The Case for Jet Substructure

Jesse Thaler

DESY Theorist of the Month — June 2, 2014

The Case for Jet Substructure

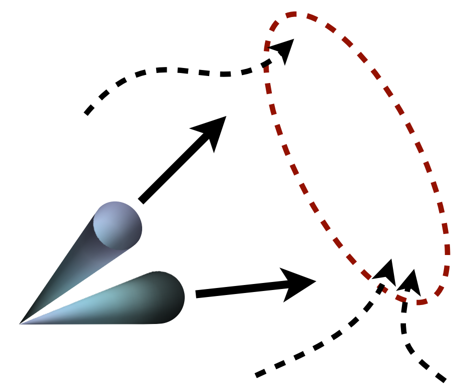
Maximize **discovery** potential of LHC

Boosted Objects: [JDT, Ken Van Tilburg, 2010, 2011]
SUSY Implications: [JDT, Zachary Thomas, 2011]
Quark/Gluon Discrimination: [Andrew Larkoski, Gavin Salam, JDT, 2013]
Jet Counting: [Daniele Bertolini, Tucker Chan, JDT, 2013]
Pileup Mitigation: [Andrew Larkoski, Simone Marzani, Gregory Soyez, JDT, 2014]
Plus: TJ Wilkason, Frank Tackmann

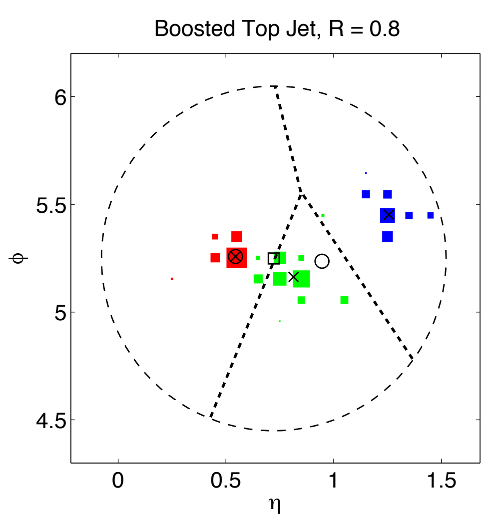
Enhance **understanding** of QCD

Boosted Color Singlets: [Ilya Feige, Matthew Schwartz, Iain Stewart, JDT, 2012]
Hadronization Effects: [Vicent Mateu, Iain Stewart, JDT, 2012]
Ratio Observables: [Andrew Larkoski, JDT, 2013]
Track-Based Observables: [Hsi-Ming Chang, Massimiliano Procura, JDT, Wouter Waalewijn, 2013]
Recoil-Free Observables: [Andrew Larkoski, Duff Neill, JDT, 2014]
Plus: Dan Kolodrubetz

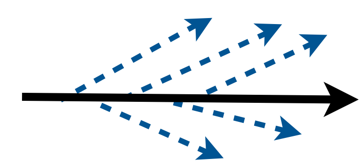
Outline



Why Jet Substructure?

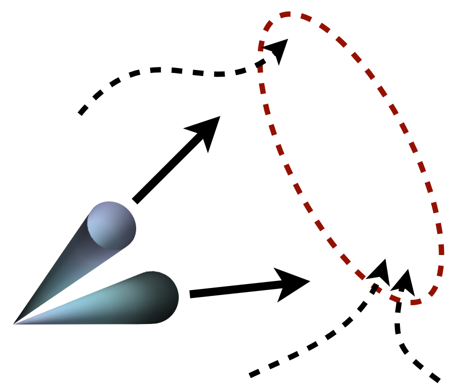


Boosted Objects
with N-subjettiness



$$\frac{\text{IRC Safe}}{\text{IRC Safe}} = \text{Sudakov Safe}$$

Introducing
"Sudakov Safety"



Why Jet Substructure?

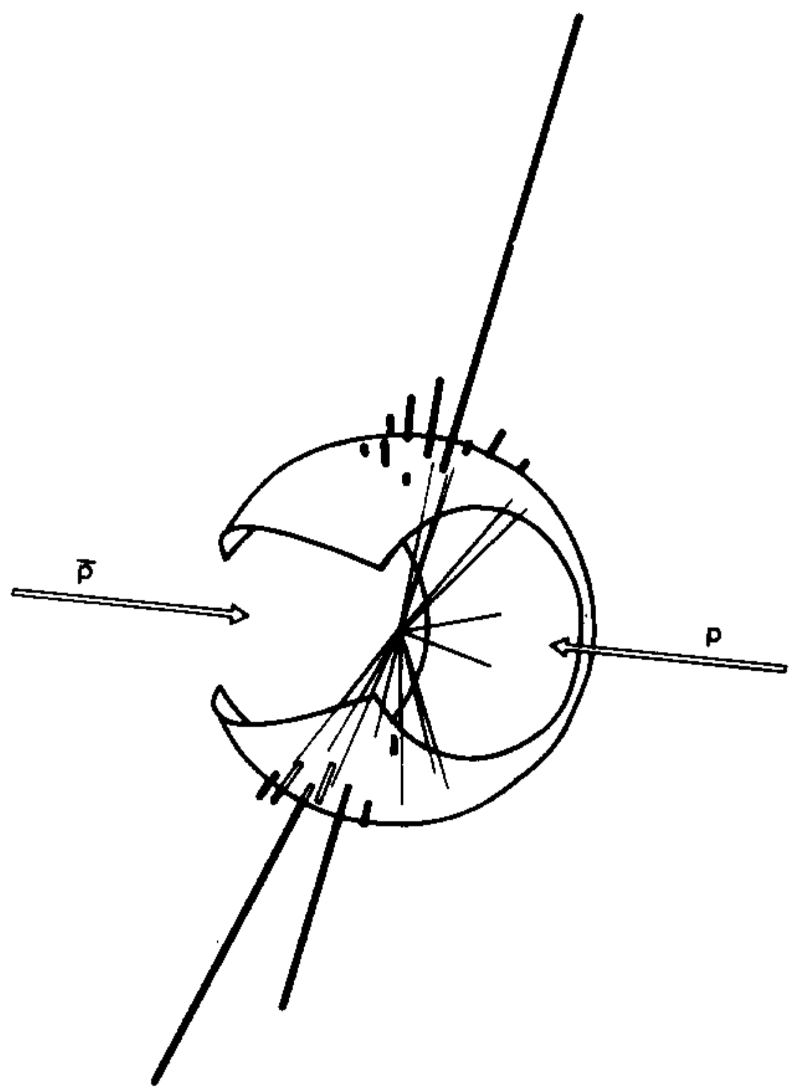
Boosted Objects
with N-subjettiness

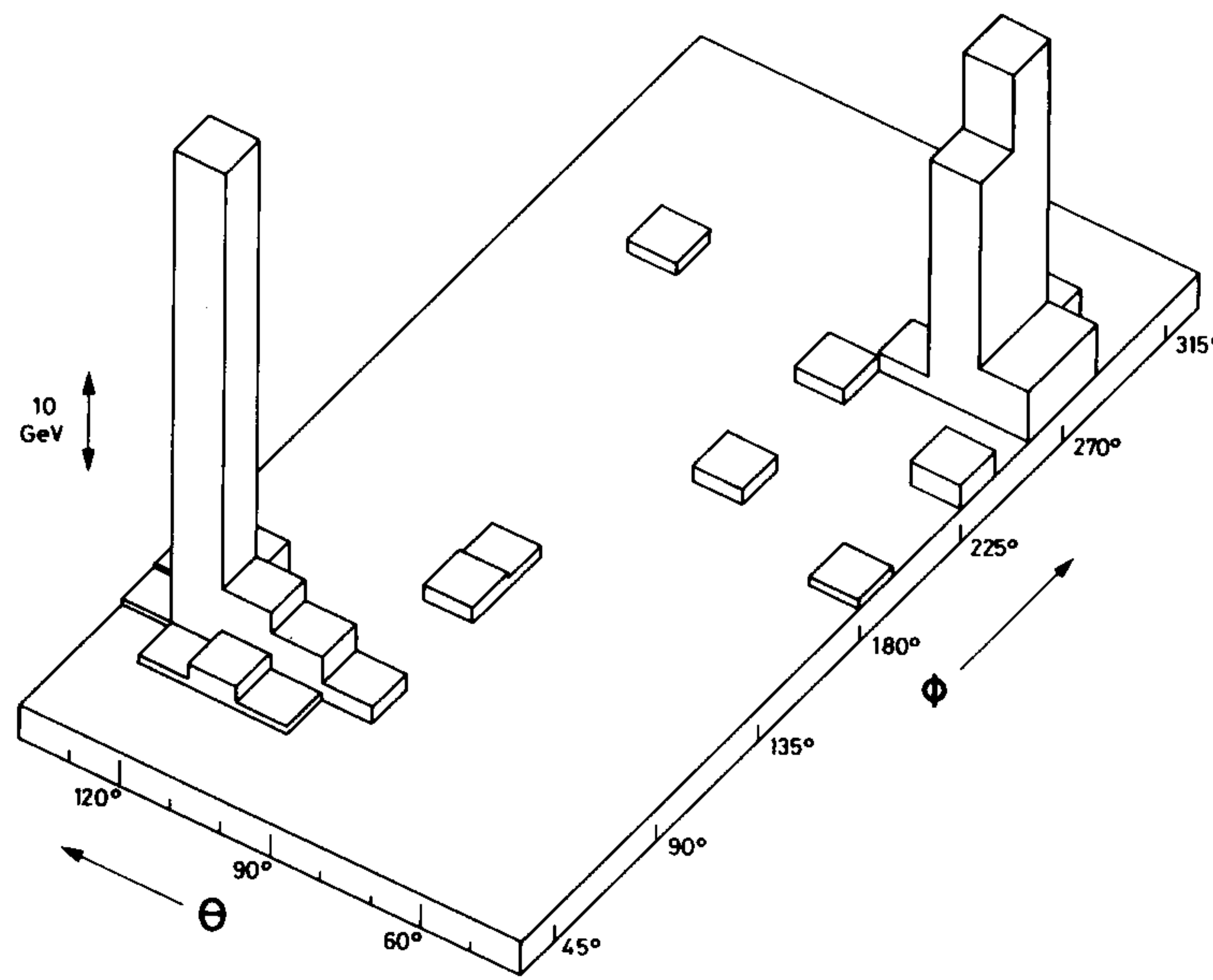
$$\frac{\text{IRC Safe}}{\text{IRC Safe}} = \text{Sudakov Safe}$$

Introducing
"Sudakov Safety"

UA2 Jet Production

1982



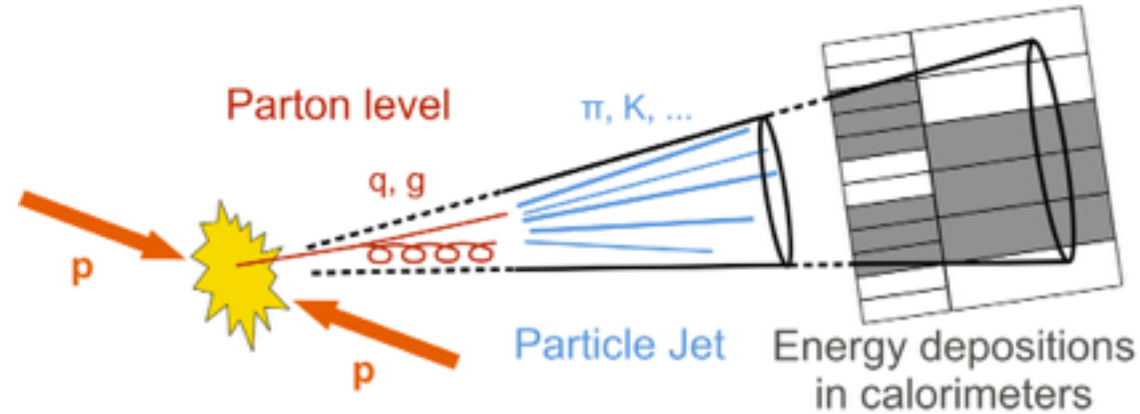


Almost 40 years of jet physics!

[see also SPEAR, 1975; PETRA, 1979]

A QCD Renaissance!

c. 2008–present

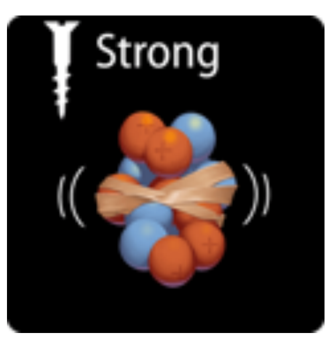


LHC *(vs. Tevatron)*

Higher Energy *(≈ x3.5–7)*

Higher Luminosity *(≈ x10–20)*

Finer Segmentation *(≈ x5)*



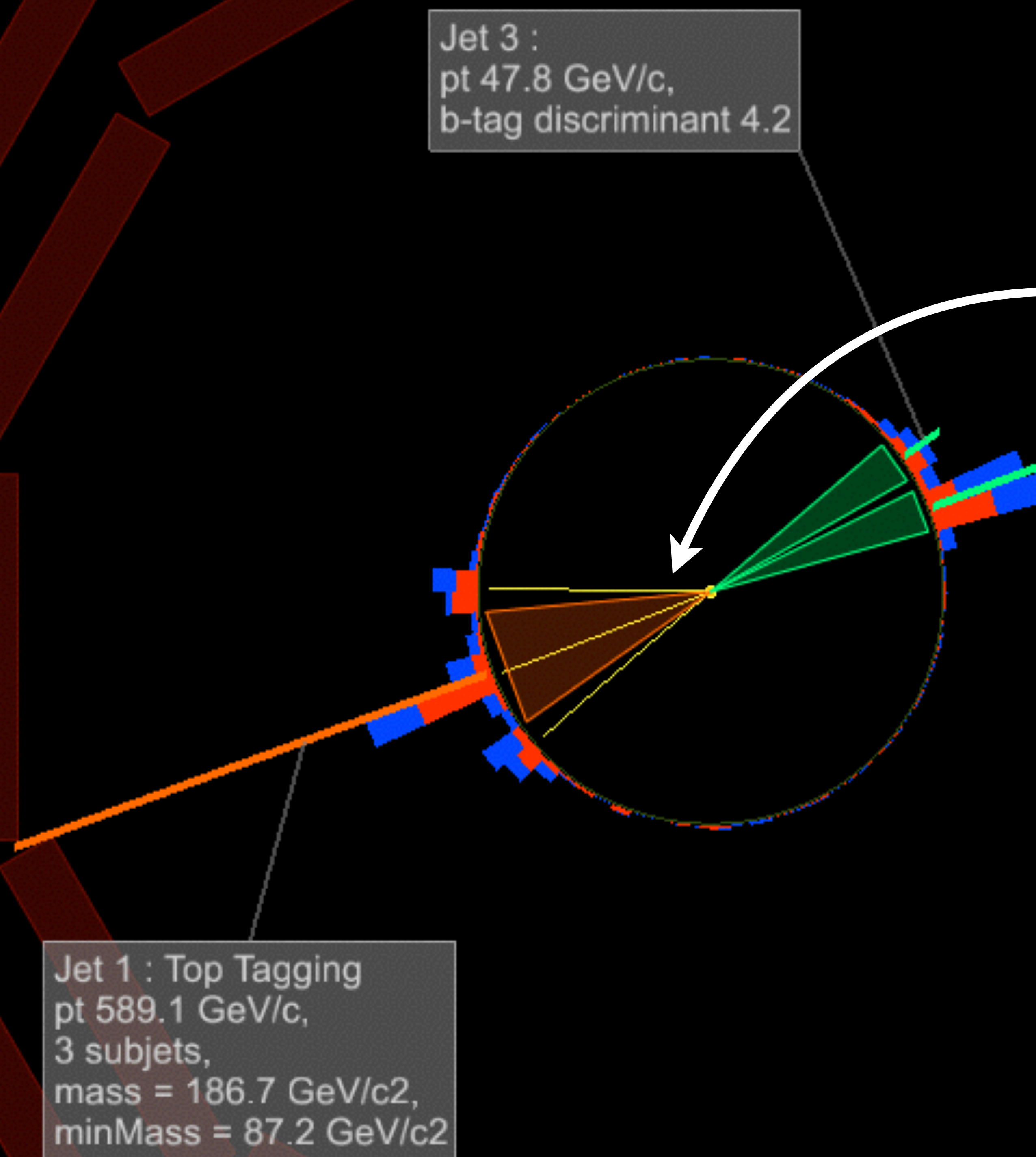
Theoretical Progress

New Jet Algorithms (esp. anti-k_T) [Cacciari, Salam, Soyez, 2008]

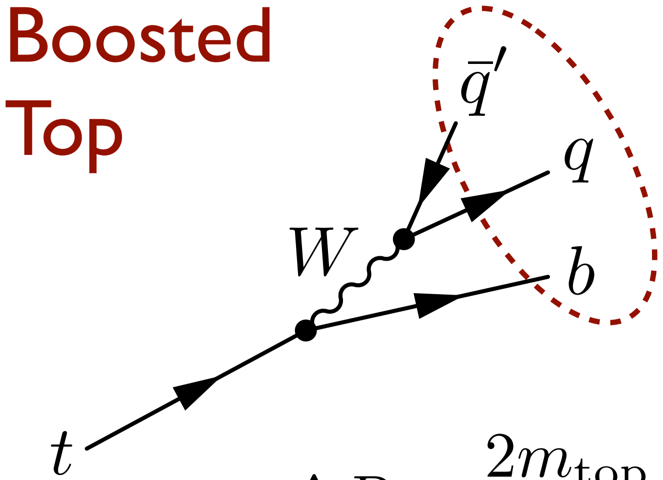
Loop/Leg/Log Explosion

Jet Substructure

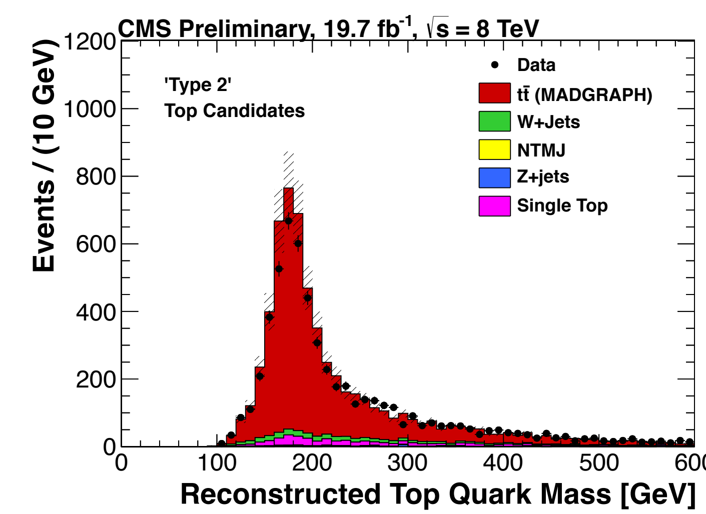
Jets or Jet Substructure?



Boosted Top

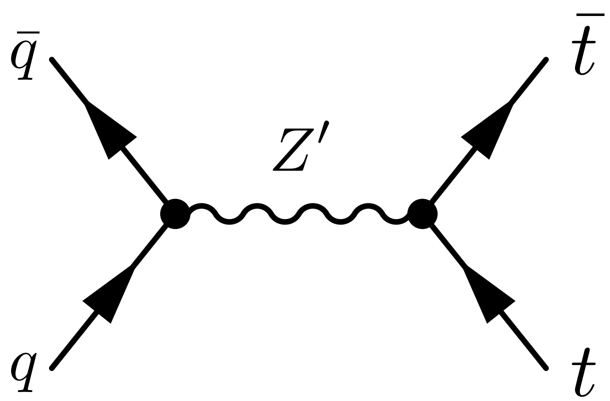


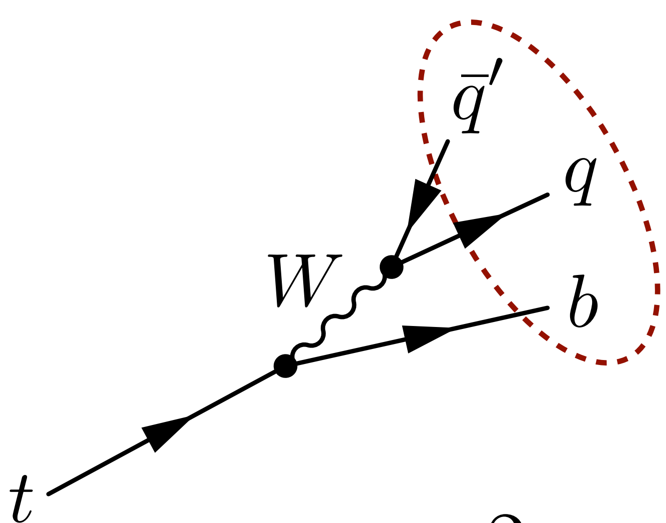
$$\Delta R \simeq \frac{2 m_{\text{top}}}{p_T}$$



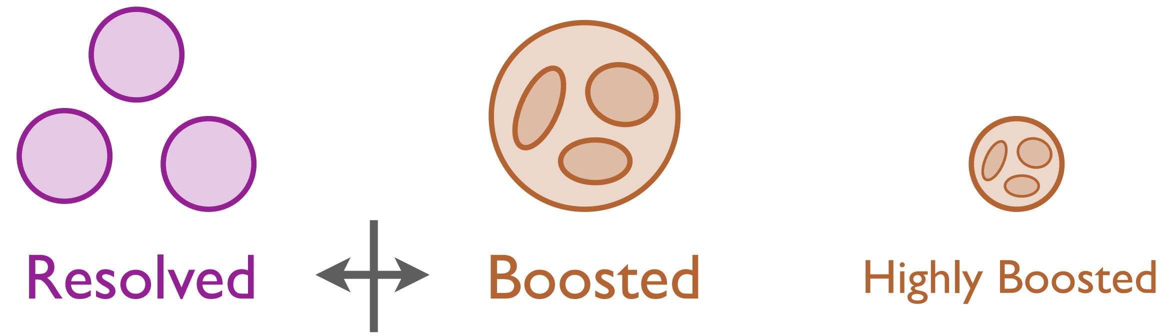
[CMS EXO-11-006, JME-13-007]
[Using Kaplan, Rehermann, Schwartz, Tweedie, 2008]
[Using Ellis, Vermilion, Walsh, 2010]

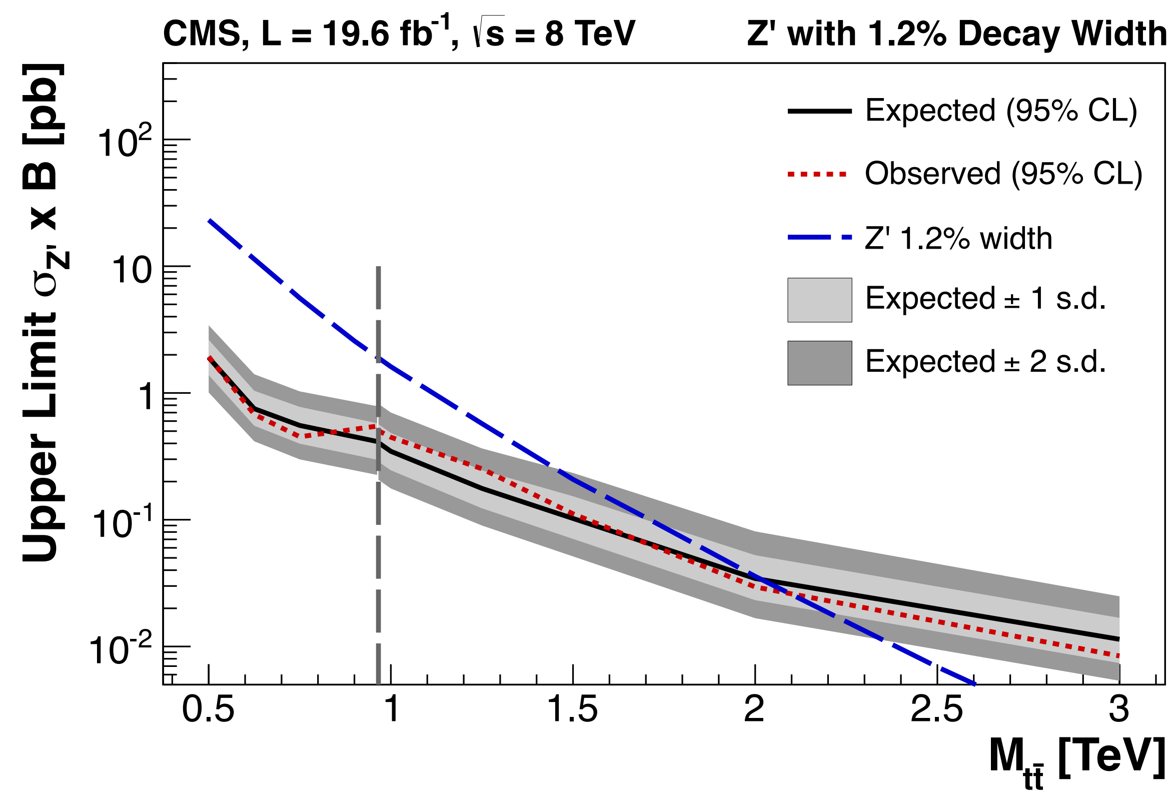
High Energy: Boosted Regime is Inevitable





