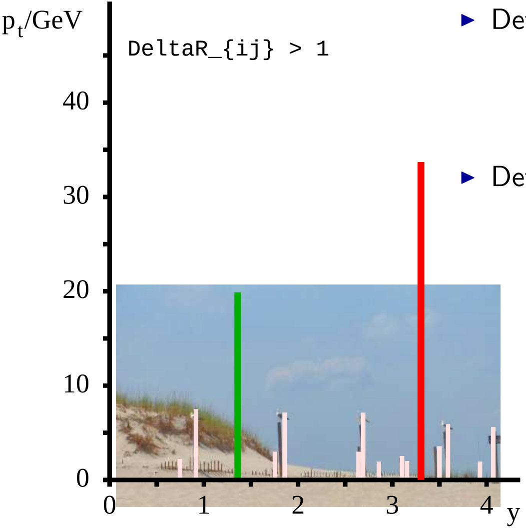

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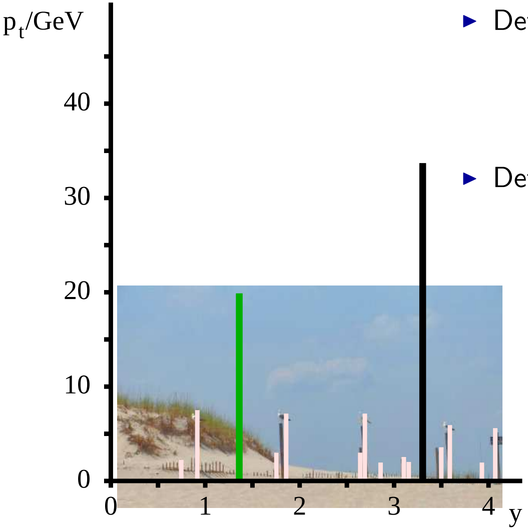

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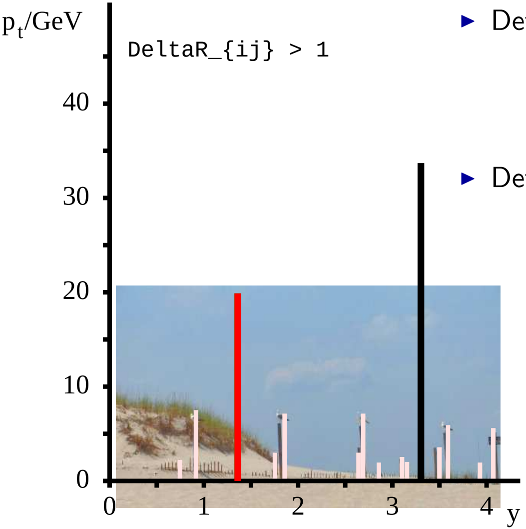

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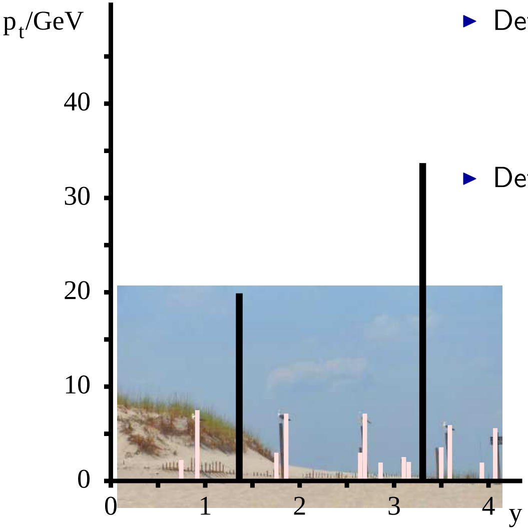

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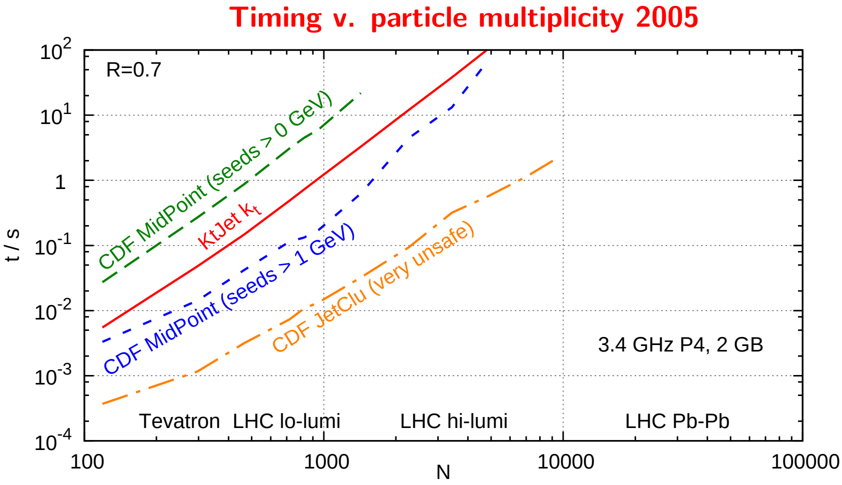
How does anti-k_t fare?



