# Top physics after Higgs discovery



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### The top quark Lagrangian in the SM quark Lagrangian in *P*(*z*) ⇠ angian in the SM I he top qu top quark Lagrangian in the SM *<sup>m</sup>*<sup>2</sup> (88)  $L_{\text{max}}$   $\alpha$  *i*<sub>l</sub>  $\alpha$ *L*  $\alpha$  $\mathcal{L}$ *L* The top quark I garangian in the SM

Gauge interactions: *<sup>L</sup>* <sup>=</sup> *iQ*¯*LDQ*/ *<sup>L</sup>* <sup>+</sup> *it*  $\alpha$  *DZ* **+** *ig***<sub>z</sub>**  $\alpha$ *j***s***a***<sup>***g***</sup> +** *ig***<sub>z</sub>**  $\alpha$ *D<sup>µ</sup>* = @*<sup>µ</sup>* + *igsG<sup>a</sup>*  $\underline{\mathbf{u}}$  *n*  $\underline{\mathbf{v}}$  and  $\underline{\mathbf{v}}$ *<sup>µ</sup>T <sup>a</sup>* + *igW<sup>i</sup>*

$$
\mathcal{L} = i\bar{Q}_L \not\!\!D Q_L + i\bar{t}_R \not\!\!D t_R + i\bar{b}_R \not\!\!D b_R
$$

*M*  $\blacksquare$  *M* covariant derivative (*T <sup>a</sup>, G<sup>a</sup> <sup>µ</sup>, gs*) (91)

$$
D_\mu = \partial^\mu + i g_s G_\mu^a T^a + i g W_\mu^i T^i + i g' B_\mu Y
$$

in terms of the generators and gauge bosons of SU(3)  $(T^a,G^a_\mu,g_s)$ SU(2)  $(T^i,W^i_\mu,g)$  and U(1)  $(Y,B_\mu,g')$  and  $\mathbf{g}$  and gauge bosons of  $\mathbf{g}$   $(3)$  (1,  $\mathbf{g}$ ,  $\mathbf{g}$ ) *Z<sup>µ</sup>* = cos ✓*<sup>W</sup> W*<sup>3</sup> *<sup>µ</sup>* sin ✓*<sup>W</sup> <sup>B</sup><sup>µ</sup> , A<sup>µ</sup>* = sin ✓*<sup>W</sup> <sup>W</sup>*<sup>3</sup> *<sup>µ</sup>* + cos ✓*<sup>W</sup> B<sup>µ</sup>* (94)

$$
Z_{\mu} = \cos \theta_W W_{\mu}^3 - \sin \theta_W B_{\mu} \quad , \quad A_{\mu} = \sin \theta_W W_{\mu}^3 + \cos \theta_W B_{\mu}
$$

with the Weinberg angle  $\,\theta_{W}$  $\theta_W$ ✓*<sup>W</sup>* (95)

Eventually, the coupling to the Higgs boson field is

$$
\mathcal{L}_{\text{Yukawa}} = -y_t \bar{t} t H \quad \text{with} \quad y_t = m_t/v
$$

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After spontaneous symmetry breaking and rotating into the mass eigenstate basis, the charged current interactions introduce flavor mixing in the SM mmetry breaking and rotating into the mass<br>charoed current interactions introduce

$$
\mathcal{L}_{W^{\pm}} = g W_{\mu}^{-} \sum_{i,j=\text{flavors}} V_{ij} \bar{q}_{i} \gamma^{\mu} q_{j} + \text{h.c.}
$$

with the Cabibbo-Kobayashi-Maskawa matrix:

$$
V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}
$$

Need 3 generations for CP-violation in SM

top quark related to origin of CP and possibly baryogenesis

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### Early indirect evidence for heavy top quark <sup>.</sup> heavy t *z P* quark

- After discovering of b-quark existence of top expected  $\overline{P}$  of tapex *Vcd Vcs Vcb Vtd Vts Vtb* 1027 sec (1007 sec (<br>1007 sec (1007 sec (
- Indirect evidence from B and K meson mixing CP phase - CP pnase



- $\bullet$  Vtb measurement: single top (Tevatron)  $V_{tb} = 0.88 \pm 0.07$ unitarity of CKM Mat.  $V_{tb} = 0.999135$ *Vtb* = 0*.*88 *±* 0*.*07 (103)
- EW precision tests at LEP give constraint of top mass

# Measurement of top quark properties



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## tt production cross sections \_

- [Nason, Dawson, Ellis ('88,'89); Beenakker, Kuijf, van Neerven, Smith]  $\rightarrow$  tt @ NLO
- 
- $\overline{\phantom{a}}$
- Czakon, Fiedler, Ferroglia, Pecjak, Yang; Mitov;<br>■ TT NNLO Calculations Bonciani, Ferroglia, Gehrmann, Maitre, Studerus Bonciani, Ferroglia, Gehrmann, Maitre, Studerus; Anastasiou, Aybat; Kniehl, Merebashvili, Korner, Rogal; Bonciani, Ferroglia, Gehrmann, Studerus; ... ]
- †† NNLL resummed [Czakon, Mitov; Kidonakis ('09,'10); Beneke, Falgari,<br>Schwinn: Czakon, Mitov, Sterman: Beneke, Czakon Schwinn; Czakon, Mitov, Sterman; Beneke, Czakon, Falgari; ...]
- $\triangleright$   $\uparrow$   $\uparrow$   $\uparrow$   $\downarrow$   $($   $\uparrow$   $\downarrow$   $Z$ , photon) [Beenakker et al.; Dawson, Reina; Dawson, Reina, Wackeroth; Dawson Rein; Lazopoulos et al.; Peng-Fei et al.]  $\overline{ }$ \_
- ‣ tt + jet @ NLO [Dittmaier, Uwer, Weinzierl ('07,'09)]
- ‣ tt + 2jet @ NLO [Bevilacqua, Czakon, Papadopoulos, Worek]
- ‣ tt including decays @ NLO  $\overline{\phantom{a}}$

[Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek]

 $\overline{\phantom{a}}$ 



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## tt production cross sections \_



CMS Preliminary,  $\sqrt{s} = 8$  TeV



production cross section in very good agreement with theory prediction

## **Single top production**



- production modes discriminated by # of tagged b-jets and their kinematics
- Cross sections for top / anti-top [pb]:



• At Tevatron with ~10 ifb per experiment in total 60 000 single top events vs 150 000 pair top events

Single top production subleading but useful for measurements



• Anomalous couplings in production



• Perfect factorization through NLO, like DIS and DY



[Graphs Z. Sullivan]



# Top Quark decays *h,*SM <sup>4</sup>*m*<sup>2</sup>

Decays before hadronizes via EW interaction. Since  $m_t > m_W + m_b$  (147) interaction.

$$
t \rightarrow W^{+} + b
$$
  
\n
$$
\downarrow t^{+} + \nu
$$
  
\n
$$
t \rightarrow W^{+} + b
$$
  
\n
$$
\downarrow q + \overline{q}
$$

with 
$$
\Gamma_t \simeq 1.4 \text{ GeV}
$$

Top decay modes determined there is a contract of  $\mathbb{R}^n$ by W decay, e.g.

BR(
$$
W^+ \rightarrow e^+ \bar{\nu}
$$
) =  $\frac{1}{3+3+3} \approx 11\%$ .  
\n $\sqrt{3 \times 3 \times 10^{-10}}$ 



# Rare/Anomalous Top Quark decays



FCNC can be loop-induced in the SM and enhanced by New Physics

$$
\mathscr{L}_{\text{eff}} = g_s \sum_{q=u,c} \frac{\kappa_{qgt}}{\Lambda} t \sigma^{\mu\nu} T^a (f_q^L P_L + f_q^R P_R) q G_{\mu\nu}^a + h.c.,
$$

ATLAS study at 7 TeV with 2 ifb

$$
\kappa_{cgt}/\Lambda < 1.6 \cdot 10^{-2} \text{ TeV}^{-1} \qquad \mathscr{B}(t \to cg) < 2.7 \cdot 10^{-4}
$$
  
\n
$$
\kappa_{ugt}/\Lambda < 6.9 \cdot 10^{-3} \text{ TeV}^{-1} \qquad \mathscr{B}(t \to ug) < 5.7 \cdot 10^{-5}
$$
  
\nfrom single top prod

No evidence for t -> Zq decay found  $d$  *dence for t -> Zg decay found* 

 $BR(t \to Zq) < 0.73\%$ 

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#### Top quark spin and polarization *<u><u>Enin</u>* and nolarization</u>  $p$  quark spin  $d$ 2 p*s n* and polarization  $\overline{1}$  $\overline{a}$ *n | arization*

 $f(n) \rightarrow h(n) \frac{W^+(n)}{m}$  is since by The decay amplitude for  $t(p_t) \rightarrow b(p_b) W^+(p_W)$  is given by *<sup>t</sup>*(*pt*) ! *<sup>b</sup>*(*pb*)*W*<sup>+</sup>(*p<sup>W</sup>* ) (106)

$$
\mathcal{M}(t \to bW^+) = -\frac{ig}{2\sqrt{s}} V_{tb} \bar{u}(p_b) \gamma^{\mu} (1 - \gamma_5) u(p_t) \epsilon^{\lambda *}_{\mu}(p_W)
$$

*p*<sub>c</sub> = (*p*<sup>*x*</sup>) *p*<sup>*x*</sup> *p*<sup>*x*</sup> *p*<sup>*x*</sup> *p*<sup>*x*</sup> *p*<sup>*x*</sup> *is calculated es: p<sup>t</sup>* = (*mt,* 0*,* 0*,* 0) (108) =  $\mathsf{d}$  th *decay* raie for a given w-boson polarize .<br>izat *dLIP S* <sup>X</sup> *|M*(*<sup>t</sup>* ! *bW*<sup>+</sup>)*<sup>|</sup> <sup>t</sup>*(*pt*) ! *<sup>b</sup>*(*pb*)*W*<sup>+</sup>(*p<sup>W</sup>* ) (106) and the decay rate for a given W-boson polarization is calculated as:

$$
\Gamma = \frac{1}{2m_t} \int dLIPS \, \overline{\sum} \, |{\cal M}(t\rightarrow bW^+)|^2
$$

Assuming the top quark is unpolarized, working in its rest frame, the momentum configuration can be parametrized as: 2*m<sup>t</sup> p<sup>b</sup>* = (*Eb,* 0*, p* sin ✓*, p* cos ✓) (110) *m*<sup>2</sup> *<sup>t</sup>* + *M*<sup>2</sup> ssuming the top quark is unpolarized, working in its rest frame, the

$$
p_t = (m_t, 0, 0, 0) \quad p_W = (E_W, 0, p \sin \theta, p \cos \theta) \quad p_b = (E_b, 0, -p \sin \theta, -p \cos \theta)
$$
  
with 
$$
E_W = \frac{m_t^2 + M_W^2}{2m_t} \quad \text{and} \quad p = \frac{m_t^2 - M_W^2}{2m_t}, \text{ W polarization vectors are}
$$

$$
\epsilon_0 = \frac{1}{M_W}(p, 0, E_W \sin \theta, E_W \cos \theta) \qquad \epsilon_{\pm} = \frac{1}{\sqrt{2}}(0, 1, \pm i \cos \theta, \mp \sin \theta)
$$

School on the Future of Collider Physics IPMU I5 Michael Spannowsky 16.07.2013  $\frac{1}{2}$ *h*e Future of Collid (*p,* 0*, E<sup>W</sup>* sin ✓*, E<sup>W</sup>* cos ✓) (113) *p* = *m*<sup>2</sup>

