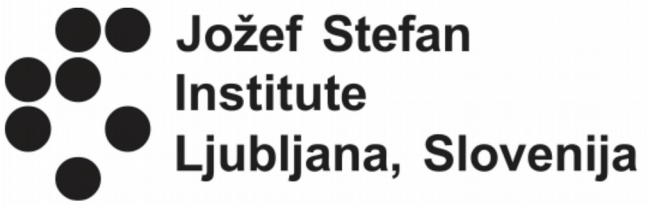
$|V_{tx}|$ mixing (at the LHC)

Darius A. Faroughy



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-- Physics of HL-LHC and perspectives at HE-LHC --

CERN, June 19, 2018

Overview

- Very breaf overview of $|V_{tx}|$ at the LHC.
  (where we stand)

- Measuring $\sqrt{|V_{ts}|^2 + |V_{td}|^2}$ at HL/HE-LHC.

  Light-quark-jet tagger!

  Based on **D.F, Kamenik, Patra, Zupan 1807.XXXXX**

- Improving limits for $|V_{td}|$ at HL-LHC.

  Based on **Alvarez, Da Rold, Estevez, Kamenik 1709.07887**

- Conclusions

Disclaimer: LHC = LHC as a top-factory (ATLAS/CMS)

$|V_{tx}|$ mixing

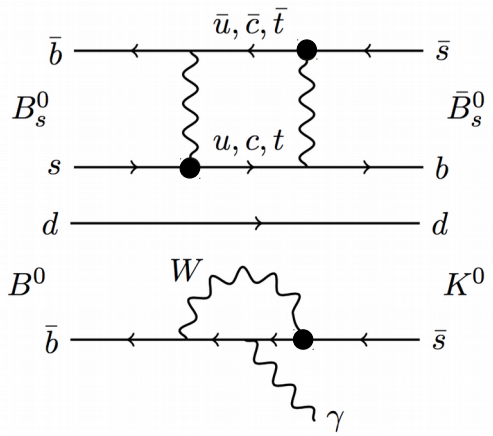
- Global CKM fit:

$$|V_{tb}| = 1 - 8.81^{+0.12}_{-0.24} \times 10^{-3}$$

$$|V_{ts}| = 41.08^{+3.0}_{-5.7} \times 10^{-3}$$

$$|V_{td}| = 8.575^{+0.076}_{-0.098} \times 10^{-3}$$

Charles et al. [1501.05013]



Assumptions:

- 3 x 3 CKM Unitarity

- No New Physics in loops!

- $|V_{tx}|$: indirect determination (loop level) and model dependant!!
- **Top-philic** New Physics could spoil unitarity in 3rd row of CKM.

Alwall et al. [0607115]

e.g. Vector-like top partner T (Q=2/3)

Aguilar-Saavedra et al. [1306.0572]

T mixes with SM right-handed top quark $\sum_{x=d,s,b} |V_{tx}|^2 < 1$

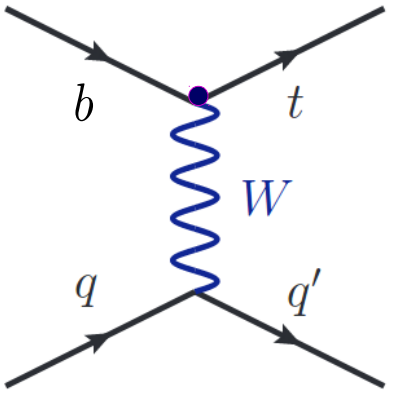
- Important to extract Vtx with a **direct measurment**! and confront unitarity hypothesis.

$$\sum_{x=d,s,b} |V_{tx}|^2 = 1 \ ?$$

$|V_{tx}|$ at LHC

- t-channel Single-top production Alwall et al. [0607115]

$$pp \to tj \qquad \sigma_{tj}^{\rm SM} \propto |V_{tb}|^2$$



- A measurement on $|V_{tb}|$ can be extracted from x-section ATLAS 13 TeV [1609.9920]

$$\boxed{|V_{tb}| = 1.07 \pm 0.09}$$ assuming $|V_{tb}| >> |V_{ts}|, |V_{td}|$

See also Lacker et al. [1202.4694]

- What can the LHC say about $|V_{ts}|, |V_{td}|$?

- Measure top-decay branching ratios

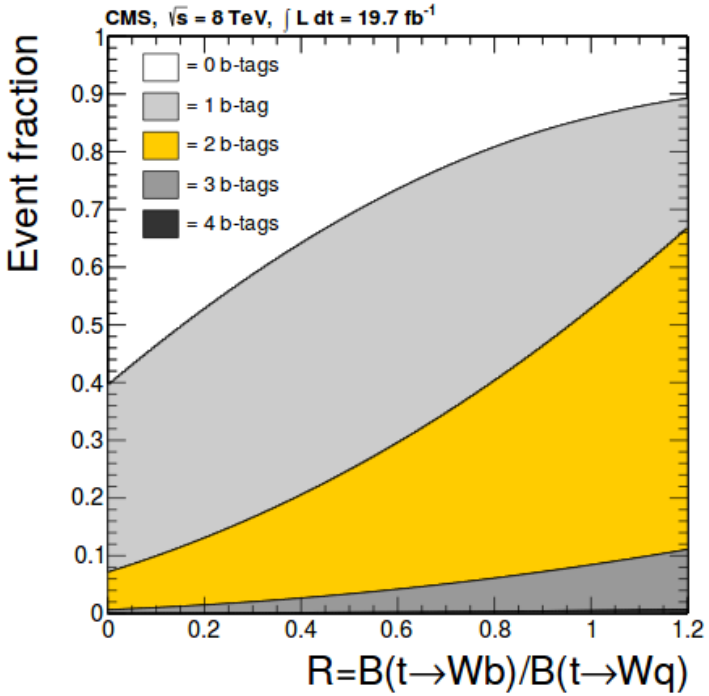
$$\mathcal{B}(t \to bW^{\pm}) \sim 1$$
$$\mathcal{B}(t \to sW^{\pm}) \sim \mathcal{O}(10^{-3})$$
$$\mathcal{B}(t \to dW^{\pm}) \sim \mathcal{O}(10^{-4})$$

- Count fraction of b-jets in top-decays:

  8 TeV CMS [1404.2292]

$$\mathcal{R} = \frac{\mathcal{B}(t \to bW)}{\sum_i \mathcal{B}(t \to d_i W)}$$

$\mathcal{R} > 0.995$ at 95% CL



- $\sqrt{|V_{ts}|^2 + |V_{td}|^2} < 0.217\,|V_{tb}|$

No sign yet of large hierarchy in 3rd row of CKM matrix...