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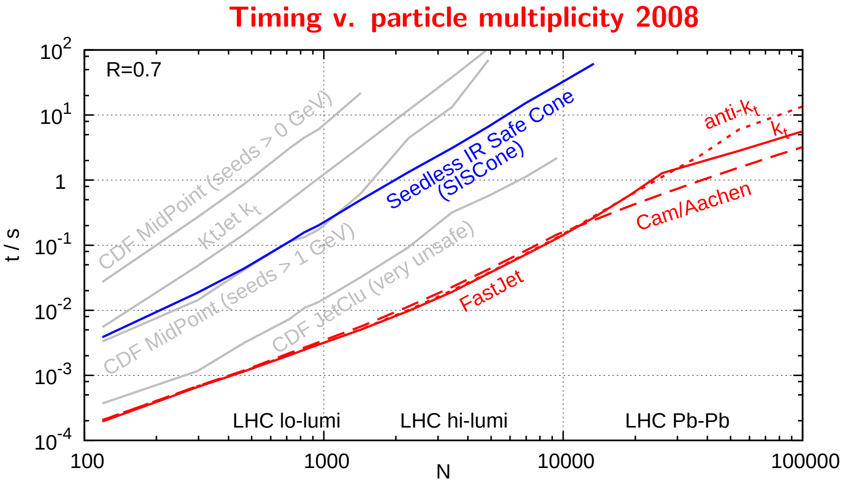


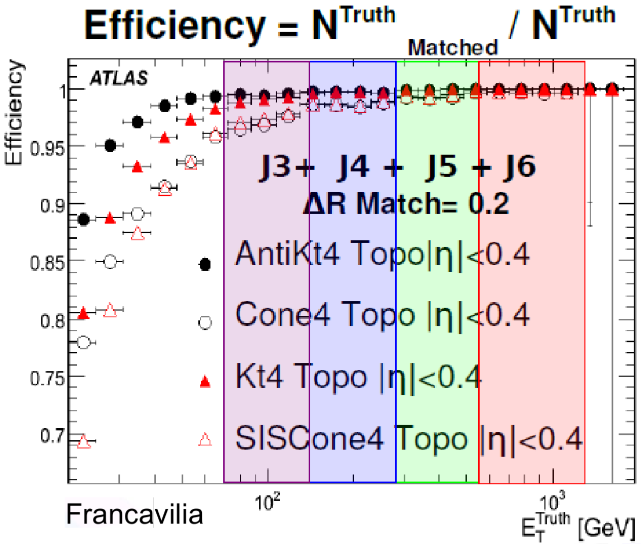
in critical region of $N \sim 2000 - 4000$

1000 times faster than previous attempts with similar jet algorithms

FastJet code available publicly at `http://fastjet.fr/`

How does anti-k_t fare?

Experimental sensitivity to noise

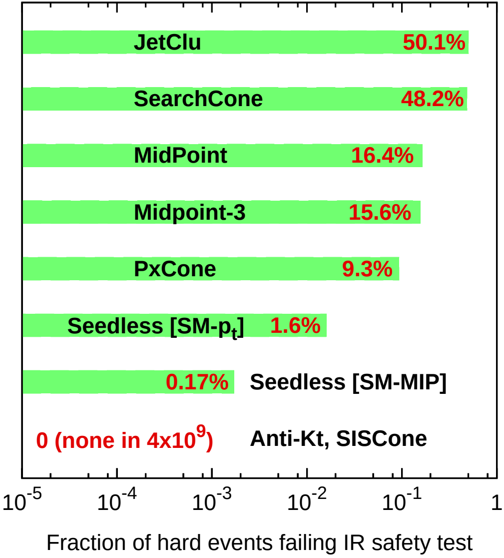


As good as, or better than all previous experimentally-favoured algorithms.

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

How does anti-k_t fare?

Coefficient of "infinity"



Safe for perturbative QCD predictions:

No "leakage" of infinities to higher orders

Anti-k_t contained in FastJet

A program that brings together theoretical physics and computational geometry.

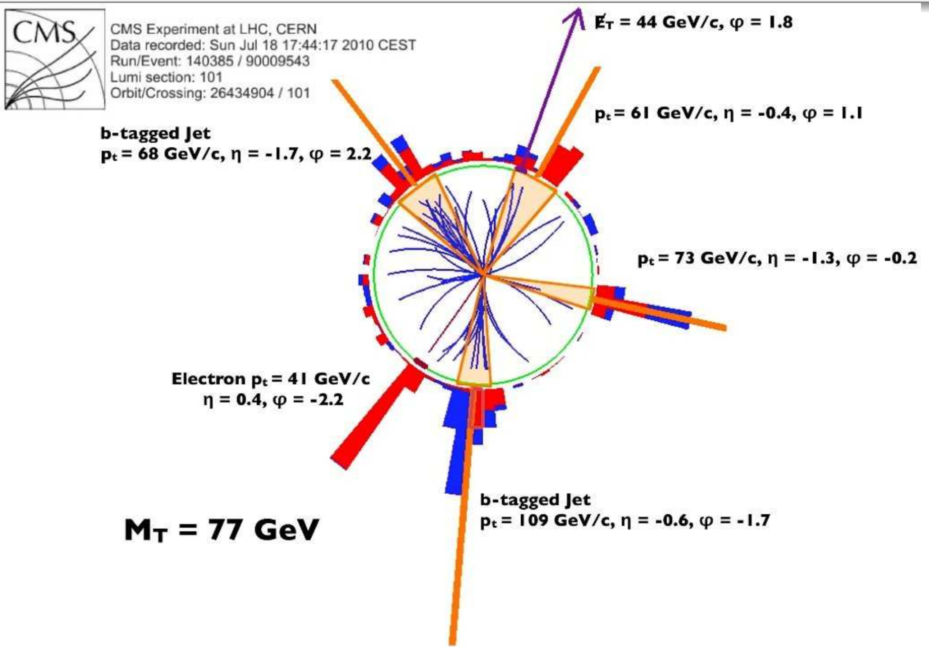
Cacciari, GPS & Soyez '06-

program downloads   manual + doxygen   other (main page, FAQ, etc.)

