Jets at the LHC

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What is a jet? What is a Jet?

• Energetic quarks and gluons radiate and hadronize → Produce sprays of collimated hadrons Energetic quantie dinast gluichte rateillete dinast

What is a jet?

- Jet definition must be easy to implement and infrared safe
- Two basic approaches:

Jet vetoes important for new physics searches

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Why do jets matter?

Standard Model background

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 $\left| \bigoplus_{i=1}^{\infty}$ O.6 $\left| \bigoplus_{i=1}^{\infty}$ d-quark \searrow $\frac{\text{exp}^{\text{out}}}{\text{sin}^{\text{in}}}$ 0.0 $\frac{1}{3}$ -2 $\frac{1}{2}$ $\frac{1}{2}$ 0.6 $\frac{1}{2}$ d-quark $\frac{1}{2}$ s measured varian define this obser
 $\frac{1}{4}$ and $\frac{1}{4}$ are shown in fig. 10 (fig. where the sum is $\exp\left(-\frac{1}{2}t\right)$ teger charge of κ is a $\nu_{\mu} p \rightarrow \mu^{-} u X$ $\qquad \qquad \frac{\partial^{\kappa} \mathcal{L}}{\partial_{\mu} p \rightarrow \mu^{+} d X} \qquad \frac{\partial^{\kappa} \mathcal{L}}{\partial_{\mu} p \rightarrow \mu^{+} d X}$ tum in $\frac{1}{2}$ i. $\frac{1}{2}$ are $\frac{1}{2}$ if the algebra $\frac{1}{2}$ is the algebra $\frac{1}{2}$ in the algebra $\frac{1}{2}$ is the algebra $\frac{1}{2}$ in the algebra $\frac{1}{2}$ is the algebra $\frac{1}{2}$ in the algebra $\frac{1}{2}$ is stu \mathbb{R}^n and \mathbb{R}^n on the projection of u and \mathbb{R}^n on the three through u momentum on the three through u momentum on the three terms of u momentum on the term of u momentum on the term of $\cos \theta = \frac{1}{2} \cos \theta$ $\log th \leqslant \frac{20}{2}$ experi \longrightarrow 00.1 \longrightarrow 00.1 \longrightarrow 0.1 \longrightarrow in [10]. 24
 H. Berge et al. /

C WAVS. $\begin{array}{ccc} \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \end{array}$ where the sum $\frac{1}{2}$ **o.8** $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$ \vec{r} \approx $\tilde{\mathcal{L}}$ $\tilde{}$ $\overline{}$ $\frac{3}{3}$ ' i i i (a) and \sim 1.1 \sim 1 d - quark ~,~,", / / *,,.?/~* u-quark d - quark ~,~,", / / *,,.?/~* u-quark $u_{\varepsilon} = u_{\varepsilon} = u$ -2 - 1 0 -1 2 -1 $Q |e|$ $\overline{}$ axis define this obser
reveriment are shown in fig. 10 (fig. 11 where the sum is $\int_{\alpha}^{\alpha} f(x) \, dx$ is the integration $\int_{\alpha}^{\alpha} f(x) \, dx$ tum in $\frac{10}{4}$ and $\frac{10}{4}$ similar results. In the alephant $\frac{1}{4}$ of $\frac{1}{4}$ and $\frac{1}{4}$ stu \mathbb{S}^{13} , \mathbb{S}^{13} , \mathbb{S}^{13} and \mathbb{S}^{14} on the thrust \mathbb{S}^{14} on the thrust \mathbb{S}^{14} $\text{axis} = \frac{1}{2}$ is the $\frac{1}{2}$ was found on $\frac{1}{2}$ is $\frac{1}{2}$ was found on $\frac{1}{2}$ is $\frac{1}{2}$ $\log th \leq \frac{1}{2}$ experi $\begin{array}{c} \begin{array}{c} \text{ex} \\ \text{ex} \end{array} \end{array}$ Mays.
 J.P. Berge et al. / $\overline{5}$ O.4 $\overline{5}$ O.4 $\overline{5}$ where the sum $\frac{1}{2}$ sum irge. $|O|$ $\frac{1}{2}$ 0.8 **o.6** 0.4 $Q2$ ' i i i -2 - I 0 I 2 - I 2 - I 2 - I 2 - I 2 - I 2 - I 2 - I 2 - I 2 - I 2 - I 2 - I 2 - I 2 - I 2 - I 2 - I 2 - I 2 tum in stuck $\overline{}$ */*(*d /dQ*) [*e*

