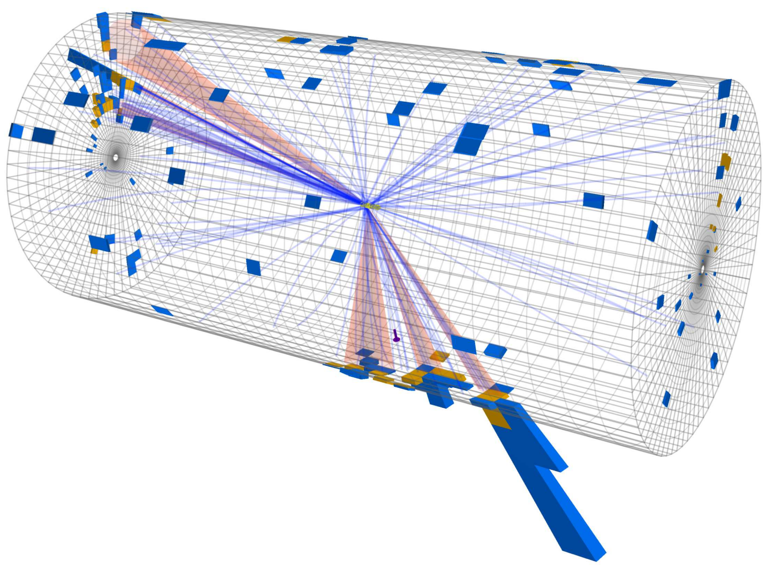
Jets at the Frontier of Perturbative QCD

Jesse Thaler

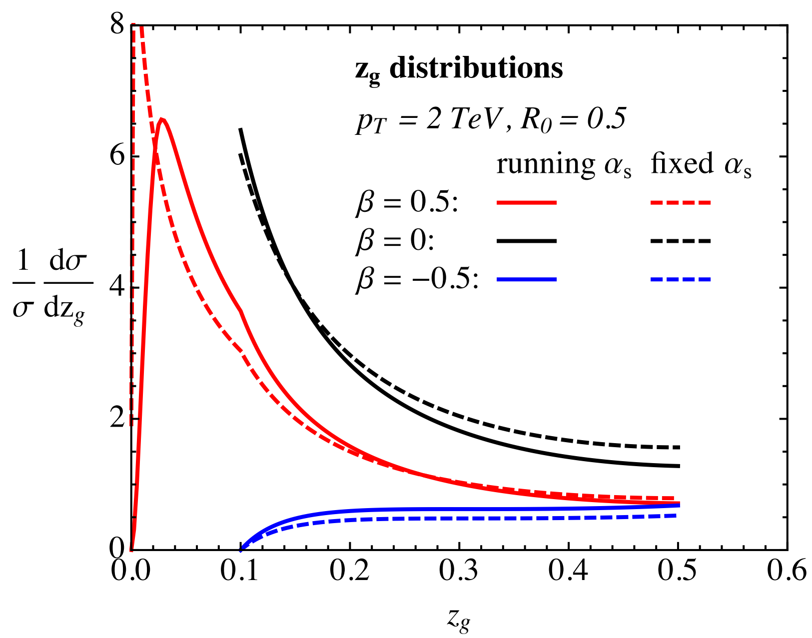
KEK — January 17, 2017

Jet Substructure



Boosting the Search for New Phenomena

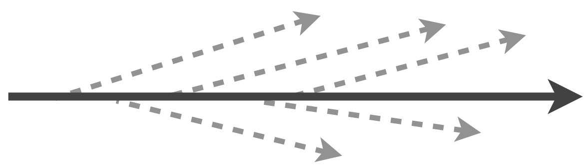
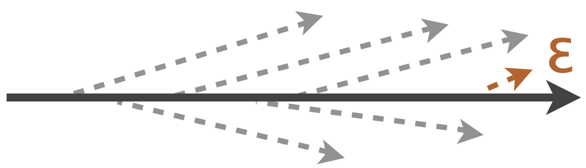
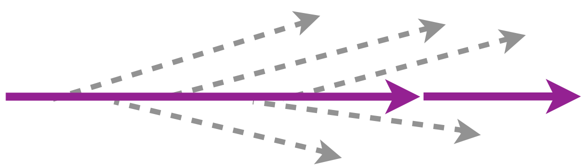
[Last Thursday & Friday]



Pushing the Boundaries of Quantum Field Theory

[Monday & **Today**]

Last Time: Infrared/Collinear Safety

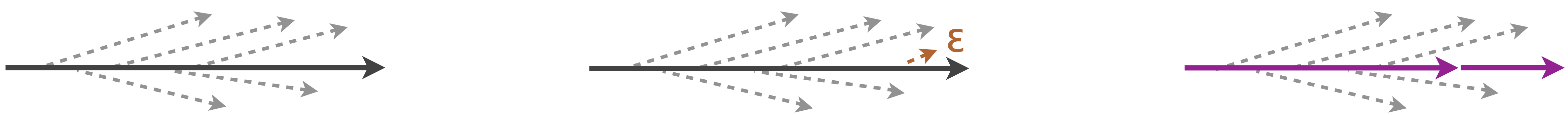
Original Jet	Infrared	Collinear
		

IRC Safe Observable: Insensitive to IR or C emissions

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

Last Time: Infrared/Collinear Safety

Original Jet | Infrared | Collinear

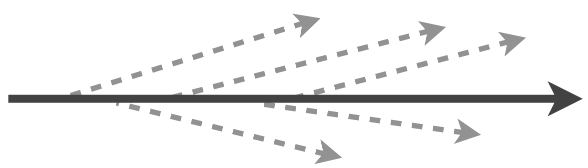


IRC Safe Observable: Insensitive to IR or C emissions

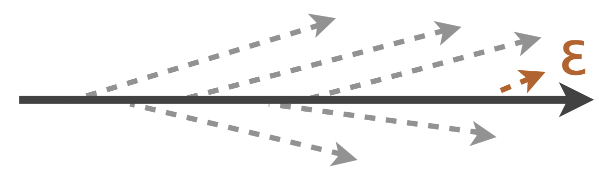
New Lore:		IRC Safe	IRC Unsafe
	Calculable in pQCD?	✓	✓*
	Controlled Λ_{QCD} Effects?	✓*	✓*

Last Time: Infrared/Collinear Safety

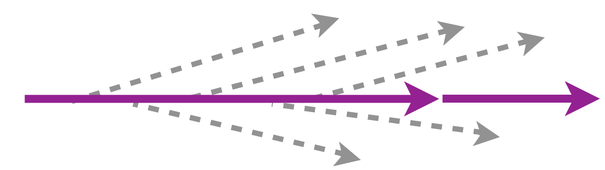
Original Jet



Infrared



Collinear



IRC Safe Observable: Insensitive to IR or C emissions

New Lore:

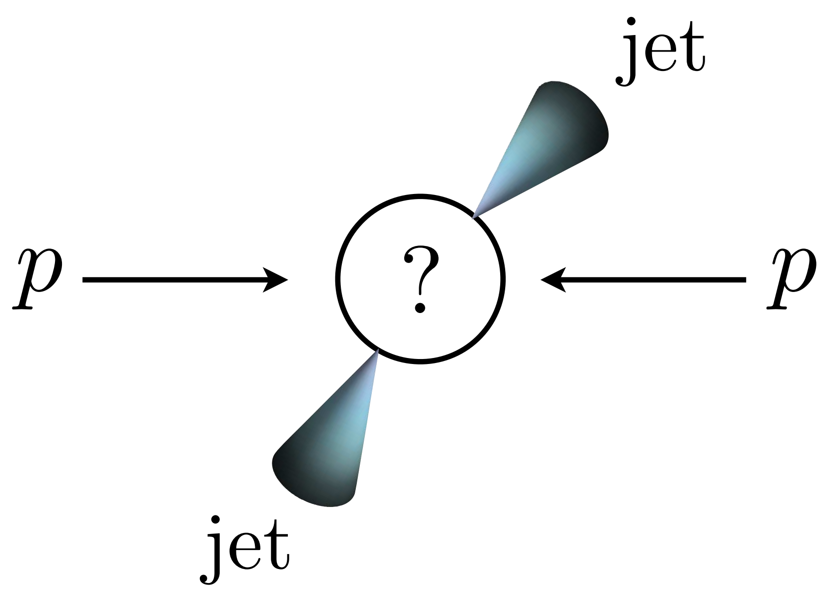
	IRC Safe	IRC Unsafe
Calculable in pQCD?	✓	$\boxed{✓*}$
Controlled Λ_{QCD} Effects?	✓*	✓*

"Sudakov Safety":

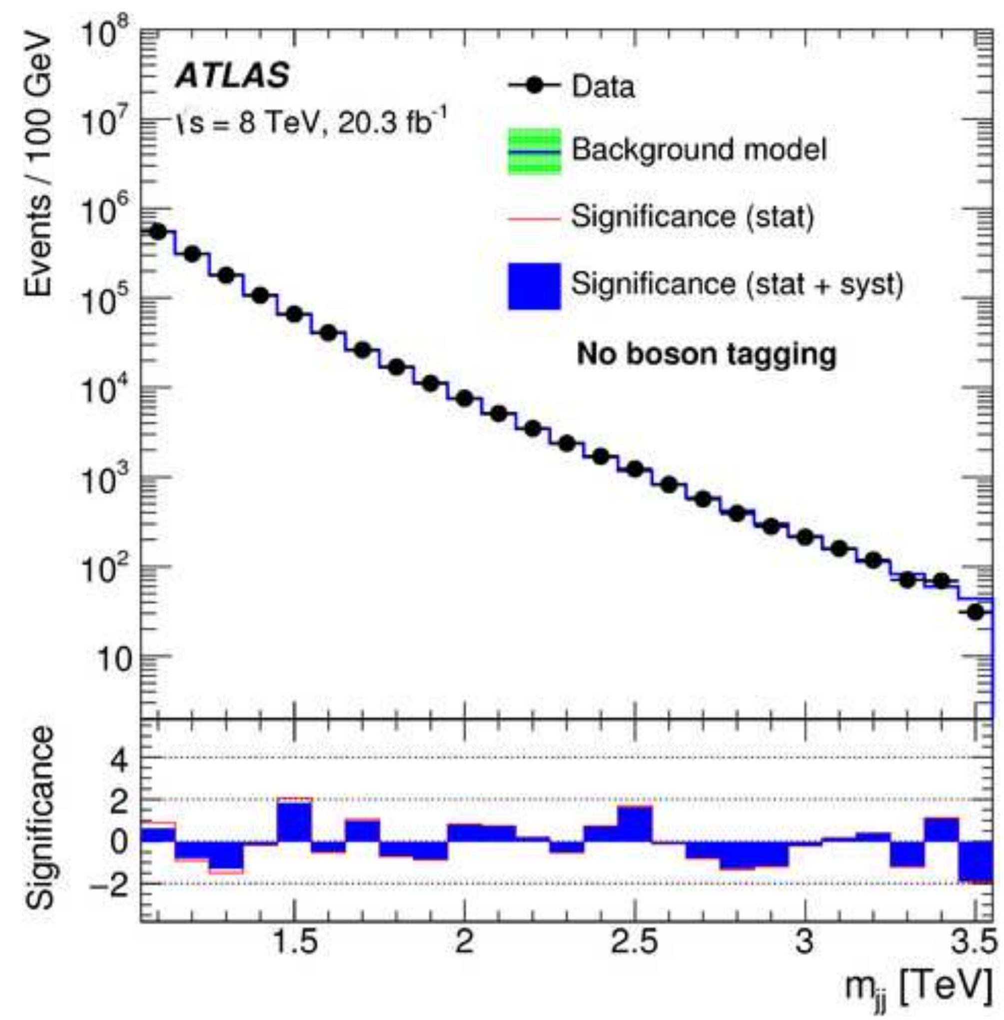
[Andrew Larkoski, JDT, 1307.1699, 1406.7011]
[Andrew Larkoski, Simone Marzani, Gregory Soyez, JDT, 1402.2657]
[Andrew Larkoski, Simone Marzani, JDT, 1502.01719]

From New Physics to QCD Calculations

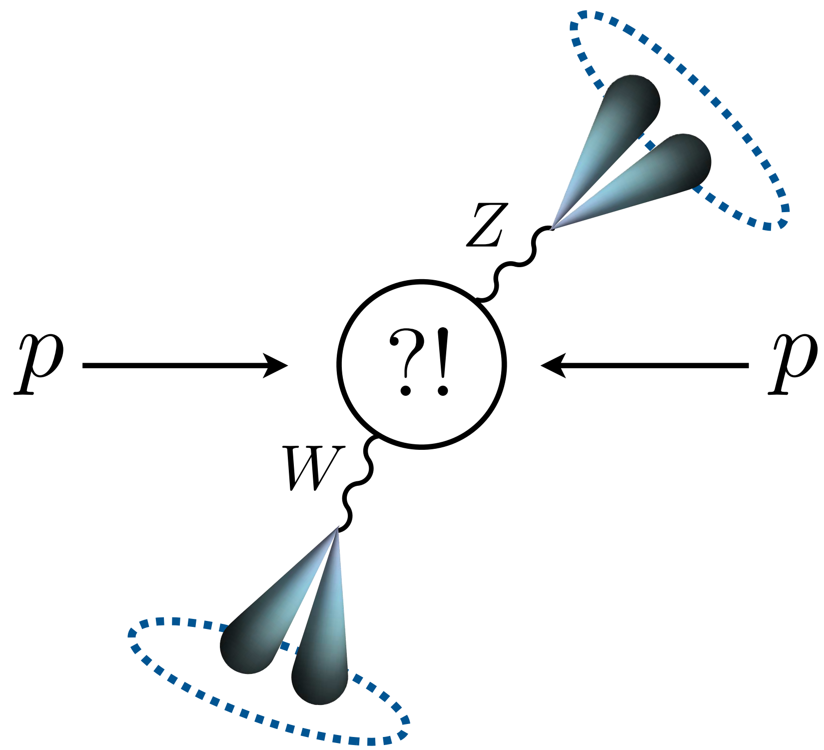
Flashback to 2015: Dijet Excess?



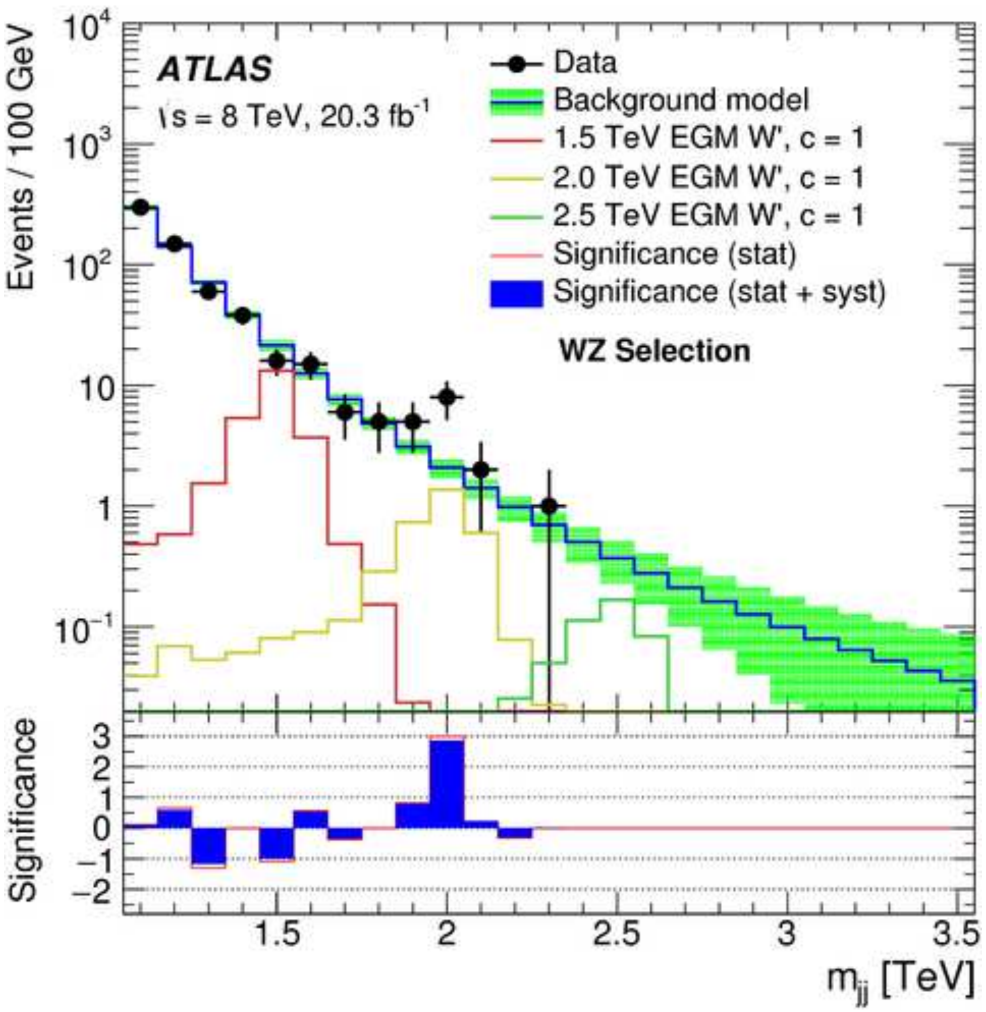
[ATLAS, 1506.00962]



Flashback to 2015: Diboson Excess!

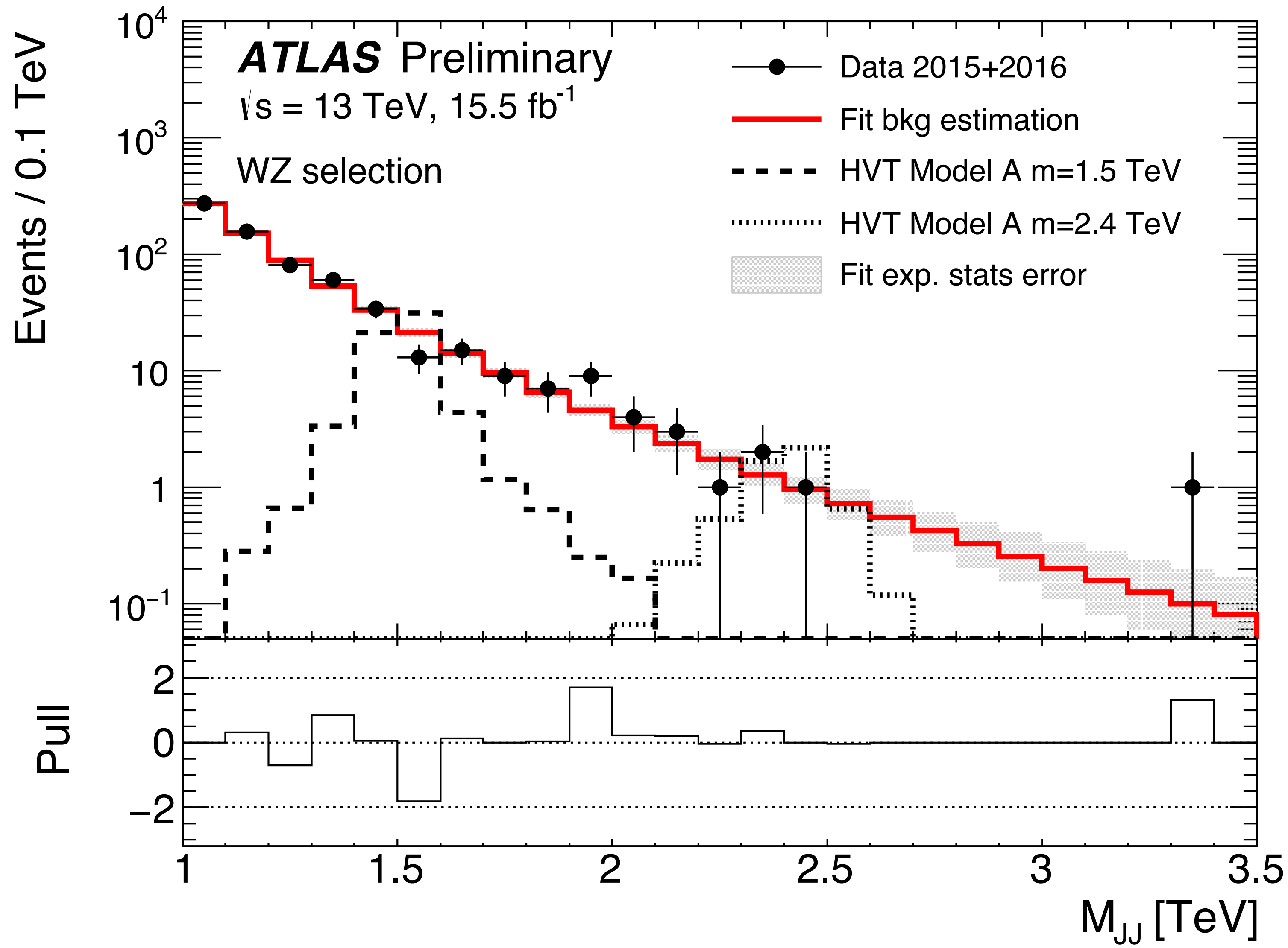


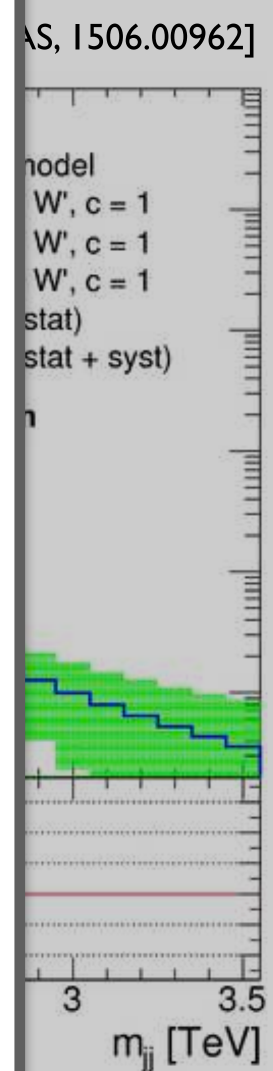
[ATLAS, 1506.00962]



Flashback to 2015: Diboson Excess!