In 2009: about 40 000 page loads from 3 300 IP addresses, in $\gtrsim$ 1000 locations.

[After exclusion of robots]

ATLAS & CMS use anti-k_t for all their jet-finding



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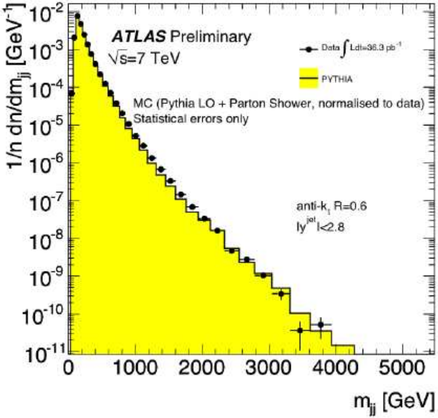
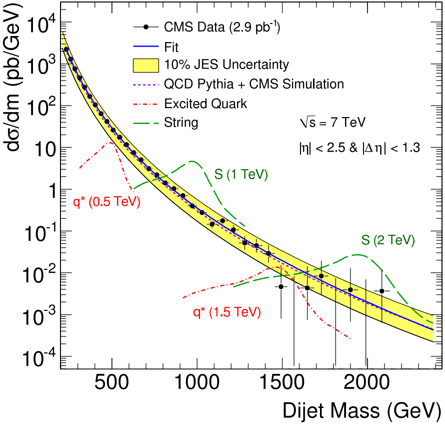
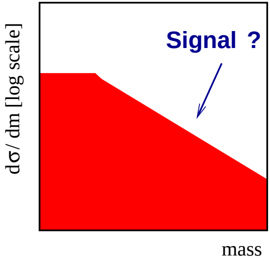


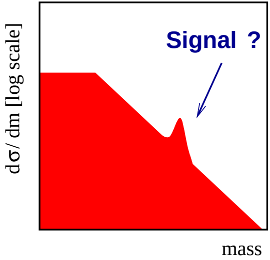


Among the handful of LHC searches so far, anti-k_t jets have probed the highest scales, $\sim$ 2 TeV, about twice as high as Tevatron.

Anti-k_t solves a long-standing problem, crucial in providing a common language to compare theory and experiment.



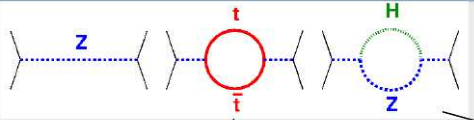
But is QCD really about nothing other than comparing theory and experiment?



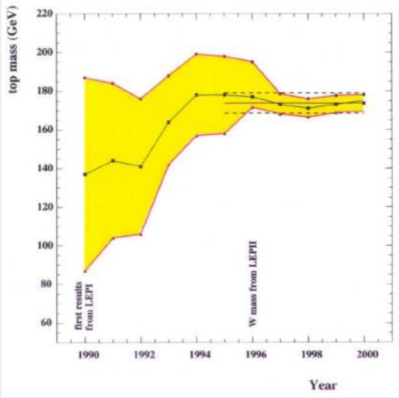
The quest for the Higgs

Using jets better, in order to make discoveries possible

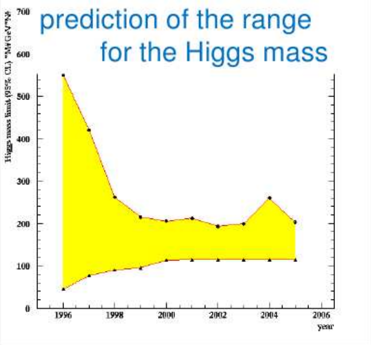
Test of the SM at the Level of Quantum Fluctuations



indirect determination of the top mass



prediction of the range for the Higgs mass

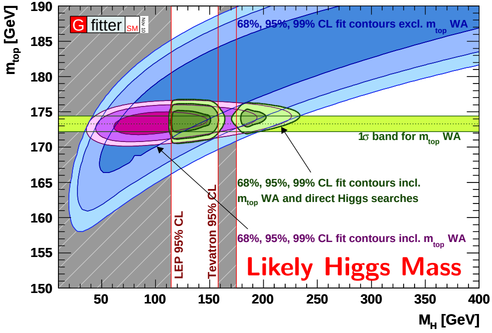


possible due to

- precision measurements
- known higher order electroweak corrections

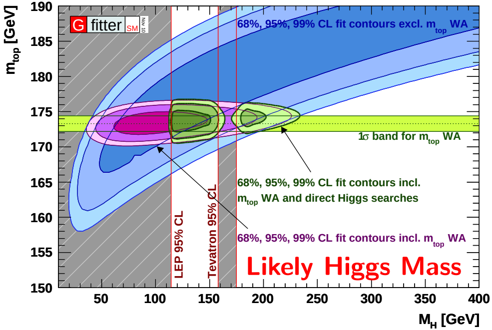
$$\propto \left(\frac{M_t}{M_W}\right)^2, \ln\left(\frac{M_h}{M_W}\right)$$

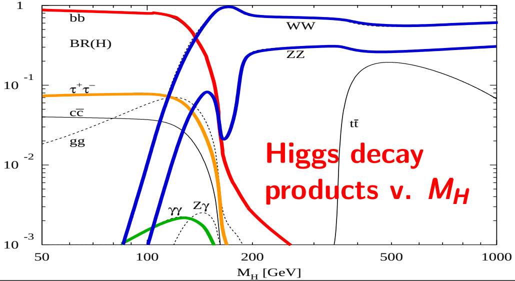
Higgs mass and Higgs decays?



