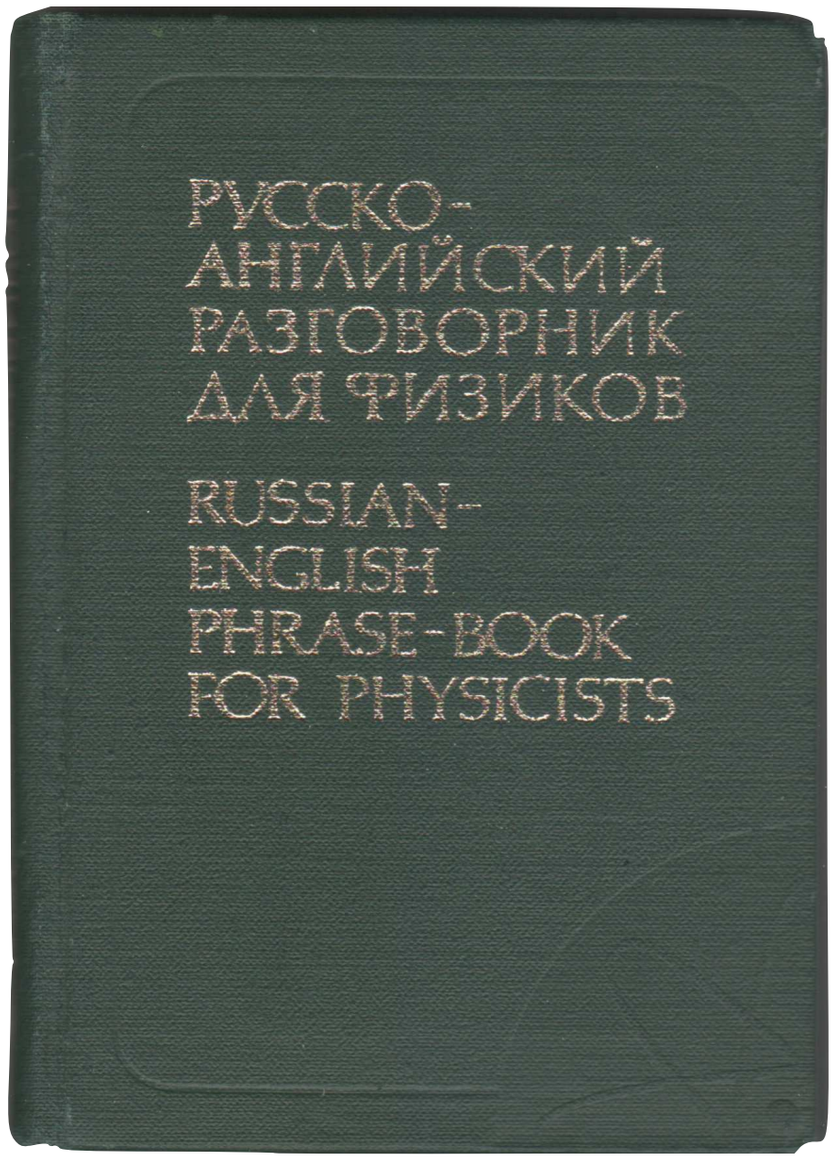
Jets in QCD

The Case for Jet Substructure

Jesse Thaler

QCHS XI, St. Petersburg — September 8, 2014

Кварки. Quarks



1977

Существуют ли кварки в действительности? Do quarks really exist?

Барионы строятся из трёх кварков. Baryons are built up of three quarks.

Барионы строятся из кварков со спином 1/2. Baryons are built up out of spin 1/2 quarks.

Барионы считаются сложными структурами. Baryons are regarded as composite structures.

Предполагается, что кварки довольно тяжёлые. Quarks are assumed to be fairly heavy.

Непосредственно наблюдать кварки нам ещё не приходилось. We have never seen a quark directly.

Модель «мешка» предполагает, что кварки заключены внутри частицы. The «bag» model has quarks confined within the particle.

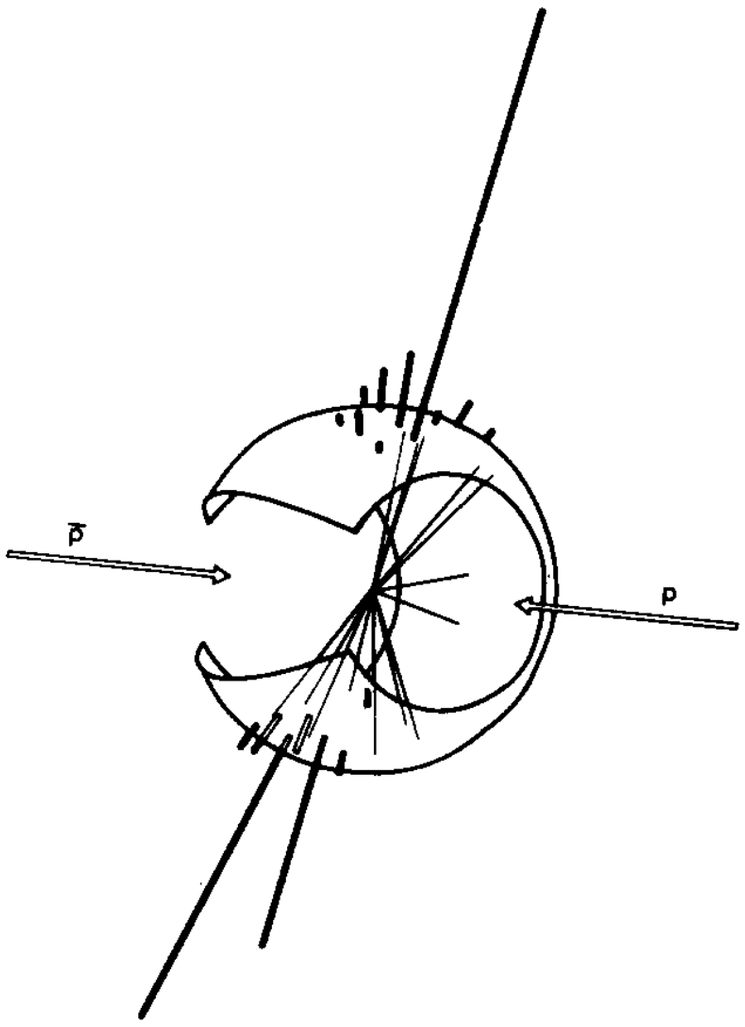
Имеются некоторые соображения о невозможности создания или высвобождения отдельного кварка. There are some considerations about the impossibility to create or to liberate a single quark.

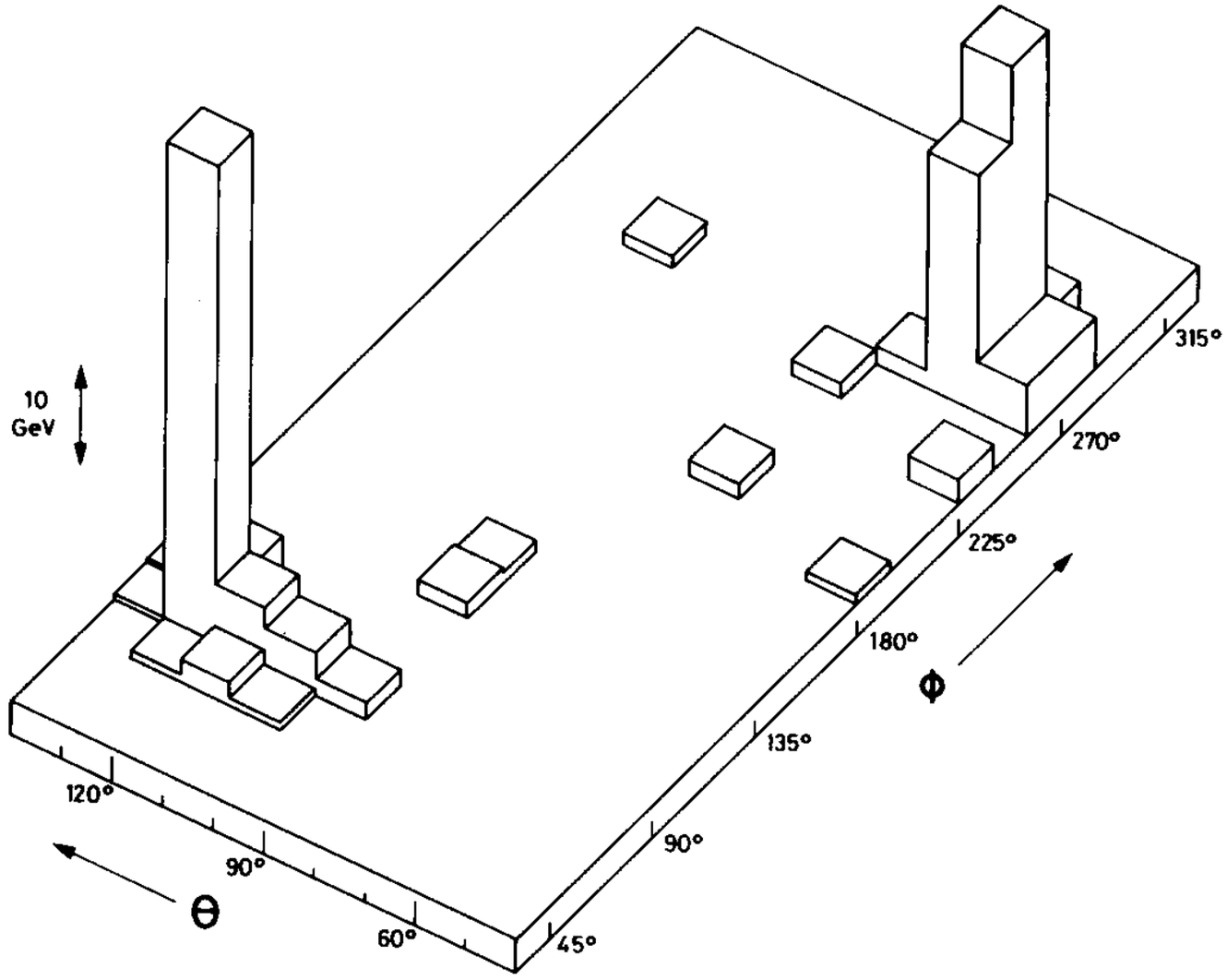
Почему нам не удалось расщепить адрон и извлечь из него отдельный кварк? Why have we failed to break open an hadron and get at an individual quark?

У теоретиков имеется множество идей, объясняющих неудачи попыток получения изолированных кварков. The theoreticians have a variety of ideas as to why we cannot have an isolated quark.

UA2 Jet Production

1982



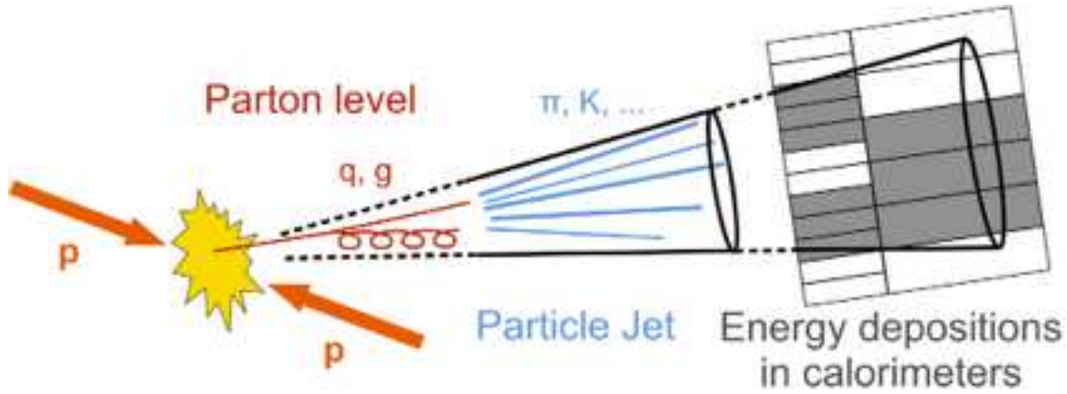


Almost 40 years of jet physics!

[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)

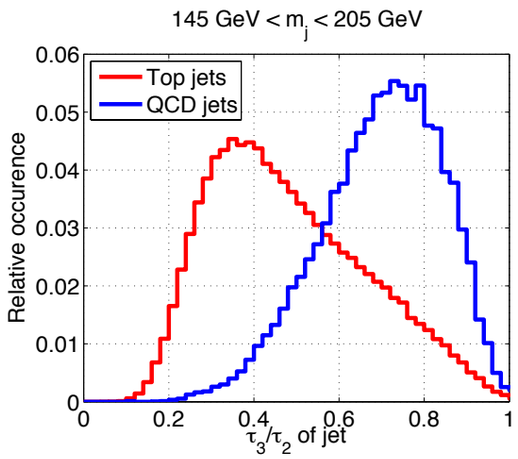
Loop/Leg/Log Explosion

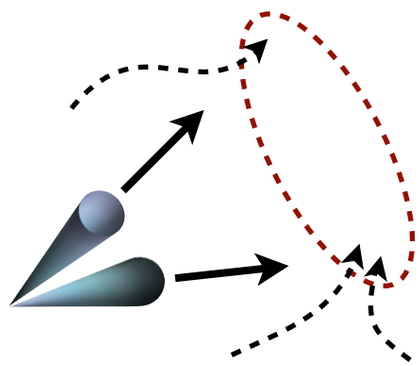
Jet Substructure

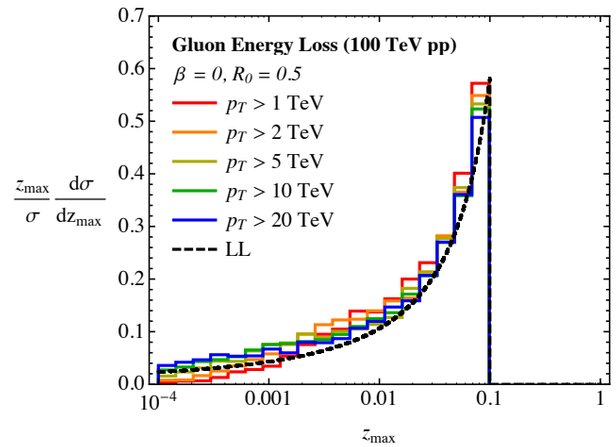
[Anti-k_T: Cacciari, Salam, Soyez, 2008]
[BDRS: Butterworth, Davison, Rubin, Salam, 2008; see also Seymour, 1991, 1994]

Ввиду ограниченности времени я остановлюсь на двух аспектах проблемы. Because of the very limited time available, I will restrict myself to two aspects of the problem.

