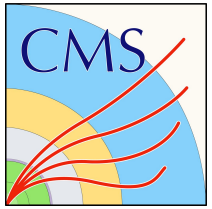
Department of Physics
UNIVERSITY OF WISCONSIN–MADISON



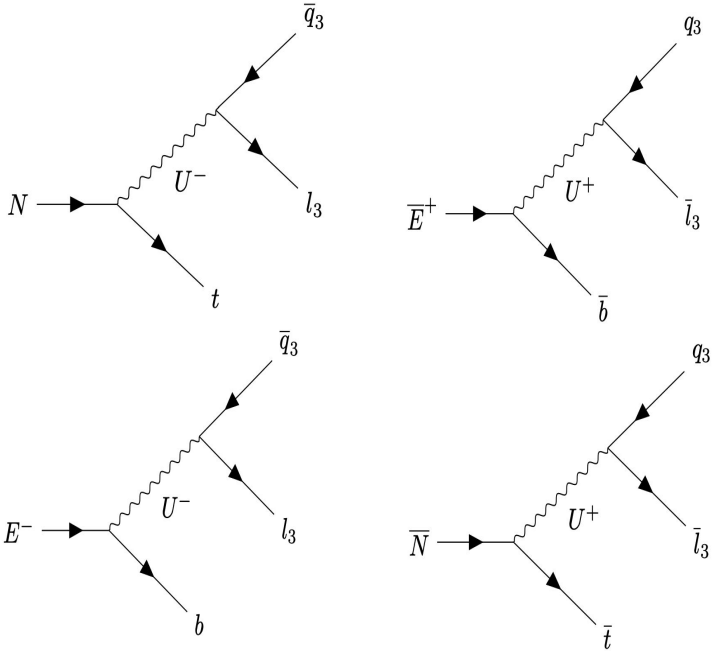
Fermilab

A Search for Vector Like Leptons (VLLs)

Elise Chavez
University of Wisconsin Madison
USLUA December 13, 2023
Advisors: Tulika Bose and Charis Koraka

What are VLLs? Why do we care?

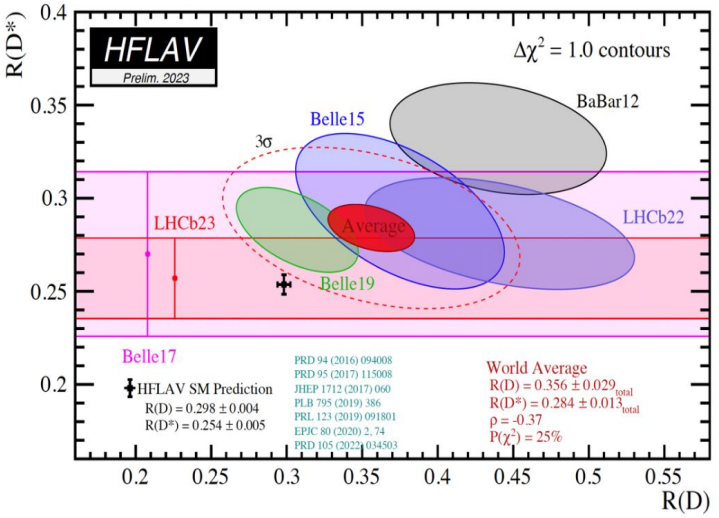
- Standard model is incomplete
  - Possible lepton non-universality?
  - Dark matter?
  - Need to look beyond
- Vector-like leptons (VLLs) predicted by a BSM extension of the standard model, the 4321 model
  - One charged and one neutral - same masses
  - Decay through a leptoquark, which couples most strongly to the third generation



Theory Papers: [Gauge leptoquark as the origin of B-physics anomalies](), [Maximal flavour violation: a Cabibbo mechanism for leptoquarks]()

What are VLLs? Why do we care?

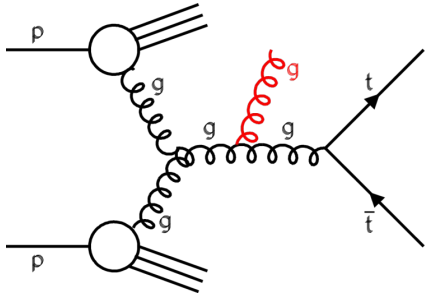
- VLLs and the leptoquark help reconcile discrepancies with the standard model
  - Resolve B-hadron anomalies => lepton non-universality
  - Possible decay to dark matter => dark matter
  - Contribute to muon and electron magnetic moment => anomalous magnetic moment



Charged current R(D) and R(D*) as of 2023 [F1]

VLL Signal and Background

- Dilepton decays
- Main source of background is tt-bar
  - Produces opposite signed leptons
- Exploit by separating signal into same sign (SS) and opposite sign (OS) lepton pairs in final states

