Jets and heavy flavours: an introduction

Grégory Soyez

IPhT, CEA Saclay

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Plan

- generic introduction: QCD and strong interactions

  What is QCD? Why do we need it (at the LHC)?

- heavy flavour:

  Why is it special, important, interesting?

  What are the main issues?

- jets:

  Why is it important? What are the main issues?

Strong interactions

Quantum Chromodynamics: basics

QCD is the quantum theory for string interactions

	QED	QCD
matter	e, μ, τ	6 quarks flavours
		u, d, s, c, b, t
vector	photon	gluon
quantum nr	charge	colour
sym. group	U(1)	SU(3)

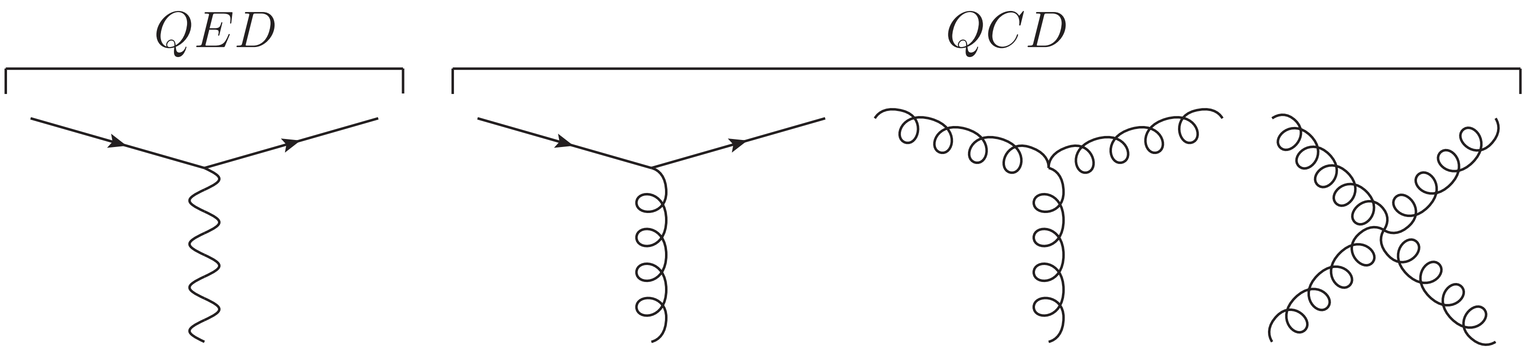
Notes:

- quarks also carry elm charge/interact with photons
- SU(3): 3 fundamental colours (RGB) *i.e.* 3 for quarks, 8 for gluons
- SU(3) is non-abelian

Quantum Chromodynamics: a non-abelian theory

2 main consequences:

- the gluons interact together



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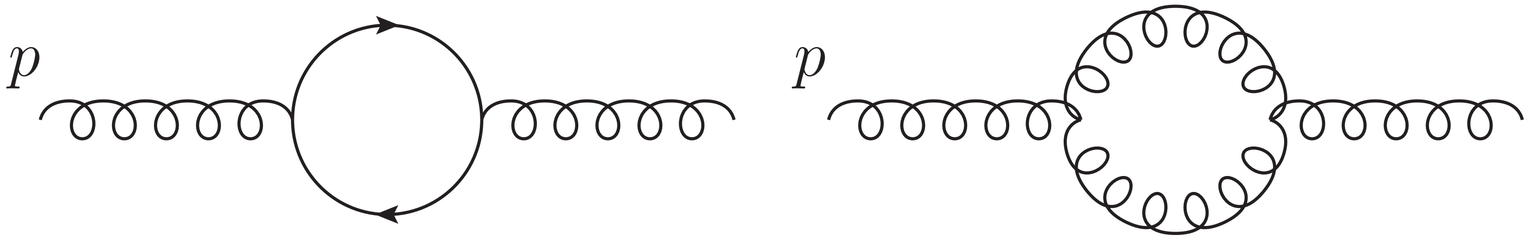
- the gluons interact together
- The “running” coupling constant ($\alpha_s = g_s^2/(4\pi)$) decreases with energy



$$\alpha_s(p) = \frac{1}{b_0 \log(p^2/\Lambda^2_{\mathrm{QCD}})} \qquad \text{with} \qquad b_0 = \frac{11N_c - 2n_f}{12\pi}$$

$b_0 > 0$ for $N_c = 3$ and $n_f = 3\ldots 6$.

Quantum Chromodynamics: a non-abelian theory

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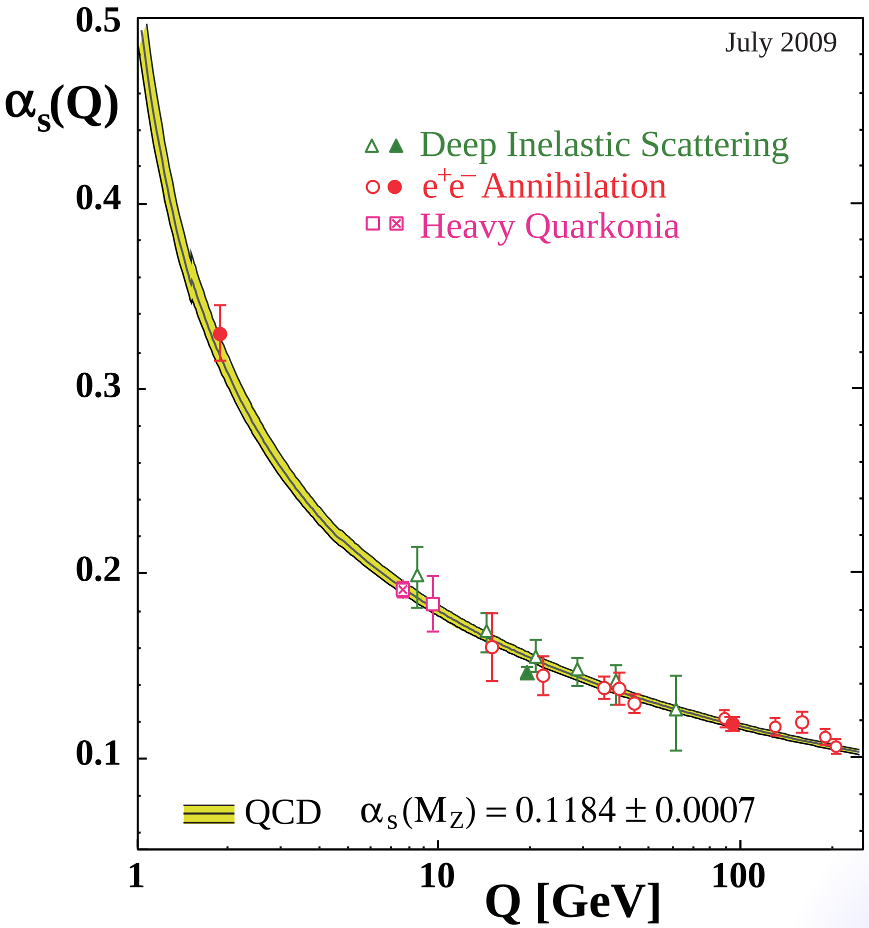

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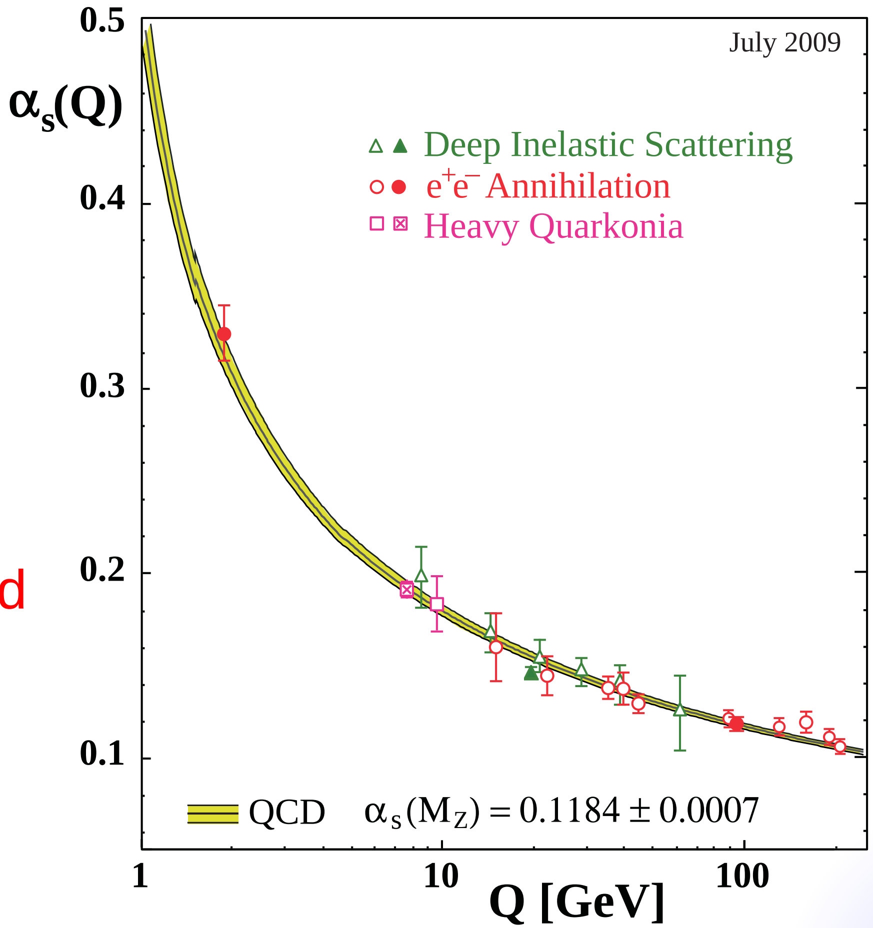


Note:

- $\alpha_s \sim 0.2 \gg \alpha_e$
  perturbarive corrections larger
- Non-perturnative in the infrared ($\lesssim 1$ GeV)

QCD at hadron colliders

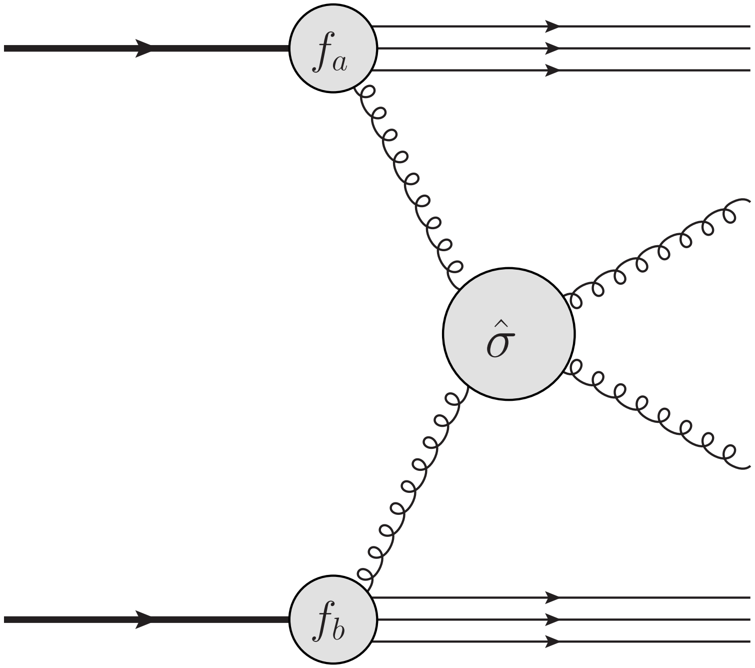
Why is it important at the LHC?