The Case for Jet Substructure

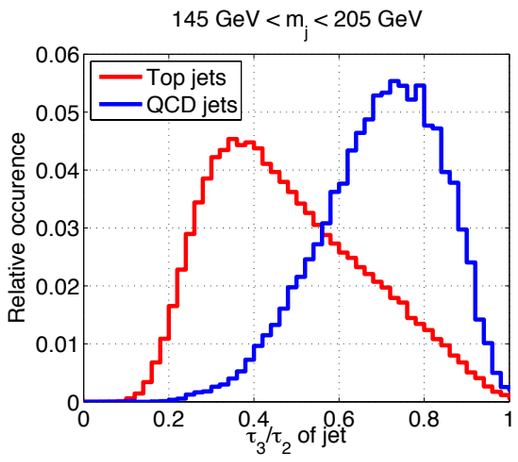


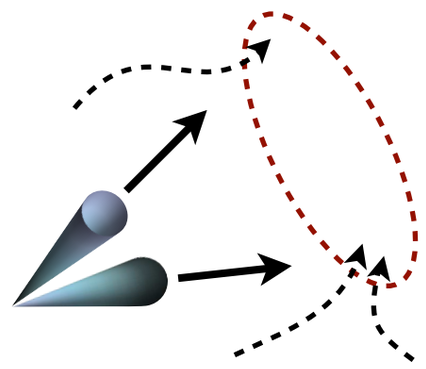




Maximize **discovery** potential of LHC

Enhance **understanding** of QCD





Maximize **discovery** potential of LHC

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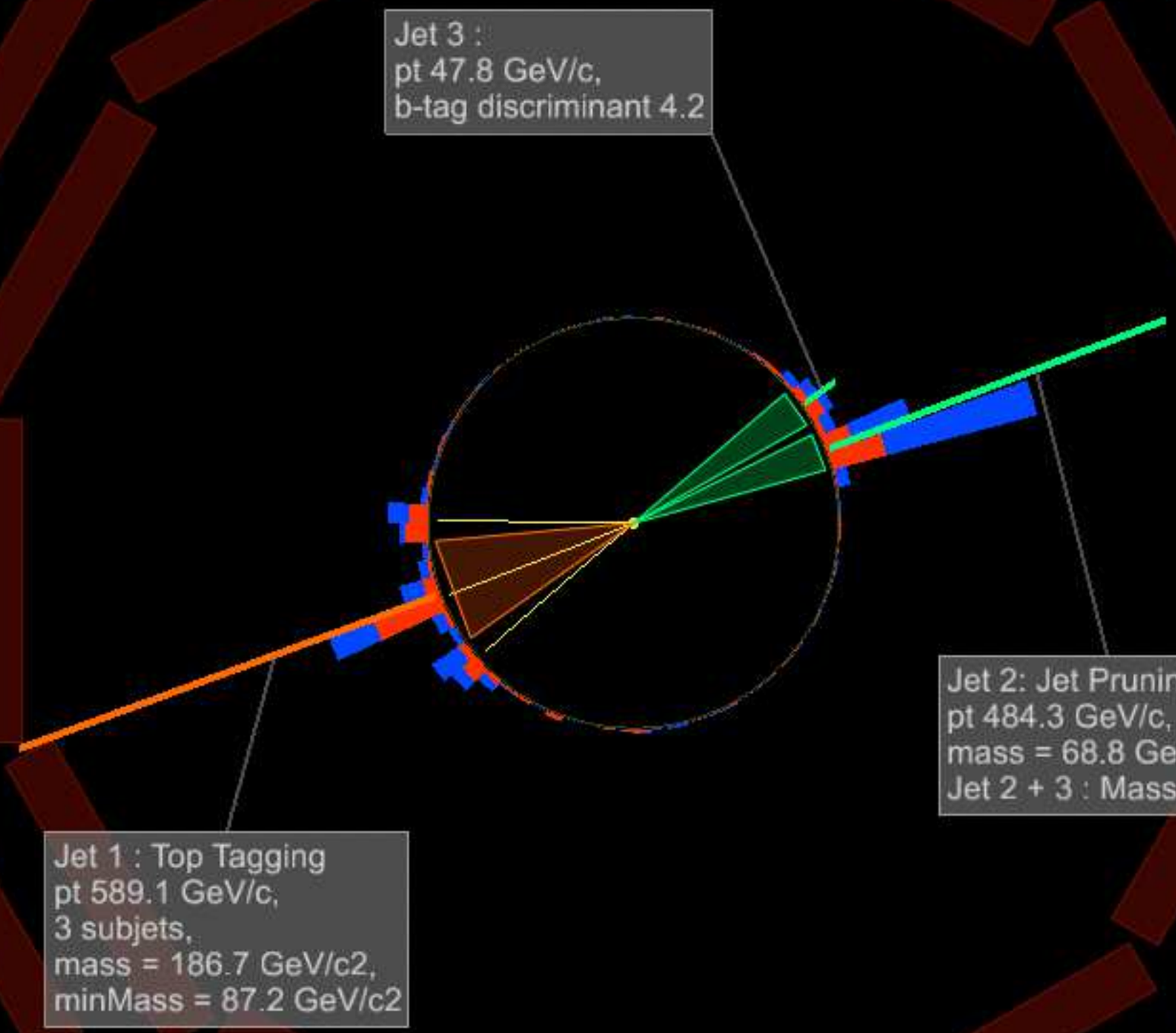
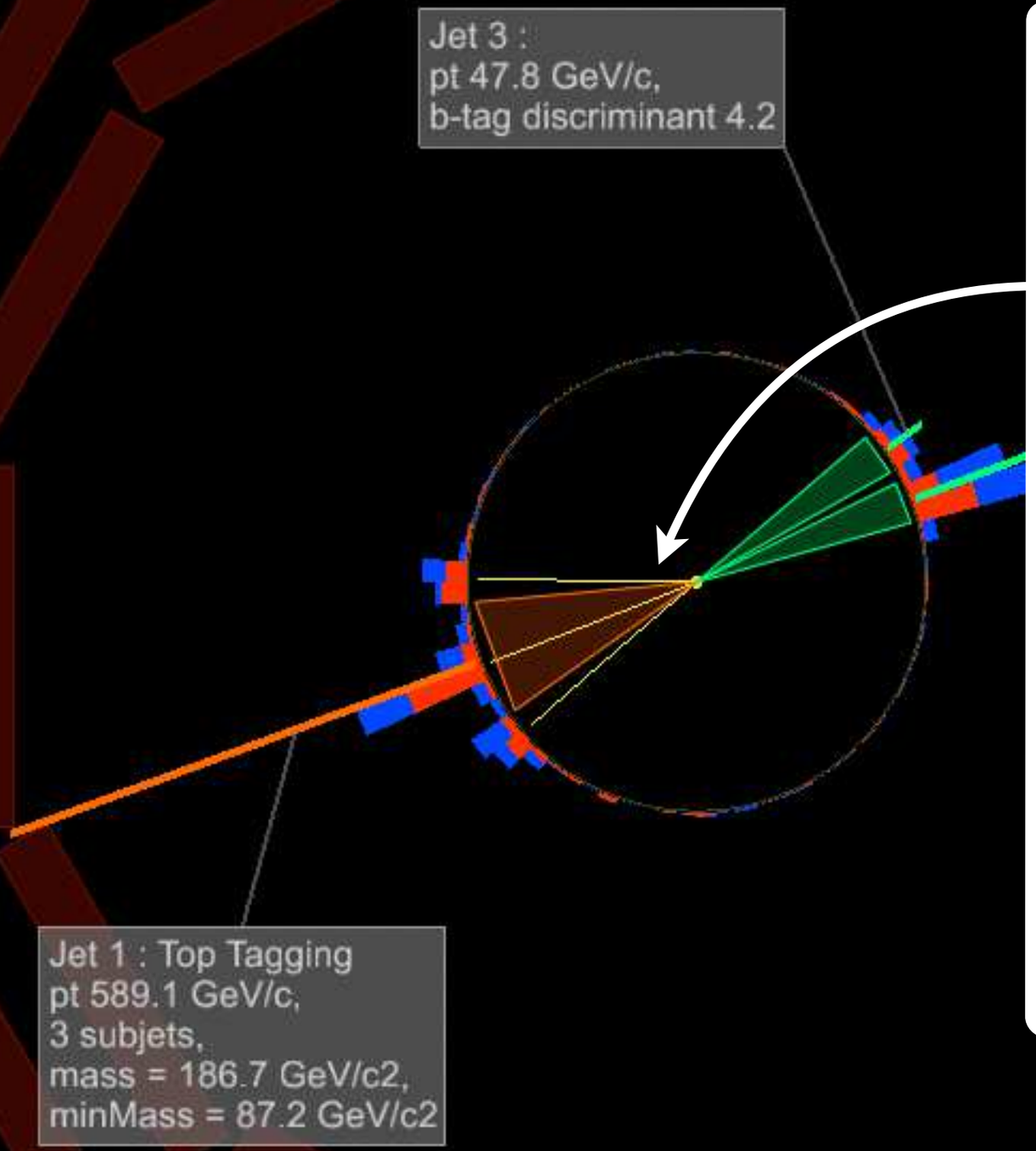
Jets or Jet Substructure?

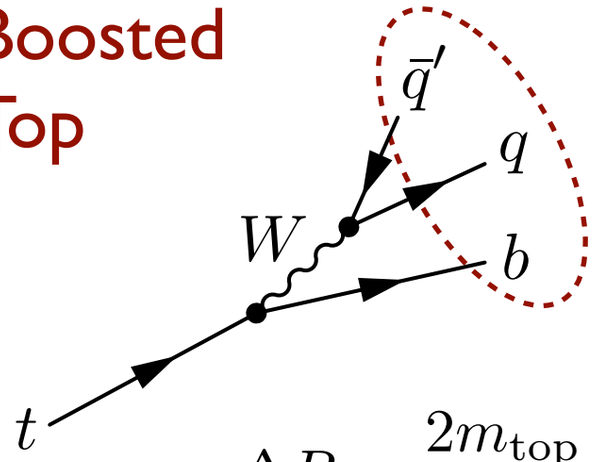


[CMS EXO-11-006, CMS JME-13-007]
[Using JHU/CMSTopTagger: Kaplan, Rehermann, Schwartz, Tweedie, 0806.0848]
[Using Pruning: Ellis, Vermilion, Walsh, 0903.5081]

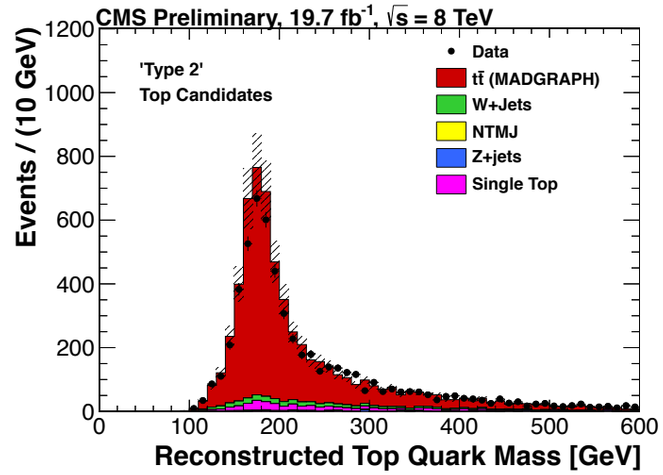
Jets or Jet Substructure?



