Flavor physics @ the EIC with b-jet tagging

(or: "b-parity" for flavor physics @ the EIC & beyond)

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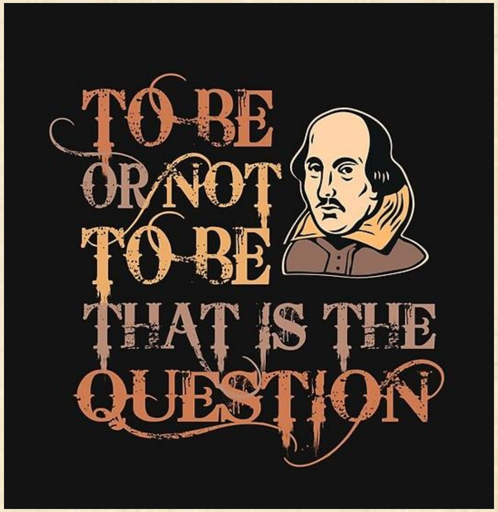
Based on:

- "**Counting inclusive b-jets as an efficient probe of new physics**"
  SBS (Technion), J. Wudka (UCR), PRL 2001 (hep-ph/9904365)

- "Flavor physics at the EIC with b-jet tagging"
  SBS (Technion), J. Wudka (UCR), PRD 2026 (arxiv: 2601.03345)

+ work in progress

- 2 b or not 2 b …



Counting b-jets as a method for probing new flavor physics of the 3rd gen.

Introducing "b-parity": a useful approx. quantum No. for collider experiments

SBS, Wudka, PRL 2001 (hep-ph/9904365)

- **Basic motivation:**
  find a simple (though perhaps not optimal) PROCESS-INDEPENDENT way of detecting ANY TYPE of new flavor physics involving the 3rd gen. quarks

Consider the reaction:

$$n_i \cdot b + X \rightarrow n_f \cdot b + Y$$

- X , Y = light-quarks/jets, leptons, missing energy …
- n_i , n_f = number of $(b + \bar{b})$ quark/jets (j_b)

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Key observation: in the SM, to a high accuracy

$$(-1)^{n_i} = (-1)^{n_f}$$

Or: defining **b-Parity** of a process to be:

$$b_P \equiv (-1)^{n_f - n_i}$$ ➤ b_p (SM)= + 1

the SM is "mostly" b_P-even (b_p = + 1)

(an odd # of b-quarks is rarely generated in a SM process !)

In the limit V_{3j} , $V_{j3} \to 0$ ($j \neq 3$) the SM acquires an additional global

$U(1)_b$ symmetry ("bottomness")

which holds to any order in perturbation theory

$$V_{CKM} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \to (\lambda^2 \to 0) \to \begin{pmatrix} 1 & \lambda & 0 \\ \lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

* b_p-violation$|_{SM} \propto |V_{3j}|^2$ or $|V_{j3}|^2$ $(j \neq 3)$

SM : $\frac{b_p=-1\, processes}{b_p=+1\, processes} \sim \lambda^4 \sim 10^{-3}$ at best !

SM irreducible backg to b_p-odd NP signals is strongly suppressed !

b-parity for collider experiments

The goal:

search for b_p-odd signatures of new flavor physics @ the EIC & FCC-ee

Consider the inclusive multiple b-jet production processes:

- EIC : $e + p/A \rightarrow n \cdot j_b + X$
- FCC-ee : $e^+ + e^- \rightarrow n \cdot j_b + X$

n = # of $(b + \bar{b})$ – jets (j_b)

b-parity for collider experiments

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- FCC-ee : $e^+ + e^- \to n \cdot j_b + X$

n = # of $(b + \bar{b})$ – jets (j_b)

For these processes:

$b_p = (-1)^n$ is an approximate symmetry in the SM

(@ EIC: to the extent that the b-quark content in the proton can be neglected …)

b-parity for collider experiments

The method – counting b-jets:

determine the b_p of the final state by simply counting # of b-jets

- relies primarily on b-tagging & purity of the sample

- does not require :

- The particular structure of the final state
- The identification of any particle BUT the b
- The identification of the charge of the b

b-parity for collider experiments

Leading potential background:

(1) Purity: SM reducible backg due to light-jet mis-identification as a b-jet, i.e., non-perfect purity of the sample

(2) b-tagging: SM reducible backg due to non-perfect b-tagging efficiency

(3) off-diag CKM: SM irreducible backg due to $|V_{3j}|^2$ or $|V_{j3}|^2$ ($j \neq 3$), i.e., $\propto \lambda^4$

*** turns out that: (1) > (2) >> (3) !

SM is "almost" b_p-even …

b-parity for collider experiments

Let (e.g., @ EIC):

$$\sigma_{nml} = \sigma(e + p/A \rightarrow n \cdot j_b + m \cdot j_c + l \cdot j_l + X)$$