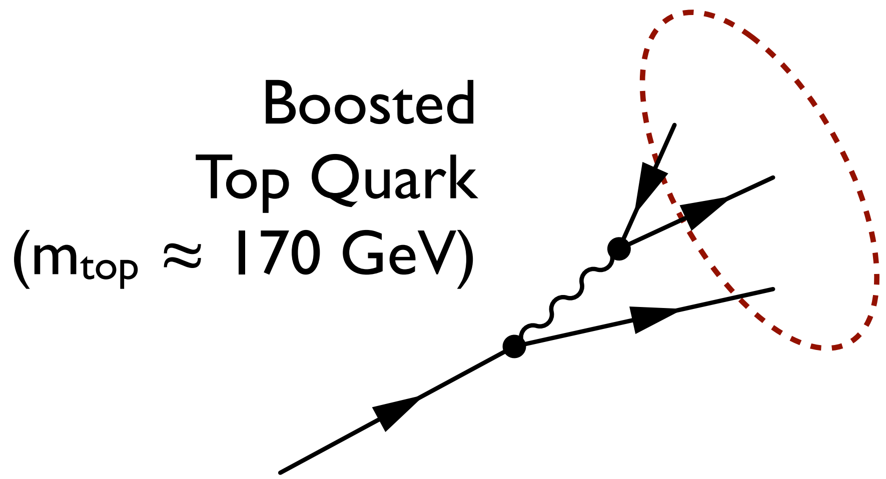
$$\Delta R \simeq \frac{2m_{\text{top}}}{p_T}$$



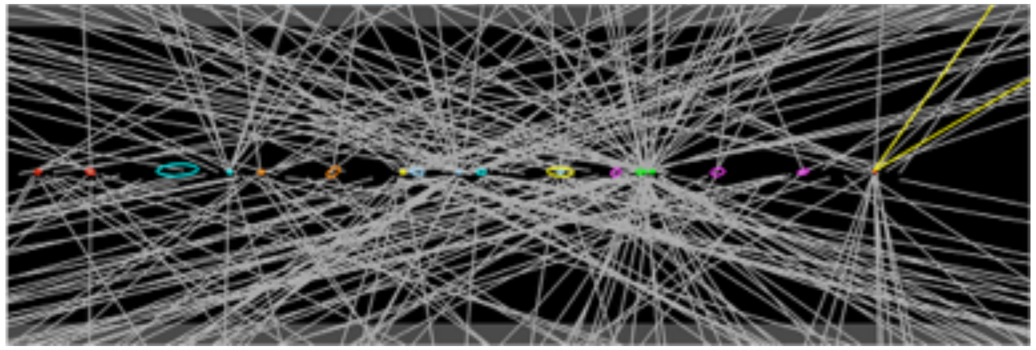


[CMS B2G-12-006]

High Luminosity: Pileup is Inevitable

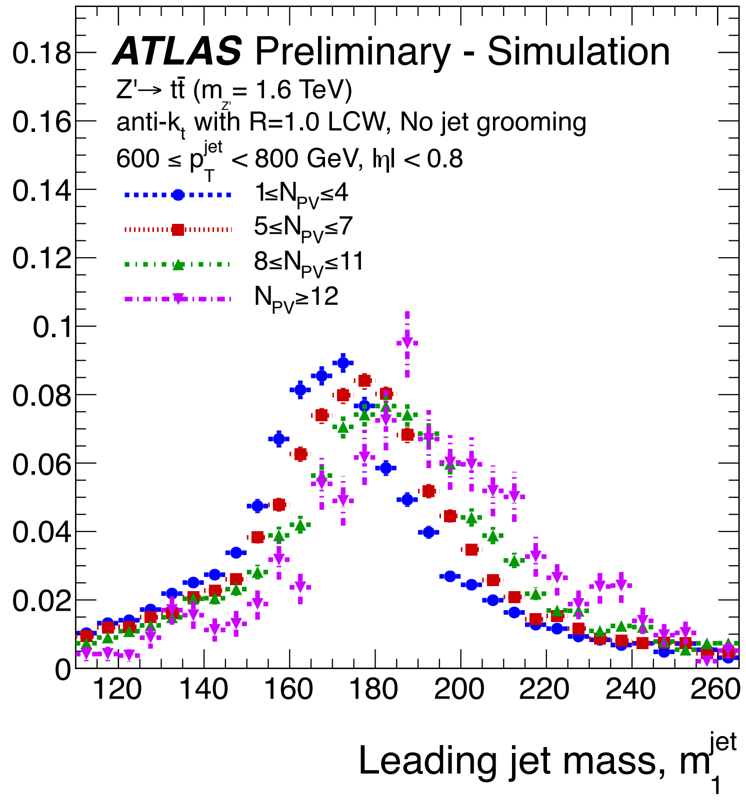


+

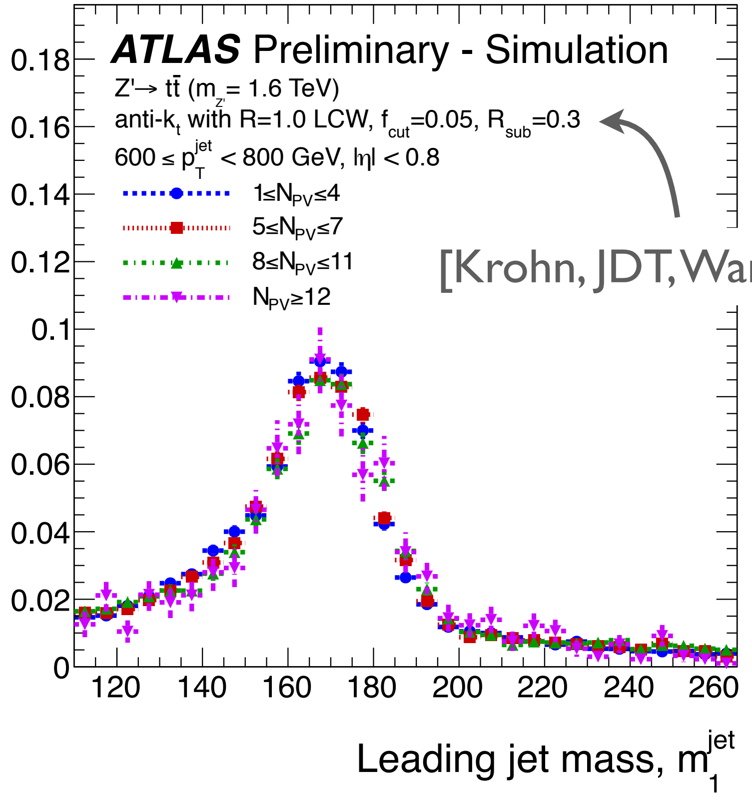


Secondary Collision Debris

[ATLAS CONF-2012-066]

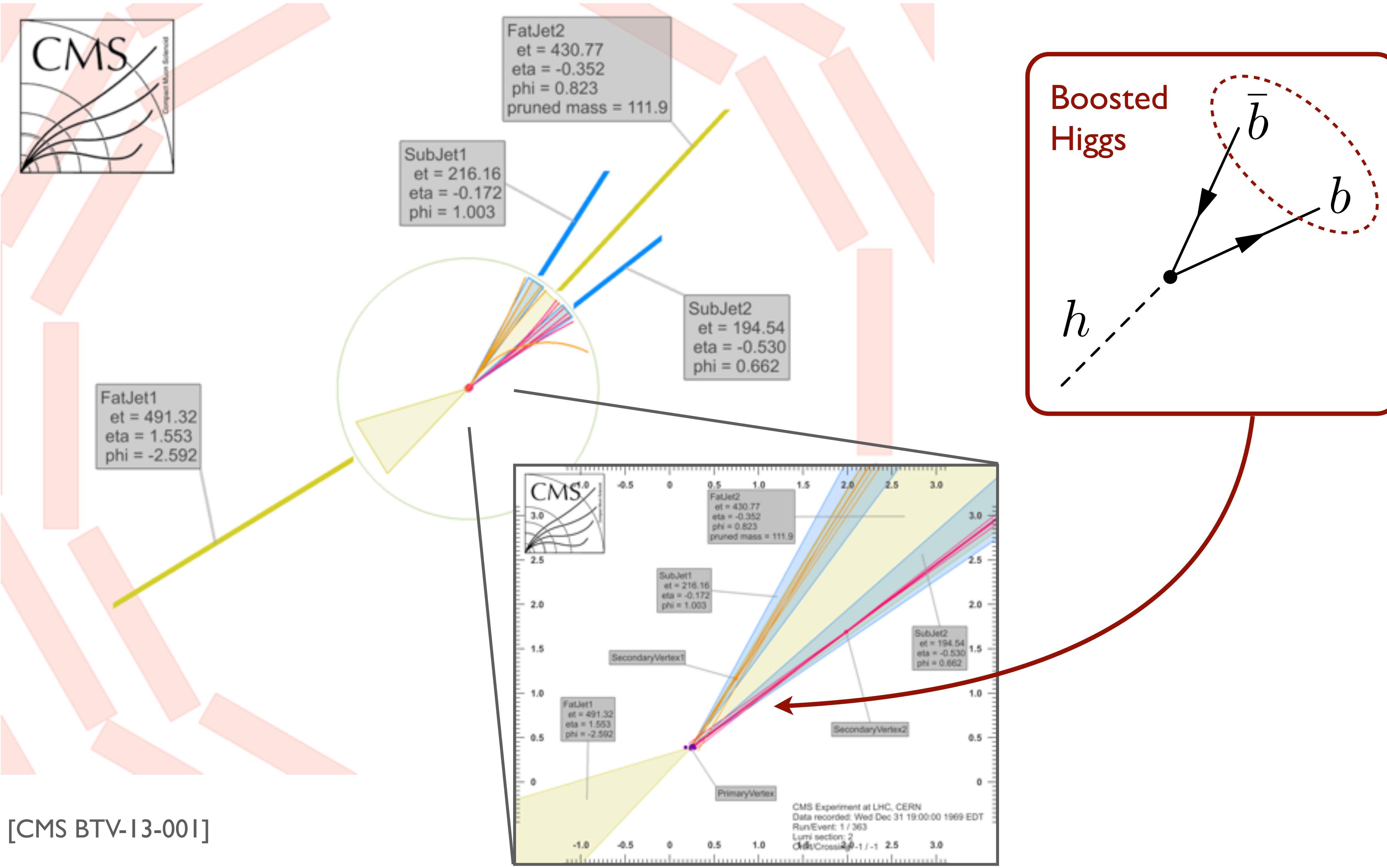


⇒



[Krohn, JDT, Wang, 2009]

Finer Segmentation: Cleverness is Inevitable



[CMS BTV-13-001]

The Case for Jet Substructure

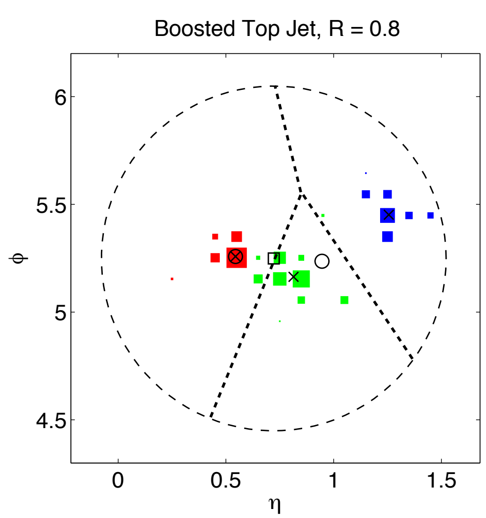
Maximize **discovery** potential of LHC

Creative analysis strategies for hadronic final states

Enhance **understanding** of QCD

New analytic results in (non)perturbative field theory

Why Jet Substructure?

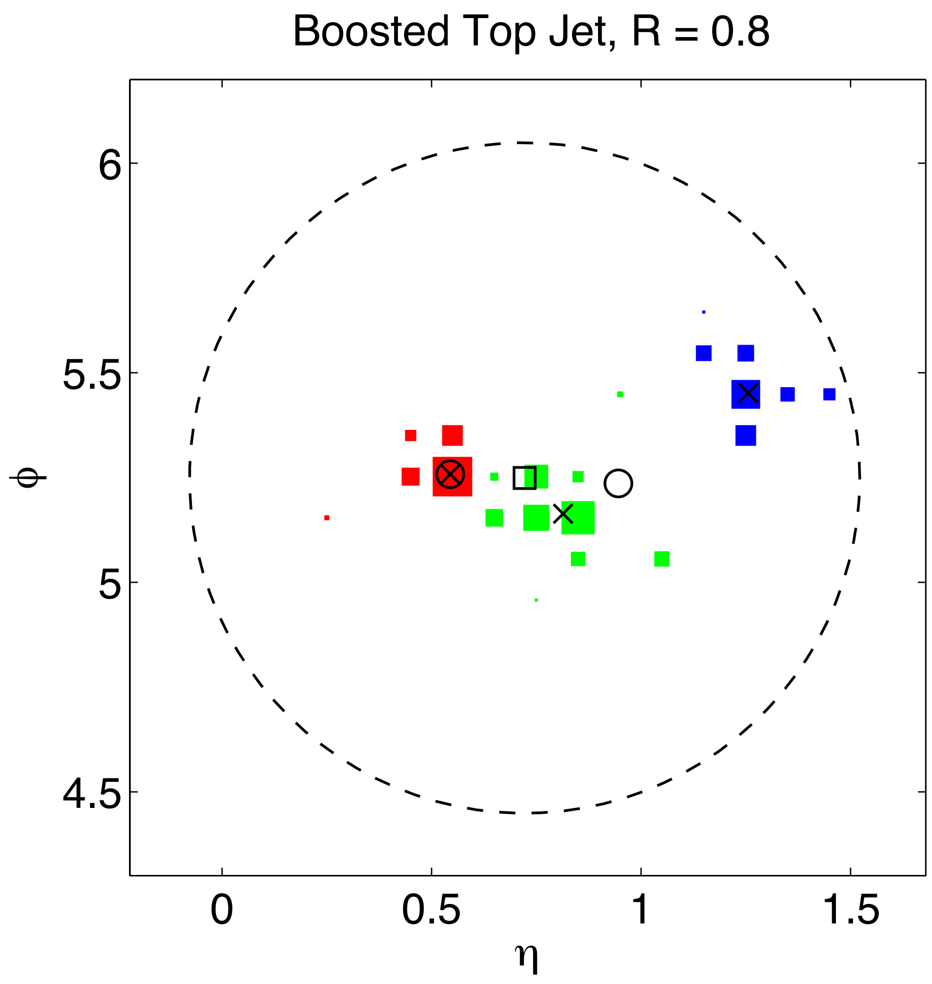


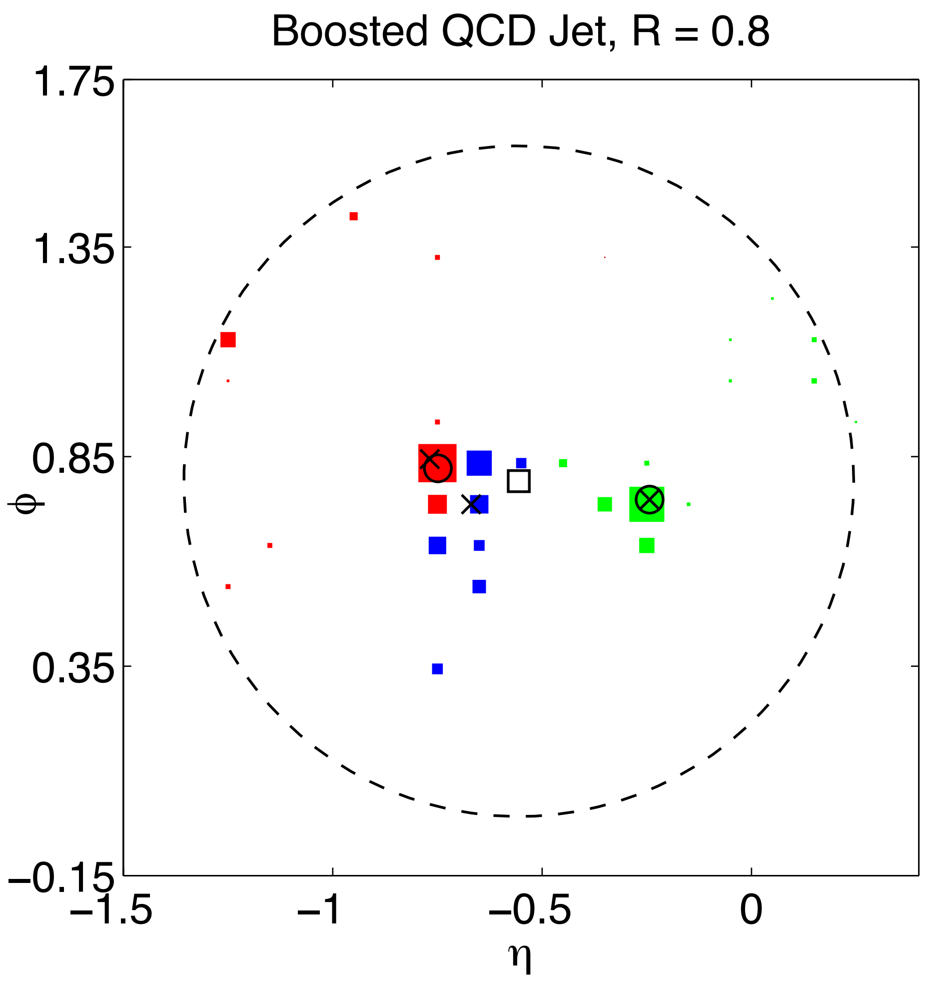
Boosted Objects with N-subjettiness

$$\frac{\text{IRC Safe}}{\text{IRC Safe}} = \text{Sudakov Safe}$$

Introducing “Sudakov Safety”

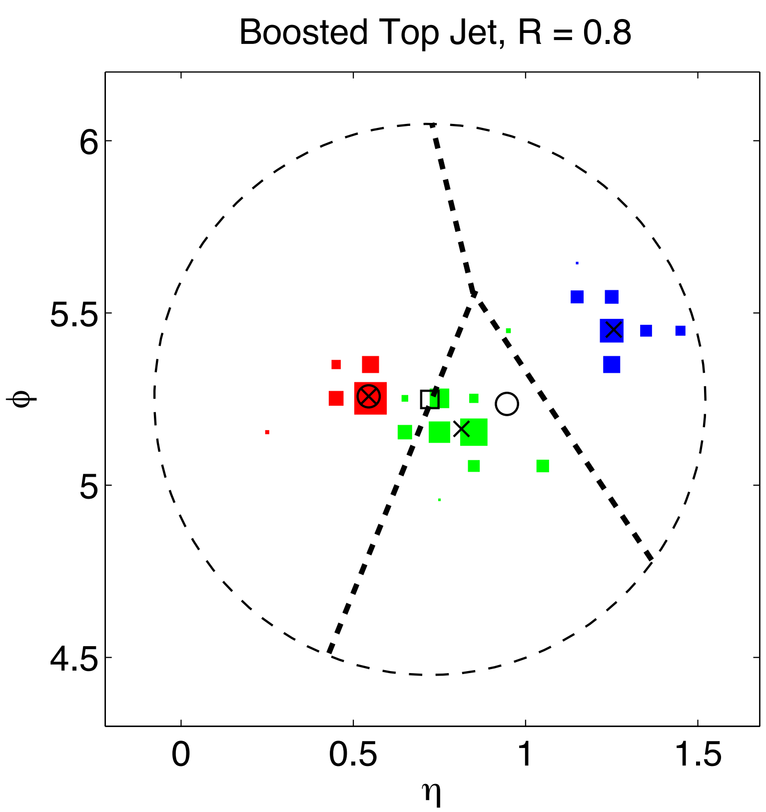
Jet Substructure by Eye





Introducing N-subjettiness

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left\{\Delta R_{k,1}, \Delta R_{k,2}, \ldots, \Delta R_{k,N}\right\}^{\beta}$$



Subtlety: which axes?

subjets: $\leq$ N > N

τ_N: 0 1

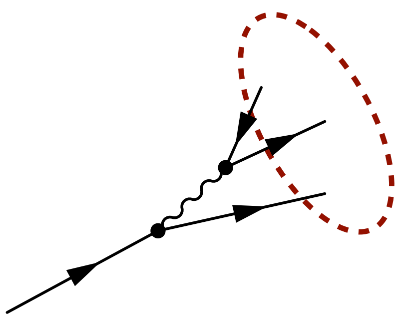
τ_3/τ_2: Tops

τ_2/τ_1: W/Z/H

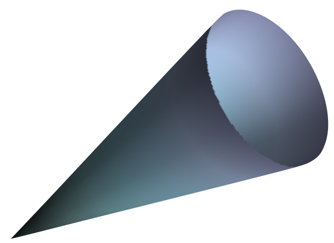
N-jettiness: [Stewart, Tackmann, Waalewijn, 2010]
N-subjettiness: [JDT, Van Tilburg, 2010, 2011]
See also: [Farhi, 1977; Brandt, Dahmen, 1979; Kim, 2010]