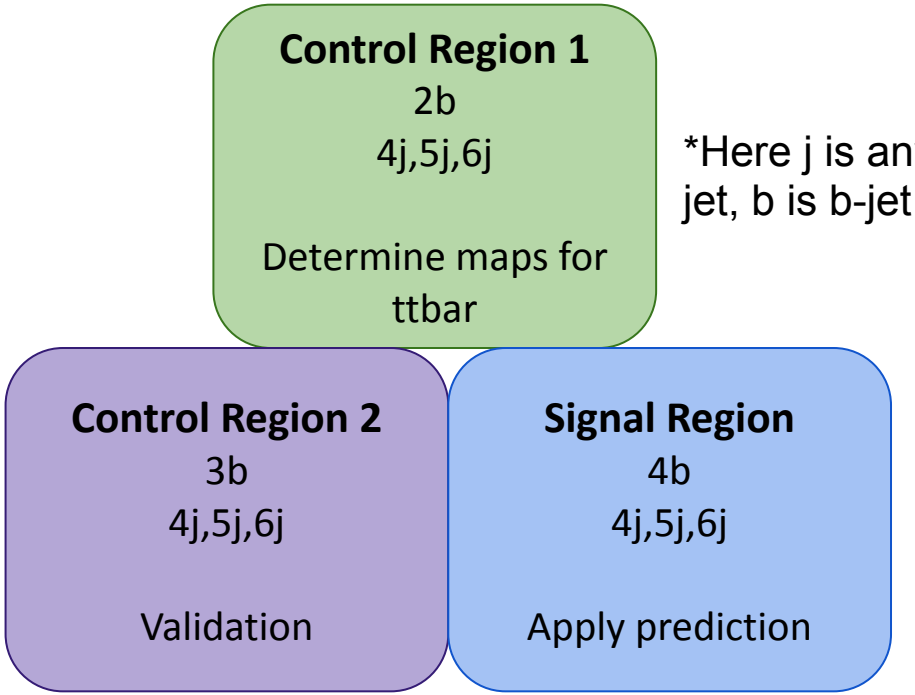


Feynman diagram of ttbar produced by proton-proton collision. [F2]

Lepton Pair Charge	VLL Pair	Final States
SS	EE	–
	EN	2l + 4b + 2j + MET
	$N\bar{N}$	2l + 4b + 4j + MET
OS	EE	2l + 4b + MET
	EN	2l + 4b + 2j + MET
	$N\bar{N}$	2l + 4b +4j + MET

Distinguishing Signal and Background

- To deal with the uncertainties coming from simulation, decided to use a data-driven background prediction method called a tag rate function
  - Use H_T
  - Define Regions

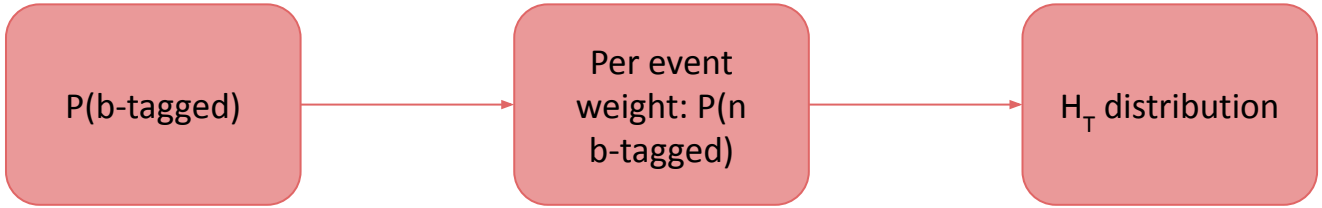


*Here j is any jet, b is b-jet

Tag Rate Function

- Simulation: know jet flavors => determine tagging probabilities => derive weight
- Treat Simulation like data: don't know jet flavors => make assumptions => derive weight

$$P_{b-tagged} = \frac{N_{b-tagged}(p_T, \eta, c)}{N_{Total}(p_T, \eta, c)}$$



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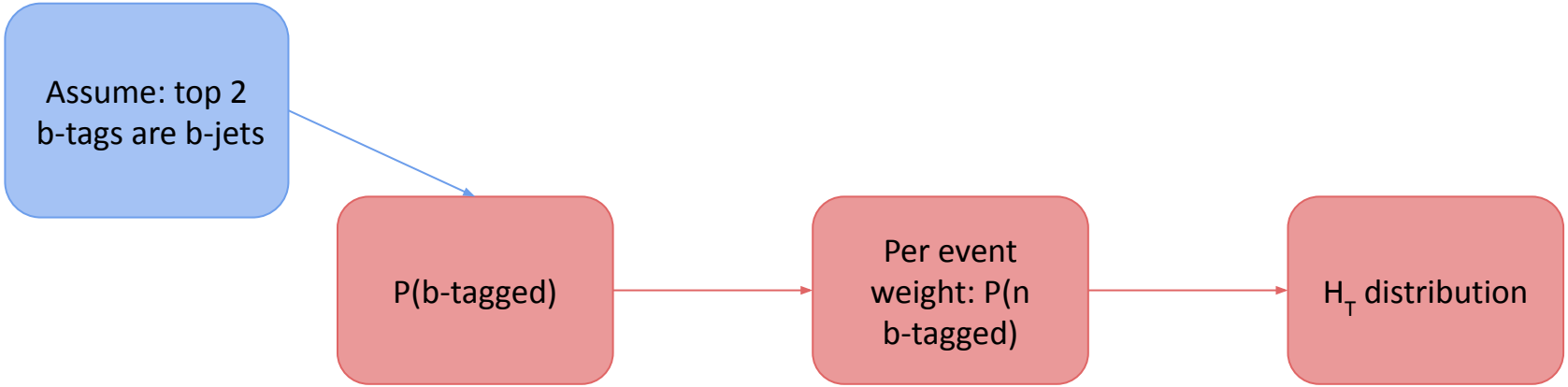