Bumps may come and go…



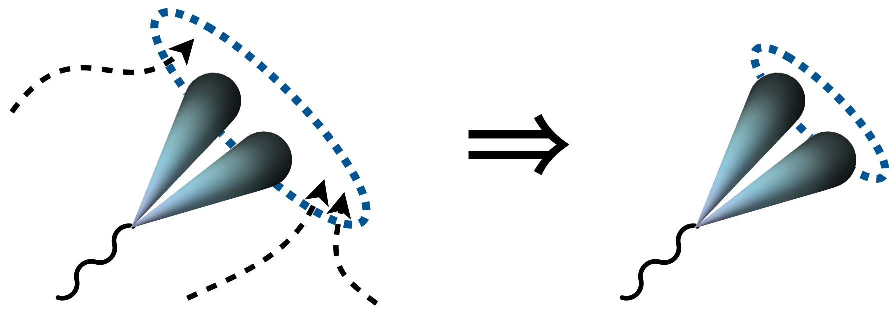


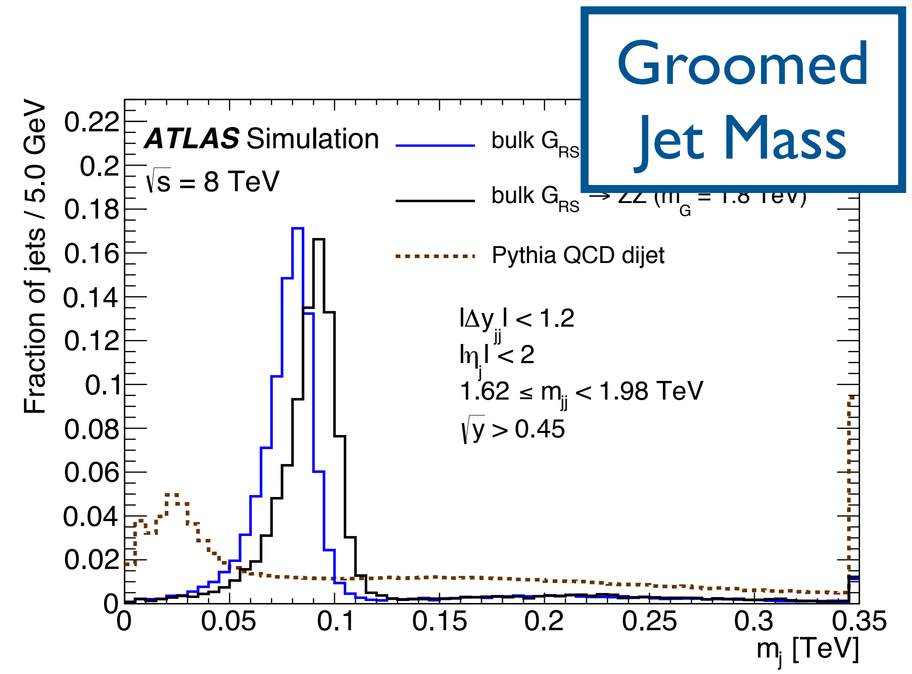
Key Substructure Techniques

ATLAS @ 8 TeV: BDRS Tagging

Grooming:

e.g. ISR/UE/pileup



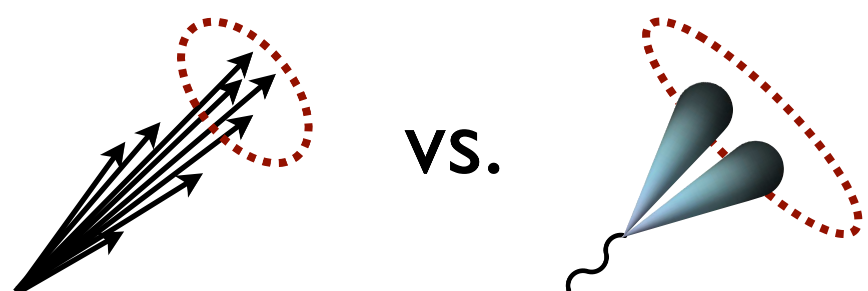


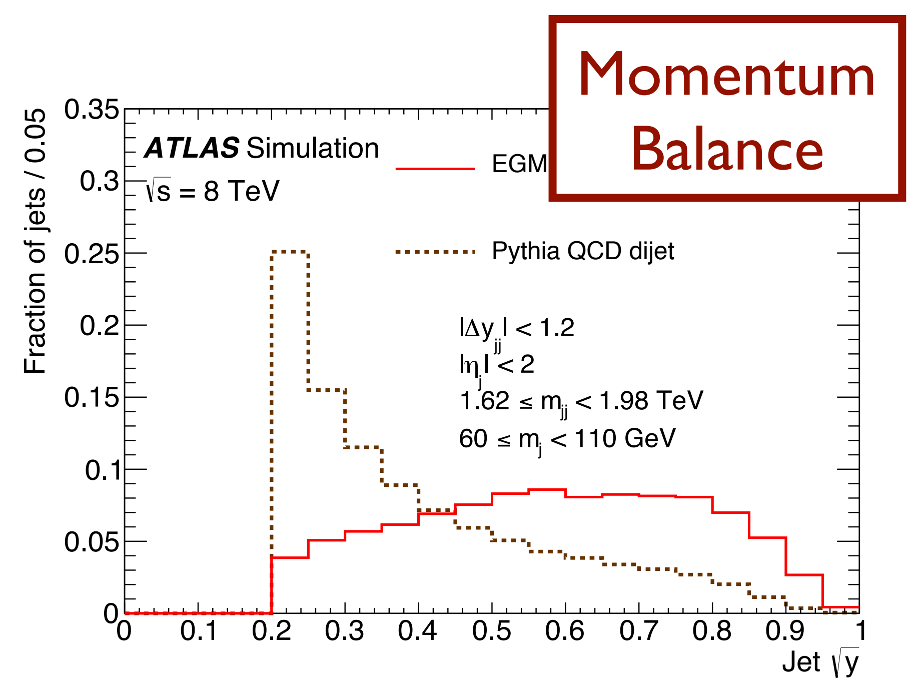
[Mass Drop/Filtering, Trimming, Pruning, Soft Drop, Jet Reclustering…;
for pileup: Area Subtraction, Jet Cleansing, SoftKiller, PUPPI, Constituent Subtraction…]

[using Butterworth, Davison, Rubin, Salam, 0802.2470]

Discrimination:

e.g. 1-prong vs. N-prong

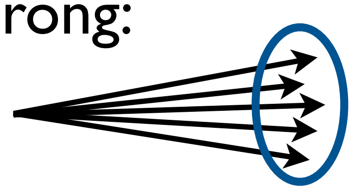




[p_T Balance, Y-splitter, Angularities, Planar Flow, N-subjettiness, Angular Structure Functions, Jet Charge, Jet Pull, Energy Correlation Functions, Dipolarity, p_T^D, Zernike Coefficients, LHA, Fox-Wolfram Moments, JHU/CMSTopTagger, HEPTopTagger, Template Method, Shower Deconstruction, Subjet Counting, Wavelets, Q-Jets, Telescoping Jets…]

First-Principles Calculations

1-prong:



Jet mass: Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky, 1207.1640; Chien, Kelley, Schwartz, Zhu, 1208.0010; Jouttenus, Stewart, Tackmann, Waalewijn, 1302.0846

Jet shapes: Ellis, Vermilion, Walsh, Hornig, Lee, 1001.0014; Banfi, Dasgupta, Khelifa-Kerfa, Marzani, 1004.3483; Li, Li, Yuan, 1107.4535; Larkoski, Neill, JDT, 1401.2158; Hornig, Makris, Mehen, 1601.01319

Angular scaling: Jankowiak, Larkoski, 1201.2688; Larkoski, 1207.1437

Quarks vs. gluons: Larkoski, Salam, JDT, 1305.0007; Larkoski, JDT, Waalewijn, 1408.3122; Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, Webber, 1501.04794

QCD grooming: Dasgupta, Fregoso, Marzani, Salam, 1307.0007; Dasgupta, Fregoso, Marzani, Powling, 1307.0013; Larkoski, Marzani, Soyez, JDT, 1402.2657; Frye, Larkoski, Schwartz, Yan, 1603.06375, 1603.09338

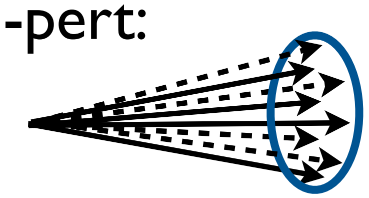
Double differential: Larkoski, JDT, 1307.1699; Larkoski, Moult, Neill, 1401.4458; Procura, Waalewijn, Zeune, 1410.6483

In heavy ions: Chien, Vitev, 1405.4293; Chien, 1411.0741

p_T balance: Larkoski, Marzani, JDT, 1502.01719; Chien, Vitev, 1608.07283

Small R jets: Dasgupta, Dreyer, Salam, Soyez, 1411.5182, 1602.01110

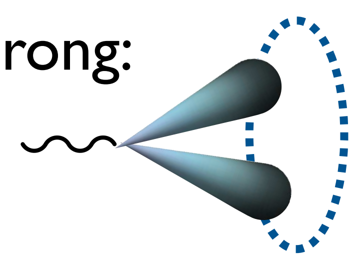
Non-pert:



Jet charge: Krohn, Schwartz, Lin, Waalewijn, 1209.2421; Waalewijn, 1209.3019

Track-only shapes: Chang, Procura, JDT, Waalewijn, 1303.6637, 1306.6630

2-prong:

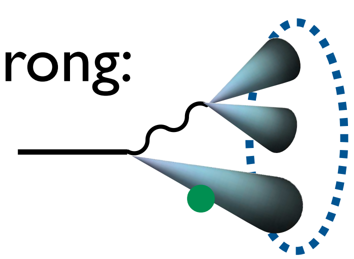


Signal grooming: Rubin, 1002.4557; Dasgupta, Powling, Siodmok, 1503.01088

2-prong jet shapes: Feige, Schwartz, Stewart, JDT, 1204.3898; Isaacson, Li, Li, Yuan, 1505.06368

Separation power: Larkoski, Moult, Neill, 1409.6298, 1507.03018; Dasgupta, Schunk, Soyez, 1512.00516; Dasgupta, Powling, Schunk, Soyez, 1609.07149

3-prong:

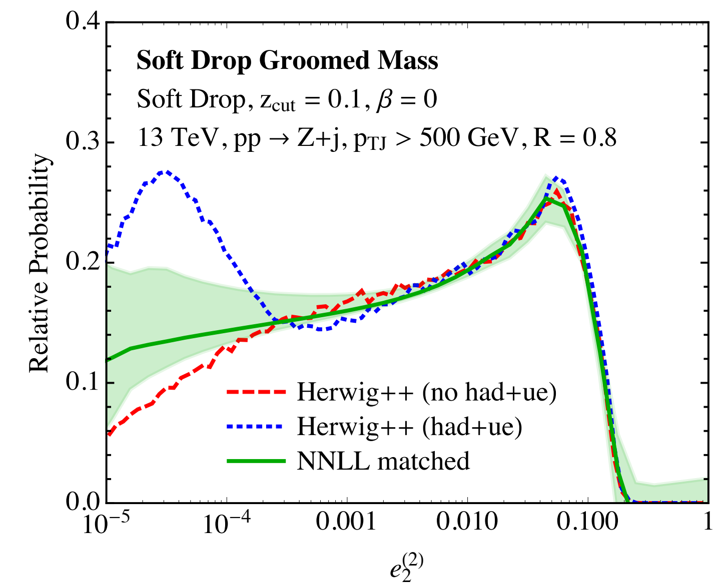


Planar flow: Field, Gur-Ari, Kosower, Mannelli, Perez, 1212.2106

Fractional jets: Bertolini, JDT, Walsh, 1501.01965

Power counting: Larkoski, Moult, Neill, 1411.0665

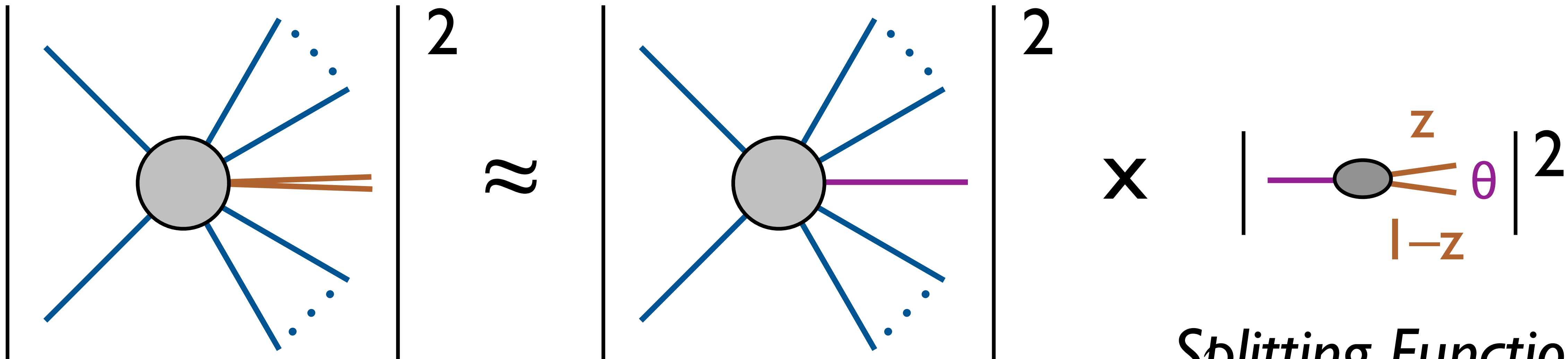
First NNLL + $O(\alpha_s^2)$ calculation for substructure in pp



Combination of fixed-order, direct resummation, SCET, RG evolution, and new techniques (e.g. Sudakov safety, multi-differential projections)

Calculating Momentum Balance?

Textbook QCD: Universal Collinear Limit

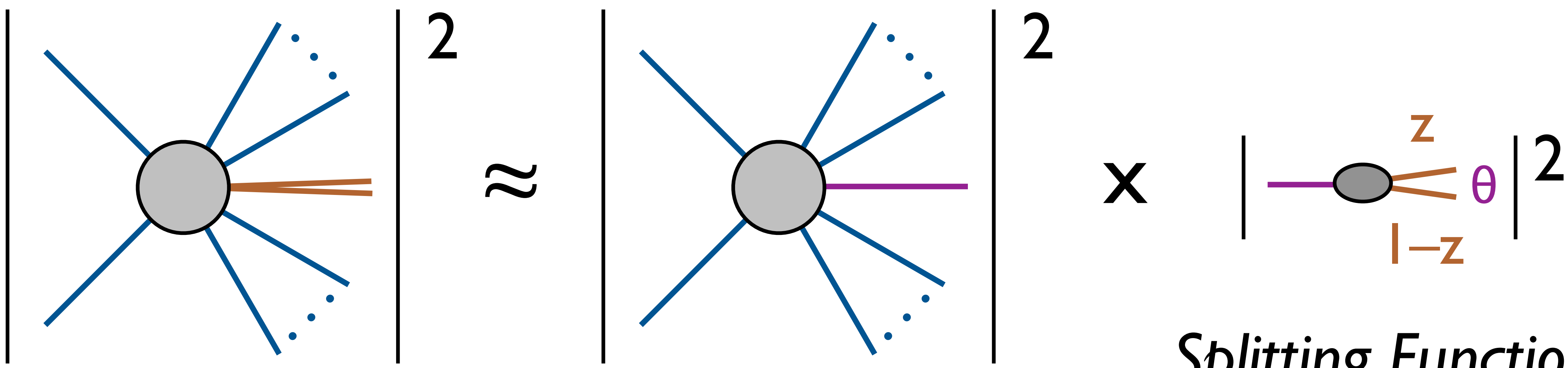


Splitting Function

2→n　　2→n−1　　1→2

$$\mathrm{d}P_{i\to jk} = \underbrace{\frac{\mathrm{d}\theta}{\theta}}_{\text{Collinear singularity}} \mathrm{d}z \, \underbrace{P_{i\to jk}(z)}_{\text{Altarelli-Parisi splitting function}}$$

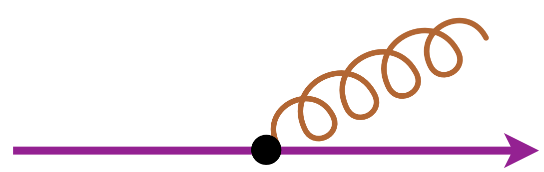
Textbook QCD: Universal Collinear Limit



Splitting Function

2→n | 2→n–1 | 1→2

For this talk:



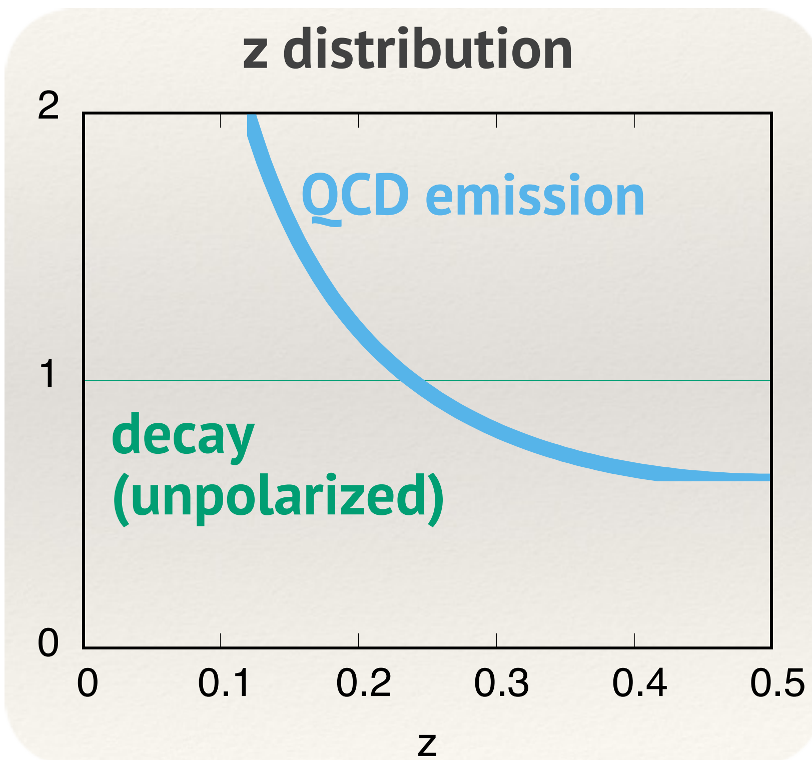
$C_q = 4/3$
$C_g = 3$

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

QCD Splitting Functions

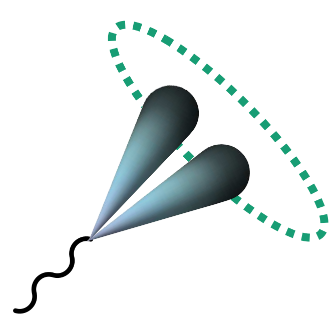
Basis for DGLAP evolution of PDFs, parton shower generators, fixed-order subtractions, k_t jet clustering…

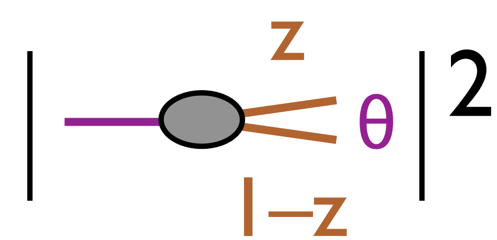
Jet Substructure Discrimination



[From Gavin Salam FCC talk, March 2015]

vs.



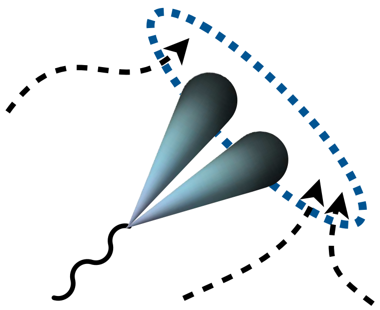


Splitting Function

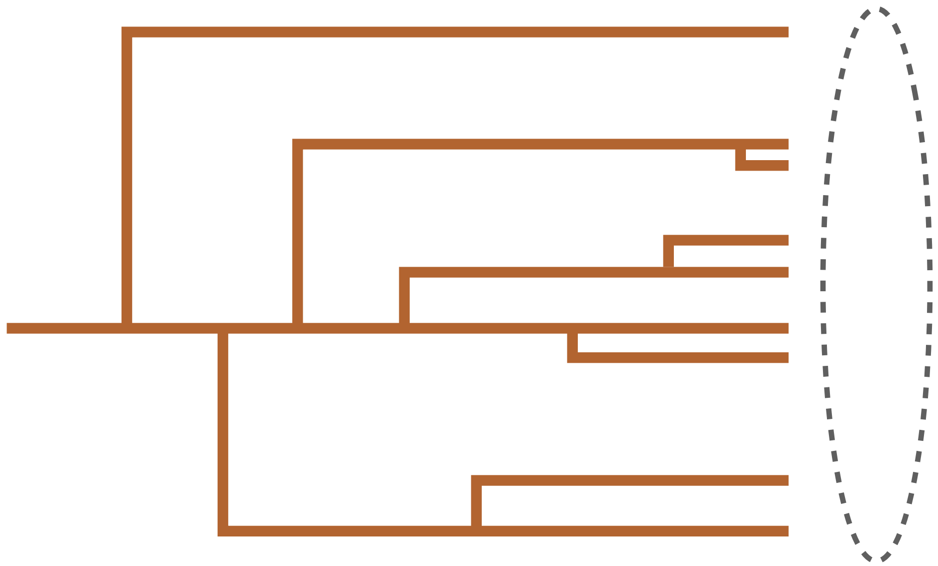
1→2

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

ATLAS: Boson Tagging with BDRS

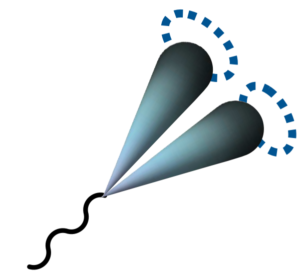


Angular-ordered clustering tree:

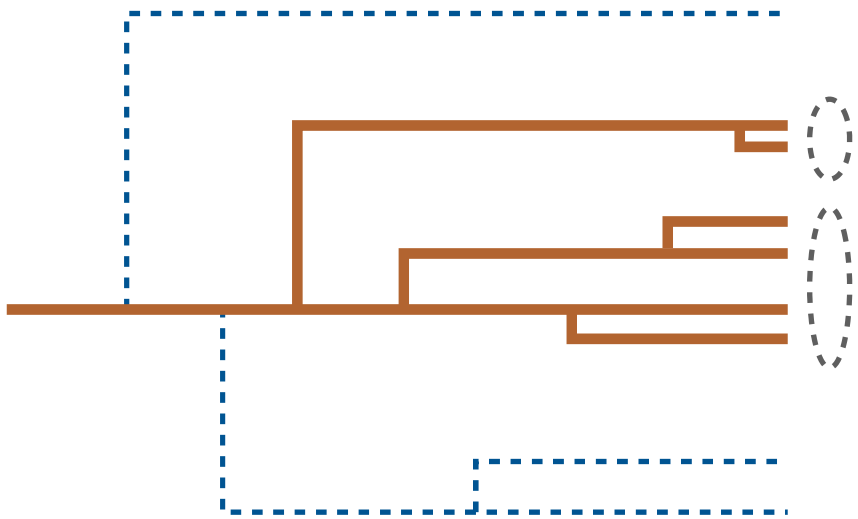


[Butterworth, Davison, Rubin, Salam, 0802.2470; see also Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

ATLAS: Boson Tagging with BDRS



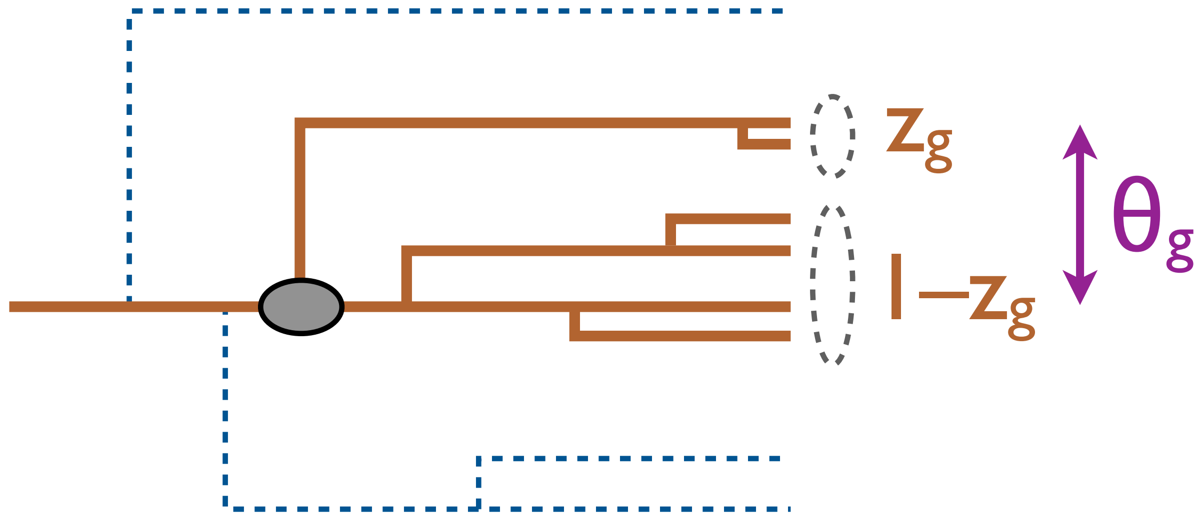
Groomed angular-ordered clustering tree:

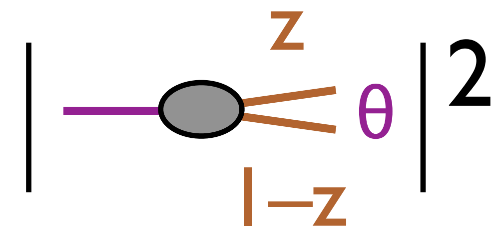


[Butterworth, Davison, Rubin, Salam, 0802.2470; see also Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

ATLAS: Boson Tagging with BDRS

Groomed angular-ordered clustering tree:

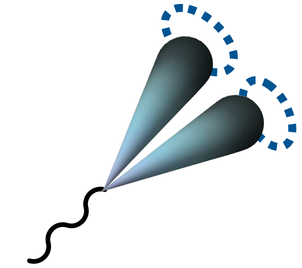


cf. 

