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Novel method to indirectly reconstruct neutrinos in collider experiments

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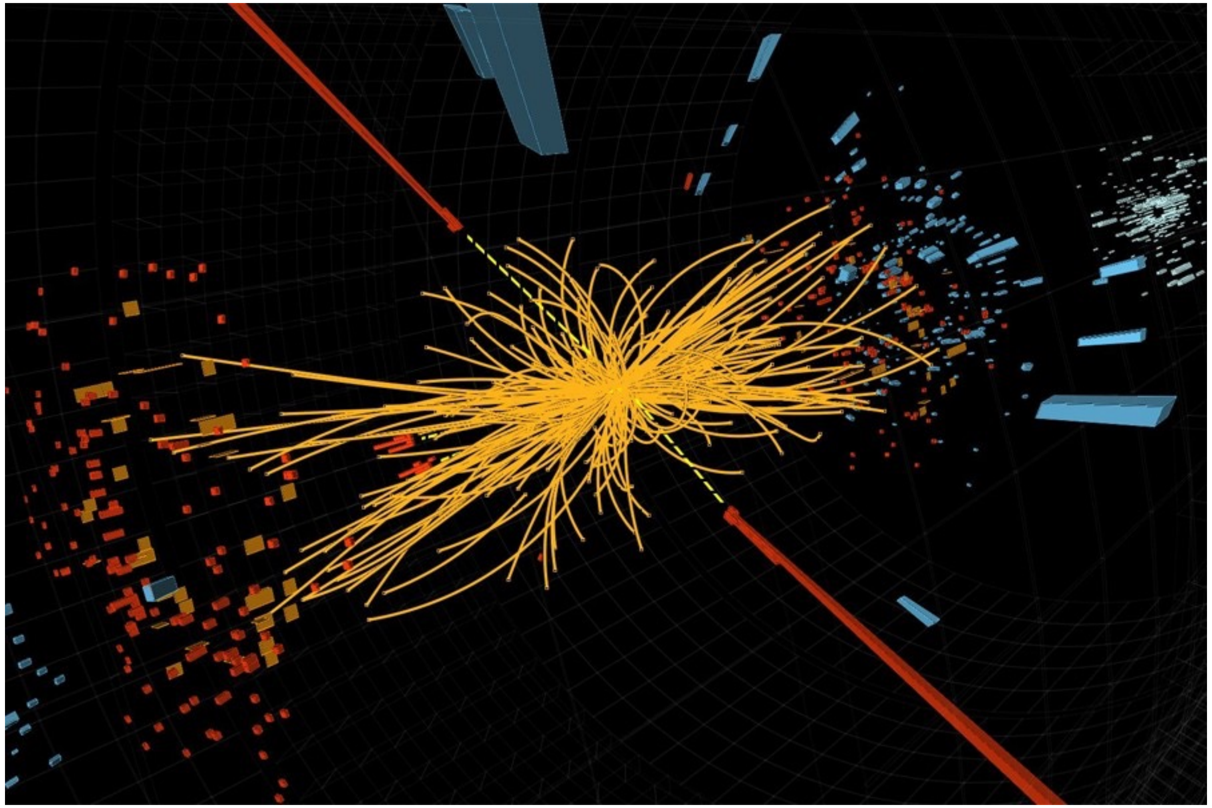
Primary goals of most collider experiments

- Improve the precision of measurements of Standard Model (SM) parameters.

- Search for new physics (NP) beyond SM.



