Seeing Color Flow in $t\bar{t}$

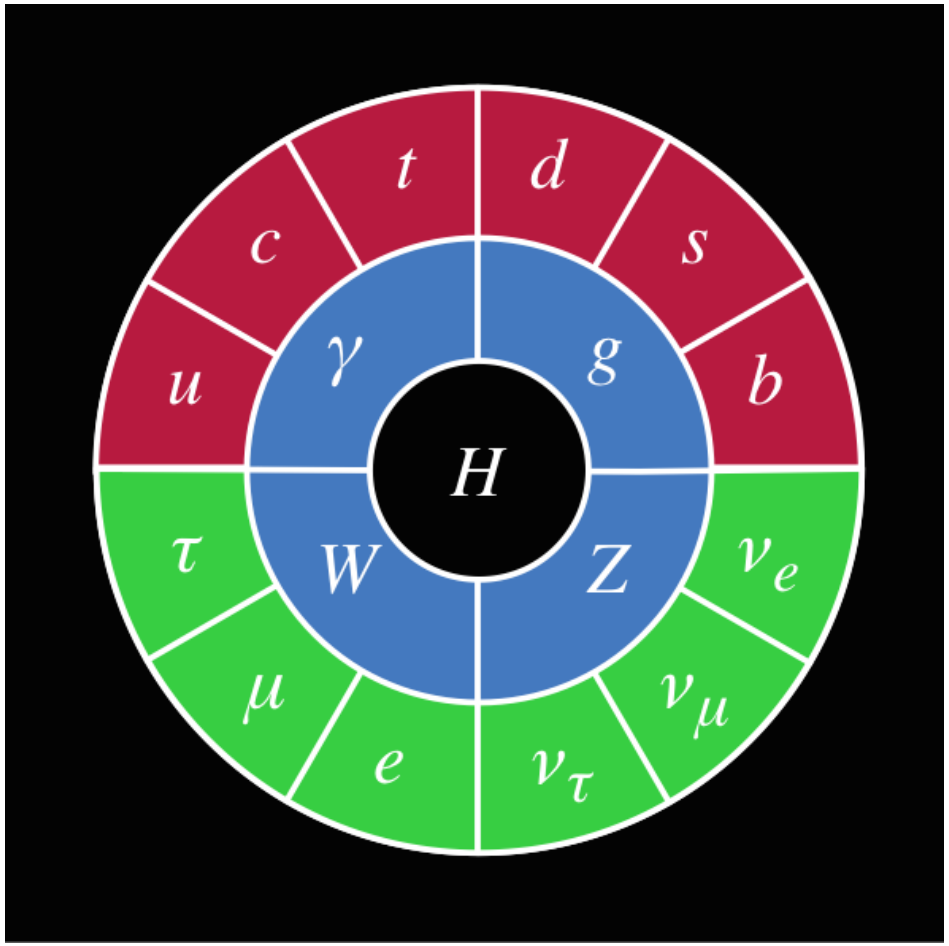
UC HEP Seminar

Maximilian Swiatlowski[1]

[1] *University of Chicago, Enrico Fermi Institute*

19 October, 2015

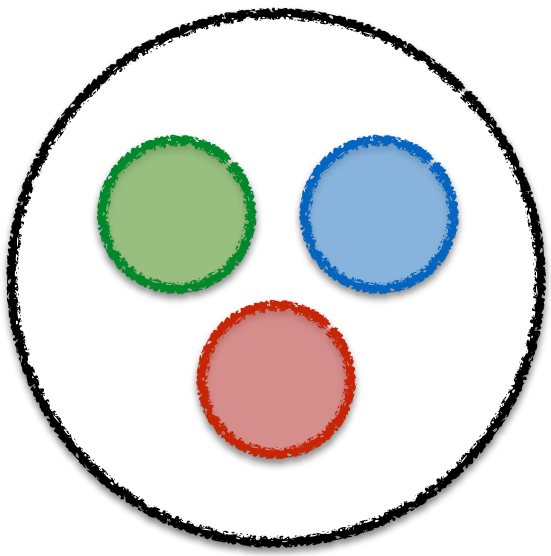
The Standard Model



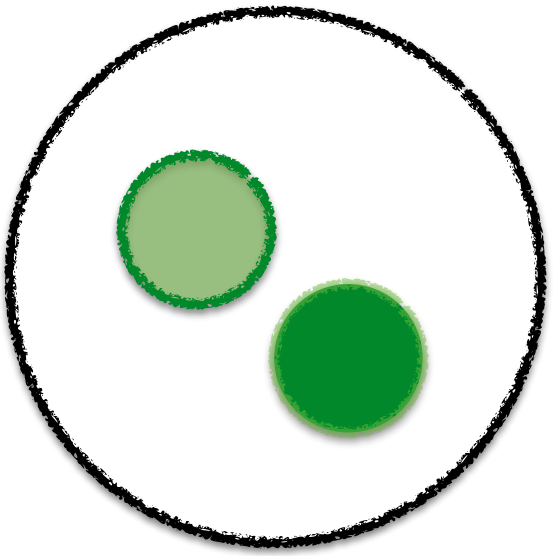
- SM is the enormously successful theory of the world around us
- Matter particles interact via force particles
- Forces interact with particles *charged* under that force

Color: The Charge of QCD

- QCD, described by $SU(3)_C$, has **rich structure**
  - Only some particles are charged under it— refer to them as *colored*
  - Quarks referred to as **triplets**: single color
  - Gluons referred to as **octets**: two colors
  - All others referred to as **singlets**: no color
- Several ways to make **color-neutral** combinations (*hadrons*):

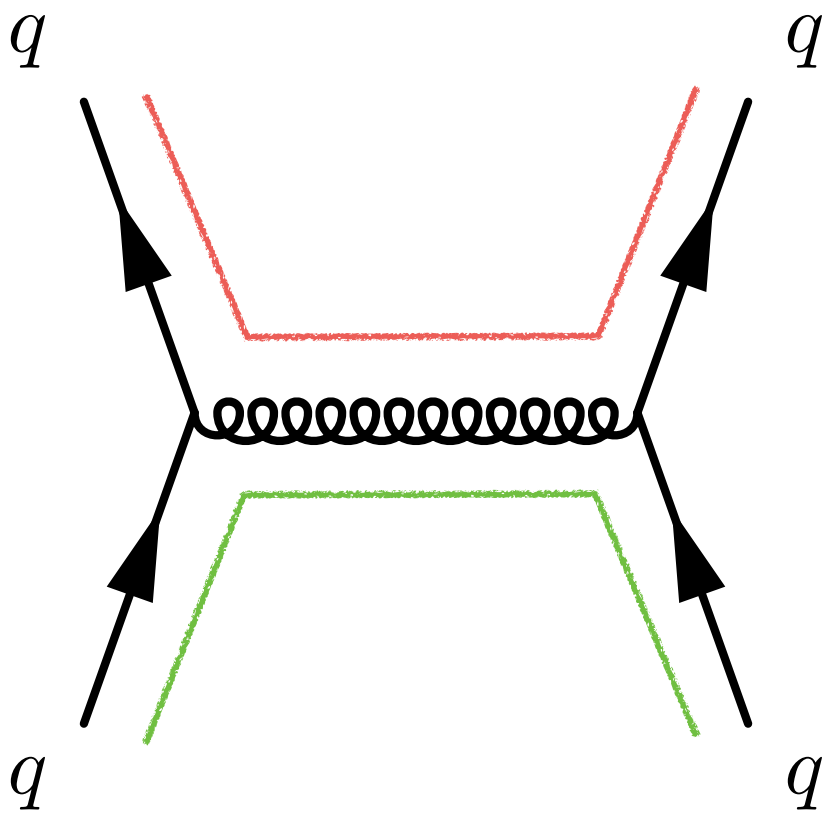


Baryons



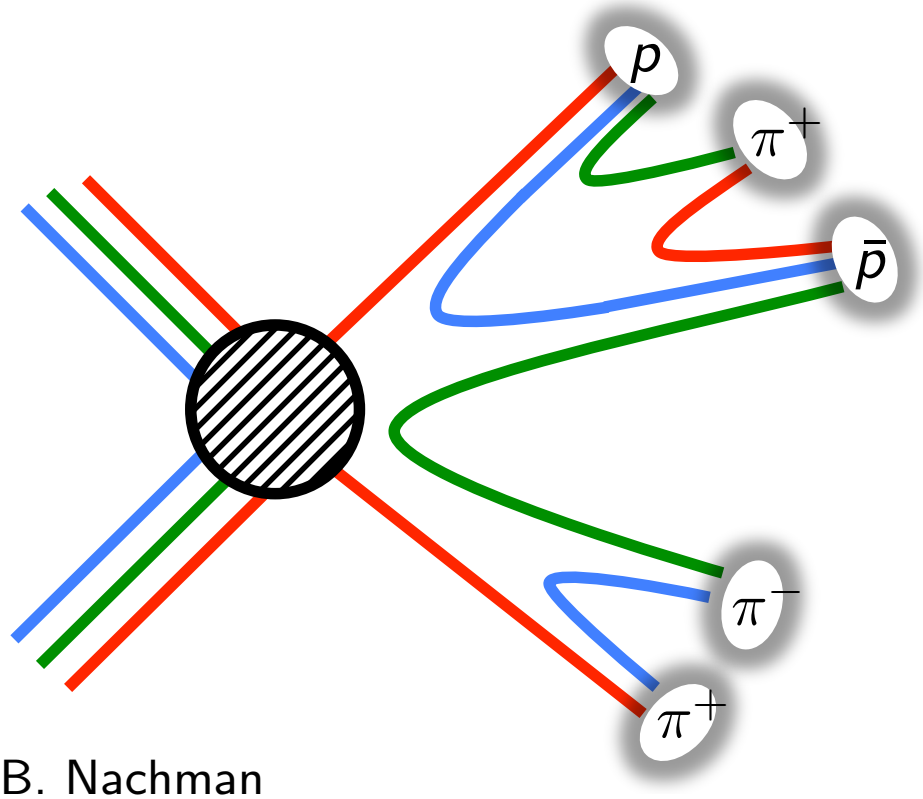
Mesons

Jets, and Hadronization



- Because of asymptotic freedom, never observe un-confined color
- Knocking loose a colored particle at a hadron collider leads to *jets*
- Given these issues, how can we study the effects of color?

Jets, and Hadronization



B. Nachman

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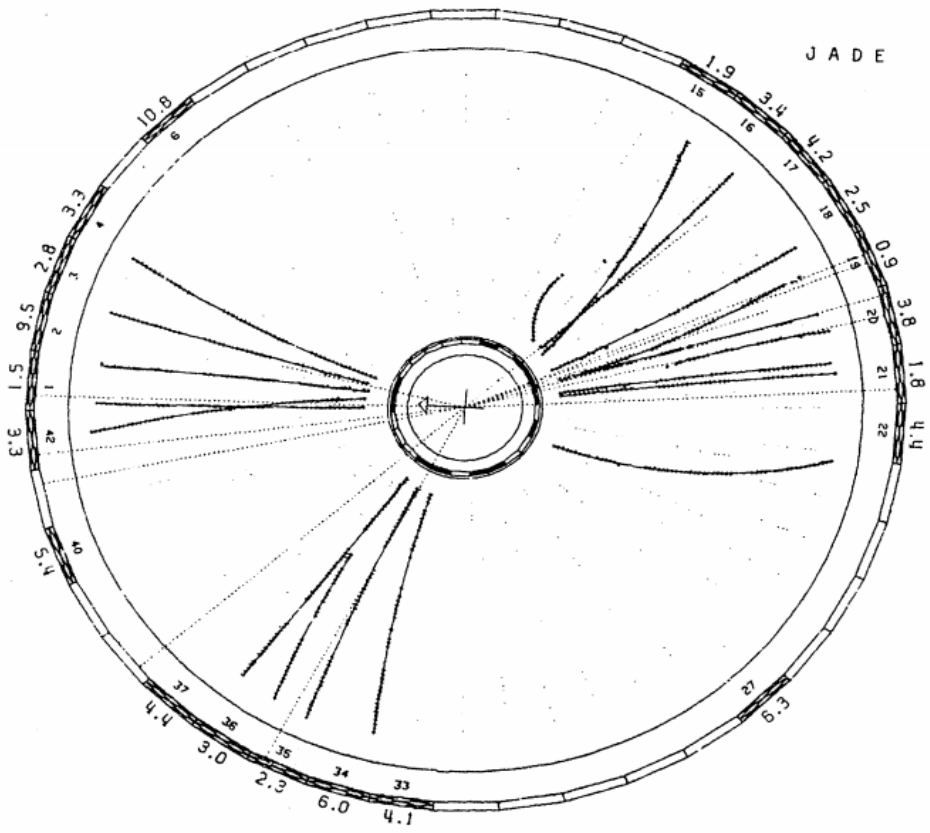
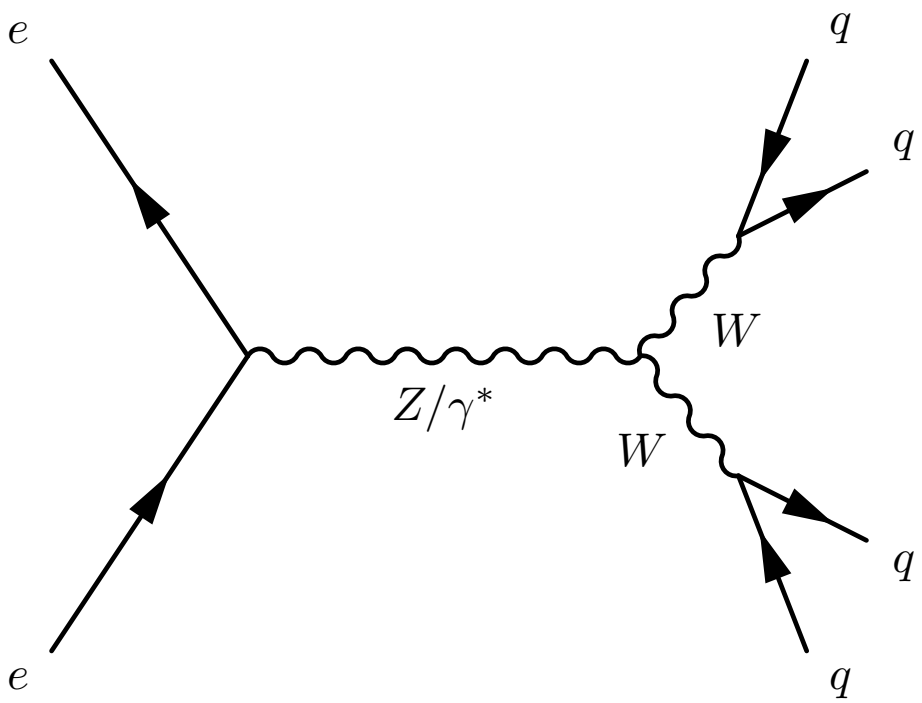
Color Has an Impact on Jets



- *Gluon* jets discovered at JADE/TASSO/PLUTO and others
  - Following Ellis, Gaillaird, Ross
- Gluons have **higher color charge**: hadronize into **greater number of particles**
  - Also observed at LEP, LHC, and elsewhere
- Certainly one effect of color—but says nothing about the **color lines**

LEP: Color Reconnection



- LEP experiments studied many aspects of color as well: one example, **color reconnection**
  - Do the jets from W-decays hadronize independently?
  - Or do they *reconnect* during this process?
- Going from observation of color effects, to **measurements of color properties**
  - Study particles *between* pairs of jets: re-connection "color strings" would produce particles there
  - Most extreme radiation models rule out

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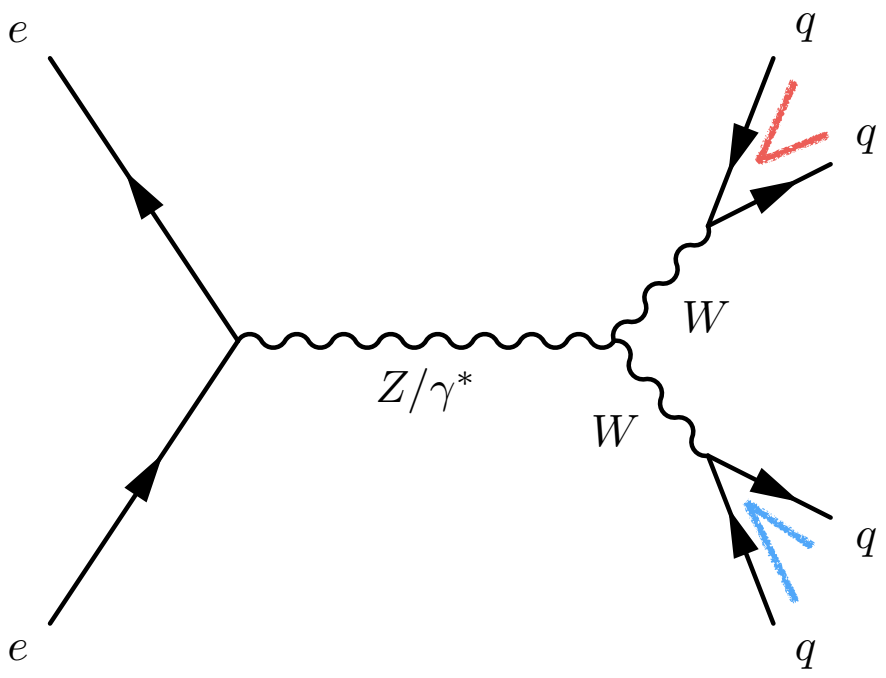

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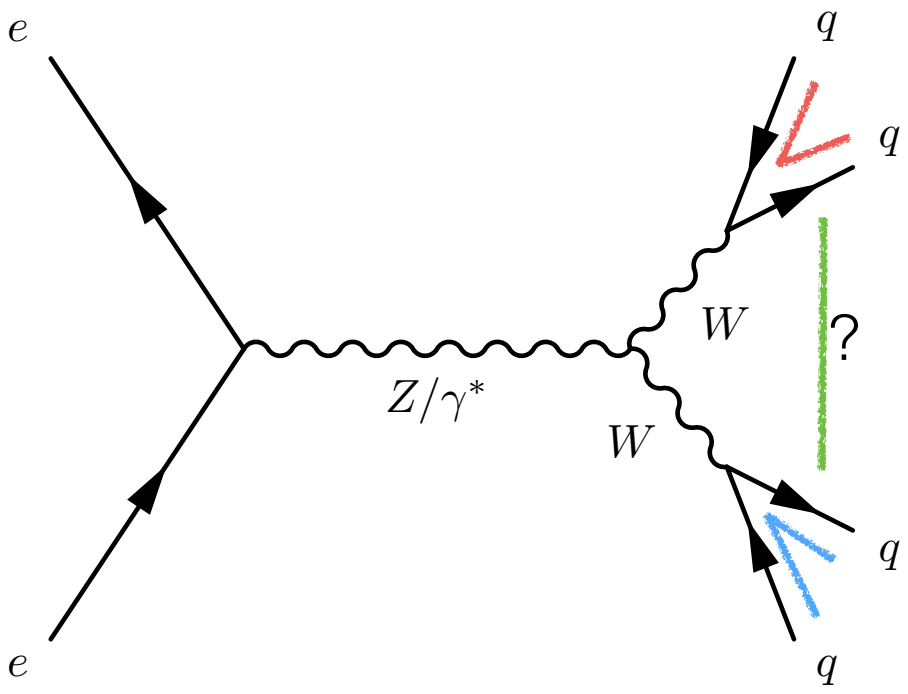