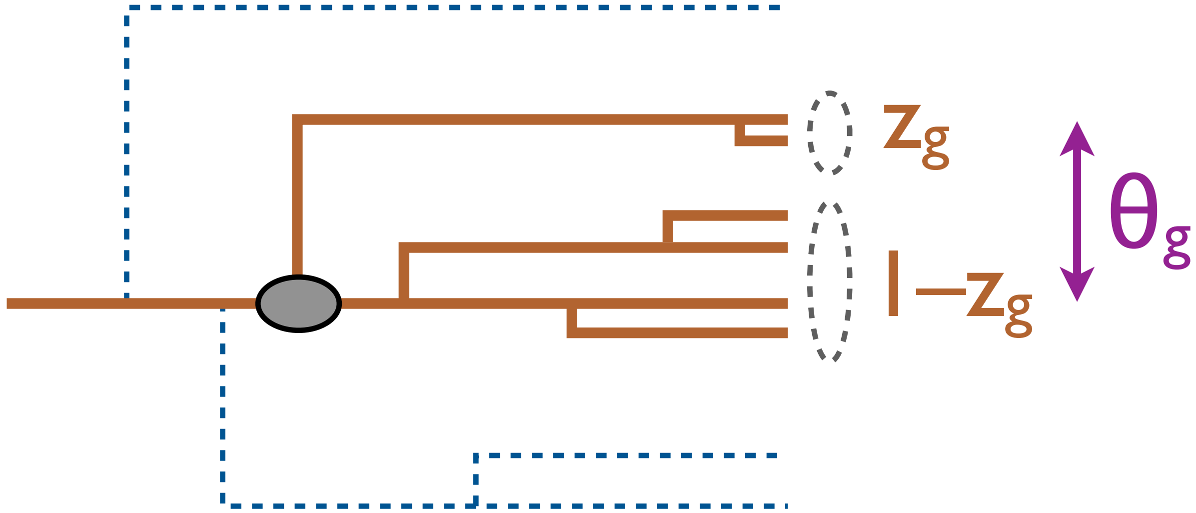
$$\frac{2\alpha_s C_i}{\pi} \frac{d\theta}{\theta} \frac{dz}{z}$$

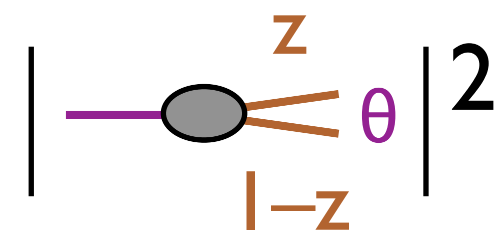
[Butterworth, Davison, Rubin, Salam, 0802.2470; see also Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

ATLAS: Boson Tagging with BDRS

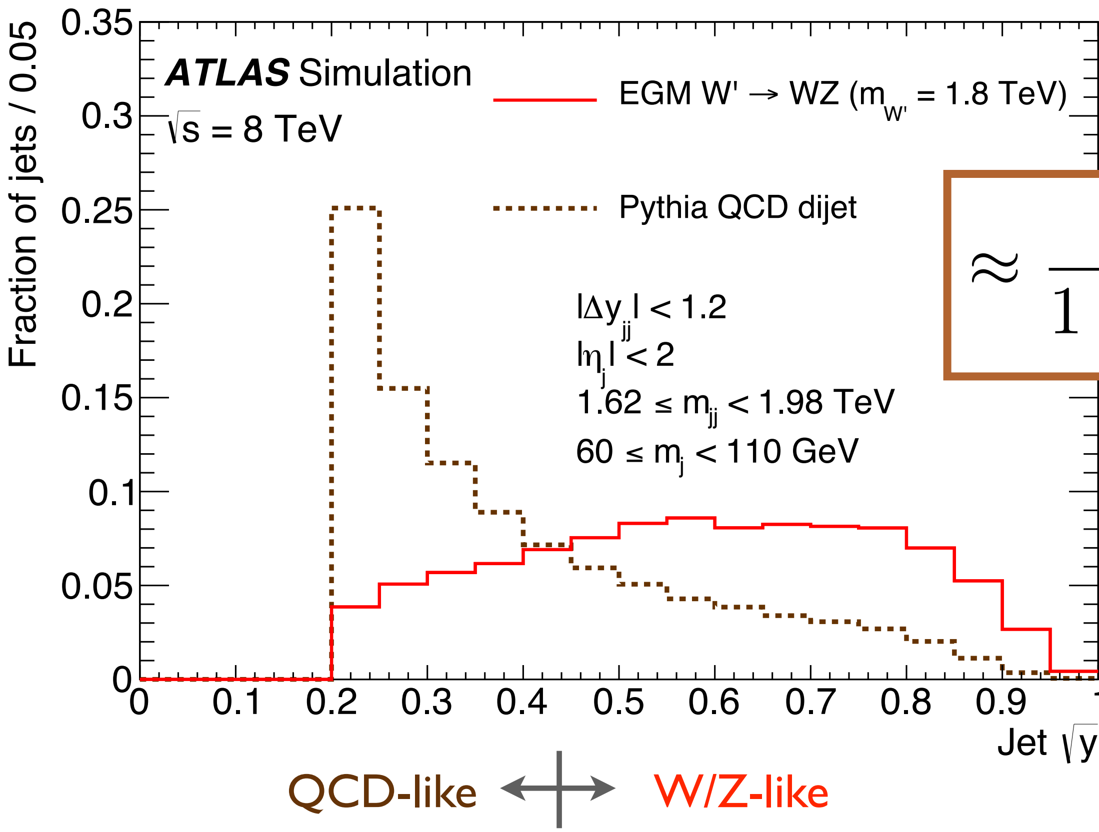


Groomed angular-ordered clustering tree:

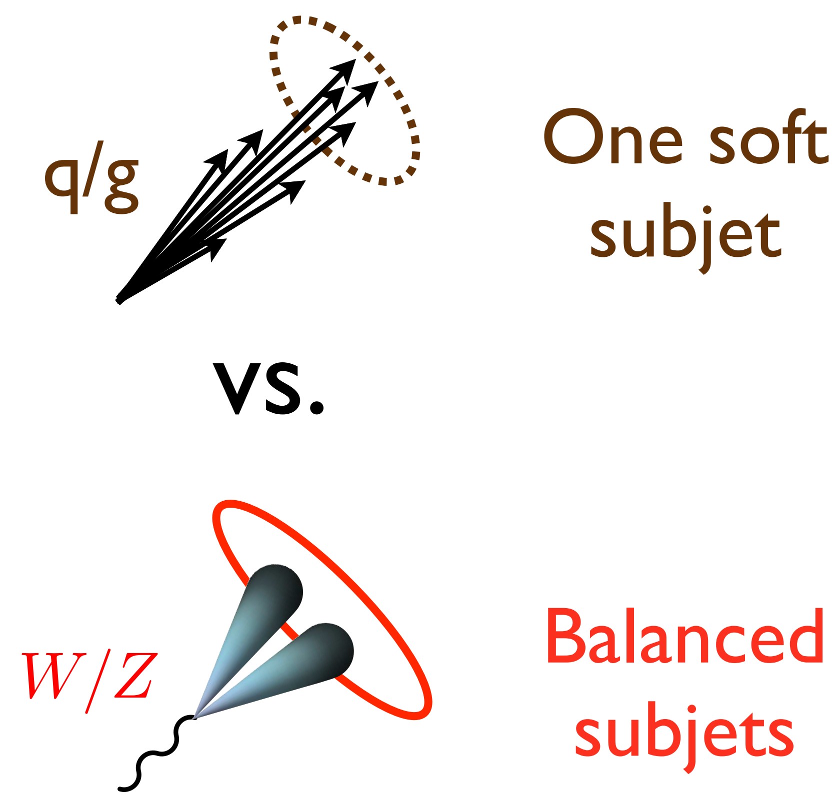


cf. 

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

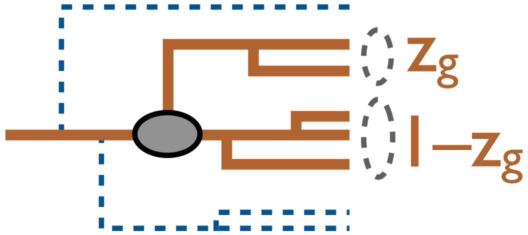


$$\approx \frac{z_g}{1-z_g}$$



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

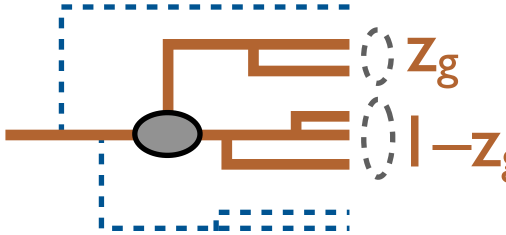
Calculating Momentum Balance?



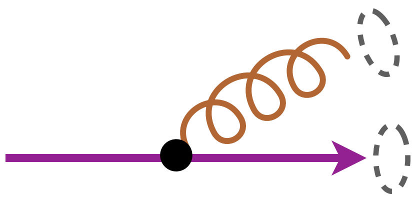
$$\frac{d\sigma}{dz_g} = \left(\textit{undefined} \right) + \alpha_s \left(\qquad\qquad \right) + \alpha_s^2 \left(\qquad\qquad \right) + \ldots$$

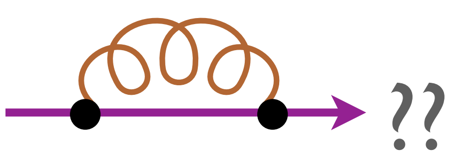
$\longrightarrow$??

Calculating Momentum Balance?

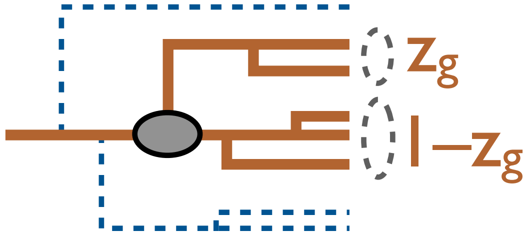


$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \Big(\textit{undefined} \Big) + \alpha_s \Big(\textit{infinity} \Big) + \alpha_s^2 \Big(\qquad \Big) + \ldots$$

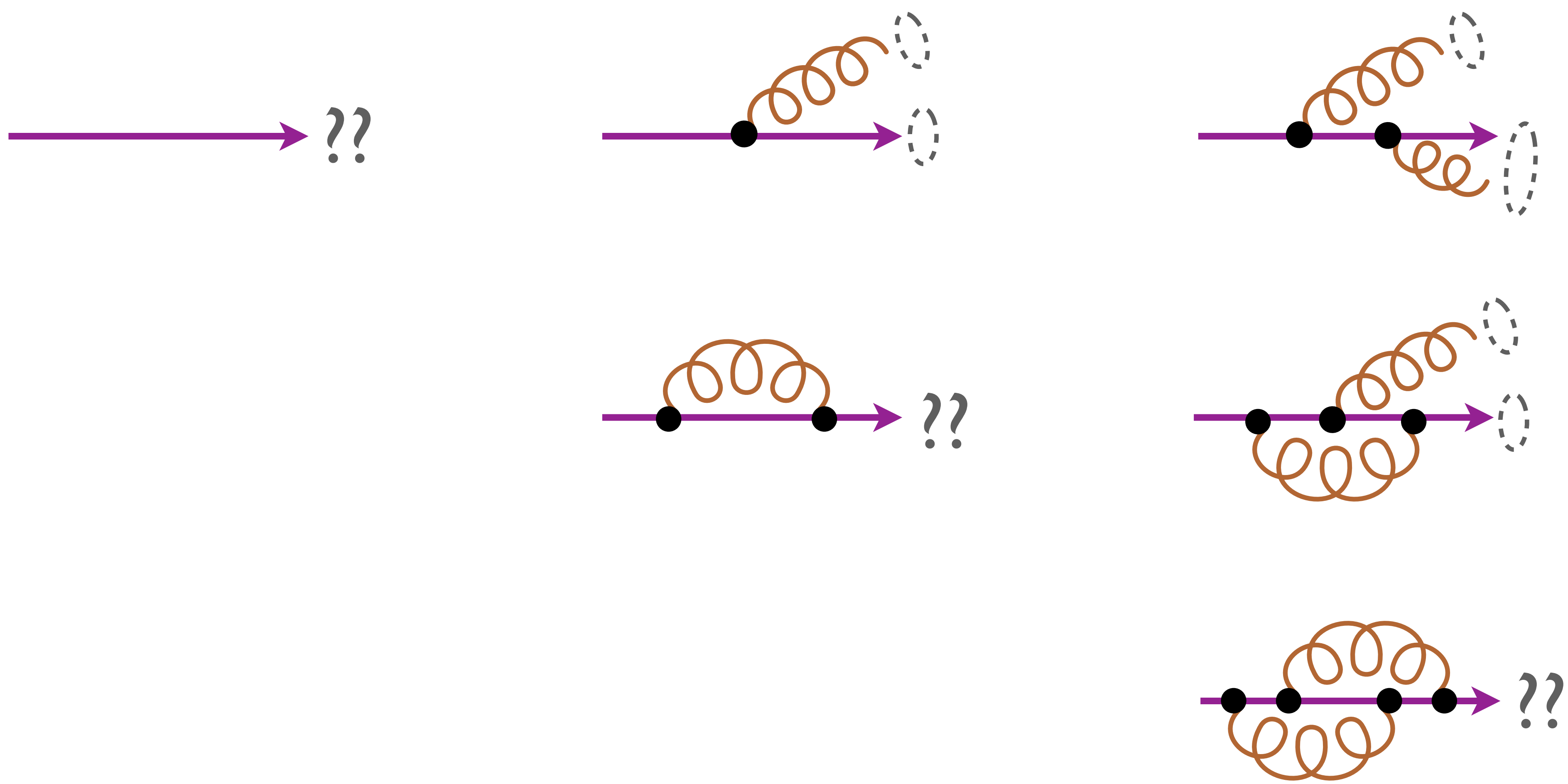




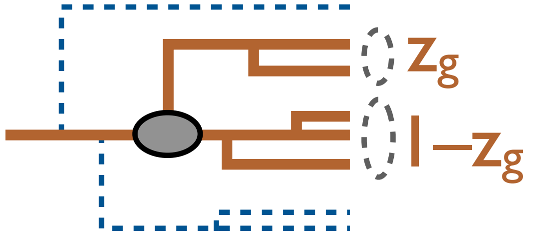
Calculating Momentum Balance?



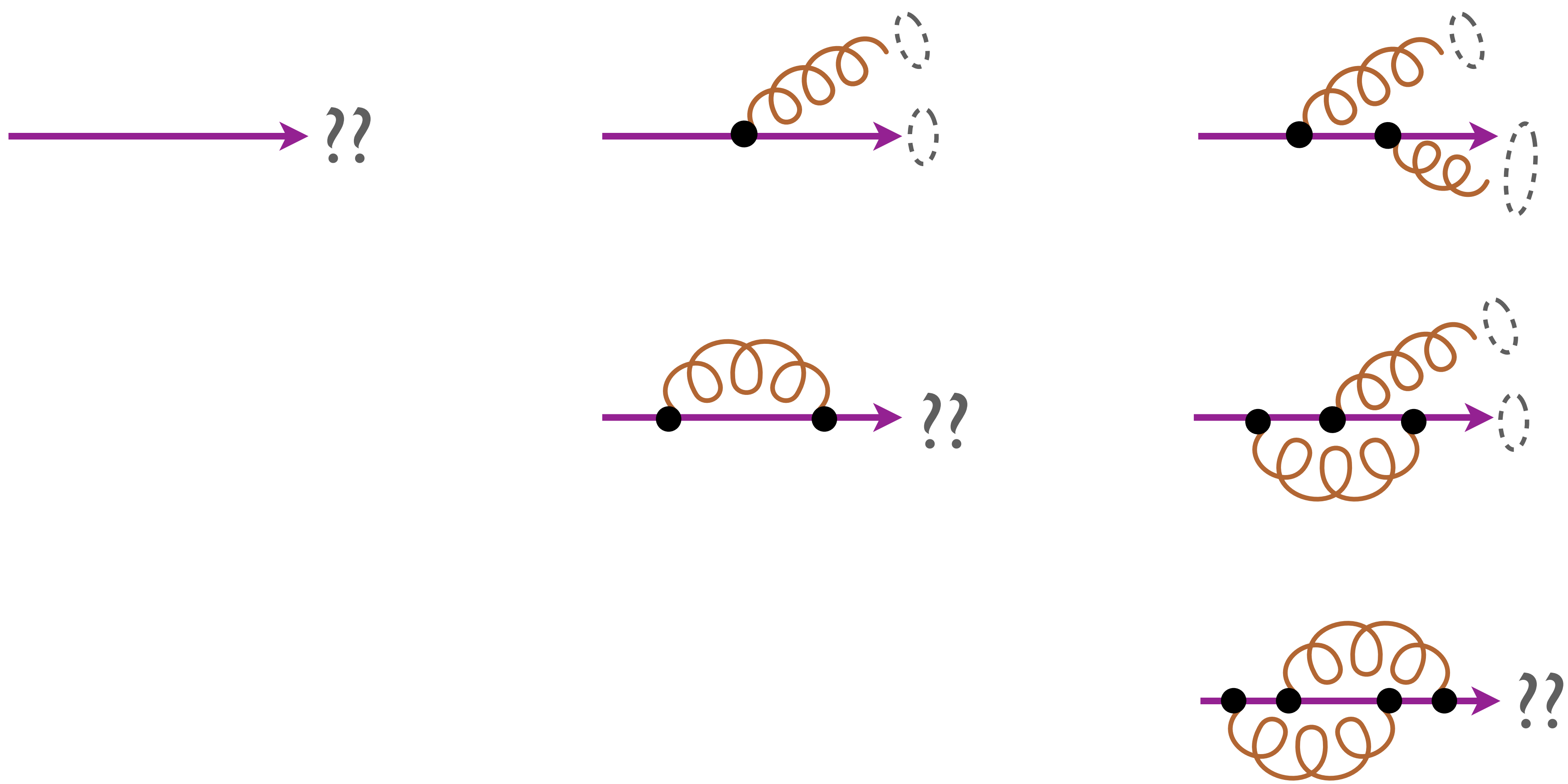
$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \Big(\textit{undefined} \Big) + \alpha_s \Big(\textit{infinity} \Big) + \alpha_s^2 \Big(\textit{infinity}^2 \Big) + \ldots$$



Calculating Momentum Balance?



$$\frac{d\sigma}{dz_g} = \Big(\textit{undefined} \Big) + \alpha_s \Big(\textit{infinity} \Big) + \alpha_s^2 \Big(\textit{infinity}^2 \Big) + \ldots$$



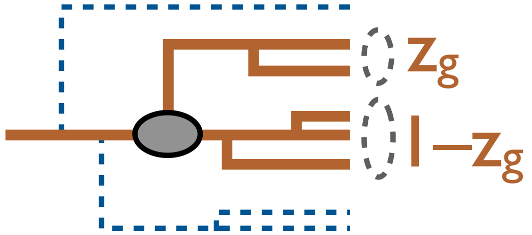
$\mathbf{z_g}$

Collinear Unsafe*

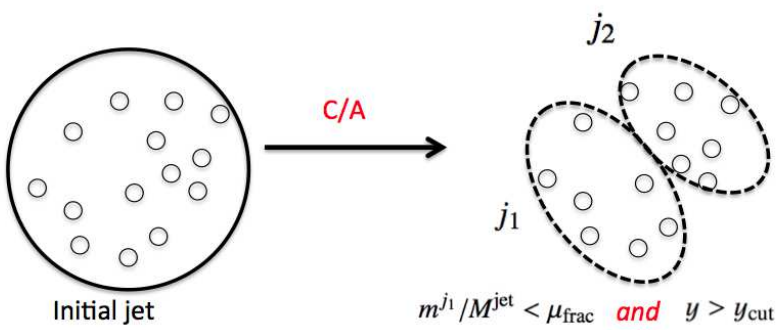
Can't make prediction from perturbative QCD (?)