(Semi-)leptonic decays

- Provide precision tests in the electroweak sector of SM
- Involve neutrinos, cannot be tracked up to now

Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs. LHCb	vs. Belle	Anomaly	NP
$B \to \pi \ell \nu_\ell$	$\lvert V_{ub}\rvert$	★★★	10–20	★★★	★★★	★★	★
$B \to X_u \ell \nu_\ell$	$\lvert V_{ub}\rvert$	★★	2–10	★★★	★★	★★★	★
$B \to \tau \nu$	Br	★★★	>50 (2)	★★★	★★★	★	★★★
$B \to \mu \nu$	Br	★★★	>50 (5)	★★★	★★★	★	★★★
$B \to D^{(*)} \ell \nu_\ell$	$\lvert V_{cb}\rvert$	★★★	1–10	★★★	★★	★★	★
$B \to X_c \ell \nu_\ell$	$\lvert V_{cb}\rvert$	★★★	1–5	★★★	★★	★★	★★
$B \to D^{(*)} \tau \nu_\tau$	$R(D^{(*)})$	★★★	5–10	★★	★★★	★★★	★★★
$B \to D^{(*)} \tau \nu_\tau$	P_τ	★★★	15–20	★★★	★★★	★★	★★★
$B \to D^{**} \ell \nu_\ell$	Br	★	—	★★	★★★	★★	—

"Reconstruct" neutrinos in collider experiments

- Only one neutrino ⟷ recoiling technique
- Two or more neutrinos ⟷ all traditional methods failed

Now we try to introduce an innovative inclusive-tagging scheme that can capture the four-momentum of an undetected particle, such as a neutrino, K_L^0 , etc.

Introduce innovative scheme

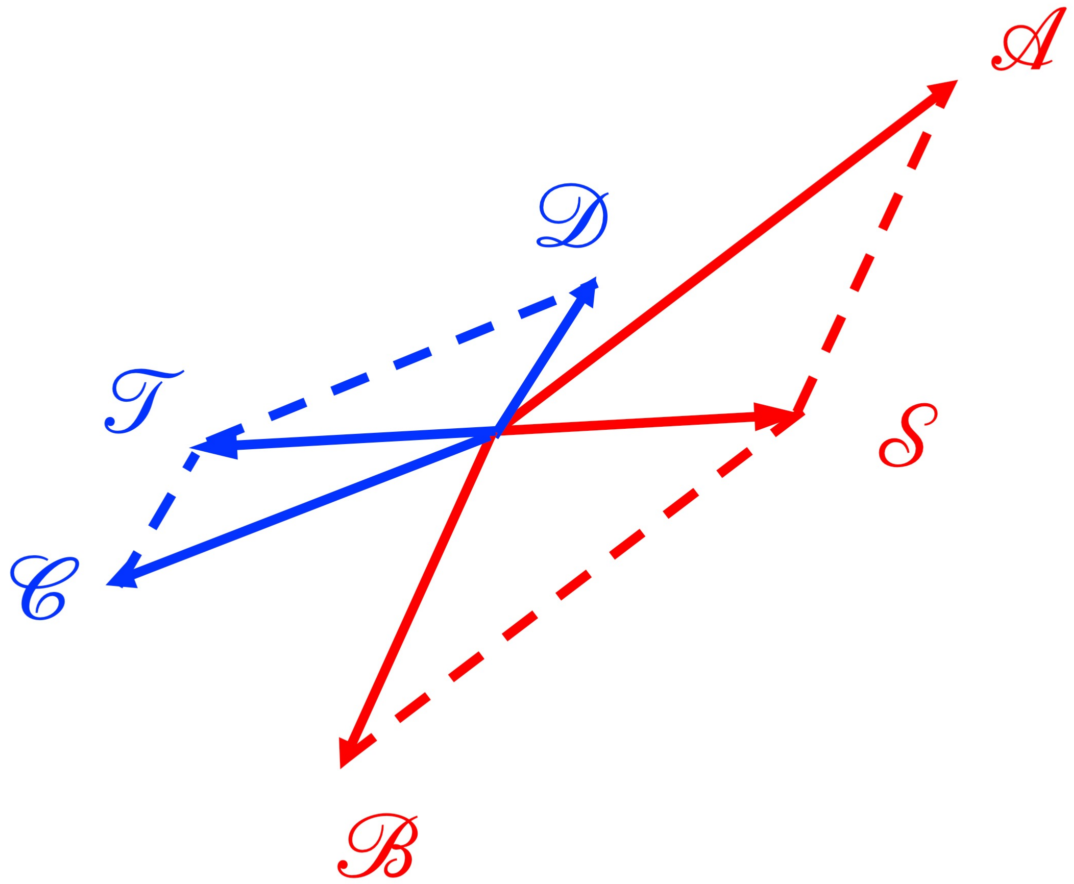
A candidate can be commonly classified as signal ($\mathcal{S}$) and tagged ($\mathcal{T}$) sides:

$\mathcal{S} \to \mathcal{A} + \mathcal{B}$ → neutrino

detected part

$\mathcal{T} \to \mathcal{C} + \mathcal{D}$ → Missing in tagged side

Rest of Event (ROE)



In the rest frame of the $\mathcal{S}\mathcal{T}$ system, it has always

$$\boldsymbol{p}(\mathcal{B}) + \boldsymbol{p}(\mathcal{D}) \equiv -[\boldsymbol{p}(\mathcal{A}) + \boldsymbol{p}(\mathcal{C})]$$

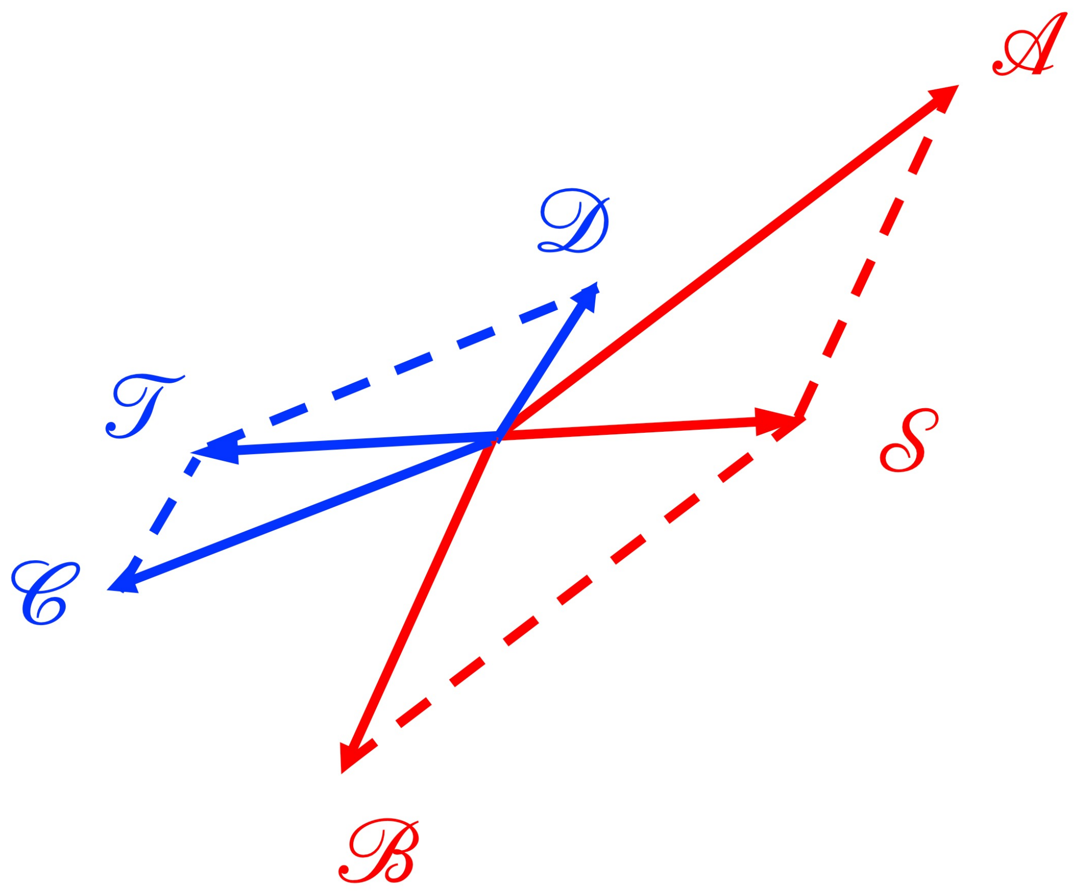
Construct asymptotically recursive vector sequences