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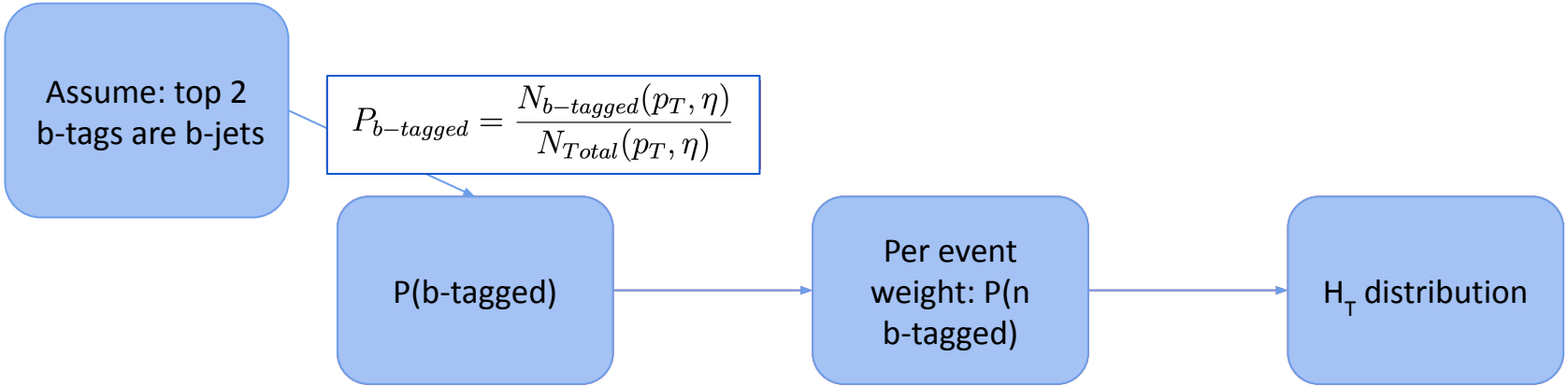
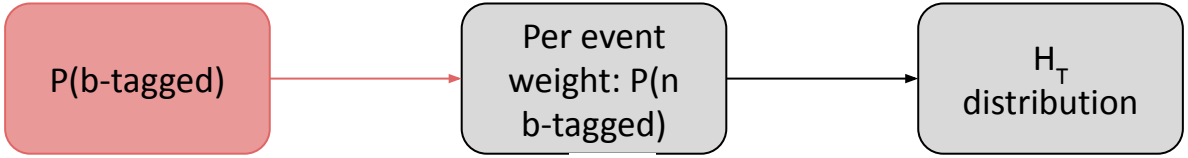
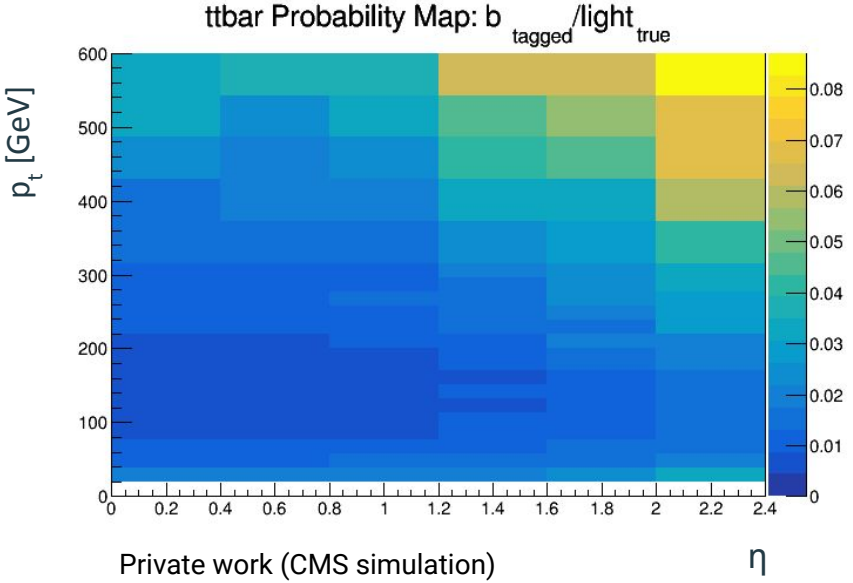
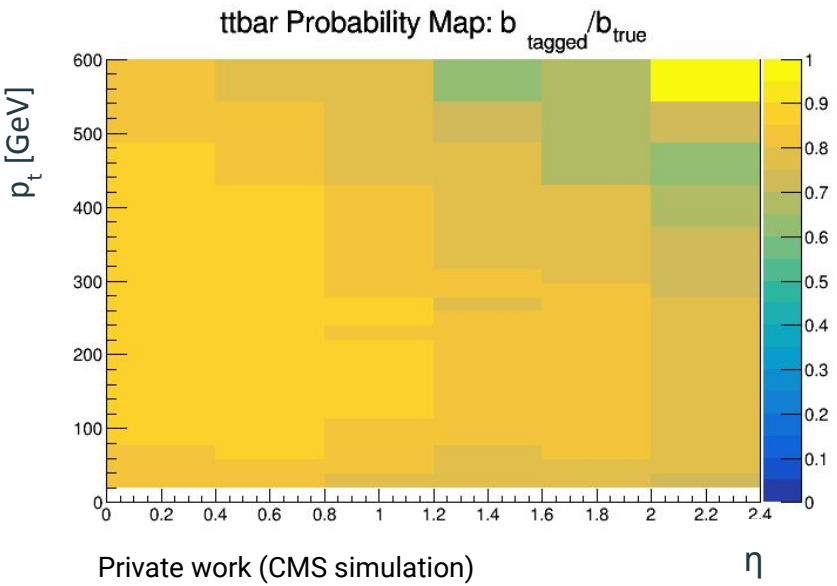


Tag Rate Function - Simulation





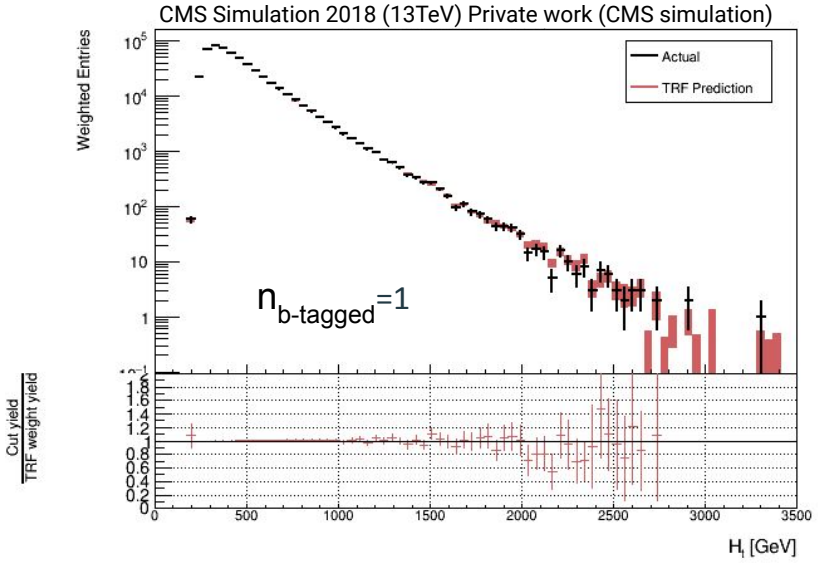
Private work (CMS simulation)