*unless you simultaneously restrict jet mass

Generalizing to Soft Drop with β



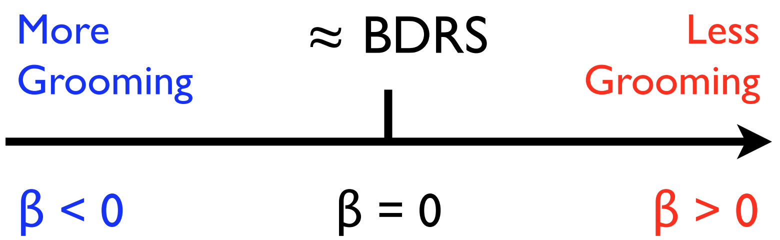
BDRS, a.k.a. Mass Drop



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

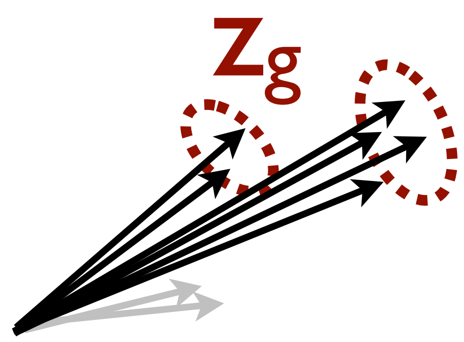
Soft Drop

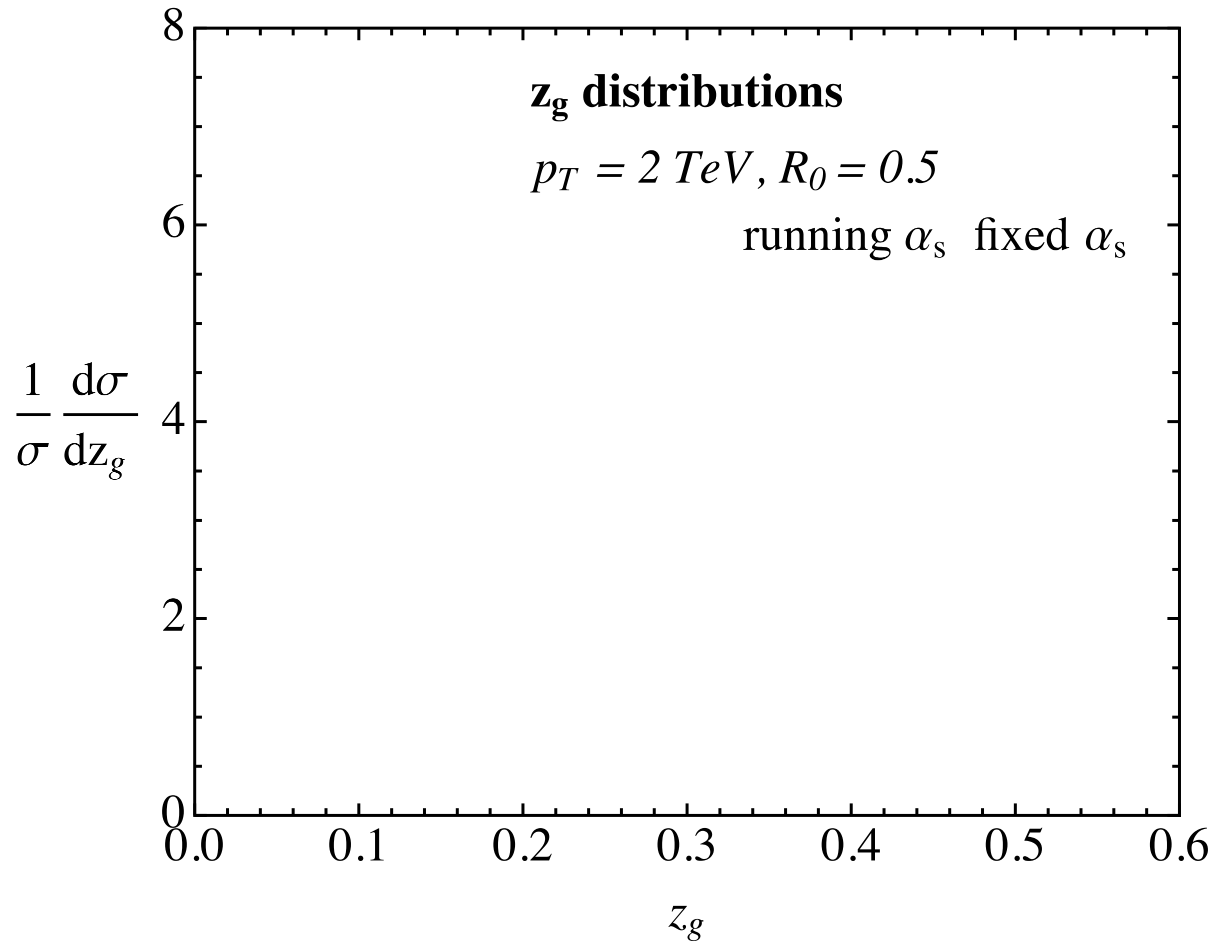
$$z > z_{\rm cut}\,\theta^{\beta}$$

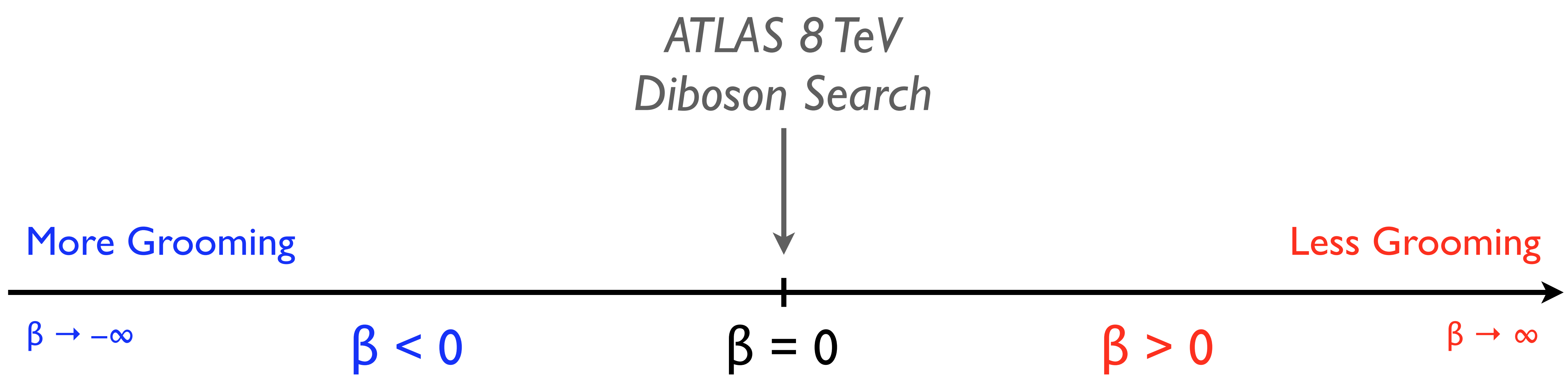


[Larkoski, Marzani, Soyez, JDT, 1402.2657]

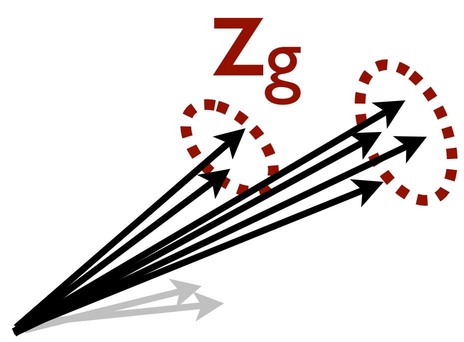
First-Principles QCD

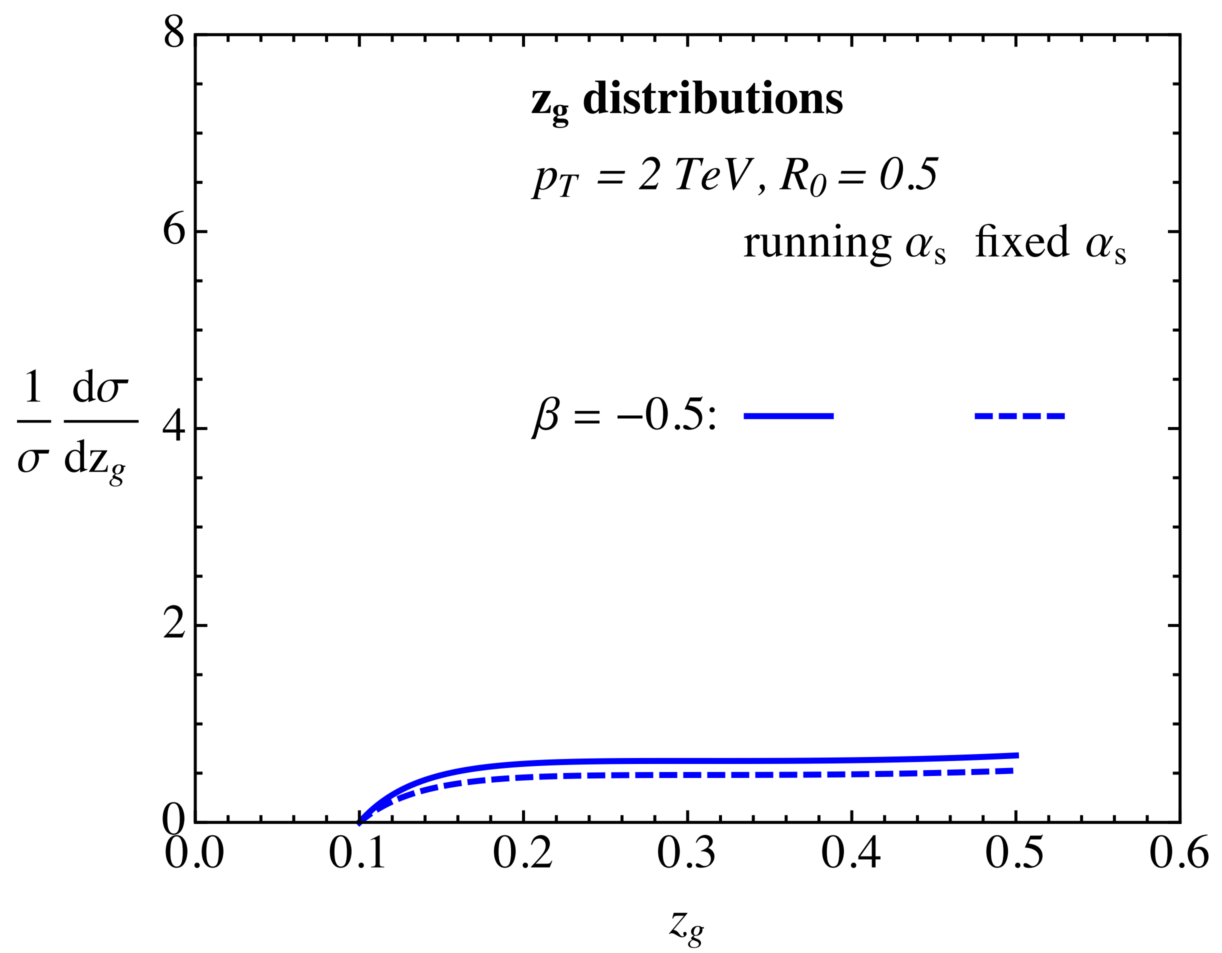






First-Principles QCD





C_q = 4/3
C_g = 3

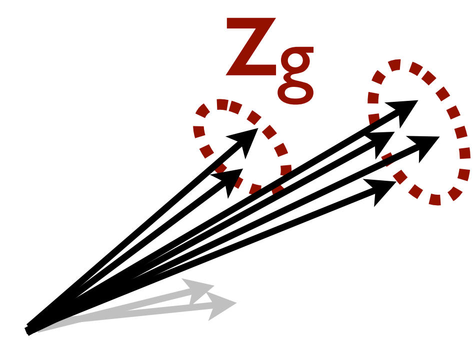
$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\frac{1}{z_g}\log\frac{z_g}{z_{\text{cut}}}$$

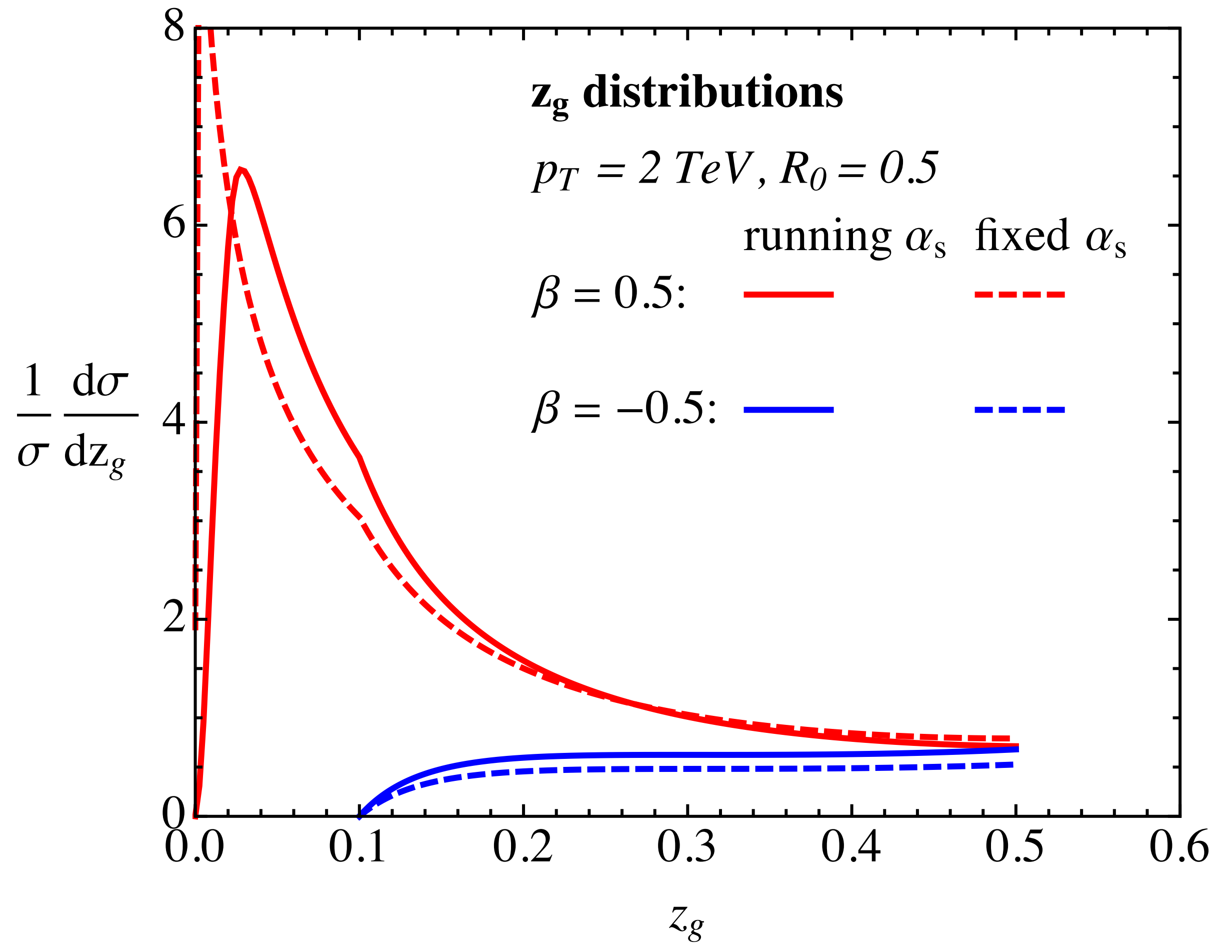
More Grooming

Less Grooming

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

First-Principles QCD





$C_q = 4/3$
$C_g = 3$

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

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

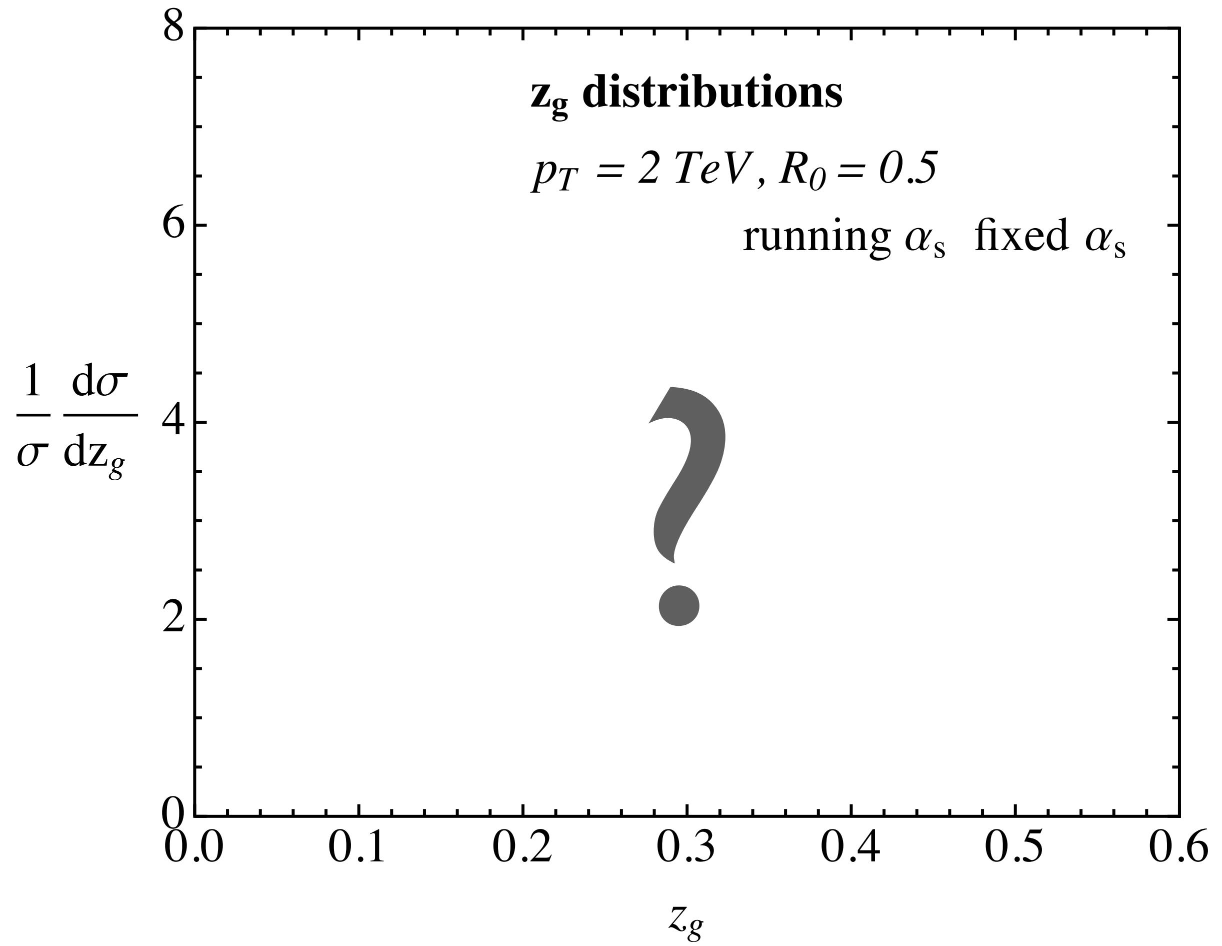
Beyond traditional perturbation theory (Sudakov safe)

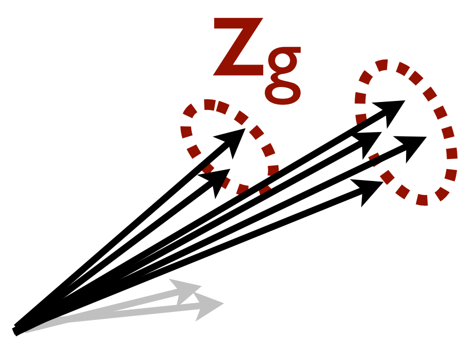
More Grooming

Less Grooming

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

First-Principles QCD





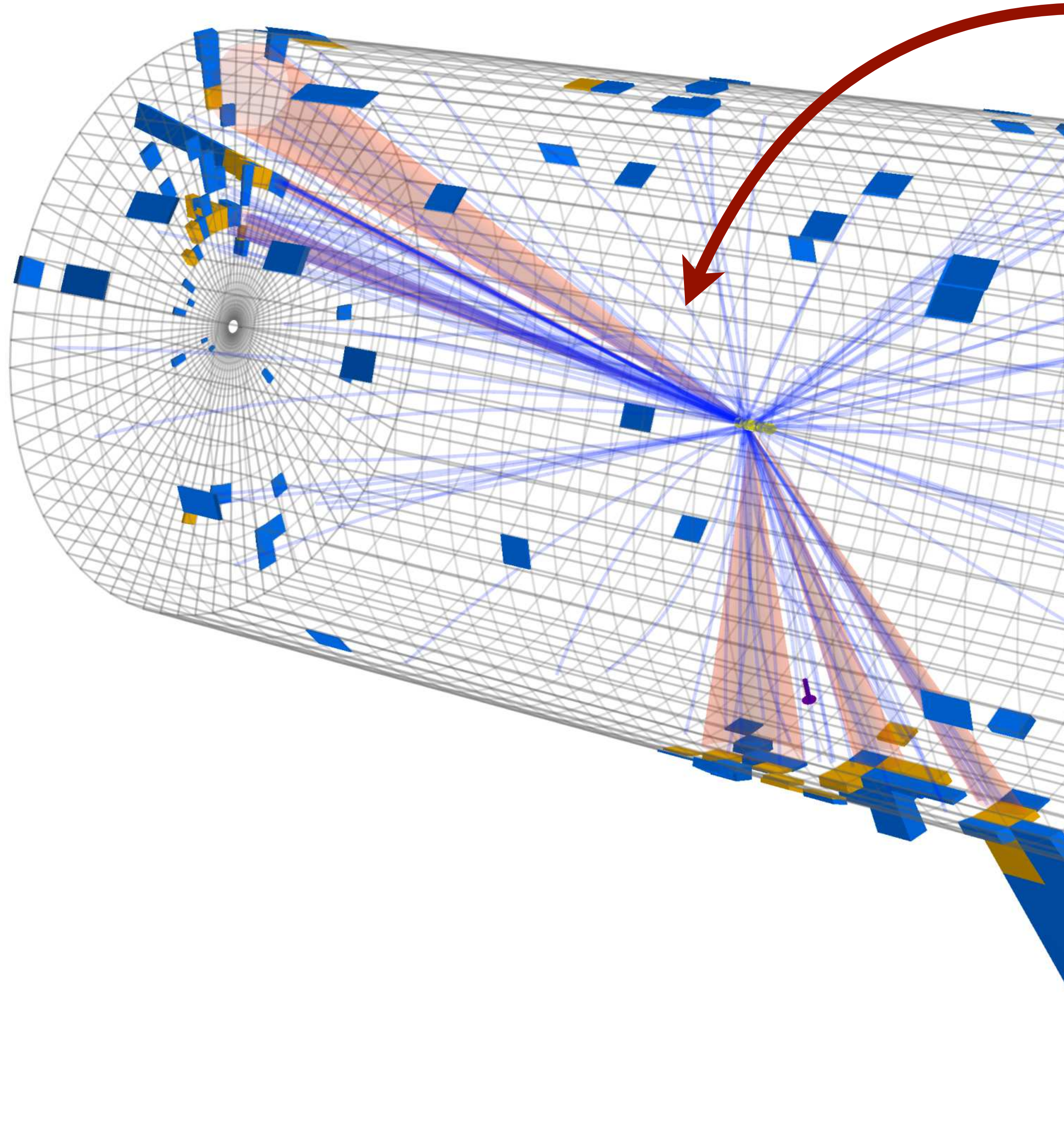
ATLAS 8 TeV
Diboson Search

More Grooming | Less Grooming

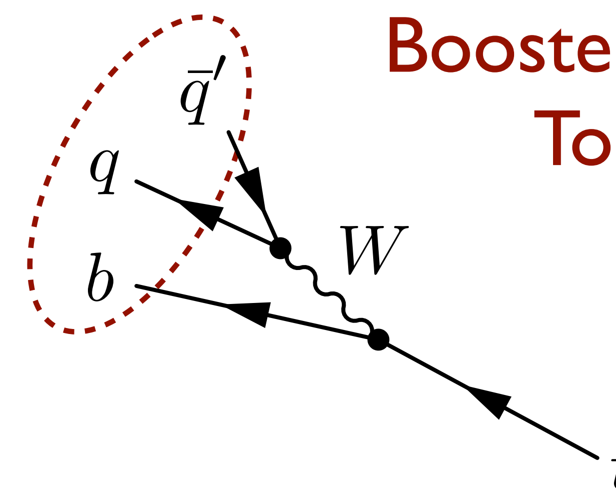
$\beta \to -\infty$ | $\beta < 0$ | $\beta = 0$ | $\beta > 0$ | $\beta \to \infty$