$$\boldsymbol{p}(\mathcal{B})_0 = -\boldsymbol{p}(\mathcal{A}) - \boldsymbol{p}(\mathcal{C}) \ ,$$

$$\begin{aligned}
\boldsymbol{p}(\mathcal{B})_1 &= \frac{\boldsymbol{p}(\mathcal{B})_0 + \boldsymbol{p}(\mathcal{B})_0'}{2} \\
&= \frac{\boldsymbol{p}(\mathcal{B})_0 + [-\boldsymbol{p}(\mathcal{A}) - \boldsymbol{p}(\mathcal{C}) - \boldsymbol{p}(\mathcal{D})_0]}{2} \\
&= -\boldsymbol{p}(\mathcal{A}) - \boldsymbol{p}(\mathcal{C}) - \boldsymbol{p}(\mathcal{D}) + \boldsymbol{p}(\mathcal{D}) - \frac{1}{2}\boldsymbol{p}(\mathcal{D})_0 \\
&\simeq \boldsymbol{p}(\mathcal{B}) + \frac{1}{2}\boldsymbol{p}(\mathcal{D}) \ ,
\end{aligned}$$

$$\vdots$$

$$\begin{aligned}
\boldsymbol{p}(\mathcal{B})_k &= \frac{\boldsymbol{p}(\mathcal{B})_{k-1} + \boldsymbol{p}(\mathcal{B})_{k-1}'}{2} \\
&= \frac{\boldsymbol{p}(\mathcal{B})_{k-1} + [-\boldsymbol{p}(\mathcal{A}) - \boldsymbol{p}(\mathcal{C}) - \boldsymbol{p}(\mathcal{D})_{k-1}]}{2} \\
&\simeq \boldsymbol{p}(\mathcal{B}) + \frac{1}{2^k}\boldsymbol{p}(\mathcal{D}) \ ,
\end{aligned}$$

