# Quantum Chromodynamics - 2

Caterina Doglioni - Lund University

Note on references: all the images from experiments are taken from the experiment websites unless otherwise noted + diagrams and tables taken from Cahn&Goldhaber / Martin&Shaw (see end of lecture for references)

# Outline of the QCD lectures

- **Lecture 1: Quarks gluons and strong interactions**
  - 1.1 From the hadron zoo to the quark model
  - 1.2 Experimental proof of the quark model
  - 1.3 Strong force: confinement and asymptotic freedom
- **Lecture 2 (Tuesday): Experimental aspects of QCD**
  - How to see quarks and gluons: jets
  - Jet substructure
  - Measurements of QCD at the LHC
  - Looking for bumps above QCD

# Recap: concepts for part 1.1

- **Part 1.1: Quarks gluons and strong interactions**
  - From the hadron zoo to the quark model
    - Protons and neutrons: **isospin** multiplet
  - Characterizing hadrons: the eightfold way, color
    - **Classification** by isospin / hypercharge
    - Where there's structure there is substructure: **baryons** and **mesons** contain quarks
    - **Color** is theorised and experimentally verified

# Recap: concepts for part 1.2

- **Part 1.2: Experimental verification of quarks**
  - Elastic scattering
    - The proton is not point-like, but what's its structure?
  - Deep inelastic scattering: 'break' protons using photons
    - Structure functions (approximately) do not scale with momentum transfer: sign that there are point-like constituents within proton
    - The proton is not just three quarks: sea and gluons

# Recap: concepts for part 1.3

- **Part 1.3: The strong force**
  - Strong force as a spring: confinement
  - QCD vs QED
    - The gluon self-interacts, the photon does not
      - Antiscreening vs screening
      - Running of the coupling constant: asymptotic freedom
  - From partons to jets (in MC generators)

# 2.1 Jet algorithms

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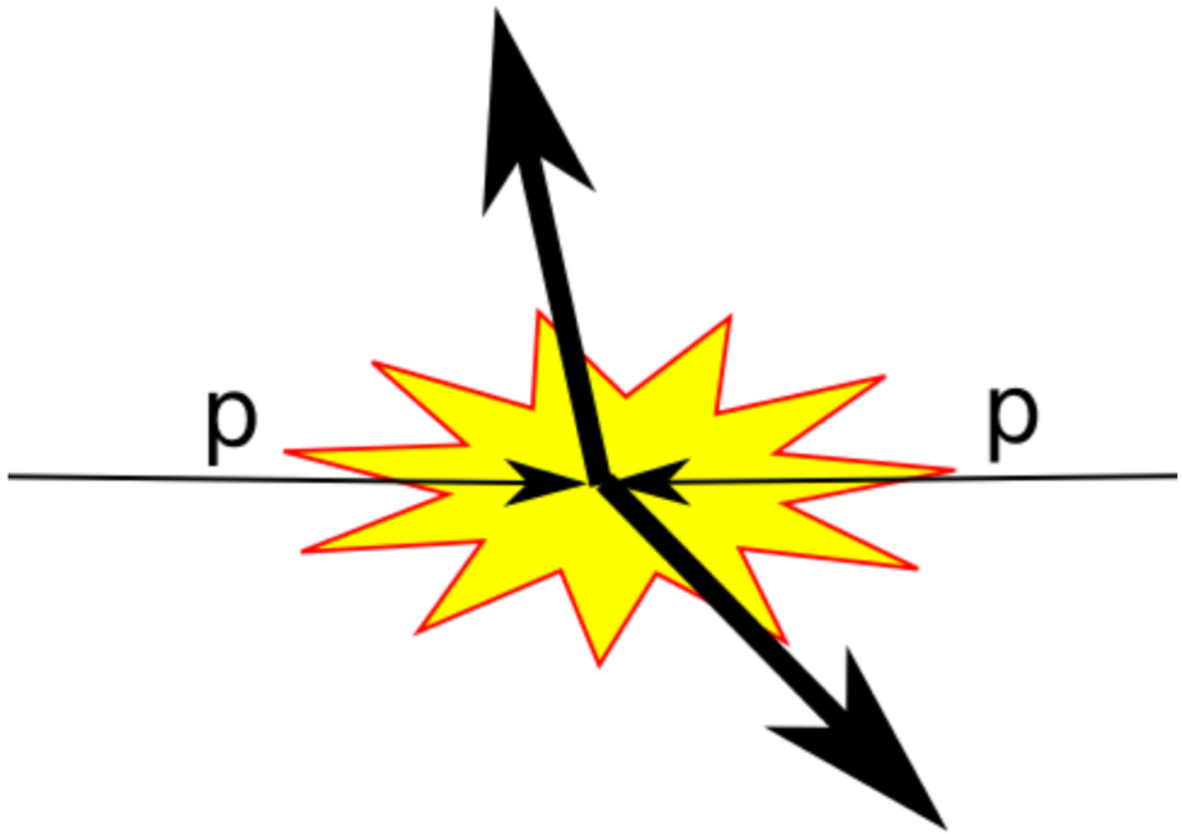
# What is a jet?

Collision of two protons → two highly energetic objects are produced

*high-pT jets*



# What is a jet?

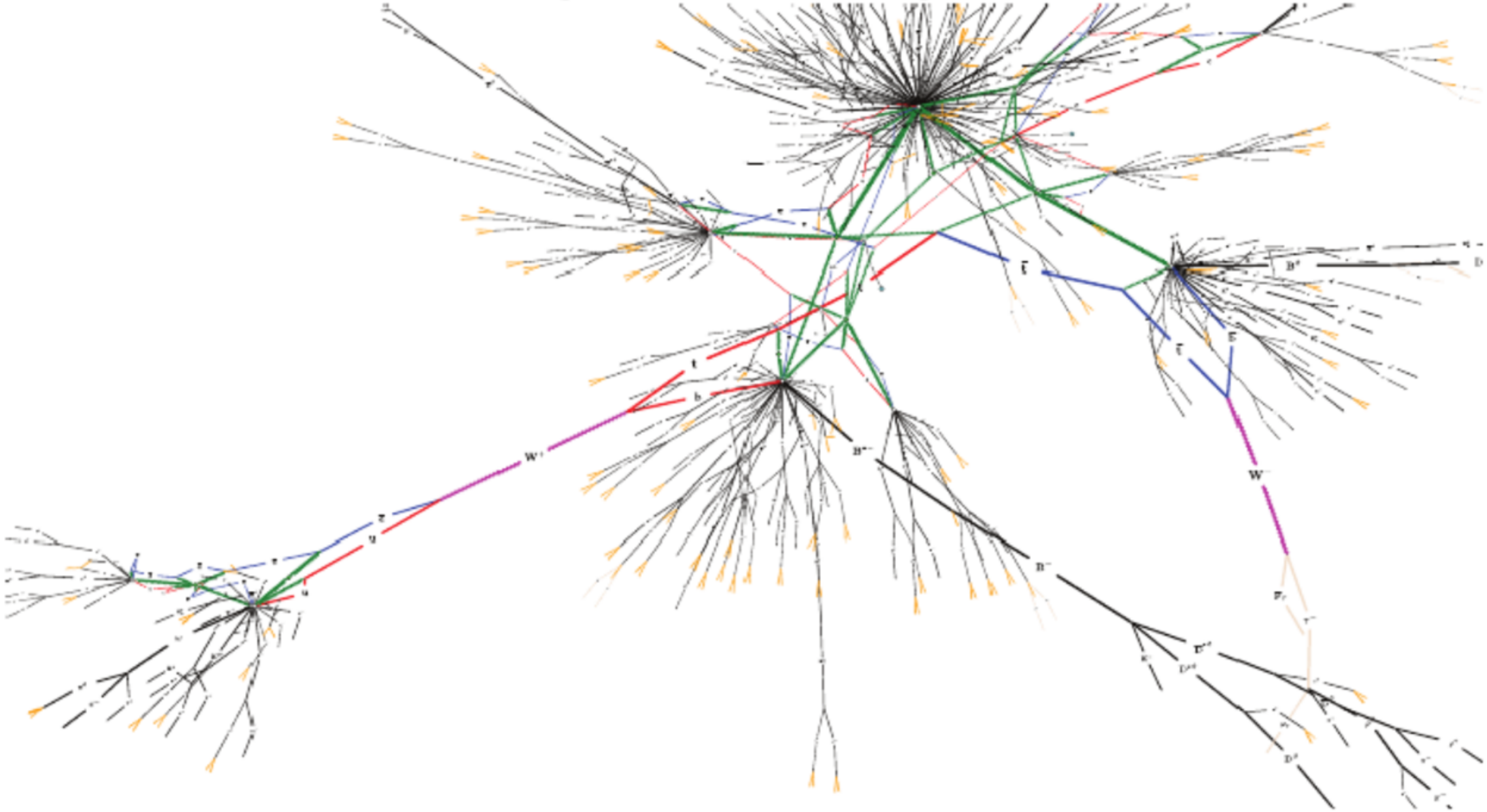
A high-$p_T$ dijet event: how we see it

...from the back of an envelope...

# What is a jet?

A high-$p_T$ dijet event: how we see it

...according to QCD from a MC generator...

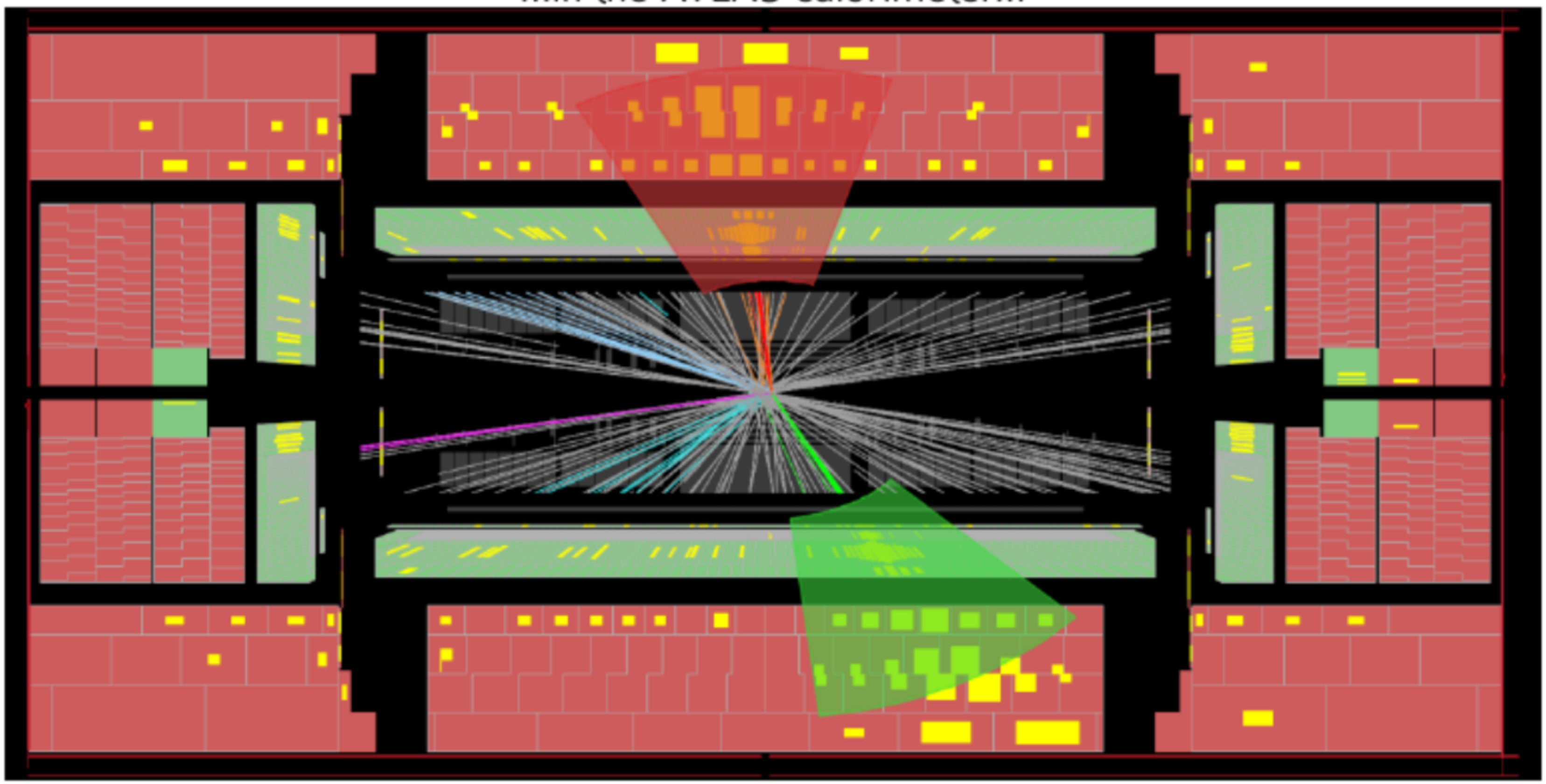


I cheated: this is a semileptonic $t\bar{t}$ event from MCViz, but you get the idea

# What is a jet?

A high-$p_T$ dijet event: how we see it

...in the ATLAS calorimeter...

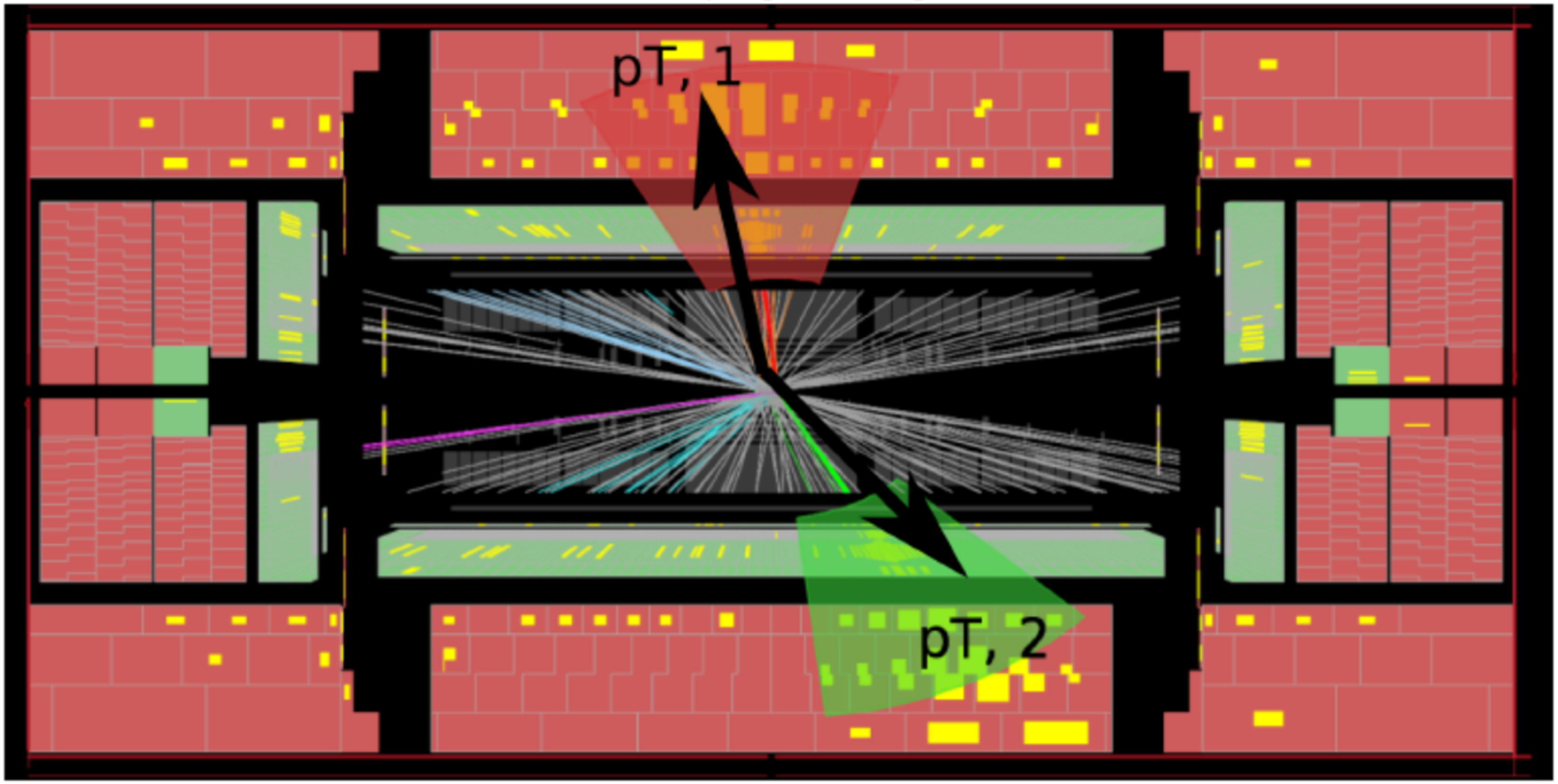


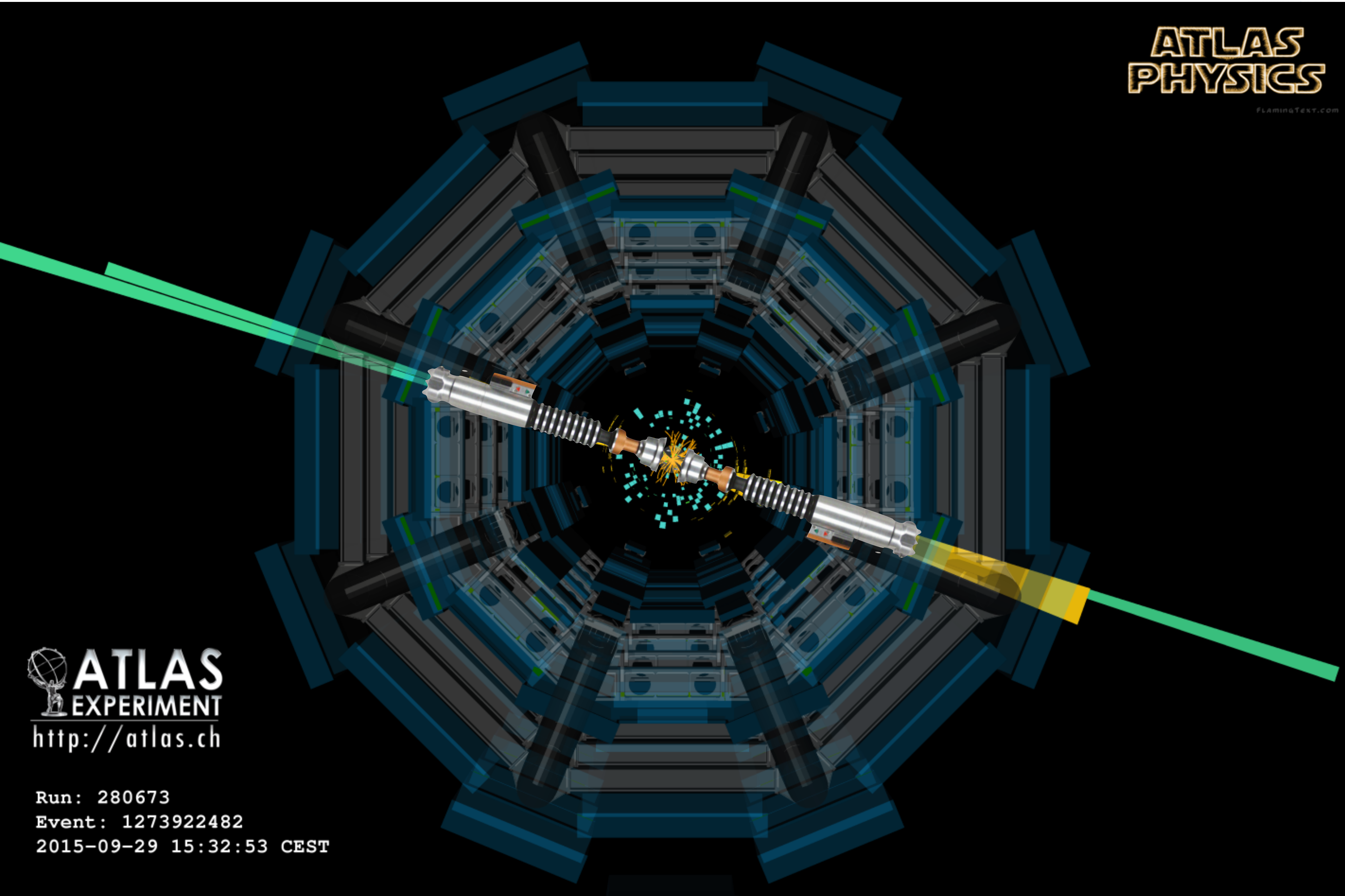
Note: some 'cleaning' already performed: ATLAS topological clustering algorithm

# What is a jet?

A high-$p_T$ dijet event: how we see it

...after applying a jet algorithm.




ATLAS
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ATLAS
EXPERIMENT
http://atlas.ch
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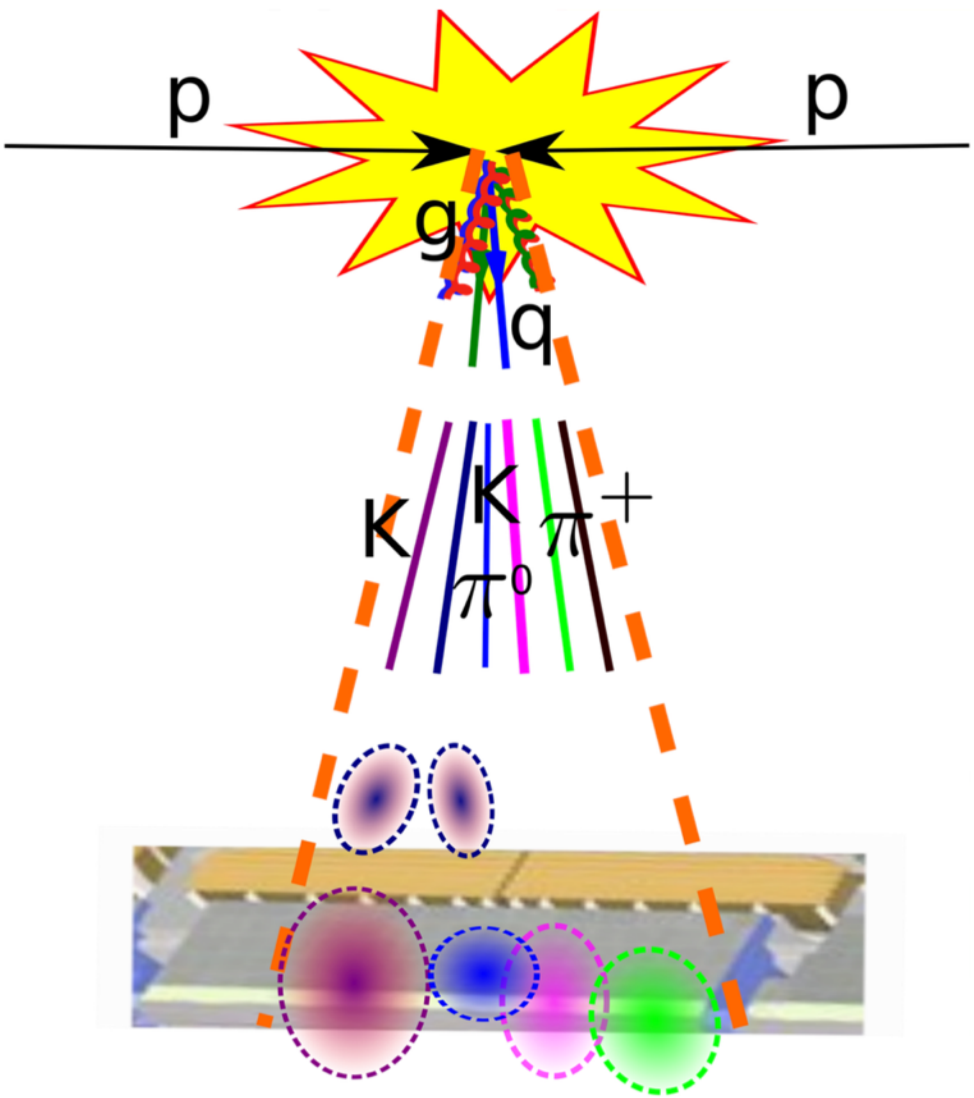
# What is a jet?




## Parton level
Quarks and gluons
from the hard scattering

## Particle level
Particles from the hadronization of
quarks and gluons

## Calorimeter level
Energy deposited in the calorimeters

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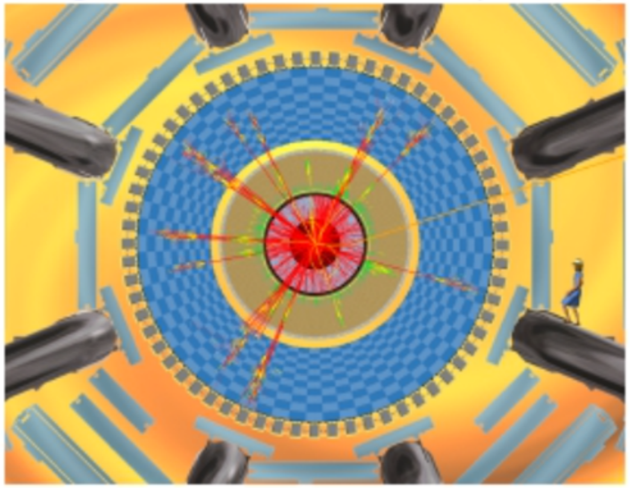
# What is a jet?