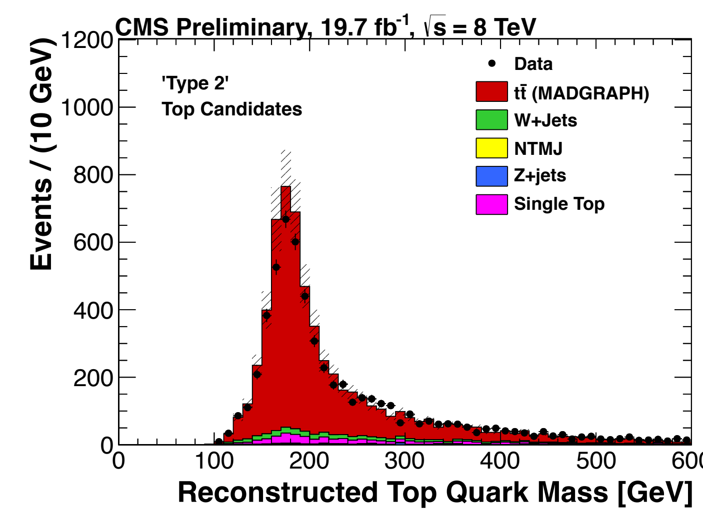
Introducing Sudakov Safety

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

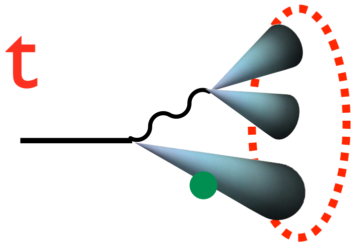


Boosted Top

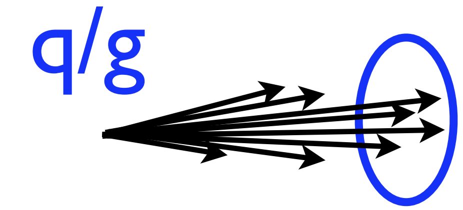


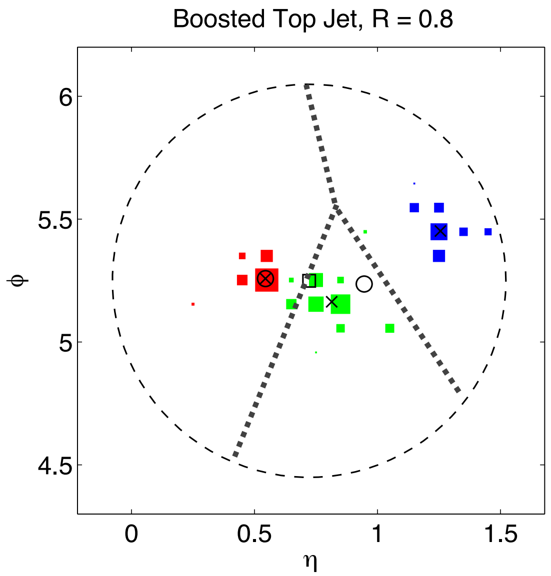


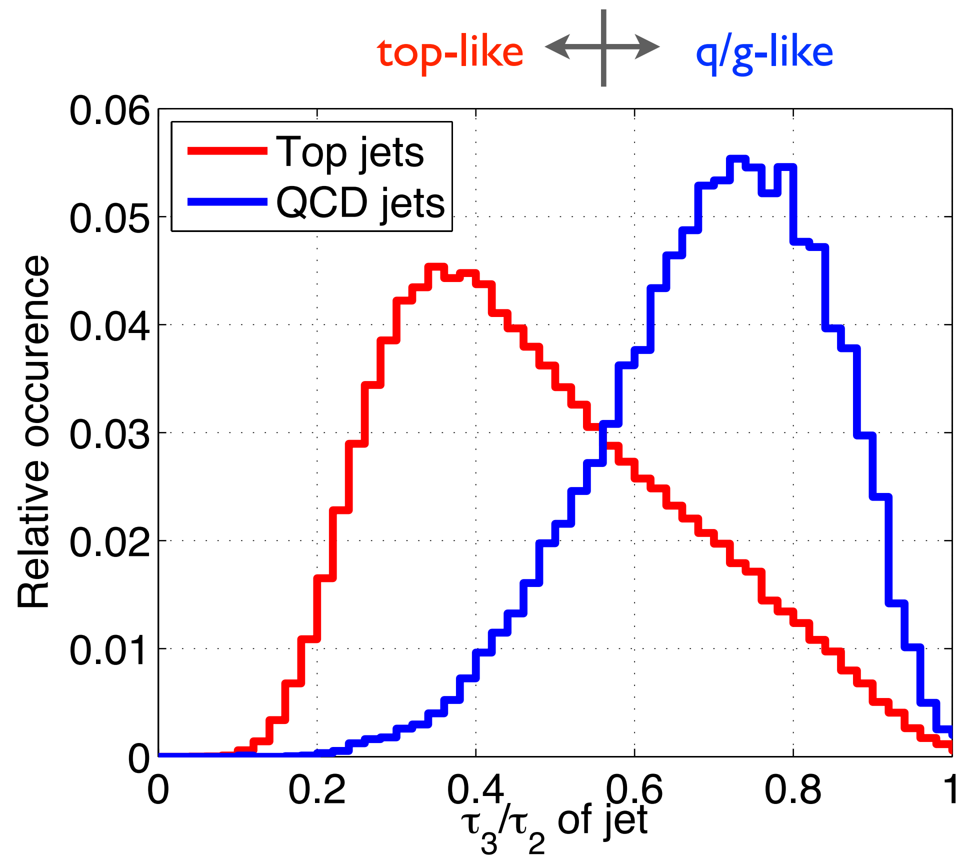
[CMS 2011, 2013, 2015; using Kaplan, Rehermann, Schwartz, Tweedie, 2008; Ellis, Vermilion, Walsh, 2009]

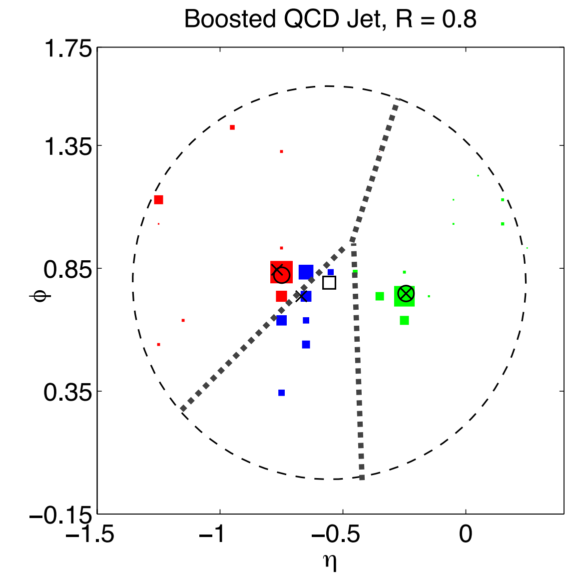


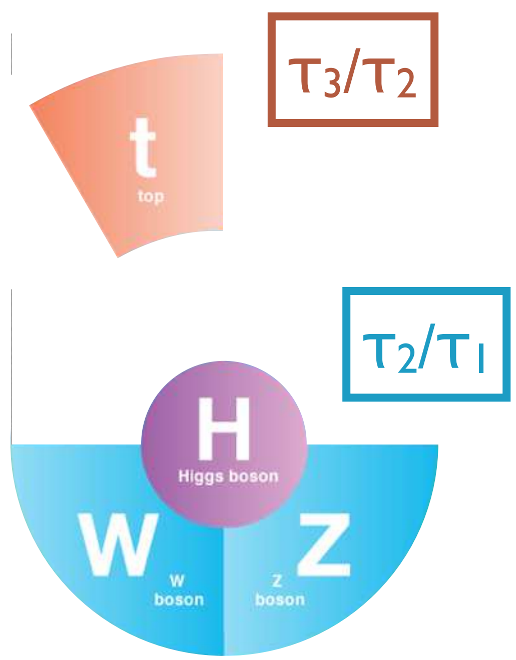
N-Prong vs. 1-Prong











N-subjettiness

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

IRC Safe

[JDT, Van Tilburg, 2010, 2011; see also Stewart, Tackmann, Waalewijn, 2010; Kim, 2010]

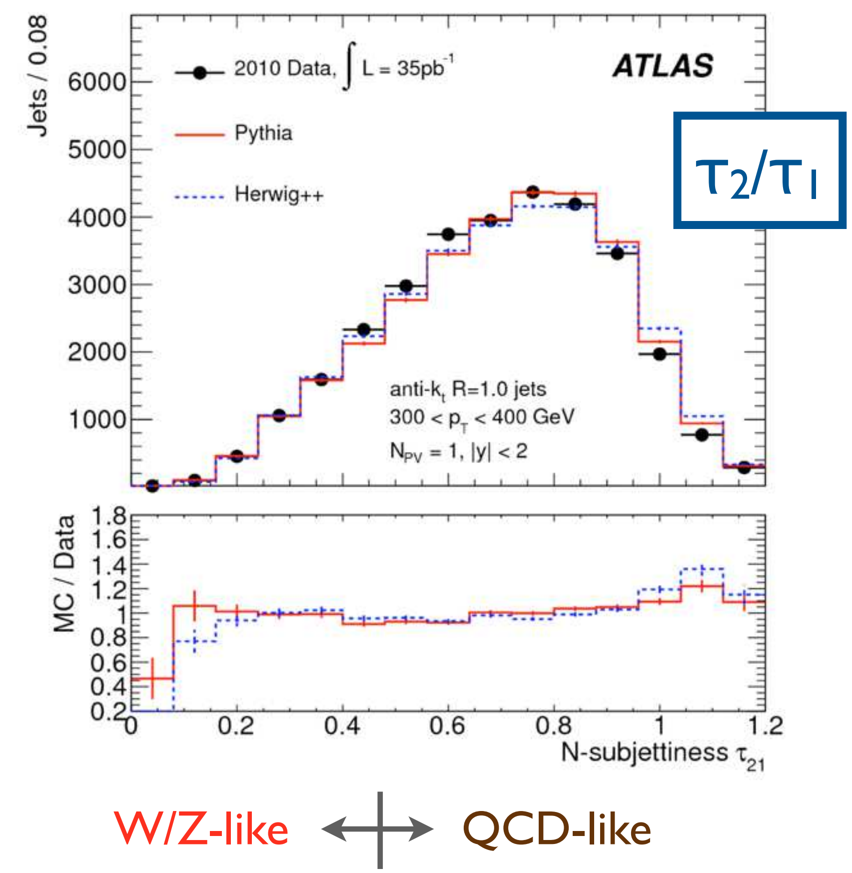
N-subjettiness Ratios?

IRC Safe $\Rightarrow$ Useful Ratio

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

Ubiquitous in jet substructure

[ATLAS,1203.4606]



N-subjettiness Ratios?

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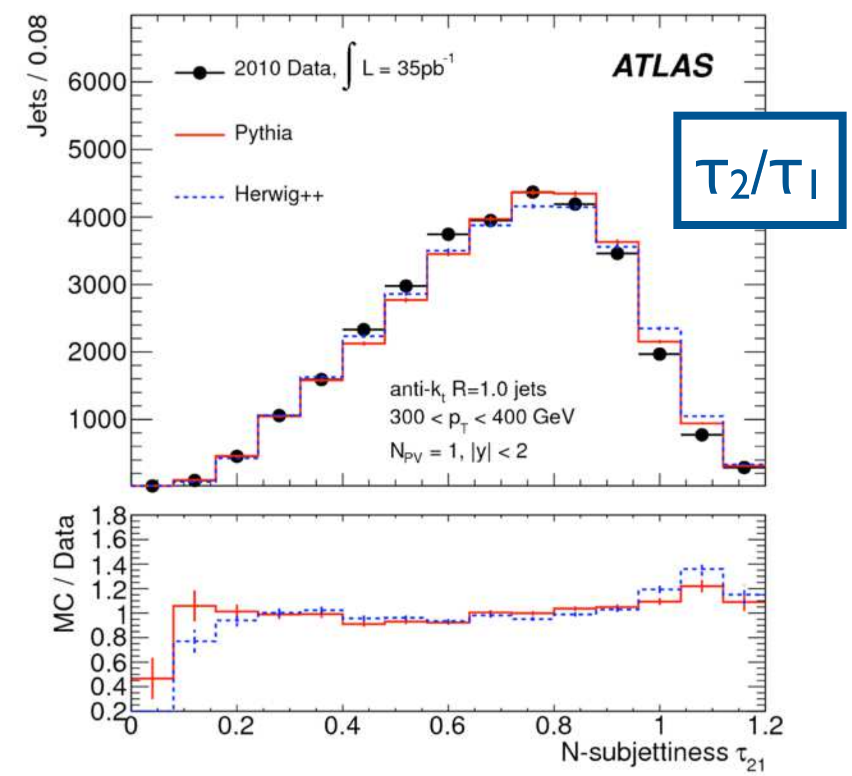
Ubiquitous in jet substructure

[ATLAS,1203.4606]

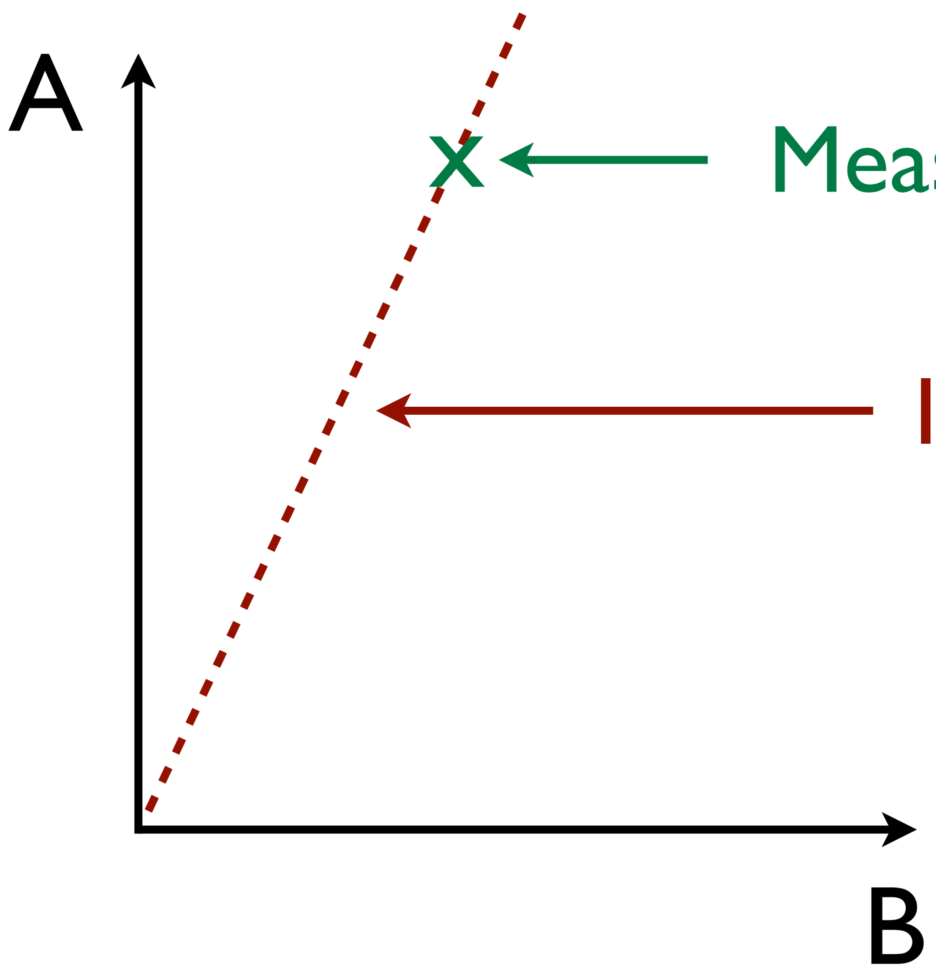


W/Z-like ⟷ QCD-like

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

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

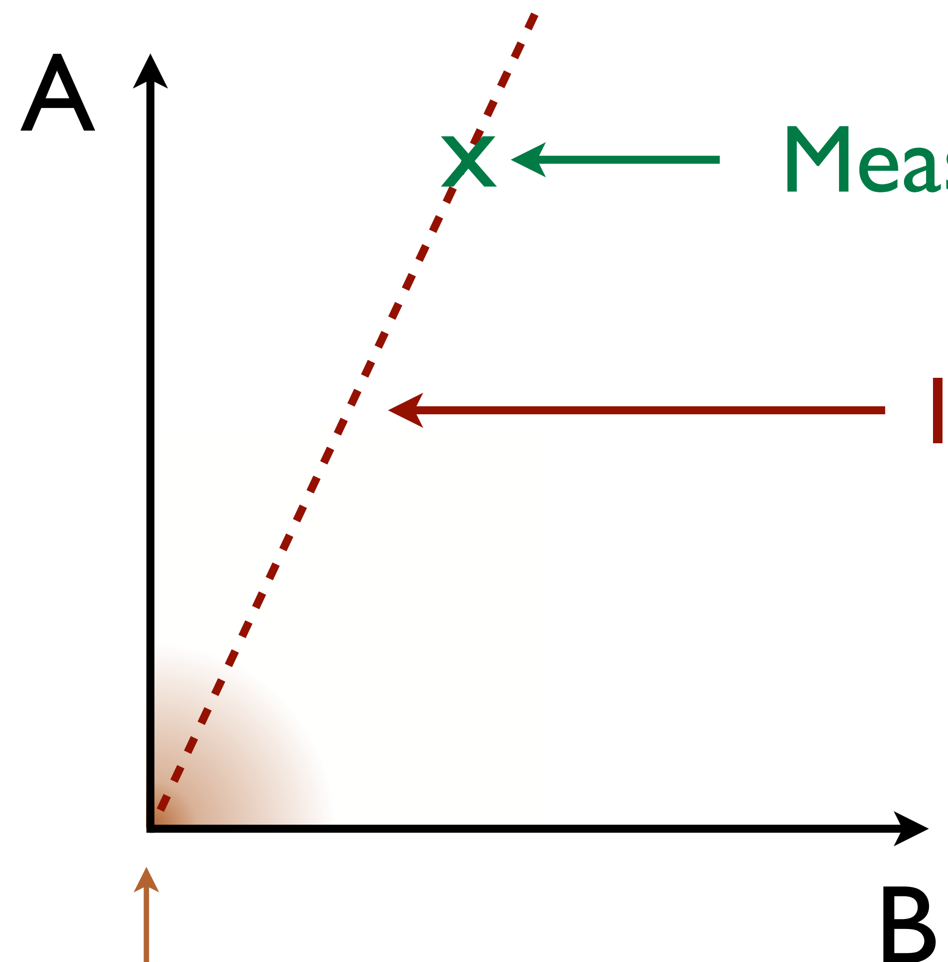
Safe/Safe = Unsafe?!



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

Infer: R = A/B (IRC Unsafe)

Safe/Safe = Unsafe?!

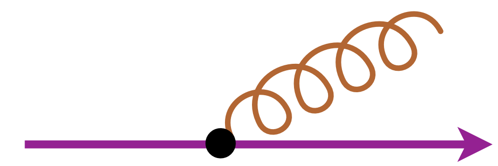


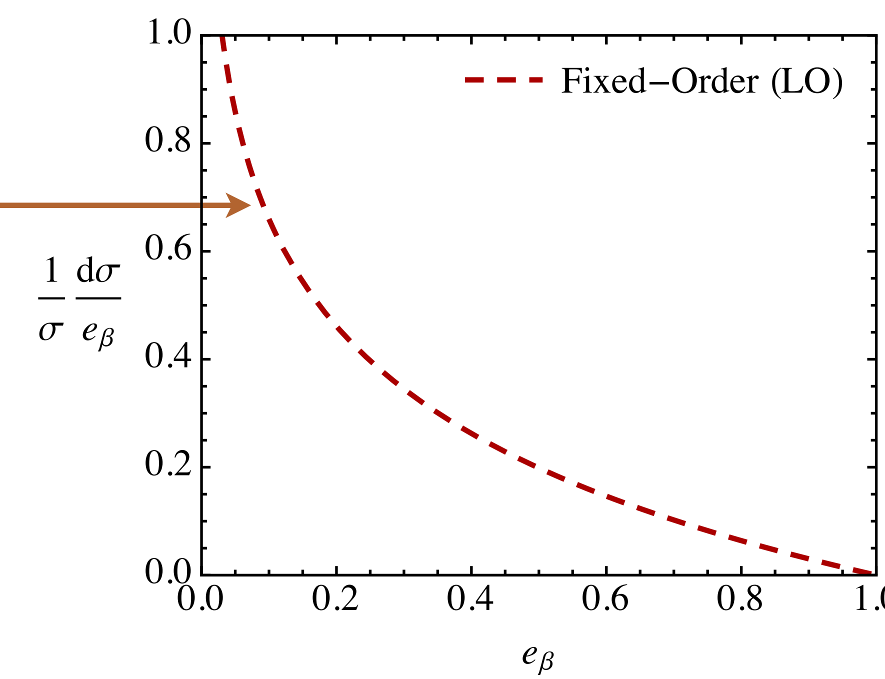
Measure: A (IRC Safe)
B (IRC Safe)

Infer: R = A/B (IRC Unsafe)

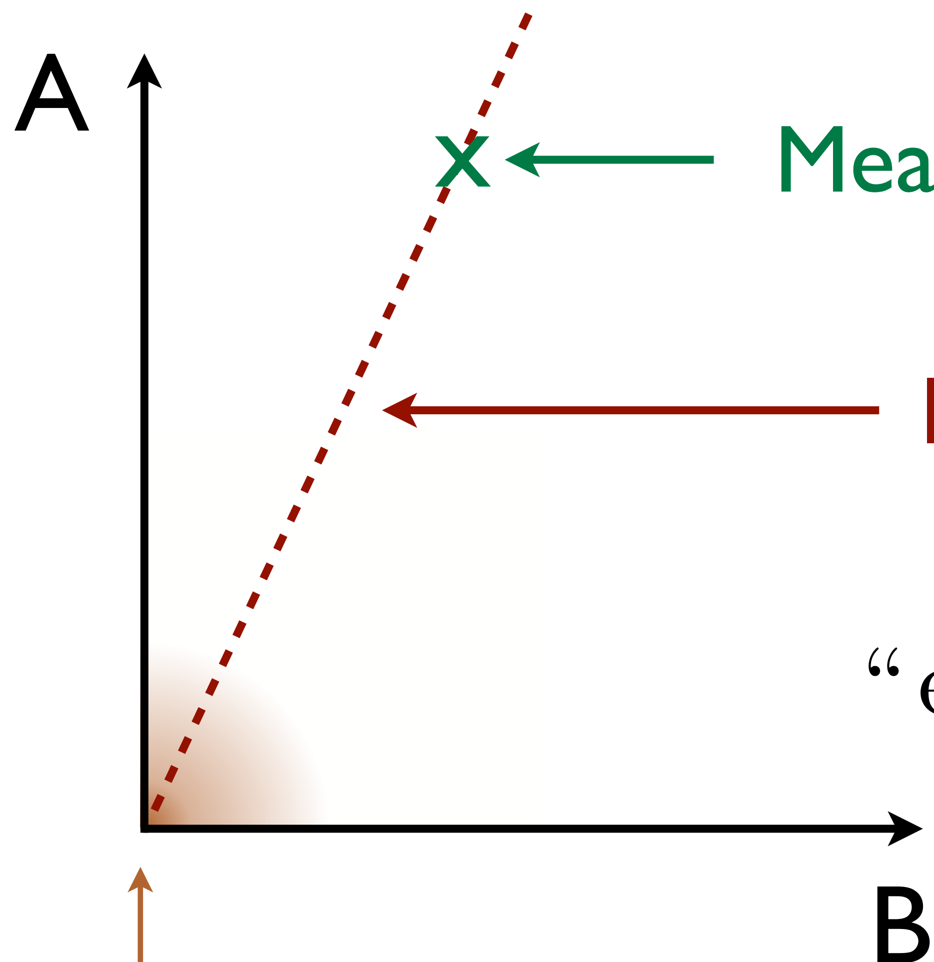
Singularity …

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





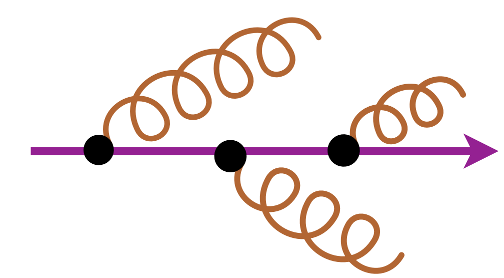
Safe/Safe = Unsafe?!



