Unsafe but Calculable

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MIT

University of Toronto, THEP Seminar — December 8, 2015

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

New Lore:

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

Sudakov Safety

[Andrew Larkoski, JDT, 1307.1699, 1406.7011]
[Andrew Larkoski, Simone Marzani, Gregory Soyez, JDT, 1402.2657]
[Andrew Larkoski, Simone Marzani, JDT, 1502.01719]

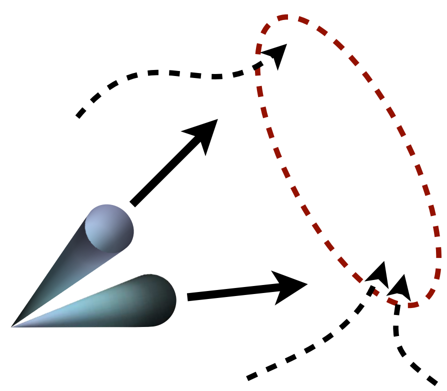
Offline: Generalized Fragmentation Functions

[Hsi-Ming Chang, Massimiliano Procura, JDT, Wouter Waalewijn, 1303.6637, 1306.6630]
[Andrew Larkoski, JDT, Wouter Waalewijn, 1408.3122]

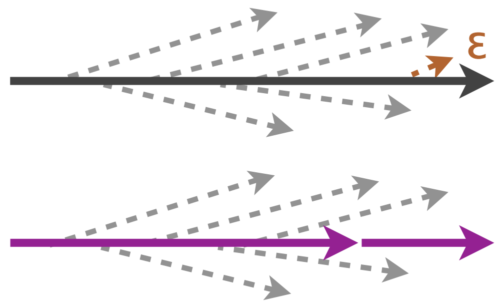
All observables are calculable,
but some observables are
more calculable than others.

≈ George Orwell, *Animal Farm*

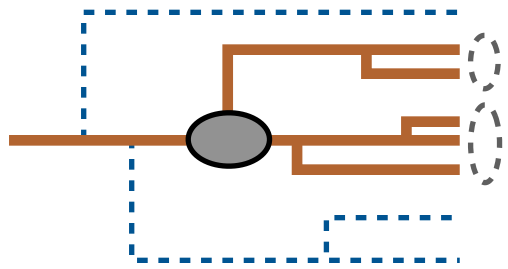
Outline



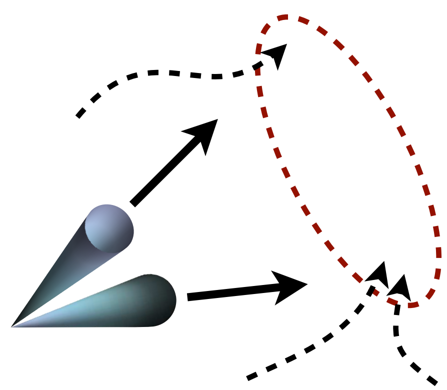
Inspiration from Jet Substructure



From IRC Safe to Sudakov Safe



Probing the Core of QCD

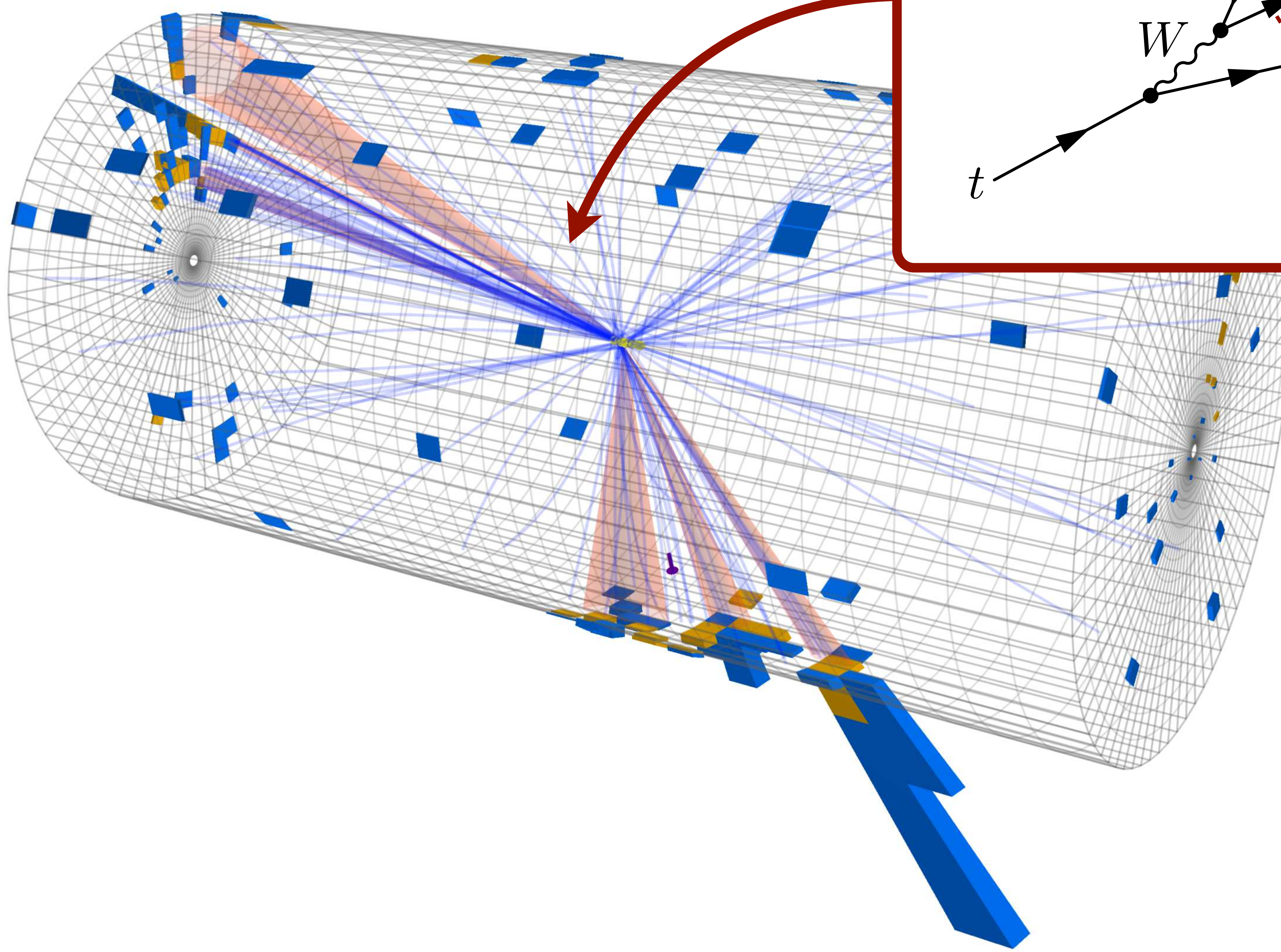


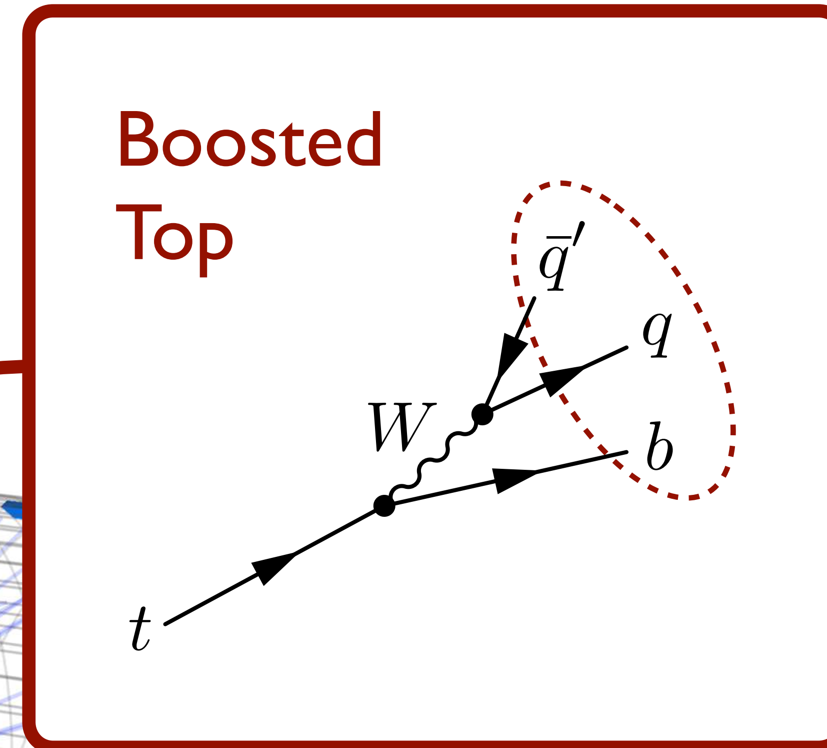
Inspiration from Jet Substructure

From IRC Safe to Sudakov Safe

Probing the Core of QCD

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253

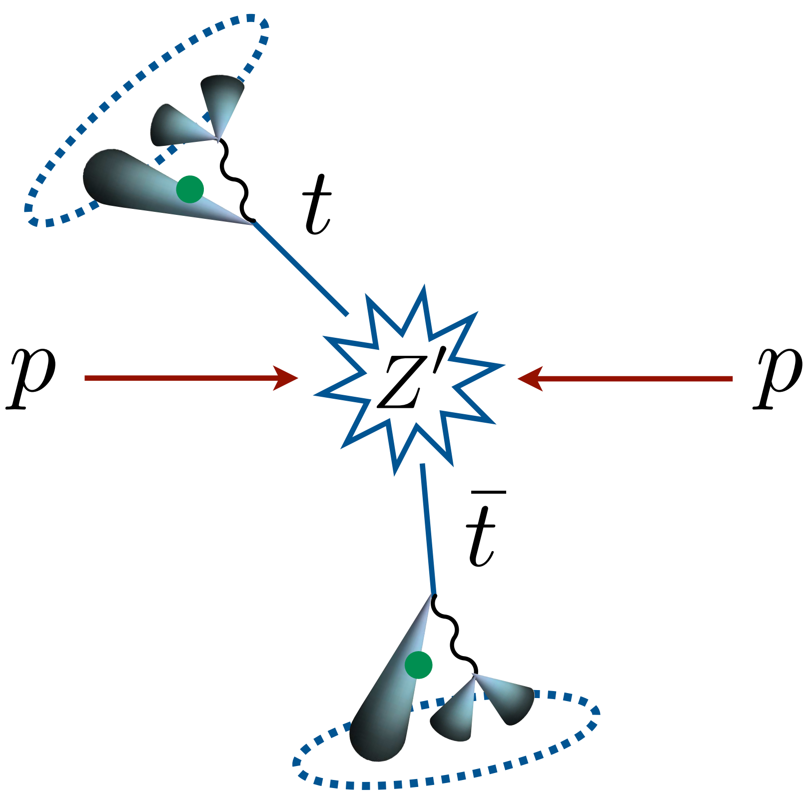


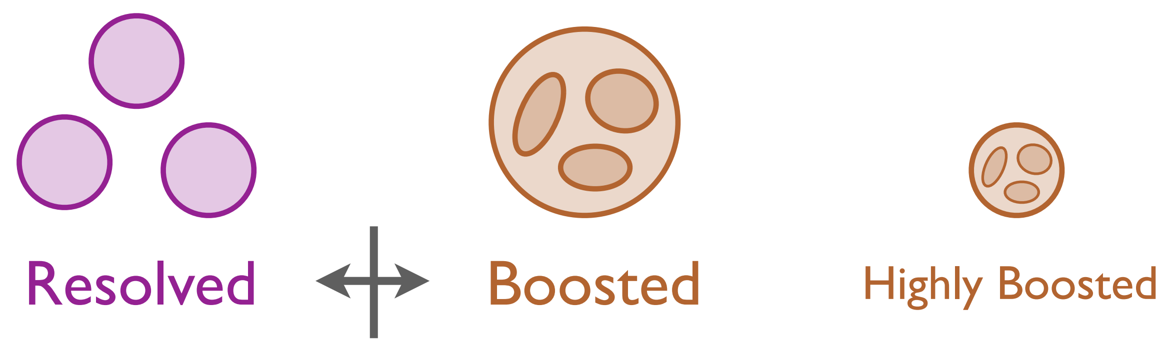


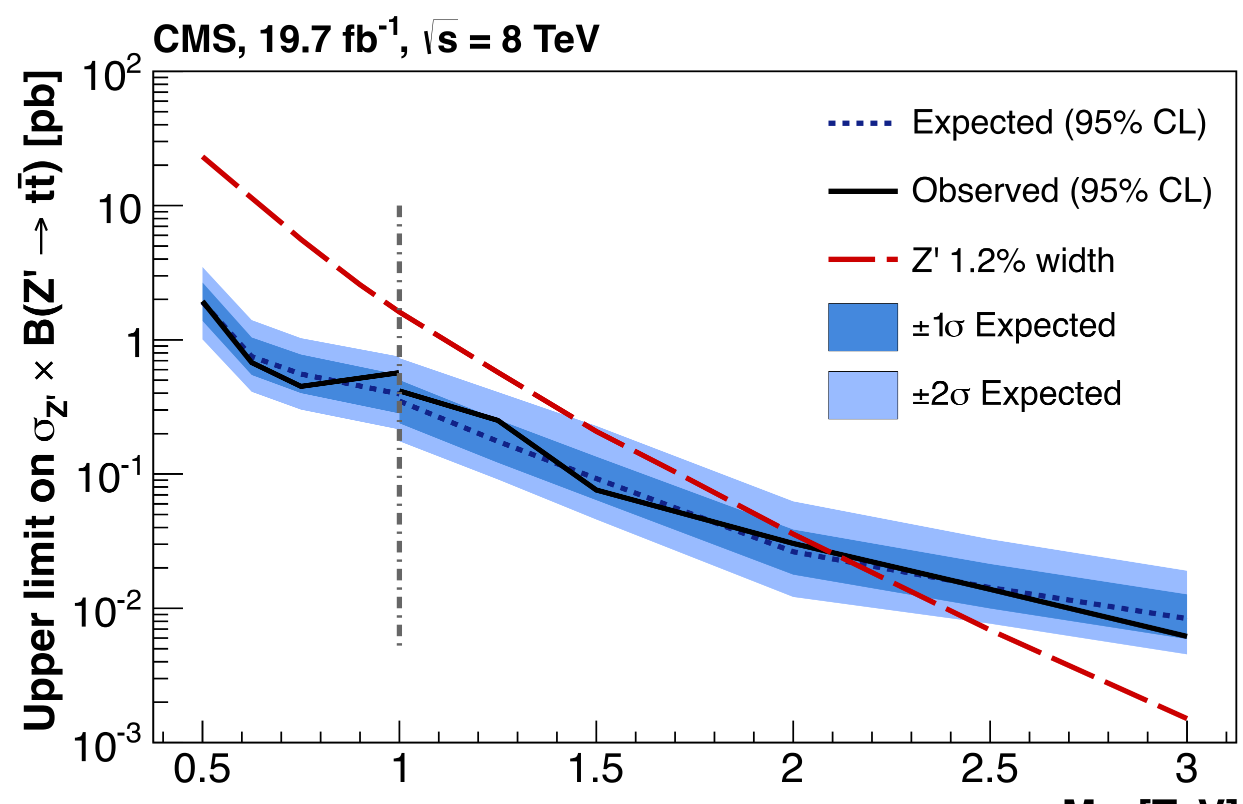
[CMS 2011, 2013, 2015]
[using Kaplan, Rehermann, Schwartz, Tweedie, 2008; using Ellis, Vermilion, Walsh, 2009]

High Energy ⇒ Boosted Regime

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

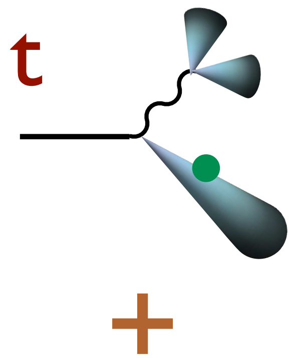


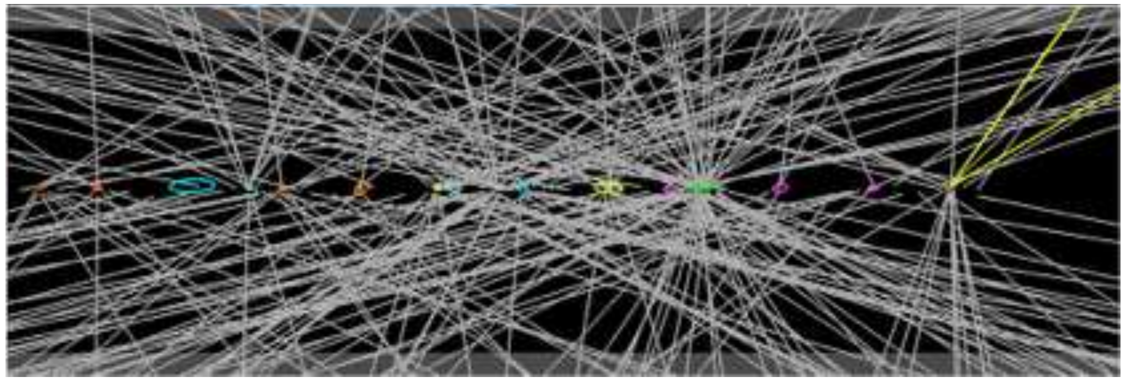


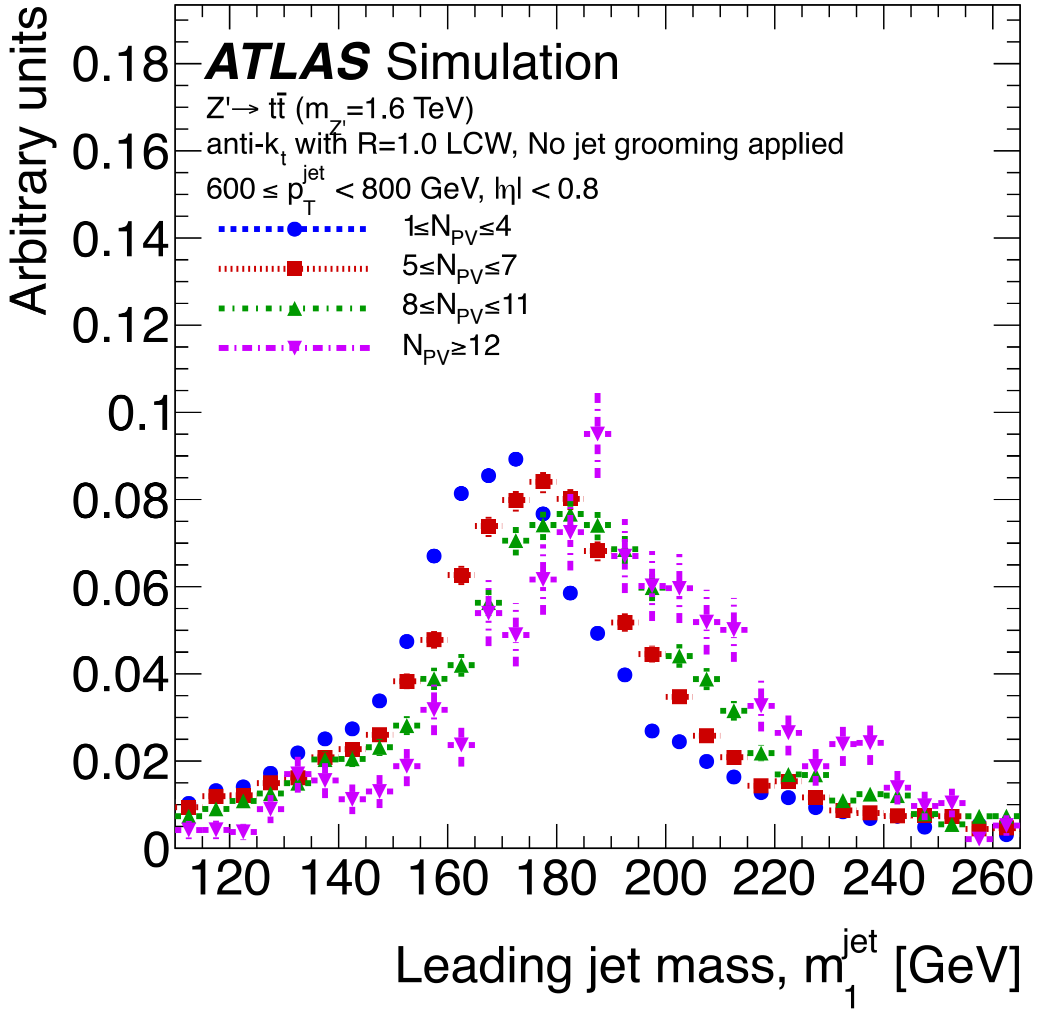


[CMS, 2013, 2015]