X = leptons, photons &/or missing energy …

Then, the probability (CSX) for detecting precisely k b-jets :

$$\overline{\sigma_k} = \sum_{u+v+w=k} P_n^u P_m^v P_l^w \left[\epsilon_b^u (1 - \epsilon_b)^{n-u}\right]\left[t_c^v (1 - t_c)^{m-v}\right]\left[t_j^w (1 - t_j)^{l-w}\right] \cdot \sigma_{nml} \cdot \delta_{u+v+w,k}$$

$$P_j^i \equiv \frac{i!}{j!\,(i-j)!}$$

New Physics: model independent approach

EFT prescription:

$$L = L_{SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_i \alpha_i Q_i^{(n)}$$

Relevant NP parameter (dim.6): $\Lambda_{eff} = \frac{\Lambda}{\sqrt{\alpha}}$

e.g., $(\bar{L}R)(\bar{L}R)$ tensor operator: $Q_{lequ}^{(3)} = (\bar{\ell}^j \sigma_{\mu\nu} e_R) \varepsilon_{jk} (\bar{q}^k \sigma_{\mu\nu} u_R)$

more types of NP considered in: **SBS, J. Wudka, PRD 2026 (arxiv: 2601.03345)**

effective operator	Chirality (type)	Interactions
$Q_{\ell q}^{(3)}(1113) = (\bar{\ell}_1 \gamma_\mu \tau^I \ell_1)(\bar{q}_1 \gamma^\mu \tau^I q_3)$	$(\bar{L}L)(\bar{L}L)$ (vector)	$eetu$, $eebd$, $e\nu_e bu$
$Q_{\ell equ}^{(1)}(1131) = \left(\bar{\ell}_1^j e\right) \epsilon_{jk} (\bar{q}_3^k u)$	$(\bar{L}R)(\bar{L}R)$ (scalar,tensor)	$eetu$, $e\nu_e bu$
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$Q_{Hud}(13) = i\left(\tilde{H}^\dagger D_\mu H\right)(\bar{u}\gamma^\mu b)$ +h.c.	$(\bar{R}R)$ (vector,fermion)	Wub
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New Physics: model independent approach

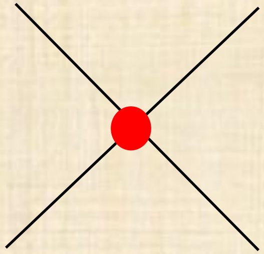
$$Q_{lequ}^{(3)} = (\bar{\ell}^j \sigma_{\mu\nu} e_R)\varepsilon_{jk}(\bar{q}^k \sigma_{\mu\nu} u_R)$$

EIC , $E_{CM} \approx 140\ GeV$

$(\bar{\nu}_{eL}\sigma_{\mu\nu}e_R)(\bar{b}_L\sigma_{\mu\nu}u_R)$ $(e\nu bu\ - tensor)$

$e\ u \rightarrow b\ \nu_e$

$Q_{lequ}^{(3)}(1131)$ SU(2)



$e\ e \rightarrow t\ u$

$(\bar{e}_L\sigma_{\mu\nu}e_R)(\bar{t}_L\sigma_{\mu\nu}u_R)$ $(eetu\ - tensor)$

FCC-ee , $E_{CM} \approx 240\ GeV$

EIC : E_{CM} ~ 140 GeV

(E_p=275 GeV , E_e=18 GeV)

$L=100\ fb^{-1}$

SBS, J. Wudka, PRD 2026 (arxiv: 2601.03345)

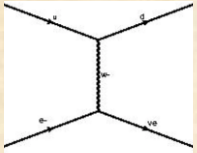
EIC : E_{CM} ~ 140 GeV
(E_p=275 GeV , E_e=18 GeV)

CC single-jet production:

SM: e + p/A → j_ℓ + MET

light-jet

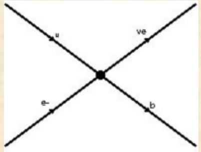
$\sigma_{SM} \sim 13\,pb$ (90% from e u → d ν_e)



NP: e + p/A → j_b + MET

b-jet

$\sigma_{NP} \sim 0.2\,pb$ (from e u → b ν_e)



$$\bar{\sigma}_{1j_b}(\epsilon_b, t_j, \Lambda_{eff}) = t_j \cdot \sigma_{SM} + \epsilon_b \cdot \sigma_{NP}(\Lambda_{eff})$$

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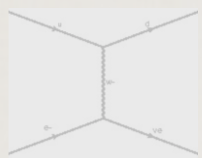


$$\bar{\sigma}_{1j_b}(\epsilon_b, t_j, \Lambda_{eff}) = t_j \cdot \sigma_{SM} + \epsilon_b \cdot \sigma_{NP}(\Lambda_{eff})$$

<u>NOTE:</u>

- NC single-jet (e + p/A $\rightarrow$ j + e) won't work: SM-backg too large …
- di-jet CC production (e + p/A $\rightarrow$ 2j + MET) less sensitive to NP
- no single top-quark production (E_{CM} < m_t) …
- SM background processes yielding a charm-jet are negligible