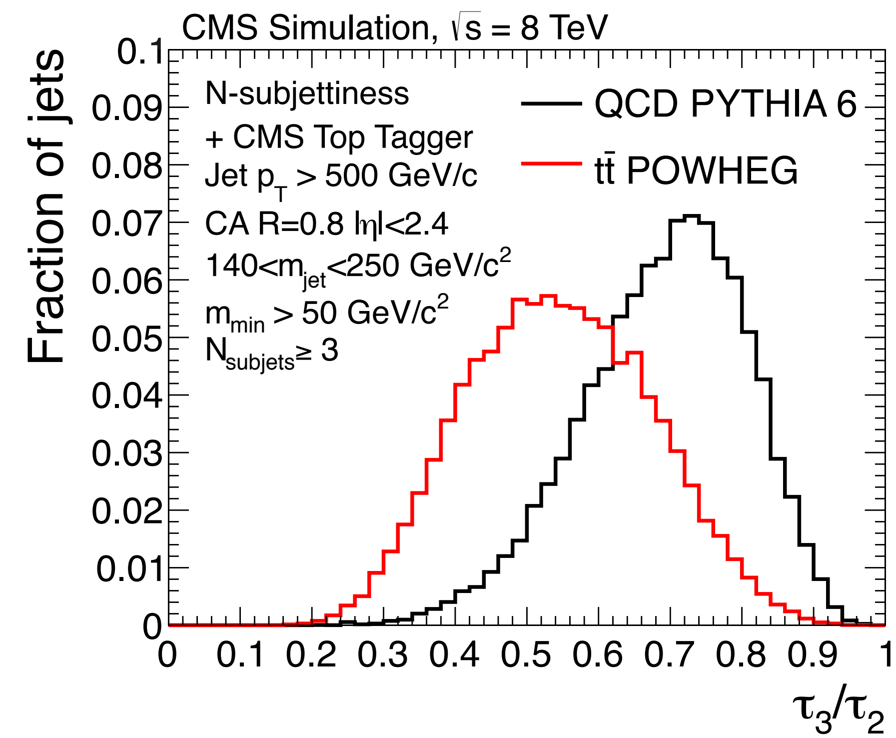
3 Prong Substructure

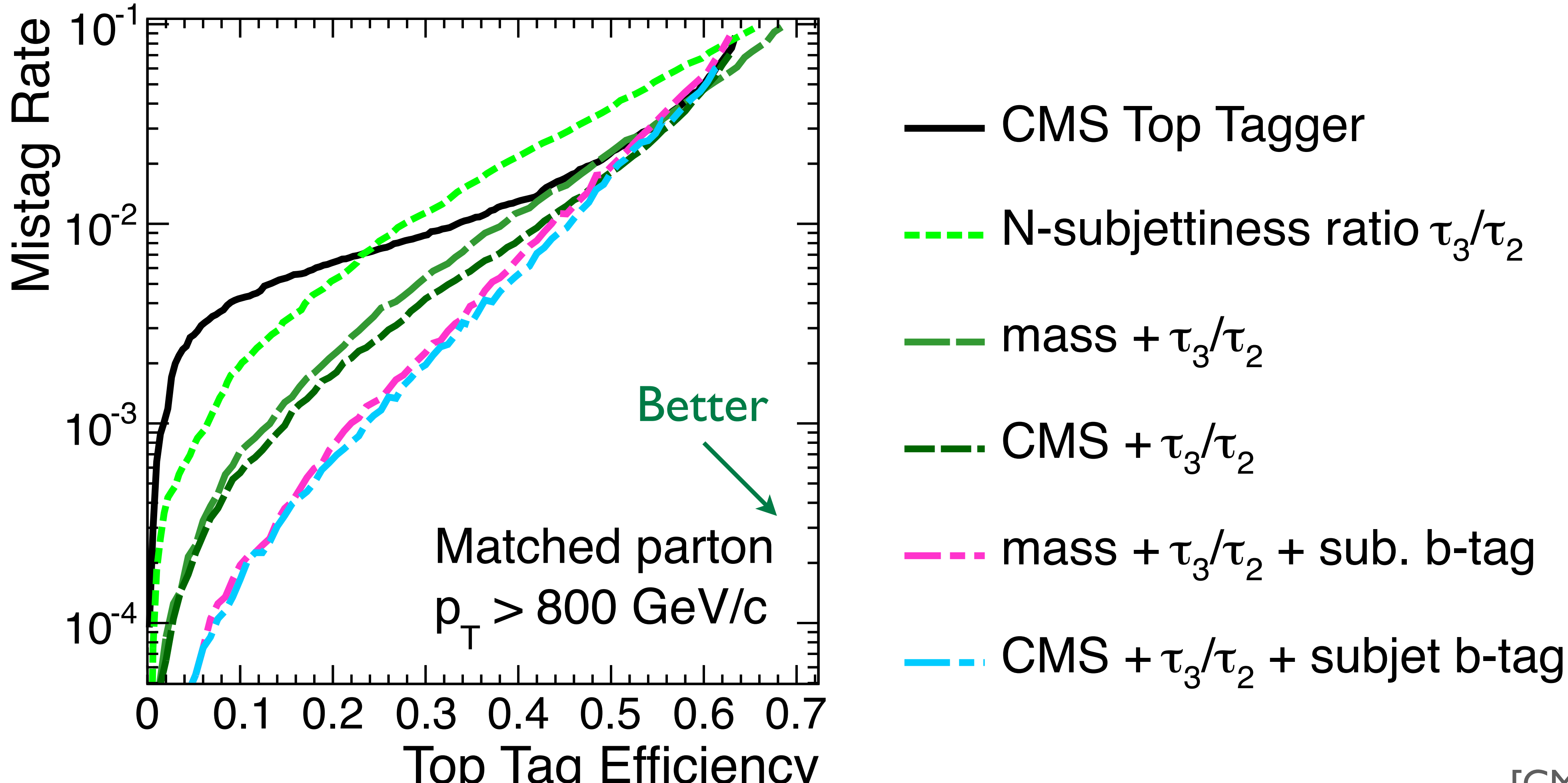
τ_3/τ_2 for Boosted Tops



vs.





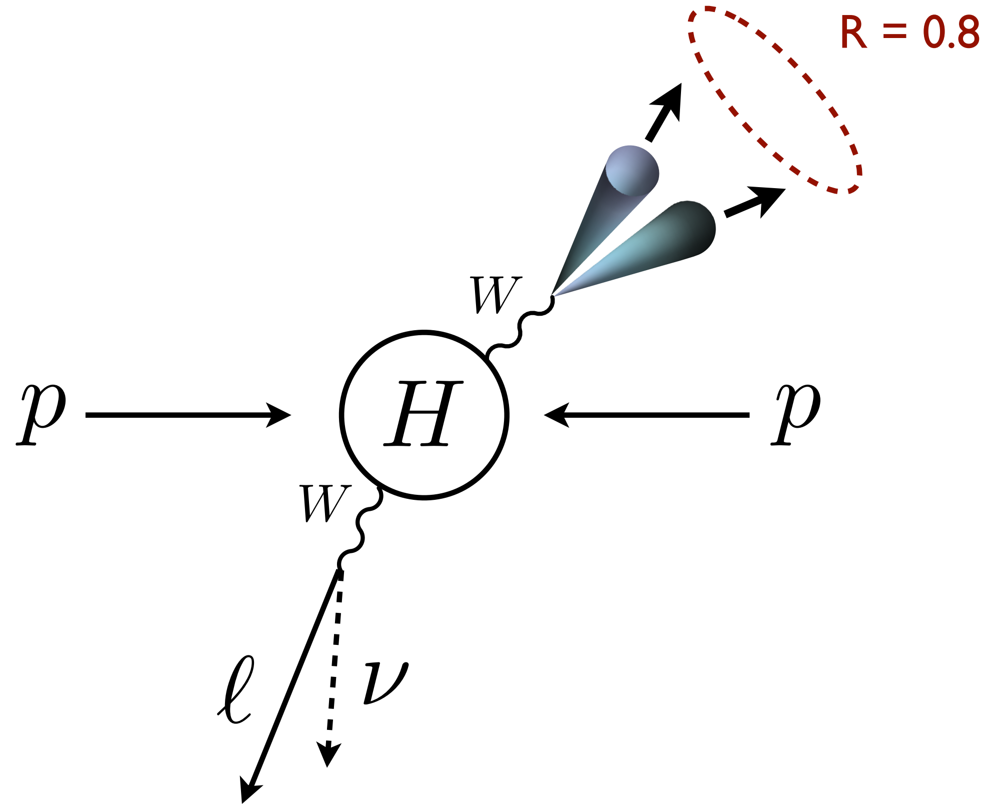


[CMS JME-13-007]

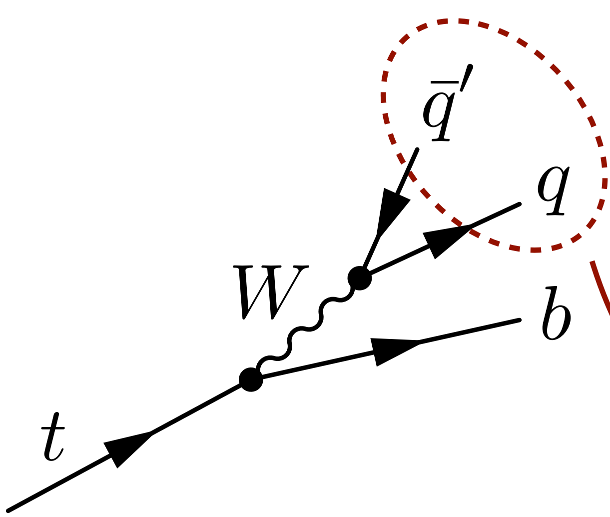
2 Prong Substructure

τ_2/τ_1 for High Mass Higgs

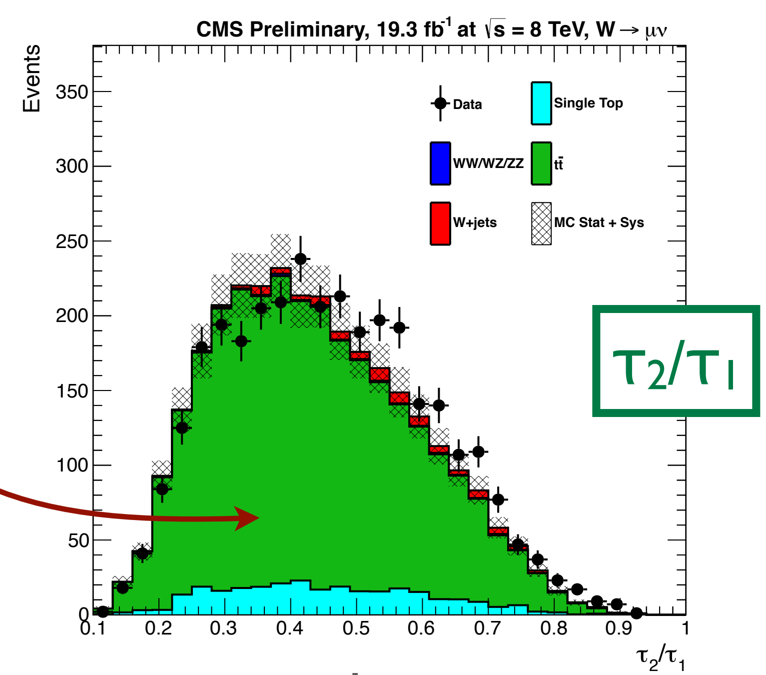
$$H \to \begin{cases} W \to q\bar{q}' \quad \text{(boosted)} \\ W \to \ell\nu \end{cases}$$

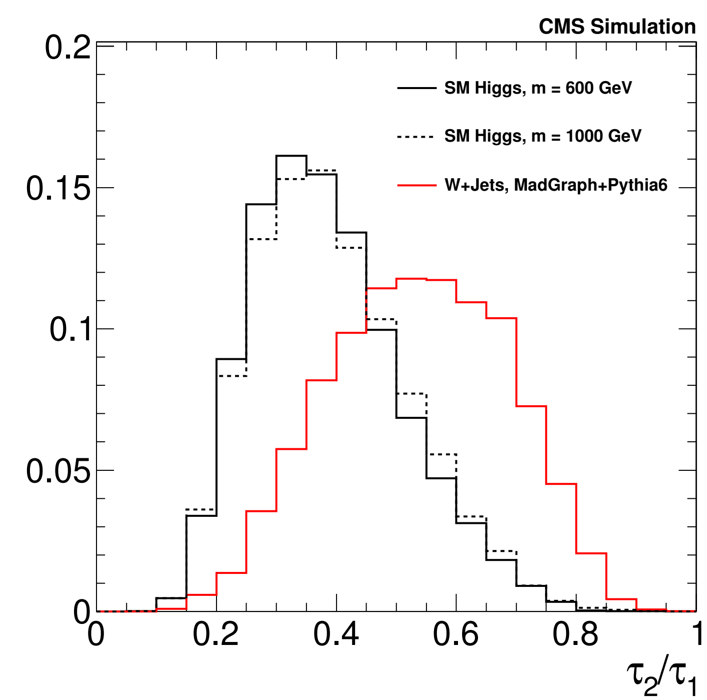


[CMS HIG-13-008]



Validated on tops



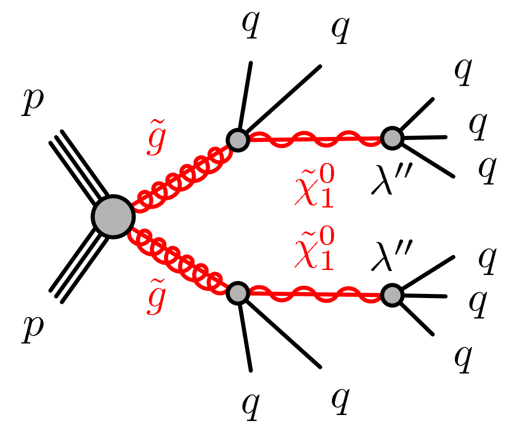


W-like ⟷ QCD-like

Quark/Gluon Discrimination

The White Whale of Jet Substructure

[see Gallicchio, Schwartz, 2011]



[ATLAS CONF-2013-091]

Often:

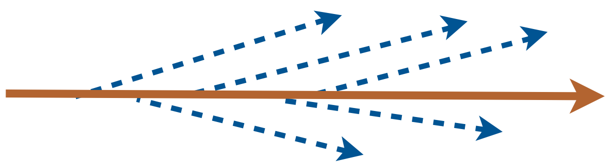
BSM Signals ⇒ Quarks

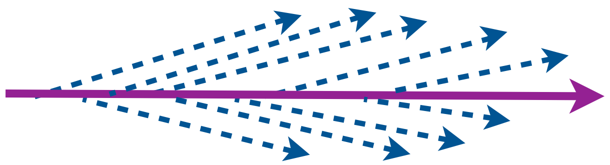
SM Backgrounds ⇒ Gluons

Quark Jet

Gluon Jet

Jets, Simplified:





$C_F = 4/3$

$C_A = 3$

Casimir Scaling:

Quark Efficiency = 50%

Gluon Mistag = $(50\%)^{9/4}$ = 21%

1 Prong Substructure

τ_1 for Quark/Gluon Discrimination?

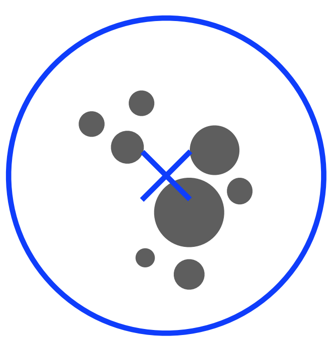
a.k.a. Angularities

$$e_\beta \simeq \sum_{i \in \text{jet}} z_i \, (\theta_i)^\beta$$

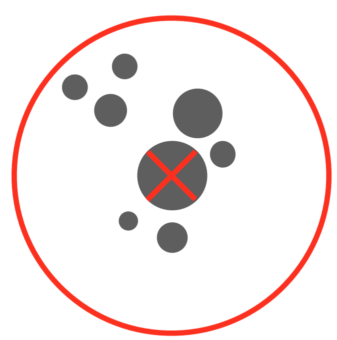
energy fraction   angle to axis

[Berger, Kucs, Sterman, 2003;
Ellis, Vermilion, Walsh, Hornig, Lee, 2010]

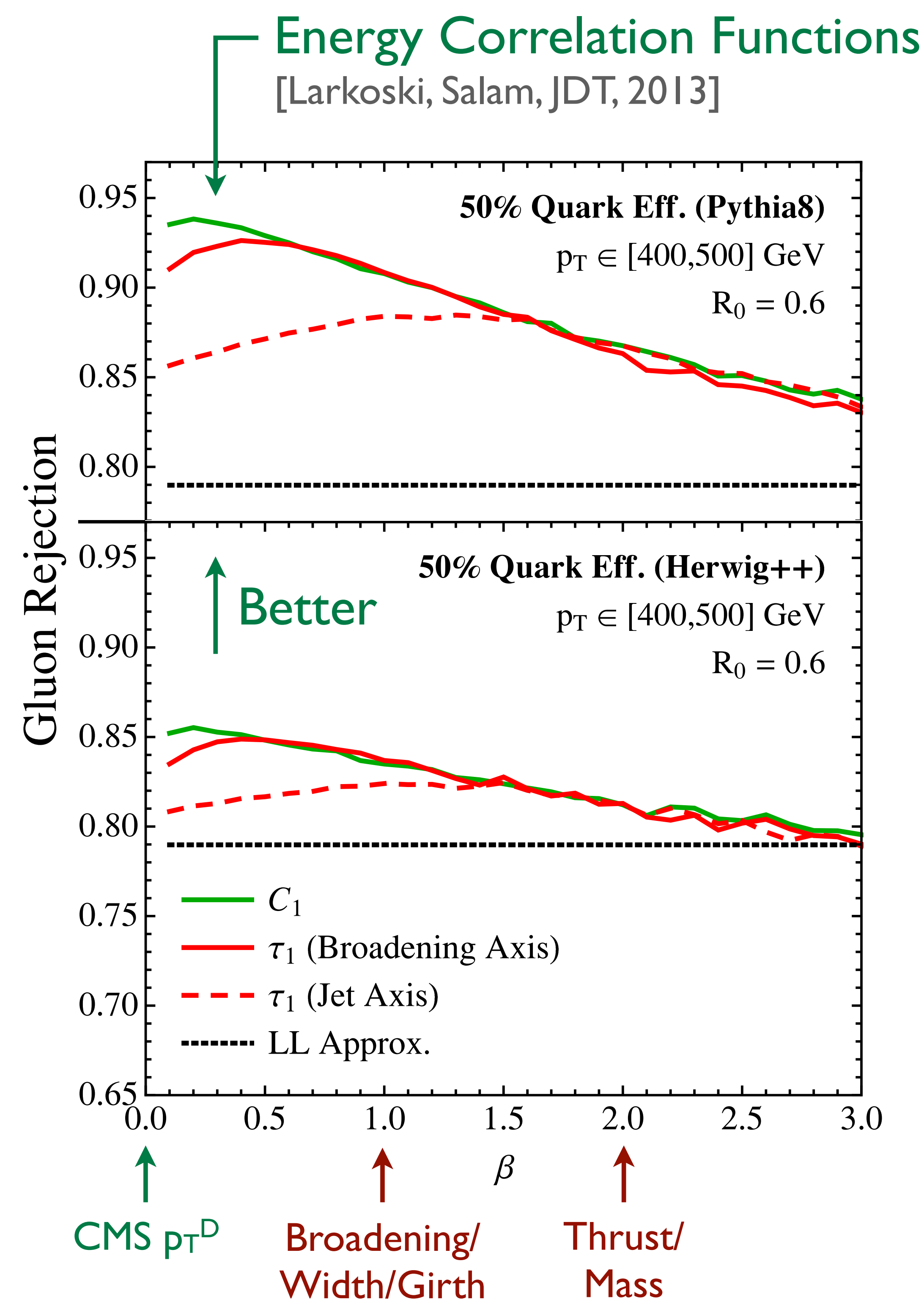
Jet Axis



Broadening Axis



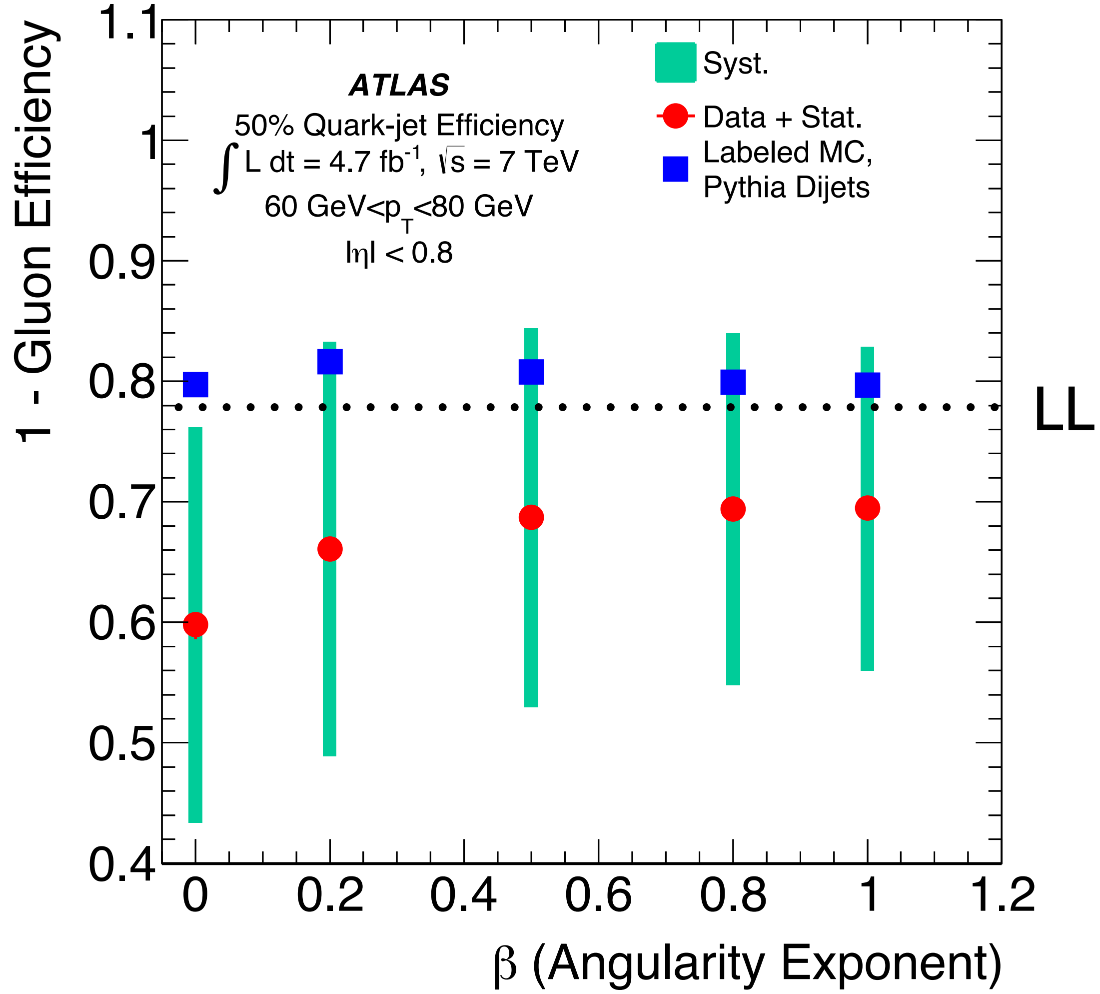
[Larkoski, Neill, JDT, 2014]

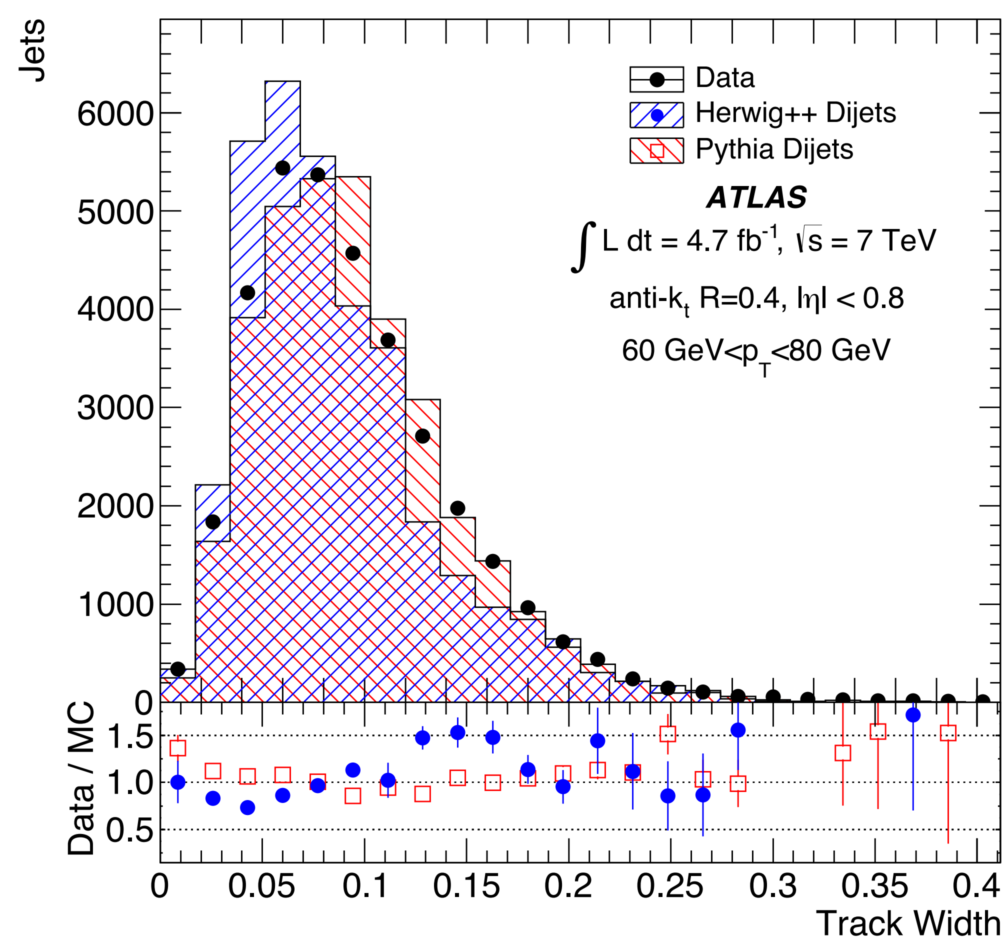


Hot Off the Press!