- Soon limited by systematics at the LHC..
  Not much gain from higher-lumi...

New approach is necessary!

$|V_{ts}|^2 + |V_{td}|^2$ at LHC

DF, Kamenik, Patra, Zupan [1807.XXXX]

12.2.7. $|V_{td}|$ ***and*** $|V_{ts}|$ **:** CKM section PDG 2016

The CKM elements $|V_{td}|$ and $|V_{ts}|$ are not likely to be precisely measurable in tree-level processes involving top quarks, so one has to rely on determinations from B–$\overline{B}$ oscillations mediated by box diagrams with top quarks, or loop-mediated rare K and B

- Why not? Strange and Down quark jets are indistinguishable at ATLAS/CMS.

  $K^{\pm} \sim \pi^{\pm}$ since no particle ID

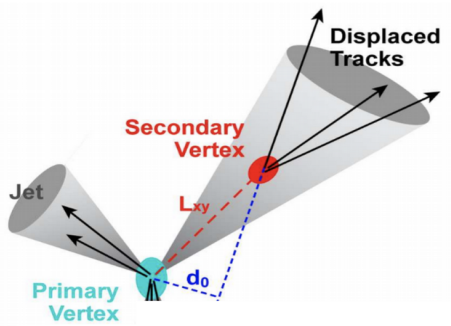
- Can we measure $\sqrt{|V_{ts}|^2 + |V_{td}|^2}$ at the LHC?

- $t \to s(d) W^{\pm}$ vs $t \to b W^{\pm}$

We need a light-quark jet tagger! (u,d,s)

- **Jet-tagging technology:** b-jets, tau-jets, quark/gluon jets, jet substructure techniques, etc...

Light-quark tagging



Rejects b-jets

- Require all tracks in jet to be prompt.

  All tracks in jets: $d_0(\text{track}) < 30\,\mu\text{m}$

  d_0 : Transverse Impact Parameter

- light-quark tagger should be a quark-tagger.

  Rejects gluon jets from ISR/FSR

  Many powerful discriminators in literature...

  Gallicchio, Schwartz [1106.3076]

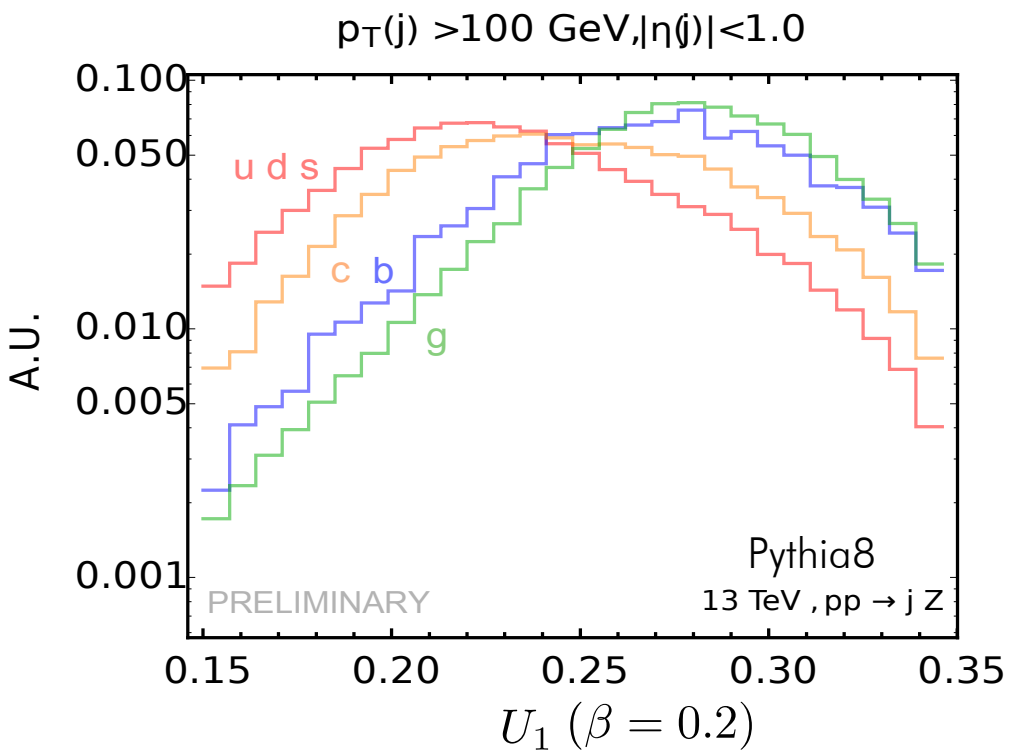
  Larkowski, Salam, Thaler [1305.0007]

  - Multiplicity of (charged) particles in jet.

  - 2-point Energy Correlation Functions (ECF)