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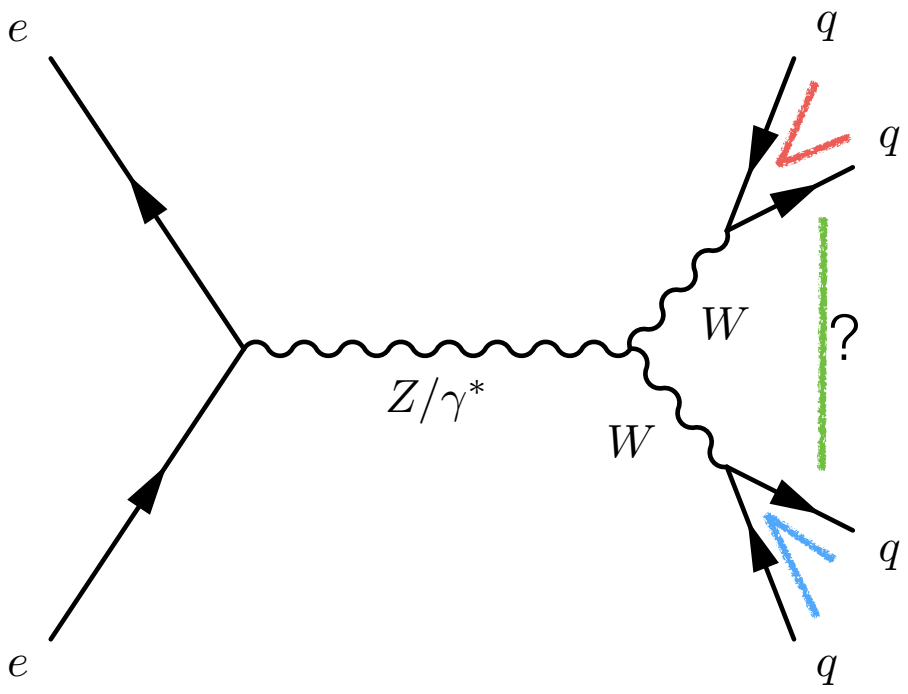

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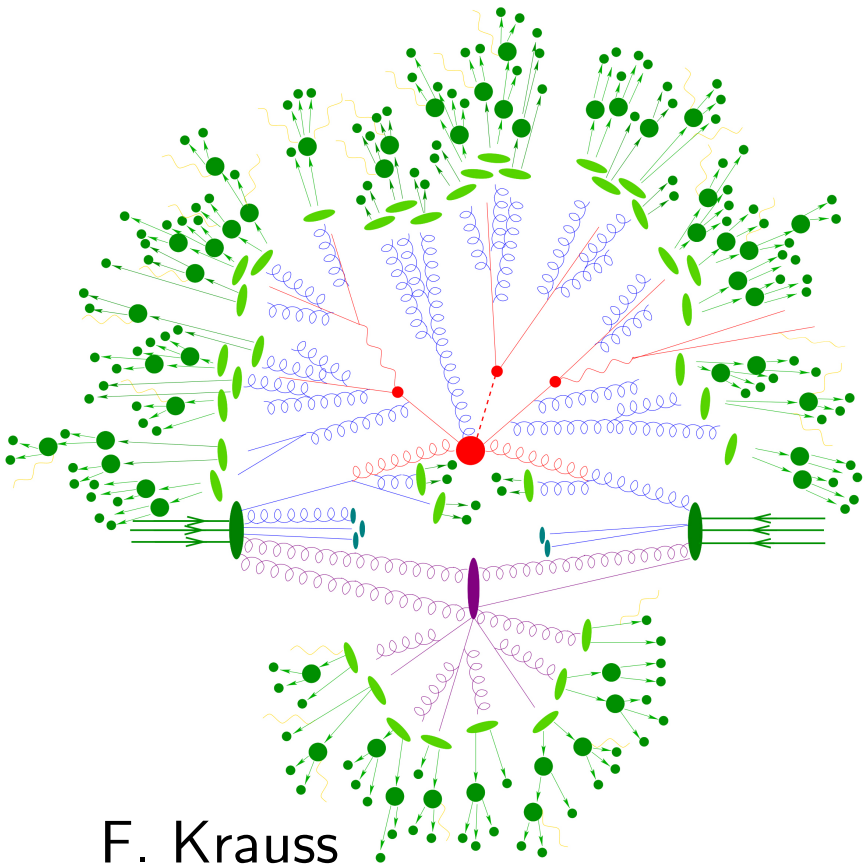
But What About Hadron Colliders?



F. Krauss

- e^+/e^- collisions are **clean**: point particles colliding and annihilating
- Hadron colliders are a completely different story:
  - Accelerate protons, but collide quarks and gluons
  - Proton remenants hadronize, as well as the colliding particles
  - *Underlying event* pollutes the environment
- Can we hope to learn anything about color in this environment?
- Can color help with *discovery* of new particles?

A New Observable: Jet Pull (hep-ph/1001.5027)

- What about looking **inside** jets for connections?

Pull (Vector)

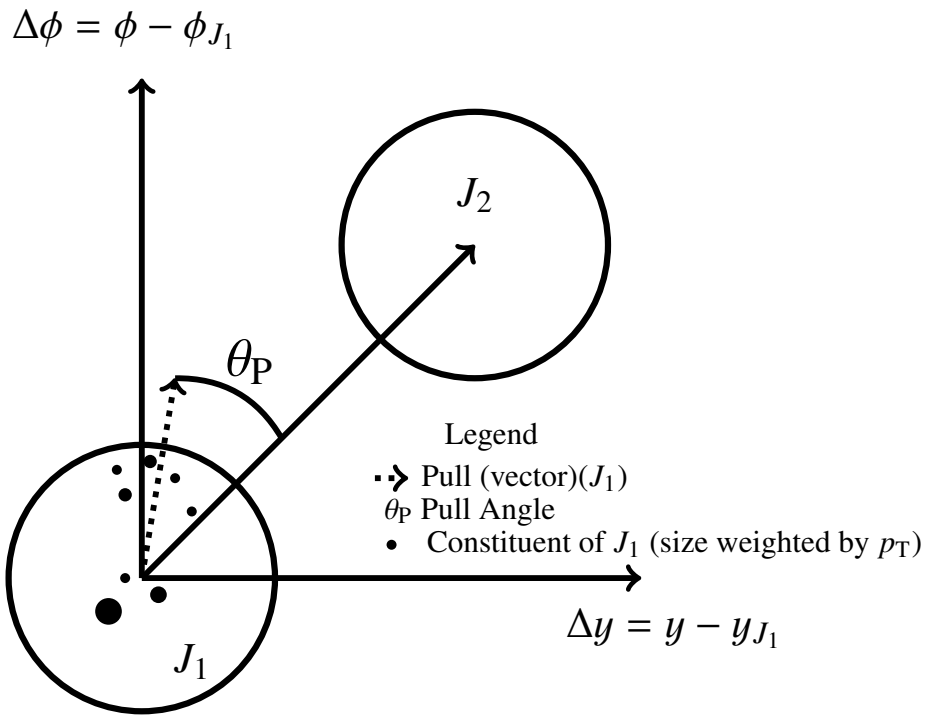
$$\vec{v}_P(J) = \sum_{i \in \mathrm{J}} \frac{p_T^i |r_i|}{p_T^{\mathrm{J}}} \vec{r}_i$$

- The direction a jet *leans*

Pull (Angle)

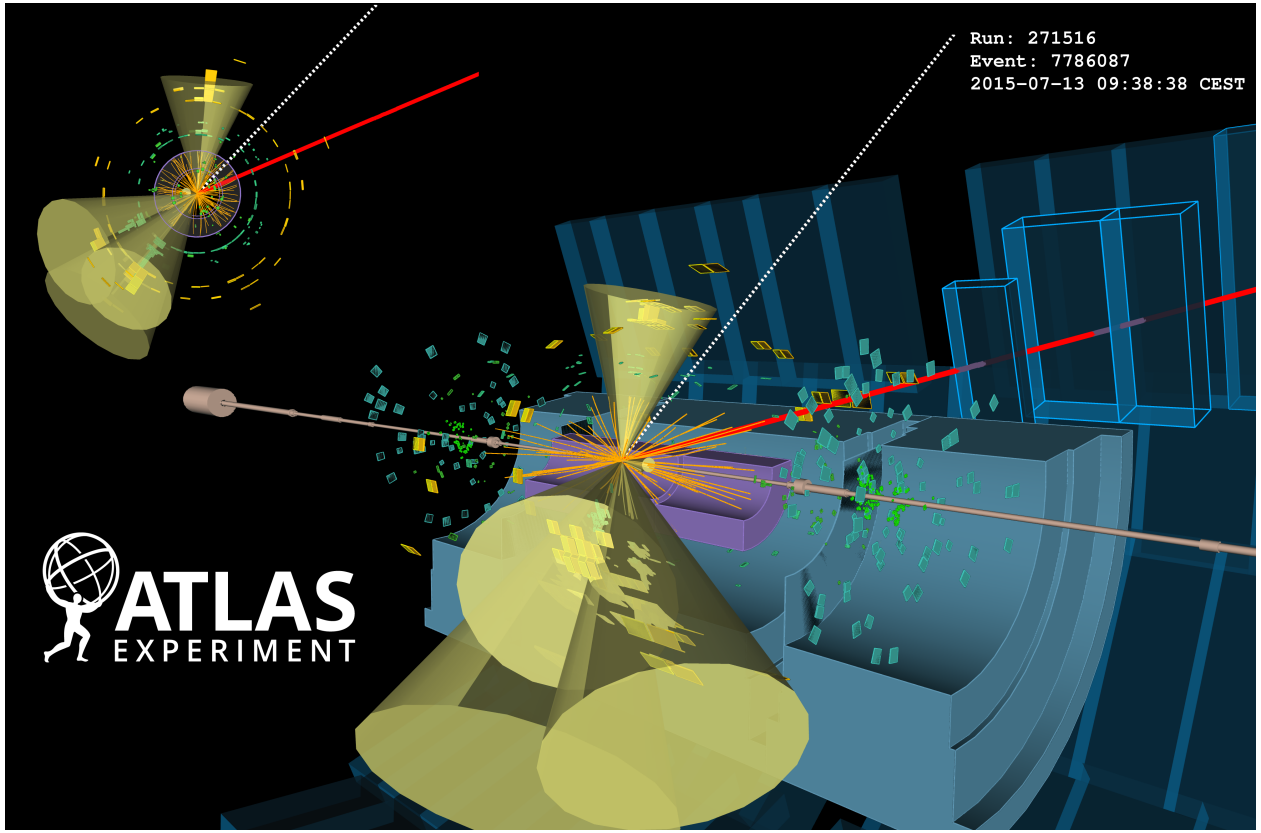
$$\theta_P(J_1, J_2) = |\vec{v}_P(J_1) - \vec{J}_2|$$

- Does the jet *lean towards another jet*?



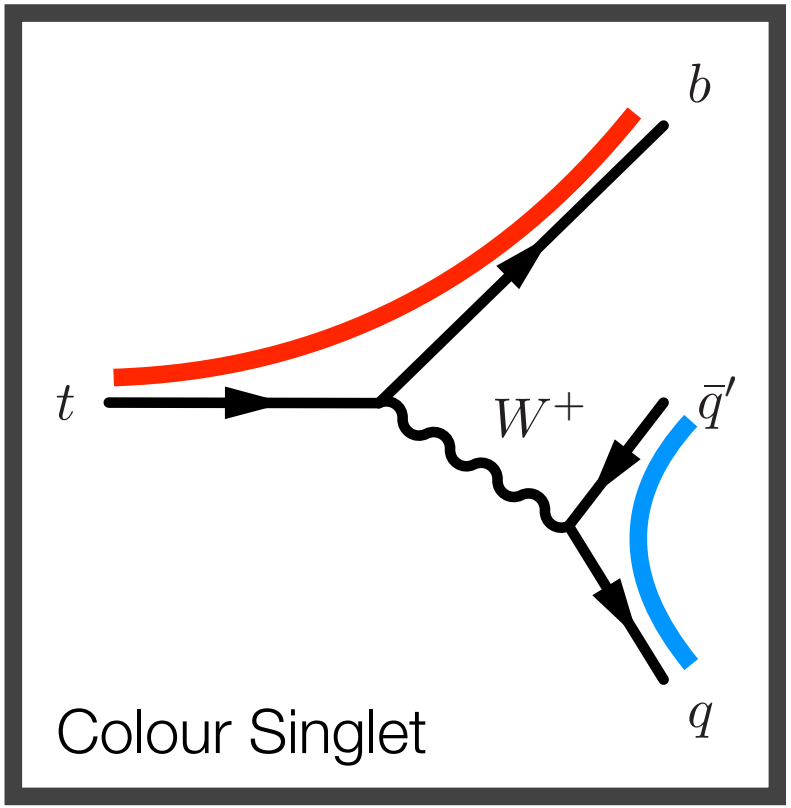
Small θ_P indicates a connection between jets!
Generic observable: should be usable in any topology

A New System to Study: $t\bar{t}$



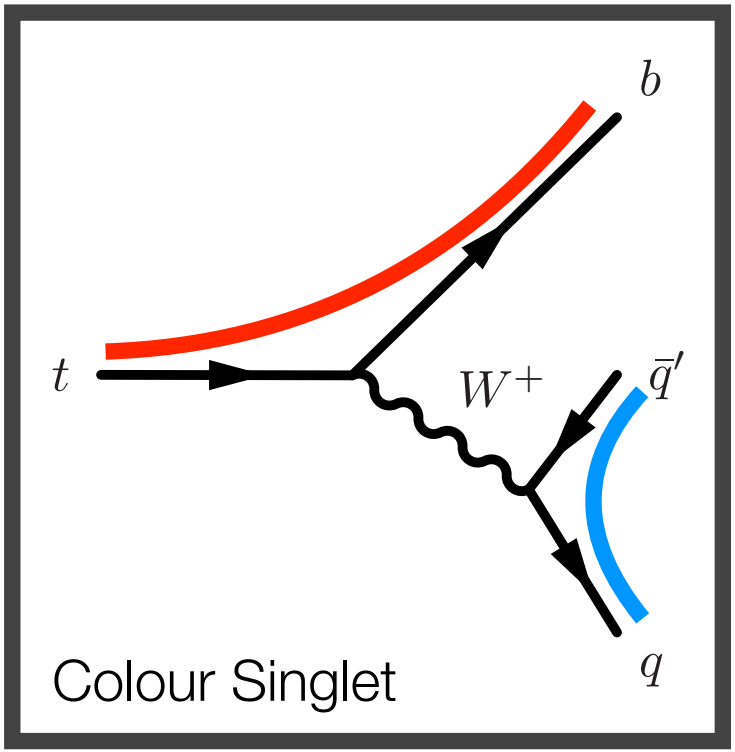
- Top pair events are easy to identify in the semi-leptonic channel
  - Leptonic decay, and b-tagging, provide very clean signature

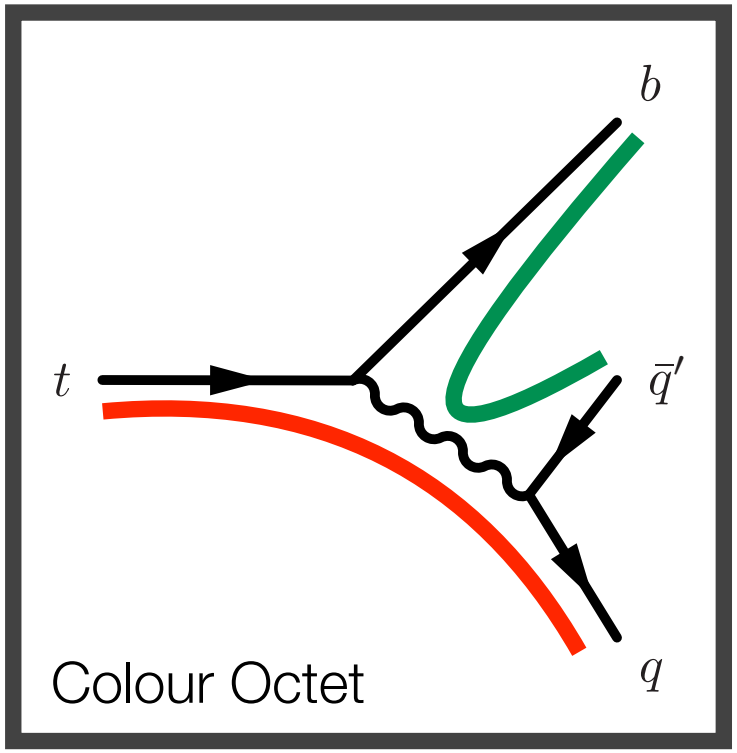
Why Is $t\bar{t}$ Interesting?



- Large sample of clean, hadronic decays with **known color configuration**
  - W-boson is a *color singlet*: does not carry color itself
  - But its decay products must: color is conserved, so jets will be **connected**

Alternative Color Structure





- When performing the measurement, how can we be sure we are observing this **color connection?**
  - Simulate events with **alternative color flow**: W as an *octet*
    - Also referred to as 'flipped' sample: color lines are 'flipped'
  - We know this gluon-like structure should not exist: can we confirm?

Is This Observable?