Ealt admuent contrating to the fraction of the same experiment, on the other hand, gives $p_s/p = 0.36$ (in the same experiment, on the other hand, gives $p_s/p = 0.36$ (ref. [26]), which is experiments. From the K^+/ π^+ ratio in high energy proton-proton experiments [23] extrapolated to the Feynman x of one (to avoid resonance contributions), we estimate $p_s / p \sim 0.50$. Another estimate of p_s / p can be obtained from the cross section ratios $(J/\psi \rightarrow K^+ K^*)/(J/\psi \rightarrow \rho \pi)$ corrected for phase-space factors [24]. The result $p_s / p = 0.49 \pm 0.11$ implies $p = 0.40 \pm 0.02$. An electroproduction experiment obtains for the ratio $(K^{\circ} + K^{\circ})/(\pi^+ + \pi^-)$ a value of 0.13 ± 0.03 which the authors interpret as the ratio p_s/p (ref. [25]); this value would mean considerably stronger SU(3) symmetry violation in the quark jets. A jet net charge measurement again consistent with our measurements. again consistent with our measurements.

> Most of the ϵ large fractional energy z (further from the overlap region) get a large weight; i.e., the measured varian weighted charge is defined as $Q_w = Z_i(z_i) e_i$, where r is a small number and e_i is the
integer charge of the *i*th hadron in the final state. Resulting distributions from our Field and Feynman have proposed an alternative way of distinguishing quark jets Field and Feynman have proposed an alternative way of distinguishing quark jets of different flavour $[6]$. There, one weights each particle with a z-dependent weight such that particles closer to the overlap region get a small weight and particles with weighted charge is defined as $Q_w^{\nu,\nu} = \sum_i (z_i)^r e_i$, where r is a small number and e_i is the experiment are shown in fig. 10 (fig. 11) for antineutrino (neutrino) charged current experiment are shown in fig. 10 (fig. 11) for antineutrino (neutrino) charged current

 $\lim_{R \to \infty} \frac{\prod_{i=1}^{n} \prod_{i=1}^{n} \prod_{i=1}^{$ Fig. II. Weighted charge Q~ = *]~,(zi)rei* for the neutrino charged current induced hadrons traveling forward in the hadronic'c.m.s. (a) for r= 0.2, and (b) for r = 0.5. The solid curves represent the Field and neutrino ! up quark jet anti-neutrino ! down quark jet Fig. II. Weighted charge Q~ = *]~,(zi)rei* for the neutrino charged current induced hadrons traveling forward in the hadronic'c.m.s. (a) for r= 0.2, and (b) for r = 0.5. The solid curves represent the Field and

Outline

- 1. Jet cross sections
- 2. Jet substructure for boosted objects
- 3. Probing partons with substructure
- 4. Probing the medium with jets

1. Jet cross sections

Fixed-order calculations

• NLO calculations are automated [MCFM, BlackHat, Rocket, NJet, MadLoop, ...]

• Large uncertainties at LO reduced at NLO WAADOM AL FILL

Fixed-order calculations

• Certain observables require NNLO precision. E.g.

[CMS-PAS-SMP-14-023]

• Lots of new NNLO results due to slicing with *N*-jettiness [Stewart, Tackmann, WW; Boughezal, Focke, Liu, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh] *T^N*

$$
\sigma(X) = \int_0^{\delta} d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N} + \int_{\delta} d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N}
$$

analytic up to $\mathcal{O}(\delta)$ from NLO

Resummed calculations

• Tight restriction on radiation → large logarithms and uncertainties

$$
\sigma(H+0\text{ jets}) \propto 1 - \frac{6\alpha_s}{\pi} \ln^2 \frac{p_T^{\text{veto}}}{m_H} + \dots
$$

• Resummation captures dominant effect of all emissions

Resummation for jets

• Jet radius resummation

[Dasgupta, Dreyer, Salam, Soyez; Chien, Hornig, Lee; Kolodrubetz, Pietrulewicz, Stewart, Tackmann, WW; Kang, Ringer, Vitev; Dai, Kim, Leibovich; …]

• Nonglobal logarithms

[Caron-Huot; Larkoski, Moult, Neill; Becher, Neubert, Rothen, Shao,…]

• Resummation of kinematic jet hierarchies [Bauer, Tackmann, Walsh, Zuberi; Larkoski, Moult, Neill; Pietrulewicz, Tackmann, WW]

[Pietrulewicz, Tackmann, WW]

2. Jet substructure for boosted objects

When does a top quark become a jet?