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

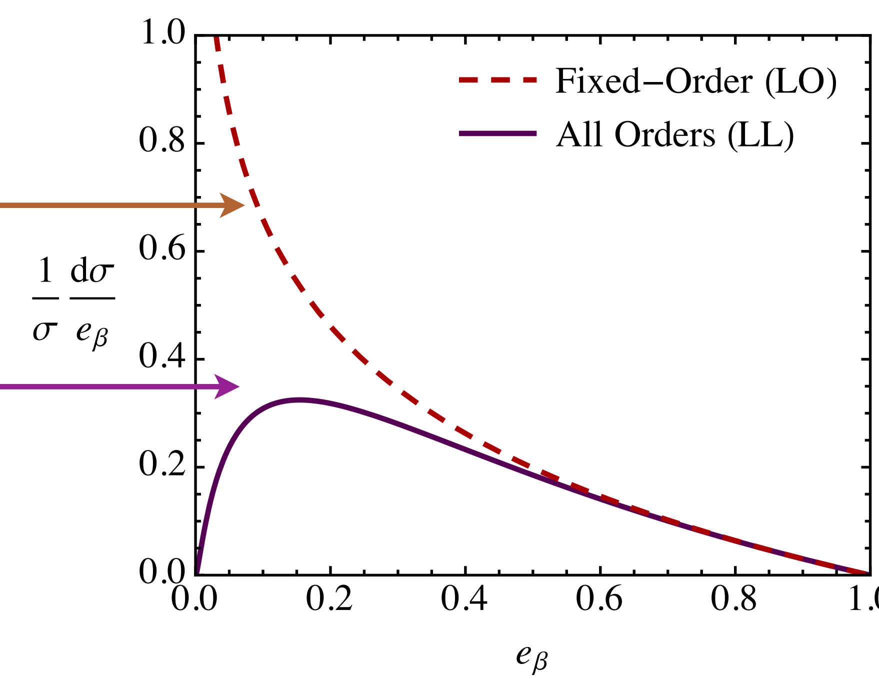
Infer: R = A/B (IRC Unsafe)

$$\text{“}\exp\left[\int \frac{2\alpha_s C_i}{\pi}\frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}z}{z}\right]\text{”}$$



Singularity …

… Regulated by
Sudakov Form Factor

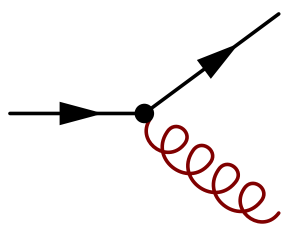


The Key Realization

$$\frac{\mathrm{d}\sigma}{\mathrm{d}r} = \int \mathrm{d}a\,\mathrm{d}b\,\frac{\mathrm{d}^2\sigma}{\mathrm{d}a\,\mathrm{d}b}\,\delta\left(r - \frac{a}{b}\right)$$

IRC Unsafe

Infinity at $O(\alpha_s)$



IRC Safe

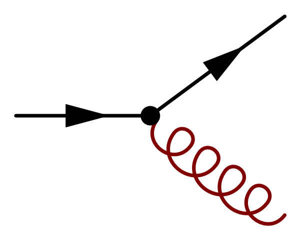
"I can simultaneously measure *a* and *b*"

The Key Realization

$$\frac{d\sigma}{dr} = \int da\, db\, \frac{d^2\sigma}{da\, db}\, \delta\left(r - \frac{a}{b}\right)$$

IRC Unsafe

Infinity at $O(\alpha_s)$



IRC Safe

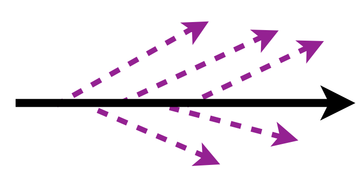
"I can simultaneously measure *a* and *b*"

"Sudakov Safe"

Non-analytic in α_s

e.g. square roots

[Larkoski, JDT, 1307.1699]



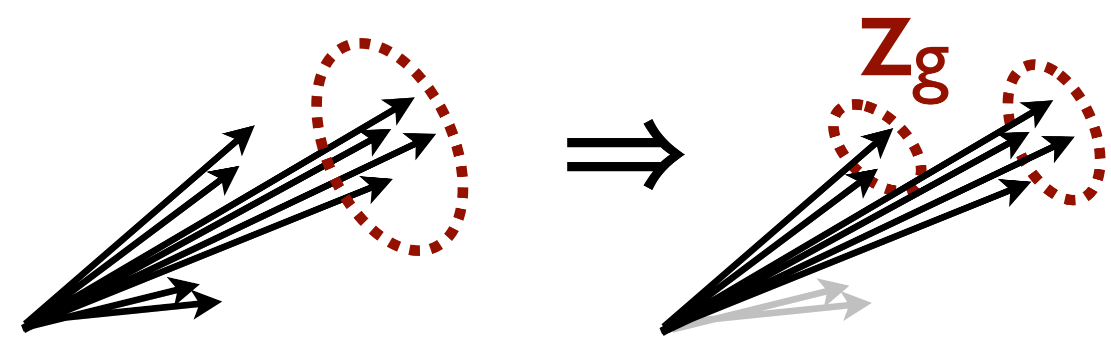
Joint Resummable

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

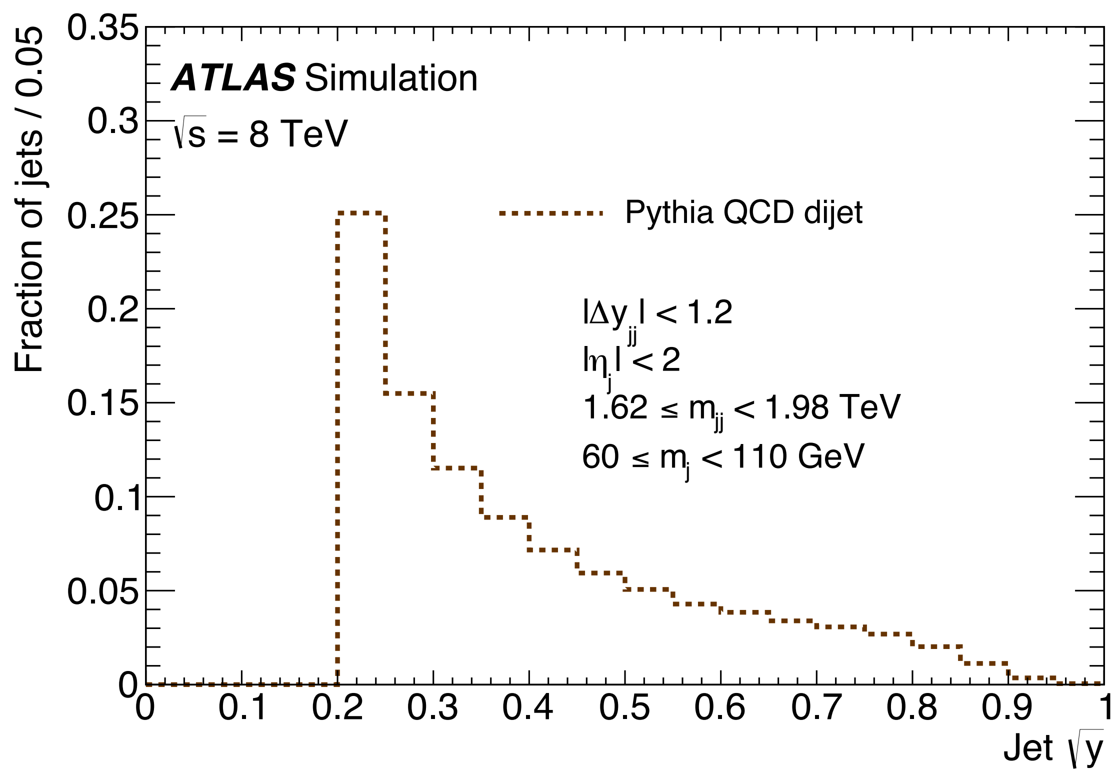
[see Larkoski, Moult, Neill, 1401.4458; Procura, Waalewijn, Zeune, 1410.6483]

Returning to Momentum Balance

Back to BDRS…



$$\frac{d\sigma}{dz_g} = \Big(\textit{undefined} \Big) + \alpha_s \Big(\textit{infinity} \Big) + \alpha_s^2 \Big(\textit{infinity}^2 \Big) + \ldots$$



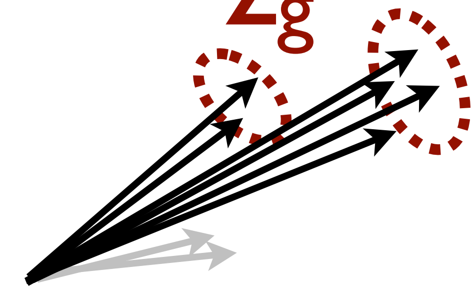
$\boxed{z_g}$

Collinear Unsafe*

Predict using pQCD?

Calculating Momentum Balance?

z_g



Collinear Unsafe

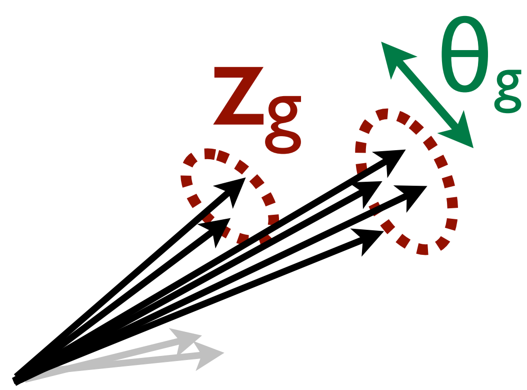
$\downarrow$

$$p(z_g)$$

$\longrightarrow$ z_g ??

[Larkoski, JDT, 1307.1699;
Larkoski, Marzani, JDT, 1502.01719]

Calculating Momentum Balance?

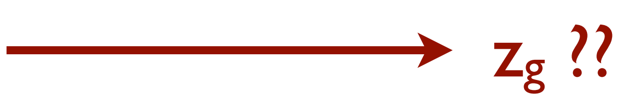


Collinear Unsafe

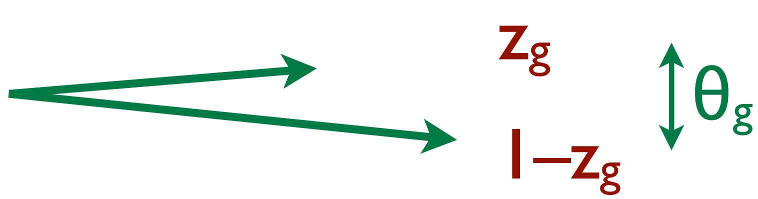
$$p(z_g)$$

Calculable
order-by-order in α_s

$$p(z_g|\theta_g)$$

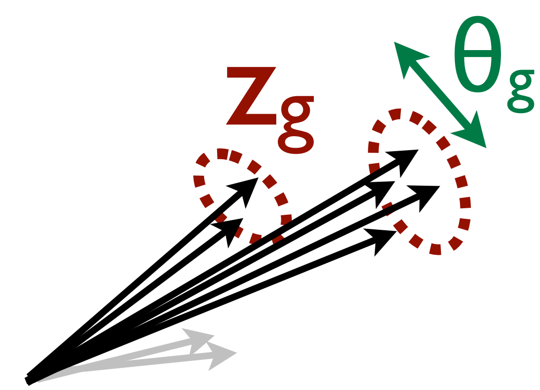


vs.



[Larkoski, JDT, 1307.1699;
Larkoski, Marzani, JDT, 1502.01719]

Calculating Momentum Balance?

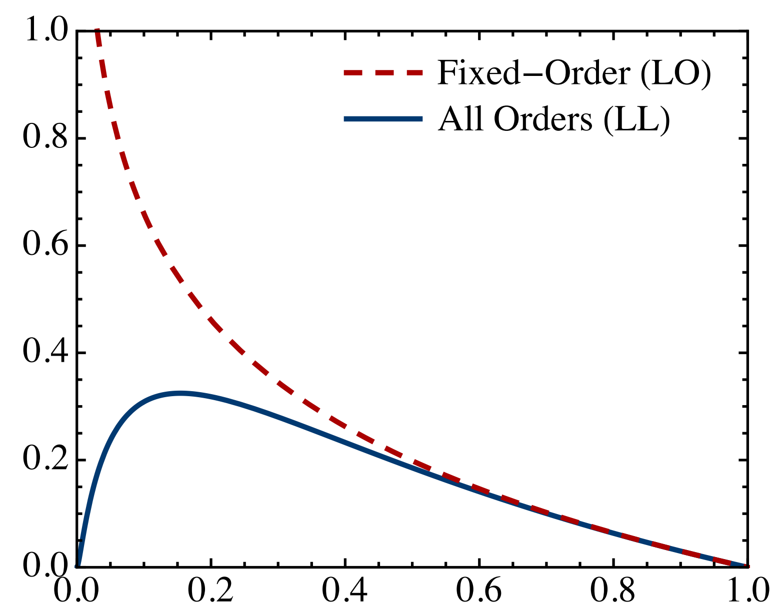


“Sudakov Safe”

Calculable order-by-order in α_s

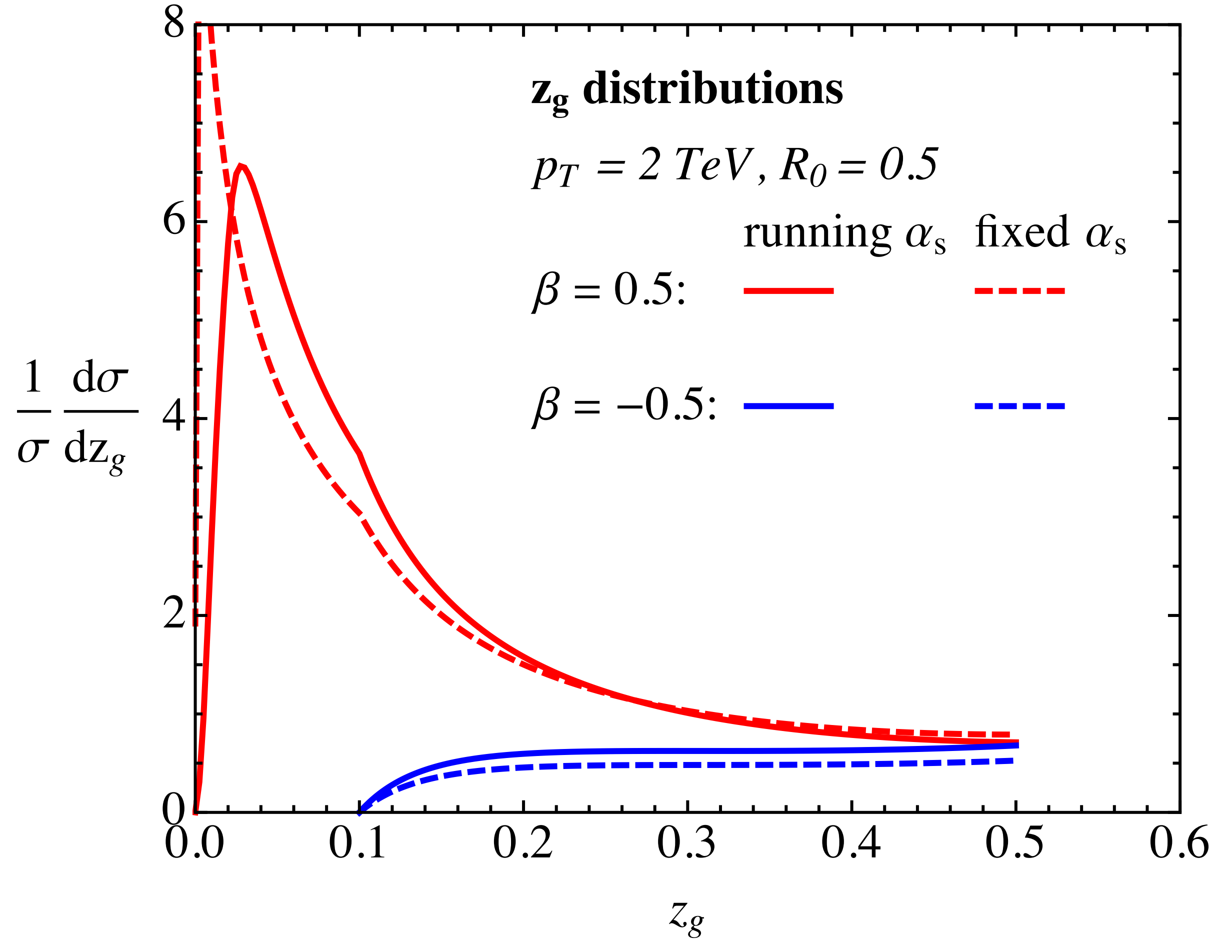
$$p(z_g) = \int d\theta_g \, p(\theta_g) \, p(z_g | \theta_g)$$

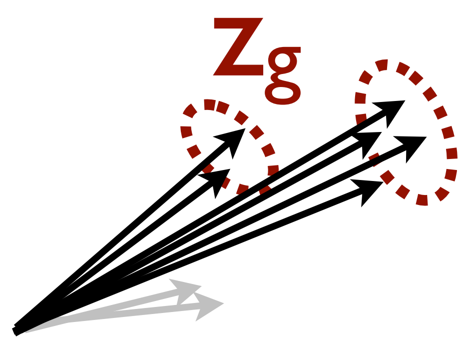
Form factor suppresses singularities at all orders in α_s



[Larkoski, JDT, 1307.1699; Larkoski, Marzani, JDT, 1502.01719]

First-Principles QCD





$C_q = 4/3$
$C_g = 3$

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

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

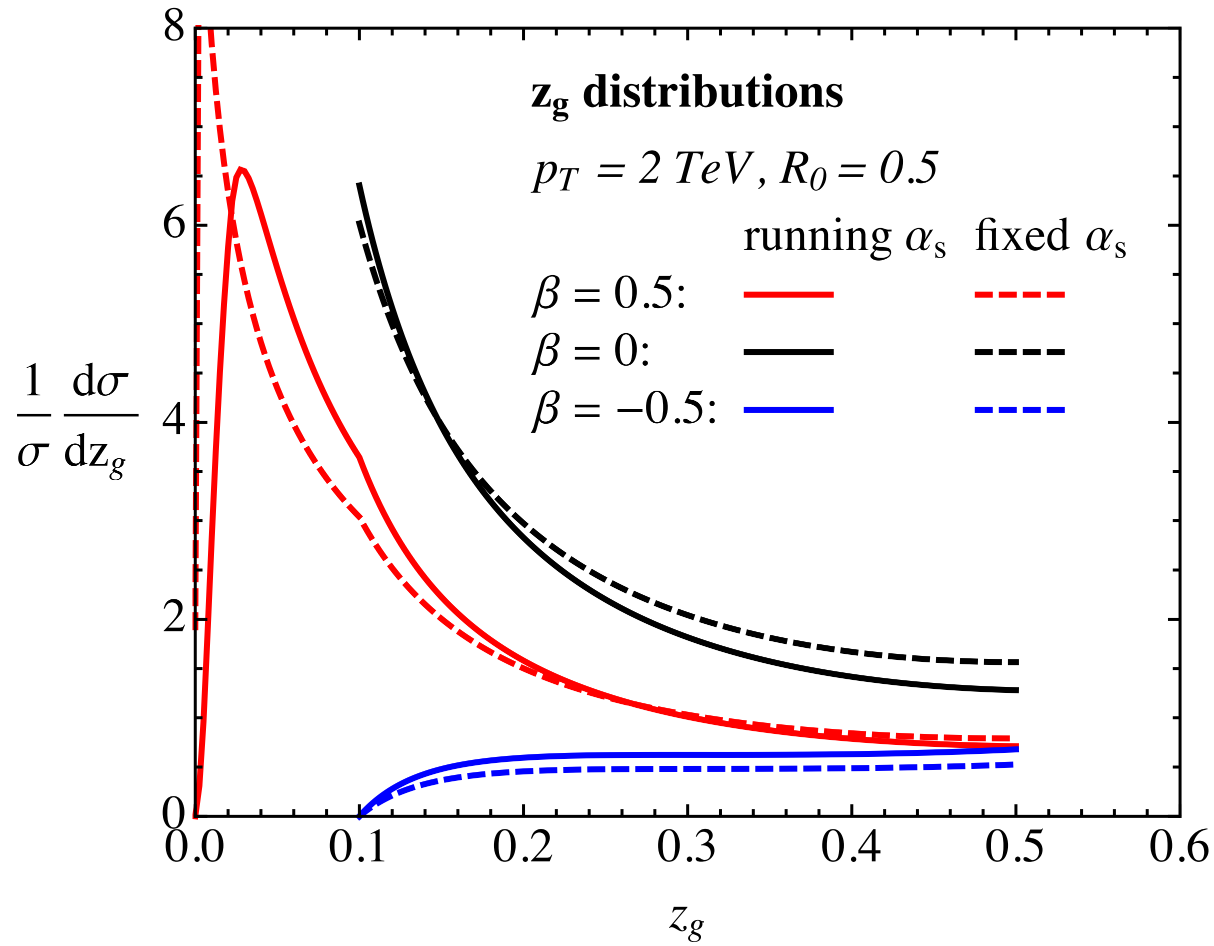
Beyond traditional perturbation theory (Sudakov safe)