Protons made of quarks and gluons

$\Rightarrow$ interact mostly through string interactions

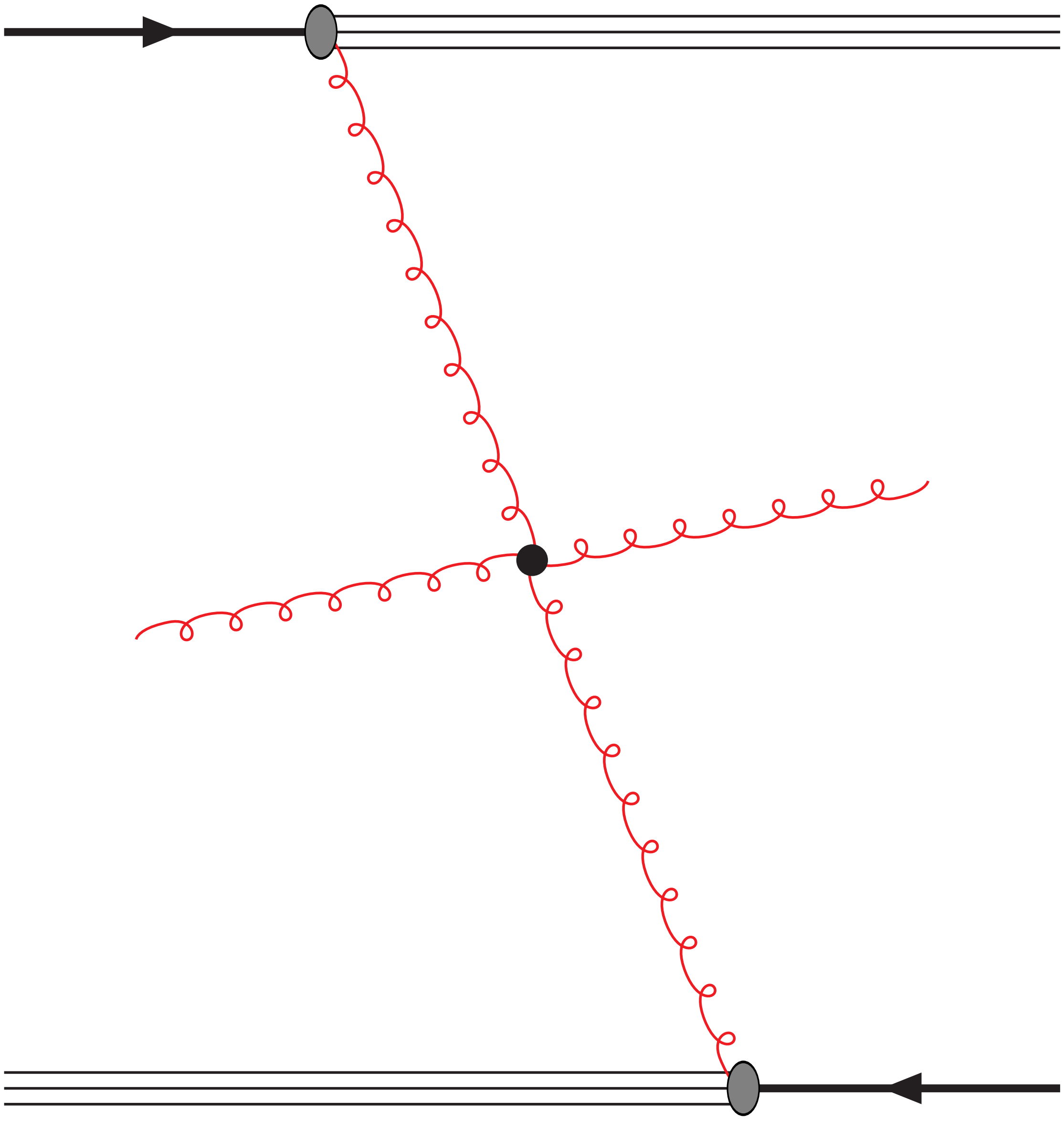
$\Rightarrow$ QCD needed for any single event
even for electro-weak, Higgs or BSM!

QCD at hadron colliders



Typical example: QCD needed for the PDF
i.e. the quark and gluon contents of the proton

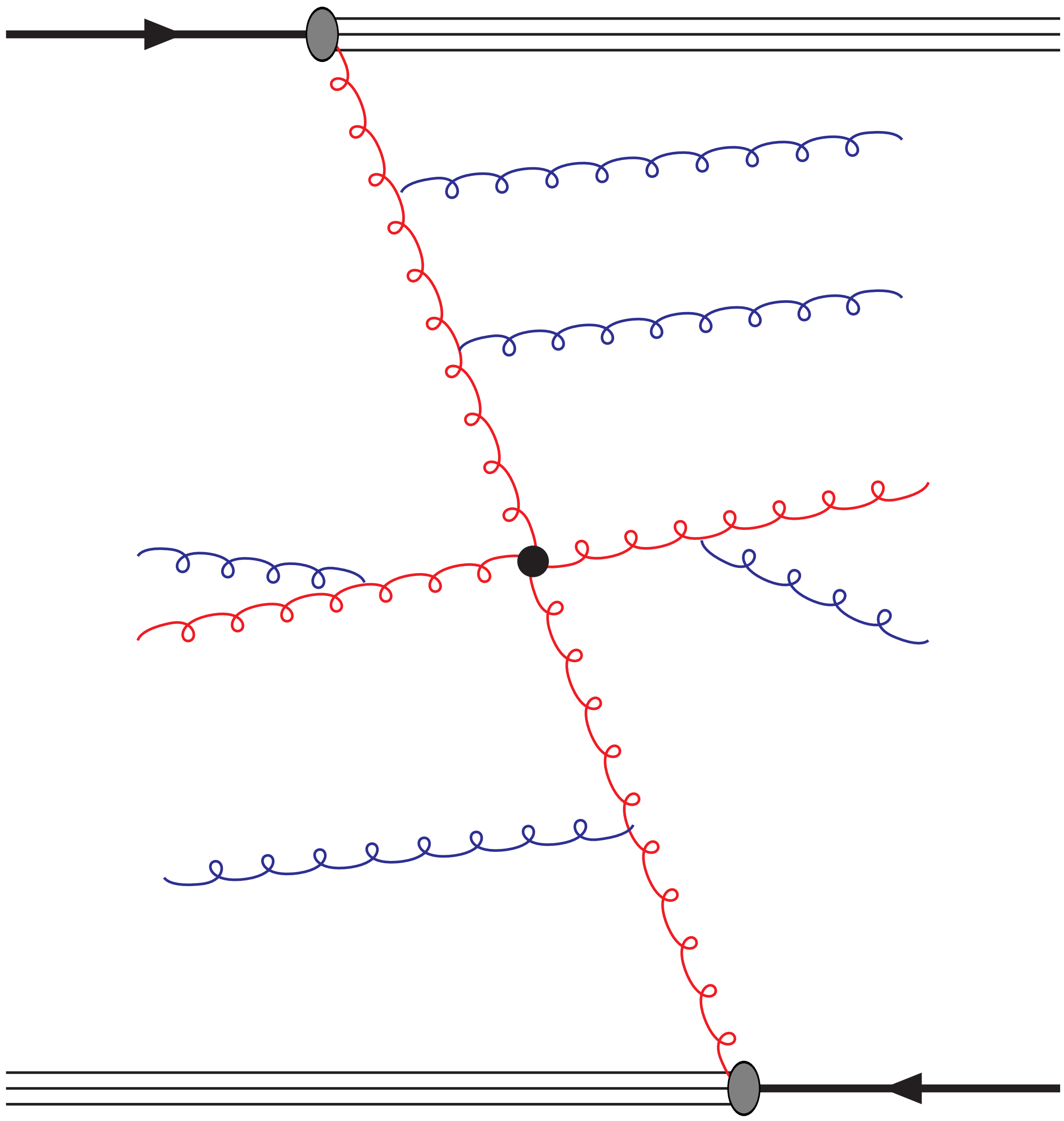
The more realistic version



- Hard ME

  perturbative

The more realistic version



- Hard ME
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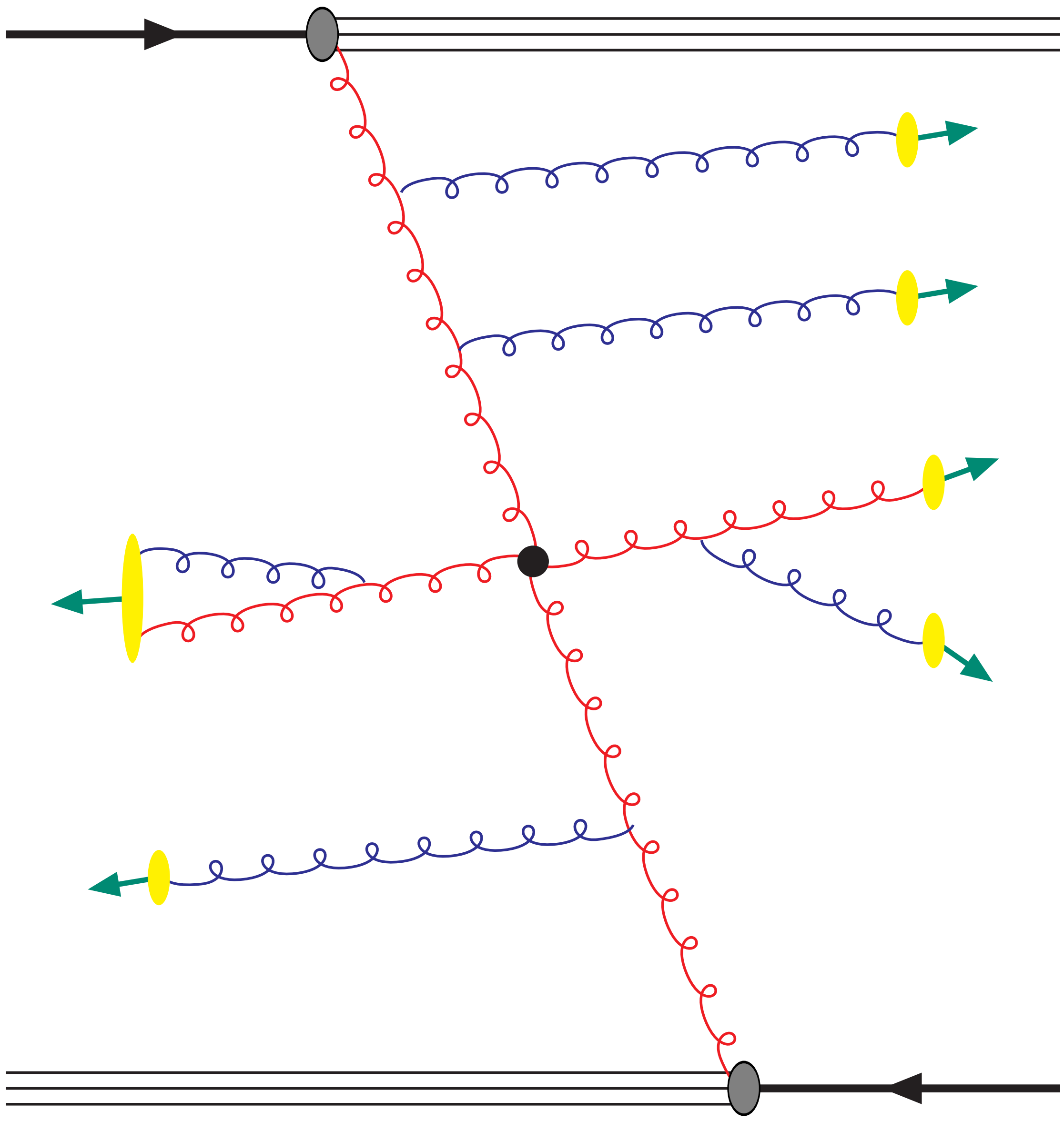
- Parton branching
  initial+final state radiation