Boosted Top



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



[CMS EXO-11-006, CMS JME-13-007]
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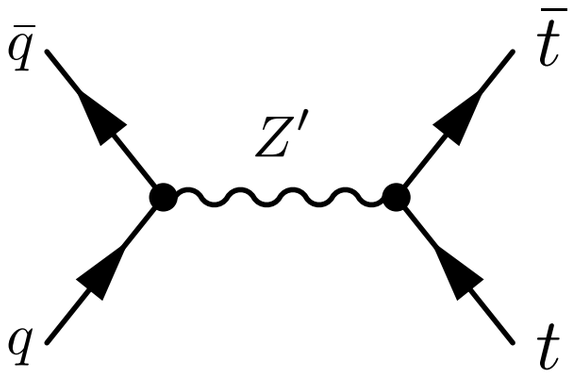
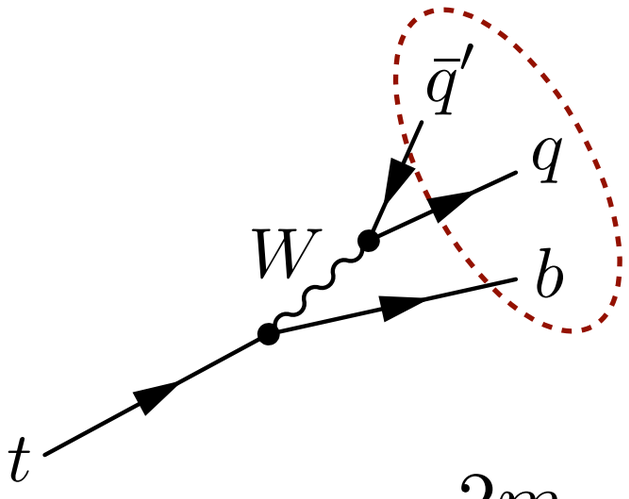
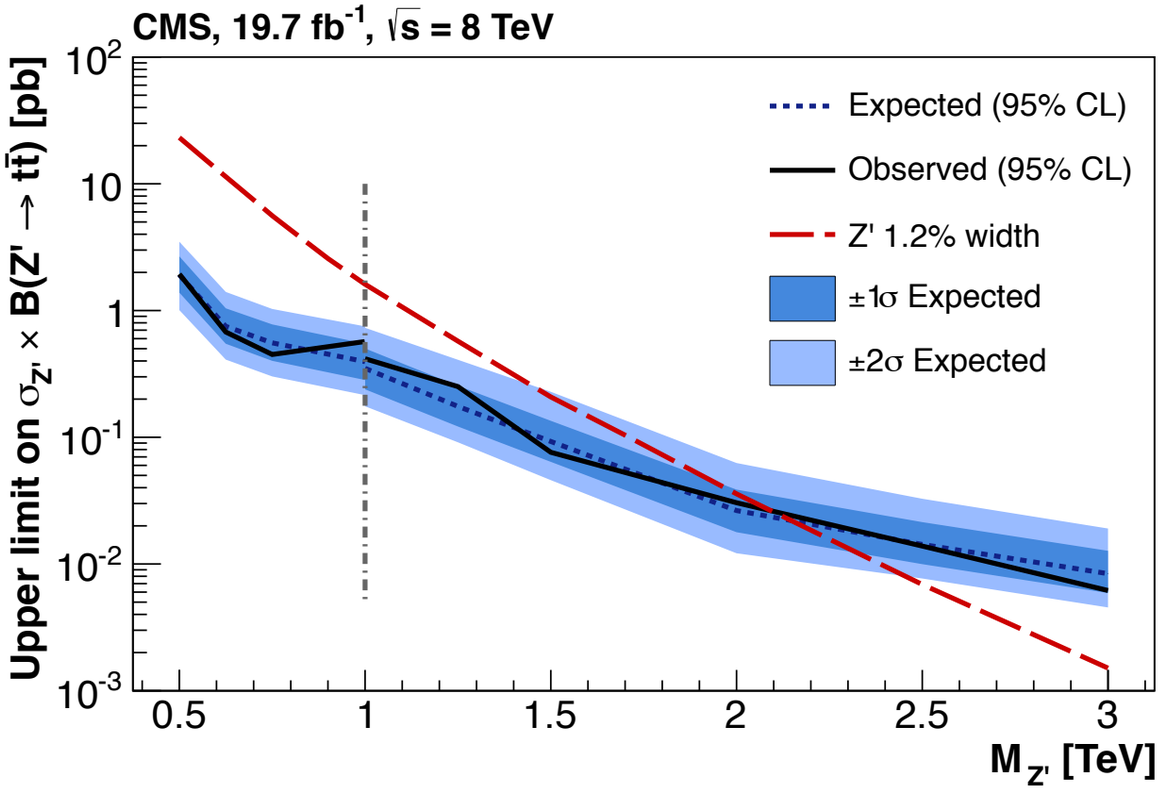
High Energy: Boosted Regime is Inevitable





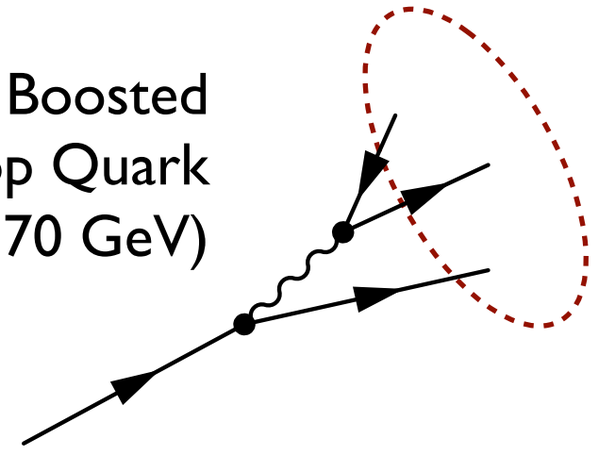
$$\Delta R \simeq \frac{2m_{\text{top}}}{p_T}$$



[CMS B2G-13-001]

High Luminosity: Pileup is Inevitable

Boosted
Top Quark
($m_{top} \approx 170$ GeV)



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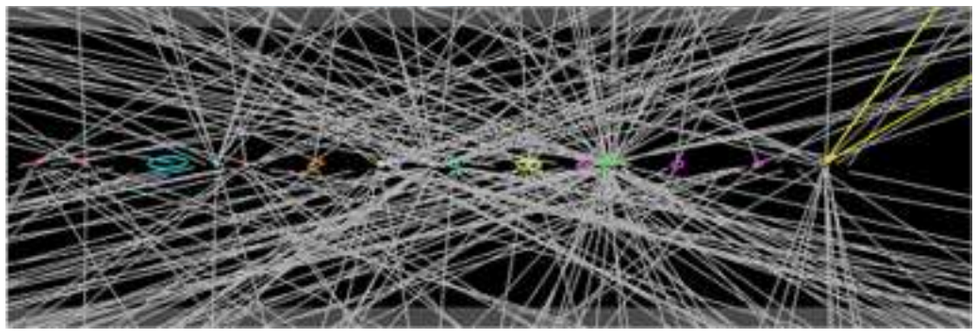
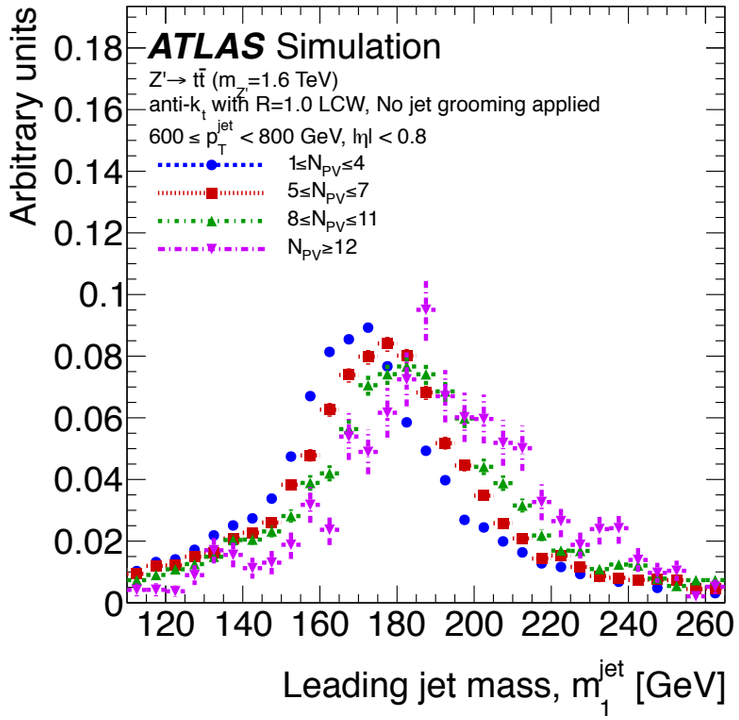


Secondary Collision Debris



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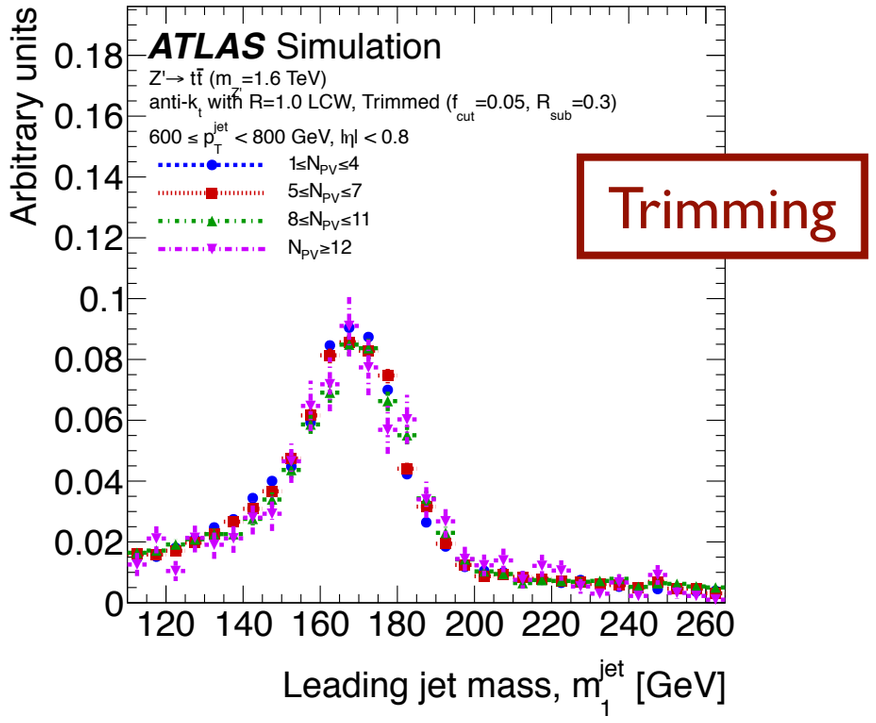
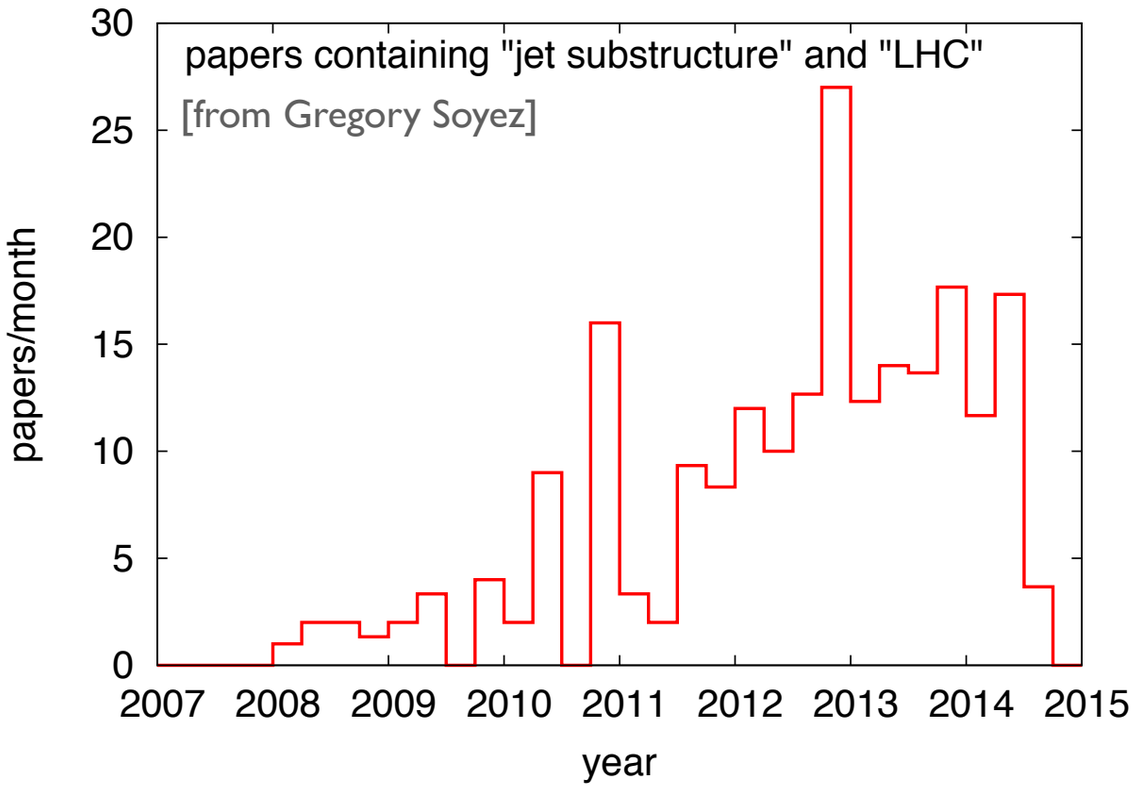


[ATLAS PERF-2012-02]
[Krohn, JDT, Wang, 0912.1342]

High Stakes: Cleverness is Inevitable



Mass Drop, p_T Balance, Y-splitter, Filtering, Trimming, Pruning, Soft Drop, Angularities, Planar Flow, N-subjettiness, Angular Structure Functions, Jet Charge, Jet Pull, Energy Correlation Functions, Dipolarity, p_T^D, Zernike Coefficients, Fox-Wolfram Moments, JHU/CMSTopTagger, HEPTopTagger, Template Method, Shower Deconstruction, Jets Without Jets, Subjet Counting, Wavelets, Q-Jets, Telescoping Jets, Jet Reclustering, etc.

