Seeing in color:
Jet Superstructure

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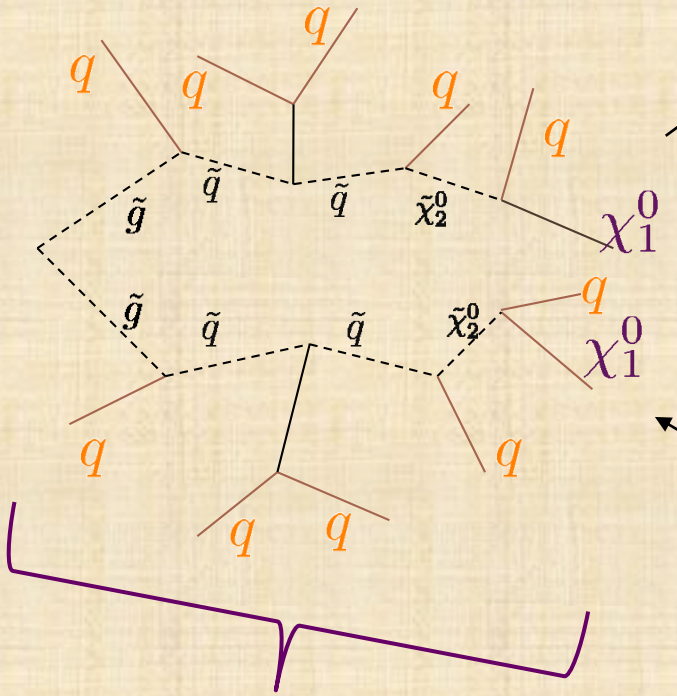
(with Jason Gallichio)

INTERPRETING JETS

We want to see quarks and gluons:

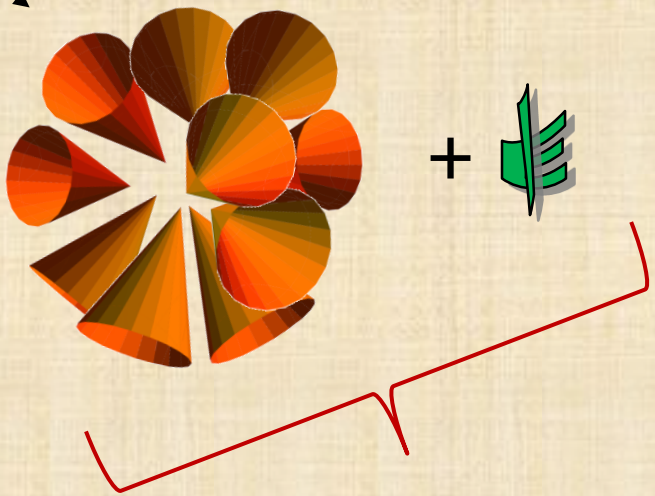


Assumption: this exists

QCD

Can we invert ?

We observe jets:

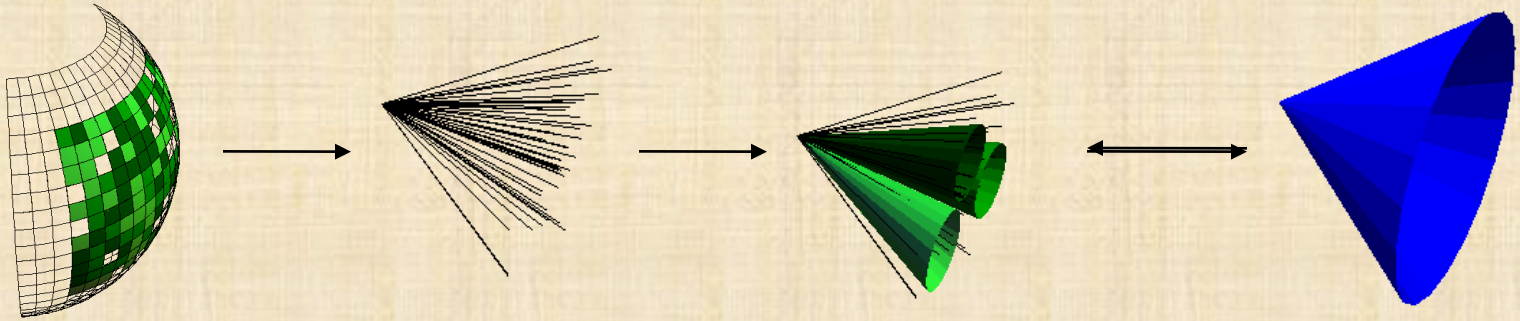


Reality: this exists

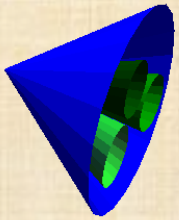
JET-TO-PARTON MAP

- Find jet momenta
- Set quark momenta = jet momenta

JET SUBSTRUCTURE



- Clean out soft radiation
- Clean out collinear radiation
- Helps with, $H \to b\bar{b}$, top-tagging
- Helps find merged subjets



- Helps get jet momenta “closer to parton momenta”

↳ Improves **JET-TO-PARTON MAP**

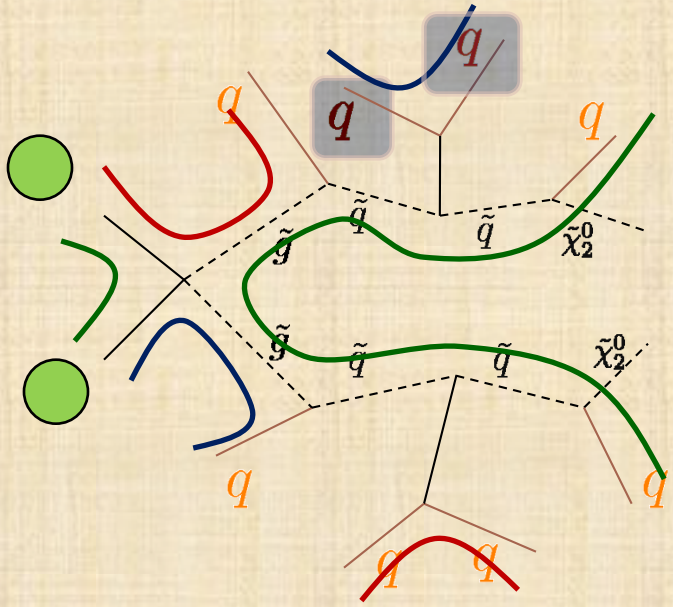
Is there information **not** in the parton momenta?