*t*  $\frac{1}{2}$  $15$ 

 $\overline{\phantom{0}}$  $|e|$ 

with  $m_b=0$  we get  $\sum |\mathcal{M}(t \to bW^+)|^2 =$  $g^2$  $|V^+|\rangle|^2 = \frac{g}{8} |V_{tb}|^2 Tr \left[ (p_t^{\prime} + m_t) \epsilon_{\lambda}^* (1 - \gamma_5) p_b^{\prime} \epsilon_{\lambda}^{\prime} \right]$  $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$  $\overline{1}$ *we ge* (*p, 0, e, 0, e,*  $= \frac{3}{8} |V_{tb}|^2 Tr \left[ (p'_t + m_t) \epsilon^*_{\lambda} (1 - \gamma_5) p'_b \epsilon^*_{\lambda} \right]$  $\sum_{\mu=1}^{\infty} |M(\mu + k)M(\mu + k)|^2$ *g*2  $\sum_{i=1}^{\infty} |\mathcal{M}(t \to bW^+)|^2 = \frac{g^2}{2} |V_{th}|^2 Tr \left[ (\hat{p}'_+ + \hat{m}_t) \epsilon^*_{\lambda} (1 - \gamma_5) \hat{p}'_t \epsilon^{\prime}_{\lambda} \right]$  $\overline{a}$ ge (<del>1)</del><br>(1), *−i* cos ∠*i* cos ∠*i* cos ∠i cos  $\frac{1}{\beta}$  |  $Vtb$  |  $\perp T$  |  $(p_t + m_t) \phi_{\lambda} (1 - \gamma_5) p_b \phi_{\lambda}$  |

t polarization vectors one derives ituting the explic *t* <sup>2</sup> *<sup>|</sup>Vtb<sup>|</sup>* <sup>2</sup>2*x*<sup>2</sup>(1 *<sup>x</sup>*<sup>2</sup>) (117) <sup>X</sup>*|M*(*<sup>t</sup>* ! *bW*<sup>+</sup>)*<sup>|</sup>* 2 *g*2 PULATIZATIVIT VECT  $\overline{116}$ and substituting the explicit polarization vectors one derives

$$
\sum |\mathcal{M}_0|^2 = \frac{2G_F m_t^4}{\sqrt{2}} |V_{tb}|^2 (1 - x)
$$

$$
\overline{\sum}|\mathcal{M}_-|^2 = \frac{2G_F m_t^4}{\sqrt{2}} |V_{tb}|^2 2x^2 (1 - x^2)
$$

that the fr 2*G<sup>F</sup> m*<sup>4</sup> **POI**  $x = \frac{M_{W}}{m_{t}}$ , such that the fraction of longitudinally polarized W is:  $M_W$  $m_t$ long  $\overline{\mathsf{r}}$  ac  $ion$ for  $x = \frac{m}{m}$ , such that the fraction of longitudinally polarized W is:

$$
F_0 = \frac{\Gamma_0}{\Gamma_{\text{tot}}} = \frac{1}{1 + 2x^2} = \frac{m_t^2}{m_t^2 + 2M_W^2} \simeq 0.70
$$

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#### Structure of elw. top interactions Structure of elw ton interaction of e  $\frac{1}{2}$ top ir  $\mathbf{L}$  $\alpha$ ctions  $\blacksquare$  Structure ot elw. top 2*G<sup>F</sup> m*<sup>4</sup>  $\overline{\phantom{a}}$ *x*. Top interactions

For  $m_b = 0$  the W coming from  $t \to bW^+$ can either be left-handed or longitudinal, never right-handed, because of angular momentum conservation  $\mathbf{y}_b = 0$  the W coming from  $\mathbf{y}_b$ because of angular momentum conserve <sup>X</sup>*|M*0*<sup>|</sup>* 2 = 2*G<sup>F</sup> m*<sup>4</sup> *t*  $\iota$  → *UVV*<br>|it $\iota$ dinal never right-handed  $\overline{a}$ *servation F*<sup>0</sup> = **16**  $\overline{\phantom{0}}$ 1<sup>|</sup>  $\overline{a}$ *m*<sup>2</sup>



• Probes Weak interactions near EW symmetry breaking scale

• Test of V-A interaction in Standard Model

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Including second stage decay  $W^+ \rightarrow l$ will build upon prior works  $\mathcal{L}_{\mathcal{A}}$  and prior works  $\mathcal{L}_{\mathcal{A}}$  and present a detailed build upon  $\mathcal{L}_{\mathcal{A}}$  $\overline{v}$ of relevant  $B$  relevant  $B$  relevant  $B$  for  $\mathbb{R}$  fb1 of  $\mathbb{R}$  fb1 of  $\mathbb{R}$  of  $\mathbb{R}$  of  $\mathbb{R}$  of  $\mathbb{R}$  of  $\mathbb{R}$  fb1 of  $+$ <sub>V</sub> cond st  $= 1.26$ 

allows to use charged lepton to measure W helicity fractions tonic charge asymmetry in dileptonic *tt* + *F*  $\overline{1}$ harged lepton to measure W helicit:  $\overline{\phantom{a}}$ *d* **d** change ed lepton to measure W helicity



 $\overline{(\ }$  $\overline{)}$ r summing all W helicities the was heaven a polarization. The information  $\mathcal{P}$ ing all W nelicities the  $\sim$ or to measure top quark polarization. After summing all W helicities the 8 squared matrix element is  $\overline{a}$ 

$$
\sum |M|^2 \sim \frac{\left(m_b^2 p_t \cdot p_l - m_t^2 p_t \cdot p_l + 2p_t \cdot p_l\right)}{((p_l + p_\nu)^2 - m_W^2)^2}
$$

lepton - top perfectly correlated to check for top polarization 1  $\Gamma$  $d\Gamma$  $d\cos\theta_{l,n}$ 

 $\overline{\phantom{a}}$  $\frac{1}{2}$ *d d* cos ✓*i,n*  $\overline{C}$  $\mathbf{S}$  $O(l, n)$ = 1 2  $(1 + \mathcal{P}_n \cos \theta_{l,n})$ 

top completely polarized:  $\mathcal{P}_n=\pm 1$ [Mahlon, Parke 1996]

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### top polarization: Important for many applications  $\alpha$ olarization: Important tor many applications

*<sup>T</sup> ·* <sup>p</sup><sup>0</sup>

Example: Polarized tops from stop decays  $\tilde{t} \to \chi_1^0$  $\frac{0}{1}t$  [Bhattacherjee, Mandal, Nojiri JHEP]

stop mass terms in MSSM:

$$
\mathcal{L} = (\tilde{t}_L^*, \tilde{t}_R^*) M^2 (\tilde{t}_L, \tilde{t}_R)^T
$$

[Perelstein, Weiler JHEP] [Han, Katz, Krohn, Reece JHEP] BR(*t* ! *W b*) + BR(*t* ! *Zq*)=1 (149) BR(*t* ! *Zq*) *<* 0*.*73% (148) *m<sup>t</sup> > m<sup>W</sup>* + *m<sup>b</sup>* (145)

 $\cos 2\theta_{\text{eff}} = 1$ 

 $\cos 2\theta_{\text{eff}} = 1$ 

### BR(*t* ! *W b*) + BR(*t* ! *Zq*)=1 (149) mass eigenstates *<sup>L</sup>* <sup>=</sup> *t* ˜⇤ *<sup>L</sup>,t* ˜⇤ *<sup>t</sup>* ' 1*.*3 GeV (146) *R*  $intates$

$$
\tilde{t}_1 = \cos \theta_t \tilde{t}_L + \sin \theta_t \tilde{t}_R,
$$
\n
$$
\tilde{t}_2 = \sin \theta_t \tilde{t}_1 + \cos \theta_t \tilde{t}_R.
$$

$$
\big)^T \qquad \qquad \tilde{t}_2 \ = \ -\sin\theta_t \, \tilde{t}_L \, + \, \cos\theta_t \, \tilde{t}_R \, ,
$$

resulting vertex: 600 BR(*t* ! *W b*) + BR(*t* ! *Zq*)=1 (149) 400 *<sup>T</sup>* (150) *<sup>L</sup>* <sup>=</sup> È *M*<sup>2</sup> ˜⇤ Maybe can be used to measure stop mixing angle, i.e. composition of mass eigenstates  $\cos 2\theta_{\text{eff}} = 0.2$  $0.4$ 0.6 0.8  $1.0$  $0.0$ angle between lepton and neutralino from same stopFOD  $\cos (\theta_l)$ School on the Future of Collider Physics IPMU 19 Michael Spannowsky 16.07.2013

### Top Quark mass  $T_{\Omega}$  *Quark* mass

## See talks by Brian and CP

The top quark mass is fundamental parameter of SM and input to electroweak precision measurements  $\frac{1}{2}$   $\int_{0}^{2\pi} f(x) \, dx$  $2aK$  precision measurements

**Problem:** the top quark mass is not an observable, unlike decay rates or cross sections, but is scheme and scale dependent quantity.

Measurement of mass of colored object by color neutral decay products inherently ambiguous -> Cannot be determined better than  $\mathcal{O}(\Lambda_{\rm QCD})$ 

[Smith, Willenbrock PRL 79]



Figure 2: The production and decay of a top quark in (a) perturbation theory, and (b) nonperturbatively.

# top quark mass measurements



ATLAS and CMS combined top mass measurement:

m<sub>top</sub> = 173.3 ± 1.8 GeV [CMS-PAS-TOP-12-001] Measured mass is the input parameter of the used Monte Carlo

# Top reconstruction/tagging

## You cant measure what you cant detect

Top physics at LHC systematics limited, not statistics!



#### Top reconstruction/tagging *i*⌃*H*(*p*<sup>2</sup>)=4*n<sup>f</sup>* Top red  $2n$ Str  $\ddot{\bullet}$ <sup>+</sup> *<sup>O</sup>*(1*/*⇤<sup>2</sup>) (131) *<sup>W</sup>* = (*p<sup>l</sup>* + *p*⌫) 2 = *m*<sup>2</sup> *<sup>l</sup>* + 2(*ElE*⌫ *p* ~ *lp i*⌃*H*(*p*<sup>2</sup>)=4*n<sup>f</sup>* ~⌫) (132) ✓ *y<sup>f</sup>* ◆<sup>2</sup> 1 <sup>16</sup>⇡<sup>2</sup> (130) *m*<sub>2</sub>  $\frac{1}{2}$  *p*  $\frac{1}{2}$   $\frac{1}{2}$  *m<sup>f</sup>* <sup>+</sup> *<sup>O</sup>*(1*/*⇤<sup>2</sup>) (131) <u>inni</u> *m*<sup>2</sup> *pZ,l ±*  $\mathsf{I}$ *p* ~2 *<sup>l</sup>* (<sup>2</sup> *p*<sup>2</sup>

You cant measure what you cant detect  $2$ ⇤<sup>2</sup> + 6*m*<sup>2</sup> p2 *p*  $\frac{1}{2}$  $E$ *i*  $\alpha$ Ire e what you cant defect *m<sup>l</sup>* = 0 (135) *<sup>W</sup>* = (*p<sup>l</sup>* + *p*⌫)  $\mu$  cant mogeting what you cant  $p$  *p*  $p$  *delect hat* v tec

#### Leptonic top reconstruction  $\overline{\phantom{0}}$  $H$  *p*<sub>2</sub> *p*<sub>2</sub>  $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$ <u>re</u> nstruction  $\rho$  <u>Personic top reconstruction</u> *<i><i><u></u> ±*<sub>*z*</sub> *i*</del> *<sup>l</sup>* (<sup>2</sup> *p*<sup>2</sup> *T ,lp*<sup>2</sup> *T ,*⌫) *p*2 *<sup>i</sup>* (133)