High Luminosity ⇒ Pileup

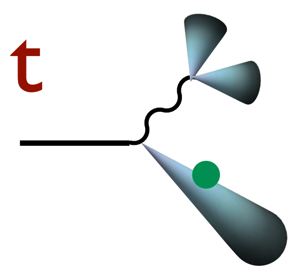






[ATLAS, 2012]

High Luminosity ⇒ Pileup



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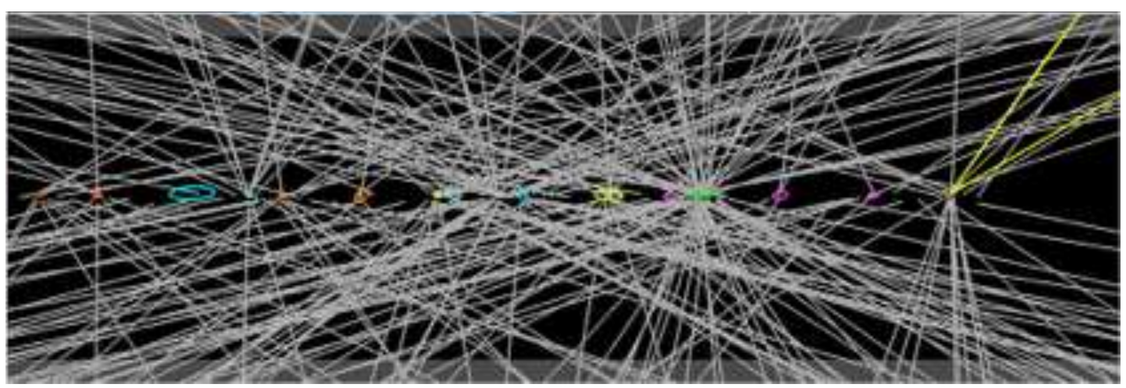

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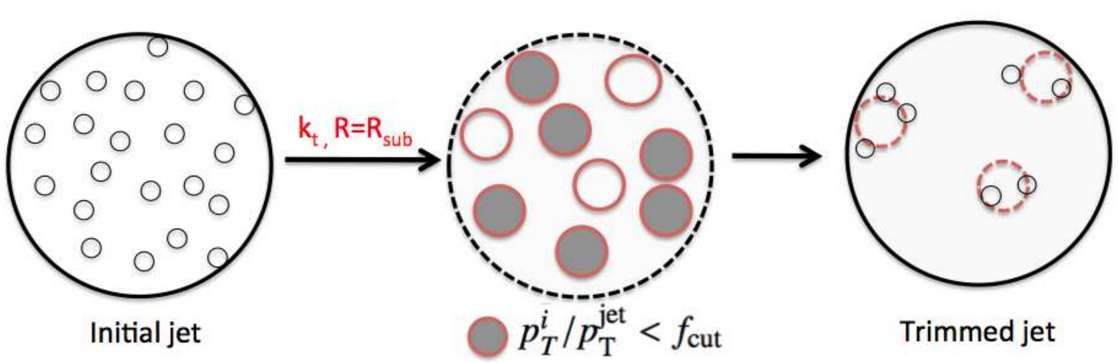
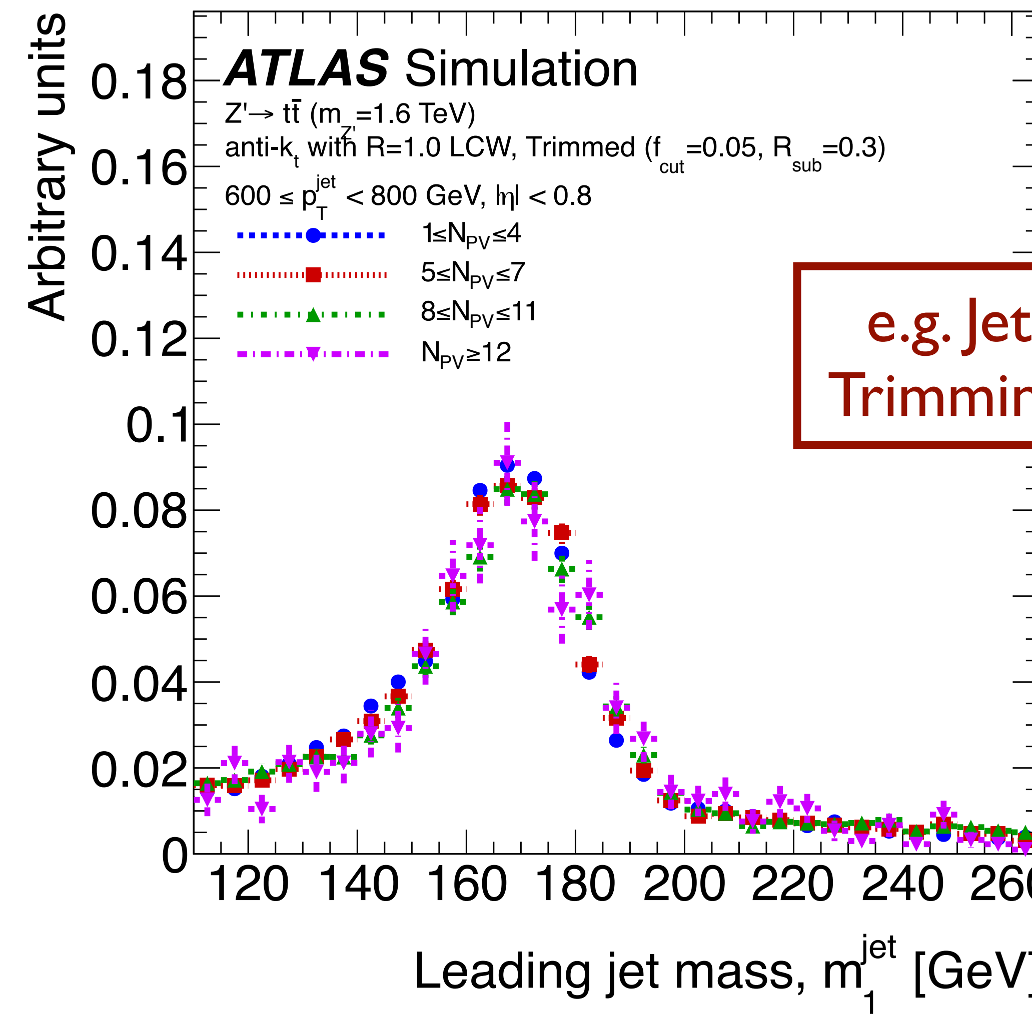
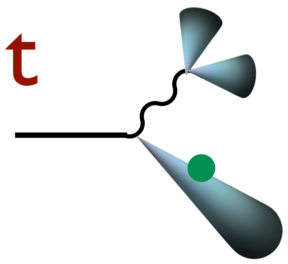


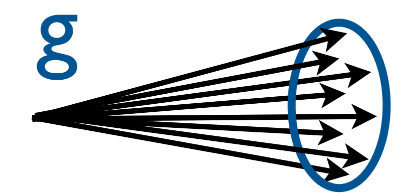


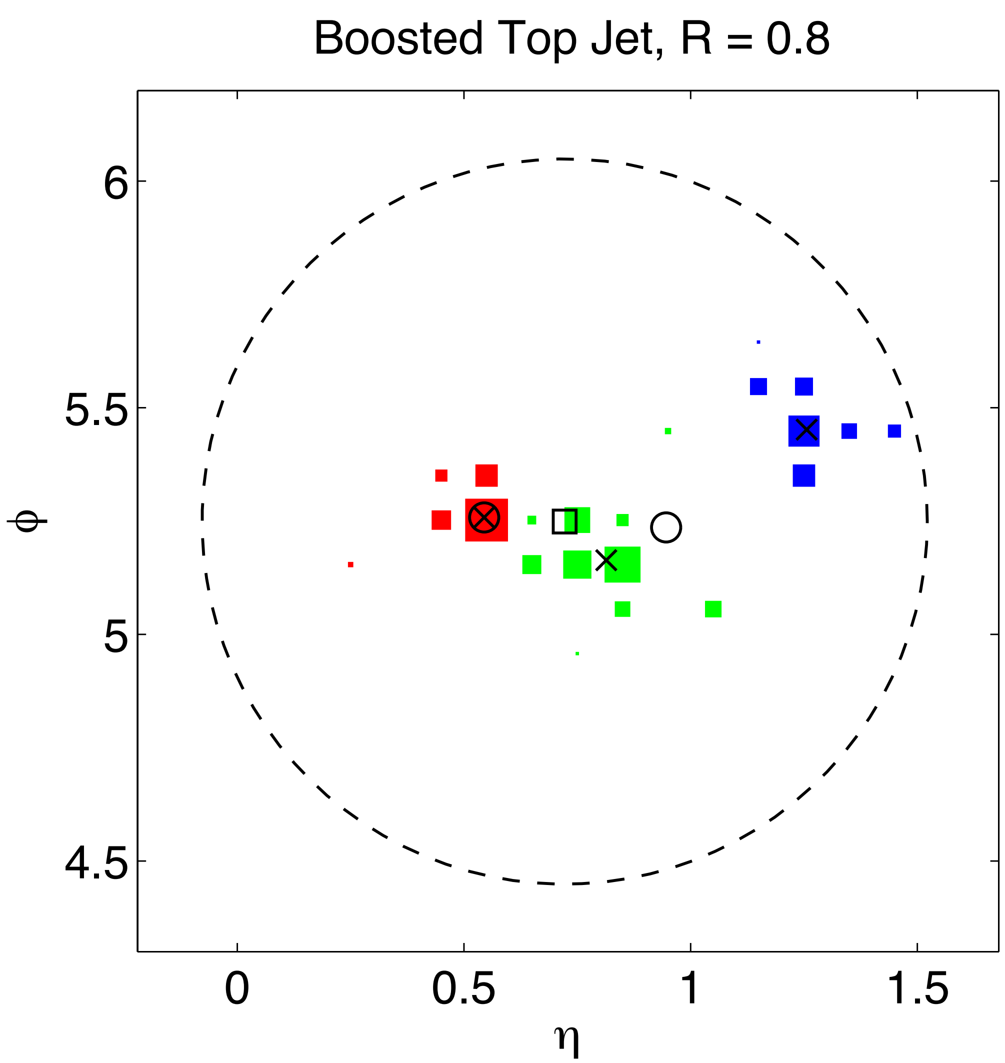
e.g. Jet Trimming

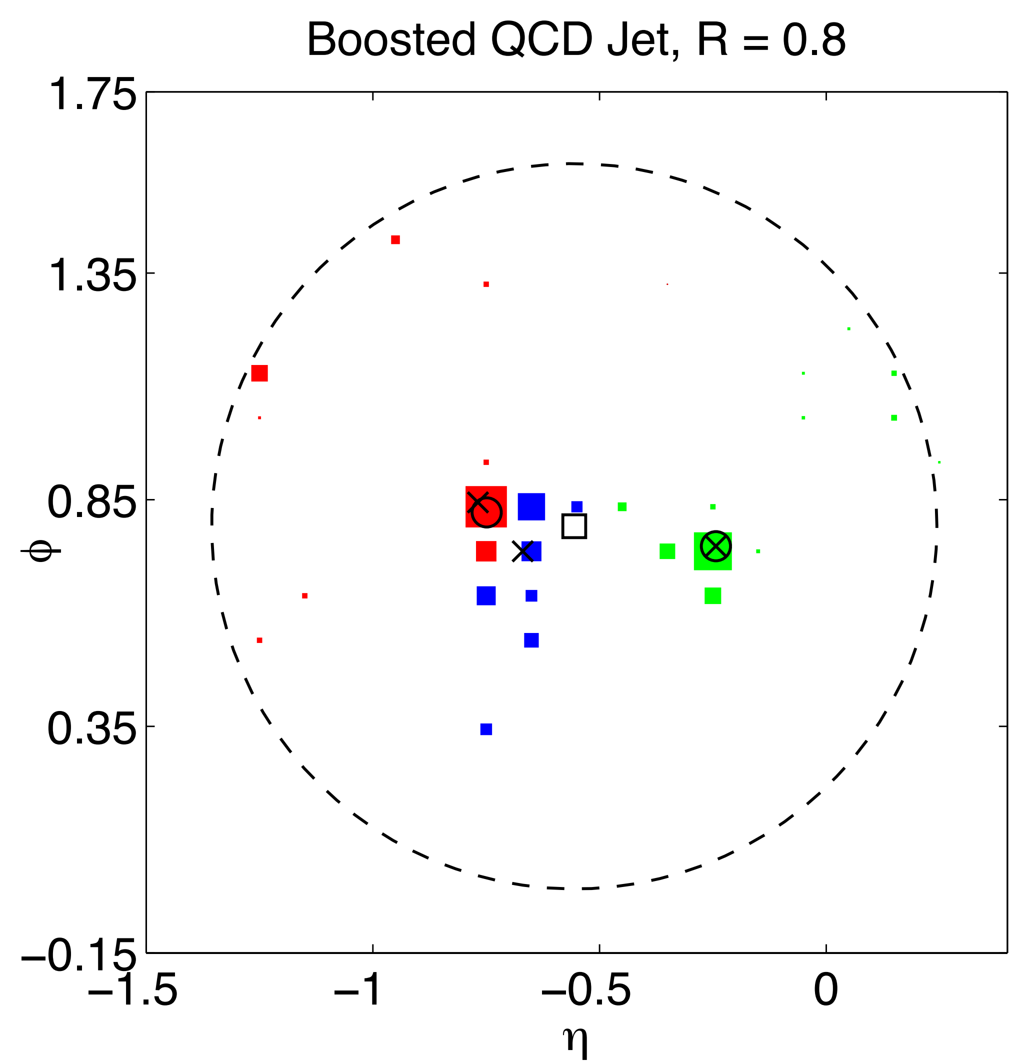
[ATLAS, 2012; using Krohn, JDT, Wang, 2009]



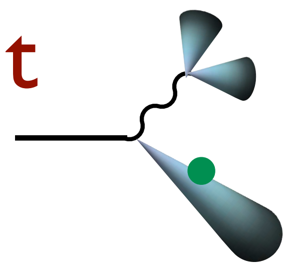
N-Prong vs. 1-Prong



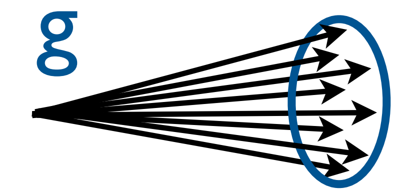


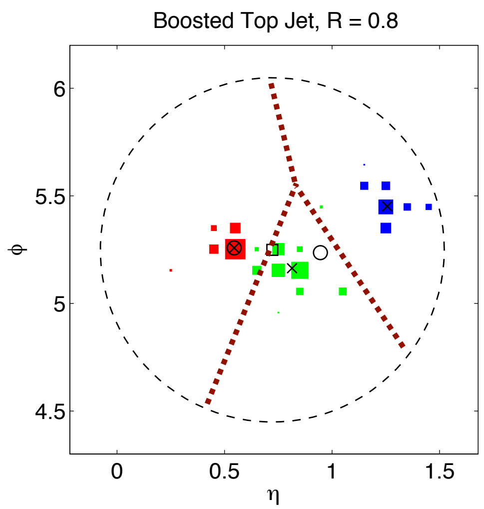


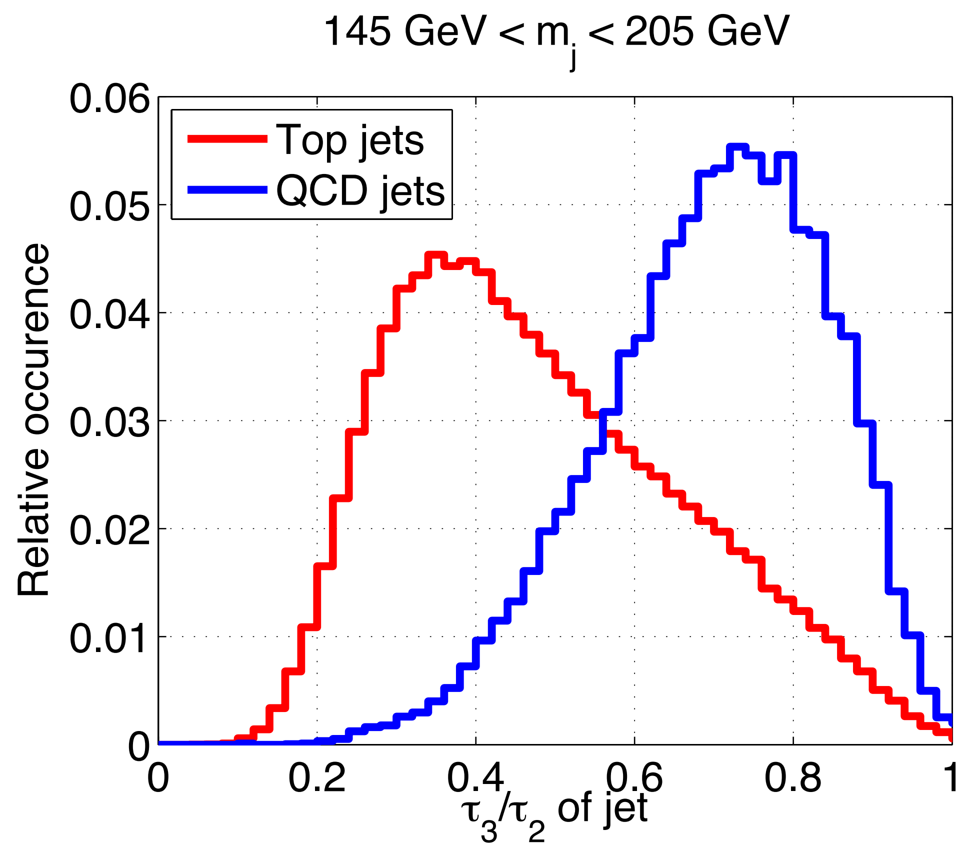
(Both jets have m ≈ 170 GeV)