JET SUPERSTRUCTURE

What is not in the **JET-TO-PARTON MAP** ($p_{parton}=p_{jet}$)?

- Global information
  - Event shapes, H_t, missing energy
  - Useful for testing QCD, validating Monte Carlos
  - No obvious new physics applications
- Color:
  - Color charge: Quark vs. Gluon jets
  - Color connections

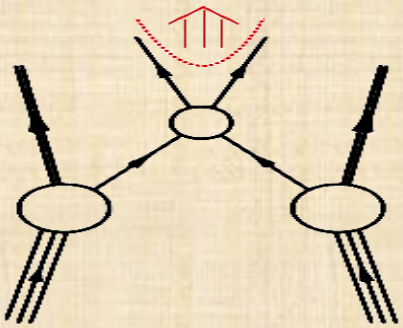
$$\mathrm{Tr}[T^A T^B] \propto \delta^{AB}$$

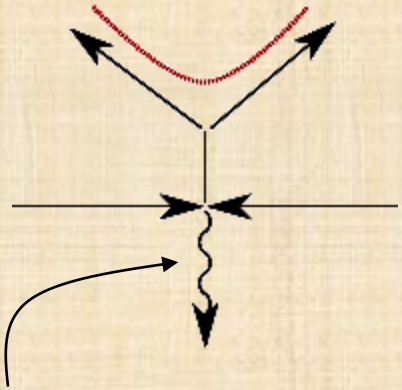


- What can be calclated?
  - SCET?
- What can be seen?
  - What are good observables?

EXAMPLE: $H \to b\bar{b}$

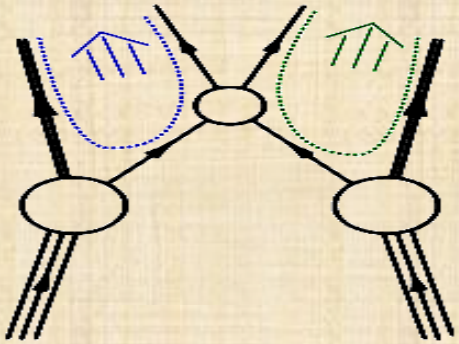
Signal

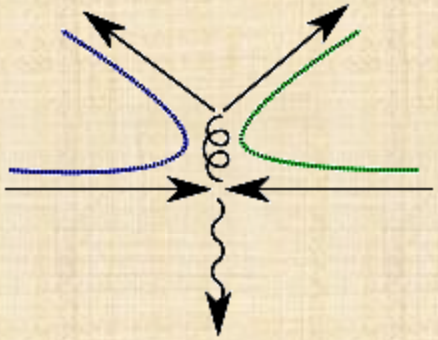




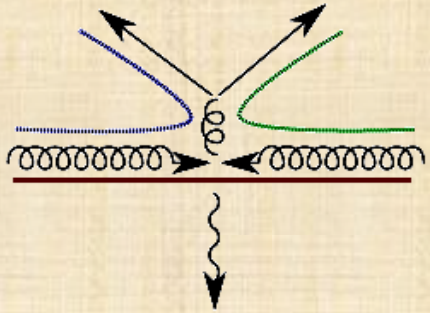
Associated production with a Z (for tag/boost)