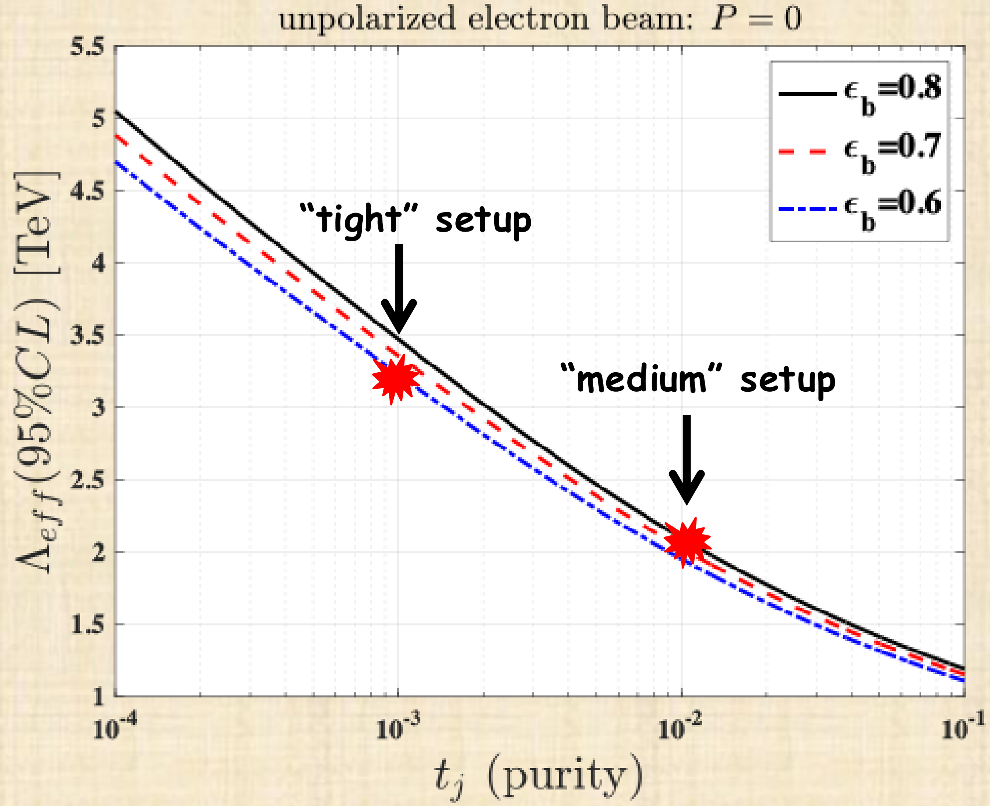
95% CL bound on the scale of NP Λ_{eff} :

$$Q_{lequ}^{(3)} = (\bar{\ell}^j \sigma_{\mu\nu} e_R)\varepsilon_{jk}(\bar{q}^k \sigma_{\mu\nu} u_R)$$

NP: $e + p/A \to j_b + MET$

Purity dominates the BG

analysis benefits more from purity rather than from higher b-tagging efficiency



$$\Lambda_{eff}(95\%CL) > 3.2\ TeV\ (\text{"tight"})$$

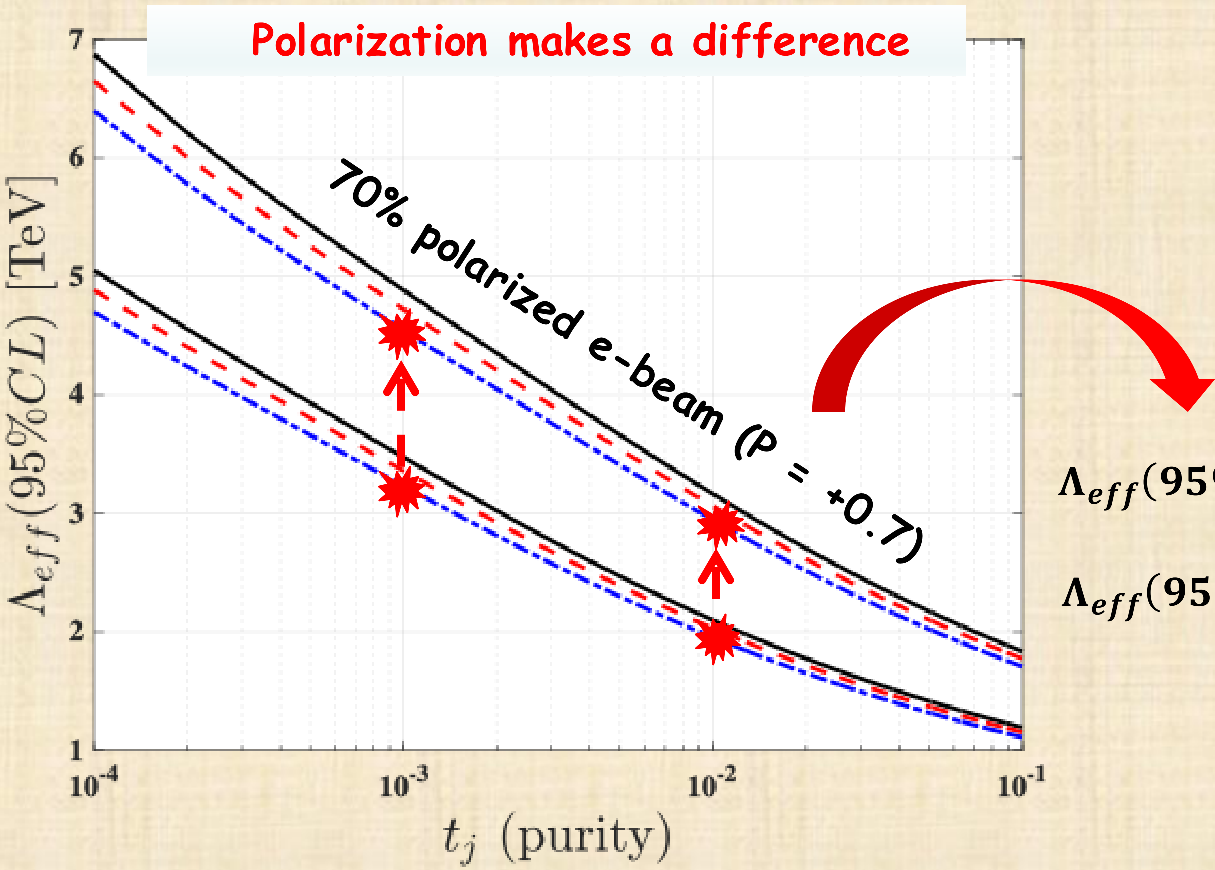
$$\Lambda_{eff}(95\%CL) > 2\ TeV\ (\text{"medium"})$$