The more realistic version



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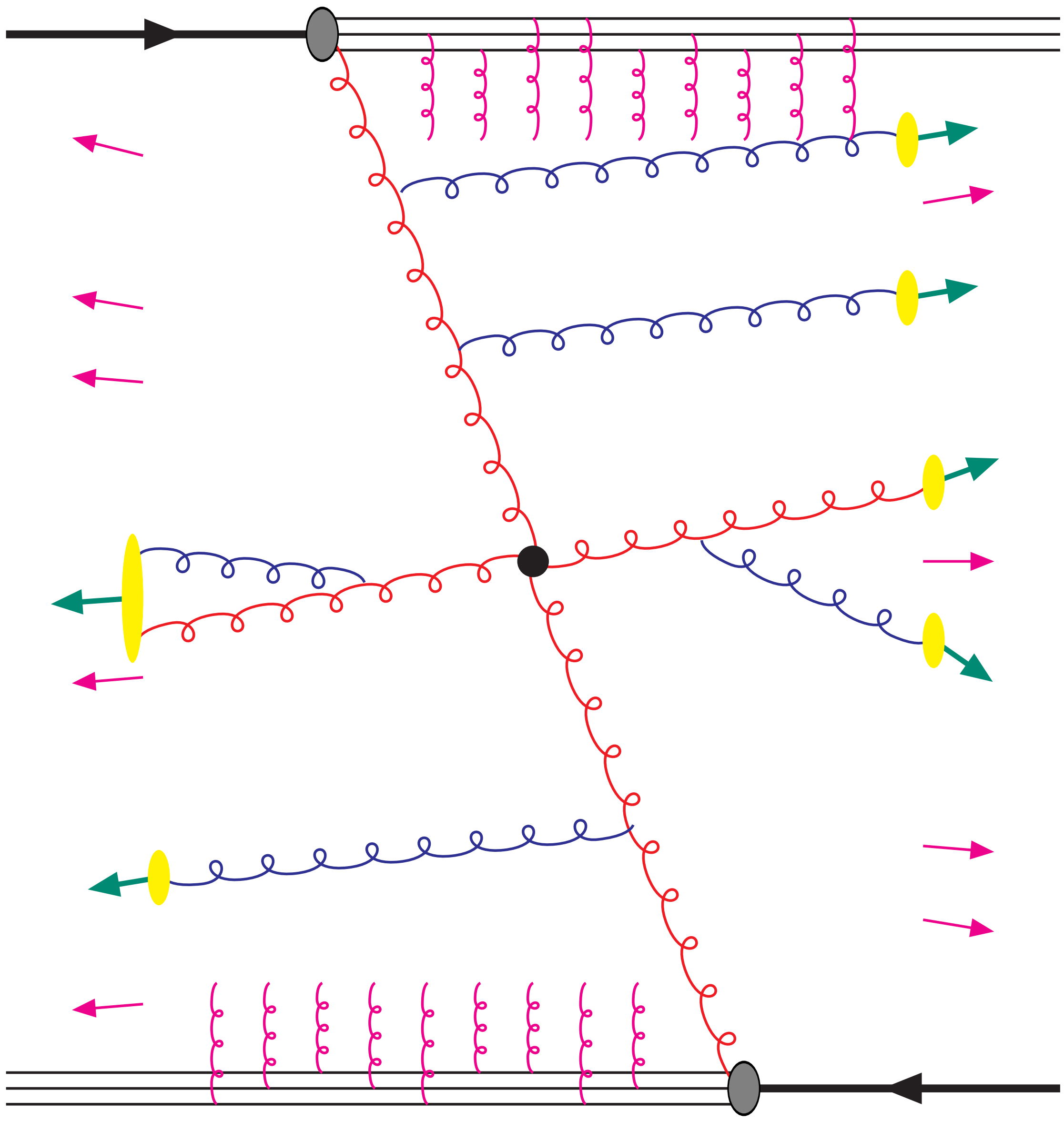


- Hard ME
  perturbative
- Parton branching
  initial+final state radiation
- Hadronisation
  $q, g \to$ hadrons
- Multiple interactions
  Underlying event (UE)

Heavy quarks

Light and heavy quarks

6 quark flavours:

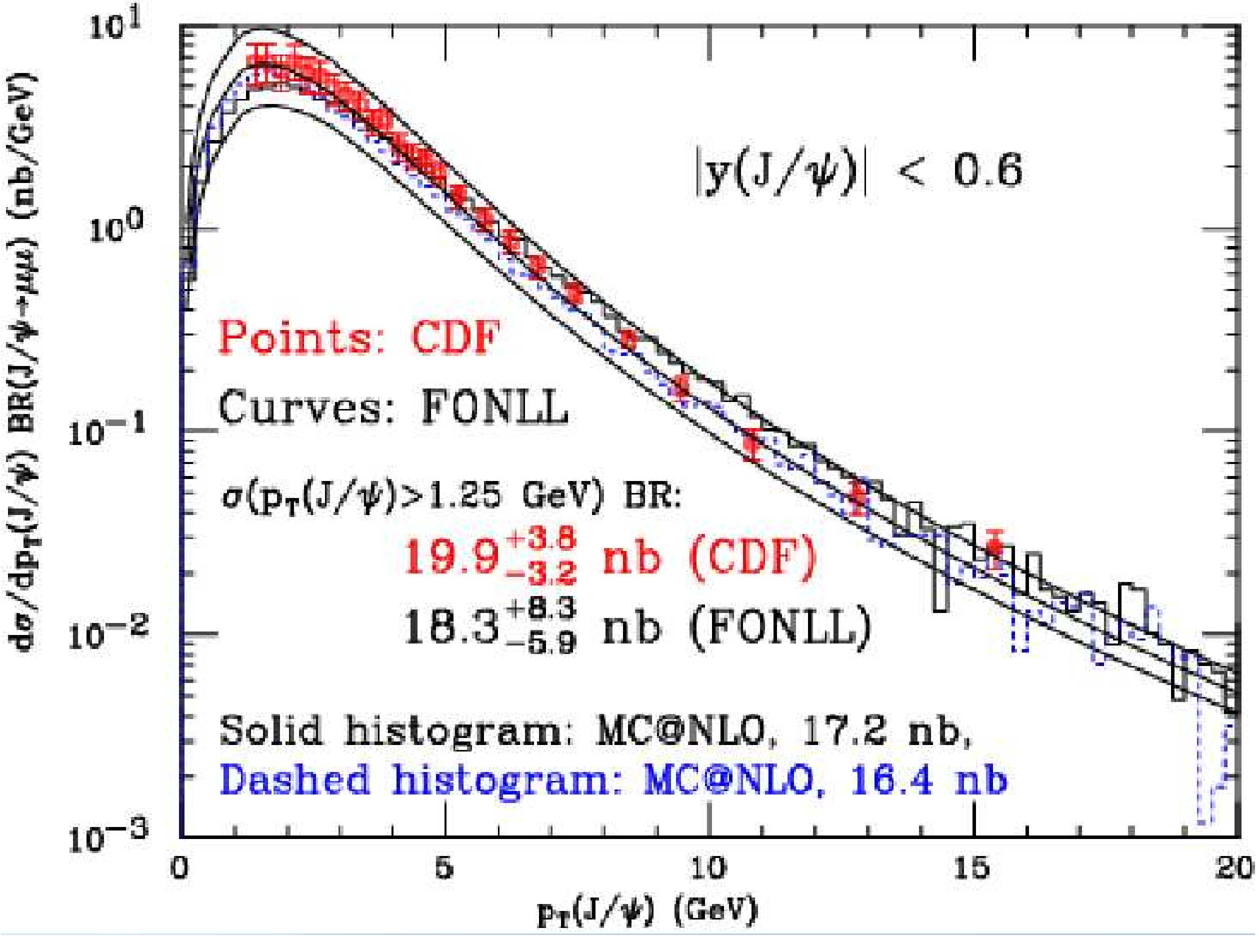
- u, d, s: mass ≈ 0
- c: $m \sim 1.5$ GeV
  Etat typique: $J/\Psi \equiv c\bar{c}$
- b: $m \sim 4.5$ GeV
  Etats typiques: B, Υ
- t: $m \sim 172$ GeV
  Decay into W and b
  $W \to q\bar{q}$ ($\approx$ 66%), $W \to \ell\nu$ ($\approx$ 33%)

Why am I here?