Background





$q\bar{q} \to Zb\bar{b}$

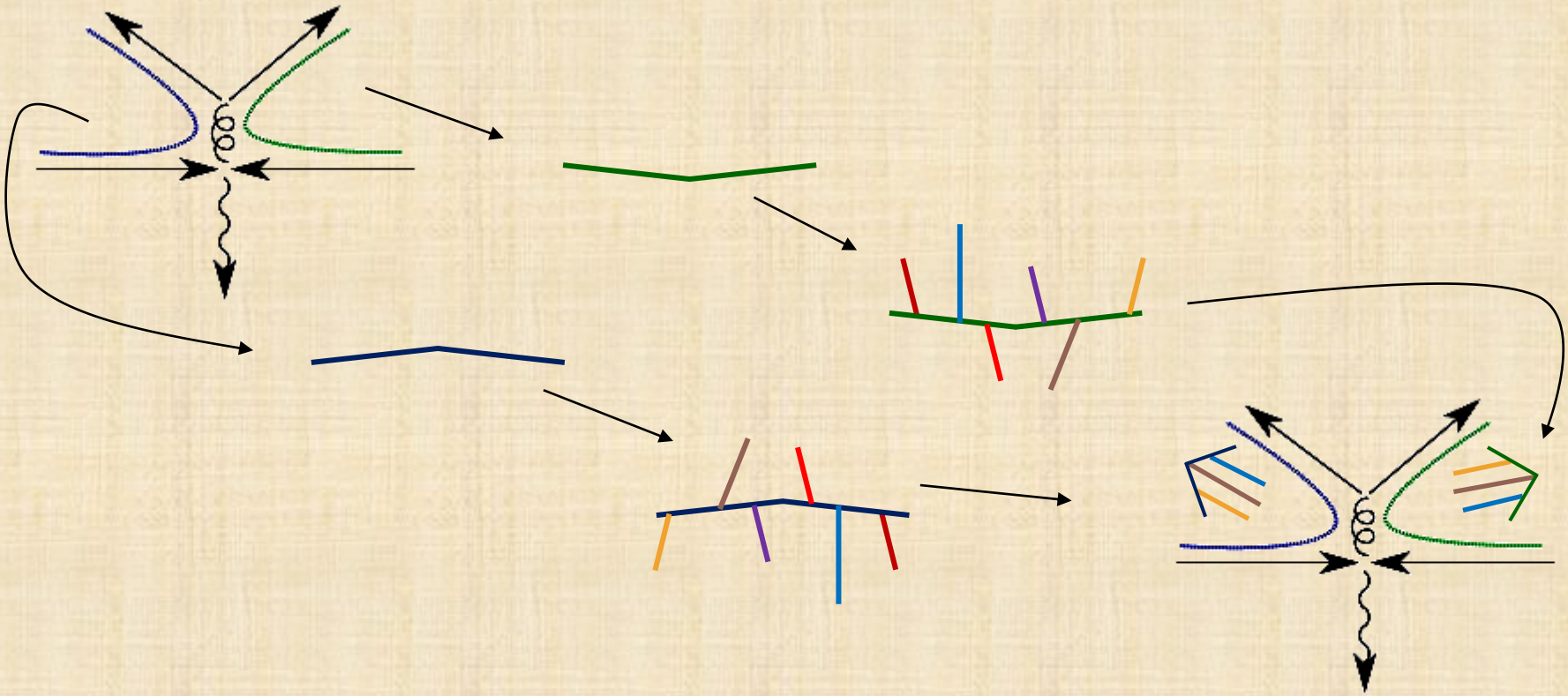


$gg \to Zb\bar{b}$

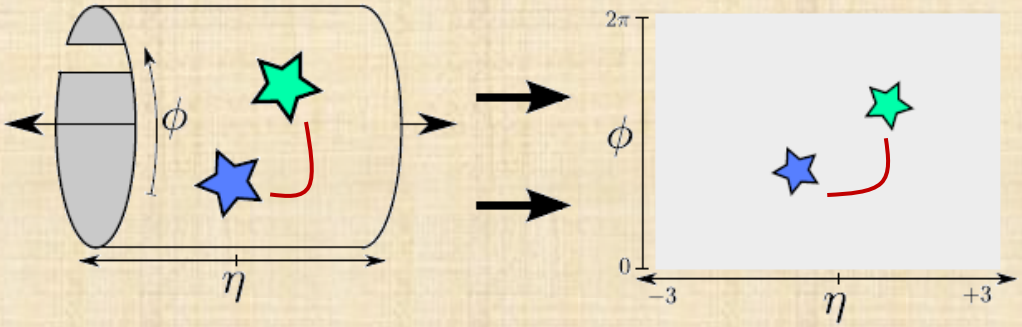
HOW DO THEY SHOW UP?

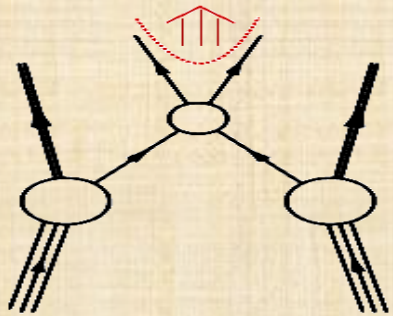
Monte Carlo simulation

- Color coherence (angular ordering, e.g. Herwig)
- Color string showers in its rest frame (pt ordering, e.g. Pythia)
  - Boost → string showers in string-momentum direction



CAN THEY BE SEEN?



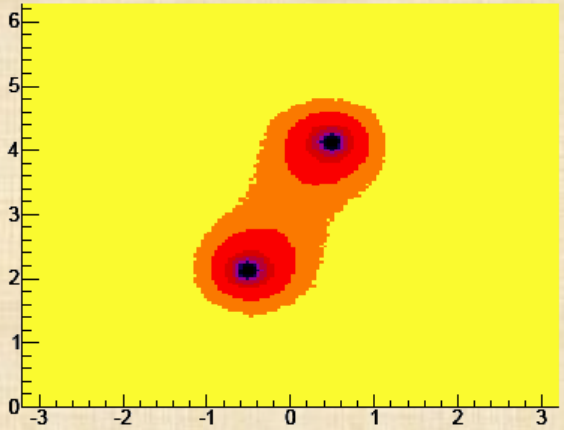


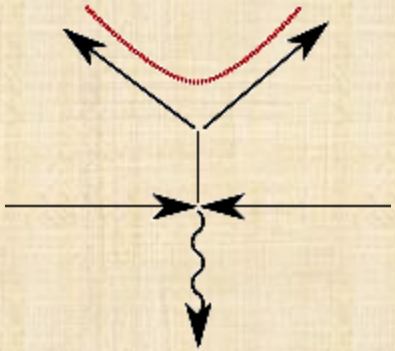
Shower same event
millions of times

Higgs:

$$\Delta\eta_{b\bar{b}} = 1$$
$$\Delta\phi_{b\bar{b}} = 2$$

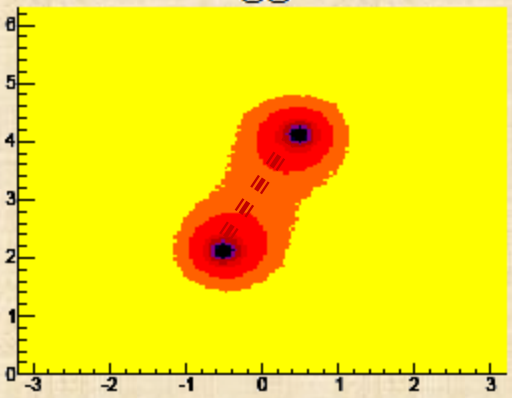
Add up E_T in each cell:

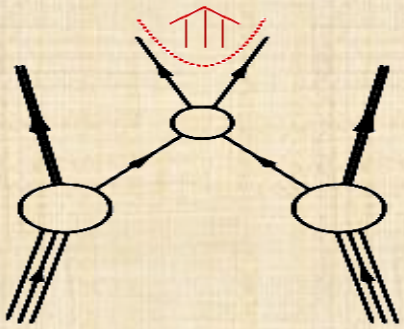




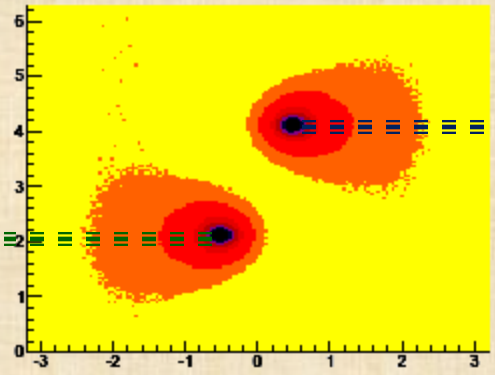
SIGNAL VS BACKGROUND

Higgs:

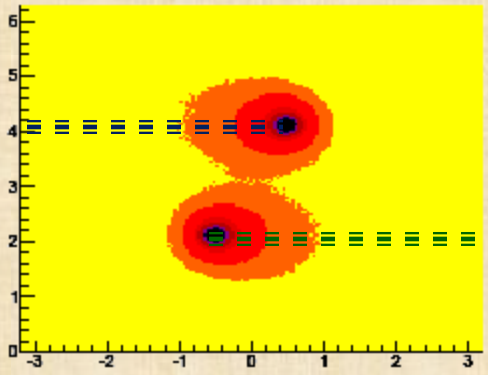




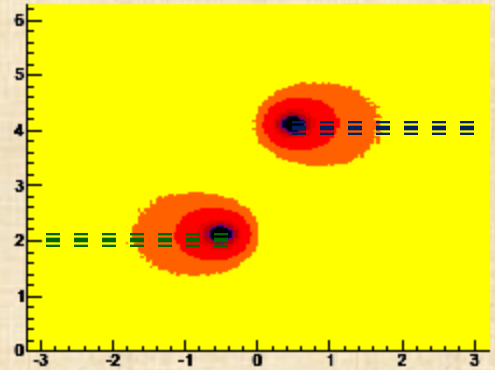
$q\bar{q}$



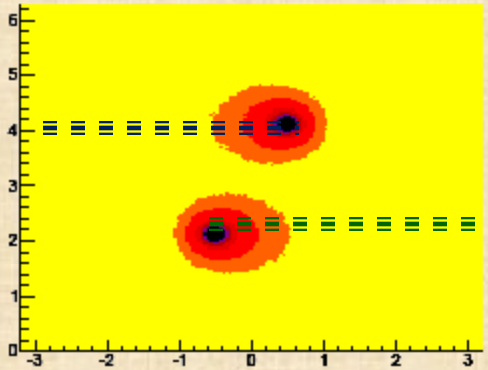
$q\bar{q}X$

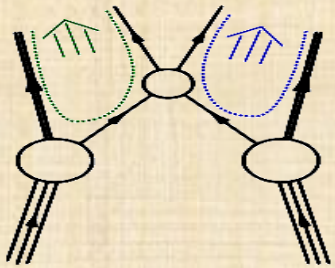


gg



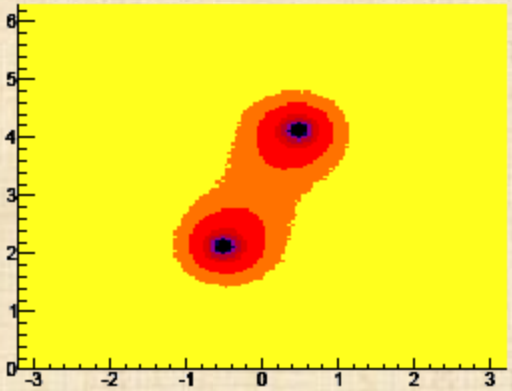
ggX



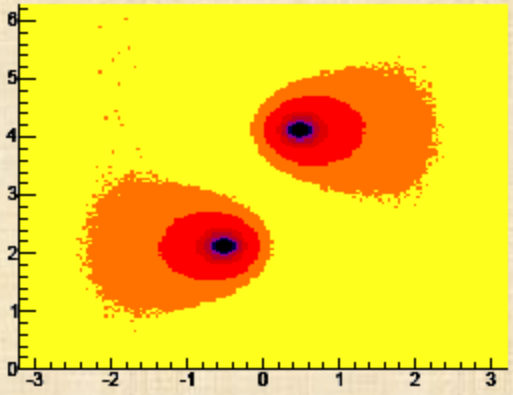


HOW CAN WE USE IT?

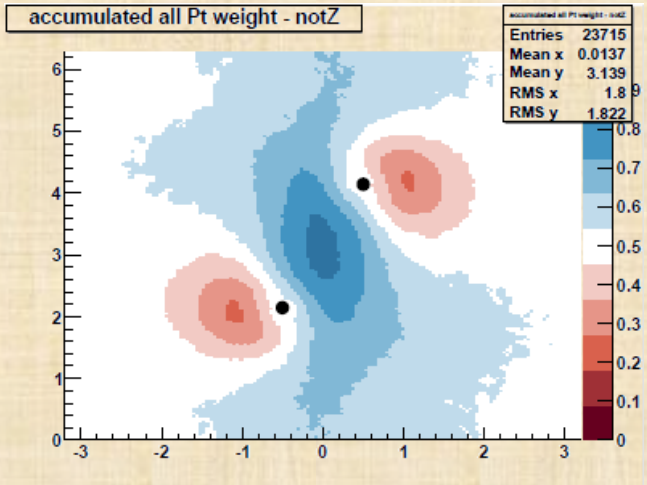
Higgs:



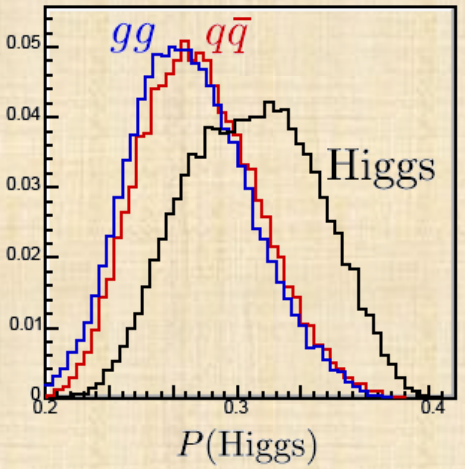
$q\bar{q}$



Baysean **probability** that each bit of radiation is **signal**

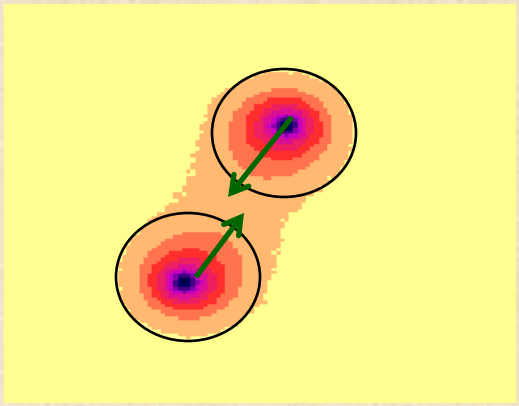


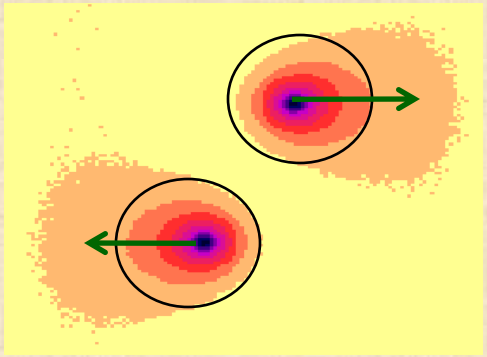
Event-by-event **discriminant**

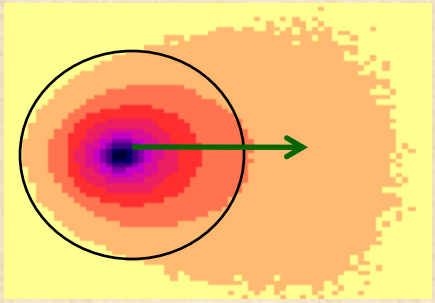


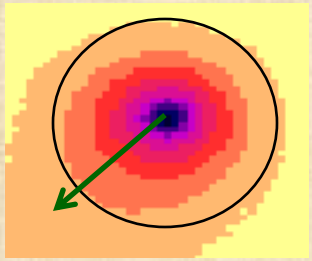
- Most useful radiation is **R = 0.5 – 1.5** away
- Pattern depends strongly on **kinematics**
- Can we find a ***simpler*** or more ***universal*** discriminant?

PULL







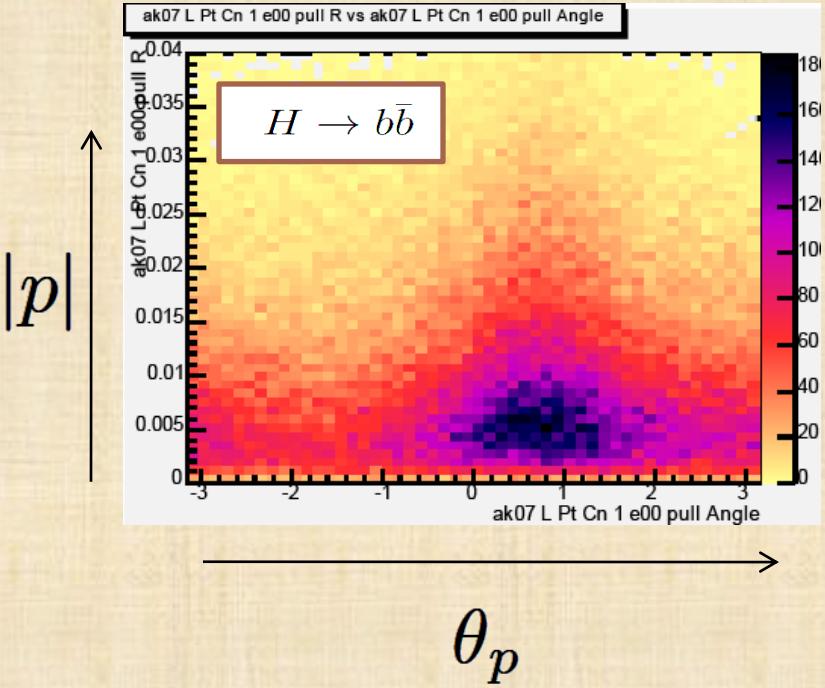


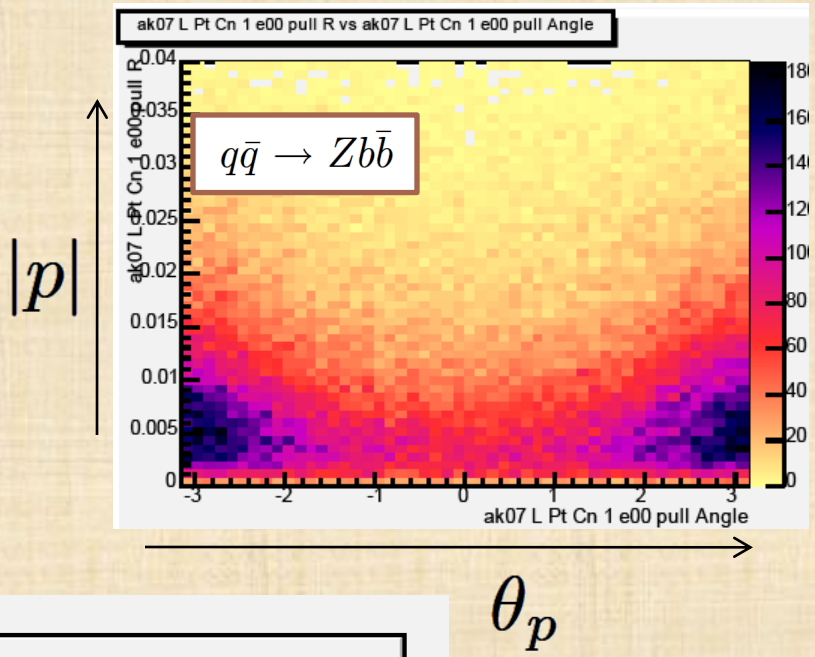
- Find **jets** (e.g. anti-k_T)
- Construct **pull vector** (~ dipole moment) on radiation in **jet**