Quark/Gluon Discrimination at ATLAS

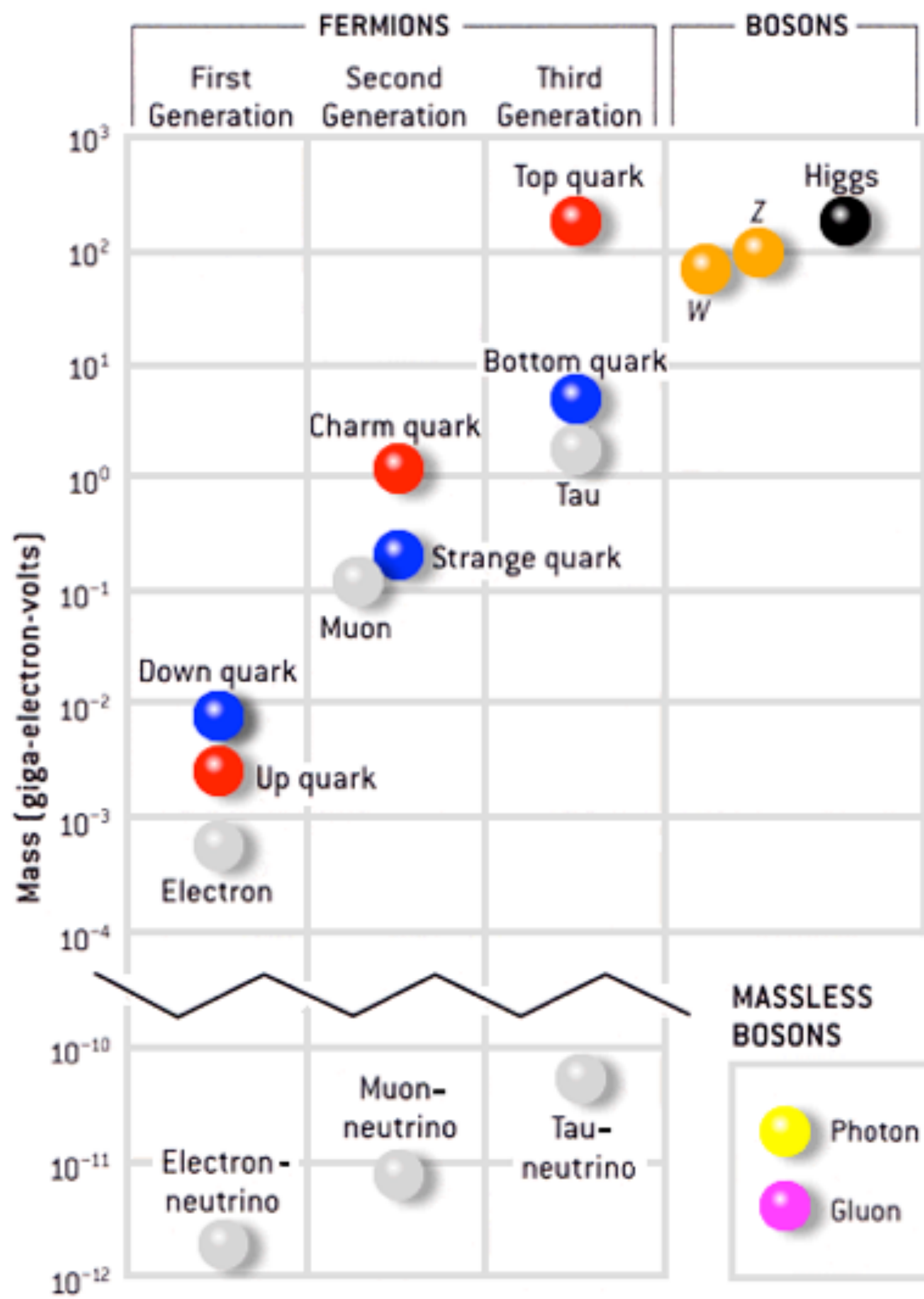
[ATLAS PERF-2013-02; 1405.6583]

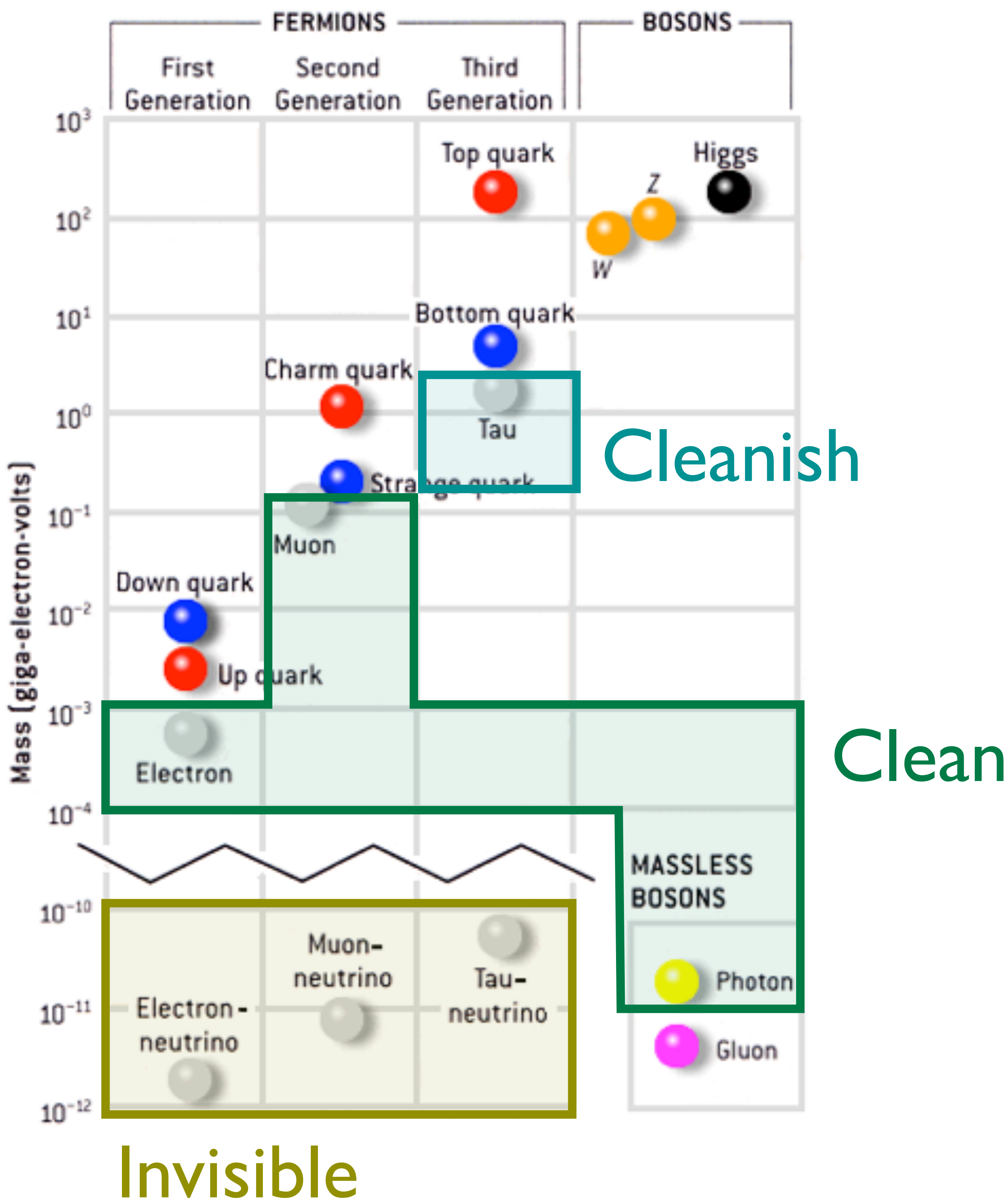




$\approx \beta=1$

Chasing the White Whale


FERMIONS
BOSONS
First Generation
Second Generation
Third Generation
Mass (giga-electron-volts)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-10}
10^{-11}
10^{-12}
Top quark
Higgs
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
MASSLESS BOSONS
Muon-neutrino
Tau-neutrino
Electron-neutrino
Photon
Gluon



FERMIONS
BOSONS
First Generation
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Mass (giga-electron-volts)
10^3
10^2
10^1
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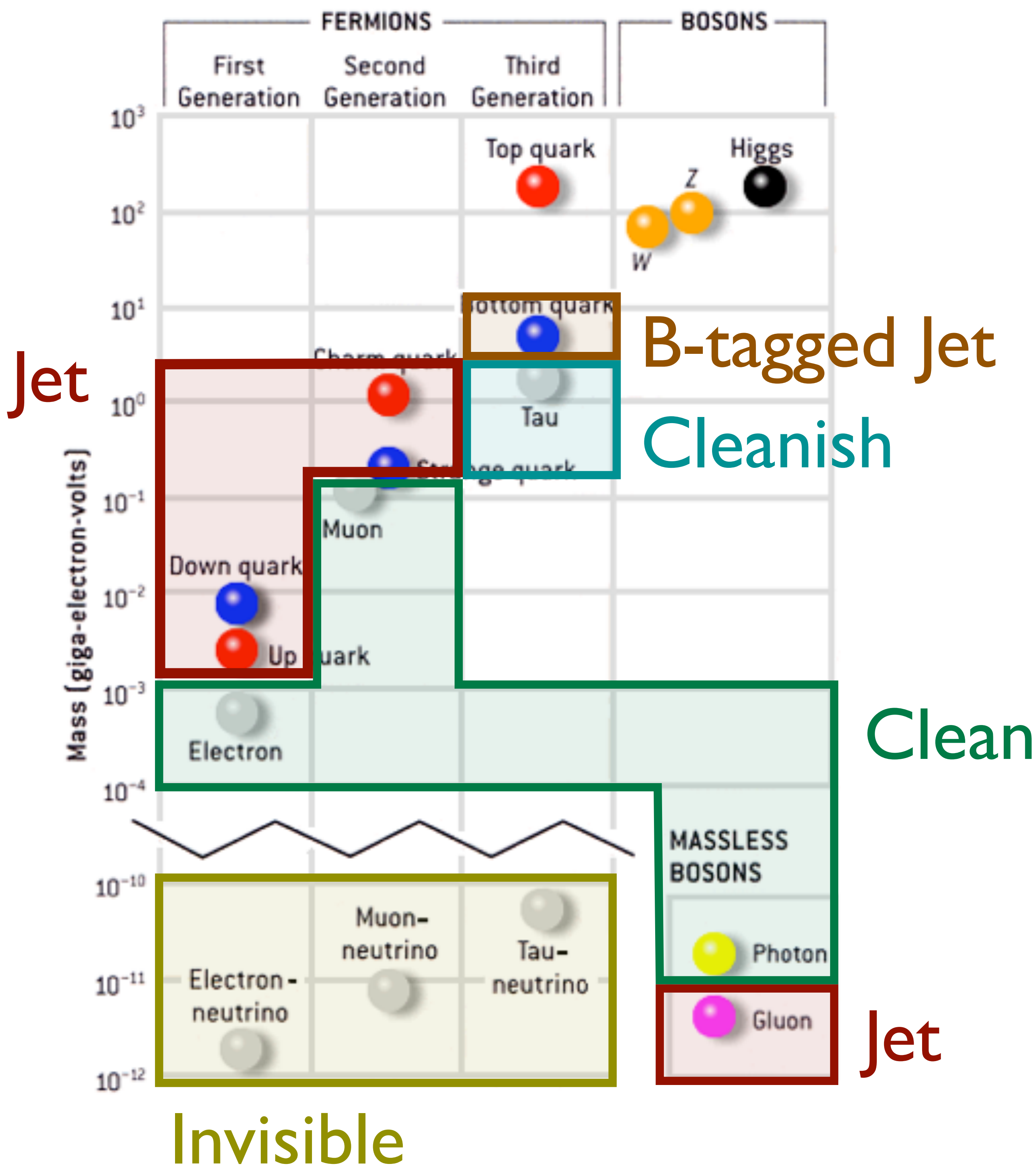
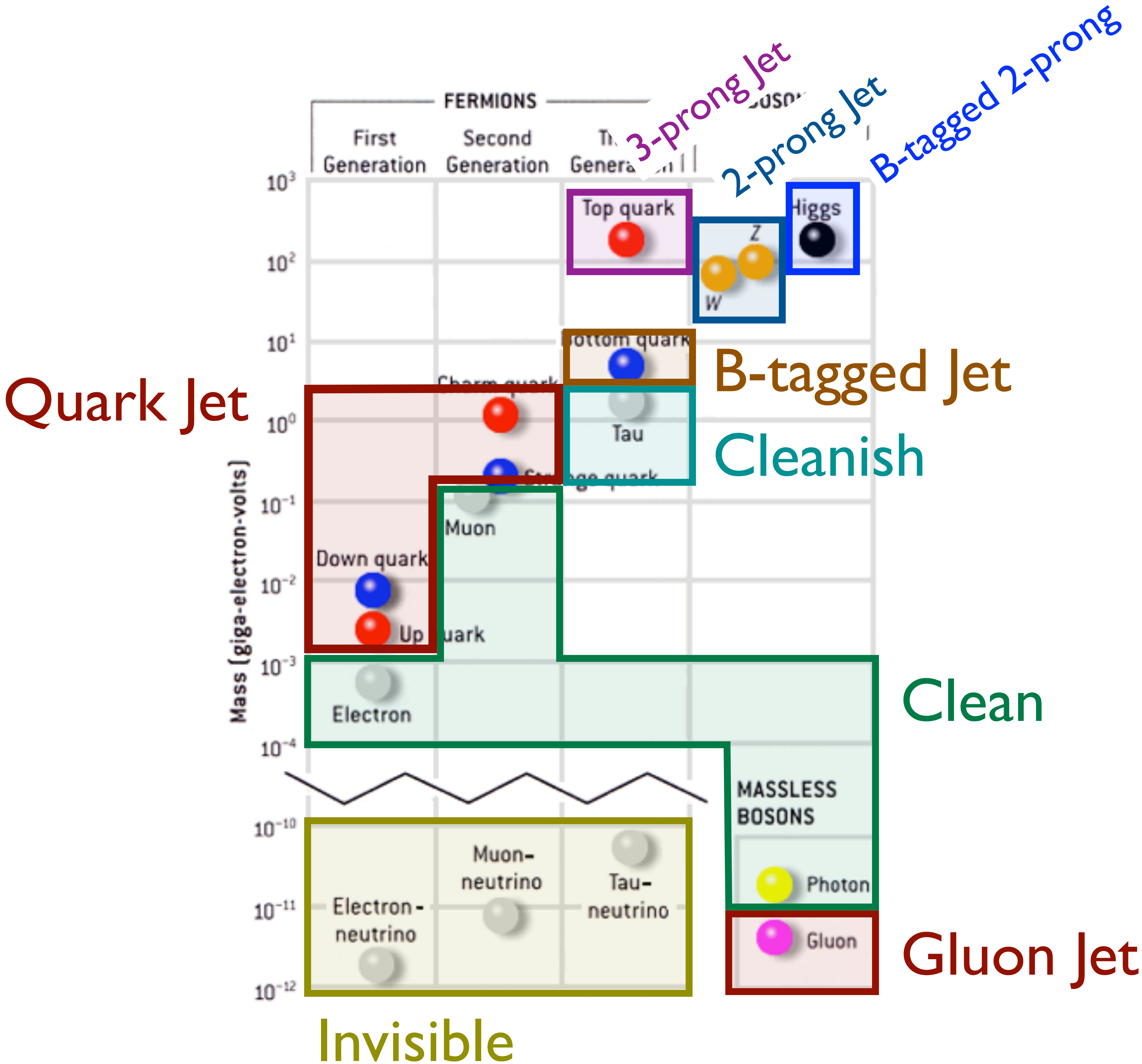
10^-1
10^-2
10^-3
10^-4
10^-10
10^-11
10^-12
Top quark
Higgs
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
MASSLESS BOSONS
Photon
Gluon
Electron-neutrino
Muon-neutrino
Tau-neutrino
Cleanish
Clean
Invisible



FERMIONS
BOSONS
First Generation
Second Generation
Third Generation
Mass (giga-electron-volts)
Top quark
Higgs
Z
W
Charm quark
Strange quark
Bottom quark
Tau
Muon
Down quark
Up quark
Electron
MASSLESS BOSONS
Photon
Gluon
Electron-neutrino
Muon-neutrino
Tau-neutrino
Jet
B-tagged Jet
Cleanish
Clean
Jet
Invisible



FERMIONS
First Generation
Second Generation
Mass (giga-electron-volts)
3-prong Jet
2-prong Jet
B-tagged 2-prong
Top quark
Z
W
Higgs
B-tagged Jet
Cleanish
Quark Jet
Tau
Muon
Down quark
Electron
Clean
MASSLESS BOSONS
Photon
Gluon
Gluon Jet
Electron-neutrino
Muon-neutrino
Tau-neutrino
Invisible

“Why does N-subjettiness work so well?”

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Maximize **discovery** potential of LHC

Creative analysis strategies for hadronic final states

Enhance **understanding** of QCD

New analytic results in (non)perturbative field theory

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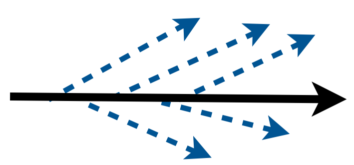
Boosted Objects
with N-subjettiness

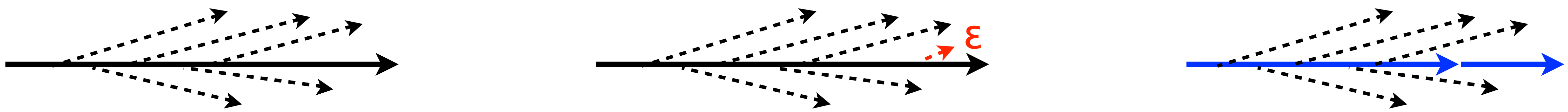


$$\frac{\text{IRC Safe}}{\text{IRC Safe}} = \text{Sudakov Safe}$$

Introducing
"Sudakov Safety"

Infrared/Collinear Safety

Original Jet | Infrared | Collinear

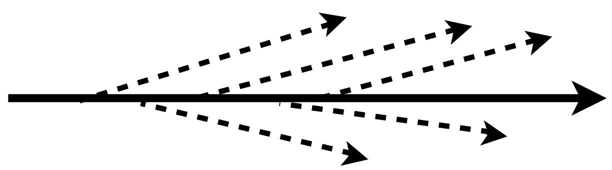


IRC Safe Observable: Insensitive to IR or C emissions

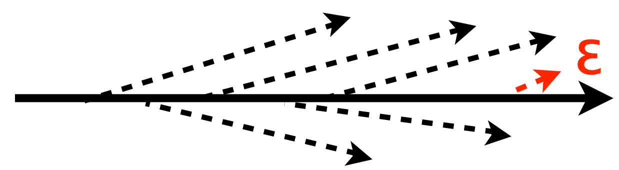
		IRC Safe	IRC Unsafe
Lore:	Calculable in pQCD?	✓	✗
	Controlled Λ_{QCD} Effects?	✓	✗

Infrared/Collinear Safety

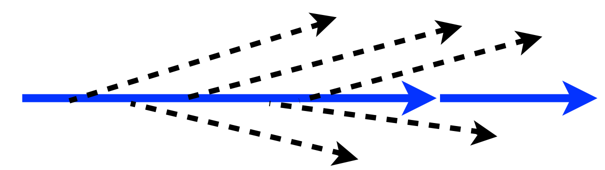
Original Jet



Infrared



Collinear



IRC Safe Observable: Insensitive to IR or C emissions

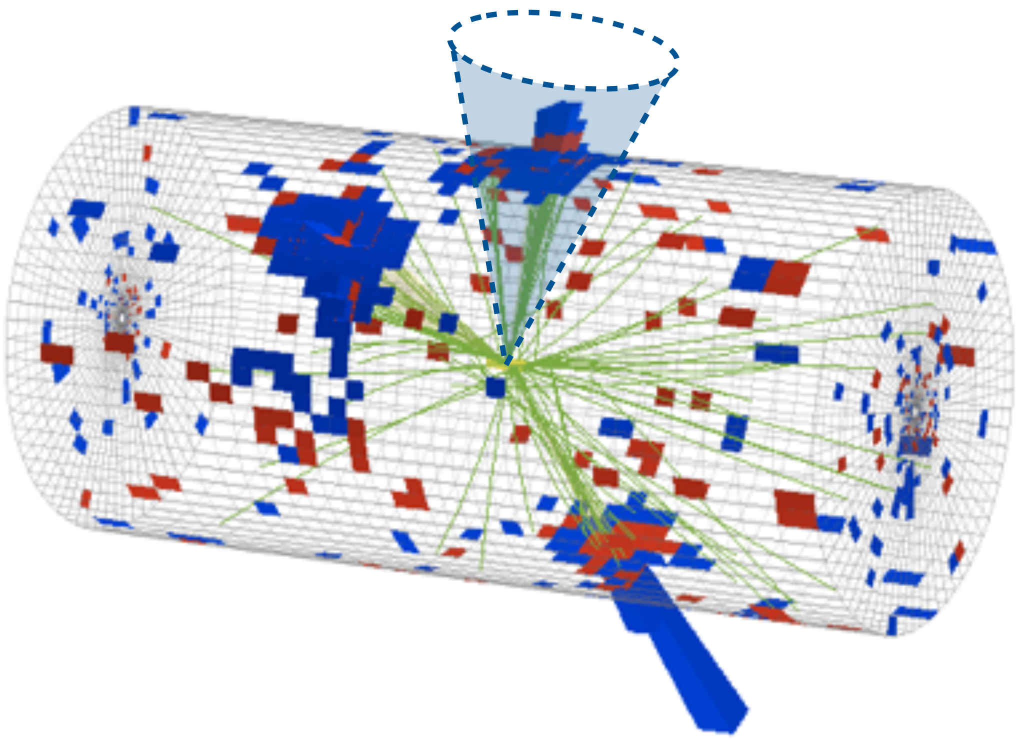
New Lore:

	IRC Safe	IRC Unsafe
Calculable in pQCD?	✓	$\boxed{✓*}$
Controlled Λ_{QCD} Effects?	✓*	✓*

Examples

Jet p_T: $$\sum_{i \in \text{jet}} p_{T,i}$$ IRC Safe

$p_T{}^D$:
[CMS HIG-11-027]
$$\sum_{i \in \text{jet}} \frac{p_{T,i}^2}{p_{T\text{jet}}^2}$$
IR Safe
C Unsafe



Multiplicity: $$\sum_{i \in \text{jet}} 1$$ IRC Unsafe

Jet Mass: $$\sum_{i,j \in \text{jet}} p_i \cdot p_j$$ IRC Safe

N-subjettiness: $$\sum_{i \in \text{jet}} p_{T,i} \min \left\{ \Delta R_{i,1}, \Delta R_{i,2}, \dots, \Delta R_{i,N} \right\}^\beta$$ IRC Safe

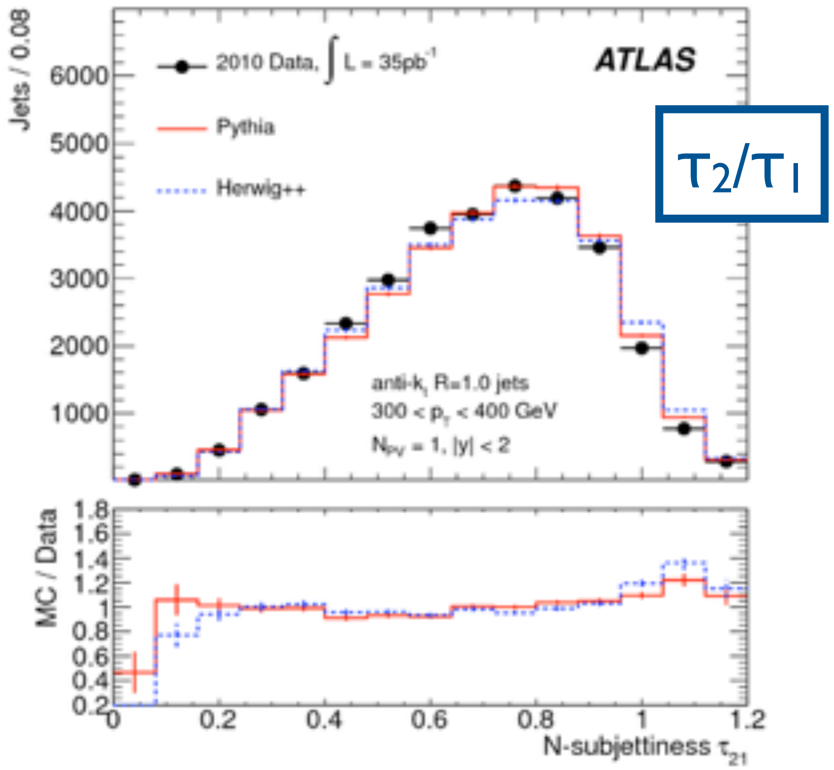
Ratio Observables?