Core Principles of Jet Substructure:

Prong-like Behavior
Radiation Patterns
Flavor Tagging

(& Pileup Mitigation)

$$t \to bW$$

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

$$Z \to q\bar{q}$$

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

b

c

s

d

u

g

N-Prong vs. 1-Prong

$t \to bW$ } τ_3/τ_2

$H \to b\bar{b}$

$Z \to q\bar{q}$ } τ_2/τ_1

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

b

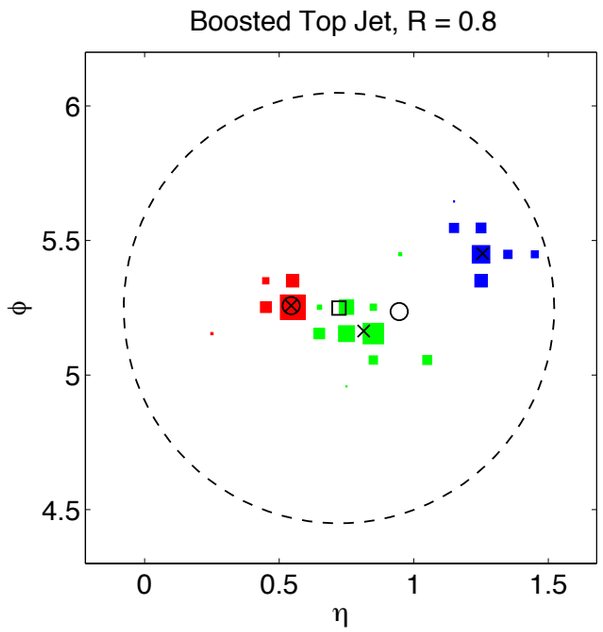
c

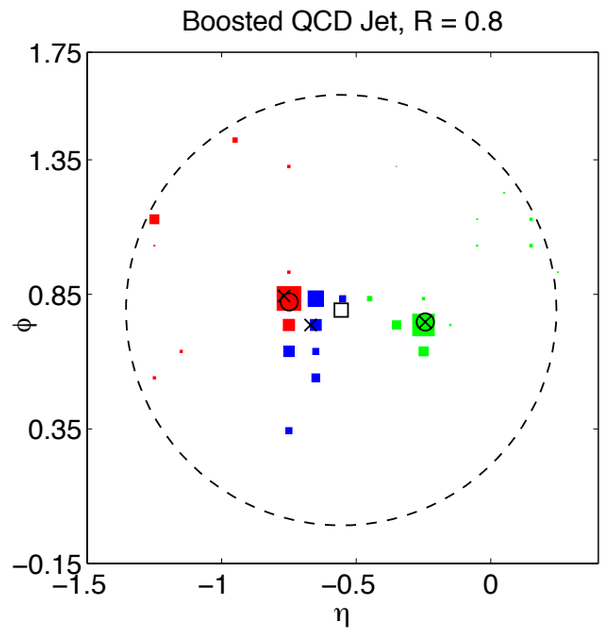
s

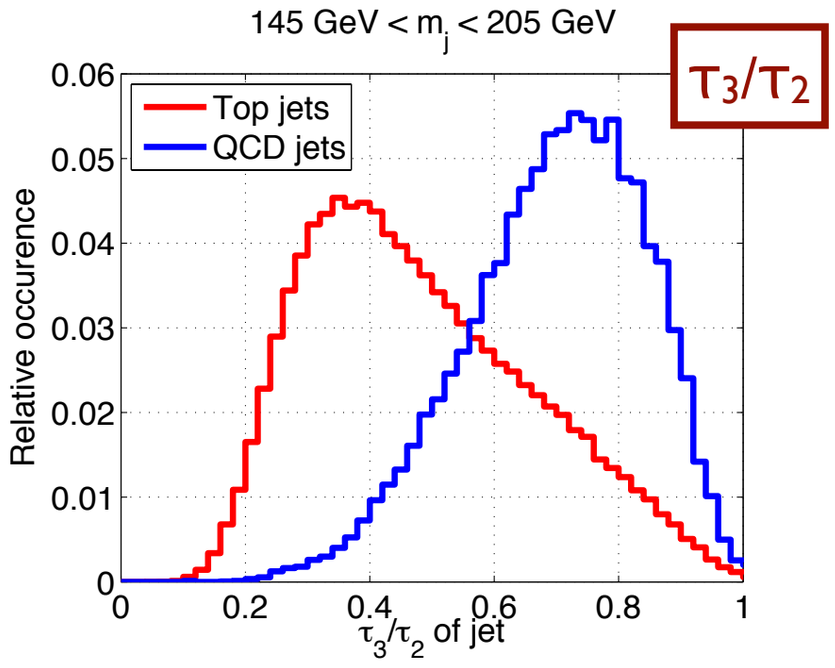
d

u

g







e.g. N-subjettiness:

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

(transverse) momentum

distance to subjet core

[JDT, Van Tilburg, 1011.2268, 1108.2701]
[See also N-jettiness: Stewart, Tackmann, Waalewijn, 1004.2489]

$$t \to bW$$
$$H \to b\bar{b}$$
$$Z \to q\bar{q}$$
$$W \to q\bar{q}'$$

b

c

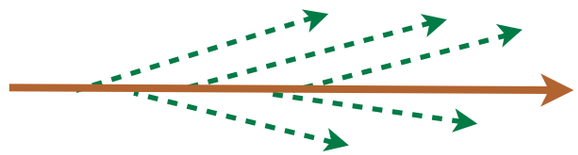
s

d

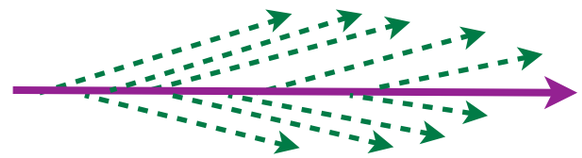
u

g

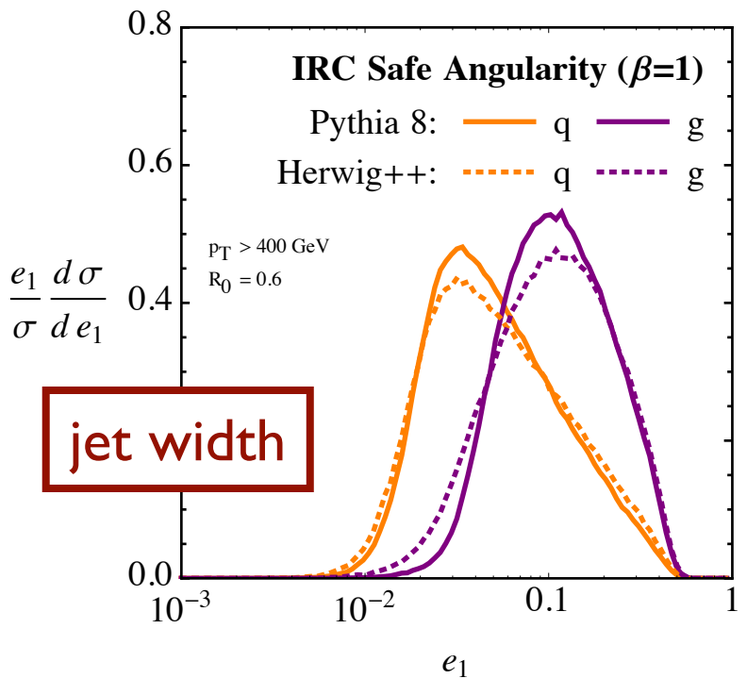
Quark-like vs. Gluon-like



$C_F = 4/3$



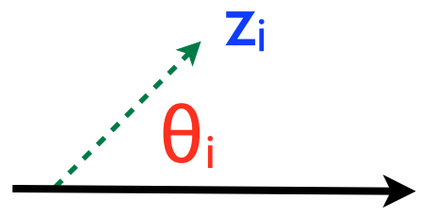
$C_A = 3$



e.g. *Angularities:*

(a.k.a. 1-subjettiness)

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



energy fraction angle to axis

[Berger, Kucs, Sterman, 2003; Ellis, Vermilion, Walsh, Hornig, Lee, 2010]
[Recoil-free Versions: Larkoski, Salam, JDT, 1305.0007; Larkoski, Neill, JDT, 2014]

(Sub)jet B-tagging

$$t \to bW$$
$$H \to b\bar{b}$$
$$Z \to q\bar{q}$$
$$W \to q\bar{q}'$$

b

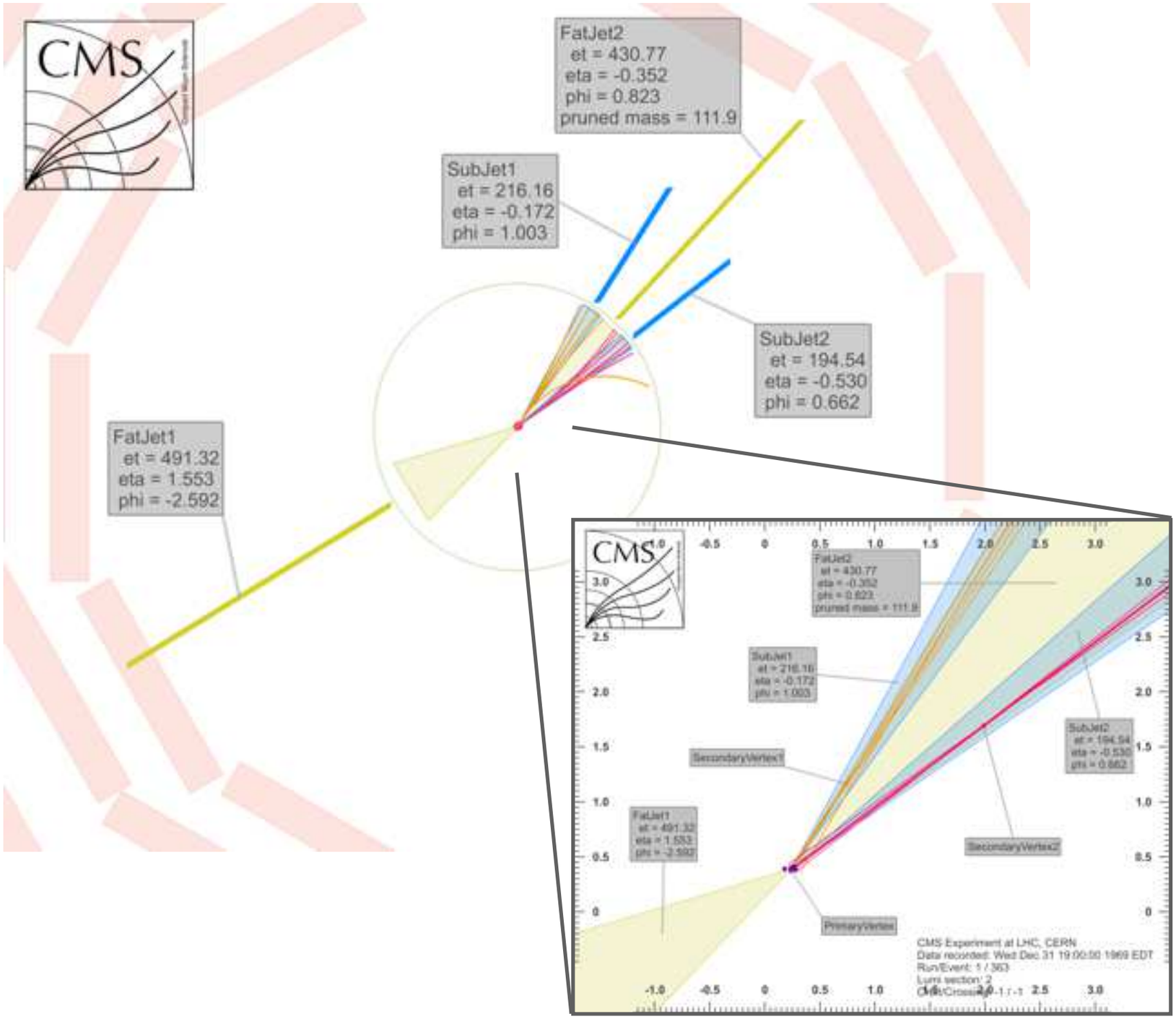
c

s

d

u

g

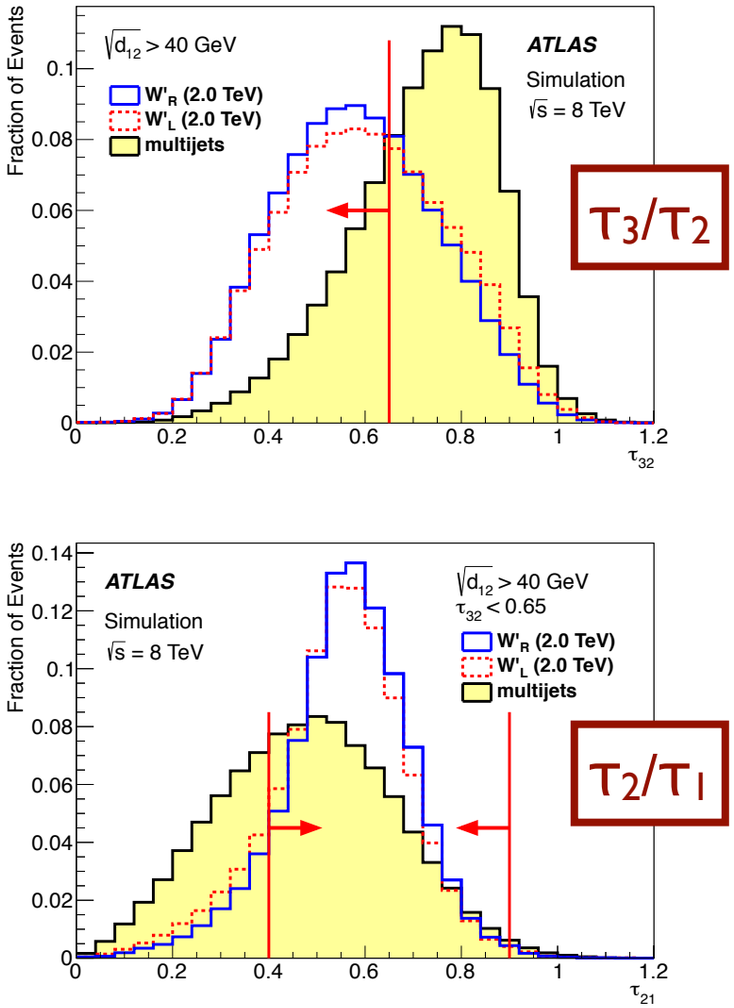


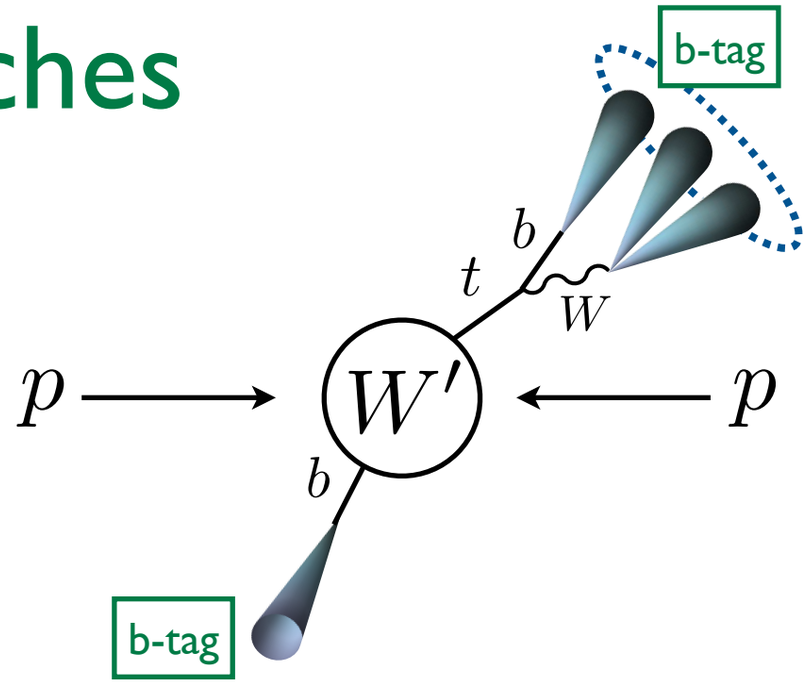
[CMS BTV-13-001]