$$\vec{p} = \sum_i \frac{E_T^i \, |r_i|}{E_T^{jet}} \vec{r}_i$$

- Can use bigger jets for pull, but R = 0.7 seems optimal

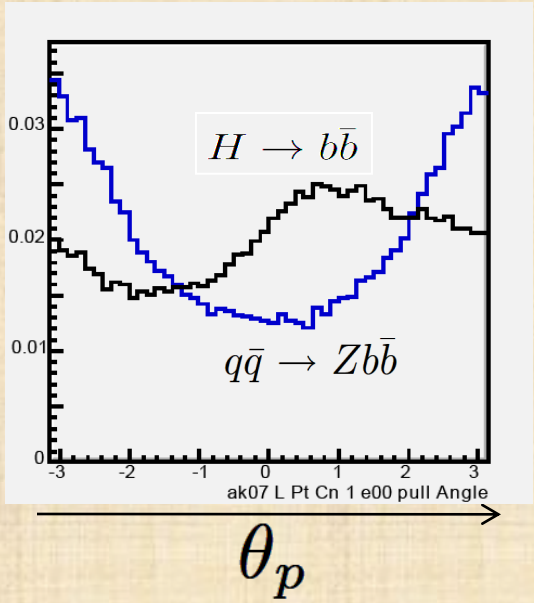
RESULTS





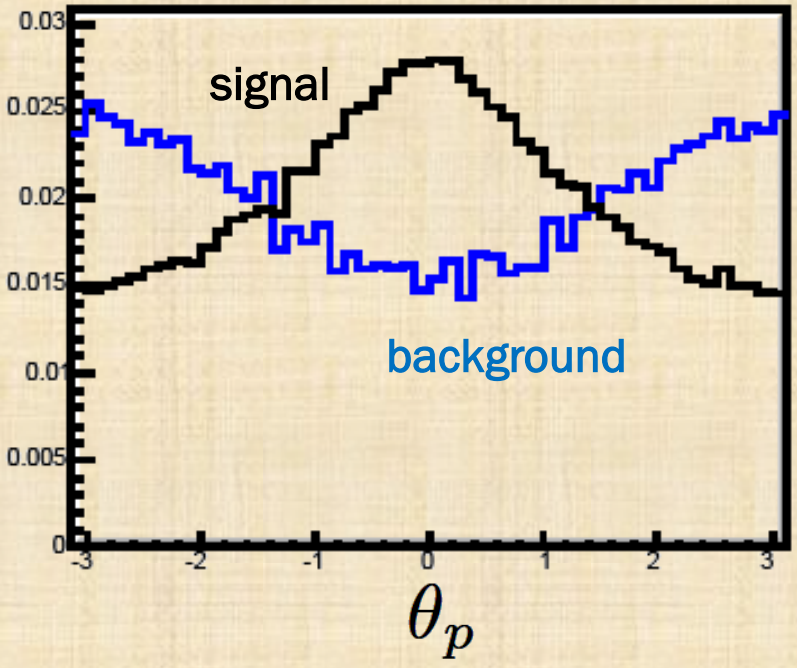
$$\vec{p} = \sum_i \frac{E_T^i \, |r_i|}{E_T^{jet}} \vec{r}_i$$