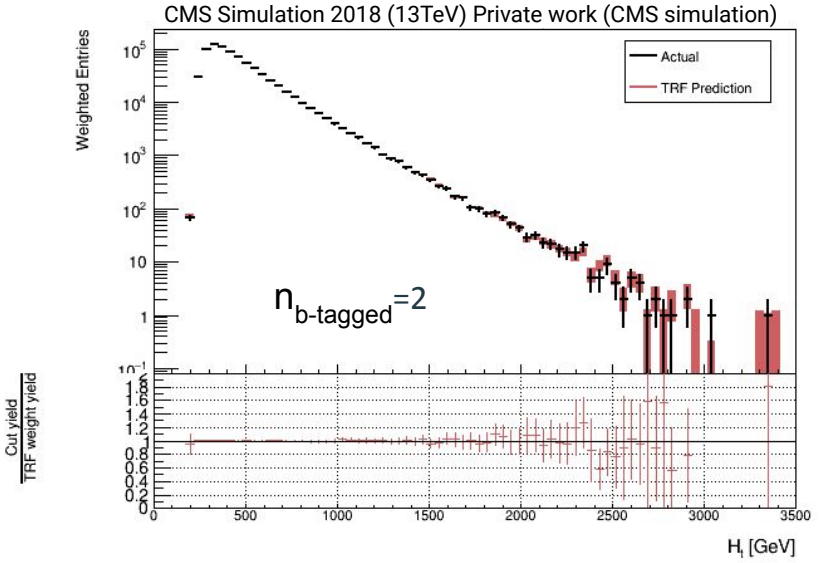


Private work (CMS simulation)

Tag Rate Function - Simulation

P(b-tagged) → Per event weight: P(n b-tagged) → H_T distribution





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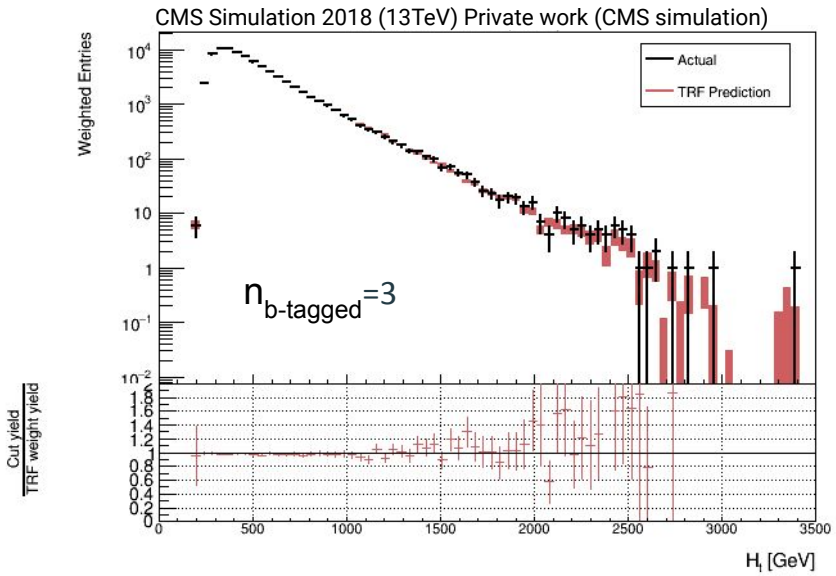
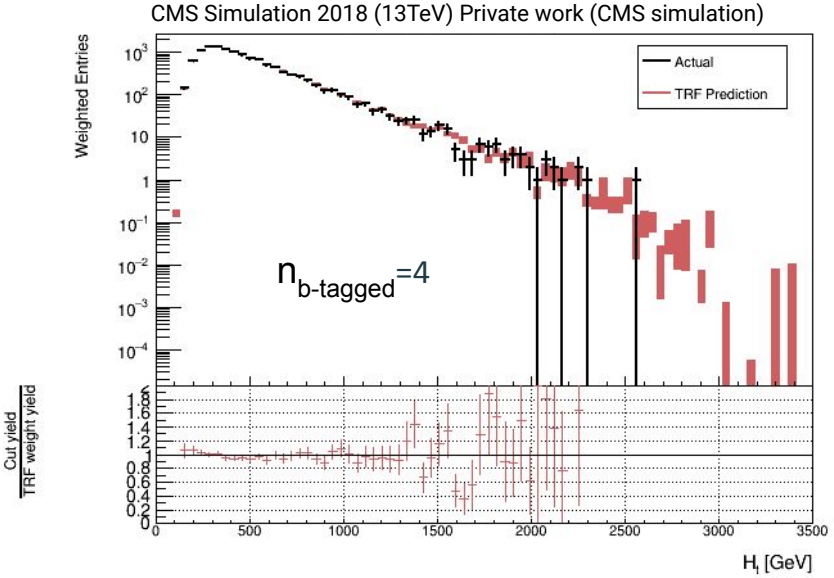