There's some likelihood that the Higgs boson will be "light", $M_H \sim 120$ GeV

Higgs mass and Higgs decays?





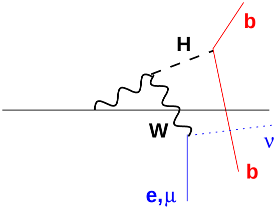
There's some likelihood that the Higgs boson will be "light", $M_H \sim 120$ GeV

If it is, crucial test of whether it **is** the Higgs, will come from measuring several different decays

Remember: Higgs couplings intimately related to origin of particle masses

$H \to b\bar{b}$ (main light-Higgs decay) v. hard to see

Best hope is $pp \to W^{\pm}H$, $W^{\pm} \to \ell^{\pm}\nu$, $H \to b\bar{b}$.



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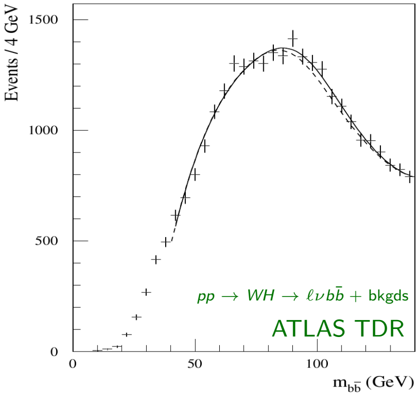
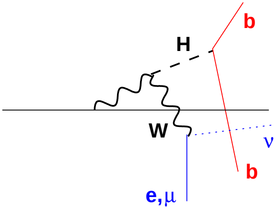


Conclusion (ATLAS TDR):

"The extraction of a signal from $H \to b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions [...]"

Low efficiency, huge backgrounds, e.g. $t\bar{t}$



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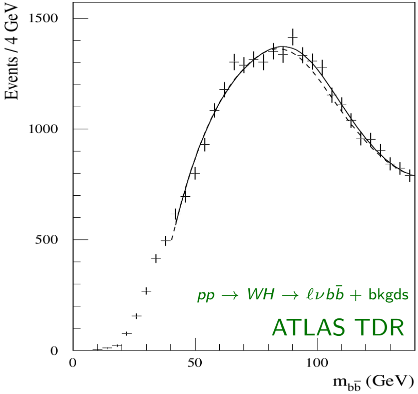

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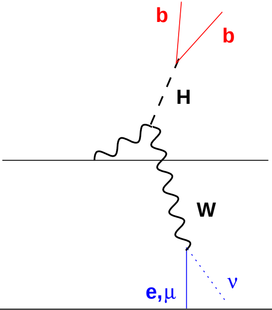

Try a long shot?

- Go to high p_t ($p_{tH}, p_{tW} > 200$ GeV)
- Lose 95% of signal, but more efficient?
- Maybe kill $t\bar{t}$ & gain clarity?

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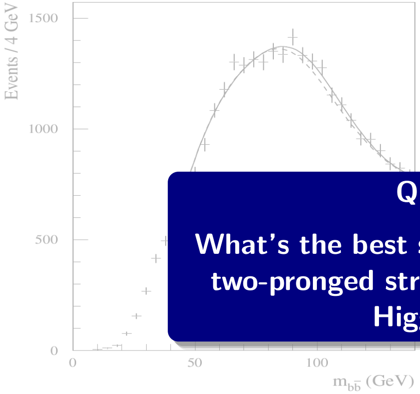

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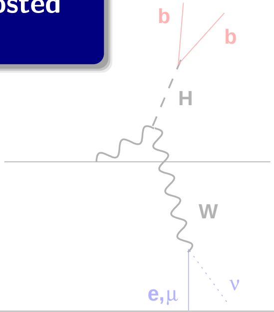
Question:

What's the best strategy to identify the two-pronged structure of the boosted Higgs decay?



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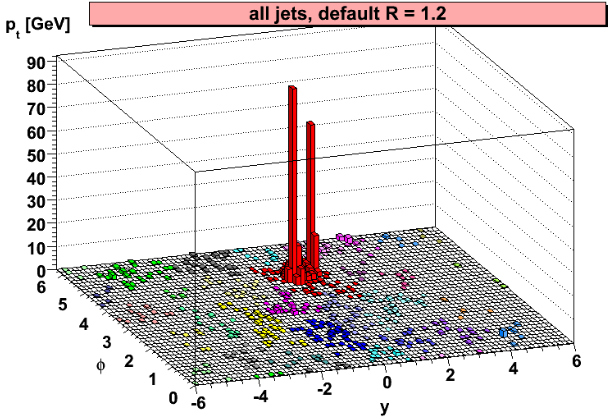
3 QCD principles help guide our analysis

- QCD radiation from a boosted Higgs decay is limited by angular ordering
- Higgs decay shares energy symmetrically, QCD background events with same mass share energy asymmetrically
- QCD radiation from Higgs decay products is point-like, noise (UE, pileup) is diffuse

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

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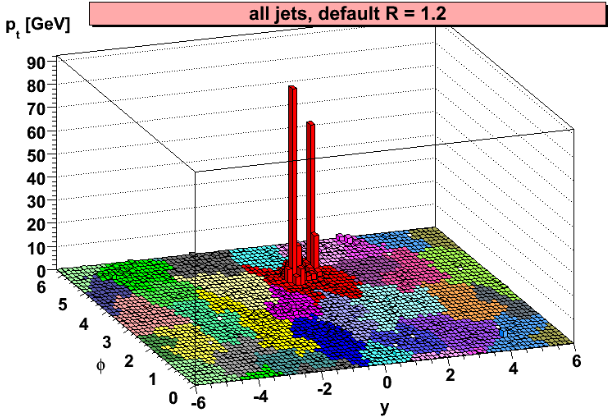