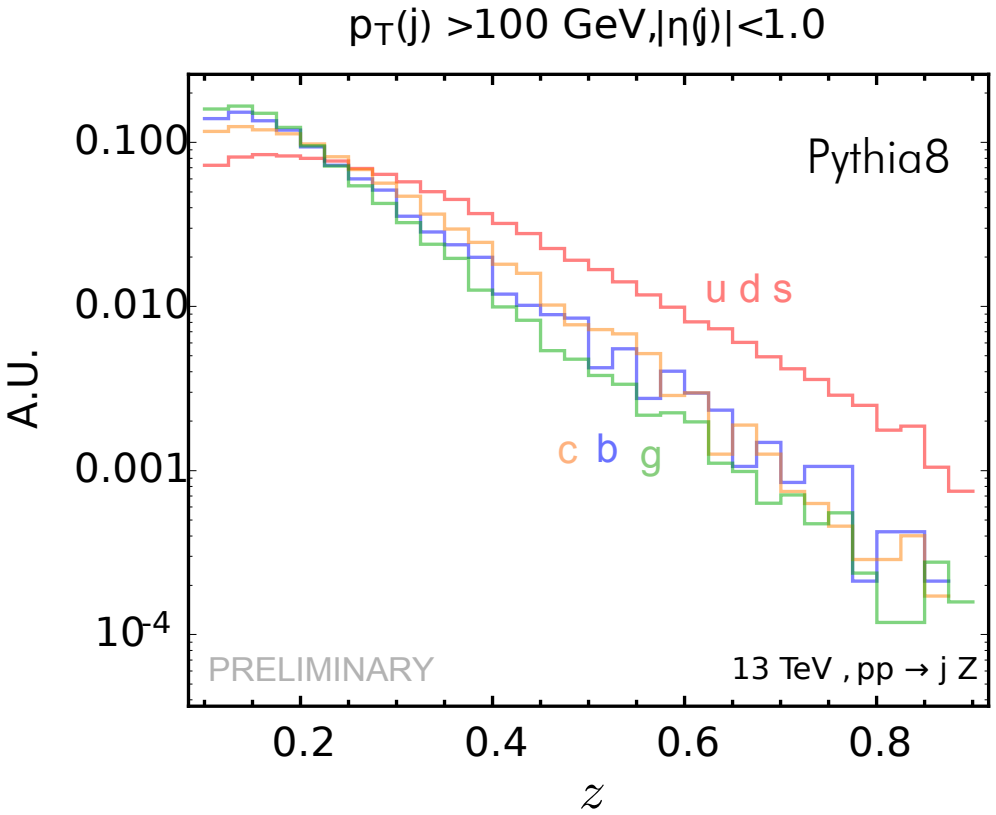
$$U_1 = \sum_{i,j \in \text{jet}} p_T^i p_T^j (R_{ij})^\beta$$

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



- Fraction of jet momentum carried by the hardest track.

$$z \equiv \frac{\max_{i \in \text{jet}}(p_i)}{p_{\text{jet}}}$$



- z is related to the fragmentation function of $K^{\pm}$, $\pi^{\pm}$
- Observable has been studied at ATLAS and CMS. Good agreement with Pythia

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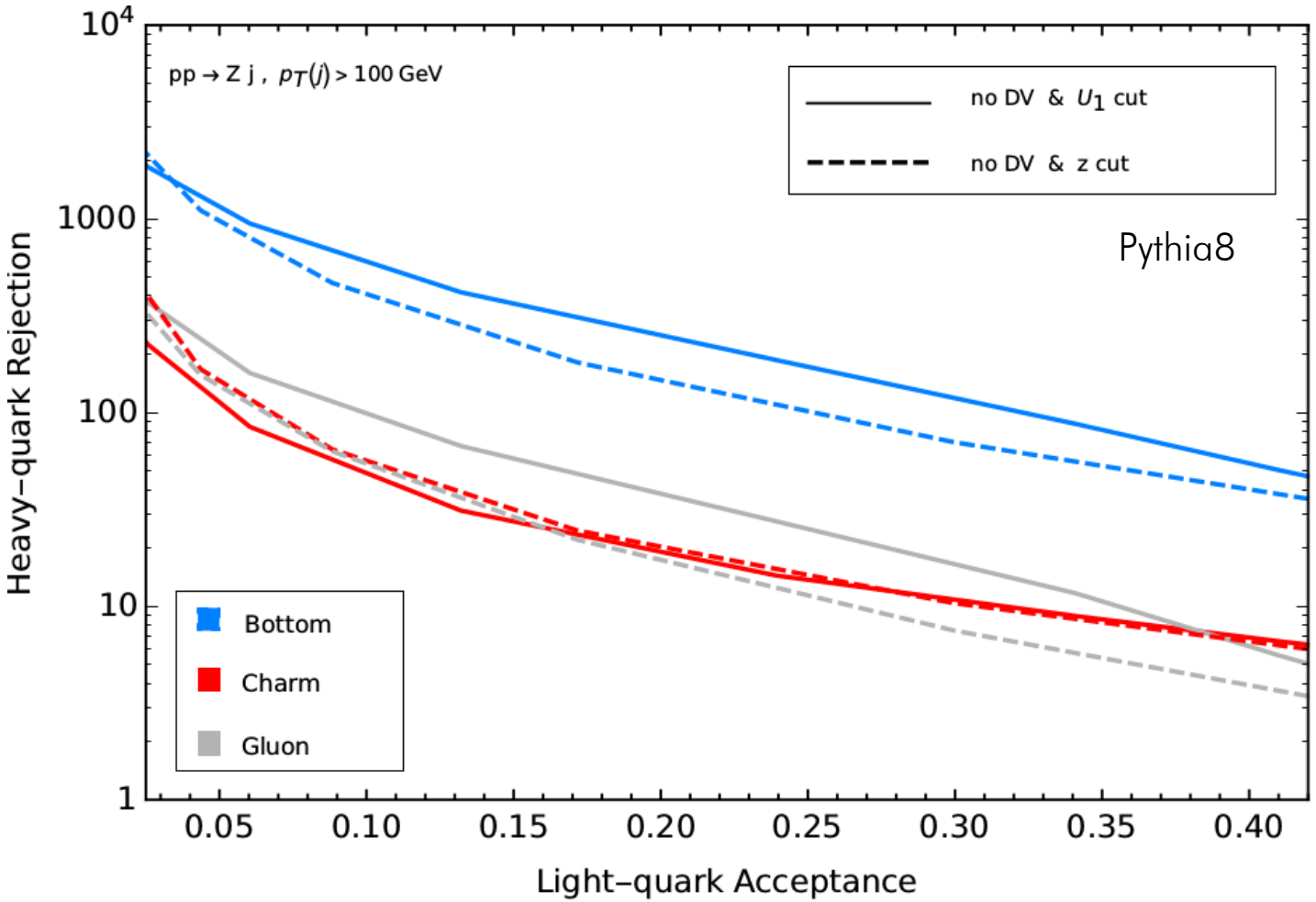
M. Patra, J. Zupan 1807.XXXXX



MC results: Excellent bottom rejection, good charm and gluon rejection!