Goal: kinematics of jet ↔ kinematics of underlying physics objects
Use a jet algorithm to cluster objects into a jet

Basic algorithm: event display + physicist



"Everyone knows a jet when they see it"

Note: don't try this at home when the LHC is running

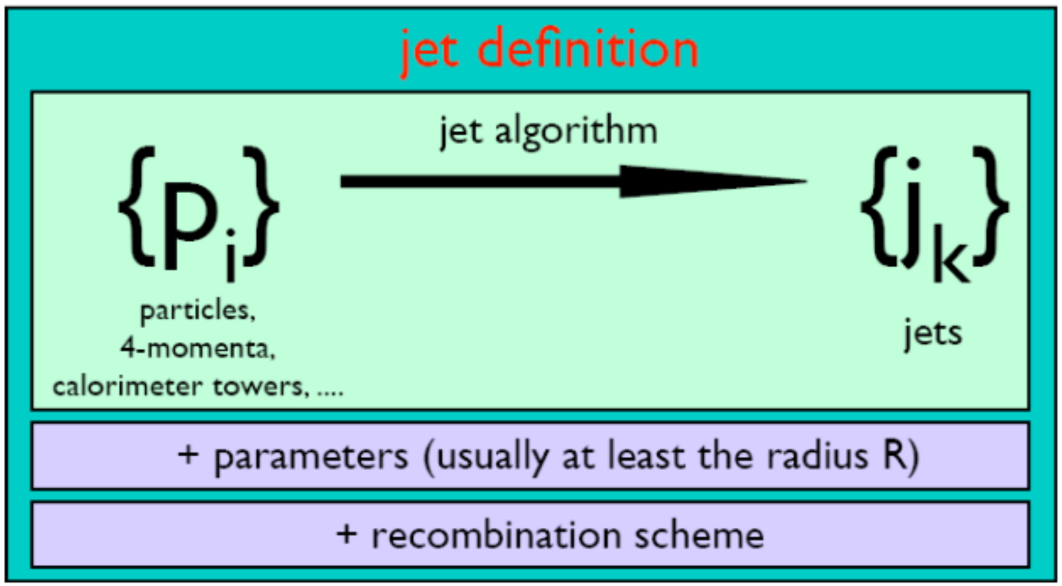
...but what is really needed for communicating results:

1. full specification of algorithm and parameters → how to group objects
2. recombination scheme → how to merge objects characteristics
3. treatment of overlapping jets (if any) → how to avoid double counting

# What is a jet?

Goal: kinematics of jet ↔ kinematics of underlying physics objects
Use a jet algorithm to cluster objects into a jet

Les Houches 2007 proceedings, arXiv:0803.0678



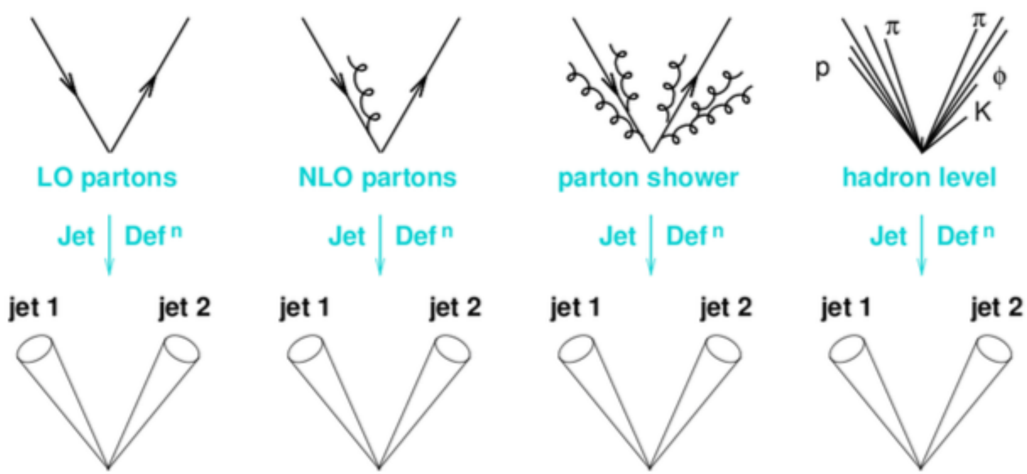

From M. Cacciari, MPI@LHC08

Apply same jet definition to objects on different levels:

1. Partons
2. Particles
   → Truth Jets
   (only particles from the hard scattering)
3. Calorimeter objects (ATLAS: Topoclusters)
   → Reconstructed Jets
4. Tracks
   → Track Jets
5. A combination of calorimeter and tracking information (CMS)
   → Particle Flow Jets

# What is a jet?

Goal: kinematics of jet ↔ kinematics of underlying physics objects
Use a jet algorithm to cluster objects into a jet




From G. Salam, MCNet School 2008

Apply same jet definition
to objects on different levels:

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2. Particles
   → Truth Jets
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   (ATLAS: Topoclusters)
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5. A combination of calorimeter and tracking information (CMS)
   → Particle Flow Jets

# Wishlist for jet algorithms

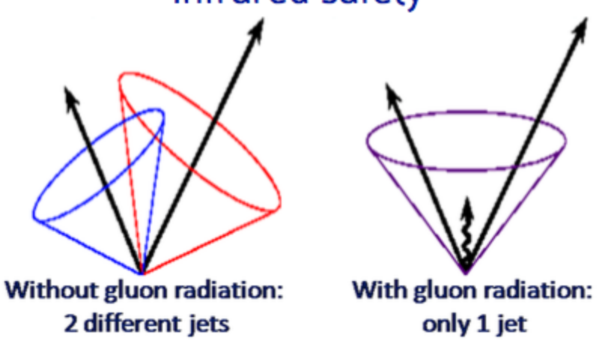
**No right jet algorithm**

Different processes ↔ different algorithms / parameters
(we'll see more of this later...)

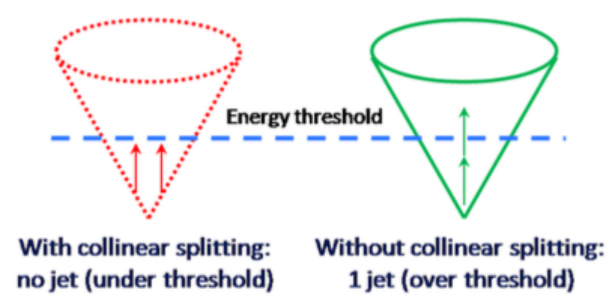
Requirements:

1. Theoretically well behaved → no $\alpha_s$ dependence of jet configuration:

Infrared safety




Collinear safety




2. Computationally feasible → fast
3. Detector independent

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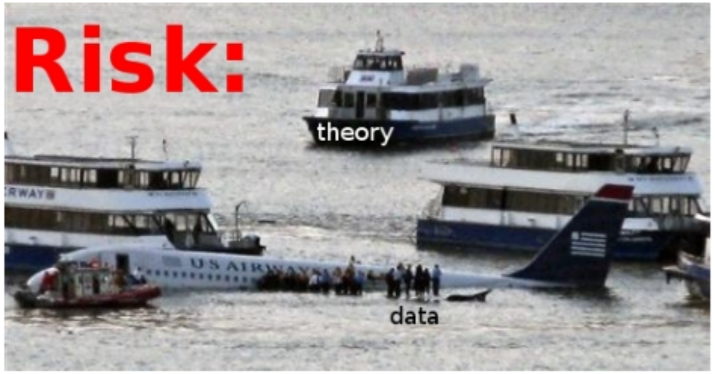
# Wishlist for jet algorithms

Crucial to analyse data
with infrared / collinear safe
jet algorithm!




Real life does not have infinities, but pert. infinity leaves a real-life trace

$$\alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \infty \to \alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \ln p_t/\Lambda \to \alpha_s^2 + \underbrace{\alpha_s^3 + \alpha_s^3}_{\text{BOTH WASTED}}$$

Among consequences of IR unsafety:

Gavin Salam, CFHEP lectures, April 2014

| | *Last meaningful order* | | | |
|---|---|---|---|---|
| | JetClu, ATLAS cone [IC-SM] | MidPoint [IC$_{mp}$-SM] | CMS it. cone [IC-PR] | Known at |
| Inclusive jets | LO | NLO | NLO | NLO ($\to$ NNLO) |
| $W/Z + 1$ jet | LO | NLO | NLO | NLO ($\to$ NNLO) |
| 3 jets | none | LO | LO | NLO [nlojet++] |
| $W/Z + 2$ jets | none | LO | LO | NLO [MCFM] |
| $m_{\rm jet}$ in $2j + X$ | none | none | none | NLO [Blackhat/Rocket/...] |

NB: 50,000,000\$/£/CHF/€ investment in NLO

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# Wishlist for jet algorithms

**Cone-based algorithms**

- Cone in $y - \phi$ space around object momentum vector
- Jet = objects in cone

Available on the (ATLAS and CMS) market:

- ATLAS Cone unsafe!
- Seedless Infrared Safe Cone (SISCone)

**Sequential recombination algorithms**

- Group objects based on minimum relative distance
- Jet = grouped objects

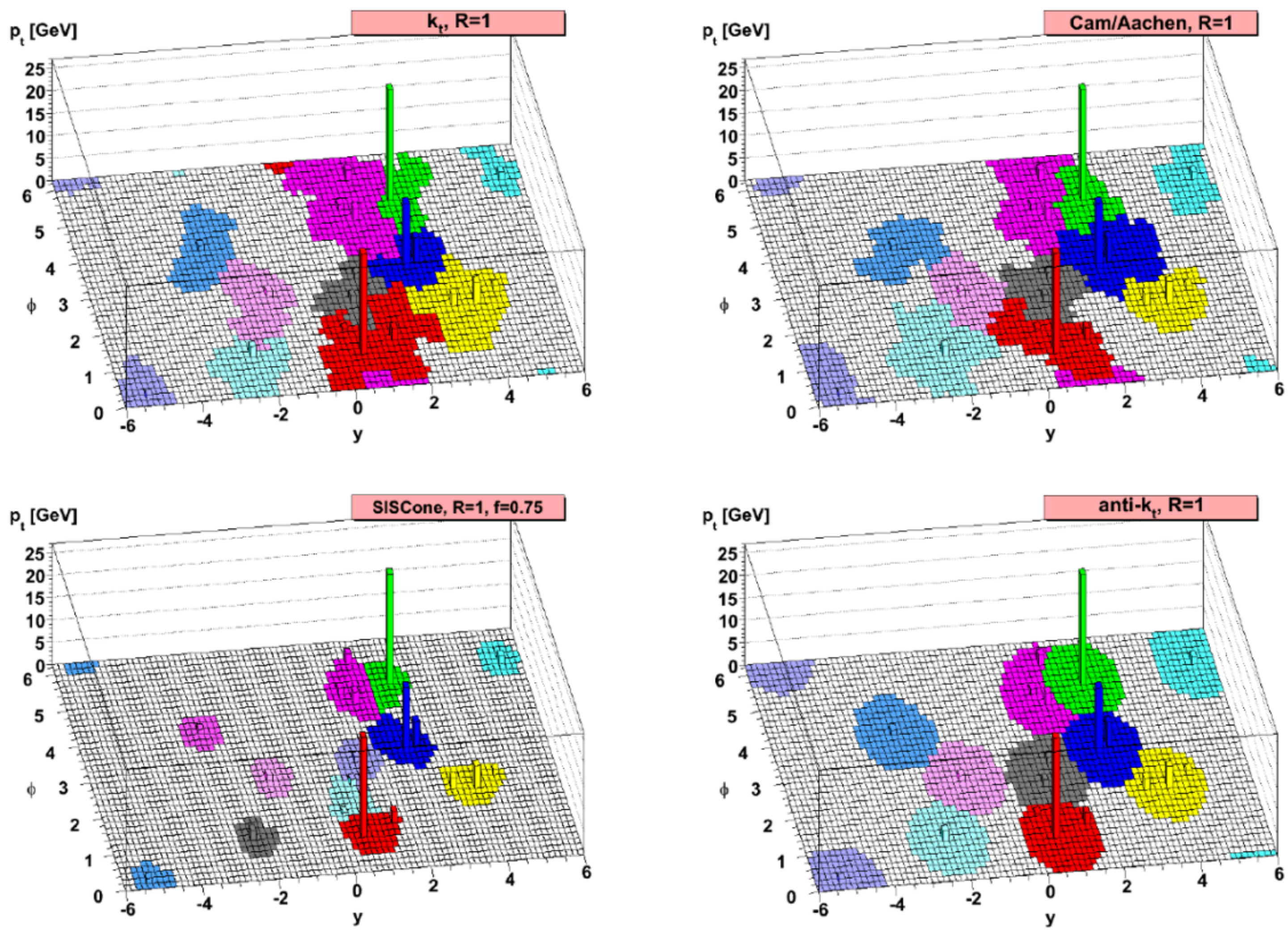
Available on the (ATLAS and CMS) market:

- $K_t$
- Cambridge-Aachen
- Anti-$K_t$

What algorithms for data?


From G. Salam, MCNet School 2008

# Different jet algorithms




http://arxiv.org/abs/0802.1189

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# A jet algorithm in action

**Algorithm specification: Anti-$k_t$**

- $d_{i,j} = min(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2})\frac{\Delta R^2}{D^2}$ ;

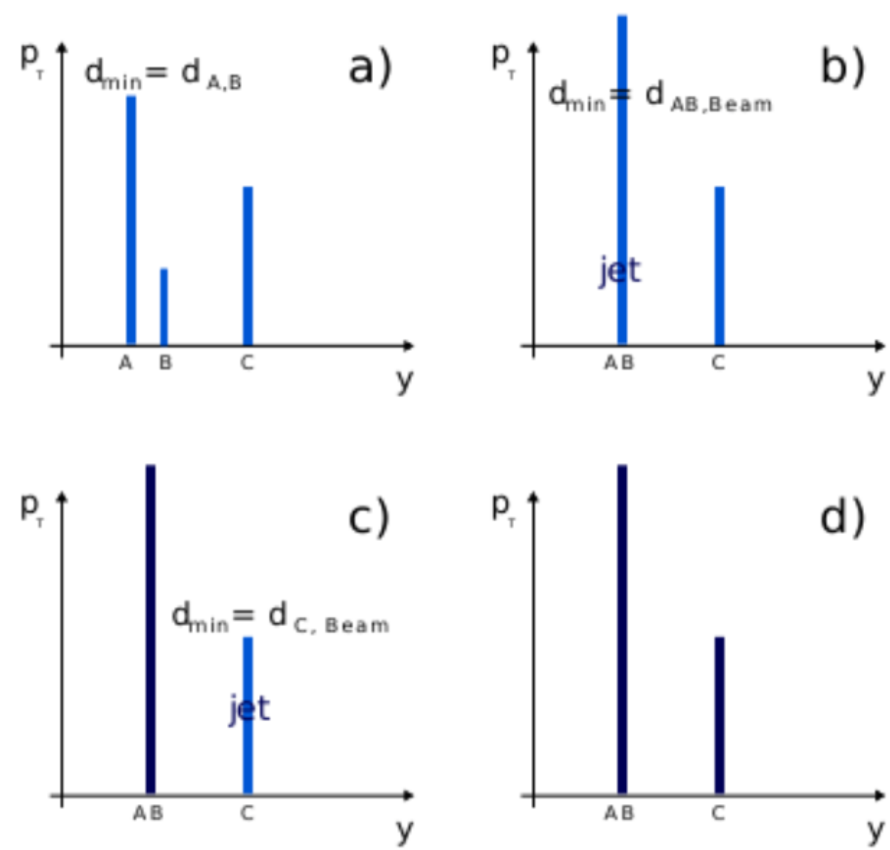
  $d_{i,Beam} = \frac{1}{p_{T,i}^2}$
- D : algorithm parameter
- Iterate:

1. For every pair of objects $i, j$ calculate $d_{min} = min(d_{i,j}, d_{i,beam})$
2. If $d_{min} = d_{i,j}$ recombine objects
   Else $i$ is a jet, remove it from list [a]

- Recombination starts from hard objects

[a] ATLAS default: inclusive algorithm

Idea:



# A jet algorithm in action

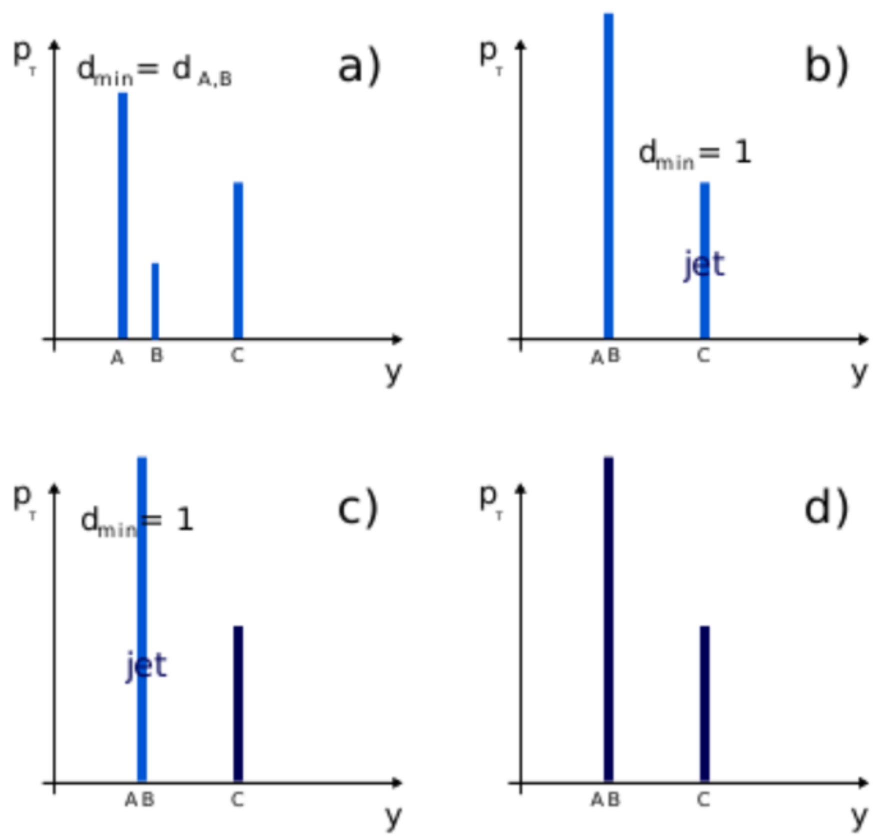
**Algorithm specification: Cambridge-Aachen**

- $d_{i,j} = \frac{\Delta R^2}{D^2}$ ; $d_{i,Beam} = 1$
- D : algorithm parameter
- Iterate:

1. For every pair of objects $i, j$ calculate $d_{min} = min(d_{i,j}, d_{i,beam})$
2. If $d_{min} = d_{i,j}$ recombine objects
   Else $i$ is a jet, remove it from list [a]

- Distance-based recombination

Idea:



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# A jet algorithm in action

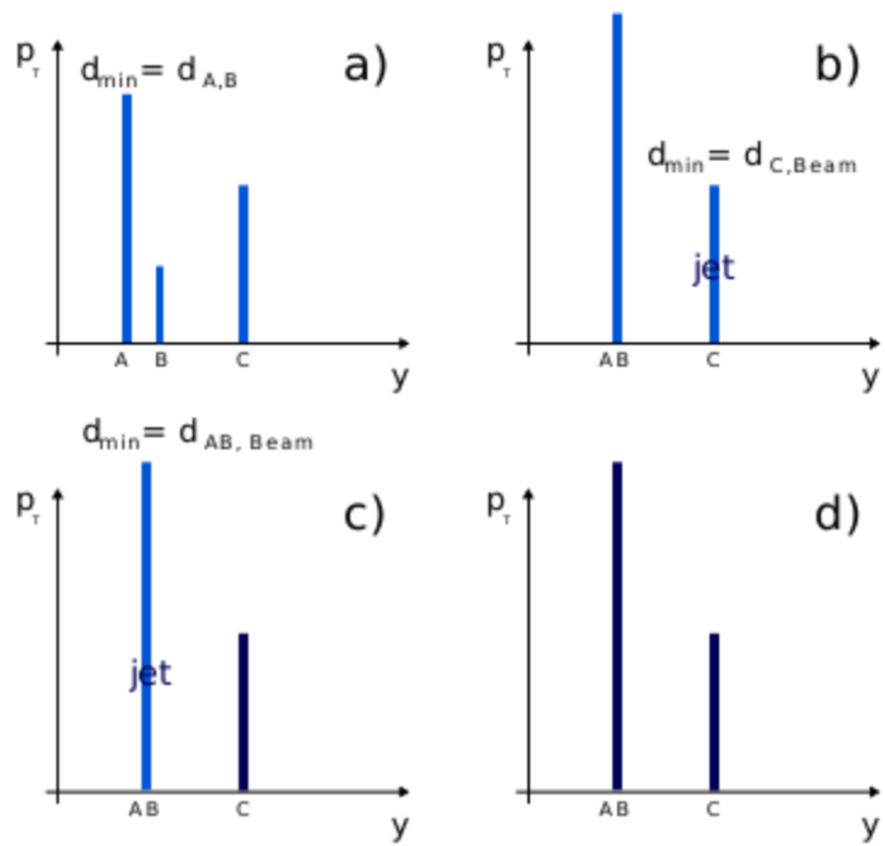
**Algorithm specification: $k_t$**

- $d_{i,j} = min(p_{T,i}^2, p_{T,j}^2)\dfrac{\Delta R^2}{D^2}$ ;
  $d_{i,Beam} = p_{T,i}^2$
- D : algorithm parameter (≈ weight for angular distance $\Delta R$)
- Iterate:

1. For every pair of objects $i, j$ calculate $d_{min} = min(d_{i,j}, d_{i,beam})$
2. If $d_{min} = d_{i,j}$ recombine objects
   Else $i$ is a jet, remove it from list [a]

- Recombination starts from soft objects

Idea:



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# Other jet algorithms

Computational time for N inputs

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

| | Alg. name | Comment | time |
|---|---|---|---|
| $p = 1$ | $k_t$<br>CDOSTW '91-93; ES '93 | Hierarchical in rel. $k_t$ | $N \ln N$ exp. |
| $p = 0$ | Cambridge/Aachen<br>Dok, Leder, Moretti, Webber '97<br>Wengler, Wobisch '98 | Hierarchical in angle<br>Scan multiple $R$ at once<br>$\leftrightarrow$ QCD angular ordering | $N \ln N$ |
| $p = -1$ | anti-$k_t$ Cacciari, GPS, Soyez '08<br>$\sim$ reverse-$k_t$ Delsart | Hierarchy meaningless, jets like CMS cone (IC-PR) | $N^{3/2}$ |
| SC-SM | SISCone<br>GPS Soyez '07 + Tevatron run II '00 | Replaces JetClu, ATLAS MidPoint (xC-SM) cones | $N^2 \ln N$ exp. |

Gavin Salam, CFHEP lectures, April 2014

# A jet algorithm in action

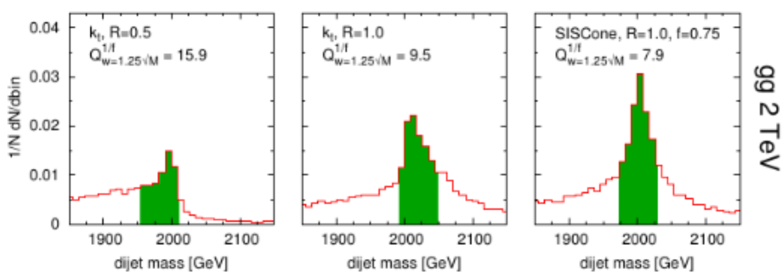
Decision: choice of jet algorithm distance parameter (R)

"It's all fun and games until someone loses a hard constituent"

Example figures from original jetography paper arXiv 0810.1304:
Quantifying the performance of jets, G. Salam, J. Rojo, M. Cacciari

Advantages of wider distance parameters (large-R):

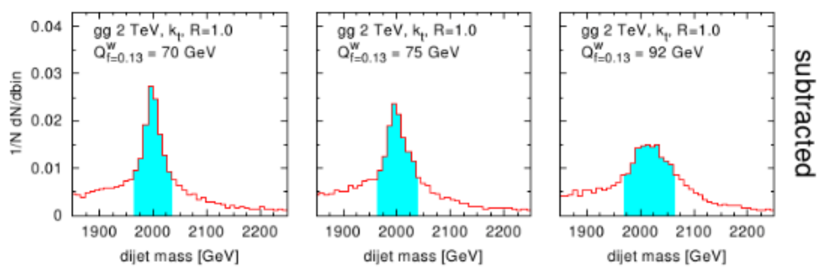
- Captures more QCD radiation:
  → Smaller non-perturbative corrections when comparing data to theory
  → Better mass resolution for dijet resonances




Dijet mass for resonance decaying into two gluons: improvement in resolution when increasing radius

Disdvantages of wider distance parameters (wider jets):

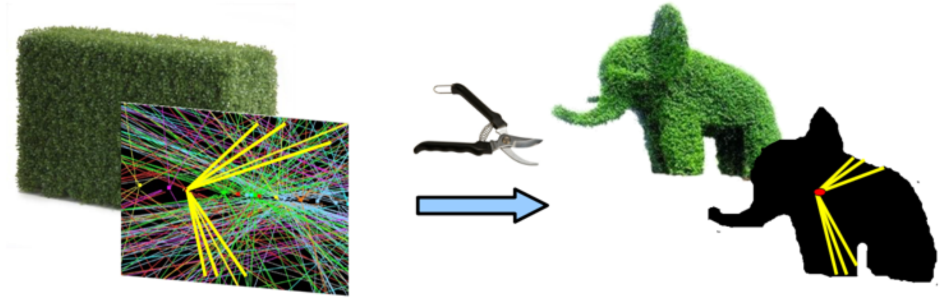
- Captures more of anything else:
  → extra energy not from hard scattering (calorimeter noise, other $pp$ collisions)




Dijet mass for resonance decaying into two gluons, large-radius: deterioration in resolution when increasing pile-up as in left to right plot

- with large kinematic boost, decay products of heavy objects more collimated
  ...can we use this to our advantage?
  Yes, with jet substructure!