Using 
$$
m_W^2 = (p_l + p_\nu)^2 = m_l^2 + 2(E_l E_\nu - \vec{p}_l \vec{p}_\nu)
$$
 and  $E_i = \sqrt{m_i^2 + \vec{p}_i^2}$   
\nwith  $\vec{p}_i = (p_{T,i}, p_{Z,i})$  and  $m_l = 0$  one obtains  
\n
$$
p_{Z,\nu} = \frac{\kappa p_{Z,l} \pm \sqrt{\vec{p}_l^2 (\kappa^2 - p_{T,l}^2 p_{T,\nu}^2)}}{p_{T,l}^2}
$$
 with  $\kappa = \frac{m_W^2}{2} + \vec{p}_{T,l} \cdot p_{T,\nu}^2$ 

often the solution is chosen which yields the best *m*<sub>*l*</sub>  $\frac{1}{2}$   $\frac$ hosen which yields the best  $\; m_t^2 = (p_b + p_l + p_{\nu}) \;$  $\overline{2}$ *n* which yields the best  $m_t^2 = (p_b + p_l + p_i)$  $m^2$ <br>*n* solution is chosen which vialds the hest  $m^2$  $\overline{z}$  $\mathsf{p}(\mathsf{u} + p_l + p_\nu)^2 = (p_b + p_l + p_\nu)^2$ 

#### Hadronic top reconstruction *pZ,l ±* <u>rr</u> <u>*<u></u></u></u>*  $+$ *r* uction *m*<sub>2</sub> top reconstruction <u>c top reconstruction</u>

*pZ,*⌫ =  $m_W^2$ Often simple  $\chi^2$  -fit with  $m_W^2 = m_{j_1j_2}^2$  and  $m_t^2 = m_{b,j_1,j_2}^2$ *j*<sub>1</sub>*, <i>j*<sub>2</sub> (140) *<i>j*<sub>2</sub> (140) *<i>j*<sub>2</sub> (140) *<i>j*<sub>2</sub> (140) *<i>j*<sub>2</sub> (140) *j*<sub>1</sub> (140 -fit with  $m_W^2=m_{j_1j_2}^2$  and  $m_t^2=m_{b,j_1,j_2}^2$ 

*<sup>t</sup>* = (*p<sup>b</sup>* + *p<sup>l</sup>* + *p*⌫)

*m*<sup>2</sup> School on the Future of Collider Physics IPMU 23 Michael Spannowsky 16.07.2013

# Top reconstruction in boosted final states

In many scenarios where top quarks have to be measured they are produced with large transverse momentum



- Here jet substructure cannot be avoided
- Many reconstruction techniques have been proposed and compared

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### $\Delta$  hrigf rovious of jot physics A brief review of jet physics

### At the LHC many sources of radiation: particles, in our case the top quark. It can be described well using the parton shower, and radiation our case the parton shower, and radiation our case of the parton shower, and radiation our case of the parton shower, an arising because the income the income to bridge the gap in scale between the gap in scale between the proton an  $r + 1$ **UNDERLY SOFT ACTIVITY SOFT ACTIVITY ACTIVITY ACTIVITY ACTIVITY AND INTERNATIVE PROT**

 $\bullet$  Pileup  $\rightarrow$  Can add up to 100 GeV of soft radiation per unit rapidity rounding the hard event. It is caused by semi- or non-perturbative interactions between the proton remnants. The soft continuous under radiation can have radiation can have a large e $\sim$  [Cacciari, Salam, Sapeta JHEP 1004] on the size *R* of the fat jet [57] *<u>Loacelary</u>* balant, supera or on the size *R* of the fat jet [57] [Cacciari, Salam, Sapeta JHEP 1004]

\n- Underlying Event 
$$
\rightarrow \langle \delta m_j^2 \rangle \simeq \Lambda_{\text{UE}} p_{T,j} \left( \frac{R^4}{4} + \frac{R^8}{4608} + \mathcal{O}(R^{12}) \right)
$$
 with  $\Lambda_{\text{UE}} \sim \mathcal{O}(10)$  GeV [Dasgupta, Magnea, Salam JHEP 0802]
\n

a, salam JHCP VOVZJ

- Initial state radiation (ISR) is roughly *O*(10) GeV [58].  $\textsf{ind}\,$  state-radiation (ISR) and collisions in one beam collisions in one beam crossing. Its e $\textsf{ind}\,$ observed now and are expected to become even harder to deal with once the LHC runs at design energy and observed now and are experienced to be control with one to deal with one the LHC runs at  $\mathcal{L}(\mathbf{L})$ design luminosity. Pile-up to 100 GeV of software per unit rapidity for some solution per unit rapidity for so
- Hard radiation from many resonances in event As discussed in Sec. II the *k<sup>T</sup>* and C/A algorithms, for a virtuality and an angular ordered shower, aim to **• Hard radiation from many resonances in eveni**
- Need methods to separate final state radiation (FSR) from rest of event and picture at the development of the detailed the jet clustering. Jet also the jet-mass-based algorithms using subjects to the subject of the subject of the subjects of the subjects of the subjects of the subjects of the **2** inversitive reverse-engineer consister to a distortion to a distortion by uncorrelated socialists radiation. and picture and picture and add noise to this picture and add noise to the jet-mass-based algorithms using subjection  $\mathcal{L}$  $\rightarrow$  Need methods to separate final state radiation (FSR) from rest of event

re raidie of complete firms for a color factors for gluon (quark) in the color for very hard jets the color of  $\mu$ ⌦ *m*<sup>2</sup> *j*  $\ddot{\phantom{1}}$  *C<sup>i</sup>* ↵*<sup>s</sup> p*<sup>2</sup> *T ,j R*<sup>2</sup> School on the Future of Collider Physics IPMU 25 Michael Spannowsky 16.07.2013 *j*PMU 25 Michael Spannowsky where *C*<sup>*i*</sup>  $\sim$  16.07.2013

### Jets are collimated sprays of hadrons *p*<sup>1</sup> + *p*<sup>2</sup> (155)  $\overline{z}$ *Jets are collimated sprays of nadrons <u>O</u>* Tets are collimated sprays of hadrons cos 2✓e↵ = 1 (151)





 $\mathsf{soft}$  and collinear region due to  $\sim \, 1/(p_1 + p_2)$  $2<sub>5</sub>$ Probability enhanced in soft and collinear region due to  $\sim$  $\overline{\phantom{a}}$  $p$  oft and collinear region due to  $\sim 1/(p_1+p_2)^2$ robability enhanced in soft and collinear regior bability enhanced in soft and collinear regic

- If  $p_1 \to 0$ , then  $1/(p_1 + p_2)^2 \to \infty$ 1*/*(*p*<sup>1</sup> + *p*2) *p*<sup>1</sup> ! 0 (160)
- 1*/*(*p*<sup>1</sup> + *p*2) • If  $p_2 \to 0$  , then  $1/(p_1 + p_2)^2 \to \infty$  For 1*/*(*p*<sup>1</sup> + *p*2)  $p_2 \rightarrow 0$  , then  $1/(p_1+p_2)^2 \rightarrow \infty$  . Bri *p*<sup>1</sup> ! 0 (160) *p*<sub>2</sub>  $\sim$  0, men  $1/(p_1 + p_2) \rightarrow \infty$  **b**
- $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $p_2$  |  $\rightarrow \infty$ *p*<sub>1</sub> 2  $\frac{1}{2}$ • If  $p_2 \to \lambda p_1$ , then  $1/(p_1 + p_2)^2 \to \infty$  $f(p_2 \to \lambda p_1)$ , then  $1/(p_1 + p_2)^2 \to \infty$  $p_2 \rightarrow \lambda p_1$  , then  $1/(p_1+p_2)^2 \rightarrow \infty$

For more detail see also talk by talk by *p*<sub>1</sub>  $\frac{1}{2}$  **p**<sub>1</sub>  $\frac{1}{2}$  $\mathcal{P}^{(P1 + P2)}$   $\sim$   $\mathcal{P}$  Brian, CP or Dave Soper at summer school  $2 \rightarrow \infty$  1 or more detail see also fair by<br>Brian, CP or Dave Soper at CTEQ summer school

IR safe definition of jets: *R*em = ets: *i*:  $\frac{1}{2}$  $\overline{Y}$ 

Observables must be insensitive to modification of final state with respect to soft and/or collinear splitting nsitive to *Observables must be insensitive to modification of final state i* in respect to so ft and/or collinear splitting

Seeded cone algorithms are infrared unsafe! Example: Take the hardest constituent of event as seed for jet cone ~ *p/<sup>T</sup>* = X*p* ~*<sup>T</sup>* (observed) (229) Seeded cone algorithms are infrared unsafe! as seed tor  $T \cup T$  (*T*  $T \cup T$ *p*<sub>2</sub> (231) *p*<sup>2</sup> (231) *p*<sup>2</sup> (231) **p**<sup>2</sup> (231)

Assume 3 constituents in event with cone size R=0.5



• Sequential recombination, e.g. inclusive kT algorithm [Catani, Doksh S.D. Elli)<br>Carombination e σ inclusive kT algorithm ab  $\frac{1}{2}$ ES.D. Ellis & Soper, '93]<br>Francisco de Talgorithm  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani, <sup>F</sup> )fb/P (x2, µ<sup>2</sup> *iB* (171) diB = p<sup>2</sup> T i (167)  $\overline{c}$ The second of the second sex in the second ion, e.g. inclusive kT algorithm [Catani, Doks] • Sequential recombination, e.g. inclusive kT  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (16 *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* )  $R$  Soper '931  $\mathsf{R}^2$  (27) [S.D. Ellis & Soper, '93] [Catani, Dokshitzer, Seymour Webber '93]

$$
_{i},p_{Tj}^{2})\frac{\Delta R_{ij}^{2}}{R^{2}} \qquad \Delta R_{ij}^{2} = (y_{i} - y_{j})^{2} + (\phi_{i} - \phi_{j})^{2}
$$

**Distance** 
$$
d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) \frac{\Delta R_{ij}^2}{R^2}
$$
  $\Delta R_{ij}^2 = (y_i - y_j)$    
measure 
$$
d_{iB} = p_{Ti}^2
$$

 $R^2$  (i)  $R^2$  (i)

 $\epsilon$ achi (1711). The particles it is

if i i recombine them

 $ij$  recombine them  $ij$ 

 $\frac{d}{dt}$  and  $\frac{d}{dt}$  (i.e.  $\frac{d}{dt}$  ) and  $\frac{d}{dt}$  (i.e.