Zbb BACKGROUND

Fill it in, → show jets more clearly

Butterworth, Davison, Rubin & GPS '08

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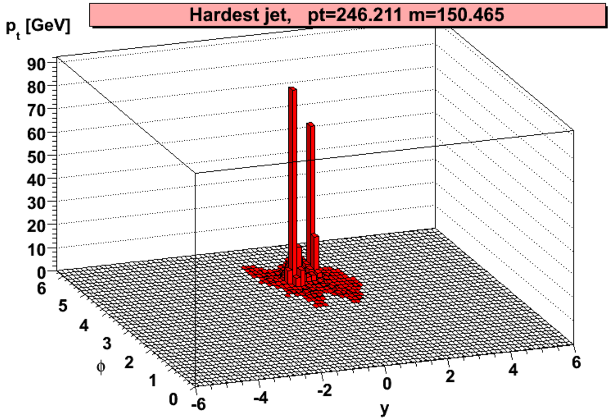

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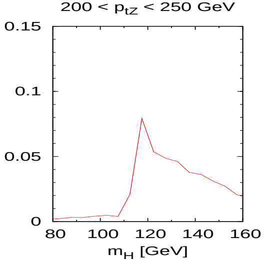

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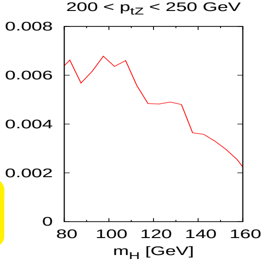

Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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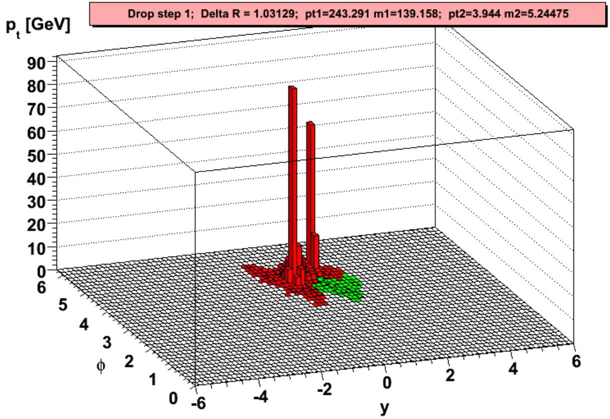
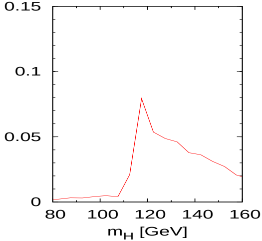


split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

Butterworth, Davison, Rubin & GPS '08

SIGNAL

$200 < p_{tZ} < 250$ GeV



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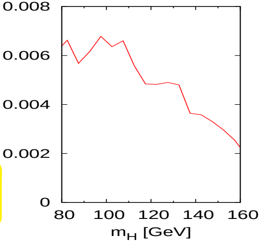

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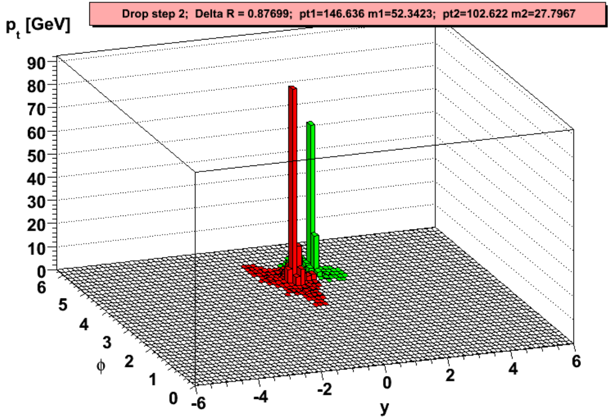
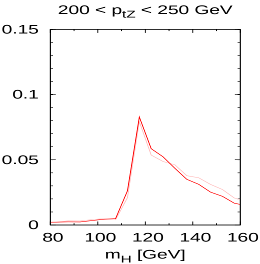


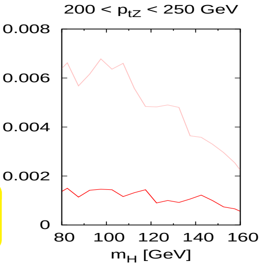
split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

Butterworth, Davison, Rubin & GPS '08

SIGNAL



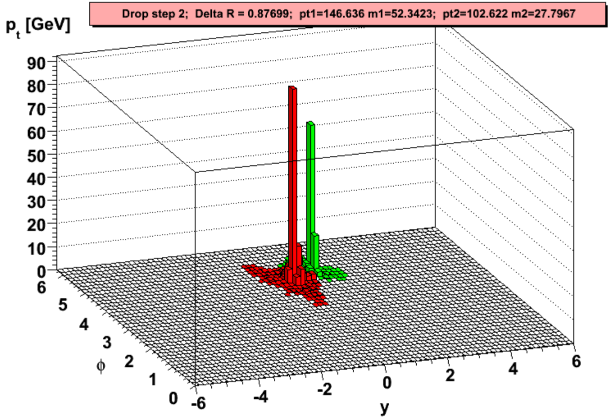
Zbb BACKGROUND



arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

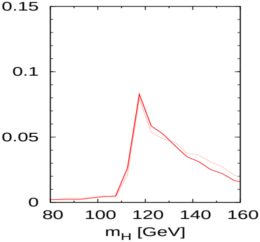


check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

Butterworth, Davison, Rubin & GPS '08

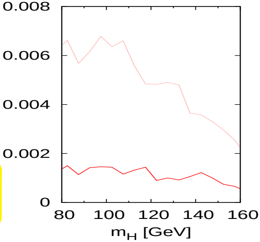
SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