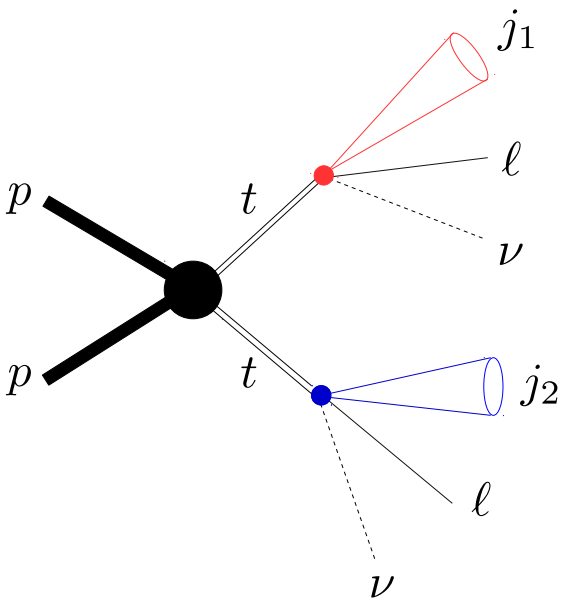
- Search strategy:

  - 1) Select pair of candidate jets $j_1\, j_2$ from first stage top-decays. $t\bar{t} \to j_1\, j_2\, W^+W^-$

  - 2) Tag pair with light-quark and bottom tagger.

  Signal Region: $j_1\, j_2$ are $sb-$jets

- **Resolved leptonic ttbar category**



- Event-by-event Selections:

  - 1) Select 2 isolated leptons.

  - 2) Select $j_1\, j_2$ candidates:

    leading & sub-leading jets $p_T(j_1, j_2) > 100\mathrm{GeV}$
    $|\eta(j_1, j_2)| < 1$

  - 3) **Tag $j_1\, j_2$ as bottom or light-quark jets.**

- Cleanest environment at LHC.

Irreducible background: $pp \to t\bar{t}\, j$ j=u,d valence quark ISR

- Results from MC: MadGraph 5 @ LO + Pythia 8

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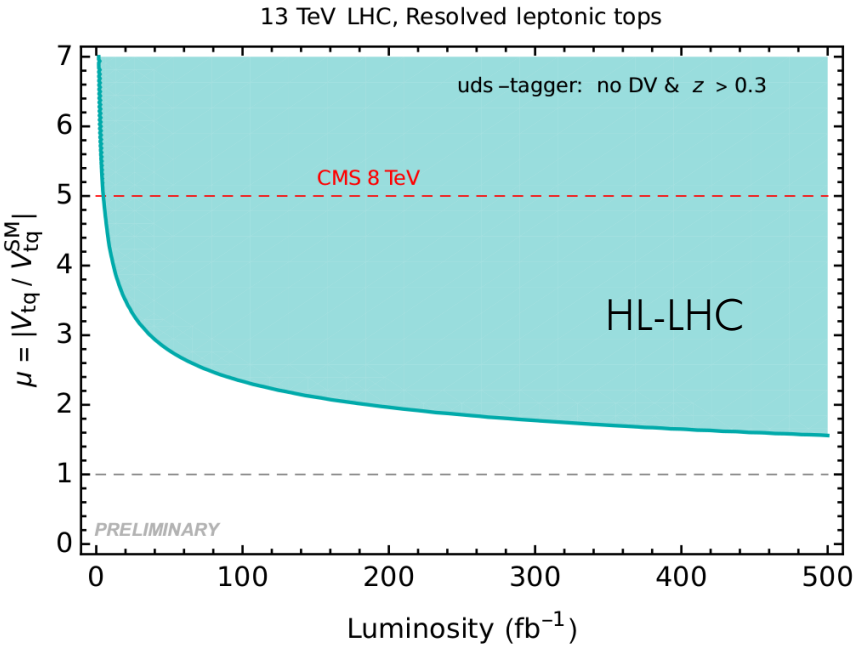
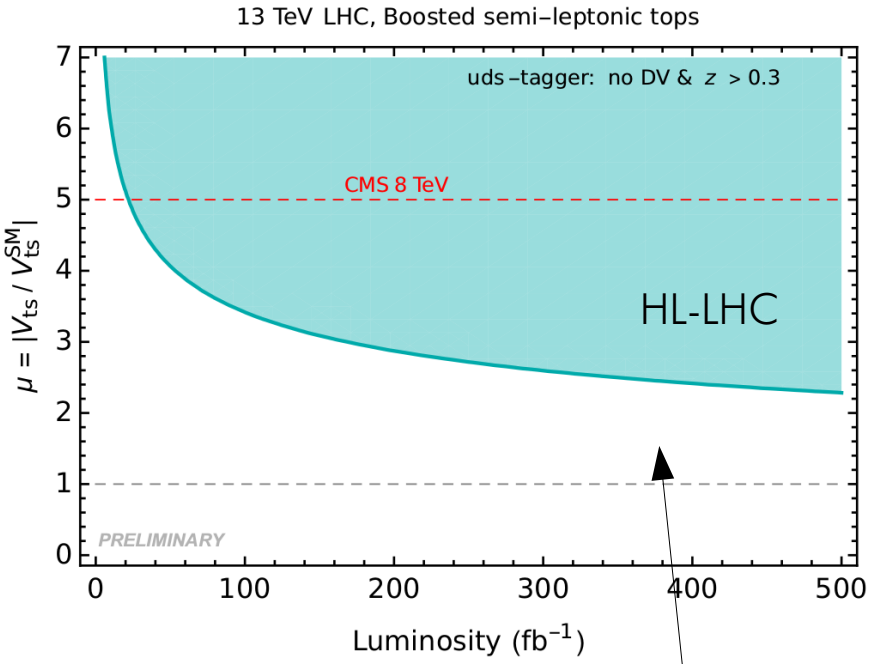
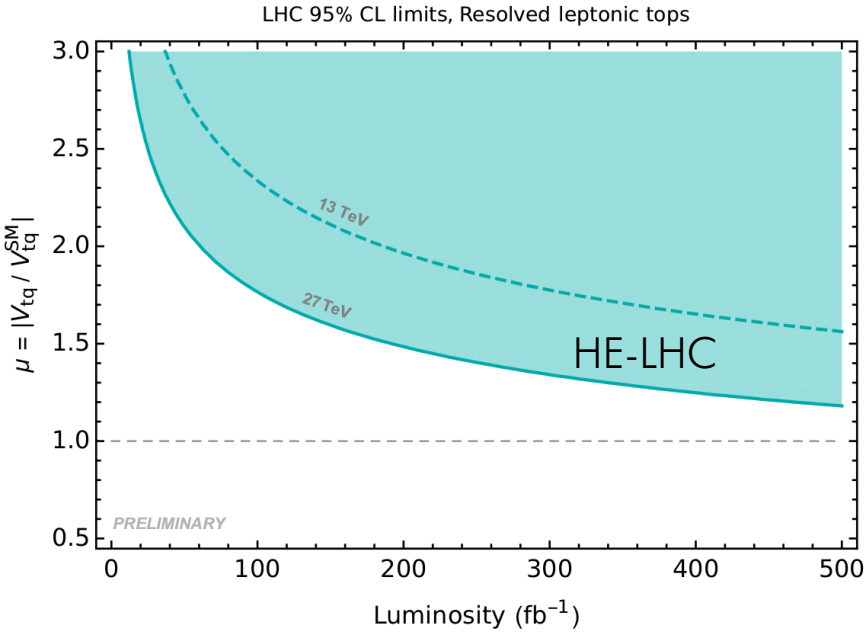
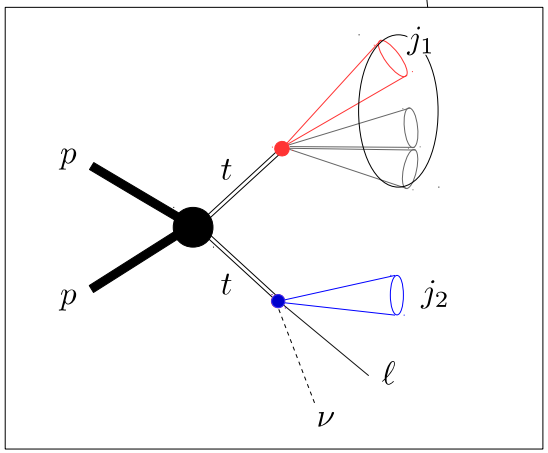