$a_iB - PT_i$
1. Find smallest of $d_{ij} d_{iB}$
2. if $ij$ recombine them
3. if $iB$ call $i$ a jet and remove from list of particles
4. repeat from 1. until no particles left

*iB* (171)

 $d = \Delta R_{ij}^2$  ,  $d_{ip} = 1$ 

*T i , p*<sup>2</sup>

 $p_{Ti}^{-2}$ 

Minimum distance between jets is R

4. repeat from 1. until no particles left

1. Find smallest of  $d_{ij}$  d

2. if  $ij$  recombine them

Only number of jets above pt cut is IR safe  $\frac{1}{2}$  above pt  $\frac{1}{2}$  $\frac{1}{\pi}$  is a hours of *max* (175) *pT* , *m*in

P

 $\frac{d}{dt}$ 

Cambridge/Aachen alg. - distance measure:

anti-kT alg. - distance measure:

$$
\begin{array}{ll}\n\text{measure:} & d_{ij} = \frac{\Delta R_{ij}}{R^2} & d_{iB} = 1 \\
d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2} & d_{iB} = p_{Ti}^{-2}\n\end{array}
$$

 $\frac{-2}{Ti}$ 

 $\overline{2}$ 

mbination, e.g. inclusive k1 algorithm [Catani, Doksh S.D. Elli)<br>Carombination e σ inclusive kT algorithm ab  $\frac{1}{2}$ ES.D. Ellis & Soper, '93]<br>Francisco de Talgorithm  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani, <sup>F</sup> )fb/P (x2, µ<sup>2</sup> *iB* (171) diB = p<sup>2</sup> T i (167)  $\overline{c}$ The second of the second sex in the second ion, e.g. inclusive kT algorithm [Catani, Doks] • Sequential recombination, e.g. inclusive kT algorithm  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (16 *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* )  $R$  Soper '931  $\mathsf{R}^2$  (27) [S.D. Ellis & Soper, '93] [Catani, Dokshitzer, Seymour Webber '93]

$$
_{i},p_{Tj}^{2})\frac{\Delta R_{ij}^{2}}{R^{2}} \qquad \Delta R_{ij}^{2} = (y_{i} - y_{j})^{2} + (\phi_{i} - \phi_{j})^{2}
$$

*iB* (171)

 $\Delta R_{ij}^2$  , p<sub>176</sub>

 $\Delta R_{ii}^2$ 

**Distance** <u>⇒Beance</u><br>measure ance

$$
\begin{array}{ll}\n\text{Distance} & d_{ij} = \min(p_{Ti}^2, p_{Ti}^2) \frac{\Delta R_{ij}^2}{R^2} & \Delta R_{ij}^2 = (y_i - y_j)^2 + (q_i - q_i) \Delta R_{ij}^2 \\
& d_{iB} = p_{Ti}^2 & \Delta R_{ij}^2 = (q_i - q_j)^2 + (q_i - q_i) \Delta R_{ij}^2\n\end{array}
$$

 $\mathbf{R}$  ( $\mathbf{R}$ ) and smallest of  $d$  :  $d$  :  $\mathbf{R}$ 

 $\epsilon$ achi (1711). The particles it is

 $\frac{d}{dt}$  is the internal order to  $\frac{d}{dt}$  and  $\frac{d}{dt}$  is the  $\frac{d}{dt}$ 

 $ij$  recombine them  $ij$ 

3. if *iB* call i a jet and remove from list of particles  $\frac{1}{2}$  $\frac{d}{dt}$  $\mathcal{L}$  $\overline{\phantom{a}}$ ∆R<sup>2</sup> ij <sup>R</sup><sup>2</sup> (166)  $\bigcup$  $\overline{X}$  $\Delta$ <sup>R</sup><sup>2</sup> (169)  $d_{iB}$  and  $\sqrt{1/2}$ *ij* (172) *Tmin* (173) *Rmin* (174) *max* (175)

Minimum distance between jets is R

4. repeat from 1. until no particles left

1. Find smallest of  $d_{ij}$  d

2. if  $ij$  recombine them

Only number of jets above pt cut is IR safe  $\frac{1}{2}$  above pt  $\frac{1}{2}$  $\frac{1}{\pi}$  is a hours of *max* (175) *pT* , *m*in

Cambridge/Aachen alg. - distance measure:

anti-kT alg. - distance measure:

$$
\begin{aligned}\n\text{sure:} \qquad d_{ij} &= \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = 1 \\
&= \min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{Ti}^{-2}\n\end{aligned}
$$

 $\frac{-2}{Ti}$ 

 $p_{Ti}^{-2}$ 

 $d_{ij}$ 

mbination, e.g. inclusive k1 algorithm [Catani, Doksh S.D. Elli)<br>Carombination e σ inclusive kT algorithm  $d = \min(n$ ab  $\frac{1}{2}$ ES.D. Ellis & Soper, '93]<br>Francisco de Talgorithm  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani, <sup>F</sup> )fb/P (x2, µ<sup>2</sup> *iB* (171) diB = p<sup>2</sup> T i (167)  $\overline{c}$ The second of the second sex in the second ion, e.g. inclusive kT algorithm [Catani, Doks]  $d_{\text{max}} = \min(n_{\text{max}}^2, n_{\text{max}}^2) \frac{\Delta R_{ij}^2}{\Delta k_{ij}}$ • Sequential recombination, e.g. inclusive kT algorithm  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $\Delta D^2$ *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* )  $R$  Soper '931  $\mathsf{R}^2$  (27) [S.D. Ellis & Soper, '93] [Catani, Dokshitzer, Seymour Webber '93]

 $\mathbf{a}$ 

 $\overline{a}$  +  $\overline{a}$  +

 $\frac{2}{T}i$ 

R2 (169)

$$
_{i},p_{Tj}^{2})\frac{\Delta R_{ij}^{2}}{R^{2}} \qquad \Delta R_{ij}^{2} = (y_{i} - y_{j})^{2} + (\phi_{i} - \phi_{j})^{2}
$$

**Distance** <u>⇒Beance</u><br>measure  $\frac{1}{2}$  are  $\frac{1}{2}$  and  $\frac{1}{2}$  if  $\frac{1}{2}$  i ance are  $d_{\text{in}} = n^2$ 

1. Find smallest of $d_{ij}$ $d_{iB}$
2. if <i>ij</i> recombine them
3. if <i>iB</i> call <i>i</i> a jet and remove from list of particles
4. repeat from 1. until no particles left

 $d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)$ 

 $^{\prime}$ 

 $-\rho_{Ti}$ 

 $\frac{d}{dt}$  and  $\frac{d}{dt}$  (i.e.  $\frac{d}{dt}$  ) and  $\frac{d}{dt}$  (i.e.

 $d_{iB}=p_{T}^{2}$ 

 $i = \frac{1}{2}$ 

ab

Minimum distance between jets is R

Only number of jets above pt cut is IR safe  $\frac{1}{2}$  above pt  $\frac{1}{2}$  $\frac{1}{\pi}$  is a hours of *max* (175) *pT* , *m*in

 $\overline{\phantom{a}}$ 

∆R<sup>2</sup>

ij

 $\Delta$ 

 $\Delta R_{ij}^2$   $\qquad$  1

 $\frac{1}{\sqrt{1}}$ 

*iB* (171)

*p<sup>T</sup> < p*parton

Cambridge/Aachen alg. - distance measure:

anti-kT alg. - distance measure:

$$
\begin{aligned}\n\text{sure:} \qquad d_{ij} &= \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = 1 \\
&= \min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{Ti}^{-2}\n\end{aligned}
$$

 $d_{ij}$ 

 $p_{Ti}^{-2}$ 

<sup>R</sup><sup>2</sup> (166)

*Tmin* (173)

*Rmin* (174)

*max* (175)

 $\frac{-2}{Ti}$ 

mbination, e.g. inclusive k1 algorithm [Catani, Doksh S.D. Elli)<br>Carombination e σ inclusive kT algorithm  $d = \min(n$ ab  $\frac{1}{2}$ ES.D. Ellis & Soper, '93]<br>Francisco de Talgorithm  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani, <sup>F</sup> )fb/P (x2, µ<sup>2</sup> *iB* (171) diB = p<sup>2</sup> T i (167)  $\overline{c}$ The second of the second sex in the second ion, e.g. inclusive kT algorithm [Catani, Doks] • Sequential recombination, e.g. inclusive kT algorithm  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $\Delta D^2$ *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* )  $R$  Soper '931  $\mathsf{R}^2$  (27) [S.D. Ellis & Soper, '93] [Catani, Dokshitzer, Seymour Webber '93]

 $\mathbf{a}$ 

 $\overline{a}$  +  $\overline{a}$  +

 $\frac{2}{T}i$ 

$$
_{i},p_{Tj}^{2})\frac{\Delta R_{ij}^{2}}{R^{2}} \qquad \Delta R_{ij}^{2} = (y_{i} - y_{j})^{2} + (\phi_{i} - \phi_{j})^{2}
$$

**Distance** <u>⇒Beance</u><br>measure  $\frac{1}{2}$  are  $\frac{1}{2}$  and  $\frac{1}{2}$  if  $\frac{1}{2}$  i ance are  $d_{\text{in}} = n^2$ 

$u_iB - PT_i$
1. Find smallest of $d_{ij}$ $d_{iB}$
2. if $ij$ recombine them
3. if $iB$ call $i$ a jet and remove from list of particles
4. repeat from 1. until no particles left

 $d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)$ 

 $d_{\text{max}} = \min(n_{\text{max}}^2, n_{\text{max}}^2) \frac{\Delta R_{ij}^2}{\Delta k_{ij}}$ 

 $^{\prime}$ 

 $d_{iB}=p_{T}^{2}$ 

 $i = \frac{1}{2}$ 

Only number of jets above pt cut is IR safe  $\frac{1}{2}$  above pt  $\frac{1}{2}$  $\frac{1}{\pi}$  is a hours of *max* (175) *pT* , *m*in

 $\mathcal{L}$ 

 $\overline{\phantom{a}}$ 

 $\sim$  17

∆R<sup>2</sup>

ij

 $\Delta$ 

 $\Delta R_{ij}^2$   $\qquad$  1

 $\sqrt{2}$ 

*p<sup>T</sup> < p*parton

Cambridge/Aachen alg. - distance measure:

anti-kT alg. - distance measure:

Minimum distance between

jets is R

$$
a \text{sure:} \qquad d_{ij} = \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = 1
$$
\n
$$
= \min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{Ti}^{-2}
$$

 $d_{ij}$ 

 $p_{Ti}^{-2}$ 

<sup>R</sup><sup>2</sup> (166)

*Tmin* (173)

*Rmin* (174)

*max* (175)

 $\frac{-2}{Ti}$ 

mbination, e.g. inclusive k1 algorithm [Catani, Doksh S.D. Elli)<br>Carombination e σ inclusive kT algorithm ab  $\frac{1}{2}$ ES.D. Ellis & Soper, '93]<br>Francisco de Talgorithm  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani, <sup>F</sup> )fb/P (x2, µ<sup>2</sup> *iB* (171) diB = p<sup>2</sup> T i (167)  $\overline{c}$ The second of the second sex in the second ion, e.g. inclusive kT algorithm [Catani, Doks] • Sequential recombination, e.g. inclusive kT algorithm  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (16 *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* )  $R$  Soper '931  $\frac{1}{\sqrt{2}}$  $\mathsf{R}^2$  (27) [S.D. Ellis & Soper, '93] [Catani, Dokshitzer, Seymour Webber '93]

**Distance**  
\n
$$
d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) \frac{\Delta R_{ij}^2}{R^2}
$$
\n
$$
\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2
$$
\n
$$
d_{iB} = p_{Ti}^2
$$

1. Find smallest of $d_{ij}$ $d_{iB}$
2. if $ij$ recombine them
3. if $iB$ call $i$ a jet and remove from list of particles
4. repeat from 1. until no particles left

Minimum distance between jets is R

Only number of jets above pt cut is IR safe  $\frac{1}{2}$  above pt  $\frac{1}{2}$  $\frac{1}{\pi}$  is a hours of *max* (175) *pT* , *m*in

 $\overline{\phantom{a}}$ 

∆R<sup>2</sup>

ij

 $\Delta$ 

 $\Delta R_{ij}^2$   $\qquad$  1

*diB* = 1 (170)

*iB* (171)

*p<sup>T</sup> < p*parton

 $\mathcal{F}$ 

Cambridge/Aachen alg. - distance measure:

anti-kT alg. - distance measure:

$$
\begin{array}{ll}\n\text{measure:} & d_{ij} = \frac{\Delta R_{ij}^2}{R^2} & d_{iB} = 1 \\
d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2} & d_{iB} = p_{Ti}^{-2}\n\end{array}
$$