$200 < p_{tZ} < 250$ GeV



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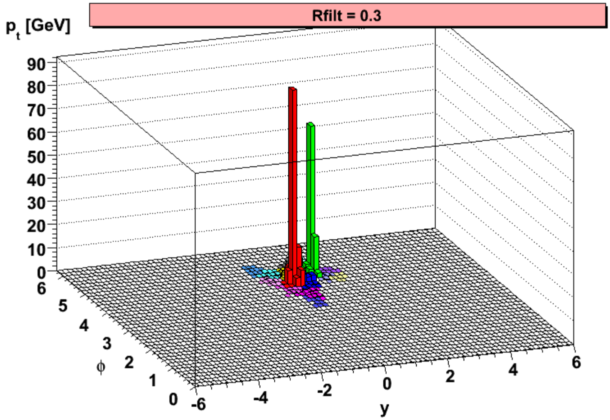
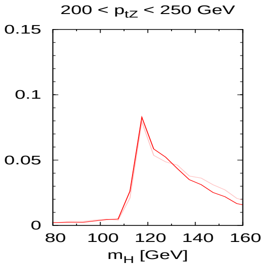
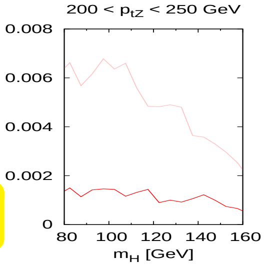


SIGNAL



Zbb BACKGROUND



$R_{filt} = 0.3$

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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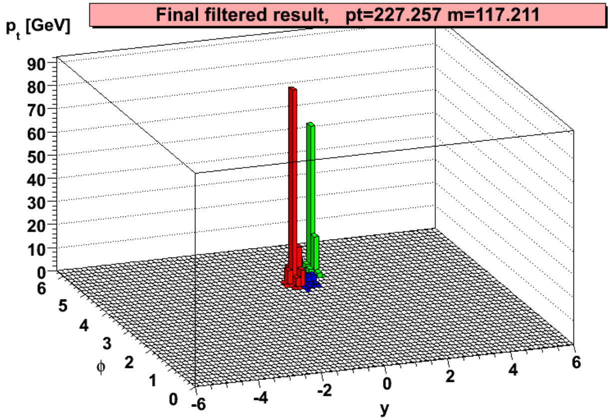
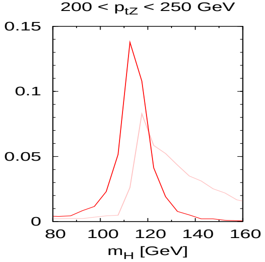
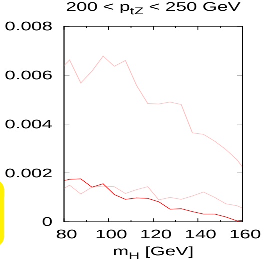


SIGNAL



Zbb BACKGROUND



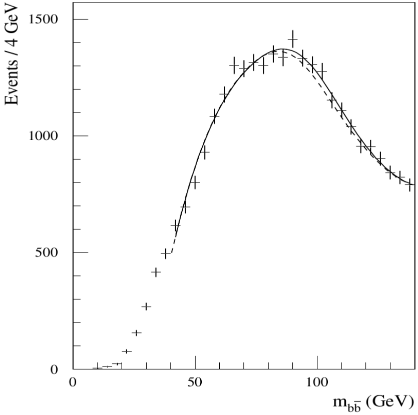
$R_{filt} = 0.3$: take 3 hardest, **$m = 117$ GeV**

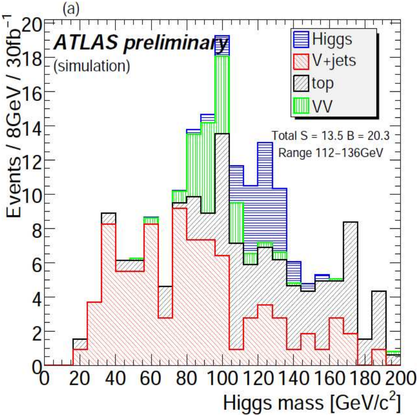
Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

How well-designed jet-finding helps you

Search for main decay of light Higgs boson, W/Z+H, $H \to b\bar{b}$
(The only way of seeing this decay — other than the next slide)



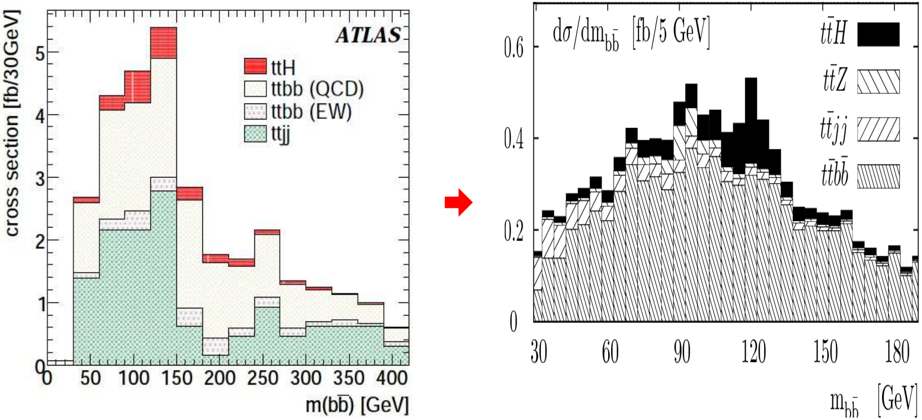


using the method from Butterworth, Davison, Rubin & GPS '08

Other recent work focuses on v. high background rejection (lower efficiency)