Boon for New Physics Searches

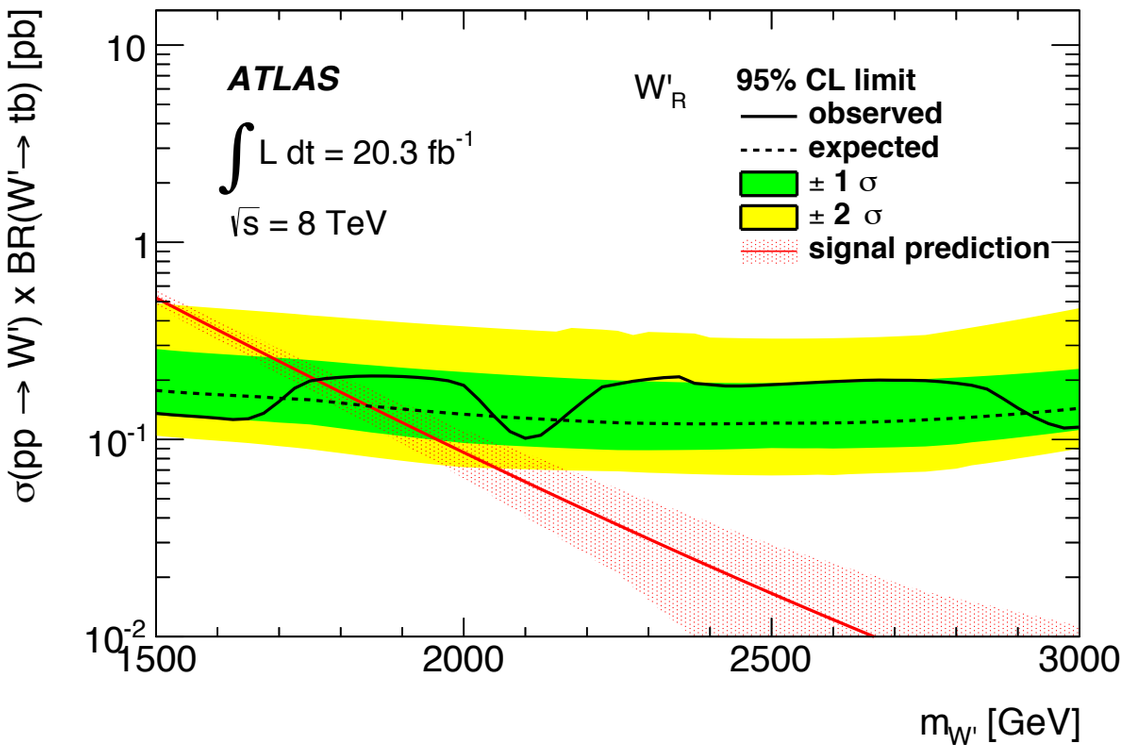
e.g. Heavy W′ Search

Trimming + B-tagging +
k_T Splitting + N-subjettiness



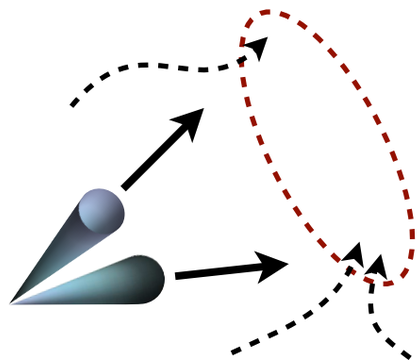


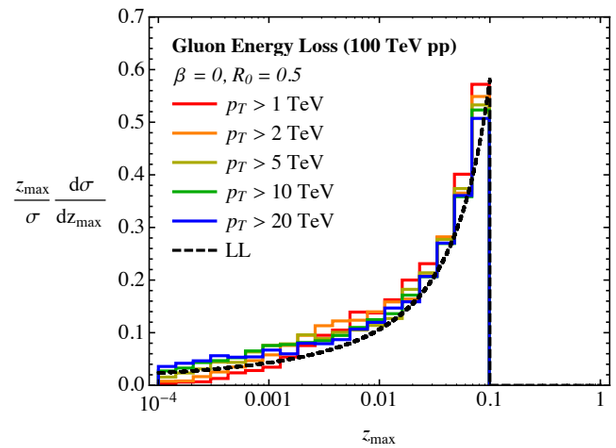
$$W' \to t\bar{b} \to Wb\bar{b} \to q\bar{q}'b\bar{b}$$



[ATLAS,1408.0886]

Уверены ли вы, что на основе вашей схемы можно предсказать существование других частиц? Are you sure that in your scheme extra particles can be predicted?



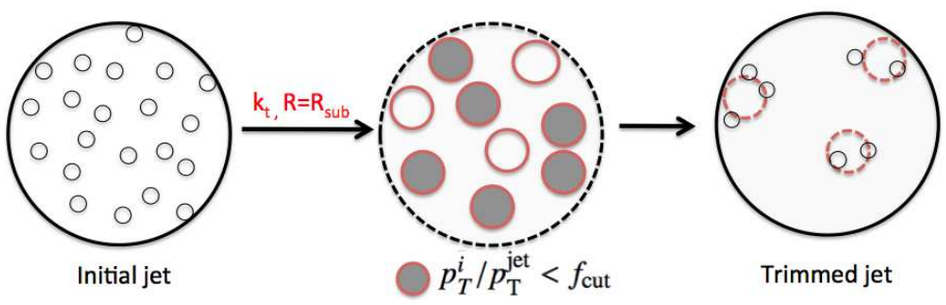


Maximize **discovery** potential of LHC

Enhance **understanding** of QCD

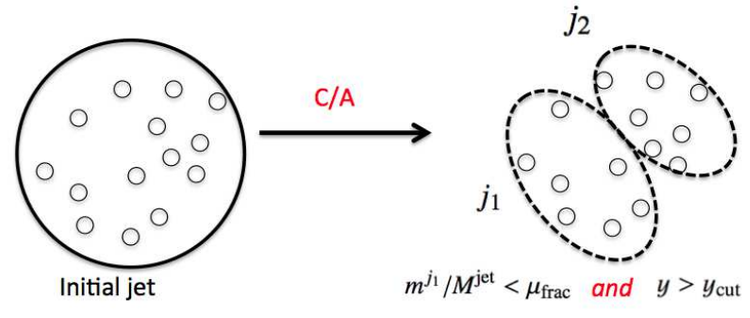
Techniques Inspire Analytics…

Jet Trimming



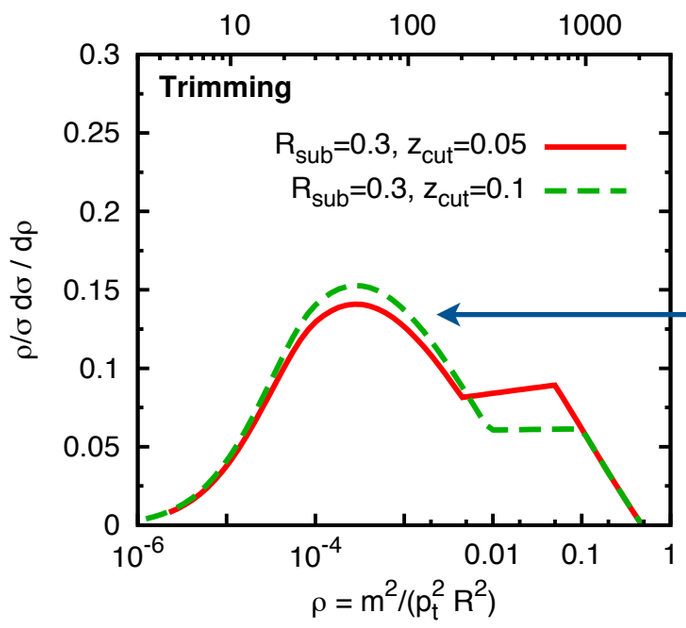
[Krohn, JDT, Wang, 0912.1342]

(Modified) Mass Drop



[Butterworth, Davison, Rubin, Salam, 0802.2470]

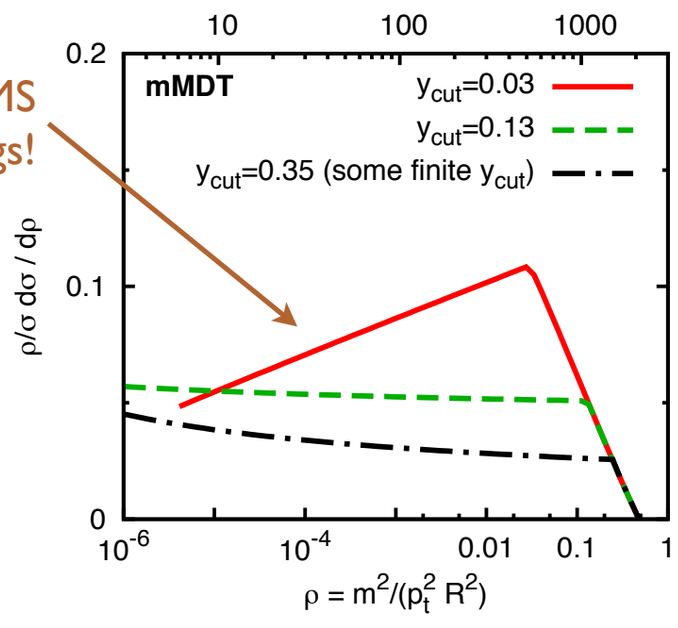
Trimmed Jet Mass



Sudakov Double Logs

Mass-Dropped Jet Mass

DFMS Single Logs!



[Diagrams from ATLAS, 1306.4945]
[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

…Inspire Techniques (and Analytics)…

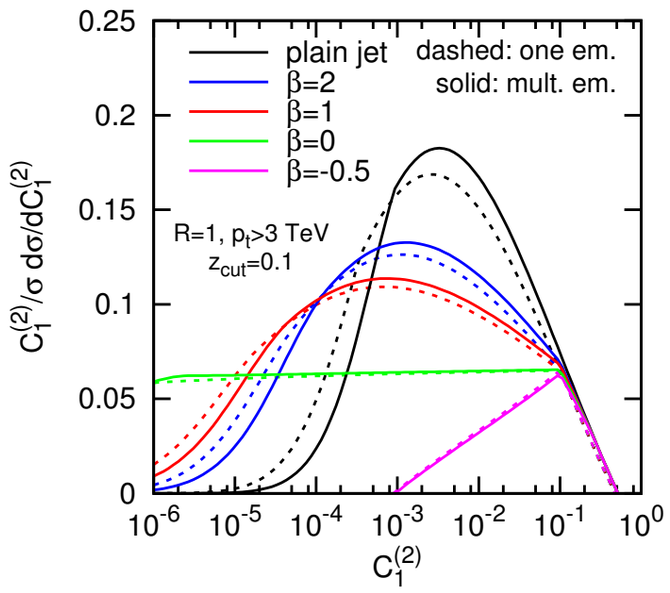
Soft Drop

$\beta = 0$ $\beta > 0$ $\beta \to \infty$

Adjustable — Jet Unchanged

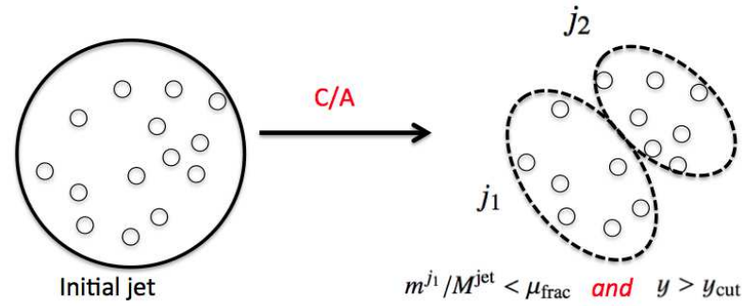
Mass Drop

Soft-Dropped Jet Mass



[Larkoski, Marzani, Soyez, JDT, 1402.2657]

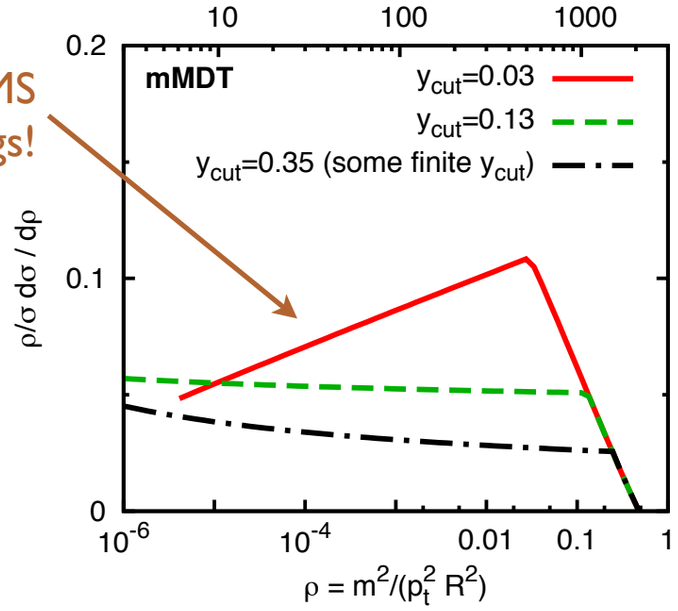
(Modified) Mass Drop



[Butterworth, Davison, Rubin, Salam, 0802.2470]

Mass-Dropped Jet Mass

DFMS
Single Logs!



[Diagrams from ATLAS, 1306.4945]
[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

…Inspire Measurements!