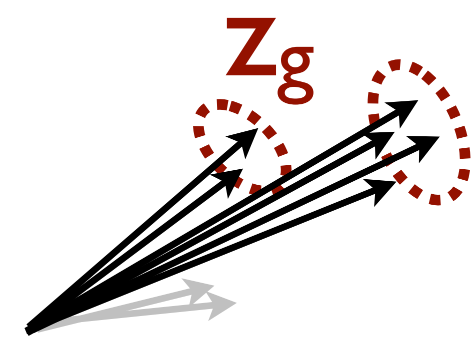
More Grooming

Less Grooming

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

First-Principles QCD





$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\frac{1}{z_g}\log\frac{z_g}{z_{\text{cut}}} \qquad \simeq \frac{1}{z_g}\ (!) \qquad \simeq \sqrt{\frac{\alpha_s C_i}{\beta}}\frac{1}{z_g}$$

Beyond traditional perturbation theory (Sudakov safe)

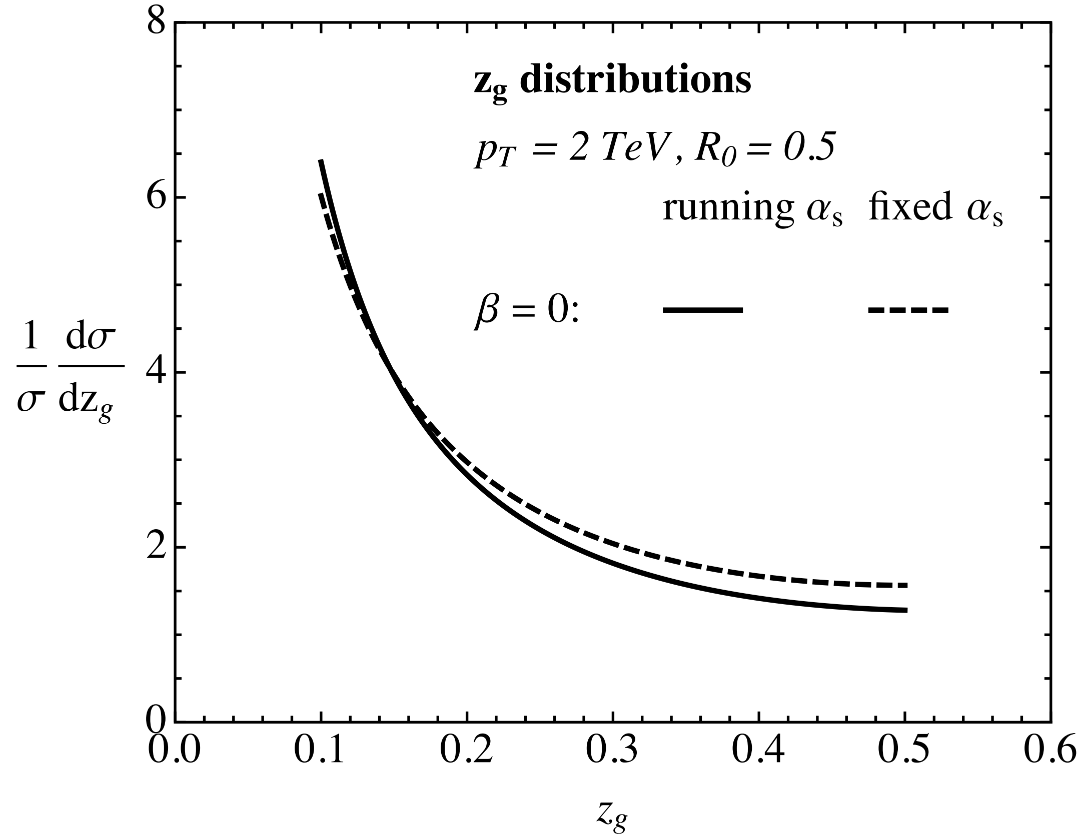
More Grooming

Less Grooming

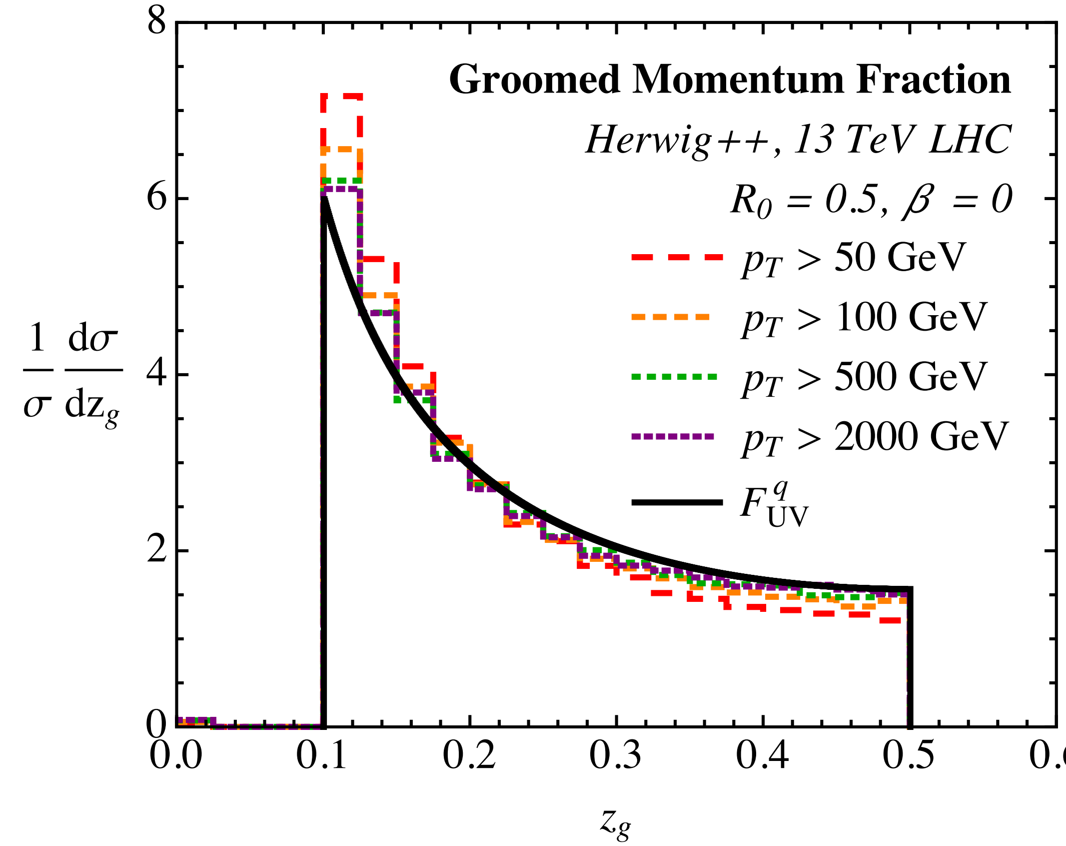
$\beta \to -\infty$ $\quad \beta < 0 \quad \beta = 0 \quad \beta > 0 \quad \beta \to \infty$

A Standard Candle for Jets

First-Principles QCD



Simulated LHC Data

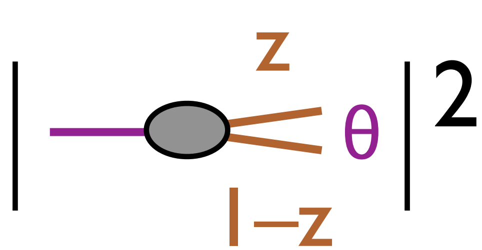


Core Feature of QCD: $\simeq \dfrac{1}{z_g}$

$\updownarrow$

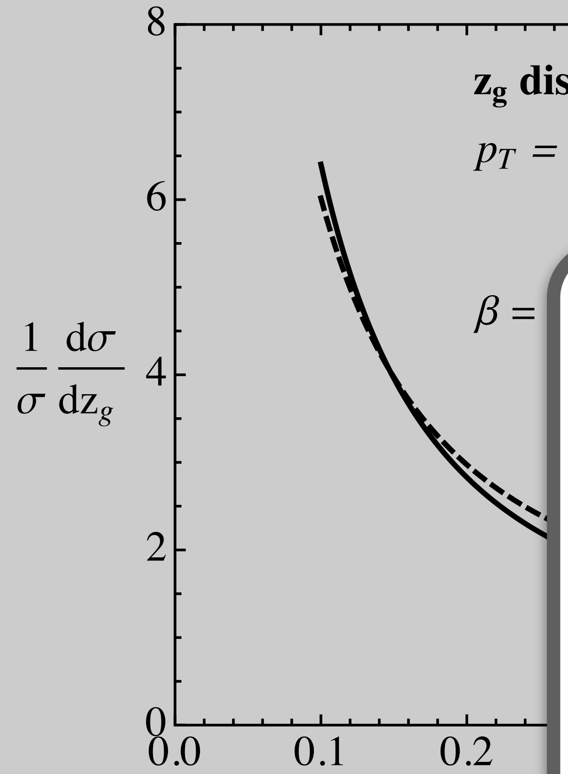
$$dP_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

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

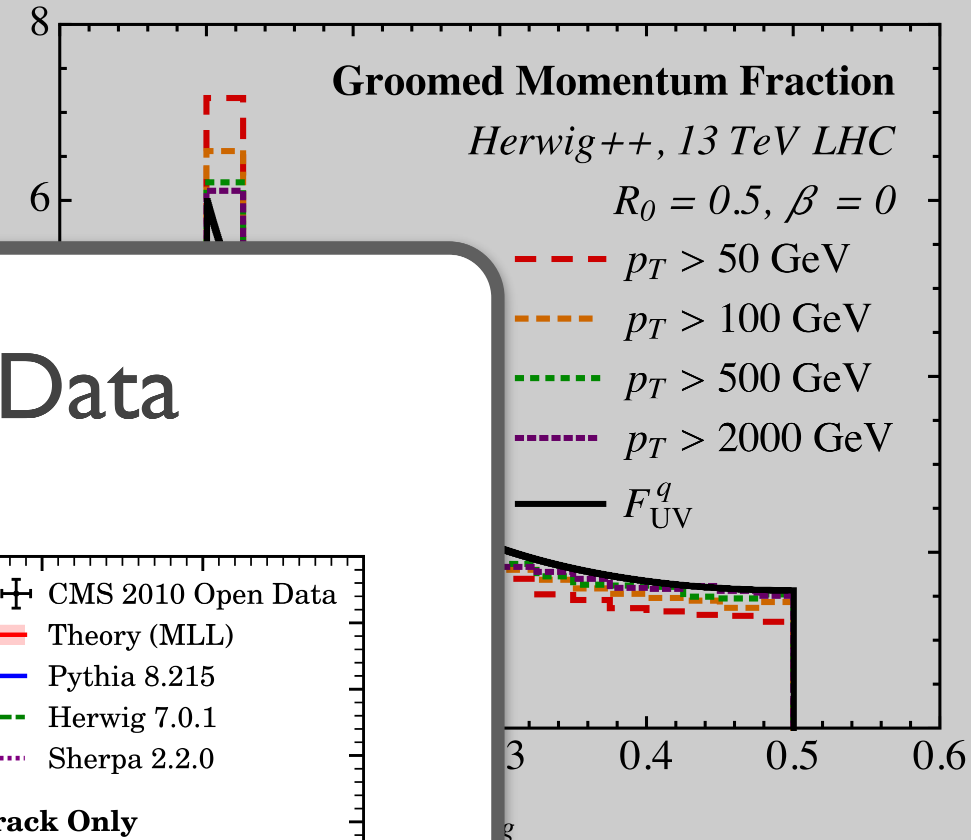
cf. 

[Larkoski, Marzani, JDT, 1502.01719; using Larkoski, JDT, 1307.1699]

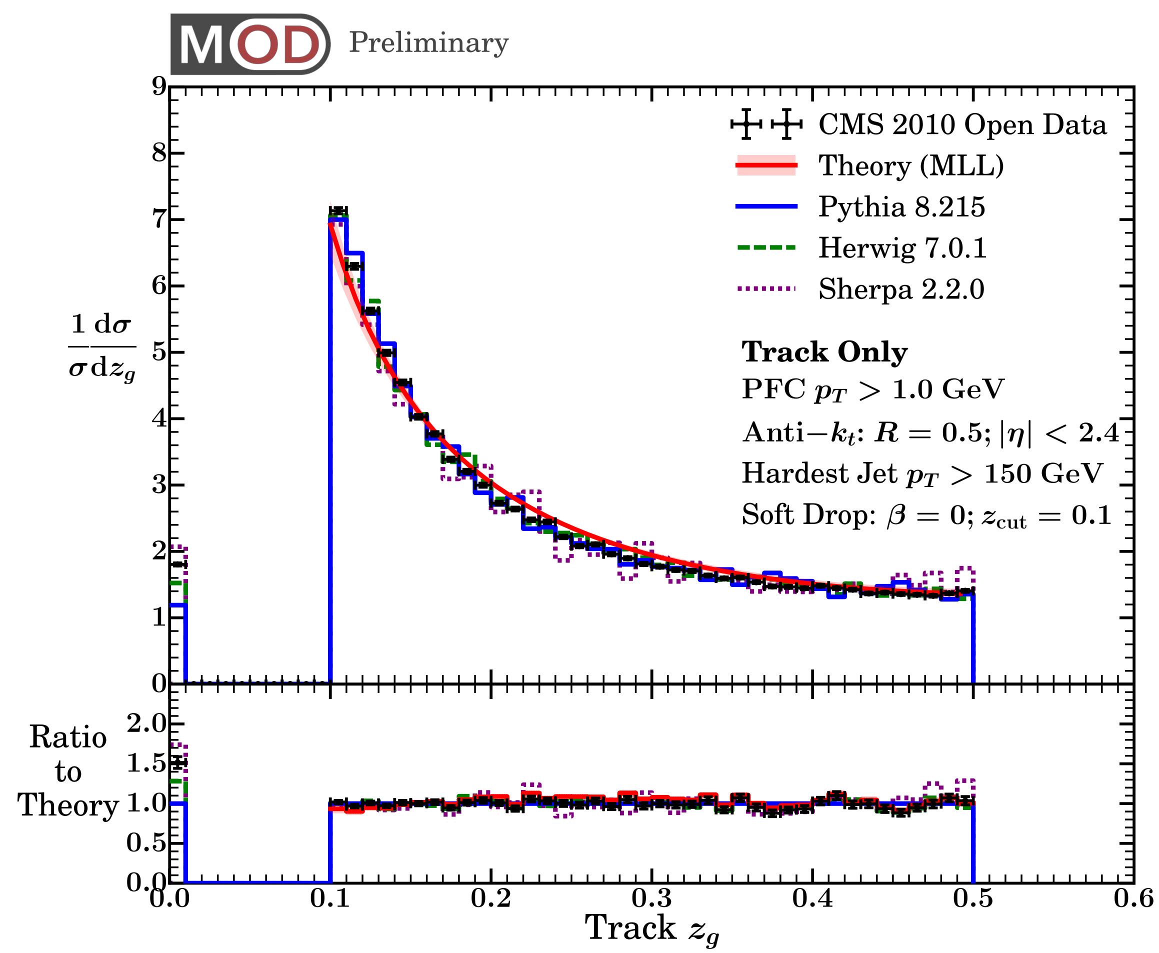
First-Principles QCD



Simulated LHC Data



CMS Open Data



[Larkoski, Marzani, Romero, Tripathee, Xue, JDT, in progress]

Core … o…

… α_s (!)

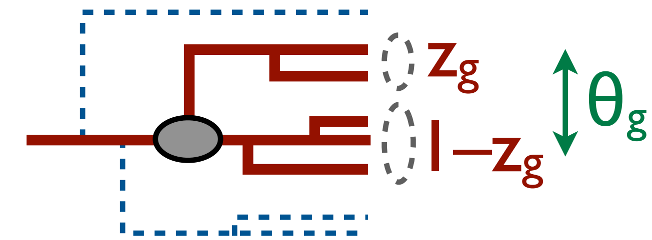
… jet energy/radius

…s/gluons

$$\mathrm{d}P_{i\to ig} \simeq \ldots \theta\,\Big|^2$$

[Larkoski, Marzani, JDT, 1502.01719; using Larkoski, JDT, 1307.1699]

1. Explicit Computation



Master Formula: $$p(z_g) = \int \mathrm{d}\theta_g \, p(\theta_g) \, p(z_g|\theta_g)$$

$$p(\theta_g) \simeq \frac{\mathrm{d}}{\mathrm{d}\theta_g} \exp\left[-\frac{\alpha_s C_i}{\pi}\left(\beta \log^2 \frac{1}{\theta_g} + 2\log\frac{1}{\theta_g}\log\frac{1}{2\,z_{\mathrm{cut}}}\right)\right]$$

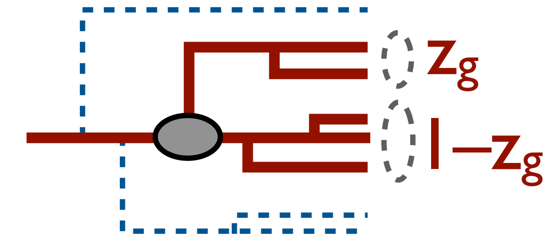
$$p(z_g|\theta_g) \simeq \frac{1}{\mathrm{norm}}\frac{1}{z_g}\Theta(z_g - z_{\mathrm{cut}}{\theta_g}^{\beta})$$

$$p(z_g) \simeq \sqrt{\frac{\alpha_s C_i}{\beta}}\frac{1}{z_g}\exp\left[\frac{\alpha_s C_i}{\pi\beta}\log^2\frac{1}{2z_{\mathrm{cut}}}\right]\mathrm{erfc}\left[\sqrt{\frac{\alpha_s C_i}{\pi\beta}}\log\frac{1}{\min[2z_{\mathrm{cut}},2z_g]}\right]$$

$$\Rightarrow \frac{1}{\mathrm{norm}}\frac{1}{z_g}\Theta(z_g - z_{\mathrm{cut}}) \quad (\beta = 0)$$

[Larkoski, Marzani, JDT, 1502.01719;
using Larkoski, JDT, 1307.1699; Larkoski, Marzani, Soyez, JDT, 1402.2657]

2. Renormalization Group Flow

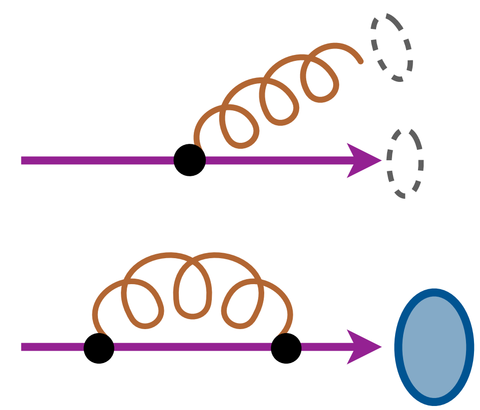


Collinear Unsafe?

Absorb singularities into universal nonperturbative function (cf. PDFs)

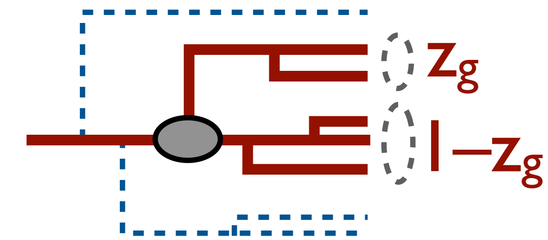
$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \left(\textit{fragmentation function} \right) + \alpha_s \left(\textit{collinear singularities} \right) + \mathcal{O}(\alpha_s^2)$$

absorb



[Larkoski, Marzani, JDT, 1502.01719]

2. Renormalization Group Flow

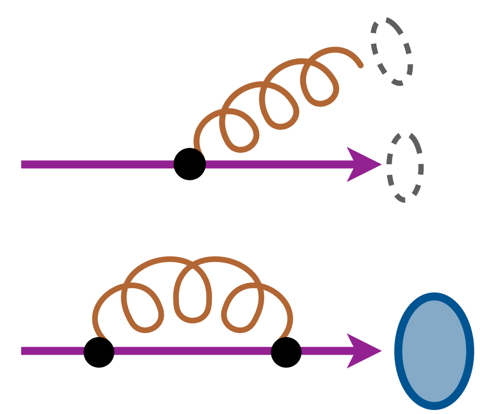


Collinear Unsafe?