- $m_{c,b,t} \gg \Lambda_{\rm QCD}$: we may apply perturbation theory
- b:
  - could be tagged: displaced vertex
  - SM: b production vs. QCD, top decay
  - new physics search:
    - D0: like-sign $\mu\mu$ charge asym (from b decay)
    - $H \to b\bar{b}$ dominant at low Higgs mass
- top:
  - top in the standard model *e.g.* mass measurement
  - BSM: coupling $\propto m$
    $\Rightarrow$ modifications in the top sector
    $\Rightarrow$ very important at the LHC

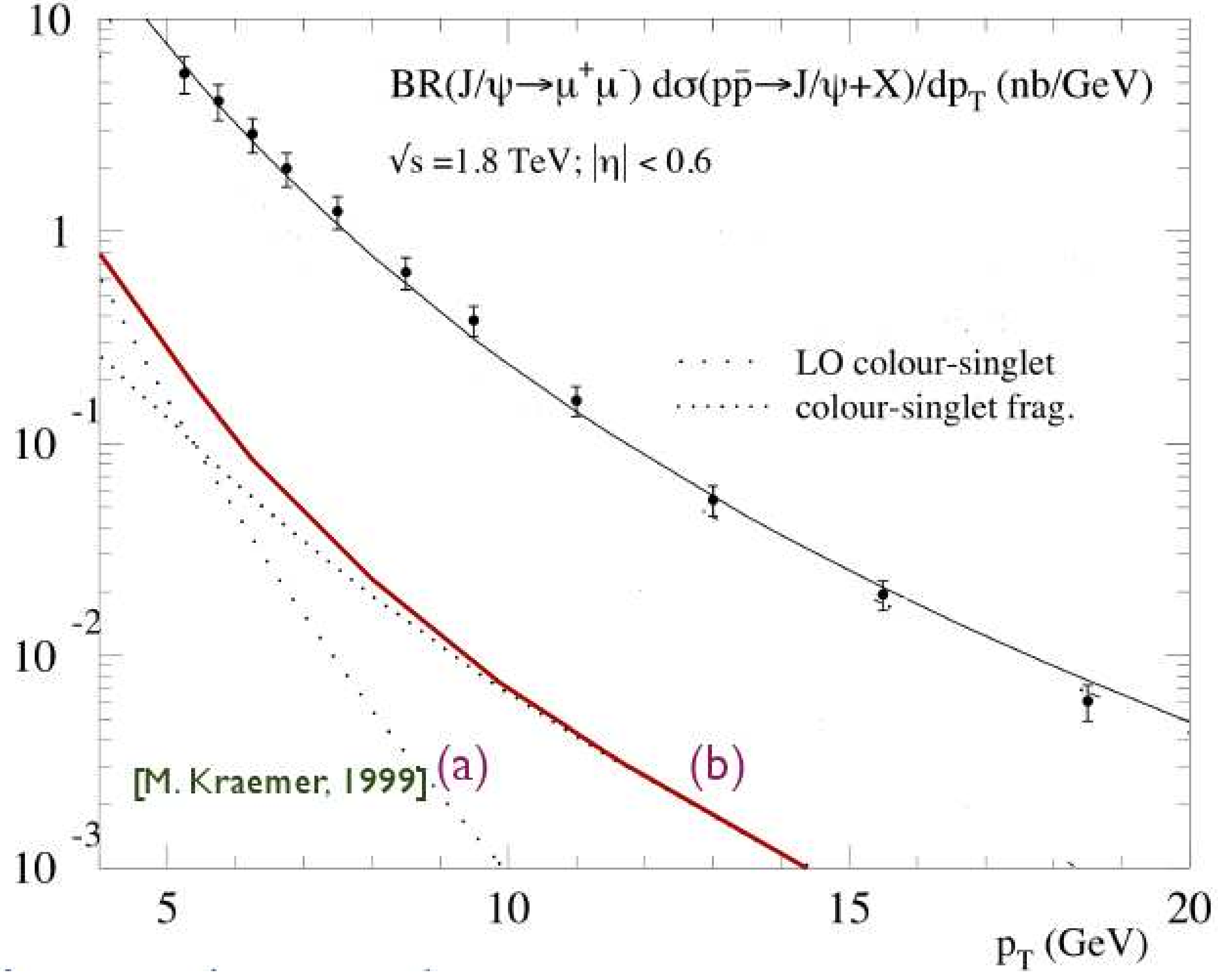
Perturbative QCD: charm

J/Ψ production: $J\Psi$ from b decay



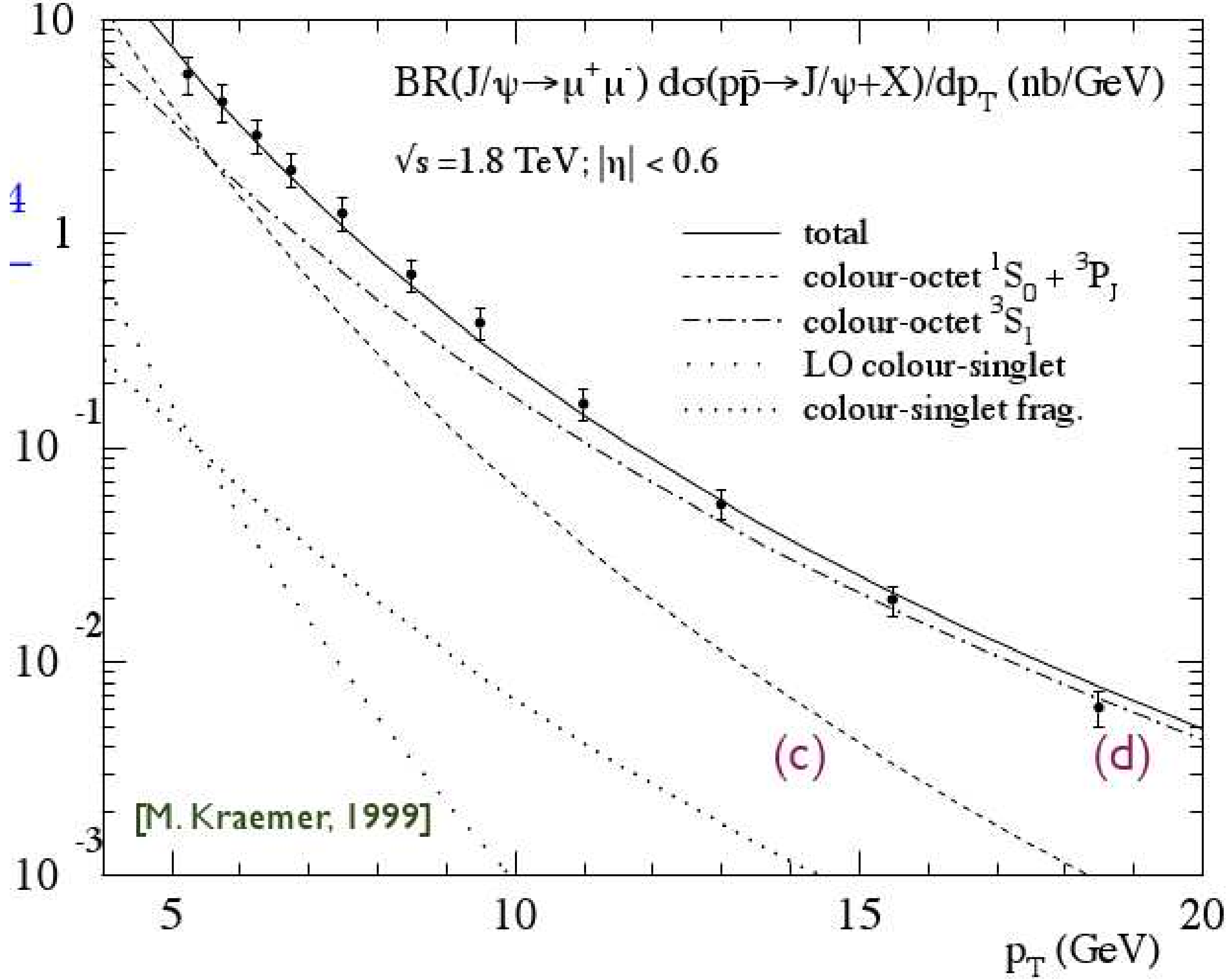
Perturbative QCD: charm

J/Ψ production: Not the best agreement ever



Perturbative QCD: charm

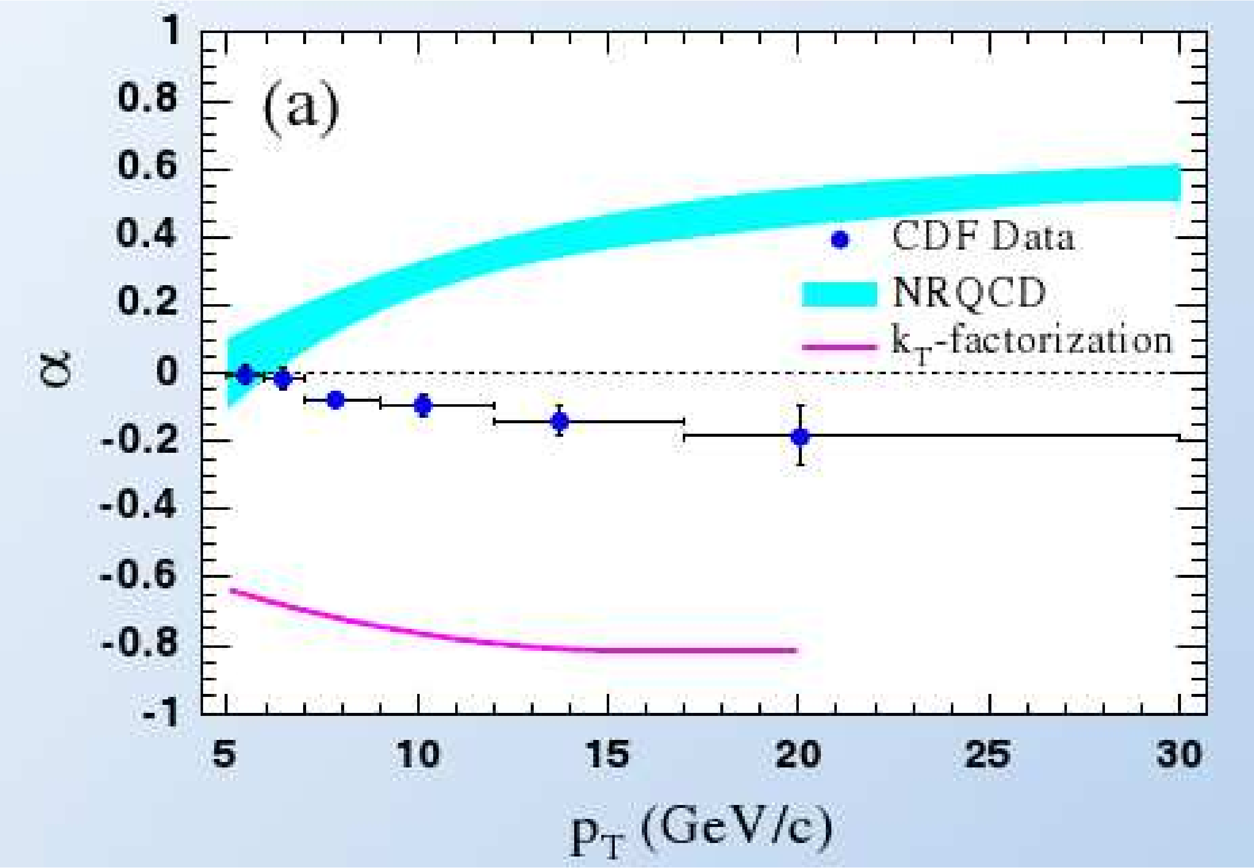
J/Ψ production: better with higher-order corrections*