# Jet grooming

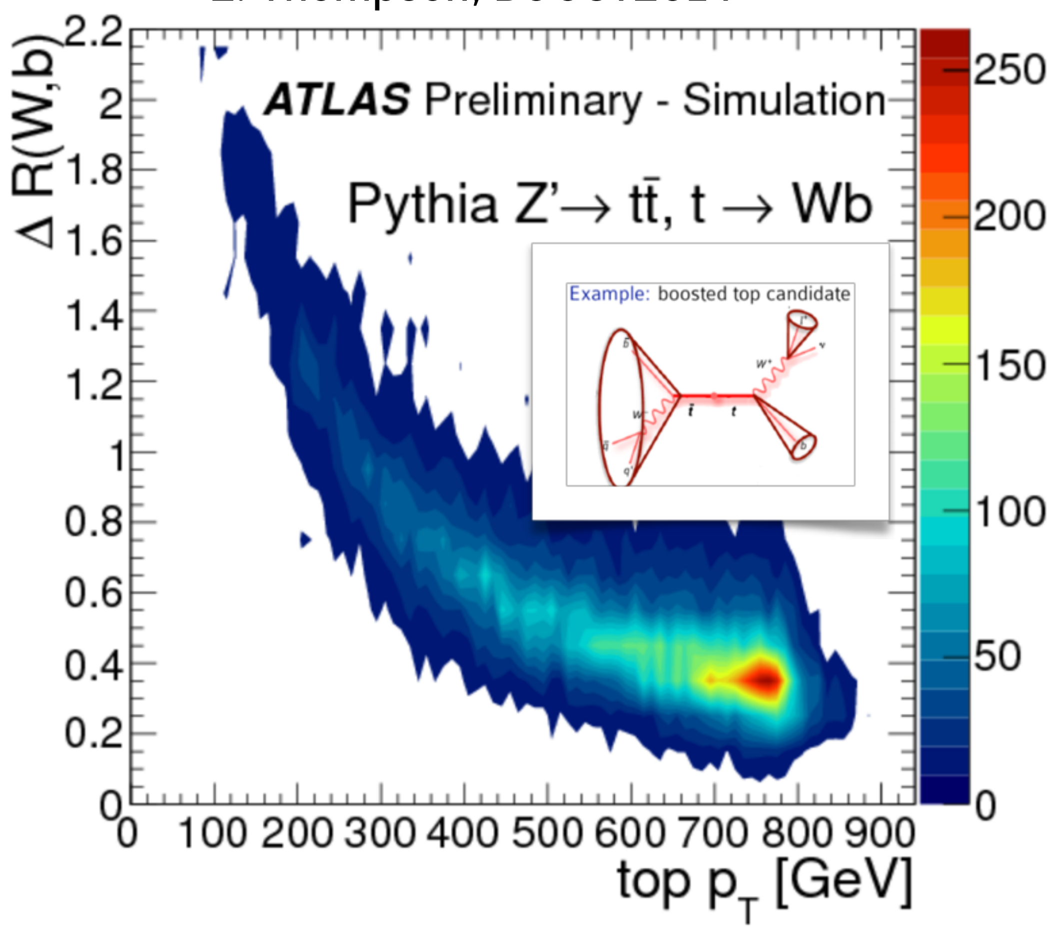


**Jet grooming:**
"trying to make fat jets leaner"

**Basic operative idea:**
Start with a large-radius jet
Select which sub-components to keep

**Why?**
- a necessity for boosted objects
(all decay products end up in a single jet)
- can be useful to remove pile-up

E. Thompson, BOOST2014

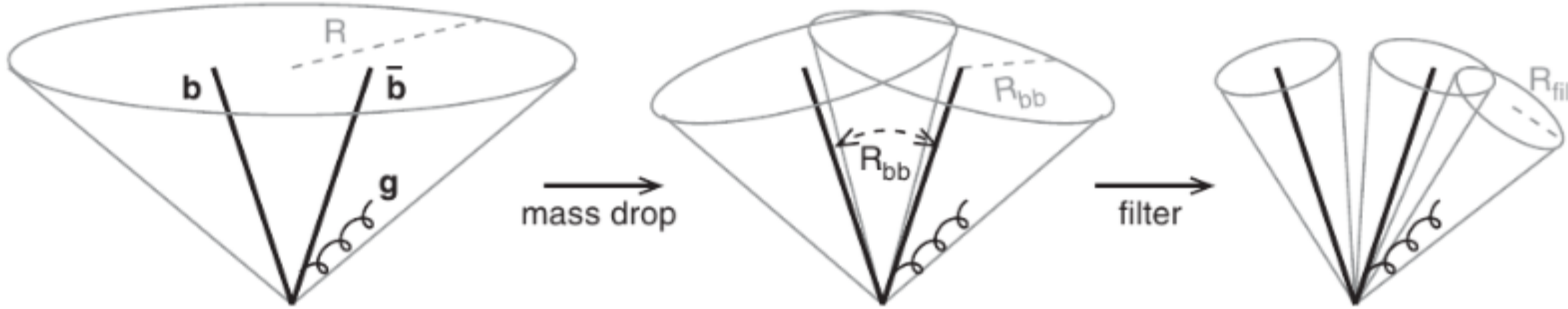




(C) ATLAS JetETMiss WG

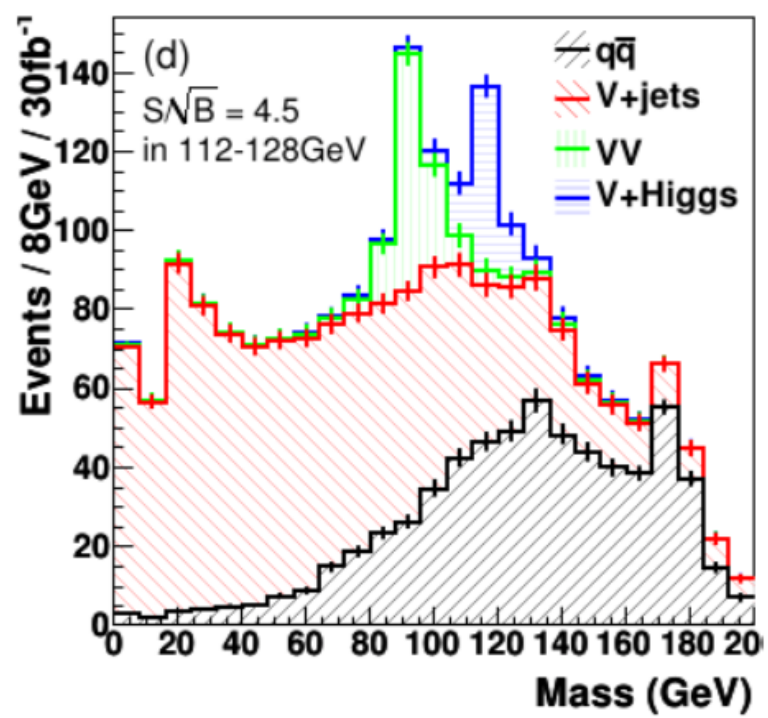
# Jet substructure: basic idea

https://arxiv.org/pdf/0802.2470.pdf




If we know **what we want to find inside a jet** (e.g. decay products of another more massive particle), we can use this information to distinguish from QCD

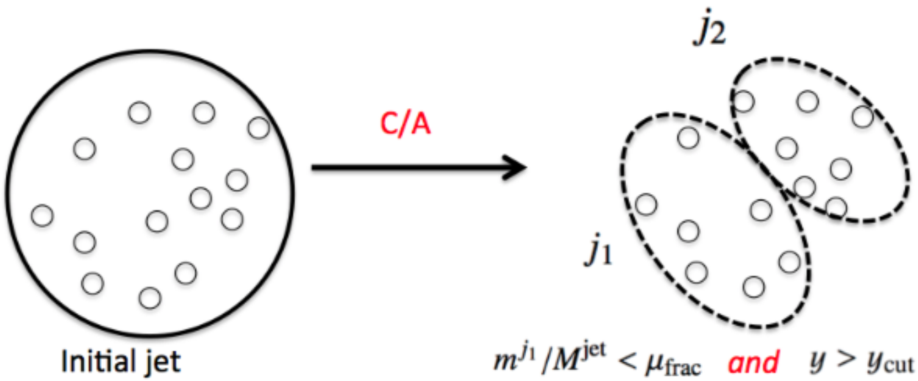
(sometimes this is a necessity: **boosted decay products**)



# A famous substructure technique: BDRS

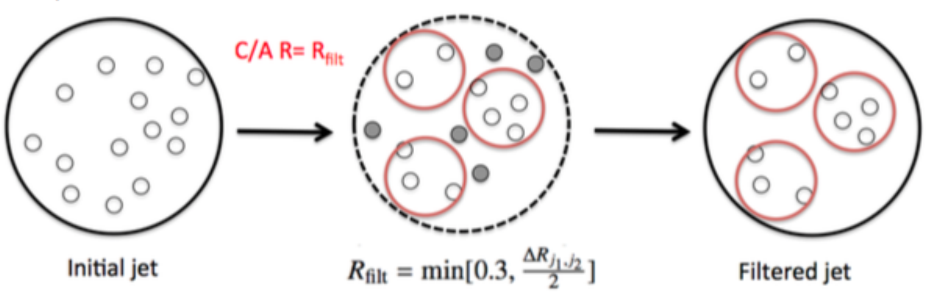
1. Find Cambridge/Aachen R=1.2 jets
2. Undo last step of jet algorithm and obtain two proto-jets ($j1, j2$)
3. Only keep C/A jets where:
   - significant difference between original jet and $j1$: $m^{j1}/m^{C/A\ jet} < \mu_{frac}$
   - symmetric splitting between $j1, j2$: $y = \frac{min[(p_T^{j1})^2, p_T^{j2})^2]^2}{m^{C/A jet}} \Delta R^2_{j1,j2} > y_{cut}$

Note that $y \simeq \min(p_{tj_1}, p_{tj_2})/\max(p_{tj_1}, p_{tj_2})$




4. Recluster constituents of the jet using C/A with distance parameter=$R_{filt}$, only keep three hardest subjets

(C) ATLAS JetETMiss WG

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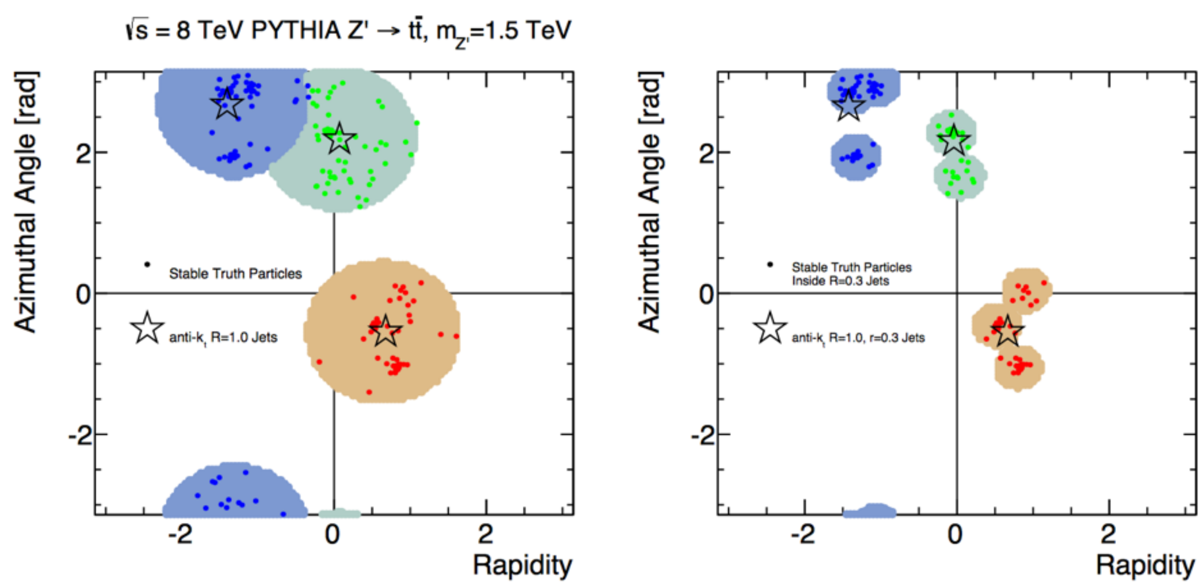
# Can we use Anti-kT? Reclustering


https://arxiv.org/pdf/1407.2922v2.pdf

Jets from Jets:
Re-clustering as a tool for large radius jet reconstruction and grooming at the LHC



# 2.1.A Practical demonstration

# Concepts for part 2.1

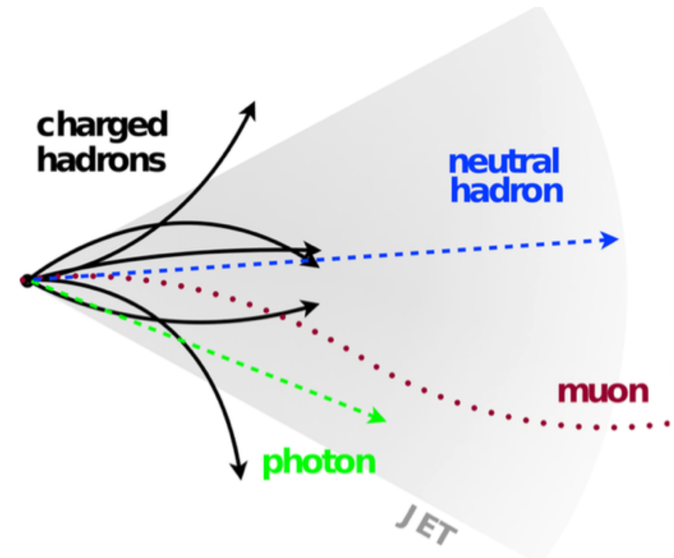
- Jets as representative of hard scatter patrons
  - Definition of jet algorithm:
    - Rules to cluster inputs
    - Recombination scheme
    - Split/merge (if needed)
  - Requirements for jet algorithm:
    - Theoretically viable
    - Computationally fast
    - Detector-independent
- A jet algorithm in action: Anti-kT
- Jet substructure and jet grooming

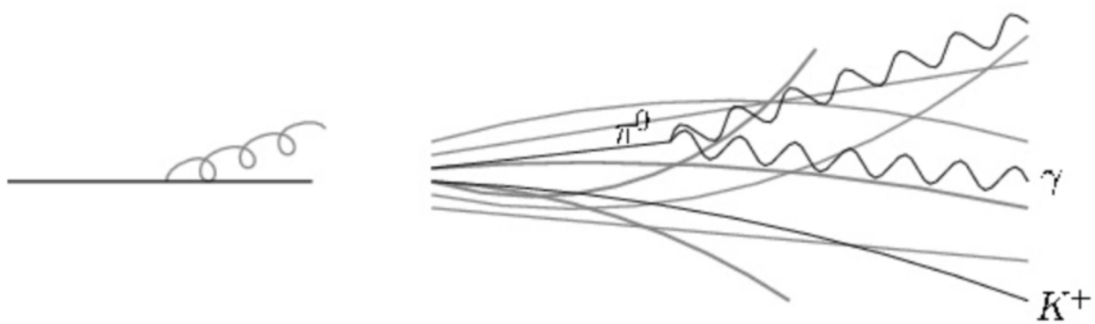
# 2.2 Measuring jets at the LHC (with a strong ATLAS bias)

# Jets in ATLAS and CMS

CMS: particle flow jets

using both tracking and calorimeter info



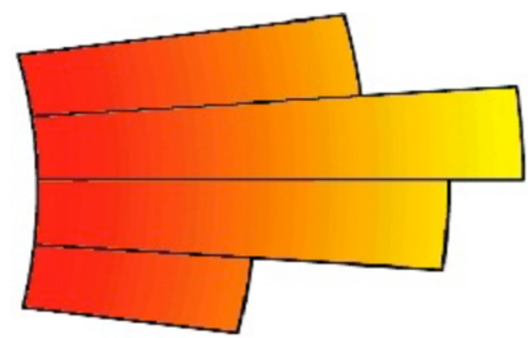




parton level jet    particle level jet

ATLAS: calorimeter jets

using topological clusters as input

particle flow jets being commissioned



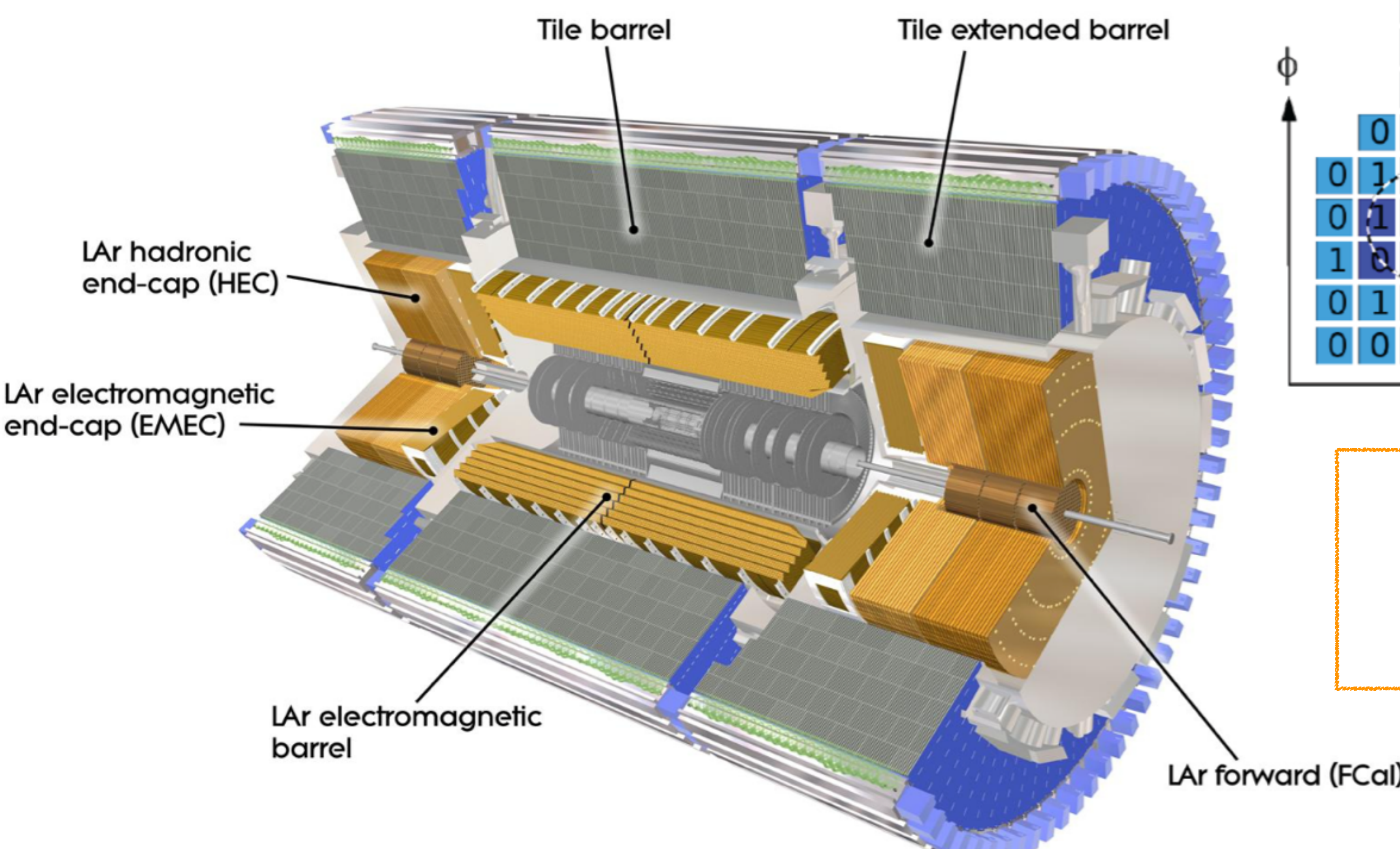
calorimeter level jet

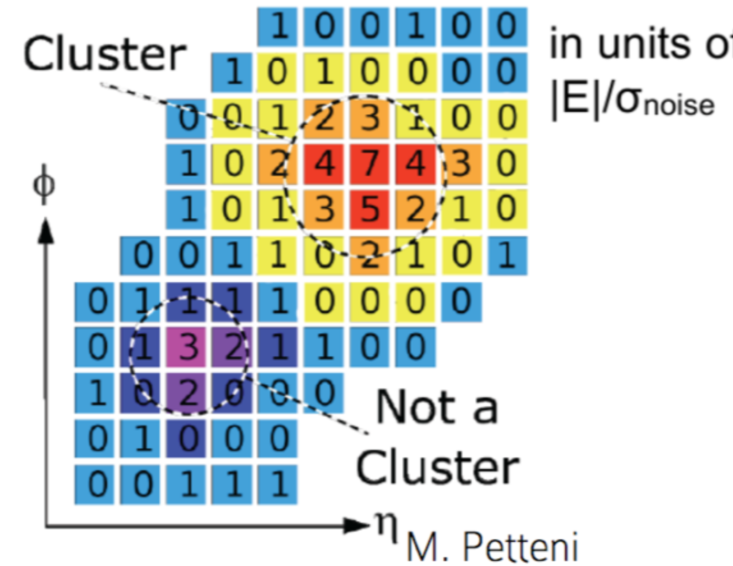
Images by Dag Gillberg

# Recap: calorimeters (ATLAS only)

Subsystem **technology** and **granularity** follows **shower characteristics**

Energy deposits grouped in noise-suppressed **3D topological clusters**



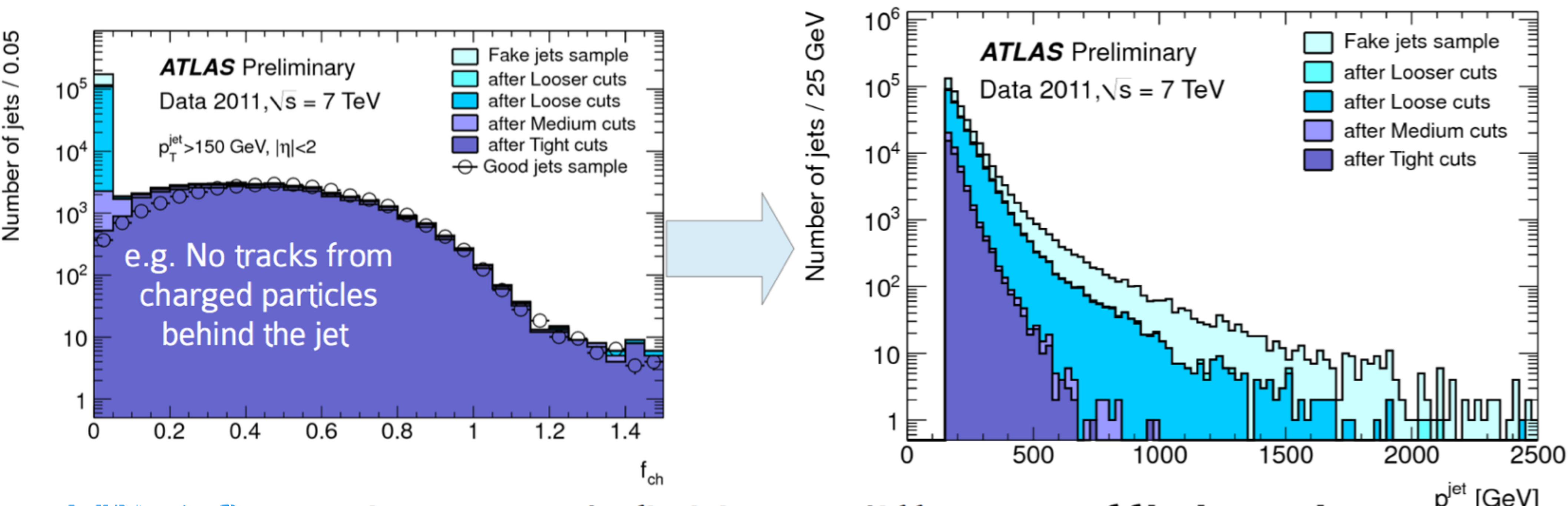

See more in G. Eigen's lectures about detectors

# Fake jets, too

Energy deposits in calorimeters → jet

But: energy deposits in calorimeters != always real jets

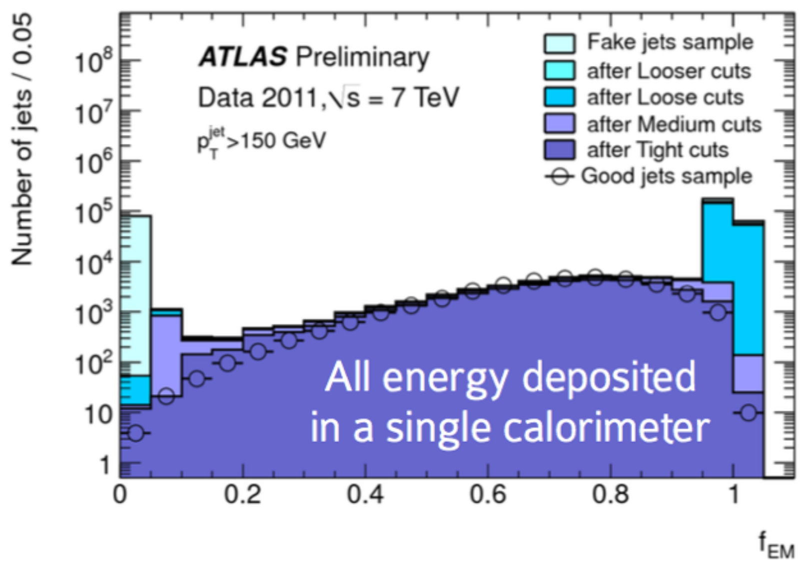
→ experiments need criteria to **remove fake jets**