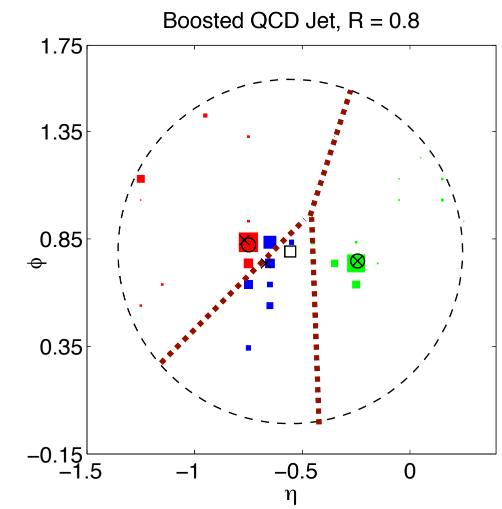


N-Prong vs. 1-Prong









N-subjettiness

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

transverse momentum

distance to subjet core

angular exponent

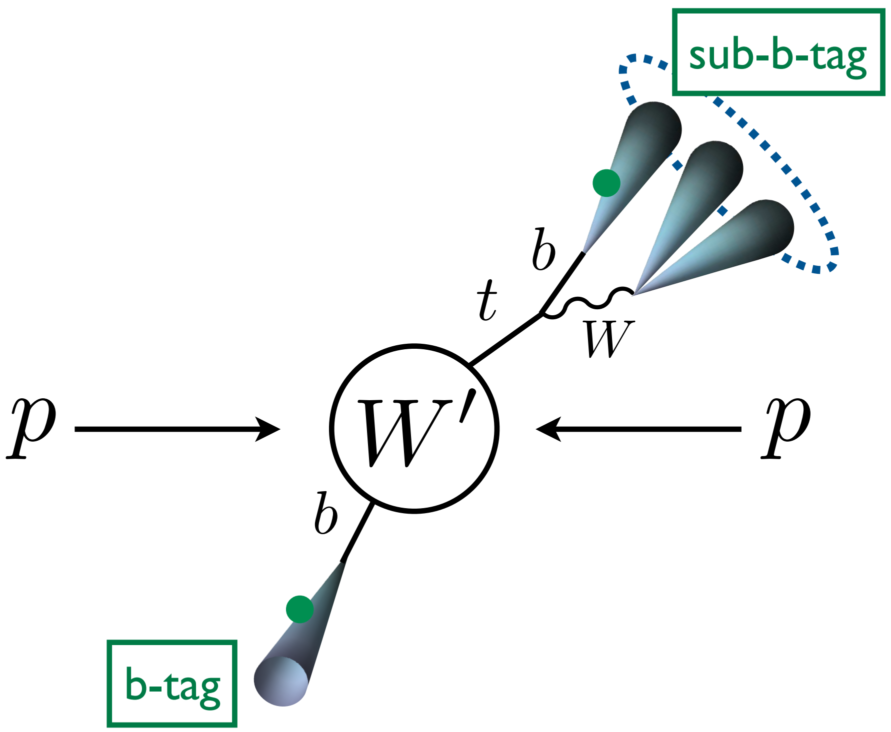
τ_3/τ_2: $\boxed{t \to bW}$

τ_2/τ_1: $\boxed{\begin{array}{c} H \to b\bar{b} \\ Z \to q\bar{q} \\ W \to q\bar{q}' \end{array}}$

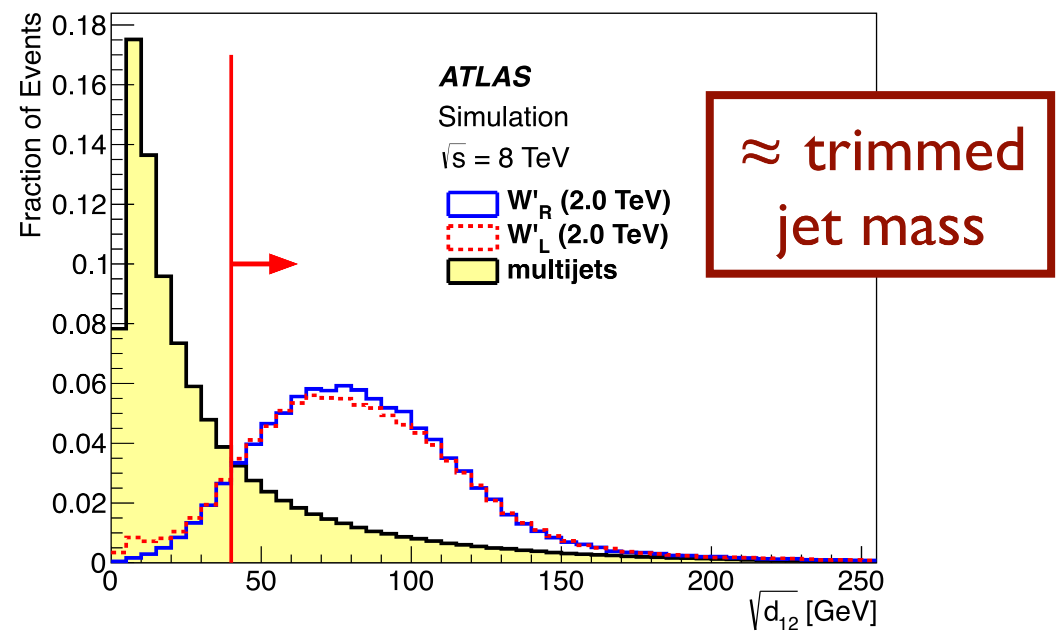
[JDT, Van Tilburg, 2010, 2011]
[see also Stewart, Tackmann, Waalewijn, 2010; Larkoski, Moult, Neill, 2014]

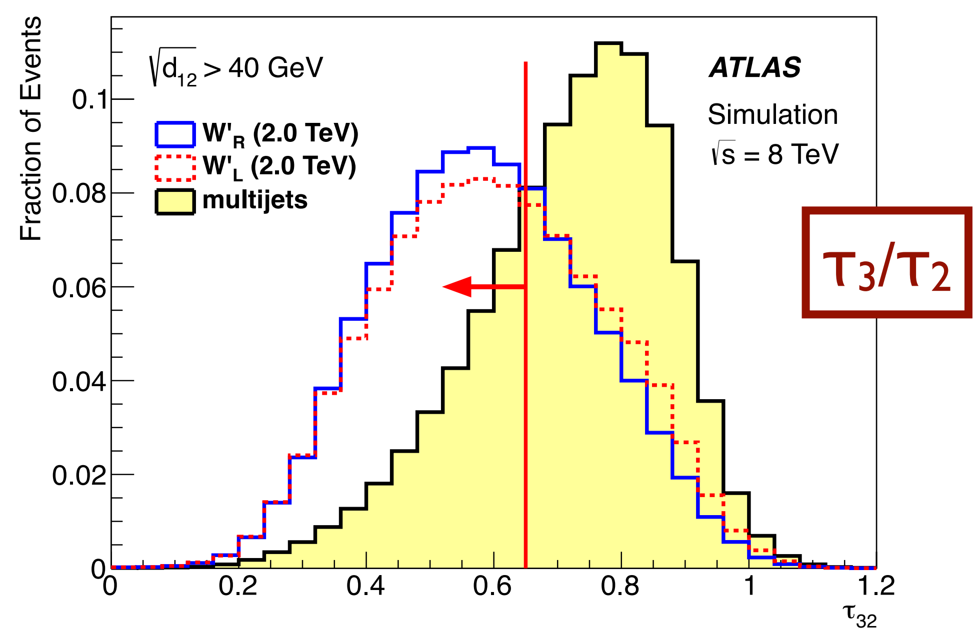
ATLAS Search for Heavy W Bosons

Trimming + *B-tagging*
+ *N-subjettiness*



Similar techniques used for
ATLAS diboson excess



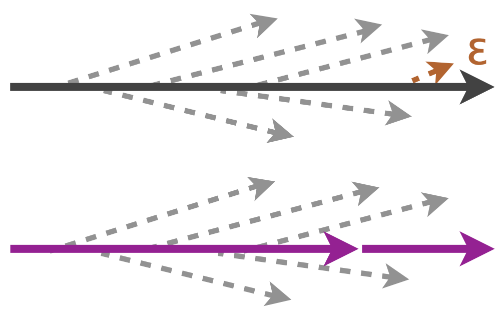


[ATLAS, 2014]

Rest of this talk:

Jet substructure as motivation to delve into subtleties of QCD

Inspiration from Jet Substructure

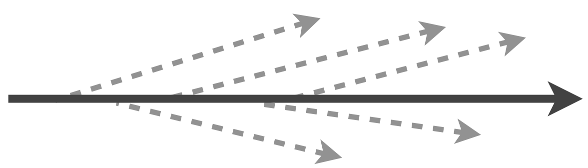


From IRC Safe to Sudakov Safe

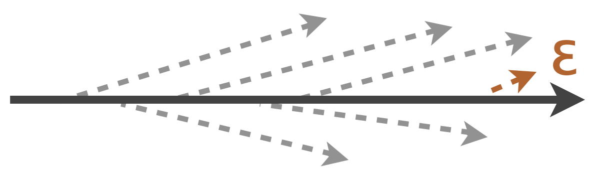
Probing the Core of QCD

Infrared/Collinear Safety

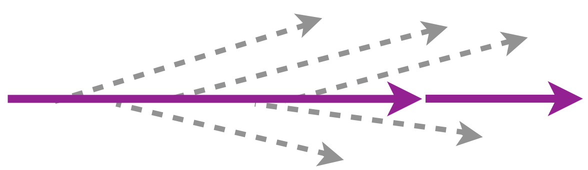
Original Jet



Infrared



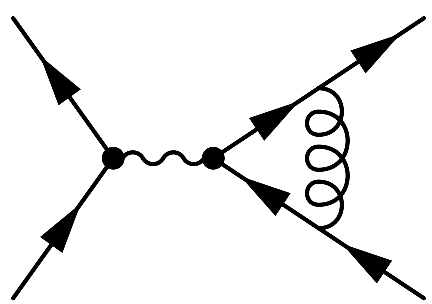
Collinear



IRC Safe Observable: Insensitive to IR or C emissions

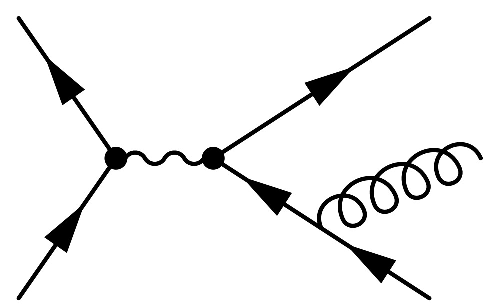
Formally:

Virtual Diagrams



⇔

∑ Real Emissions



IRC divergences cancel order-by-order in α_s

Examples from Jet Substructure

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

p_T^D: $\sum_{i \in \text{jet}} \frac{p_{T,i}^2}{p_{T\text{jet}}^2}$ IR Safe, C Unsafe

[CMS HIG-11-027]

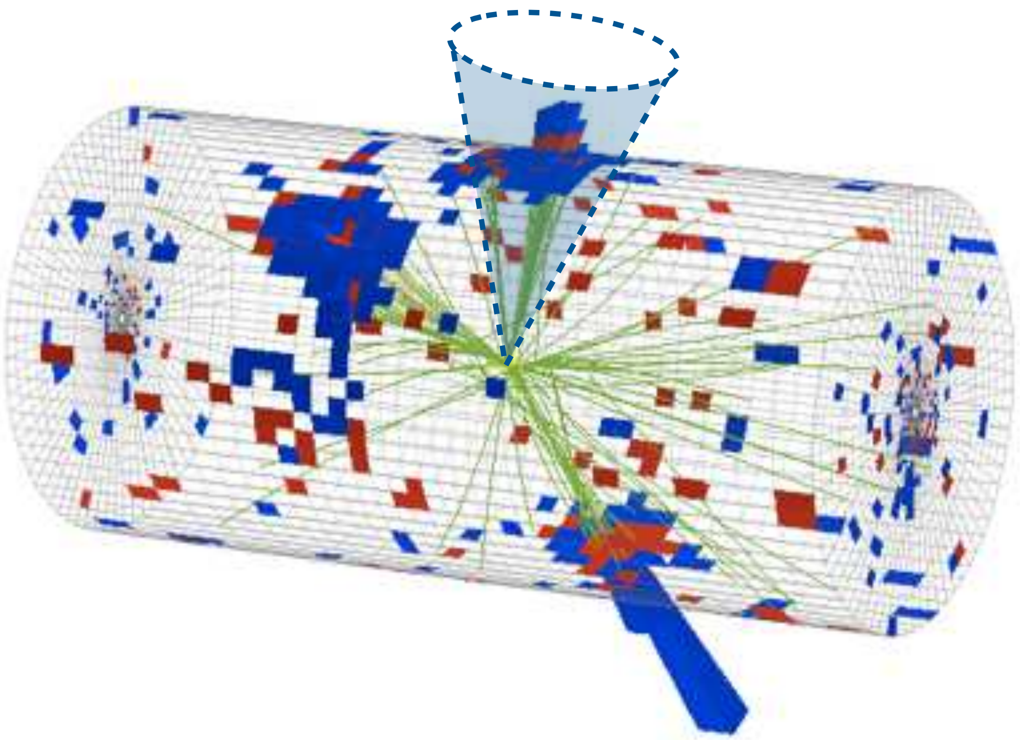
Multiplicity: $\sum_{i \in \text{jet}} 1$ IRC Unsafe

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

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

[JDT, Van Tilburg, 1011.2268, 1108.2701]

With IRC safe
jet algorithm
(e.g. anti-k_T)



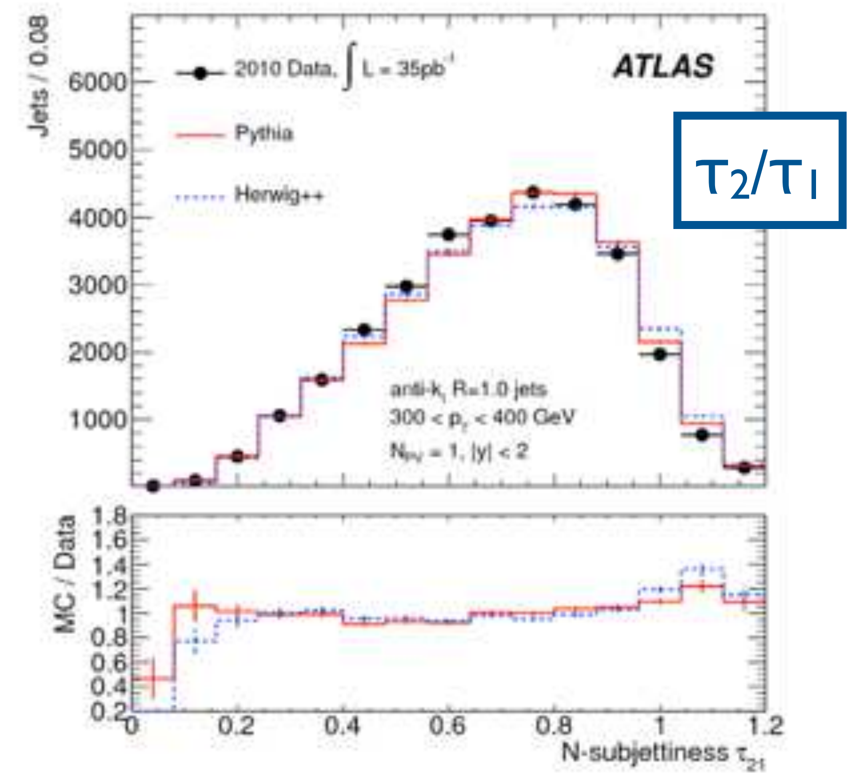
Ratio Observables?

[ATLAS, 1203.4606]

IRC Safe $\Rightarrow$ Useful Ratio

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

Ubiquitous in jet substructure
(esp. N-subjettiness)



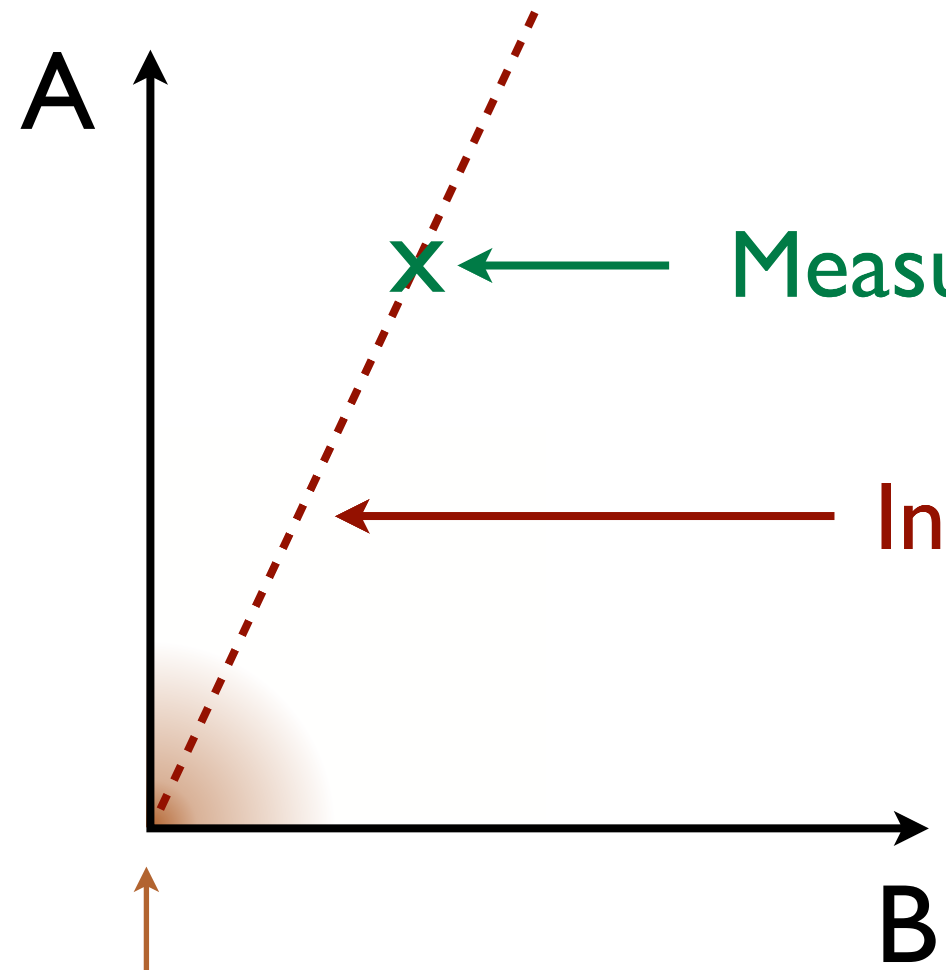
W-like ↔ QCD-like

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

[Soyez, Salam, Kim, Dutta, Cacciari, 1211.2811]

WHAT?!