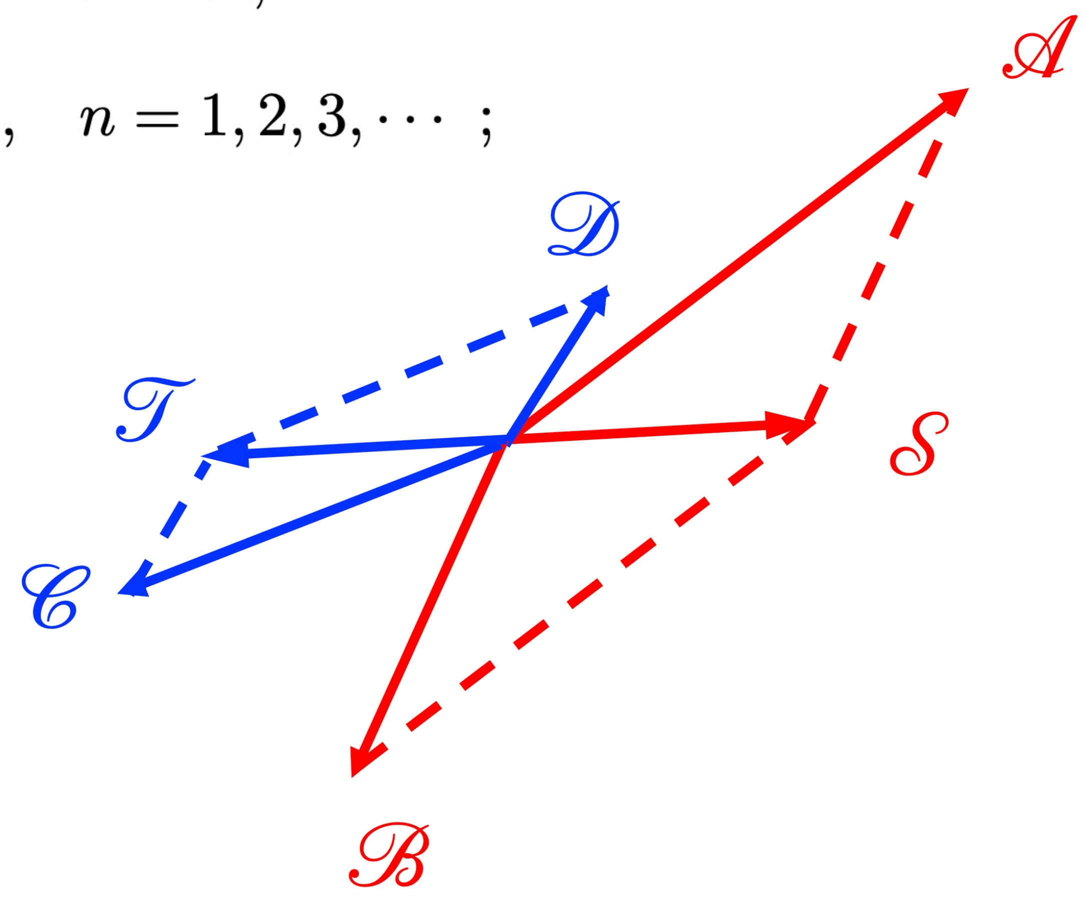


General term of the sequences

$$\boldsymbol{p}(\mathcal{B})_n = \begin{cases} -\boldsymbol{p}(\mathcal{A}) - \boldsymbol{p}(\mathcal{C}), & n = 0\ ; \\ \dfrac{\boldsymbol{p}(\mathcal{B})_{n-1} + \boldsymbol{p}(\mathcal{B})'_{n-1}}{2} \simeq \boldsymbol{p}(\mathcal{B}) + \dfrac{1}{2^n}\boldsymbol{p}(\mathcal{D}), & n = 1, 2, 3, \cdots\ ; \end{cases}$$

where $\boldsymbol{p}(\mathcal{B})'_{n-1} = -\boldsymbol{p}(\mathcal{A}) - \boldsymbol{p}(\mathcal{C}) - \boldsymbol{p}(\mathcal{D})_{n-1}$

$\boldsymbol{p}(\mathcal{D})_{n-1}$ can be parameterized below



The symbols without subscripts, $\boldsymbol{p}(\mathcal{B})$ and $\boldsymbol{p}(\mathcal{D})$, denote the corresponding truth values

Asymptotically vector sequences

As n becomes infinite,

$$\lim_{n\to\infty} \boldsymbol{p}(\mathcal{B})_n = \lim_{n\to\infty} \left[\boldsymbol{p}(\mathcal{B}) + \frac{1}{2^n}\boldsymbol{p}(\mathcal{D})\right] = \boldsymbol{p}(\mathcal{B})$$

That is, $\boldsymbol{p}(\mathcal{B})_n$ is asymptotic to the truth $\boldsymbol{p}(\mathcal{B})$. It is additionally noteworthy that $\boldsymbol{p}(\mathcal{D})$ of the missed particle(s) will be "eaten" by infinite iterations.

Initialization of $p(\mathcal{D})_k$

- For initialization when $k = 0$

Generate a radom $p(\mathcal{D})_0$ → **Constraint** $-p(\mathcal{C}) - p(\mathcal{D})_0$ to $\sqrt{E^2(S) - m^2(S)}$ → Constraint $m(\mathcal{B})_0$ to its mean mass

Thus,

$$\mathbf{p}(\mathcal{D})_0 = -\mathbf{p}(\mathcal{A}) - \mathbf{p}(\mathcal{C}) - \mathbf{p}(\mathcal{B})_0$$