 $\mathcal{F}$ 

 $\mathcal{P}$ 

*Tmin* (173)

*Rmin* (174)

 $\overline{2}$ 

*max* (175)

 $\frac{-2}{Ti}$ 

mbination, e.g. inclusive k1 algorithm [Catani, Doksh S.D. Elli)<br>Carombination e σ inclusive kT algorithm  $\mathsf{R}^2$  (27) [Catani, Dokshitzer,<br>Sexmanual *Ala*kkan 2021 ab  $\frac{1}{2}$ ES.D. Ellis & Soper, '93]<br>Francisco de Talgorithm  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani,  $\overline{c}$ The second of the second sex in the second ion, e.g. inclusive kT algorithm [Catani, Doks] • Sequential recombination, e.g. inclusive kT algorithm  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (16 *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* )  $R$  Soper '931  $\frac{1}{\sqrt{2}}$ [S.D. Ellis & Soper, '93] Seymour Webber '93]

 $\Omega$ 

**Distance**  
\n
$$
d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) \frac{\Delta R_{ij}^2}{R^2}
$$
\n
$$
\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2
$$
\n
$$
d_{iB} = p_{Ti}^2
$$

\n- 1. Find smallest of 
$$
d_{ij} d_{i}
$$
\n- 2. if *ij* recombine them
\n- 3. if *i* B call *i* a jet and remove from list of particles
\n- 4. repeat from I. until no particles left
\n

Minimum distance between jets is R

Only number of jets above pt cut is IR safe  $\frac{1}{2}$  above pt  $\frac{1}{2}$  $\frac{1}{\pi}$  is a hours of *max* (175) *pT* , *m*in

 $\overline{\phantom{a}}$ 

∆R<sup>2</sup>

ij

 $\Delta$ 

 $\Delta R_{ij}^2$   $\qquad$  1

*diB* = 1 (170)

*iB* (171)

*p<sup>T</sup> < p*parton

Cambridge/Aachen alg. - distance measure:

anti-kT alg. - distance measure:

$$
\begin{array}{ll}\n\text{measure:} & d_{ij} = \frac{\Delta R_{ij}^2}{R^2} & d_{iB} = 1 \\
d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2} & d_{iB} = p_{Ti}^{-2}\n\end{array}
$$

 $\overline{2}$ 

*Tmin* (173)

*max* (175)

 $\frac{-2}{Ti}$ 

 $\mathcal{F}$ 

 $\mathcal{P}$ 

mbination, e.g. inclusive k1 algorithm [Catani, Doksh S.D. Elli)<br>Carombination e σ inclusive kT algorithm ab  $\frac{1}{2}$ ES.D. Ellis & Soper, '93]<br>Francisco de Talgorithm  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani, <sup>F</sup> )fb/P (x2, µ<sup>2</sup> *iB* (171) diB = p<sup>2</sup> T i (167)  $\overline{c}$ The second of the second sex in the second ion, e.g. inclusive kT algorithm [Catani, Doks] • Sequential recombination, e.g. inclusive kT algorithm  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (16 *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* )  $R$  Soper '931  $\frac{1}{\sqrt{2}}$  $\mathsf{R}^2$  (27) [S.D. Ellis & Soper, '93] [Catani, Dokshitzer, Seymour Webber '93]

**Distance**  
\n
$$
d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) \frac{\Delta R_{ij}^2}{R^2}
$$
\n
$$
\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2
$$
\n
$$
d_{iB} = p_{Ti}^2
$$

1. Find smallest of  $d_{ij}$  d 2. if  $ij$  recombine them 3. if *iB* call i a jet and remove from list of particles 4. repeat from 1. until no particles left limit  $\sim$   $/$  $\frac{d}{dt}$ <sup>R</sup><sup>2</sup> (169)  $d_{iB}$  $R^2$  (i)  $R^2$  (i) if i i recombine them  $\epsilon$ achi (1711). The particles it is  $ij$  recombine them  $ij$ 

Minimum distance between jets is R

Only number of jets above pt cut is IR safe  $\frac{1}{2}$  above pt  $\frac{1}{2}$  $\frac{1}{\pi}$  is a hours of *max* (175) *pT* , *m*in

 $\mathcal{L}$ 

 $\overline{\phantom{a}}$ 

 $\sqrt{2}$ 

∆R<sup>2</sup>

ij

 $\Delta$ 

*Tmin* (173)

*diB* = 1 (170)

*iB* (171)

*p<sup>T</sup> < p*parton

*ij* (172)

Cambridge/Aachen alg. - distance meas

anti-kT alg. - distance measure:

**sure:** 
$$
d_{ij} = \frac{\Delta R_{ij}^2}{R^2}
$$
  $d_{iB} = 1$   
=  $\min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2}$   $d_{iB} = p_{Ti}^{-2}$ 

 $d_{ij}$ 

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*T i , p*<sup>2</sup>

 $\mathcal{F}$ 

 $\mathcal{P}$ 

*Tmin* (173)

 $\overline{2}$ 

*max* (175)

 $\frac{-2}{Ti}$ 

mbination, e.g. inclusive k1 algorithm [Catani, Doksh S.D. Elli)<br>Carombination e σ inclusive kT algorithm ab  $\frac{1}{2}$ [S.D. Ellis & Soper, '93]<br>thm\_I*Ceten*: Delshitzen  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani, <sup>F</sup> )fb/P (x2, µ<sup>2</sup> *iB* (171) diB = p<sup>2</sup> T i (167)  $\overline{c}$ S.D. Ellis & S.<br>Lusive kT algorithm Freess: Dele The second of the second sex in the second ion, e.g. inclusive kT algorithm [Catani, Doks] • Sequential recombination, e.g. inclusive kT algorithm  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (16 *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* )  $R$  Soper '931  $\frac{1}{\sqrt{2}}$  $\mathsf{R}^2$  (27) [S.D. Ellis & Soper, '93] [Catani, Dokshitzer, Seymour Webber '93]

**Distance**  
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d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) \frac{\Delta R_{ij}^2}{R^2}
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\n
$$
\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2
$$
\nmeasure\n
$$
d_{iB} = p_{Ti}^2
$$

\n- 1. Find smallest of 
$$
d_{ij} \, d_{i}
$$
\n- 2. if  $ij$  recombine them
\n- 3. if  $i$  call  $i$  a jet and remove from list of particles
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\n

Minimum distance between jets is R

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 $\mathcal{L}$ 

 $\overline{\phantom{a}}$ 

die min $\sqrt{2}$ 

∆R<sup>2</sup>

ij

 $\Delta$ 

 $\Delta R_{ij}^2$   $\qquad$  1

*Tmin* (173)

*diB* = 1 (170)

*iB* (171)

*p<sup>T</sup> < p*parton

Cambridge/Aachen alg. - distance measure:

anti-kT alg. - distance measure:

$$
\begin{array}{ll}\n\text{measure:} & d_{ij} = \frac{\Delta R_{ij}^2}{R^2} & d_{iB} = 1 \\
d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2} & d_{iB} = p_{Ti}^{-2}\n\end{array}
$$

 $\mathcal{F}$ 

 $\mathcal{P}$ 

*Tmin* (173)

 $\overline{2}$ 

*max* (175)

 $\frac{-2}{Ti}$ 

mbination, e.g. inclusive k1 algorithm [Catani, Doksh S.D. Elli)<br>Carombination e σ inclusive kT algorithm ab  $\frac{1}{2}$ [S.D. Ellis & Soper, '93]<br>thm\_I*Ceten*: Delshitzen  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani, <sup>F</sup> )fb/P (x2, µ<sup>2</sup> *iB* (171) diB = p<sup>2</sup> T i (167)  $\overline{c}$ S.D. Ellis & S.<br>Lusive kT algorithm Freess: Dele The second of the second sex in the second ion, e.g. inclusive kT algorithm [Catani, Doks] • Sequential recombination, e.g. inclusive kT algorithm  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (16 *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* )  $R$  Soper '931  $\frac{1}{\sqrt{2}}$  $\mathsf{R}^2$  (27) [S.D. Ellis & Soper, '93] [Catani, Dokshitzer, Seymour Webber '93]

 $\Omega$ 

**Distance**  
\n
$$
d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) \frac{\Delta R_{ij}^2}{R^2}
$$
\n
$$
\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2
$$
\nmeasure\n
$$
d_{iB} = p_{Ti}^2
$$

\n- 1. Find smallest of 
$$
d_{ij} \, d_{i}
$$
\n- 2. if  $ij$  recombine them
\n- 3. if  $i$  call  $i$  a jet and remove from list of particles
\n- 4. repeat from 1. until no particles left
\n

Minimum distance between jets is R

Only number of jets above pt cut is IR safe  $\frac{1}{2}$  above pt  $\frac{1}{2}$  $\frac{1}{\pi}$  is a hours of *max* (175) *pT* , *m*in

 $\mathcal{L}$ 

 $\overline{\phantom{a}}$ 

die min $\sqrt{2}$ 

∆R<sup>2</sup>

ij

 $\Delta$ 

 $\Delta R_{ij}^2$   $\qquad$  1

*Tmin* (173)

*diB* = 1 (170)

*iB* (171)

*p<sup>T</sup> < p*parton

Cambridge/Aachen alg. - distance measure:

anti-kT alg. - distance measure:

$$
\begin{array}{ll}\n\text{measure:} & d_{ij} = \frac{\Delta R_{ij}^2}{R^2} & d_{iB} = 1 \\
d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2} & d_{iB} = p_{Ti}^{-2}\n\end{array}
$$

 $\mathcal{F}$ 

 $\mathcal{P}$ 

*Tmin* (173)

 $\overline{2}$ 

*max* (175)

 $\frac{-2}{Ti}$
mbination, e.g. inclusive k1 algorithm [Catani, Doksh S.D. Elli)<br>Carombination e σ inclusive kT algorithm ab  $\frac{1}{2}$ ES.D. Ellis & Soper, '93]<br>Francisco de Talgorithm  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani, <sup>F</sup> )fb/P (x2, µ<sup>2</sup> *iB* (171) diB = p<sup>2</sup> T i (167)  $\overline{c}$ The second of the second sex in the second ion, e.g. inclusive kT algorithm [Catani, Doks] • Sequential recombination, e.g. inclusive kT algorithm  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (16 *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* )  $R$  Soper '931  $\frac{1}{\sqrt{2}}$  $\mathsf{R}^2$  (27) [S.D. Ellis & Soper, '93] [Catani, Dokshitzer, Seymour Webber '93]

$$
\begin{array}{ll}\n\text{Distance} & d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) \frac{\Delta R_{ij}^2}{R^2} \\
\text{measure} & d_{iB} = p_{Ti}^2\n\end{array}\n\qquad\n\begin{array}{ll}\n\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2\n\end{array}
$$

1. Find smallest of  $d_{ij}$  d 2. if  $ij$  recombine them 3. if  $iB$  call i a jet and remove from list of particles 4. repeat from 1. until no particles left  $\frac{1}{2}$  $\frac{d}{dt}$ <sup>R</sup><sup>2</sup> (169)  $d_{iB}$  $R^2$  (i)  $R^2$  (i) if i i recombine them  $\epsilon$ at fibrili i. unun no particies ieit  $ij$  recombine them  $ij$ *ij* (172)

Minimum distance between jets is R

Only number of jets above pt cut is IR safe  $\frac{1}{2}$  above pt  $\frac{1}{2}$  $\frac{1}{\pi}$  is a hours of *max* (175) *pT* , *m*in

 $\frac{1}{2}$ 

 $\sqrt{ }$ 

die min $\sqrt{2}$ 

∆R<sup>2</sup>

*diB* = 1 (170)