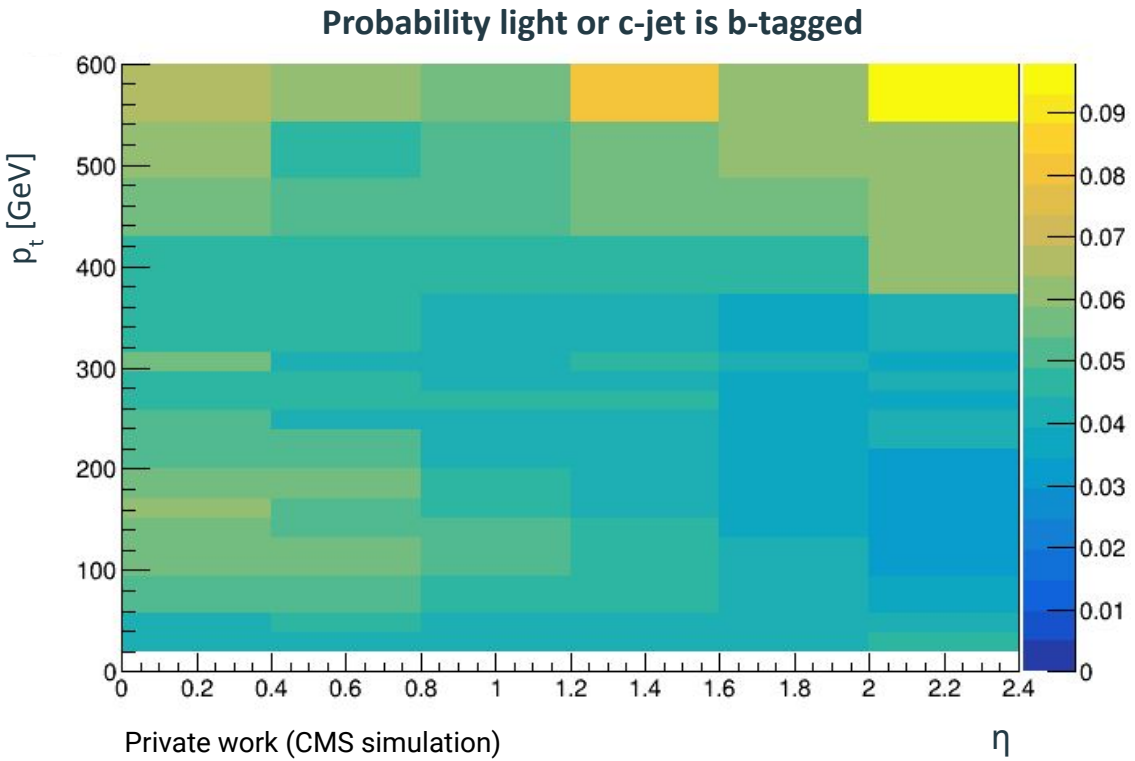
Tag Rate Function - Treat Simulation like Data

Assume: top 2 b-tags are b-jets

P(b-tagged)

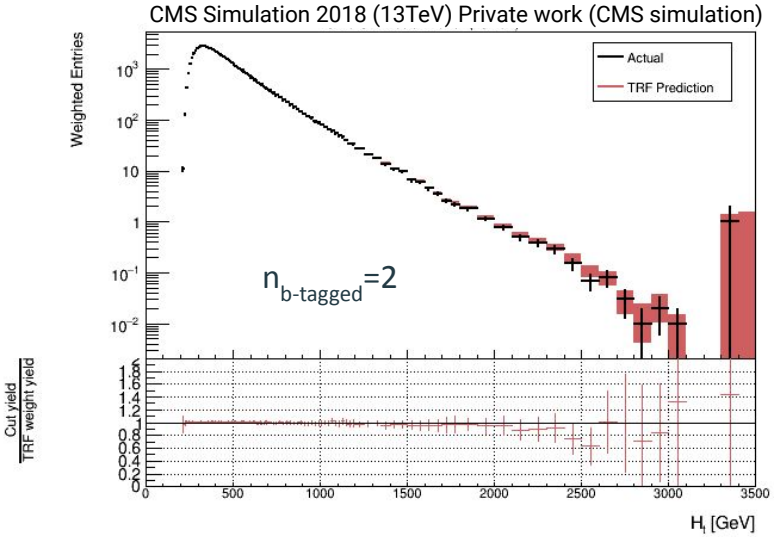
Per event weight: P(n b-tagged)

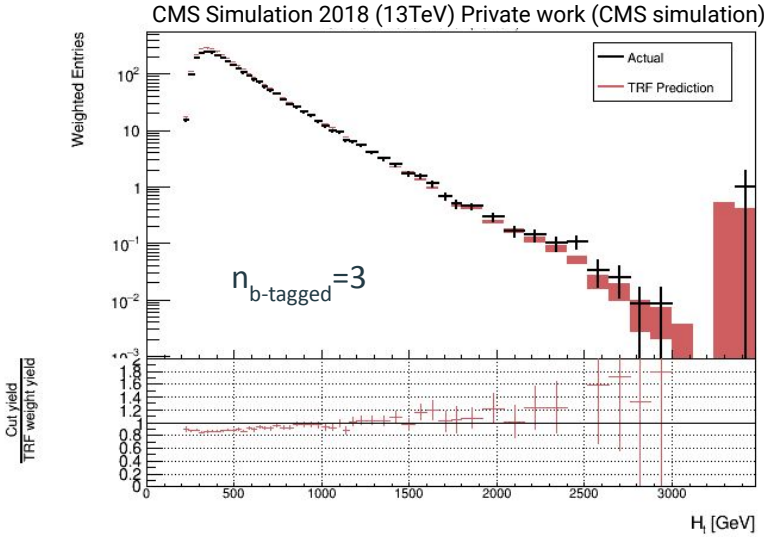
H_T distribution



Tag Rate Function - Treat Simulation like Data

Assume: top 2 b-tags are b-jets → P(b-tagged) → Per event weight: P(n b-tagged) → H_T distribution