Absorb singularities into universal nonperturbative function (cf. PDFs)

$$\frac{d\sigma}{dz_g} = \Bigg(\begin{array}{c}\textit{fragmentation}\\ \textit{function}\end{array} \Bigg) + \alpha_s \Bigg(\begin{array}{c}\textit{collinear}\\ \textit{singularities}\end{array} \Bigg) + \mathcal{O}(\alpha_s^2)$$

absorb

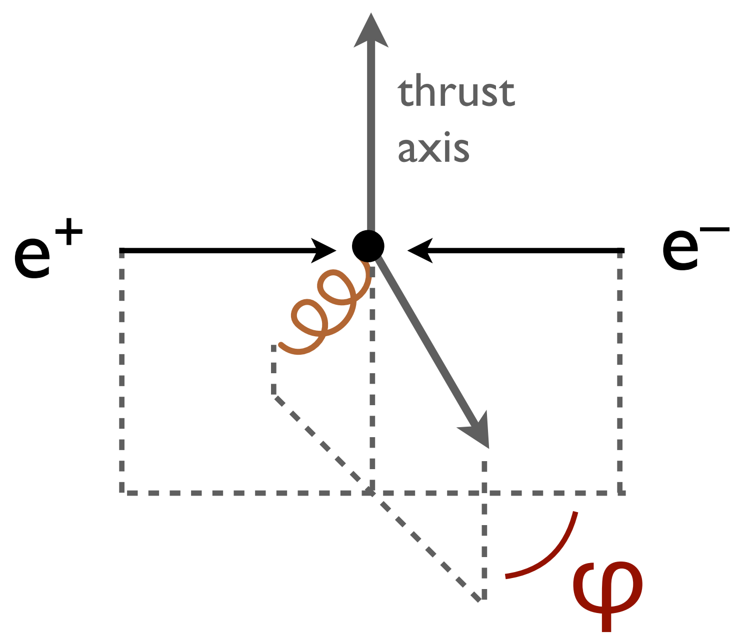


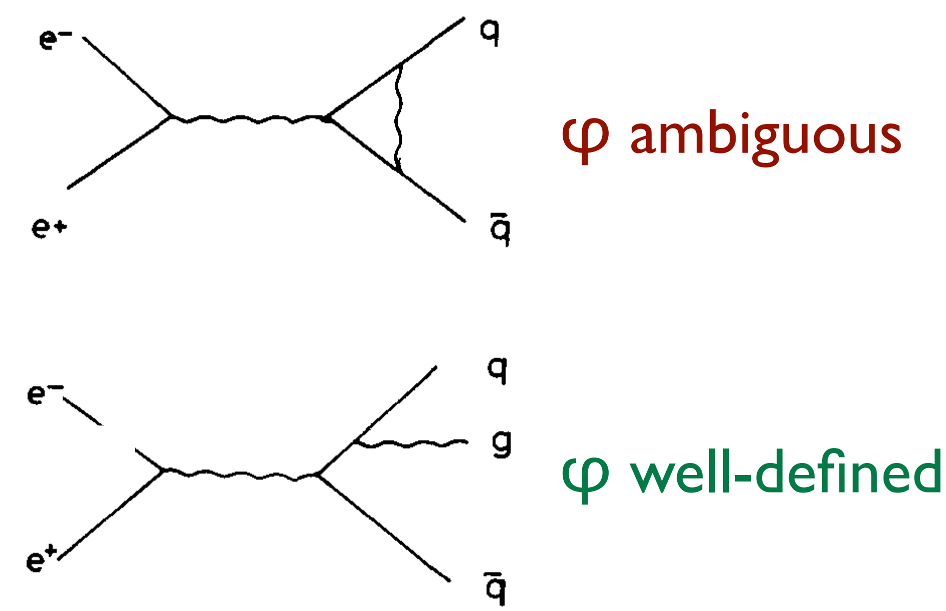
$$\mu \frac{\partial}{\partial \mu} F_i(z_g;\mu) \simeq \frac{\alpha_s C_i}{\pi} \Big(p(z_g) - F_i(z_g;\mu) \Big)$$

UV fixed point

[Larkoski, Marzani, JDT, 1502.01719]

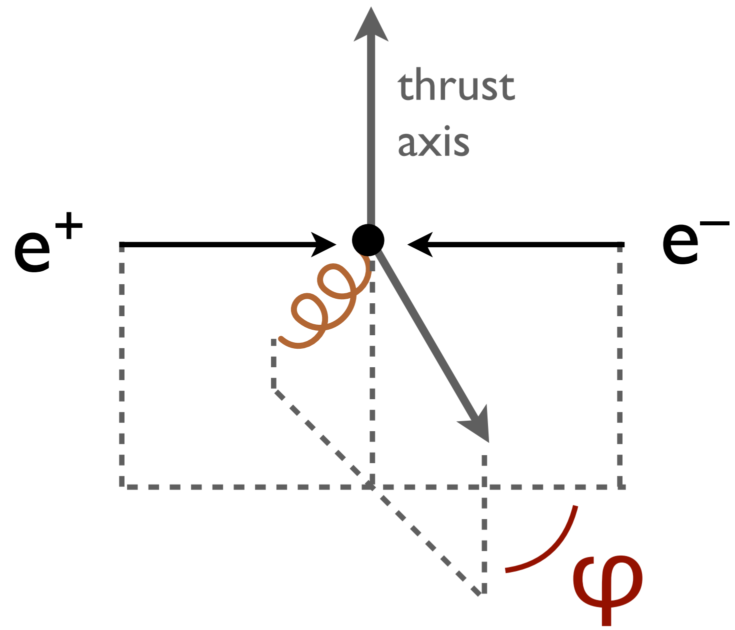
3. Learn from our Elders

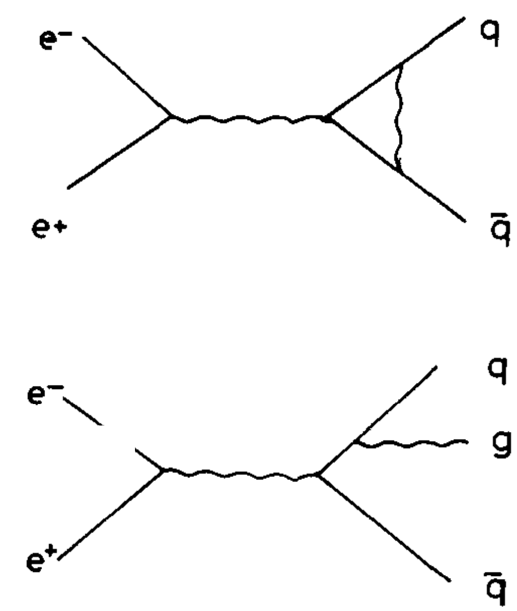




[Pi, Jaffe, Low, 1978; Kramer, Schierholz, Willrodt, 1978]

3. Learn from our Elders



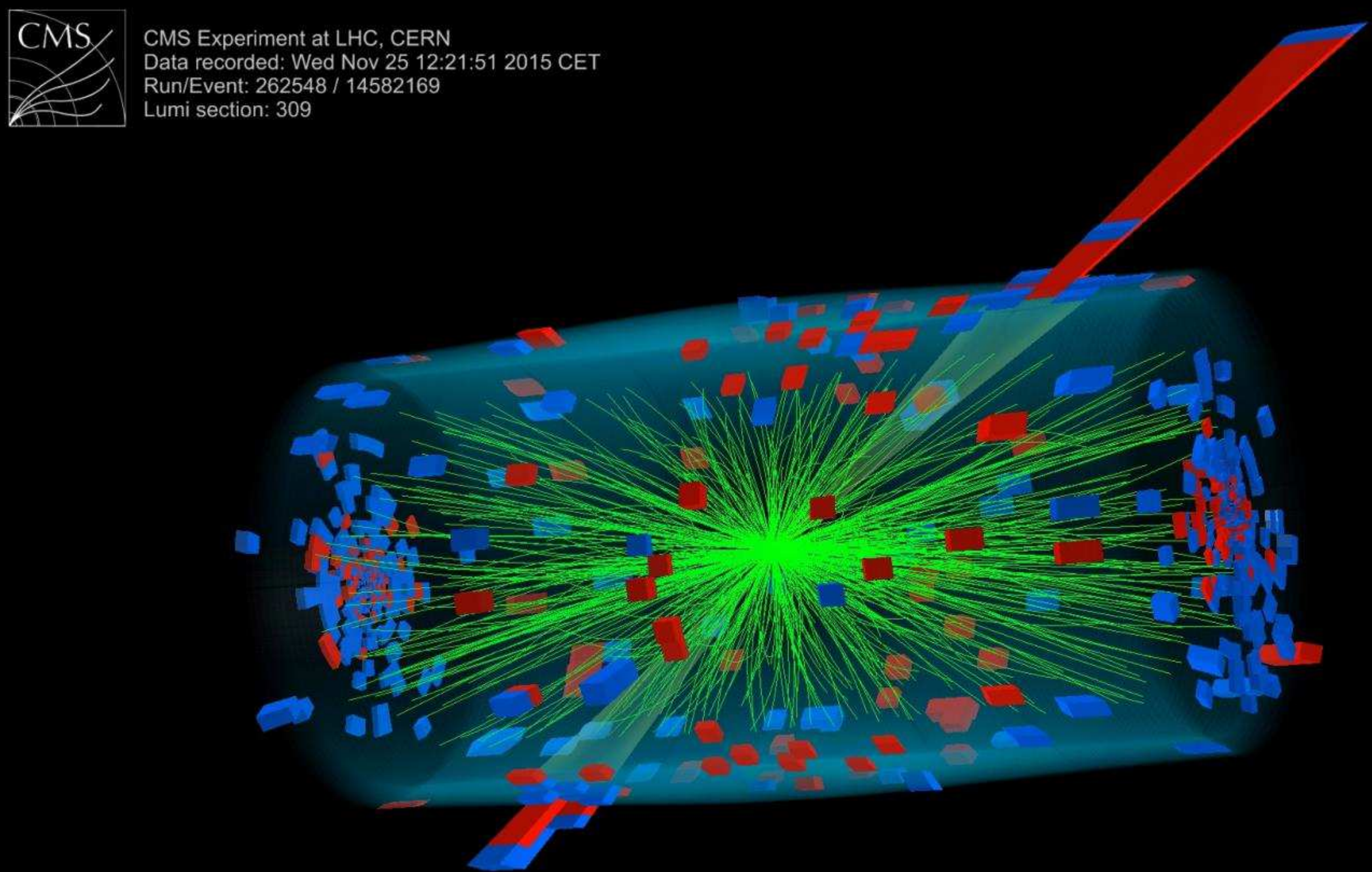


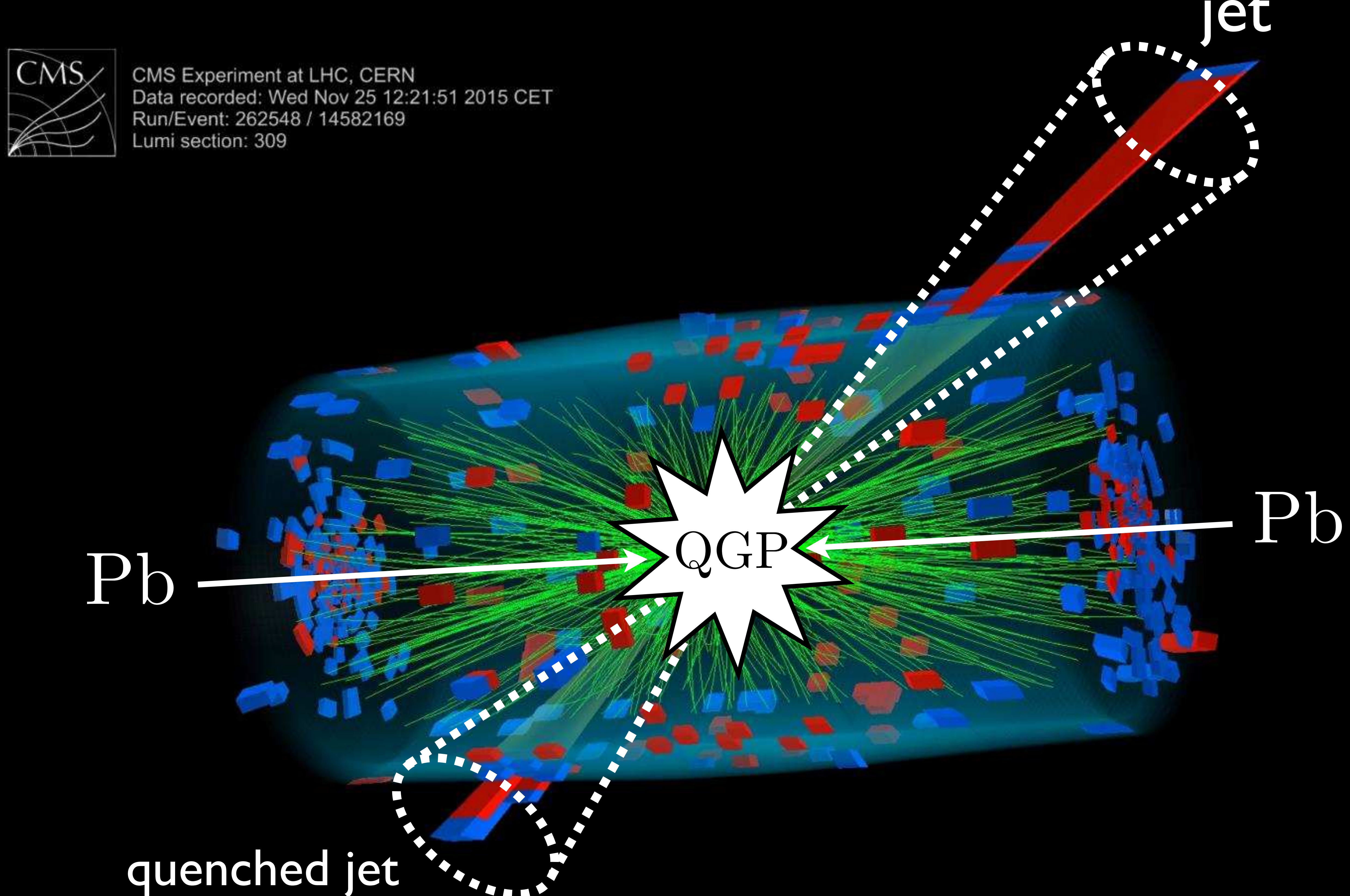
$$\frac{2\pi}{\sigma_0}\frac{d\sigma}{d\varphi} = 1 + O(\alpha_s(Q^2)) + \frac{\alpha_s(Q^2)}{\pi}\left(\frac{16}{3}\ln\frac{3}{2} - 2\right)\cos 2\varphi$$

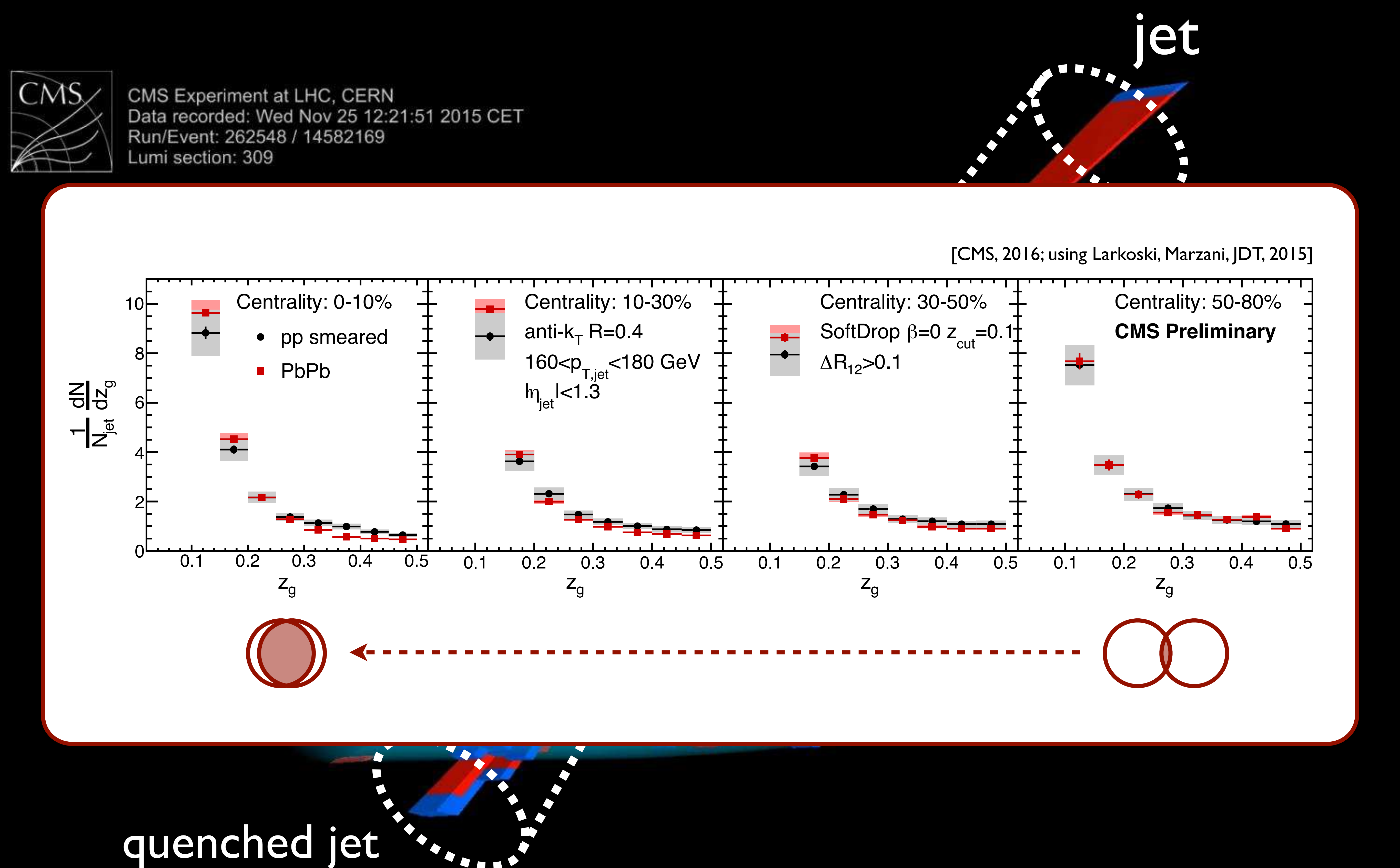
Born cross section despite ambiguity (!)

Exploits generalized notion of "observable"

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

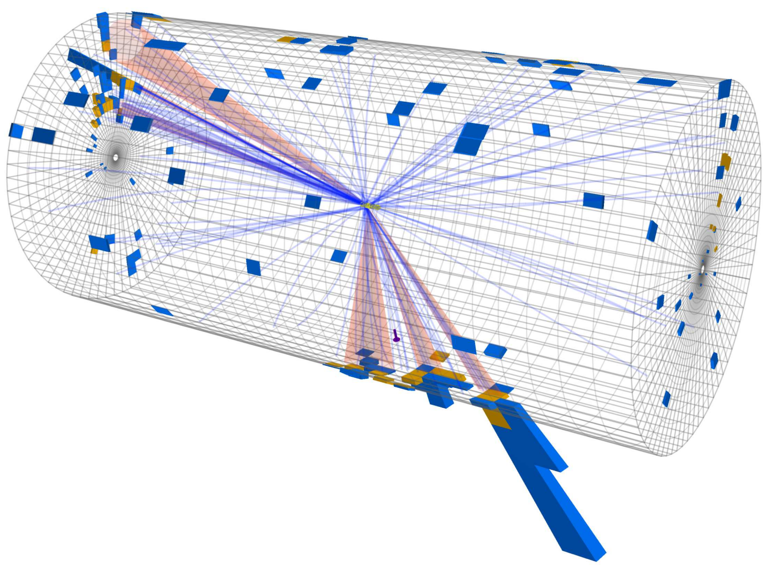

CMS
CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309


jet
CMS
CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309
Pb
QGP
Pb
quenched jet



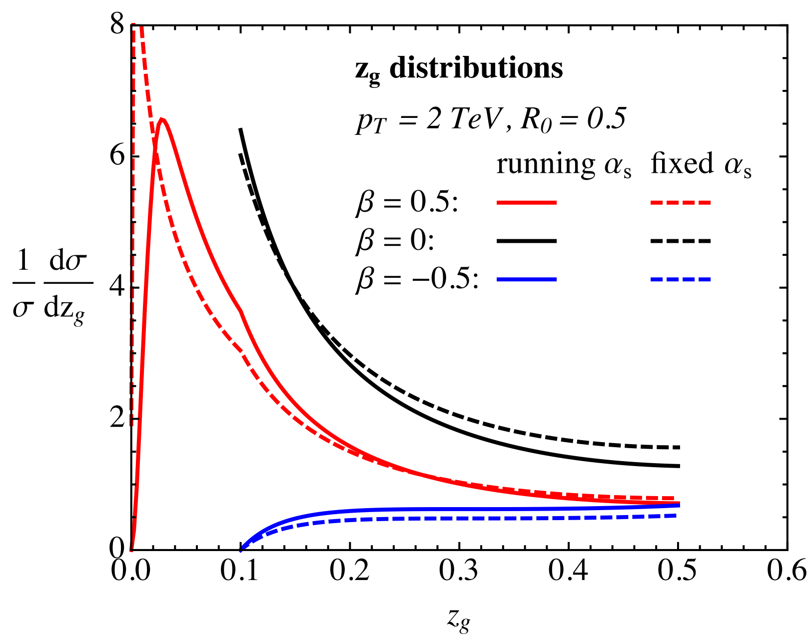
jet
CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309
[CMS, 2016; using Larkoski, Marzani, JDT, 2015]
Centrality: 0-10%
pp smeared
PbPb
Centrality: 10-30%
anti-k_T R=0.4
160<$p_{T,jet}$<180 GeV
|η_{jet}|<1.3
Centrality: 30-50%
SoftDrop β=0 z_{cut}=0.1
ΔR_{12}>0.1
Centrality: 50-80%
CMS Preliminary
$\frac{1}{N_{jet}}\frac{dN}{dz_g}$
z_g
quenched jet

Jet Substructure



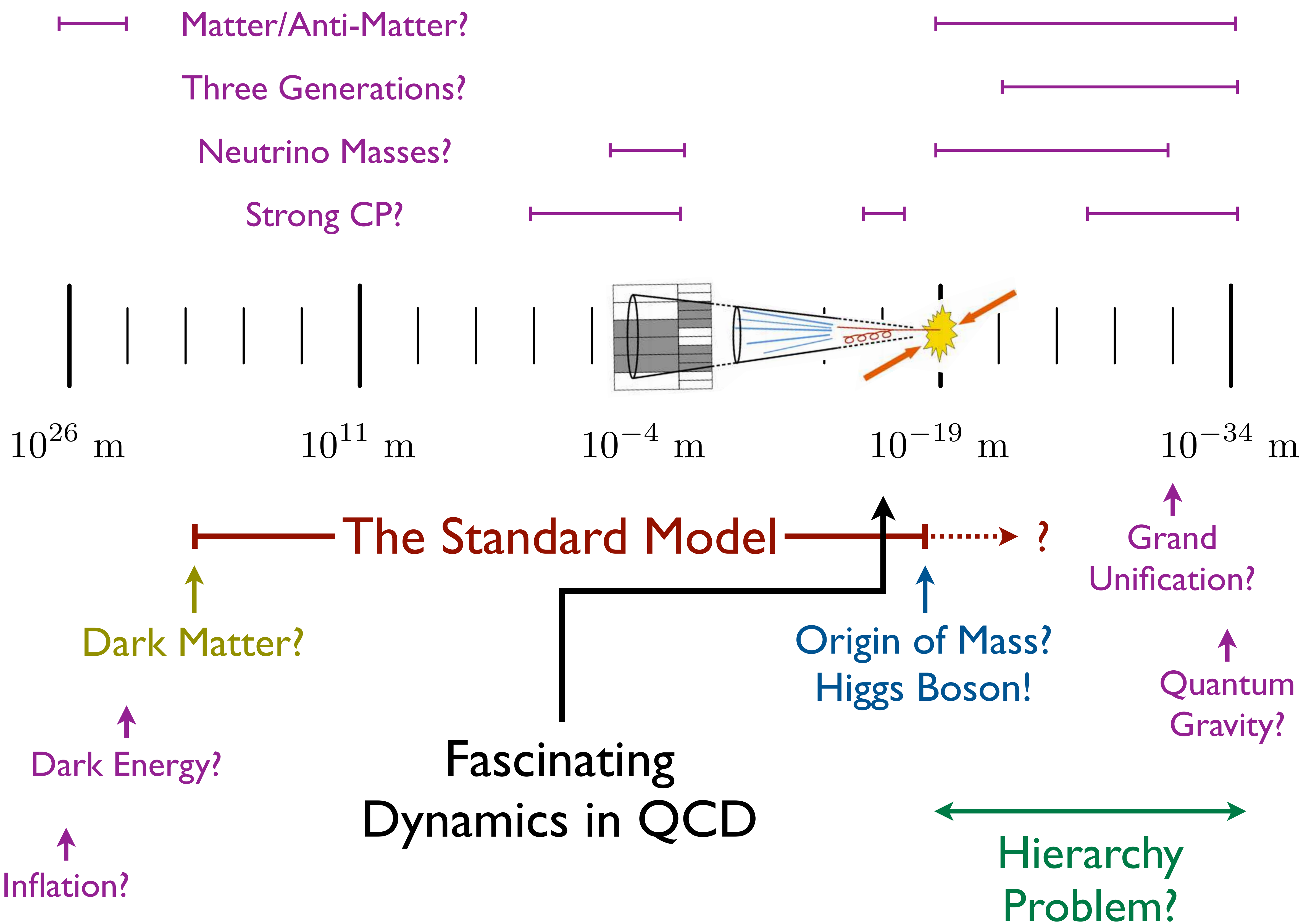
Boosting the Search for New Phenomena

Planar Flow, Trimming, Variable R, N-subjettiness, Energy Correlators, Winner-Take-All Axes, Soft Drop, Jets Without Jets, XCone, Generalized Correlators, …



Pushing the Boundaries of Quantum Field Theory

Boosted Event Shapes, Transverse Velocity Flow, Track Functions, Recoil-Free Observables, Sudakov Safety, Quark/Gluon Mutual Information, …



Matter/Anti-Matter?
Three Generations?
Neutrino Masses?
Strong CP?
10^{26} m
10^{11} m
10^{-4} m
10^{-19} m
10^{-34} m
The Standard Model
?
Grand Unification?
Dark Matter?
Origin of Mass? Higgs Boson!
Quantum Gravity?
Dark Energy?
Fascinating Dynamics in QCD
Inflation?
Hierarchy Problem?