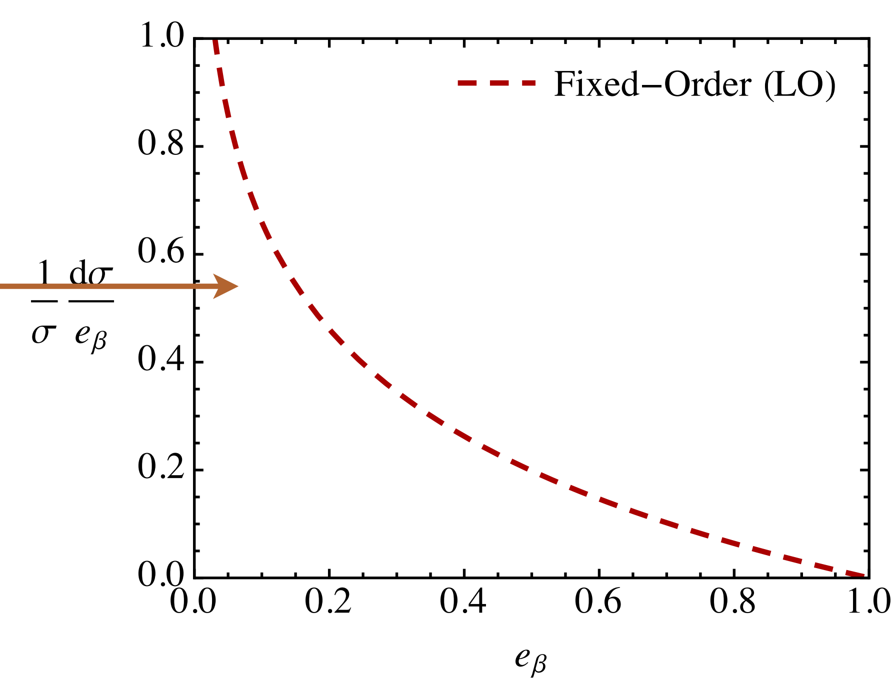
Safe/Safe = Unsafe?!



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

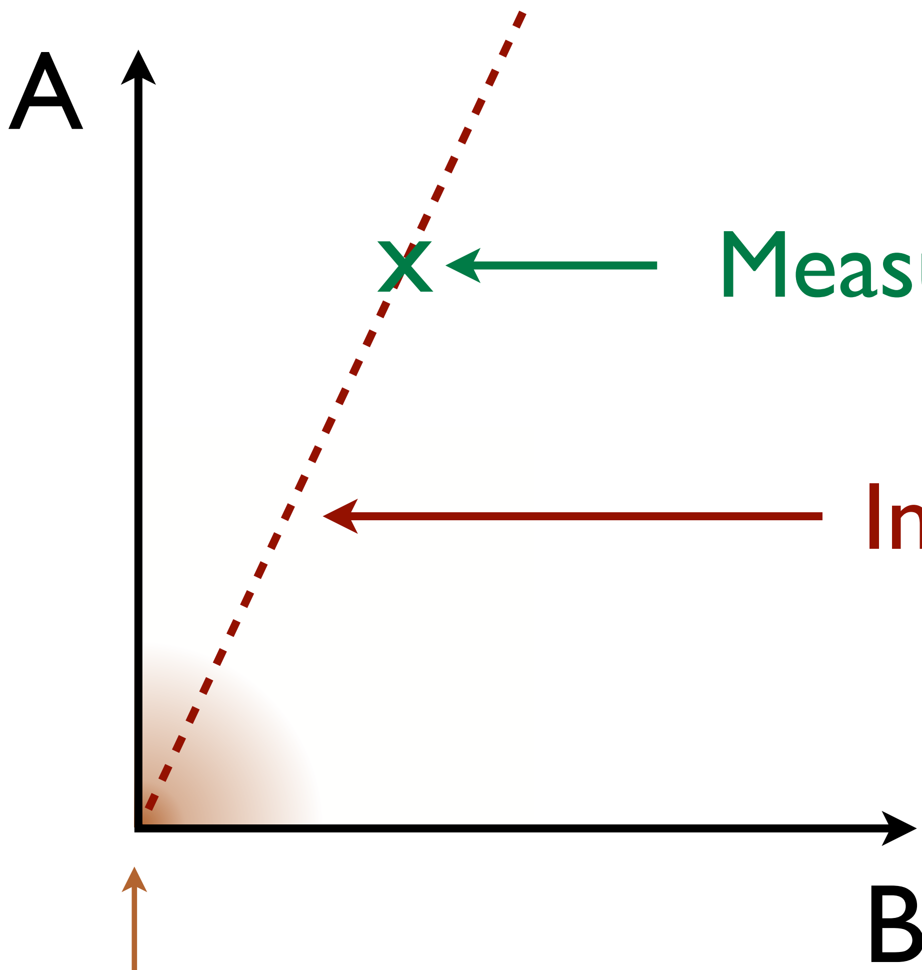
Infer: R = A/B (IRC Unsafe)

Singularity …



WHAT?!

Safe/Safe = Unsafe?!

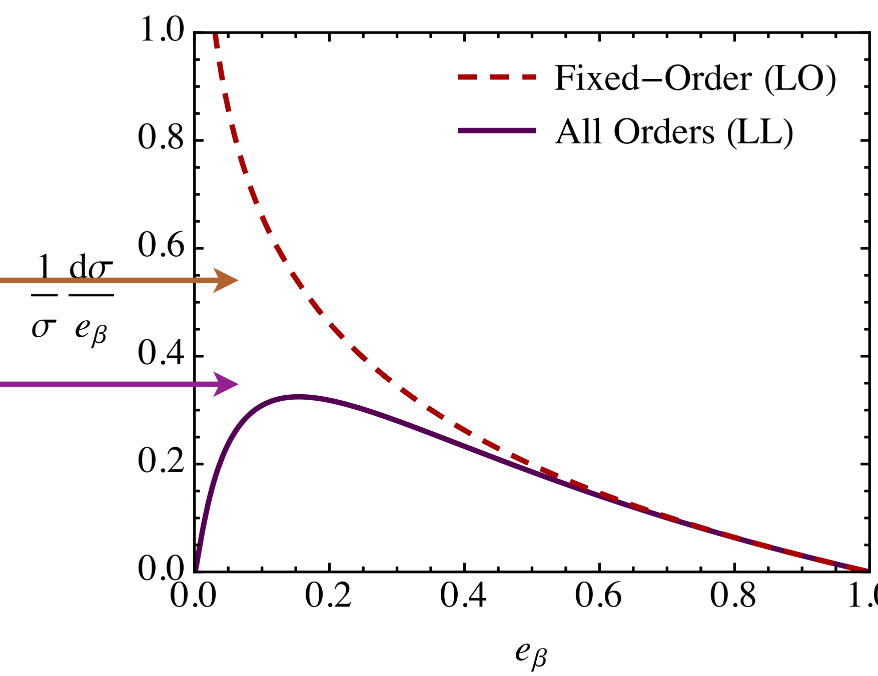


Measure: A (IRC Safe)
B (IRC Safe)

Infer: R = A/B (IRC Unsafe)

Singularity …

… Regulated by
Sudakov Form Factor



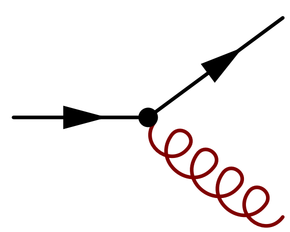
The Key Realization

Generalization in backup

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

IRC Unsafe

Infinity at $O(\alpha_s)$



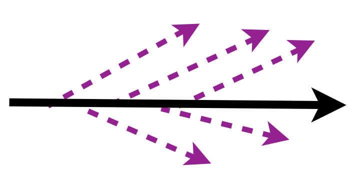
IRC Safe

"I can simultaneously measure e_α and e_β"

"Sudakov Safe"

Non-analytic in α_s

[Larkoski, JDT, 1307.1699]



Joint Resummable

"I can find a Sudakov form factor that resums large logarithms in e_α and e_β to *all orders* in α_s (e.g. a parton shower)"

Sudakov Safety in Action

Ratios of angularities (1-subjettiness)

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

IRC Safe

momentum fraction

angle to axis

IR Limit

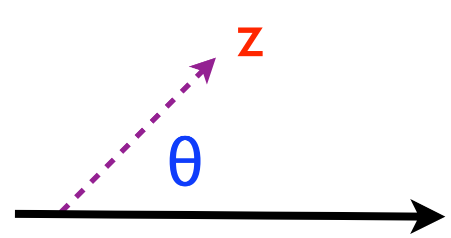
$z \to 0$

C Limit

$\theta \to 0$

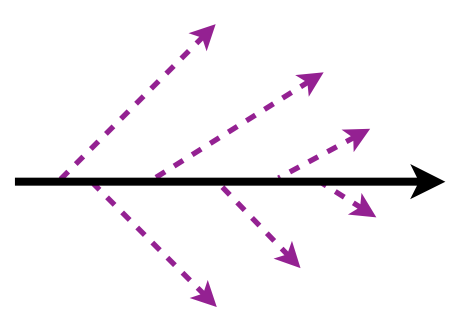
Single emission:

Order α_s (LO)



Many emissions:

All orders in α_s (LL)



$$r = \frac{e_\alpha}{e_\beta} = \cancel{\theta^{\alpha-\beta}}$$

IRC Unsafe

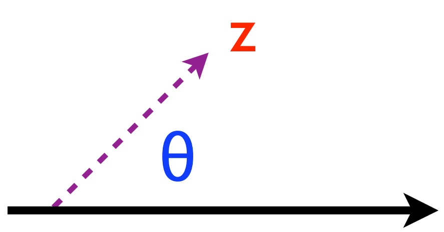
"Sudakov Safe"

[Larkoski, JDT, 1307.1699]

[Berger, Kucs, Sterman, 2003; Ellis, Vermilion, Walsh, Hornig, Lee, 2010]
[Recoil-free Versions: Larkoski, Salam, JDT, 1305.0007; Larkoski, Neill, JDT, 1401.2158]

Turning the Crank

$$e_\beta \simeq \sum_{i \in \text{jet}} z_i \left(\theta_i\right)^\beta \qquad \frac{d\sigma}{dr} = \int de_\alpha \, de_\beta \, \frac{d^2\sigma}{de_\alpha de_\beta} \, \delta\left(r - \frac{e_\alpha}{e_\beta}\right)$$



$$\frac{d^2\sigma^{\text{FO}}}{de_\alpha de_\beta} \simeq \frac{2\alpha_s}{\pi} \frac{C_F}{\alpha - \beta} \frac{1}{e_\alpha e_\beta}$$

Single emission:
Order α_s (LO)

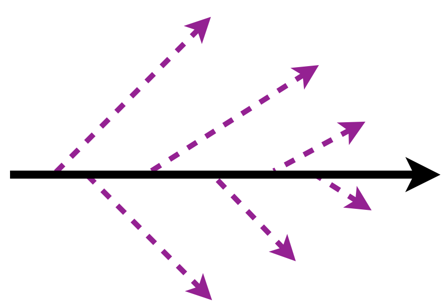
$$\frac{d\sigma^{\text{FO}}}{dr} \Rightarrow$$ Not integrable! (IRC Unsafe)

[Larkoski, JDT, 1307.1699]

Turning the Crank

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

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



Many emissions:
All orders in α_s (LL)

$$\frac{d^2\sigma^{\mathrm{LL}}}{de_\alpha de_\beta} \simeq \frac{2\alpha_s}{\pi} \frac{C_F}{\alpha - \beta} \frac{1}{e_\alpha e_\beta} \overbrace{e^{-\frac{\alpha_s}{\pi} \frac{C_F}{\beta} \log^2 e_\beta}}^{\text{Sudakov form factor}}$$

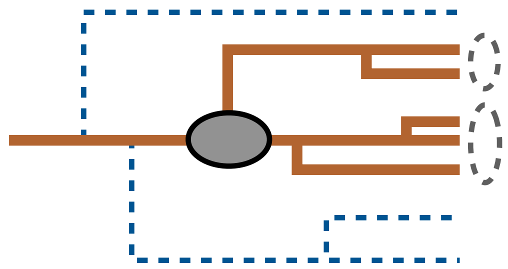
$$\frac{d\sigma^{\mathrm{LL}}}{dr} \simeq \sqrt{\alpha_s} \frac{\sqrt{C_F \beta}}{\alpha - \beta} \frac{1}{r} e^{-\frac{\alpha_s}{\pi} \frac{C_F}{\alpha - \beta} \log^2 r}$$

Unsafe… but Calculable (Sudakov Safe)

[Larkoski, JDT, 1307.1699]

Inspiration from Jet Substructure

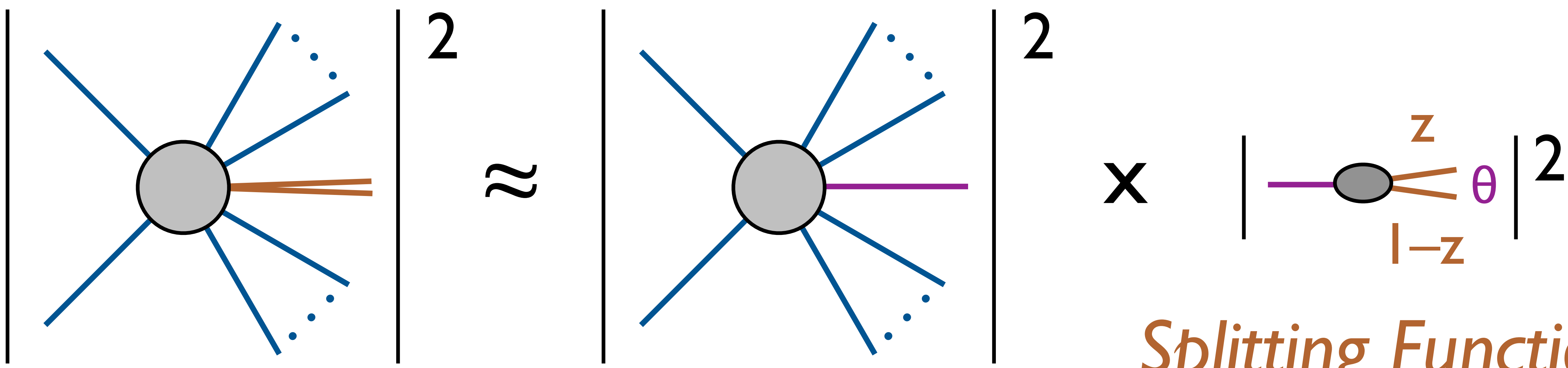
From IRC Safe to Sudakov Safe



Probing the Core of QCD

Textbook QCD

Universal collinear limit



Splitting Function

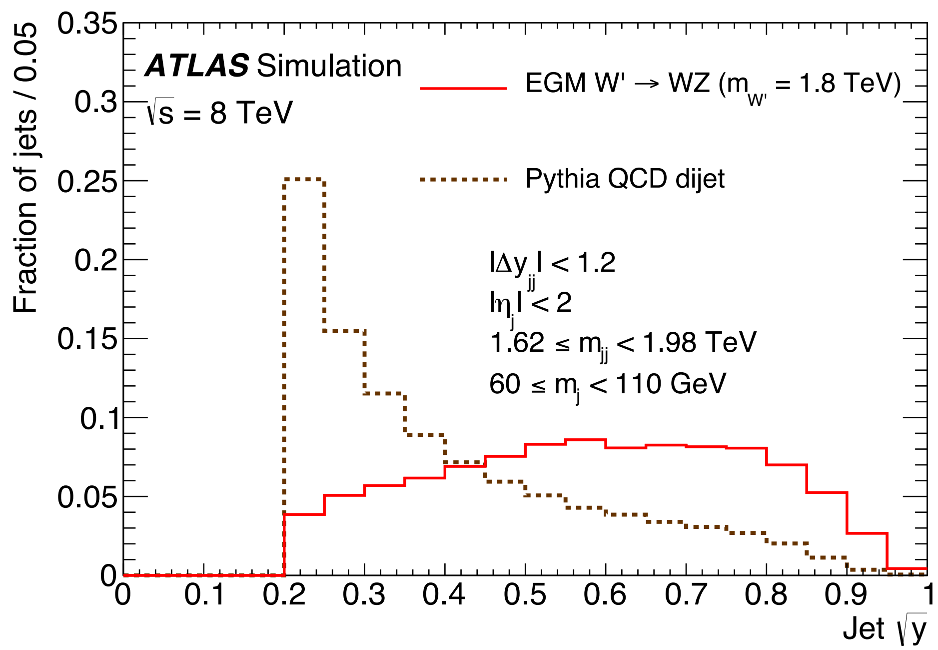
2→n   2→n–1   1→2

$$d\sigma_{2\to n} = d\sigma_{2\to n-1}\, dP_{i\to jk}$$

$$dP_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \underbrace{\frac{d\theta}{\theta}}_{\text{Collinear singularity}} \underbrace{\frac{dz}{z}}_{\text{Soft singularity}}$$

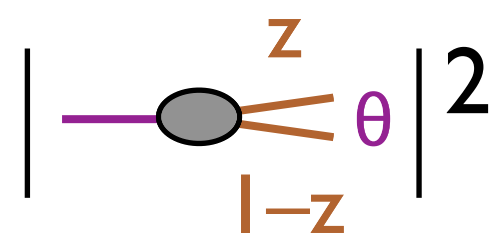
The Core of QCD

Basis for parton shower MC generators,
PDF evolution, NLO subtractions,
k_t clustering, jet substructure studies…



QCD-like ↔ W/Z-like

[ATLAS, 2015]



Splitting Function

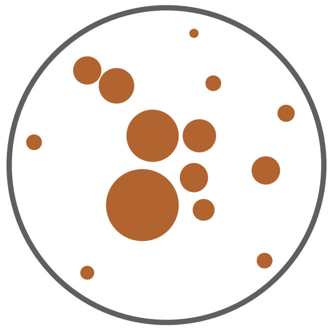
1→2

$$\frac{2\alpha_s}{\pi} C_i \underbrace{\frac{\mathrm{d}\theta}{\theta}}_{\text{Collinear singularity}} \underbrace{\frac{\mathrm{d}z}{z}}_{\text{Soft singularity}}$$

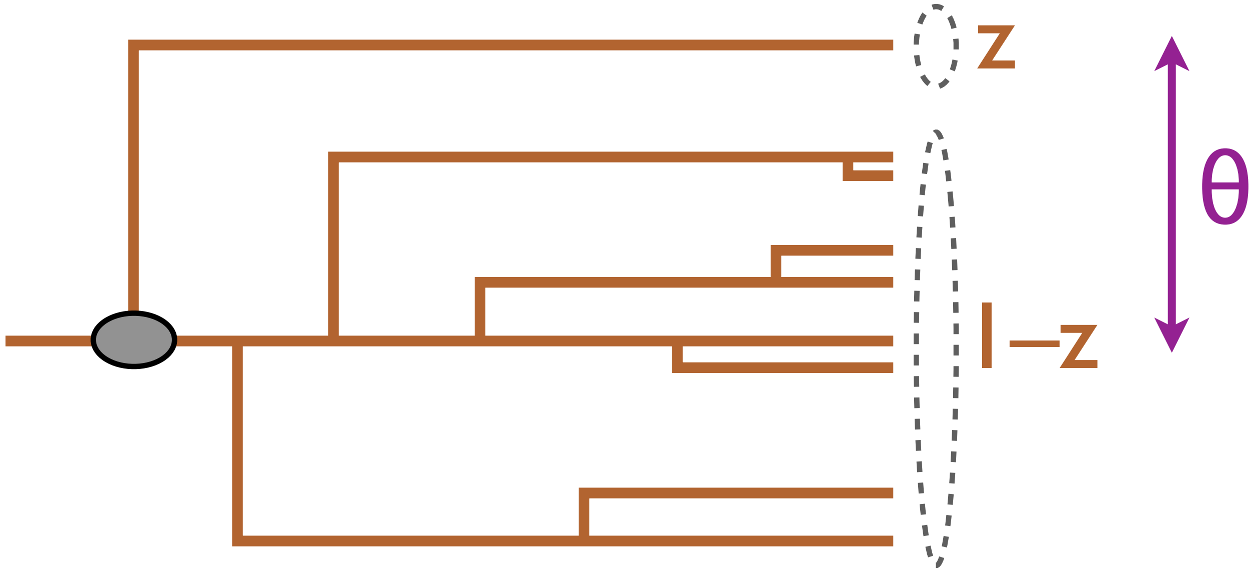
Measurable? Calculable?