*iB* (171)

*p<sup>T</sup> < p*parton

*Tmin* (173)

 $\Delta R_{ij}^2$   $\qquad$  1

Cambridge/Aachen alg. - distance measure:

anti-kT alg. - distance measure:

$$
\begin{array}{ll}\n\text{measure:} & d_{ij} = \frac{\Delta R_{ij}^2}{R^2} & d_{iB} = 1 \\
d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2} & d_{iB} = p_{Ti}^{-2}\n\end{array}
$$

 $\mathcal{F}$ 

 $\mathcal{P}$ 

*Tmin* (173)

 $\overline{2}$ 

 $\frac{-2}{Ti}$ 

- mbination, e.g. inclusive k1 algorithm [Catani, Doksh  $d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)$  $\Delta R_{ij}^2$  $\frac{y_j}{R^2}$   $\Delta n_{ij} = (y_i - y_j) + (\varphi)$ S.D. Elli)<br>Carombination e σ inclusive kT algorithm  $\frac{\Delta R_{ij}^2}{\Delta R_{ij}^2} \hspace{1.5cm} \Delta R_{ij}^2 = (y_i - y_j)$  $d_{iB}=p_{T}^{2}$  $\frac{2}{T}i$ **Distance** <u>⇒Beance</u><br>measure ab  $\frac{1}{2}$ ES.D. Ellis & Soper, '93]<br>Francisco de Talgorithm  $^{\prime}$  $\mathbf{a}$  $\mathcal{F}$  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani, <sup>F</sup> )fb/P (x2, µ<sup>2</sup> *iB* (171) diB = p<sup>2</sup> T i (167)  $\overline{c}$  $\mathcal{P}$ The second of the second sex in the second  $\frac{1}{\omega} = x^2$  $\overline{a}$  +  $\overline{a}$  + ion, e.g. inclusive kT algorithm [Catani, Doks]  $d_{\text{max}} = \min(n_{\text{max}}^2, n_{\text{max}}^2) \frac{\Delta R_{ij}^2}{\Delta k_{ij}}$  $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$  $-\rho_{Ti}$ <sup>R</sup><sup>2</sup> (169) • Sequential recombination, e.g. inclusive kT algorithm  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $\frac{1}{2}$  are  $\frac{1}{2}$  and  $\frac{1}{2}$  if  $\frac{1}{2}$  i  $\Delta D^2$ ance are  $d_{\text{in}} = n^2$  $\frac{d}{dt}$  and  $\frac{d}{dt}$  (170)  $\frac{d}{dt}$ *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* ) *diB* = 1 (170) *iB* (171)  $R$  Soper '931  $\frac{1}{\sqrt{2}}$ *p<sup>T</sup> < p*parton *Tmin* (173)  $\mathsf{R}^2$  (27)  $\overline{2}$ [S.D. Ellis & Soper, '93] [Catani, Dokshitzer, Seymour Webber '93]
	- 1. Find smallest of  $d_{ij}$  d 2. if  $ij$  recombine them 3. if *iB* call i a jet and remove from list of particles 4. repeat from 1. until no particles left  $\frac{1}{2}$  $\frac{d}{dt}$ <sup>R</sup><sup>2</sup> (169)  $d_{iB}$  $R^2$  (i)  $R^2$  (i) if i i recombine them  $\epsilon$ at fibrili i. unun no particies ieit  $ij$  recombine them  $ij$ *ij* (172)

Minimum distance between jets is R

Only number of jets above pt cut is IR safe  $\frac{1}{2}$  above pt  $\frac{1}{2}$  $\frac{1}{\pi}$  is a hours of *max* (175) *pT* , *m*in

die min $\sqrt{2}$ 

Cambridge/Aachen alg. - distance measure:  $d_{ij} =$ 

 $\frac{\Delta R_{ij}^2}{R^2}$   $d_{iB} = 1$  $d_{iB} = p_{Ti}^{-2}$  $d_{iB} = 1$  $d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})$ anti-kT alg. - distance measure:  $\quad d_{ij} = \min(p_{Ti}^{-2},p_{Tj}^{-2})\frac{\Delta R_{ij}^2}{R^2} \quad d_{iB} = p_{Ti}^{-2}$  $d_{iB}=p_{Ti}^{-2}$ 

 $\frac{-2}{Ti}$ 

 $\Delta R_{ij}^2$  , 1

 $\Delta R_{ij}^2$  *i* 1

mbination, e.g. inclusive k1 algorithm [Catani, Doksh  $\Delta R^2$ S.D. Elli)<br>Carombination e σ inclusive kT algorithm ab  $\frac{1}{2}$ ES.D. Ellis & Soper, '93]<br>Francisco de Talgorithm  $\ddot{\phantom{0}}$ g. in  $\mathsf{cl}$  $\frac{1}{2}$  digorithiii [Catani, <sup>F</sup> )fb/P (x2, µ<sup>2</sup> *iB* (171) diB = p<sup>2</sup> T i (167)  $\overline{c}$ The second of the second sex in the second ion, e.g. inclusive kT algorithm [Catani, Doks] • Sequential recombination, e.g. inclusive kT algorithm  $T_{\rm eff}$  is the contract of  $\sim 10^{16}$  in  $\sim 10^{16}$  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (168)  $2^{16}$  (16 *R*<sup>2</sup> *ij* = (*y<sup>i</sup> y<sup>j</sup>* )  $R$  Soper '931  $\mathsf{R}^2$  (27) [S.D. Ellis & Soper, '93] [Catani, Dokshitzer, Seymour Webber '93]

**Distance** 
$$
d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) \frac{\Delta R_{ij}^2}{R^2} \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_{ij} - \phi_{ij})^2
$$

$$
\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2
$$

1. Find smallest of  $d_{ij}$  d 2. if  $ij$  recombine them 3. if  $iB$  call i a jet and remove from list of particles  $\overline{a}$ 4. repeat from 1. until no particles left  $\frac{d}{dt}$  $E_{\text{max}}$  $d_{iB}$  $R^2$  (i)  $R^2$  (i) if i i recombine them  $\epsilon$ at fibrili i. unun no particies ieit  $ij$  recombine them  $ij$ 

 $\frac{d}{dt}$  and  $\frac{d}{dt}$  (170)  $\frac{d}{dt}$ 

∆R<sup>2</sup> diB = p<sup>2</sup> Found 4 Jets *Tmin* (173) *Rmin* (174)

 $\Delta R_{ij}^2$  , 1

 $\Delta R_{ij}^2$  *i* 1

Minimum distance between jets is R

Only number of jets above pt cut is IR safe  $\frac{1}{2}$  above pt  $\frac{1}{2}$  $\frac{1}{\pi}$  is a hours of *max* (175) *pT* , *m*in

Cambridge/Aachen alg. - distance measure:  $d_{ij} =$ 

 $\frac{\Delta R_{ij}^2}{R^2}$   $d_{iB} = 1$  $d_{iB} = p_{Ti}^{-2}$  $d_{iB} = 1$  $d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})$ anti-kT alg. - distance measure:  $\quad d_{ij} = \min(p_{Ti}^{-2},p_{Tj}^{-2})\frac{\Delta R_{ij}^2}{R^2} \quad d_{iB} = p_{Ti}^{-2}$  $d_{iB}=p_{Ti}^{-2}$ 

 $\frac{-2}{Ti}$ 

652 Eur. Phys. J. C (2010) 67: 637–686 652 Eur. Phys. J. C (2010) 67: 637–686 652 Eur. Phys. J. C (2010) 67: 637–686 [G. Salam, Towards Jetography]





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# For jet substructure study reverse cluster history and analyze internal structure



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#### Different scenarios based on pT vs mass *Different scenarios based on p1 vs mass* ¯ ' 2 *m<sup>t</sup>* (48)



 $m_{t\bar{t}} > 2 m_t$ b W

 $\ddagger$ 

 $\bar{t} \simeq 2 \ m_t \qquad \qquad m_{t\bar{t}} > 2 \ m_t \qquad \qquad m_{t\bar{t}} \gg 2 \ m_t$ b W  $\ddagger$ 

#### Leptonic top reconstruction in boosted final states *x Justice Construction in Doosted Timel States*

Due to reconstruction of invariant masses in boosted and unboosted case very similar: *a*<br>Mariant masses in boosted and unbor

$$
m_t^2 = (p_b + p_l + p_\nu)^2 \quad \text{ and } \quad m_W^2 = (p_l + p_\nu)^2
$$

ا۱۲<br>Prii *z*pron isot<br>ium *<sup>j</sup>*1*j*<sup>2</sup> (139) *E<sup>i</sup>* = *m*<sup>2</sup> *<sup>i</sup>* + *p* However, for large boost lepton isolation a problem. Define mini-isolation criterium [Rehermann, Tweedie JHEP]

$$
R_{iso}=\frac{15~{\rm GeV}}{p_{T\mu}}\simeq\frac{3m_B}{p_{T\mu}}
$$

momentum [ Plehn, MS, Takeuchi JHEP]  $\cdots$   $\cdots$   $\cdots$ In boosted final states it is even possible to "guess" the full neutrino

 $\hat{p}_{\pmb{\lambda}}^{\perp}$ *<i><i>i*</del>  $\frac{1}{2}$ 2 assumptions:  $\alpha_{\text{D}} p + \alpha_{\parallel} p$  $x_y = 0$  or  $x_y = 0$ or  $\cdot$ ....  $-7$ good top momentum reconstruction  $\overline{b}$ <br> $\overline{b}$ *<sup>Z</sup>* + *m*<sup>2</sup> *h,*SM <sup>4</sup>*m*<sup>2</sup> *<sup>t</sup>* )*, µ*<sup>2</sup> <sup>=</sup> 2*v*<sup>2</sup> (143) School on the Future of Collider Physics IPMU 46 Michael Spannowsky 16.07.2013 *t*  $16.07.2013$ 

### Hadronic top reconstruction: Many approaches



Tagger important to purify final state

-> bridge gab between parton and hadron level

Comparison of taggers in BOOST proceedings:

Taggers compared:

- ‣ ATLAS
- ‣ CMS
- ‣ HEP
- ‣ JH
- ‣ NSubjettiness
- ‣ Pruning-Tagger
- ‣ Thaler/Wang Tagger
- ‣ Trimming-Tagger

Samples used: fully hadronic tt vs dijet events in pT slices of 100 GeV

- ‣ Herwig 6.5
- ‣ Herwig++
- ‣ Sherpa incl. matching

Event selection cuts: anti-kT jets with  $R=1.0$ ,  $pT > 200$  GeV

Efficiency:

# tagged jets  $/$  # jets after selection cuts



# Angular separation of boosted top's decay products in 14 TeV ttbar samples



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[Plehn, Salam, MS, Takeuchi]

I. Find fat jets (C/A, R=1.5, pT>200 GeV)

#### II. Find hard substructure using mass drop criterion ⇧(*pp* ⇤ *t* ⇤ *b* ⌅*ll* <sup>+</sup>) ⌅ <sup>13</sup>*.*2 fb (82)

Undo clustering,  $m_{\mathrm{daughter}_1} < 0.8 \; m_{\mathrm{mother}}$  to keep both daughters



### I. Find fat jets (C/A, R=1.5, pT>200 GeV)

#### II. Find hard substructure using mass drop criterion ⇧(*pp* ⇤ *t* ⇤ *b* ⌅*ll* <sup>+</sup>) ⌅ <sup>13</sup>*.*2 fb (82)

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### I. Find fat jets (C/A, R=1.5, pT>200 GeV)

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I. Find fat jets (C/A, R=1.5, pT>200 GeV)