Boosted Analysis! (in backup slide)

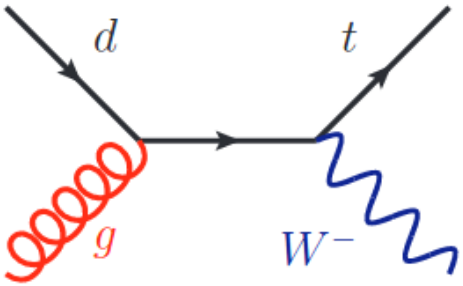
$|V_{td}|$ at LHC

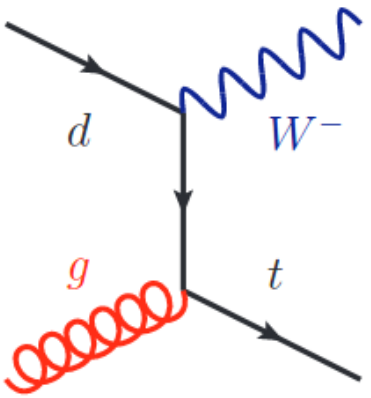
- Proposal: tW associated production at the LHC $dg \to tW^-\,, \quad \bar{d}g \to \bar{t}W^+ \qquad \propto |V_{td}|^2$

  Alvarez, Da Rold, Estevez, Kamenik [1709.07887]

- 13 TeV LHC:

$$\sigma(dg \to tW^-) \simeq 20\,\text{fb}$$
$$\sigma(\bar{d}g \to \bar{t}W^+) \simeq 6\,\text{fb}$$





- Signal Features:

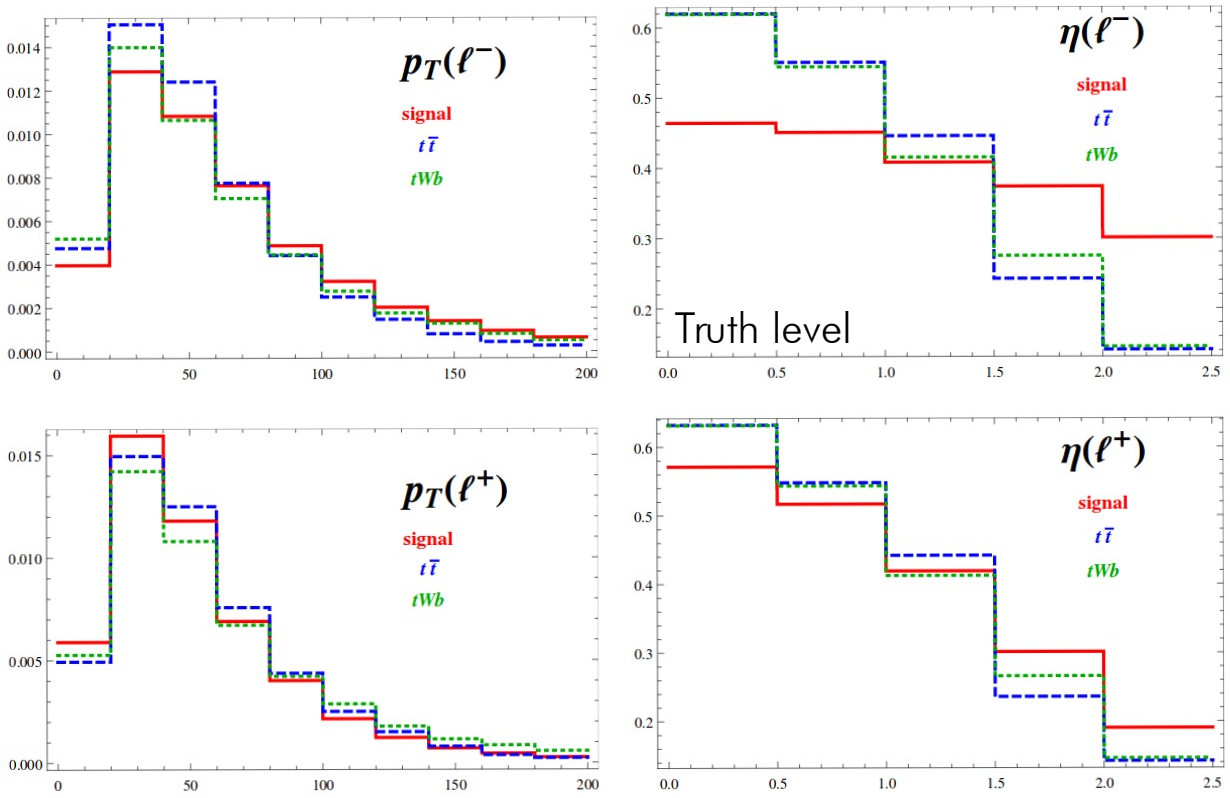
  - Charge asymmetry from **(valence) d-quark** vs **(sea) anti-d-quark.**
  - W^- is more foward than W^+