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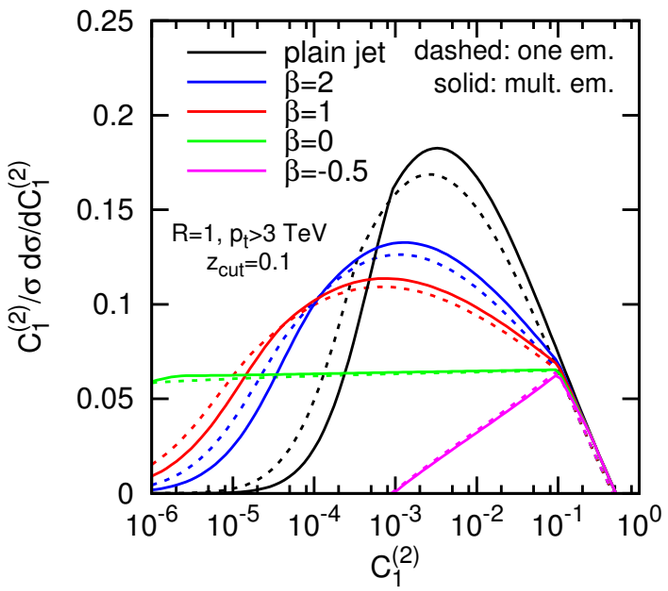
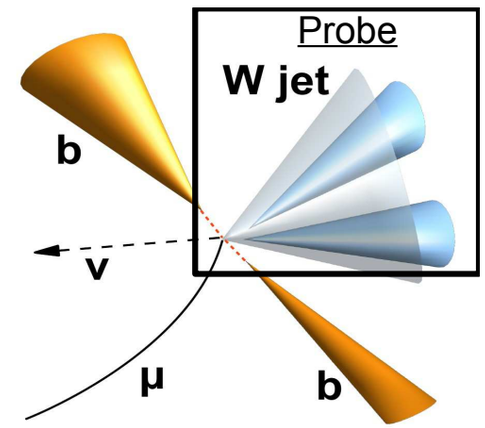
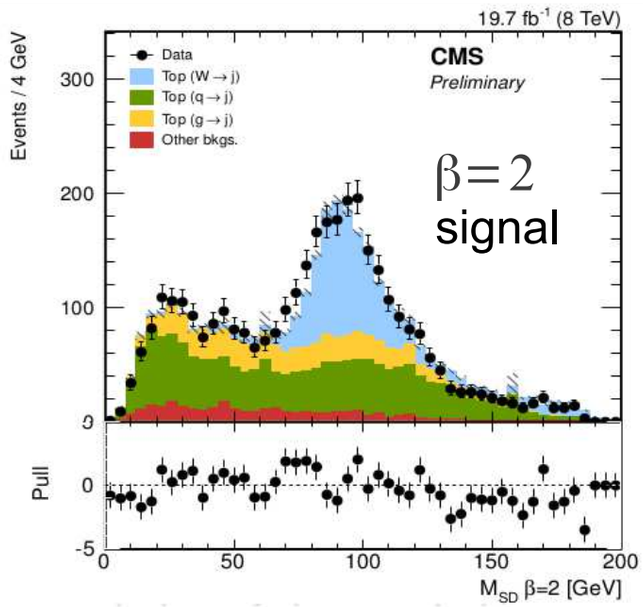
Soft-Dropped Jet Mass



[Larkoski, Marzani, Soyez, JDT, 1402.2657]

CMS W-Tagging Study



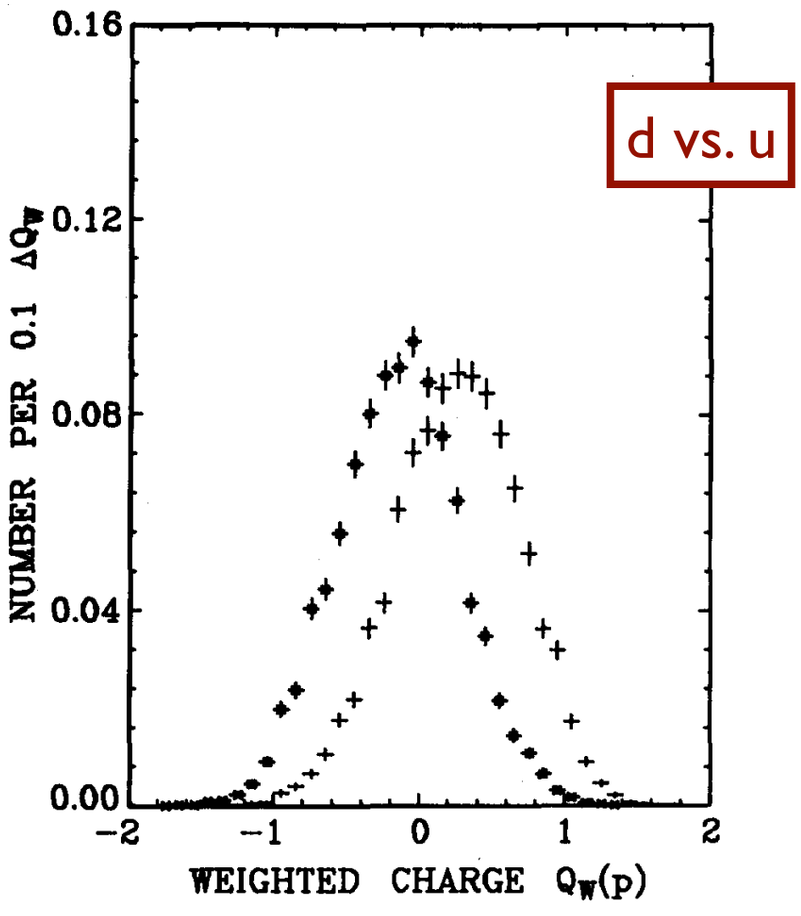


[CMS PAS JME-14-002]

Old Ideas Revisited

Weighted Jet Charge…

$$Q_W(p) = \sum_i z_i^p q_i$$

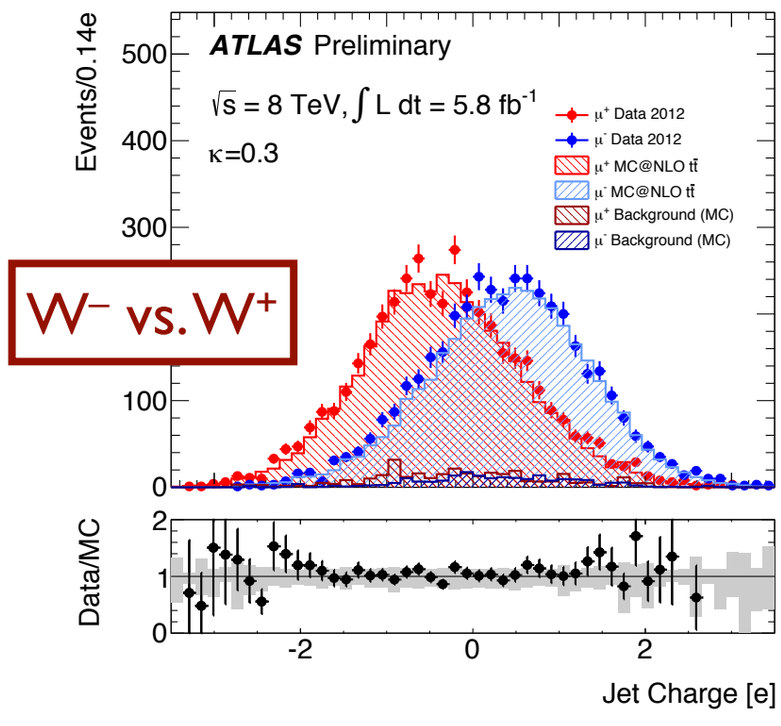


[Feynman, Field, 1978]

…on Firm Theoretical Ground

Generalized Fragmentation Function

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} D_i(Q,\kappa,\mu) = \frac{1}{2}\sum_j \int \mathrm{d}Q_1\,\mathrm{d}Q_2\,\mathrm{d}z\,\gamma_{ij}^D(z,\mu) \times D_j(Q_1,\kappa,\mu) D_{a(ij)}(Q_2,\kappa,\mu) \times \delta[Q - z^\kappa Q_1 - (1-z)^\kappa Q_2]$$



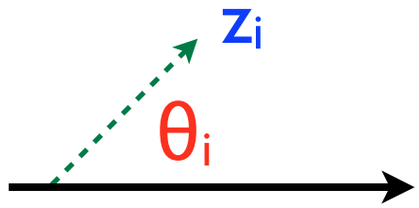
[Krohn, Schwartz, Lin, Waalewijn, 1209.2421; Waalewijn, 1209.3019]
[ATLAS-CONF-2013-086]

New Calculational Paradigms

Angularities:

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

energy fraction — angle to axis

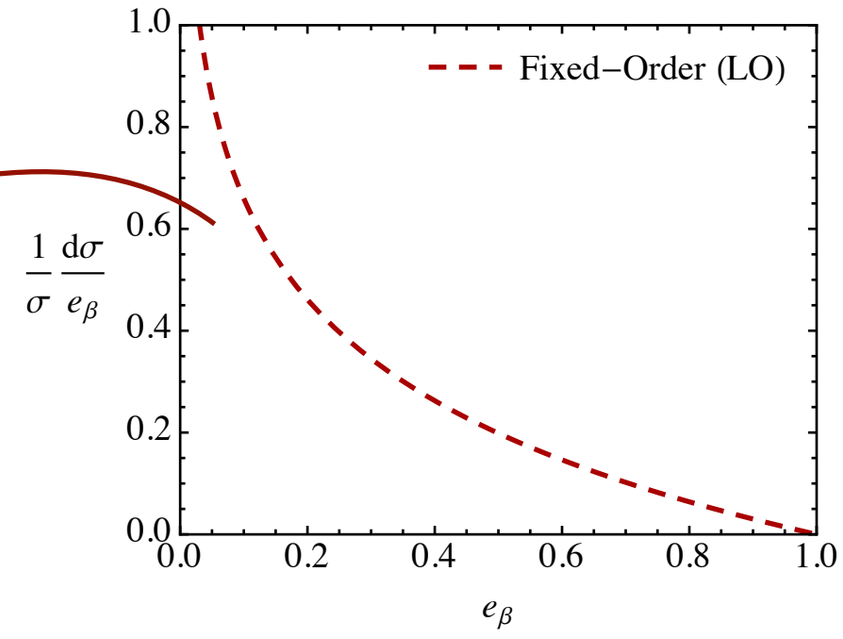


Ratio Observables:

(Ubiquitous in Jet Substructure)

$$r = \frac{e_\alpha}{e_\beta}$$

Divide by Zero
⇒ Infrared Unsafe



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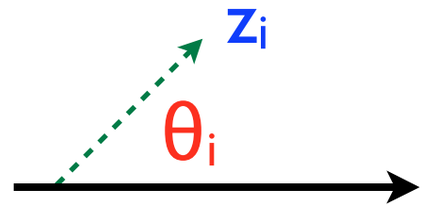


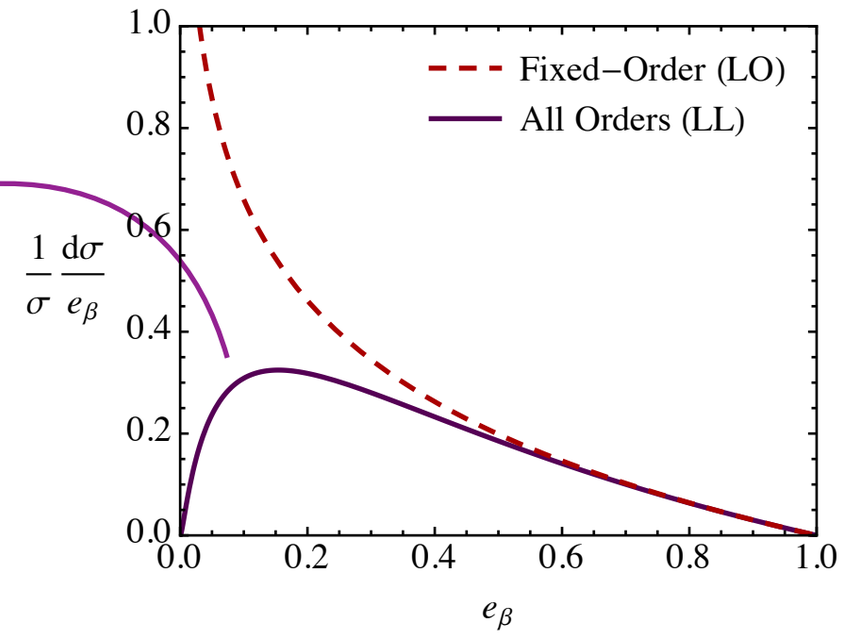
energy fraction angle to axis

Ratio Observables:

(Ubiquitous in Jet Substructure)

$$r = \frac{e_\alpha}{e_\beta}$$

Sudakov Form Factor
⇒ "Sudakov Safe"



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

Unsafe…but Calculable

[Larkoski, JDT, 1307.1699]

A Standard Candle for Jets?