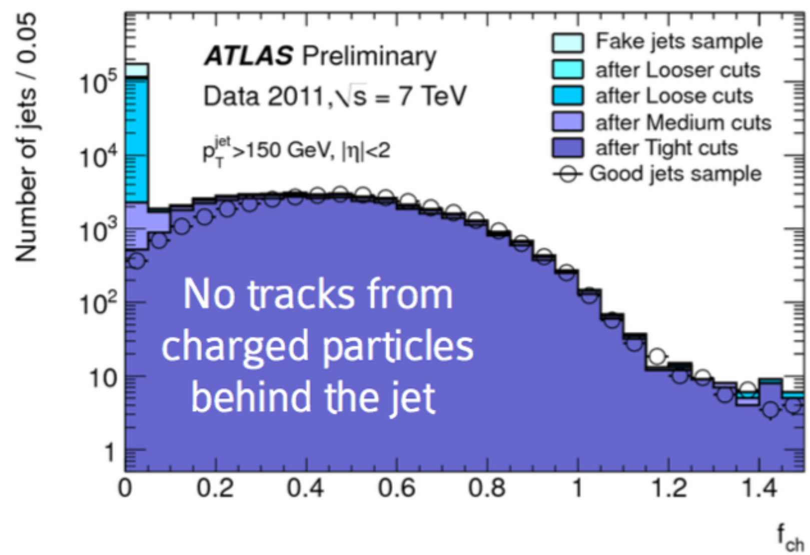


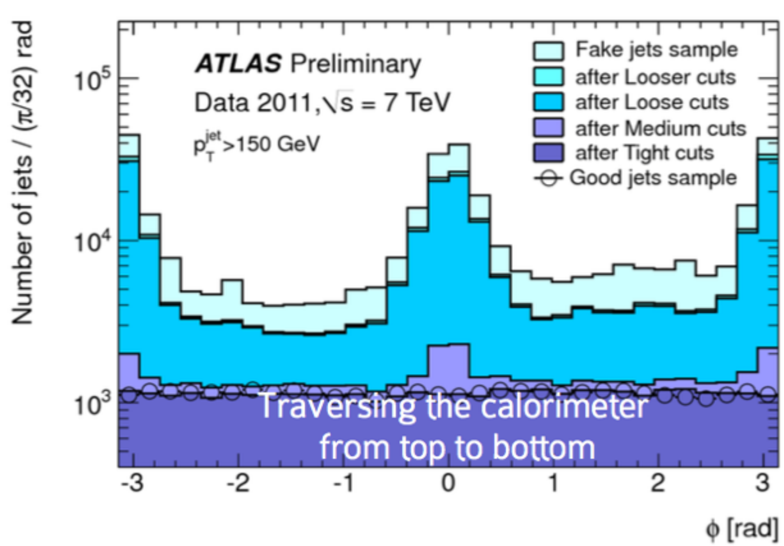

ATLAS: various cut definitions, different **efficiencies** and **purities** + rejection of **jets from pile-up**

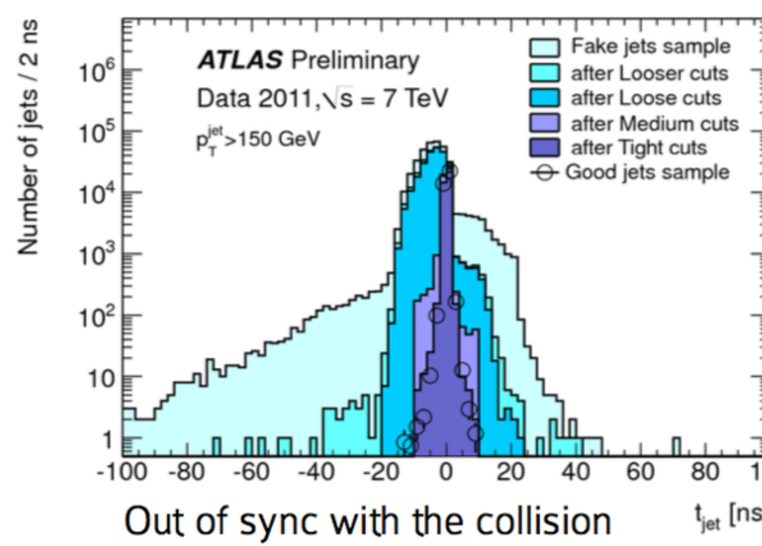
# Fake jets, too

Characteristics of fake jets include:



# Intro to jet calibration

How will a calorimeter react to a particle?

Thought (blackboard) experiment (1):

shoot 10000 pions of E=100 GeV in our calorimeter

Draw the energy distribution of the jets

(assuming one pion per jet)

# Intro to jet calibration

**How will a calorimeter react to a particle?**

Thought (blackboard) experiment (2):
Our calorimeter is non-compensating
there is inactive material (a tracker!) in front of it
Not all the shower is captured by the jet
There is extra energy due to pile-up (...)

**What happens to our energy distribution?**

# Intro to jet calibration

How will a calorimeter react to a particle?

Thought (blackboard) experiment (3):

There are fluctuations in the shower properties

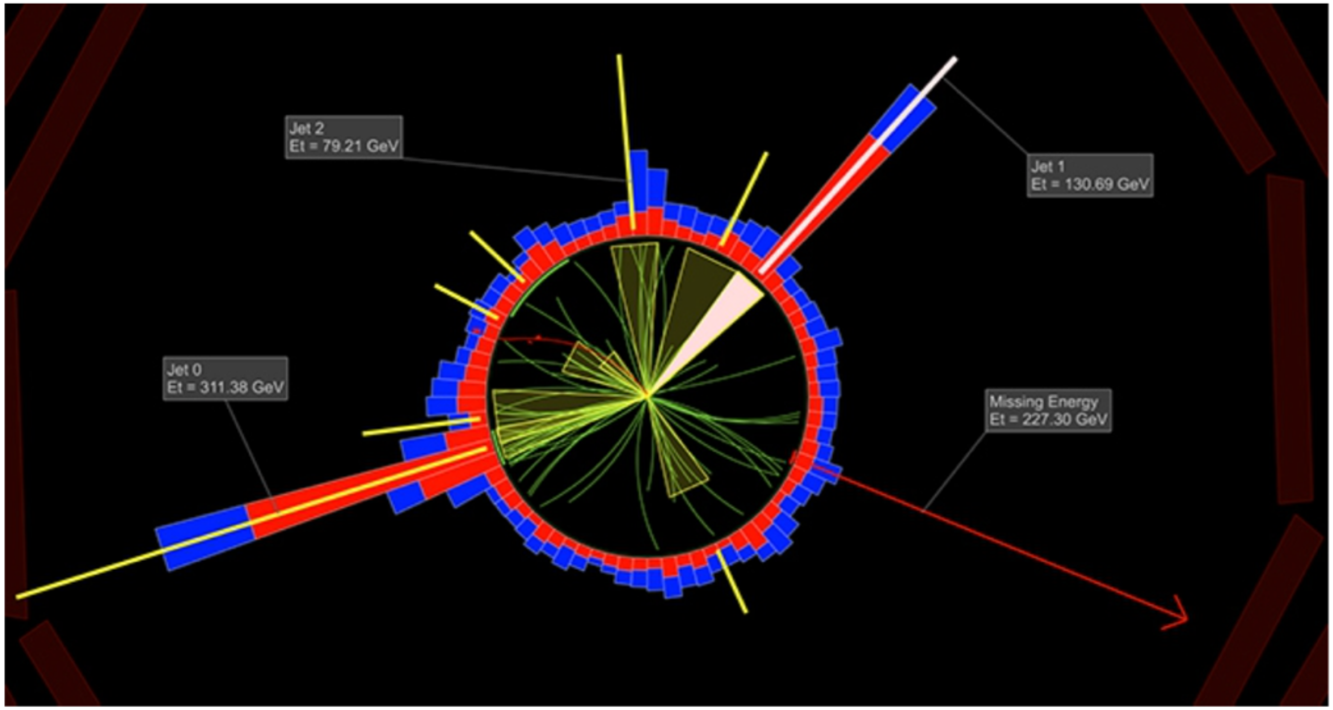
→ fluctuations in the collected energy

There is leakage (punch-through)

What happens to our energy distribution?

# Related: Missing transverse momentum

Missing transverse momentum: particles escaping undetected...but also mismeasured jets!




Jet energy response and resolution need to be well performing and well understood to discover e.g. SUSY

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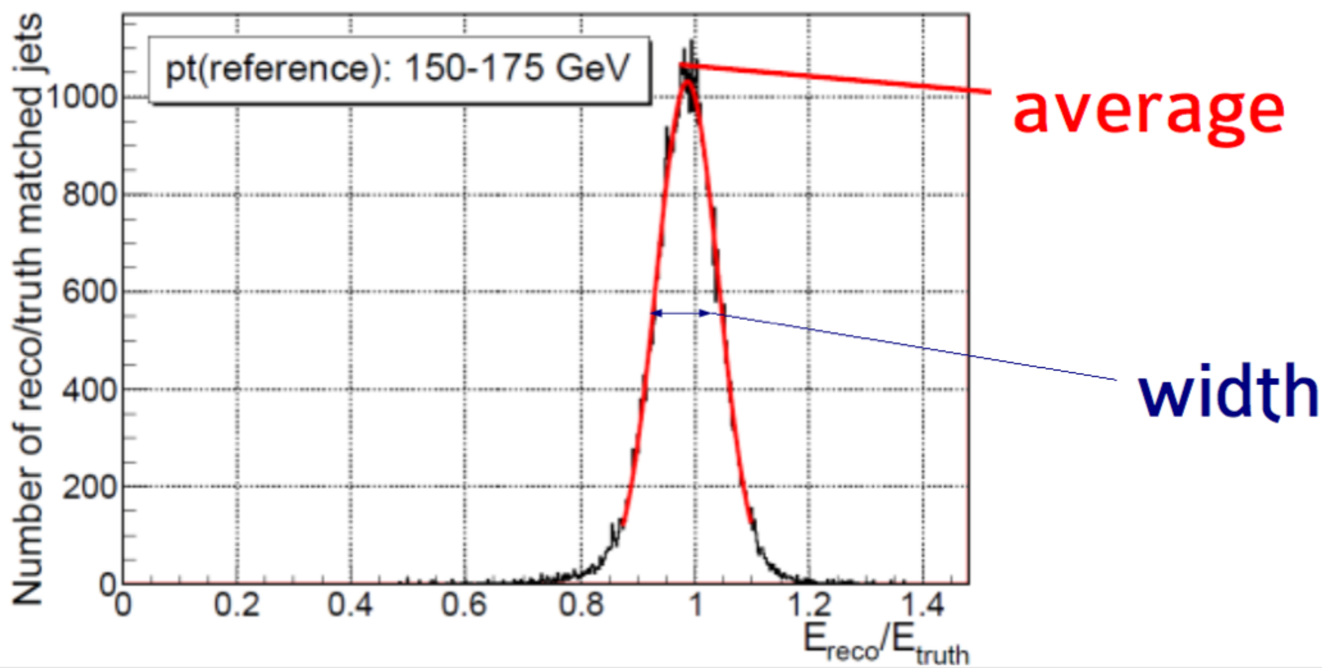
# Jet energy response and resolution

Divide measured jet energy by original (truth) jet energy

average → jet response

width → jet resolution



# Jet energy response and resolution

Energy resolution:

e.g. inhomogeneities
shower leakage

e.g. electronic noise
sampling fraction variations

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus \frac{C}{E}$$

Fluctuations:

- Sampling fluctuations
- Leakage fluctuations
- Fluctuations of electromagnetic fraction
- Nuclear excitations, fission, binding energy fluctuations ...
- Heavily ionizing particles

Typical:

A: 0.5 – 1.0 [Record:0.35]
B: 0.03 – 0.05
C: few %

http://www.kip.uni-heidelberg.de/~coulon/Lectures/DetectorsSoSe10/

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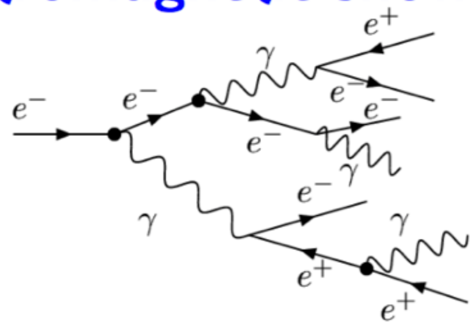
# Jet calibration

Hadronic component of showers of particles in jets
involves **invisible** particles/processes (to non-compensating calorimeters)

## Electromagnetic showers




## Hadronic showers


\+ energy is lost in inactive material before calorimeters or outside jet cone

→ calibration needed to restore jet energy scale

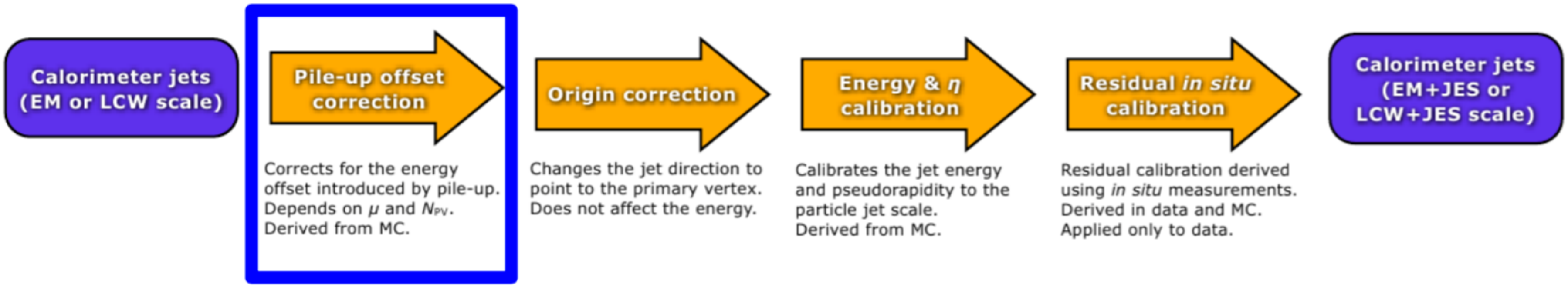
**Calorimeter jets (EM or LCW scale)** → **Pile-up offset correction** → **Origin correction** → **Energy & $\eta$ calibration** → **Residual *in situ* calibration** → **Calorimeter jets (EM+JES or LCW+JES scale)**

arXiv:1406.0076

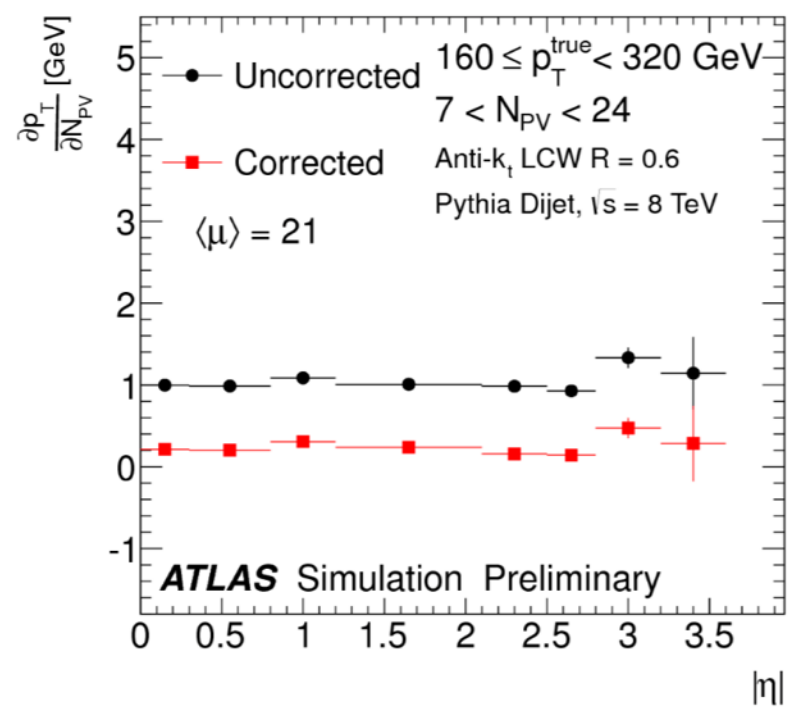
- **Pile-up offset correction**: Corrects for the energy offset introduced by pile-up. Depends on $\mu$ and $N_{PV}$. Derived from MC.
- **Origin correction**: Changes the jet direction to point to the primary vertex. Does not affect the energy.
- **Energy & $\eta$ calibration**: Calibrates the jet energy and pseudorapidity to the particle jet scale. Derived from MC.
- **Residual *in situ* calibration**: Residual calibration derived using *in situ* measurements. Derived in data and MC. Applied only to data.

Refinements to this calibration scheme (e.g. calibrating constituents before jet finding, using jet properties to reduce differences between quark- and gluon-initiated jets) are in use but not covered here

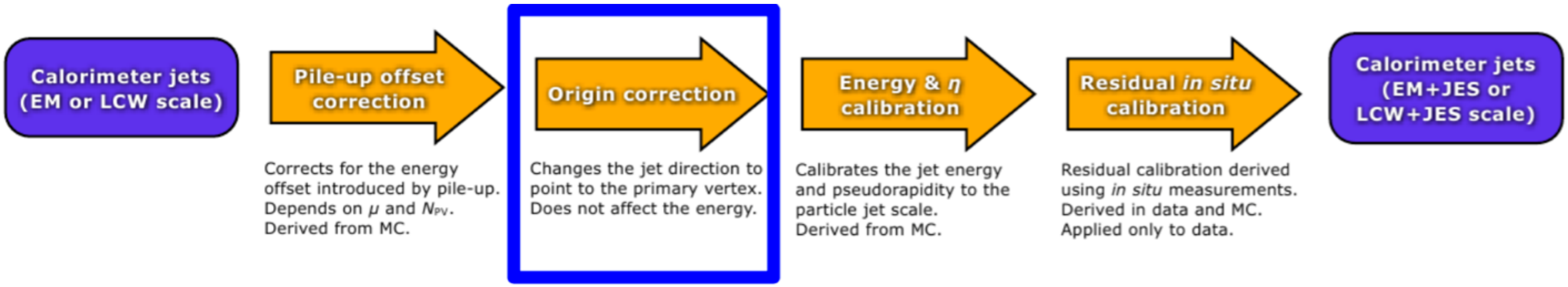
# Pile-up subtraction



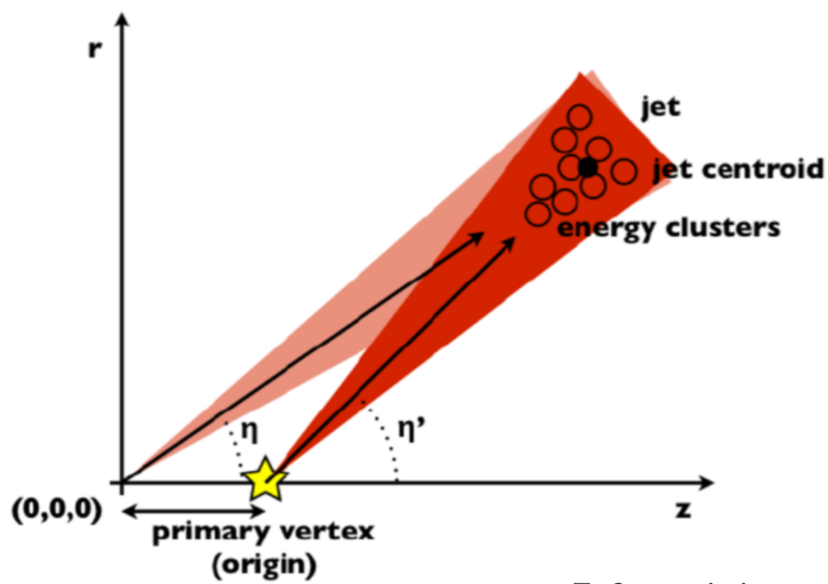

- **Pile-up:** effects of **additional interactions** within the same or neighboring bunch crossing
  → Need to **restore jet energy scale** and optimal MET resolution
    - Event-by-event calibrations for jets and MET (based on **jet areas/tracks**)
    - Identification of jets from pile-up: Jet Vertex Fraction



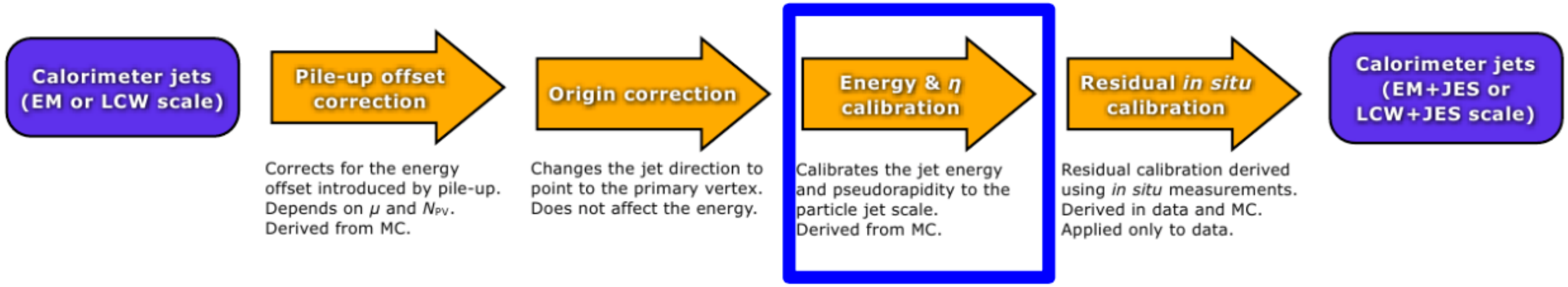
# Jet origin correction



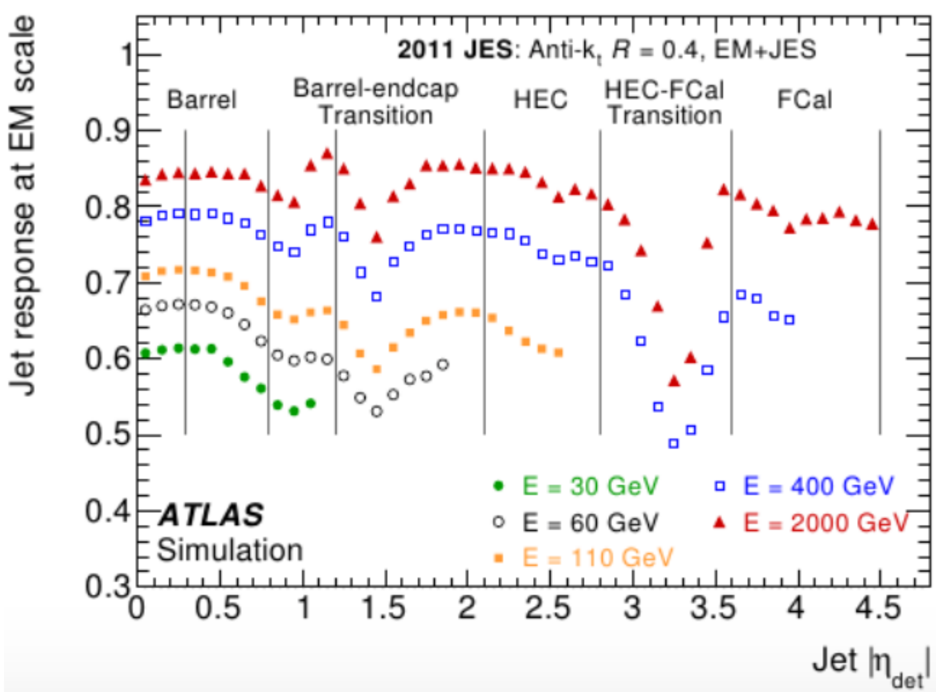

Point the jet to the **primary collision vertex**, rather than to the center of the detector