- Angle much more important than length

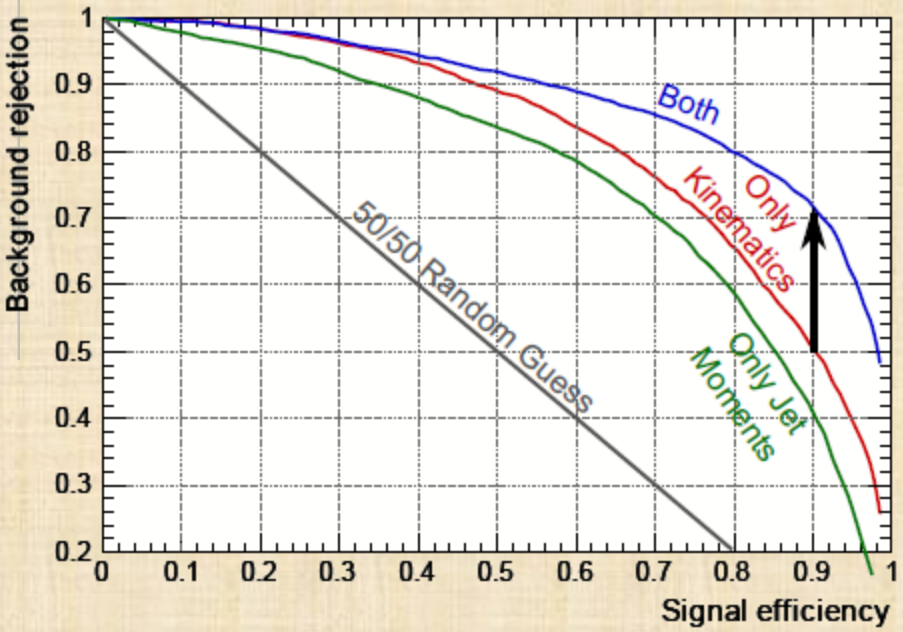


FULL H+Z TEST

Pull angle of one b-jet
with respect to other b-jet

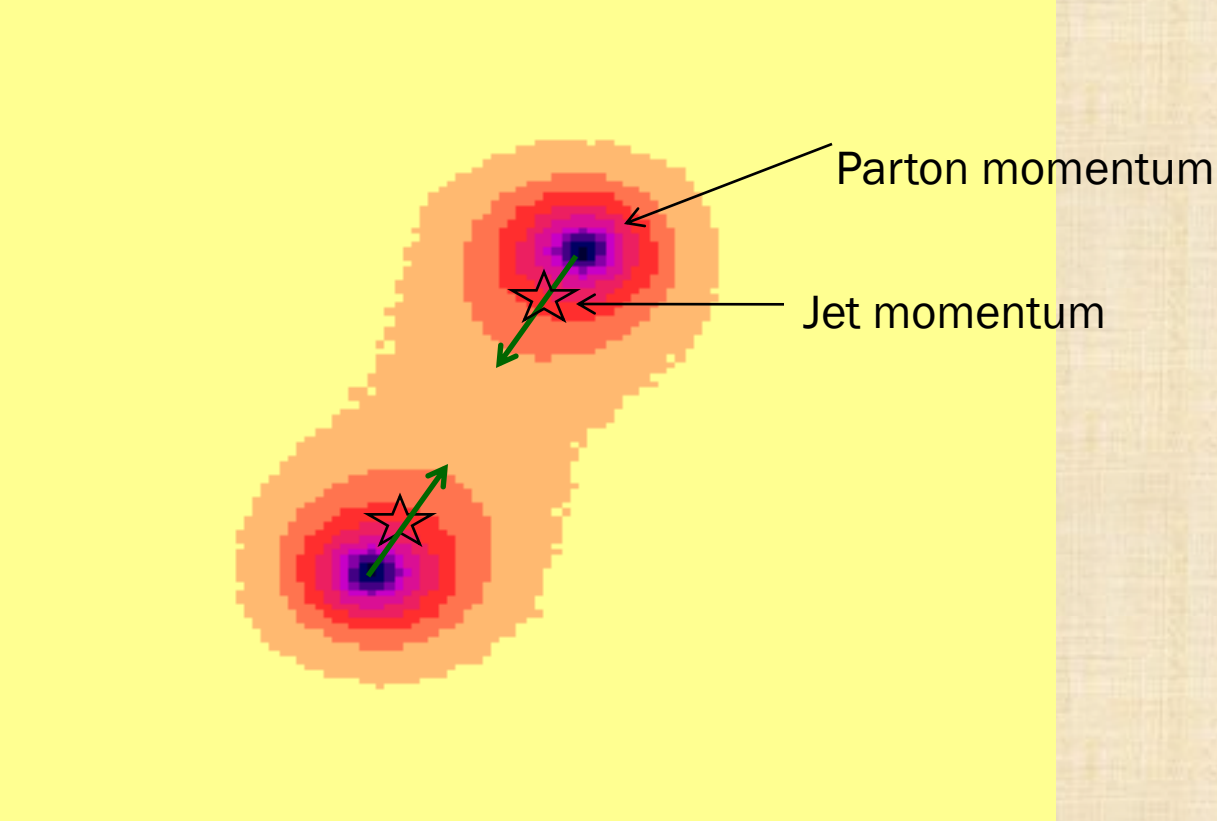


How much does this help?



JET MIGRATION

Another application of pull could be jet migration



Can use pull to correct for migration

- Better kinematics → improve JET-TO-PARTON MAP

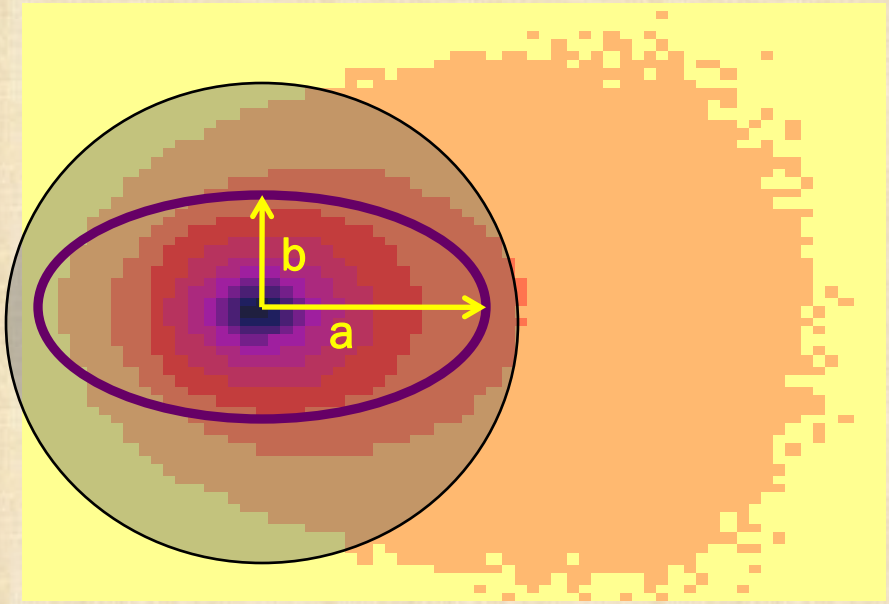
SECOND MOMENTS

What about **higher moments**?

$$\mathbf{I} = \sum_i \frac{E_T^i |r_i|}{E_T^{jet}} \begin{pmatrix} \Delta\phi_i^2 & -\Delta\phi_i \, \Delta\eta_i \\ -\Delta\eta_i \, \Delta\phi_i & \Delta\eta_i^2 \end{pmatrix} \longrightarrow$$