Parameterization of $p(\mathcal{D})_k$

- For parameterization when $k = 1,2,3,\ldots$

$$\boldsymbol{p}(\mathcal{D})_k^{\mathrm{I}} = -\boldsymbol{p}(\mathcal{S})_{k-1}^{\mathrm{scale}} - \boldsymbol{p}(\mathcal{C}) \ ,$$
$$\boldsymbol{p}(\mathcal{D})_k^{\mathrm{II}} = -\boldsymbol{p}(\mathcal{A}) - \boldsymbol{p}(\mathcal{C}) - \boldsymbol{p}(\mathcal{B})_{k-1}^{\mathrm{I}}$$

Constraint the magnitude of $\boldsymbol{p}(\mathcal{A}) + \boldsymbol{p}(\mathcal{B})_{k-1}$ to $\sqrt{E^2(\mathcal{S}) - m^2(\mathcal{S})}$

$$\boldsymbol{p}(\mathcal{B})_{k-1} - \frac{1}{2^k}\boldsymbol{p}(\mathcal{D})_{k-1}^{\mathrm{I}}$$

Thus,

$$\boldsymbol{p}(\mathcal{D})_k = \frac{\boldsymbol{p}(\mathcal{D})_k^{\mathrm{I}} + \boldsymbol{p}(\mathcal{D})_k^{\mathrm{II}}}{2}$$

Parameterization's validation and other remarks

$$\begin{aligned}
\lim_{k\to\infty} \boldsymbol{p}(\mathcal{D})_k^{\mathrm{II}} &= -\boldsymbol{p}(\mathcal{A}) - \boldsymbol{p}(\mathcal{C}) - \lim_{k\to\infty} \boldsymbol{p}(\mathcal{B})_{k-1}^{\mathrm{I}} \\
&= -\boldsymbol{p}(\mathcal{A}) - \boldsymbol{p}(\mathcal{C}) - \lim_{k\to\infty} \left[\boldsymbol{p}(\mathcal{B}) + \frac{1}{2^{k-1}}\boldsymbol{p}(\mathcal{D}) - \frac{1}{2^k}\boldsymbol{p}(\mathcal{D})_{k-1}^{\mathrm{I}}\right] \\
&= -\boldsymbol{p}(\mathcal{A}) - \boldsymbol{p}(\mathcal{C}) - \boldsymbol{p}(\mathcal{B}) + \lim_{k\to\infty} \left[\frac{1}{2^{k-1}}\left(\boldsymbol{p}(\mathcal{D}) - \frac{1}{2}\boldsymbol{p}(\mathcal{D})_{k-1}^{\mathrm{I}}\right)\right] \\
&= \boldsymbol{p}(\mathcal{D}) \; .
\end{aligned}$$

As for iteration times, $k = 15$ is generally enough as $1/2^{15} = 1/32768 < 0.01\%$.

It should be noted that other approaches for initializing/parameterizing $\boldsymbol{p}(\mathcal{D})_k$ that satisfy users' requirements and have no bias peaks are also desirable.

Test in pseudo-experiment data

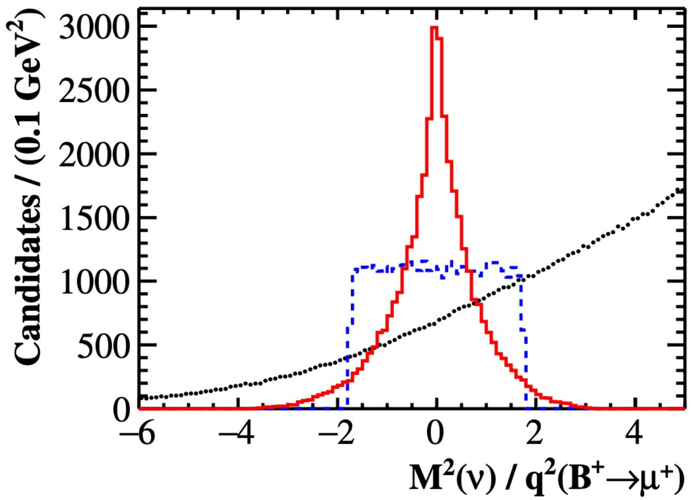
- $\Upsilon(4S) \to B^+B^- \to \mu^+\nu_\mu + X$, in the c.m. frame, available for Belle2
- $B^0 \to \tau^+\tau^- \to \pi^+\pi^-\pi^+\bar{\nu}_\tau + X$, in the b-hadron rest frame, available for Belle2 and LHCb
- $e^+e^- \to \Lambda_c^+\Lambda_c^- \to \Lambda e^+\nu_e + X$, in the c.m. frame, available for Belle2 and BESIII