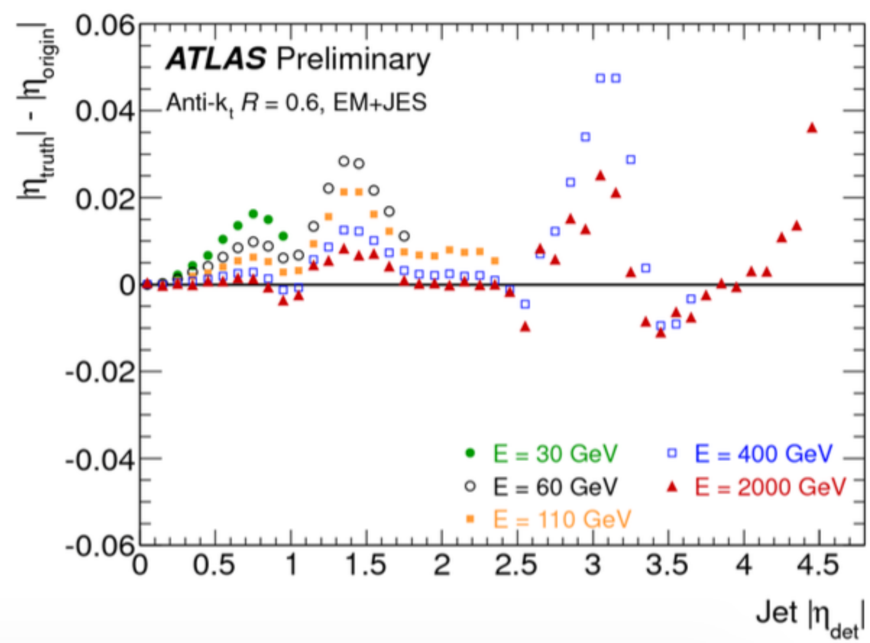


# Energy correction

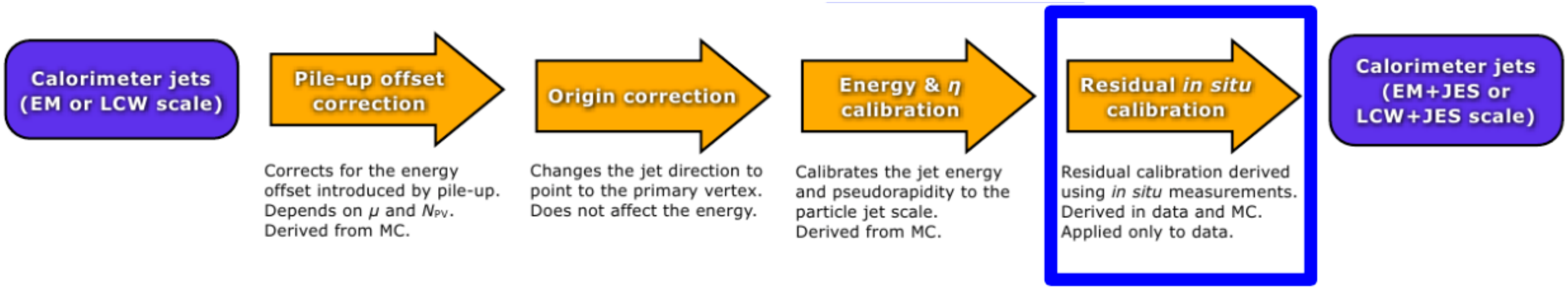



**Compensate** for energy losses in e.g. out-of-cone, dead material...



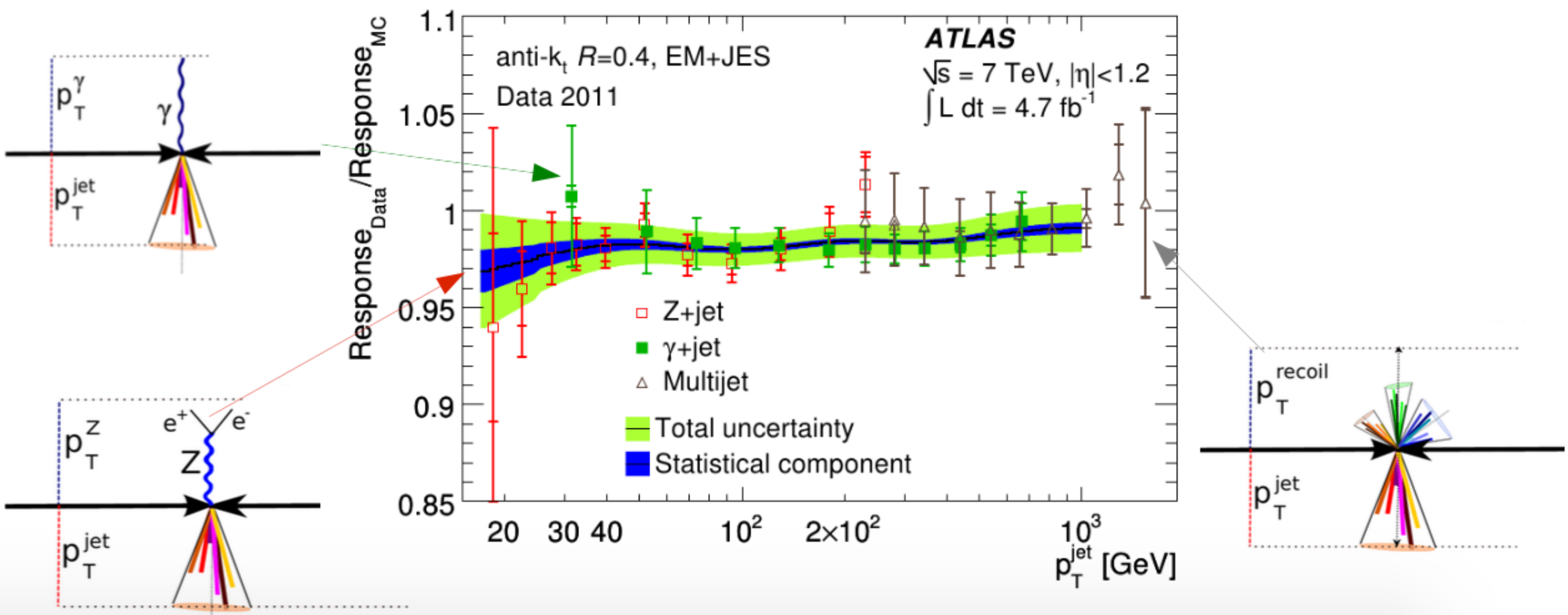



# In-situ correction

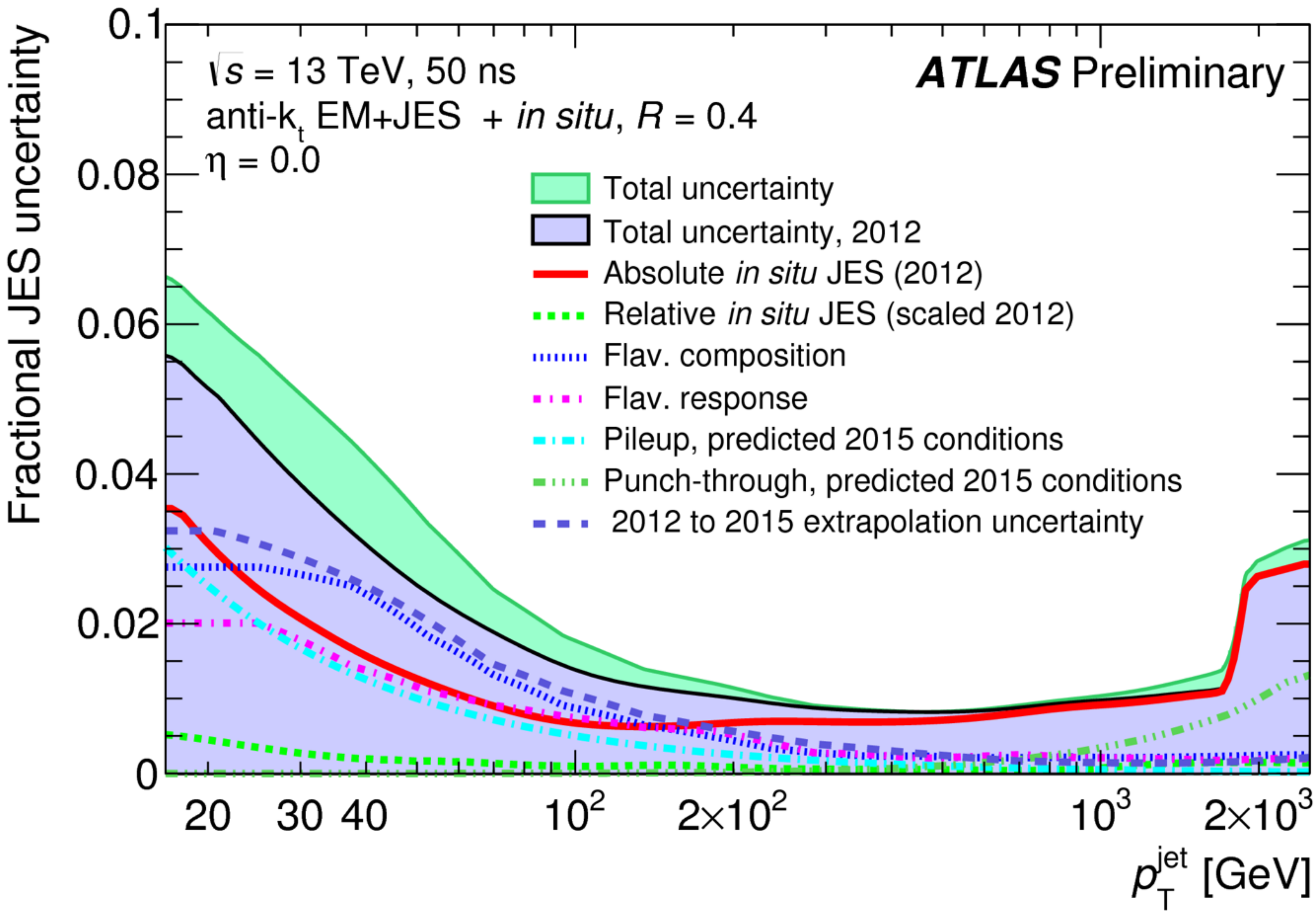



Use **well-measured objects** to **check the scale** of the **calibrated jets**

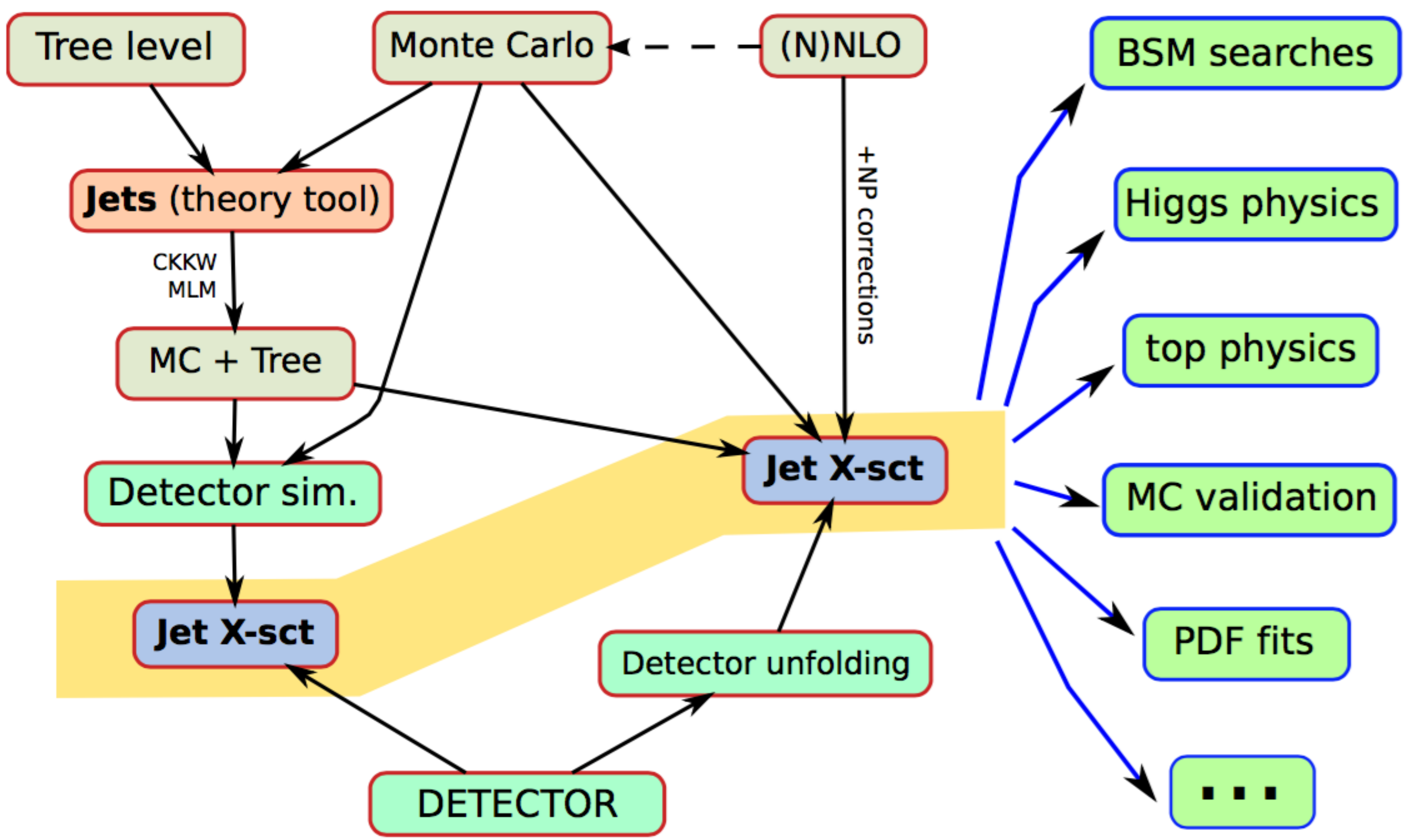
**Compare balance in data and MC** → combine, correct for differences



# The jet energy scale uncertainty

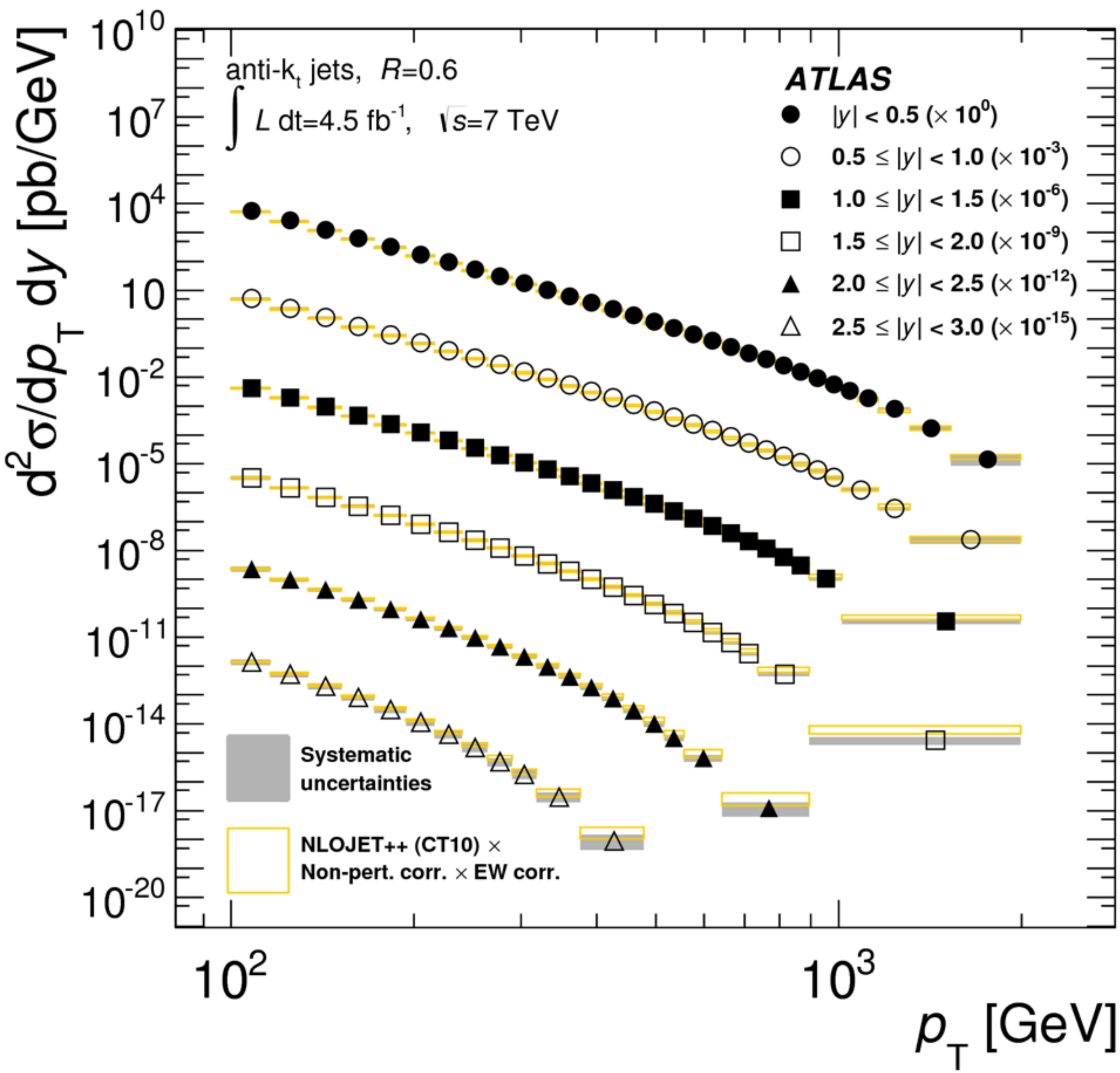


# Jets are everywhere

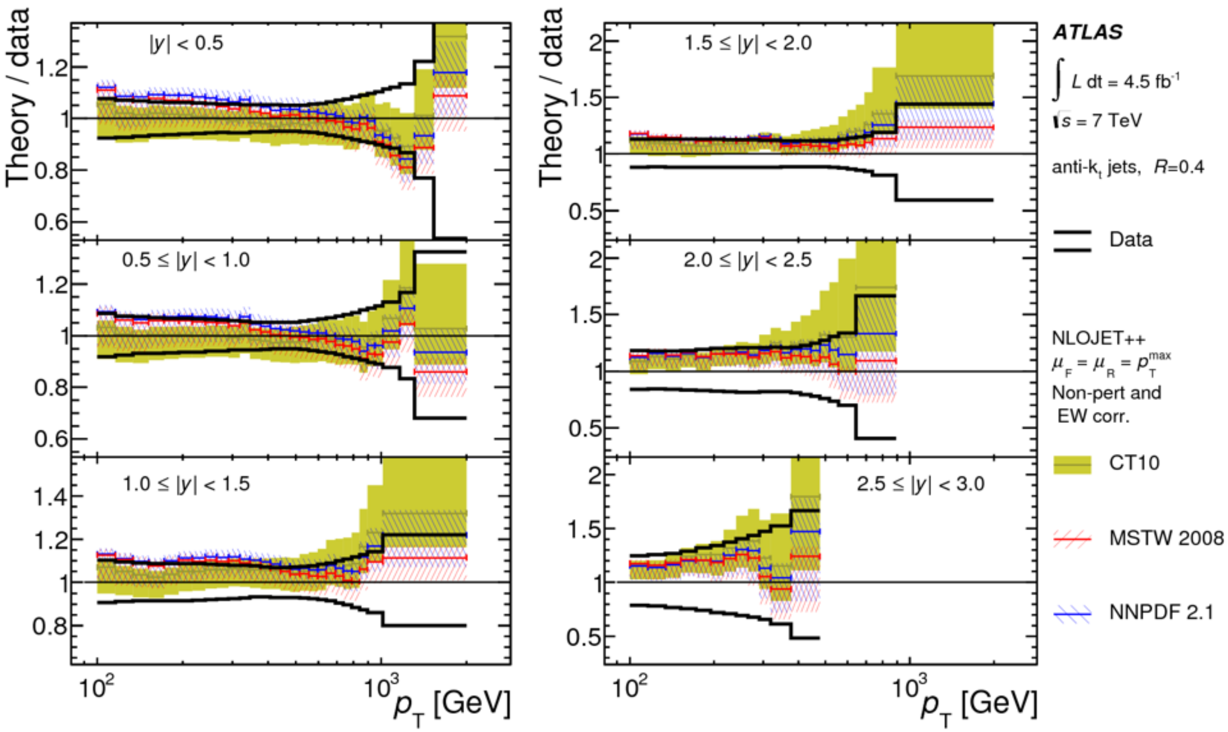


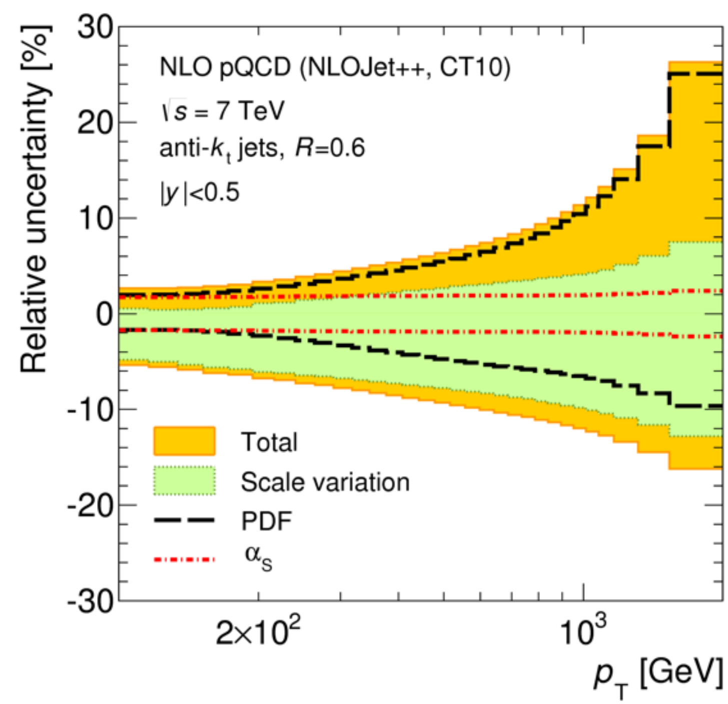

[Gavin Salam, CFHEP lectures, April 2014]

# Inclusive jet cross-section measurement



# Inclusive jet cross-section uncertainties



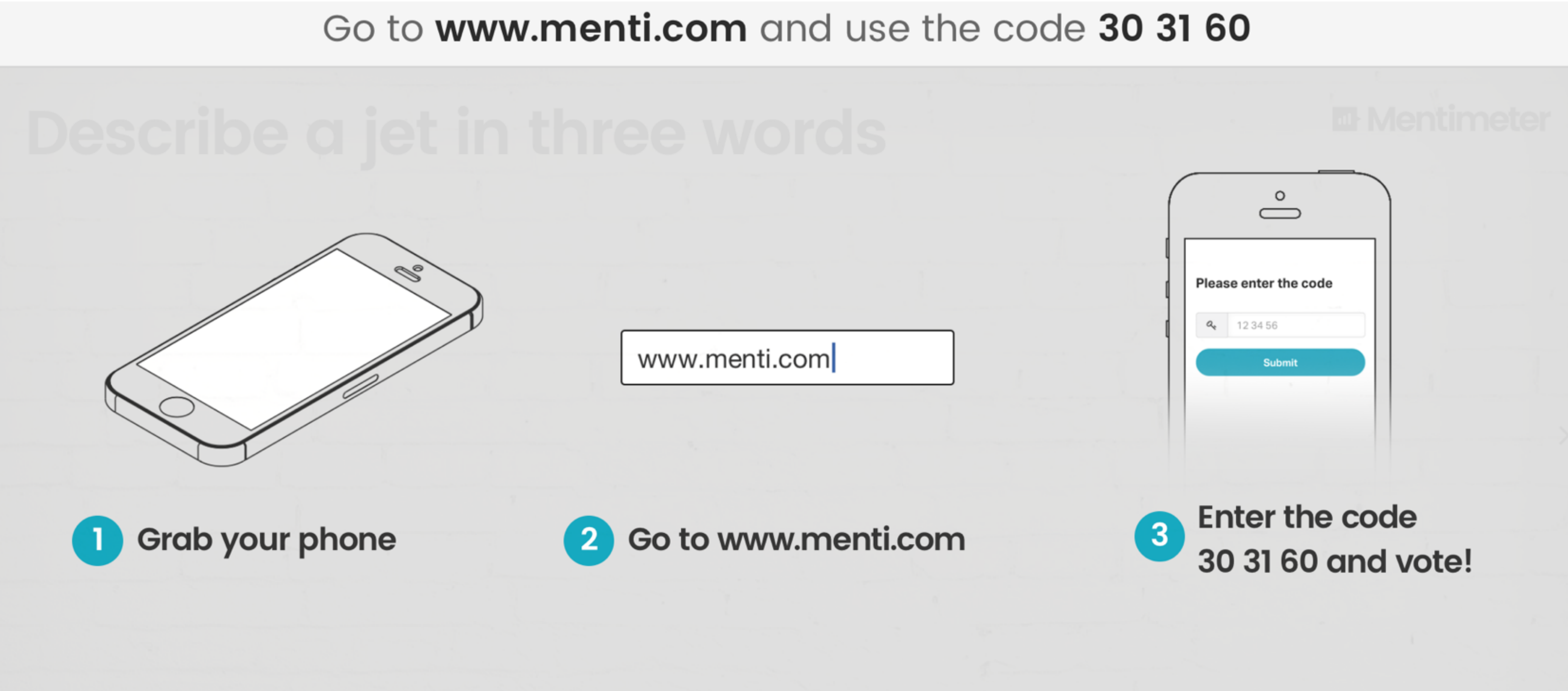




In order to proceed with precision QCD measurements, both theory and experiment need to make progress on uncertainties