#### II. Find hard substructure using mass drop criterion ⇧(*pp* ⇤ *t* ⇤ *b* ⌅*ll* <sup>+</sup>) ⌅ <sup>13</sup>*.*2 fb (82)

Undo clustering,  $m_{\mathrm{daughter}_1} < 0.8 \; m_{\mathrm{mother}}$  to keep both daughters

*S/*⇧ III. Apply jet grooming to get top decay  $\sqrt{W^2 + W^2 + W^2}$ candidates



I. Find fat jets (C/A, R=1.5, pT>200 GeV)

#### II. Find hard substructure using mass drop criterion ⇧(*pp* ⇤ *t* ⇤ *b* ⌅*ll* <sup>+</sup>) ⌅ <sup>13</sup>*.*2 fb (82)

Undo clustering,  $m_{\mathrm{daughter}_1} < 0.8 \; m_{\mathrm{mother}}$  to keep both daughters

*S/*⇧ III. Apply jet grooming to get top decay  $\sqrt{W^2 + W^2 + W^2}$ candidates

IV.0 Like JH Tagger take, mtop, mW and W helicity angle

[Kaplan, et al. PRL 101 (2008)]





#### IV.1 - better - check mass ratios IV.I – DETTET – CHECK MASS FATIOS 3. iterate through all pairings of three hard subjets: first, filter them with resolution *R*filter = min(0*.*3*, Rjk/*2). Next, use the five hardest filtered constituents and calculate their jet mass (for less 3. iterate through all pairings of three hard subjets: first, filter them with resolution *R*filter =

Cluster top candidate into 3 subjets  $j_1, j_2, j_3$ assuming *p*<sup>2</sup> *Cluster top candidate into 3 sub*. than filtered constituents use all of them). Finally, select the set of three-subject three-subject pairings with a jet of three-subject three-subject pairings with a jet of three-subject pairings with a jet of three-subj ato into 3 cubjets  $\dot{a}$ ,  $\dot{a}$  is  $\dot{a}$ mass closest to *mt*.



# Top quark momentum reconstruction



# First generation taggers, e.g. Hopkins, CMS, HEP

make use of many properties of the top for reconstruction (top mass, W mass, EW structure of decay)

However, QCD radiation pattern are left mostly aside.



#### One can be more quantitative... *J* ne can be more quantitative...  $a$  uantitative...

use emission prob. from [Soper, MS PRD 87]



pT top 500 GeV, pT gluon 20 GeV



 $pT$  bottom =  $pT$  top / 3

Radiation off bottom quark down

to hadronization scale

angular distribution for radiation off W decay products Newer taggers, e.g. based on the method shower deconstruction, make explicitly use of the fact that the top and its decay products have special QCD radiation profile:

Idea: Reverse engineer CKKW [Catani, Krauss, Kuhn, Webber JHEP]



# Using the top quark to find new physics



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#### The Standard Model after the 4th of July *a* = *m*2 and a manufacture in the set of the

The discovery of a Standard-Model-like scalar resonance marked milestone in increasing understanding of nature. And raises questions: *w* = *m*2<br>*W* = *m*2<br>*W* = *m*2<br>*W* = *max*<br>*W* = *max*<br>*Max*<br>*Milostone j*<br>*j*<sub>2</sub> (140)<sup>*j*</sup>1 (140)<sup>*j*</sup><sub>1</sub> (140)<sup>*j*</sup>



- Up to which scale  $\Lambda$  is SM valid? How to avoid excessive fine-tuning? *m*<sub>2</sub> + *y*<sub>2</sub> + *p*<sub>2</sub>  $\mathsf{s}~\Lambda$  i
- aue to large<br>nty 2) Is Higgs potential stable? No definite answer due to large top mass uncertainty

[Elias-Miro et al, PLB 709]





Elementary scalar:

- naturalness
	- Coleman-Weinberg potential

 $\bullet$  ....

Composite scalar:

• Higgs as Pseudo-Nambu-Goldstone boson

 $\bullet$  ....

# Energetic tops are often the key



- Almost all signal events are boosted, e.g. heavy Z' or KK gluon...
- Background drops faster than signal, e.g. tth, top partner
- Couplings require large momentum (mtt), e.g. Afb, top radius

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<u>ነ</u>0 ፤ the #ut@e>dty  $H \rightarrow WW \rightarrow [vjj]$ <br>
<del>100</del> Total significance  $H \rightarrow WW^{(*)} \rightarrow lvlv$  $\lim_{n \to \infty} \frac{1}{n}$  is  $\lim_{n \to \infty} \frac{1}{n}$  in  $\lim_{n \to \infty}$  denotes the luminosity of 10 fb $^{-1}$ , for  $(n)$  the lower mass range (b) for masses up to  $\lim_{n \to \infty}$  $\mathbf{v} \mathbf{w}^{(*)} \rightarrow \mathbf{v} \mathbf{w}$ !**?e** df Collide School on the Future of Collider Physics IPMU 191111110Sity of TOTO Michael Spannowsky 18.09.2013 Ses up to

 $\bf{Total}$  significance

# Present results by CMS and ATLAS



Both experiments are sensitive at X-times the SM cross section However, tth coupling measurement will be systematics limited. Low S/B will render measurement notoriously difficult with

standard reconstruction techniques.



#### Problems in event reconstruction: Problems in event reconstruction



# Results for tth



- 5 sigma sign. with 100 1/fb
- -Development of Higgs and top tagger for busy final state
	- -Improvement of S/B from 1/9 to 1/2

Can use Z peak to calibrate Higgs-top coupling

tth might be a window to Higgs-top coupling

#### Forward backward asymmetry and anti-top rapidities, from which we derive the form which we derive the forwardand antitop rapidities:  $\mathbf{y}$   $\mathbf{y}$ system longitudinal motion and is simply related to the 1<sub>102</sub>, <u>...</u>

DO and CDE observed anomalously large values of Afb  $t_{\text{min}}$  and  $t_{\text{max}}$  are production and production and production and production and production angles,  $t_{\text{max}}$ 

- DO and CDF observed anomalously large values of Afb<br>asymmetry small NLO effect (~6%) [Kühn, Rodrigo]  $\triangleright$  Charge asymmetry small NLO effect (~6%) [Kühn, Rodrigo] an asymmetry in *y* is identical to the asymmetry in the *N*cos *>*<sup>0</sup> *N*cos *<*<sup>0</sup>  $\zeta$ *b* charge asymmently single inconediction the therm, nowing the  $\frac{1}{2}$ ¯ rest frame.  $($   $\sim$  6%) *N*cos *>*<sup>0</sup> + *N*cos *<*<sup>0</sup>
	-



 $\Omega$  Aft  $(9 + \ell(\text{stat}) + 1(\text{syst}))$  $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$  $\overline{r}$   $\overline{$  $\overline{D}$ D0: Afb = (8 ± 4(stat) ± 1(syst))%

 $CDF:$  (leptonic)  $A_{FB} = 0.21 \pm 0.07(stat) \pm 0.02(bkg-shape)$  $S_{\text{c}} = 0.150 + 0.050$  $\ddotsc$  is not the SM prediction for the  $\ddotsc$ CDF: (semileptonic)  $A_{FB}$  = 0.150  $\pm$  0.050(stat)  $\pm$  0.024(syst)

more pronounced at large invariant mass (> 450 GeV) *A*p¯p =

[Almeida, Sterman, Vogelsang]

$$
A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}
$$

$$
\Delta y = y_t - y_{\bar{t}}
$$



# Models to account for asymmetry



s-channel resonance:

[Frampton, Shu, Wang; Chivukula, Simmons, Yuan; Bai, Hewett, Kaplan, Rizzo]

-gu,d gt to get pos. asymmetry requires flavor non-universal coupling

### t-channel resonance:

[Jung, Murayama, Pierce et al.; Shu, Tait, Wang; Cheung, Keung, Yuan; Barger, Keung, Yu; Shelton, Zurek; Grinstein, Kagan, Trott, Zupan; Ligeti, Schmaltz, Tavares]

requires flavor off-diagonal coupling

Overview: [Gresham, Kim, Zurek]
## We will have to measure asymmetry at the LHC *N*cos *>*<sup>0</sup> + *N*cos *<*<sup>0</sup>  $\overline{1}$



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### Study for charge asymmetry @ LHC Study for charge asymmetry @ LHC  $Study$  for charge a  $\sim$  sample, does sample at

Aquilar Saqvadra Tusto Dubbol l Aguilar-Saavedra, Juste, Rubbo<u>l</u> [Aguilar-Saavedra, Juste, Rubbo]



Event reconstruction: Consider moderately boosted semileptonic tops . Consider inoderately boosted semileptome tops  $\mathsf{S}$  in the invariant mass and velocity in the interval  $\overline{\phantom{a}}$ 

- $\triangleright$  require isolated lepton with pT > 15 GeV,  $y_1 = y_{\text{lep.}}$  top l <sup>=</sup> <sup>y</sup>lep. top  $\epsilon$  require isolated lepton with  $\eta T \times 15$  GeV  $\mu = \mu$  $I = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$ on with p1 > 15 GeV, Y<sub>1</sub> = Y<sub>lep. top</sub>  $\blacktriangleright$  require isolated lepton with pT  $>15$ 
	- ▶ require jet with pT>200 GeV, use HEPTopTagger ↑ require jet with pT>200 GeV, use HEPTopTagger **F** require jet with procoo vev, use fil
	- ▶ demand b-tag in hadronic top  $\frac{1}{2}$  and fraction built a line function built of several function built of several function built of several function  $\frac{1}{2}$



 $\rightarrow$  W+jets negligible 14 Previous literature already includes proposals on this topic. In the so-called forward may suffer from important systematic uncertainties.

[Hewett, Sheldon, MS, Takeuchi, Tait] *N*<br>Thewett, Sheldon,  $s_i$  is defined to usefulness of  $r$  showing the usefulness of requiring a minimum term of requiring a minimum term of  $r$ 

- $\blacktriangleright$   $5\sigma$  for SM after 60 ifb *N*cos *>*<sup>0</sup> + *N*cos *<*<sup>0</sup> 14 TeV:  $\mathbf{g}$ ible it. It iev:  $\mathbf{v}$  such a cut at the actual equipment of such a cut at the actual effect of such a cu significant asymmetry increase with β, showing the usefulness of requiring a minimum tt velocity is it. In Fig. 3 (left) we plot the actual effect of such a cut at the actual effect of such a cut at the at the actual effect of such a cut at the actual effect of such at the actual effect of such a cut at the a
- $\blacktriangleright$   $5\sigma$  for BSM after 2 ifb  $p_{\text{U}}(T)$  integrated as integrated to the differential ones in Fig. 3 are related to the differential ones in Fig. 3 and 2 and 3 are related to the differential ones in Fig. 3 and 3 are related to the differential ones  $p \cdot s \cdot t$  is the integrated asymmetries in Fig. 3 are related to the differential ones in  $\mathcal{I}$

Afwd = School on the Future of Collider Physics IPMU 74 Michael Spannowsky 16.07.2013

### Anomalous top gluon couplings  $A$ nomalous ton aluon countings order 1 Term is the compatible with bounds on contact interactions in the Tevatron and LHC interactions from Te *µ* = 150 GeV*,* tan = 6*.*5 (47) *µ* = 150 GeV*,* tan = 6*.*5 (47)