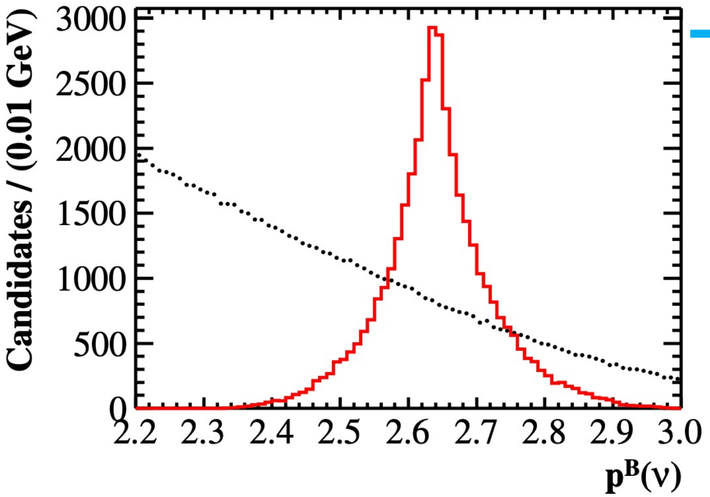
TGenPhaseSpace Class Reference

The resolutions are also considered.

Test in pseudo-experiment data

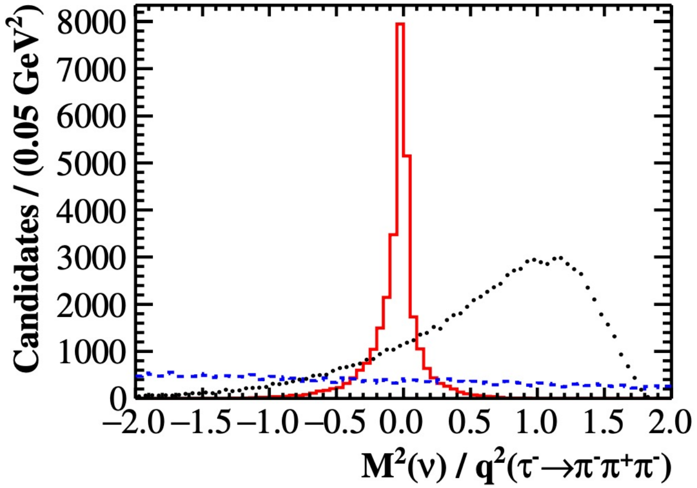
$B^+ \to \mu^+ \nu_\mu$



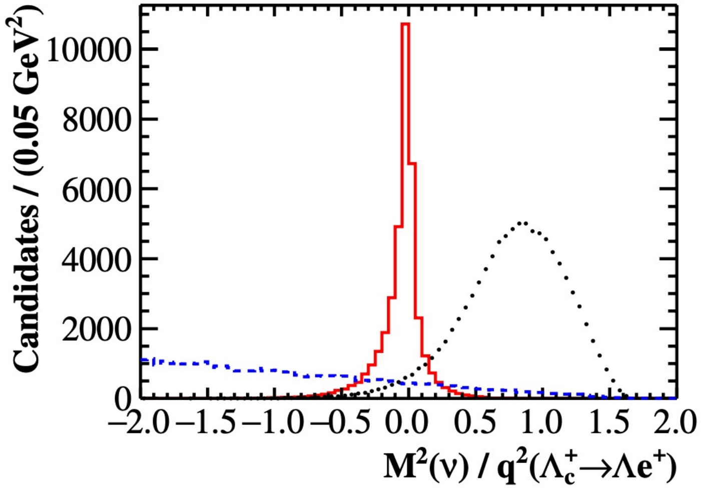


Fit result: 2.6391±0.0004 GeV, consistent well with the calculated value of 2.639 GeV