# Concepts for part 3.2

- Inputs for jets in ATLAS and CMS: calorimeter energy deposit but also tracks
- Jets need to be calibrated
  - ATLAS “EM+JES” calibration scheme as example
    - Pile-up correction
    - Origin correction
    - MC-based correction
    - In-situ correction
- Jet energy scale uncertainty
- Jets are everywhere: inclusive jet cross-section

# 2.2.A Some questions about jets



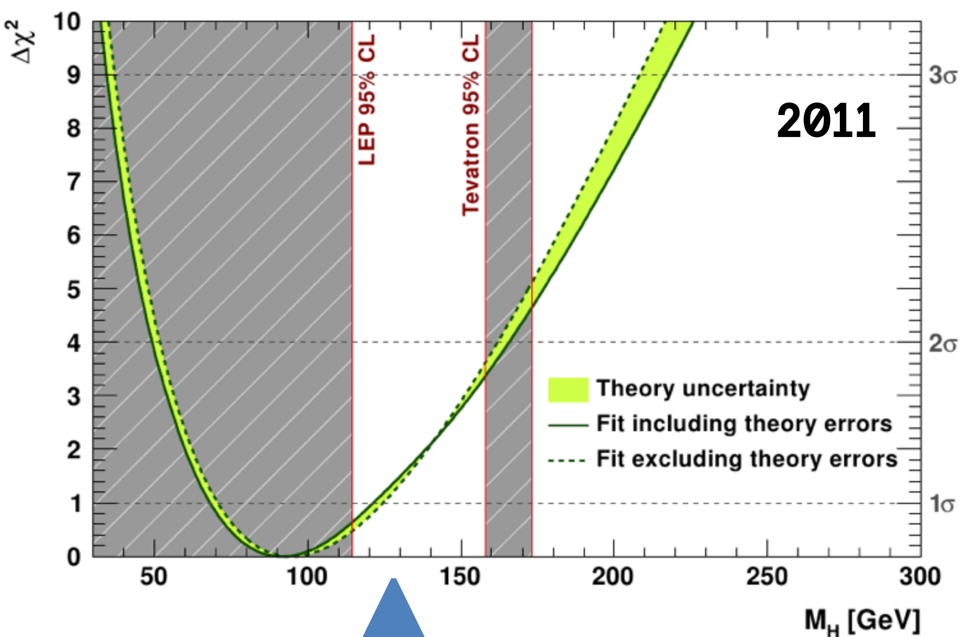

https://www.mentimeter.com/s/ea0581bbc5e4ea2e91ce762d7d1339a5/3f41305ef092

# 2.3 Searching above QCD

# The heart of the matter

## Discovery of the Higgs boson:

guided by **clues** from the **Standard Model** of particle physics



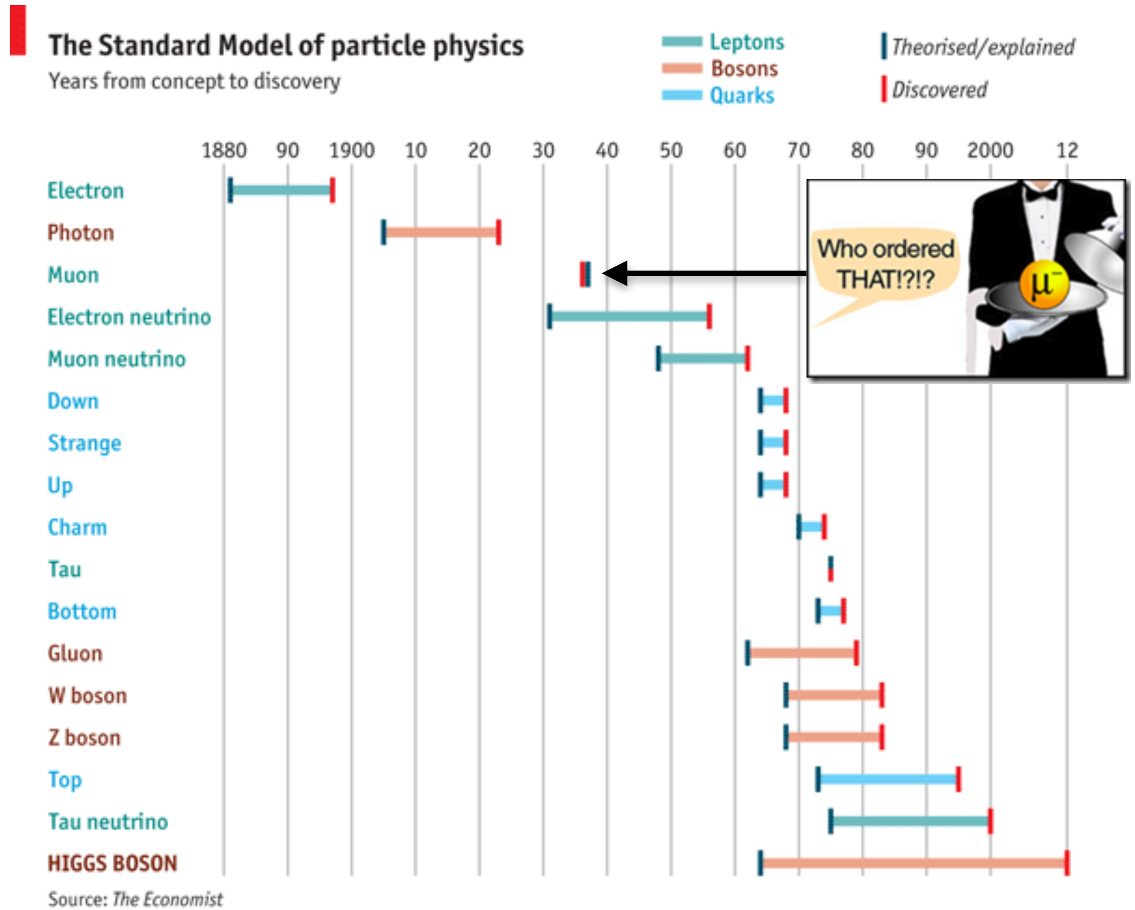


The Higgs boson mass as of May **2015**

arXiv:1503.07589

$$m_H = 125.09 \pm 0.24\ \mathrm{GeV}$$

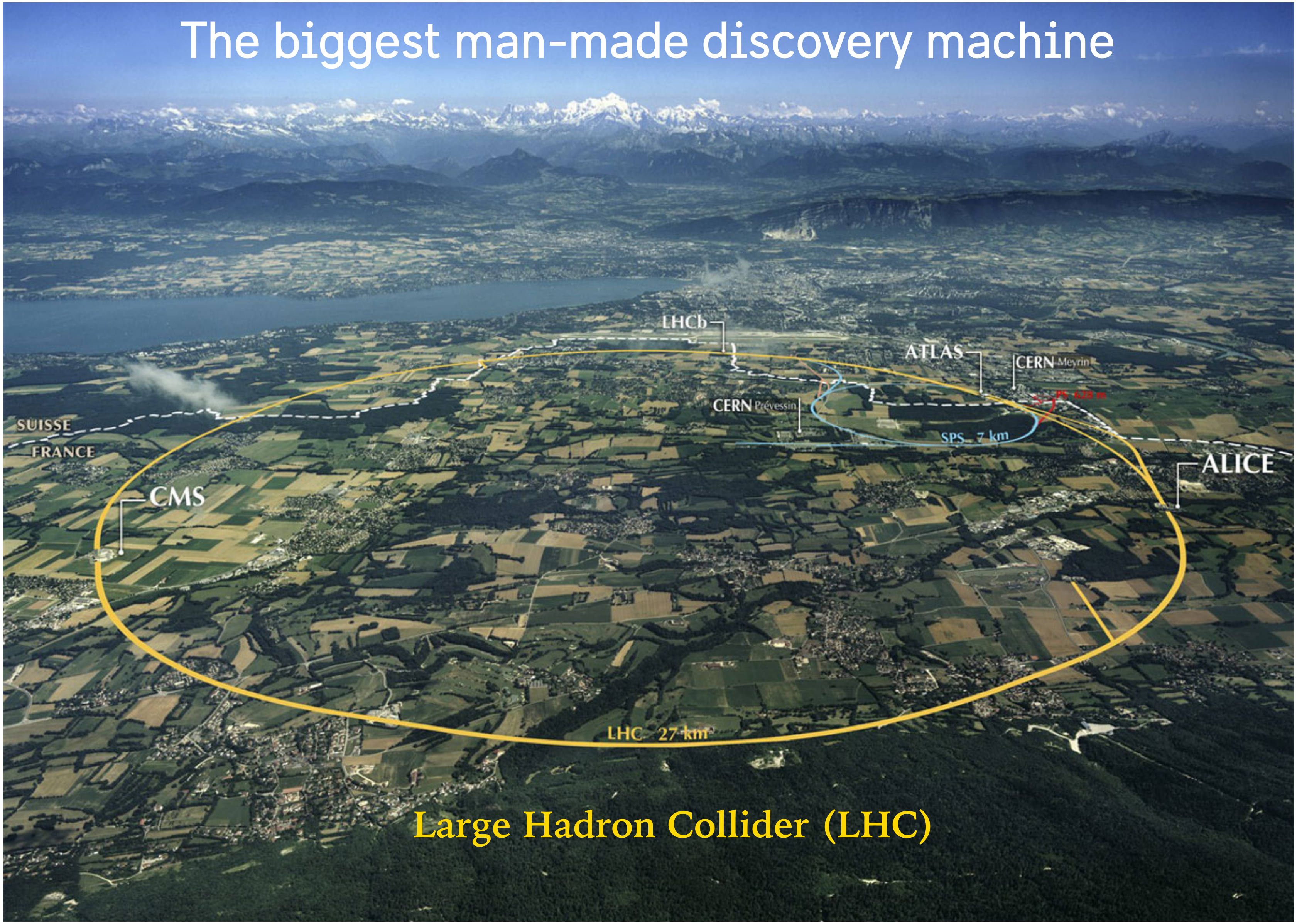
# Where to look for new particles?




**Everywhere!**

design **model-independent searches** for new phenomena

# How to look for new particles?

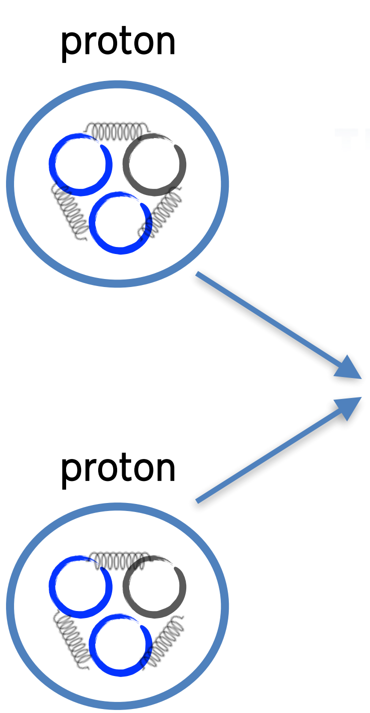


# Proton-proton collisions at the LHC

Look for new particles

decaying to quarks and gluons (jets)

**if they're created they should decay!**



# Proton-proton collisions at the LHC

Look for new particles
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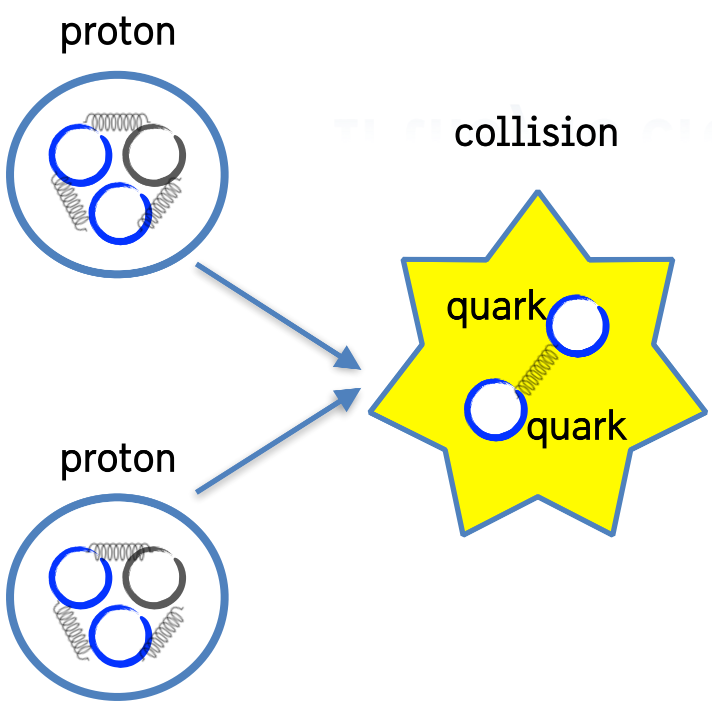

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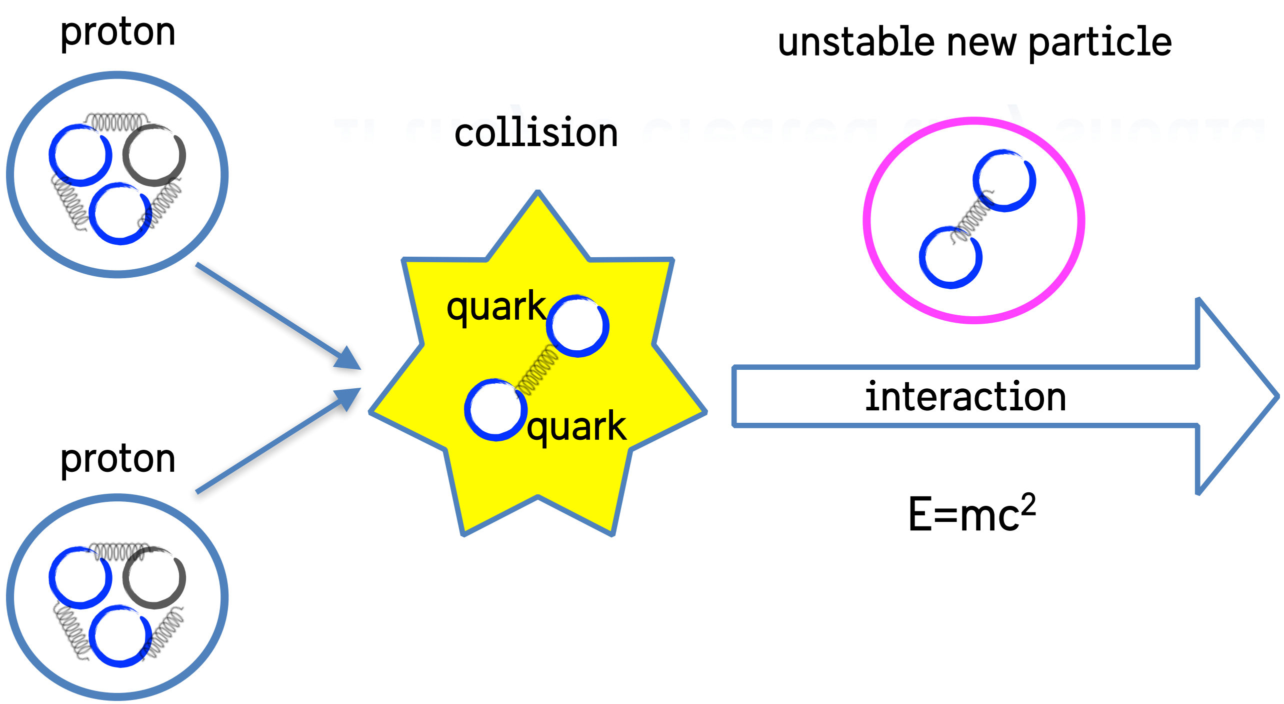

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Look for new particles
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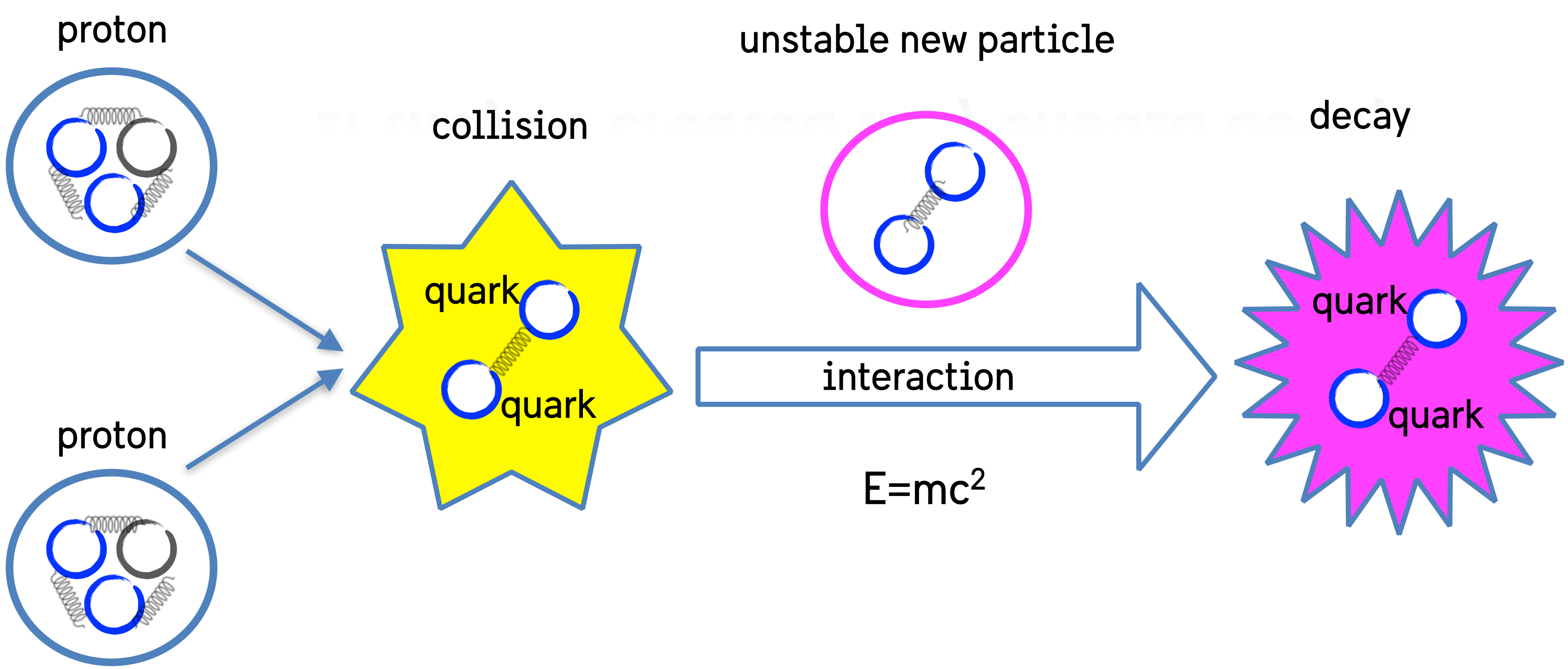
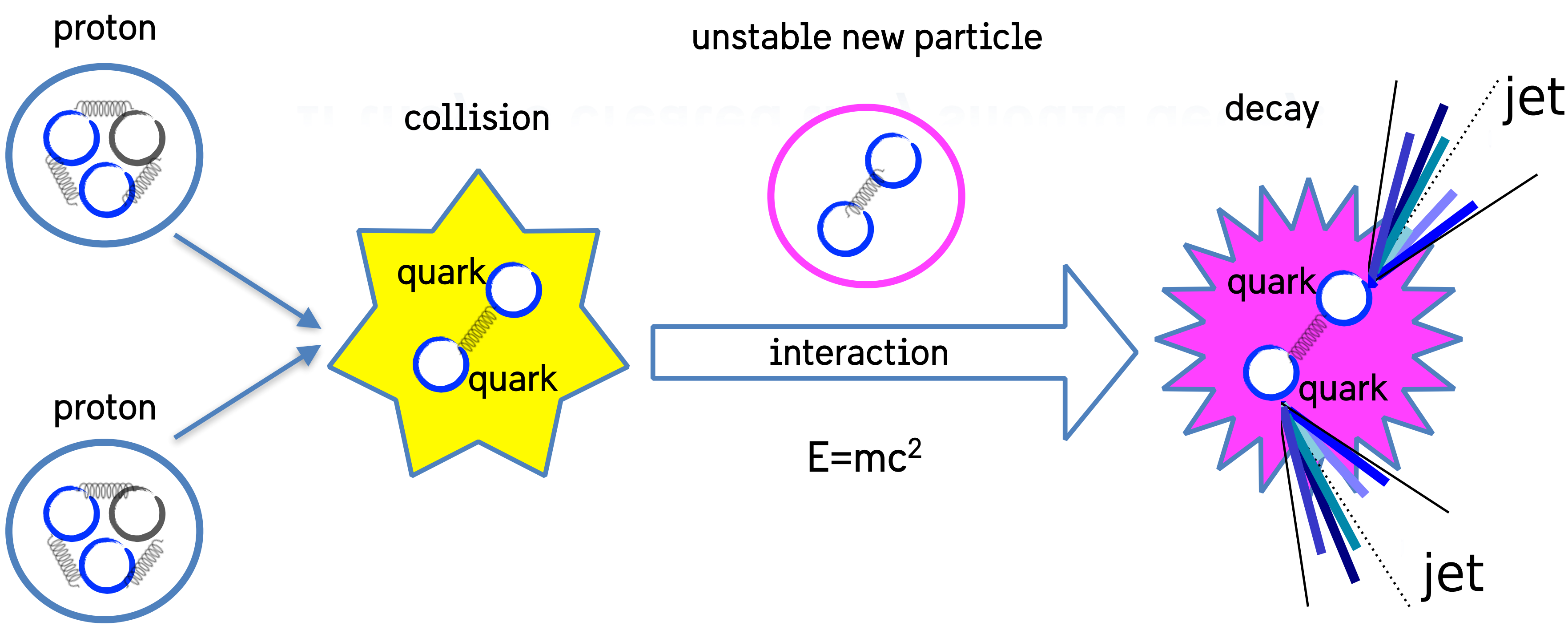
**if they're created they should decay!**



# Proton-proton collisions at the LHC

Look for new particles
decaying to quarks and gluons (jets)
**if they're created they should decay!**



# The first 2015 ATLAS search paper

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Lett. B

CERN-PH-EP-2015-311
4th December 2015

x] 4 Dec 2015

**Search for new phenomena in dijet mass and angular distributions from *pp* collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector**

The ATLAS Collaboration

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# Search for new physics with jets 101

Get the **jets**

Build distributions of **interesting observables**

**Search phase:** compare data and background

see any deviations?

No

**Limit setting phase:** constrain new physics models

Yes

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# Search for new physics with jets 101

Get the **jets**

Build distributions of **interesting observables**

**Search phase:** compare data and background

see any deviations?

No

**Limit setting phase:** constrain new physics models

Yes

# Search for new physics with jets 101

Get the **jets**

Build distributions of **interesting observables**

**Search phase:** compare data and background

see any deviations?