Eigenvalues
a and b

JET



Eccentricity

$$e = \sqrt{\frac{a^2 - b^2}{a^2}}$$

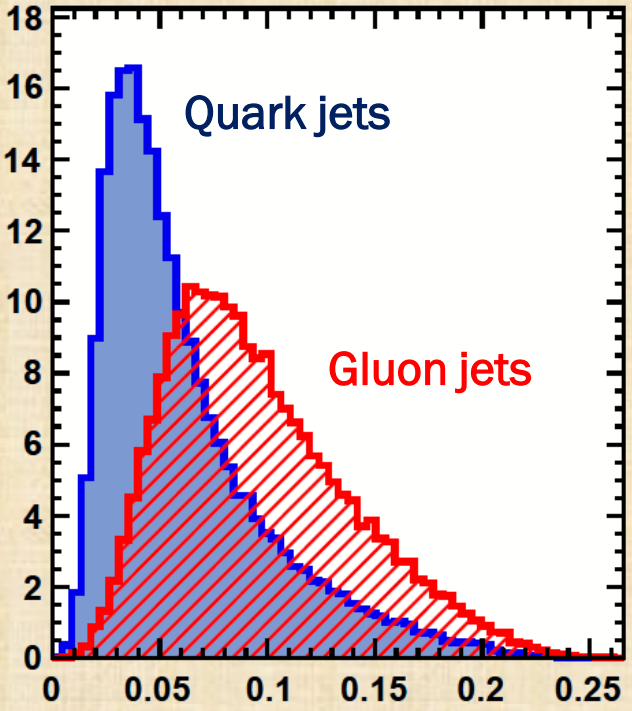
- No obvious use (that we see)

Girth

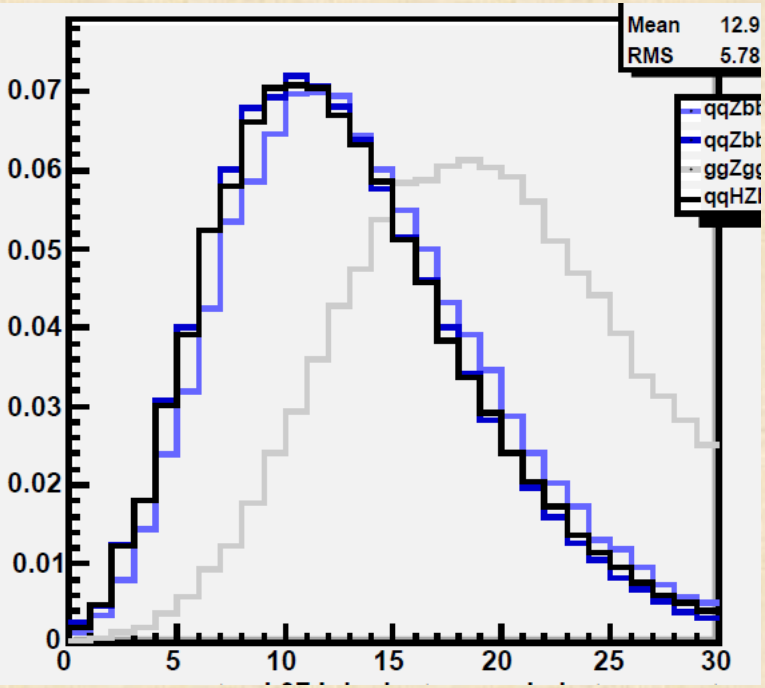
$$g = \sqrt{a^2 + b^2}$$

- Useful for quark vs gluon jets

QUARKS VS GLUONS



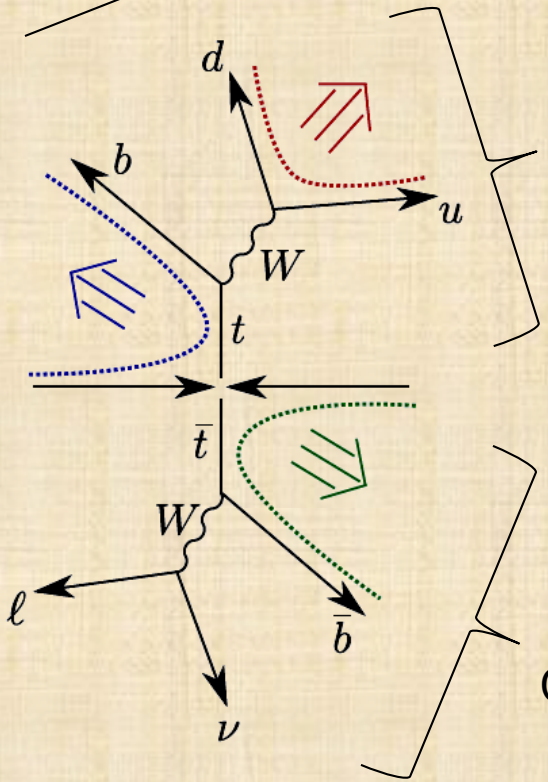
Girth



multiplicity

HOW TO TEST WITH DATA?

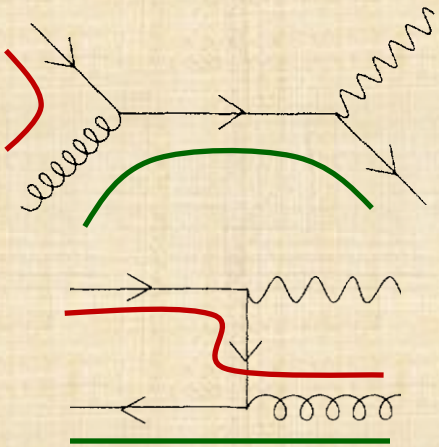
$t\bar{t}$



Clean color-singlet jet pair

Clean top tag

- W/Z/γ + jet



- Jet is color connected to the beam
- At LHC, mostly quark jets

- Good gluon jet sample???

QUARK VS GLUON JETS

- More radiation
  - (charged) particle multiplicty
    - Used already by experimentalists
    - confirmed by LEP data
  - larger jet area

- Different radiation
  - Gluon jets have larger masses
    - sensitive to grooming
  - Jet shapes (e.g. angularities)

- Color flow
  - Two color connections
  - Girthier – less sensitive to grooming

- **JET-TO-PARTON MAP** not very useful

Jet Superstructure

SUMMARY

- We're getting good at contructring the
  JET-TO-PARTON MAP

- There is information not in the map, which we call

Jet Superstructure

- Examples include color flow and color charge

Pull
(first moment)

Girth
(second moment)