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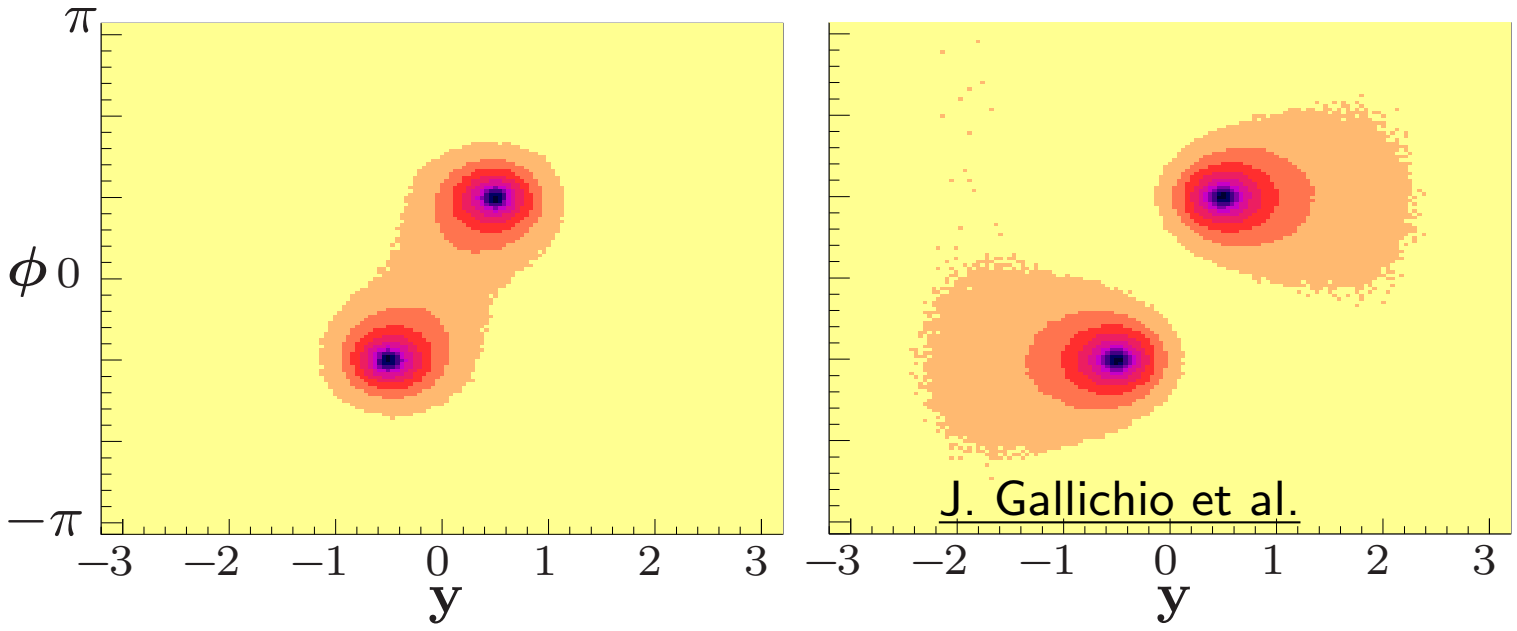
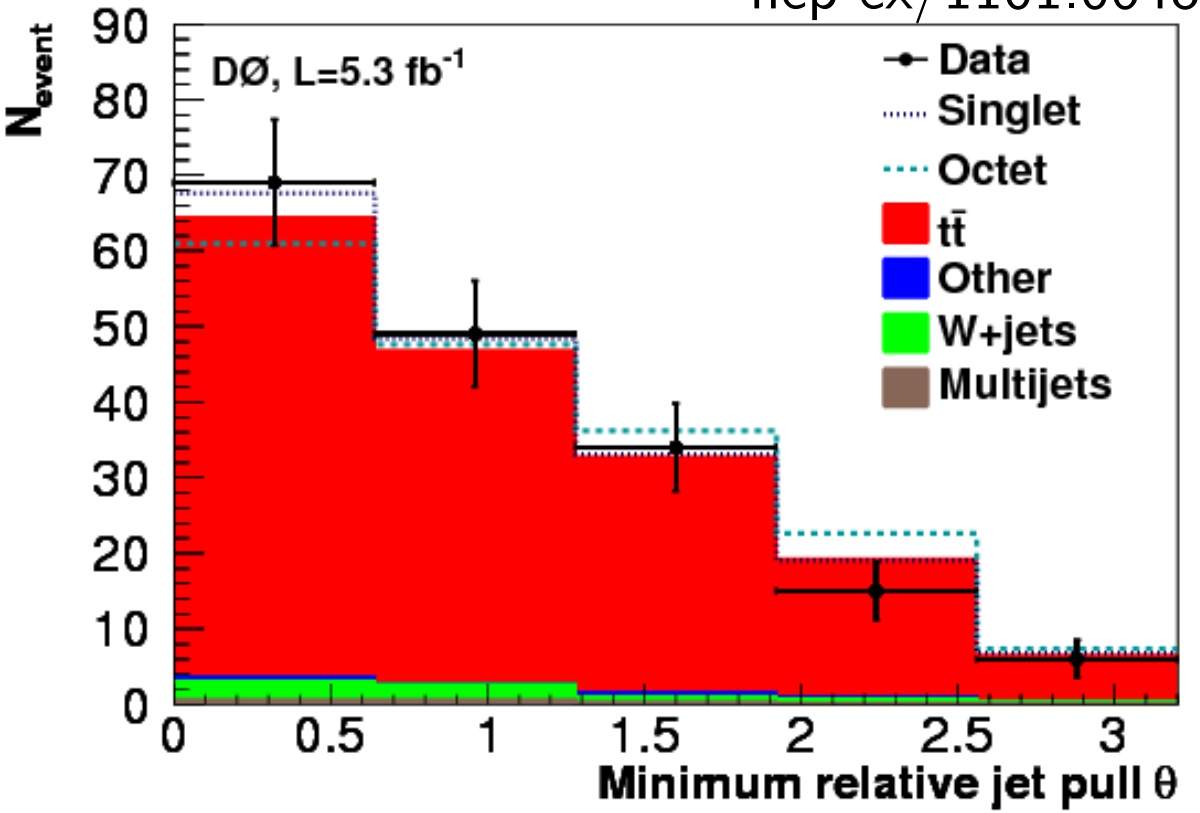


Singlet Structure Octet Structure

- Truth-level simulation from theorists indicate *yes*: a measurable connection between jets caused by **color connections**
  - But experiment has a way of being more difficult than simulation...

DØ Measurment

hep-ex/1101.0648

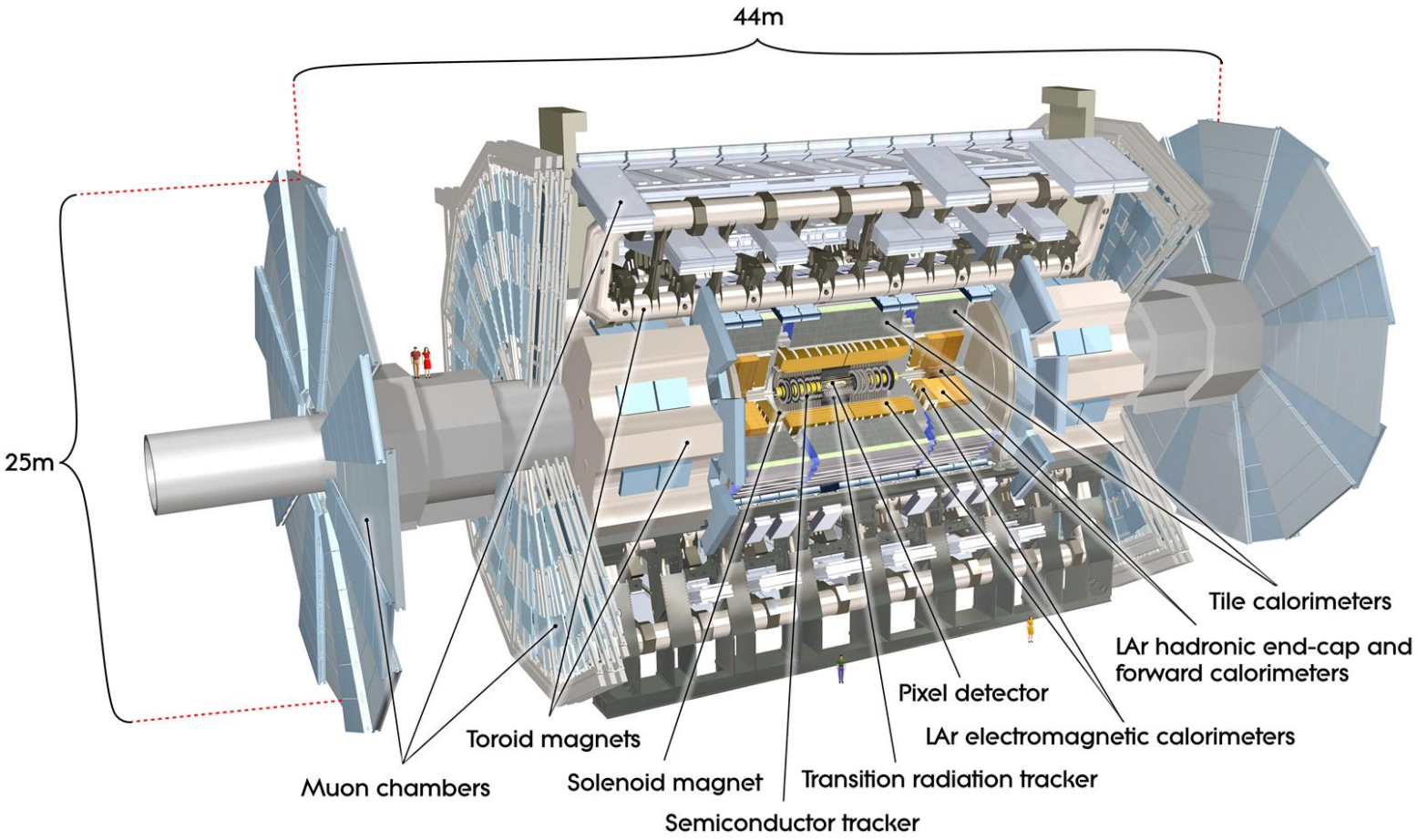


- Measured fraction of singlet vs. octet W in $t\bar{t}$ data
  - Result: $f_{singlet} = 0.56 \pm 0.42$: not significant
  - Strongly statistically limited: only 500 events used in analysis

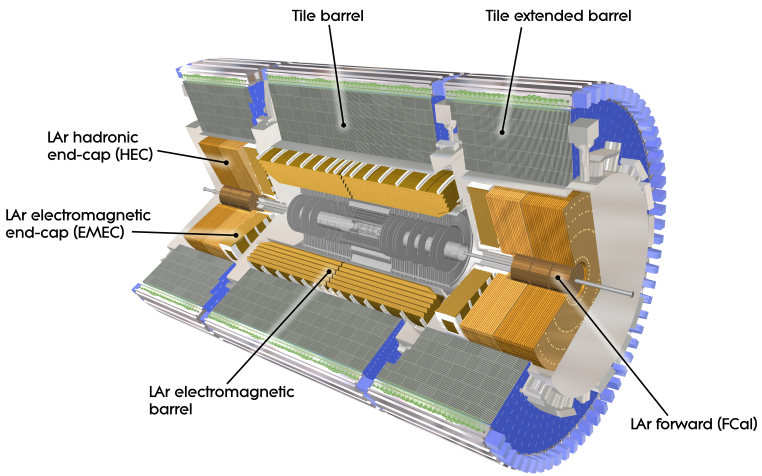
But Now, the LHC

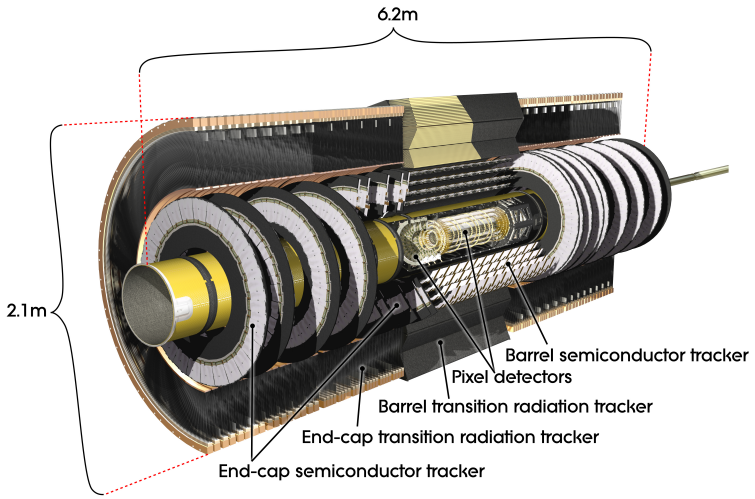
The world's leading top quark factory!

The ATLAS Detector



ATLAS Subdetectors





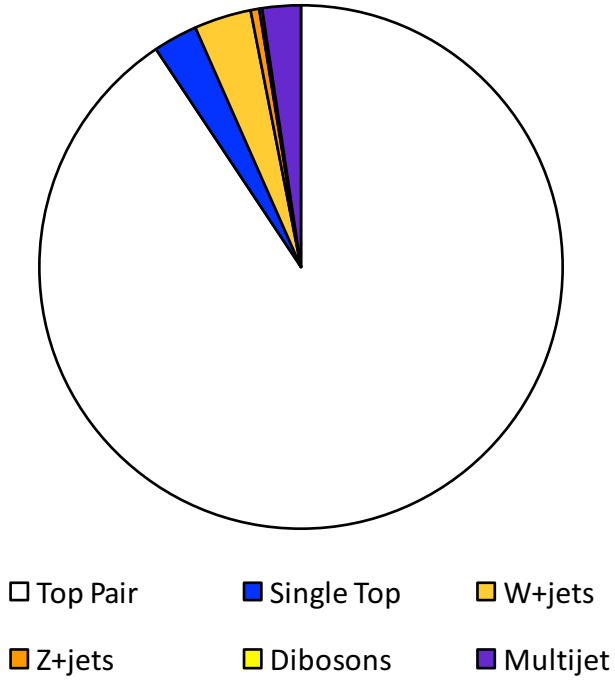
- Calorimeter measures energy deposits from **all particles**
- Very good energy resolution
- Highly segmented, longitudinal segmentation as well
  - Used in *local calibration* of topological clusters

- Tracker measures curved tracks from **charged particles**
- Extremely good energy resolution at low p_T
- Extremely precise angular resolution

Selections

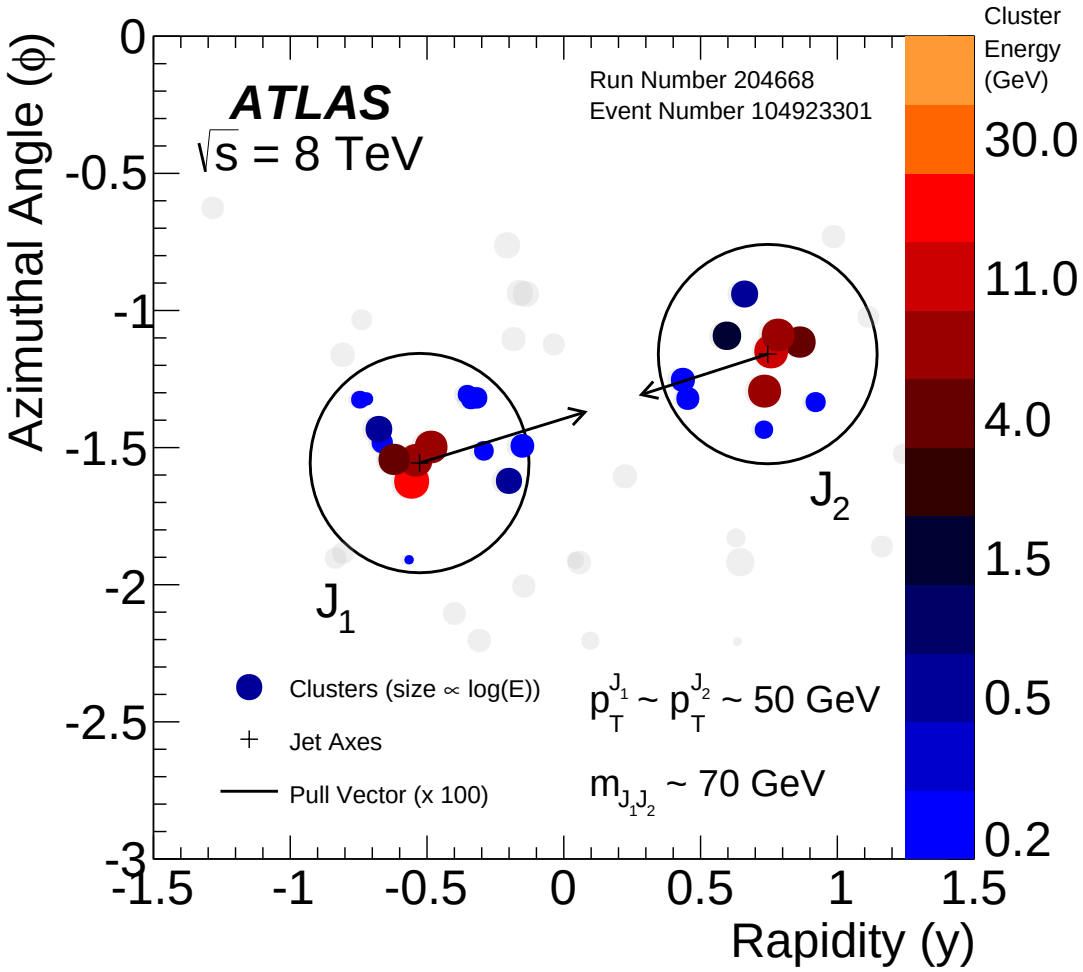
- Single, high quality lepton, $p_T^\ell > 25$ GeV, $|\eta^\ell| < 2.5$
  - Matched to μ or e trigger
- $E_T^{miss} > 20$ GeV
- $E_T^{miss} + m_T > 60$ GeV
  - $m_T = \sqrt{2p_T^\ell E_T^{miss}(1 - \cos(\Delta\phi(\ell, \nu))}$
- ≥ 4 jets, $p_T^j > 25$ GeV, $|\eta^j| < 2.1$
- Exactly 2 jets b-tagged, 70% O.P.

$\rightarrow$ Leading pair of non-b-tagged jets labelled as W-candidate
  - Mass window can bias reconstruction when testing new models



- Greater than 90% $t\bar{t}$ purity, and over 100k events!
- Similar purity to DØ, but 200x more events

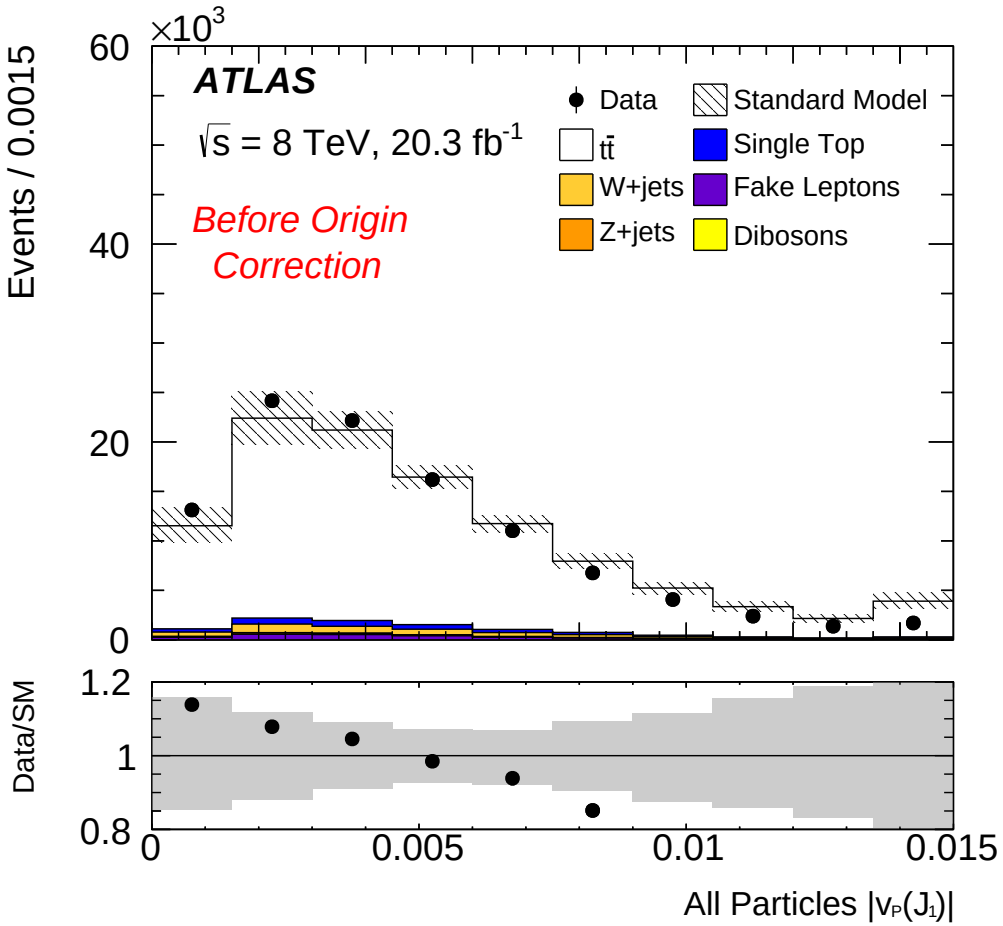
First Look at Pull in Datum



Can see the **connection** between these jets!