* agreement not 100% understood

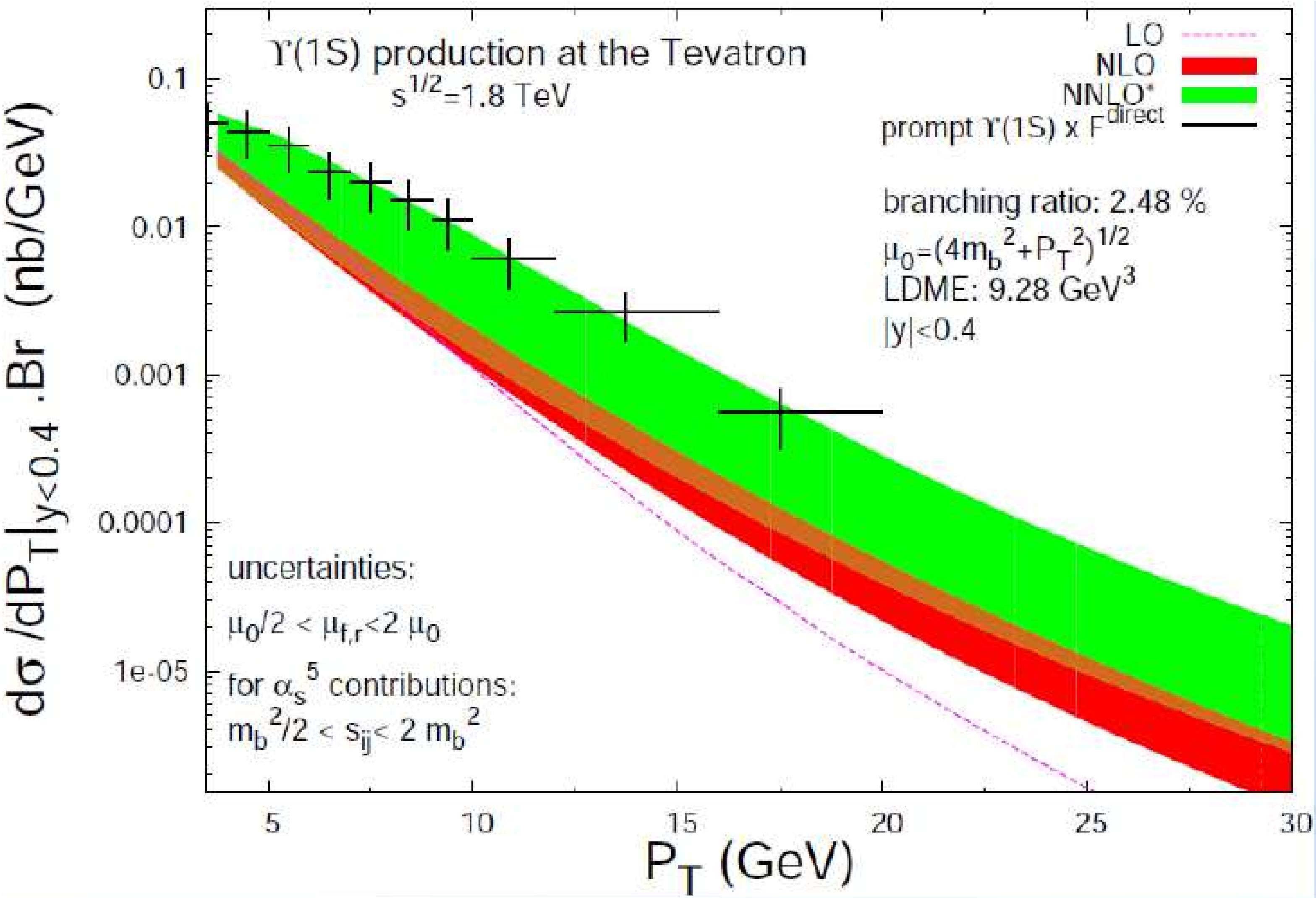
Perturbative QCD: charm

J/Ψ production: room for improvement



Perturbative QCD: bottom

J/Ψ production: again, higher-order important



top physics

- Production:
  - Mostly $gg \to t\bar{t}$
  - Tevatron: $\sigma_t \approx 10$ pb: discovery!
  - LHC: $\sigma_t \approx 1$ nb: $\approx 10/$s LHC$\equiv$ top factory
- Decay:
  - Mostly $t \to Wb$
    $t \to q\bar{q}b$ ($\approx 66\%$) or $t \to \ell\nu_\ell b$ ($\approx 33\%$)
  - for $t\bar{t}$: 3 options
    - leptonic: not-so-easy because 2 neutrinos
    - semi-leptonic: ℓ, 4 jets (2b) and $\not{E}_t$
      (the most convenient)
    - hadronic: 6 jets *i.e.* technical to reconstruct
      but $\approx$ 45% of the stat!

Top discovery

“discovery” at the Tevatron

FERMILAB-PUB-94/097-E

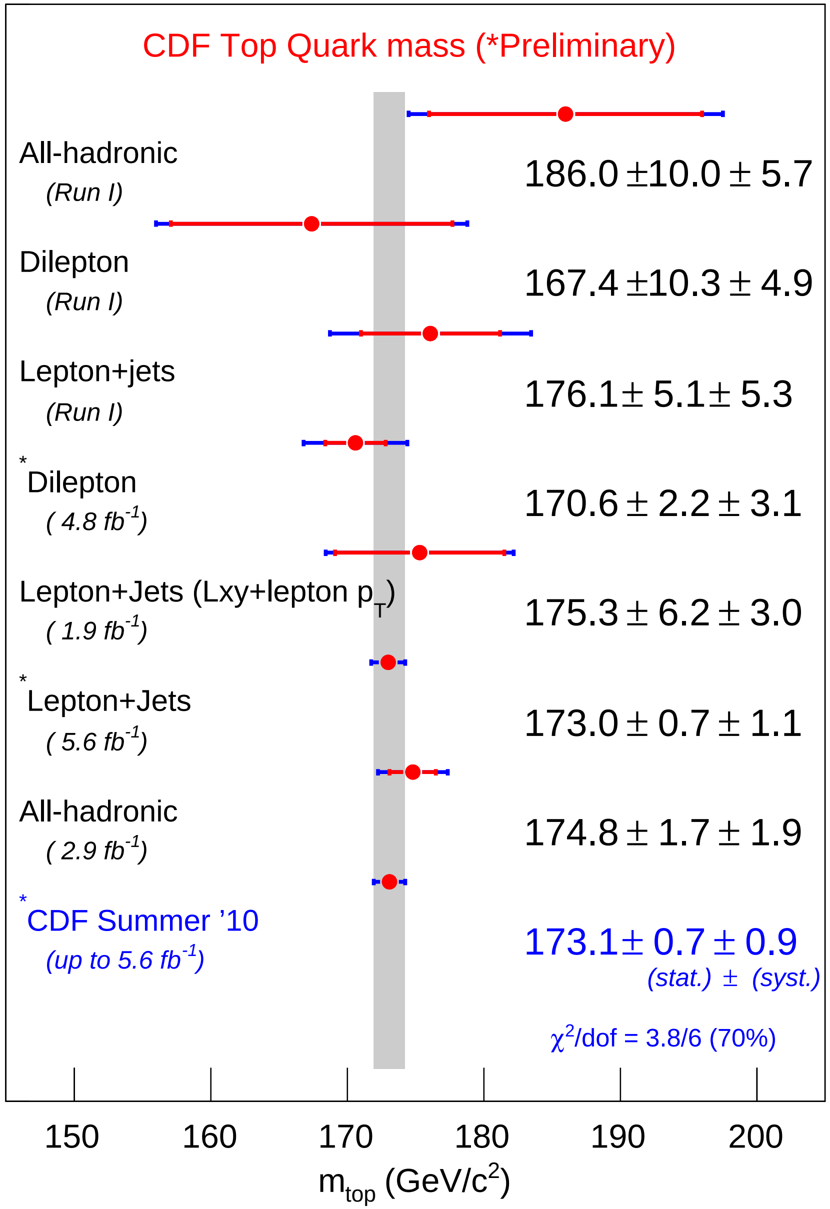
Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

Abstract

We present the results of a search for the top quark in 19.3 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The data were collected at the Fermilab Tevatron collider using the Collider Detector at Fermilab (CDF). The search includes Standard Model $t\bar{t}$ decays to final states $ee\nu\bar{\nu}$, $e\mu\nu\bar{\nu}$, and $\mu\mu\nu\bar{\nu}$ as well as $e + \nu$ + jets or $\mu + \nu$ + jets. In the (e, μ) $+\nu$ + jets channel we search for b quarks from t decays via secondary-vertex identification and via semileptonic decays of the b and cascade c quarks. In the dilepton final states we find two events with a background of $0.56^{+0.25}_{-0.13}$ events. In the e, μ $+\nu$ + jets channel with a b identified via a secondary vertex, we find six events with a background of 2.3±0.3. With a b identified via a semileptonic decay, we find seven events with a background of 3.1±0.3 . The secondary-vertex and semileptonic-decay samples have three events in common. The probability that the observed yield is consistent with the background is estimated to be 0.26%. The statistics are too limited to firmly establish the existence of the top quark, however a natural interpretation of the excess is that it is due to $t\bar{t}$ production. We present several cross checks. Some support this hypothesis, others do not. Under the assumption that the excess yield over background is due to $t\bar{t}$, constrained fitting on a subset of the events yields a mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2 for the top quark. The $t\bar{t}$ cross section, using this top quark mass to compute the acceptance, is measured to be $13.9^{+6.1}_{-4.8}$ pb.