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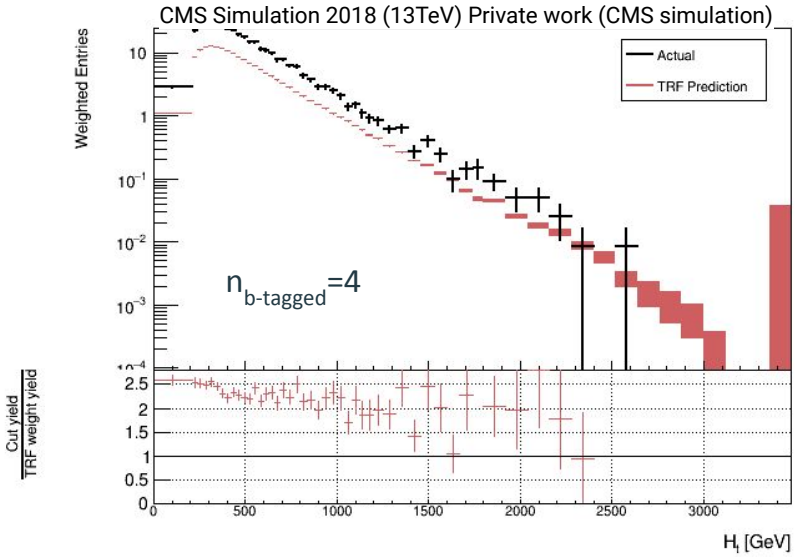


New Analysis Tools

- Coffea (Columnar Object Framework For Effective Analysis)
  - Prototype package aimed at making high energy analysis easier and at reducing the time it takes to get from data to plots
- Elastic Analysis Facility (EAF)
  - Fermilab's multi-VO analysis facility
  - Suite of analysis tools accessible through a jupyter-hub based interface

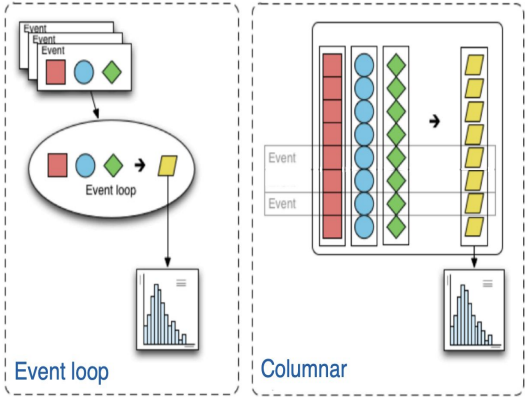


Diagram showing the difference between columnar and event loop programming (Nick Smith) [F2]

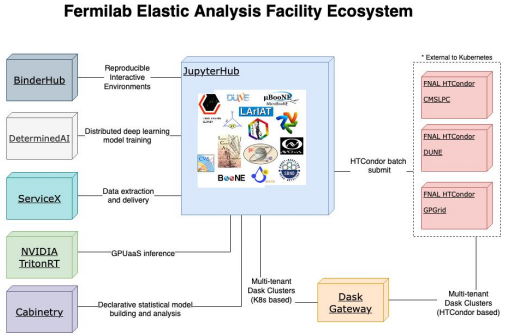


Diagram of the EAF ecosystem [F3]

Summary

- Ultimate goal is to use the predicted background distribution for ttbar distribution in the signal region
  - Produce a sensitivity plot for Run II with all backgrounds
- To-do
  - Need to understand the offsets in the tag rate predictions
    - Planning to determine a suitable sideband region to extract normalization from
  - Determine if using H_t results in the best sensitivity
    - Explore machine learning techniques to discriminate between signal and background
  - Perform the analysis for full Run II

Thank you!

Backup Slides

4321 Model

- Extends the Standard Model to SU(4) x SU(3)' x $SU(2)_L$ x U(1)'
- Ultraviolet complete
  - Works at arbitrarily large energies
- VLLs come in an electroweak doublet
  - Branching fractions depend on their mass
- VLLs are non-chiral
  - Expected not to couple to the Higgs
- Leptoquarks
  - Couple strongly to the third generation
  - Mediate VLL decays
  - Interact with both leptons and quarks
  - Have baryon and lepton numbers

Lepton Non-Universality

- Leptons have the same coupling to gauge bosons according to the Standard Model
  - Interactions between leptons and bosons should be identical -> lepton universality
- Evidence for non-universality come from B anomalies
  - Measured the B meson decay to D and D* mesons
  - Deviates from the SM prediction

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}l\nu_l)}$$

Anomalous Magnetic Moment

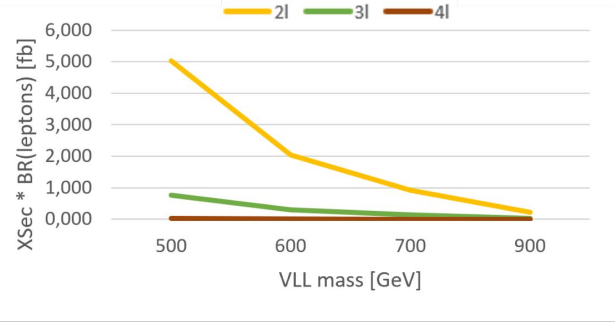
- Magnetic moment is a measure of magnetic strength
  - Also called magnetic dipole moment
    - Refers to component of the magnetic moment that can be represented by the equivalent dipole
  - Determines magnitude of torque an object experiences in a magnetic field
- Anomalous moment is contribution of quantum mechanic affect
- Can be explained by mixing with VLLs
  - Produces contributions to electron and muon anomalous magnetic moments
  - Many theories exist for VLLs reconciling the moments

$$\Delta \equiv a_{\mu}^{exp} - a_{\mu}^{SM} = 268(63)(43)x10^{-11}$$

$$\Delta \equiv a_{e}^{exp} - a_{e}^{SM} = -88(28)(23)x10^{-14}$$

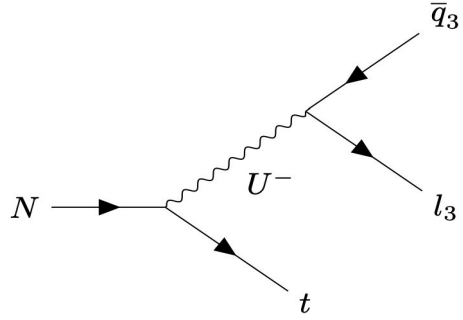
VLL Signal

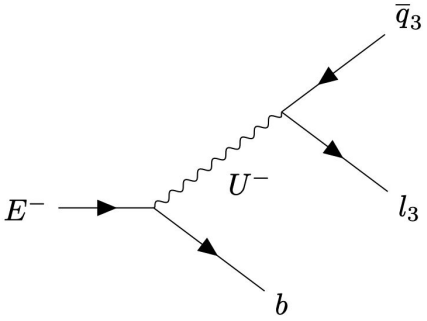
- A previous analysis looked into the hadronic channels and saw an excess
  - Scanned mass range from 500 to 1050 GeV
  - Leptonic channels are interesting to investigate since they are orthogonal
- This analysis will probe the leptonic channel
  - Similar mass range 500 to 1000 GeV
  - Look into the dilepton final states