Polarization of electron beam :

$$\sigma(P_e) = \frac{1}{2}\left[(1 - P_e)\cdot\sigma_- + (1 + P_e)\cdot\sigma_+\right]$$

$\sigma_- = \sigma(P_e = -1)$

$\sigma_+ = \sigma(P_e = +1)$



$\Lambda_{eff}(95\%CL) > 4.6\ TeV$ ("*tight*")

$\Lambda_{eff}(95\%CL) > 3.1\ TeV$ ("*medium*")

"tight" setup with 70% *pol*: $\Lambda_{eff}(95\%CL) > 30 \times E_{CM}(EIC)$

FCC-ee: E_{CM} ~ 240 GeV

($E_{e+,e-}$=120 GeV)

Work in progress …

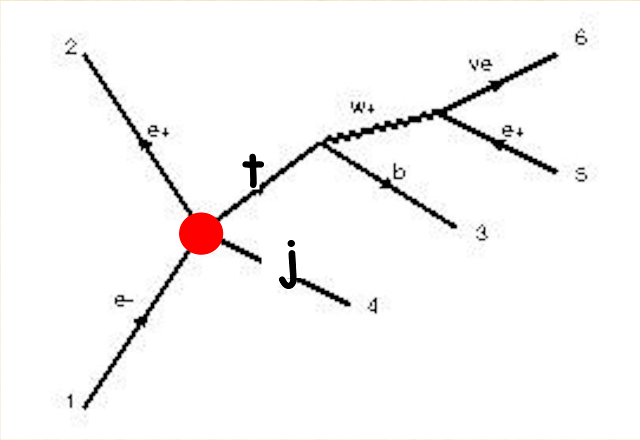
Example:

2-jets + charged lepton + MET:

NP(single-top prod):

$e^+ e^- \to t\, j \to j_b + j + \ell + \text{MET}$

($t \to bW$; $W \to \ell \nu_\ell$)

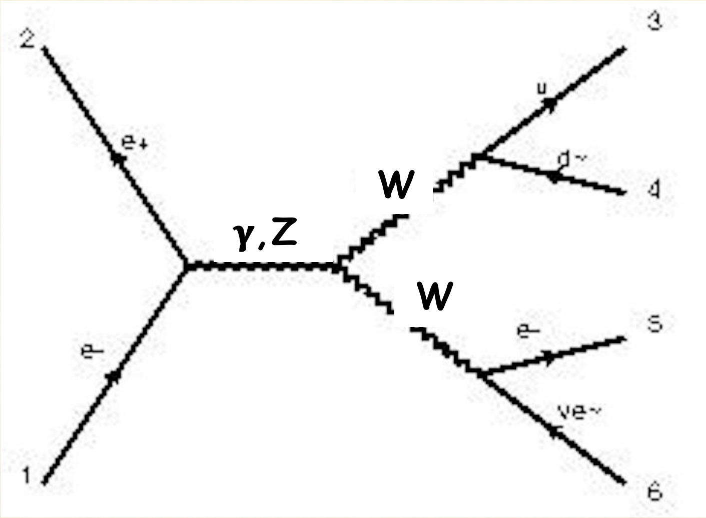


$(\bar{e}_L \sigma_{\mu\nu} e_R)(\bar{t}_L \sigma_{\mu\nu} u_R)$: *eetu – tensor*

SM:

$e^+ e^- \to 2\, j + \ell + \text{MET}$

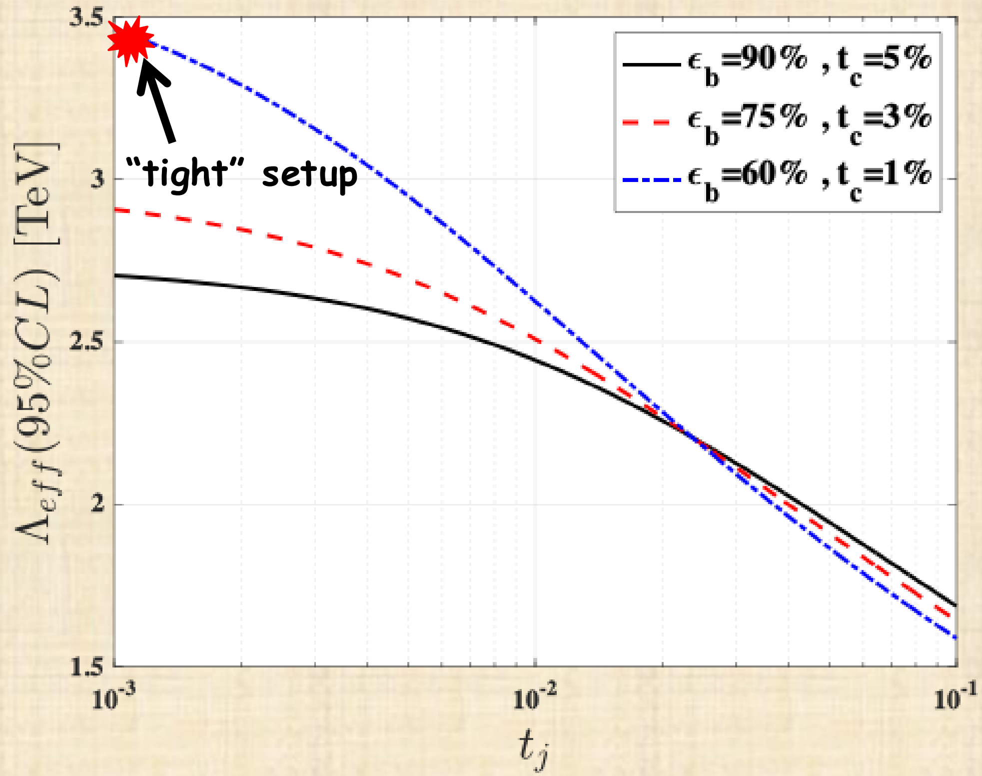
e.g., from $ee \to WW$; $W \to u\, d\, /\, \ell\, \nu_\ell$



95% CL bound on the scale of NP :

$$Q_{lequ}^{(3)} = (\bar{\ell}^j \sigma_{\mu\nu} e_R) \varepsilon_{jk} (\bar{q}^k \sigma_{\mu\nu} u_R)$$

$(\bar{e}_L \sigma_{\mu\nu} e_R)(\bar{t}_L \sigma_{\mu\nu} u_R)$: *eetu − tensor*



- Charm mis-identification makes a difference
- analysis benefits more from purity rather than from higher b-tagging efficiency

$$\Lambda_{eff}(95\%CL) > 3.5\, TeV \; (\text{"tight"})$$

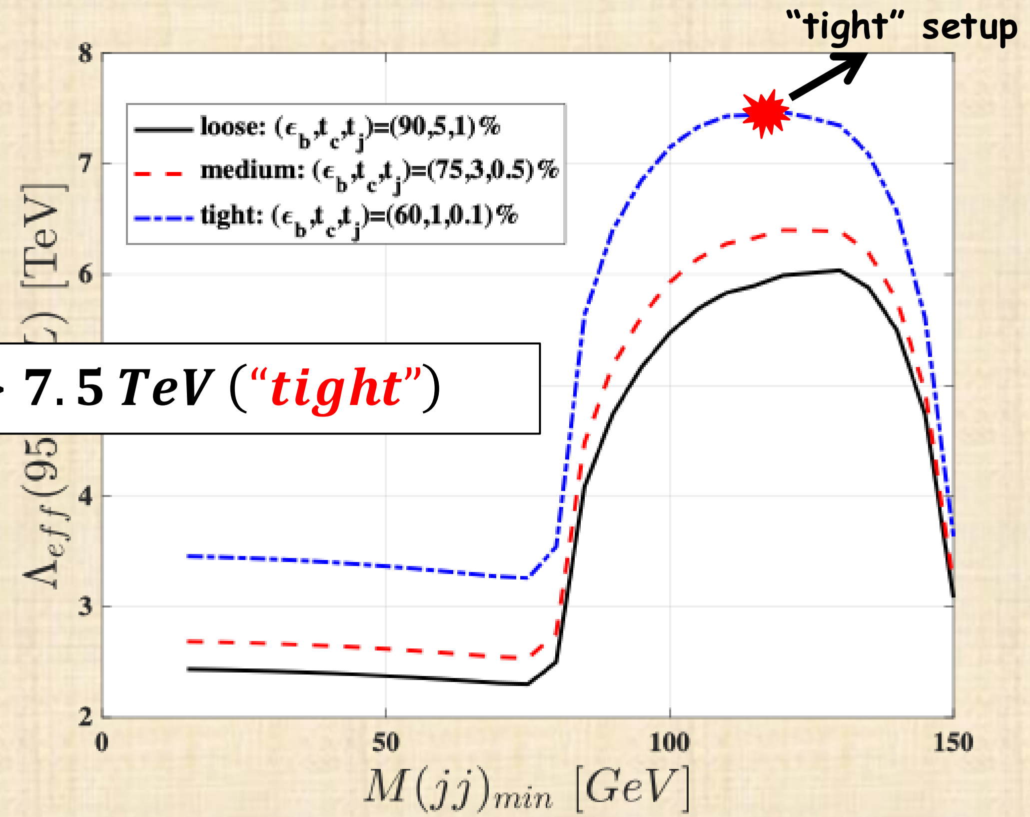
Sensitivity with kinematics:

$$Q_{lequ}^{(3)} = (\bar{\ell}^j \sigma_{\mu\nu} e_R)\varepsilon_{jk}(\bar{q}^k \sigma_{\mu\nu} u_R)$$

$(\bar{e}_L \sigma_{\mu\nu} e_R)(\bar{t}_L \sigma_{\mu\nu} u_R)$: $eetu - tensor$

$M(jj)_{min}$ cut in:

$e^+ e^- \rightarrow 2\, j + \ell + MET$



$$\Lambda_{eff}(95\%CL) > 7.5\, TeV \text{ ("tight")}$$

$$\text{"tight" setup with kinmatics: } \Lambda_{eff}(95\%CL) > 30 \times E_{CM}(ee) \text{ !}$$

SUMMARY

CONCLUSION

- **b-parity (b_P):** counting b-jets as a simple and sensitive probe of new flavor physics in 3rd gen. quark sector

  look for a final state with an odd # of b-jets …

  - **process independent:** does not necessarily require the particular structure and identification of final state
  - **model independent:** b_P will "capture" ANY type of new flavor physics that generates 3rd -> 2nd & 3rd -> 1st gen transitions
  - **Relies on:**
    - Purity of the b-jets sample
    - negligible b-quark content in the initial state – problematic for LHC …

relatively "easy" method …

SUMMARY – CONCLUSION

- possible applications for future searches:
  - single jet events @ EIC
  - 2,4,6 jets events @ FCC-ee

- Expected sensitivity for such searches:

$$\Lambda_{eff}(95\%CL) > 30 \times E_{CM}(collider)\ !$$

Thank you!

Backups

Observability:

Luminosity → L, acceptance → A

define

- $N_k = L \cdot A \cdot \overline{\sigma_k}$ => # of events with k b-jets

uncertainties:

- statistical: $\Delta_{stat} = \sqrt{N_k}$
- systematic: $\Delta_{sys} = N_k \cdot \delta_s$
- theory: $\Delta_{the} = N_k \cdot \delta_t$

e.g.,

$A = 80\%$, $\delta_s = 2\%$, $\delta_t = 2\%$

$L = 100\, fb^{-1}$ (EIC) , $L = 2000\, fb^{-1}$ (FCC-ee)

- **Total uncertainty:** $\Delta = \sqrt{\Delta_{stat}^2 + \Delta_{sys}^2 + \Delta_{the}^2}$

then, significance of the signal (N_{SD} = # of SD):

$$\left| N_k - N_k^{(SM)} \right| > N_{SD} \cdot \Delta$$

“Proof”:

SM’s FC transitions (generation transitions) are due to charged current interactions ∝ off diagonal CKM’s:

$$V_{CKM} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \rightarrow (\lambda^2 \rightarrow 0) \rightarrow \begin{pmatrix} 1 & \lambda & 0 \\ \lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

In the limit $\lambda^2 \rightarrow 0$ ($V_{3j} = V_{j3} \rightarrow 0$, $j \neq 3$) 3rd gen. do not mix with others

⬇

Conservation of 3rd family fermion number

In addition:

Fast top decay + BR($t \rightarrow bW$) ~ 1

(# of t) = (# of b)

t "=" b for this purpose

The experimentally approximate conserved flavor number
is carried only by the b-quarks !

In the limit V_{3j} , $V_{j3} \rightarrow 0$ ($j \neq 3$) the SM acquires an additional global

$U(1)_b$ symmetry ("bottomness")

which holds to any order in perturbation theory

b-quarks are generated/produced only in even multiples in the SM

b-parity for collider experiments

The strategy:

define

- ϵ_b = b-tagging efficiency
- t_c = probability of mis-identifying a c-jet for a b-jet
- t_j = probability of mis-identifying a light-quark (or gluon) jet for a b-jet

recall: backg $\in$ $\epsilon_b < 1$ & $t_c\,, t_j \neq 0$ (impurity of the sample)

Let:

$$\sigma_{nml} = \sigma(e^+e^- \; or \;\; e + p/A \rightarrow n \cdot j_b + m \cdot j_c + l \cdot j_l + X)$$

FCC-ee. EIC

X = leptons, photons &/or missing energy …

Then, the probability (CSX) for detecting precisely k b-jets :

$$\overline{\sigma_k} = \sum_{u+v+w=k} P_n^u P_m^v P_l^w \left[\epsilon_b^u (1-\epsilon_b)^{n-u}\right]\left[t_c^v (1-t_c)^{m-v}\right]\left[t_j^w (1-t_j)^{l-w}\right] \cdot \sigma_{nml} \cdot \delta_{u+v+w,k}$$

$$P_j^i \equiv \frac{i!}{j!\,(i-j)!}$$

Bounds ...