PACS Numbers: 14.80.Dq, 13.85.Qk, 13.85.Ni

Top mass today



CDF today

top physics

top very important at the LHC

- precision mass measurement
- many new physics scenario involve the top (mostly because of its large mass)

$\Rightarrow$ need to reconstruct as many tops as possible

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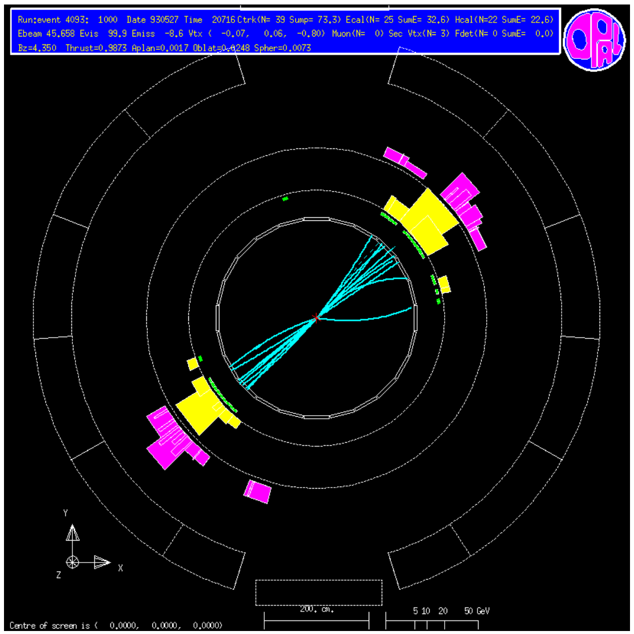
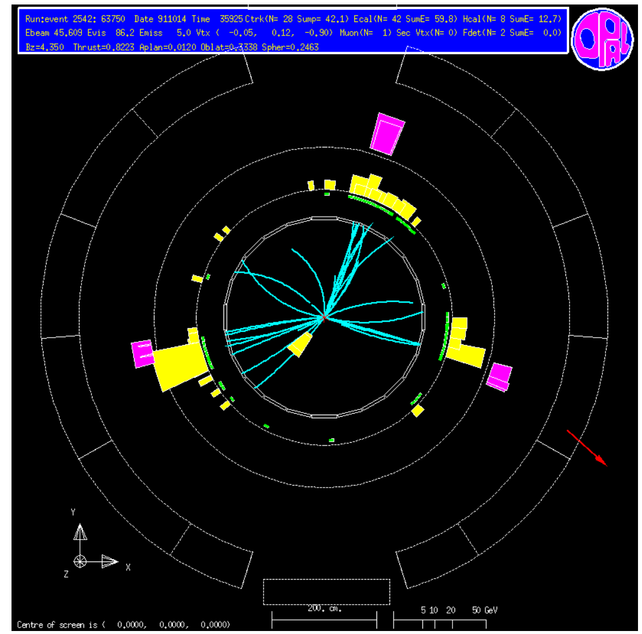
Issues:

- W+jets background
- b mis-tagging
- combinatorial background (especially for full hadr.)
- efforts *e.g.* in boosted-top reconstruction

Jets

Jets

- Final-state events are pencil-like (already observed in e^+e^- collisions)

- Consequence of the collinear divergence
  QCD branchings are most likely collinear
  ($dP/d\theta \propto \alpha_s/\theta$)

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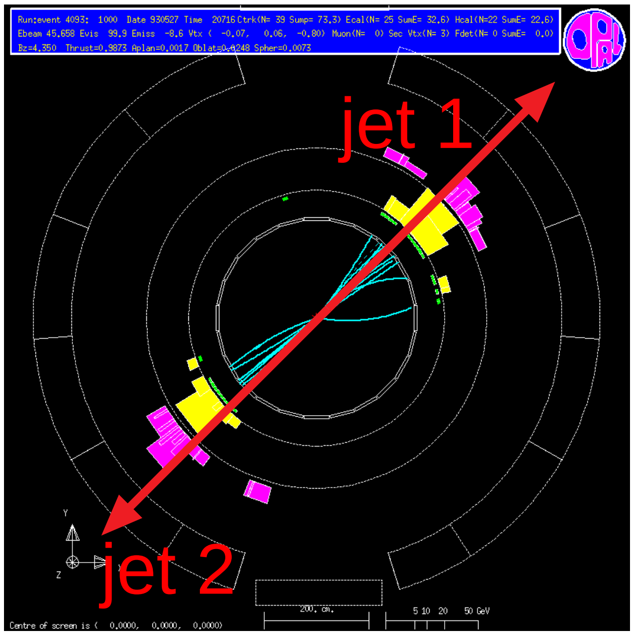

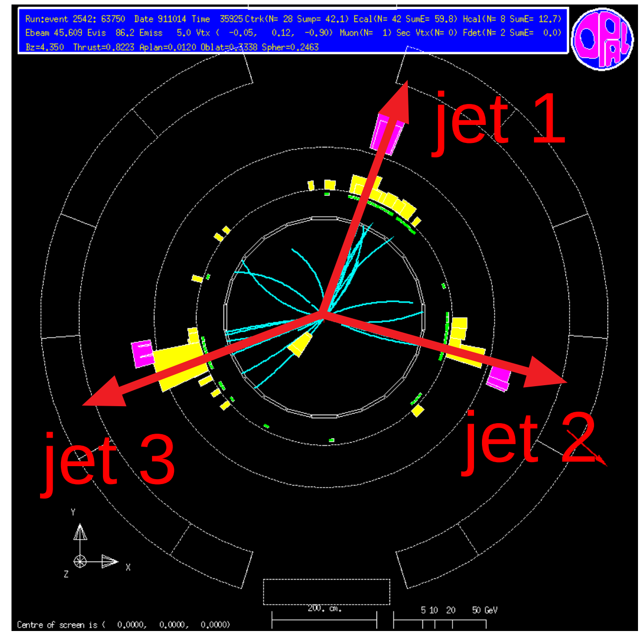

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"Jets" $\equiv$ bunch of collimated particles $\cong$ hard partons

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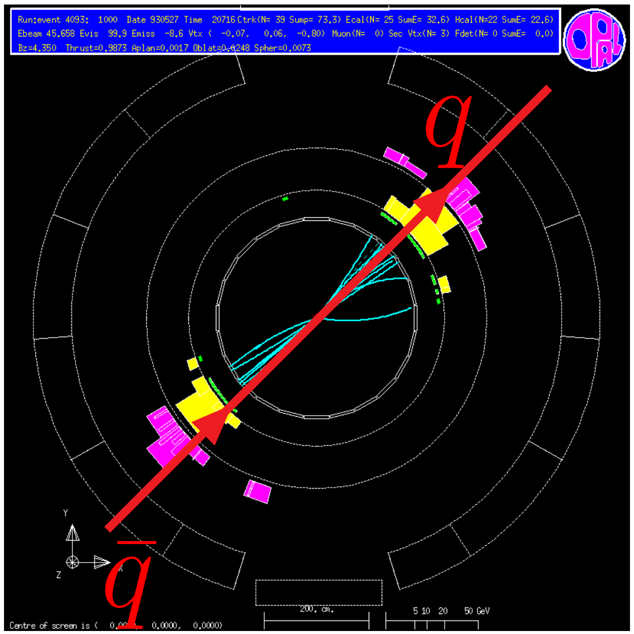

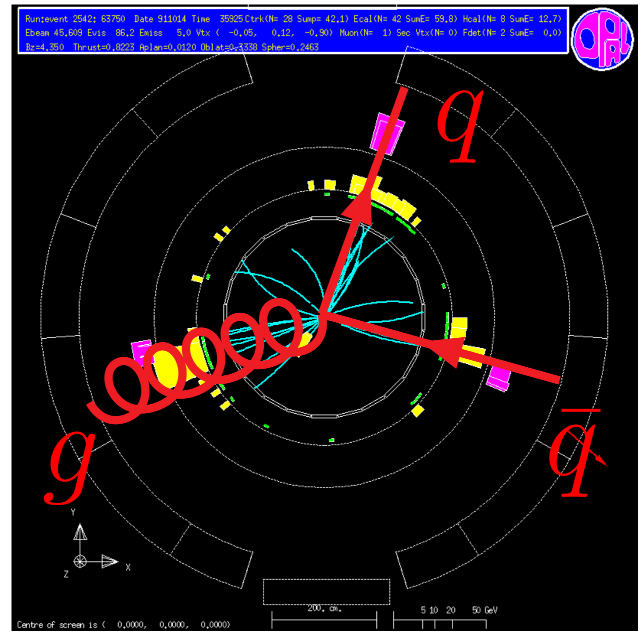

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Why worry

"Jets" $\equiv$ bunch of collimated particles $\cong$ hard partons

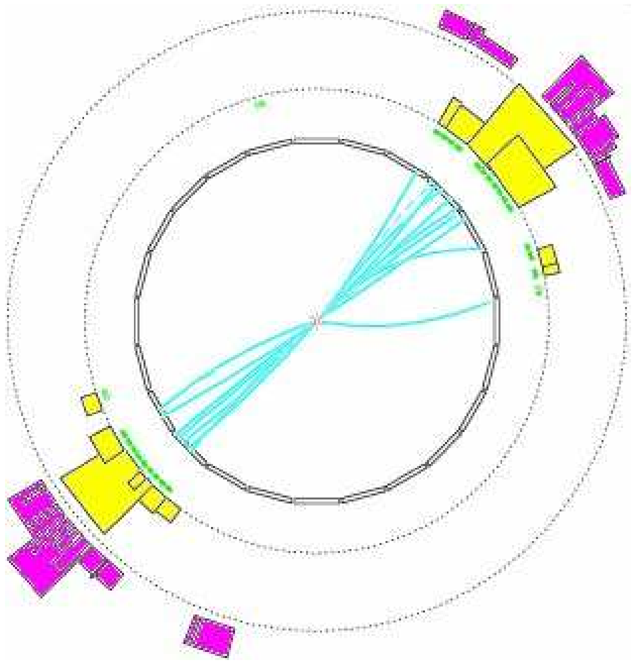
$\Rightarrow$ whenever you have QCD in the final state, you have jets in the final states!

i.e. jets useful mostly everywhere

Jets and partons

"Jets" $\equiv$ bunch of collimated particles $\cong$ hard partons

obviously 2 jets



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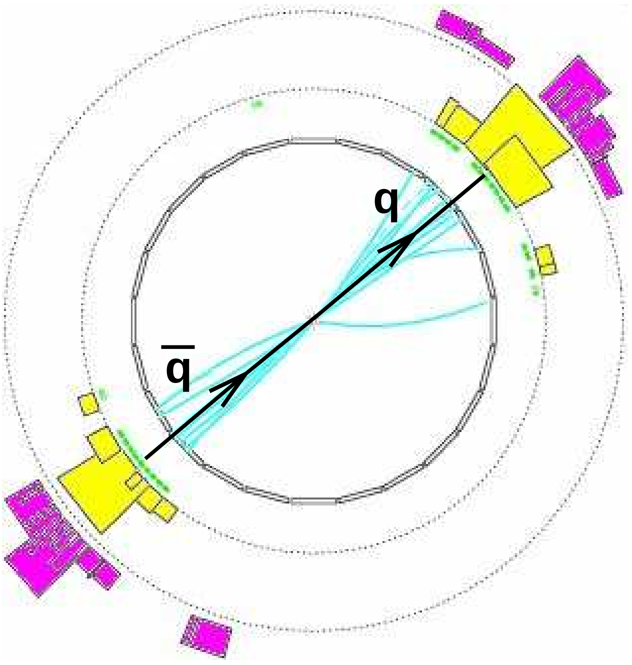