$\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$



$\Lambda_c^+ \to \Lambda e^+ \nu_e$



Red line: this scheme

Blue line: traditional method

Dotted: background

Summary and prospect

We innovatively proposed an inclusive-tagging scheme that can obtain the four-momentum of an undetected long-lived particle (ν, K_L^0, neutron, etc.) in collider experiments (Belle- II, BESIII, LHCb, and other potential experiments).

This novel scheme can be expected to be further confirmed, applied, and developed by future experiments.

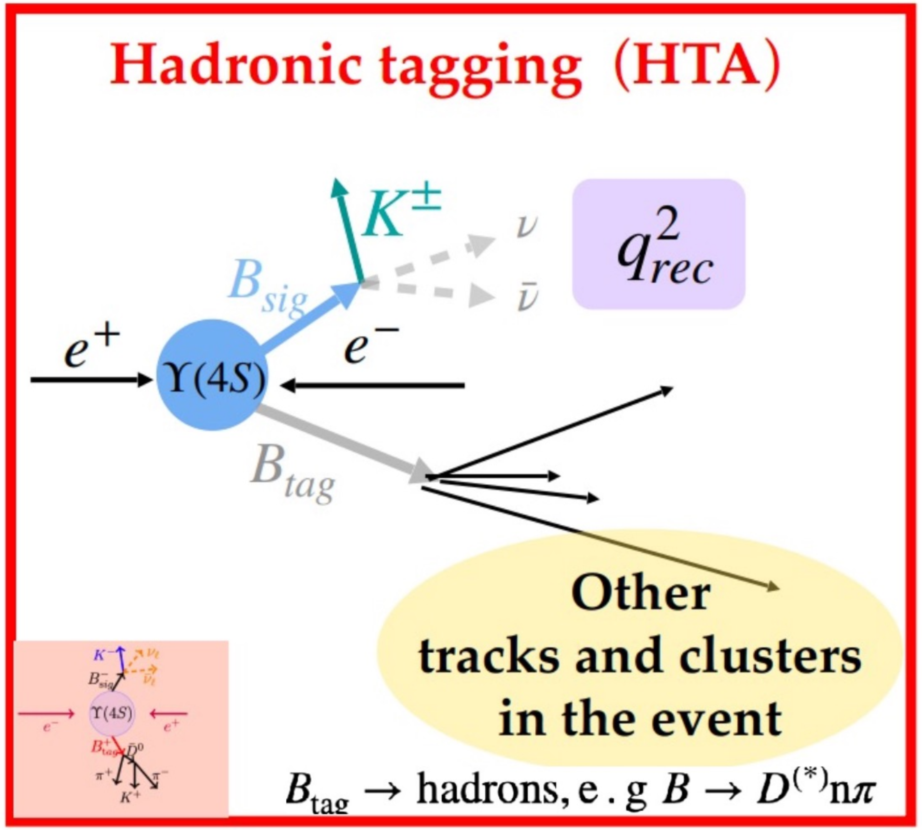
The asymptotically recursive (vector) sequences from this scheme might be taken as one of the filters in machine learning so that some missed/unknown information will be "eaten" by infinite iterations. [Long-term plan]

Thank you for your attention!

Back up

Hadronic tagging vs inclusive tagging

From Jiasen's report yesterday



Efficiency

q^2_{rec} : mass squared of the neutrino pair

Purity, Resolution