IRC Safe $\Rightarrow$ Useful Ratio

$$\tau_N \Rightarrow \frac{\tau_N}{\tau_{N-1}}$$

Ubiquitous in jet substructure

[ATLAS EP-2012-031]



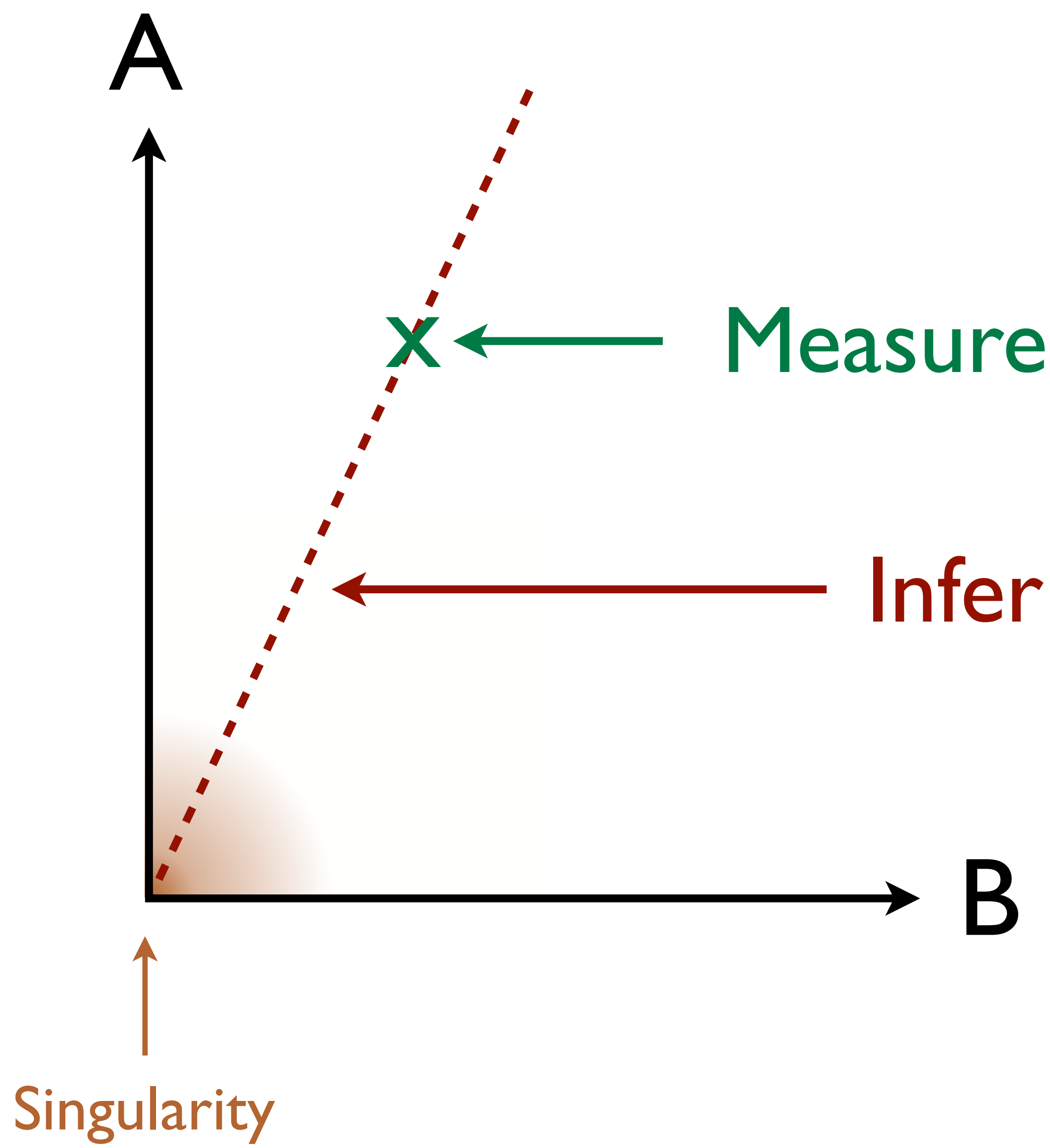
W-like ⟷ QCD-like

$$\frac{\text{IRC Safe Numerator}}{\text{IRC Safe Denominator}} = \text{IRC Unsafe Ratio}$$

[Soyez, Salam, Kim, Dutta, Cacciari, 2012]

WHAT?!

Safe/Safe = Unsafe?!



Measure: A (IRC Safe)
B (IRC Safe)

Infer: R = A/B (IRC Unsafe)

Simple Example

Ratios of Angularities

$$e_\beta \simeq \sum_{i \in \text{jet}} z_i \, (\theta_i)^\beta \qquad\qquad r = \frac{e_\alpha}{e_\beta}$$

energy fraction

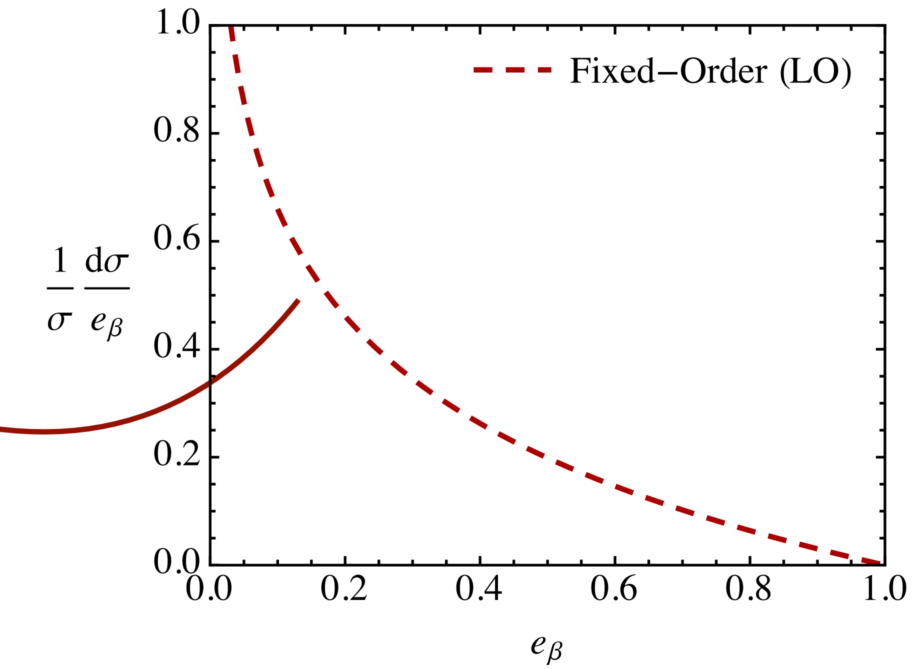
angle to axis

IR Limit

z → 0

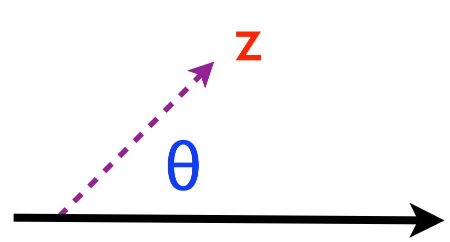
C Limit

θ → 0



Single emission:

Order α_s (LO)



$$e_\beta = z\,\theta^\beta \qquad \text{IRC Safe}$$

$$r = \theta^{\alpha-\beta} \qquad \text{IRC Unsafe}$$

Simple Example

Ratios of Angularities

$$e_\beta \simeq \sum_{i \in \text{jet}} z_i \, (\theta_i)^\beta \qquad r = \frac{e_\alpha}{e_\beta}$$

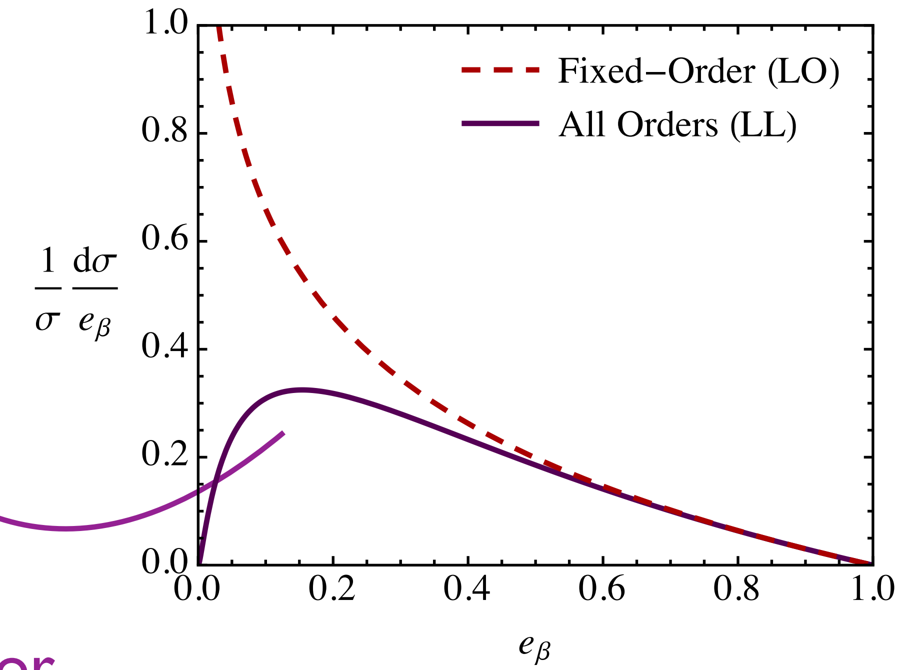
energy fraction

angle to axis

IR Limit
z → 0

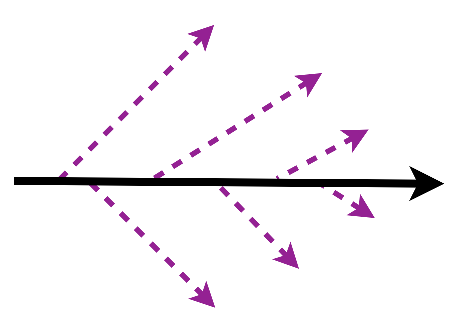
C Limit
θ → 0

Sudakov
Form Factor



Many emissions:

All orders in α_s (LL)



$$e_\beta = z\,\theta^\beta$$ IRC Safe

$$r = \cancel{\theta^{\alpha-\beta}}$$ "Sudakov Safe"

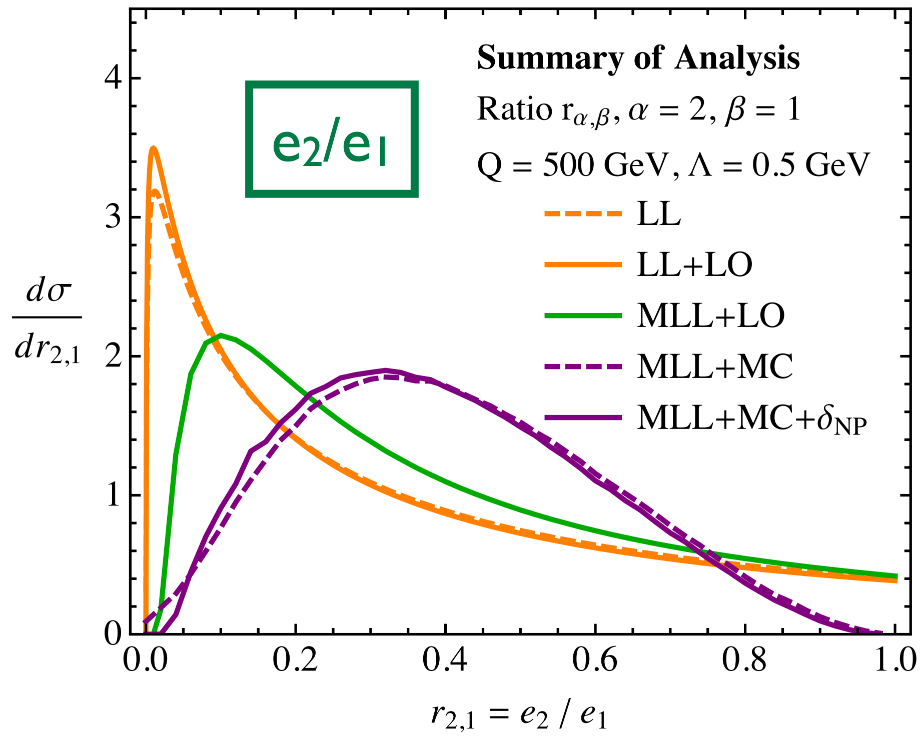
[Larkoski, JDT, 2013]

After the Dust Settles

Ratio Cross Section:

$$\frac{d\sigma^{\mathrm{LL}}}{dr} = \frac{\sqrt{\alpha_s C_F \beta}}{\alpha-\beta}\frac{1}{r}\left(1-2\frac{\alpha_s}{\pi}\frac{C_F}{\alpha-\beta}\log^2 r\right)\left(\mathrm{erf}\left[\frac{\sqrt{\alpha_s C_F \beta}}{\sqrt{\pi}(\alpha-\beta)}\log r\right]+1\right)e^{-\frac{\alpha_s}{\pi}\frac{C_F}{\alpha-\beta}\log^2 r}$$
$$-2\frac{\alpha_s}{\pi}\frac{C_F}{\alpha-\beta}\frac{\log r}{r}e^{-\frac{\alpha_s}{\pi}C_F\frac{\alpha}{(\alpha-\beta)^2}\log^2 r}$$

Systematic Improvements:



[Larkoski, JDT, 2013]

NLL: [Larkoski, Moult, Neill, 2014]

After the Dust Settles

Ratio Cross Section:

$$
\begin{aligned}
\frac{d\sigma^{\mathrm{LL}}}{dr} = & \frac{\sqrt{\alpha_s C_F \beta}}{\alpha-\beta}\frac{1}{r}\left(1-2\frac{\alpha_s}{\pi}\frac{C_F}{\alpha-\beta}\log^2 r\right)\left(\mathrm{erf}\left[\frac{\sqrt{\alpha_s C_F \beta}}{\sqrt{\pi}(\alpha-\beta)}\log r\right]+1\right)e^{-\frac{\alpha_s}{\pi}\frac{C_F}{\alpha-\beta}\log^2 r} \\
& -2\frac{\alpha_s}{\pi}\frac{C_F}{\alpha-\beta}\frac{\log r}{r}e^{-\frac{\alpha_s}{\pi}C_F\frac{\alpha}{(\alpha-\beta)^2}\log^2 r}
\end{aligned}
$$

Expand in small α_s:

$$
\frac{d\sigma^{\mathrm{LL}}}{dr} = \sqrt{\alpha_s}\frac{\sqrt{C_F \beta}}{\alpha-\beta}\frac{1}{r} + \mathcal{O}(\alpha_s)
$$

No Taylor expansion

Finite cross section

Unsafe... ...but Calculable

The Case for Jet Substructure

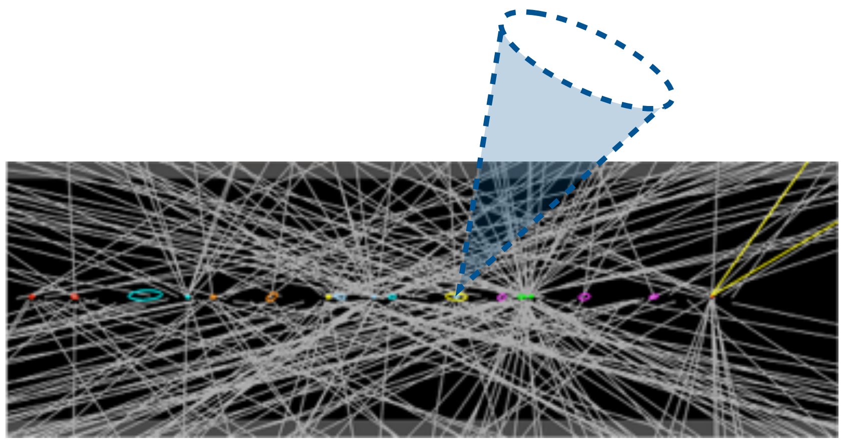
Maximize **discovery** potential of LHC

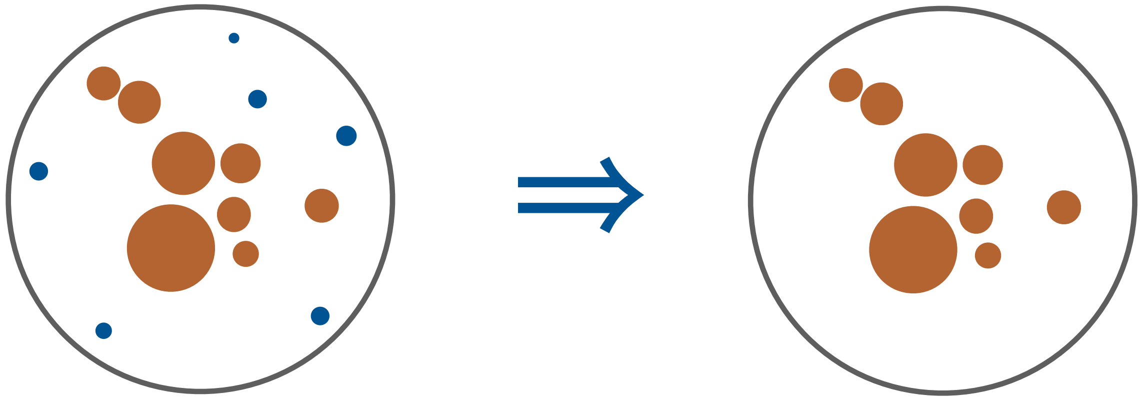
Creative analysis strategies for hadronic final states

Enhance **understanding** of QCD

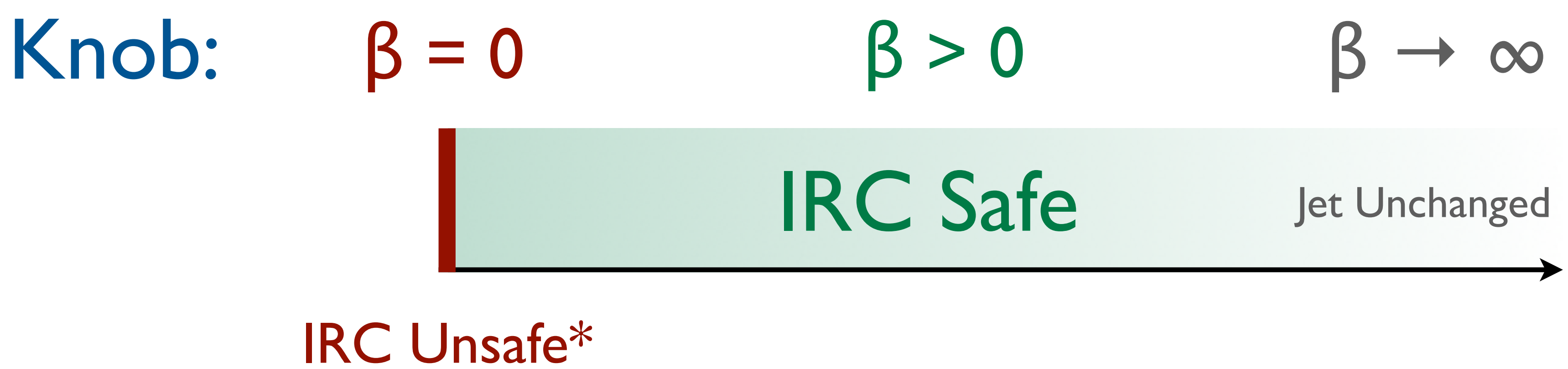
New analytic results in (non)perturbative field theory

Soft Drop





[Larkoski, Marzani, Soyez, JDT, 2014]

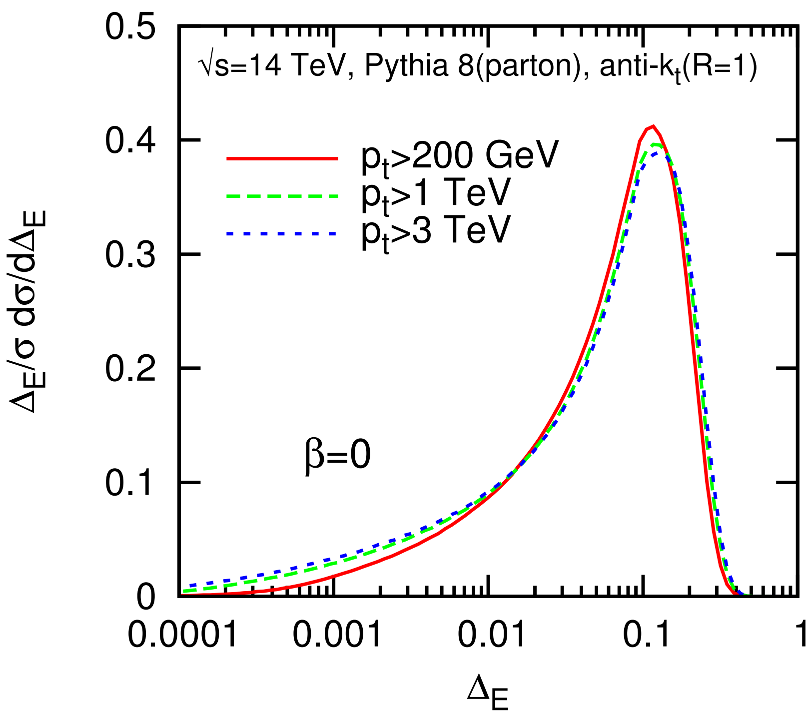


MDT: [Butterworth, Davison, Rubin, Salam, 2008]
mMDT: [Dasgupta, Fregoso, Marzani, Salam, 2013]

Energy Loss from Soft Drop

$$\left.\frac{d\sigma}{d\log\Delta_E}\right|_{\beta=0} \propto \frac{1}{\log^2\Delta_E}$$

no α_s at
fixed coupling!

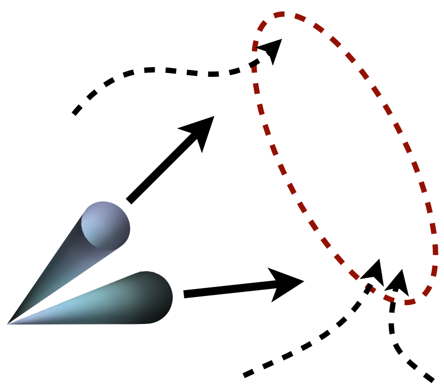


A standard candle for jets?

≈ Independent of α_s, jet p_T, jet radius

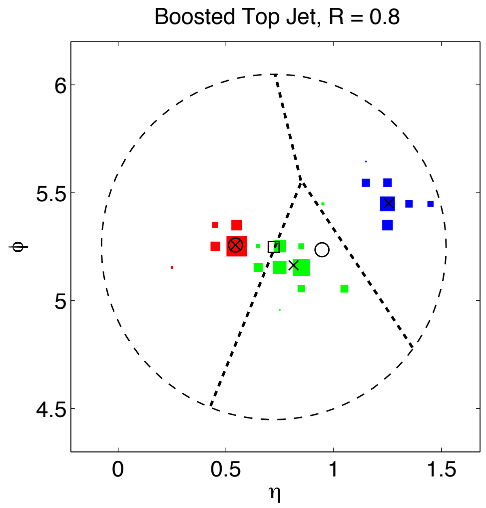
≈ Independent of quark vs. gluon

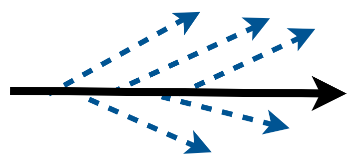
Summary



Why Jet Substructure?