- Most backgrounds are charge-symmetric $bg \to tW^-\,, \quad \bar{b}g \to \bar{t}W^+$

  Total x-section $\sigma_{tW}^{\text{SM}} \simeq 28\,\text{pb}$

- Top-pairs have a small charge-asymmetry at NLO $\qquad \sigma_{t\bar{t}}^{\text{SM}} \simeq 680\,\text{pb}$

- Purely Leptonic channel $pp \to tW \to \ell^+\ell^- b\,\nu$



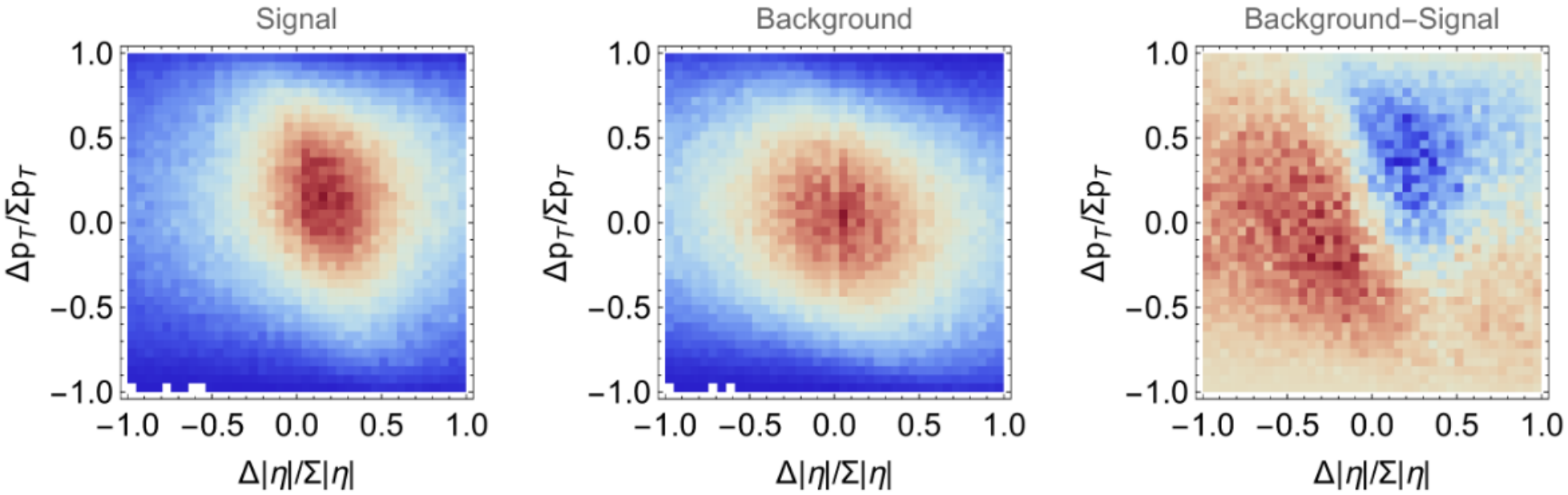
Alvarez, Da Rold, Estevez, Kamenik [1709.07887]

- Motivates the kinemaical variables:

$$\Delta|\eta(\ell)| = |\eta(\ell^+)| - |\eta(\ell^-)| \qquad \Sigma|\eta(\ell)| = |\eta(\ell^+)| + |\eta(\ell^-)|$$

$$\Delta p_T(\ell) = p_T(\ell^+) - p_T(\ell^-) \qquad \Sigma p_T(\ell) = p_T(\ell^+) + p_T(\ell^-)$$

Alvarez, Da Rold, Estevez, Kamenik [1709.07887]



- Signal Region: **1st quadrant.**

  Background Region: **symmetric.**

- Construct the **dilepton charge-asymmetry observable**:

$$A(\eta, p_T) = \frac{N^+ - N^-}{N^+ + N^-}$$

Event count in 1st and 3rd quadrants:

$$N^{\pm} = N\left(\Delta|\eta(\ell)| \gtrless 0 \,\&\, \Delta p_T(\ell) \gtrless 0\right)$$

- Analysis performed on MC samples with detector effects included (Delphes)

- Search Strategy:

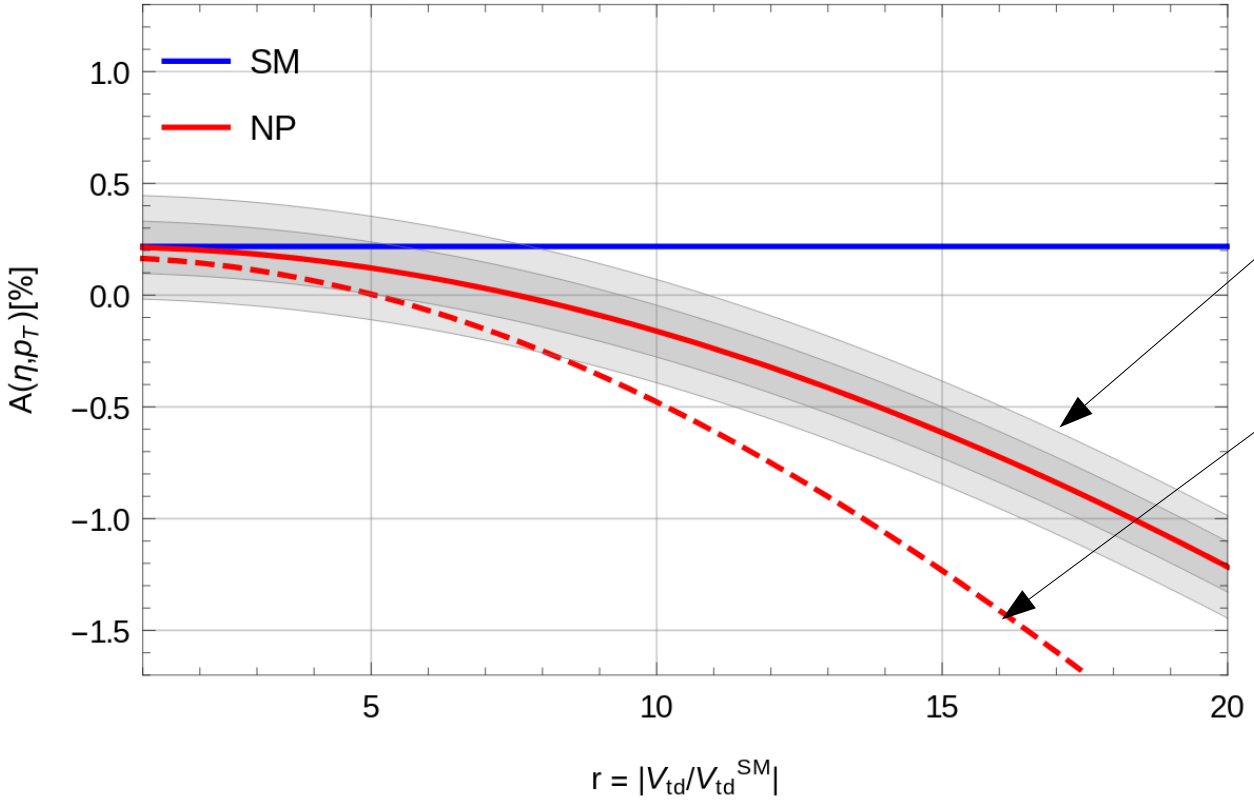
  - Select events with $\ell^+\ell^- b, \quad |\eta| < 2.5 \;\; \& \;\; p_T > 20\,\mathrm{GeV}$