First Look at **Pull Magnitude** in Data

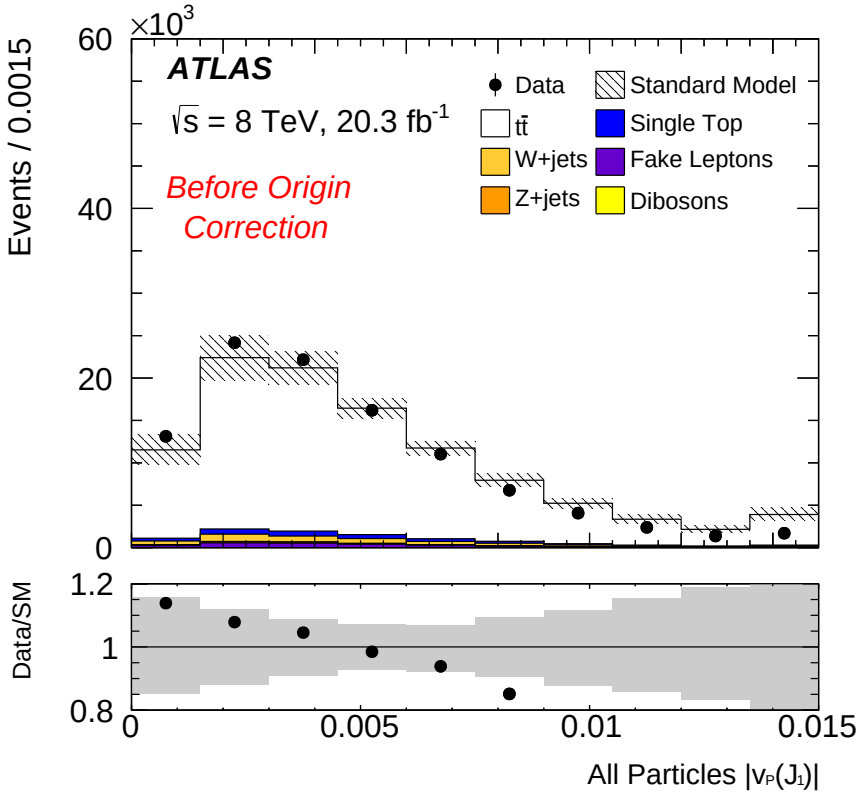
- To check our understanding of the *performance*, before we look at the *physics*, look at pull *vector magntitude*

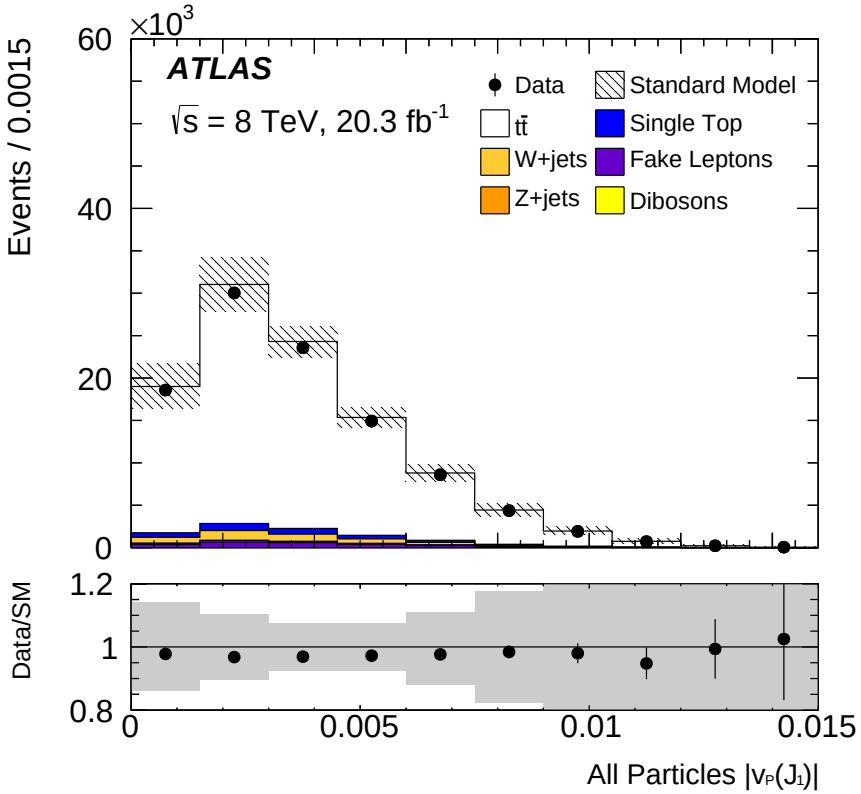


- Terrible agreement with simulation— what's going wrong?

Beamspot Corrections

- Pull is very sensitive to **location of beamspot**— which is not well modeled in MC!

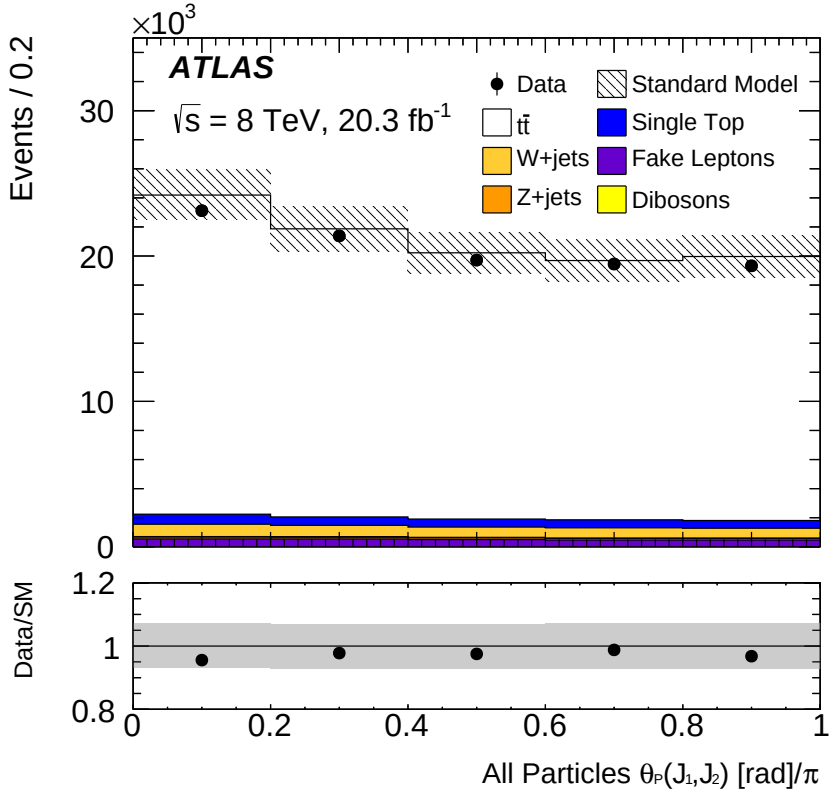




- Dedicated **origin correction** used to correct p_T of clusters based on measured location of beamspot
  - Same correction applied to data and MC: agreement restored!

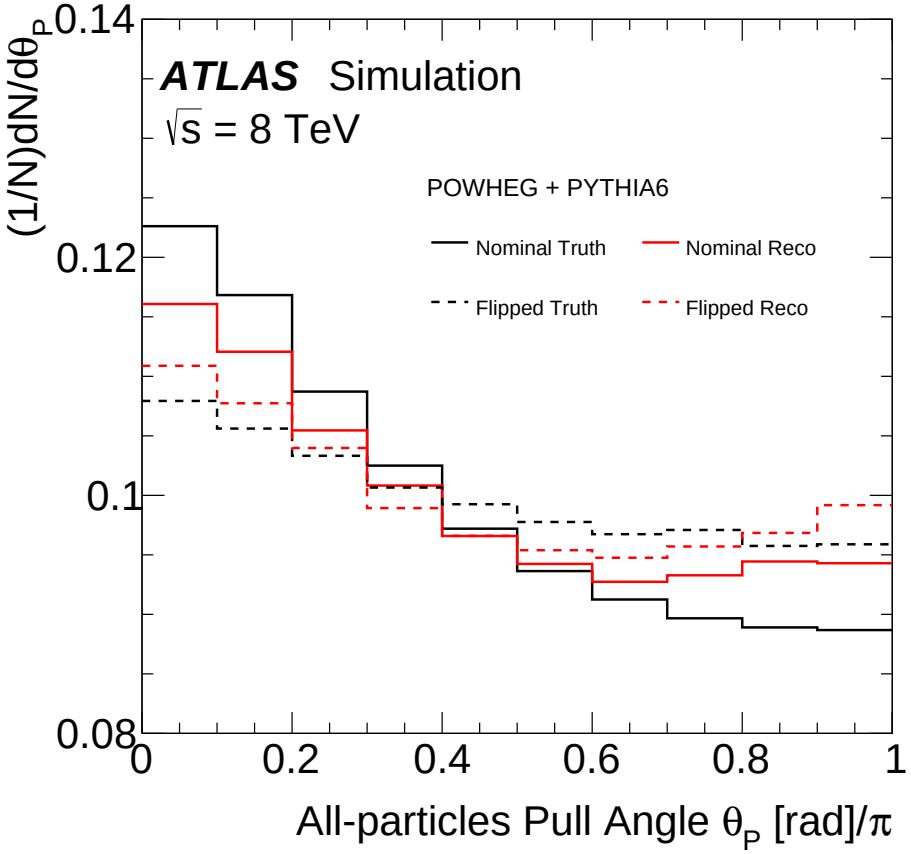
First Look at **Pull Angle** in Data

- First thought: data/MC agreement is great— good news!
- Second thought: slope is *flat*: are we actually going to be sensitive?
  - Calorimeter is smearing out our observable



Calorimeter Smearing

- Compare **truth** to **reconstructed**: can directly see the size of the smearing
  - Good news: "flipped" samples (dashed) are still different at reconstructed level!
  - Bad news: smearing brings nominal and "flipped" much closer
  - → Very good control over systematic uncertainties will be necessary to preserve sensitivity!
- Is there another approach which smears less?



What Causes Calorimeter Smearing?

- Three main factors can make calorimeter measurements difficult:
  1. Pileup: simultaneous pp collisions
     - Calorimeter cannot distinguish between particles different vertices
  2. Finite angular precision
     - Calorimeter readout size is large, inherently limits angular measurements
  3. Large fluctuations in response at low E_t
     - Energy resolution at low energy is poor

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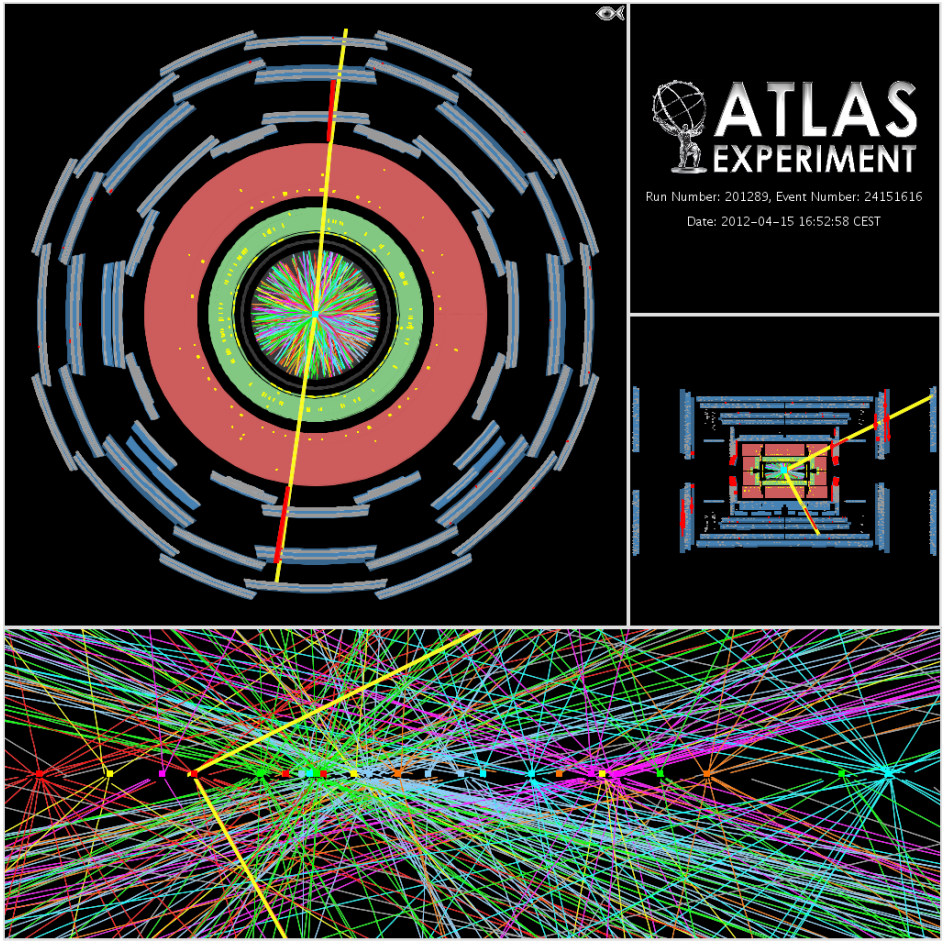

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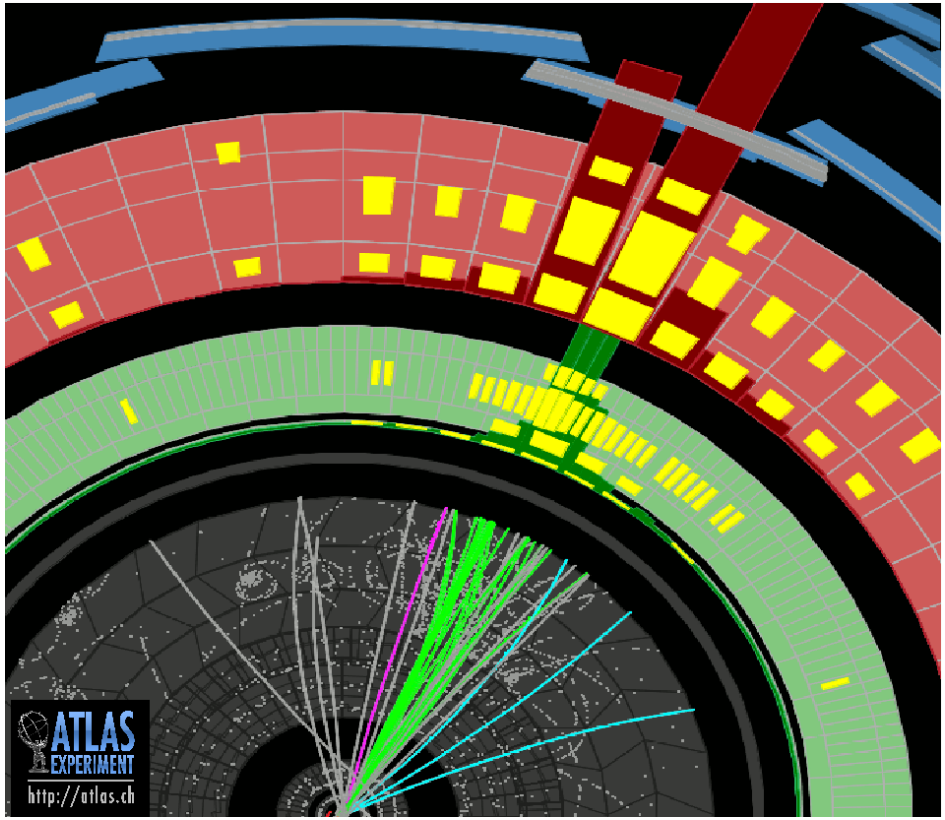

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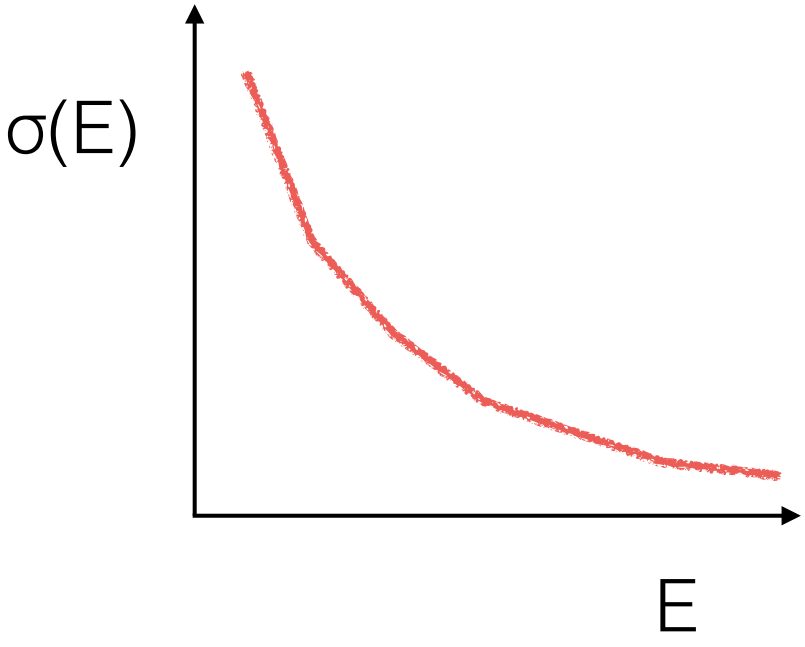
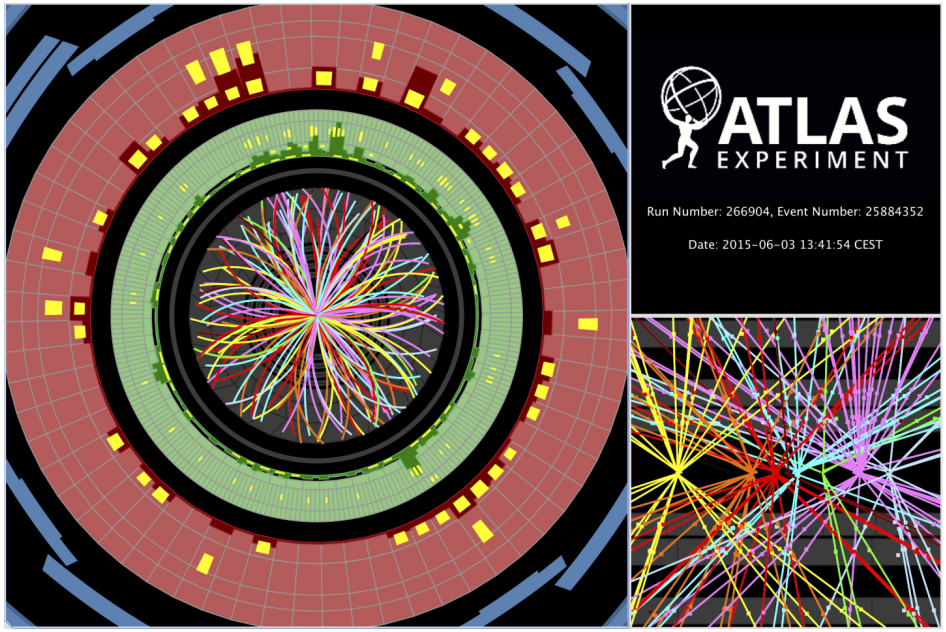


Another Picture of the Event: Tracks

- Tracking provides another view of the events by precisely reconstructing **charged particles**
  - Necessarily an incomplete picture: missing neutrals ($\sim 1/3$ of the event!)
  - Also subject to fluctuations in hadronization
  - Often not useful for scale-measurements like p_T^{jet}
- But many improvements to jet properties are possible!
  - b-tagging, quark-gluon separation, etc. done with tracks
  - Can tracking help with substructure reconstruction?