Jets and partons

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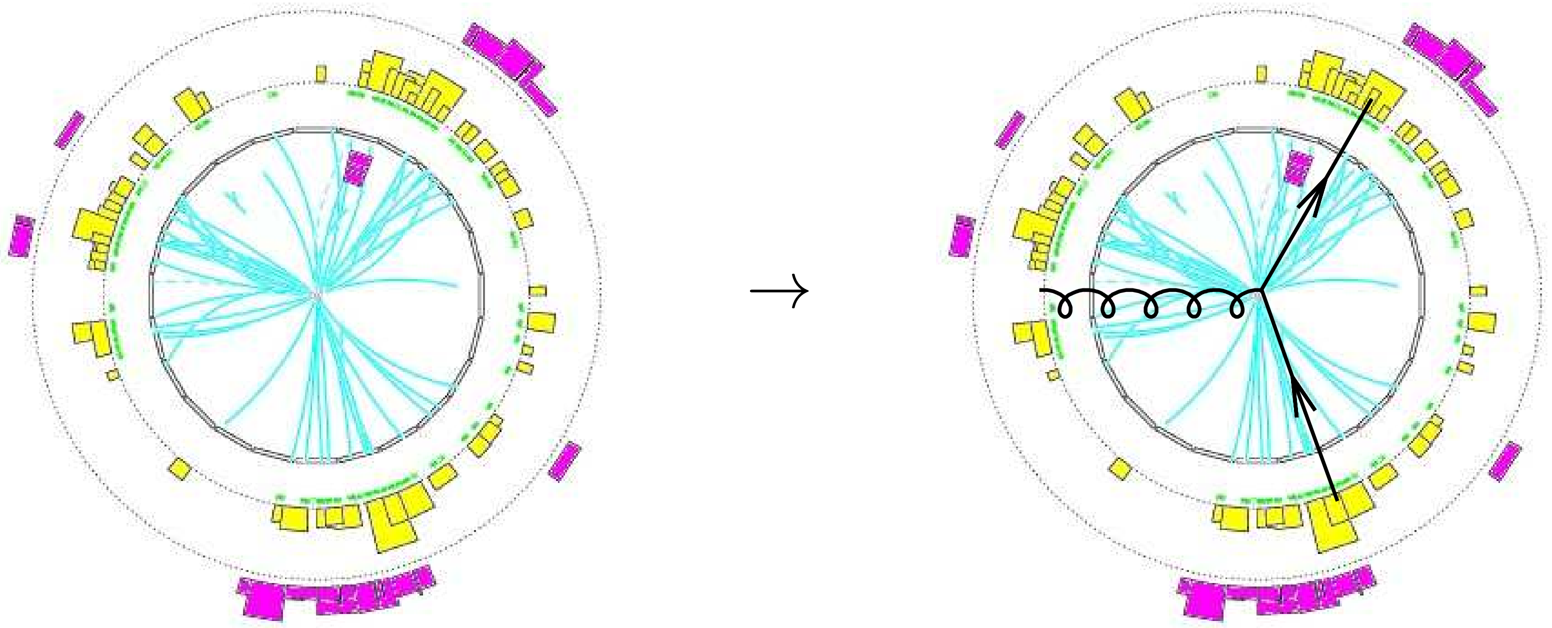
3 jets



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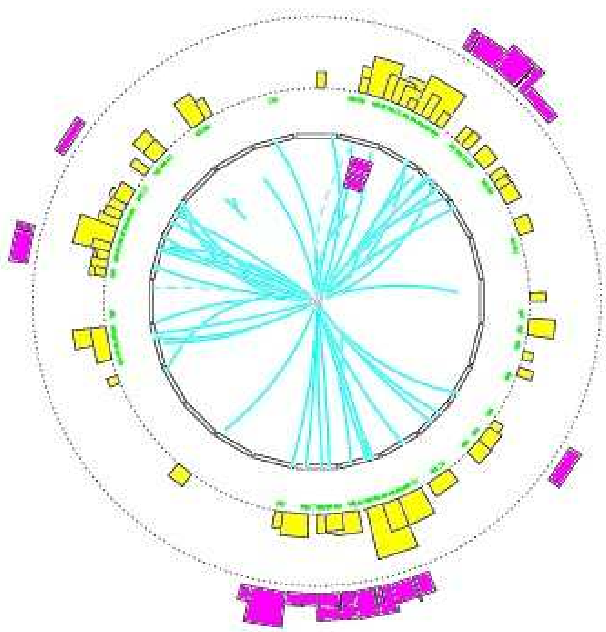
3 jets... or 4?



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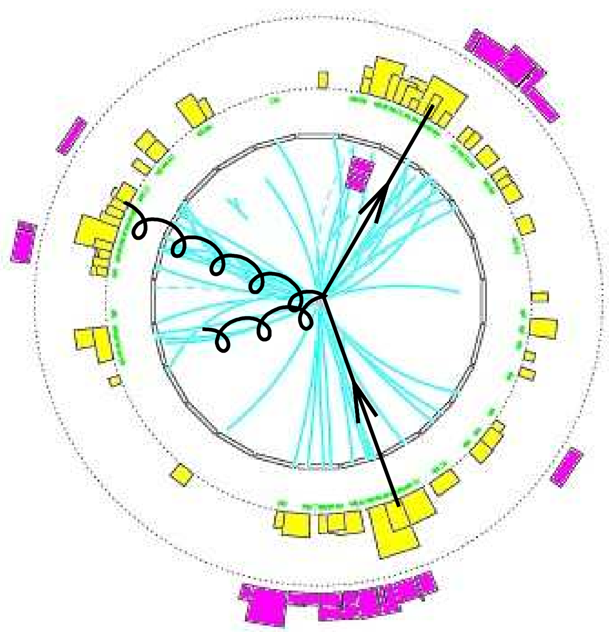

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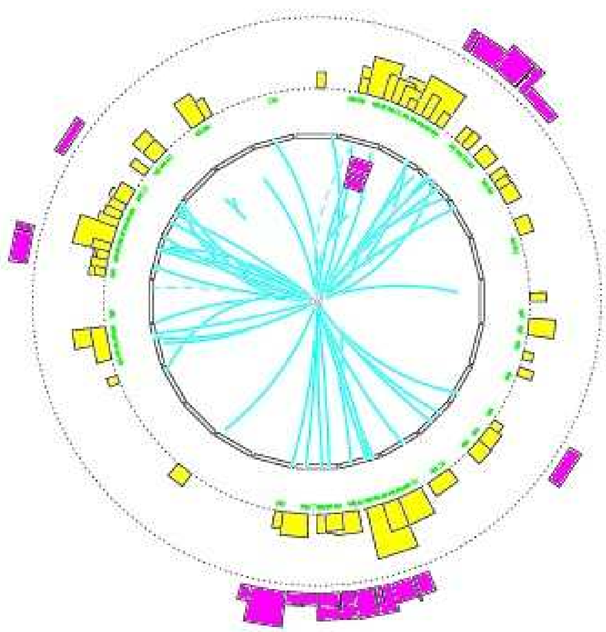

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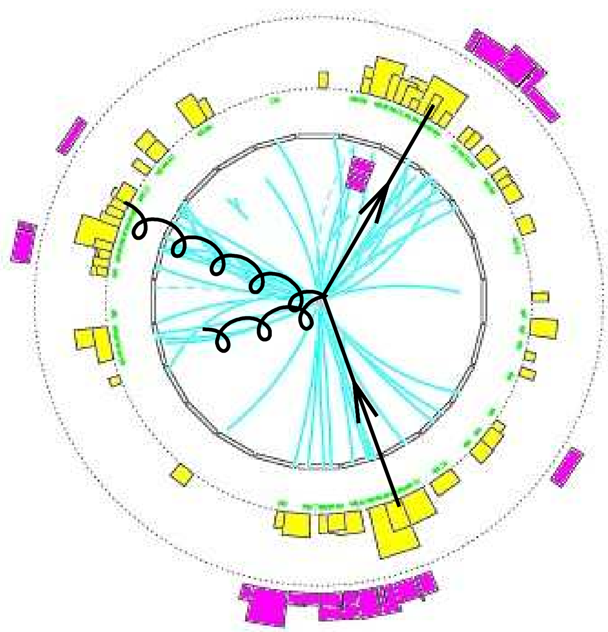
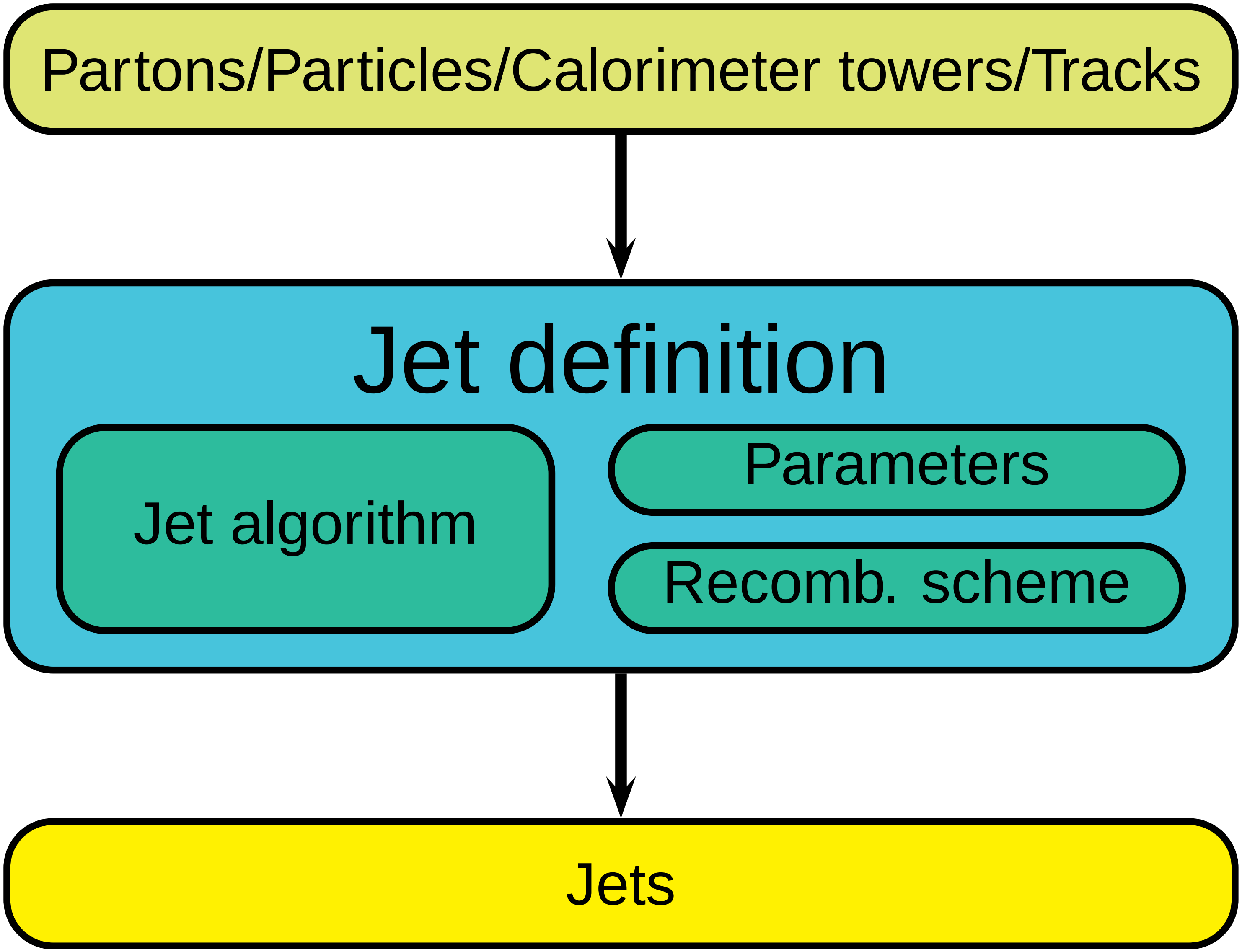