↳ IRC Unsafe

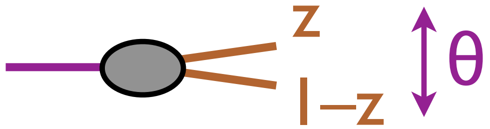
Measure Universal Singularity?



Angular-ordered tree…



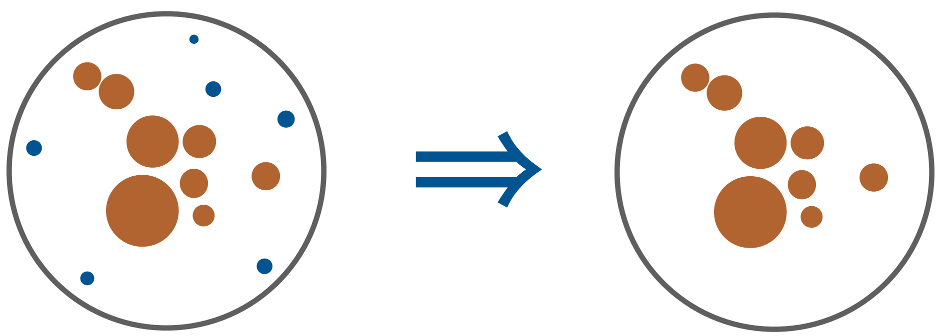
…gives splitting function?



$$\frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$

$\boxed{z}$ IRC Unsafe

Measure Universal Singularity?



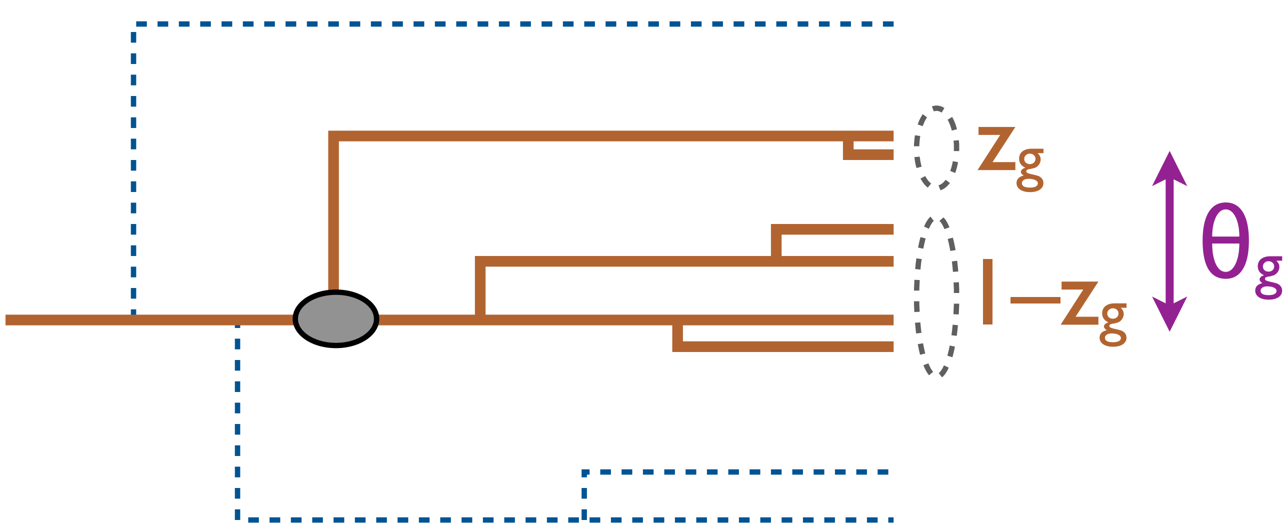
Soft Drop

$$z > z_{\text{cut}}\, \theta^{\beta}$$

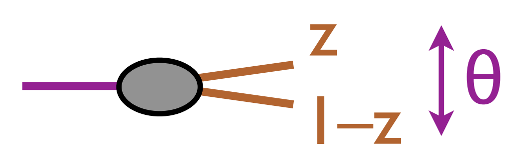
energy threshold

angular exponent

Groomed angular-ordered tree…



…gives splitting function?



$$\frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

$\boxed{z_g}$

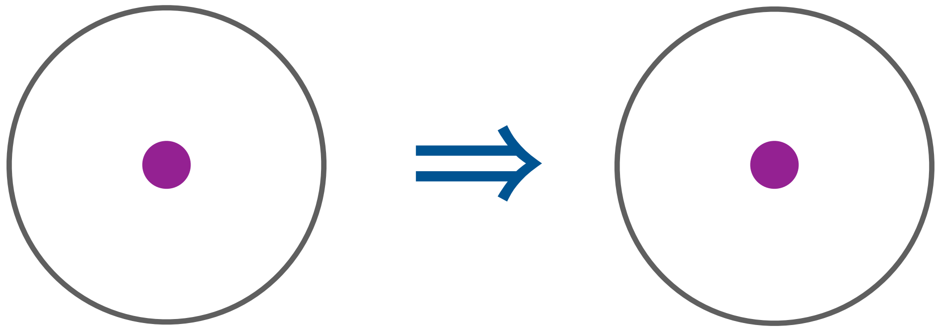
IR Safe

C Unsafe ($\beta \geq 0$)

[Larkoski, Marzani, Soyez, JDT, 1402.2657]

[see also Butterworth, Davison, Rubin, Salam, 0802.2470; Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Measure Universal Singularity?



Soft Drop

$$z > z_{\mathrm{cut}}\,\theta^{\beta}$$

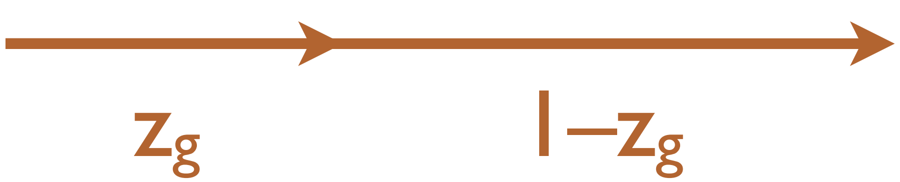
energy threshold

angular exponent

One prong jet…

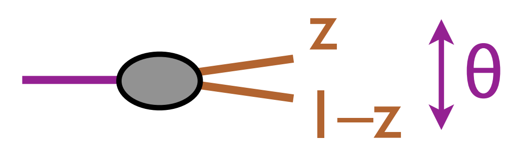
$\theta_g = 0$

vs.



$\theta_g = 0$

…gives splitting function?



$$\frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta}\frac{dz}{z}$$

$\boxed{z_g}$

IR Safe

C Unsafe ($\beta \geq 0$)

[Larkoski, Marzani, Soyez, JDT, 1402.2657]

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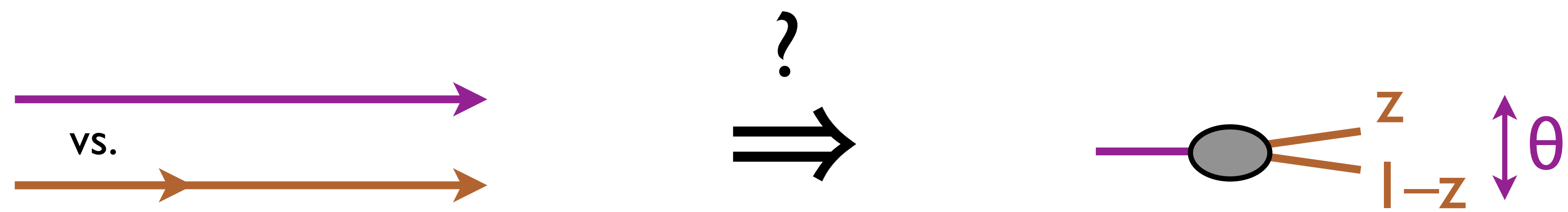


$\boxed{z_g}$

IR Safe
C Unsafe ($\beta \geq 0$)

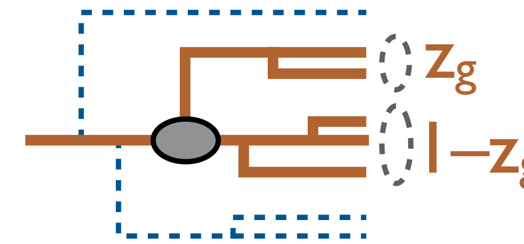
How to calculate from first principles?

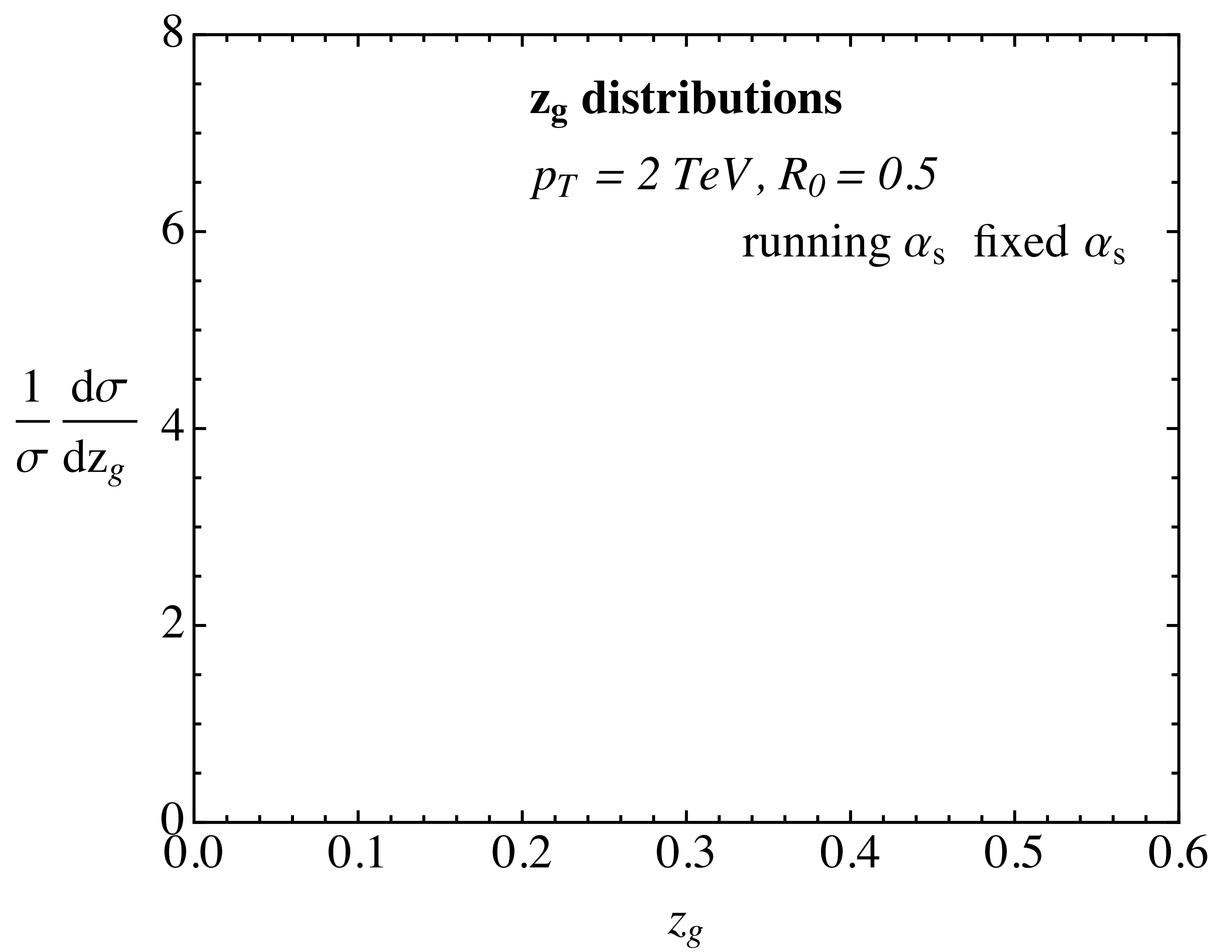
Exploit Sudakov Safety

(see backup for two additional approaches)

First-Principles QCD

$z > z_{\text{cut}}\, \theta^{\beta}$





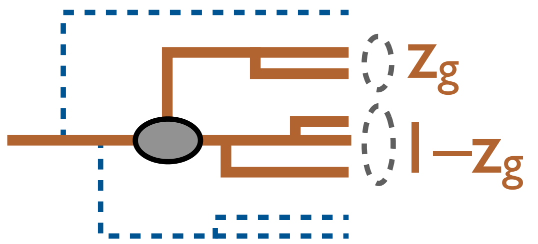
No Jet | No Change

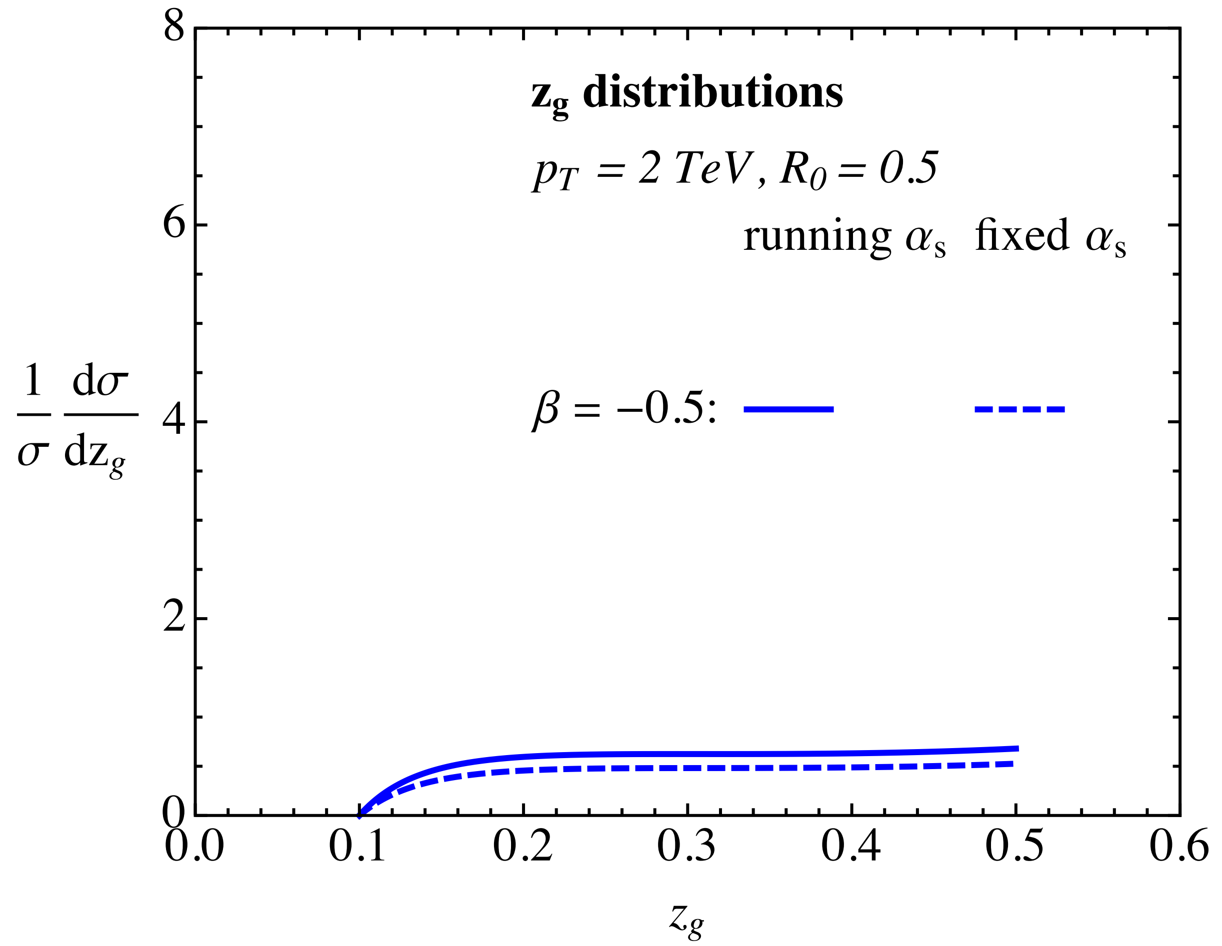
$\beta \to -\infty$ | $\beta < 0$ | $\beta = 0$ | $\beta > 0$ | $\beta \to \infty$

[Larkoski, Marzani, JDT, 2015; using calculational techniques in Dasgupta, Fregoso, Marzani, Salam, 2013; Larkoski, JDT, 2013]

First-Principles QCD

$z > z_{\mathrm{cut}}\ \theta^\beta$





$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\frac{1}{z_g}\log\frac{z_g}{z_{\mathrm{cut}}}$$