Why Tracking Can Be Powerful

- Going back to the difficulties from calorimetry:
  1. Pileup: simultaneous pp collisions
     $\rightarrow$ Tracks can be selected to originate from only the hard-scatter vertex
  2. Finite angular precision
     $\rightarrow$ Track angular resolution several orders of magnitude better than calorimeters
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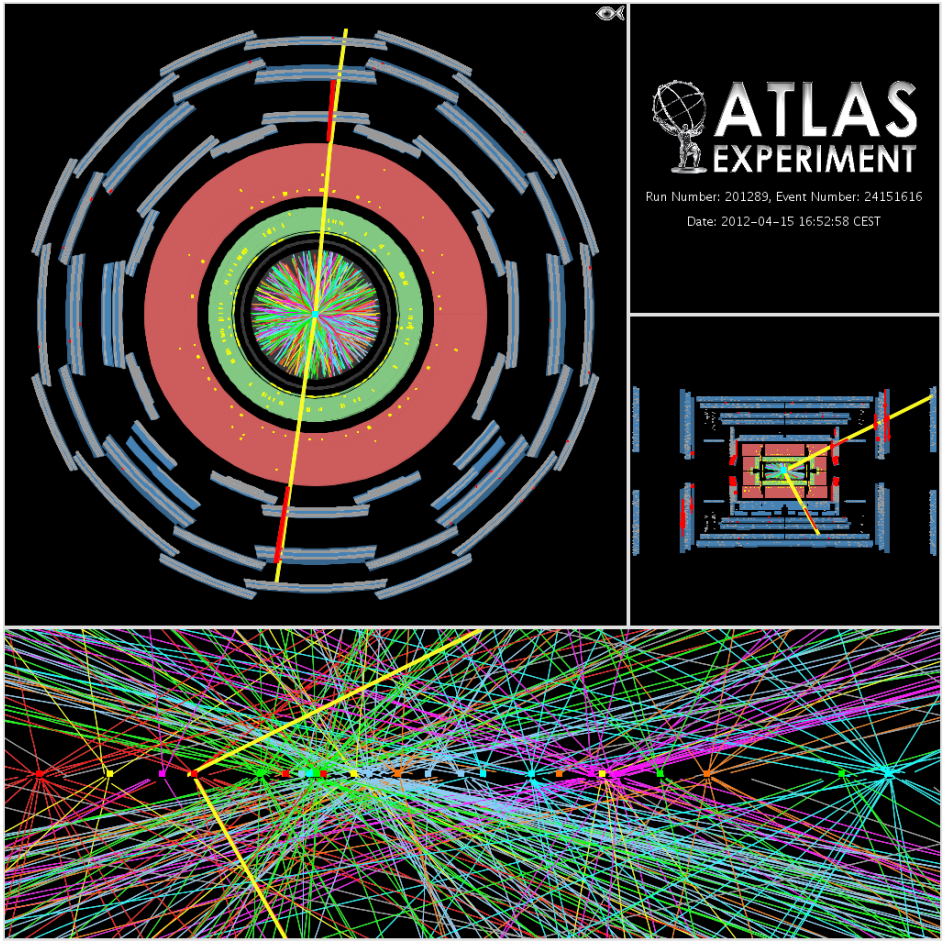

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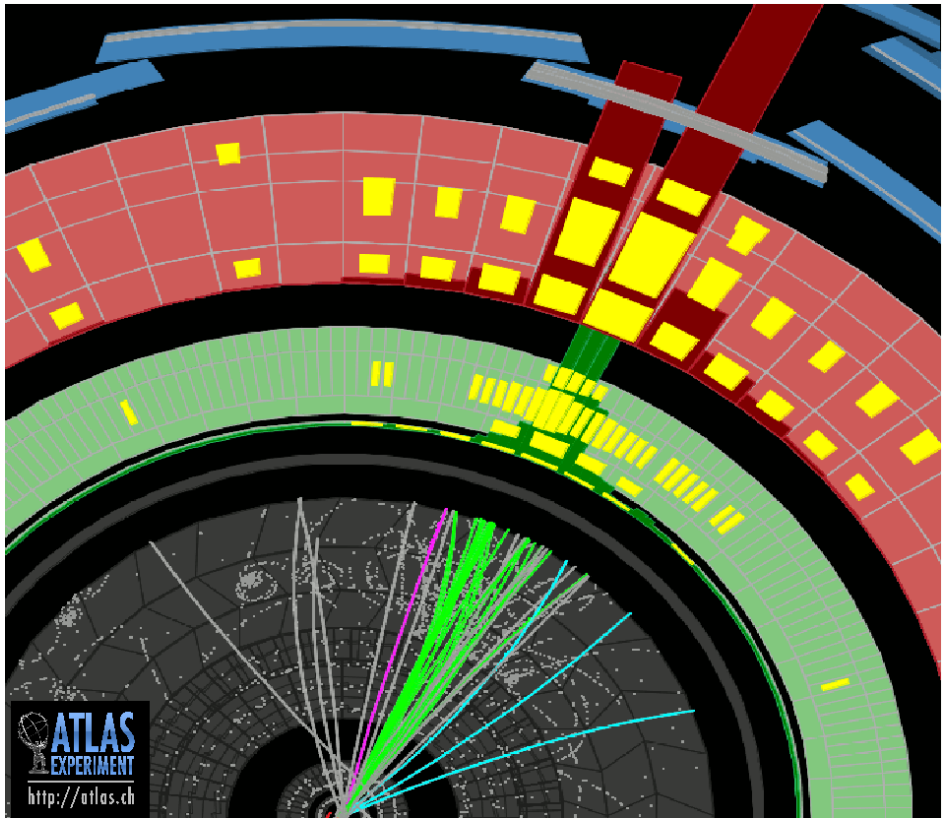

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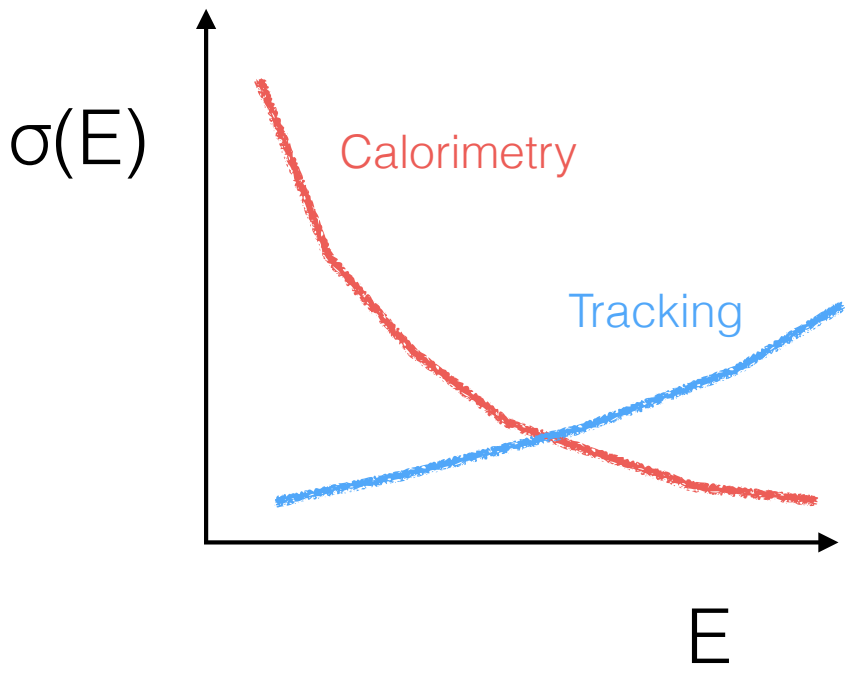
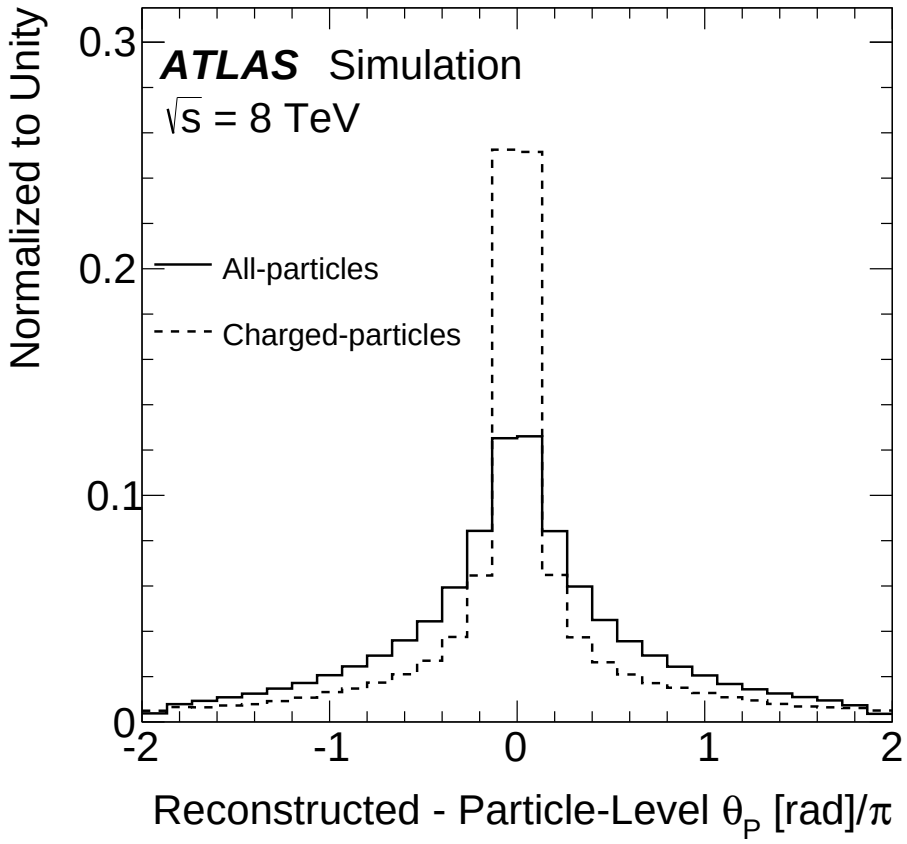
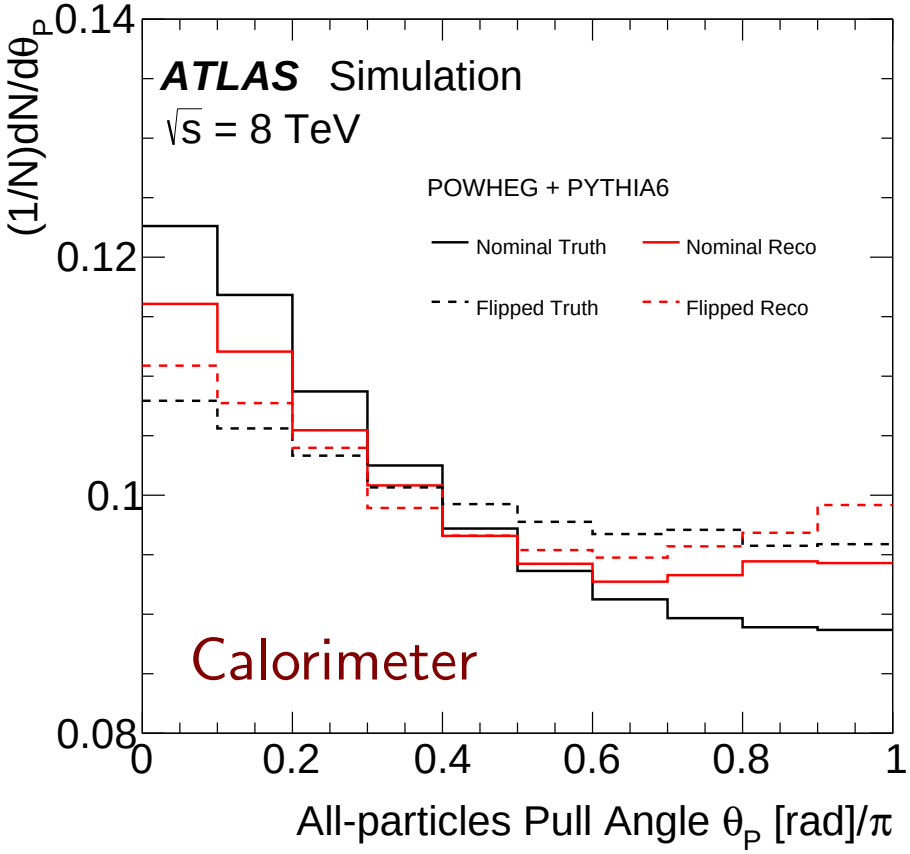


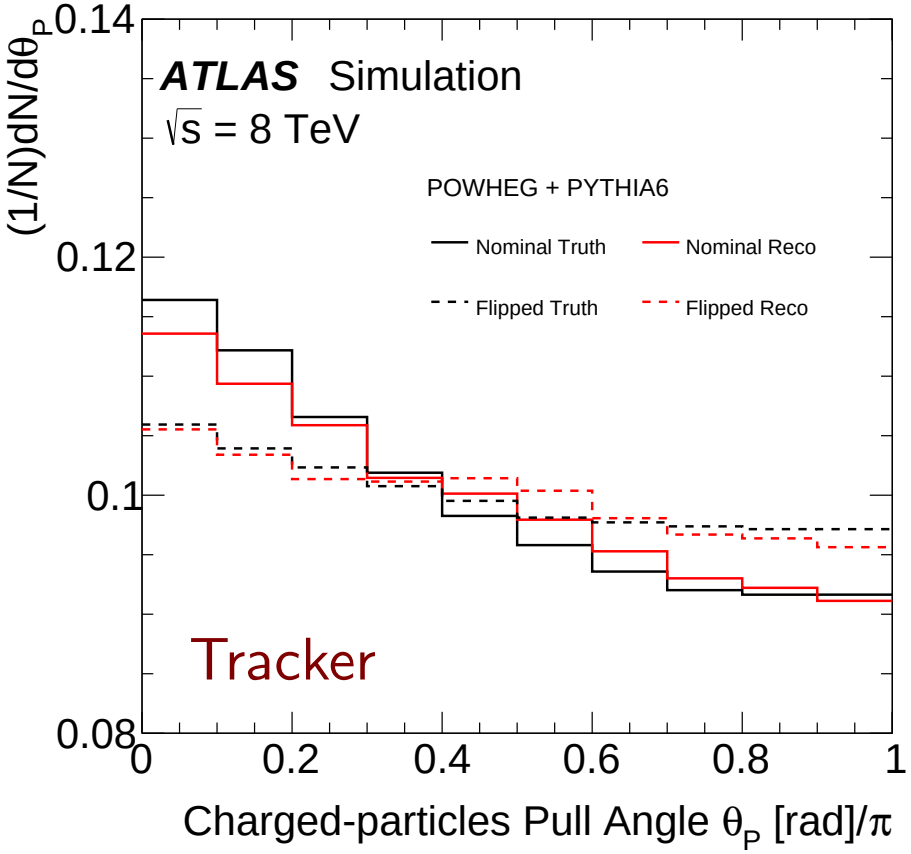
Comparing Resolution

- As expected, resolution is significantly improved compared to calorimeter!
- Not measuring the "full picture," but what is measured is measured better
- What is the balance between losing information, and improving resolution?



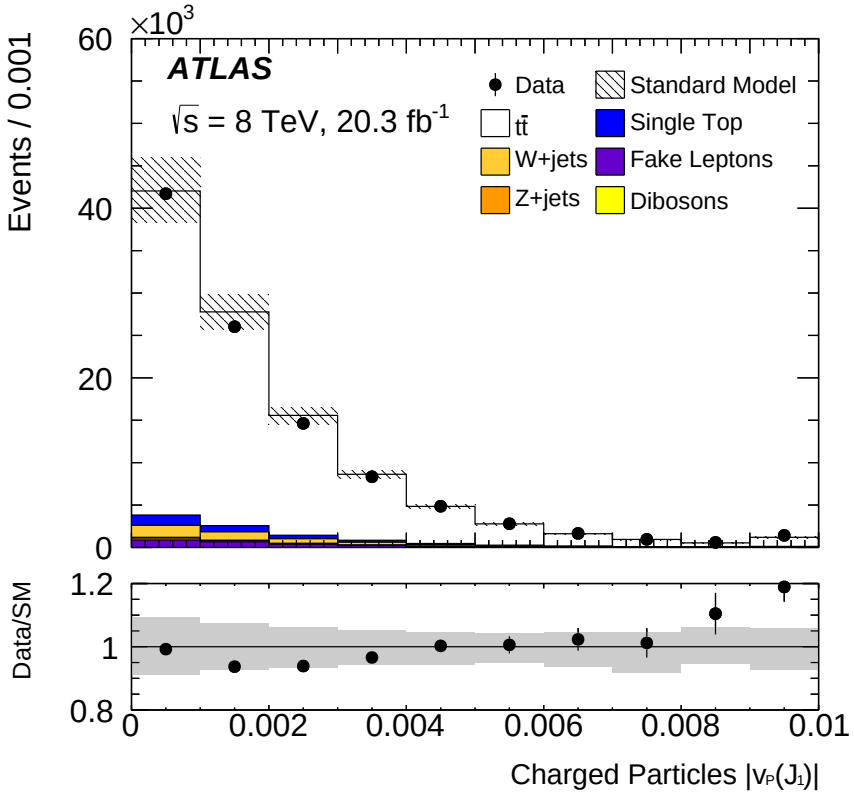
Calorimetry vs. Tracking

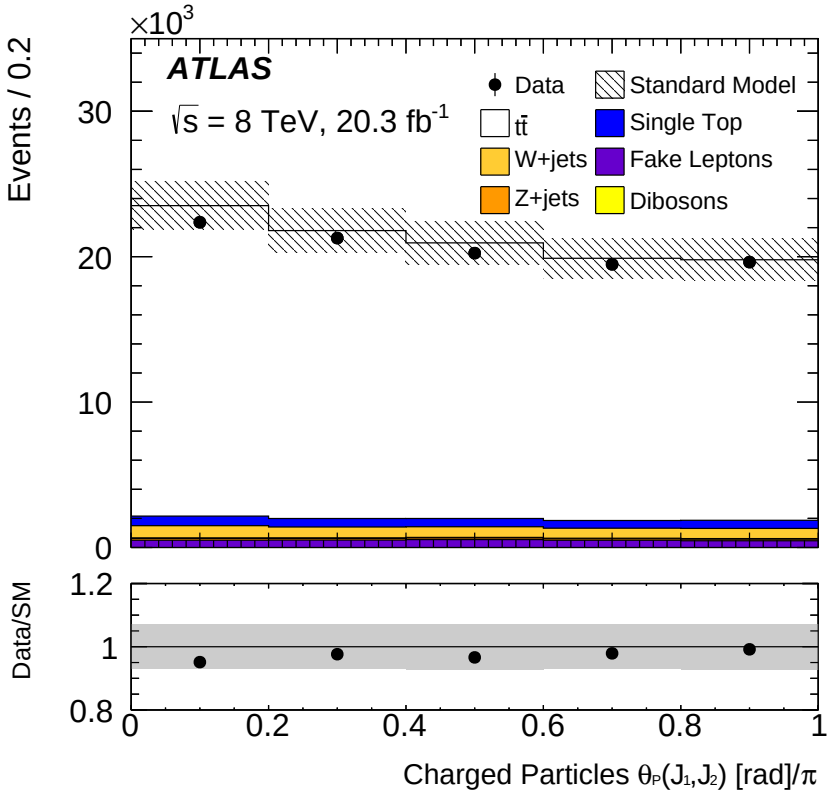




- **Truth** is smeared compared **reconstructed** level: but tracking measurement is smeared much less!
  - Truth level separation is smaller— but reco level is larger!