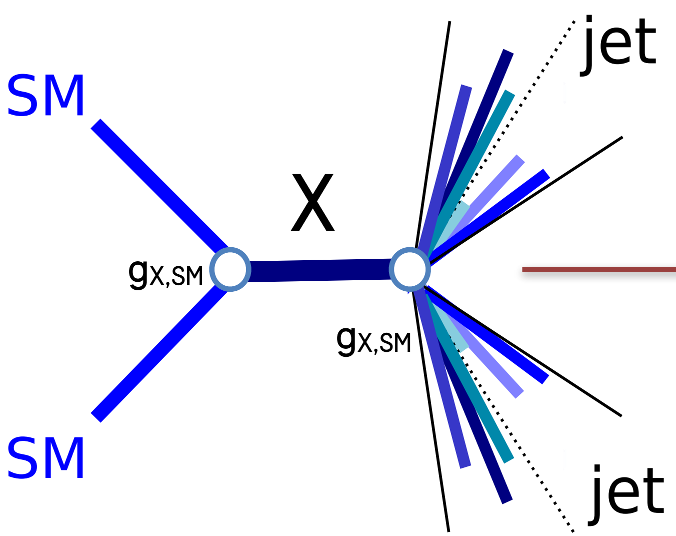
No

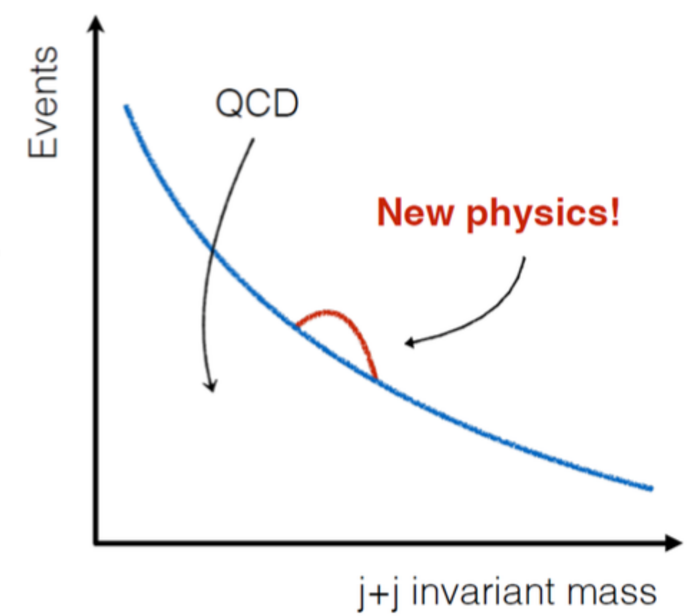
**Limit setting phase:** constrain new physics models

Yes

# Resonant phenomena producing jets

Look for new particles decaying to quarks and gluons (→jets)
appearing as "bump" over QCD background
(or dips, if interference with QCD)




Many models fit the bill: excited quarks, heavy boson partners…see Exotics lectures!

# Search for new physics with jets 101

Get the **jets**

Build distributions of **interesting observables**

**Search phase:** compare data and background

see any deviations?

No

**Limit setting phase:** constrain new physics models

Yes

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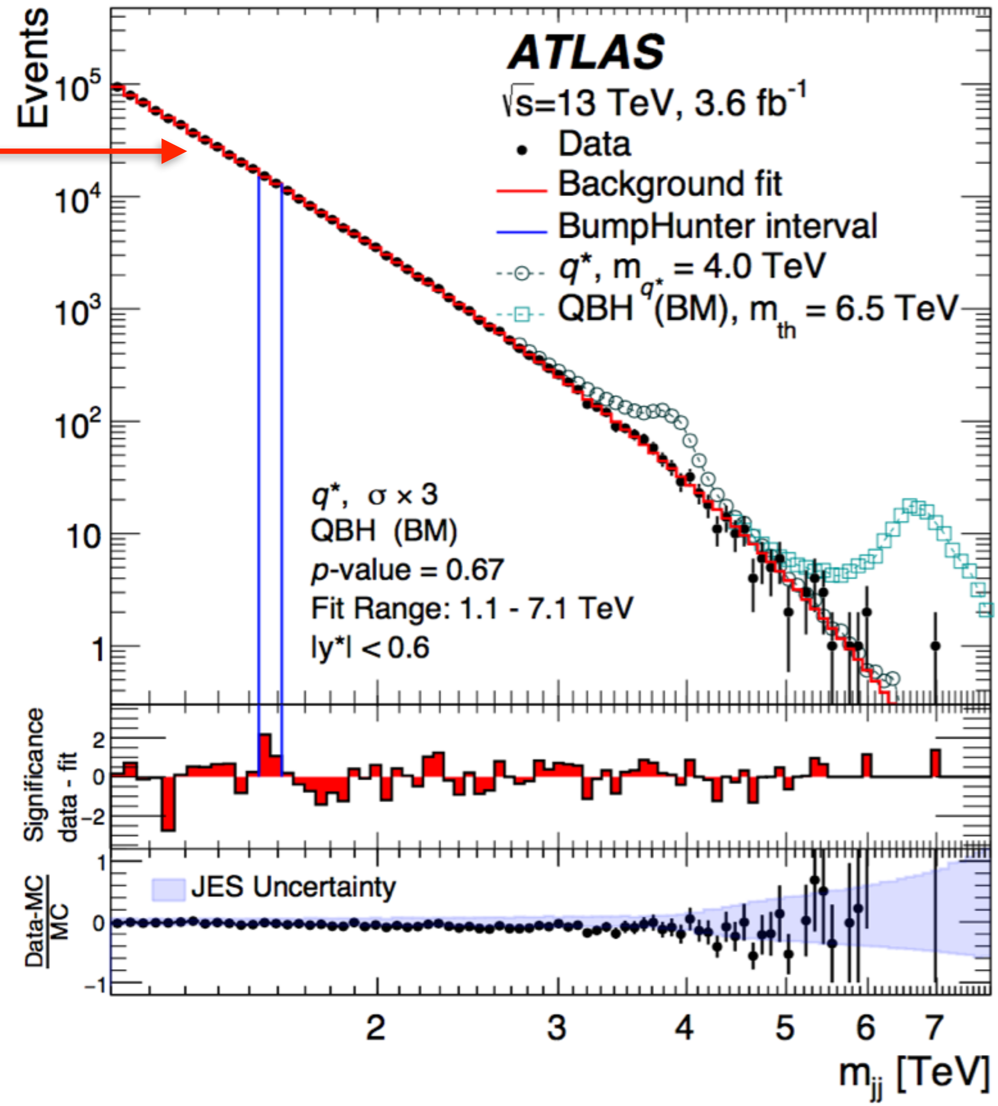
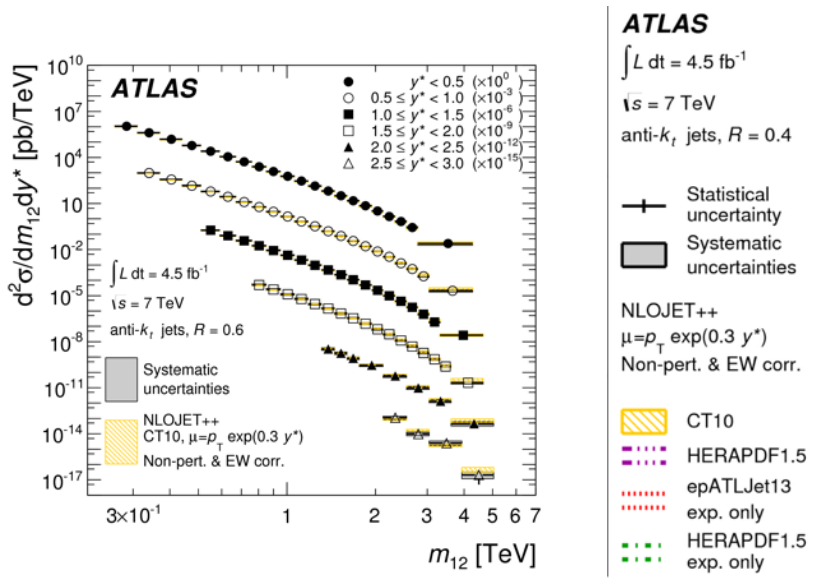
# Search phase: fit

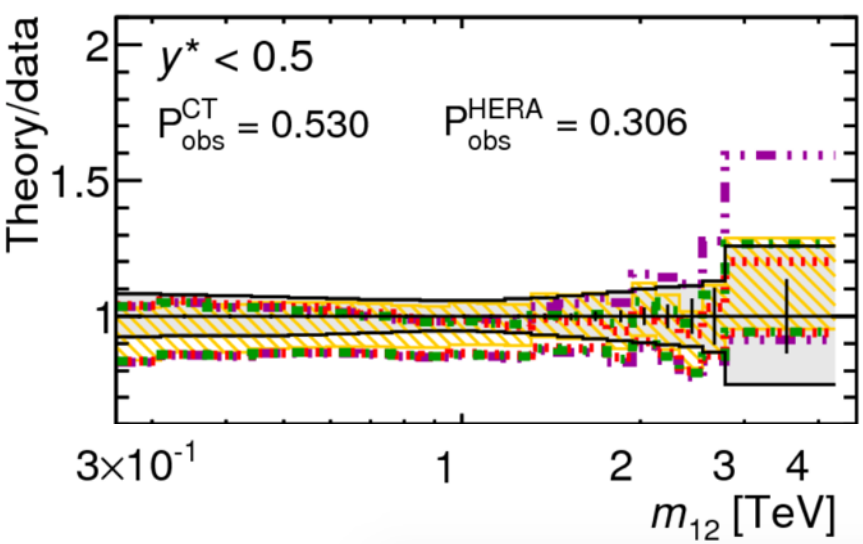
Compare **data** with **smooth fit**:

$$f(z) = p_1(1-z)^{p_2} z^{p_3}$$

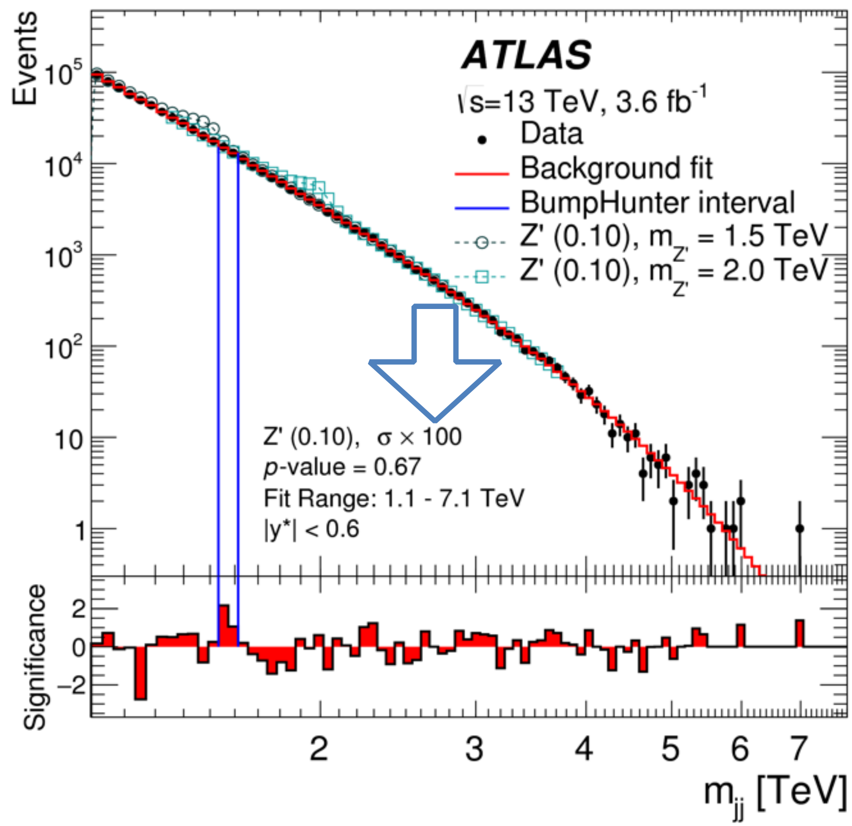


# Why fit? Because QCD is uncertain…




## Extremely small signals!



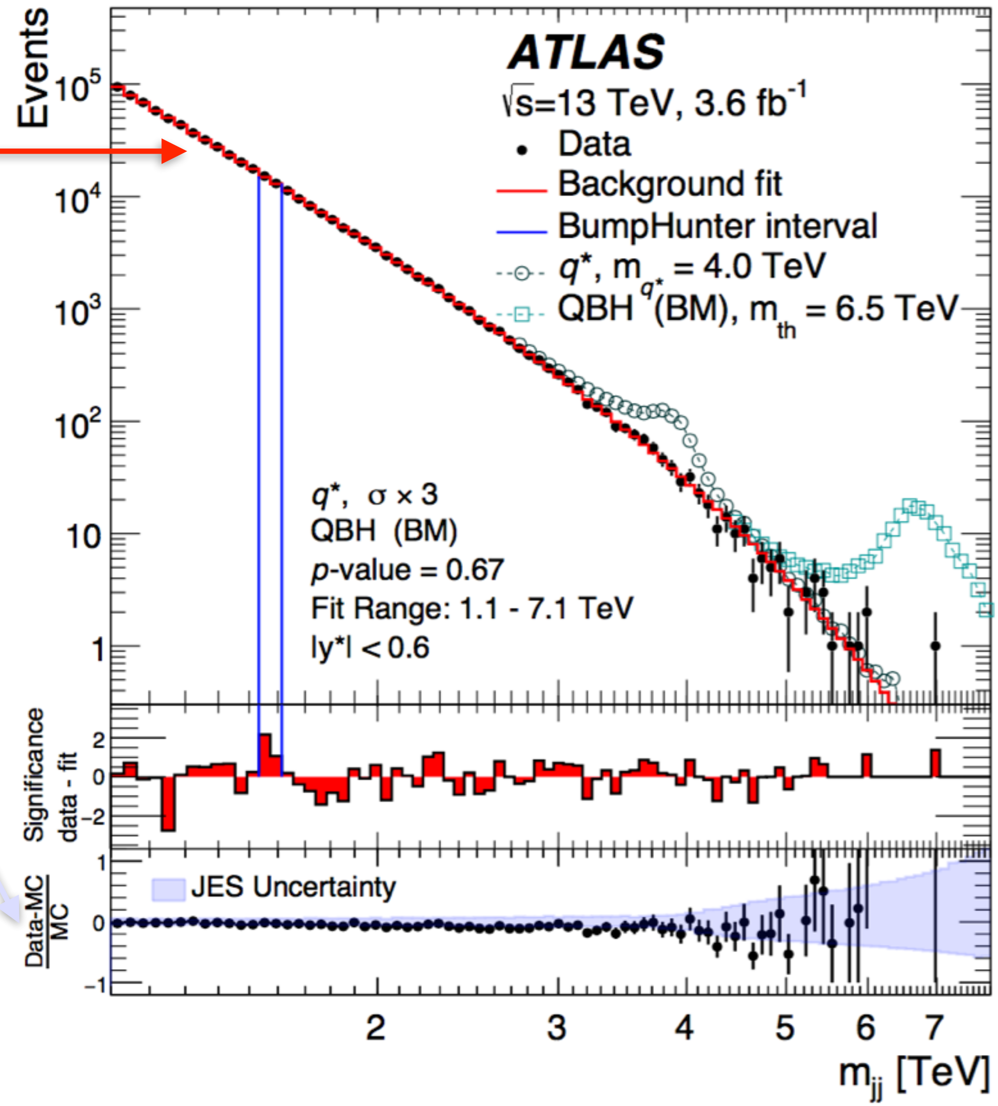

Note: fit function has uncertainties/issues as well, and one can also do a full search for new physics using a MC background by profiling uncertainties

# Search phase: mass selection

Compare **data** with **smooth fit**:

$$f(z) = p_1(1-z)^{p_2} z^{p_3}$$

Compare **data** with **simulation** (Pythia) as a cross-check



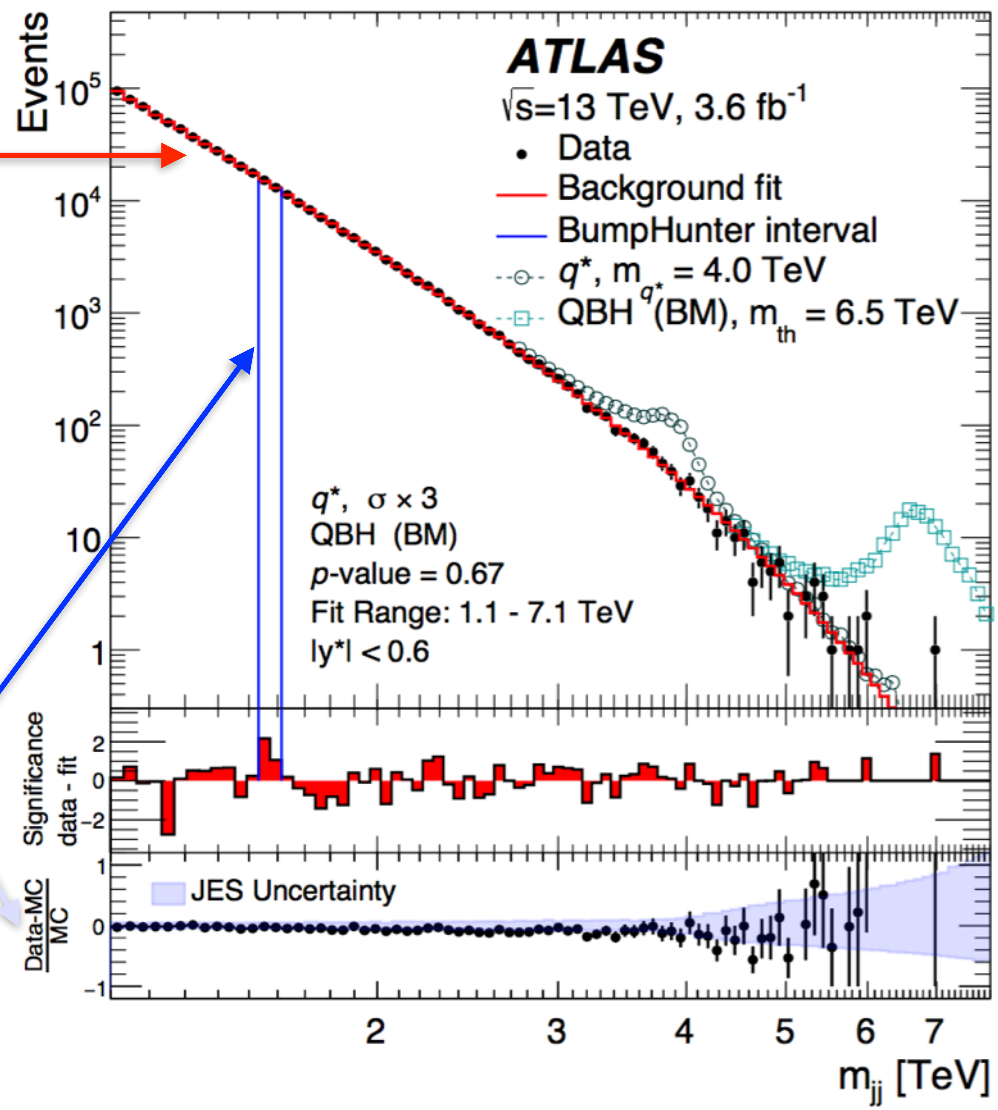
# Search phase: mass selection

Compare **data** with **smooth fit**:

$$f(z) = p_1(1-z)^{p_2} z^{p_3}$$

Compare **data** with **simulation** (Pythia)

Run **BumpHunter** algorithm to find most significant **excess** (not significant)



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# Search for new physics with jets 101

Get the **jets**

Build distributions of **interesting observables**

**Search phase:** compare data and background

see any deviations?

No

**Limit setting phase:** constrain new physics models

Yes


not this time, sorry…

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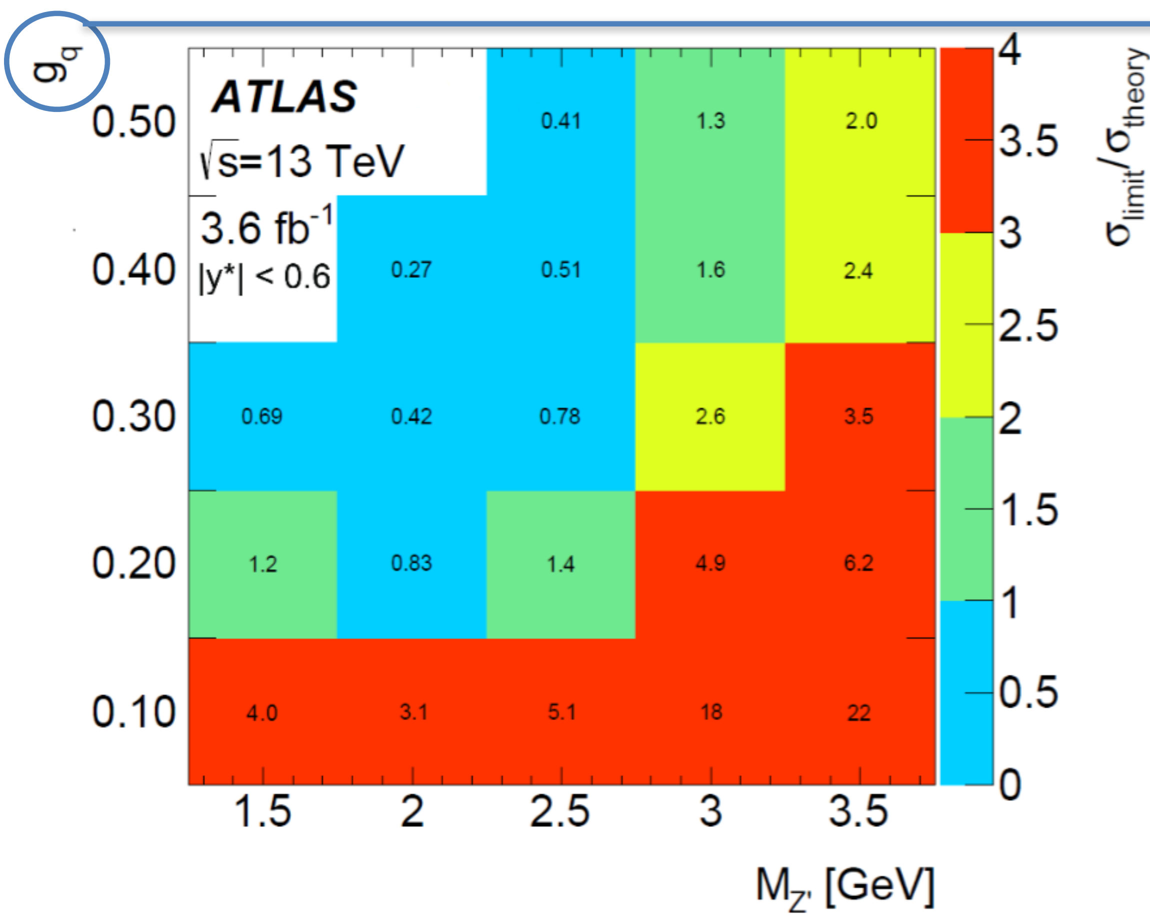
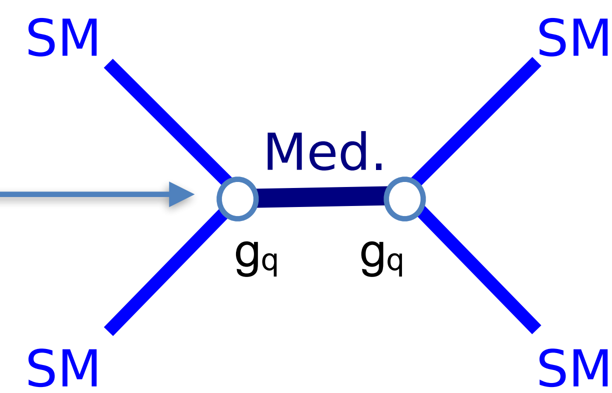
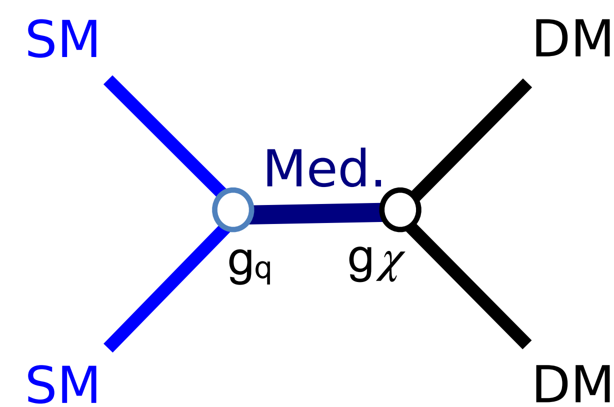
# Constraining new physics models