Trigger

• Boosted analysis overtakes resolved at p poivou di p_T and ∞ s • Boosted analysis overtakes resolved at p_T^{top} $T^{\rm top} \sim 400\,{\rm GeV}$

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• Important as BSM searches move to ever higher energies

Tagging by kinematics

• Test whether jet consists of three subjets with kinematics of top decay, using templates *T* [Almeida, Lee, Perez, Sterman, Sung]

$$
\text{Overlap} = \max_T \exp\bigg[-\frac{\text{grad}\max\limits_{i \in T} \max\limits_{j \in T} \max\limits_{j \in S} \text{grad} \sum\limits_{j \in T} \text{grad} \sum\limits_{j \in T} \text{grad} \max\limits_{j \in S} \text{grad} \max\limits_{j \in S} \text{grad} \sum\limits_{j \in S} \text{grad} \max\limits_{j \in S} \text{grad} \max\limits_{j \in S} \text{grad} \sum\limits_{j \in S} \text
$$

• Output is not only overlap but also the best matching template *Result: Ov AND template which maximizes overlap. For each template*

Tagging by power counting

• Start from energy correlation functions [Larkoski, Salam,Thaler]

$$
e_2^{(\beta)} = \sum_{i < j \in J} z_i z_j \theta_{ij}^{\beta} \qquad e_3^{(\beta)} = \sum_{i < j < k \in J} z_i z_j z_k \theta_{ij}^{\beta} \theta_{ik}^{\beta} \theta_{jk}^{\beta}
$$

 $\frac{1}{2}$ Power counting determines the counting $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ are continuous to $\frac{1}{2}$ and $\frac{1}{2}$ are continuous to $\frac{1}{2}$ and $\frac{1}{2}$ are continuous to $\frac{1}{2}$ and $\frac{1}{2}$ are cont เทเ ² , *e* ${\cal H}_{\bm i}$, σ_{ij} and any σ with z_i the energy fraction of *i* and θ_{ij} the angle between *i* and *j*

 $\overline{}$

• Power counting determines structure of *e* ² , *e* ³ phase space: α and α <u>dl</u> • Parametric discrimination of 1 vs. 2 prong [Larkoski, Moult, Neill]

Cauchbolic Problem	CA. 2 pionly [LahosA, World, New]		
$\begin{array}{r}\n \begin{array}{r}\n \text{Collinear} \\ \text{Collinear} \\ \end{array}\n \end{array}$ \n	$e_2^{(\beta)} \sim \theta_{cc}^{\beta} + z_s$	$e_2^{(\beta)} \sim \theta_{cc}^3 + \theta_{cc}^2 z_s + z_s^2$	$(e_2^{(\beta)})^3 \leq e_3^{(\beta)}$
$\begin{array}{r}\n \begin{array}{r}\n \text{Softlinear} \\ \text{C.5off} \\ \end{array}\n \end{array}$ \n	$e_2^{(\beta)} \sim \theta_{12}^{\beta}$	$e_3^{(\beta)} \sim \theta_{12}^{\beta} z_s + \theta_{12}^{2\beta} \theta_{cc}^{\beta} + \theta_{12}^{3\beta} z_{cs}$	

Predicting the tagger efficiency

• Tag *W* boson jets using
$$
D_2^{(\beta,\beta)} \equiv \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}
$$

• Soft-Collinear Effective Theory yields resummed prediction for the cross section of D_2 , compatible with Monte Carlos

Tagging with deep learning

- Use methods from image recognition r
I Fraction of Events L \sim \sim \sim \sim \sim
- As powerful as combination of (expert) substructure observables l
J 0.04 $| \cdot |$ \blacksquare i
C acon iobloc $H \rightarrow T$ r comh 0 20 40 60 80 100 120 140 160 180 200 0 0.2 0.4 0.6 0.8 1 l
I \sim 0.06 QCD Γ $U\cup U\subset U$.
C 0.04 QCD $N\triangle C$ ハレい