Data and MC with Charged Pull

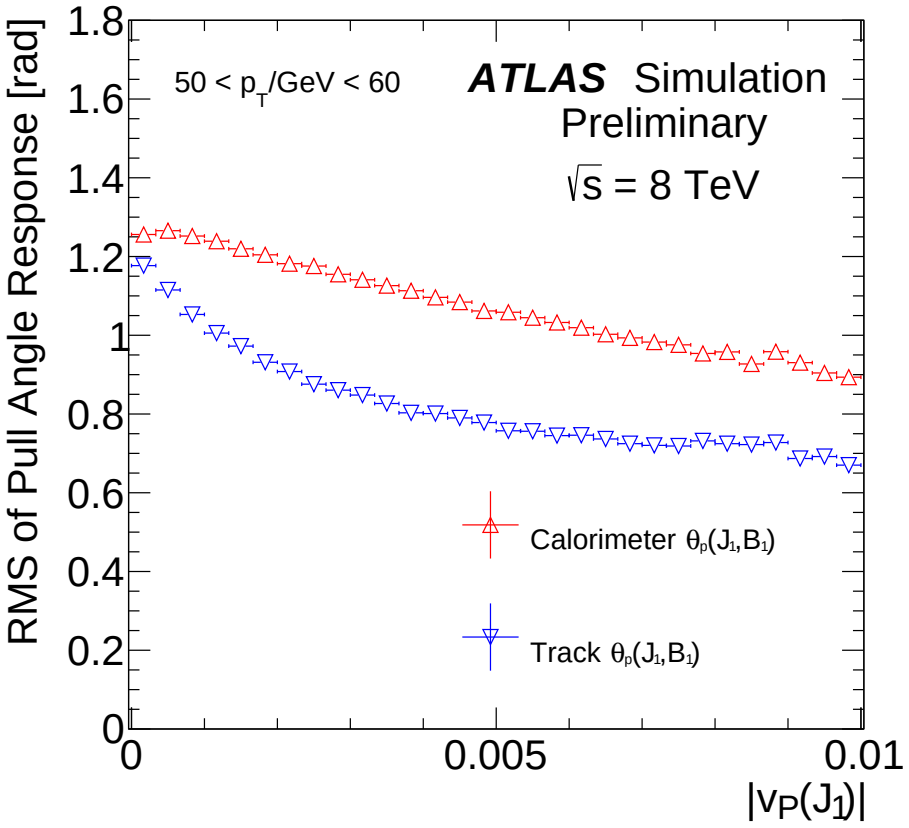




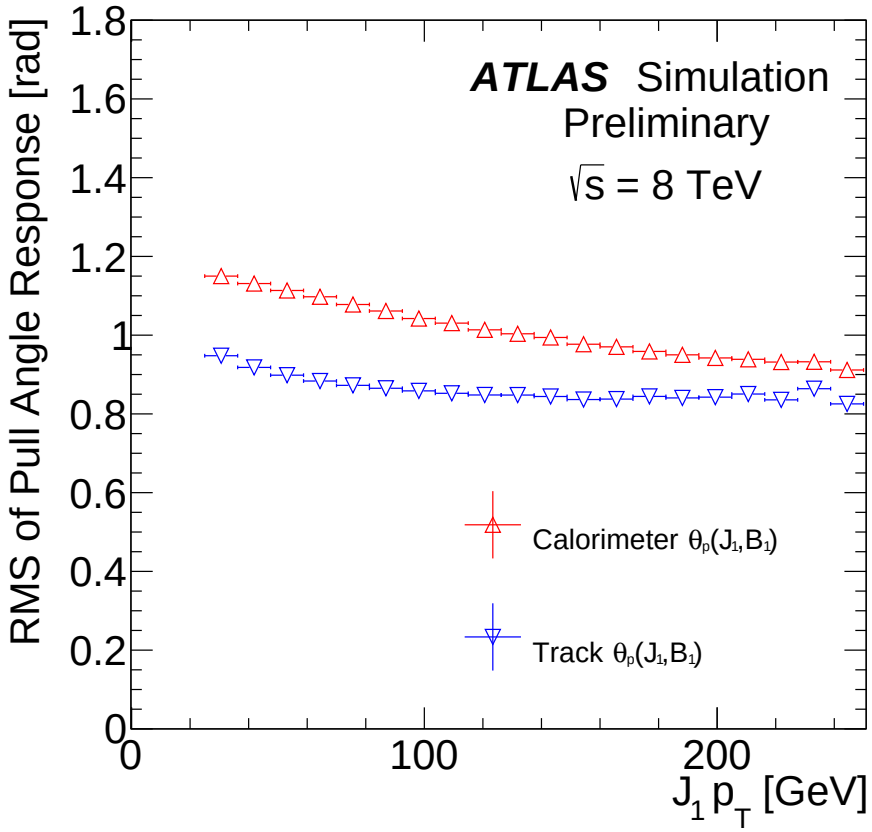
- Data and simulation agree very well also for charged pull magnitude and angle!
- As expected, angle is even flatter: losing information from neutrals

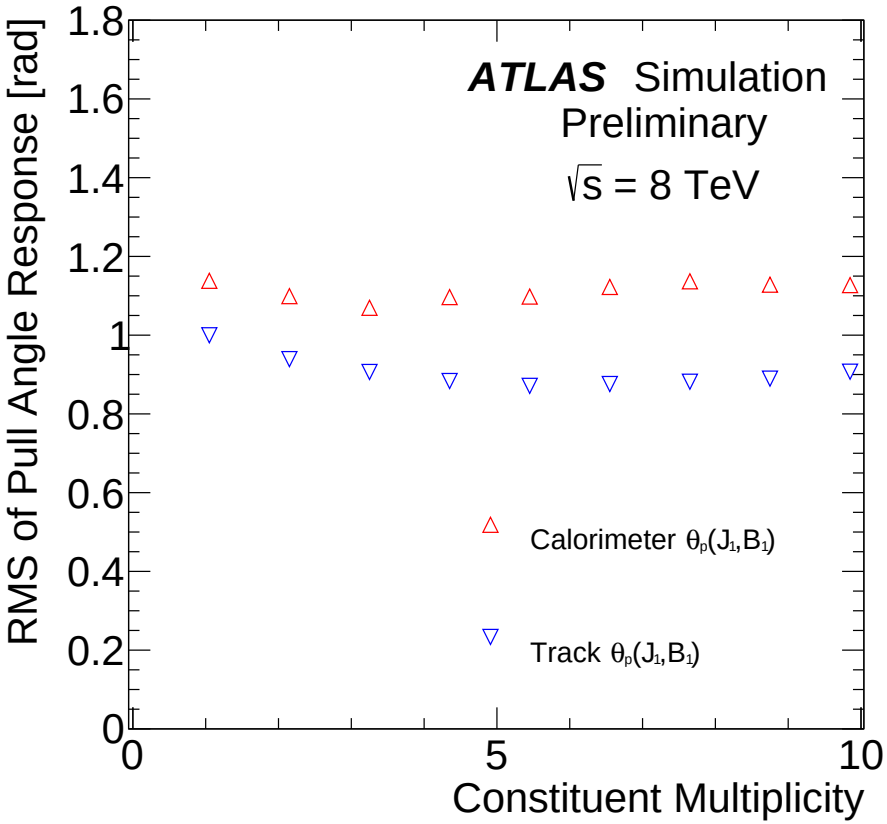
Possible Resolution Improvements

- Can we improve the resolution of the measurements in other ways?
- One possibility: cut on the *magnitude*
  - The stronger the *lean* of the jet, the more robust the measurement!
- Resolution clearly affected by cutting on the magnitude!
  - Ultimately not used, because loss in statistical power outweighs benefit



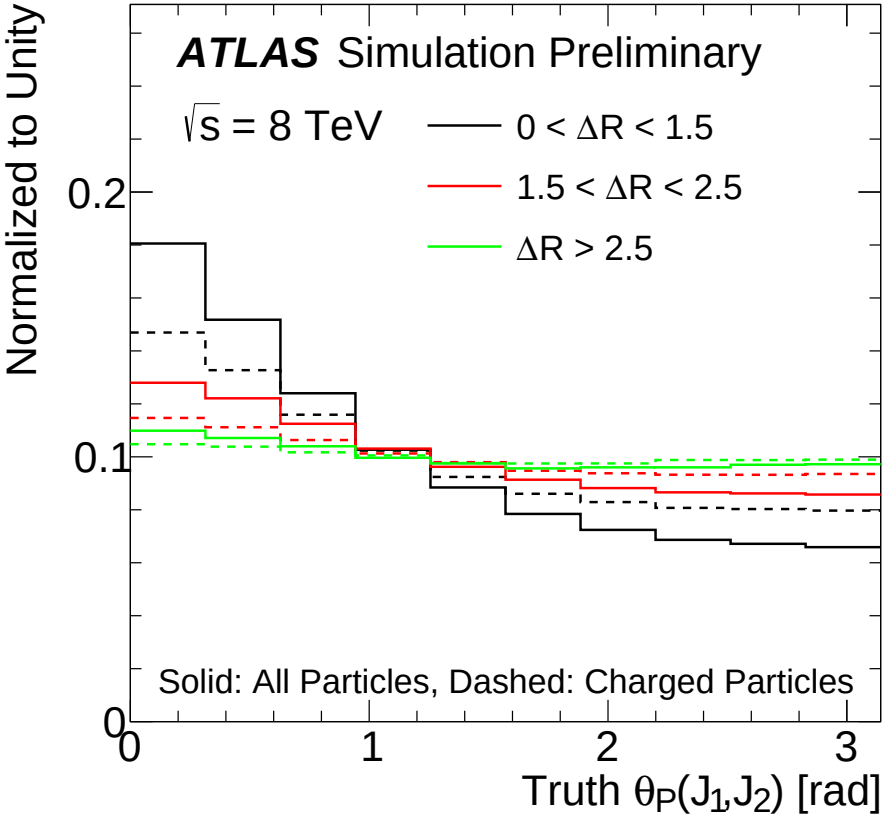
Other Resolution Possibilities

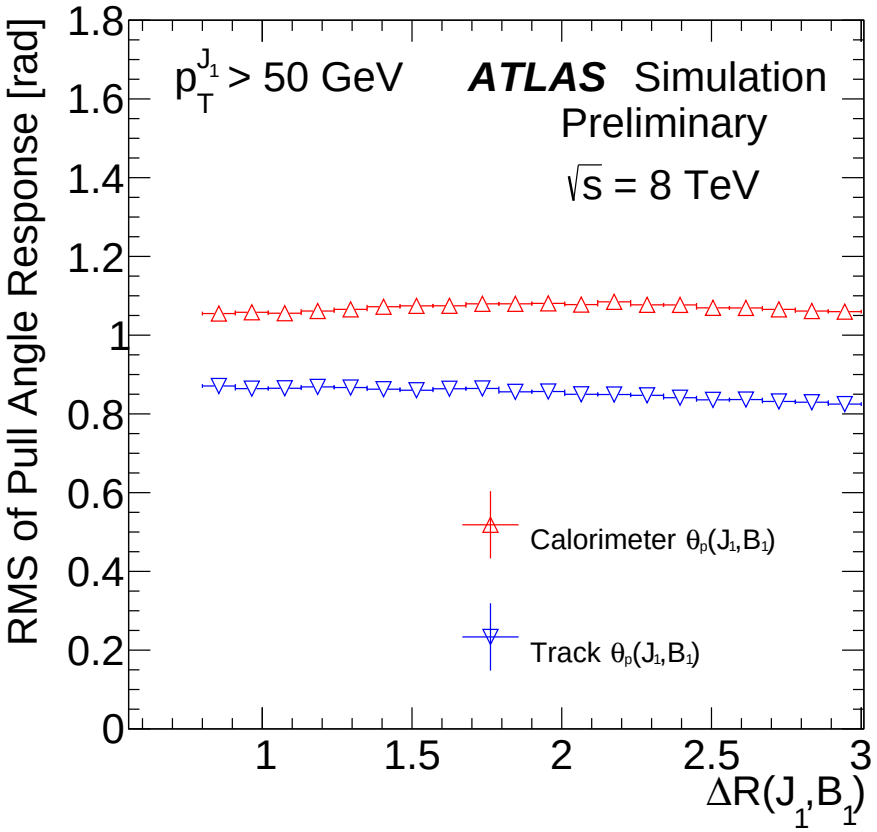




- Many other effects on resolution also studied
- p_T has small effect on resolution: ability to reconstruct connections improves with energy
- Jet constituent multiplicity has no impact: limitations not arising from low charged fraction, etc.

ΔR Between Jets

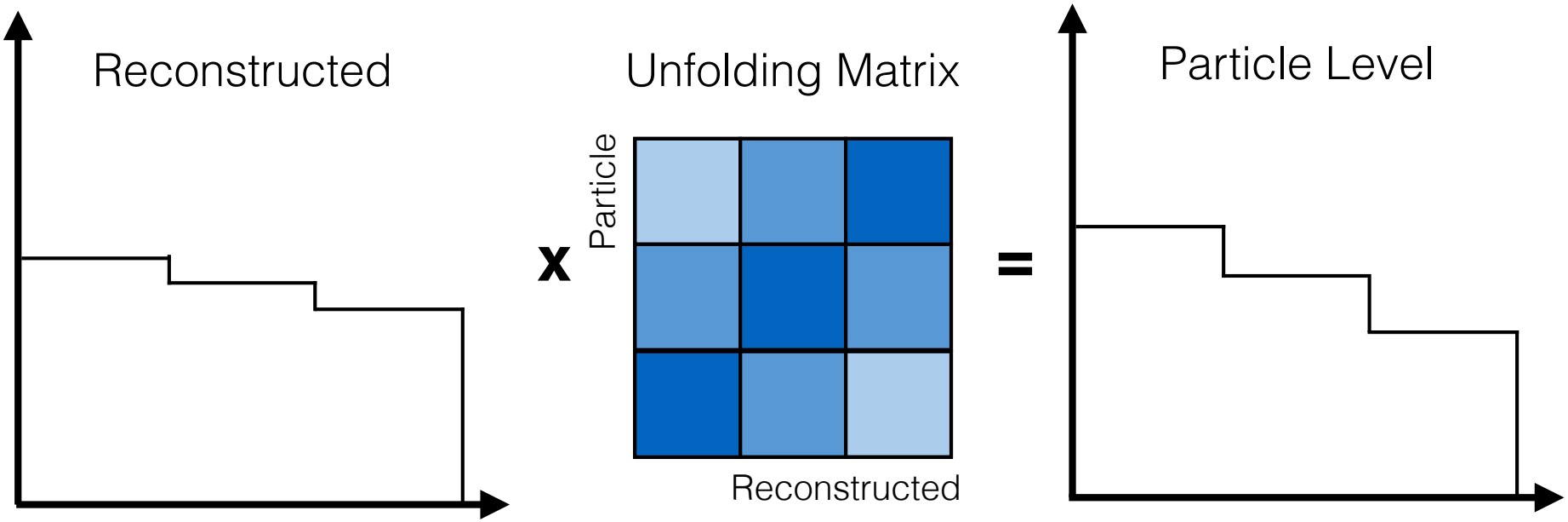




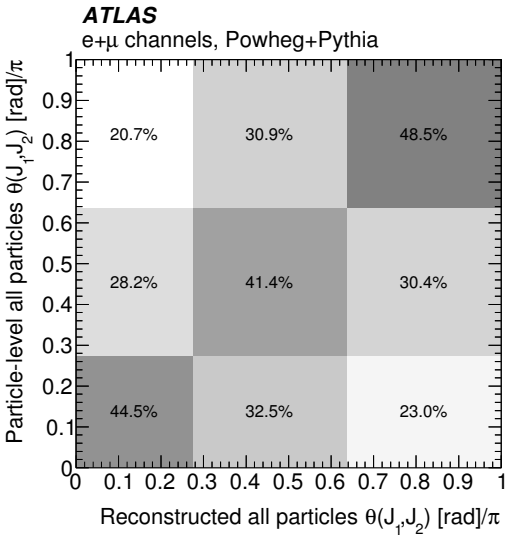
- ΔR between jets is *distance between jets*
- Significantly larger connection between jets when they are close-by!
  - However, resolution does not change: particle level simulation and reconstructed simulation change similarly

Unfolding

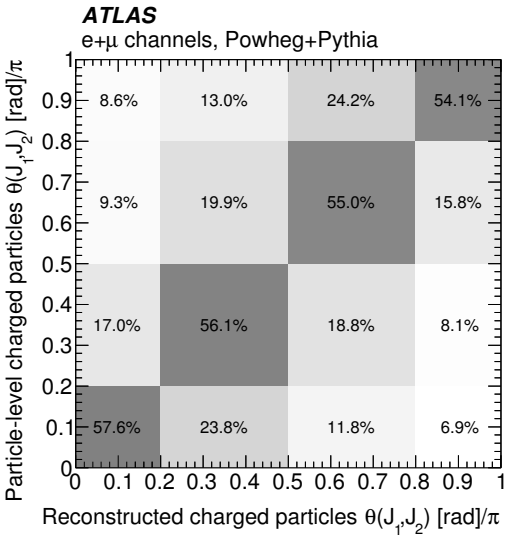
- Ultimately, our result should be **accessible**
  - We want to compare color flow models, but also hadronization models— and more than just what we can think of!
- **Unfolding** corrects reconstructed quantities to the particle level, using *response matrix* from simulation
  - Once at particle level, anyone can compare to the results!



Response Matrices



All particles

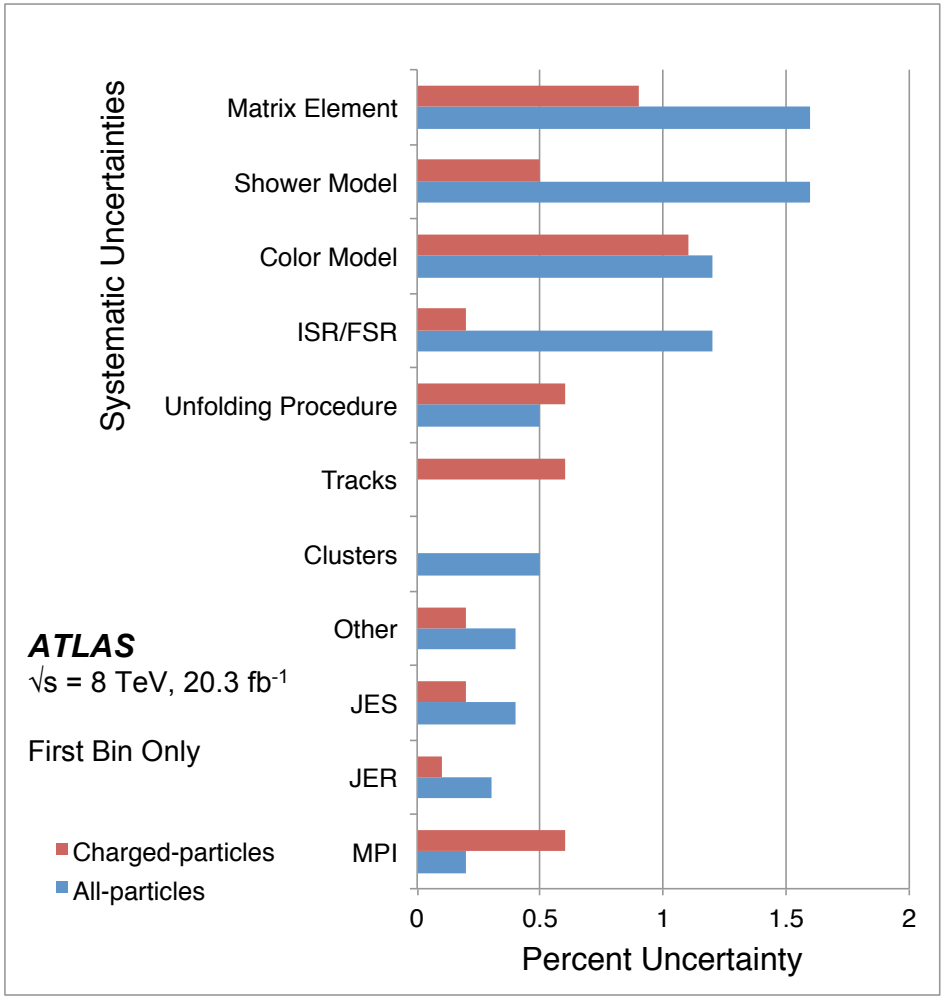


Charged particles

- Use Iterative Bayseian Unfolding to iteratively apply response matrix to reconstructed result
  - Use 15 and 4 iterations for calorimeter and tracker measurements
- Both calorimeter and track measurements have broad resolution: large off-diagonal terms
- Size of bins, number of iterations, and size of pull magnitude cut optimized for best separation