Exceptional LHC performance + Extreme kinematics + Jet contamination + (B)SM physics





$$\frac{\text{IRC Safe}}{\text{IRC Safe}} = \text{Sudakov Safe}$$

Boosted Objects with N-subjettiness

Powerful, intuitive measure of prong-like structure

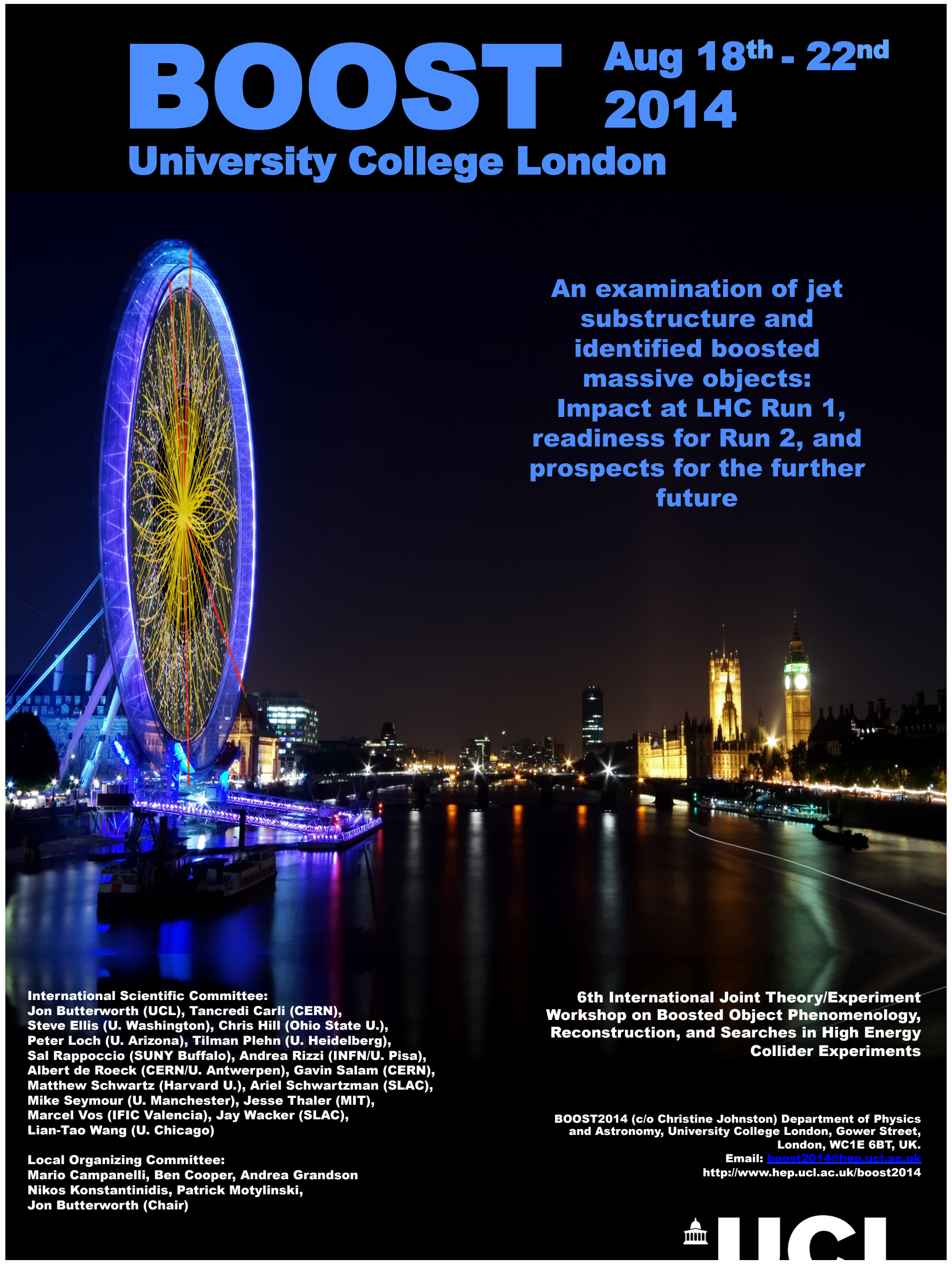
Introducing "Sudakov Safety"

Need all orders in α_s; new insights into QFT?

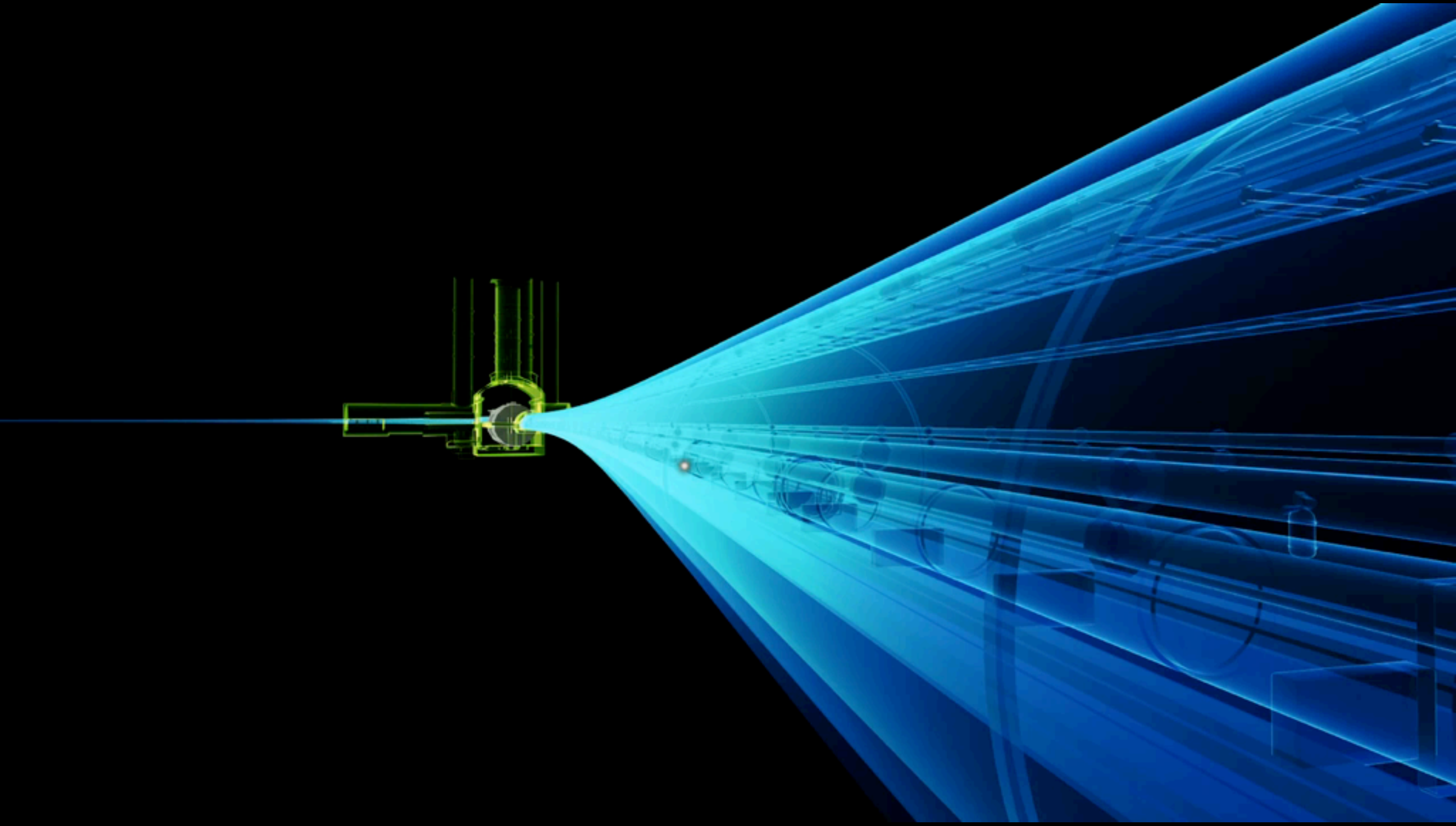
Want to Learn More?

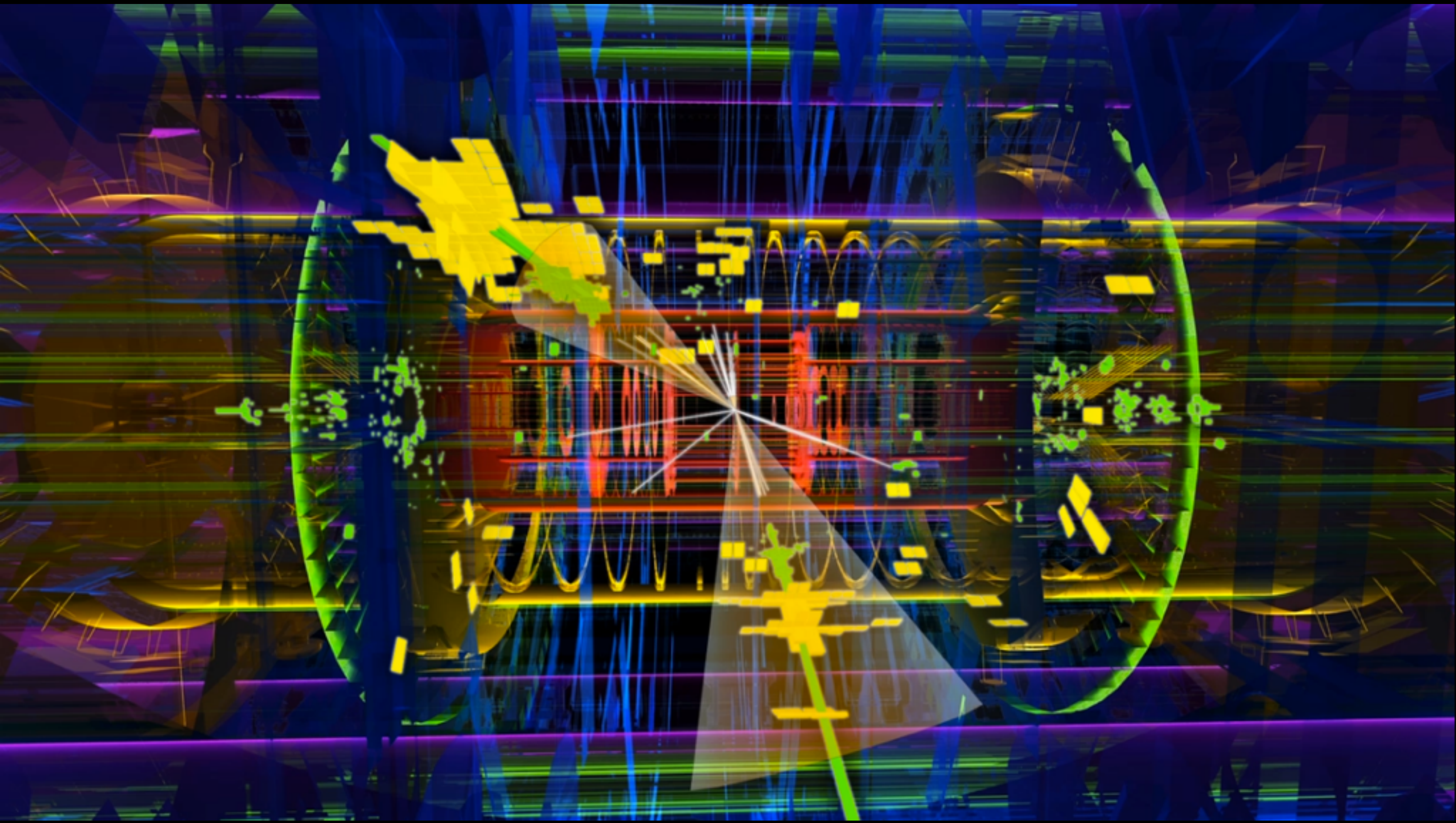
Theorist of the Month

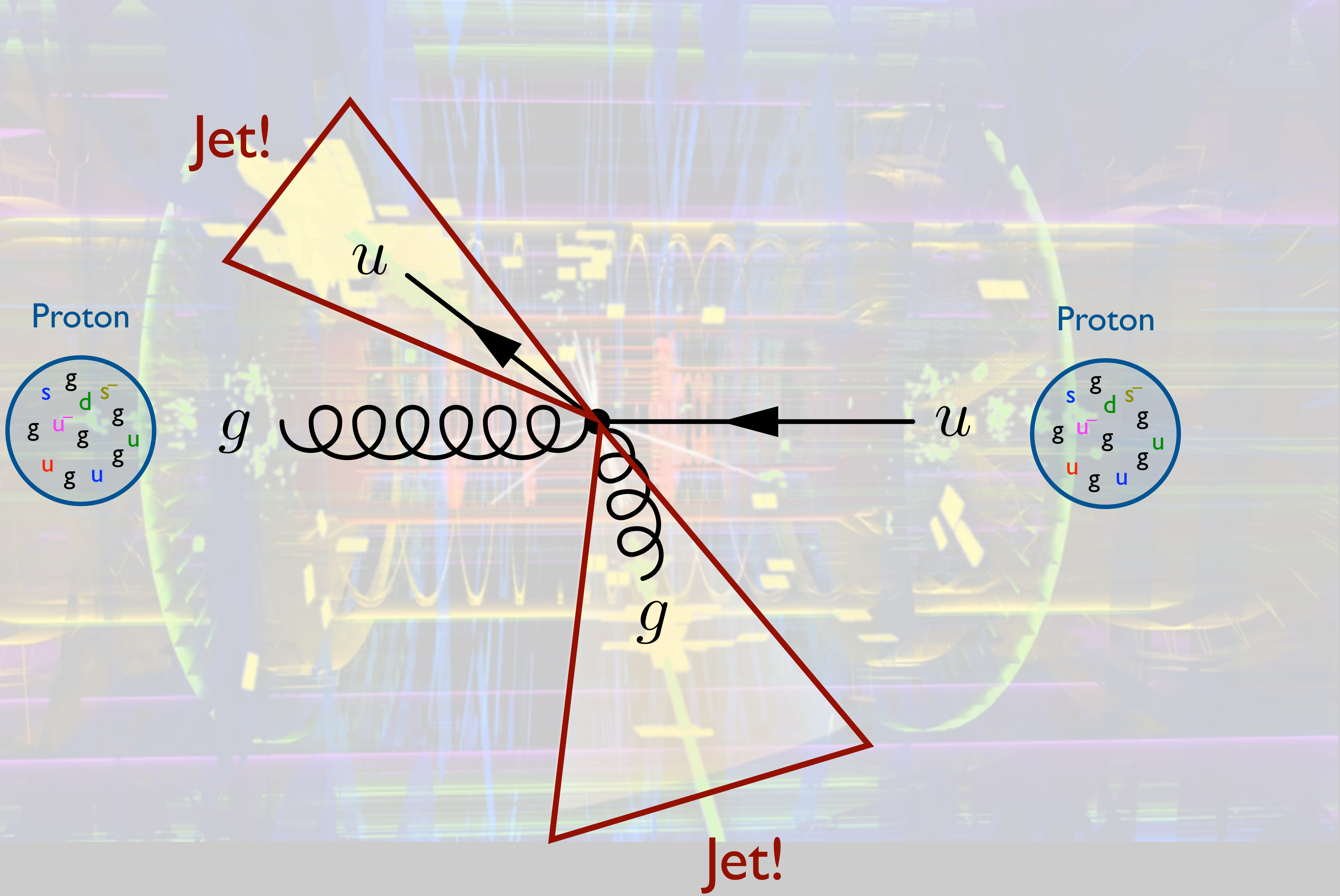
N-subjettiness
Energy Correlation Functions
Jets Without Jets
Jet Trimming
Soft Drop
Sudakov Safety
Track Functions
Power Corrections
Recoil-Free Observables
Broadening Axes
Winner-Take-All Scheme
...



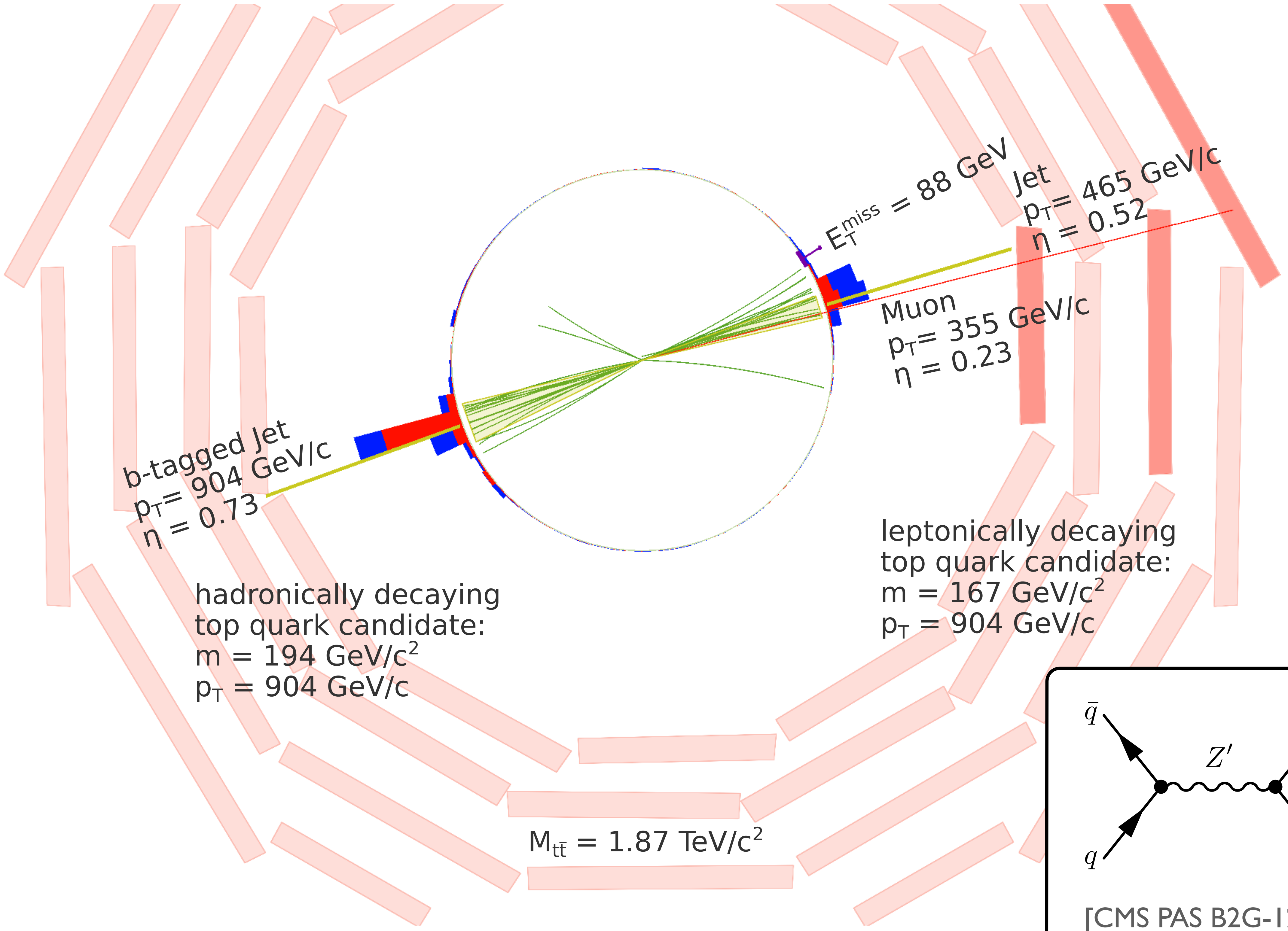
Backup Slides





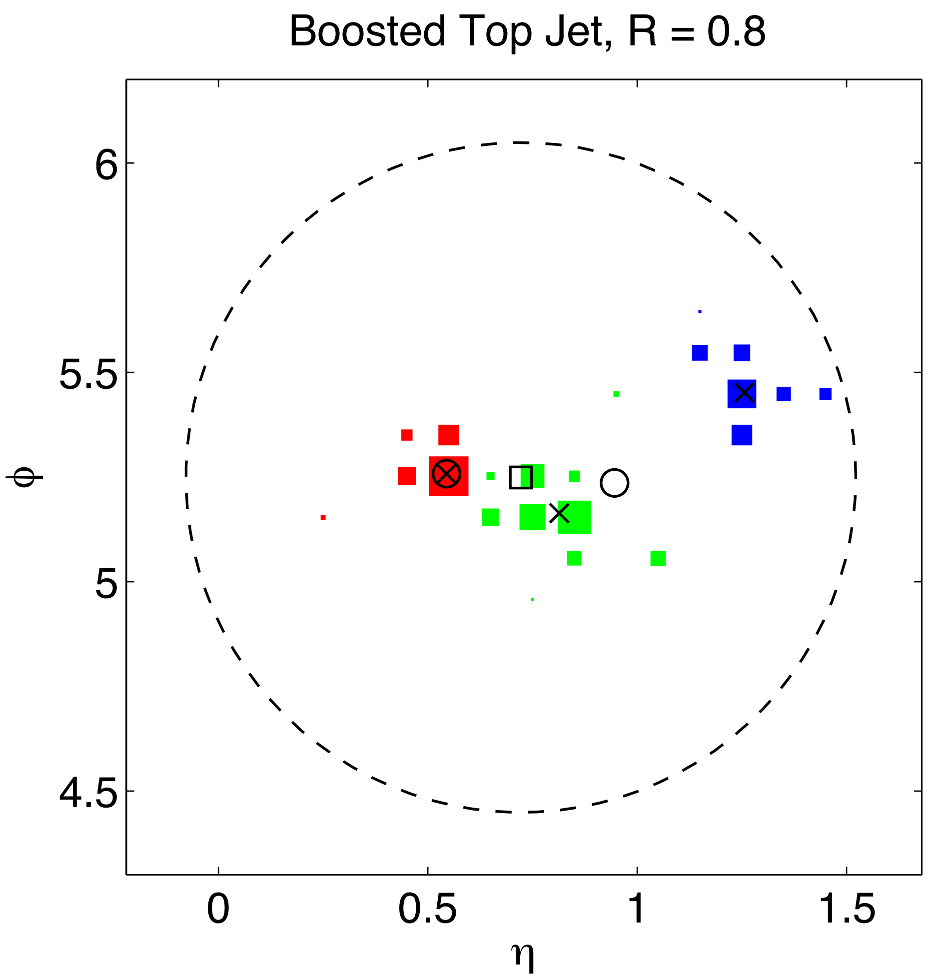

Jet!
Proton
s g d s̄ g u̅ g g u u g g u
u
g
u
Proton
s g d s̄ g u̅ g g u u g g u
g
Jet!

Jets or Jet Substructure?