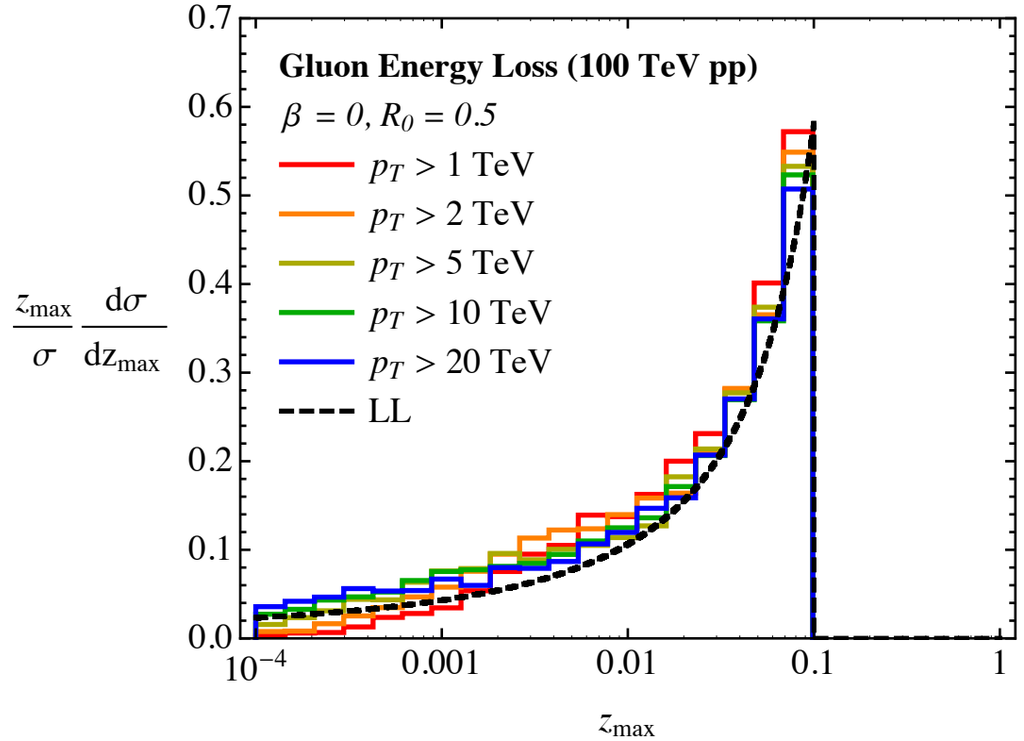
Soft Drop ($\beta \to 0$)

(a.k.a Modified Mass Drop)

Fractional Energy Loss

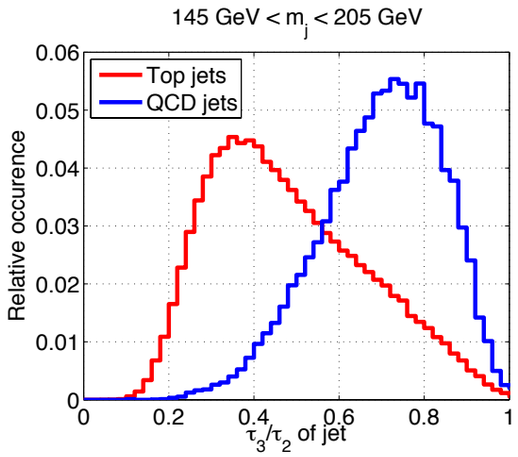
$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\log\Delta_E}\right|_{\beta=0} \propto \frac{1}{\log^2\Delta_E}$$

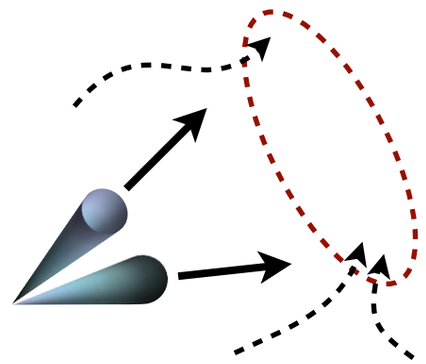
no α_s at fixed coupling (!)
≈ independent of quark vs. gluon
≈ independent of jet p_T, jet radius

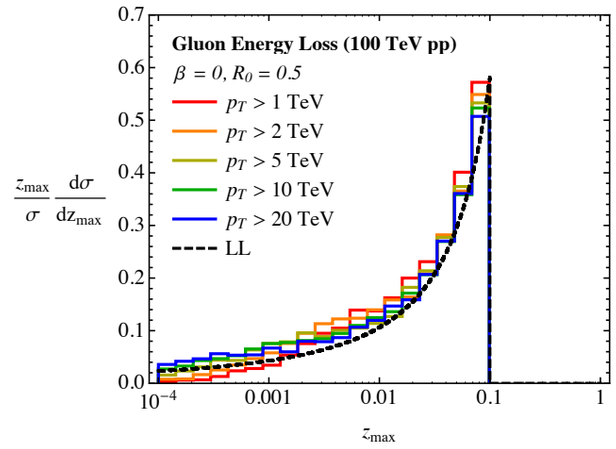


[Larkoski, Marzani, Soyez, JDT, 1402.2657; Larkoski, JDT, 1406.7011]

The Case for Jet Substructure







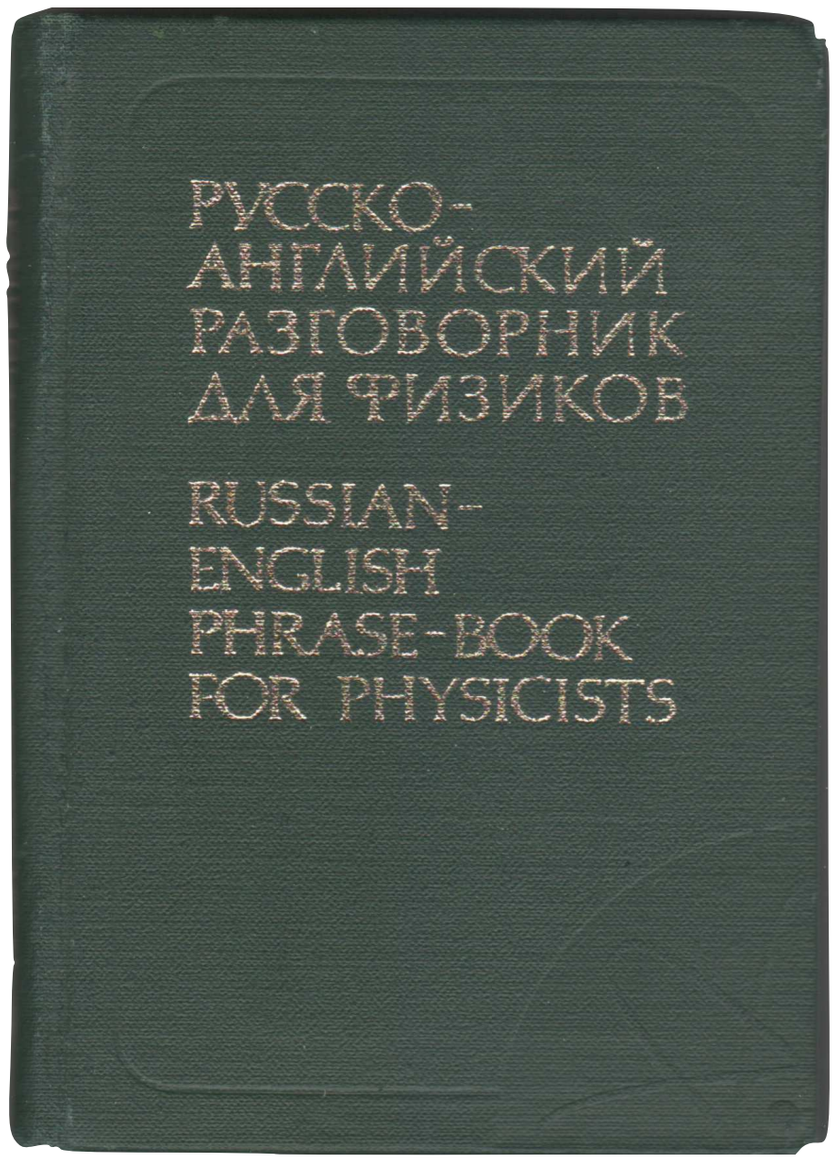
Exceptional LHC performance + Extreme kinematics + Jet contamination + (B)SM physics

Maximize **discovery** potential of LHC

Creative analysis strategies for hadronic final states

Enhance **understanding** of QCD

New analytic results in (non)perturbative field theory



Вопрос. Question

У меня есть к вам вопрос. I have a question.

Разрешите мне задать вам вопрос? May I ask you a question?

Есть ли ещё какие-нибудь вопросы? Any other questions?

Мой вопрос заключается в следующем... My question is the following... [is as follows...]

Если больше нет вопросов, то мы перейдём к... If there are no more questions we shall go on to...

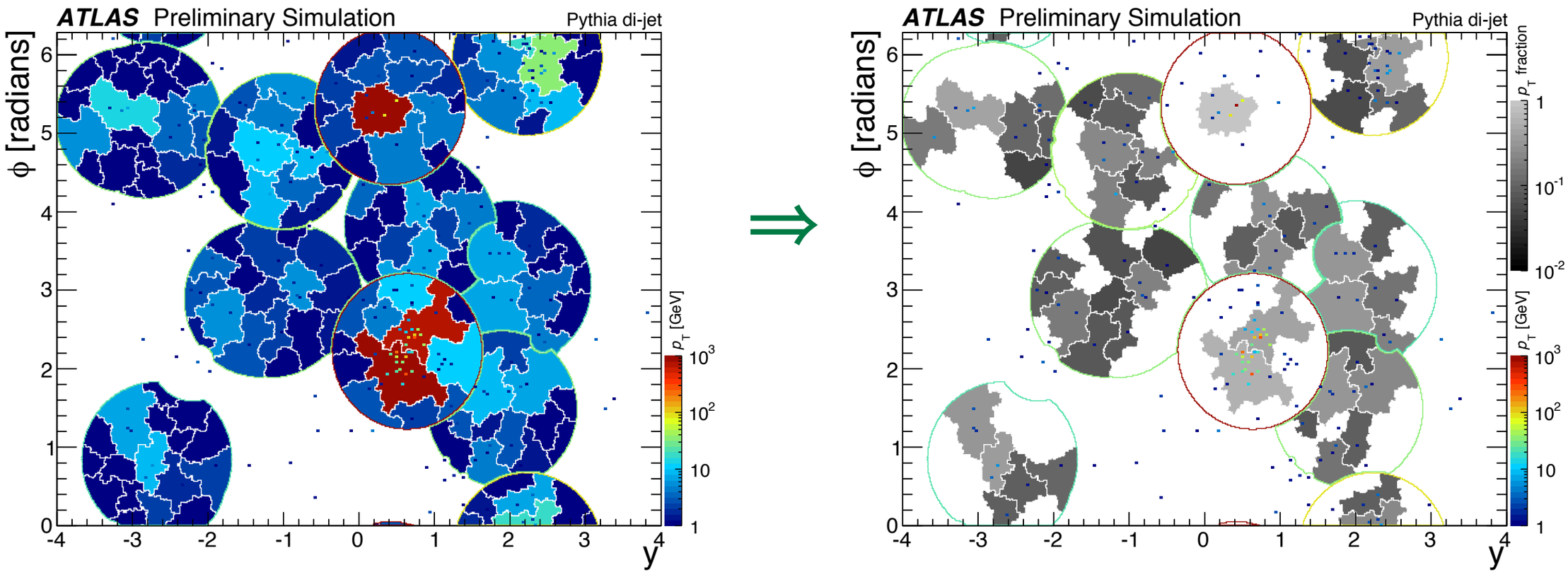
Я с удовольствием отвечу на ваши вопросы. I shall be very happy to answer questions.

У меня есть к вам один вопрос частного характера... Now there's something special I want to ask you...

Backup Slides

The Case for Jet Substructure

Maximize **discovery** potential of LHC

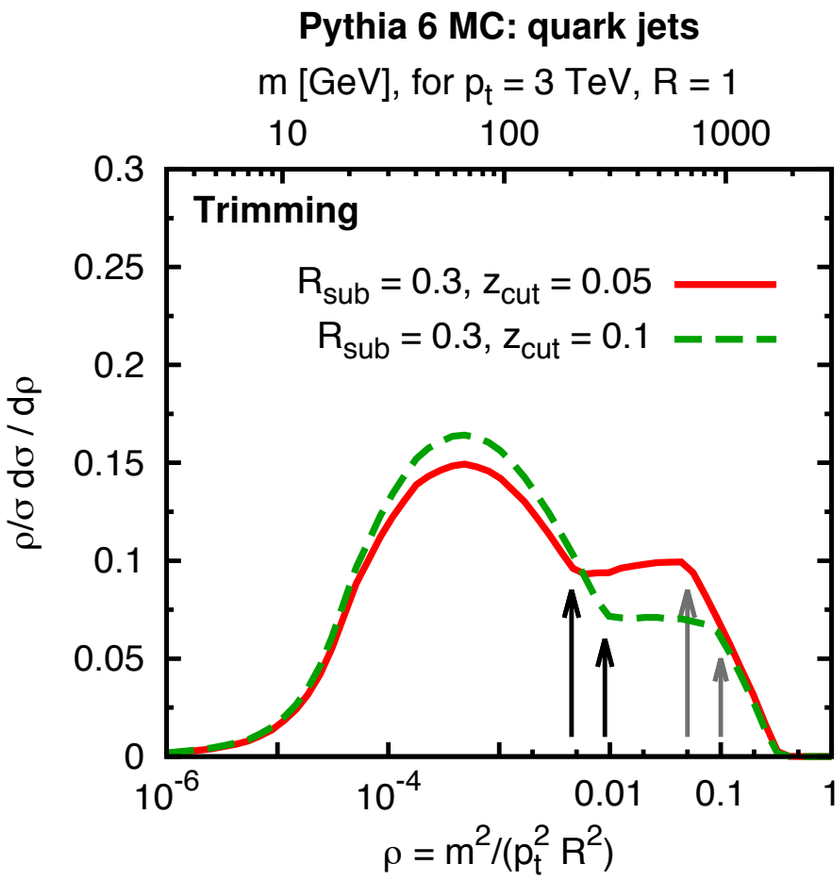


Creative analysis strategies for hadronic final states

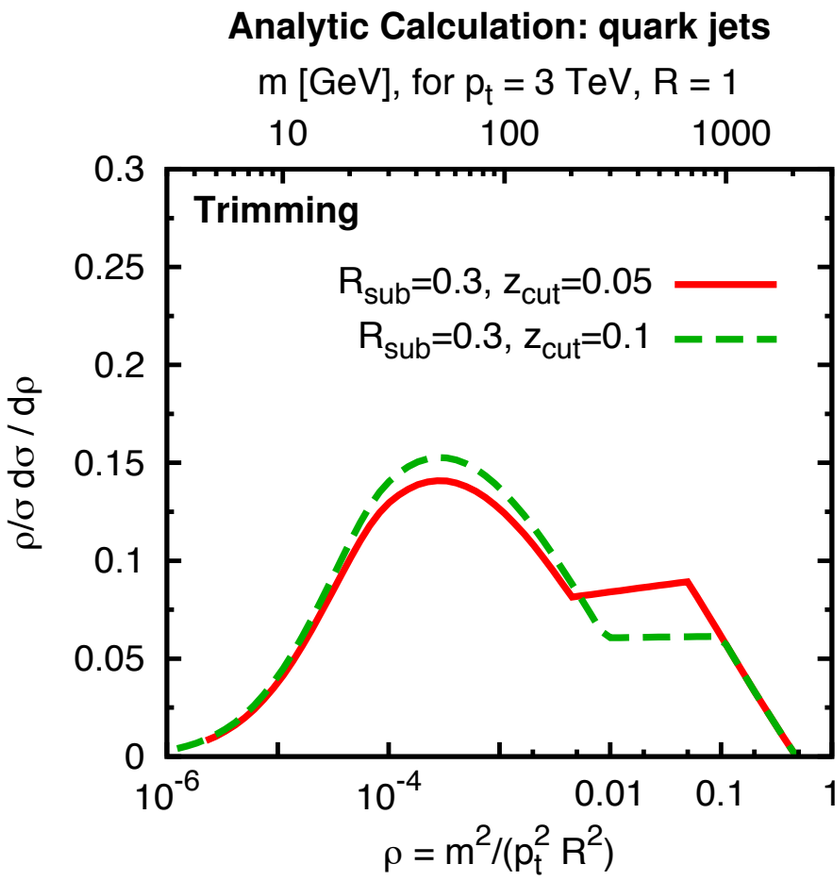
[Using Jet Trimming: Krohn, JDT, Wang, 0912.1342]

The Case for Jet Substructure

Enhance **understanding** of QCD



vs.