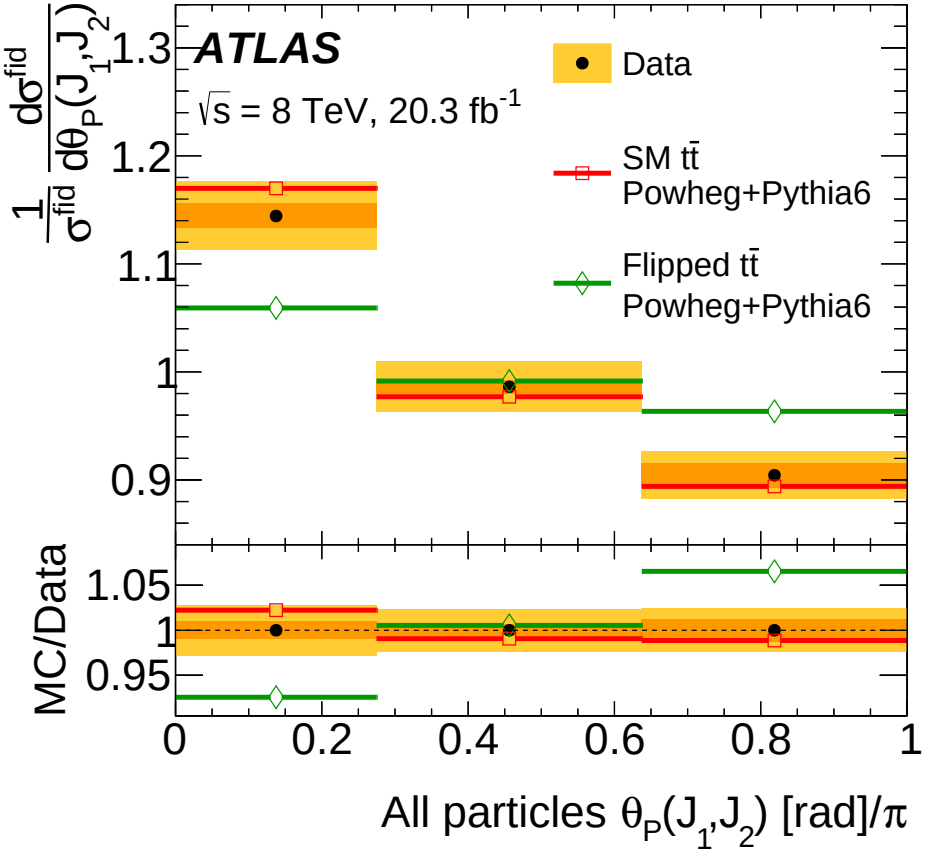
Systematic Uncertainties

- Systematic uncertainties dominated by **theory uncertainties**
  - Unfolded result changes when changing the simulation used to unfold
- Experimental uncertainties on tracking and calorimeter reconstruction carefully addressed
  - Studied energy, efficiency, and angular uncertainties
  - All sub-dominant to theory uncertainties



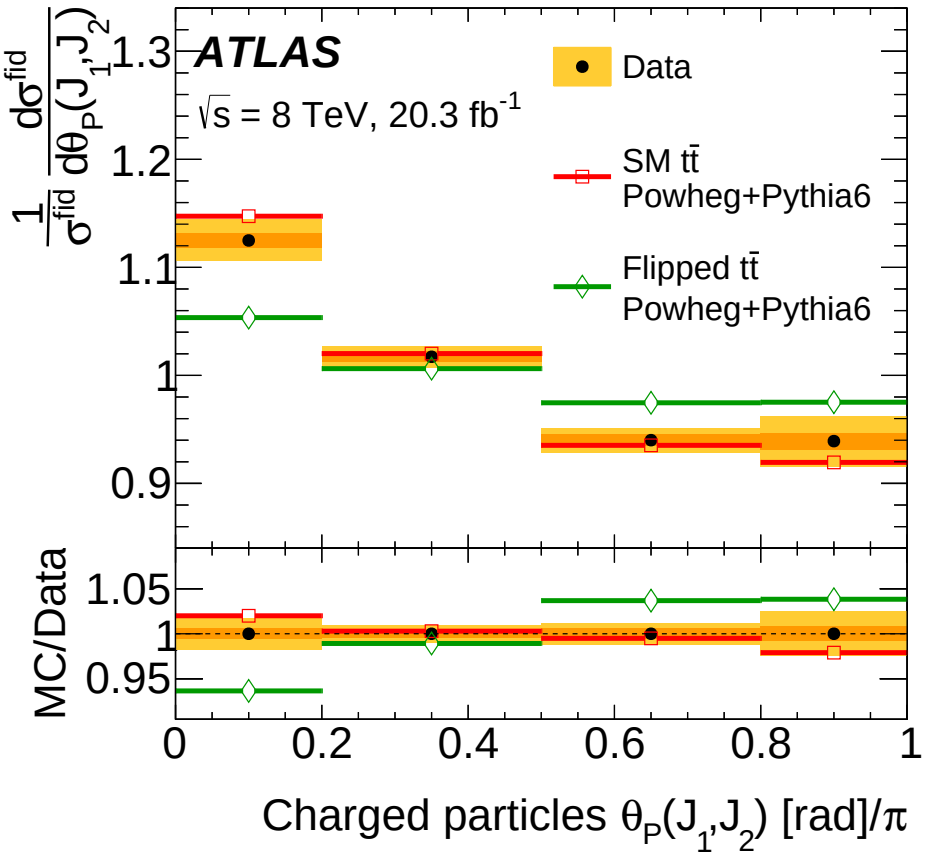
Results with Calorimeter

- **Data** compared to **SM** and **flipped** simulation
  - $\Delta\chi^2$ used to calculate compatibility to models
  - Data agrees with SM to 0.8σ
  - Data differs from flipped model at 2.9σ
  - Clearly room for improvement in simulation— but can clearly distinguish between the two models!

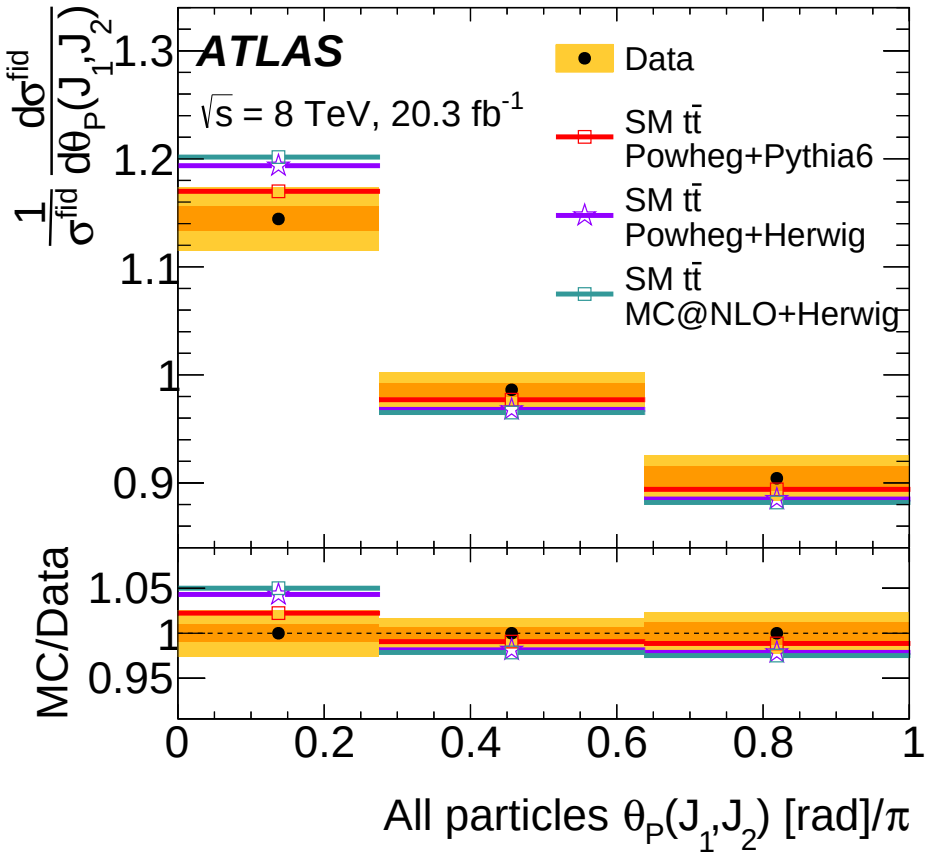


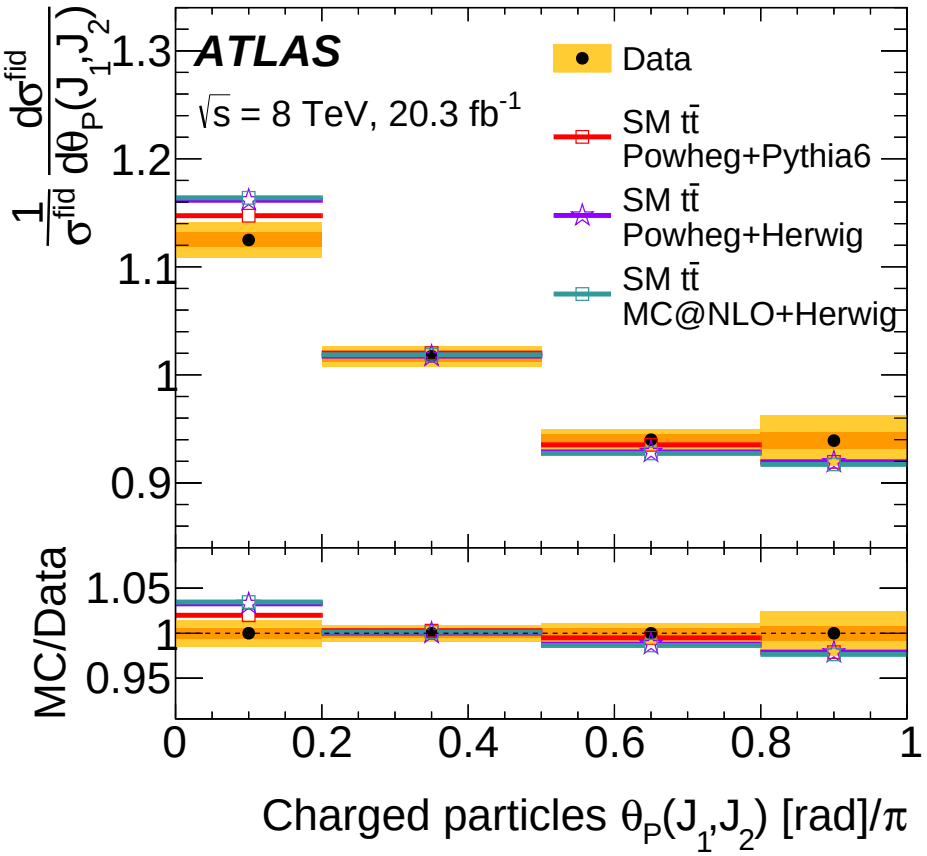
Results with Tracker

- Similar story with tracker measurement— but even more separation!
  - Data agrees with SM to 0.9σ
  - Data disagrees with flipped model at 3.7σ
  - Once again room for improvement, but a **significant observation** that the W-boson does not decay like a color octet, using only color flow information!
- Tracker measurement ultimately proves more powerful
  - More narrow, but more precise, measurement can be better



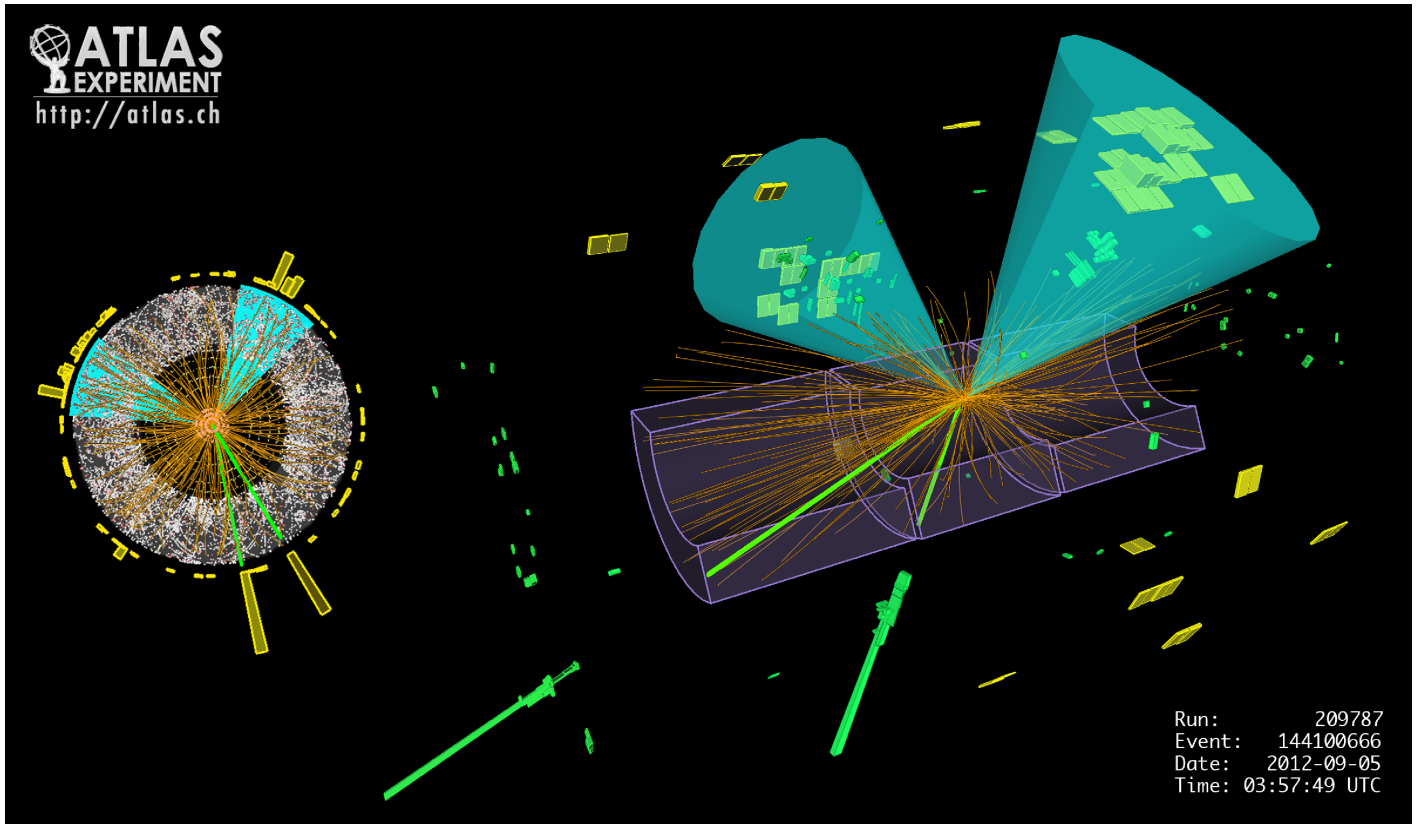
Comparing Simulations





- Result is useful beyond the color flow model— can also see which simulations do best!
- Changing hard-scatter does not have large effect, but parton shower model does
  - `Pythia6` does substantially better than `Herwig`

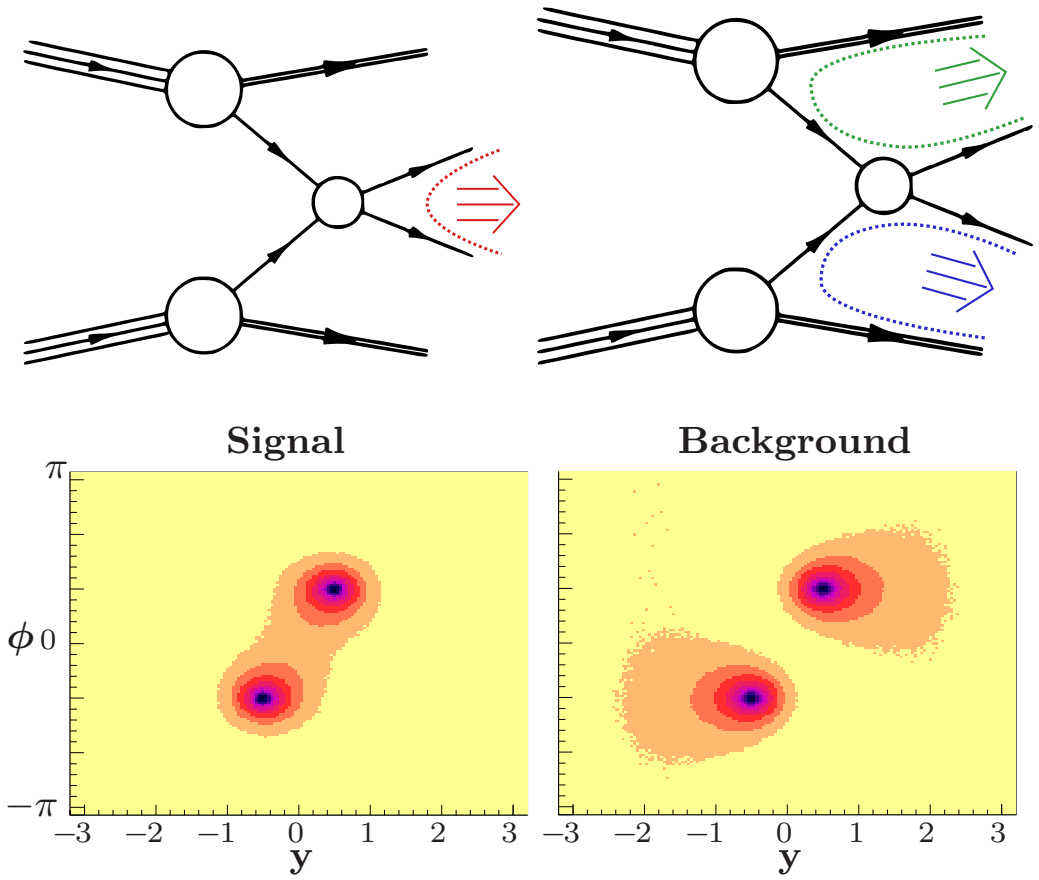
The Future



$ZH \to \ell\ell + b\bar{b}$ candidate

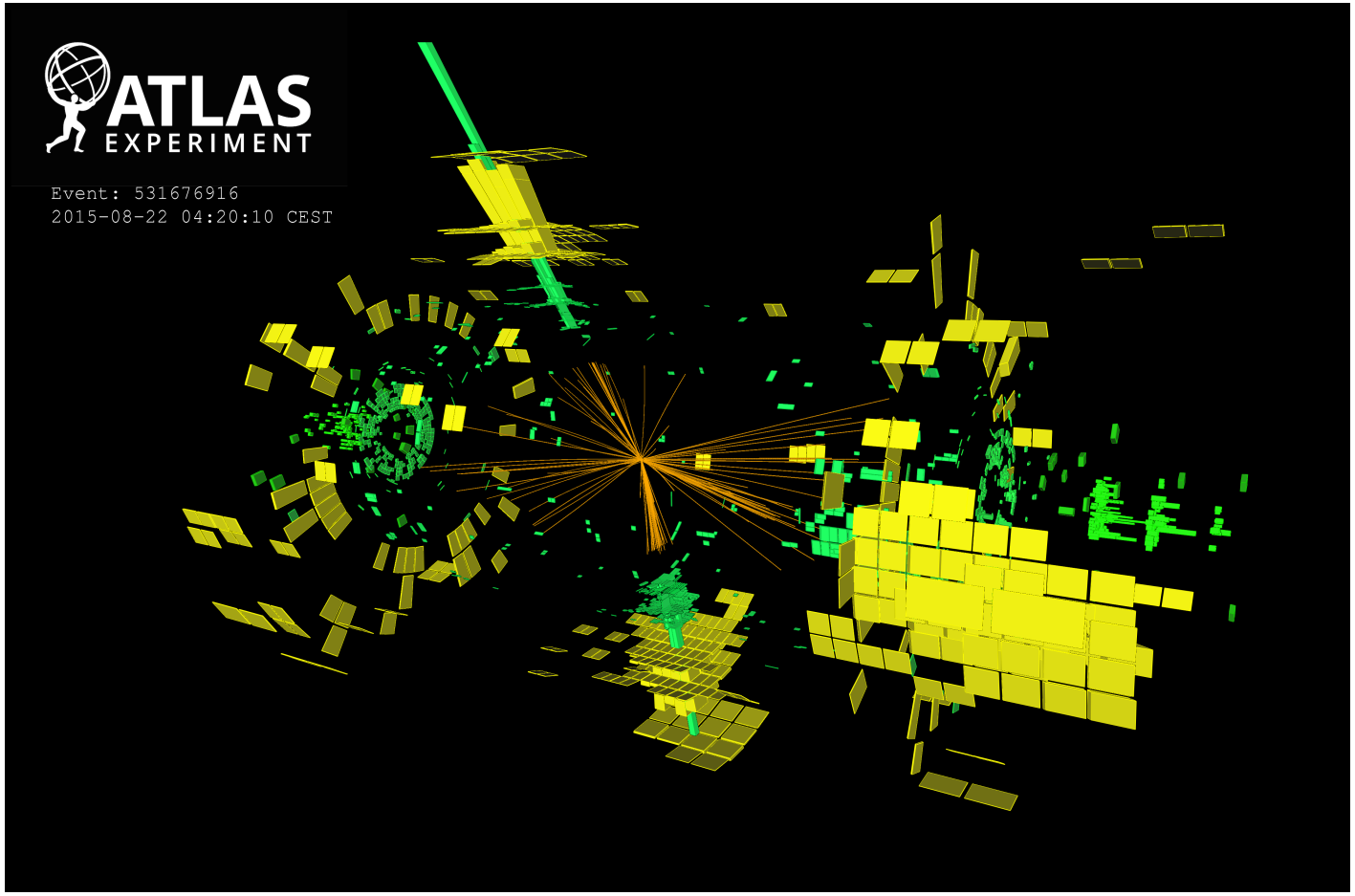
- Higgs Bosons decay to pairs of jets: perfect candidate for color flow!