How well-designed jet-finding helps you

Recovering the ttH, $H \to b\bar{b}$ Higgs channel

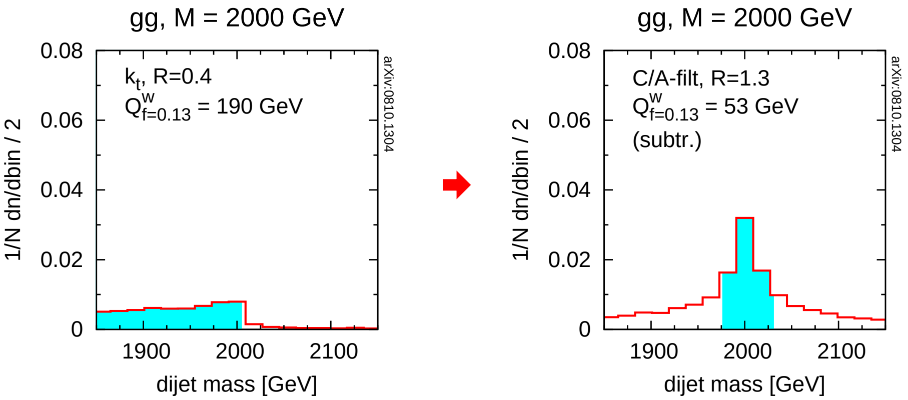


Plehn, GPS & Spannowsky '09

based in part on Johns Hopkins top tagger '08

How well-designed jet-finding helps you

Dijet mass reconstruction for new heavy resonance $X \to gg$

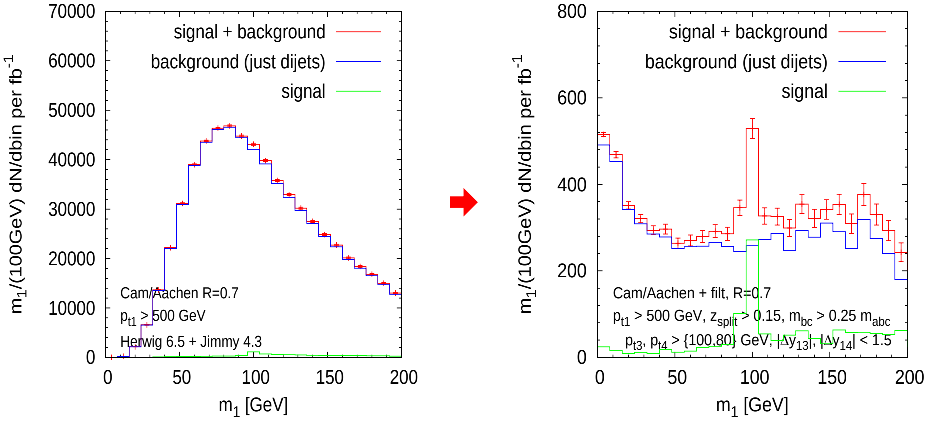


Cacciari, Rojo, GPS & Soyez '08

Other recent work: Krohn, Thaler & Wang '09

How well-designed jet-finding helps you

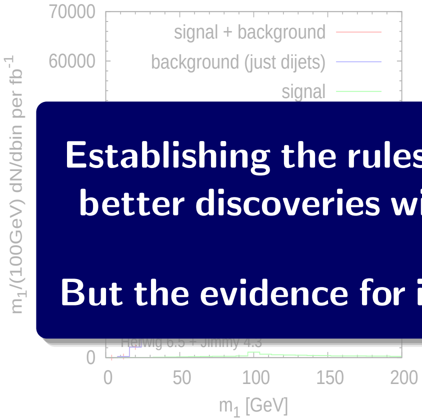
Supersymmetry with R-parity violating decays $\tilde{\chi}_1^0 \to qqq$
One of its most difficult incarnations

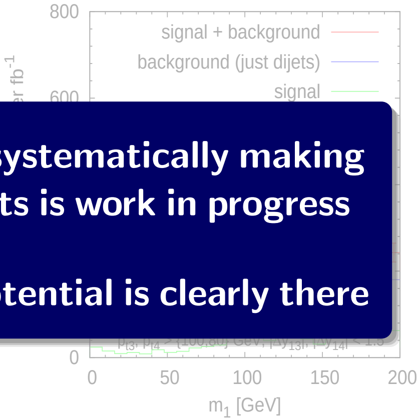


Butterworth, Ellis, Raklev & GPS '09

How well-designed jet-finding helps you

Supersymmetry with R-parity violating decays $\tilde{\chi}_1^0 \to qqq$
One of its most difficult incarnations