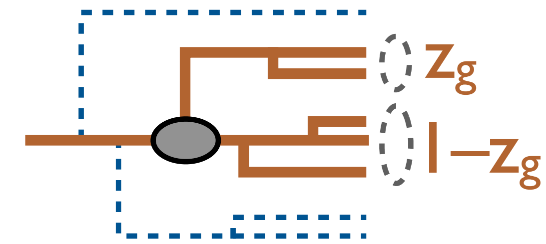
No Jet | No Change

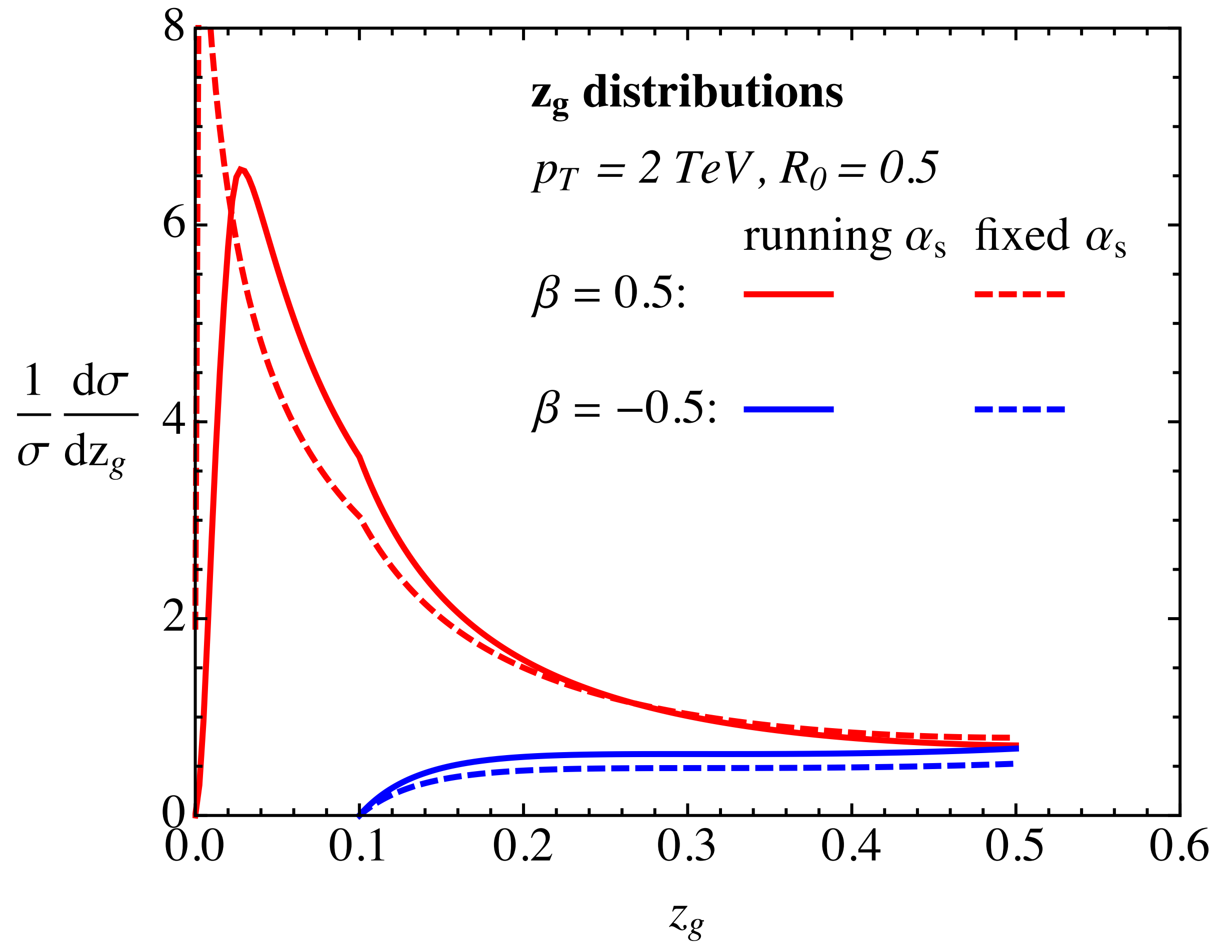
$\beta \to -\infty$ | $\beta < 0$ | $\beta = 0$ | $\beta > 0$ | $\beta \to \infty$

[Larkoski, Marzani, JDT, 2015; using calculational techniques in Dasgupta, Fregoso, Marzani, Salam, 2013; Larkoski, JDT, 2013]

First-Principles QCD

$z > z_{\mathrm{cut}}\,\theta^{\beta}$





$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\frac{1}{z_g}\log\frac{z_g}{z_{\mathrm{cut}}}$$

$$\simeq \sqrt{\frac{\alpha_s C_i}{\beta}}\frac{1}{z_g}$$

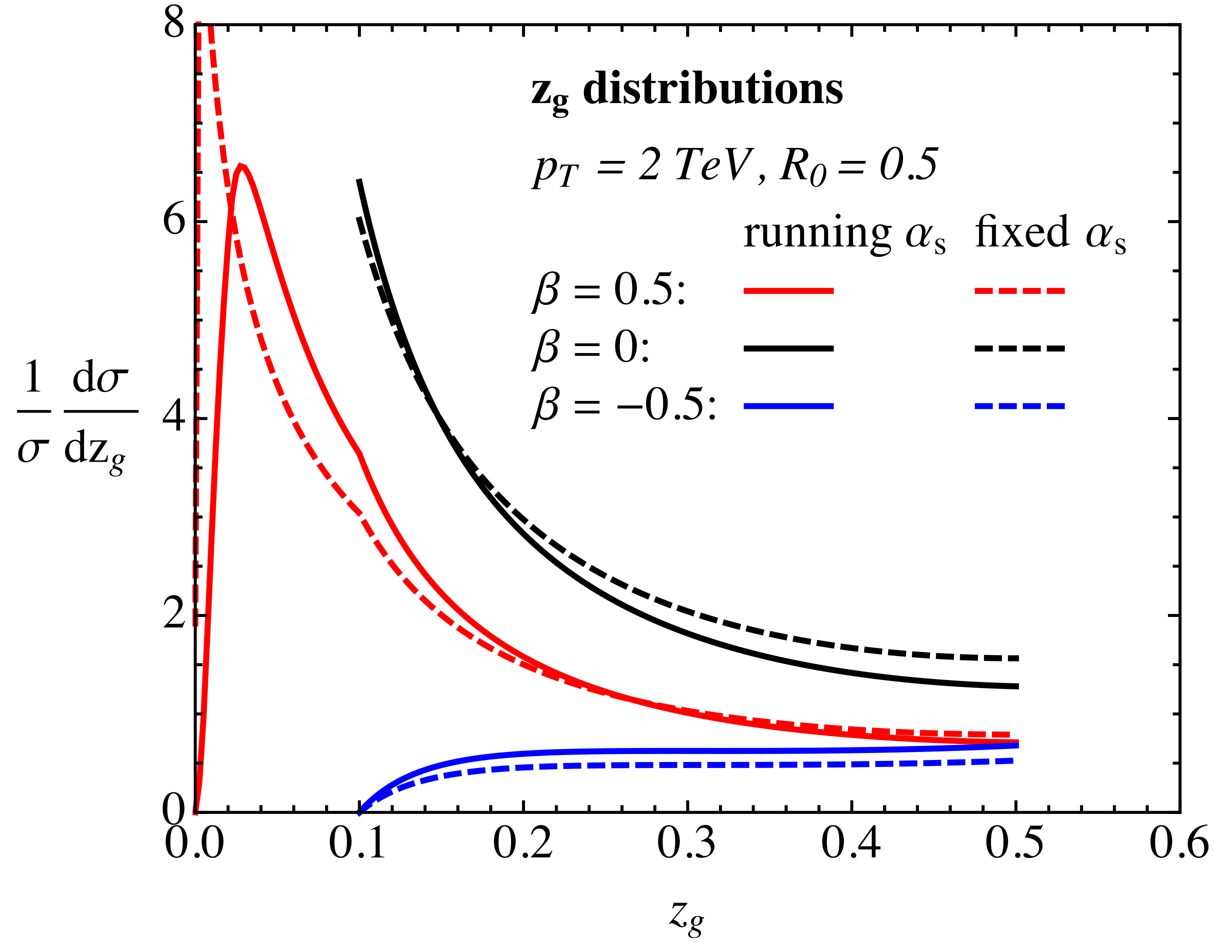
Non-analytic because of Sudakov safety

No Jet | No Change

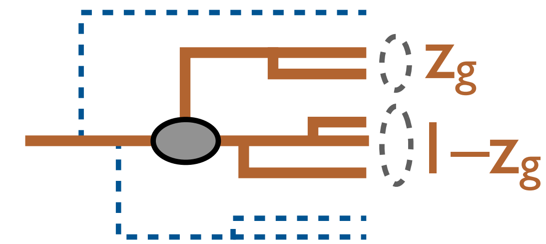
β → −∞ | β < 0 | β = 0 | β > 0 | β → ∞

[Larkoski, Marzani, JDT, 2015; using calculational techniques in Dasgupta, Fregoso, Marzani, Salam, 2013; Larkoski, JDT, 2013]

First-Principles QCD



$$z > z_{\rm cut}\,\theta^\beta$$



$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\frac{1}{z_g}\log\frac{z_g}{z_{\rm cut}}$$

$$\simeq \frac{1}{z_g}\ (!)$$

$$\simeq \sqrt{\frac{\alpha_s C_i}{\beta}}\,\frac{1}{z_g}$$

Non-analytic because of Sudakov safety

No Jet

No Change

β → −∞

β < 0

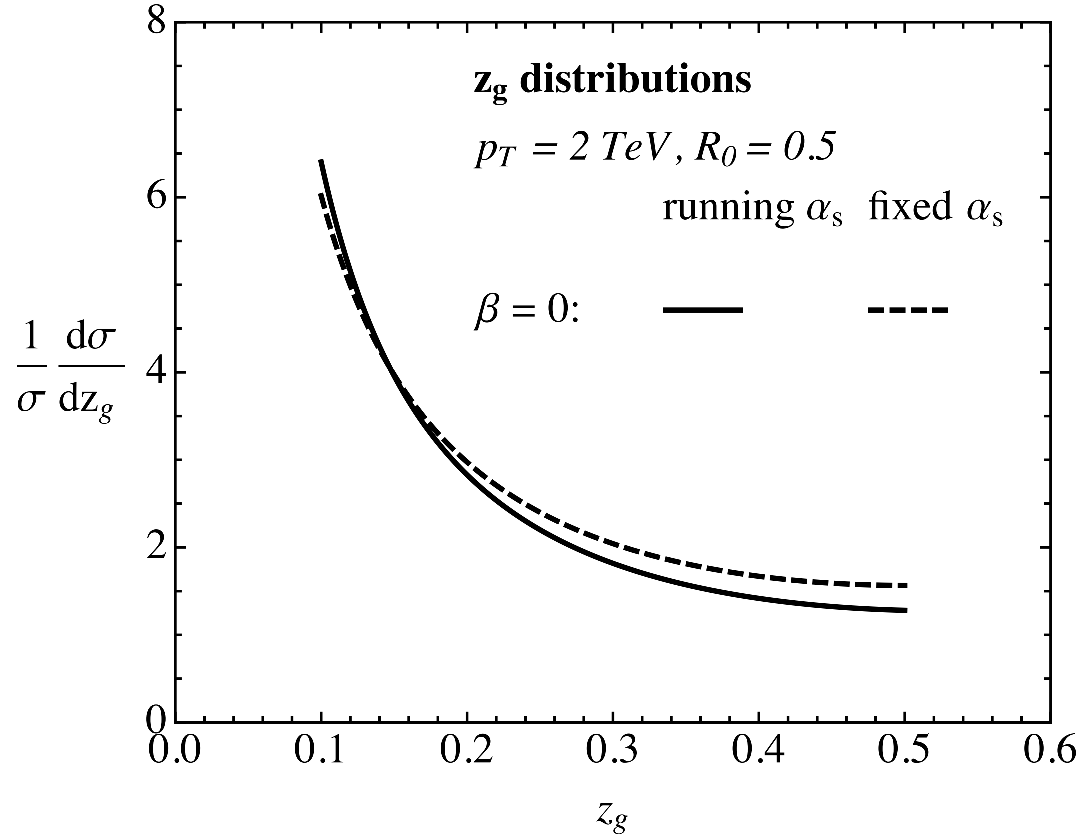
β = 0

β > 0

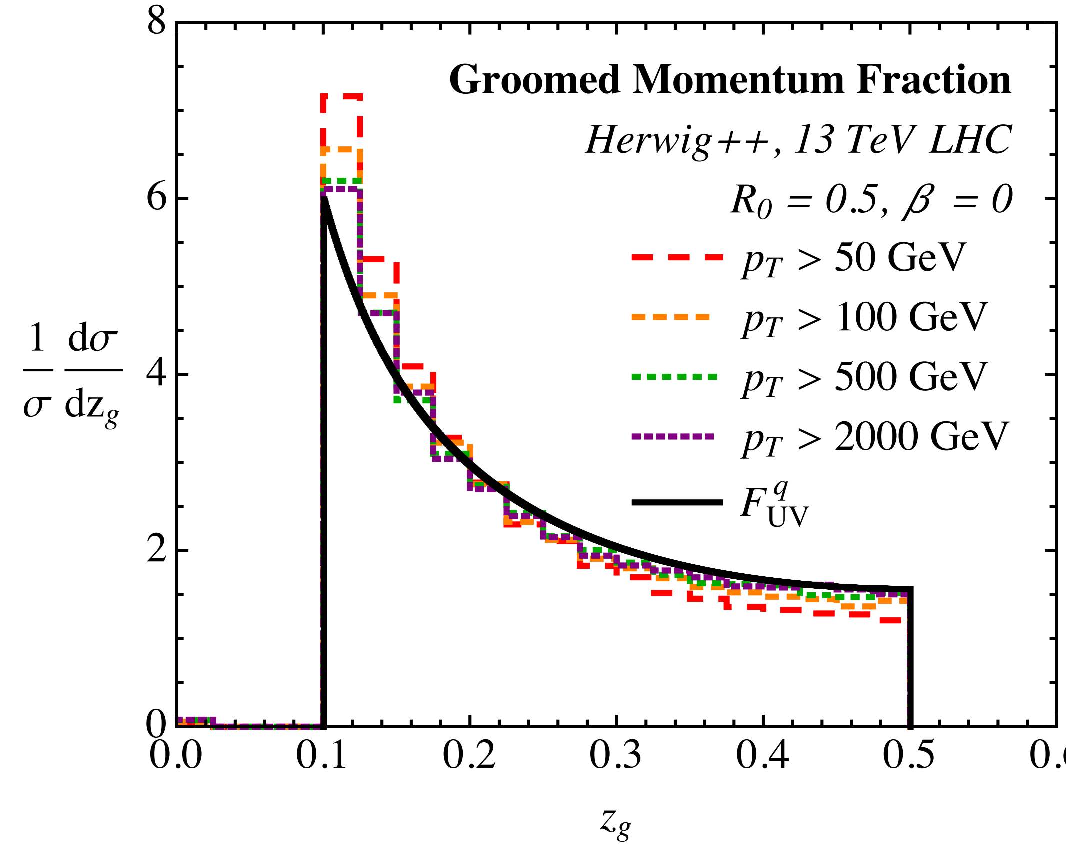
β → ∞

[Larkoski, Marzani, JDT, 2015; using calculational techniques in Dasgupta, Fregoso, Marzani, Salam, 2013; Larkoski, JDT, 2013]

First-Principles QCD



Simulated LHC Data

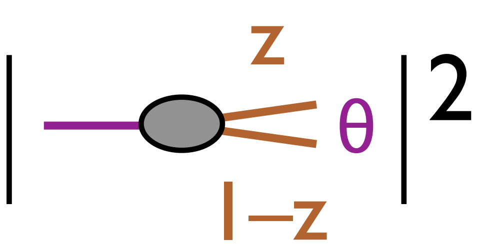


Core Feature of QCD: $\simeq \dfrac{1}{z_g}$

≈ independent of α_s (!)
≈ independent of jet energy/radius
≈ same for quarks/gluons

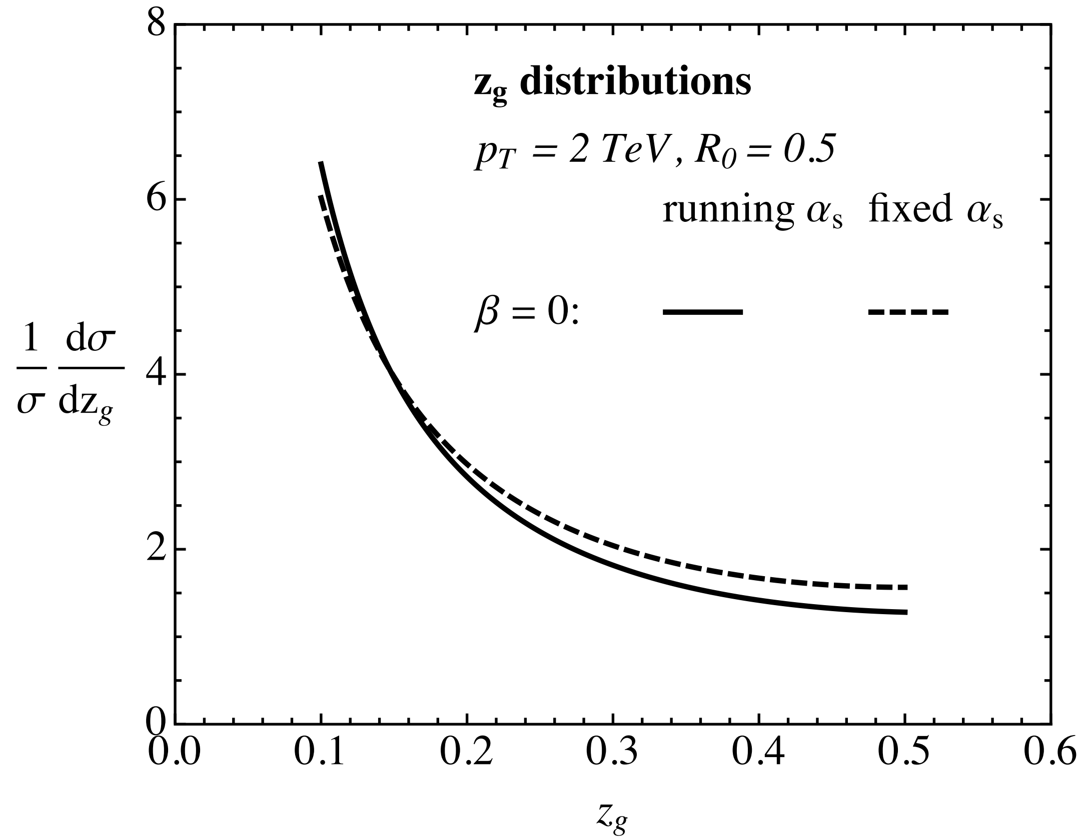
$$dP_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

cf. $\left|\right|^2$

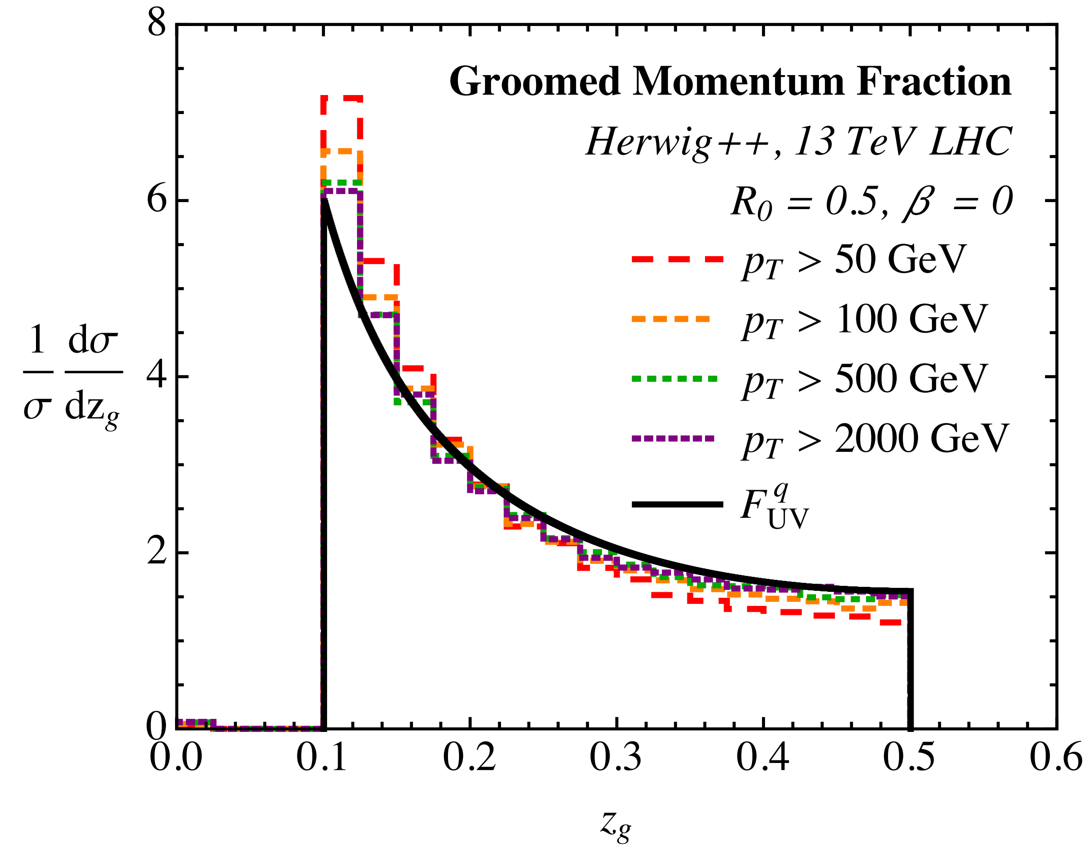


[Larkoski, Marzani, JDT, 2015; using Larkoski, JDT, 2013]