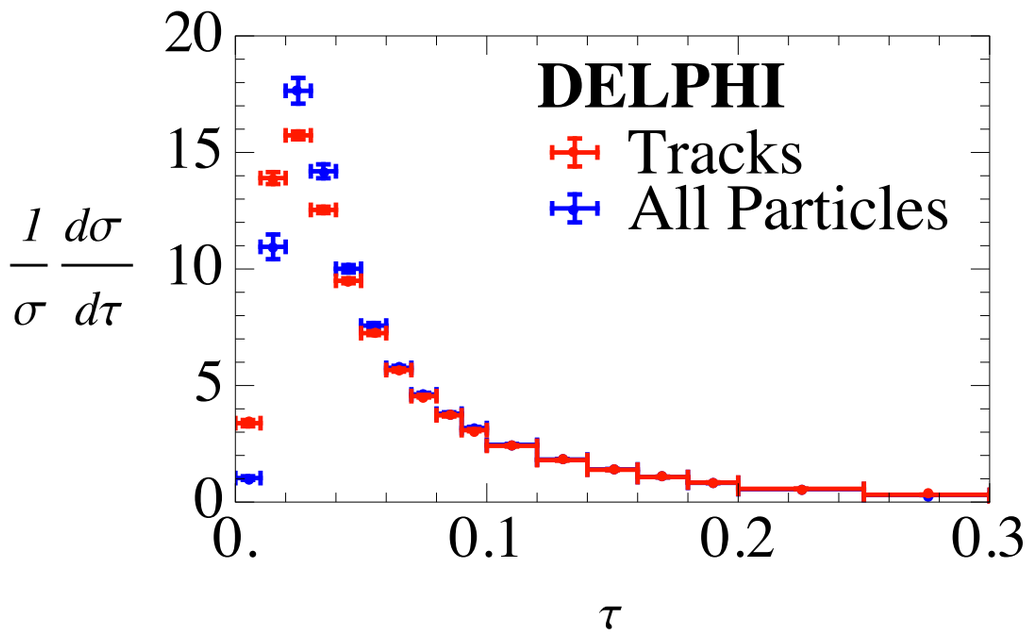
New analytic results in (non)perturbative field theory

[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

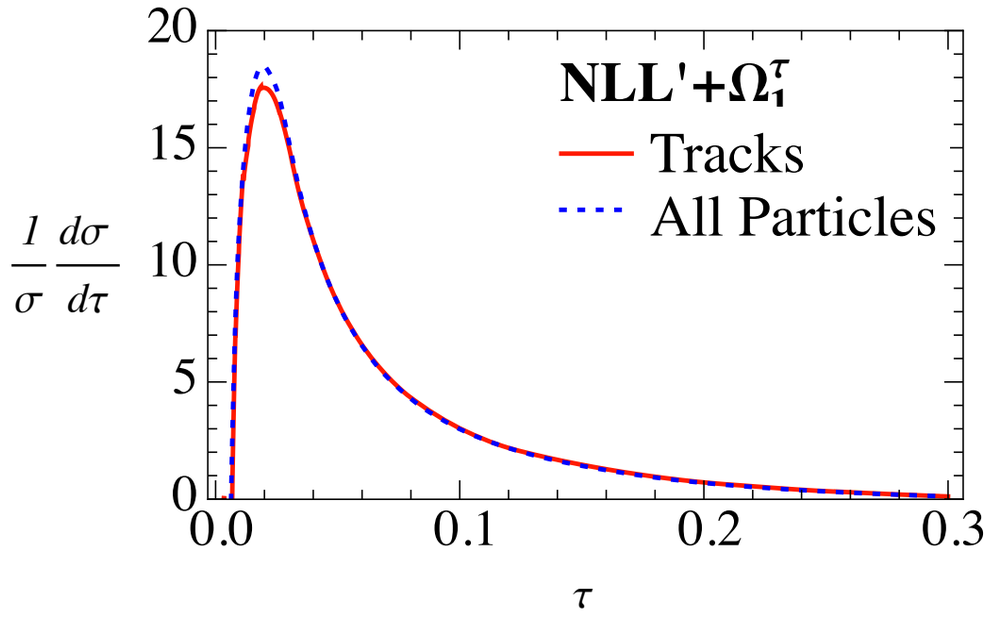
Old Measurements Revisited

Track-Based Observables

Thrust @ LEP



SCET + "Track Functions"



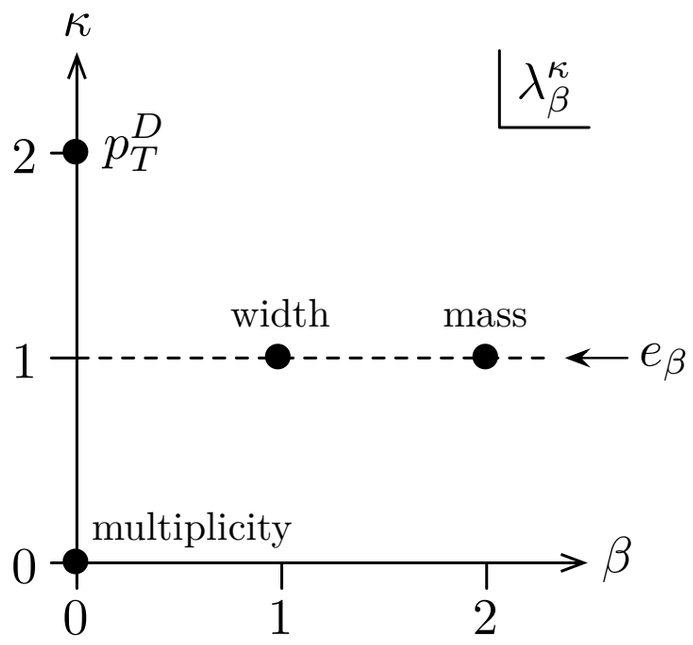
Theme: Non-perturbative Objects with Perturbative Evolution

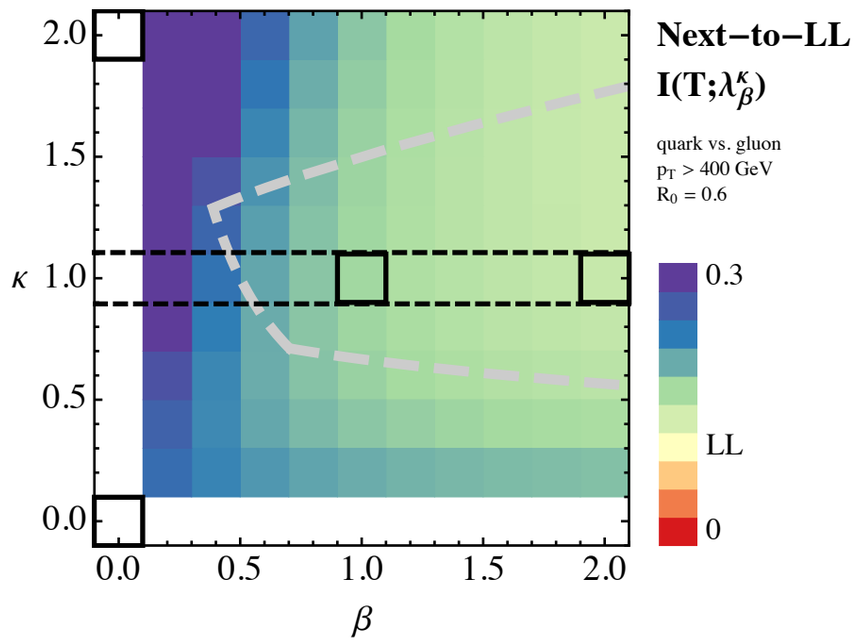
[Chang, Procura, JDT, Waalewijn, 1303.6637, 1306.6630]

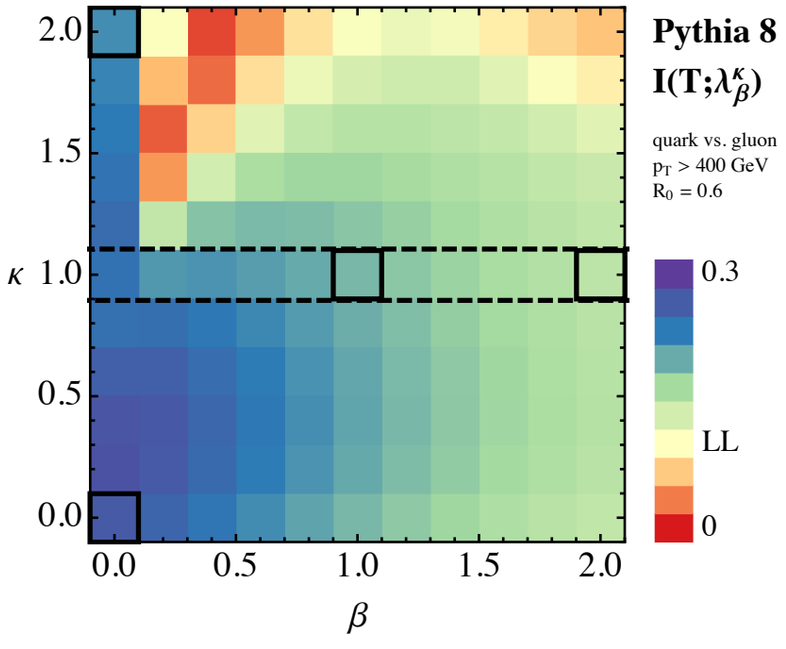
New Measurements Required

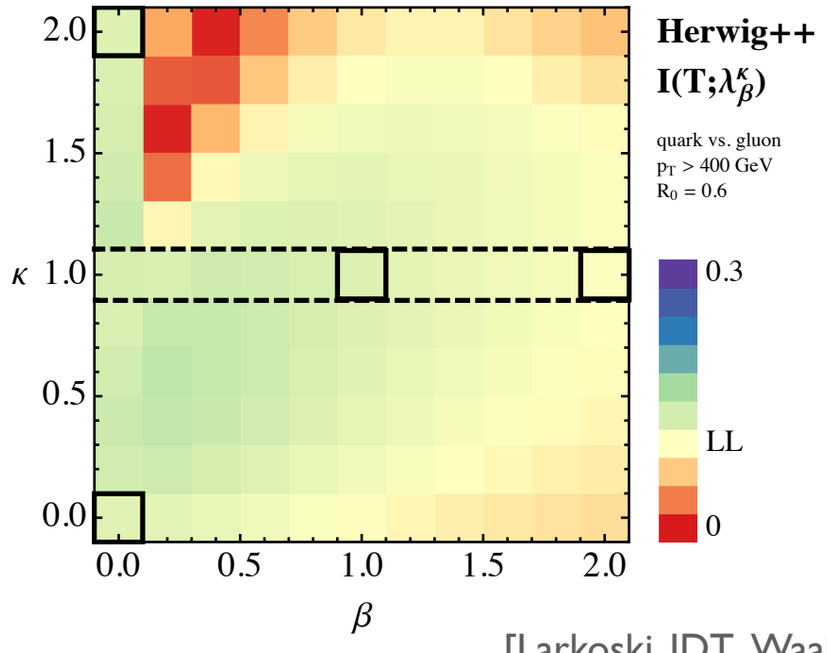
$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta$$

Quark/Gluon Truth Overlap









[Larkoski, JDT, Waalewijn, 1408.3122]

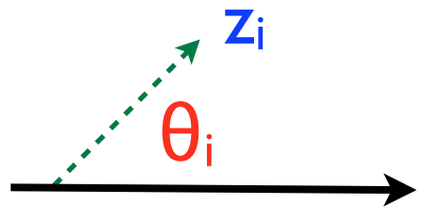
Reconsidering Old Assumptions

Recoil-Sensitive vs. Recoil-Free Angularities

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

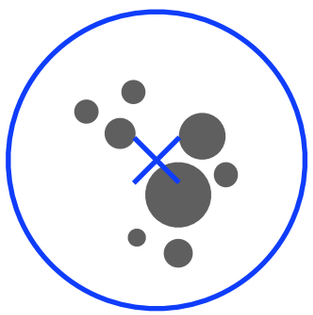
energy fraction — angle to axis

Measure of gluon radiation about hard jet core

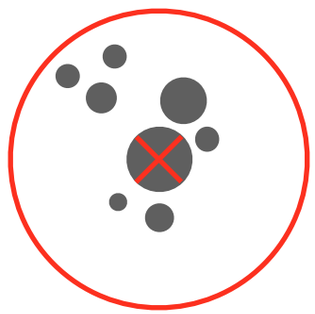


Which Axis?

Recoil-Free: Measurement Axis ≈ Hard Parton



Jet Momentum Axis (Mean)



Winner-Take-All Axis (Median)

[Bertolini, Chan, JDT, 1310.7584; Larkoski, Neill, JDT, 1401.2158; Salam, unpublished]

Было бы преждевременно говорить о справед-ливости этой теории. It would be premature to comment on the validity of this theory.