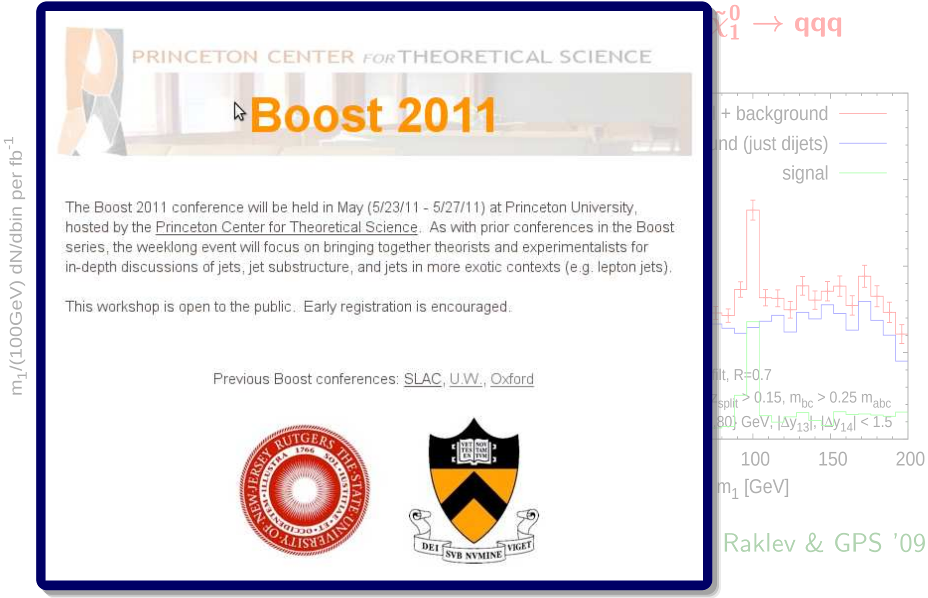


Establishing the rules for systematically making better discoveries with jets is work in progress

But the evidence for its potential is clearly there

Butterworth, Ellis, Raklev & GPS '09

How well-designed jet-finding helps you



Raklev & GPS '09

Conclusions

Conclusions

QCD is unavoidable at LHC

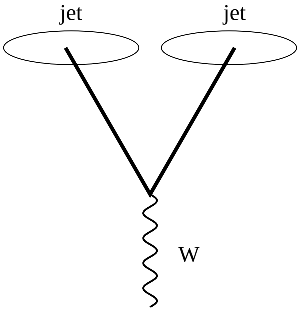
The simplicity of its formulation contrasts with the richness of its phenomenology

Even after 20 years of planning for the LHC, QCD still has surprises for us

Both in its own right
And as a tool for discovery

EXTRAS

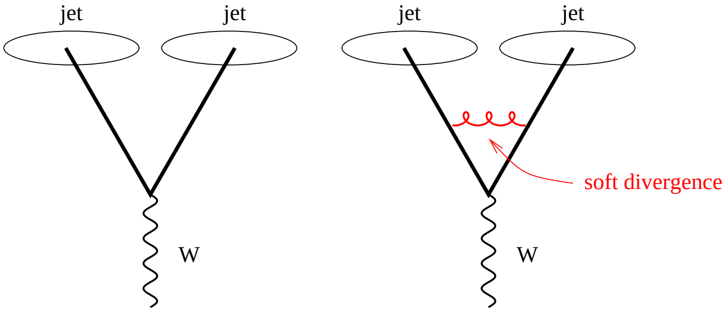
JetClu (& Atlas Cone) in Wjj @ NLO



	$\alpha_s^2\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$
1-jet			$+\infty$
2-jet	$\mathcal{O}(1)$	$-\infty$	**0**

With these (& most) cone algorithms, perturbative infinities fail to cancel at some order $\equiv$ **IR unsafety**

JetClu (& Atlas Cone) in Wjj @ NLO



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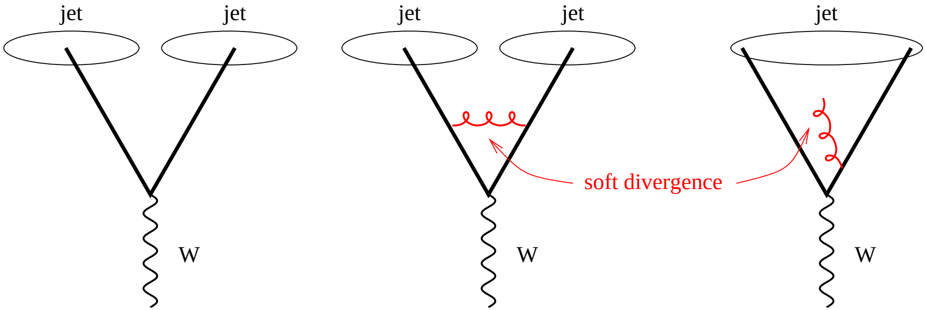

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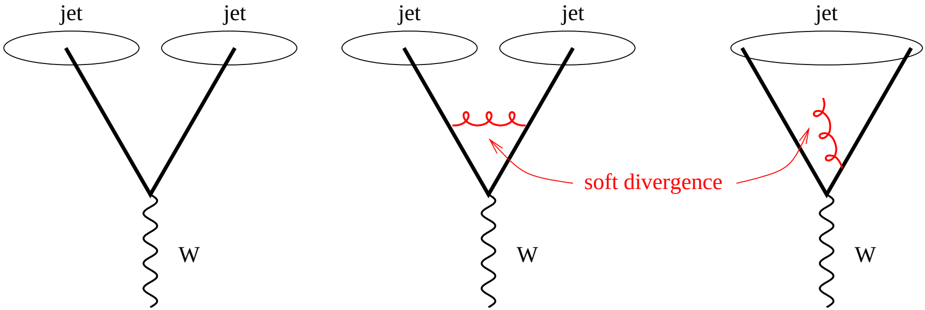

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