First-Principles QCD

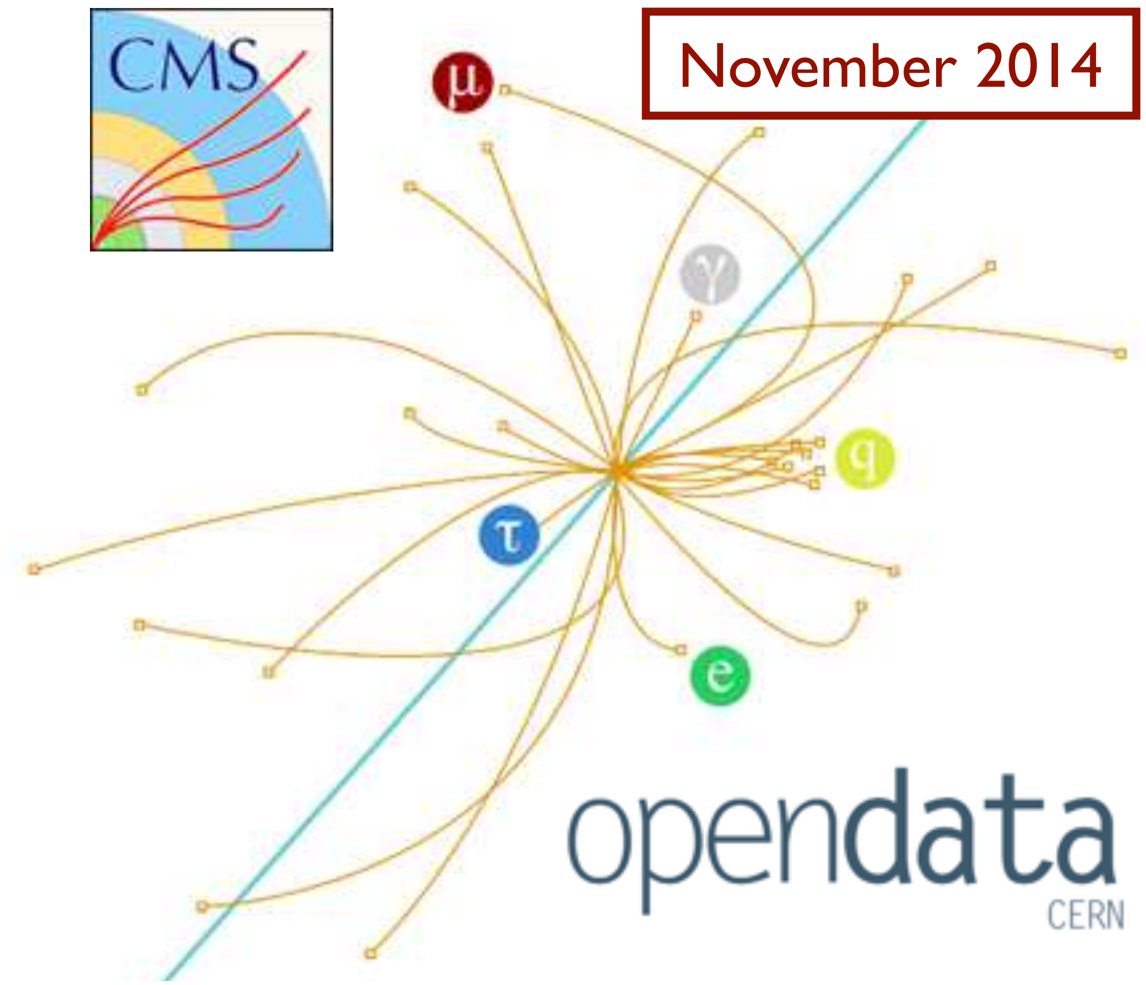


Simulated LHC Data



Actual LHC Data?

The Future is Open

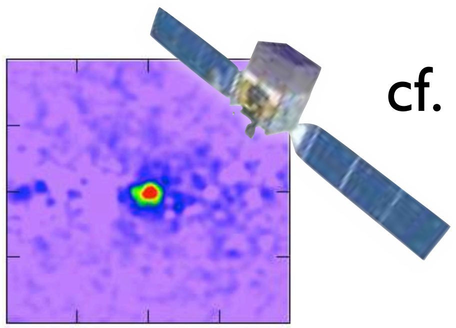


November 2014

CMS 2010:

Unique data set
with very low pileup

Accelerating science
through public data

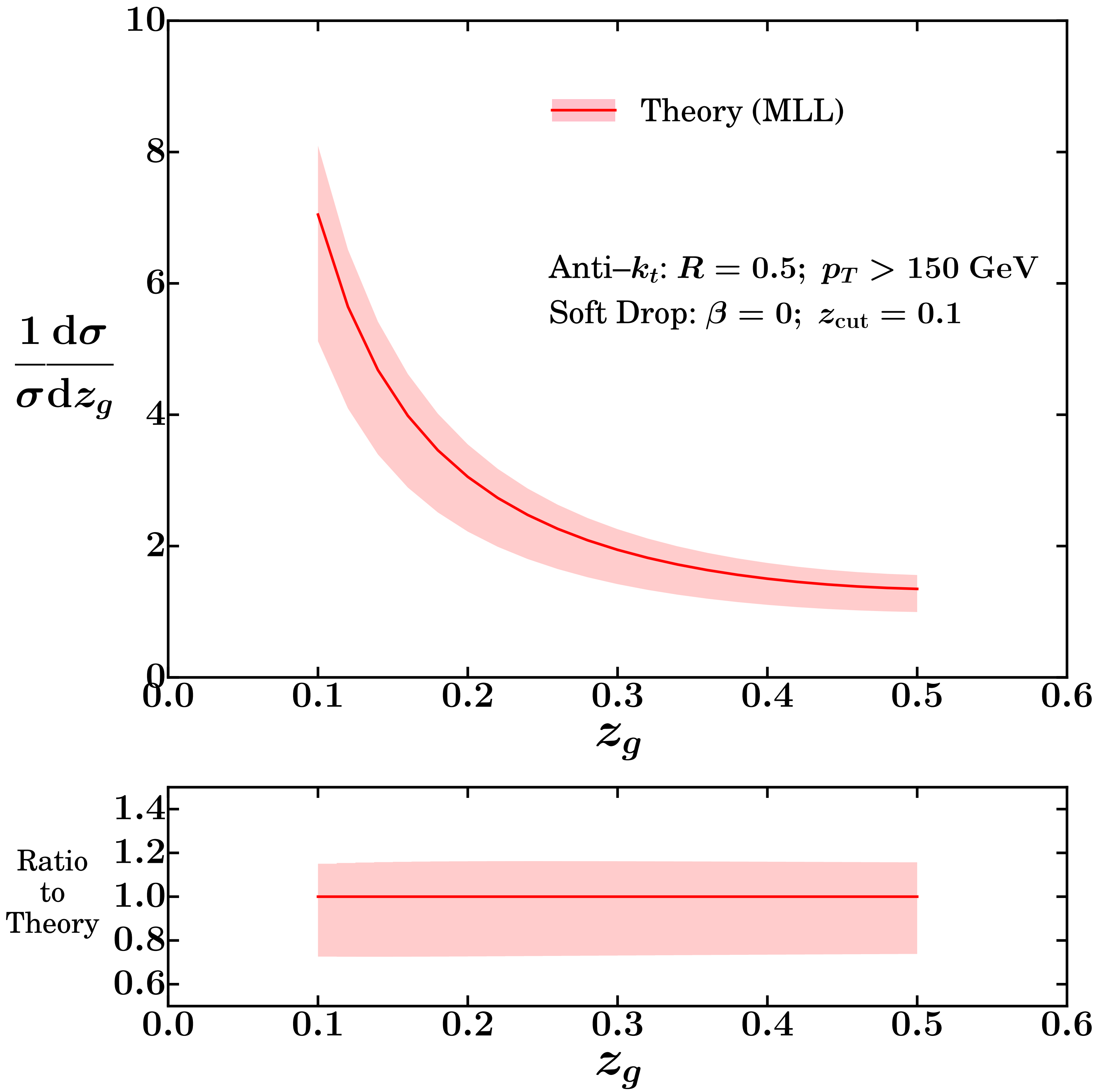


cf. Fermi

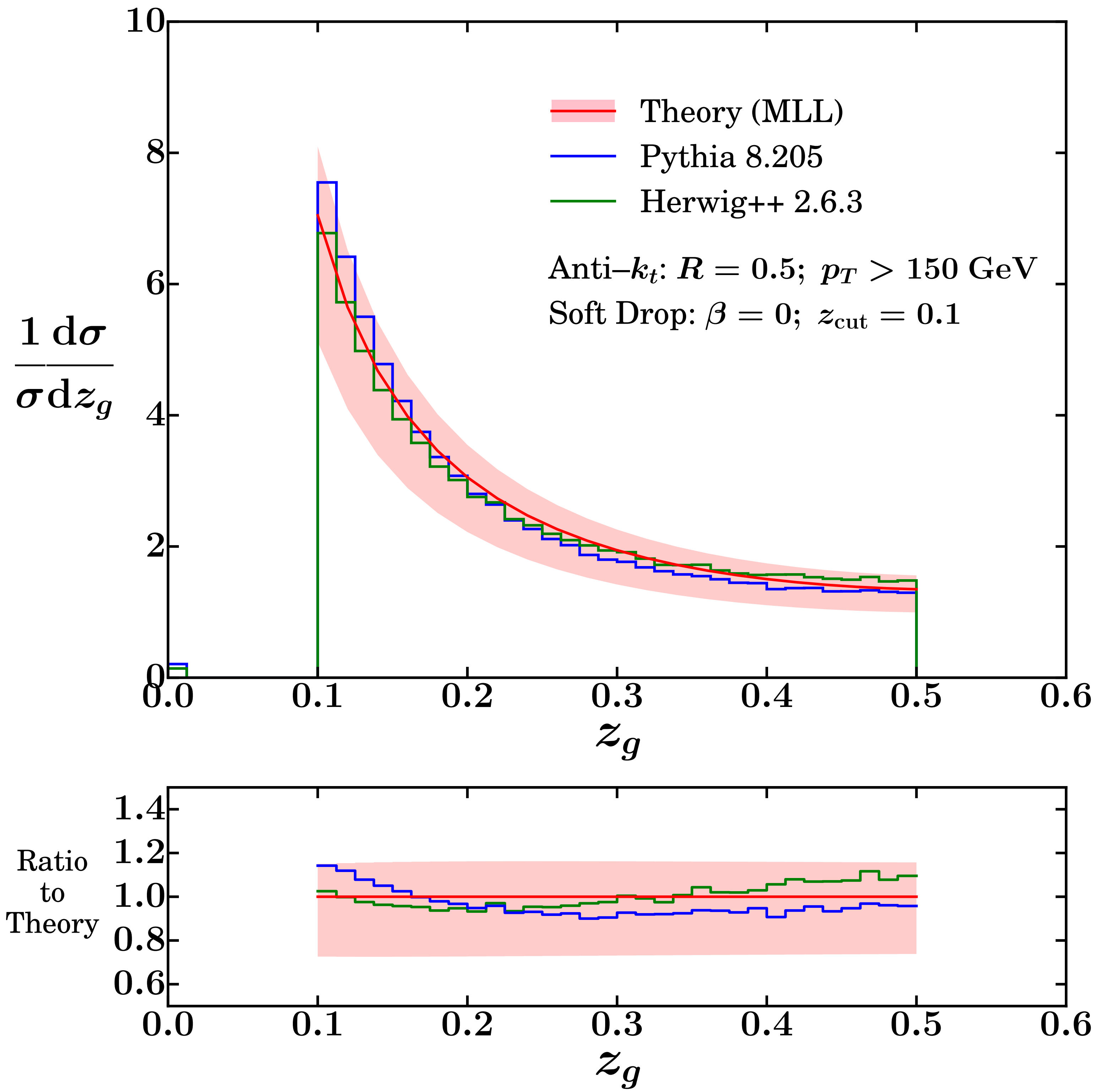
Theory Calculation

Andrew Larkoski

Simone Marzani



Simulated LHC Data



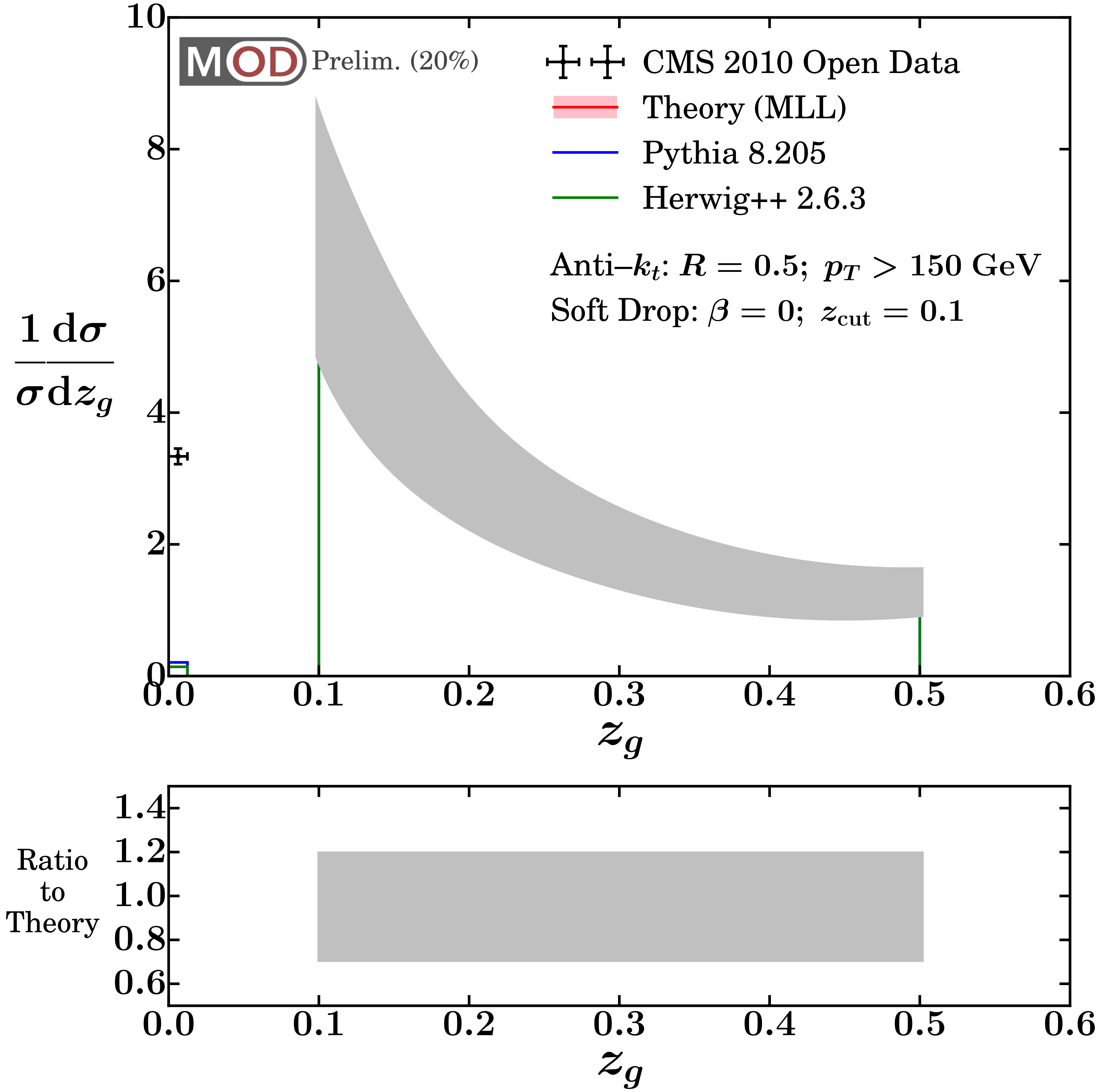
Andrew
Larkoski

Simone
Marzani

Alexis
Romero

CMS Open Data

*



Andrew Larkoski

Simone Marzani

Alexis Romero

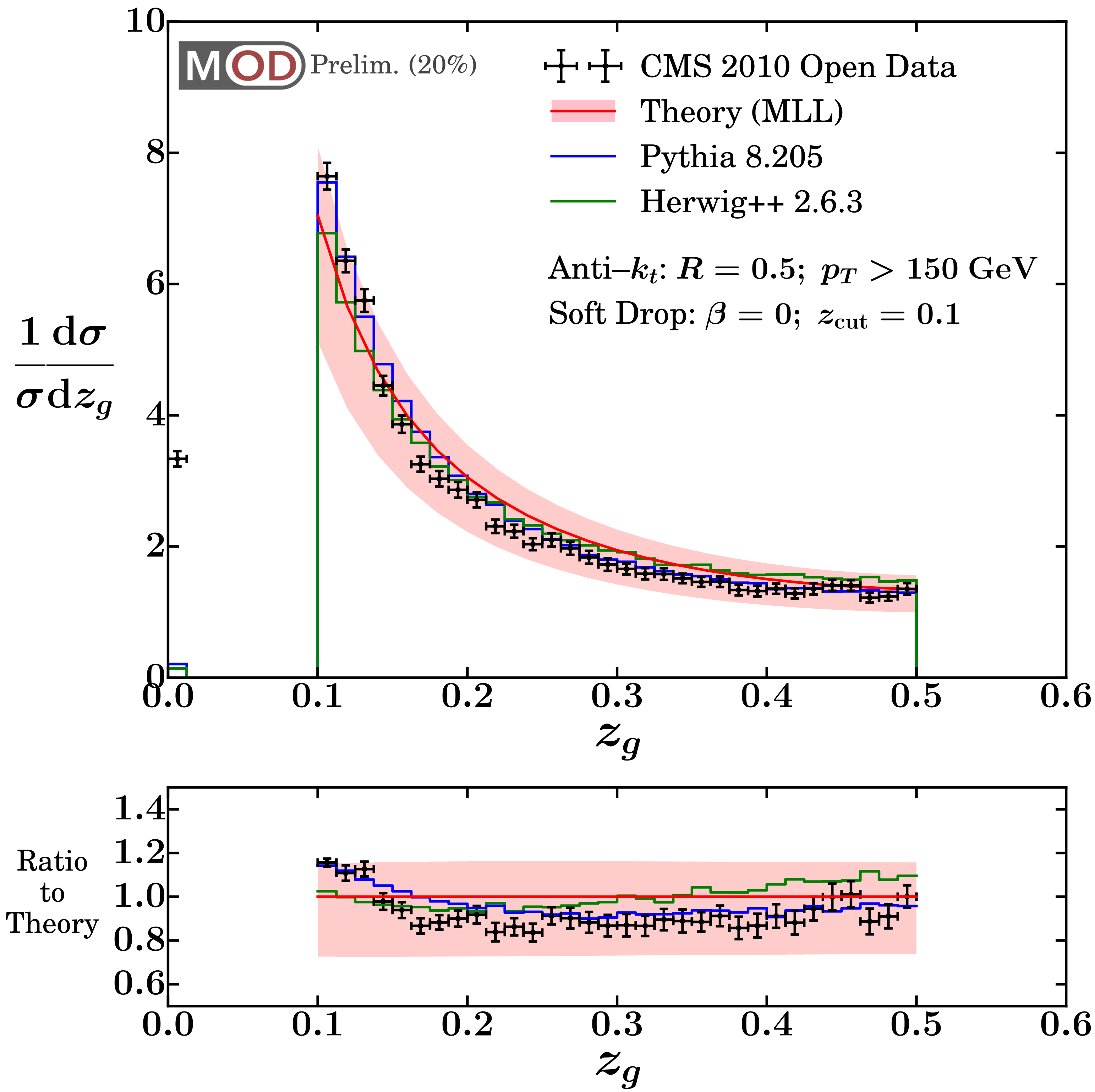
Aashish Tripathee

Wei Xue

CMS advice from Sal Rappoccio

CMS Open Data

*



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Alexis Romero

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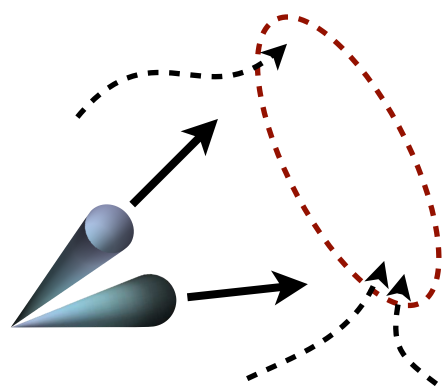
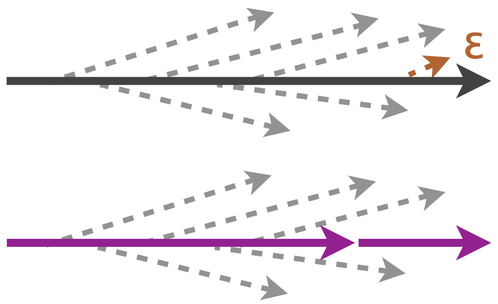
CMS advice from Sal Rappoccio

Summary



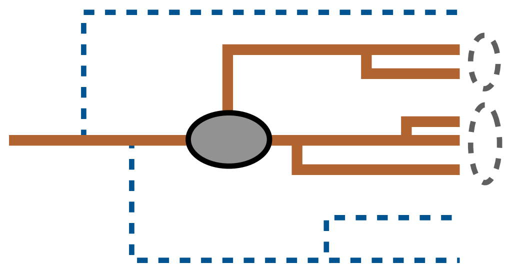
Inspiration from Jet Substructure

Exceptional LHC performance + (B)SM physics



From IRC Safe to Sudakov Safe

All orders in α_s yields new insights into QFT



Probing the Core of QCD

Measuring the universal singularity structure of gauge theories

All IRC safe observables are alike;
each IRC unsafe observable
is unsafe in its own way.

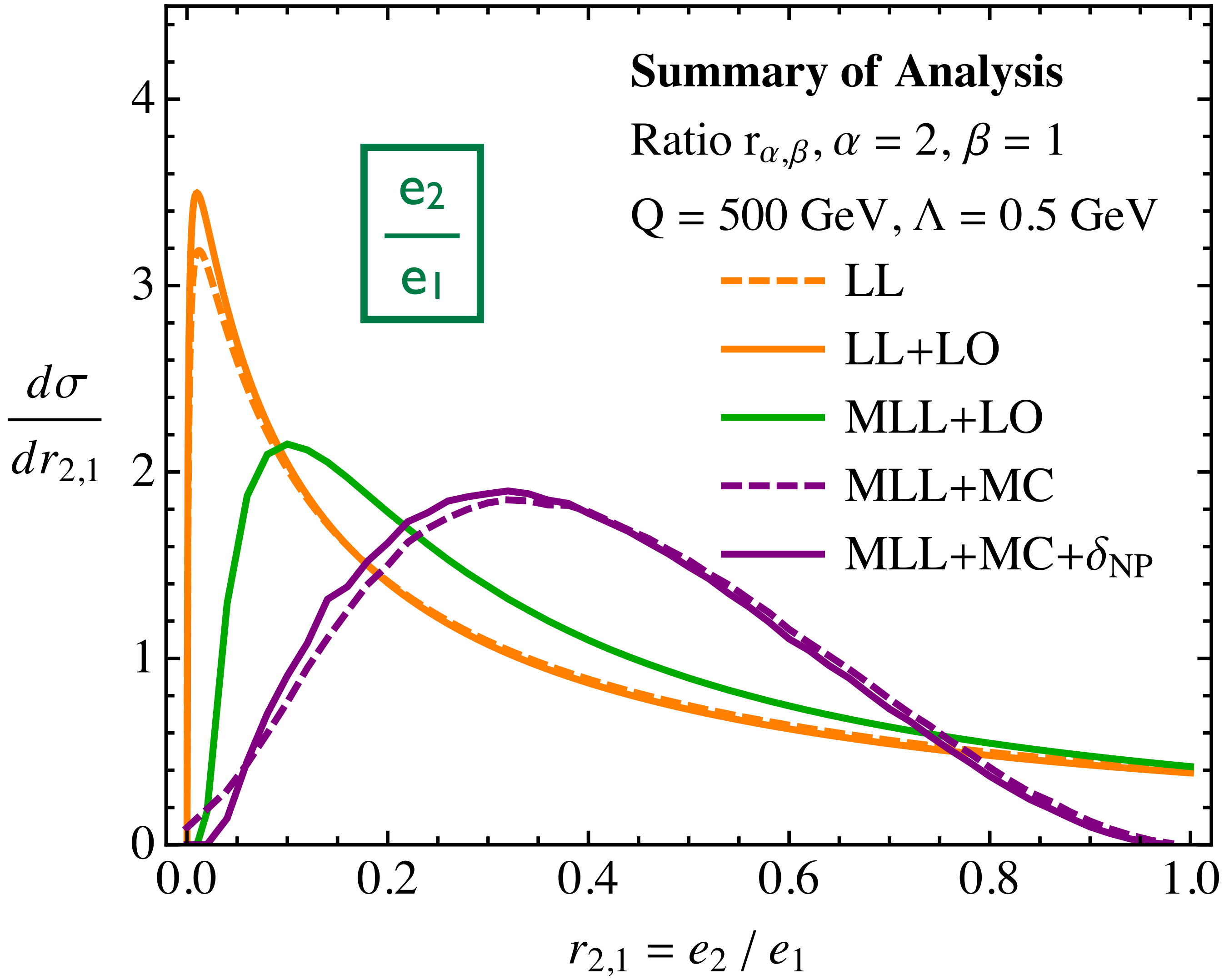
≈ Leo Tolstoy, *Anna Karenina*

Backup Slides

IRC safe observables, useful, measurable, and calculable…seemed to unite some of the best blessings of $p$erturbation theory; and have existed nearly forty years in the world with very little to distress or vex them.

≈ Jane Austen, *Emma*

Systematically Improvable



Minimal set of effects for comparison to LHC data:

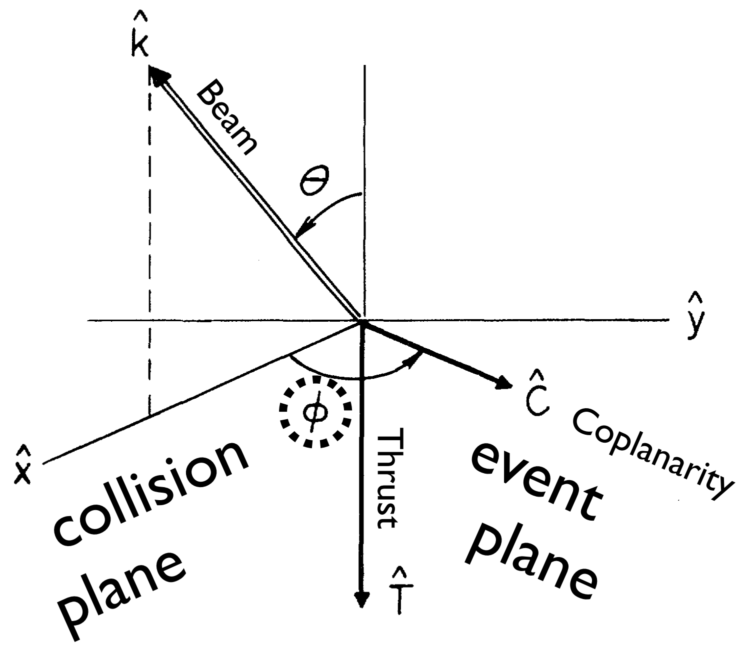
= Sudakov factor
+ tree-level matching
+ running α_s
+ multiple emissions
+ hadronization correction

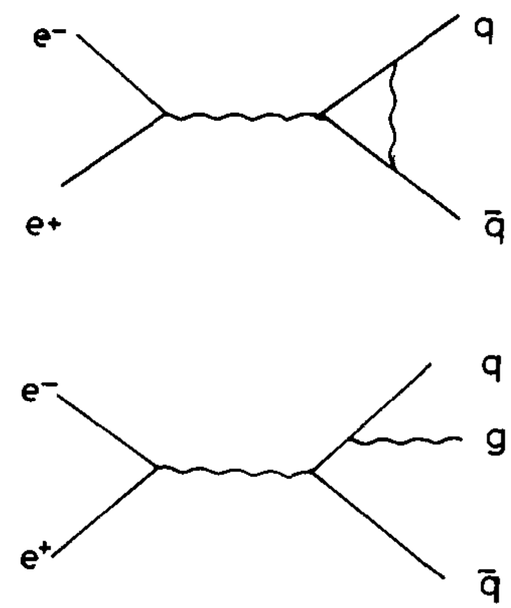
[Larkoski, JDT, 1307.1699]

NLL: [Larkoski, Moult, Neill, 1401.4458]
[Procura, Waalewijn, Zeune, 1410.6483]

Predictions for jet substructure from first-principles QCD

0. Learn from Our Elders





φ ambiguous

φ well-defined

Me: "φ is IRC unsafe"

My Elder: "We explicitly calculated dσ/dφ in 1978"

$$\frac{2\pi}{\sigma_0}\frac{d\sigma}{d\varphi} = 1 + O(\alpha_s(Q^2)) + \frac{\alpha_s(Q^2)}{\pi}\left(\frac{16}{3}\ln\frac{3}{2} - 2\right)\cos 2\varphi$$

Born cross section despite ambiguity (!)

Lesson: Use IRC limit to resolve ambiguities

[Pi, Jaffe, Low, 1978; Kramer, Schierholz, Willrodt, 1978]

1. Use Sudakov Form Factors

z_g — IR Safe, C Unsafe

Measure jet mass?

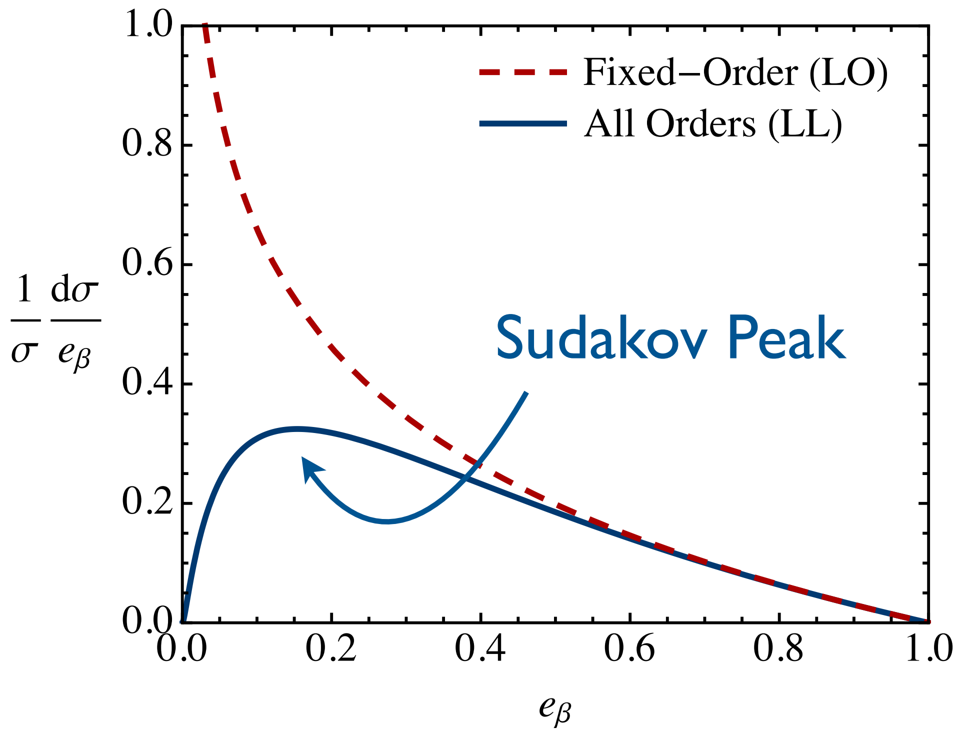
$z_g^{m>0}$ — IRC Safe

$\Rightarrow$

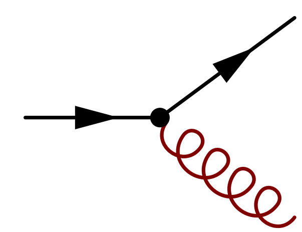
Jet mass never zero!

z_g — Sudakov Safe

Jet mass distribution



Fixed $O(\alpha_s)$

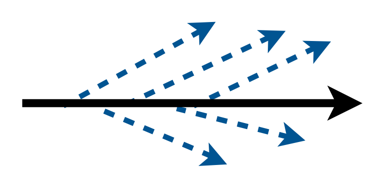


m=0 singular

vs.

All α_s Orders

(resummed logs)



m=0 suppressed

[Larkoski, JDT, 1307.1699]

1. Use Sudakov Form Factors

Unsafe

Want: $$p(u) = \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}u}$$

Calculable…

Need: $$p(u|s) = \frac{p(u,s)}{p(s)}$$

…with Safe companion

Sudakov Safe

Insight: $$p(u) = \int \mathrm{d}s\, p(s)\, p(u|s)$$

Sudakov form factor
(all orders in α_s)

Perturbative
(fixed order in α_s)

Suppresses isolated singularities…

…at each perturbative order

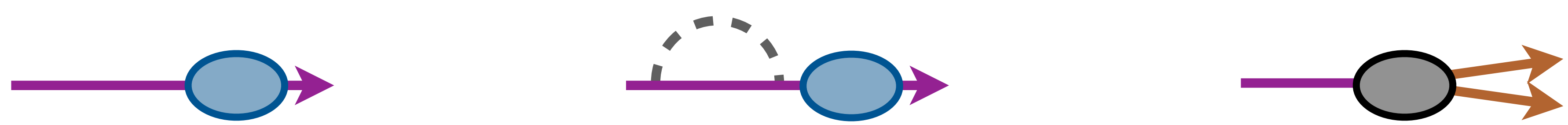
[Larkoski, Marzani, JDT, 1502.01719]

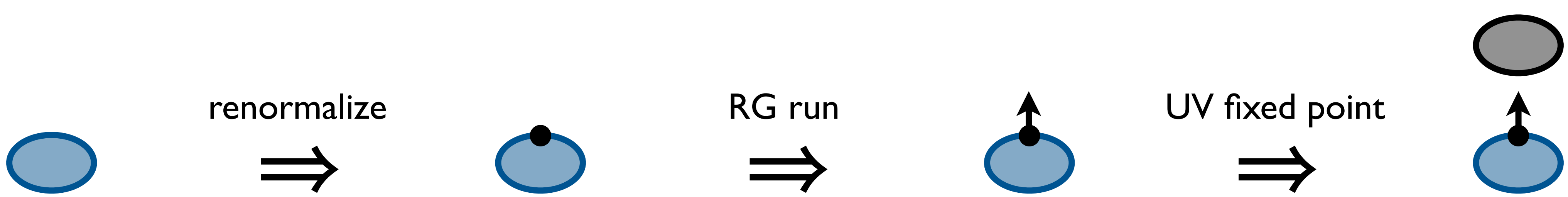
2. Use Fragmentation Functions

z_g — IR Safe / C Unsafe

Absorb singularities into universal function (just like PDFs!)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} \simeq F(z_g) - \frac{1}{2\epsilon}\frac{\alpha_s C}{\pi} F(z_g) + \frac{\alpha_s C}{\pi}\int \frac{\mathrm{d}\theta}{\theta} P(z_g)$$





$$F(z_g) \xRightarrow{\text{renormalize}} F(z_g;\mu) \xRightarrow{\text{RG run}} \mathrm{d}/\mathrm{d}\mu \xRightarrow{\text{UV fixed point}} P(z_g)$$

[Larkoski, Marzani, JDT, 1502.01719]