- τ^{β=1}+mass

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jets from *W* ! *qq* in some can be some care can be seen to retain the slightly higher frace- σ of σ is a signal-dominated region. The signal-dominated region σ

3. Probing partons with substructure

Jet charge as discriminant

• Jet charge can help characterize BSM. E.g. hadronic *Z*' vs. *W*'

[Krohn, Lin, Schwartz, WW]

- Optimal κ : trade off between soft contamination vs. sensitivity
- Jet charge not infrared safe \rightarrow only evolution calculable

Calculating jet charge Introduction Calculation and Results Measurements Tracks Conclusions

• Jet charge = nonlinear DGLAP evolution \otimes hadronization Full Jet Charge Distribution of the Charge Distribution of the Charge Distribution of the Charge Distribution
The Charge Distribution of the Charge Distribution of the Charge Distribution of the Charge Distribution of th $\arg e =$ nonlinear DGLAP evolution \otimes hadronization

• Taking Pythia as input and evolving gives good agreement: *µ ER 2009 ER*

Jet charge measurements

- The largest dependence on jet $\frac{3}{8}$ o.7 F More Central Jet **Julian Premig++** 2.63 EE3 $\frac{1}{3}$ 1 M^2 r: Acor r **Pythia** 8.175 AU2 andan*re*
- Observing scale violation is the $\frac{1}{9}$ out the characteristic change of the ible h
I

correlations between values can be determined using the bootstrapped datasets: about 0.9 between *c*0.³

21

Quark-gluon discrimination **50** $\left\{$ Linear Radial Moment Concert

30

- New physics often more quarks than QCD backgrounds **20 .1**
- **Largest difference between quark and gluon jet is color charge 0** \mathfrak{g} l i yudin ahu yiu Charged Track Multiplicity

.6

• Extensive Pythia study: track multiplicity + girth are best two

Current limitations of Monte Carlos

- Many quark-gluon discriminants are generalized angularities
- Big spread between predictions from different Monte Carlos · Big s

4. Probing the medium with jets

Dijet inbalance

- Jets lose energy as they propagate in medium (quenching)
- Leads to a distortion of the p_T balance of dijets Strong modification of splitting observed in central PbPb collisions \log to a distortion of the ρ_{T} k Marta Verweig 17 des 17 des 17 desember 17 des 17 des 17 desember 17 desember 17 des 17 desember 17 desember 1 $S_{\rm eff}$ modification of splitting observed in central PbPb collisions observed in central PbPb collisions of σ B D_T balance of diiets

$$
x_J = \frac{p_{T,2}}{p_{T,1}}
$$

Splitting fraction

- Cluster jet using Cabridge/Aachen (purely angular) Total smearing - 2.2 2.2 2.2 2.2 number of f is the grooming procedure. PyTHIA has a slightly step \mathbb{R} has a slightly steeper distribution than \mathbb{R} the data. Here is a shown in Fig. 2, it is also shown in Fig. 2, it will be a set of α in α in α and α in α is α is
- Go through clustering tree until splitting satisfies **6 Results**

$$
z_g \equiv \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \t r_g \equiv \Delta R_{12} > \Delta
$$

\n[Larkoski, Marzani, Soyez, Thaler]

• At LO this is proportional to Altarelli-Parisi splitting function 2 \mathbf{I} 2 3

MC statistical uncertainty - 0.1 0.1 0.1 0.1

PYTHIA 6 (tune Z2) and PYTHIA 8 (tune CUETP8M1). The measurement is normalized by the

• Medium effect on splitting functions described by Glauber gluons compared to pp data. For this comparison the pp data is determined to the pp edium effect on splitting functions described by Gla the variation of calculations with the variations with the variation of 2.01

The groomed momentum sharing z^g and its normalized

Conclusions

- Jets play a crucial role in many LHC measurements
- Jet (substructure) as probe of
	- boosted heavy particles
	- initiating parton of QCD jets
	- medium in heavy ion collisions
- There is room for new ideas, new observables, new calculations…