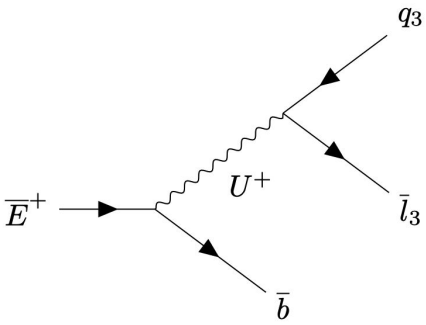
Leptonic decays

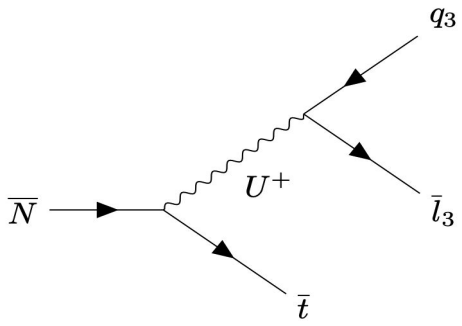
VLL Signal and Background





Index	
$\overline{E}^+$, E^-, N, $\overline{N}$	VLLs
$\overline{q}_3$, q_3	b, $\overline{b}$, t, $\overline{t}$
l_3, $\overline{l}_3$	τ^+, τ^-, ν_τ, $\overline{\nu}_\tau$
U^+, U^-	Leptoquarks





Selection Criteria - Objects

Jets	p_T > 30 GeV	|η| < 2.4	mediumJetIDbit	$\Delta R_{e,\mu,\tau}$ > 0.4
Electrons	p_T > 10 GeV	|η| < 2.4	CutBasedIdTight	eleEtaGapVeto
Muons	p_T > 10 GeV	|η| < 2.4	tightId	pfRelIso04_all < 0.25
MET	> 40 GeV	–	–	–

- 2018 Run II data
- These criteria ensure good quality of final state objects
- $\Delta R_{e,\mu,\tau}$: Distance between jet and lepton, reject jets that are too close to leptons
- eleEtaGapVeto : Reject electrons located in the gap between endcap and barrel
- pfRelIso04_all : Particle flow relative isolation, make sure muon is a prompt muon

Selection Criteria - Events

- Collected a lot of data from CMS, need to narrow down the events where we expect signal
  - Look at simulation to determine the relevant kinematic cuts and triggers
- Cut variables
  - Exactly 2 leptons
  - Leading lepton p_T > 30 GeV: transverse momentum of the lepton with the highest value of transverse momentum
  - M_{ll} > 20 GeV: invariant mass of the two leptons, ee and μμ
  - Z peak veto m_{ll} < 76 GeV and m_{ll} > 106 GeV: reject masses around z-peak of 91 GeV, ee and μμ
  - n_{jets} > 3: Number of jets in the event
  - Leading Jet p_T > 100 GeV: transverse momentum of the jet with the highest value of transverse momentum
  - Sub Leading Jet p_T > 50 GeV: transverse momentum of the jet with the second highest value of transverse momentum
  - H_T > 300 GeV: Sum of all the jets transverse momentum in an event

CMS Coordinate System

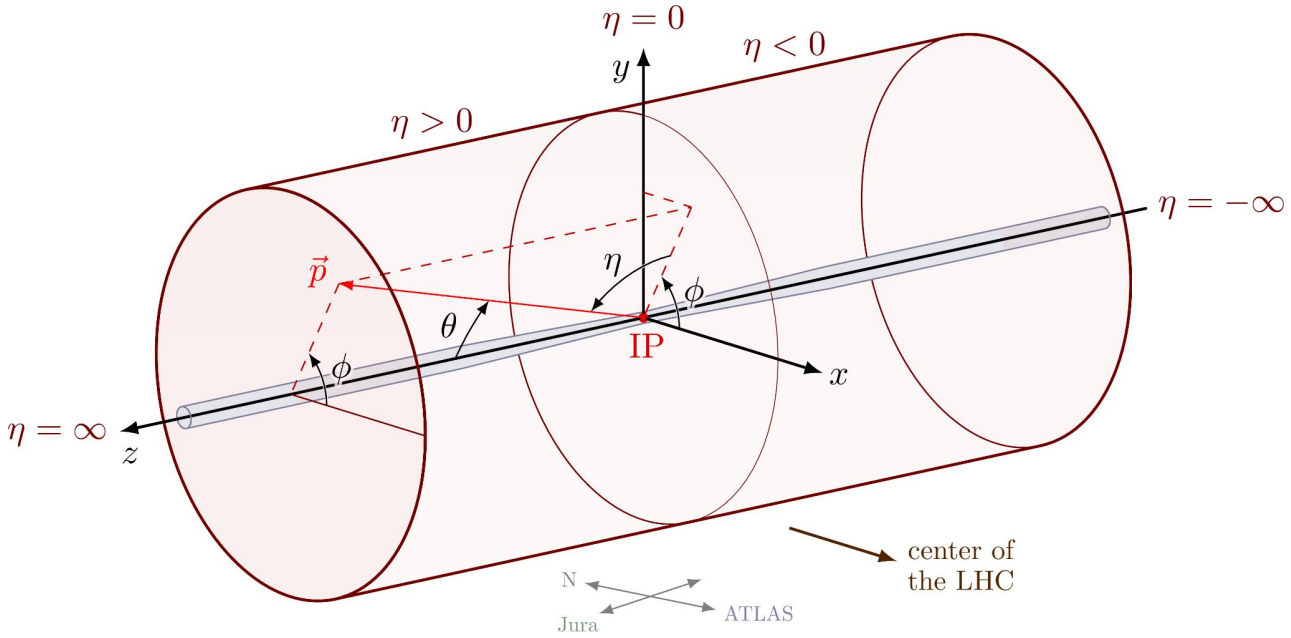


Figure 17: Diagram of the coordinate system used in the CMS [F17]