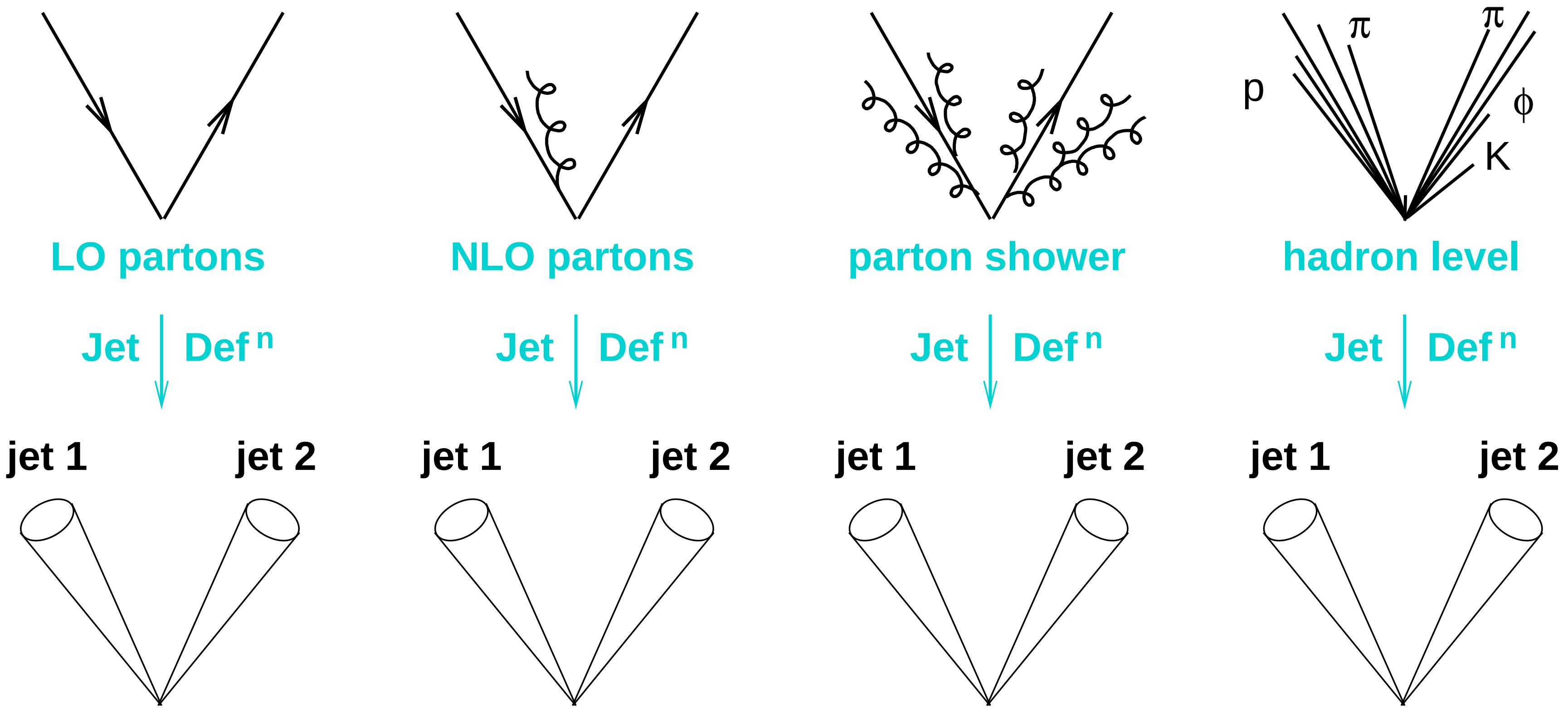
- "collinear" is arbitrary
- "parton" concept strictly valid only at LO

Jets


Partons/Particles/Calorimeter towers/Tracks
Jet definition
Jet algorithm
Parameters
Recomb. scheme
Jets

Jets

A jet definiton is supposed to be (as) consistent (as possible) across different view of an event



Jet definitions: constraints

SNOWMASS accords (FermiLab, 1990)

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

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30 years later, these are only recently satisfied!!!

Proposal:

hire (many) PhD students

to look at the (many) millions of events

Proposal:

hire (many) ~~PhD students~~ grad students
to look at the (many) millions of events

Proposal:
hire (many) PhD students
to look at the (many) millions of events

Unless you have a better proposal?

Jet definition: successive recombinations

Idea: Undo the QCD cascade

- Define an inter-particle distance d_{ij}
  and a beam distance d_{iB}
- Successively
  - Find the minimum of all d_{ij}, d_{iB}
  - If d_{ij}, recombine $i + j \to k$ (remove i, j; add k)
  - If d_{iB}, call i a jet (remove i)
- Until all particles have been clustered

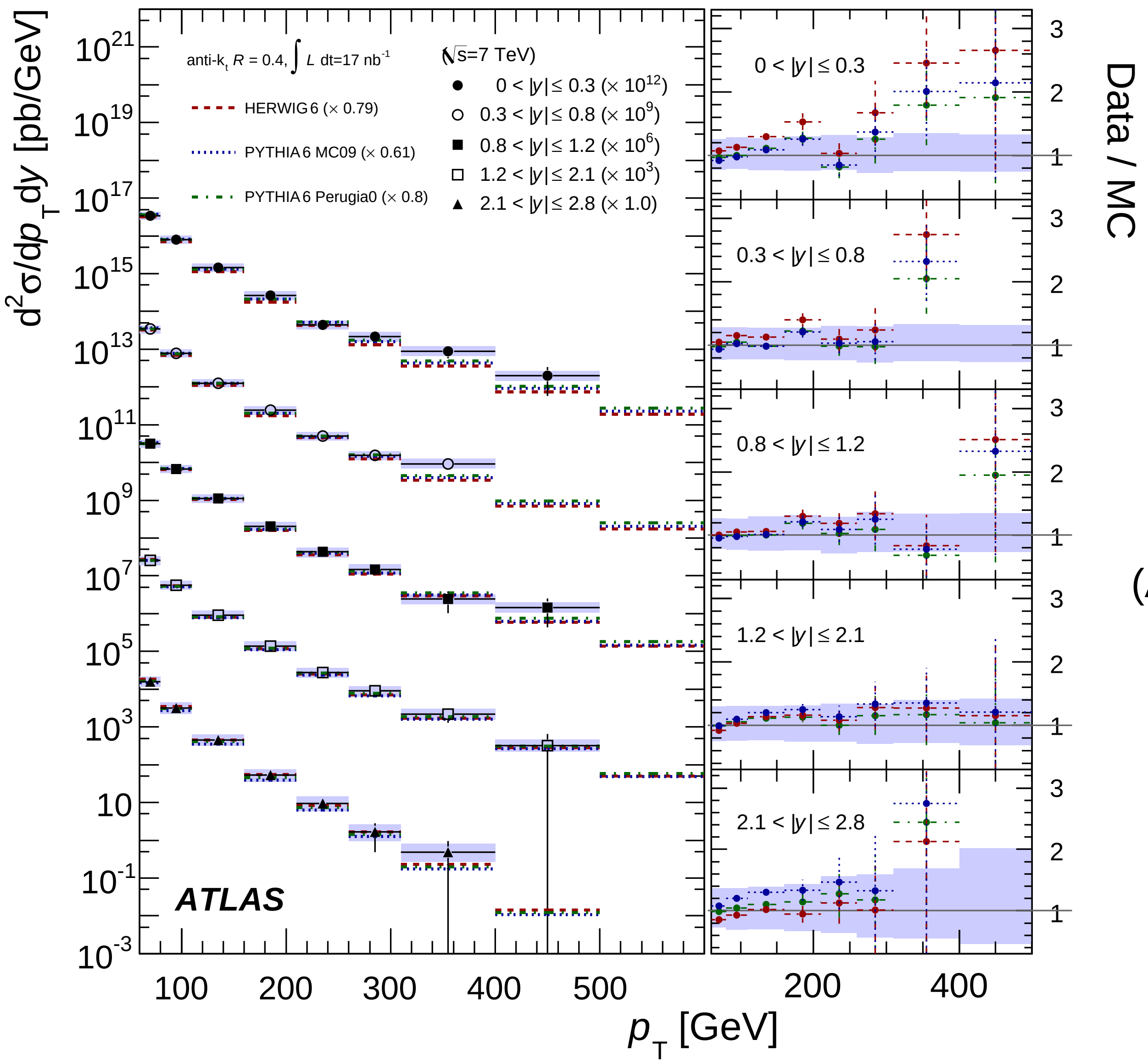
Jet definition: successive recombinations

Typical choice of distances:

$$
\begin{aligned}
d_{ij}^2 &= \min(k_{t,i}^{2p}, k_{t,j}^{2p})(\Delta y_{ij}^2 + \Delta\phi_{ij}^2) \\
d_{iB}^2 &= k_{t,i}^{2p} R^2
\end{aligned}
$$

- $p = 1$: k_t algorithm (1993)
  (as close as possible to pQCD)
- $p = 0$: Cambridge-Aachen algorithm (1997)
  (close to pQCD; useful for substructure)
- $p = -1$: anti-k_t algorithm (2008)
  (circular/soft-resilient jets)

Jet definition at the LHC



Both CMS and ATLAS use the anti-k_t

(ATLAS: $R = 0.4$ and 0.6

CMS: $R = 0.5$ and 0.7)

Jets are alive

Still room for improvement:

- Experimentally:
  jet energy scale
- Theoretically/Experimentally:
  handle UE/pileup contamination
- Theoretically/Experimentally:
  Tag boosted objects

Don't leave now...

...especially if you're on this list

- Sequential calibration (GSC) in ATLAS at the LHC
  Reina CAMACHO
- Vers une mesure de la section efficace de production de paires des quarks top dans les canaux multileptons dans l'expérience ATLAS
  Timothée THEVENEAUX-PELZER
- Mesure de l'efficacité de l'étiquetage de jets beaux dans l'expérience ATLAS
  Nancy TANNOURY
- Recherche de nouvelle physique avec ATLAS au LHC grace à l'identification des jets de saveur b
  Nicolas BOUSSON
- Four top events at the LHC from top-philic new physics
  Léa GAUTHIER