  - Veto events with extra jets within $|\eta| < 5$

  - Z-mass veto $|m_{\ell\ell} - m_Z| < 15\,\mathrm{GeV}$ and $E_T^{\mathrm{miss}} > 30\,\mathrm{GeV}$

- Sensitivity at the HL-LHC 3000 fb^{-1}

Alvarez, Da Rold, Estevez, Kamenik [1709.07887]

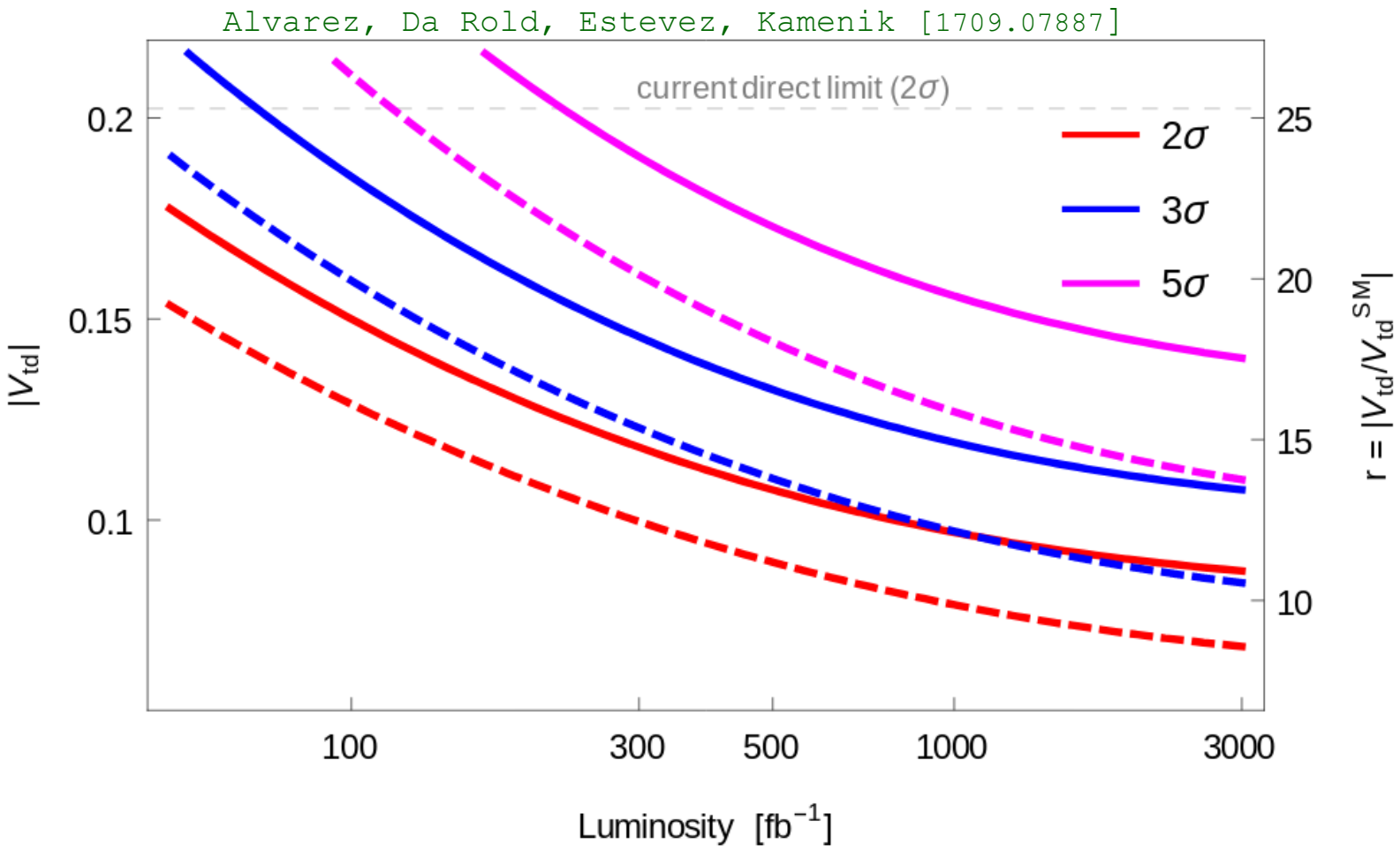


Estimation of total unc. ~ 0.2%

Top-pair background reduced by half.

Anticipating Multi-variate analysis (Boosted decision trees, etc...)

- HL-LHC reach


Alvarez, Da Rold, Estevez, Kamenik [1709.07887]
current direct limit (2σ)
2σ
3σ
5σ
0.2
0.15
0.1
|V_td|
25
20
15
10
r = |V_td/V_td^SM|
100
300
500
1000
3000
Luminosity [fb^-1]

Conclusions

- We discussed the HL-HE LHC prospects of measuring directly $|V_{tx}|$ mixing elements

- Current measurements of single-top and top-decays provide $|V_{tb}| \approx 1 \quad |V_{td}|, |V_{ts}| < 0.2$

  These will soon be limited by systematics.