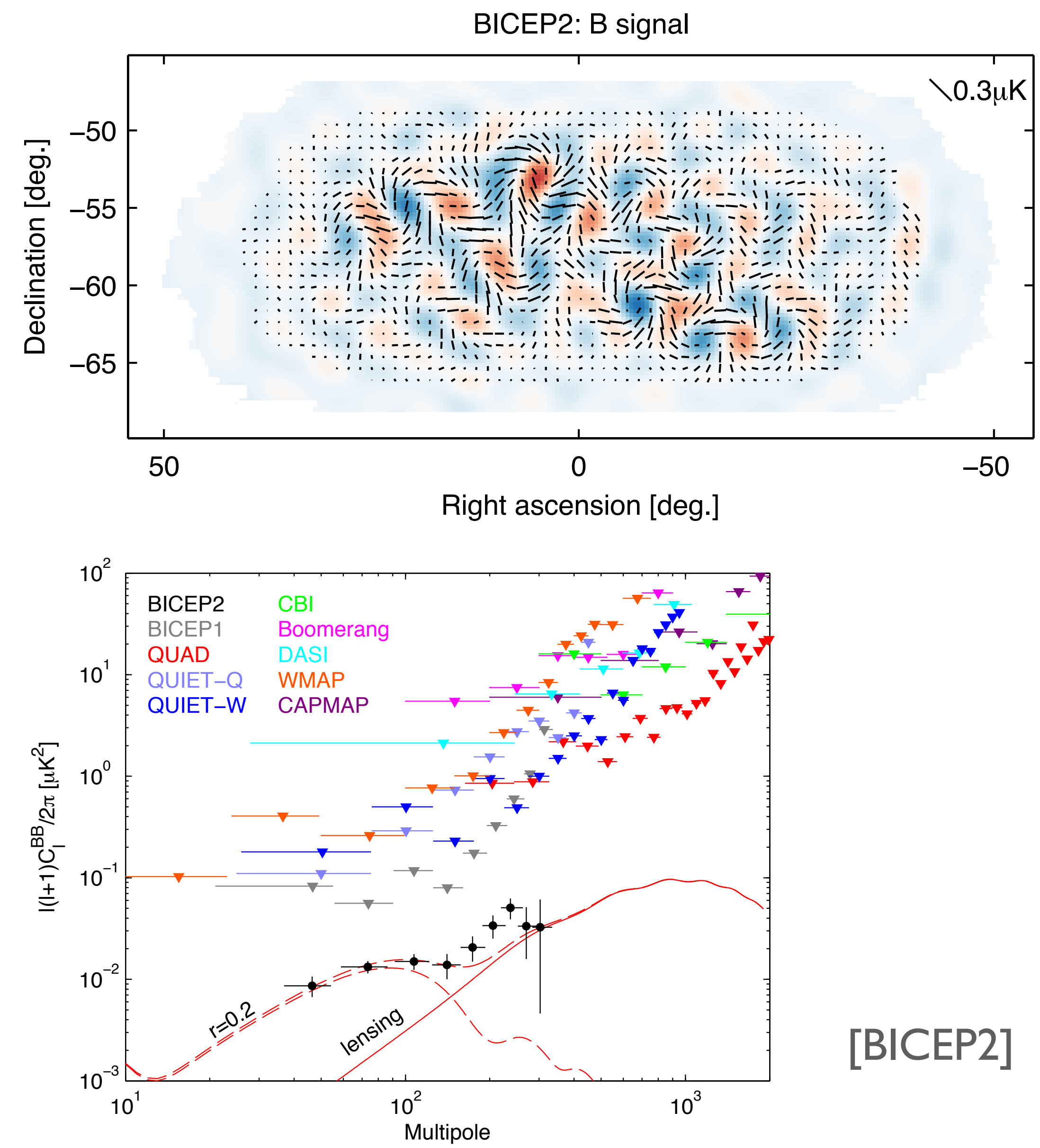


[CMS PAS B2G-12-006]

Jet Substructure by Power Spectrum?



$\neq$



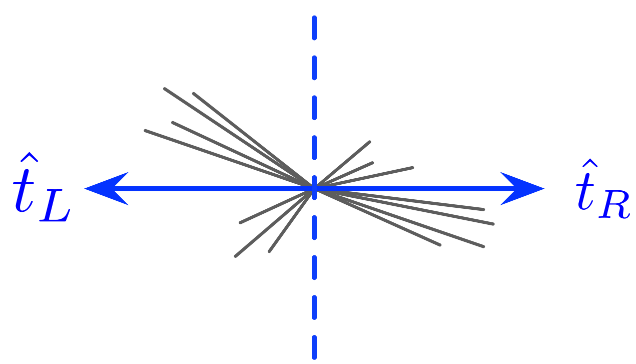
[BICEP2]

Axes Finding = Cluster Optimization

$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k}\min\left\{\Delta R_{k,1}, \Delta R_{k,2}, \dots, \Delta R_{k,N}\right\}^{\beta}$$

k-means clustering

Minimize β = 2



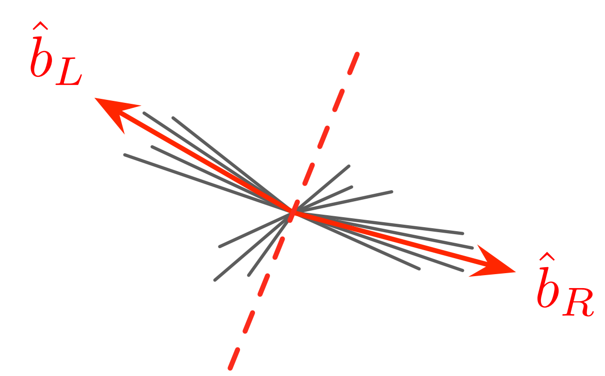
thrust axes

[Farhi, 1977]

k-medians clustering

(actually called R1-k-means)

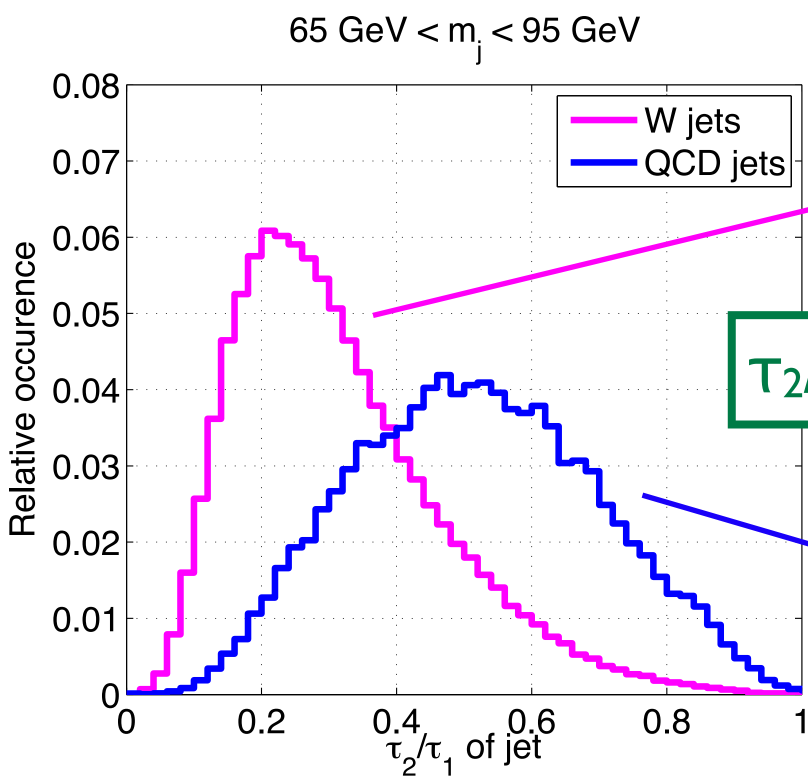
Minimize β = 1



broadening axes

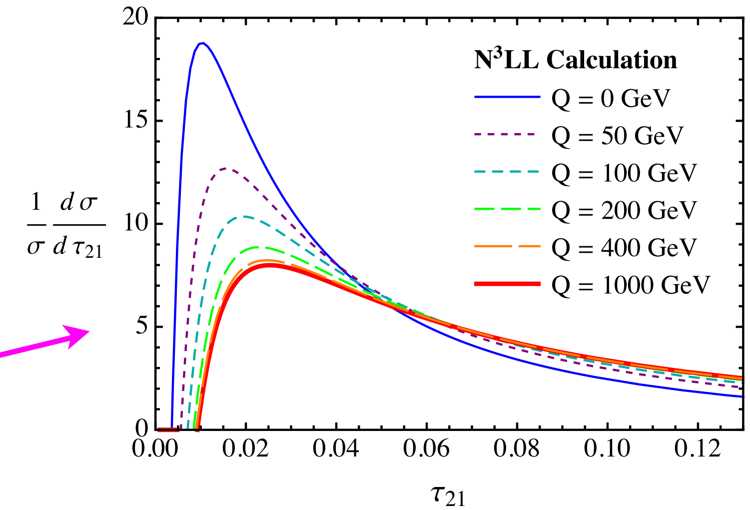
[Larkoski, Neill, JDT, 2014]

Predict Substructure Performance?



τ_2/τ_1

Signal

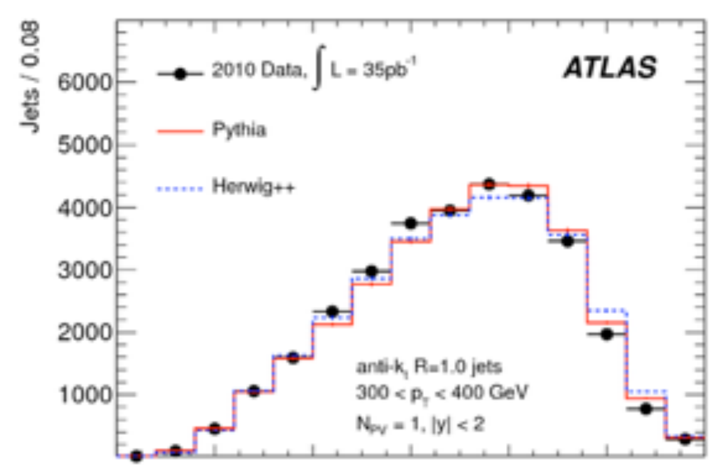


Boosted color singlet

$$W \longrightarrow q\bar{q}'$$

β = 2: [Feige, Schwartz, Stewart, JDT, 2012]

Background



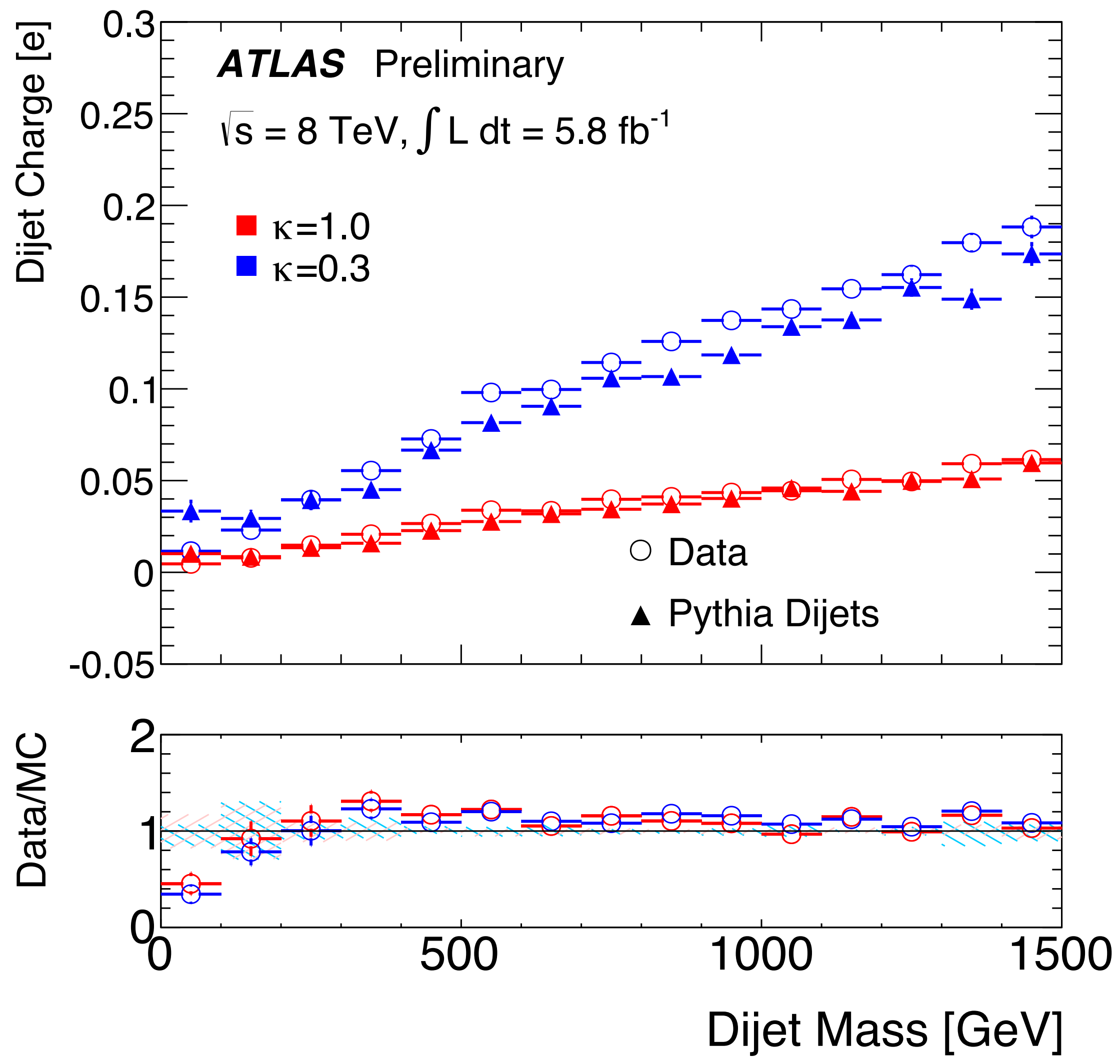
[ATLAS EP-2012-031]

Active area of study

Why so challenging?

Beautiful LHC Measurements

[ATLAS CONF-2013-086]



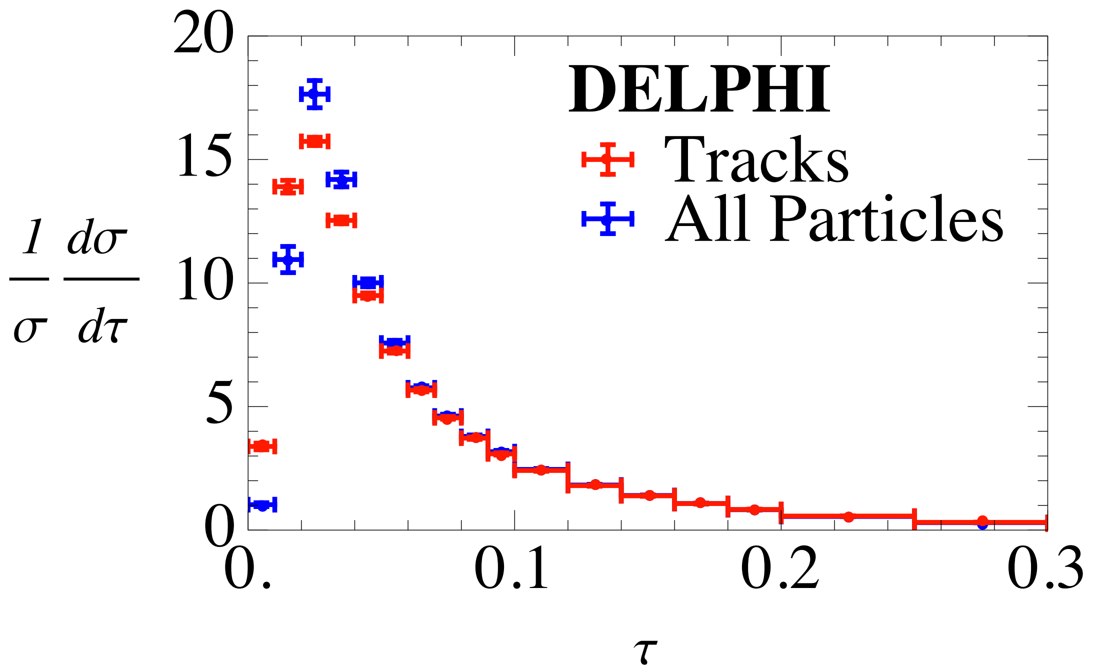
Jet Charge:

$$Q_\kappa = \sum_{j \in \text{jet}} q_j z_j^\kappa$$

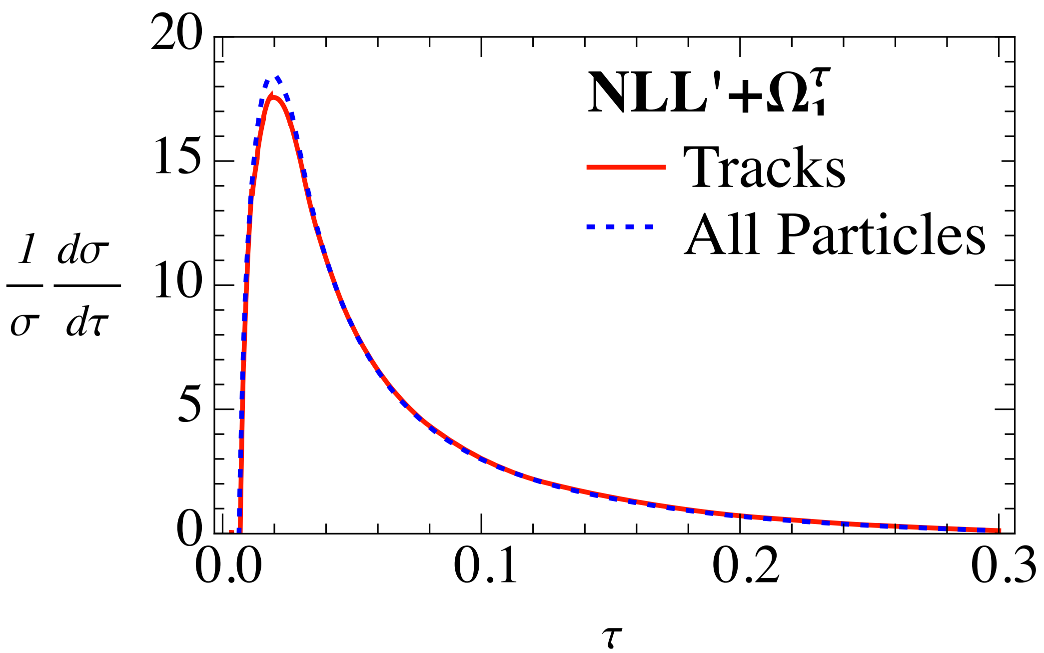
[revisiting Feynman, Field, 1978; Krohn, Lin, Schwartz, Waalewijn, 2012; Waalewijn, 2012]

Revisiting Thrust @ LEP

LEP Data



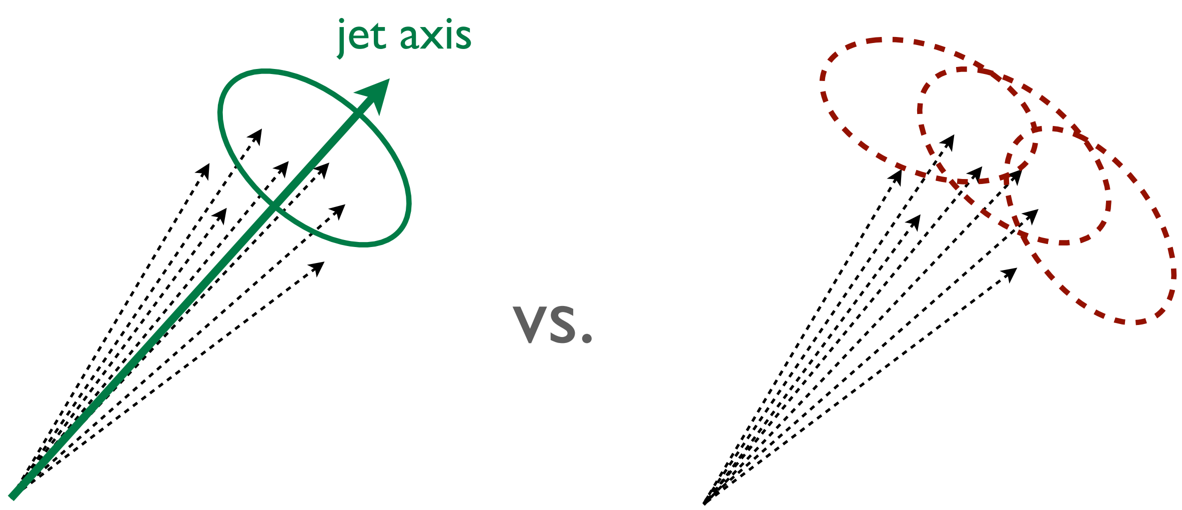
SCET + "Track Functions"



[Chang, Procura, JDT, Waalewijn, 2013]