Color Flow with Higgs



- Color flow in signal/background processes is extremely different!
- Can be used to improve searches for Higgs: sensitivity is now proven!
  - Alternatively: *characterize* Higgs once it is observed (similar to this measurement)

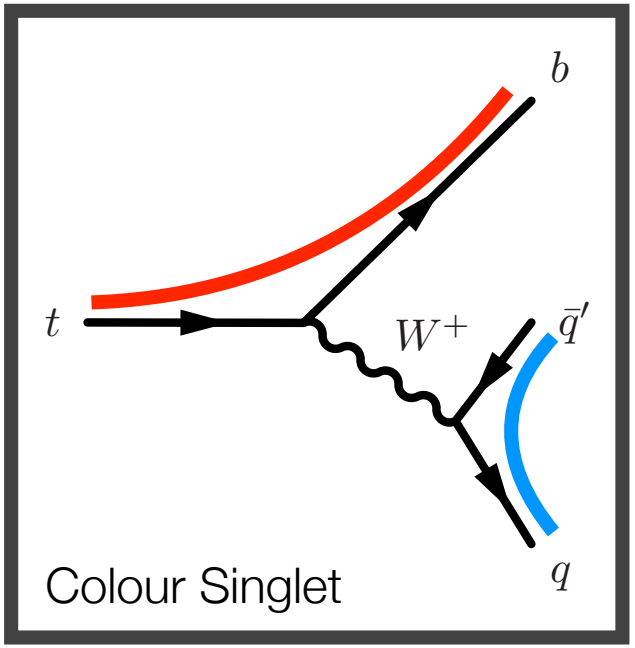
Characterizing New Physics



$\sqrt{s} = 13$ TeV, 5.2 TeV Dijet Event

- What happens when we find new physics decaying to jets?
- Will need to identify the SM properties: including **color charge**
  - The pull angle is an understood handle: perhaps uniquely sensitive!

Conclusions: Seeing in Color



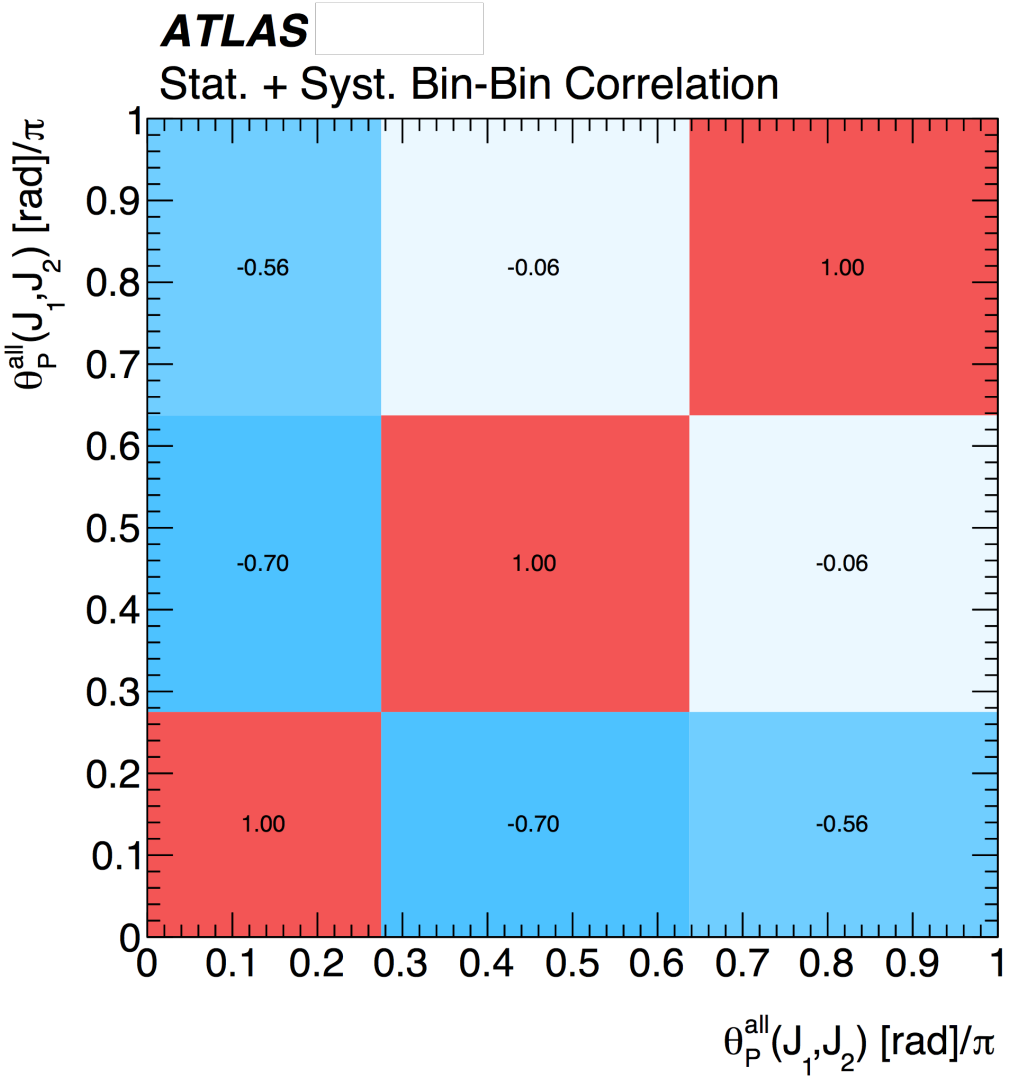
- QCD has a strong impact on the world: we are all hadrons!
- But **direct observation** of color is exceedingly difficult at colliders
  - Hadronization makes most observations color-blind
- We have taught ATLAS to see in **color**, a first for a hadron collider
  - Looking forward to many more analyses using these techniques!

Thank You For Your Attention!

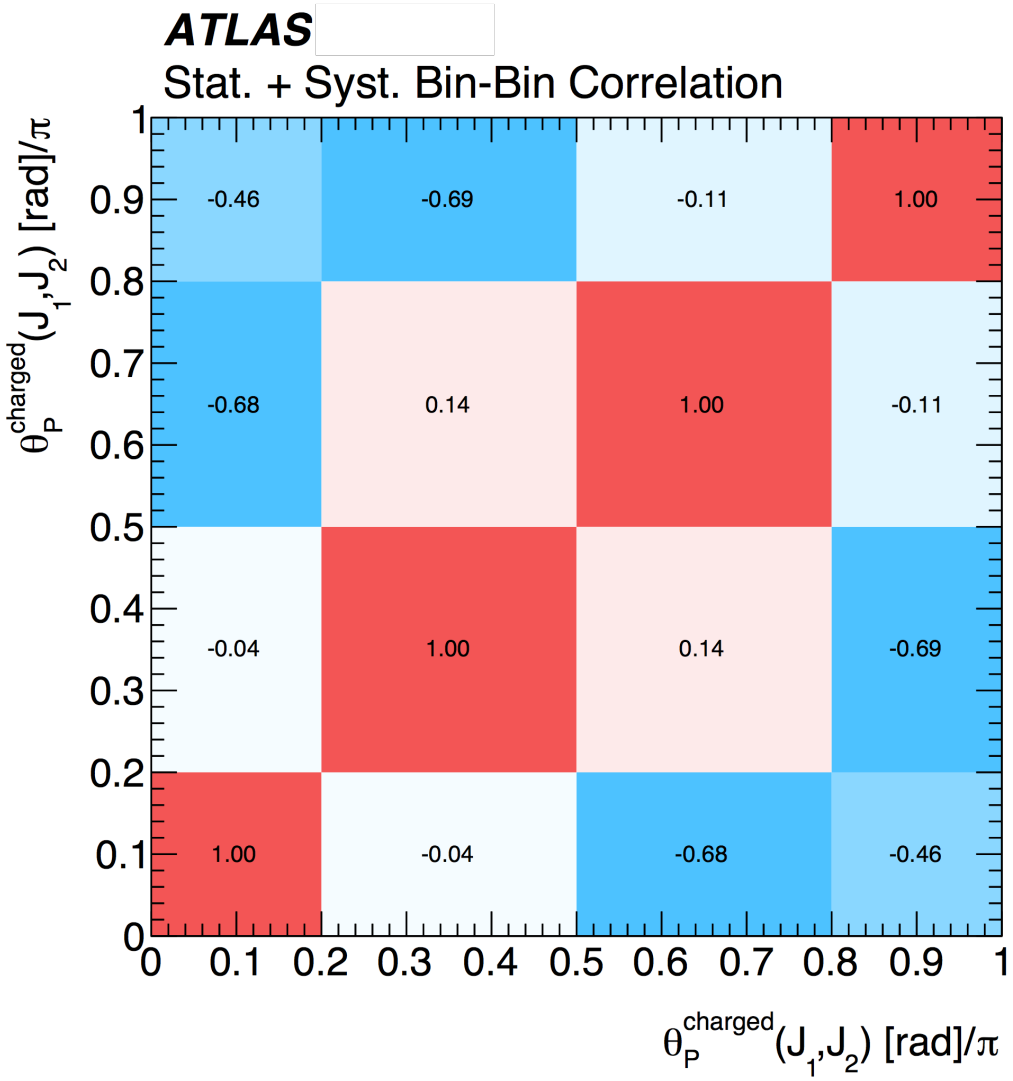
More details in hep-ex/1506.05629

Backup

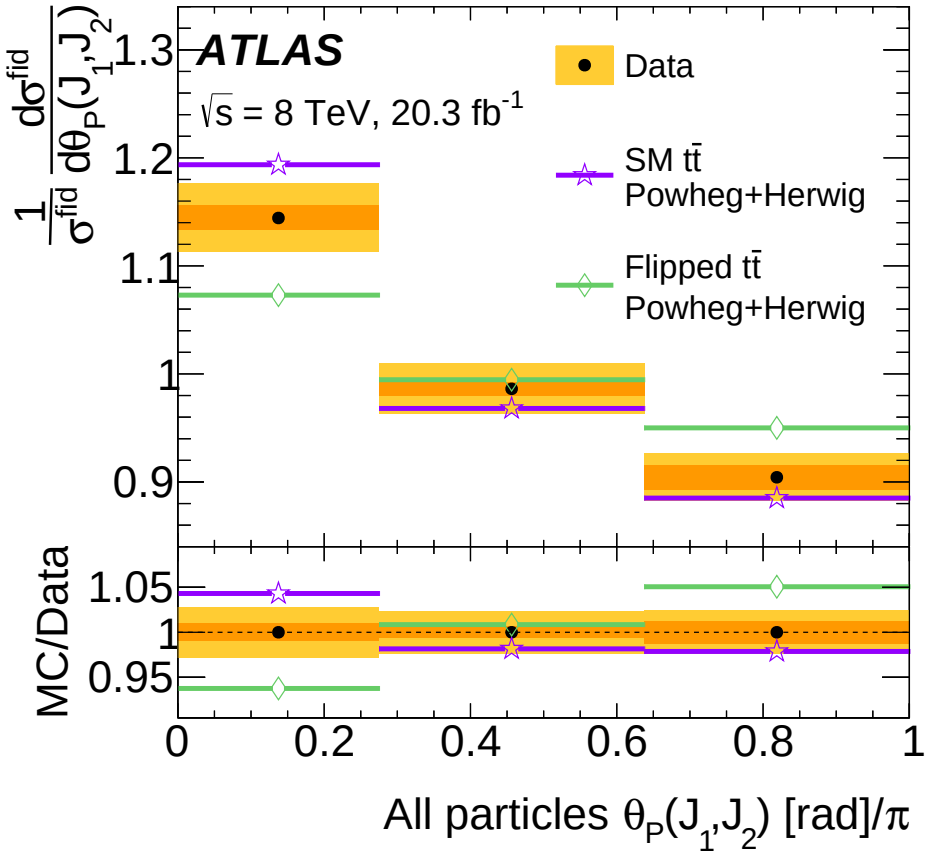
Covariance Matrix, All Particles

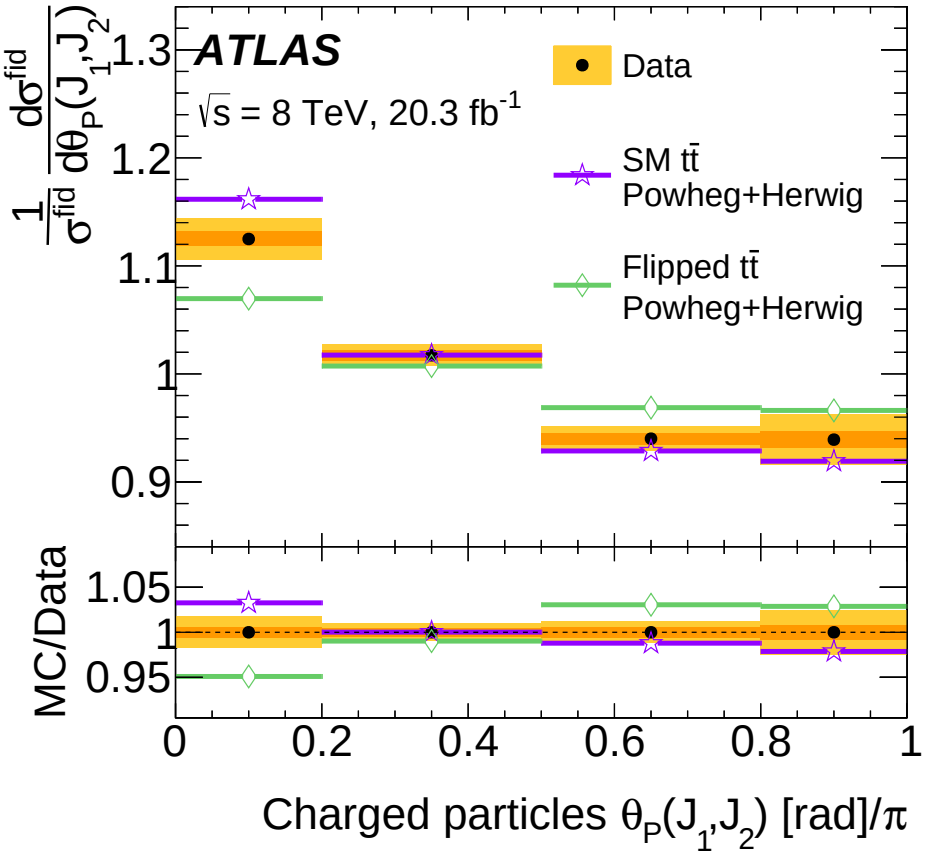


Covariance Matrix, Charged Particles

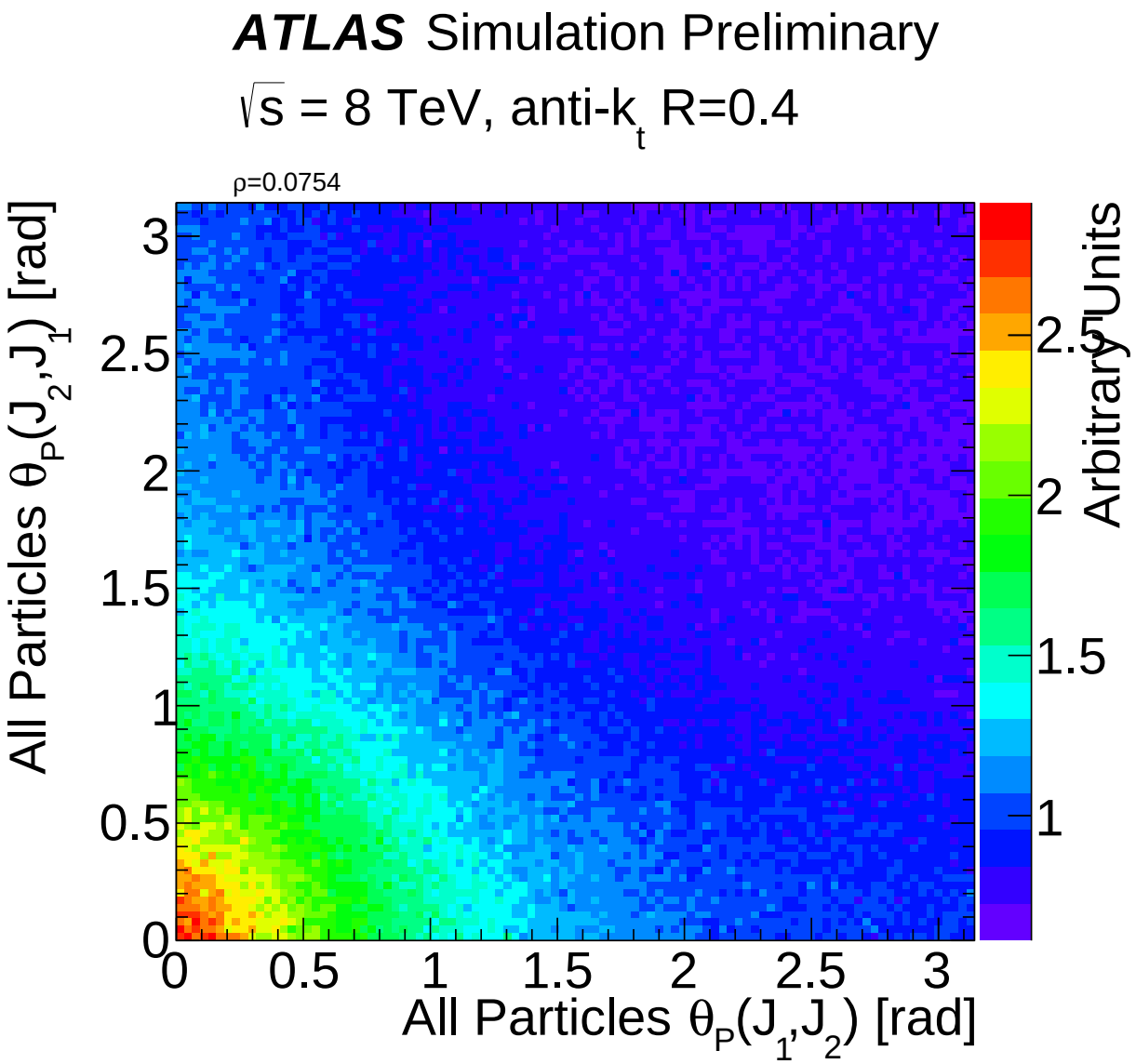


More Herwig Results





Pull Angle for J_1 vs. J_2



Quark/Gluon at ATLAS