- We showed that with help of a light-quark tagger the HL/HE - LHC can potentially measure directly in top-decays the quantity:

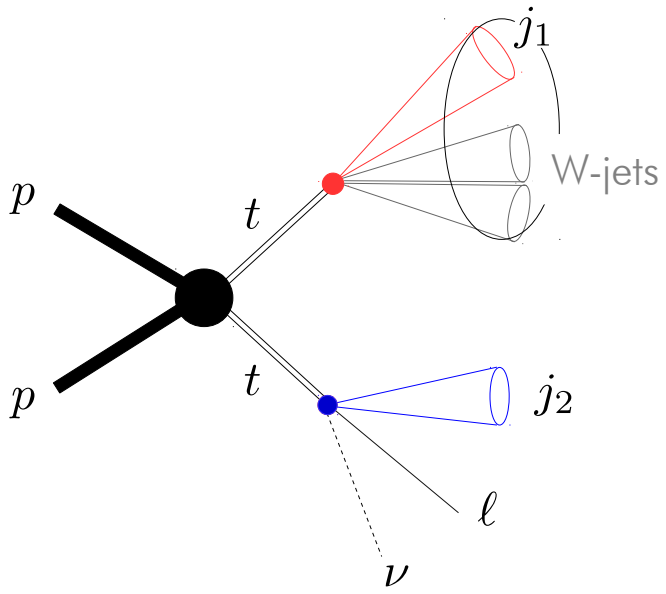
$$\sqrt{|V_{ts}|^2 + |V_{td}|^2}$$

  This would confirm the large hierarchy in the 3rd row of the CKM matrix obtained indirectly from low-energy experiments.

- We showed that $|V_{td}|$ can be constrained using W-associated single-top production. Dilepton charge asymetry is in particular sensitive to this CKM element. HL-LHC could establish that: $|V_{td}| < |V_{ts}|$

Thank you for your attention!

- **Boosted semi-leptonic ttbar category**

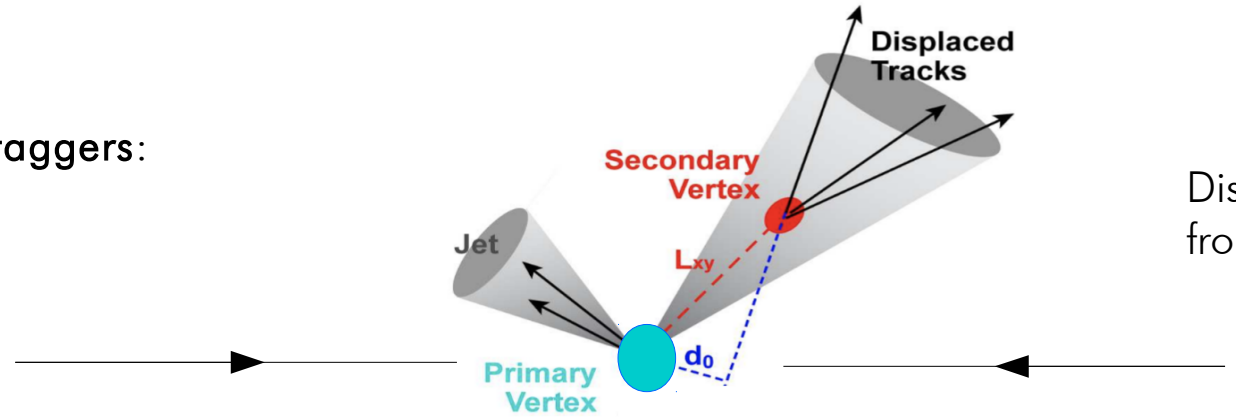


- 1) Selection:
  - 1 isolated lepton.
  - 1 Fat-Jet with $R = 1.5, \quad p_T > 250\,\mathrm{GeV}$
  - Tag the **top-jet** (John Hopkins Top tagger).
- 2) Select j_1 as top subjet.
- 3) **Tag j_1 as bottom or light-quark jet.**
- 4) Remove top-jet from event and Re-cluster jets with $R = 0.4 \quad p_T > 100\,\mathrm{GeV}$
- 5) Select j_2 best reconstructs leptonic top
- 6) **Tag j_2 as bottom or light-quark jet.**

- This category provides a *tag and probe* environment.

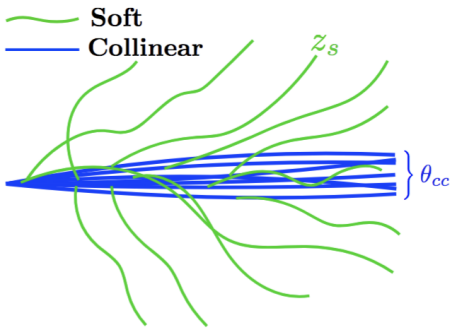
- The **Jet tagging industry** is currently booming!

- Bottom-taggers:



Displaced vertex (DV) from B-meson decays

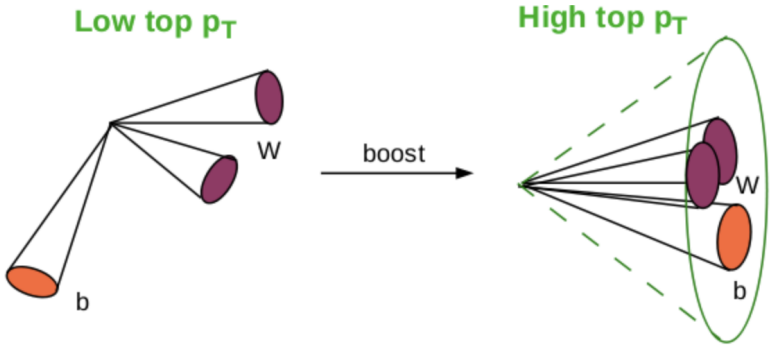
- Quark/gluon taggers:



Exploits observables sensistive to difference in QCD radiation pattern of parton

(jet shape, angularities...)

- Fat-jet-taggers:



$$R \sim 2m_t/p_t \sim \mathcal{O}(1)$$

Jet-substructure:

3-prong: Tops

2-prongs: W, Z, Higgs