Background Types

- tt-bar
  - t and t-bar are pair produced and then decay through a W, each can decay to a lepton, lepton neutrino and b-jet
- Drell-Yan + Jets
  - Quark and antiquark from two hadrons annihilate and create two leptons through either a virtual photon or Z, jets produced by the hadrons
- Di-boson production
  - Pair produced bosons (WW, ZZ, ZW) decay to leptons and jets
- Tri-boson production
  - Production of 3 bosons (WWW,ZZZ,WWZ), decay to leptons and jets
- tt(V/H)+jets
  - t and t-bar are pair produced along with a boson or Higgs, the t and t-bar can decay through the W to lepons, lepton neutrinos, and b-jets while the boson or higgs also can decay hadronically or leptonically
- tt+VV
  - t and t-bar are pair produced along with a pair of bosons or a pair of higgs, similarly the t and t-bar can decay leptonically through a W and the bosons/Higgs can decay hadronically or leptonically
- 4-top
  - Two pair produced top quarks that decay like tt-bar through W bosons and can produce leptons, b-jets, and other particles

VLL Background

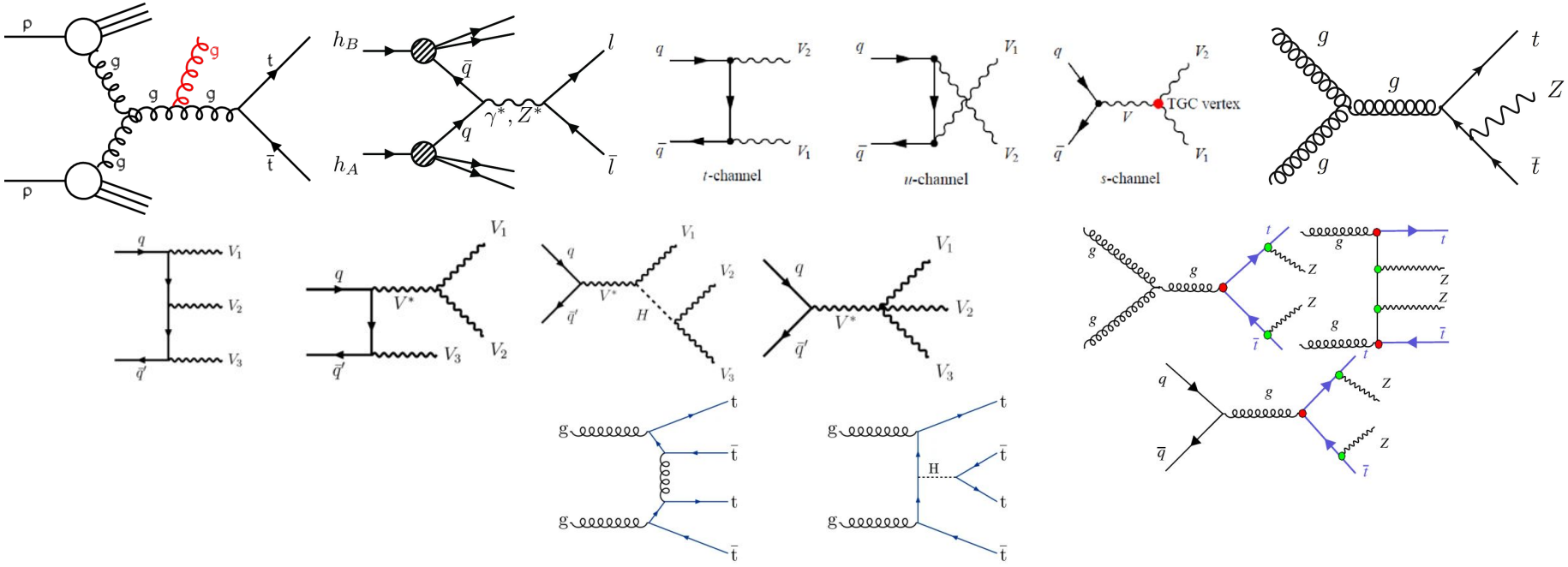


Figure 18: Feynman diagrams of all the backgrounds. From left to right: (1st row) tt-bar [F18], Drell Yan + Jets [F19], Di-Boson [F20], tt(V/H) + Jets [F22] (2nd row) Tri-Boson [F21], ttVV [F23] (3rd row) 4-top [F24]

Works Cited - Papers and Sites

[P1] Review+(partial) combination of VLQ + VLL + HNL (short and long-lived)
[P2] Search for pair-produced vector-like leptons in final states with third-generation leptons and at least three b quark jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV
[P3] Why should we search for vector-like leptons?
[P4] New leptons with exotic decays: collider limits and dark matter complementarity
[P5] Vector-like Leptons: Muon g-2 Anomaly, Lepton Flavor Violation, Higgs Decays, and Lepton Non-Universality
[P16] Coffea Documentation
[P17] Gauge leptoquark as the origin of B-physics anomalies
[P18] Maximal flavour violation: a Cabibbo mechanism for leptoquarks

Works Cited - Figures/Other

[F1] R(D) vs R(D*) Plot

[F2] ttbar

[F3] Columnar vs Loop Programming

[F4] EAF Documentation