Effective operator	Chirality (type)	Interactions
$Q_{\ell q}^{(3)}(1113) = (\bar{\ell}_1\gamma_\mu\tau^I\ell_1)(\bar{q}_1\gamma^\mu\tau^I q_3)$	$(\bar{L}L)(\bar{L}L)$ (vector)	$eetu$, $eebd$, $e\nu_e bu$
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$Q_{Hud}(13) = i(\tilde{H}^\dagger D_\mu H)(\bar{u}\gamma^\mu b) + \text{H.c.}$	$(\bar{R}R)$ (vector, fermion)	Wub
$Q_{Hq}^{(3)}(13) = i(H^\dagger i\overleftrightarrow{D}^I{}_\mu H)(\bar{q}_1\gamma^\mu\tau^I q_3)$	$(\bar{L}L)$ (vector, fermion)	Wub

Drell-Yan processes @ LHC:

$b\ u \to e\ \nu_e$ & $b\ d \to e\ e$ ⇒ Λ_{eff} >~ 3-7 TeV (depending on opt)

B decays:

$b \to u\ e\ \nu_e$ & $b \to d\ e\ e$ ⇒ Λ_{eff} >~ O(10 TeV)

Single top prod. @ LEP2:

$e\ e \to t\ u$ ⇒ Λ_{eff} >~ O(1 TeV)

tt prod. @ LHC followed by FC top decay:

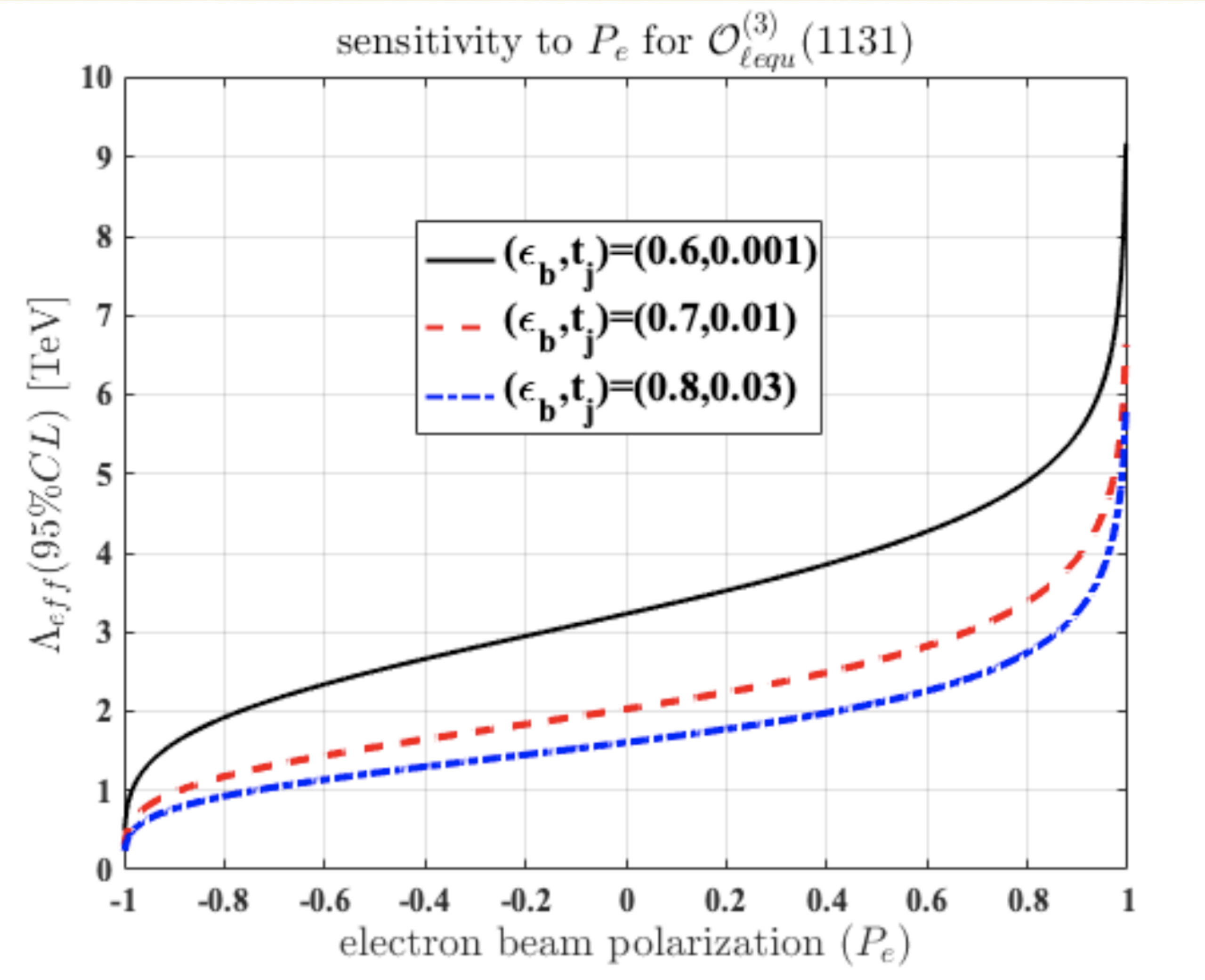
$p\ p \to t\ t\ ;\ \ t \to u\ e\ e$ ⇒ Λ_{eff} >~ O(1 TeV)