Example of model-dependent limits:
**Z' Dark Matter mediator**

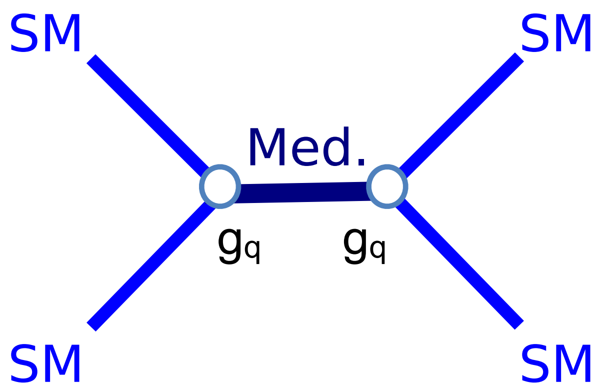


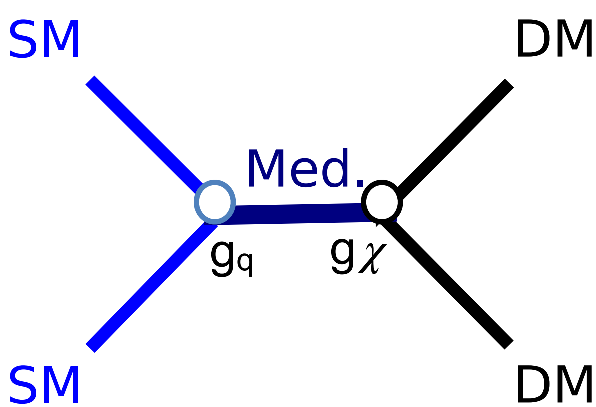



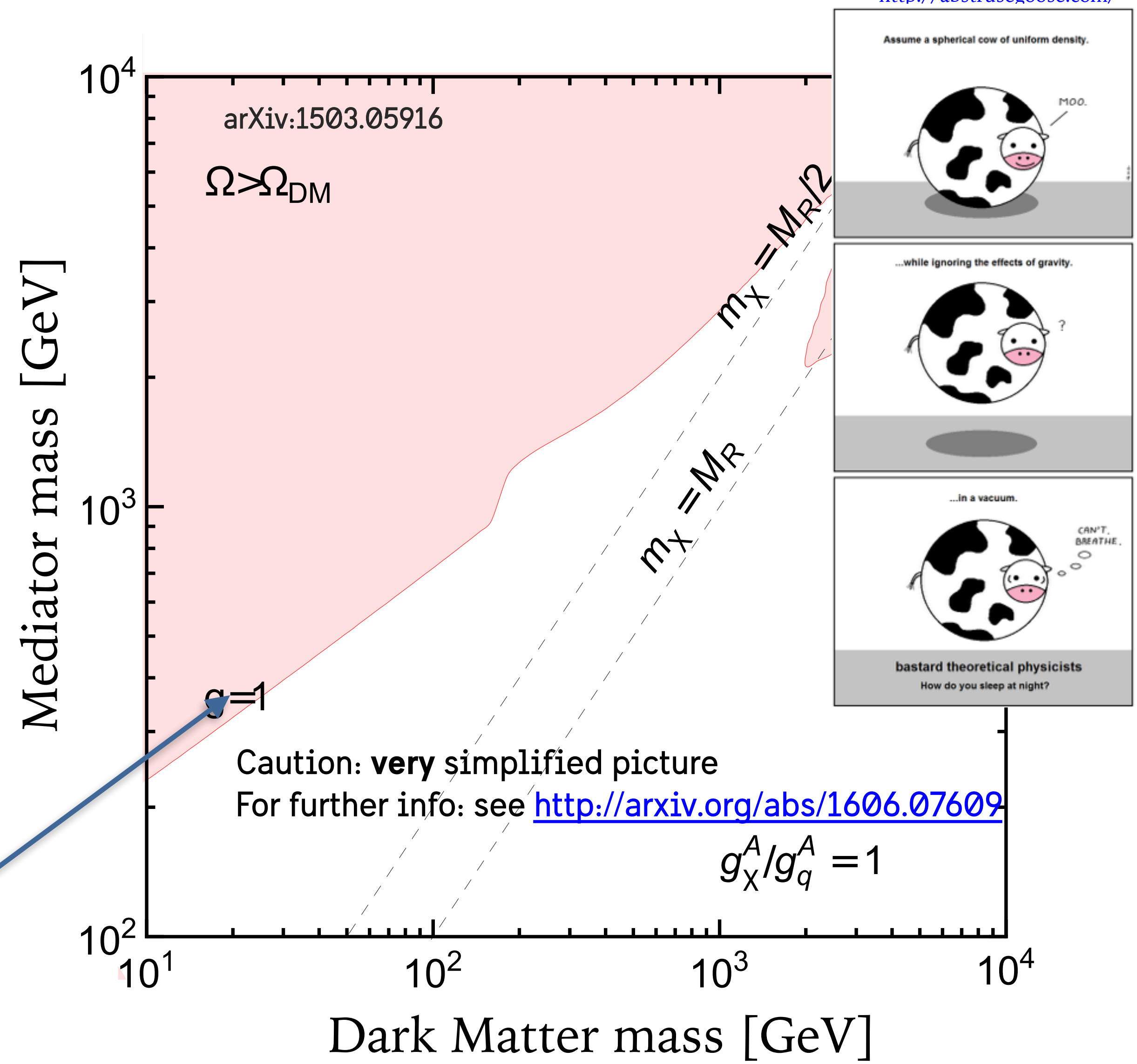

See more in M. Martinez's lectures about BSM processes

# More on Dark Matter Mediator decays to jets



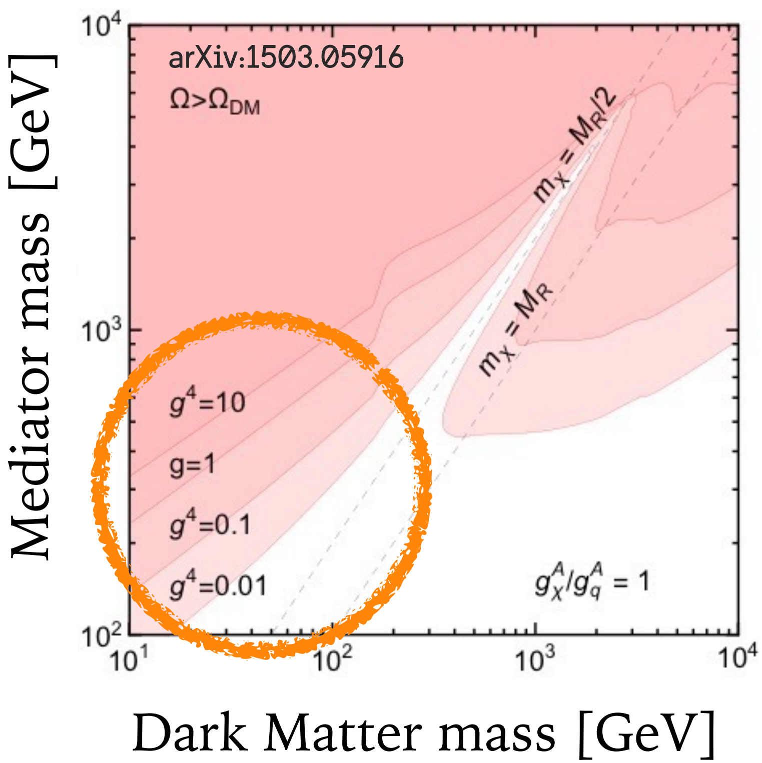

$$g \equiv (g_q^A\, g_\chi^A)^{1/2}$$

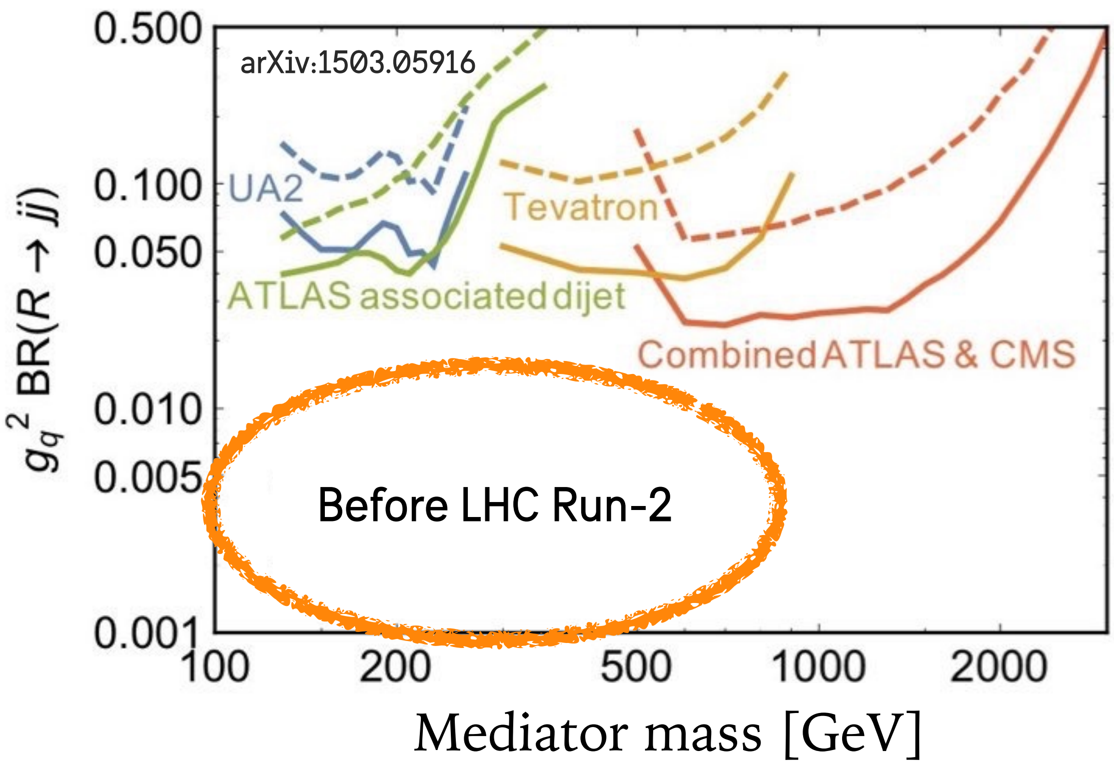


# More on Dark Matter Mediator decays to jets

Most interesting region: low mediator masses

Least constrained region: low mediator masses




**Reason:** compatibility with relic density

**Reasons:** **trigger!** large backgrounds difficult to record all events

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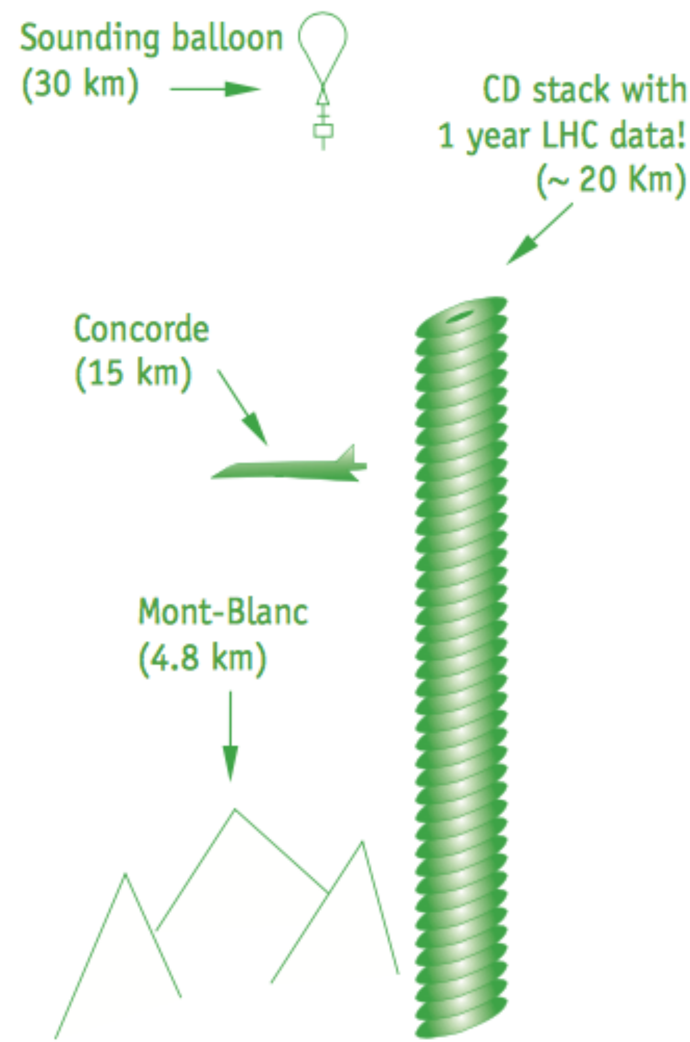
# Why? Too much data (mostly QCD)

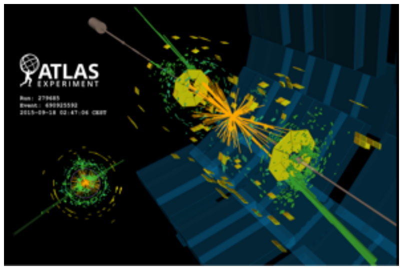
- LHC: if everything was recorded…
  - up to 40 million collisions/second (MHz)
  - 1-1.5 MB/data per collision
  - 40 MHz * 1 MB = 40 TB/s
  - 40 TB/s * 10e+6 s/year = 0.05 ZB/year
- Facebook:
  - 600 TB/day ~ 200 PB/year [Facebook]

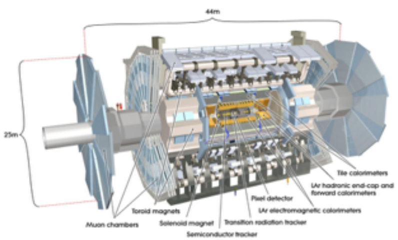
**LHC experiments need to:**
1. **process** all data, fast
2. **select** only interesting events




(**after** selecting interesting events)

# Select interesting data only: jet triggers



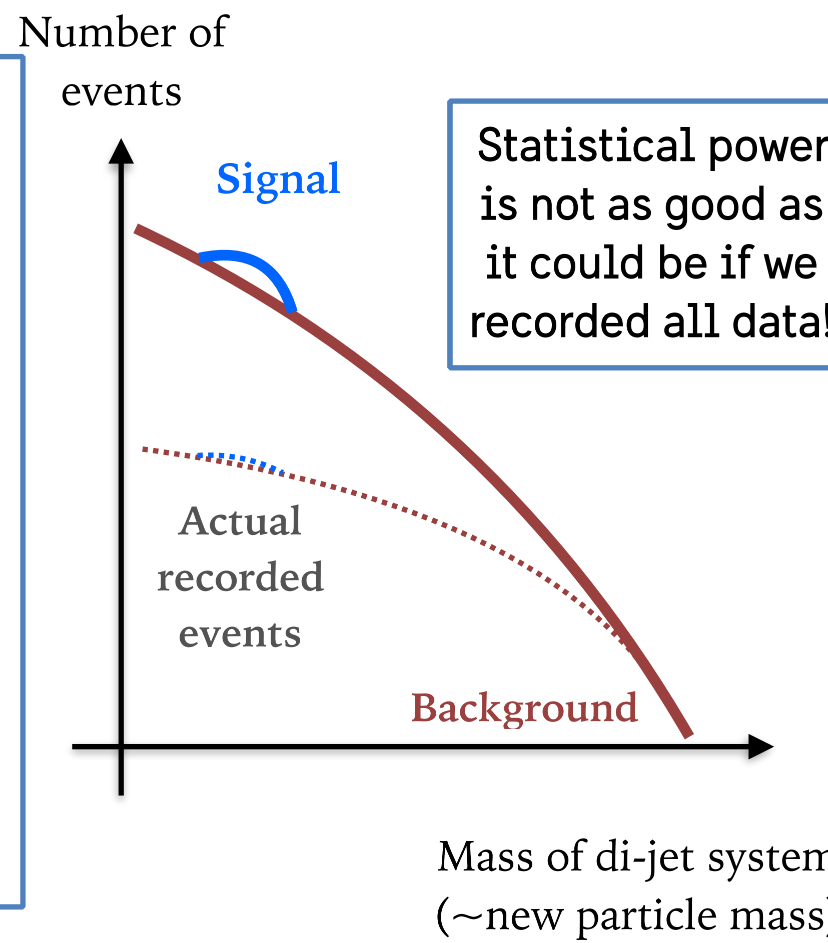



Event selection (trigger) → Object reconstruction and calibration → Data analysis

**Trigger and data acquisition:**
select interesting events

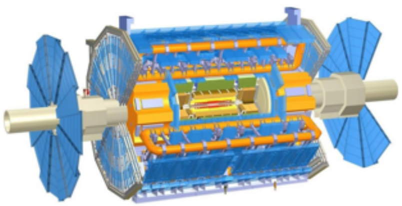
First step: **fast hardware selection (Level 1)**
select max. 100000 events/second
Second step: **computer farm (High-Level Trigger)**
record max. 1000 events/second

**What this means for QCD** (we need it all as signals look like regular QCD jets):
Only a **fraction** of lower-energy jets are saved




Statistical power is not as good as it could be if we recorded all data!

# Let's record trigger jets! (and make them good enough)



Other L1/HLT event reconstruction

Calorimeter event reconstruction

Trigger decision

**if passed trigger**

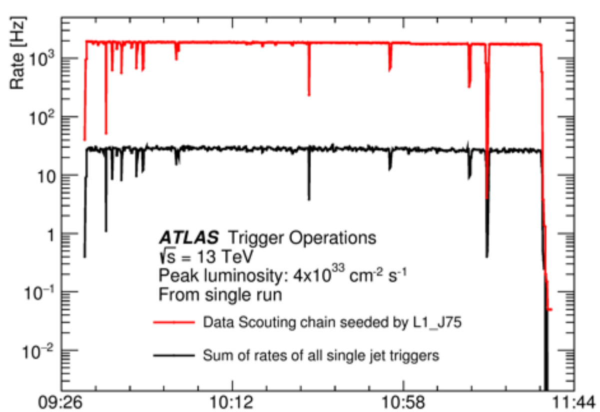
Full event reconstruction

**Standard data analysis**

**In any case**

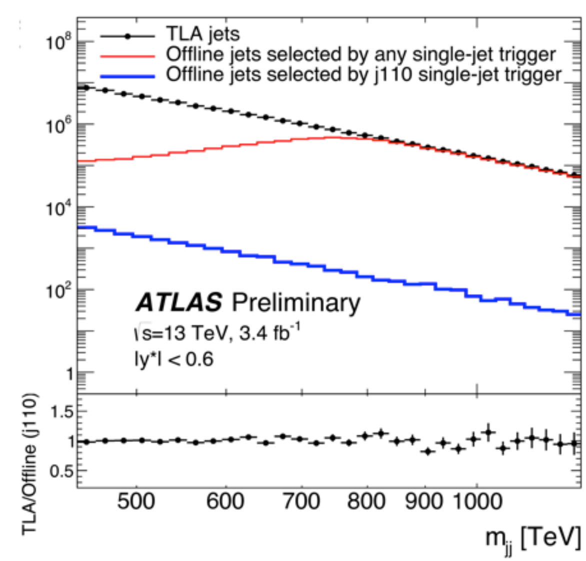
Partial (trigger-jet-only) event reconstruction

**Trigger-Level Analysis (TLA)**



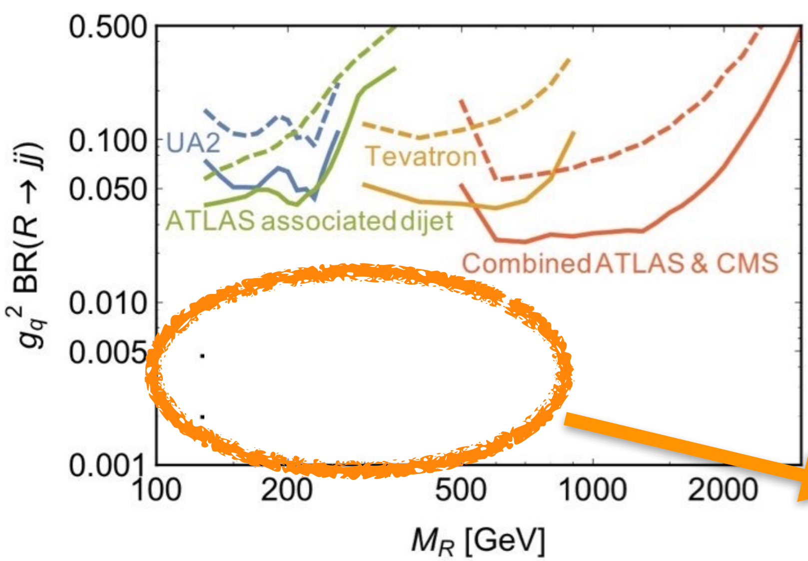

**Bandwidth** = Event rate x Event size

https://en.wikipedia.org/wiki/Three-letter_acronym
https://en.wikipedia.org/wiki/RAS_syndrome

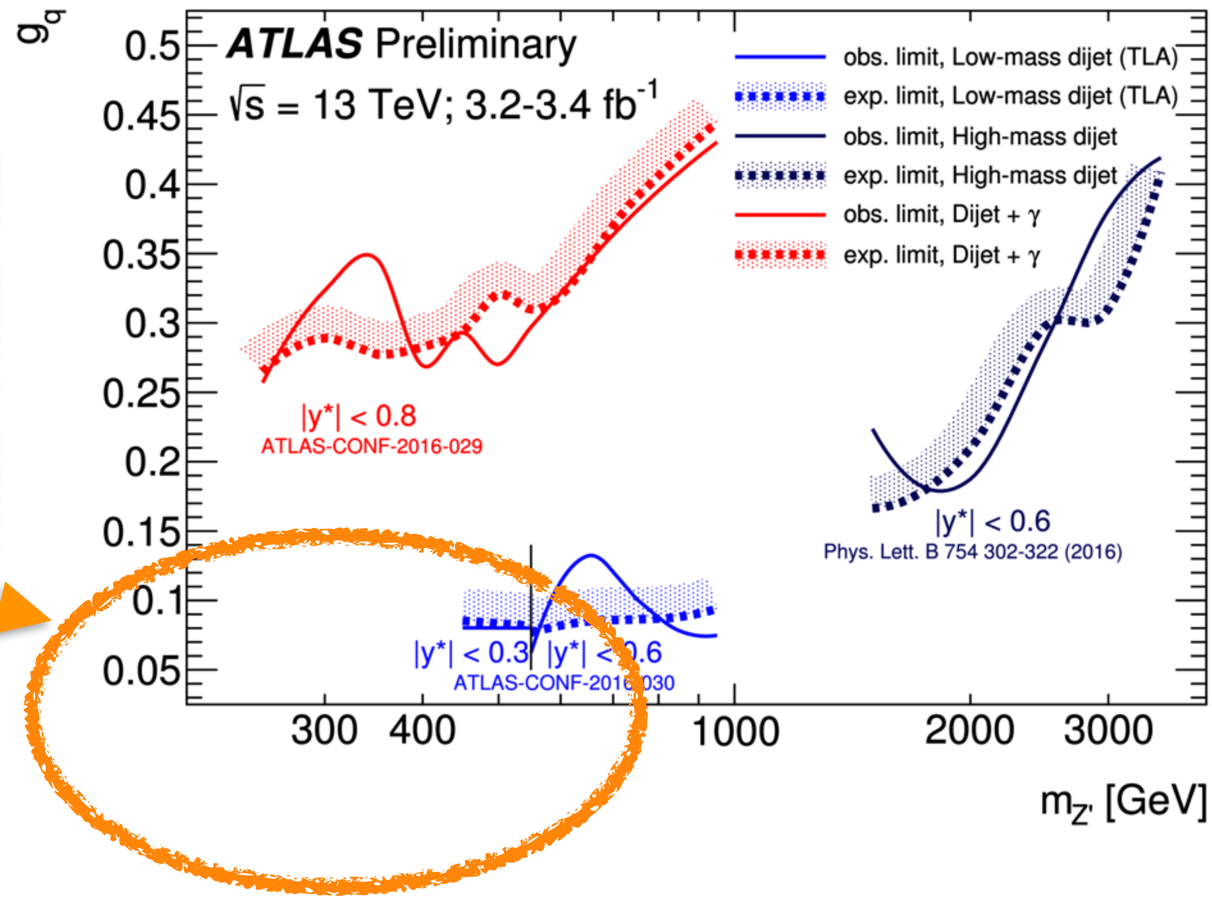


# No jetty new physics found anywhere (yet)

Before 2015 LHC data




After 2015 LHC data




…but we have a long way ahead with the LHC Run-2!
(LHC delivered ~4x the 2015 data as of this morning)

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# Concepts for part 3.3

- Jets are everywhere at the LHC:
  let's search in hadronic final states
- Search for new particles in dijet final states
  - Look for resonances ('bumps') above QCD background
  - Fit with a smooth function to avoid QCD uncertainties
  - No new physics found -> constrain new physics models
- There is too much QCD to record it all
  - Jet trigger system
  - Overcome bandwidth limitation:
    search at the trigger level

# General recap of the QCD lectures

- **Lecture 1: Quarks gluons and strong interactions**
  - From the hadron zoo to the quark model
  - Characterizing quarks: the eightfold way, color
  - Experimental proof of the quark model
  - Strong force: confinement and asymptotic freedom
- **Lecture 2 (Tuesday): Experimental aspects of QCD**
  - How to see quarks and gluons: jets
  - Jet substructure
  - Measurements of QCD at the LHC
  - Looking for bumps above QCD

# Some references (out of many)

**The Experimental Foundations of Particle Physics, Cahn and Goldhaber (Cambridge 2009)**
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