Technique applicable to IR Safe but C Unsafe

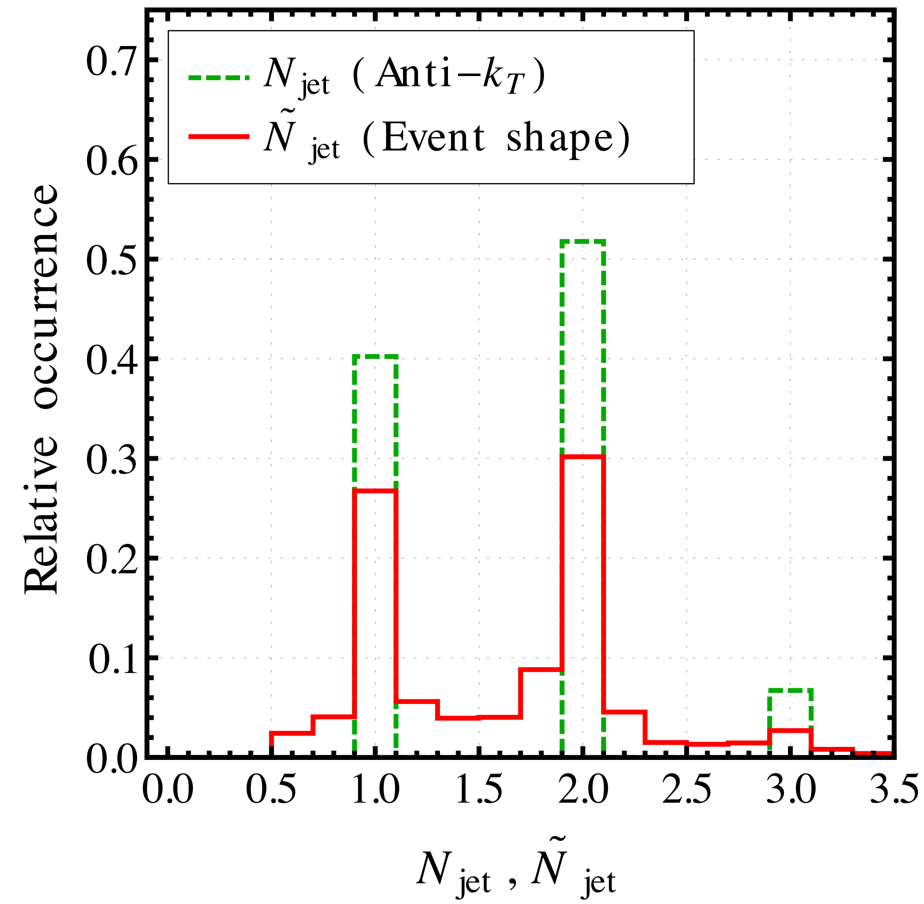
Embracing Jet Ambiguities



Jet Algorithm

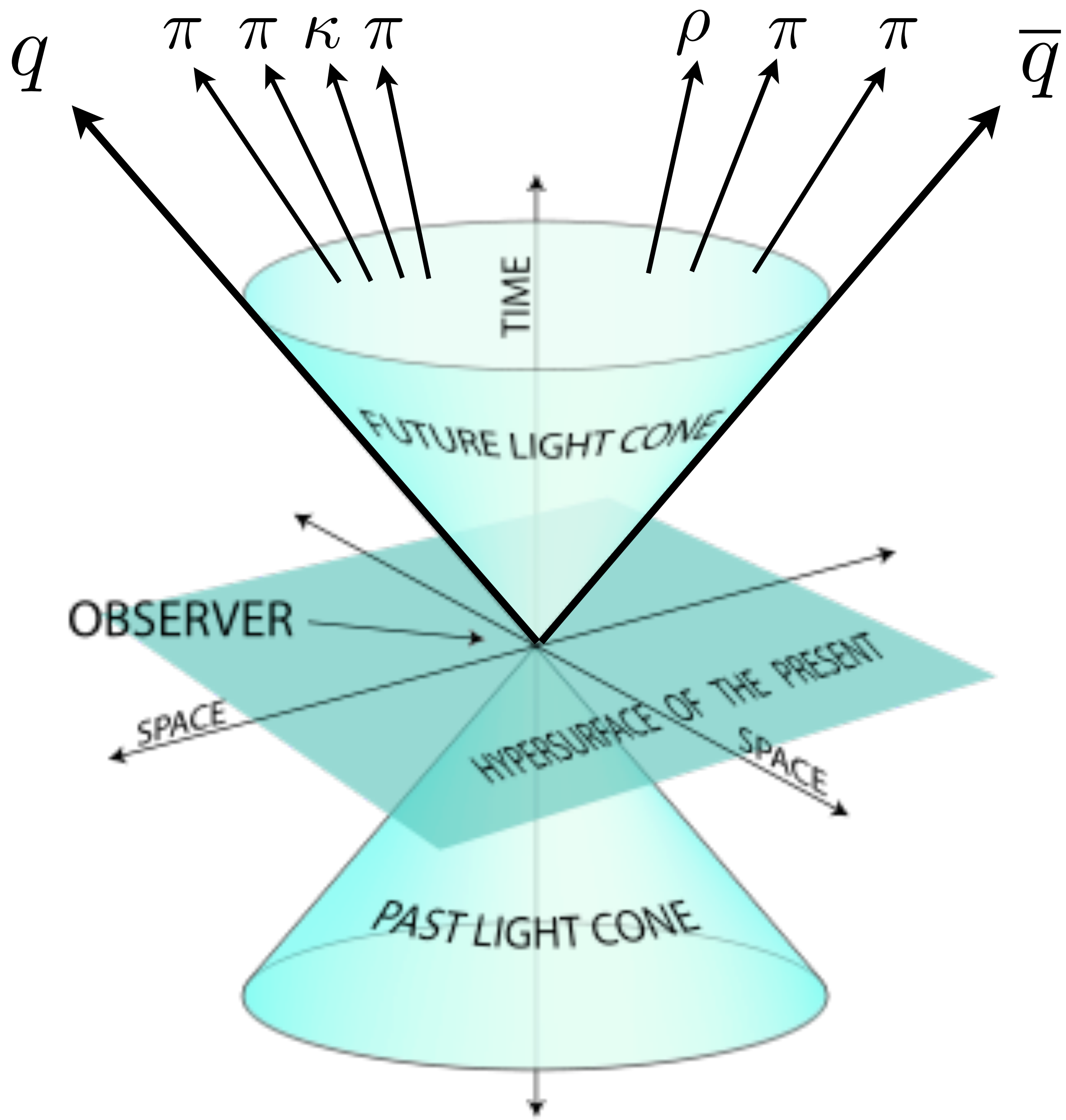
Jets Without Jets

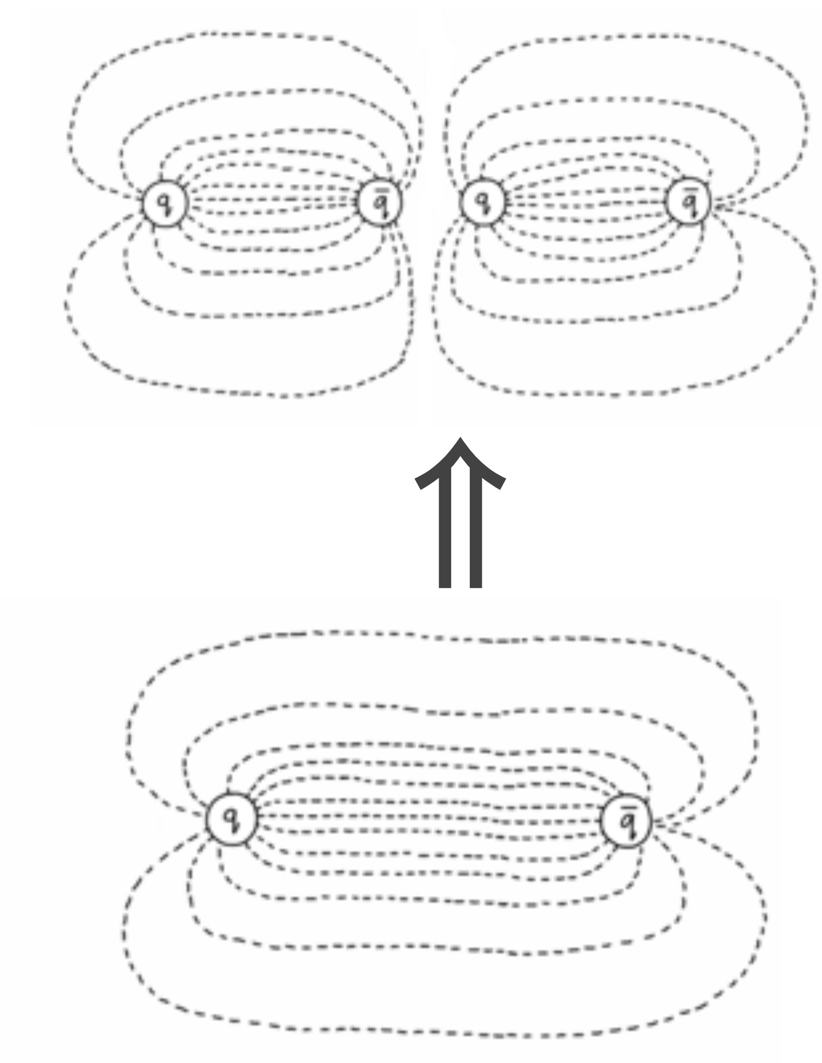
[Bertolini, Chan, JDT, 2013]



Fractional jets ⇒ Probe of soft QCD

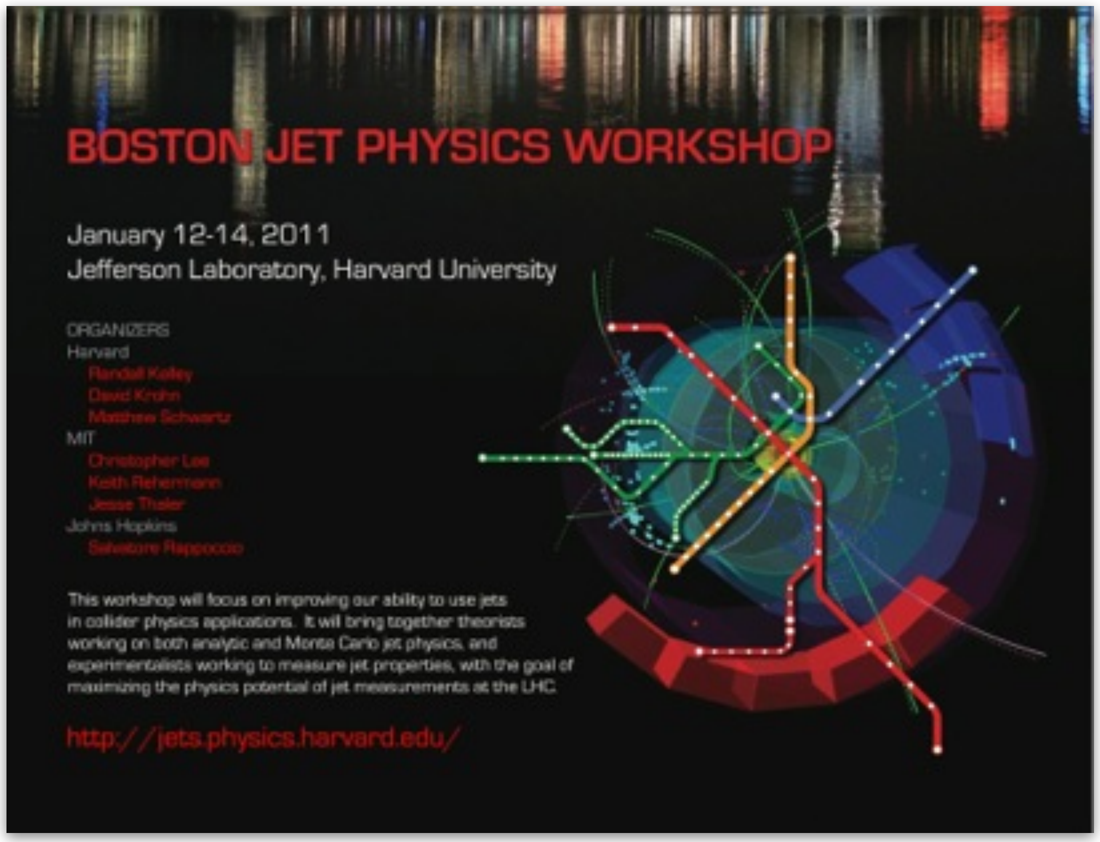
Handles on Hadronization





[coffeeshopphysics.com]

[revisiting Salam, Wicke, 2001;
Mateu, Stewart, JDT, 2012]



Jan 2011 Boston Jet Physics Workshop

Jan 2014 Boston Jet Physics Workshop

Turning the Crank

Sudakov Factor:

$$\Delta(e_\alpha, e_\beta) =$$ Probability to get measurement below a certain value of both e_α & e_β

Double Differential Cross Section:

$$\frac{d^2\sigma^{\mathrm{LL}}}{de_\alpha\, de_\beta} = \frac{\partial}{\partial e_\alpha}\frac{\partial}{\partial e_\beta}\Delta(e_\alpha, e_\beta)$$

Ratio Cross Section:

$$\frac{d\sigma^{\mathrm{LL}}}{dr} = \int de_\alpha\, de_\beta\, \frac{d^2\sigma^{\mathrm{LL}}}{de_\alpha de_\beta}\,\delta\left(r - \frac{e_\alpha}{e_\beta}\right)$$

Turning the Crank

Sudakov Factor:

$$\Delta(e_\alpha, e_\beta) = \exp\left[-\frac{\alpha_s}{\pi} C_F \left(\frac{1}{\beta}\log^2 e_\beta + \frac{1}{\alpha-\beta}\log^2\frac{e_\alpha}{e_\beta}\right)\right]$$

Double Differential Cross Section:

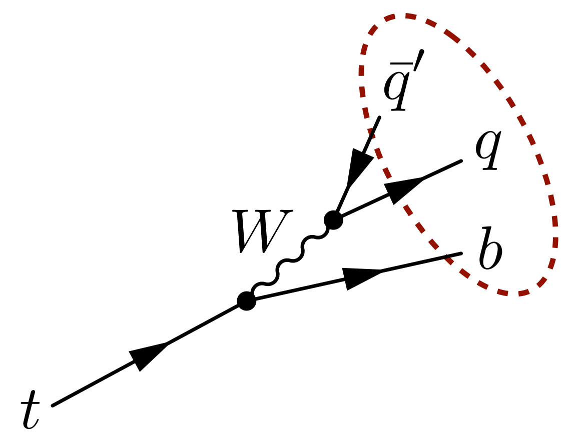
$$\frac{d^2\sigma^{\mathrm{LL}}}{de_\alpha\, de_\beta} = \left(\frac{2\alpha_s}{\pi}\frac{C_F}{\alpha-\beta}\frac{1}{e_\alpha e_\beta} + \frac{4\alpha_s^2}{\pi^2}\frac{C_F^2}{\beta(\alpha-\beta)^2}\frac{1}{e_\alpha e_\beta}\log\frac{e_\beta}{e_\alpha}\log\frac{e_\alpha^\beta}{e_\beta^\alpha}\right)\Delta(e_\alpha, e_\beta)$$

(Cross check: Reduces to known single differential)

Ratio Cross Section:

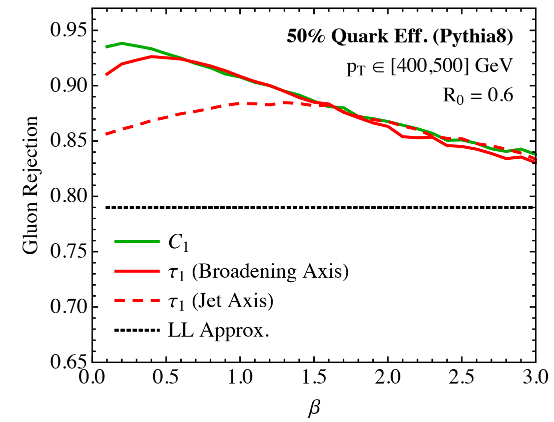
$$\frac{d\sigma^{\mathrm{LL}}}{dr} = \frac{\sqrt{\alpha_s C_F \beta}}{\alpha-\beta}\frac{1}{r}\left(1 - 2\frac{\alpha_s}{\pi}\frac{C_F}{\alpha-\beta}\log^2 r\right)\left(\mathrm{erf}\left[\frac{\sqrt{\alpha_s C_F\beta}}{\sqrt{\pi}(\alpha-\beta)}\log r\right]+1\right)e^{-\frac{\alpha_s}{\pi}\frac{C_F}{\alpha-\beta}\log^2 r} - 2\frac{\alpha_s}{\pi}\frac{C_F}{\alpha-\beta}\frac{\log r}{r}e^{-\frac{\alpha_s}{\pi}C_F\frac{\alpha}{(\alpha-\beta)^2}\log^2 r}$$

Discovery: New techniques for...



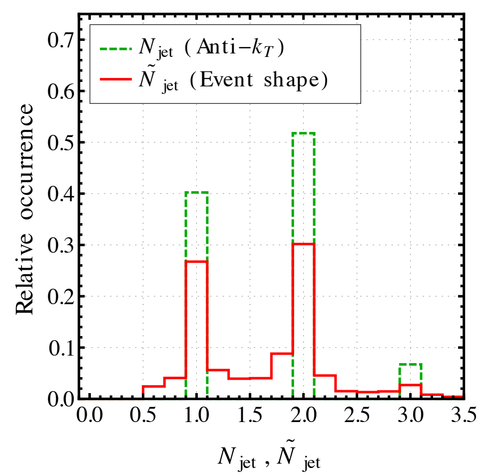
... Boosted Objects

[JDT, Ken Van Tilburg, 2010, 2011]



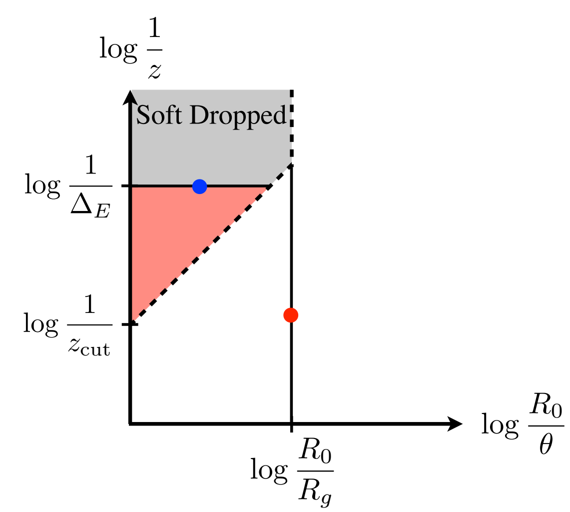
... Quark/Gluon Discrimination

[Andrew Larkoski, Gavin Salam, JDT, 2013]



... Jet Counting

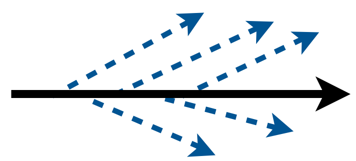
[Daniele Bertolini, Tucker Chan, JDT, 2013]



... Pileup Mitigation

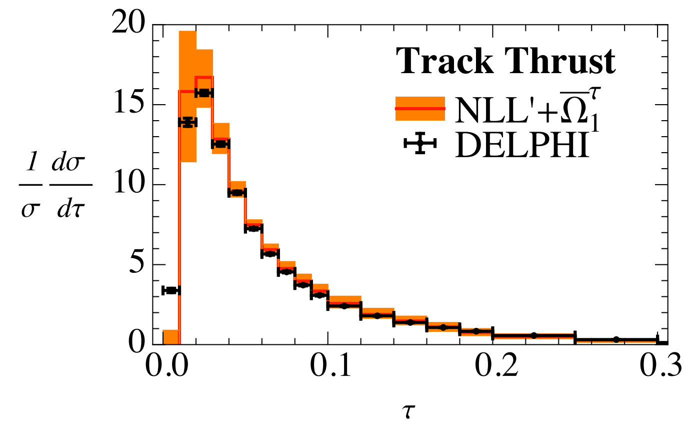
[Andrew Larkoski, Simone Marzani, Gregory Soyez, JDT, 2014]

Understanding: New analytic methods for...

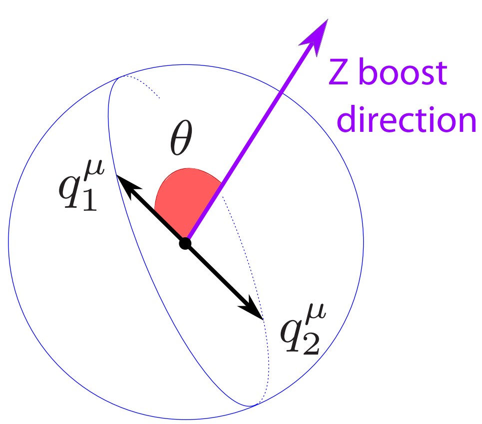


$$\frac{\text{IRC Safe}}{\text{IRC Safe}} = \text{Sudakov Safe}$$

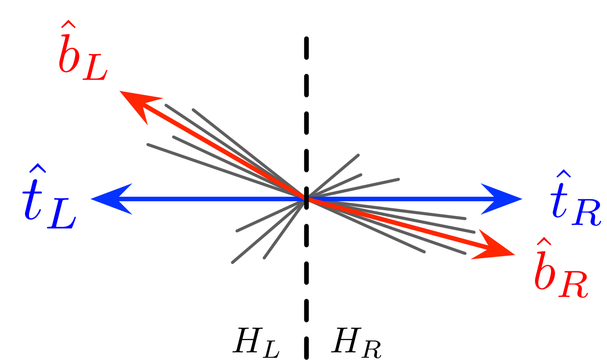
... Ratio Observables
[Andrew Larkoski, JDT, 2013]



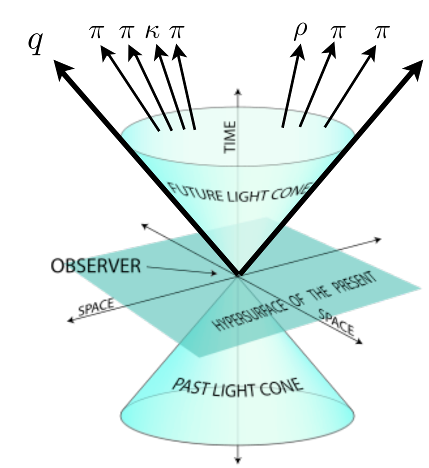
... Track-Based Observables
[Hsi-Ming Chang, Massimiliano Procura, JDT, Wouter Waalewijn, 2013]



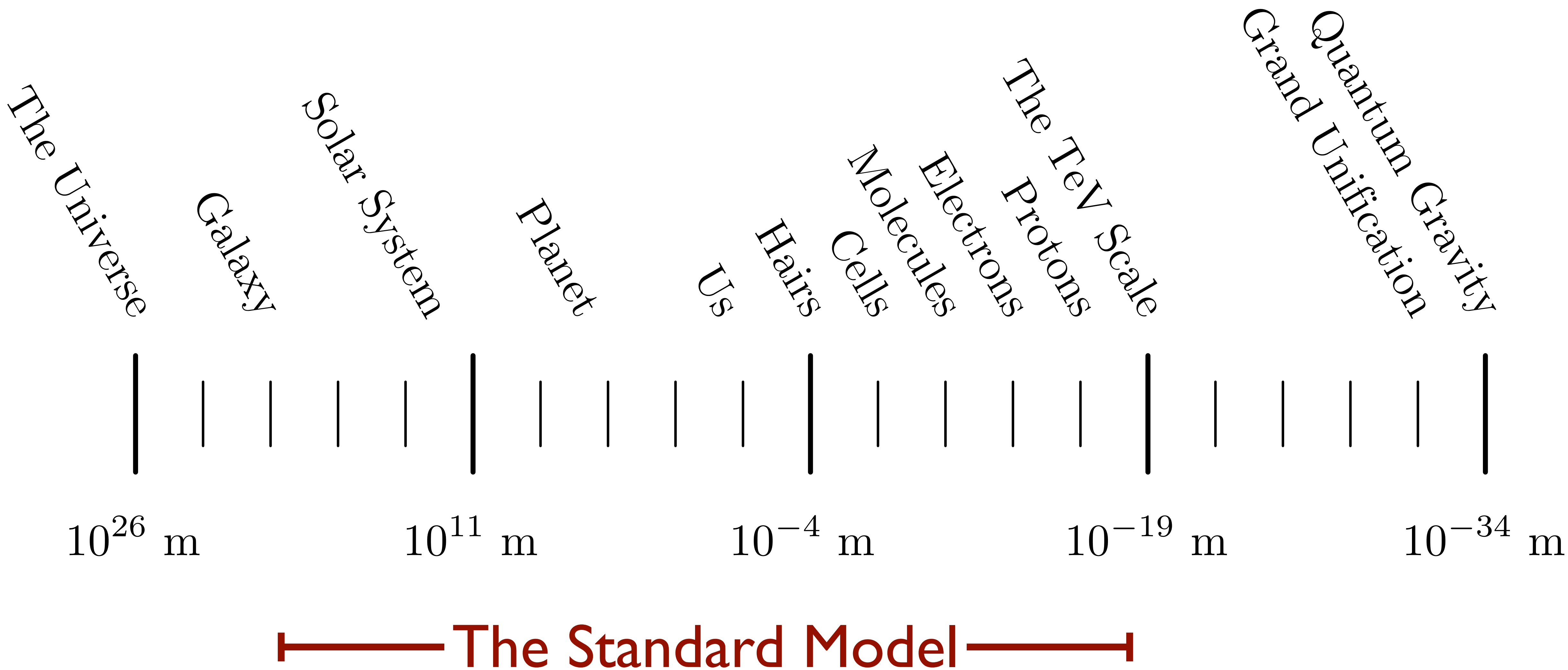
... Boosted Color Singlets
[Ilya Feige, Matthew Schwartz, Iain Stewart, JDT, 2012]



... Recoil-Free Observables
[Andrew Larkoski, Duff Neill, JDT, 2014]



... Hadronization Effects
[Vicent Mateu, Iain Stewart, JDT, 2012]


The Universe
Galaxy
Solar System
Planet
Us
Hairs
Cells
Molecules
Electrons
Protons
The TeV Scale
Grand Unification
Quantum Gravity
10^{26} m
10^{11} m
10^{-4} m
10^{-19} m
10^{-34} m
The Standard Model


Gravity
Electro Magnetic
Strong
Weak
Graviton
Photon
Gluon
W/Z Bosons
+
u d e ν_e
s c μ ν_μ
t b τ ν_τ
Quarks
Leptons

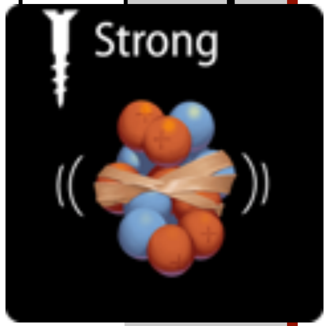
Matter/Anti-Matter?

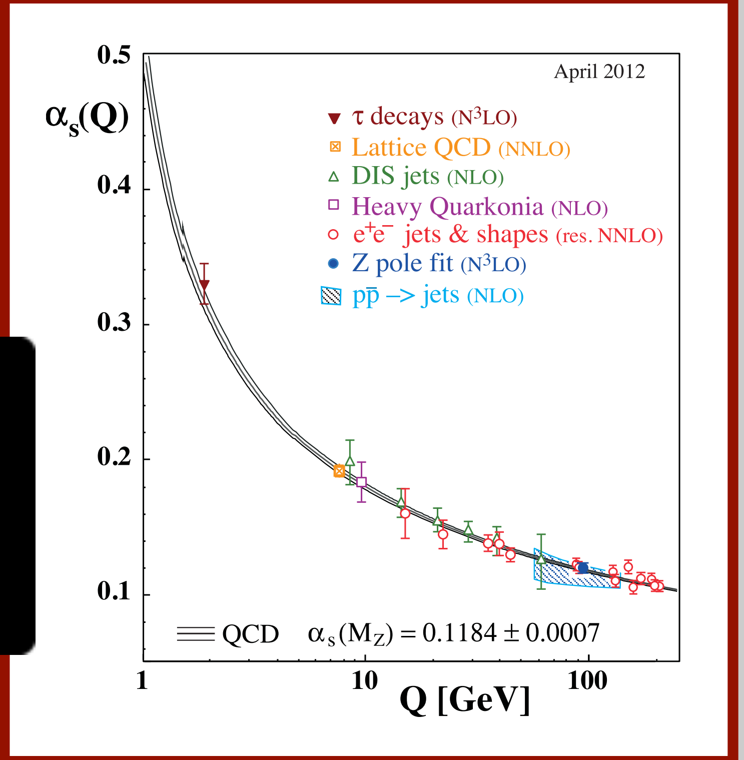
Three Generations?

Neutrino Masses?

Strong CP?

10^{26} m 10^{11} m 10^{-4} m





The Standard Model

Unification?

Dark Matter?

Origin of Mass?
Higgs Boson (!)

Quantum Gravity?

Dark Energy?

Inflation?

Hierarchy Problem?