*m m*<sub>tt</sub> (48) *m*  $\frac{1}{2}$ *mtt* ¯ ' 2 *m<sup>t</sup>* (48) Top-compositeness can induce magnetic moment and radius

g Effect of non-pointlike top structure via of non-pointlike top structure via  $\overline{\mathbf{C}}$ 

$$
\mathcal{L}_R = -g_s \frac{R_t^2}{6} \bar{t} \gamma^\mu \mathcal{G}_{\mu\nu} D^\nu t + \text{h.c.}
$$
\n
$$
\mathcal{L}_\kappa = g_s \frac{\kappa_t}{4m_t} \bar{t} \sigma^{\mu\nu} \mathcal{G}_{\mu\nu} t
$$

gluon-fusion induced top production does  $\frac{1}{10.1}$  and depend on  $R_t$  at leading order gluon-fusion induced top production does *R<sup>t</sup>* (51)

**Fig. 2 production** at Tevatron and Production and 2 Tevatron and 2 Te

Combination of Tevatron, incl. LHC measurement

(−)

## stop reconstruction using all hadronic top quarks

[ Plehn, MS, Takeuchi, Zerwas JHEP 1010]

Strategy:



#### mT2 as an observable to look for stops  $\overline{1}$ mT2 as an obs <u>ervable to Ic</u>  $\overline{1}$ <u>look for stops</u> *m*<sup>2</sup> *<sup>T</sup>* (p*<sup>t</sup>* <u>**SEI VADIE 10 100N 101 SIOPS</u>**</u> <sup>1</sup> ) = *<sup>m</sup>*<sup>2</sup> *<sup>t</sup>* + *m*<sup>2</sup>

Consider the decay: 
$$
\tilde{t} \to \chi_1^0 t
$$

One can express the invariant stop mass squared by: .<br>∴ 000 | 000 | 000<br>| 000 | 000 | 000 | 000 | <sup>1</sup>*t* (383)  $\alpha$  can express External invariant stop mass squared by:

can express the invariant stop mass squared by:  
\n
$$
m_{\tilde{t}}^2 = m_t^2 + m_{\chi_1^0}^2 + 2 \left[ E_T^t E_T^{\chi_1^0} \cosh(\Delta y) - \mathbf{p}_T^t \cdot \mathbf{p}_T^{\chi_1^0} \right]
$$

26 inferred. Thus use transverse mass: *m*<sup>2</sup>  $r$ S $\epsilon$ Of the invisible LSP only the transverse component could be **T**  $\overline{\phantom{a}}$ 

$$
m_T^2(\mathbf{p}_T^t,\mathbf{p}_T^{\chi_1^0};m_{\chi_1^0})=m_t^2+m_{\chi_1^0}^2+2\left(E_T^tE_T^{\chi_1^0}-\mathbf{p}_T^t\cdot\mathbf{p}_T^{\chi_1^0}\right)
$$

where  $m_T^2 \leq m_{\tilde{t}}^2$ 

 $\tilde{t}$   $\implies$  for stop mass (see also W) If  $p^{\chi_1^0}$  known  $m_T$  lower-bound for stop mass (see also W mass measurement)

However, in R-parity conserved SUSY mostly squark-pair production, thus two stops decay. Since only sum of two LSP momenta known, the best one can do<br>is to ovaluate is to evaluate the missing transverse momentum of the two neutralinos is known, the best However, in R-parity conserved SUSY mostly squark-pair<br>needvetien, thus two stans descu has four to intervention  $\mathbf{r}$  of dummy two-vectors  $\mathbf{r}$  $\overline{a}$  and  $\overline{a}$ production, thus two stops decay. only be known with limited precision. In order to make our ignorance of my order to make our ignorance of my  $0.9$ about the two stops assay.<br>Sum of two LSP momenta known, the best one can do under most circumstances, the value of my  $\alpha$ -parity conserved sust mosity squark-pair<br>ius two stops decav red SUSY mostly squark-pair

$$
\min_{\mathbf{q}_T^{(1)} + \mathbf{q}_T^{(2)} = \mathbf{p}_T} \left[ \max \left\{ m_T^2(\mathbf{p}_T^{\mathbf{t}} \quad, \mathbf{q}_T^{(1)}; m_{\chi_1^0}), \ m_T^2(\mathbf{p}_T^{\mathbf{t}} \quad, \mathbf{q}_T^{(2)}; m_{\chi_1^0}) \right\} \right] \le m_T
$$

with the dummy vectors  $\,{\sf q}_{T}^{(1)}\,$  and  $\,{\sf q}_{T}^{(2)}\,$ with the dummy vectors  $\bm{\not} q_T^{(1)}$  and  $\bm{\not} q_T^{(2)}$  $m \nmid \phi^{(1)}$  and  $\phi^{(2)}$ WITH THE GUITTING VECTORS  $\mathcal{H}_T$  and  $\mathcal{H}_T$  $\boldsymbol{q}^{(1)}_T$  and  $\boldsymbol{q}^{(2)}_T$ 

$$
m_{T2}^{2}(\chi) = \min_{\mathbf{q}_{T}^{(1)} + \mathbf{q}_{T}^{(2)} = \mathbf{p}_{T}^{'}}\left[\max\left\{m_{T}^{2}(\mathbf{p}_{T}^{t}, \mathbf{q}_{T}^{(1)}; \chi), m_{T}^{2}(\mathbf{p}_{T}^{t}, \mathbf{q}_{T}^{(2)}; \chi)\right\}\right]
$$
  

$$
\sum_{\sum_{\pi} \in \mathbb{Z}^{(N)}} \max_{\mathbf{M}_{\text{tot}}^{\text{test}} = 98 \text{ GeV}}
$$

under deminion of muz. It nearlamo mo not known replace by  $\chi$  is the matrix of  $\mathbb{R}^{0.4}$ Final definition of mT2. If neutralino mass  $\frac{1}{2}$  in  $\frac{M_{LSP}^{max}-98 \text{ GeV}}{1}$  $\Gamma$  not known replace by  $\chi$ mass parameter', intending it to denote any guess we might have as to the Statistically  $\lambda$  on the framework of the framework of the framework of the set of the set of the set of top  $\frac{1}{2}$ Final definition of mT2. If neutralino mass not known replace by  $\chi$  $\frac{1}{2}$ *mmal definition of mT2. It neutralino mass*  $\frac{3}{5}$  *state*  $\frac{3}{5}$  *state \*  $m \neq 0$   $m \neq 2$   $m \neq 1$   $m \neq 0$ 

 $\overline{\sigma}$  is to denote any guess we might have any guess we might have a to the might have as to the might have as to the might have as to the might have a stress we might have a stress we might have a stress we might have miz is kinematic enapoint variable:  $\textsf{mT2}$  is kinematic endpoint variable:  $\begin{array}{ccc} \textsf{mT2} & \textsf{if} & \textsf{M}_{\text{stop}}=340\,\text{GeV} \end{array}$ *n*tic endnoint variable <sup>1</sup> ) *m<sup>t</sup>*  $\overline{\sigma}$  is certainly not immediately clear, however, that events can always exists can always exists can always exists can always exists consider  $\overline{\sigma}$  $f(x) = \frac{1}{2}$  is killentatic endpoint variable.

$$
m_t + m_{\chi_1^0} \le m_{T2}(m_{\chi_1^0}) \le m_{\tilde{t}}
$$
  

$$
m_t + \chi \le m_{T2}(\chi)
$$
  

$$
\max_{\text{many events}} [m_{T2}(\chi)] = m_t
$$

ents<br>''' '  $\int \cos \theta \cos \theta$  $\frac{1}{2}$  is the camerial order in  $\frac{1}{2}$  variable matrix  $\frac{1}{2}$  variable which is the calculate which is the calculate measurement of  $\frac{1}{2}$ School on the Future of Collider Physics IPMU 78 Michael Spannowsky 16.07.2013  $\alpha$ des  $\alpha$  the the term independent properties which model is a spannows when  $\alpha$ 





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cuts:  $cuts$ : I Plehn MS Takeuchi Zerwas JHFP 1010] events where two decays of the type (1) occur. Note that this minimisation tt LSP= 0 GeV Mtest [ Plehn, MS, Takeuchi, Zerwas JHEP 1010]

 $2 \text{ fat } \text{inter } n_{\text{max}} \leq 200/200 \text{ CaV}$  $\frac{1}{2}$  constraints condition condition, parameters of  $\frac{1}{2}$  $\alpha$  about the two true neutralino momenta. Finally, we must recognise that  $\alpha$  $p_T > 150 \text{ GeV}$  $\frac{1}{c}$  $\frac{1}{2}$  be known with limited precision. In order to make  $\frac{1}{2}$ 2 tagged tops:  $p_T^{\text{ee}} > 200/200$  GeV  $h$  to  $\sigma$  for let to good top.  $\sigma$  vag ion too vagged vop 1  $m_{T2} > 250$  GeV m<sup>2</sup> <sup>T</sup>2(χ) ≡ min  $\left[\max\left\{m_T^2(\mathbf{p}_T^{\mathbf{t}^{(1)}},\pmb{q}_T^{(1)};\chi),~m_T^2(\mathbf{p}_T^{\mathbf{t}^{(2)}},\pmb{q}_T^{(2)};\chi)\right\}\right]$  $\int_{V_0}$   $\int_{V_1}$  $=$  min  $\left[\max_{m} \left\{m_{m}^{2}\right\}\right]$ T2 dM  $\frac{1}{\sqrt{2}}$ 





### $T_{\alpha\alpha\alpha\alpha\alpha}$  is  $mT2$  and  $mdl$  the  $nL$ Tagger + mT2 go well together the unknown parameter χ. Ideally, χ would ideally be set equal to the mass and reconstructed. Finally, after requiring one *b* tag inside the first tagged top we construct *mT*<sup>2</sup> [26]. Assuming

 $\mathcal{S} \mathcal{A} \mathcal{$ 3.0  $5.0$   $\epsilon_0$   $\epsilon_0$   $\epsilon_1$   $\epsilon_2$   $\epsilon_1$   $\epsilon_2$   $\epsilon_1$   $\epsilon_2$   $\epsilon_3$   $\epsilon_3$   $\epsilon_4$   $\epsilon_5$   $\epsilon_6$ 340 - 540 GeV stop:

$$
340 - 540 \text{ GeV stop:} \qquad S/B \sim 1 \qquad S/I
$$

$$
p: \tS/B \sim 1 \tS/\sqrt{B}_{10 \text{ fb}^{-1}} \simeq 6
$$

Moreover, it is clear that from the endpoints of the *mT*<sup>2</sup> distributions we should be able to measure the stop School on the Future of Collider Physics IPMU 82 Michael Spannowsky 16.07.2013

 ${\bf q}_T^{(1)}\!+\!{\bf q}_T^{(2)}\!=\!{\bf p}\!\!\!/_{T}$ 

*mT*<sup>2</sup> *>* 250 GeV *.* (7) tpMU 82 Michael Spannowsky 16.07.2013

*<sup>T</sup>* within *R <* 0*.*3 around the lepton.



# Prospects in top physics for the ILC

- Better precision less noise!
- Likely not to be systematics limited
- Potentially off-shell contributions in  $e^+e^-\rightarrow \bar{t}t$  from heavy resonances
- Improved measurement of all kinds of couplings: anomalous couplings, tth, hh, hbb, ... (need at least 500 GeV)
- Improved direct measurement of mass and width
- Polarized beams can enrich tops of specific polarization
- Study QCD radiation, event shapes, jet substructure

# Summary

- The top quark is the new elephant in the room
- In pre-Higgs times we had the EW scale as target range for new physics (top mass, W and Z, Unitarization). If not  $\sim$  200 GeV say 3 TeV for composite models
	- $\rightarrow$  Now we dont really!
	-
	- $\rightarrow$  Top partner search!



 $\rightarrow$  Last guiding principle: Naturalness (much weaker, prepared to give up, .e.g Split SUSY....)

- Top affects Higgs most and is participating in all interactions
- If Higgs looks SM-like in 3 years from now, its the top to be looked into

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