Sensitivity to other opt. @ EIC

TABLE III. The expected 95% CL bounds on the effective scale $\Lambda_{\mathsf{eff}} = \Lambda/\sqrt{\alpha}$ for the operators in Table I. Numbers are given for the three b-tagging efficiency setups: loose, medium, and tight and for unpolarized and +70% [$P_e = +0.7$, see Eq. (14)] polarized incoming electron beam. See also text.

	95% CL bounds on $\Lambda_{\mathsf{eff}}(Q)$ (TeV) with electron beam polarization $P_e = 0(+0.7)$		
Q	Tight setup $(\epsilon_b, t_j) = (0.6, 0.001)$	Medium setup $(\epsilon_b, t_j) = (0.7, 0.01)$	Loose setup $(\epsilon_b, t_j) = (0.8, 0.03)$
$Q^{(3)}_{\ell q}(1113)$	2.6 (2.4)	1.7 (1.6)	1.3 (1.3)
$Q^{(1)}_{\ell equ}(1131)$	1.0 (1.4)	0.6 (0.9)	0.5 (0.8)
$Q^{(3)}_{\ell equ}(1131)$	3.2 (4.6)	2.0 (3.1)	1.6 (2.5)
$Q^{(1)}_{\ell edq}(1131)$	1.0 (1.4)	0.6 (0.9)	0.5 (0.8)
$Q_{\mathrm{Hud}}(13)$	1.3 (1.2)	0.8 (0.7)	0.6 (0.6)
$Q^{(3)}_{\mathrm{Hq}}(13)$	2.3 (2.1)	1.5 (1.4)	1.2 (1.1)

Effect of pol. @ EIC



quite remarkable (although not realistic) that with P_e = 100% Λ_{eff}(95% CL) → 10 TeV

New flavor physics in top sector @ FCC-ee

TABLE III: The potential multi-jets signatures (final states) which result from the dim.6 FC 4-fermi effective operators of Table II, corresponding to the different final states $e^+e^- \to tj,\ tj+V$, where $V = \gamma, Z, W$.

	$t \to bW(\to jj)$	$t \to bW(\to \ell\nu)$
$e^+e^- \to tj$	$4j\ (1b)$	$2j+\ell+\not{E}_T\ (1b)$
$e^+e^- \to tj+\gamma$	$4j+\gamma\ (1b)$	$2j+\gamma+\ell+\not{E}_T\ (1b)$
$e^+e^- \to tj+Z(\to q\bar{q},\ q \neq b)$	$6j\ (1b)$	$4j+\ell+\not{E}_T\ (1b)$
$e^+e^- \to tj+Z(\to b\bar{b})$	$6j\ (3b)$	$4j+\ell+\not{E}_T\ (3b)$
$e^+e^- \to tj+Z(\to \ell^+\ell^-)$	$4j+2\ell\ (1b)$	$2j+3\ell+\not{E}_T\ (1b)$
$e^+e^- \to tj+Z(\to \nu\bar{\nu})$	$4j+\not{E}_T\ (1b)$	$2j+\ell+\not{E}_T\ (1b)$
$e^+e^- \to tj+W(\to q\bar{q}', q, q' \neq b)$	$6j\ (1b)$	$4j+\ell+\not{E}_T\ (1b)$
$e^+e^- \to tj+W(\to \ell^-\bar{\nu})$	$4j+\ell+\not{E}_T\ (1b)$	$2j+2\ell+\not{E}_T\ (1b)$

We will analyze below the effects of the operators $Q^{(1,3)}_{\ell equ}$, which contribute to all the channels considered in Table III...

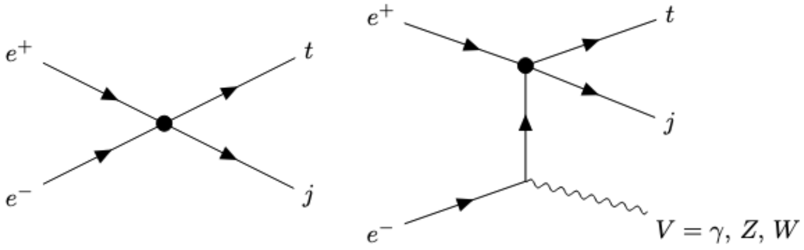


FIG. 1: Representative Feynman diagrams for $e^+e^- \to tj$ and $e^+e^- \to tj+V$, where $V = \gamma, Z$ or W.